Hydrogen Salt Storage Assessment (HYSS)

WP2 Focus Area 1 - Assessment of salt storage in Kish Bank Basin

Grant Agreement – 21/RDD/673

Final Report

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global environmental and advisory solutions

Executive Summary

Decarbonisation and enhancing energy security are policy drivers for developing hydrogen storage infrastructure in Ireland. This study is the first to assess the hydrogen storage potential within manmade salt caverns off the coast of Ireland. This first report uses legacy oil and gas exploration data with data from INFOMAR to assesses the potential for bilocation of hydrogen storage and offshore wind farms in the Kish Basin offshore Dublin. A green hydrogen production facility for the Kish Basin is likely to be constructed in three stages, stage 1 will be the construction of the offshore wind farm, stage 2 will be geological site characterisation of the proposed subsea salt storage site and stage 3 will be the construction of the subsea salt cavern by cavern solution and laying of an export hydrogen pipeline to shore. The construction timeline for a Kish Basin Offshore Green Hydrogen Production Facility is estimated to be seven years.

Four salt intervals were identified from three oil and gas exploration wells drilled in the Kish Basin during the 1980s. A robust regional interpretation of the four salt intervals away from the well control points was achieved using legacy oil and gas seismic data. In areas of poor seismic imaging a robust interpretation was achieved using gross seismic character and overall structural style. The time-based interpretation was converted to depth. The output from the depth conversion process was depth grids for the top of the four salt intervals interpreted in the Kish Bank Basin. Thickness maps were prepared for each of the four salt intervals and checked against the salt thickness seen in the three wells. In addition, wireline logs from the oil and gas exploration wells were examined to identify the purest salt intervals with a minimum amount of clay and shale. Industry knowledge and literature review (HyStorIES; Caglayan *et. al.*, 2020) has established that salt approximately 200m thick at a depth of 1000m to 1500m is optimal for hydrogen storage in man-made salt caverns. The gross salt interval in the oil and gas exploration wells ranges from 120m to 278m, including shale/silt interbeds. The seismic data exhibits signs of salt movement (halokinesis), specifically the development of localised thick salt pillows, which provides thick pure salt ideal for solution mining of salt caverns.

Cavern solution mining is accomplished by drilling a wellbore into a suitable salt formation, dissolving the salt by circulating fresh water into the wellbore and withdrawing the brine to the surface. As the salt is dissolved in a controlled fashion according to a specific plan, the wellbore grows to form a cavern in the salt formation. Once the geometrical design volume is reached, gas is injected into the cavern displacing and emptying the brine out of the cavern, making it ready for gas storage operations. The well is then engineered to establish a controlled connection between the salt cavern and the surface gas storage injection/withdrawal facilities The walls of the salt are impermeable to gas up to specific pressure thresholds, ensuring containment of the gas stored in the cavern. In addition, fractures and faults within the salt formation are healed by the viscoplastic behaviour of the salt under the overburden pressure.

Executive Summary

There is no microbial activity in salt caverns to degrade or contaminate the hydrogen stored. From an economic point of view, excessively small caverns tend to be marginal as some fixed costs are carried regardless of cavern size (leaching station construction and commissioning, connection to gas infrastructure, fixed drilling costs, etc.). From a technical point of view, excessively large caverns present some challenges too as they imply longer leaching durations, increased leaching rates that require large diameter pipe with increased lead times and costs, drilling challenges and the need for heavier duty drilling rigs. The Hystories project proposed a salt cavern with a Free Gas Volume ranging from 185,000 m^3 to 815,000 m^3 as optimum.

The calculations of cavern storage capacity were made using the methodology of Caglayan *et. al.* 2020 and Williams *et. al.* 2020. A typical salt cavern can store between 146 GWh_{H2} and 105 GWh_{H2} of hydrogen. The extent of salt occurrence in the Kish Basin at the required depth of 1,000m to 1500m and >300m thickness (providing at least 200m clean halite) is such that many salt caverns could be solution mined, sufficient for seasonal hydrogen storage. In the zone of interest that lies beneath the offshore wind licence area for the Dublin Array, 8 standard size salt caverns can be developed for hydrogen storage. This is equivalent to approximately 1.0 TWh_{H2}. . The project has identified 271 potential manmade salt caverns at the optimum depth and thickness for gas storage off the east coast, in the greater Dublin area alone, each of which could deliver in the region of 0.1 TWh of hydrogen storage, or 27 TWh_{H2} cumulatively.

Some geohazards have been identified, such as glacial boulders and scouring currents. These hazards can be managed or avoided as demonstrated by successful oil and gas drilling in the area in recent decades. There are several significant environmental constraints including the disposal of concentrated brine from salt cavern mining and the disruption to shipping and fishing activity in an exclusion zone around the hydrogen production facility. Mitigation measures have been identified to address these environmental constraints. The regulatory risk in Ireland is significant because until now the drilling of offshore wells came under petroleum legislation and regulation.

Recommendations arising from this study include promotion of hydrogen storage infrastructure in salt caverns offshore Dublin as a Project of Common/Mutual Interest; the development of a regulatory regime to facilitate development of man-made salt cavern storage offshore Ireland; investigation of the role of public private partnerships in the development of hydrogen storage infrastructure offshore Dublin; support for the development of a regional hydrogen cluster or hub in the greater Dublin Area and a detailed costing for the development of offshore salt cavern hydrogen storage and transportation infrastructure to inform commercial decisions of offshore wind developers.

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Introduction

This research assesses the potential for bilocation of hydrogen storage and wind farms, thus promoting the generation and storage of green hydrogen at offshore windfarm locations. Offshore energy storage will have the dual benefit of reducing dispatch down (which reached 11.4% in 2020) while also creating green hydrogen for domestic use or export. Finding solutions, to store excess electricity generated by offshore wind for later despatch at an optimum price, or to sell green hydrogen into a lucrative local transport fuels market or for export, will be critical in meeting Irish and European climate action targets.

Hydrogen has been stored in geological salt formations since 1972 (Teeside in the UK) and there are over 2,000 salt stores in the United States and over 300 in Germany (Panifilov, 2016). Large man-made caverns of 10,000 m^3 to 1,000,000 m^3 (4 to 400 Olympic sized swimming pools) can be leached within salt formations creating an alternative to other porous stores (Bunger *et. al.* 2016). Salt caverns are the ideal store for hydrogen as salt is non-porous and retains gases even at high pressure, it also has the advantage of ensuring purity of the stored hydrogen and allowing high injection and production rates (Panfilov, 2016). Additional advantages are low geological risk, low cushion gas requirements and high safety levels with only one well per storage cavern.

Caglayan *et. al.* (2019) assessed the potential for hydrogen storage in geological salt formations across Europe (in known salt accumulations). The overall technical storage potential was estimated at 84.8 PWh_{H2}, though there is no assessment for Ireland. This research addresses this data gap, and integrates existing technology concepts to identify the best offshore sites for combining electricity generation from wind, green hydrogen production from electrolysis, and energy storage in underlying/adjacent salt caverns. This has the benefit of utilising electricity dispatch down from offshore wind to provide green hydrogen energy storage for use in transport, electricity generation or net energy export.

The presence of geological salt formations has been proven in several sedimentary basins offshore Ireland (Naylor & Shannon, 2011) though it's extent and thickness has never been mapped for the purposes of storage assessment. The Providence Resources Plc AGM presentation of 2016 highlighted exploration wells and seismic data which proved the presence of a significant salt formation in the Kish Basin offshore Dublin (PVR, 2016). This research focuses initially on this area because the location of these salt formations is in close proximity to Dublin and adjacent to a number of proposed offshore wind farms (Fig 1).

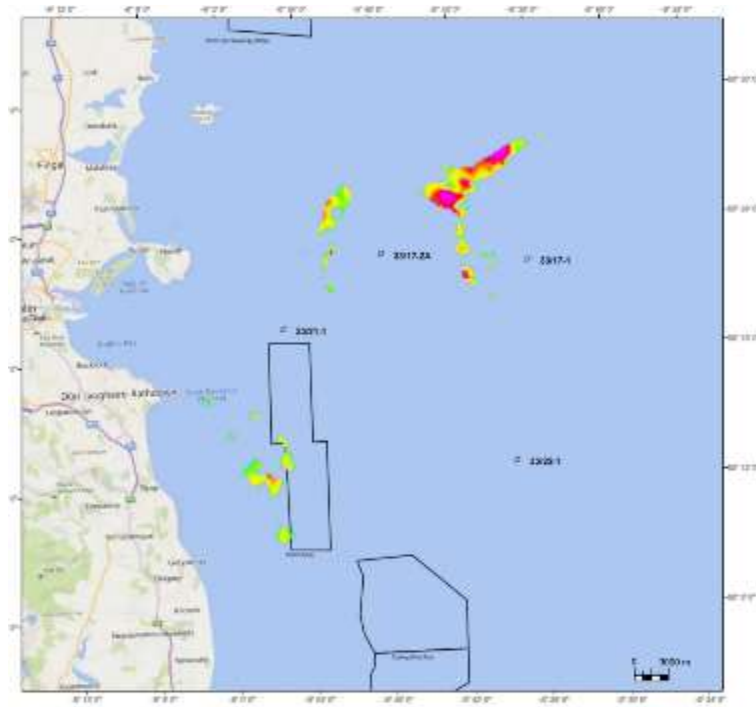

Figure 1: Map showing extent of salt >300m thick, at a depth between 1,000m and 1,500m. Exploration wells and proposed offshore wind developments annotated.

Scope of Work and Base Data

Scope of Work

WP2-O1: Evaluate salt intervals in wells, confirm signature on seismic data and interpret top and base of salt formations, including depth conversion and assessment of salt thickness and extent.

WP2-O2: Use seismic data to qualitatively assess salt characteristics (massive, interbedded, domal, evidence of halokinesis etc)

WP2-03: Engineering study to assess the maximum theoretical hydrogen storage potential using salt cavern storage methodologies suitable for geological conditions.

WP2-04: Conduct a regional geohazards study to assess the risks to surface and subsurface operations including seismic velocity and local well information.

WP2-05: Conduct a study of maritime traffic (shipping, fisheries, leisure), archaeological sites or other maritime/surface constraints (e.g. buoys or cables).

WP2-06: Undertake a high-level review of the potential environmental issues or constraints that may impact surface or subsurface operations.

WP2-07: Produce common risk segment maps of surface and subsurface risks, integrating with planned or potential offshore renewable energy sites to delineate high graded areas for potential hydrogen storage in man-made salt caverns.

Base Data (acquired from GSRO, INFOMAR, EMODNet, Marine.ie)

- 2D seismic data
- Well data
- Gravity Data
- Magnetic Data
- INFOMAR Bathymetry Data
- INFOMAR subsurface imaging Data
- Maritime traffic density maps
- Fisheries activity maps
- Marine Atlas Data

Offshore Green Hydrogen Production Facility Concept

Project Description

The key components for an offshore green hydrogen production facility in the Kish Basin are:

- Offshore wind turbines with seabed foundations
- Offshore Platform(s) or an offshore substation (OSS)with:
    - AC Collector
    - HVDC Transformer
    - Water purification
    - Electrolyser 500MW
    - Power unit
    - Wellhead equipment
    - Compressor
- Inter turbine array cables to the offshore platform
- Export DC electricity cable to shore
- Export Hydrogen pipeline to shore
- Subsea salt cavern
- Onshore substation

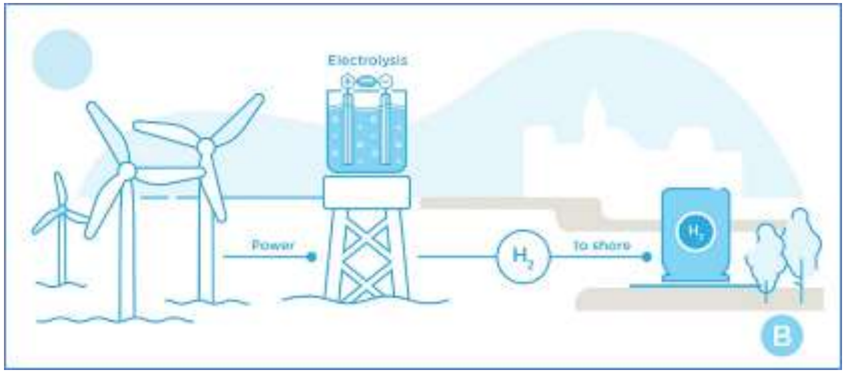

Figure 2: Offshore Hydrogen Production. Source: Ramboll

The green hydrogen production facility for the Kish Basin is likely to be constructed in three stages (Fig 4). **Stage 1** will be the construction of offshore wind turbines with seabed foundations, offshore substations (OSS), inter turbine array cables to the OSS, export DC electricity cable to shore and onshore substation. **Stage 2** will be geological site characterisation to confirm the geological feasibility of the proposed subsea salt storage site identified from seismic. This will include a 3D seismic survey, drilling of an appraisal well with comprehensive formation logging and coring programme and laboratory testing and analysis of cores. The geological site characterisation will take three years to complete. A 3D seismic survey acquired early in the first year will be processed and interpreted before the appraisal well is drilled in the following year. Analysis of the well data to establish geomechanical constraints and design of the cavern solution programme will be completed in the third year. **Stage 3** will be the construction of the subsea salt cavern by cavern solution mining using a jackup drilling rig at the appraisal well, construction of an offshore platform above the salt cavern to house the hydrogen plant, installation of inter turbine array cables to the offshore platform and laying of an export hydrogen pipeline to shore. The construction of the salt cavern is likely to take two to three years and will involve the temporary installation of a jackup drilling rig, drilling of a borehole to about 1,000 m subsea, cavern solution mining within the salt formation, and completion of the borehole to establish a controlled connection between the salt cavern, where hydrogen gas will be stored, and the surface facilities at the wellhead. The installation of the offshore platform and laying of an export hydrogen pipeline to shore will take several months (Fig 5).

Offshore Green Hydrogen Production Facility Concept

Stage 1 Construction of Offshore Wind Farm

The **wind turbines** in the Kish Basin will be in water depths of between 2m and 26m on a series of north-south trending offshore banks. Each offshore wind project could have up to 60 wind turbines with tip heights of 308m and indicative hub heights of 165m above mean high water springs (MHWS). **Foundations** will be required for the wind turbines, meteorological masts and offshore substation platforms which will be fixed to the seabed. A range of foundation types are under consideration but a multileg jacket is the most likely for the substation platforms. Each **offshore substation platform** will be supported by up to six legs and each leg will be secured to the seabed by a foundation structure. Up to three offshore substations will be required for each offshore wind project. The power from the turbines will be delivered to the offshore substations by subsea cables. Transformers housed in the substations will increase the voltage from 66 or 132kV to 220kV or 400kV for delivery to the shore via the export cables.

Submarine inter-array cables of 66kV will be required to connect turbines together into groups or strings. Each string will then be connected to an offshore substation. Several higher voltage (220 - 400kV) cables will then export electricity from the offshore substations towards the shore, where they will be joined to the onshore cables. Submarine intra-array cables may also be required to connect individual offshore substation platforms to each other.

The installation of the offshore wind farm infrastructure is likely to take twelve months spread over a two-year period to allow cable and pipeline installation under relatively calm sea conditions. The sequence of installation will include the following activities: seabed preparation, cable duct installation at landfall, wind turbine and ancillary infrastructure foundation installation, installation of scour protection, installation of wind turbine generators, installation of offshore topsides and met masts and cable laying.

Once operational the wind farm infrastructure will require regular maintenance throughout the expected lifetime of 35 years. At the end of the wind farm's design life the infrastructure will be decommissioned. The decommissioning process is likely to follow a reverse programme of the construction process outlined above.

Stage 2 Geological Site Characterisation of Subsea Salt Cavern

The potential sites for subsea salt caverns have been identified on legacy 2D seismic. The acquisition of new 3D seismic data will be necessary to identify drilling targets more precisely for an appraisal well to develop the most promising salt cavern prospects. The appraisal well will acquire petrophysical and geophysical data from wireline logging and coring. The seismic and well data will be analysed, with laboratory testing of cores, and interpreted to characterise the lateral and vertical extent of the salt formation, local structural features, salt mineralogy, insoluble material content, mechanical strength of the salt and its solubility in water and the stratigraphic features of the overburden layers. Comprehensive data analysis with geological modelling will establish the technical feasibility of the site for salt cavern solution mining as well as cavern sizing and configuration.

Offshore Green Hydrogen Production Facility Concept

Stage 3 Cavern Solution Mining and Installation of Hydrogen Plant Offshore Platform

The salt caverns will be created by solution mining or dissolving portions of the naturally occurring salt formations that have been identified from the 3D seismic and confirmed as technically feasible hydrogen storage sites from the analysis and interpretation of the appraisal well data. The appraisal well may be re-entered and completed as the hydrogen production well if it is in the optimum position for solution mining of the sub seabed salt formation. The solution mining or leaching of the salt deposit may take several years depending on the size of the cavern to be created. Facilities downtime, well integrity testing, cavern acceptance testing, saturation time and workover every 100,000 m^3 has to be factored into the leaching time. The leaching phases and operating parameters are adjusted as the cavern construction progresses, based on sonar measurements. During the leaching process the cavern roof is protected by a blanket of nitrogen gas and/or diesel to prevent the dissolution of the salt in the salt cavern roof (Figure 3). The cavern profile is developed from the bottom to the top by pulling the leaching strings and reducing blanket depth step by step.

When the salt cavern has been leached out cavern integrity and acceptance testing will be carried out by the jackup rig. Once completed the hydrogen production well will be suspended and the jackup rig will move off location. A purpose built hydrogen production platform jacket will be installed above the underground salt cavern and connected to the existing hydrogen production well which was suspended after the mining solution process was completed. Electricity generated by the offshore wind turbines will be used to power the **hydrogen plant** on this platform, converting seawater into demineralized water, then into hydrogen via electrolysis. The hydrogen plant platform will have an AC collector, a HVDC transformer, a water purification unit, a 500MW Electrolyser, a power unit, wellhead equipment and a compressor. A high voltage cable to export electricity and a subsea hydrogen pipeline to export hydrogen will be run from the hydrogen plant platform to the shore substation.

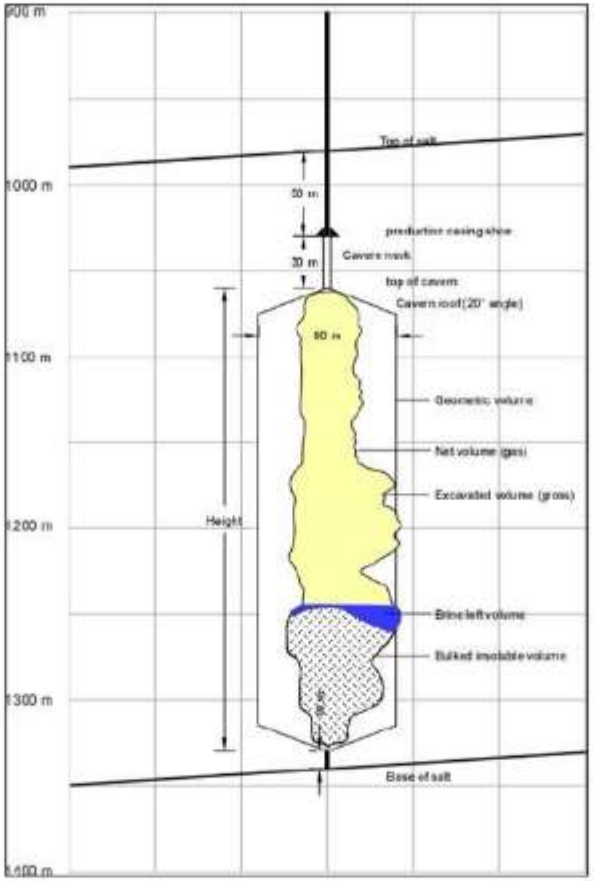

Figure 3: Cavern Geometry Source: Hystories

Hydrogen Production Platform.
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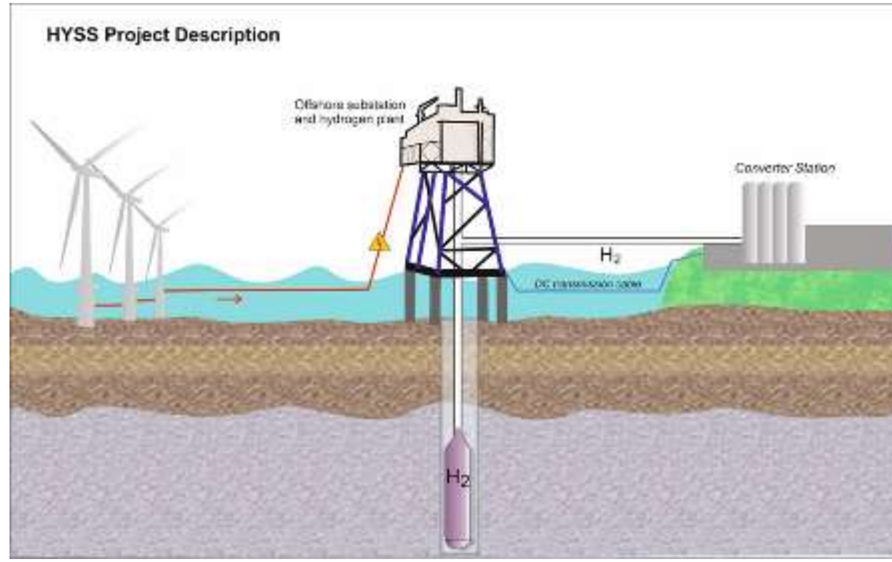


Stage 1 Construction of Offshore Wind Farm

- seabed foundations
- turbine installation
- offshore substations
- inter turbine array cables
- export DC cable to shore
- onshore substation

Stage 2 Geological Site Characterisation of Subsea Salt Cavern

- 3D seismic survey acquisition
- 3D processing & interpretation
- drill appraisal well
- data analysis & interpretation
- salt cavern modelling

Stage 3 Cavern Solution Mining and Installation of Hydrogen Plant Offshore Platform

- re-enter appraisal well
- cavern solution mining
- completion of production well
- installation of hydrogen production platform
- export hydrogen pipeline to shore

Figure 4: Kish Basin Offshore Green Hydrogen Production Facility Construction

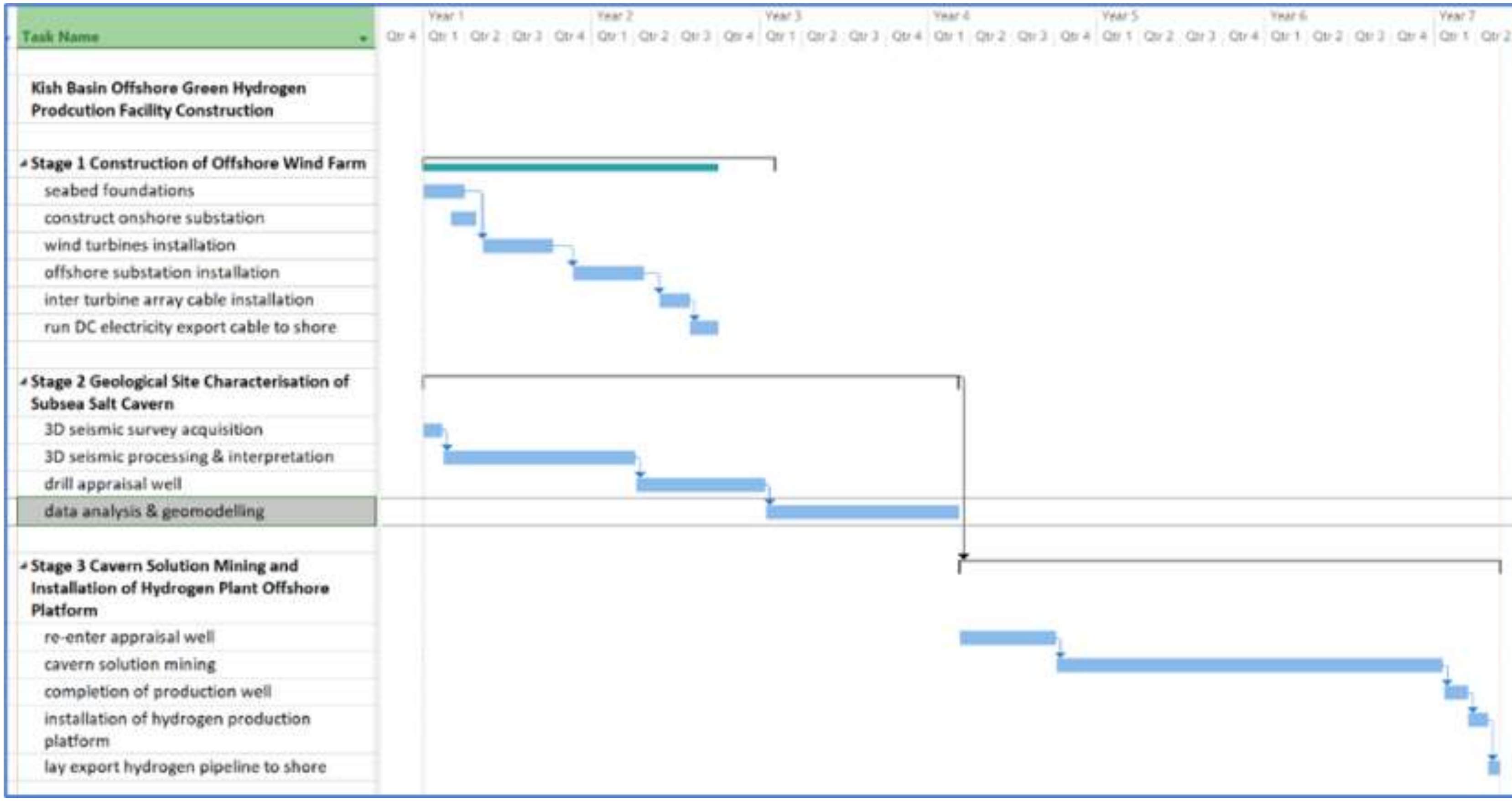


Figure 5: Kish Basin Offshore Green Hydrogen Production Facility Construction Timeline

WP2-O1: Methodology

Evaluate salt intervals in existing exploration wells

The Standard Stratigraphic Nomenclature of Offshore Ireland was reviewed to identify salt intervals in the 4 deep wells in the Kish Bank Basin. 3 of the 4 wells contained salt and the digital well logs and composite well logs were reviewed to confirm the nature of the salt signature.

33/21-1	4 salt intervals	Bedded salt and silt/shale	755m gross halite intervals (approx. 200m gross in each salt)
33/17-2A	2 salt intervals	Bedded salt and silt/shale	549m gross halite intervals
33/17-1	1 salt interval	Bedded Salt and silt/shale	120m gross halite interval
33/22-1	No Halite	Triassic section eroded / not deposited	

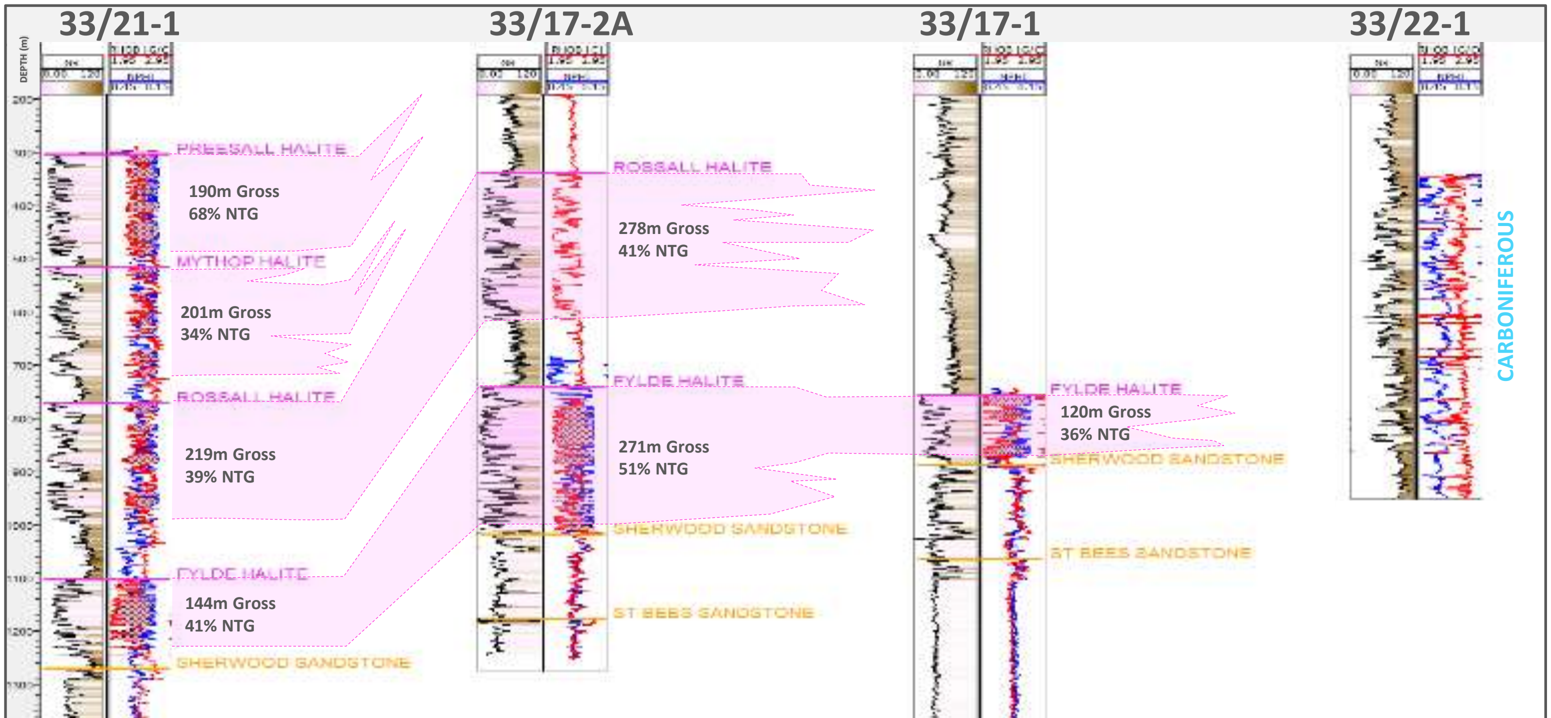


Figure 6: Kish Basin well stratigraphy highlighting salt units (halite) in pink

WP2-O1: Methodology

Available seismic dataset

The dataset available for the Kish Bank Basin focus area consisted of 2D seismic data acquired predominantly in the 1970's and early 1980's.

