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Edmundson, I.[1], Davies, R.[2], Frette, L.U.[3], Mackie, S.[2], Kavli, E.A.[4], Rotevatn, A.[1], Yielding, G.[5], Dunbar, A.[2]

[1] Department of Earth Science, University of Bergen, Allégaten 41, 5007 Bergen, Norway
[2] DEA Norge AS, Jåttåflaten 27, 4007 Stavanger, Norway
[3] Capricorn Energy, Jåttåvågveien 7, 4020 Stavanger, Norway
[4] IFP School, 232 Avenue Napoléon Bonaparte, 92852 Rueil-Malmaison, France
[5] Badley Geoscience Ltd, North Beck House, North Beck Lane, Hundleby, Spilsby Lincolnshire, PE23 5NB, UK

isabel.edmundson@uib.no, roy.davies@wintershalldea.com, lars.ulsund.frette@gmail.com, sean.mackie@wintershalldea.com, emilieak@online.no, atle.rotevatn@uib.no, graham@badleys.co.uk, alex.b.dunbar@gmail.com

This manuscript is a preprint and will be submitted to **AAPG Bulletin**. This manuscript has not undergone peer-review. Subsequent versions of this manuscript may have different content. If accepted, the final version of this manuscript will be available via the '*Peer-reviewed Publication DOI*' link on the right-hand side of this webpage. Please feel free to contact Isabel directly or to comment on the manuscript using **hypothes.is** (https://web.hypothes.is/). We welcome feedback!

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isabel.edmundson@uib.no, roy.davies@wintershalldea.com, lars.ulsund.frette@gmail.com, sean.mackie@wintershalldea.com, emilieak@online.no, atle.rotevatn@uib.no, graham@badleys.co.uk, alex.b.dunbar@gmail.com

Acknowledgements

We wish to thank DEA Norge AS for fully funding the PhD project related to this publication and for providing access to their regional seismic and well databases. In addition, we wish to thank Bernhardt Ujetz, Markus Mohr, Matthias Riede, Olaf Kuchel and Bastian Wirth at DEA AG and Graeme Keith from Decision Risk Analytics for inspirational discussions on the empirical dataset and the forward probability approach used in this study. Schlumberger are acknowledged for providing academic Petrel® licenses to the University of Bergen for seismic interpretation, as are ESRI for provision of ArcMap® licenses used to produce maps for this publication.

Abstract

Estimating pre-drill volumes in hydrocarbon exploration involves dealing with geological and technical uncertainties. The prediction of the hydrocarbon column height is widely recognized as the primary driver of uncertainty in volumetric estimates. The oil and gas industry continues to renew efforts to limit such uncertainties because of the potential economic costs of inaccurate estimation, yet estimation of pre-drill volumes remains an in-exact science. This study introduces new empirical data from the Norwegian Continental Shelf, and aims to improve accuracy in hydrocarbon column height prediction. We use column height, trap height and burial depth data to calculate the degree of hydrocarbon trap fill for each of the 242 studied discovery wells. The data is aggregated into a simple forward probability model to calculate the probability of encountering different ranges of trap-fill, based on burial depth and trap height. The distribution of trap-fill ratios clearly correlates with both trap height and burial depth, thus indicating that the same pre-drill column height distribution should not be used for all prospects. These findings strongly suggest that the prospect's dimensions and burial depth are used alongside other technical subsurface factors to determine the most suitable pre-drill hydrocarbon column height distribution. This method contributes to reducing the largest source of uncertainty, which in turn reduces the overall uncertainty associated with pre-drill volume estimation. Such an approach will increase the accuracy of pre-drill volume estimation, leading to more appropriate future development plans. We recommend

that the presented methods and lessons learnt are applied in basins settings worldwide.

1. Introduction

Estimating pre-drill volumes is an essential part of the exploration process that determines if a prospect contains a large enough volume of hydrocarbons to justify drilling an exploration or appraisal well. Yet, despite its importance and an overall improvement in available technology, the industry continues to be poor at estimating pre-drill hydrocarbon volumes (Milkov, 2017). This is largely the result of uncertainty associated with each of the ten main inputs required to calculate potential hydrocarbon volumes (Table 1). Combining these inputs further compounds the level of uncertainty resulting in errors, which can lead to surprises and often disappointment once volumes are reassessed after drilling (Garb, 1988; Skaar et al., 2000; Demirmen, 2007). Of all of the inputs, the hydrocarbon column height uncertainty generally has the largest impact on the calculated pre-drill volume range (Fig. 1). Despite this, efforts to constrain the column height are commonly bypassed in favor of work that focuses on other inputs required to calculate pre-drill volumes that carry far less uncertainty. Instead, we argue that constraining the hydrocarbon column distribution should be prioritized for the benefit of reducing the overall uncertainty of reserve estimation (Floris and Peersmann, 1998).

Hydrocarbon column heights have perhaps remained as one of the key uncertainties in reserve calculations because of the difficulty in obtaining accurate empirical data. Unlike some of the other input parameters such as porosity, the column height cannot be calculated directly from well logs alone. Instead, three measurements are required: the depth of the hydrocarbon-water contact (fluid contact), the structural apex and the spill point (Fig. 2). The fluid contact can be estimated using well logs and pressure data, however, calculation of the apex and spill point depths requires a reliable top reservoir depth map, since the majority of exploration wells tend to be drilled in down-flank positions. In turn, this requires access to 3D seismic data and a velocity model for depth conversion. This data- and time-intensive approach may explain why few studies of this kind have been carried out before.

A number of previous empirical reviews have measured hydrocarbon columns in areas such as the Norwegian Continental Shelf (NCS), Malay Basin and Gulf of Mexico, and all conclude that the observed column heights follow a lognormal distribution (Fosvold et al., 2000; Niemann, 2000; Tanjung, 2014). This result is largely representative of the type of distribution (Fig. 3A) that is widely used in oil and gas exploration as a default for pre-drill volume estimation, regardless of the size of the trap height or burial depth of the prospect. Two other types of commonly used distributions are the normal distribution (Fig. 3B) and uniform distribution (Fig. 3C). Deciding which distribution best describes the column height uncertainty has a significant impact on the pre-drill volume range of a hydrocarbon prospect, and will often determine whether an exploration well is drilled or not.

Using the geometry of a prospect to determine the pre-drill column height distribution has only been incorporated into a handful of published studies. Graham et al. (2015) concluded that integration of the trap height, genetic history and geological setting of the prospect is likely to result in the most appropriate column height distribution. Additional contributions by Schlömer and Krooss (1997) state the influence of area-to-relief ratio on the potential discoverable hydrocarbon column. There is scope therefore to introduce a new approach that directly links the pre-drill column height distribution to the prospect's geometry, specifically the trap height and burial depth / overburden thickness.

This piece of work is primarily concerned with presentation of the empirical data collected across the NCS, as well as identifying trends and correlation between subsets of the data. The 242 measured discoveries are located in a number of basins spanning the Barents Sea, Norwegian Sea and Northern North Sea, and as such, mix a range of different structural and stratigraphic settings. To explore the possible underlying causes of the identified trends presented herein, the data would have to be sub-divided allowing like-for-like basins to be compared. Subsequent technical assessment of subsurface data covering each of the basins would require additional time and methods, a process that demands its own study. It should also be noted that the 242 data points analyzed for this study correspond to discovery cases only. This study is primarily concerned with reducing the uncertainty in prediction of hydrocarbon columns in success-case scenarios, therefore dry wells and causes of failure fall outside the scope of work.

This study has three main aims. Firstly, to collect and present a large empirical dataset of measured hydrocarbon column heights, associated trap heights, burial depths, and trap-fill ratios for 242 discoveries across the NCS. Secondly, to identify trends between the measured variables, and to analyze the role of trap-height and burial depth on observed hydrocarbon column heights. Thirdly, to use the results of such analysis to challenge common assumptions regarding column height probability distributions.

2. Study area and methodology

The oil and gas discoveries used in this study are distributed across the NCS in three different regions: the Barents Sea, the Norwegian Sea and the Northern North Sea above 61°N (Fig. 4). Of the 242 discoveries, 123 are located in the Norwegian Sea, 81 in the Northern North Sea and 38 in the Barents Sea. The fields and associated structural elements that have been measured as part of the study are summarized in Table 2.

The NCS was selected for several reasons. Firstly, it is a good area to study the relationship between trap geometry and hydrocarbon column heights because the majority of the basins in the study areas have received plentiful hydrocarbon charge, so charge limitation is not a significant issue (Doré and Jensen, 1996; Ostanin et al., 2012; Hermanrud et al., 2014). For this reason, it is assumed that the observed variations in column heights and trap-fill ratios are primarily a result of seal behaviour and not because of a lack of charge (Hermanrud and Bols, 2002; Bolås and Hermanrud, 2003; Halland et al., 2013). Secondly, the Norwegian Petroleum Directorate (NPD) provides a large repository of well data, of which many details become public two years after drilling and fully public after 20 years. Access to such well-organized data is particularly helpful when ascertaining the fluid contact depth, which can be directly taken from descriptions in the well reports or from pressure data. Thirdly, the publically available seismic data covering the three regions has been widely interpreted and a large number of good quality, top reservoir maps were made available for this study. Maps were taken either from previous prospect analyses or from regional maps, which were subsequently reinterpreted in more detail where required.

