Hydrogen Salt Storage Assessment (HYSS)

WP3&4 Assessment of salt storage in Irish Sea and Celtic Sea Basins

Grant Agreement – 21/RDD/673

Final Report

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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 second report assesses the potential for bilocation of hydrogen storage and offshore wind farms in the Irish Sea and Celtic Basins. An offshore green hydrogen production facility located in the Irish Sea or Celtic Sea 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 such an Offshore Green Hydrogen Production Facility is estimated to be 7 years.

Salt intervals ranging in thickness from 30m to 769m were identified in four wells drilled in the Celtic Sea Basins. In the Irish Sea Basins four wells contained thin salt less than 50m thick, with significant thickening in the UK sector due to halokinesis. A robust regional interpretation of the 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 salt intervals interpreted in the Irish and Celtic Basins. Thickness maps were prepared for each of the salt intervals and checked against the salt thickness seen in the exploration 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 30m to 769m, including shale/silt interbeds. The seismic data exhibits signs of salt movement (halokinesis) in the UK sector, 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. 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 m3 to 815,000 m3 as optimum.

Executive Summary

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 salt occurs at the optimum hydrogen storage depth of 1,000m between 50km and 100kms offshore in water depths of between 80m and 125m in the Irish and Celtic Sea Basins. On the Labadie Bank in the Celtic Sea the water depth shallows to 62m, suitable for fixed bottom wind turbines. The salt extent 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 as part of a standalone green hydrogen production project in conjunction with floating offshore wind. The project has identified almost 6,000 potential manmade salt caverns at the optimum depth and thickness for hydrogen gas storage in the Irish Sea and Celtic Sea Basins. Assuming only 1% of the identified potential was viable, and each cavern could deliver in the region of 0.1 TWh of hydrogen storage, or >60 TWh_{H2} cumulatively, this would be more than sufficient to meet the indicative 90 day hydrogen storage needs for 2050 demand estimates of 18.4 TWh_{H2} (National Hydrogen Strategy 2023).

The geohazard study has highlighted several risks posed by the presence of shallow gas, near surface glacial channel complexes, tectonically active faults and protruding bedrocks at or near the seafloor. 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 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 offshore hydrogen storage infrastructure; support for the development of regional hydrogen clusters or hubs and a detailed costing for the development of offshore salt cavern hydrogen storage and transportation infrastructure to inform commercial decisions of offshore wind developers.