A small sub-set of the data in the western part of the focus area had previously undergone extensive reprocessing, independent of this study which provided vital velocity data.

The Kingdom Suite software was the computer software tool chosen for the project.

Seismic data was collected from the GRO on a large external hard disk in both original SEGY format, and later as a pre-loaded Kingdom project. Data provided in SEGY only was loaded to the Kingdom project using data contained within the file headers and associated navigation file (if available).

It was common for the vintage 2D seismic data files not to have a specified CRS other than European Datum 1950. The transform from the standardised satellite based WGS84 to European Datum 1950 was assumed to be a simple three parameter shift for all seismic data acquired prior to 1995 unless otherwise documented. Any data acquired after 1995 was assumed to use the updated seven parameter Bursa-Wolfe transform.

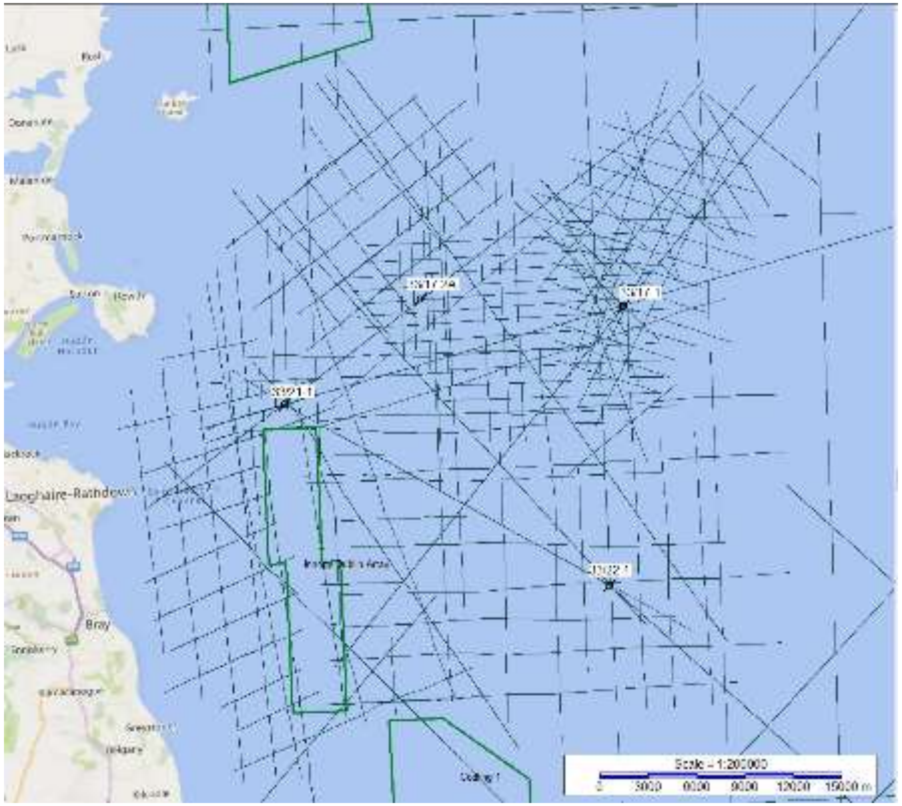


Figure 7: Kish Basin seismic database and planned windfarm locations

The uncertainty in location between the three parameter and the seven parameter transforms is approximately 30 metres, meaning accidently using an incorrect transform would result in a minor mis-positioning which was considered acceptable for this regional study.

The loaded seismic lines were quality controlled internally within a survey and also externally against other surveys to ensure intersections of data were correct. The spatial location was also compared to a shape file of all Irish seismic data.

WP2-O1: Methodology

Interpretation of seismic data

A review of the digital well logs showed (as expected) the halite (salt) intervals were high density, representing an increase in acoustic impedance which would be a hard event on seismic data. The top of salt intervals was thus interpreted as a hard seismic event.

2D seismic lines through the wells were reviewed to identify the seismic event most relevant to the salt intervals. Given the age of the 2D data there are changes in seismic phase and polarity between different surveys as well as vertical miss-ties. To balance the phase, polarity and vertical miss-tie within and between these vintage 2D surveys is beyond the scope of this project. The seabed (a hard event) was thus taken as a guide to help identify other hard events on a line by line basis.

The common principles and practices of seismic interpretation have been followed, including recognising that seismic reflections represent changes in velocity and or density in the subsurface which can be diachronous or chronostratigraphic events. Interpretation relies on recognising regional dip as well as seismic character (continuous, discontinuous, chaotic, strong, weak etc.) and interpreting a geological rationale for these changes (faults, disconformities, lithological changes etc.).

Within the Kish Basin study area the salt formations were generally seen to have a continuous hard top and an opaque internal character. The base of the salt was not a consistently strong seismic response, or were too close to the top of the underlying halite to have an independent response. As the base of a salt interval to the top of the next salt interval (or Sherwood Sandstone Group) was a shale, and shales are generally near constant thickness, it was deemed more appropriate to create shale isopachs and use these to calculate the base of the salt intervals.

Major faults were interpreted to provide a regional structural framework, they were picked based on offset of seismic reflectors or abrupt changes in dip. Minor or localised faulting was not incorporated into this regional study.

The regional interpretation of the 4 salt intervals began at the well control points and extended away from the well control. In areas of poor seismic imaging a robust interpretation was achieved using gross seismic character and overall structural style.

Two additional regional seismic markers were interpreted. An unconformity at the Top Triassic / Base Quaternary and the Top Sherwood Sandstone. The Quaternary section represents significantly lower velocity material and contains multiple erosive channels. The Top Sherwood represents the base of the confirmed salt intervals.

WP2-O1: Interpretation of Seismic Data

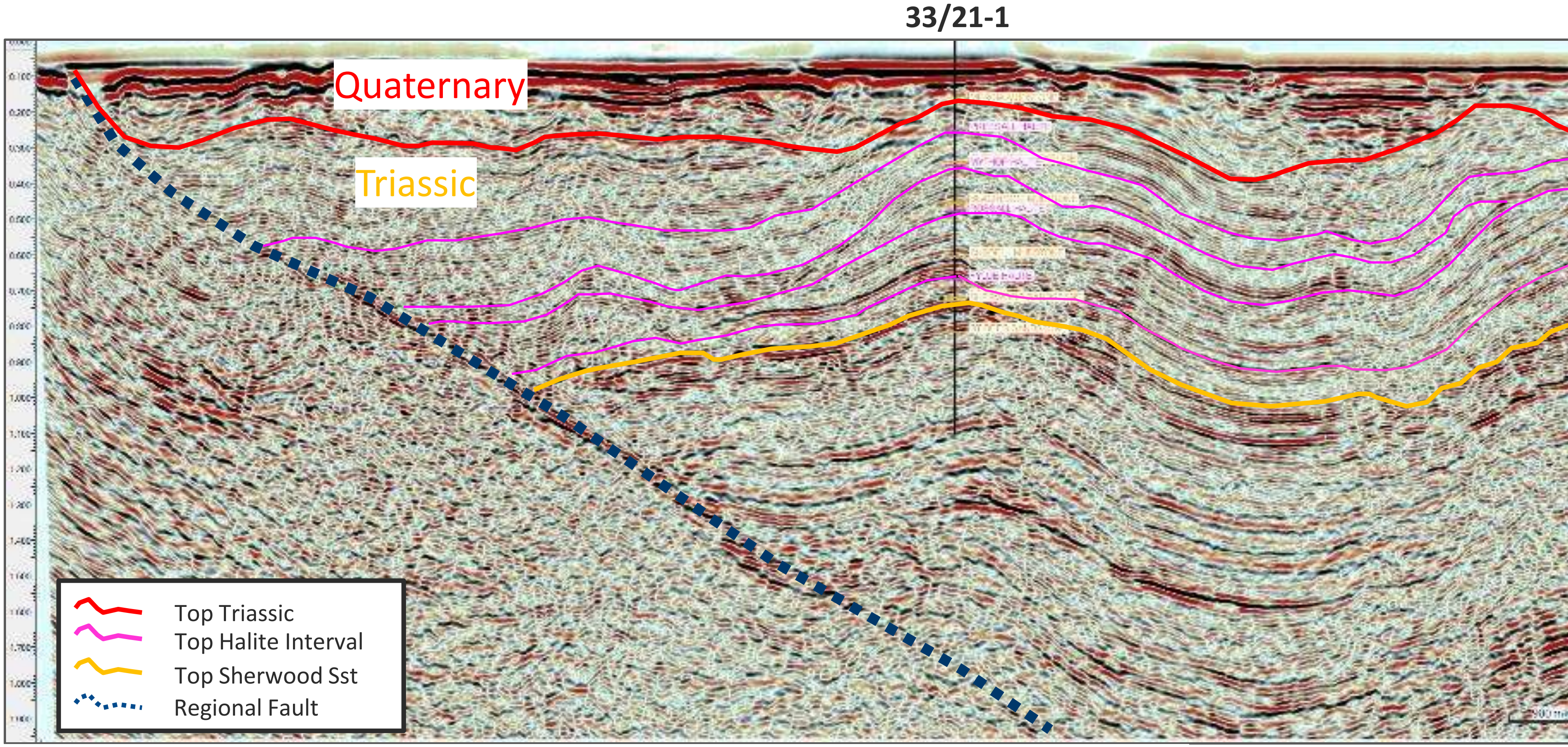


Figure 8: Kish Basin – example seismic line through 33/21-1 well with interpreted surfaces.

WP2-O1: Methodology

Gridding

As the interpretation exists only where the 2D seismic data exists the interpretation was gridded to create a full 3D interpretation over the full extent of the Kish Basin.

Figure 9 shows the input 2D interpretation of the Sherwood Sandstone and Figure 10 shows the output 3D grid.

The gridding parameters were set to allow smoothing of the input interpretation, to reduce data spikes and residual vertical miss-ties between the 2D datasets. As this is a regional project a 200 meter x 200 meter grid cell size was chosen. The extent of the grid beyond the known 2D was controlled by using a polygon to confine the area of gridding.

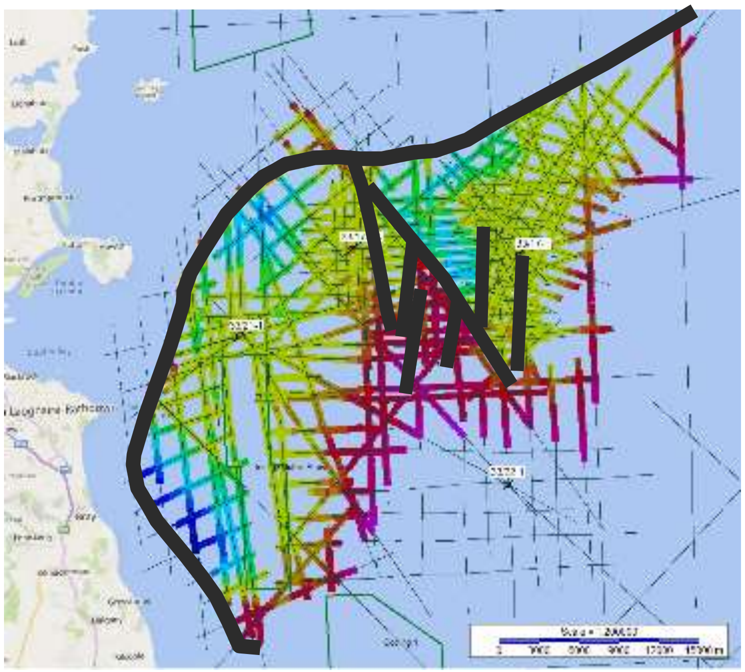


Figure 9: Sherwood Sandstone 2D interpretation extent

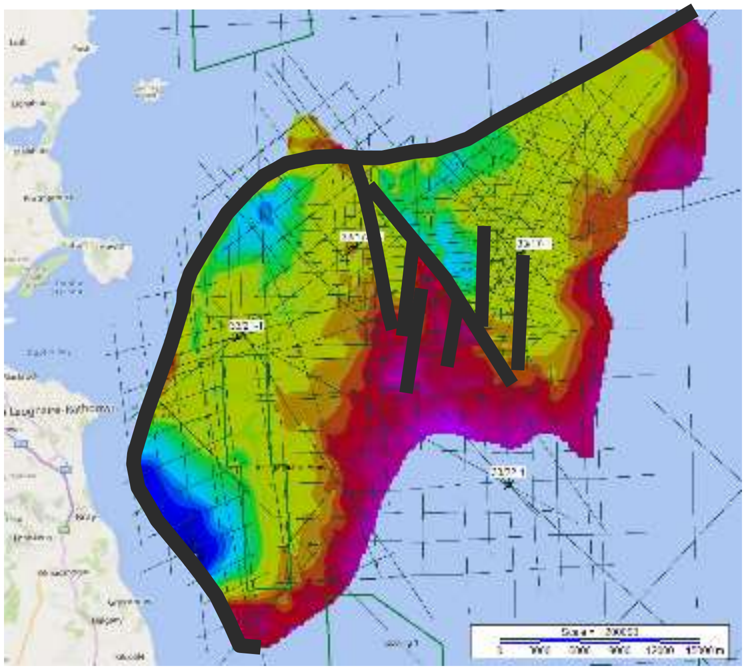


Figure 10: Sherwood Sandstone 3D grid extent

WP2-O1: Methodology

Depth Conversion

Seismic data is recorded and processed as the "time" taken for a sound to travel to a geological event and return to a receiver. Thus the interpretation prepared is in the time domain and needs to be converted to the depth domain. The conversion is: Depth = Velocity/Time

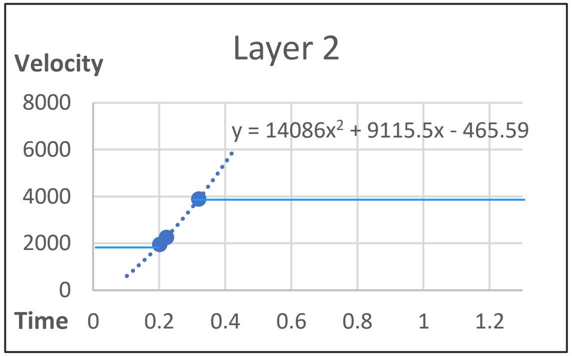
The interpretation was split into 4 layers for depth conversion, according to the velocity of the Geological section. Seismic isochron maps were created for the 4 layers and crossplot against the associated sediment thickness or the sediment velocity of that layer in the wells. The crossplots were adjusted to show the entire time range of the layer to help identify any anomalies. The data showed simple relationships at each layer and allowed creation of sediment thickness maps or velocities for each layer. Finally, the isopach maps of each layer were stacked as appropriate to create depth maps of the interpretation.

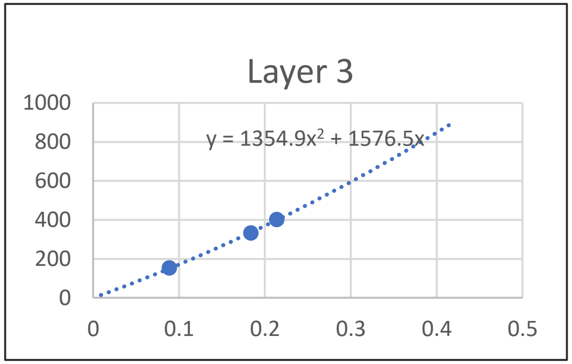
Layer 1: Water column and Quaternary
A constant velocity of 1761 m/s was used for this interval.

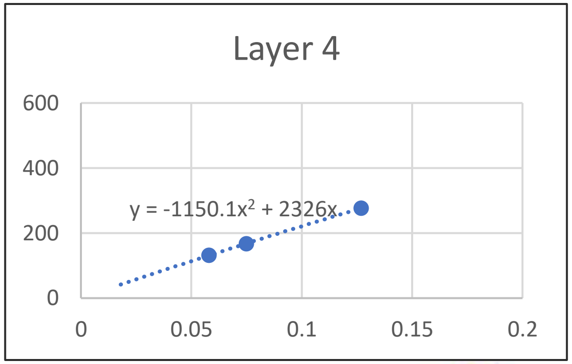
Layer 2: Quaternary to Top Rossall
This layer changes considerably from having 2 high velocity salt intervals in the 33/21-1 well, to no salt intervals in the other two wells. A correlation was drawn between time thickness and the velocity of the interval (the thicker the unit the more salt, thus the higher the velocity). This correlation was clipped at a minimum of 1950m/s and a maximum 3950m/s to avoid non geological velocities. Time thickness maps from the Top Rossall to Top Presall and Top Mythop were converted to depth thickness maps by isopaching up using a velocity of 4081m/s, an average from the wells.

Layer 3: Top Rossall to Top Flyde
This layer demonstrated a simple time thickness to depth thickness correlation which passed through zero. The average velocity of this unit is approximately 3,600m/s.

Layer 4: Top Flyde to Sherwood Sandstone
This layer demonstrated a simple time thickness to depth thickness correlation which passed through zero. The average velocity of this unit is approximately 4,400m/s.







WP2-O1: Methodology

Assessment of salt thickness and extent.

The output from the depth conversion process was depth grids for the top of the 4 salt intervals interpreted in the Kish Basin, as well as the Top Sherwood Sandstone. As discussed previously, the base of the salt intervals was not always a consistent seismic marker, or were too close to the top of the underlying halite to have an independent seismic response, but the salt intervals were separated by a mudstone unit with approximately consistent thickness across the wells. The base of the salt intervals was thus created by isopaching up from the underlying interval.

22m	Isopach up from Top Mythop to Base Presall Halite
53.5m	Isopach up from Top Rossall to Base Mythop Halite
118m	Isopach up from Top Flyde Halite to Base Rossall
13.5m	Isopach up from Sherwood to Base Flyde Halite

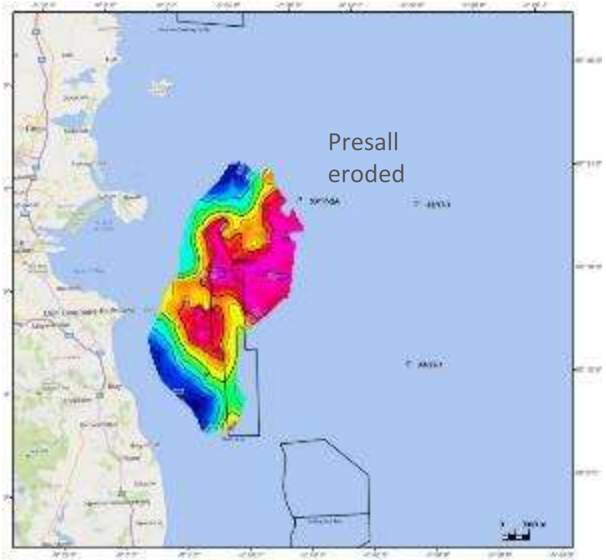
Thickness maps were prepared for each of the 4 salt intervals and QC'd against the thickness in the 3 wells. In addition, the wireline logs were examined to identify the purest salt intervals with a minimum amount of clay and shale. The presence of clays increases the amount of bulk insoluble volume in the salt cavern when the solution mining process is completed. The cleanest salt interval in the Kish Basin is the Presal Halite Formation. However, where salt movement (or halokinesis) has occurred the salt interval is likely to be pure salt with little or no clay present.

To assess the potential of these salt intervals for salt cavern storage the following assumptions were made based on industry knowledge / literature review (HyStorIES; Caglayan *et. al.*, 2020) .

- Salt at a depth of 1000m to 1500m is most optimal for salt cavern development.
- Salt caverns require approximately 200m salt thickness.

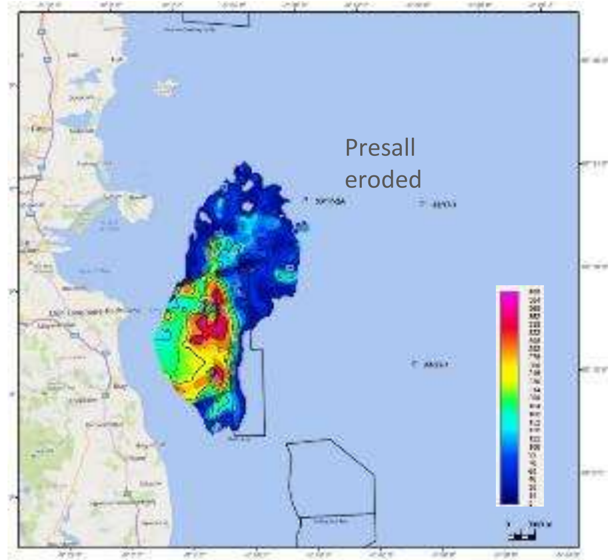
The salt in the existing wells in the Kish Basin is a depositional sequence of salt, shale and silts. The gross salt interval in the wells ranges from 120m to 278m, including shale/silt interbeds. It was thus concluded that greater than 200m of gross salt interval was required in the Kish Basin. The seismic data exhibits signs of minor halokinesis, specifically the development of localised salt pillows. It is assumed that areas where the gross salt package thickens away from the well control represent areas with halokinesis and thus likely to have less interbedded shale/silts. These areas would be more suitable to salt cavern development as they could contain a higher net salt thickness. Areas with excess of 300m gross salt interval were deemed appropriate to yield appropriate net salt thickness for cavern development.

WP2-O1: Presall Maps

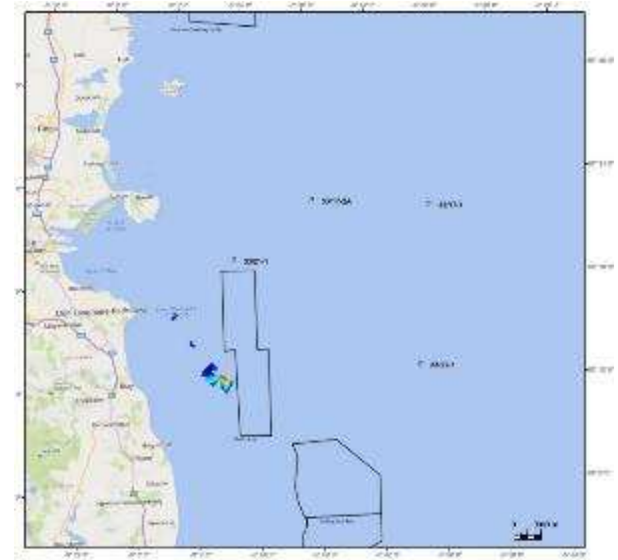


The majority of the Presall Halite is shallower than 1,000m.

Depth



Thickness



Thickness within AOI
1 to 1.5km & >300m thick

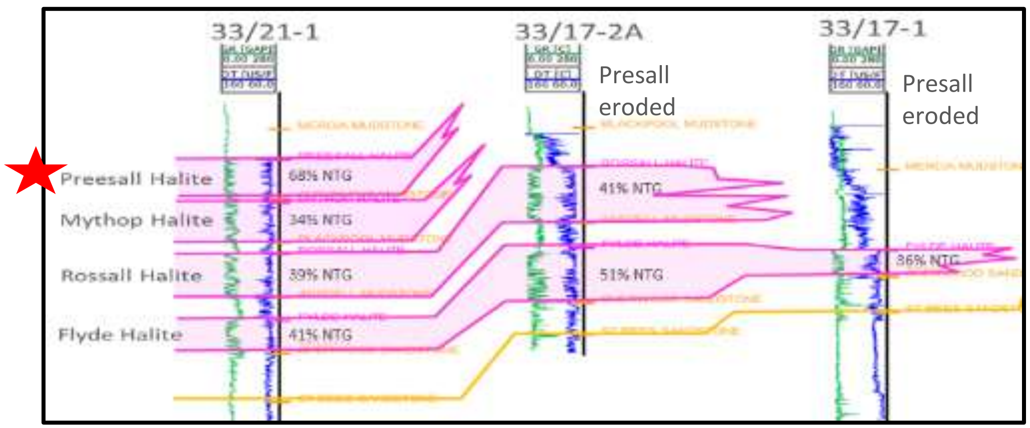
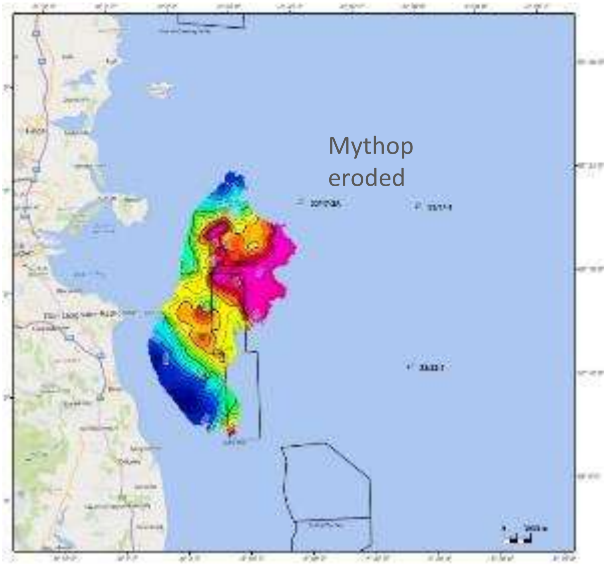
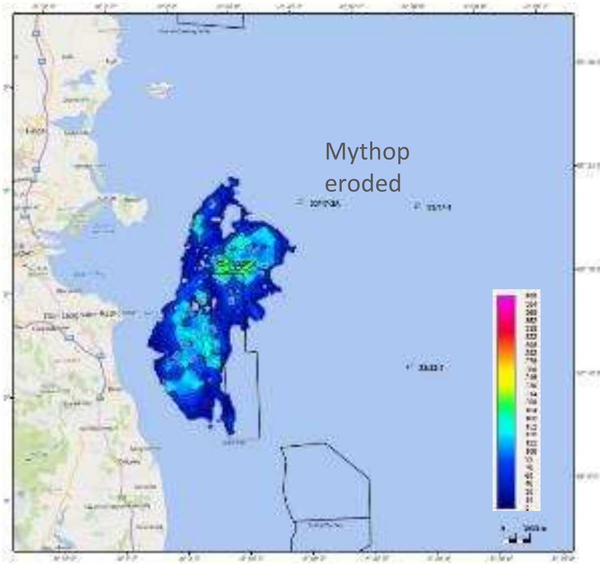
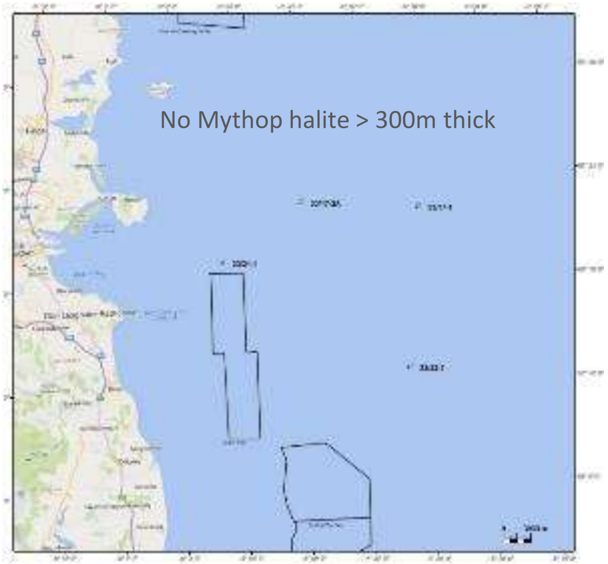


Figure 11: Presall Halite Extent in the Kish Basin.