Since the vast majority of the available seismic datasets are in the time domain, a regional velocity cube was used to depth convert the top reservoir time (TWT) maps into depth. Top reservoir depth maps were crosschecked against well tops to assess if any depth shift was required. Access to such maps and well data ensures that the relevant data required to calculate the column height, trap height and burial depth is widely available across most of the NCS. However, the assimilation and quality control of the data, which is necessary to measure the apex and spill point depths, is more time consuming. Figure 5 shows an example of such data collection for discovery wellbore 7121/7-1, which is part of the Snøhvit field in the southwestern Barents Sea (Linjordet and Olsen, 1992). The top reservoir surface was mapped in two-way-time, depth-converted and checked against the depth of the top reservoir in the well. The fluid contact was taken from the publically available NPD fact pages and crosschecked against observations and pressure measurements contained within the final well report. The trap-fill ratio was then calculated based on what proportion of the trap height was occupied by the hydrocarbon column (trap-fill ratio = hydrocarbon column height / trap height).

As with all subsurface interpretation, and in particular depth conversion, we acknowledge that there will be inaccuracies associated with the apex and spill point depths for individual discoveries (Etris et al., 2001; Pon and Lines, 2005). However, such inaccuracies are minimized in this study through local reinterpretation of regional surfaces to increase topographic detail over the structures, as well as tying the depth surfaces to the relevant well-tops after depth conversion. Consequently, confidence in the collection methods and resulting dataset is good.

3. Results

The empirical data collected in this study is presented in a series of graphs that show the range and distribution of measured variables, which includes the trap height, burial depth, column height and trap-fill ratio for each discovery. Cross plots are useful to identify potential correlations between particular variables and therefore demonstrate possible controls on the observed hydrocarbon column heights. In addition, trap-fill ratios calculated for each measured discovery are displayed as proportionally sized data points on regional geological maps.

3.1 Cross plots

Figure 6A is a cross plot of hydrocarbon column height and trap height for all 242 data points with bordering histograms showing the distribution of data for each variable. The density of data points decreases and becomes more sparsely distributed as the trap height begins to exceed 400m and when column heights begin to exceed 300m, which is shown by a broadening of the 95% confidence interval of the regression line, indicated by the shading. The R-value (the correlation coefficient between the two-plotted variables) of 0.86 indicates that there is a strong positive correlation between trap height and hydrocarbon column height. The linear dashed line on Figure 6A represents the one-to-one relationship between trap height and column height. All points that fall on this line have a trap-fill of 100%, and the structures are considered to be “filled-to-spill”. Figure 6B is a cross plot of the hydrocarbon column height and burial depth / overburden thickness. Burial depth values are distributed centrally with the density of data points decreasing towards very low and very high values. The number of hydrocarbon columns recorded in structures with burial depths exceeding 4000m is limited, which is shown by the broadening of the 95% confidence interval either side of the regression line. The R-value of 0.31 shows there is a moderate positive correlation between burial depth and hydrocarbon column height.

Figure 7 displays three trap height versus hydrocarbon column height cross plots (Figs. 7A-C) and three burial depth versus hydrocarbon column height cross plots (Figs. 7D-F) for each of the three regions covered by this study. All three regions show a strong positive correlation between hydrocarbon column height and trap height with the corresponding R-values varying between 0.76 (Barents Sea) and 0.88 (Norwegian Sea). Note the difference in measured trap heights across the three regions. In the Northern North Sea and Norwegian Sea they reach up to 700m, whereas the maximum trap height observed in the Barents Sea is just over 400m. Figures 7D-F show a weak to moderate positive correlation between burial depth and column height. The Northern North Sea has the lowest R-value of 0.16 and the Barents Sea has the highest at 0.47. Again, note the difference in the range of burial depths across the three regions. Hydrocarbon columns measured in the Northern North Sea and Norwegian Sea are buried between 1000 and 5000m. However, in the Barents Sea the discoveries are buried at shallower depths, between 200 and 3000m. The maximum hydrocarbon column observed in the Northern North Sea is 452m (well 34/8-7), 680m in the Norwegian Sea (Åsgard discovery) and 296m in the Barents Sea (Iskrystall discovery).

3.2 Spatial distribution of trap-fill

Trap-fill ratio, a measure of how much of the trap height is occupied by the hydrocarbon column, is represented in three maps in Figure 8. Each colored, proportionally sized circle represents the trap-fill ratio for each discovery. The Barents Sea (Fig. 8A) contains a broad range of trap-fill ranges, particularly in the Hammerfest Basin, which contains discoveries with all ranges of trap-fill. 100% trap-fill is most prevalent at the basin margins. The other major cluster of discoveries is located on the Polhem Sub-platform, where the measured structures range from 50 to 100% filled. Figure 8B shows the distribution of observed trap-fill ratios in the Norwegian Sea. There is a dense clustering of data points along the axis of the Revfallet Fault Complex, which borders the Halten and Donna Terrace. The majority of the discoveries have a trap-fill ratio of 75% or more, with a few interspersed discoveries with lower levels of trap-fill. The cluster of points on the Nyk High, close to the Aasta Hansteen field, shows that most discoveries in this area tend to be 100% filled. Figure 8C shows the trap-fill distribution across the Northern North Sea. Similar to the Norwegian Sea, the majority of discoveries are filled-to-spill, however, they are more widely distributed and tend to be located more closely to discoveries with lower trap-fill ratios of between 50 and 75%, for example on the Lomre Terrace and Tampen Spur.

4. Data analysis

The empirical dataset was evaluated using a forward probability model, otherwise known as a forward probability-tree, which required each input variable (trap height and burial depth) and output variable (trap-fill ratio) to be categorized into a series of discrete bins. A 3x3 probability distribution matrix is then populated by the forward probabilities calculated in the probability tree to assess how the trap fill ratio varies with trap height and burial depth. A more detailed explanation of this workflow is described below.

4.1 Forward probability model

A forward probability or ‘decision tree’ approach is a useful tool to assess what influence (if any) the trap height and burial depth have on the trap-fill ratio, and to see if the relationship between them can be used in a predictive manner. The method was chosen to display the distribution of trap-fill ratios for different ranges of trap height and burial depth. The number of bins that define the output variable, in this case, the trap-fill ratio, defines the first set of branches in the forward probability tree (Fig. 9). The number of bins associated with each input variable, i.e. the trap height and burial depth, determine the number of branches that define the second and third decision levels. The total number of branches is equal to the product of the number of bins for each input and output variable, multiplied together. Once the tree has been populated, the probability for each calculated outcome is normalized against other outcomes that share similar trap height and burial depth values. This normalization step is necessary to calculate the probability of finding a given trap-fill ratio for each combination of trap height and burial depth values.

4.2 Binning the data

A number of methods can be used to calculate a suitable number of bins for a given dataset (Miller, 1989; Wand, 1997). One of the simplest approaches is to set the number of bins equal to the square root of the total number of values in the dataset, otherwise known as the square-root choice method. This gives approximately 15 bins of equal width for each variable, as illustrated in Figures 10A-C. However, using 15 bins for each of the three variables in a probability tree would result in 3375 probabilities (15x15x15), which far exceeds the actual size of the dataset (242). For the purpose of this study, it is necessary to cap the number of bins to avoid such a large number of probabilities. Each variable is therefore divided into just five bins of equal width as shown in Figures 10D-F. This has the desired result of reducing the number of possible outcomes to 125 (5x5x5). However, because of the irregular distribution of values across each variable, some bins contain very few or no values at all. This becomes problematic when calculating probabilities for certain combinations of trap-fill, burial depth and trap height, with too many zero probabilities being returned. To avoid this issue, bins of variable width must be used in order to allow the number of values to be more evenly redistributed across each bin (Figs 10G-I) (Miller, 1989).

Burial depth was divided into three bins: 0-1500m, 1501-3000m and >3000m (Fig 10G), and the trap height was also divided into three bins: 0-150m, 151-300m and >300m (Fig. 10H). The trap-fill ratio was divided into four bins corresponding to 0-50%, 51-75%, 75-99% and 100% trap-fill (Fig. 10I). 100% trap fill is assigned its own bin since nearly half of the measured discoveries (111/242) recorded this level of trap-fill (Fig. 9). Relatively few discoveries had trap-fill values of 50% or lower (31/242), so this category was not further subdivided. The total number of bins gives a workable number of 36 possible outcomes (4x3x3), with only two out of the 36 outcomes having a zero probability. These two zero probability outcomes are both caused by a lack of discoveries where the trap-fill exceeds 75% in structures with trap heights above 300m and burial depths of less than 1500m (Fig. 9).