Location Map

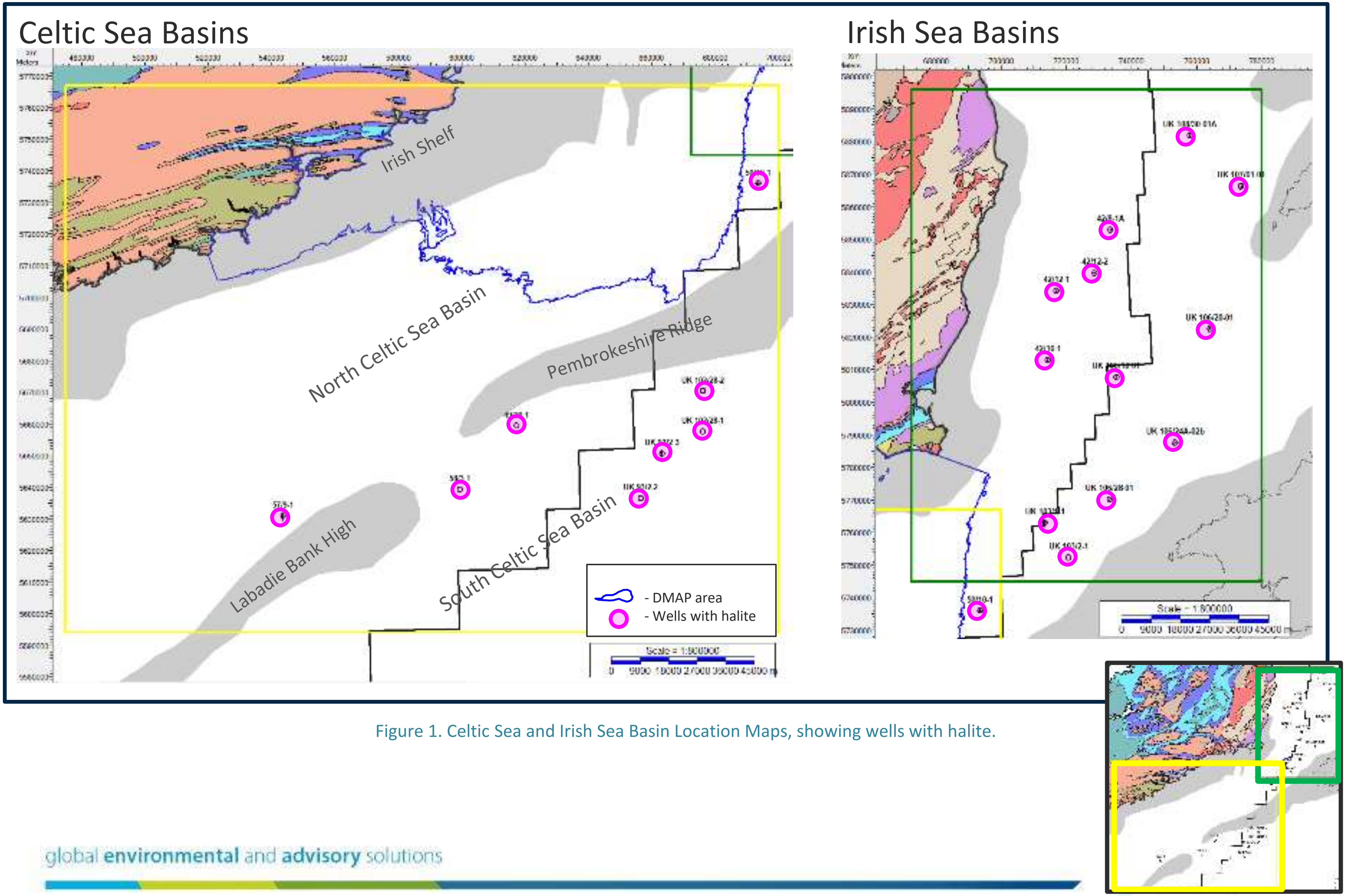


Figure 1. Celtic Sea and Irish Sea Basin Location Maps, showing wells with halite.

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 local aviation and shipping transport e-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 m3 to 1,000,000 m3 (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.

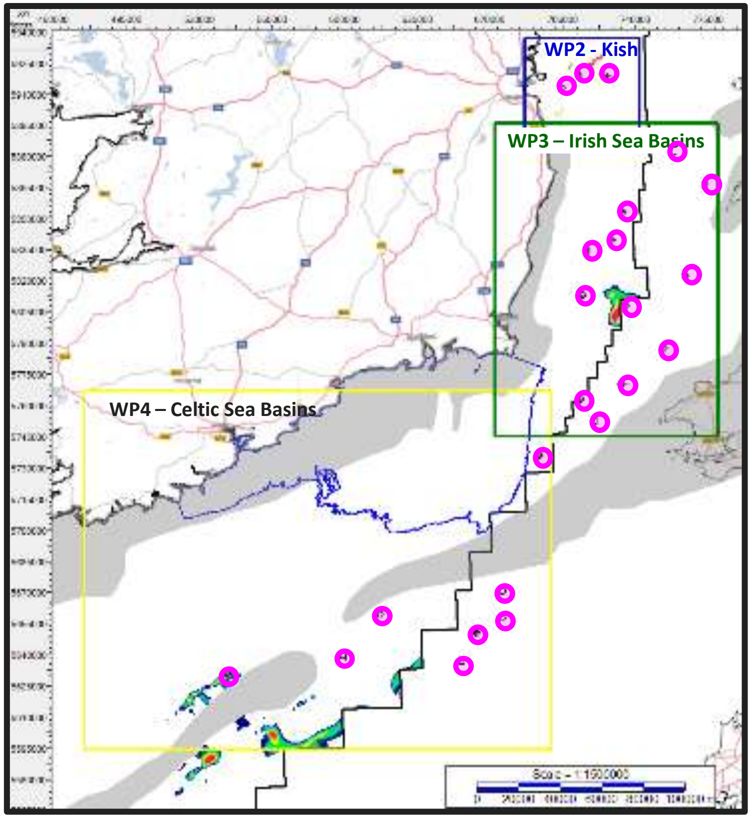


Figure 2. Map showing exploration wells with halite, work package areas and grid showing halite within zone of interest for cavern development.

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 PWhH2, 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. This report focuses on the Irish Sea and Celtic Sea areas.

Scope of Work and Base Data

Scope of Work

WP3-O1 & WP4-01: 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.

WP3-O2 & WP4-02: Use seismic data to qualitatively assess salt characteristics (massive, interbedded, domal, evidence of halokinesis etc).

WP3-O3 & WP4-03 : Using seismic velocity and local well information, undertake a pore pressure and fracture gradient study to define the geomechanics of the surrounding stratigraphy.

WP3-O4 & WP4-04 : Engineering study to assess the maximum theoretical hydrogen storage potential using salt cavern storage methodologies suitable for geological conditions.

WP3-O5 & WP4-05 : Conduct a regional geohazards study to assess the risks to surface and subsurface operations.

WP3-O6 & WP4-06 : Conduct a study of maritime traffic (shipping, fisheries, leisure), archaeological sites or other maritime/surface constraints (e.g. buoys or cables).

WP3-O7 & WP4-07: Undertake a high-level review of the potential environmental issues or constraints that may impact surface or subsurface operations.

WP3-O8 & WP4-08: 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 are:

- Offshore wind turbines (fixed or floating)
- 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

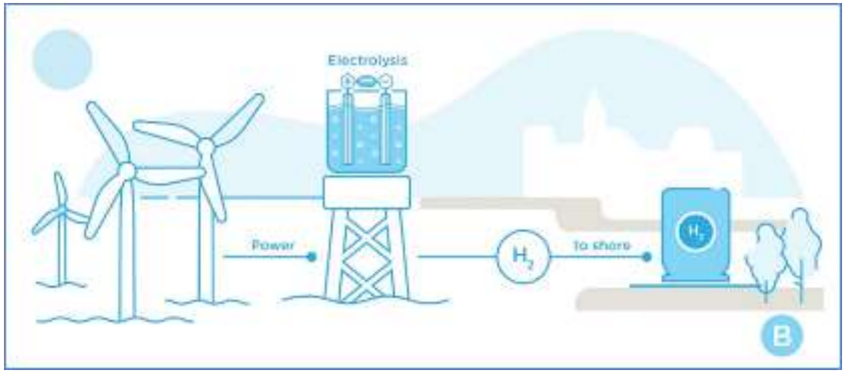


Figure 3. Offshore Hydrogen Production. Source: Ramboll

An offshore green hydrogen production facility is likely to be constructed in three stages (Figure 5).