WP2-O1: Mythop Maps







The Mythop Halite is less than 300m thickness

Depth

Thickness

Thickness within AOI
1 to 1.5km & >300m thick

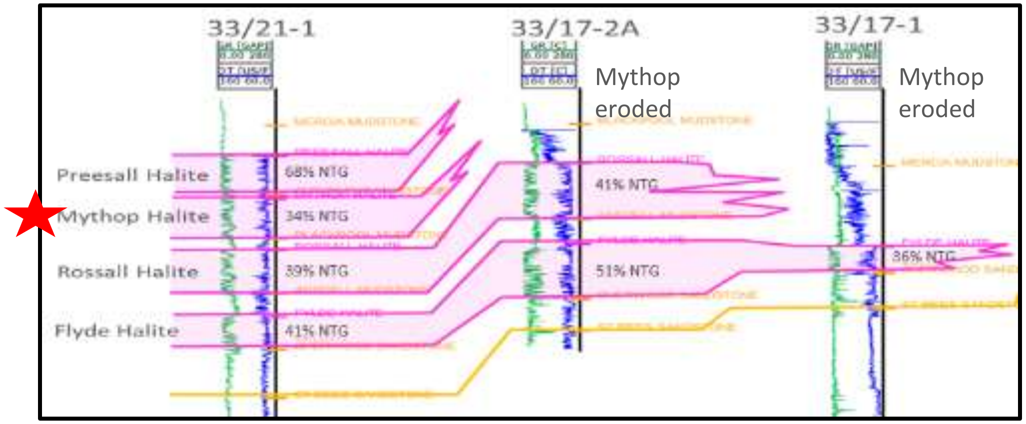
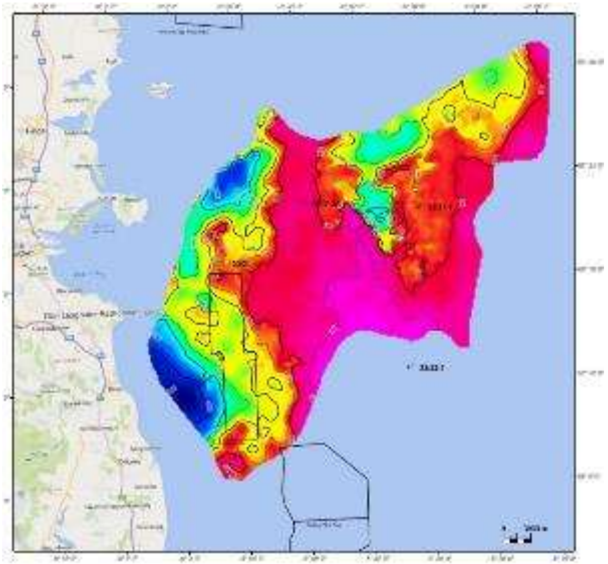
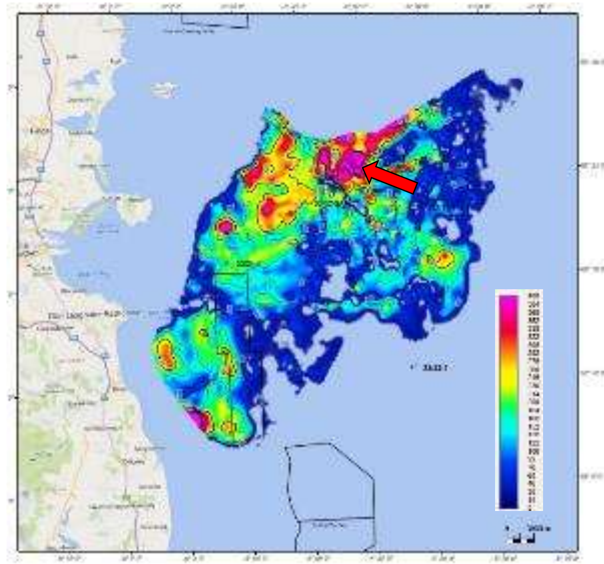


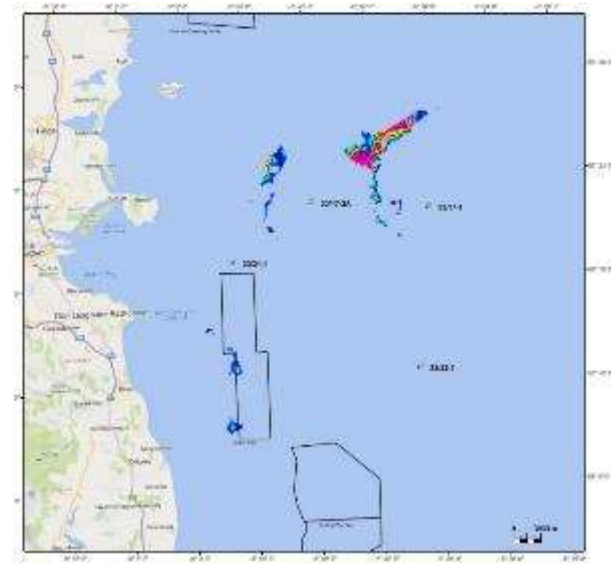
Figure 12: Mythop Halite Extent in the Kish Basin.

WP2-O1: Rossall Maps





Halokinesis evident, no halite in 33/17-1, remobilised to NW, see red arrow.

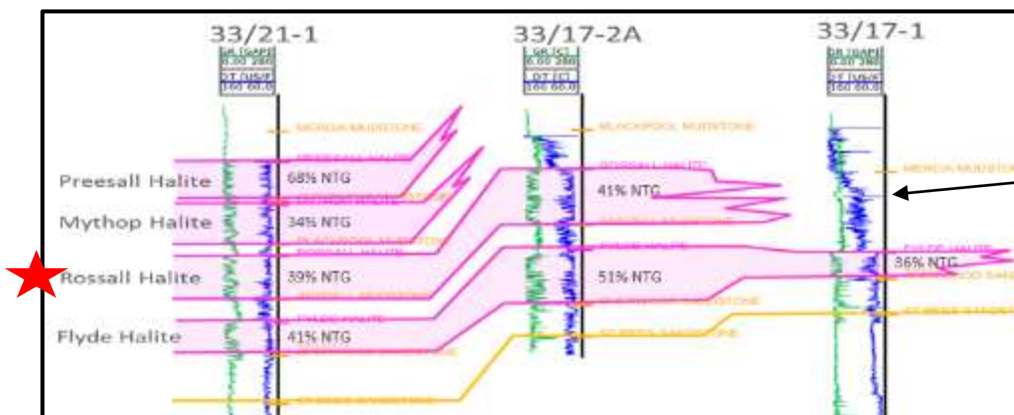


Depth

Thickness

Thickness within AOI

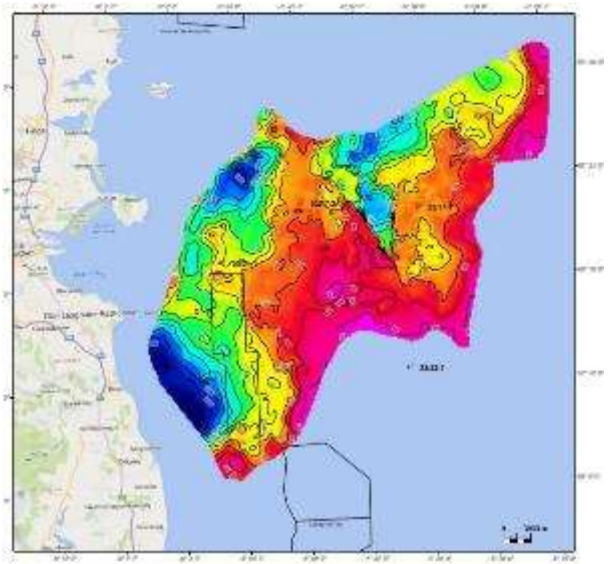
1 to 1.5km & >300m thick



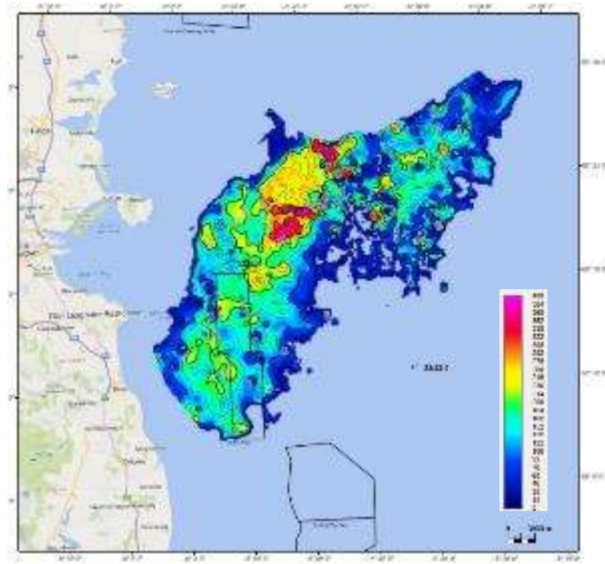
Halite remobilised away from area of 33/17-1 well, towards the northwest, highlighted with red arrow on thickness map.

Figure 13: Rossall Halite Extent in the Kish Basin.

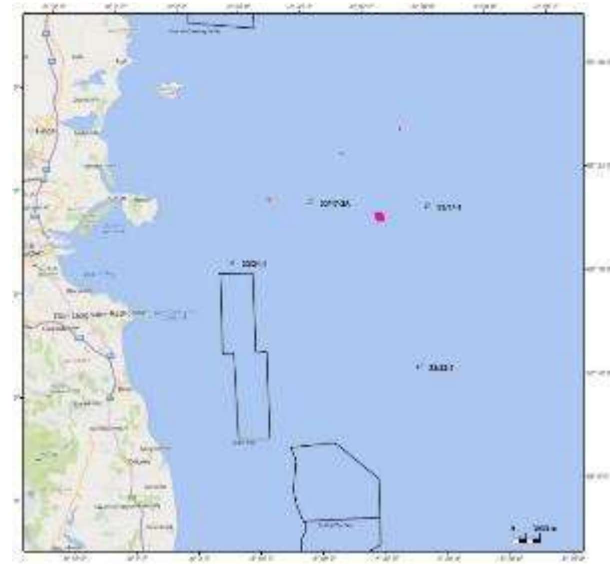
WP2-O1: Flyde Maps



Depth



Thickness



Thickness within AOI

1 to 1.5km & >300m thick

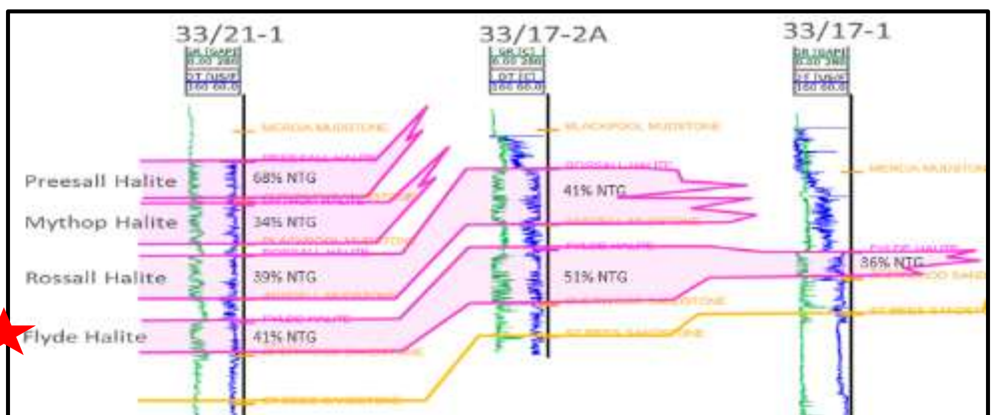


Figure 14: Flyde Halite Extent in the Kish Basin.

WP2-O2: Map of areas with >300m of halite interval, at a depth of 1,000m to 1,500m.

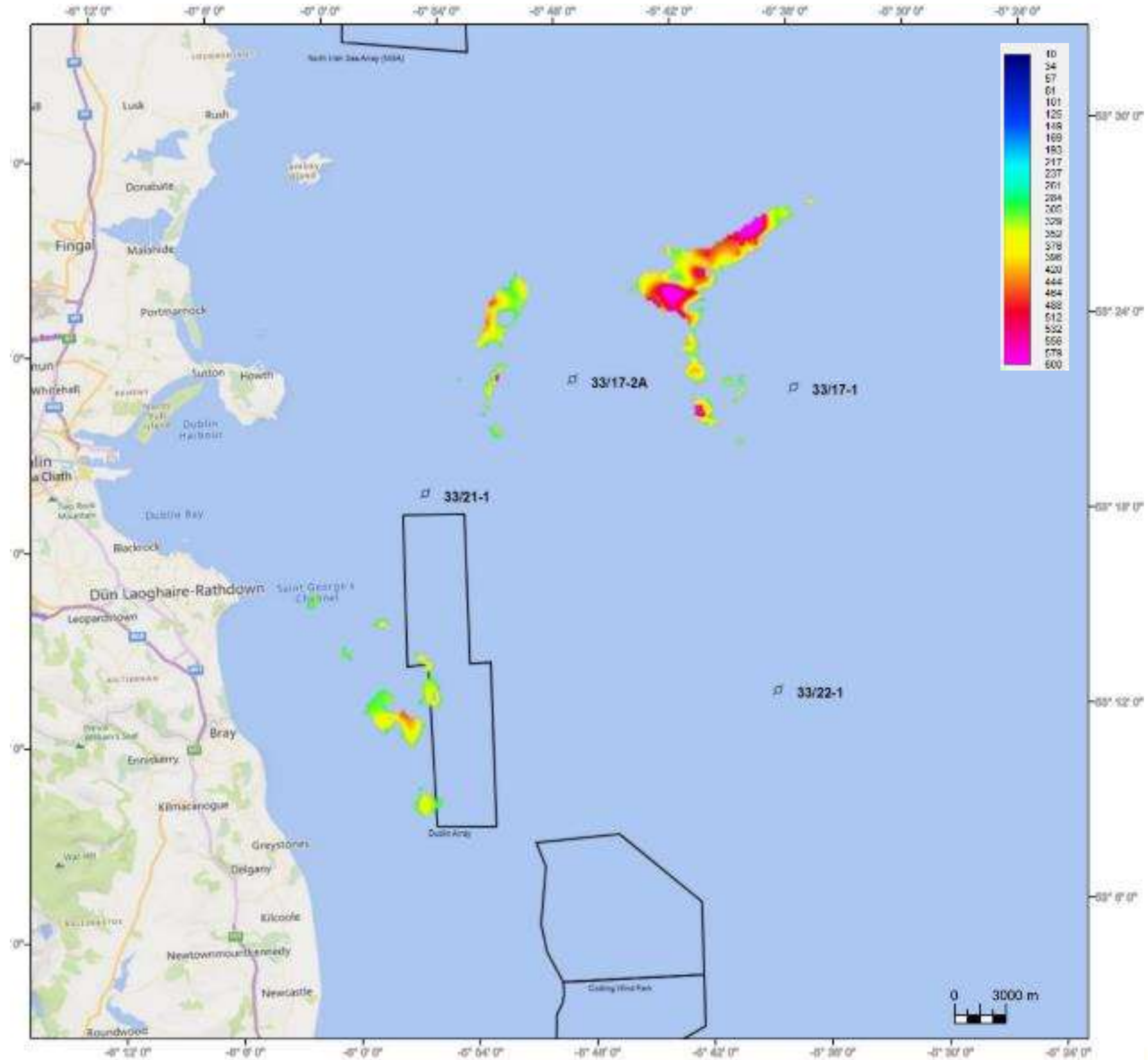


Figure 15: Halite Thickness in the Kish Basin.

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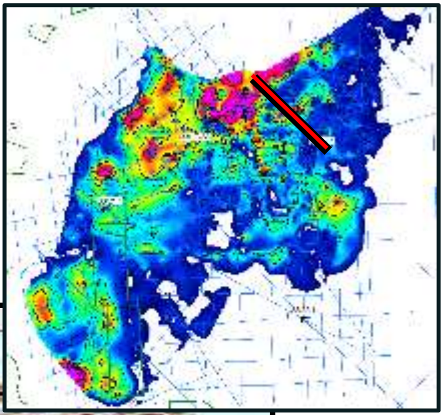
WP2-O2:Seismic Line E95IE18-24 with interpreted halokinesis

Halokinesis evident where halite has moved from thin area to thick area, as annotated by red arrow



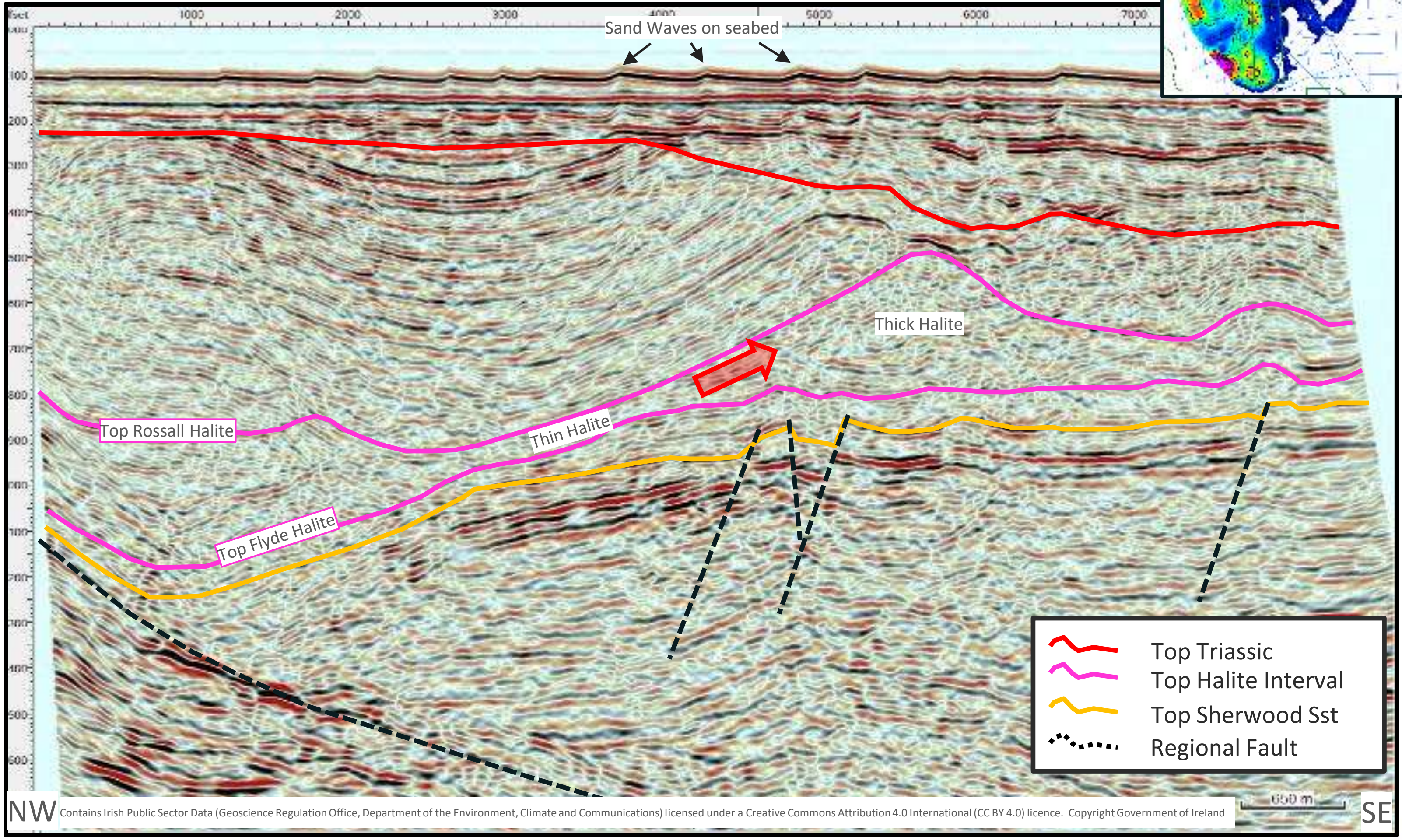
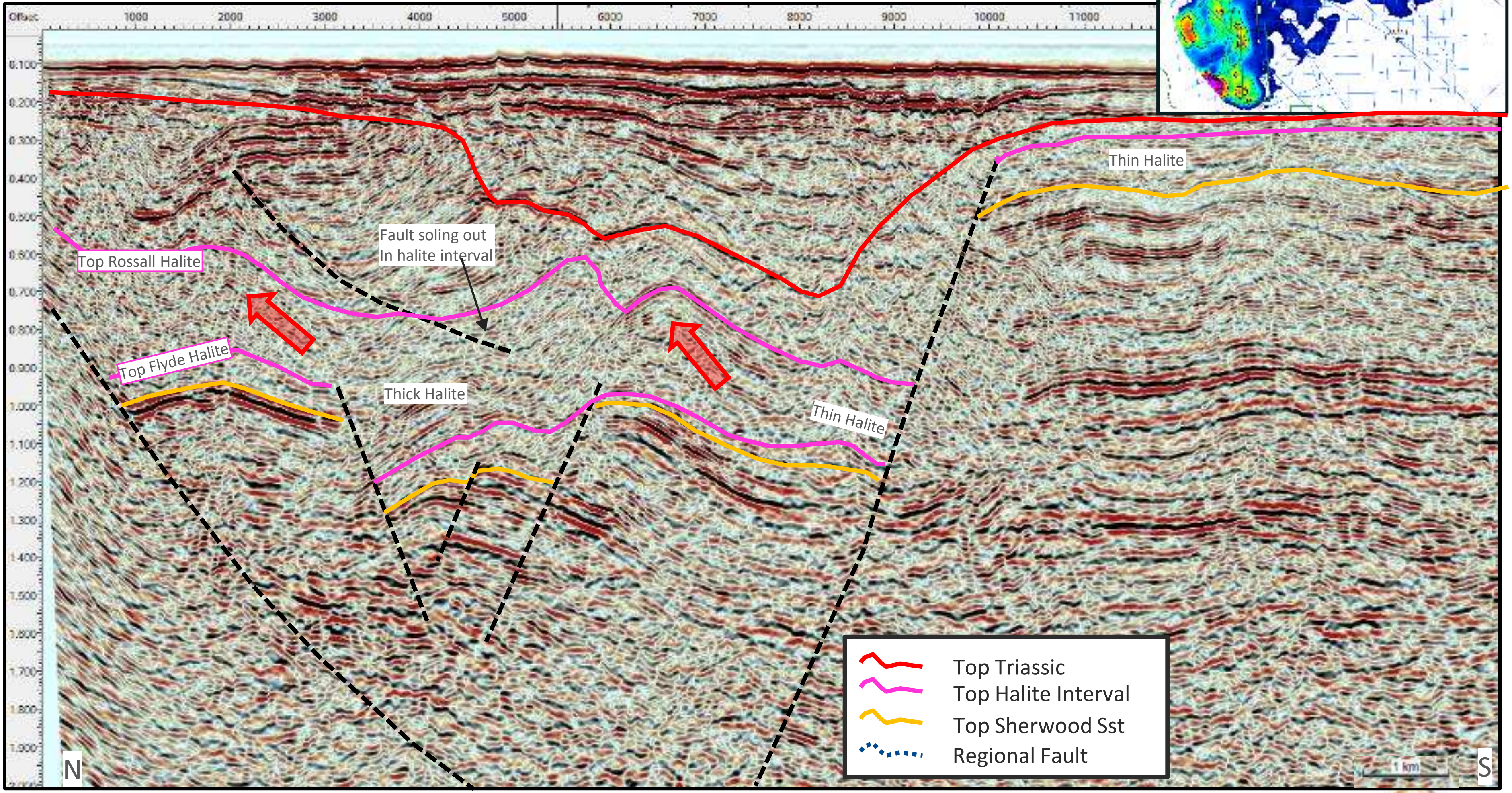


Figure 16: Halokinesis in the Kish Basin.

WP2-O2:Seismic Line E95IE18-21A with interpreted halokinesis

Halokinesis evident where halite has moved from thin area to thick area, as annotated by red arrow.
Note faults are seen to sole out within the thick halite



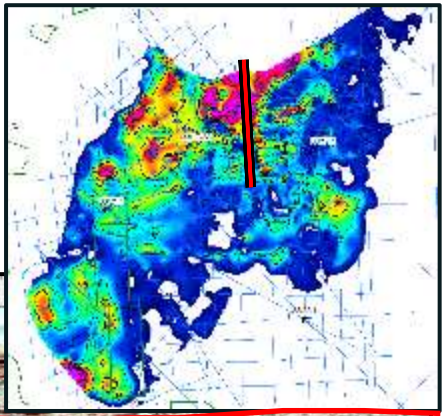


Figure 17: Halokinesis in the Kish Basin.

WP2-O2:Seismic Line E95IE18-23 with interpreted halokinesis

Halokinesis evident where halite has moved from thin area to thick area, as annotated by red arrow.

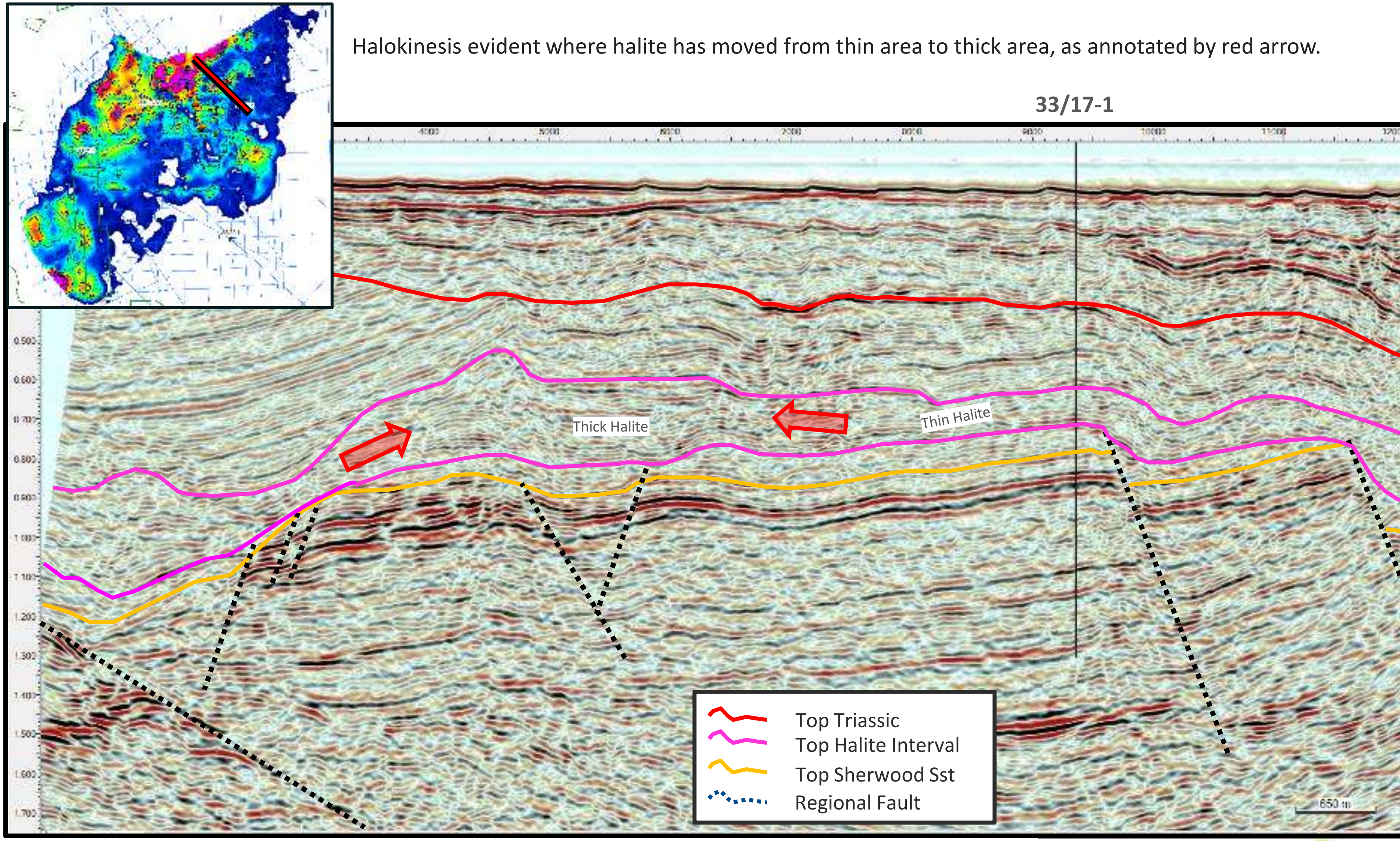


Figure 18: Halokinesis in the Kish Basin.

WP2-O3: Engineering study to assess the maximum theoretical hydrogen storage potential using salt cavern storage methodologies suitable for geological conditions

In the absence of site specific data this study adopted the high level description of an underground storage site of hydrogen in salt caverns as defined in the Hystories project, funded by the EU under the Fuel Cells & Hydrogen Joint Undertaking Program (FCH-JU) (HyStorIES 2021). Most assumptions are either based on a statistical review of existing analogues for natural gas storage or based on engineering judgment in light of existing technical constraints. For an underground storage of hydrogen in salt caverns, the considered scenarios can be summarised as follows (low case resulting in a low investment i.e. low CAPEX, and vice versa):

- Cavern Free Gas Volumes (Low – Mid – High): 815,000 – 380,000 – 185,000 m^3
- Cavern Working Gas Inventory (Low – Mid – High): 62.5 – 31.3 – 15.6 million Sm^3
- Cavern Peak Gas rates (Low – Mid – High): 5.9 – 2.8 – 1.4 million Sm^3/d
- Cavern operating pressure range: 70 – 180 bar
- Storage site with Working Gas target of 250 million Sm3 i.e. cavern / well count (Low – Mid – High): 4 – 8 – 16
- Well completion:

  30" conductor pipe
  20" surface casing string (cemented at 250 m assuming a top salt at 200 m)
  16" intermediate casing (contingent depending on top of salt depth)
  13 3/8" production casing string (last cemented casing shoe @ 1,000 m)
  10 3/4" x 7" leaching completion
  9 5/8" permanent gas completion run with production packer and Downhole Safety Valve (DHSV)

Surface facilities will include all the required equipment to safely operate the storage facility during hydrogen injection and withdrawal phases namely:

- Hydrogen gas dehydration (molecular sieve systems based on the adsorption principle) and treatment units on the withdrawal train(s).
- A gas compression package (reciprocating compressors with electric drive) on the injection train(s) along with cooling units at compressor's discharge.
- Filters and metering packages upstream/ downstream of the storage facility at the hydrogen transportation network.
- Utilities e.g. fuel gas, gas venting, drains systems, firewater, etc.

According to API 1170 (Design And Operation Of Solution-Mined Salt Caverns Used For Natural Gas Storage) cavern solution mining is accomplished by drilling a wellbore into a suitable salt formation, dissolving the salt by circulating fresh or low-salinity water into the wellbore and withdrawing or returning the brine to the surface. As the salt is dissolved in a controlled fashion according to a specific plan, the wellbore grows to form a cavern in the salt formation. Once the geometrical design volume is reached, gas is injected into the cavern displacing and emptying the brine out of the cavern, making it ready for gas storage operations. The wells previously drilled and completed as part of solution mining works are then recompleted to establish a controlled connection between the salt cavern and the surface facilities at the wellhead. They are used for gas storage service i.e. gas cycling with injection / withdrawal cycles based on business needs and storage operating strategy. The walls of caverns formed in subsurface salt structures are practically impermeable to gas up to specific pressure thresholds, ensuring containment of the gas stored in the cavern. In addition, fractures and faults within the salt formation are healed by the viscoplastic behaviour of the salt under the overburden pressure (HyStorIES 2021).

WP2-O3: Engineering study to assess the maximum theoretical hydrogen storage potential using salt cavern storage methodologies suitable for geological conditions

In the absence of specific site information typical salt cavern geometry values were taken from the Hystories project (see Fig 2). From an economic point of view, excessively small caverns tend to be marginal as some fixed costs are carried regardless of cavern size (leaching station construction and commissioning, connection to gas infrastructure, fixed drilling costs, etc.). From a technical point of view, excessively large caverns present some challenges too as they imply longer leaching durations, increased leaching rates that require large diameter pipe with increased lead times and costs, drilling challenges and the need for heavier duty drilling rigs. The Hystories project proposed a salt cavern with a Free Gas Volume ranging from 185,000 m^3 to 815,000 m^3 as optimum.