4.3 Probability distribution matrix

The 3x3-output matrix (Fig. 11) shows how the normalized trap-fill probabilities, calculated in the forward-probability tree, vary across different trap height and burial depth ranges. The observed distribution of trap-fill probabilities does not follow the same pattern for each burial depth and trap height combination and as such, there is not one type of distribution that describes all nine input scenarios. The bullet points below describe the other key observations:

- When the trap height is 150m or less (at all burial depths), the probability of 0-99% trap-fill is consistently low, whereas the probability of 100% trap-fill is very high.

Furthermore, the probability of recording 100% trap-fill is approximately twice as likely as recording a trap-fill ratio between 0 and 99%.

- For trap heights between 151 and 300m, the distribution of trap-fill ratio is less consistent at different burial depths. When the burial depth is 1500m or less, the most likely trap-fill range is between 51 and 75% and the least likely trap-fill is 100%. However, when the burial depth exceeds 1500m, this pattern is reversed and 100% trap-fill becomes the most likely outcome, whilst 0-50% trap-fill becomes the least likely.
- For trap heights exceeding 300m with a burial depth of less than 1500m, 0-50% trap-fill is most likely and there are no discoveries with a trap-fill ratio above 75%. Discoveries with trap heights exceeding 300m at depths of 1501-3000m are most likely to have a trap-fill ratio of 51-75% and least likely to have 100% trap-fill. However, when the burial depth exceeds 3000m, 100% becomes the most likely trap-fill ratio and 0-50% the least likely.

To summarize, two main trends are observed. Firstly, as the trap height increases for a given burial depth, the probability of 100% trap-fill progressively decreases and the probability of 0-50% trap-fill progressively increases. Secondly, as the burial depth increases for a given trap height, the probability of 100% trap-fill increases, whilst the probability of 0-50% trap-fill decreases. These reversals in trap-fill ratio distributions are evident across all trap height categories for a given burial depth and for all burial depths for a given trap height.

5. Discussion

5.1 Determining pre-drill hydrocarbon column height distributions

Across all three regions of the NCS, there is a strong positive correlation between the hydrocarbon column height and trap height. Although it may seem obvious, it is important to recognize that trap height exerts a significant control on the hydrocarbon column when estimating pre-drill column heights. Geometrically, a high-relief structure is more likely to be able to hold a taller hydrocarbon column than a low-relief structure. However, a high-relief structure at shallow depths is significantly less likely to be filled-to-spill than those at greater depths (Fig. 11). A weaker positive correlation exists between the column height and burial depth suggesting that the burial depth exerts some control on column heights, but that the relationship between these variables is more complicated. The correlation between column height and burial depth appears to be strongest in shallower discoveries, as shown by the relatively high correlation coefficient for the Barents Sea (Fig. 7).

The 3x3 matrix (Fig. 11) clearly shows that the observed distribution of trap-fill ratios does not stay constant for all combinations of trap height and burial depth. In order to reflect this in the pre-drill volume estimation, the burial depth and height of a prospect should be taken into consideration when selecting the type of probability distribution to use for the hydrocarbon column height. The observed trap-fill ratios for discoveries in trap heights of 150m or less at all burial depths suggest that a strongly negatively skewed distribution is most appropriate for prospects in low-relief structures. A negatively skewed distribution remains applicable when the trap height increases to between 151 and 300m at burial depths of 1500m or more. However, for intermediate trap heights at depths of less than 1500m and for trap heights exceeding 300m with less than 3000m of burial depth, the probability distribution curve should be positively skewed in order to reflect the higher probability of a lower trap-fill ratio.

These observations challenge the widely accepted view that the hydrocarbon column should always follow a log normal distribution (Fosvold et al., 2000; Niemann, 2000; Demirmen, 2007). Integration of this approach with other existing methods for column height prediction (e.g. fault seal analysis and buoyancy pressure calculations) should lead to improved estimation of pre-drill hydrocarbon volumes by reducing the prevalence of under- and over-estimation of the hydrocarbon column height in prospect analysis.

5.2 The benefits of using integrative methods

It has been acknowledged that when exploration and production companies integrate a variety of probabilistic methods into their workflows and include base-rate figures, their competitive position tends to improve (Jonkman et al., 2000; Skarr et al., 2002; Milkov, 2017). Adopting this approach when determining appropriate hydrocarbon column distributions is particularly important since it has been widely acknowledged as being the most significant contributor to uncertainty in pre-drill volume prediction. For this reason, acquisition and assessment of hydrocarbon column data will have the largest impact on reducing the overall uncertainty (Floris and Peersmann, 1998; Demirmen, 2007). However, this approach should not replace the need for detailed prospect and trap specific analysis (Graham et al., 2015). Thorough analysis of the structural and stratigraphic components of a prospect is always recommended for meaningful risking and decisions that are taken during drill or drop, or appraisal assessments. Best practice lies in integrating the probability- and geological-based approaches to create a multi-disciplinary workflow for improved assessment of hydrocarbon column uncertainty, and thus improved pre-drill volume prediction.

5.3 Universal implications

The data used in this study is collected from a range of basins located on the NCS. Nevertheless, we recommend that the trends and lessons learnt in this study be applied to basins and prospects that lie outside the NCS. The hydrocarbon column height distribution will always remain an uncertainty when calculating pre-drill volumes, regardless of where the prospect is located. This approach also has the wider benefit of improving the efficiency of the exploration and production of hydrocarbons, which will ultimately help to drive down costs. Improved placement of wildcat, appraisal and development wells will lead to a reduction in the number of redundant wells, helping to reduce emissions that are emitted during the drilling process. This in turn will reduce the negative impact of drilling on the environment, which is timely given the oil and gas industry is increasingly seeking ways to improve its environmental image.

5.4 Future work

This study strongly suggests that burial depth and trap height is used to guide trap-fill and hydrocarbon column height prediction. However, the observed patterns could be strengthened or challenged when more values are added to the dataset. A lack of values, for example in discoveries with trap heights above 300m in burial depths of less than 1500m, may weaken the strength of the observed pattern, but may also be indicative of the type of trap geometries that are encountered at different depths in the subsurface. The same approach should be extended further south on the NCS and into the UK Continental Shelf (UKCS). Where possible, it is recommended that additional data are collected further afield, for example from the Gulf Coast, to investigate if different basins settings influence trap fill distributions across variable trap heights and burial depths. Addition of more data points to the dataset will increase the statistical significance of the results and further improve its power as a tool for guiding pre-drill column height predictions.

6. Summary and conclusions

This study presents an empirical dataset across the NCS that includes measurements of the trap height, burial depth, hydrocarbon column and trap-fill ratio of 242 fields and discoveries. To the best of the authors' knowledge, this is the first study of its kind. The key findings from this work are summarized below:

- Simple statistical analysis of the dataset reveals a strong correlation between trap height and hydrocarbon column height, and a weaker correlation between burial depth and hydrocarbon column height.
- A forward probability approach was used to calculate the probability of a given trap-fill ratio for different combinations of trap height and burial depth ranges. The results are visualized in a 3x3 matrix, which can be used to demonstrate the distribution of trap-fill ratios in discoveries with similar trap heights and burial depths.
- The distribution of trap-fill ratios does not stay constant across all trap height and burial depth ranges. When the trap height starts to increase, for a given burial depth, the probability of 100% trap-fill diminishes and the probability 0-50% trap-fill increases. Similarly, as the burial depth increases for any given trap height, the probability of 100% trap-fill increases whilst the probability of 0-50% trap-fill decreases.
- Pre-drill column height prediction should be adjusted according to the geometry and burial depth of the prospect, rather than applying a fixed statistical distribution to all prospects. Integration of this empirical approach with

consideration of trap-specific details can make a significant contribution to improving the predictability of hydrocarbon column heights in undrilled prospects. This, in turn, will help to reduce the overall uncertainty associated with pre-drill volume estimation in exploration.

- This method of data collection and analysis should be repeated for more discoveries across the NCS and the neighboring UKCS. Inclusion of data from different hydrocarbon provinces, such as the Gulf Coast would also help to increase the size and geographical spread of the dataset. This leads to more meaningful statistical outcomes and enhances the predictive power of the dataset.
- Estimation of the hydrocarbon column remains a constant uncertainty when assessing pre-drill volumes for all prospects, regardless of location. It is therefore recommended that data collections methods and lessons learnt from this study are applied universally, and integrated into current methods that are used to estimate pre-drill hydrocarbon column heights for prospects worldwide.