Stage 1 will be the construction of offshore wind turbines, 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 or semi-submersible 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 or semi-submersible drilling rig, drilling of a borehole to about 1,000 m subsea, cavern solution / leaching of 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 (Figure 6).

Stage 1 Construction of Offshore Wind Farm

The **wind turbines** in the Irish Sea and Celtic Sea Basins will be in water depths of between 80m and 125m, suitable for floating offshore wind turbines, from the Labadie bank in the Celtic Sea where water depth shallows to 62m suitable for fixed bottom wind turbines. 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 on sandbanks, such as the Labadie Bank. A range of foundation types are under consideration but a multileg jacket is the most likely for the substation platforms. However, away from the sand banks floating offshore wind turbines with floating semi-submersible platforms will be required for hydrogen electrolysis and substations. Each fixed **offshore substation platform** will be supported by up to six legs and each leg will be secured to the seabed by a foundation structure. The semi-submersible floating platforms will be anchored to the seabed using slack catenary mooring lines. 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 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.

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 4). The cavern profile is developed from the bottom to the top by pulling the leaching strings and reducing blanket depth step by step.

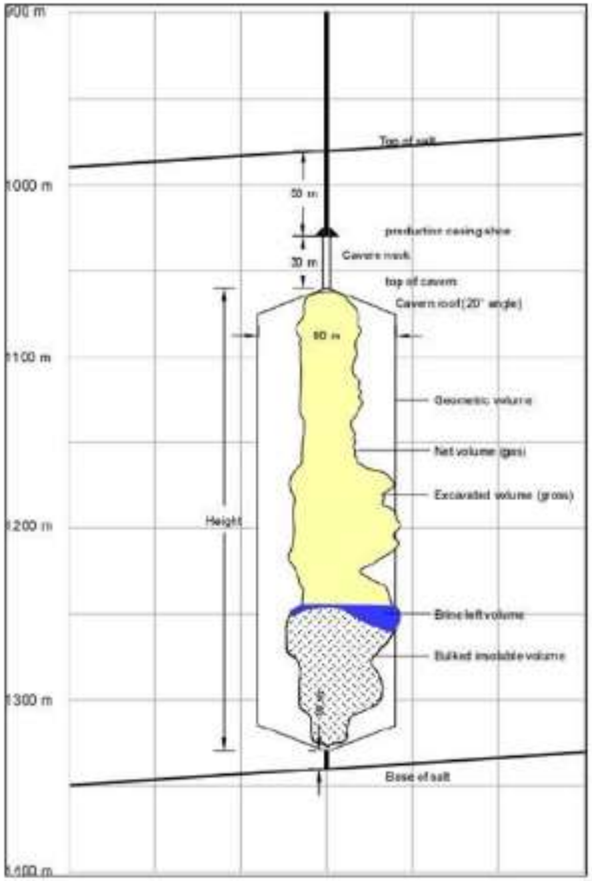
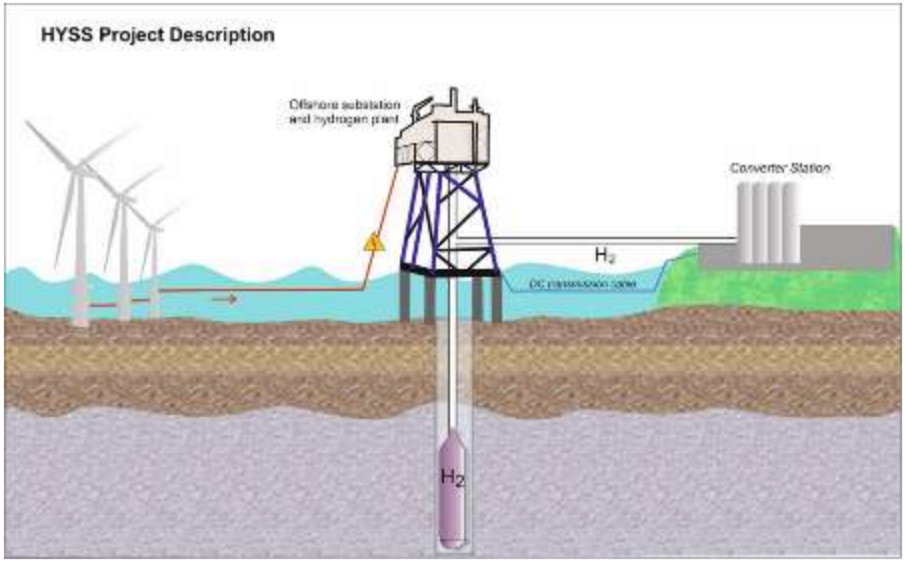


Figure 4. Cavern Geometry Source: Hystories

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 to shore and a subsea hydrogen pipeline to export hydrogen from the underground hydrogen salt storage cavern beneath the seabed to the shore substation will be run from the hydrogen plant platform to the shore substation.