The calculations of cavern storage capacity were made using the methodology of Caglayan *et. al.* 2020 and Williams *et. al.* 2020. The results are shown in Table 1 and Table 2. There is a difference of 41 GWh_{H2} for a typical salt cavern at a depth of 1,200m with a height of 120m, diameter 84m and safety factor of 70%. The safety factor is applied to take account of the bulk insoluble residue and brine volume left after the cavern solution (see Fig 2). The difference can be attributed to the slightly different methodologies used.

A typical salt cavern can store between 146 GWh_{H2} and 105 GWh_{H2} of hydrogen. The extent of salt occurrence in the Kish Basin at the required depth of 1,000m and 200m thickness is such that many salt caverns could be solution mined, sufficient for seasonal hydrogen storage. (see Figure 19).

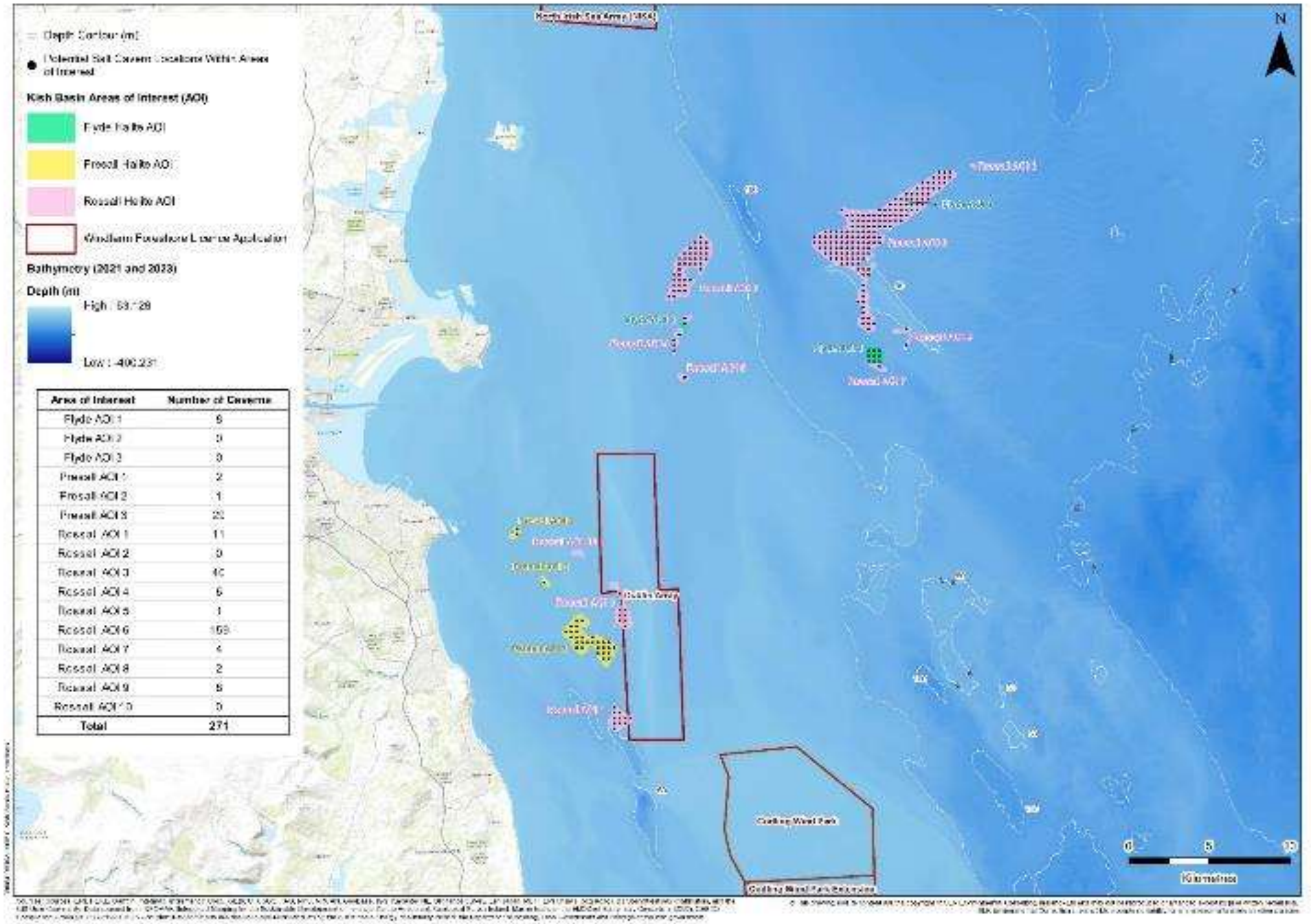
Temperature (K)	Overburden Pressure	*Compressibility Factor*	Gas Density (ρ_{H2})	*ρ_{H2} maximum*	*ρ_{H2} minimum*	Mass of Working Gas (kg) (m)	Cavern Capacity (GWh_{H2})
Temperature (T) = 288+0.025(depth-cavern height/2)	Overburden (P) = rock density (ρ) x Gravity (g) x (depth - cavern height)		(ρ_{H2}) = pressure (P) x molar mass (M) / compressability factor (Z) x universal gas constant (R) x temperature (T)	*(ρ_{H2}) = pressure (80% of overburden) x molar mass (M) / compressability factor (Z) x universal gas constant (R) x temperature (T)*	*(ρ_{H2}) = pressure (24% of overburden) x molar mass (M) / compressability factor (Z) x universal gas constant (R) x temperature (T)*	m = (ρ_{H2} max - ρ_{H2} min) x cavern volume (V) x safety factor (θ)	working gas (m) x lower heating value of gas (LHV)
K	Pa	Z	kg m^{-3}	kg m^{-3}	kg m^{-3}	kg	GWh_{H2}
316.5	23308560	*1.05(estimate)*	17.852	13.541	4.101	4394270.85	146.418

Table 1: Calculation of cavern storage capacity. Source: Caglayan *et. al.* 2020

Modelling cavern volumes	*Estimation of hydrogen storage volumes*				Caglayan		*Energy Storage Capacity*				
Volume available for storage	Temperature (Midpoint)	Lithostatic Pressure	Max Op Pressure	Min Op Pressure	ρ_{max}	ρ_{min}	Equation of State	Max H2 Density	Min H2 Density	Mass of Working Gas	Energy Storage Capacity (GWh_{H2})
V_{cav} = SCF x [1 - IF x [illegible]] x [illegible]	[illegible]	[illegible]	[illegible] = 0.8 x [illegible]	[illegible] = 0.3 x [illegible]	*(ρ_{H2}) = pressure (80% of overburden) x molar mass (M) / compressability factor (Z) x universal gas constant (R) x temperature (T)*	*(ρ_{H2}) = pressure (24% of overburden) x molar mass (M) / compressability factor (Z) x universal gas constant (R) x temperature (T)*	Williams uses equation of state from [illegible] to calculate ph2 Max and Min	[illegible]	[illegible]	[illegible]	E = [illegible] x (LHV/3,600,000)
m^3	K	Pa	Pa	Pa	kg m^{-3}	kg m^{-3}				kg	GWh_{H2}
318530.01	314.65	26977500	21582000	8093250	16	6		5045234	1891963	3153272	105.074

Table 2: Calculation of cavern storage capacity. Source: Williams *et. al.* 2020

WP2-O3: Map of Halite areas with >300m of halite interval, at a depth of 1,000m to 1,500m showing number of salt caverns in each zone of interest



Area of Interest	Number of Caverns
Flyde AOI 1	6
Flyde AOI 2	0
Flyde AOI 3	0
Frosall AOI 1	2
Frosall AOI 2	1
Frosall AOI 3	22
Rossal AOI 1	11
Rossal AOI 2	0
Rossal AOI 3	40
Rossal AOI 4	6
Rossal AOI 5	1
Rossal AOI 6	159
Rossal AOI 7	4
Rossal AOI 8	2
Rossal AOI 9	8
Rossal AOI 10	0
Total	271

This map shows the areas where the halite occurs at depths of 1,000m to 1,500m and is more than 300m thick, the optimum depth and thickness for salt cavern storage of gas in the Kish Basin.

Overlaying a simple grid of potential cavern sizes and separations (white dots) yields a potential for 271 caverns in the Kish Basin area, see table in the legend. It also shows that in the zone of interest A09, which lies beneath the offshore wind licence area for the Dublin Array, there is the potential for 8 standard size salt caverns to be developed for hydrogen storage. This is equivalent to approximately 1.0 TWh_{H2}. Additional maps are provided in the Appendices.

Figure 19: Identified areas of interest in the Kish Basin with potential caverns.

WP2-O4: Regional geohazards study to assess the risks to surface and subsurface operations

A variety of datasets have been integrated into the HYSS project to assess the potential geohazard risks on the seabed and subsurface in the Kish Basin area to any potential offshore renewable energy development. Key datasets from Geological Survey Ireland (GSI) INFOMAR and the Dept. of Environment, Climate and Communications (DECC) were reviewed, correlated and integrated to highlight the various metocean, geological and sedimentological processes at play in this region.

There is a large variation of tidal current speeds around Ireland with the currents being generally lower along the west and south coasts when compared to relatively strong currents in the Irish Sea. Dominant current direction is from the south, large asymmetric sand waves can be seen. Spring tide bottom current velocities indicate the competency of the tidal currents to transport solids and therefore localised scour around protruding subsea foundations can occur (SIPM EPI24 November 1979). Subsea scour around spud cans did occur during the drilling of well 33/22-1 by the jack up rig Penrod 81 in 1979. Large northerly migrating sand waves with a maximum height of 13 metres and a wavelength of between 400 and 500m occur 18km to the NE at well location 33/17-1 (Gardline Surveys 1986).

The last glacial event to have affected the Irish Sea (the Devensian) occurred from approximately 34,000 years before present to 12,000 year before present. Ice sheets merged across much of northern Britain and Ireland to form the British and Irish Ice Sheet (BIIS). The effects of this are found throughout the Irish Sea. The site survey for well 33/21-1 (SIPM EPI24 November 1979), just north of the Dublin Array licence area identifies on the seismic records a glacial till with point source diffractors suggesting boulders at 60m below the seabed. The presence of boulders caused delays in the driving of the steel conductor for well 33/21-1. This is a potential hazard for the drilling of a salt solution mining borehole as well as any potential cable route or pipeline.

Seismic velocities have been used to help quantify the geohazard risks in the Kish basin. They generally follow a normal compaction trend whereby recent sediments exhibiting slow velocities in the shallow section and faster velocities deeper in the stratigraphy. The higher velocity values are representative of harder more resistive rocks that are older in age.

The geohazard study has highlighted several risks posed by the presence of shallow gas, near surface glacial channel complexes, tectonically active faults and protruding Cretaceous rocks at or near the seafloor. All of which can be successfully mitigated by careful planning, additional data acquisition and processing and integration of existing disparate datasets.

WP2-O4: Regional geohazards study – Integrating Geo Datasets

INFOMAR (Integrated Mapping For the Sustainable Development of Ireland's Marine Resource) is the national seabed mapping programme managed jointly by Geological Survey Ireland and the Marine Institute.

The primary acoustic devices used by the INFOMAR programme are Multibeam Echosounder (MBES), Singlebeam Echosounder (SBES), Shallow Seismic / Sub Bottom Profiler (SBP), and Side Scan Sonar (SSS).

The bathymetric data is a dataset that has being acquired and processed is to international hydrographic standards. It produces high quality digital maps that are easily accessible through the INFOMAR data portal.

The SBP/HRSS are the most valuable geophysical datasets when constructing an accurate ground model particularly for offshore fixed bottom installations and cabling onshore. Data acquisition gaps should be considered, as there are areas where data still needs to be acquired as part of programme strategy to end 2026.

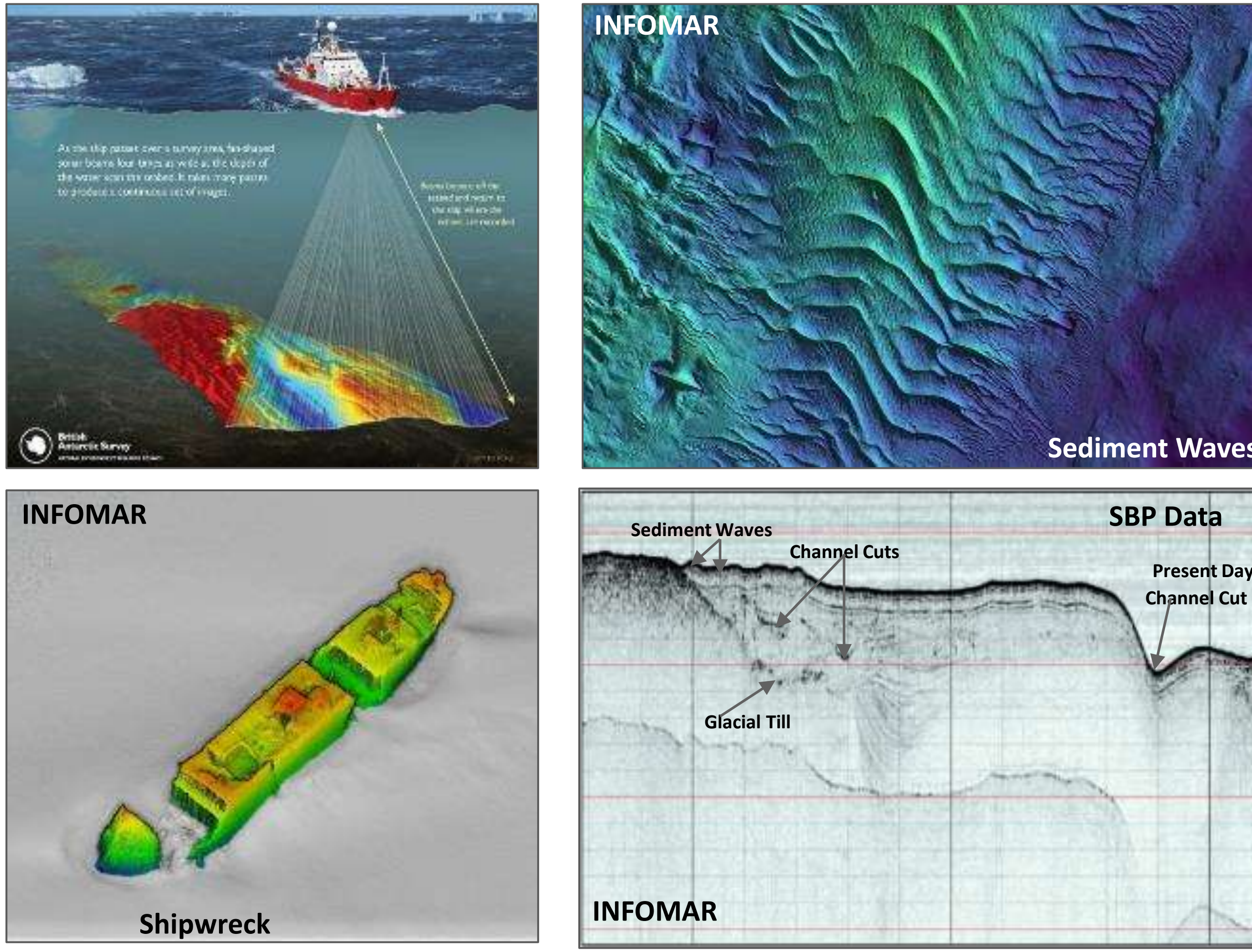


Figure 20: Geophysical datasets and outputs.

WP2-O4: Regional geohazards study – Bathymetric Data

The primary aim of INFOMAR as a marine mapping project is to describe the physical features of the seabed. This includes the measurement of water depth (bathymetry), definition of seabed structures and identifying sediment type and distribution, both on and below the seabed.

The bathymetry map is achieved using a range of hydrographic and geophysical instruments. Acoustic devices emit sound energy, in a series of continuous pulses, into the water column and detect the returning echoes. This is called sonar. Different echo strengths indicate different seabed features (or morphology) and the different physical characteristics of the seafloor. By knowing the speed at which sound travels through water (approx. 1500 m per second), depth can be calculated from the echo return time. This method produces extremely accurate measurements, which when coupled with accurate positioning systems and motion sensors can be used to produce accurate seafloor maps.

Included on the adjacent figure is the onshore geology map from the Geological Survey Ireland (GSI) as well as the INFOMAR bathymetry map. These are two of the key datasets that are crucial to integrate to understand the inherent complexities of the seabed and subsurface sediments. Even at this regional scale, differences in the seabed sediment signature can be seen, this has been driven by the erosion and transportation of the onshore geology into the offshore in conjunction with the prevailing metocean conditions.

There appears to be a large amount of sand and coarse sediments across the Kish Basin area. The sediments appear to be mobile as there are several large-scale sediment waves. It is essential to understand the rate of mobility of these features and what impact they will have on any proposed offshore development over time.

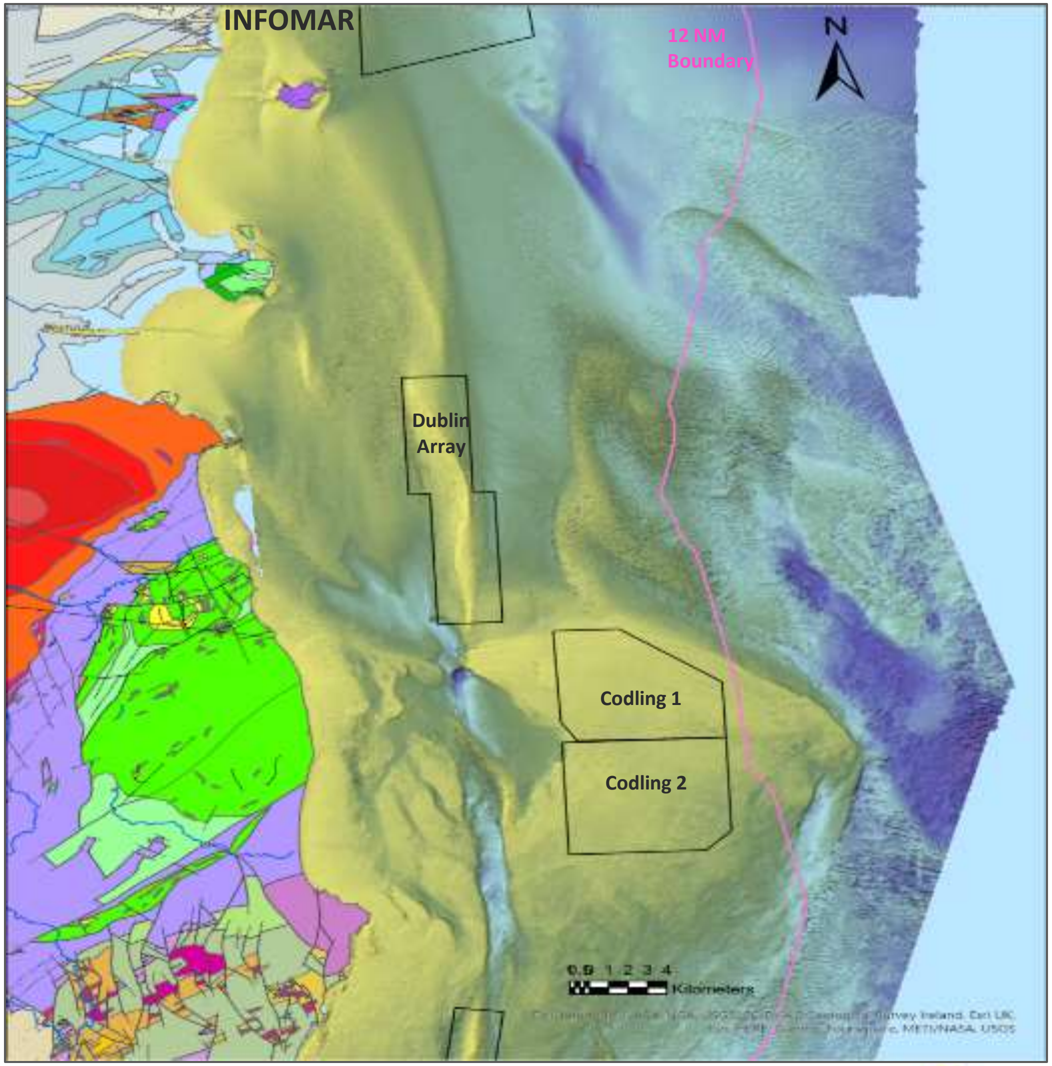
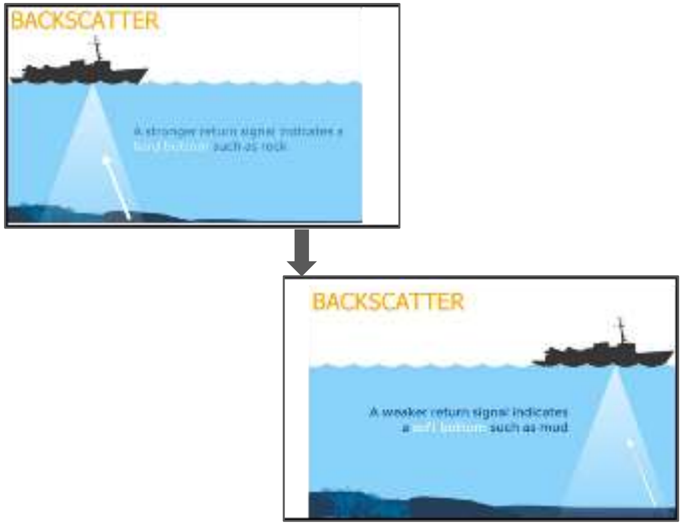


Figure 21: Onshore Geology and Bathymetry Map.

WP2-O4: Regional geohazards study – Backscatter Data



Multibeam systems also collect information about the type of seafloor and can distinguish between mud, sand, gravel, and rock. Different seafloor types return the signal with different levels of energy, this is known as backscatter.

This information can be used to determine the physical nature of the seabed, because different bottom types "scatter" sound energy differently. For example, a softer bottom such as mud will return a weaker signal than a harder bottom, like rocks or gravel. These differing values in intensity are used to examine the nature of the seafloor in a backscatter chart.

The backscatter signal in this area varies across the region as does the onshore geology. For example, the area around the Dublin Array is a low intensity signal, this coupled with the onshore granitic hinterland being eroded by modern and past river systems indicate sand deposition in this area.

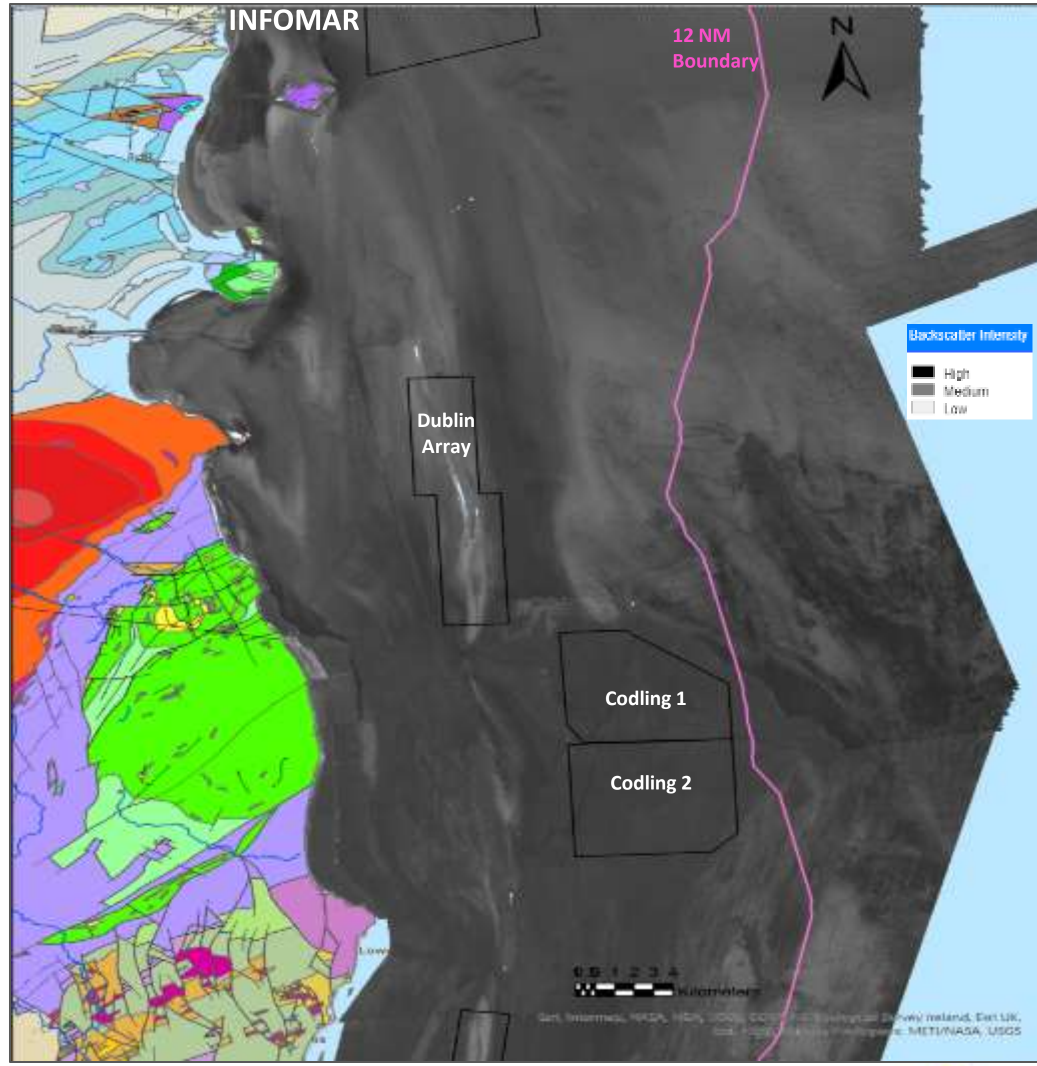


Figure 22: Onshore Geology and Backscatter Map.

WP2-O4: Regional geohazards study – Seabed Sediment Classification

Combining bathymetry, backscatter and grab samples allows for the creation of ‘sediment classification’ maps. These provide information on the type of seabed substrate with application to marine spatial planning.

Care must be taken when integrating these datasets as the backscatter is only a relative property and can easily lead to misinterpretation of the ground conditions. The sediments recorded in the grab samples may not be in situ and representative of the local seabed.

It's important to integrate these datasets correctly to understand the complex relationships between sediment deposition and erosion. It is essential to understand the regional onshore geology, drainage systems in conjunction with the tidal currents and weather patterns to build a dynamic seabed model. There is a good correlation between changes to the onshore geology and offshore sedimentology.

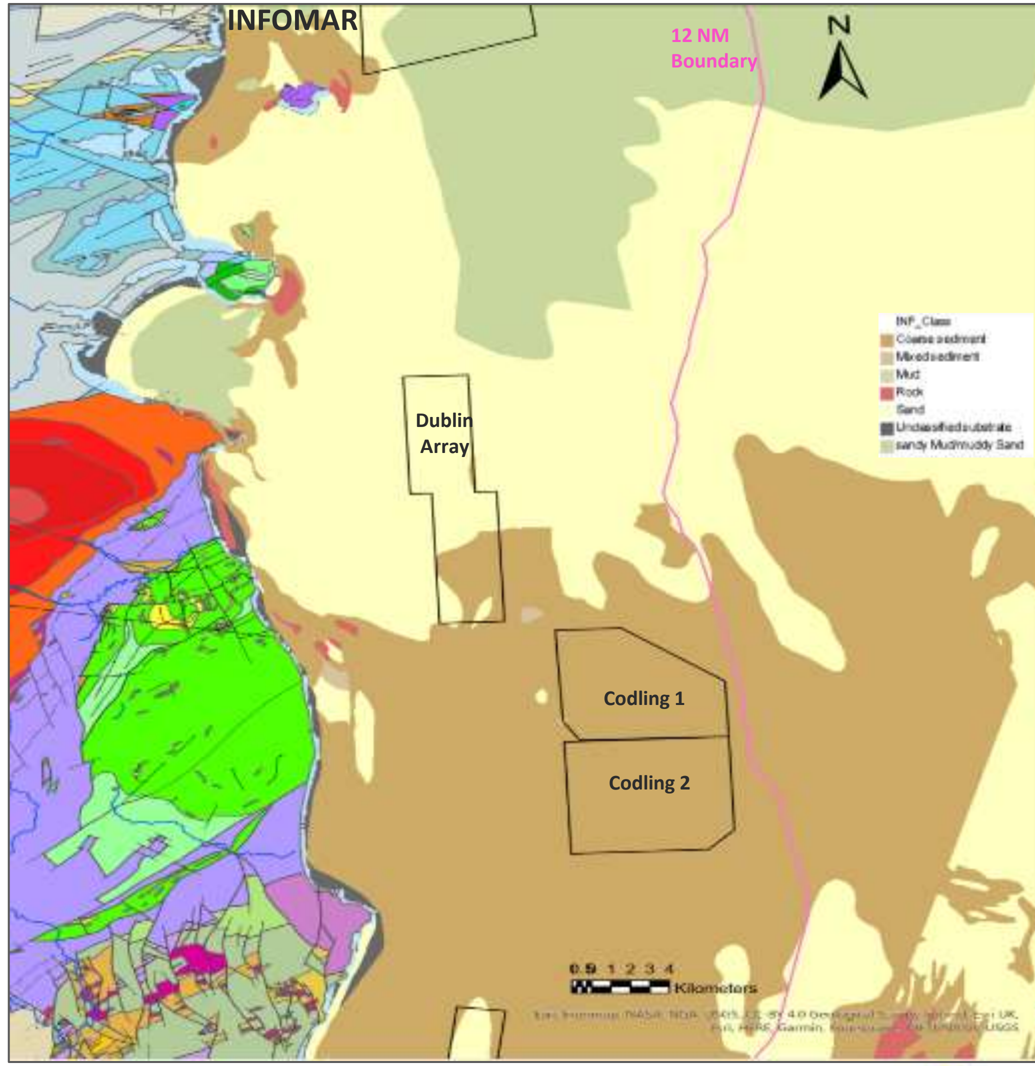
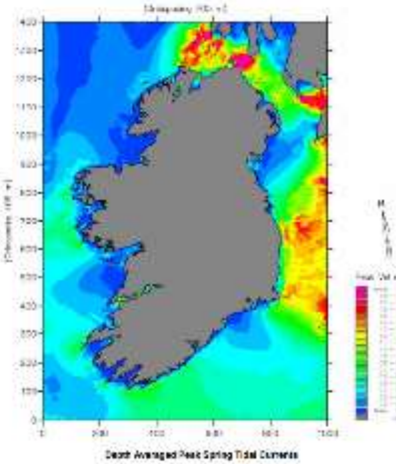


Figure 23: Onshore Geology and Sediment Classification Map.