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Table. 1 A list of defined inputs that are required to calculated hydrocarbon volumes

Input	**Definition**
Hydrocarbon column height	The height of a continuous hydrocarbon column measured from the apex of the structure down to the hydrocarbon-water contact
Recovery factor	The percentage of hydrocarbons that can be produced from the volume of hydrocarbons initially in place
Net/gross ratio	The reservoir rock thickness that has sufficient porosity/permeability from which hydrocarbons can be produced divided by the total reservoir thickness (see below for definition)
Gas fraction of column height	Proportion of the hydrocarbon column height occupied by gas
Porosity (effective)	Interconnected space within the rock that can be occupied by moveable fluids. Excludes isolated pore spaces.
Reservoir thickness	Thickness of the stratigraphic unit that contains the reservoir beds
Oil saturation	Fraction of the pore space occupied by oil
Area	Areal extent of the reservoir contained within the closure at the depth of the fluid contact
Formation volume factor (oil)	The oil volume at reservoir conditions divided by the oil volume at standard conditions (surface conditions)
Depth-dependent area	Function that describes the relationship between depth and the areal extent of the reservoir contained within the closure

Table 2. A list of structural elements, and fields and discoveries that have been measured in this study

Region	Structural elements	Fields and Discoveries
Barents Sea	Hammerfest Basin, Loppa High, Måsøy Fault Complex, Nysleppen Fault Complex, Polhem Sub-Platform, Troms-Finmark Fault Complex	Alke, Bamse, Goliat, Iskrystall, Johan Castberg, Nucula, Norvarg, Snøhvit, Wisting
Norwegian Sea	Dønna Terrace, Halten Terrace, Nyk High, Rås Basin, Vøring Basin,	Aasta Hansteen, Åsgard, Alve, Bauge, Draugen, Dvalin, Fenja, Heidrun, Hyme, Kristin, Linnorm, Maria, Marulk, Mikkel, Morvin, Njord, Norne, Ormen Lange, Skarv, Skuld, Trestakk, Tyrihans, Urd, Ærfugl
Northern North Sea	Gullfaks Block Zone, Lomre Terrace, Marflo Spur, Måloy Slope, Tampen Spur, Tjalve Terrace, Uer Terrace	Byrding, Fram, Gjøa East, Gjøa, Gullfaks, Gullfaks Sør, Knarr, Kvitebørn, Snorre, Stafjord, Statfjord Nord, Statfjord Øst, Sygna, Tordis, Tordis Borg, Tordis Øst, Vega, Vega South, Valemon, Vigdis, Vigdis Sørøst, Vigdis West, Visund

Figure captions

Fig.1. A typical tornado plot generated during pre-drill volume estimation (oil case). It shows the sensitivity of the calculated hydrocarbon reserves to changes in the input variables. Changes in the hydrocarbon column height has the largest effect of all the inputs for the majority of exploration prospects. P10 (possible) means that there is at least a 10% probability that the actual volume of hydrocarbons recovered equals or exceeds the P10 estimate (high estimate). P90 (proved) means that there is at least a 90% probability that the actual volume of hydrocarbons recovered equals or exceeds the P90 estimate (low estimate). Input data are sourced from the NCS.

Fig. 2. A schematic diagram of a fault-bounded hydrocarbon trap. The depth of the structural apex, fluid contact and spill point must be measured in order to calculate the following dimensions: burial depth (a), hydrocarbon column height (b) and trap height (c).

Fig. 3. Three different types of probability distributions. (A) shows a lognormal distribution, which is recognized by a skewed profile that is characterized by an initial steeply dipping limb leading to a peak followed by a longer more gradual dipping limb. (B) shows a normal distribution, which is typically symmetrical about x when x is equal to the mean and (C) shows a uniform distribution, in which all values are equally probable.

Fig. 4. A map of the Norwegian Continental Shelf showing the locations of discovery boreholes used in this study. The distribution of boreholes is separated into three regions: the Barents Sea, the Norwegian Sea and the Northern North Sea (above 61°N). The geological structural base map is from the Norwegian Petroleum Directorate (NPD FactMaps, 2019).

Fig. 5. An example of measurements taken from a structure targeted by exploratory well 7121/7-1, in the Snøhvit field in the southwest Barents Sea. (A) is the map of the top reservoir (Stø Fm.) and indicates the location of cross section A-A' in white, the gas-water contact contour (red) and the spill-point contour (black). (B) shows cross section A-A' with seismic and (C) shows cross section A-A' without seismic. The spill point, gas-water contact and apex depths, which are required to calculate the hydrocarbon column height, trap height, trap-fill ratio and burial depth of the discovery are marked on (B)-(C).

Fig. 6. Cross plots of the empirical data. (A) is a cross plot of the trap height and hydrocarbon column height for all measured discoveries. The linear dashed line represents discoveries that record 100% trap-fill and are referred to as 'filled-to-spill'. All points below this line indicate the structure is underfilled. (B) is a cross plot of the burial depth and hydrocarbon column height. Bordering histograms on the x- and y-axes show the distribution of each variable. Both graphs display a blue regression line bordered by a shaded area. The strength of each correlation coefficient is indicated by the rvalue and the shading indicates the 95% confidence interval of the regression line's location.

Fig. 7. Six cross plots for each of the three regions across the Norwegian Continental Shelf. The hydrocarbon column height is plotted against trap height for the Northern North Sea (A), Norwegian Sea (B) and Barents Sea (C). The hydrocarbon column height is plotted against the burial depth for the Northern North Sea (D), Norwegian Sea (E) and Barents Sea (F). Regression lines plotted on each graph indicate the line of best fit and the accompanying rvalue indicates the strength of the correlation

coefficient between the two variables. Shading either side of the regression line represents the 95% confidence interval of the regression line's location.

Fig. 8. Spatial distribution of trap-fill ratios for each measured discovery across the Barents Sea (A), Norwegian Sea (B) and Northern North Sea (C). The larger and darker colored the circle, the higher the trap fill ratio, as shown by the largest dark red circle, which represents 100% trap fill. The base map is a structural map outlining the main geological elements (NPD FactMaps, 2019).

Fig. 9. A decision tree, which is used to estimate the probability of encountering a particular trap-fill ratio, given the trap height and burial depth of the structure is known. The trap-fill ratio is the outcome variable and defines the first decision level. It is divided into four branches and the values associated with each branch is defined by the bin widths in Fig. 10I. The subsequent second and third decision levels are defined by the two input variables: the trap height and burial depth. The trap height defines the second decision level, which is divided into three branches. The values associated with each branch are shown by the bins widths in Fig. 10H. The burial depth defines the third decision level and is divided into three branches. The values for each branch are defined by the bins widths in Fig. 10G. The decision tree contains 36 different probable outcomes. Each outcome carries an absolute probability and a normalized probability. The absolute probability is the product of three probabilities, each one associated with one branch at decision level one, two and three. The normalized probability is the absolute probability normalized against other absolute probabilities that share the same trap height and burial depth ranges. There are nine different trap height/burial depth combinations in total.

Fig. 10. A series of bar charts showing the distribution of the burial depths (dark blue), trap heights (medium blue) and trap-fill ratios (light blue) for all measured discoveries across the NCS. (A), (B) and (C) splits each dataset into 15 equally spaced bins. (D) (E) and (F) divides each dataset in into five equally spaced bins. (G) divides the burial depth dataset into three bins of unequal width. (H) divides the trap height dataset into three bins of unequal width and (I) divides the trap fill ratio dataset into four bins of unequal width. The bins widths chosen in (G), (H) and (I) determine the number of branches in the decision tree shown in Fig. 9.

Fig. 11. A three by three probability distribution matrix showing how the probability of different trap fill ratios changes when the trap height and burial depth dimensions vary. Each sub-chart represents the distribution of trap-fill ratio probabilities for each of the nine burial depth (y-axis) and trap height (x-axis) combinations. The nine sub-charts are populated using the normalized probabilities calculated in Fig. 9. The number of measured discoveries in the dataset that corresponds to one of the nine trap height/burial depth combinations is indicated by n.