Figure 3 Hydrogen Production Platform. Source Poshydon



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 5. Offshore Green Hydrogen Production Facility Construction

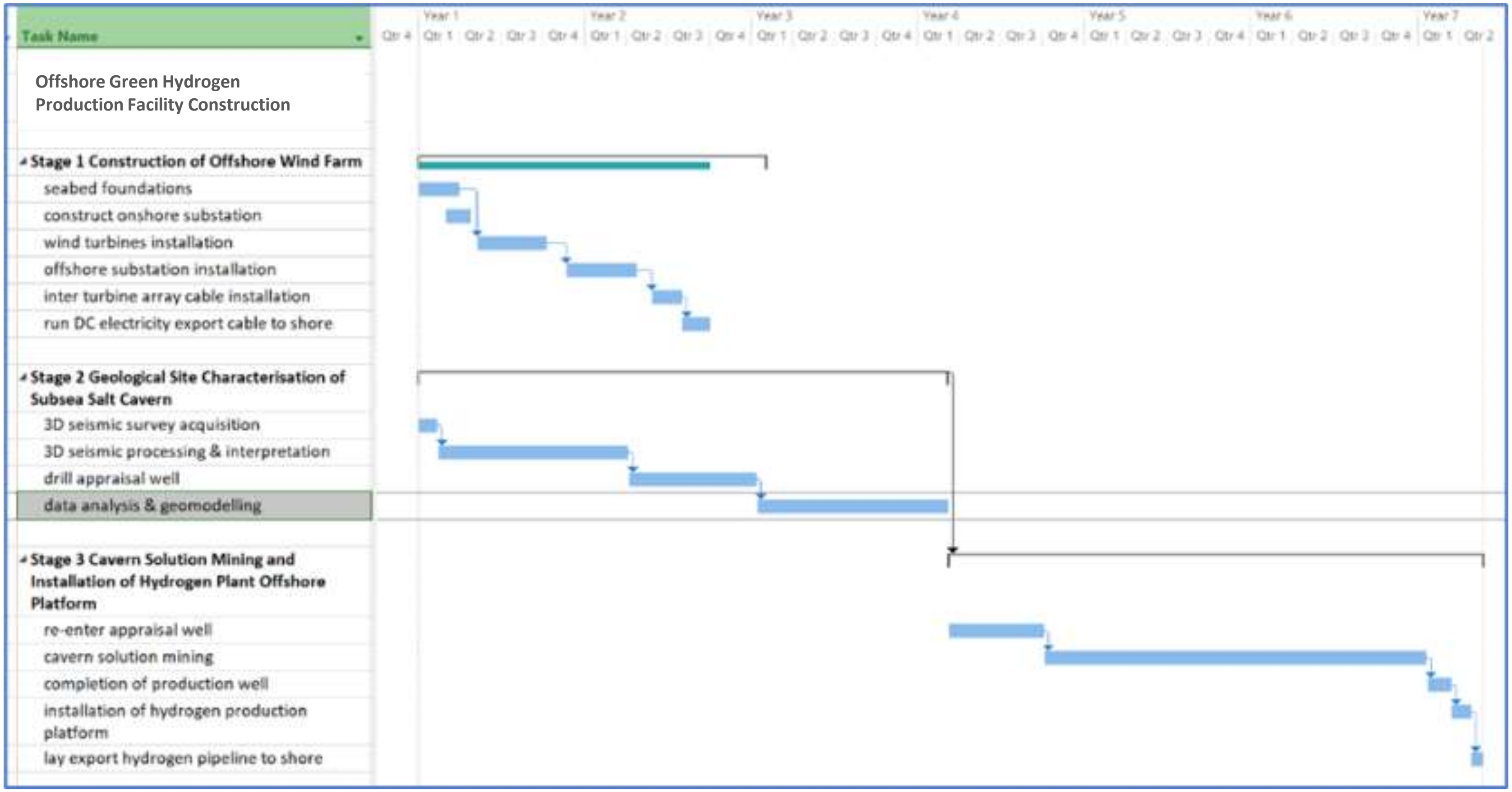


Figure 6. Offshore Green Hydrogen Production Facility Construction Timeline

Methodology

WP3-O1 & WP4-01: Evaluate salt intervals in existing exploration wells

The Standard Stratigraphic Nomenclature of Offshore Ireland was reviewed to identify salt intervals in the >100 deep wells in the Celtic Sea and Irish Sea Basins off the south and southeast coast of Ireland. In the Celtic Sea Basins 4 wells contained salt and the digital well logs and composite well logs were reviewed to confirm the nature of the salt signature, Figure7 below. The salt is interpreted as one contiguous salt member, named the Feadóg Halite, ranging in thickness from 30m to 769m, with 57/9-1 being the type section. Review of the wells in the adjacent UK sector shows halite of similar thickness.