WP2-O4: Regional geohazards study – Tidal Currents and Sediment Mobility

Source – SEAI



There is a large variation of tidal current speeds around Ireland. The currents are generally lower along the west and south coasts when compared to relatively strong currents in the Irish Sea and North Channels. The current strengths are influenced considerably by the local bathymetry.

There is a good correlation between current strength and sediment mobility. There have been several research papers published on this.

A recent publication by Creane *et. al.* 2022 looked at morpho dynamics of sediments in the Southern Irish Sea.

High-resolution, time-lapse bathymetry datasets, hydrodynamic numerical modelling outputs and various theoretical parameters were used to describe the morphological characteristics of sediment waves and their spatial and temporal evolution in a hydrodynamically complex region of the Irish Sea. Analysis reveals sediment waves in a range of sizes (height = 0.1 - 25.7 m, and wavelength = 17 - 983 m), occurring in water depths of 8.2 - 83 mLAT, and migrating at a rate of 1.1 - 79 m/yr. Combined with numerical modelling outputs, a strong divergence of sediment transport pathways from the previously understood predominantly southward flow in the south Irish Sea is revealed, both at offshore sand banks and independent sediment wave assemblages. These results improve knowledge of seabed morphodynamics in tidally dominated shelf seas, which have direct implications for offshore renewable developments and long-term marine spatial planning.

(A) location of Arklow Bank; (B) sediment wave shape with locations of cross-sections a & b; (C) and (D) sediment wave translation rates.(B) and (C) bathymetry source: composite map produced from INFOMAR datasets (https://www.infomar.ie/data) (D) bathymetry source: 2016: INFOMAR survey; 2020: MOVE survey

Source –Creane, Coughlan, O'Shea, Murphy 2022

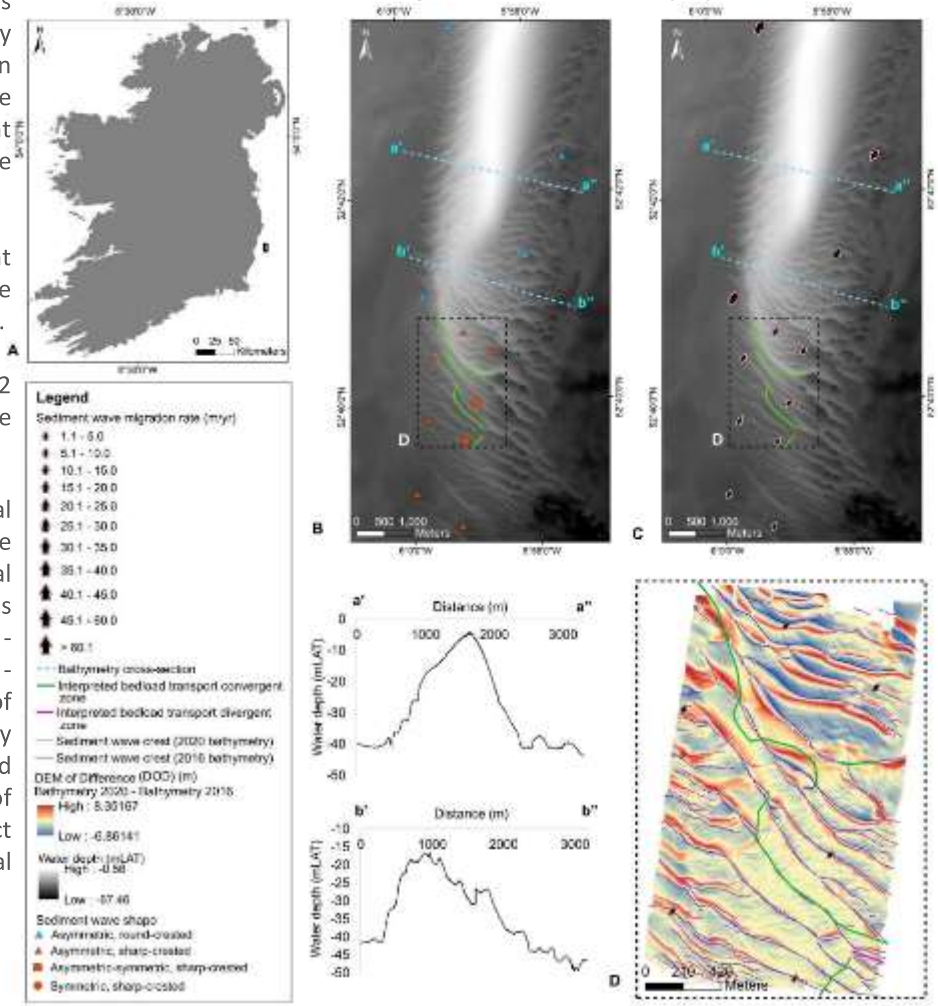
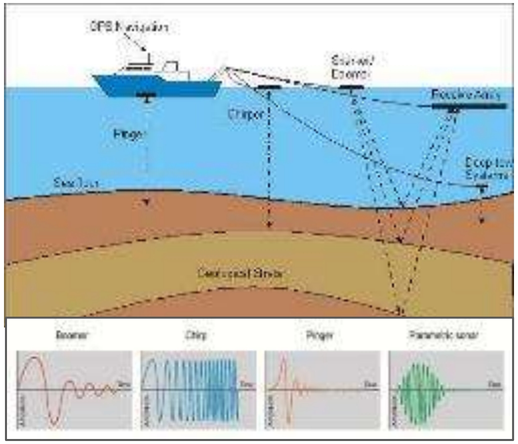


Figure 24: Sediment wave translation rates & shapes at Arklow Bank, Irish Sea.

WP2-O4: Regional geohazards study – Survey Coverage & Vintages

Figure 25: Offshore Geophysical Instruments.



The Sub Bottom Profiler (SBP) datasets includes various types of shallow seismic systems including 'Pinger' systems which transmit a single frequency (~4 kHz) and 'Chirp' systems which transmit a sweep of frequencies (e.g. 2-10 kHz) in a single pulse. These systems operate in a similar way to SBES but use lower sound frequencies that penetrate further into the sediment and examine sediment layers and the extent of bedrock. This information is crucial when building offshore marine infrastructure such as wind turbines, cables and pipelines.

It is important to note that the SBP does not identify sedimentary materials, but rather changes in the acoustic impedance (density) of the subsurface geology between each stratigraphic sequence. Sediment penetration of up to 50 m can be achieved in soft sediments in favourable conditions, however this is rarely the case as sediments with 'hard' acoustic signals often act as obstacles to achieving optimum subsurface imagery.

A Sparker/Boomer is a device used for sub-seabed investigations where deeper acoustic penetration is required. It is generally more powerful than a SBP and used to explore very coarse/compacted seabed.

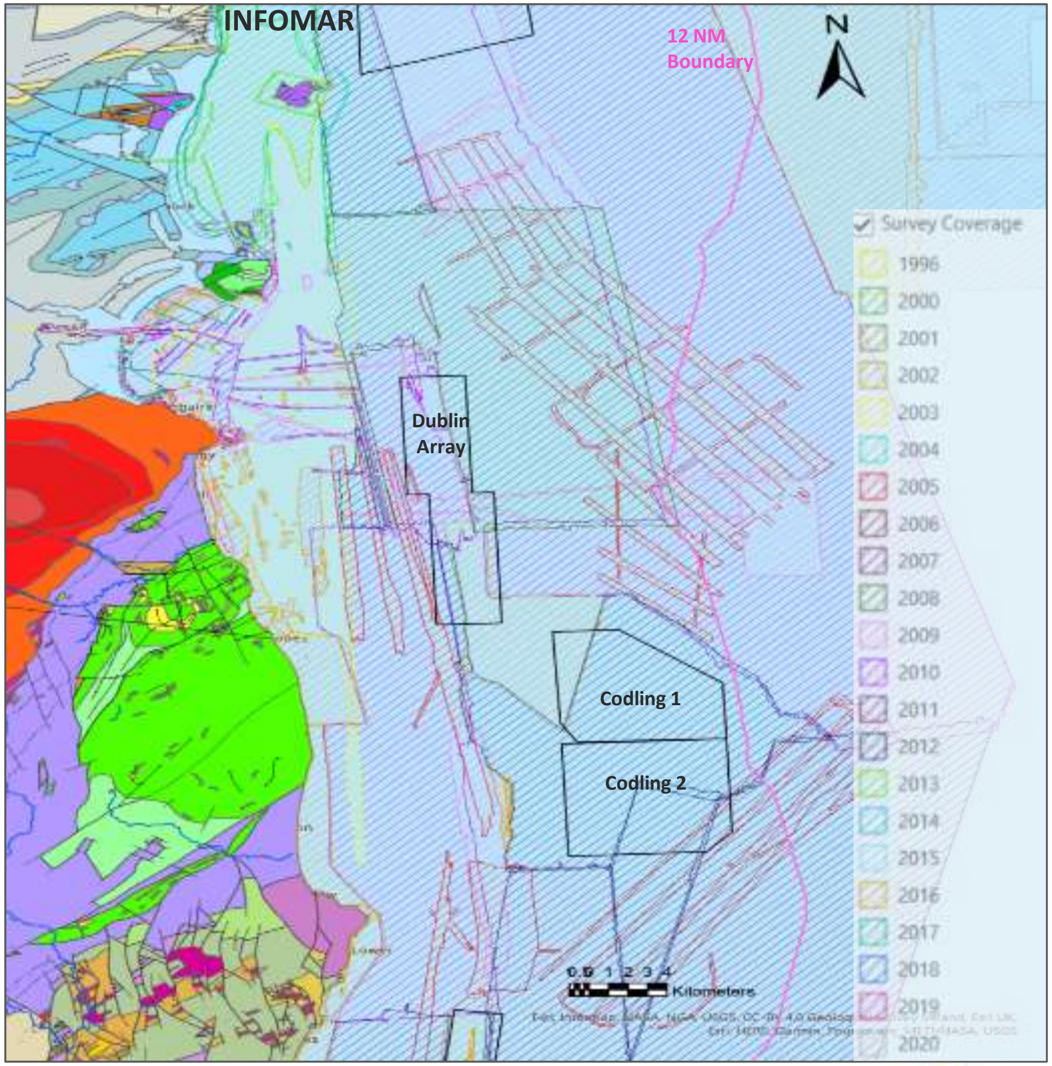


Figure 26: Onshore Geology and Survey Coverage Map.

WP2-O4: Regional geohazards study – What lies beneath?

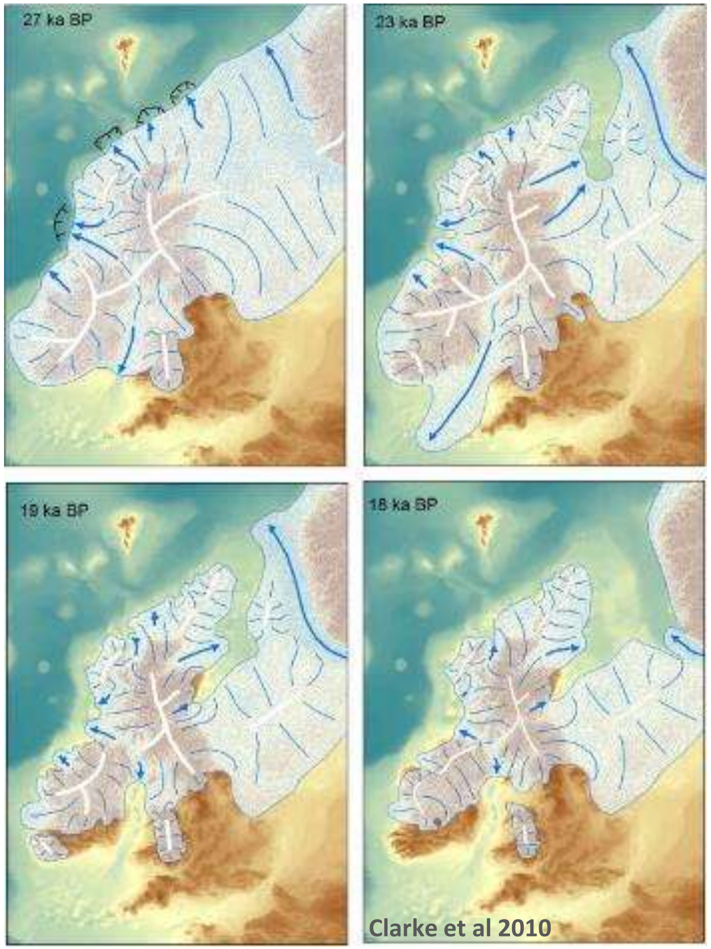


Figure 27: Extent of Ice Sheets.

When attempting to illuminate the shallow subsurface beneath the seabed it is important to understand the recent geological history of the area as this will inform the processing of the data and final deliverables. It is an iterative process between the acquisition, processing and interpretation teams to ensure the best imagery is achieved to uncover what lies beneath and expose any potential hazards and risks to the development.

The Quaternary geological period (2.59 million years ago to present) much of Northern Europe including Ireland experienced extensive ice-sheet cover during several glacial events. During these events, glaciers and ice sheets formed in upland areas before advancing across the landscape both marine and terrestrial, creating various glacial environments where sediments were deposited or eroded depending on the stage of ice sheet advance or retreat. The last glacial event to have affected the Irish Sea (the Devensian) occurred from approximately 34,000 years before present to 12,000 year before present. Ice sheets merged across much of northern Britain and Ireland to form the British and Irish Ice Sheet (BIIS). A large ice stream within the BIIS flowed through the Irish Sea, often referred to as the Irish Sea Ice Stream (ISIS), reaching its maximum geographic extent to the south at 24,000 – 23,300 years before present.

The glacial deposits can pose some problems when trying to establish the foundations for wind turbines, as well as cable and pipeline routes as large boulders can be extremely difficult to penetrate and require more expensive engineering solutions to infiltrate. Fast-flowing ice streams operated in Pleistocene ice sheets. The reconstruction of palaeo-ice streams relies on the mapping of mega-scale glacial lineations (MSGLs) and drumlins composed of soft sediment, mainly till. These are attributed to erosion of crystalline and sedimentary rock below fast flowing ice streams. Bedrock properties such as hardness, fracture spacing, and bedding can have a profound effect on the post glacial topography.

A seismic facies correlation by Coughlan *et. al.* 2019. in the Dundalk bay area calibrated CPT and cores with Sparker data to provide a litho-seismic description for varies units including an Upper Till formation.

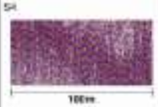
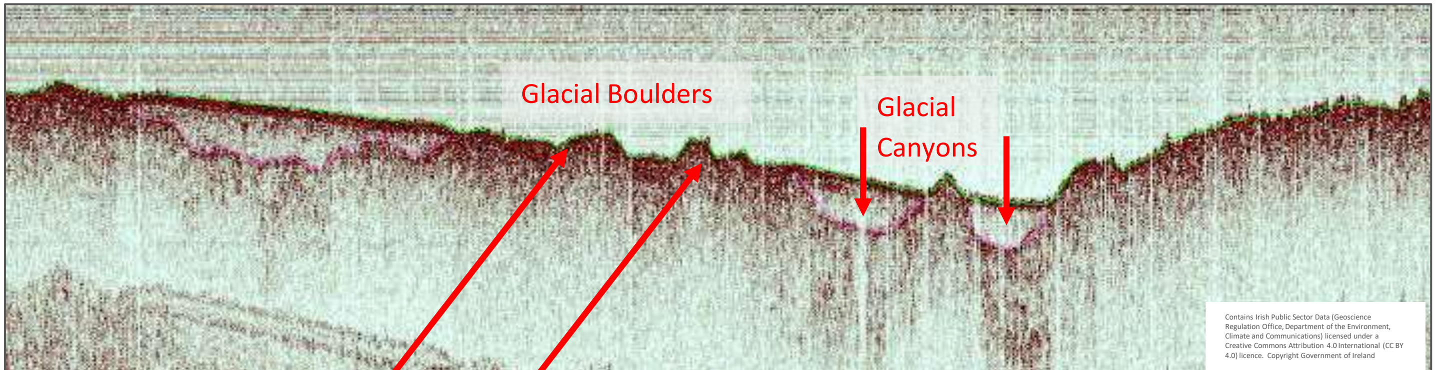
Unit Code	Seismic Unit & Facies Example	Unit Description (This Study)	Unit Thickness (m)	Cone Resistance (MPa)	Pore Pressure (MPa)	Undrained Shear Strength (kPa)	Correlation with Jackson et al. (1995)
Unit 4	S4  100m	Seismic: - Overlies R2 - Strong, high-angle reflectors - Discontinuous - Chaotic Core: - Stiff, dark clay with cobbles and pebbles	1 - 12	Up to 30	<0	Average: 148 Range: up to 1,250	Upper Till - Till comprising stiff or hard clay with clasts of sand to boulder size - Subglacial

Figure 28: Seismic Facies Correlation, Irish Sea

WP2-O4: Regional geohazards study – Sub Bottom Profiler Data

The cross sections below are from INFOMAR pinger datasets that are highlighting some of the glacial features that are found protruding and beneath the seabed in the inboard area. This dataset is needed to define the subsurface units and depth to bedrock.

SBP data quality can be variable, ranging from poor to good nationally. Most of the available SBP data is Pinger data. This has a higher frequency content than Sparker/Boomer shallow seismic data but has a shallower depth of penetration as it has a weaker source.



Whilst the seabed and its processes are important considerations when designing an offshore development, it is what lies beneath the seabed that is of greater importance to the engineering solution.

Glacial canyons are visible just beneath the seabed , the base of these canyons can be seen as a high amplitude, acoustically hard continuous reflector that subcrops on to the seabed and exhibits a surface expression that can be interpreted as being glacial boulders.

Reprocessing the pinger dataset would enhance the image and give a more thorough understanding of the subsurface.

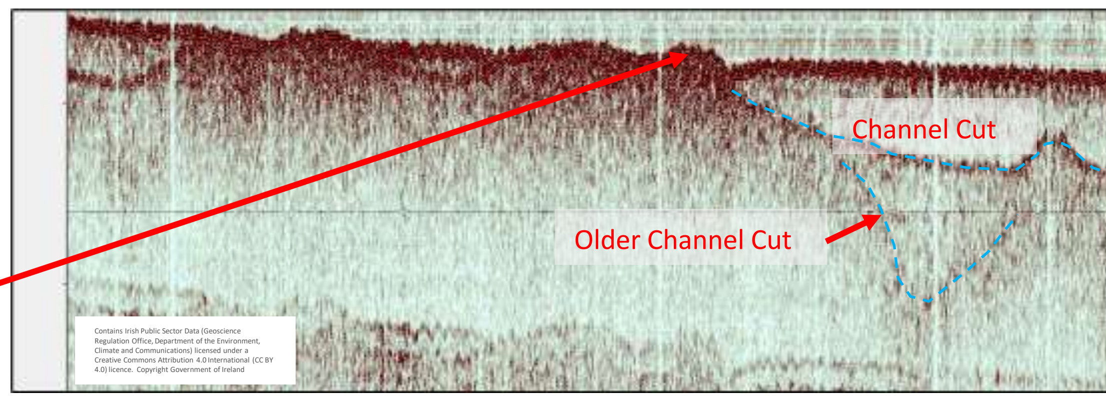


Figure 29: Glacial Features in the Irish Sea

An older channel cut lies beneath a younger glacial channel. The heterogeneous sediments found within the channels will change vertically and laterally and will need to be incorporated into the ground model.

Acoustic energy is becoming dispersed on the 'hard' unit above thus compromising the image below.

WP2-O4: Regional geohazards study – Integrating various datasets

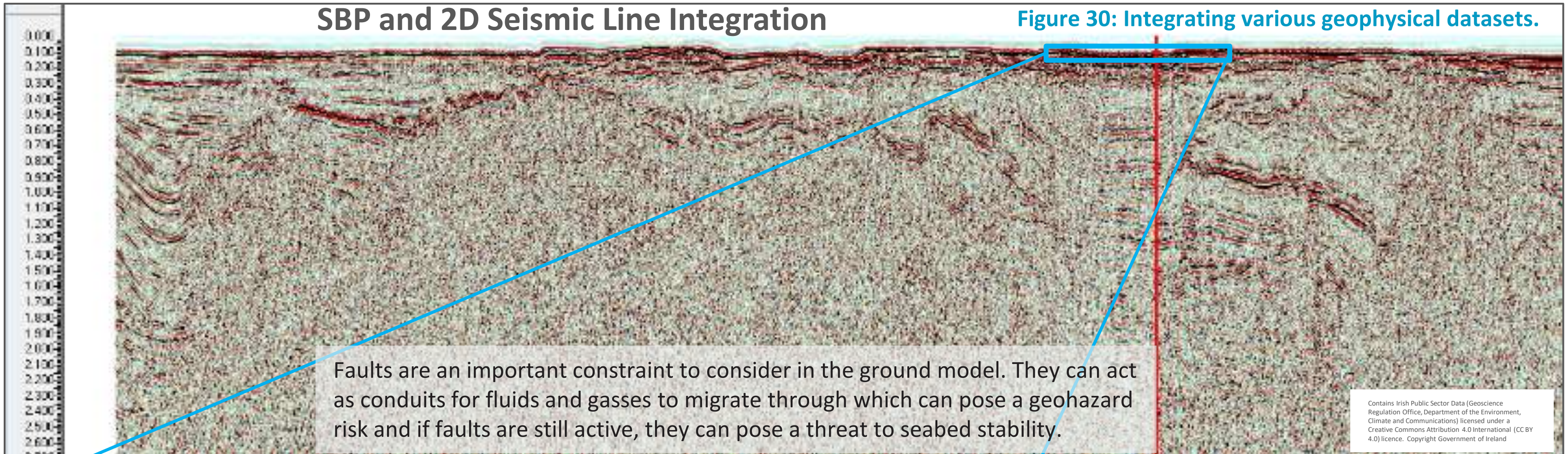
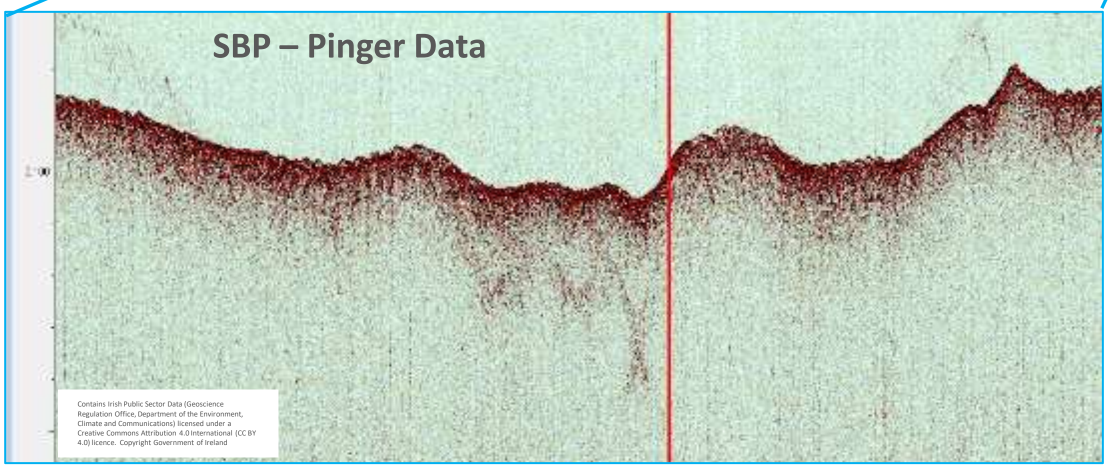


Figure 30: Integrating various geophysical datasets.



When taken in isolation the SBP line shows a possible deeper subsurface canyon and a thin covering of sediment before a transparent zone which could be interpretated as bedrock. The 2D deep seismic line is showing a much more complex tectonic story with a series of faulted grabens, rotated at different angles with some small anticlinal and larger synclinal features. The sedimentary package appears to be much deeper here compared to the SBP line and there are several deep-rooted faults that link to the seabed. The SBP line penetrates approx. 50 milliseconds (approx. 37 meters) beneath the seabed, whereas the 2D seismic line is penetrating over 2 seconds (approx. 3000 metres). A major fault that can be seen on the deep seismic line appears to be influencing the formation of the seabed canyon where both lines intersect. This is not possible to deduce from the SBP line alone.

Most INFOMAR survey acquisitions have been optimally designed for acquiring the bathymetric data, which may account for some of the poorer quality lines. There is a definite improvement in the SBP data as the INFOMAR programme evolved over time, as key learnings and advancement in techniques fed into enhanced acquisition and processing.

WP2-O4: Regional geohazards study – Data Quality and Quantity

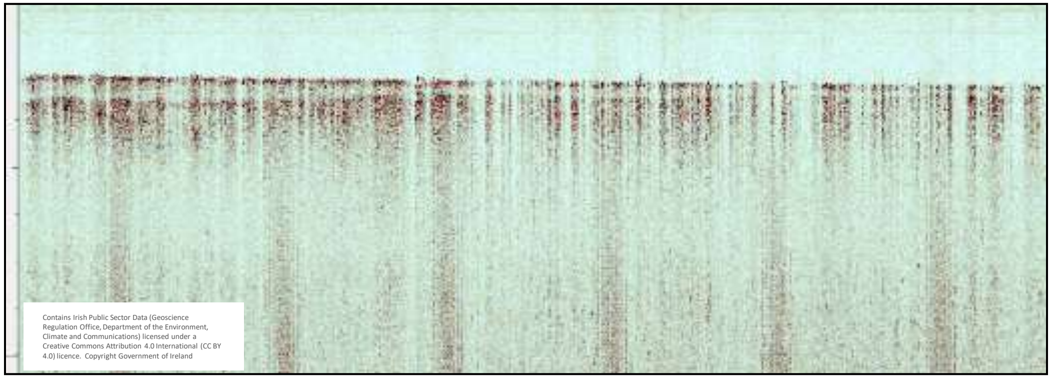


Figure 31: Poor quality pinger line from Kish Basin.

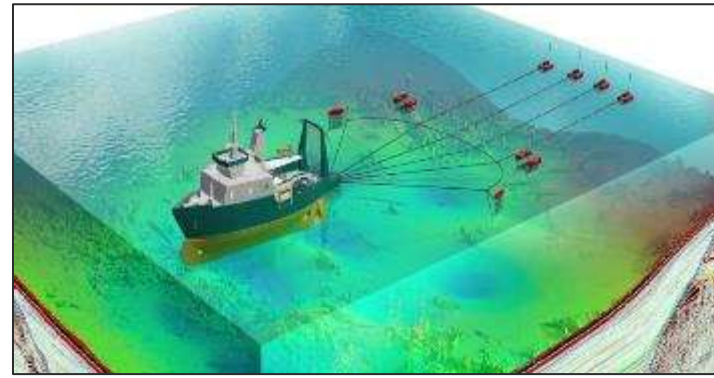


Figure 32: High quality 3D site specific survey acquisition.

The primary driver and deliverable for the INFOMAR programme is the completed baseline bathymetric mapping of the Irish seabed. Because of this, the sub bottom profile (SBP)data (shallow seismic) has suffered as it was considered a value-added product.

Data quality is variable, ranging from poor to good. The survey acquisition has been optimally designed for acquiring the bathymetric data, which may account for some of the poorer quality lines. However, in many cases the geophysical source isn't sufficient to adequately image the subsurface. As the government moves to a more plan led approach then high quality muti channel sparker surveys will be needed to high grade areas for development.

Additional site-specific geophysical surveys will need to be undertaken and carried out prior to any construction or installation in the Kish Basin. Time lapse (4D) bathymetric surveys will be required to understand if the sediments in a specified area have moved over time and if so at what rate.

Repeat surveys with specifically customised deliverables are combined with detailed borehole and near-surface geophysical (Sparker) and geotechnical (CPT) information. The geophysical data will need to be high quality in signal to noise ratio (SNR), high density re sampling and exhibit redundancy, and future datasets will be more localised to specific sites.

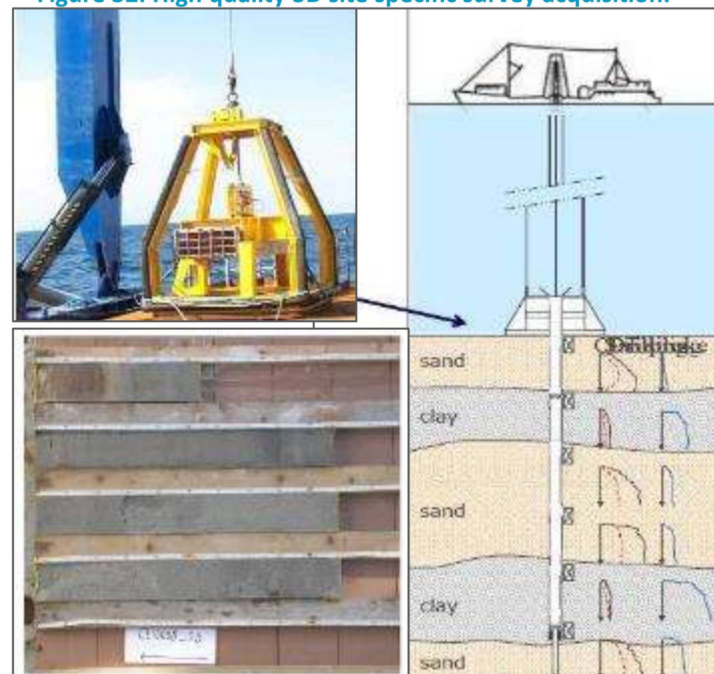


Figure 33: Cone Penetration Test (CPT) acquisition.