Figures

Figure 1

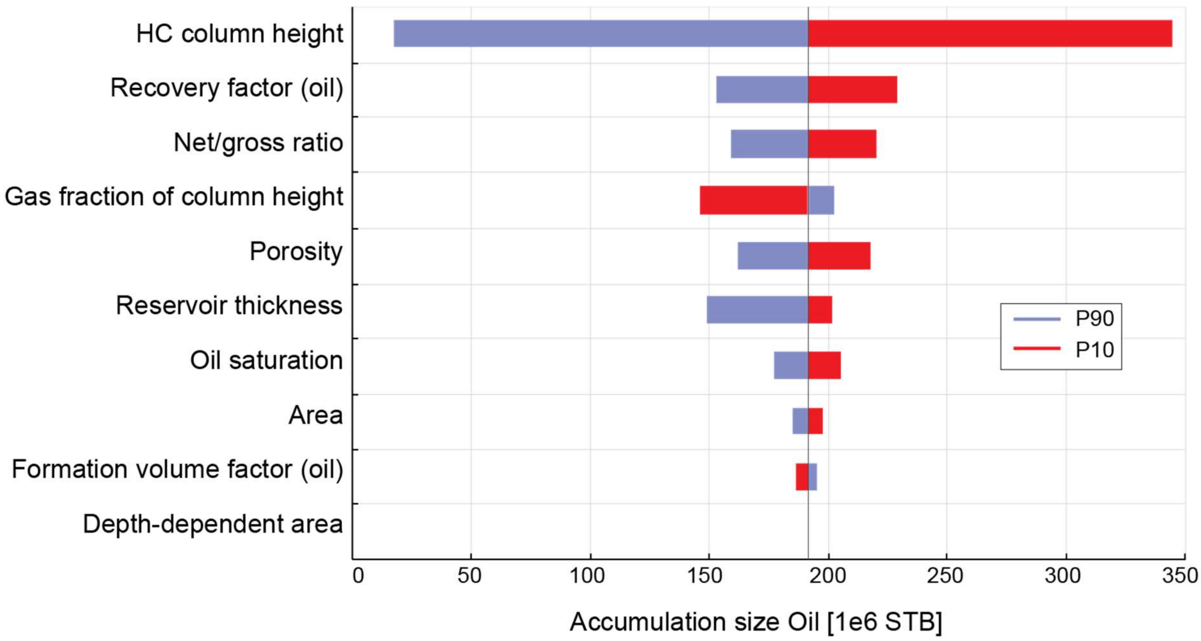


Figure 2

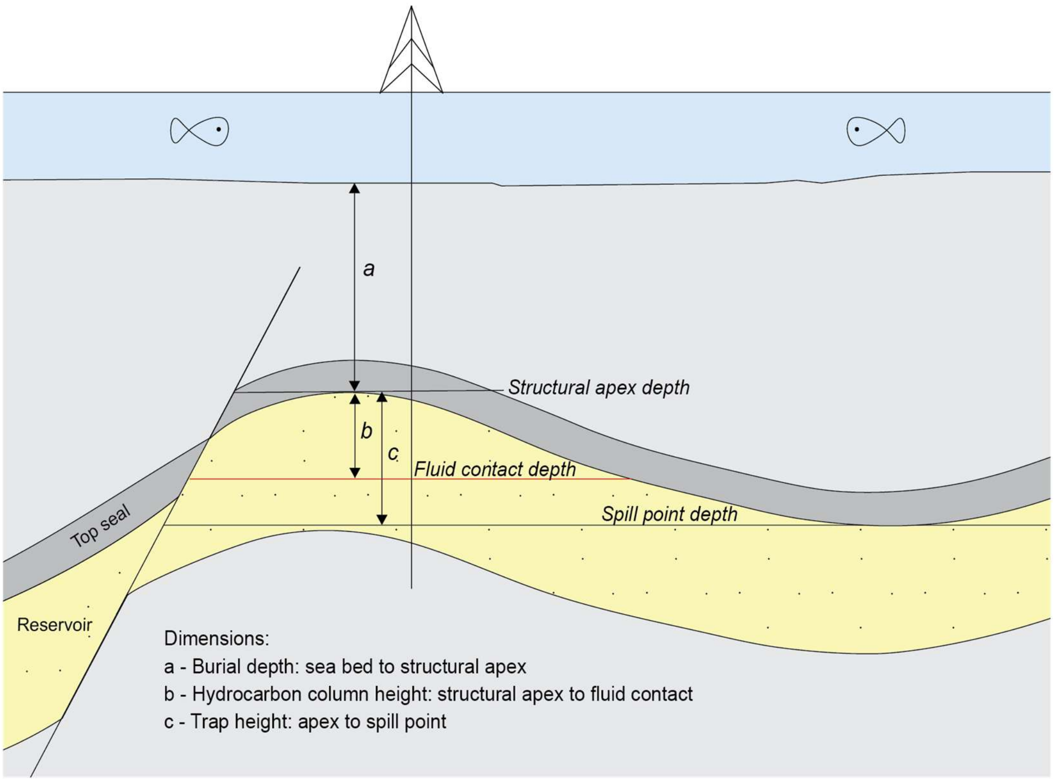
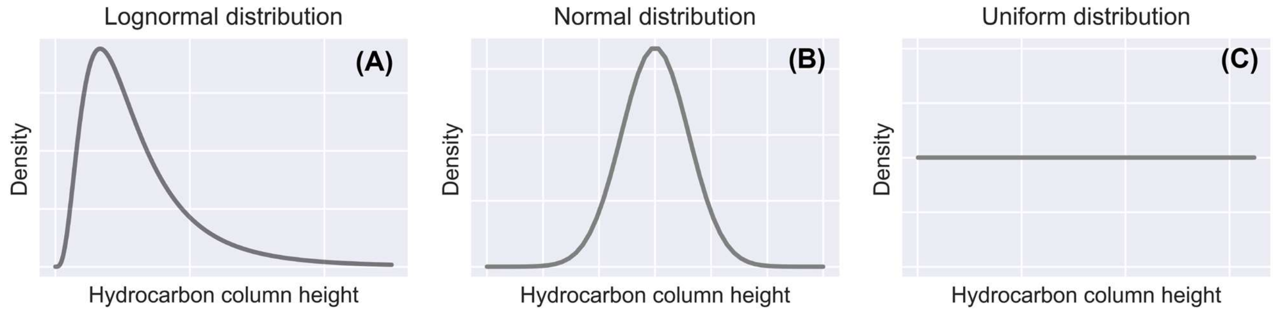
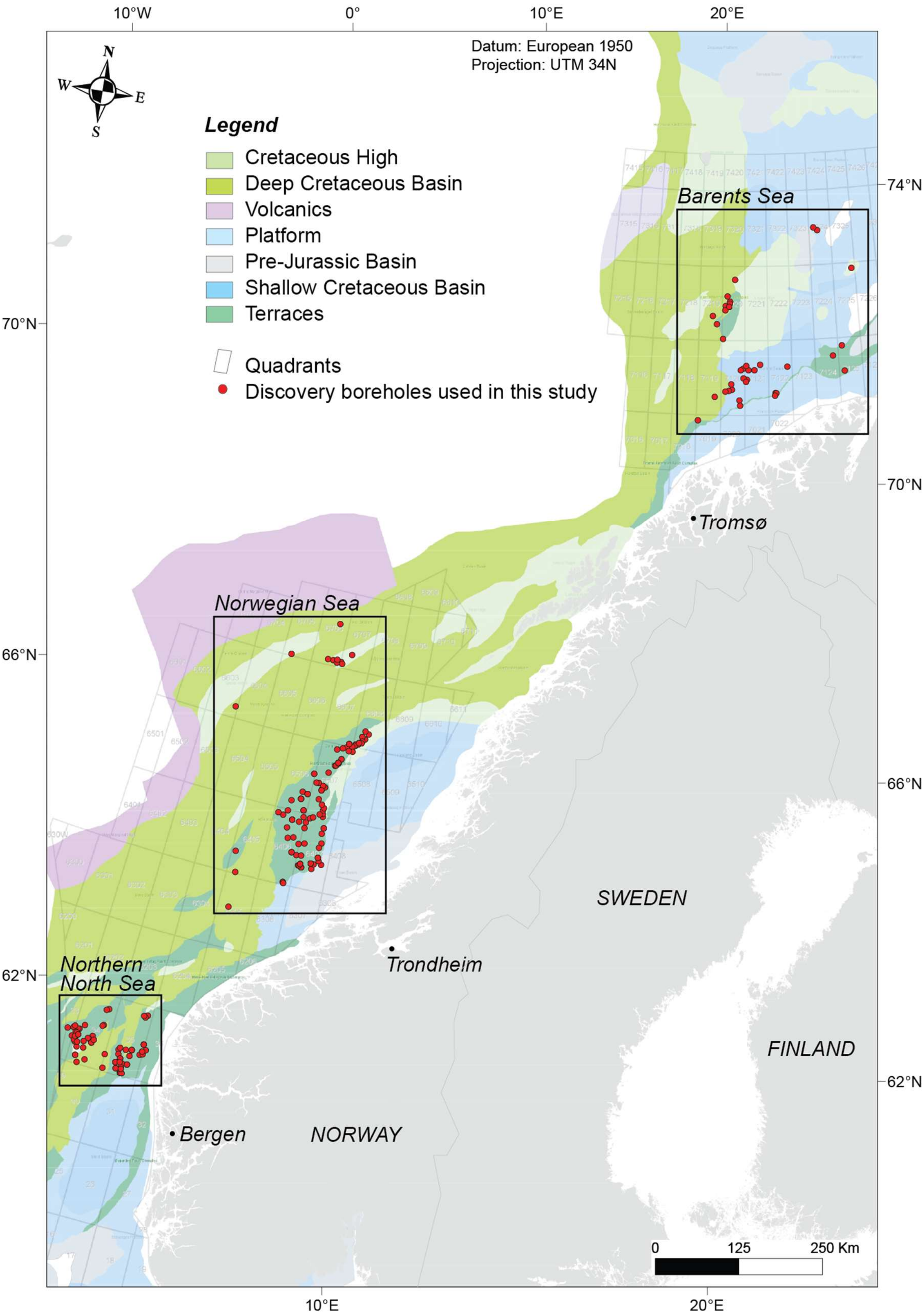


Figure 3


Lognormal distribution
(A)
Density
Hydrocarbon column height
Normal distribution
(B)
Density
Hydrocarbon column height
Uniform distribution
(C)
Density
Hydrocarbon column height