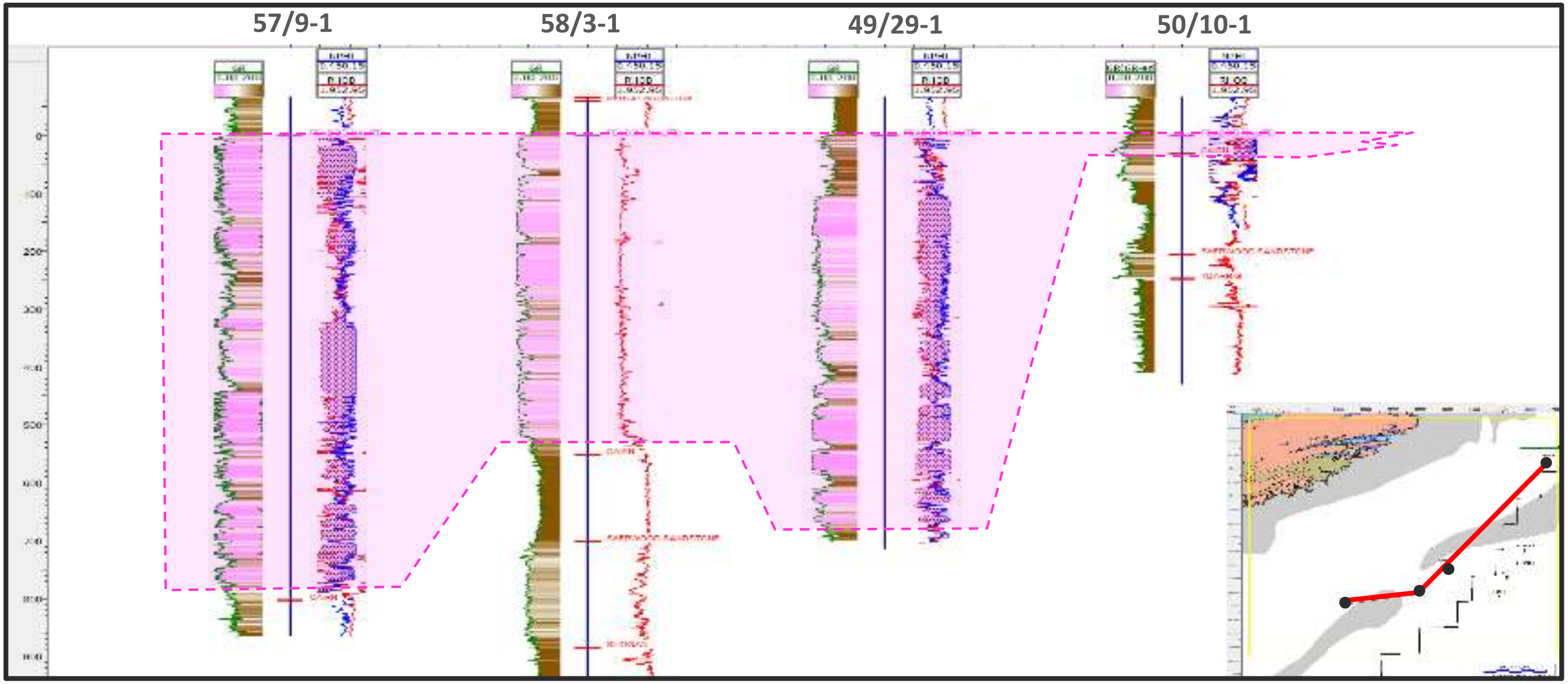


Figure 7. Celtic Sea Basins well stratigraphy highlighting salt units (halite) in pink, flattened on Feadóg Halite.

Methodology

WP3-01 & WP4-01: Evaluate salt intervals in existing exploration wells

In the Irish Sea Basins 4 wells contained salt and the digital well logs and composite well logs were reviewed to confirm the nature of the salt signature. The salt is split into 5 salt members, with only one well (42/12-1) containing all 5 members.

The Mythop, Rossall and Flyde (oldest) halites appear to have consistent thickness between wells in the Irish and UK sector, except where sections have been eroded. The average thickness of net halite within these units is less than 50 meters and there is no evidence of significant halokensis or thickening of these away from well control.

The Warton (youngest) and the Preesall halites in the Irish wells are quite thin, though the seismic data exhibits clear halokinesis, subsequently proven as several hundred meters of halite in adjacent UK wells, such as 106/28-1.