WP2-O4: Regional geohazards study – Geopressure

Pore pressure prediction is used to develop a subsurface model for the pressure regime and it is a critical property towards an effective geohazard mitigation. A quantitative predrill prediction of pore pressure is required and can be obtained from elastic wave velocities using a velocity-to-pore-pressure transform model calibrated with laboratory measurements or offset well data. Pore pressure prediction using a refined velocity field from seismic velocities can help determine the variation between vertical effective stress and porosity at depth.

As seismic velocities can correlate with effective stress in the formation, compaction trends can be correlated to existing well data and the relationship between seismic velocities and vertical effective stress established. Pore pressure prediction from seismic velocities aims to support a better visualization of the mechanisms of overpressure generation and to assist in a safer and economic project construction and development.

Seismic is sensitive to pressure changes since there is a relation between porosity, compaction, acoustic parameters and pore pressure.

An increase in burial depth leads to an increase in compaction and a decrease in porosity. Hence, shear and bulk modulus increases with depth leading to a decrease in rock compressibility and an increase in velocity.

In an overpressure zone, the compaction rate is decreased, and sometimes it even ceases. The acoustic velocity decreases in the overpressure zone because of the decrease in compaction. Hence, the seismic can be a powerful tool to detect overpressure zones which are a serious geohazard that needs to be avoided.

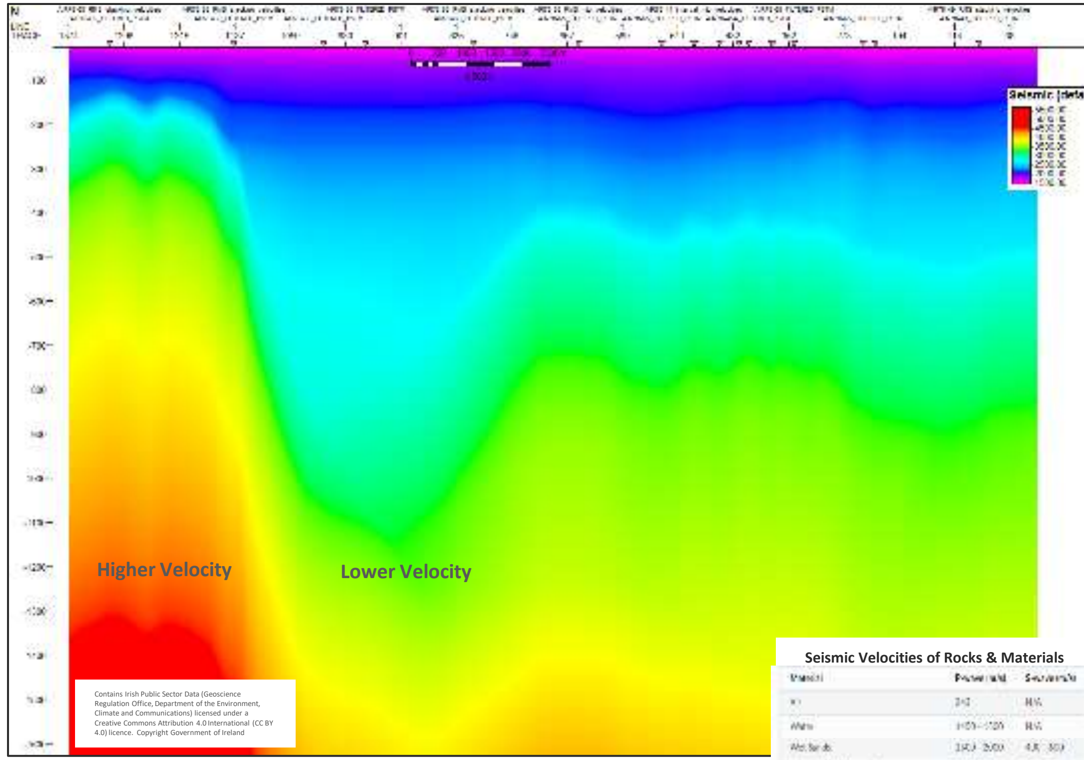


Figure 34: PRESDM Seismic Velocities from 2D Line in the Kish Basin

Seismic Velocities of Rocks & Materials

[illegible]	[illegible]	[illegible]
Air	[illegible]	[illegible]
Water	[illegible]	[illegible]
Wet Sands	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

The higher velocities seen on the 2D PreSDM seismic line above are representative of older more resistive rocks whilst the lower velocities are representative of younger more unconsolidated sediments. On the left side of the section these older harder rocks are uplifted due to the tectonic strain in the area and are sub cropping just beneath the seafloor.

The table on the right is highlighting the associated seismic velocities for both the P- Wave (Primary) and S-Wave (Secondary) that represent various rocks types and materials that are commonly encountered from shallow to deep.

WP2-O4: Regional geohazards study – Geopressure

This 2D seismic line from the Kish basin is highlighting a range of geological features from the near surface to deeper down in the stratigraphy.

The influence of the regional and local tectonics are visible on this line as several anticlinal structures, varying in size and relief can be seen. Adjacent to these are synclines that are acting as repositories for sediments eroding from the onshore hinterland into the basin.

Large scale faults are also visible on the seismic section and these appear to be acting as conduits for fluid migration.

High amplitude seismic packages can be seen at the tips of these faults and are interpreted to be gas. The origin of this gas appears to be from older sediments and therefore is likely to be thermogenic.

The faults are terminating at the seafloor which indicates that there are still active present day.

These are potential high risk geohazards that should be avoided in the construction of any offshore infrastructure in the area.

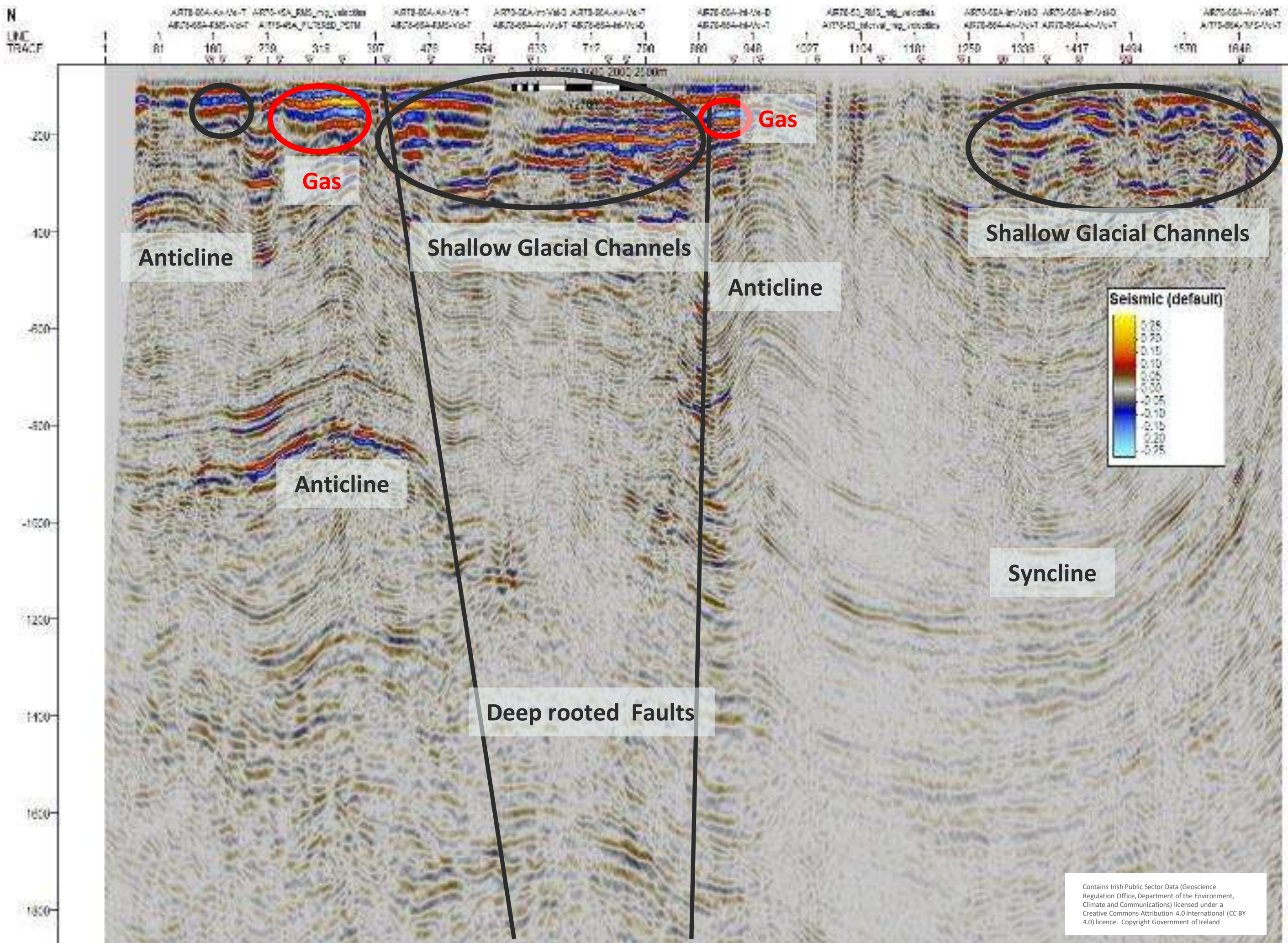


Figure 35: 2D Seismic Line in the Kish Basin highlighting potential geohazards.

WP2-O4: Regional geohazards study – Geopressure

The PreSDM seismic velocities from the 2D line are showing a range of values from 1500 m/s representing the water column to 5500 m/s representing some of the oldest rocks on the section.

The shallow section has a low velocity signature that is representative of less consolidated sediments.

Within this shallow section there are a several glacial channels relating to the last ice age approx. 23 ka BP that will contain a range of heterogenous materials within the overall channel complex.

The glacial sands within the channels have a lower velocity as they are softer and less compacted, their velocities ranging from 1700 – 2000 m/s.

The channel lag deposits at the base of the glacial channels are a relative higher velocity 2300-2500 m/s than the overlying finer sands. This is due to large boulders and clasts that are poorly sorted and held in a stiffer more mud rich matrix.

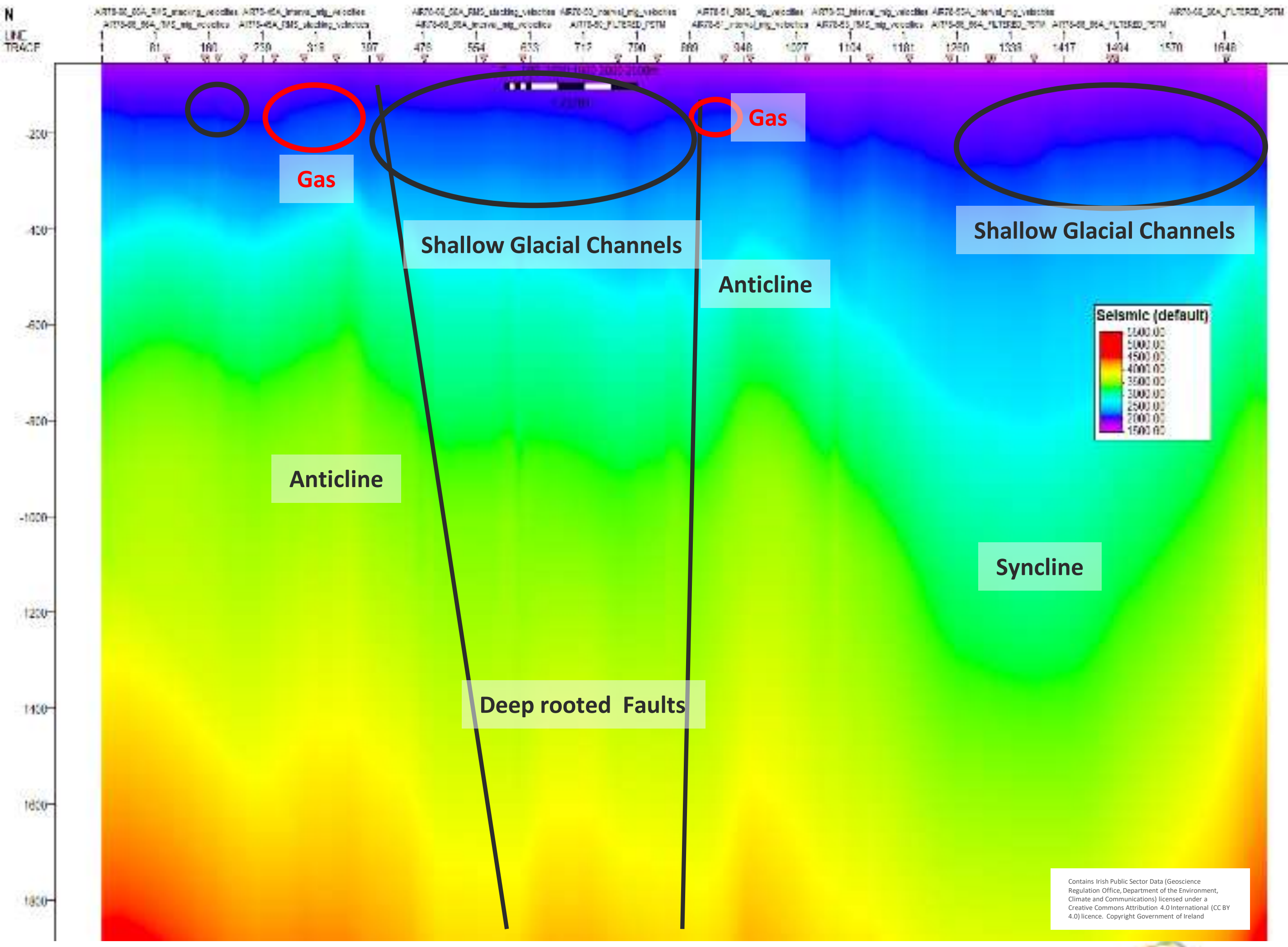


Figure 36: 2D Seismic velocities in the Kish Basin highlighting potential geohazards.

WP2-O4: Regional geohazards study – Geopressure

When the PreSDM seismic velocities are overlain on top of the 2D reflectivity data it becomes apparent that there is a relationship between the velocity values and the underlying geology.

In general, the seismic velocities are following what is known as a Normal Compaction Trend (NCT). Whereby there is an increase in seismic velocity with depth due to compaction of the sediments that is being caused by burial overtime and the weight of the overlying stratigraphy.

However due to the local and regional tectonic stresses we can see areas where older rocks in the section have been uplifted and compressed into anticlinal structures.

The velocity values inside the anticlines are much higher that you the velocity values in the surrounding sediments in the shallow section. This indicates that there is much older resistive rock being uplifted.

Conversely the sediments in the syncline are much lower velocity that the surrounds, thus indicating that this has acted as a repository for more recent sediment fill.

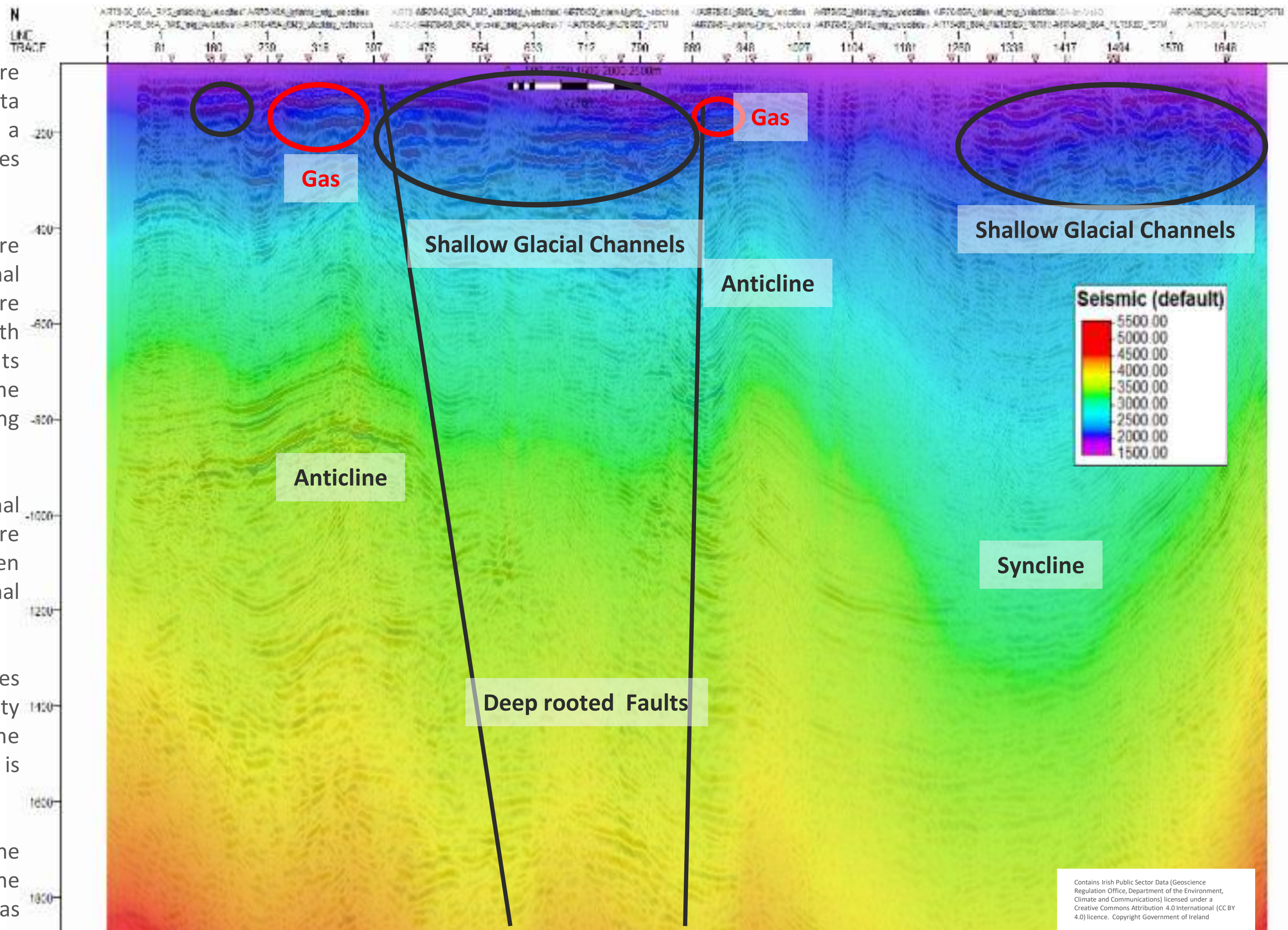


Figure 37: 2D seismic Line overlain with velocities in the Kish Basin highlighting potential geohazards.

WP2-O4: Regional geohazards study – Geopressure

This is another example of a 2D strike orientated seismic line from the Kish Basin is highlighting a range of structural geological styles from the North (L) to South (R).

The influence of the regional and local tectonics are visible on this line as anticlinal structures, varying in size and relief can be seen. On the south of the line there is a large syncline that is acting as a repository for sediments eroding from the onshore hinterland into the basin.

Large scale faults are also visible on the seismic section and these appear to be acting as conduits for fluid migration.

High amplitude seismic packages can be seen at the tips of these faults and are interpreted to be gas. The origin of this gas appears to be from older sediments and therefore is likely to be thermogenic.

The faults are terminating at the seafloor which indicates that there are still active present day.

These are potential high risk geohazards that should be avoided in the construction of any offshore infrastructure in the area.

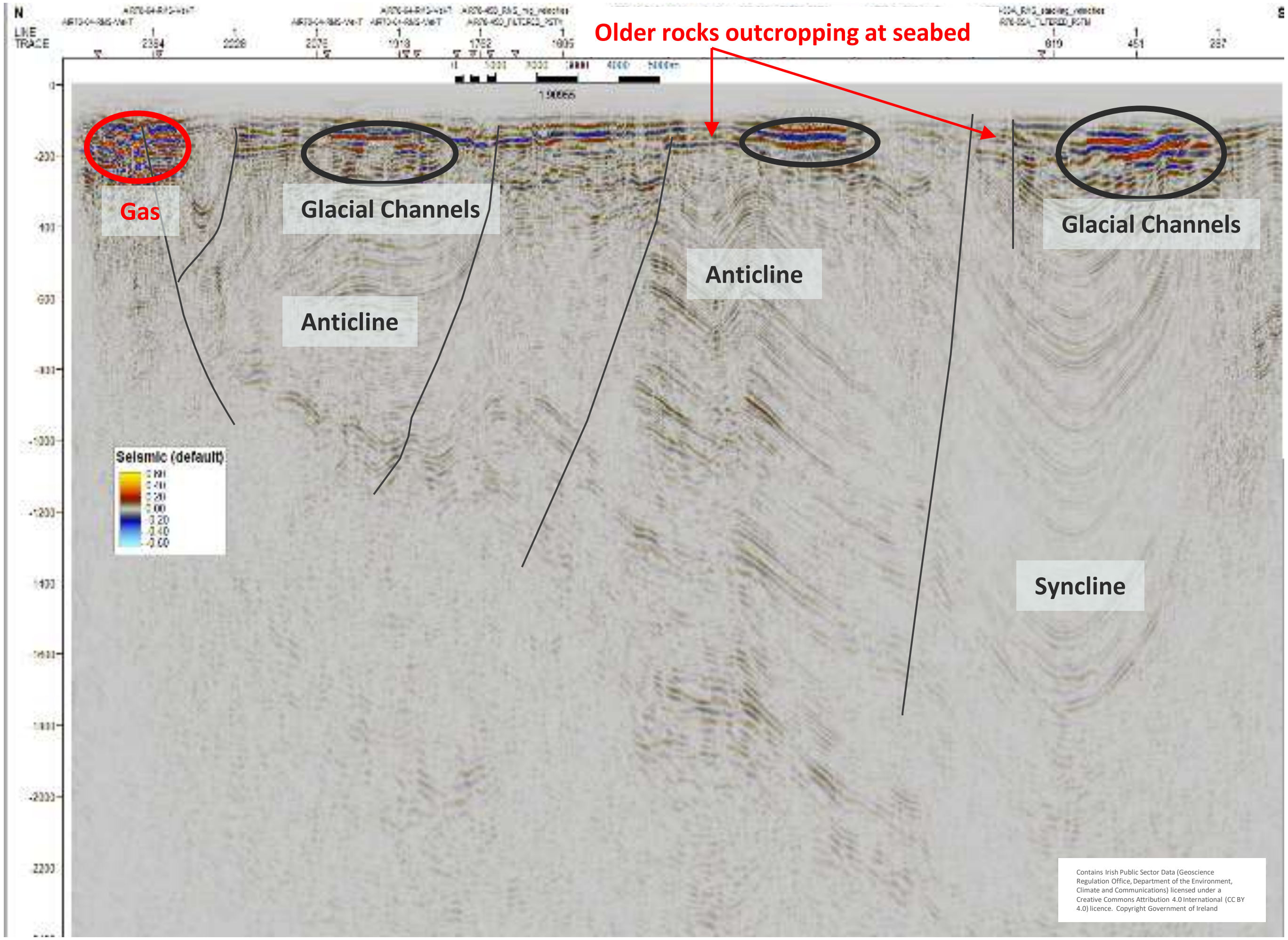


Figure 38: 2D Seismic Line in the Kish Basin highlighting potential geohazards.

WP2-O4: Regional geohazards study – Geopressure

The PreSDM seismic velocities from this 2D line are showing a range of values from 1500 m/s representing the water column to 5500 m/s representing some of the oldest rocks on the section.

The shallow section has a low velocity signature that is representative of less consolidated sediments.

In general, the seismic velocities on this 2D line are higher across the section than seen previously. This indicates that the rocks on this line are older and more resistive, with the higher velocity rocks reaching far up into the shallow section.

The large syncline on the south of the section has lower velocities than the surrounding stratigraphy. This indicates that the sediments within the syncline are less resistive, less compacted and are more recent in their deposition.

There are also several glacial channels highlighted on the seismic section which are located just beneath the seafloor. The glacial sands within the channels have a lower velocity as they are softer and less compacted, their velocities ranging from 1700 – 2000 m/s.

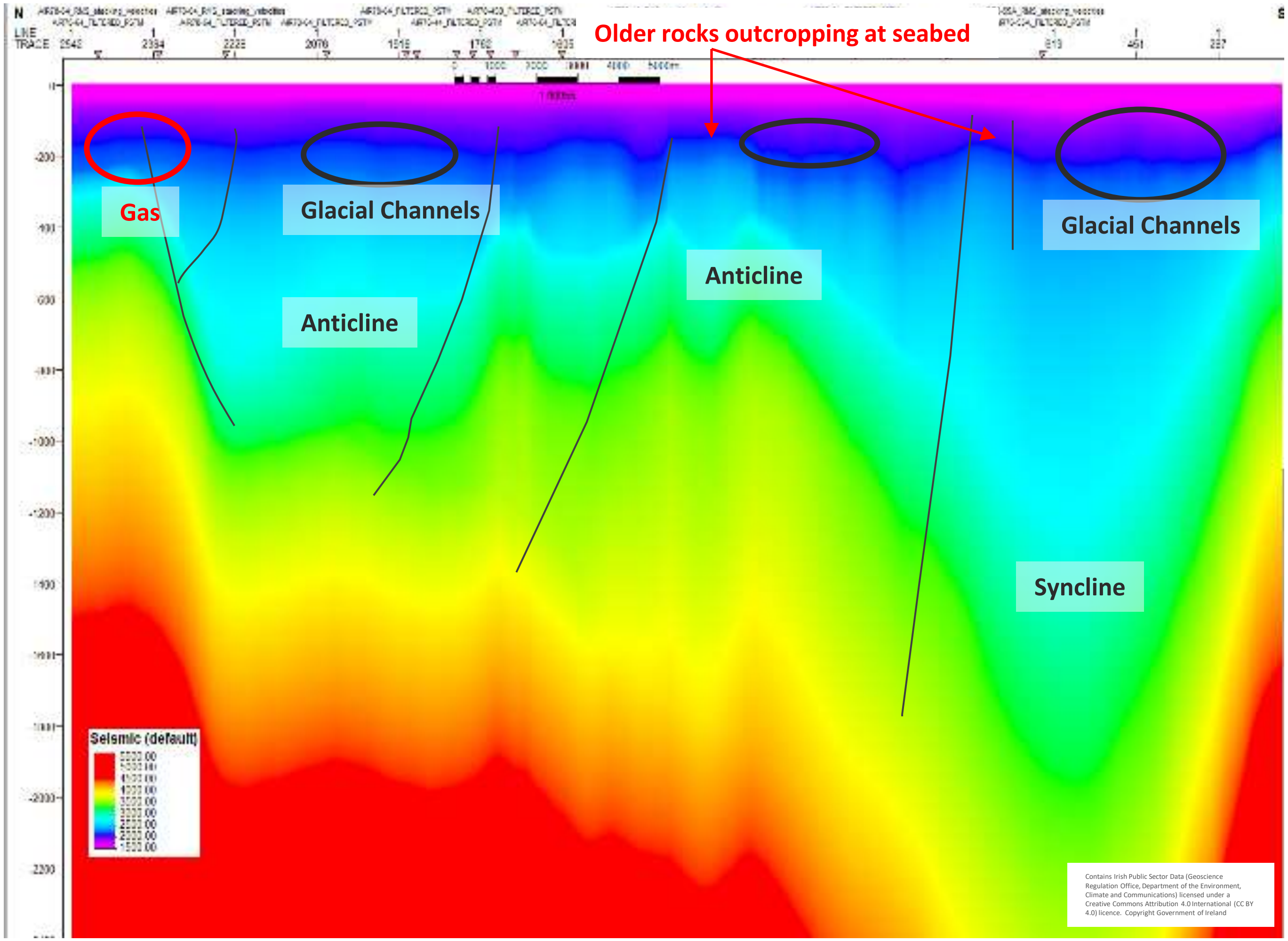


Figure 39: 2D Seismic velocities in the Kish Basin highlighting potential geohazards.

WP2-O4: Regional geohazards study – Geopressure

When the PreSDM seismic velocities are overlain on top of the 2D reflectivity data it becomes apparent that there is a relationship between the velocity values and the underlying geology.

However due to the local and regional tectonic stresses we can see areas where older rocks in the section have been uplifted and compressed into anticlinal structures.

The velocity values inside the anticlines are much higher that you the velocity values in the surrounding sediments in the shallow section. This indicates that there is much older resistive rock being uplifted.

Conversely the sediments in the syncline are much lower velocity that the surrounds, thus indicating that this has acted as a repository for more recent sediment fill.

There are areas highlighted on the seismic section that are showing relatively high velocities going to the seabed. These can be seen protruding and outcropping onto the seafloor. These pose a significant geohazard risk and should be avoided as it will add significant time and cost to any operation that wants to develop here, whether its drilling, laying foundations, cables or pipelines.