609 Figure 4



610

Figure 5

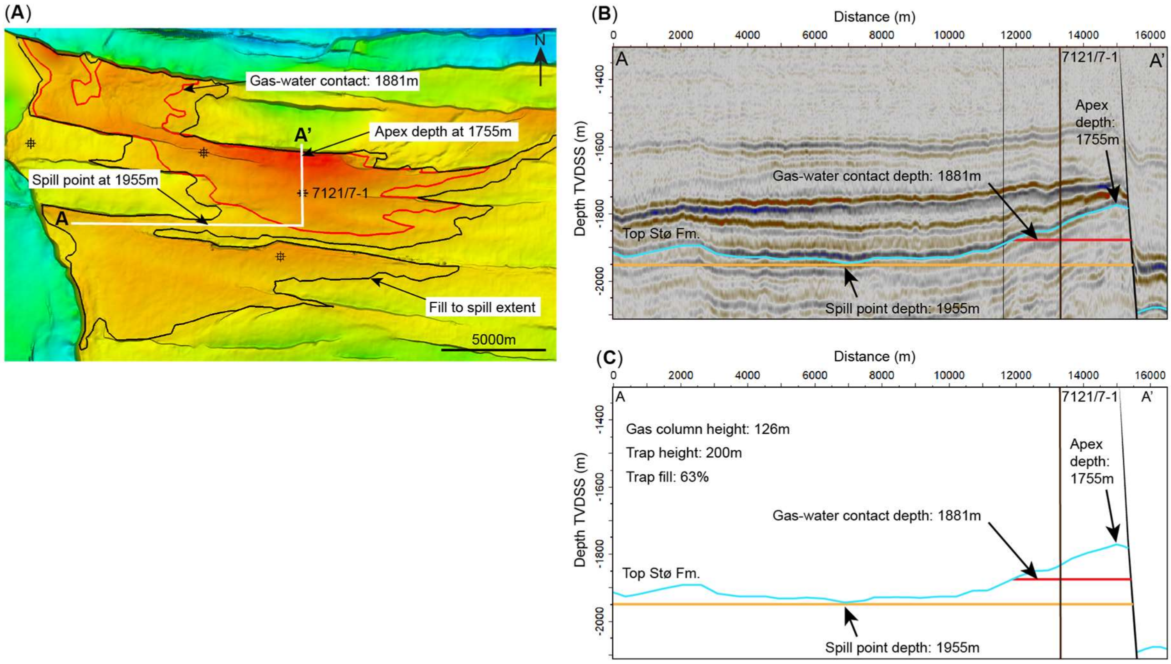

(A)
N
Gas-water contact: 1881m
Apex depth at 1755m
A'
Spill point at 1955m
A
7121/7-1
Fill to spill extent
5000m
(B)
Distance (m)
0
2000
4000
6000
8000
10000
12000
14000
16000
A
7121/7-1
A'
Depth TVDSS (m)
-1400
-1600
-1800
-2000
Apex depth: 1755m
Gas-water contact depth: 1881m
Top Stø Fm.
Spill point depth: 1955m
(C)
Distance (m)
0
2000
4000
6000
8000
10000
12000
14000
16000
A
7121/7-1
A'
Depth TVDSS (m)
-1400
-1600
-1800
-2000
Gas column height: 126m
Trap height: 200m
Trap fill: 63%
Apex depth: 1755m
Gas-water contact depth: 1881m
Top Stø Fm.
Spill point depth: 1955m

Figure 6

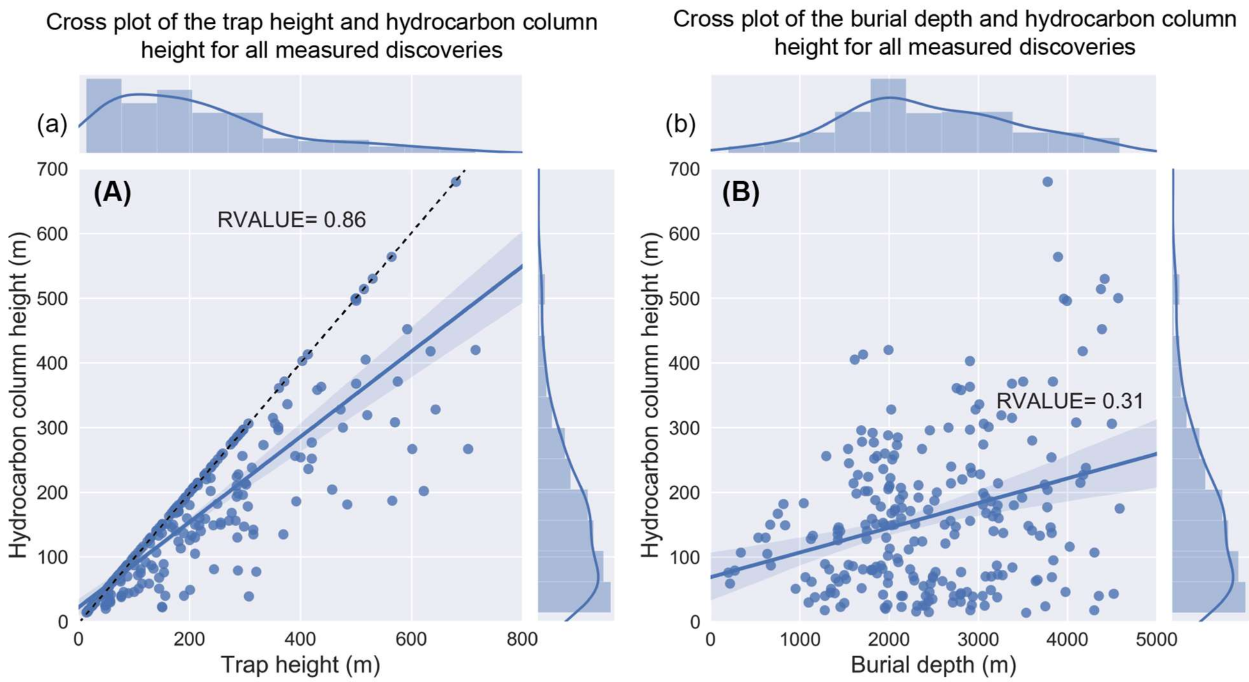

Cross plot of the trap height and hydrocarbon column height for all measured discoveries
(a)
(A)
RVALUE= 0.86
Hydrocarbon column height (m)
Trap height (m)
0
100
200
300
400
500
600
700
0
200
400
600
800
Cross plot of the burial depth and hydrocarbon column height for all measured discoveries
(b)
(B)
RVALUE= 0.31
Hydrocarbon column height (m)
Burial depth (m)
0
100
200
300
400
500
600
700
0
1000
2000
3000
4000
5000