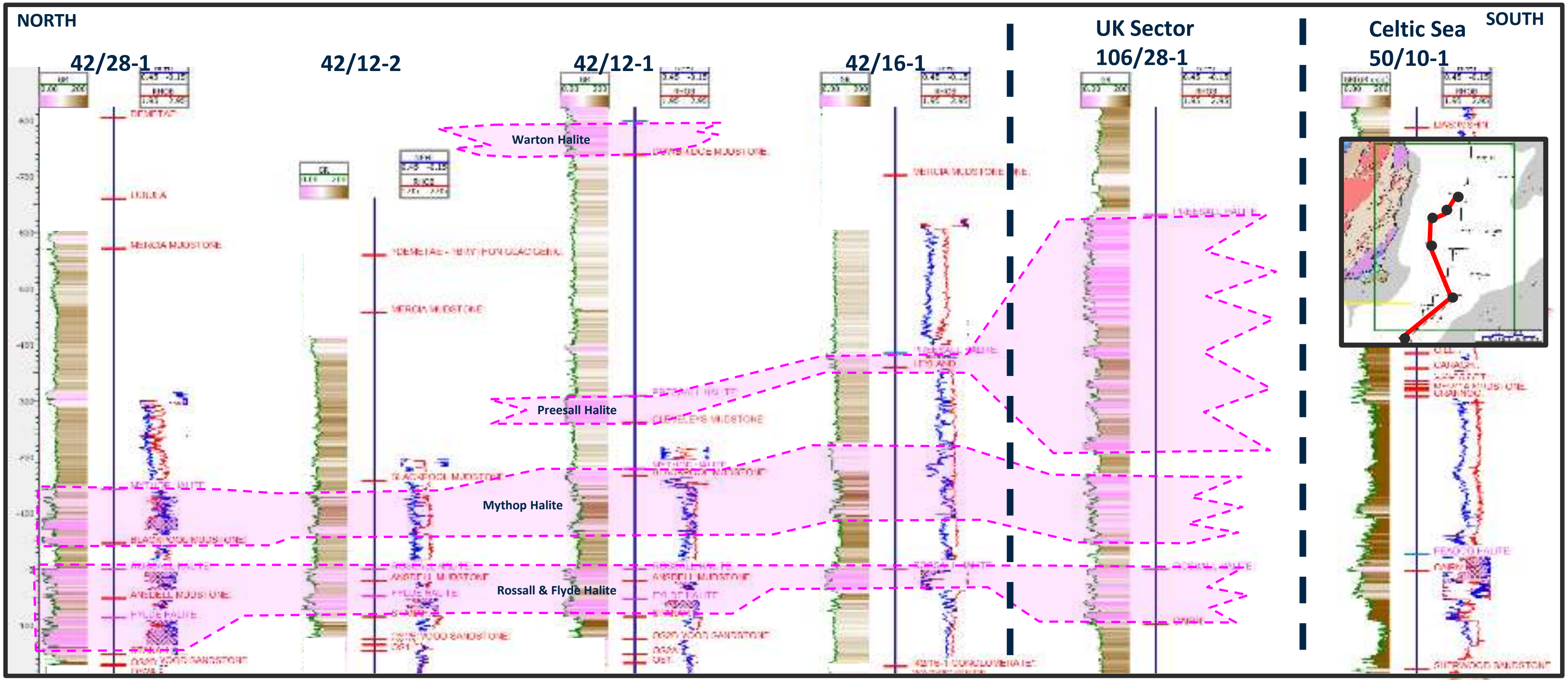


Figure 8. Irish Sea Basins well stratigraphy highlighting salt units (halite) in pink, flattened on Top Rossall Halite

Methodology

WP3-O2 & WP4-02: Available seismic dataset

The dataset available for the Irish Sea and Celtic Sea Basins consisted primarily of 2D seismic data acquired between 1969 and 2014 and some small localised 3D surveys.

Velocity data from seismic was not available during the study, though there is a significant well dataset with velocity and pressure data, as well as the team's extensive experience of the basins.

The Kingdom Suite software was the computer software tool chosen for the project. Seismic data was collected from the GRO and loaded to a single Kingdom project as described in the WP2 report.

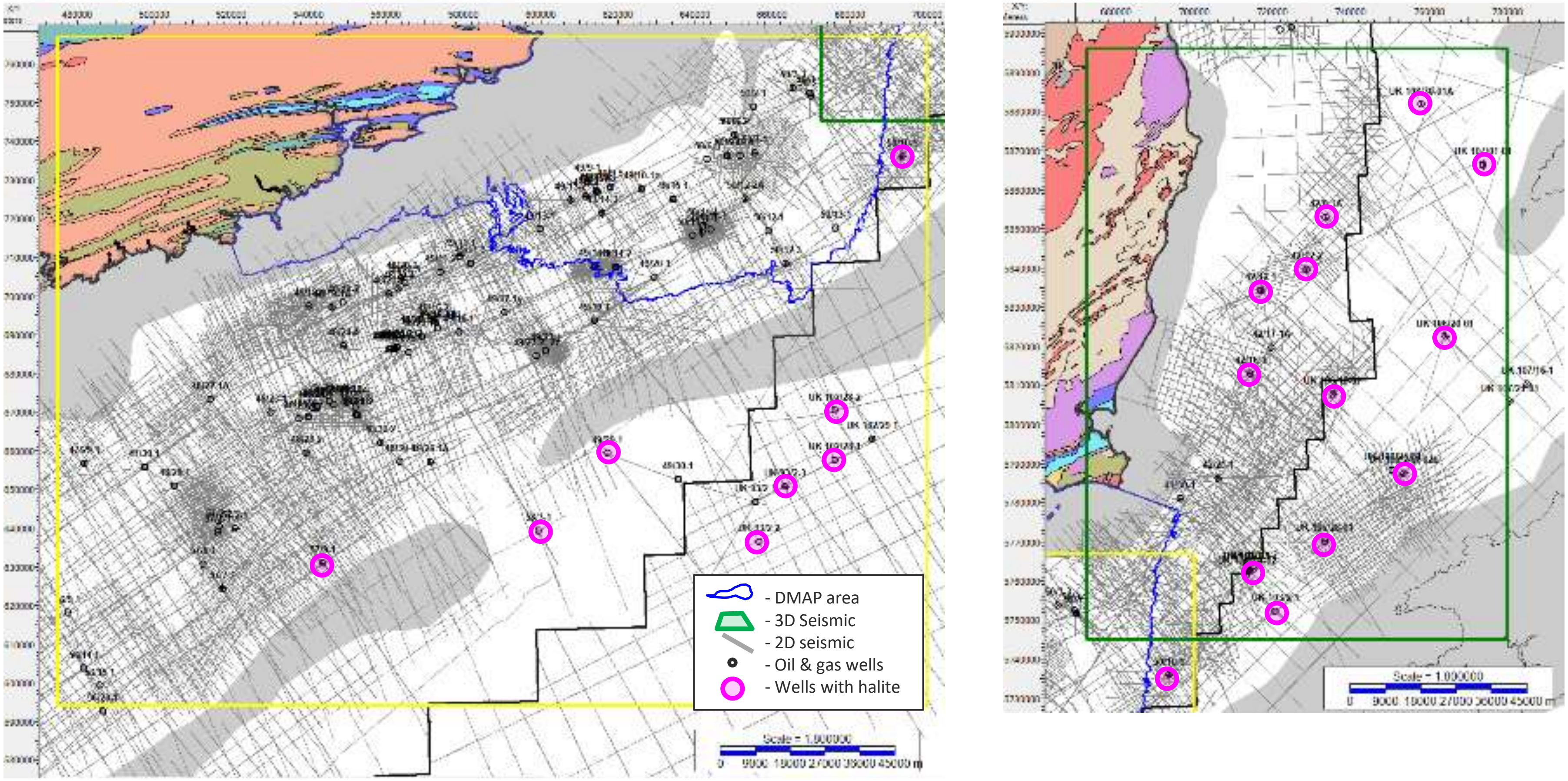
The imaging quality of the 2D data prior to 1990 is very poor and occasionally unusable. Some of these surveys, or lines within surveys, were not used for the study due to obvious positioning errors which could not be rectified. The more modern (1990-2014) datasets tended to have adequate imaging in the shallow section, but becoming poorer at depth.