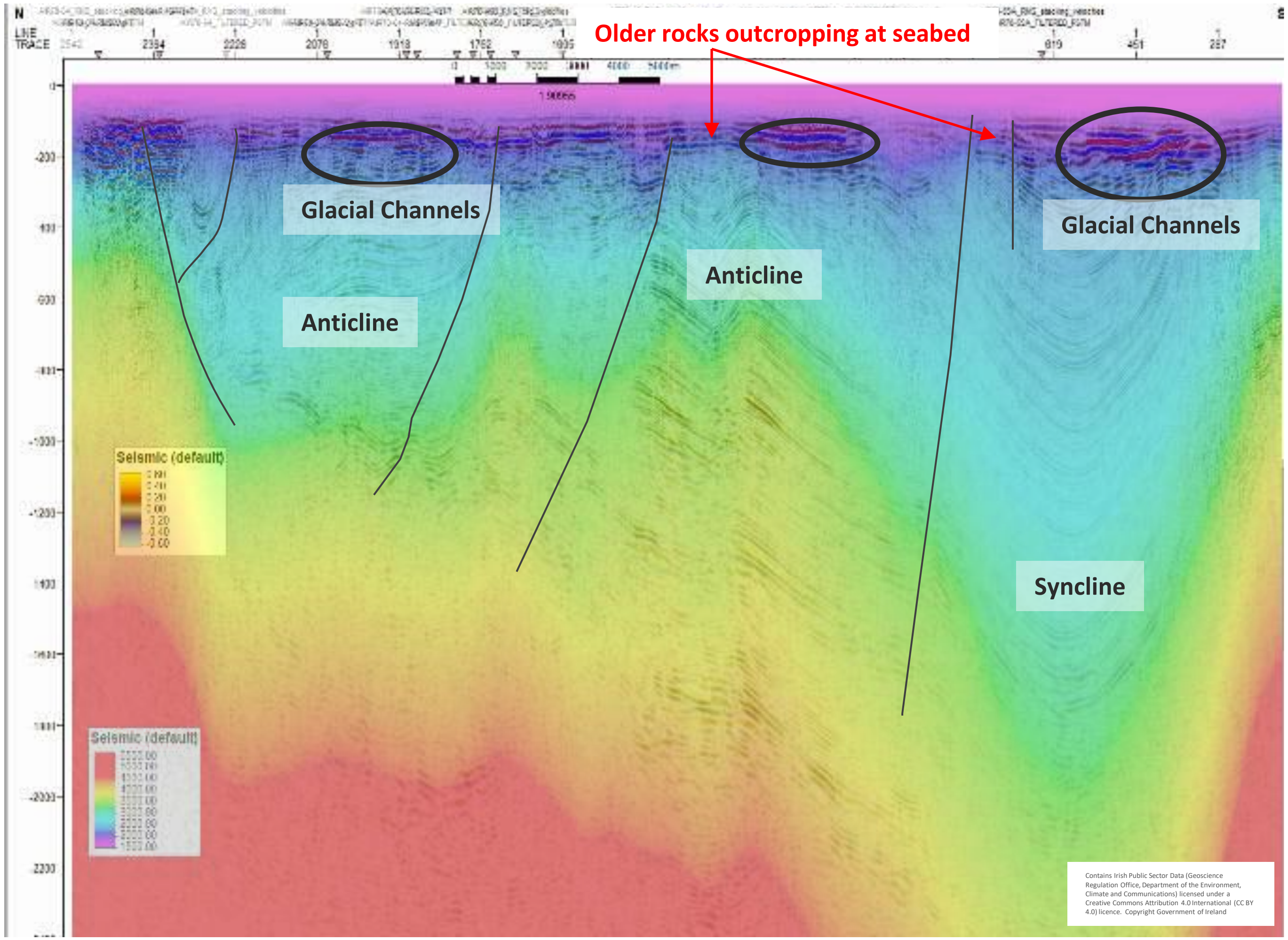


Figure 40: 2D Seismic Line with velocities overlain in the Kish Basin highlighting potential geohazards.

WP2-O5: Study of maritime traffic (shipping, fisheries, leisure), archaeological sites or other maritime/surface constraints

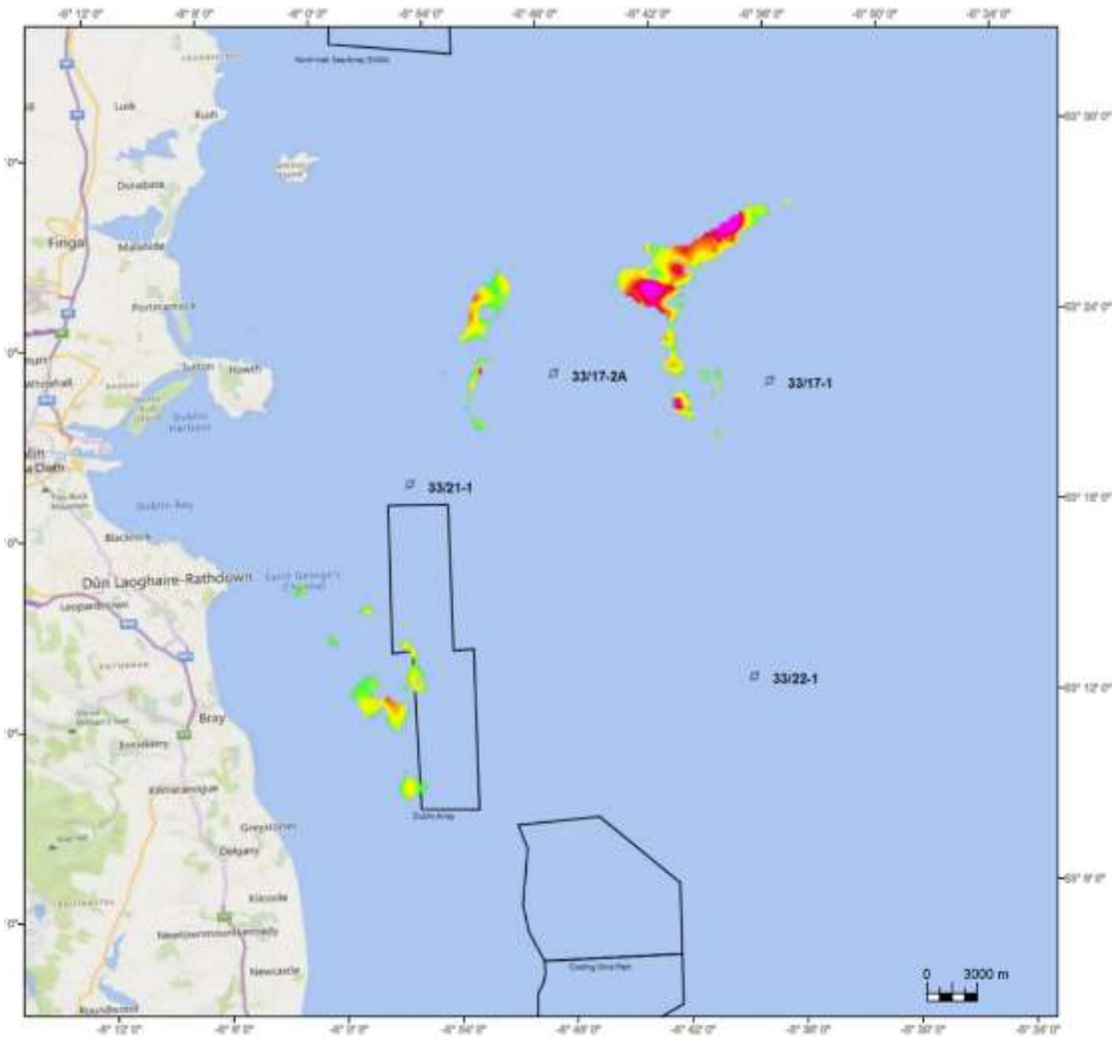


Figure 41: Map of areas with >300m of halite interval, at a depth of 1,000m to 1,500m

The potential salt cavern storage sites at the optimum depth and thickness adjacent to existing offshore wind licence areas have been identified and mapped (See Fig 19). GIS data relating to surface constraints for the development of a Kish Basin Offshore Green Hydrogen Production Facility (Fig 4) was compiled from publicly available data. The selection of data layers was informed by the requirements for environmental impact reports for offshore wind developments. The GIS layers include onshore and offshore geology, geological events (earthquakes), seabed substrate, aggregate resources, water bodies, water quality, seabird breeding distribution, wind conditions, wave conditions, sea surface temperatures, marine currents, telecommunications infrastructure, designated sites, fish spawning and nursery grounds, designated shellfish areas, pinniped distribution, marine reptiles, cetacean distribution, fishing effort inshore and offshore, marine vessel density by type and aggregated, location of aids to navigation, energy infrastructure including windfarm foreshore licence applications, and heritage areas offshore including shipwrecks. The following three maps are constraints maps generated from GIS maps showing the main environmental aspects that will restrict offshore activities associated with the development and operation of a hydrogen storage project in Kish Basin area associated with offshore wind farms.

WP2-O5: Study of maritime traffic (shipping, fisheries, leisure), archaeological sites or other maritime/surface constraints

Constraints Map 1 shows potential salt cavern locations.

Constraints Map 2 highlights Special Areas of Conservation (SACs). The area of greatest geological potential for halite cavern development is within the North-West Irish Sea SPA. The Rockabill Dalkey Island SAC is adjacent to the Kish Basin and kittiwake breeding distribution overlaps the northern end of the Dublin Array licence area. Mitigation measures will be required to reduce the impact of offshore activities on the SAC and kittiwake breeding grounds.

Constraints Map 3 highlights constraints associated with fishing, shipwrecks, SAC, birds, dumping at sea and telecommunications cables (these are all available as layers or links within a GIS project). The areas in yellow and brown are the sites where the salt deposits are sufficiently thick for solution mining of salt caverns for hydrogen storage. The occurrence of numerous shipwrecks around the Kish Basin are an obvious constraint on the siting of seabed foundations for an offshore wind farm. A telecommunications cable also runs through the Dublin Array licence area which will also constrain the siting of seabed foundations for wind turbines. To the east side of the Kish Basin there is significant fishing trawling activity, which will constrain the siting of wind turbines and any substation and hydrogen processing platform location.

Constraints Map 4 highlights constraints associated with passenger shipping. There is a high density of shipping withing the Kish Basin due to the proximity of Dublin Port. This will constrain the acquisition of seismic data in the evaluation of the salt storage site and also the supply and maintenance of substation platforms and offshore wind turbines during operation.

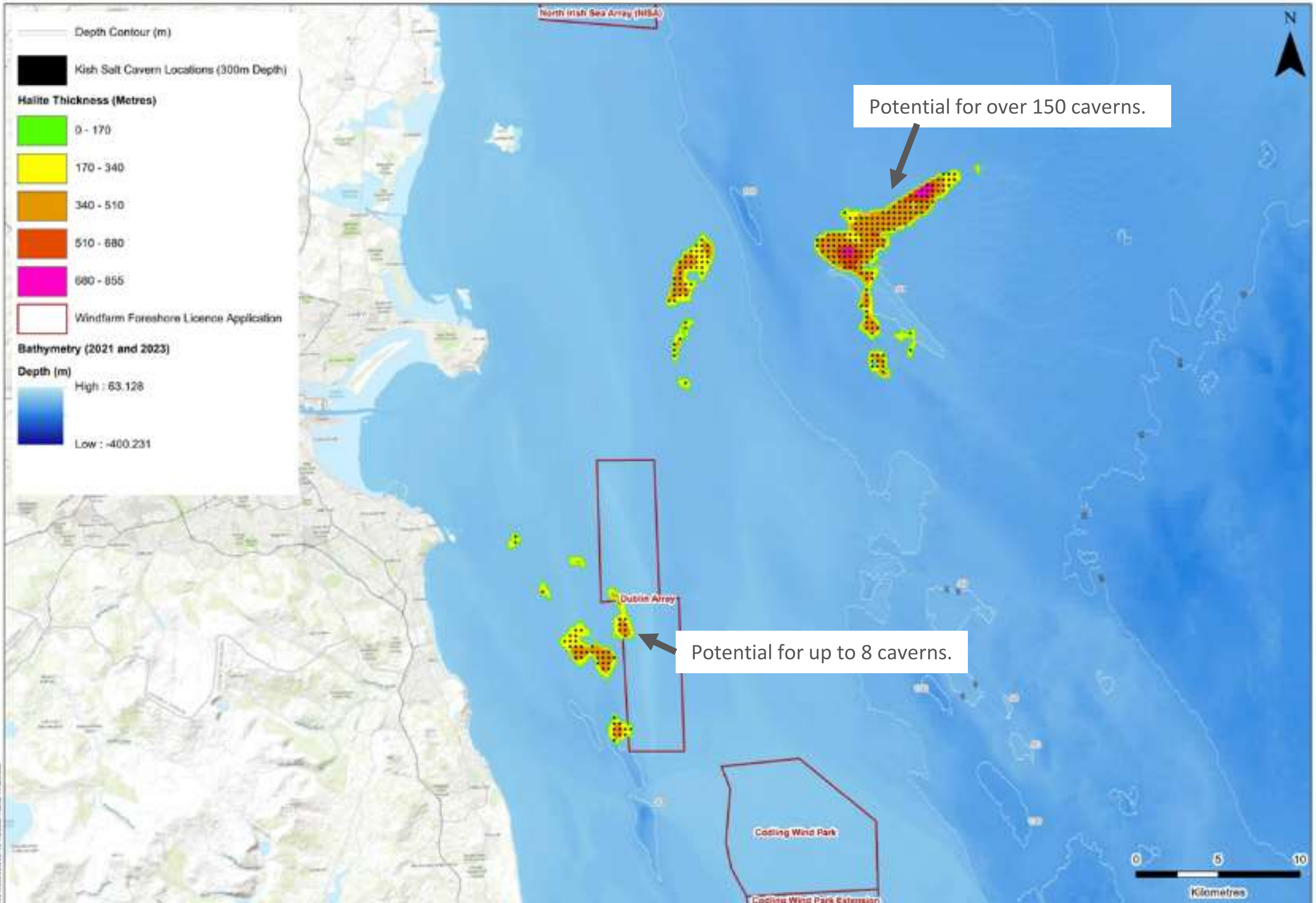
Constraints Map 5 highlights constraints associated with non-passenger shipping. Like the previous map this map shows a high density of shipping within the Kish Basin.

Constraints Map 6 highlights constraints associated with non-passenger shipping. Like the previous map this map shows a high density of shipping within the Kish Basin.

Constraints Map 7 shows Navigation Aids, Methane Derived Authigenic Substrates (MDAC's), and Earthquakes in the study area.

In summary the primary constraints on offshore activities associated with the development and operation of a hydrogen storage project identified by the GIS mapping exercise are shipwrecks, shipping lanes, fishing activity, telecommunications cables and proximity to SACs. This is reflected in the following Tables 3, 4, 5 and 6 that identify the high-level impacts and mitigation measures to be adopted during the development and operation of the offshore wind farm and associated hydrogen storage facility.

WP2-06 Constraints Map 1 – Potential Cavern Locations.



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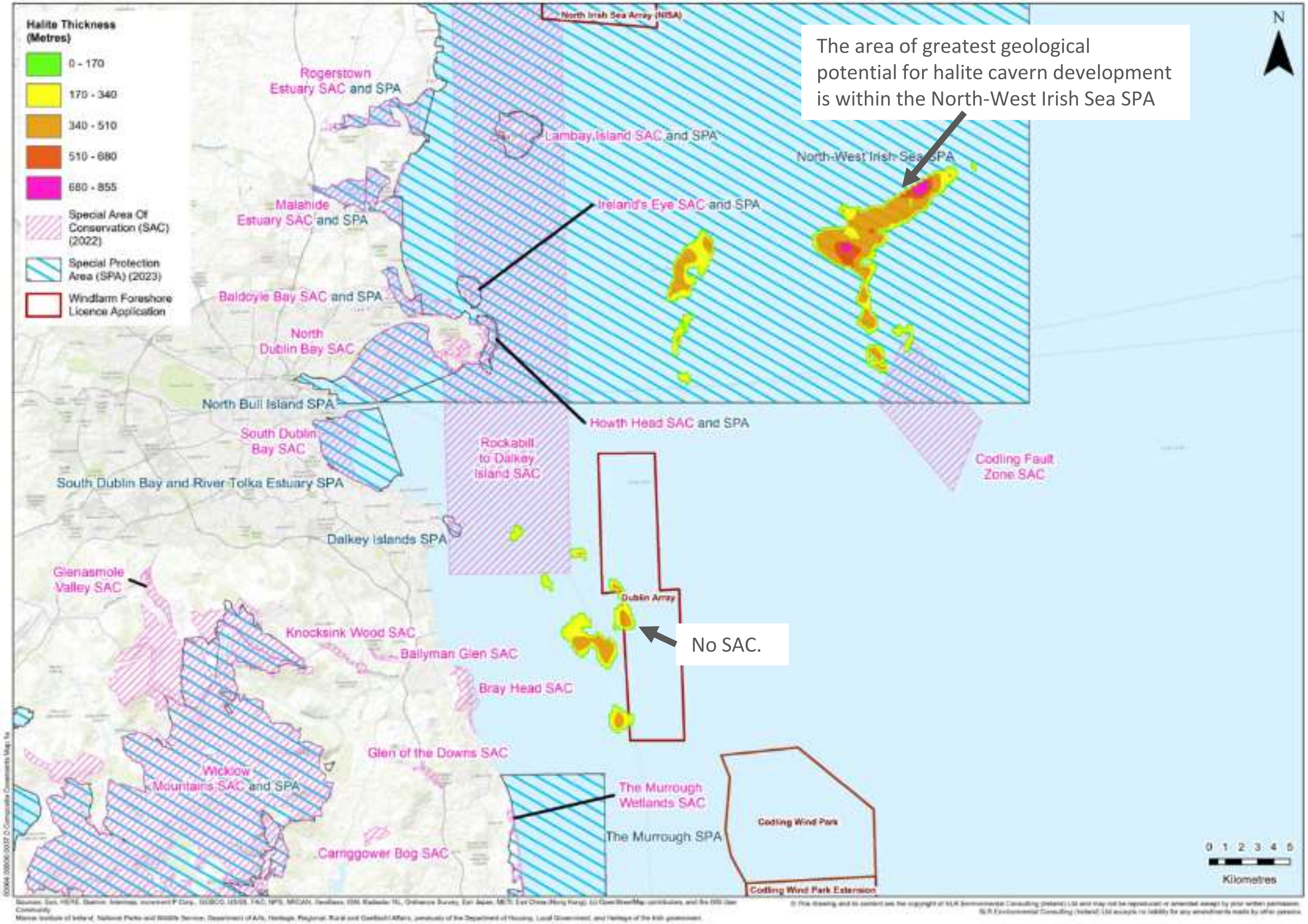
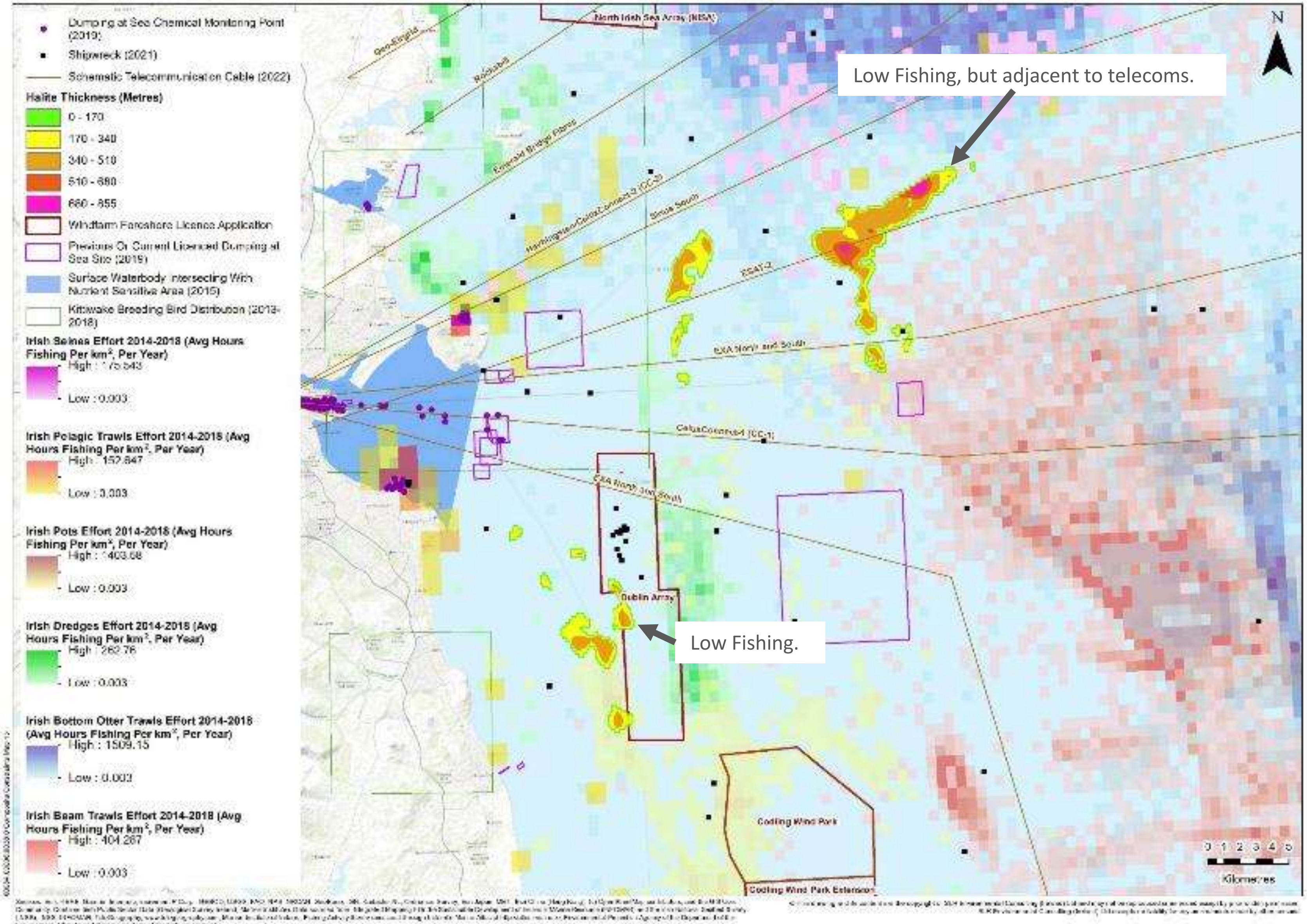
WP2-06 Constraints Map 2 – SAC's



WP2-06 Constraints Map 3 – Fishing, Shipwrecks, Birds, Dumping at Sea, Telecoms.



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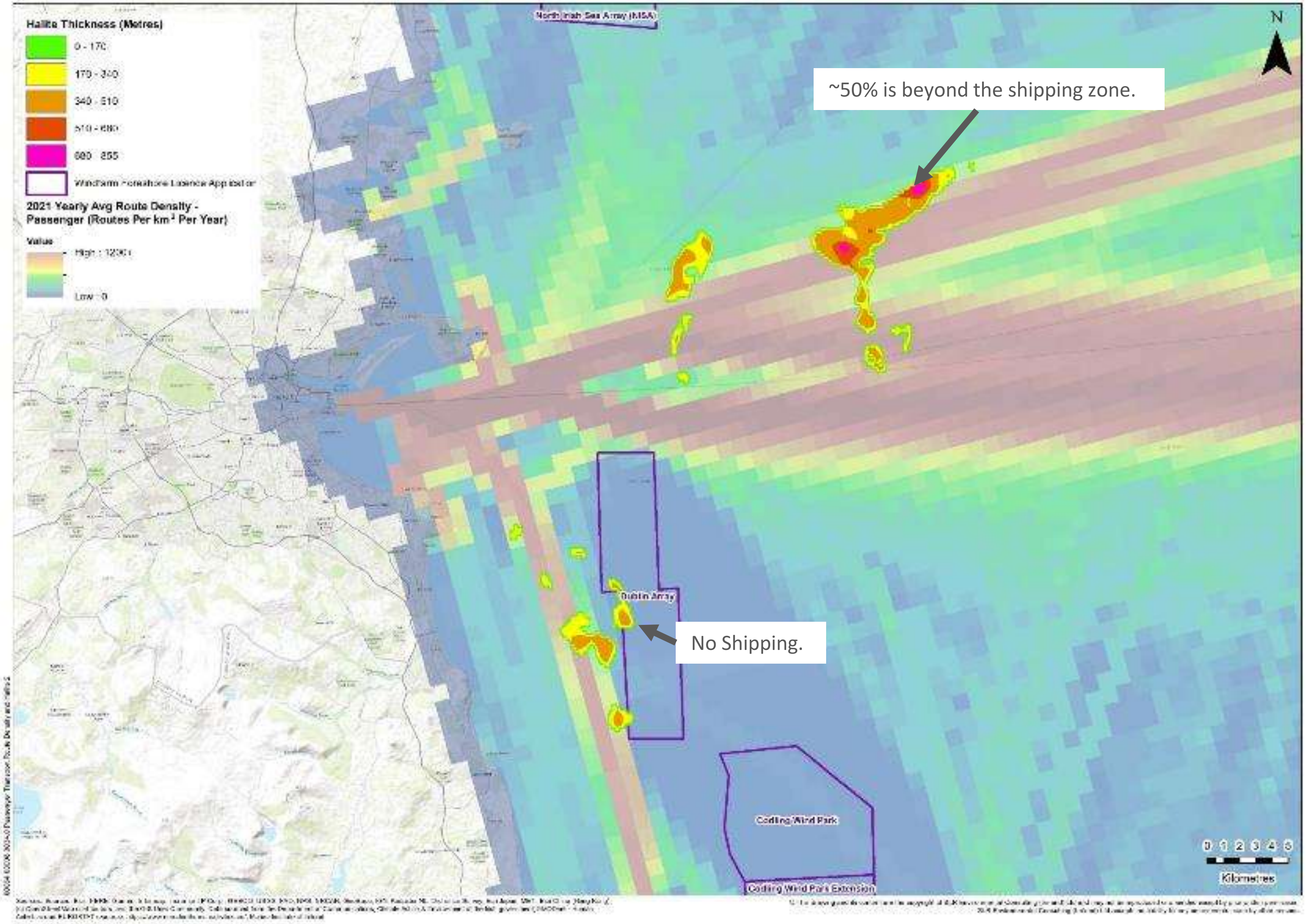
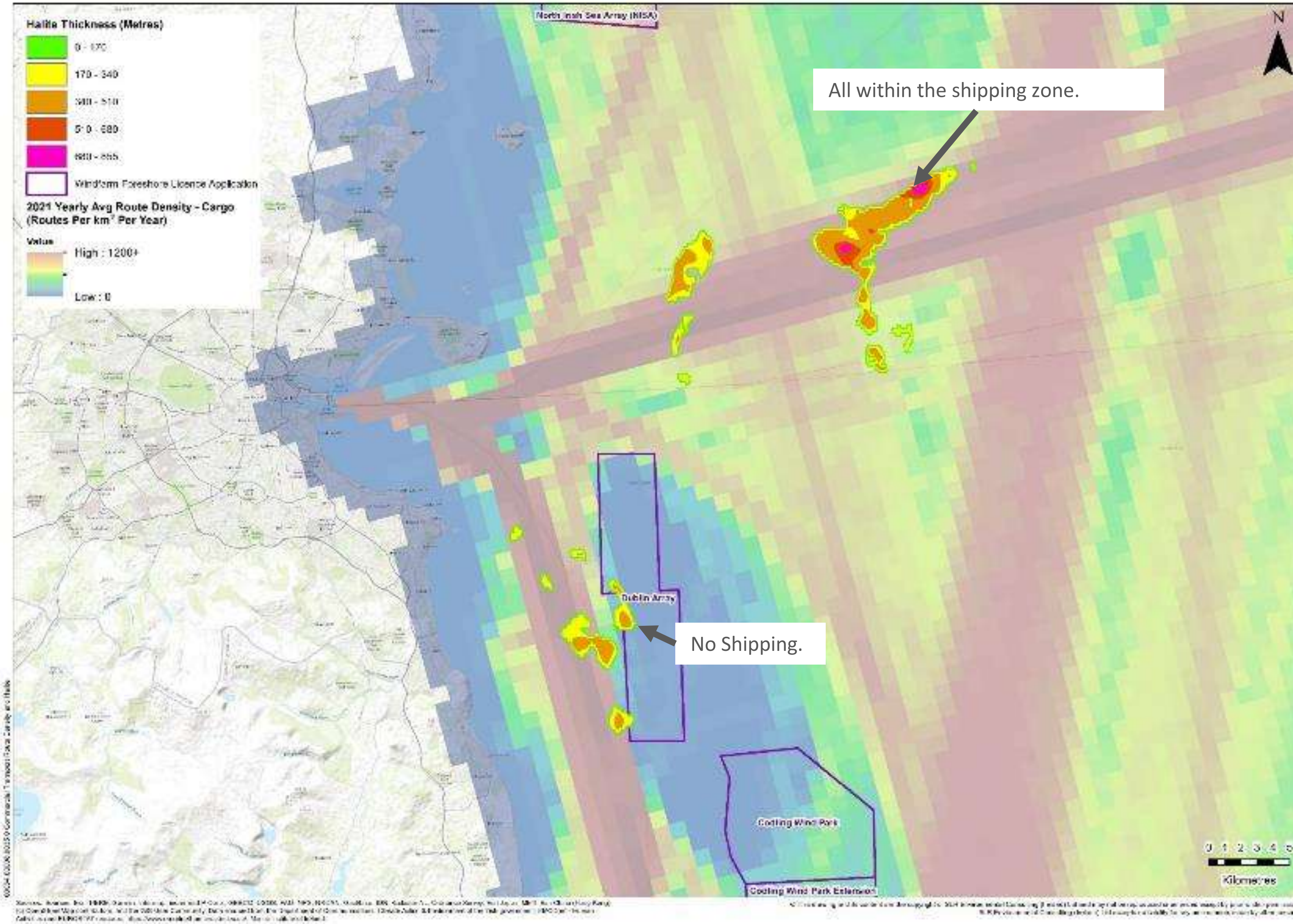
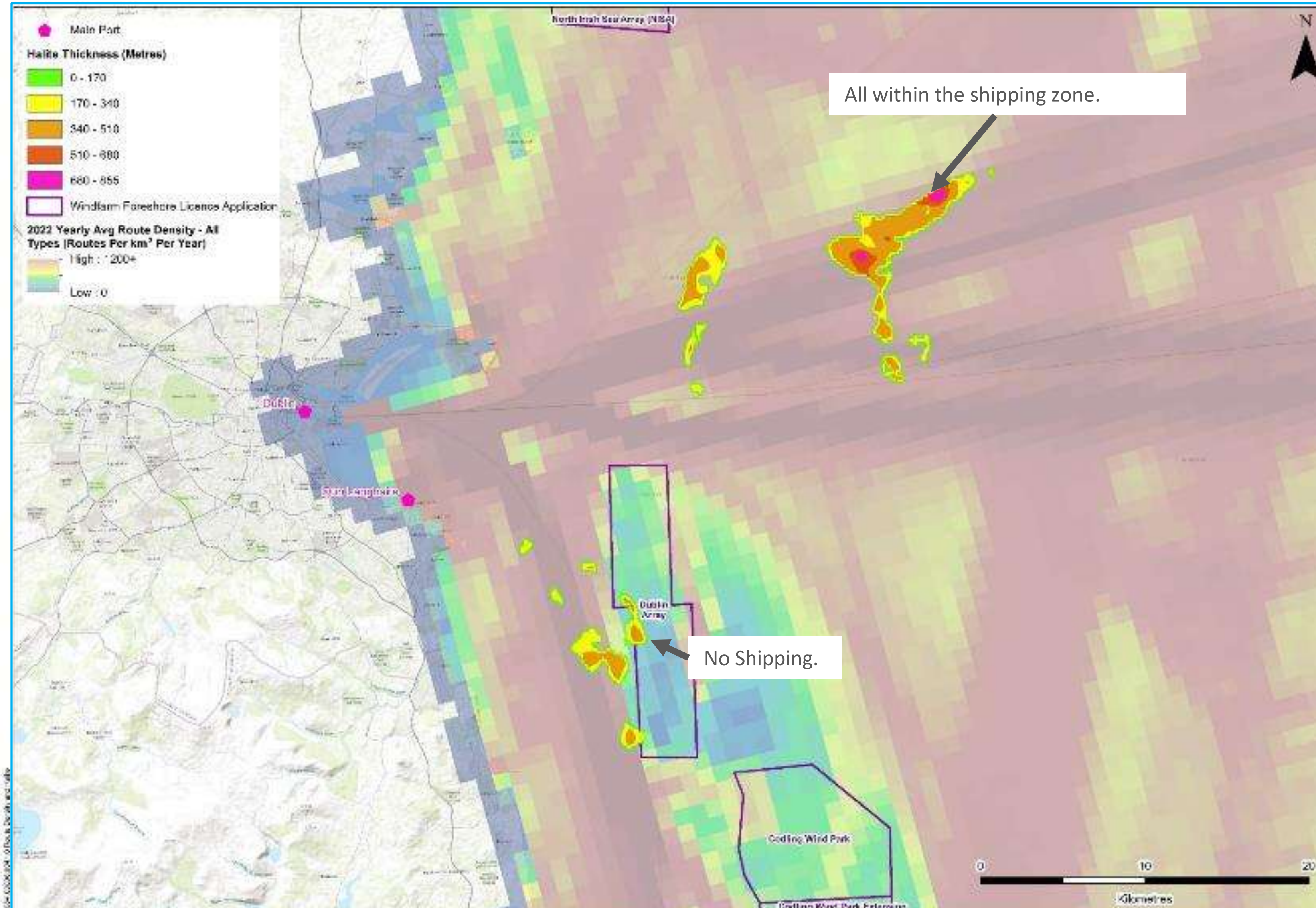
WP2-06: Constraints Map 4 – Passenger Shipping