Figure 7

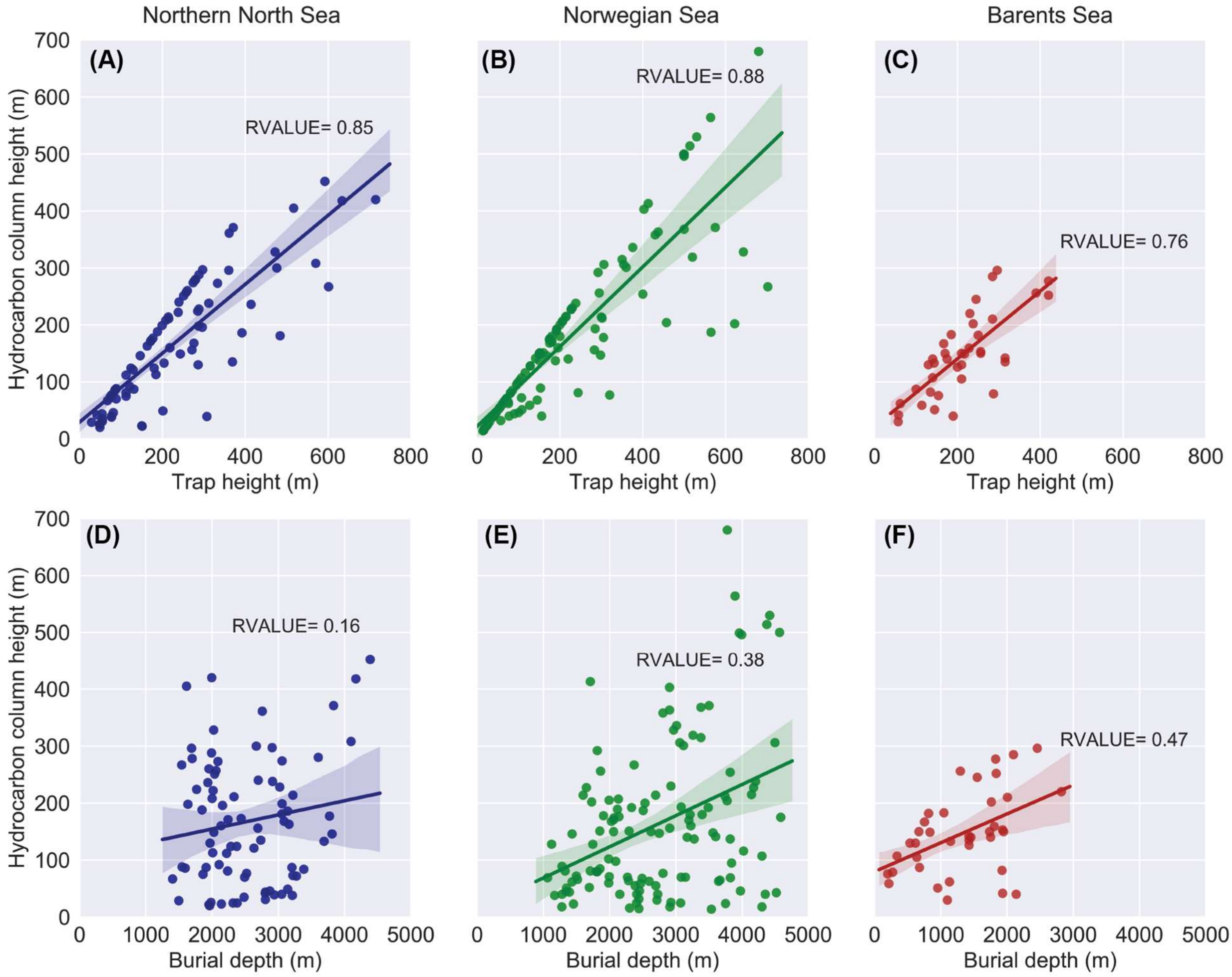

Northern North Sea
Norwegian Sea
Barents Sea
(A)
(B)
(C)
(D)
(E)
(F)
RVALUE= 0.85
RVALUE= 0.88
RVALUE= 0.76
RVALUE= 0.16
RVALUE= 0.38
RVALUE= 0.47
Hydrocarbon column height (m)
Trap height (m)
Burial depth (m)

Figure 8

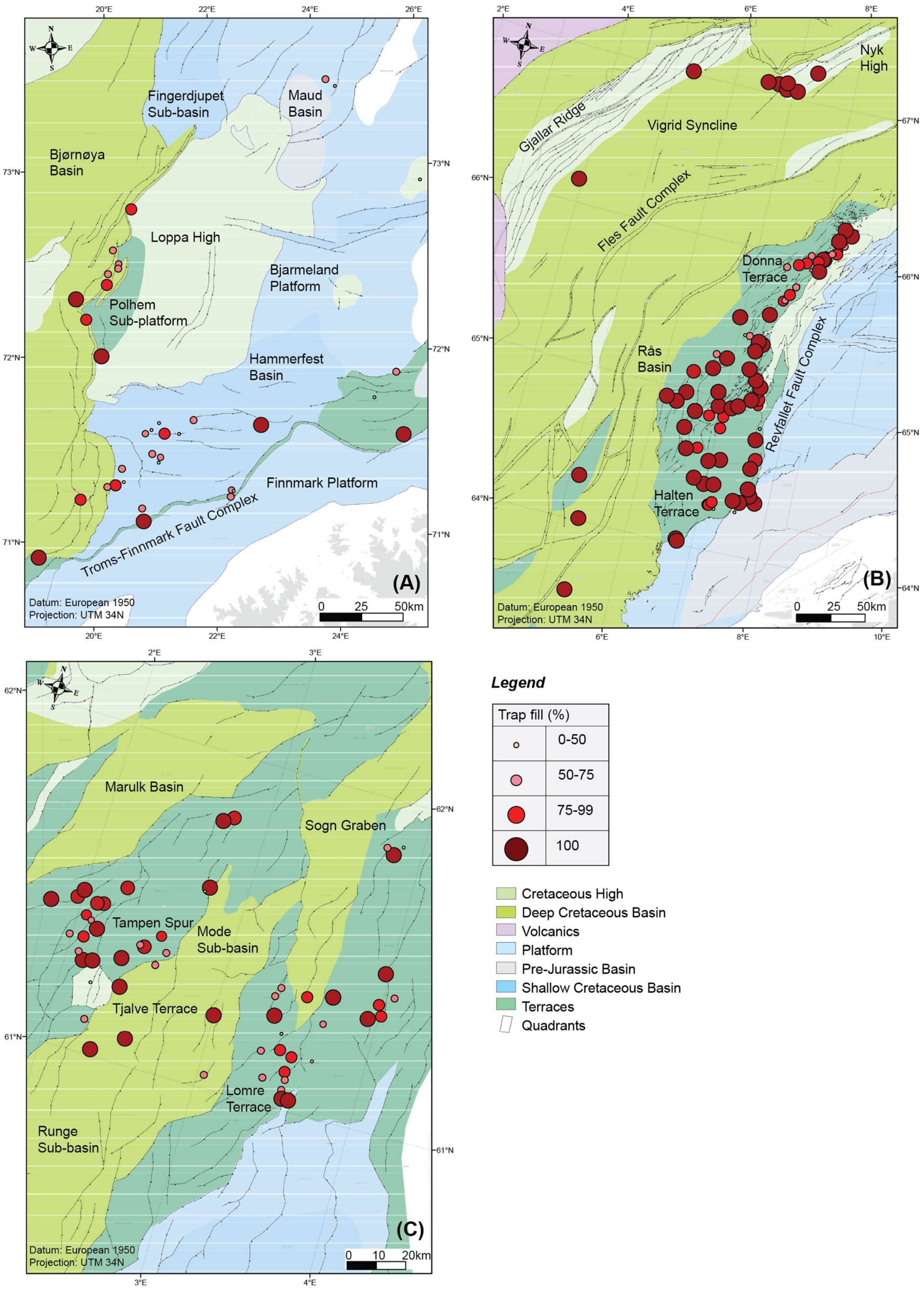

Fingerdjupet Sub-basin
Maud Basin
Bjørnøya Basin
Loppa High
Bjarmeland Platform
Polhem Sub-platform
Hammerfest Basin
Finnmark Platform
Troms-Finnmark Fault Complex
(A)
Datum: European 1950
Projection: UTM 34N
0 25 50km
Nyk High
Gjallar Ridge
Vigrid Syncline
Fles Fault Complex
Donna Terrace
Rås Basin
Revfallet Fault Complex
Halten Terrace
(B)
Datum: European 1950
Projection: UTM 34N
0 25 50km
Marulk Basin
Sogn Graben
Tampen Spur
Mode Sub-basin
Tjalve Terrace
Lomre Terrace
Runge Sub-basin
(C)
Datum: European 1950
Projection: UTM 34N
0 10 20km
Legend
Trap fill (%)
0-50
50-75
75-99
100
Cretaceous High
Deep Cretaceous Basin
Volcanics
Platform
Pre-Jurassic Basin
Shallow Cretaceous Basin
Terraces
Quadrants