The Helvick, Kinsale and Barryroe 3D surveys were of reasonable quality and were utilised in the study, the smaller Ballycotton, Amergin, Rosscarbery and Midleton surveys were located where little to no salt is interpreted.

As the Celtic Sea and Irish Sea Basins are a critical area of interest for offshore renewable energy, as demonstrated by the government defining part of the area as a Designated Maritime Area Plan, this study was significantly extended to include seismic and well data from the adjacent UK waters, downloaded from the UK National Data Repository. The seismic data utilised was from a 2016/17 UK government funded project to acquire new seismic and reprocess existing seismic. This more modern data was good to excellent quality and helped define the structural configuration of the basins and the structural-depositional relationship of halite as well as defining the seismic character, allowing a more confident and robust interpretation. This proved critical in defining the structural style of the basins and extending the interpretation onto the poorer quality Irish datasets.

Methodology

WP3-O2 & WP4-02: Available seismic dataset


Celtic Sea Basins Dataset

Irish Sea Basins Dataset

Figure 9. Irish Sea Basin seismic and well database

Methodology

WP3-O2 & WP4-02: Interpretation of seismic data

The methodology described in WP2 was followed for WP3 & 4.

A review of the digital well logs showed (as expected) the 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. The seabed (a hard event) was thus taken as a guide to help identify other hard events on a line by line basis.

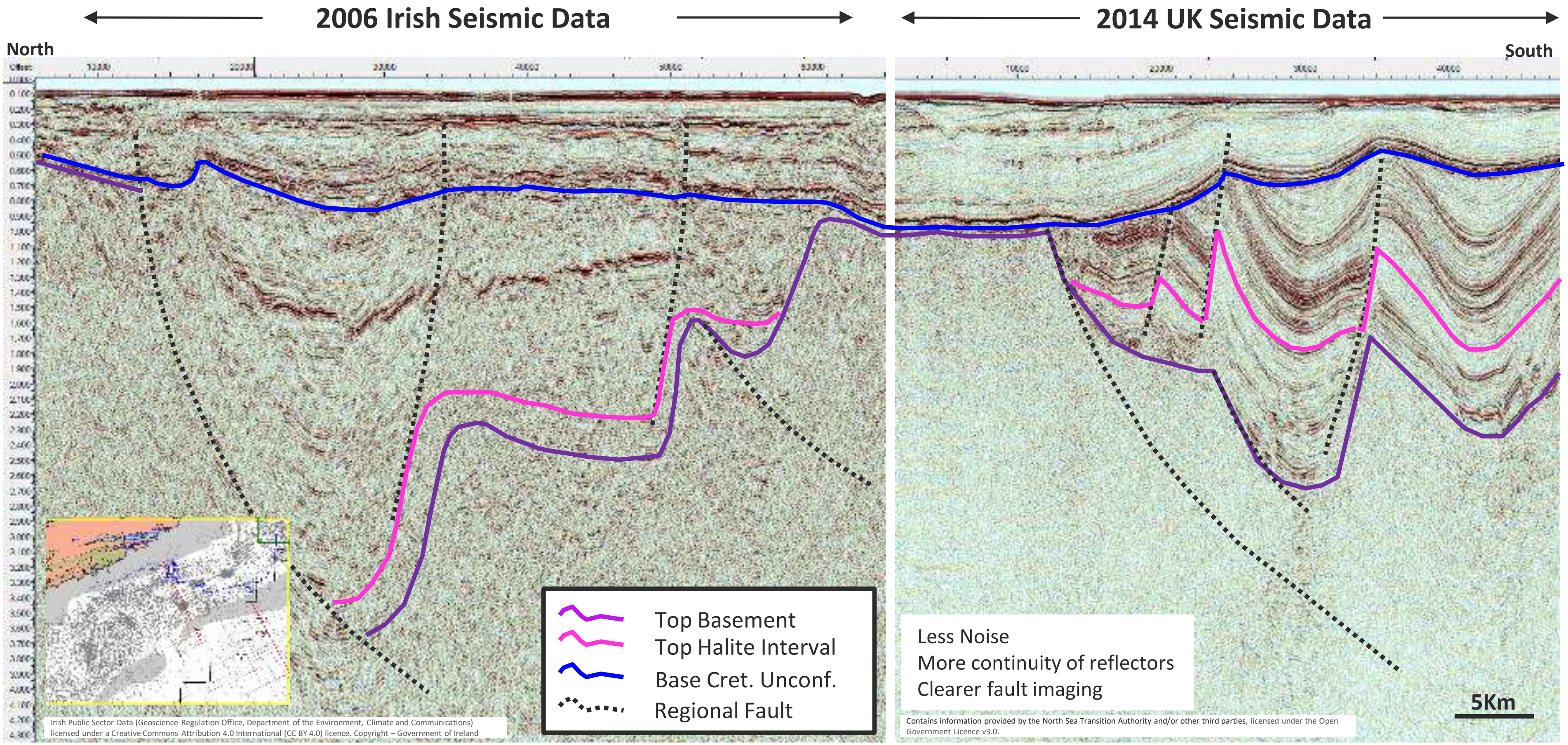
Within the study area, where the seismic data was of sufficient quality, the salt formations were generally seen to have a continuous hard top and an opaque internal character. The base of the salt was not a consistently strong seismic response, or was too close to the top of the underlying halite to have an independent response. The base salt was thus interpreted to be 50 meters below top salt, except where well control and seismic data quality allowed for manual interpretation of a base salt seismic event.