WP2-06: Constraints Map 5 – Cargo Shipping



WP2-06: Constraints Map 6 – All Shipping Density 2022



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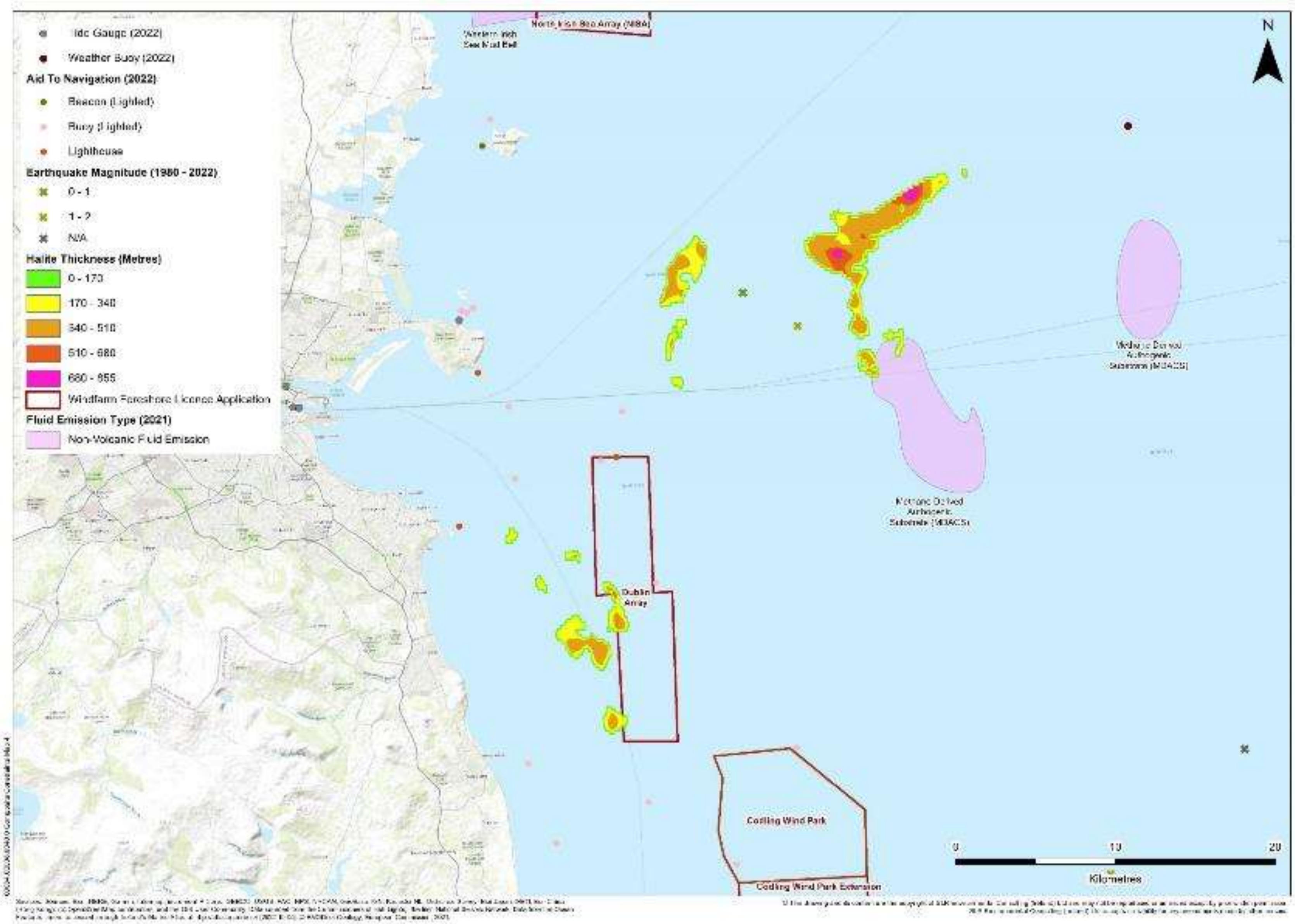
WP2-06: Constraints Map 7 – Navigation Aids, MDAC's, Earthquakes



SLR

WP2-06: High-level review of the potential environmental issues or constraints that may impact surface or subsurface operations

Pure hydrogen has been stored in salt caverns in Europe since the 1970s and the environmental issues are well known. The high level environmental impact assessment was carried out on the entire Offshore Green Hydrogen Production Facility Construction (Fig 4). The project lifecycle is examined in terms of activities, outputs and environmental impacts with associated mitigation measures. The importance of adverse impacts are classified as high medium or low reflecting their nature, scope, persistence, intensity and probability (Table 3). The results are presented in a series of tables in the form of a matrix with importance colour coded for ease of reference. The single most important environmental impact is the disposal of brine from the salt dissolution generated during the salt cavern excavation. The second most important is the impact on shipping and fisheries caused by the physical presence of the project.

Risks associated with microbial H_2 consumption include quantitative loss of hydrogen, and deterioration of gas quality due to hydrogen sulphide formation (H_2S). Research by the Hystories project indicates that the microbial risk potential is low in salt caverns because there is almost no microbial activity (see Fig 42).

The regulatory risk in Ireland is significant because until now the drilling of offshore wells came under petroleum legislation and regulation. It is unclear how the construction of an Offshore Green Hydrogen Production Facility will be regulated under the new Maritime Area Regulatory Authority (MARA). The United Kingdom is the only European country with a safety and environmental framework that has been applied for hydrogen storage for approximately 50 years.

Activity		
Brief description of activity	Type of activity	
Listed in days	Time period of activity	
Output		
	Description of the potential results of activity that may cause impact	
Impact		
Nature	Description of the impact caused by the Activity/Output	Includes what is being impacted and how.
Scope	Geographical area affected	Local, regional, continental (L, R, C)
Persistence	Duration of impact	Short (minutes-hours), medium (days-weeks), long (months-years), permanent, unknown (S, M, L, P, U)
Intensity	Severity of impact	Low, medium, high (L, M, H)
Probability	Likelihood of impact occurring	Low «25%), medium (25-75%), high (>75%) (L, M, H)
Importance	Importance of impact	Low, medium, high (L, M, H)
Type	Effect of impact	Direct, Indirect, Cumulative (D, I, C)
Effects		
Direct	Qualitative description of what is directly, indirectly and cumulatively impacted by the Activity/Output.	Direct Effects: Any first order effect, impact or consequence that may be associated with an activity
Indirect		Indirect and Second Order Effects: Any second order effect, impact or consequence that may be causally associated with an activity.
Cumulative		Cumulative Impacts: Effects, impact, or consequences that may come from similar or varied sources, but that are additive, antagonistic or synergistic in their effect, impact or consequence.
Mitigation		
Possibly	Is mitigation possible	Possibly, yes, no, unknown (P, Y, N, U)
Description	Description of mitigating actions.	

Table 3: Assessment of importance of environmental impacts

WP2-06: Microbial Risks

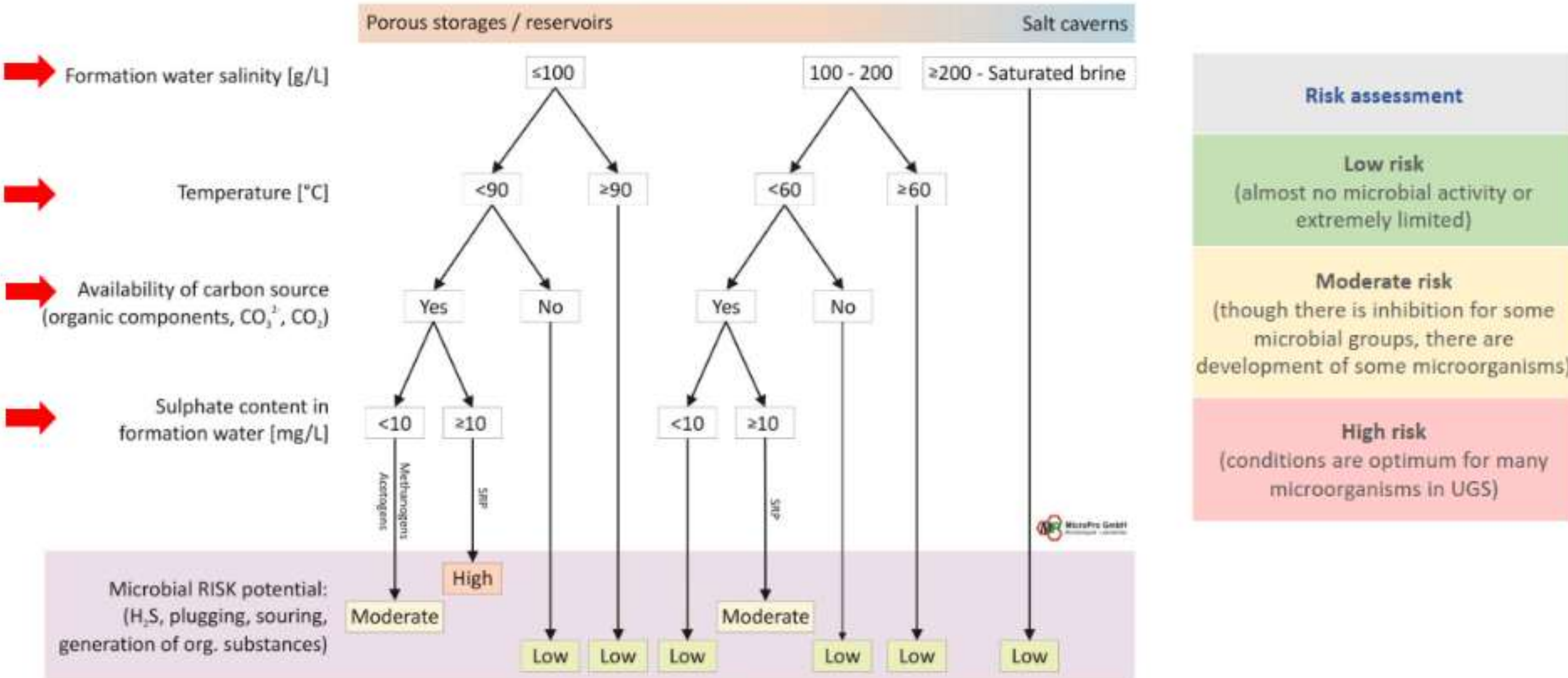


Figure 42: Simplified chart for the assessment of microbial risks (Hystories Project 2023)

Activity		Output	Impacts			Mitigation	
Nature	Duration	Type	Nature	Importance	Type	P/Y/N	Description
Stage 1 Construction, Operation & Decommissioning of Offshore Wind farm							
Seabed Foundations	3 weeks	Noise, Disturbance and release of sediment into the water column	Impacts to biological environment, fisheries, marine mammals	M	D	Y	Selection of monopile & pile driving, mechanical & acoustic soft starts
Construct onshore substation	4 weeks	Disturbance and release of sediment into the water column, Waste & emissions, noise	Impacts to human and biological environment, Traffic disruption,	M	D, C	Y	Design, exclusion zones, navigation aids
Wind turbines installation	3 weeks	Disturbance and release of sediment into the water column, noise, marine traffic	Impacts to human and biological environment, Traffic disruption, fisheries, marine mammals	H	D	P	Scheduling of operations, siting.
Offshore substation installation	2 weeks	Sediment disturbance, waste & emissions, noise	Shipping traffic, impacts to human & biological environment, fisheries	M-H	D	Y	Scheduling, exclusion zones, mechanical & acoustic soft starts
Inter turbine array cable installation	2 weeks	Disturbance and release of sediment into the water column	Shipping traffic, impacts to human & biological environment, fisheries	L	D	p	Scheduling, exclusion zones, siting, rerouting
Run DC electric cable to shore	1 week	Disturbance and release of sediment into the water column	Shipping traffic, impacts to human & biological environment, fisheries	L	D	p	Scheduling, exclusion zones, re-routing
Operation of offshore wind farm	20 years	Localised scour and sediment dispersal, Modification of tidal regimes and wave conditions, noise, light, marine traffic, EM radiation, collision risk, habitat disturbance, pollution, displacement	Navigation & fishing restrictions, Impact on coastal stability and erosion, impact on extraction of gas, coal & marine aggregates, fisheries, birds, marine mammals	L	D, I, C	Y	
Decommissioning of offshore wind farm	12 weeks	Disturbance and release of sediment into the water column, Waste & emissions, noise	Impacts to human and biological environment, Traffic disruption, fisheries, birds	M	D	P	Scheduling of operations

Table 4: Stage 1 Environmental impact of Construction, Operation and Decommissioning of the Offshore Wind Farm

WP2-07: Common Risk Segment Analysis

Activity		Output	Impacts			Mitigation	
Nature	Duration	Type	Nature	Importance	Type	P/Y/N	Description
3D Seismic Survey	Estimated 19 days in one or two phases within a 50 day window	Noise	Impacts to Biological Environment	L-M	D	Y	Use of soft start. MMO observations
		Noise	Impacts to Humans	L	D,I	Y	Notification of survey schedule
		Noise	Disruption to fishing operations	L-M	I	Y	Use of soft start Notifications of survey schedule
Seismic vessel	Estimated 19 days in one or two phases within a 50 day window	Impacts on water quality due to solid waste	Marine pollution	L	D	Y	Shore disposal at port No Impacts
		Oil spill. Collision with vessels/structures	Marine pollution	L	D,I,C	Y	Oil spill contingency Notifications of operational schedule
		Engine emissions	Air pollution	L	D,C	Y	Regular maintenance
		Physical presence	Disruption to shipping operations	M	D,C	Y	Notifications of operational schedule
			Collision with streamers	H	D	N	Low impact
Chase Boats	Estimated 19 days in one or two phases within a 50 day window	Oil Spill. Collision with vessels/structures	Marine pollution	L	D,I,C	Y	Oil spill contingency plan in place
		Engine emissions	Air pollution	L	D,C	Y	Regular maintenance
		Physical presence	Disruption to fishing/shipping operations	L	D,C	Y	Notifications of operational schedule
			Visual presence	L	D	N	Low Impact
Site Survey of Drilling Location	Estimated 10 days shallow seismic sparker survey with some seabed sampling	Oil spill. Collision with vessels/structures	Marine pollution	L	D,C	Y	Oil spill contingency plan in place
		Engine emissions	Air pollution	L	D,C	Y	Regular maintenance
		Physical presence	Disruption to shipping operations	M	D,C	Y	Notifications of operational schedule
			Collision with streamers	H			
		Noise	Disruption to fishing operations	L	D,C	Y	Use of soft start Notifications of survey schedule
		Noise	Impacts to Biological Environment	L-M	D,C	Y	Use of soft start. MMO observations
Drill Appraisal Well to identify the geotechnical & spatial aspects of the salt structures below the seabed.	Estimated 40 days using jack up drilling rig with downhole seismic VSP	Oil spill	Marine Pollution	L	D,C	Y	Oil spill contingency plan in place, Probability of a major accidental spill of hydrocarbons during the exploration drilling is very low therefore little chance of transboundary and cumulative effects.
		Engine emissions	Air pollution	L	D,C	Y	Regular maintenance
		Physical presence	Disruption to fishing/shipping operations	M	D,C	Y	Notifications of operational schedule
		Impacts on water quality due to solid waste	Marine pollution	L	D	Y	Shore disposal at port No Impacts
		Habitat disturbance, pollution, displacement	Marine, air, noise pollution impact on Wild life	L	D,I,C	Y	Implementation of management procedures to ensure environmental controls are operating effectively and efficiently
		Noise	Impacts to Biological Environment	L-M	D,C	Y	Use of soft start. MMO observations for VSP. The potential sound impacts from drilling operation are considered to be minimal and will not contribute to cumulative effects.

Table 5: Stage 2 Environmental impact of Geological Site Characterisation for Salt Cavern Selection

WP2-07: Common Risk Segment Analysis

Activity		Output	Impacts			Mitigation	
Nature	**Duration**	**Type**	**Nature**	**Importance**	**Type**	**P/Y/N**	**Description**
Re-enter appraisal well to enable installation of a leaching completion to create the salt cavern	Estimated 10 days using jack up drilling rig	This is an extension of the drilling operation with the same outputs as above – oil spill, engine & solid waste emissions, noise & habitat disturbance	Marine & air pollution, disruption to shipping & fishing operations, impact on biological environment	L-M	D,C	Y	As above for drilling operation
Cavern solution mining dissolves the naturally occurring salt formation using nitrogen gas as a blanket to prevent dissolution in the salt cavern roof	Estimated 2.5 years using jack up drilling rig	Impacts on water quality due to produced brine	Marine pollution, impacts on biological environment & wild life & fisheries	H	D,C	P	Dilute brine with seawater before disposal; disperse brine where currents are strongest;
		Oil spill	Marine Pollution	L	D,C	Y	Oil spill contingency plan in place, Probability of a major accidental spill of hydrocarbons during the exploration drilling is very low therefore little chance of transboundary and cumulative effects.
		Engine emissions	Air pollution	L	D,C	Y	Regular maintenance
		Physical presence	Disruption to fishing/shipping operations	M	D,C	Y	Notifications of operational schedule
		Impacts on water quality due to solid waste	Marine pollution	L	D	Y	Shore disposal at port No Impacts
		Habitat disturbance, pollution, displacement	Marine, air, noise pollution impact on Wild life	L	D,I,C	Y	Implementation of management procedures to ensure environmental controls are operating effectively and efficiently
		Noise	Impacts to Biological Environment	L	D,C	Y	The potential sound impacts from drilling operation are considered to be minimal and will not contribute to cumulative effects.
Completion of production wells	Estimated 10 days per well using jack up drilling rig	This is an extension of the drilling operation with the same outputs as above –oil spill, engine & solid waste emissions, noise & habitat disturbance	Marine & air pollution, disruption to shipping & fishing operations, impact on biological environment	L-M	D, C		As above for drilling operation
Installation of offshore substation and hydrogen production platform	Estimated three months using heavy lift barge to install steel jacket platform	Physical presence	Disruption to shipping & fishing operations,	L-M	D, C	Y	
		Oil spill	Marine pollution	L	D, C	Y	Oil spill contingency plan in place
		Engine & solid waste emissions,	Marine pollution	L	D, C		Regular maintenance and waste disposal to shore
		Noise – pile driving	Impact on cetaceans	H	D	Y	Soft starts, acoustic buffers/screens
		Seabed disturbance	Habitat disturbance	L			Enhanced marine habitat on artificial reef
Lay export hydrogen pipeline to shore	Using pipe laying barge	Physical presence	Disruption to shipping & fishing operations,	L-M	D, C	Y	Notifications of operational schedule
		Seabed disturbance	Impact on marine areas of conservation	L-M	D, C	P	Adjust operational schedule to minimise impact
		Habitat disturbance	SPA, SAC, Annex IV	L-M	D, C	P	Adjust operational schedule to minimise impact
Beneficial impacts							
Substation & H2 production platform	20 years	Physical presence	Impact on marine life	M	D, C		Enhanced marine life habitats due to artificial reef affect

Table 6: Stage 3 Environmental impact of Cavern Solution Mining and Installation of Hydrogen Plant Offshore Platform

Results

The Kish Basin is in the Irish Sea, east of Dublin in water depths of 3-100m. It is an erosional remnant of an inferred larger linked Permo-Triassic basin system that covered the Northern Irish Sea, North Channel and Western England. It is a NW dipping half graben divided in two by the NNW-trending Codling Fault Zone. Seismic interpretation suggests 9km of probably Early Tertiary dextral strike-slip movement on the Codling Fault Zone. Three oil and gas exploration wells drilled in the basin encountered salt. The Triassic Mercia Mudstone Group has about 30% halite in wells west of the Codling Fault compared with only 16% in well 33/17-1 in the east. Seismic interpretation suggests that a disconformable event in the hanging wall of the Codling Fault may be a surface caused by salt withdrawal during Tertiary strike slip movements. The south westerly increase in the proportion of halite in the wells indicates that during Late Triassic time the deepest part of the basin was in the west (Shannon *et. al.*, 2001). The new seismic interpretation from this study identified salt movement with the development of thick salt pillows, ideal for salt cavern solution.

Based on seismic interpretation of legacy oil and gas data, maps of the Kish Basin have been produced showing the areas where the halite formations occur at depths of 1,000m to 1,500m and are more than 300m thick, the optimum depth and thickness for salt cavern storage of gas in this area. In a zone of interest beneath the offshore wind licence area for the Dublin Array, 8 standard size salt caverns can be developed for hydrogen storage. This is equivalent to approximately 1.0 TWh_{H2}. The project has identified 271 potential manmade salt caverns at the optimum depth and thickness for gas storage off the east coast, in the greater Dublin area alone, each of which could deliver in the region of 0.1 TWh of hydrogen storage, or 27 TWh_{H2} cumulatively.

A high-level environmental impact assessment was carried out on an Offshore Green Hydrogen Production Facility. The project lifecycle was examined in terms of activities, outputs and environmental impacts with associated mitigation measures. The single most important environmental impact is the disposal of brine from the salt dissolution generated during the salt cavern excavation. The second most important is the impact on shipping and fisheries caused by the physical presence of the project. Risks associated with microbial H_2 consumption, including quantitative loss of hydrogen, and deterioration of gas quality due to hydrogen sulphide formation (H2S), is low in salt caverns because there is almost no microbial activity.

The regulatory risk in Ireland is significant because until now the drilling of offshore wells came under petroleum legislation and regulation. It is unclear how the construction of an Offshore Green Hydrogen Production Facility will be regulated under the new Maritime Area Regulatory Authority (MARA).

Discussion

This study is the first to assess the hydrogen storage potential within manmade salt caverns off the coast of Ireland. The research involved detailed seismic interpretation of legacy oil and gas well and seismic data combined with interpretation of Multibeam Echosounder (MBES), Singlebeam Echosounder (SBES) and Shallow Seismic / Sub Bottom Profiler (SBP) acquired by the INFOMAR programme. The salt occurrence in the Kish Basin is extensive and is sufficiently thick and at the optimum depth for the creation of manmade salt caverns for hydrogen storage.

Some geohazards have been identified, such as glacial boulders and scouring currents. These hazards can be managed or avoided as demonstrated by successful oil and gas drilling in the area in recent decades. There are several significant environmental constraints including the disposal of concentrated brine from salt cavern mining and the disruption to shipping and fishing activity in an exclusion zone around the hydrogen production facility. Mitigation measures have been identified to address these environmental constraints.

Conclusion

1. Salt formations occur in the Kish Basin offshore Dublin.
2. The salt is sufficiently thick and occurs at the optimum depth for hydrogen storage in man-made salt caverns.
3. The volume of hydrogen gas that can be stored in man-made salt caverns in the Kish Basin is up to 27 TWh_{H2} .
4. The geohazards identified that could impact the development of a hydrogen storage project have been successfully managed by the historical oil and gas drilling activity in the area.
5. There is a lack of high-quality 3D deep seismic, shallow seismic, SBP, and geotechnical datasets currently over the Kish Basin area.
6. The regulatory risk to the development of a hydrogen storage project offshore Dublin is significant.
7. The maps of European salt storage potential need to be updated to reflect the results of this project (H2 Infrastructure Map Europe (h2inframap.eu)).

Recommendations

Based on the above conclusions there are a number of recommendations:

1. Propose the development of hydrogen storage infrastructure in salt caverns offshore Dublin as a Project of Common/Mutual Interest under the Trans-European Network for Energy (TEN-E).
2. Develop a regulatory regime to facilitate prospecting and development of man-made salt cavern storage offshore Ireland.
3. Investigate the role of public private partnerships in the development of hydrogen storage infrastructure offshore Dublin.
4. Support the development of a regional hydrogen cluster or hub in the greater Dublin Area.
5. Acquire additional high quality geophysical and geotechnical information to high grade areas for infrastructure development.
6. Develop a detailed costing for the development of offshore salt cavern hydrogen storage and transportation infrastructure to inform commercial decisions of offshore wind developers – AACE Class 4 cost estimate for CAPEX with OPEX estimate.

References

BGS. 2012. *Irish Sea Carbon Capture and Storage Project, Final Report. Energy and Marine Geoscience Programme Commissioned Report.*

Bünger, U., Michalski, J., Crotogino, F. & Kruck, O. 2016. Large-scale underground storage of hydrogen for the grid integration of renewable energy and other applications. *In*: *Compendium of Hydrogen Energy*. Elsevier, 133–163.

Byrne, K. 2020. *A Seismic Study on the Structural Evolution of the North Celtic Sea Basin, Offshore Ireland*. University College Cork.

Caglayan, D.G., Weber, N., Heinrichs, H.U., Linßen, J., Robinius, M., Kukla, P.A. & Stolten, D. 2020. Technical potential of salt caverns for hydrogen storage in Europe. *International Journal of Hydrogen Energy*, **45**, 6793–6805.

Clark at al, 2010. Clark et al 2010, Pattern and timing of retreat of the last British Irish Ice Sheet.

Coughlan et al, 2019. Stratigraphic Model of the Quaternary sediments of the Western Irish Sea Mud Belt from core, geotechnical and acoustic data.

Creane et al, 2022. Development and Dynamics of Sediment Waves in a Complex Morphological & Tidal Dominated System: Southern Irish Sea.

Croker, P.F. & Shannon, P.M. 1995. The petroleum geology of Ireland's offshore basins: Introduction. *Geological Society Special Publication*, **93**, 1–8.

Dancer, P.N., Kenyon-Roberts, S.M., Downey, J.W., Baillie, J.M., Meadows, N.S. & Maguire, K. 2005. The Corrib gas field, offshore west of Ireland. *In*: *Petroleum Geology Conference Proceedings*. Geological Society of London, 1035–1046.

Dunford, G. M., Dancer, P. N., & Long, K. D. (2001). Hydrocarbon Potential of the Kish Bank Basin. In P. Shannon, & P. C. Haughton, *The Petroleum Exploration of Ireland's Offshore Basins* (pp. 135-154). The Geological Society of London.

Eirgrid. 2020. *All Ireland Quarterly Dispatch Down Report*.

EWE. 2021. Storing hydrogen – HyCAVmobil research project https://www.ewe.com/en/ewe-group/shaping-the-future/hydrogen/storing-hydrogen.

GENCOMM. GENerating energy secure COMMunities | Interreg NEW https://www.nweurope.eu/projects/project-search/gencomm-generating-energy-secure-communities/.

HyStorIES. n.d. Hydrogen Storage In European Subsurface https://cordis.europa.eu/project/id/101007176.

Naylor, D. & Shannon, P.M. 2011. *Petroleum Geology of Ireland*.

Oceanset https://www.oceanset.eu/.

Panfilov, M. 2016. Underground and pipeline hydrogen storage. *In*: *Compendium of Hydrogen Energy*. Elsevier, 91–115.

PVR. 2016. Providence Resources AGM Presentation https://www.providenceresources.com/presentations.

SEAI. 2008. *Assessment of the Potential for Geological Storage of CO 2 for the Island of Ireland.*

Wolf, E. 2015. Large-Scale Hydrogen Energy Storage. *In*: *Electrochemical Energy Storage for Renewable Sources and Grid Balancing*. Elsevier Inc., 129–142.

Williams et al, 2022. Does the United Kingdom have sufficient geological storage capacity to support a hydrogen economy? Estimating the salt cavern storage potential of bedded halite formations, *Journal of Energy Storage,* Elsevier, 53, 105109.

Appendices – GIS Shapefiles

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