Figure 9

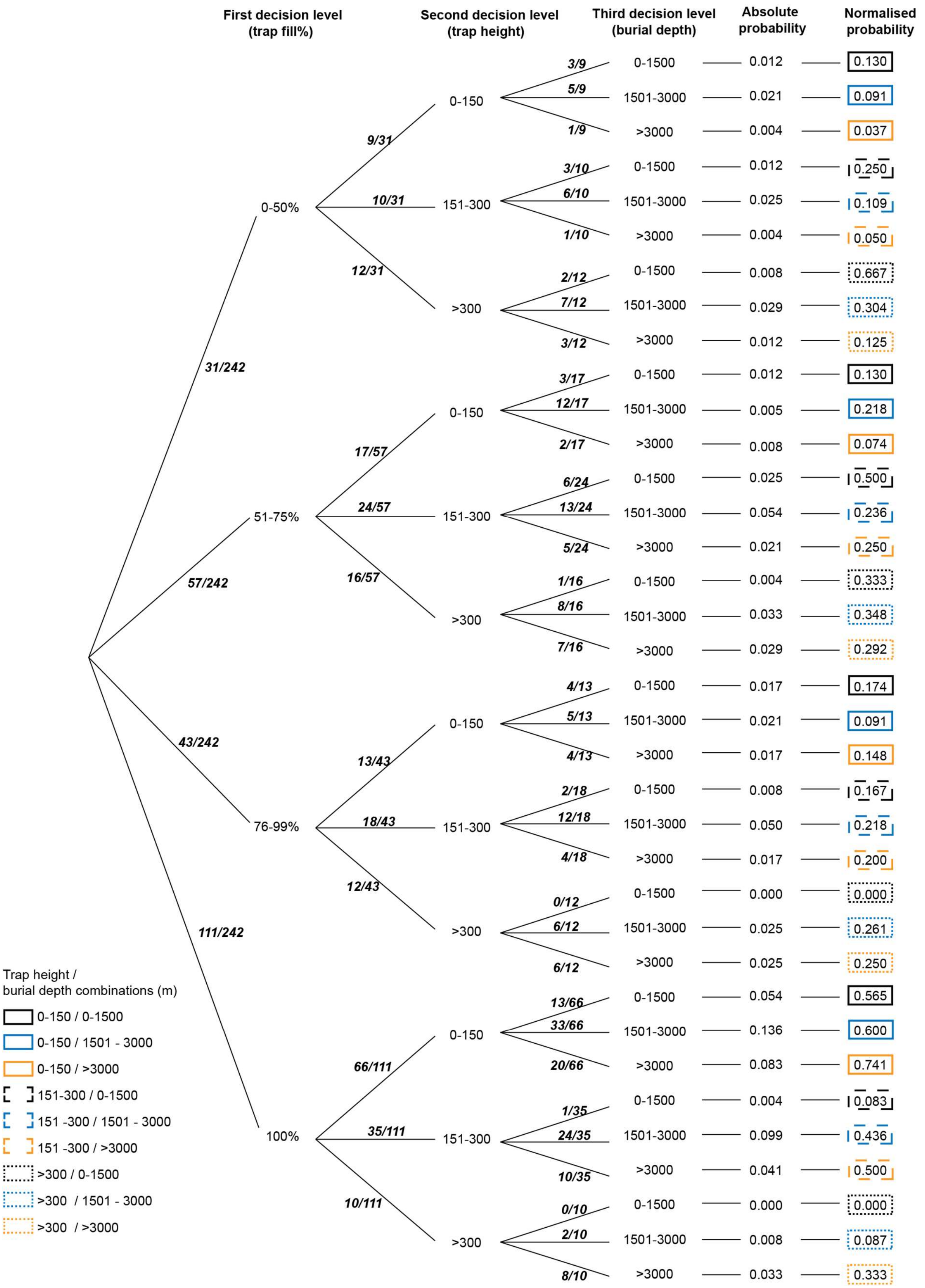

First decision level
(trap fill%)
Second decision level
(trap height)
Third decision level
(burial depth)
Absolute
probability
Normalised
probability
0-50%
51-75%
76-99%
100%
31/242
57/242
43/242
111/242
0-150
151-300
>300
9/31
10/31
12/31
17/57
24/57
16/57
13/43
18/43
12/43
66/111
35/111
10/111
3/9
5/9
1/9
3/10
6/10
1/10
2/12
7/12
3/12
3/17
12/17
2/17
6/24
13/24
5/24
1/16
8/16
7/16
4/13
5/13
4/13
2/18
12/18
4/18
0/12
6/12
6/12
13/66
33/66
20/66
1/35
24/35
10/35
0/10
2/10
8/10
0-1500
1501-3000
>3000
0.012 0.130
0.021 0.091
0.004 0.037
0.012 0.250
0.025 0.109
0.004 0.050
0.008 0.667
0.029 0.304
0.012 0.125
0.012 0.130
0.005 0.218
0.008 0.074
0.025 0.500
0.054 0.236
0.021 0.250
0.004 0.333
0.033 0.348
0.029 0.292
0.017 0.174
0.021 0.091
0.017 0.148
0.008 0.167
0.050 0.218
0.017 0.200
0.000 0.000
0.025 0.261
0.025 0.250
0.054 0.565
0.136 0.600
0.083 0.741
0.004 0.083
0.099 0.436
0.041 0.500
0.000 0.000
0.008 0.087
0.033 0.333
Trap height /
burial depth combinations (m)
0-150 / 0-1500
0-150 / 1501 - 3000
0-150 / >3000
151-300 / 0-1500
151 -300 / 1501 - 3000
151 -300 / >3000
>300 / 0-1500
>300 / 1501 - 3000
>300 / >3000

Figure 10

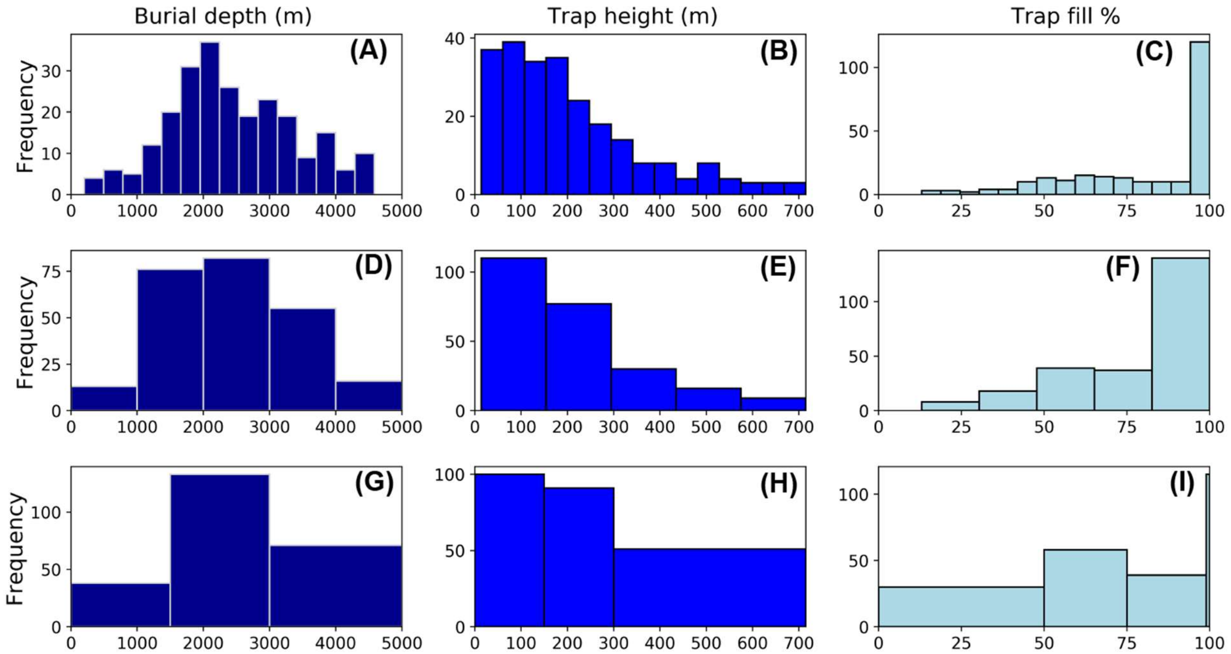
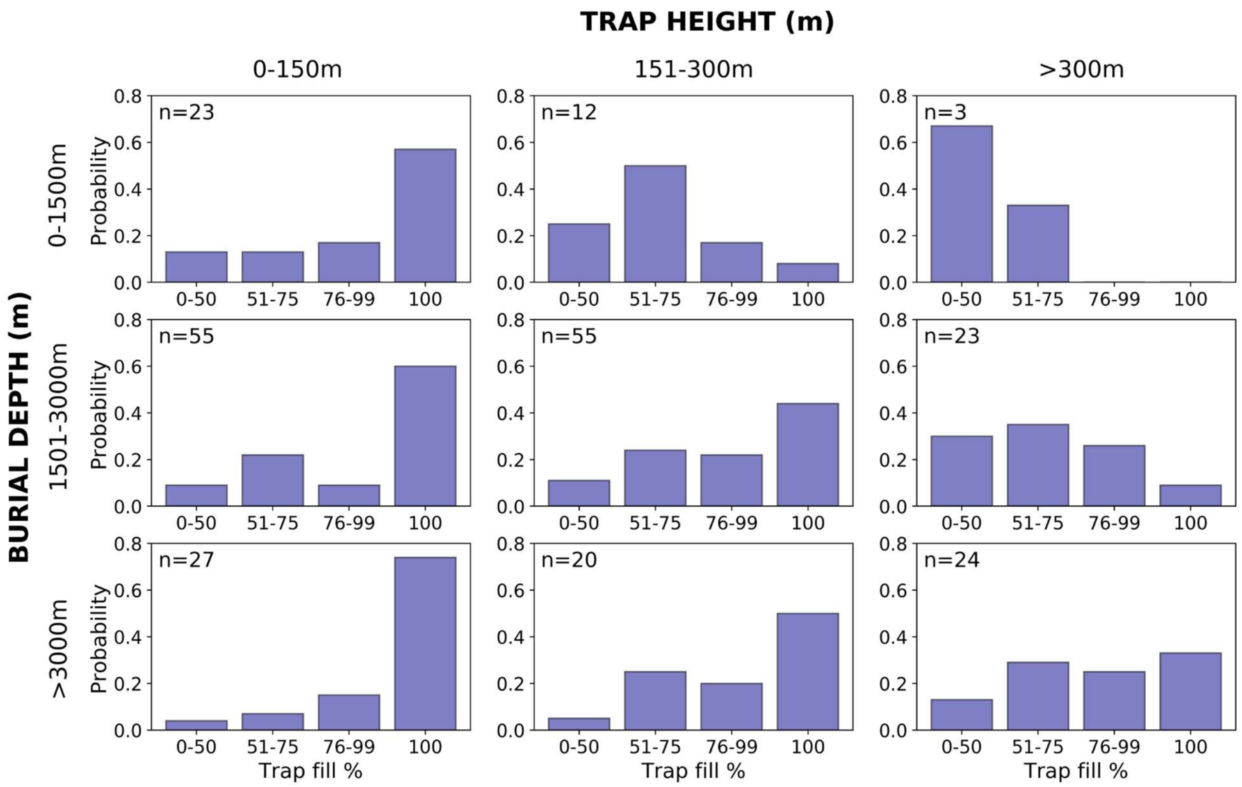


Figure 11



END