The regional interpretation of the 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. This was particularly important in the deeper parts of the Celtic Sea basins where no well control existed.

The interpretation of “Top Halite” on seismic data in the Celtic Sea Basins corresponds to the Feadóg Halite, per well control. As the seismic interpretation passes north-eastwards into the Irish Sea Basins the interpretation corresponds to the lateral equivalent, the Warton Halite. Where the Warton Halite is not seen in wells, predominantly in the shallower Irish areas where it has been eroded, the interpretation of Top Halite is the underlying Preesall Halite. The Feadóg/Warton and Preesall halites are sufficiently thick in the wells to be of interest for potential salt cavern development.

A lower halite section is encountered in the Irish Sea Basins (Mythop, Rossall, Flyde, which are also present in the Kish Basin) but the net thickness in the wells remains relatively constant at less than 50 meters thick, which is insufficient for cavern development. This interval is mapped on the seismic data where well control and seismic imaging is sufficient to provide a confident interpretation, though its extent is likely to be greater than currently mapped.

WP3-O2 & WP4-02: Interpretation of seismic data



2006 Irish Seismic Data

2014 UK Seismic Data

Less Noise

More continuity of reflectors

Clearer fault imaging

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Figure 10. Celtic Sea Basins – example seismic lines, north to south, exhibiting best quality data available. Note significantly improved modern datasets available in the UK which aided interpretation.

WP3-O2 & WP4-02: Interpretation of seismic data

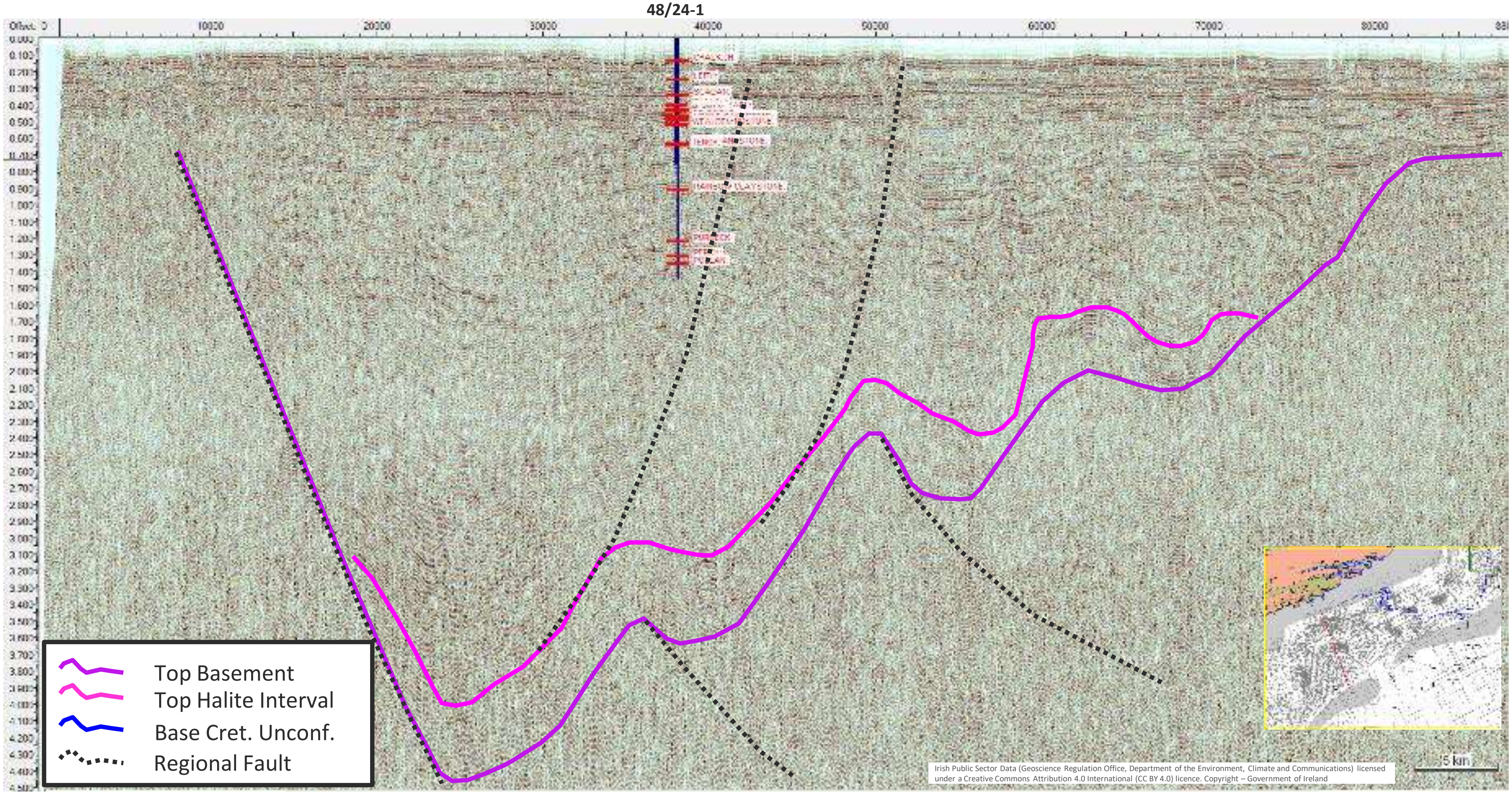

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Figure 11. Celtic Sea Basins – Typical quality of vintage 1970's & 1980's seismic data. An interpretation can be extended onto this data using structural form and character from the modern datasets.

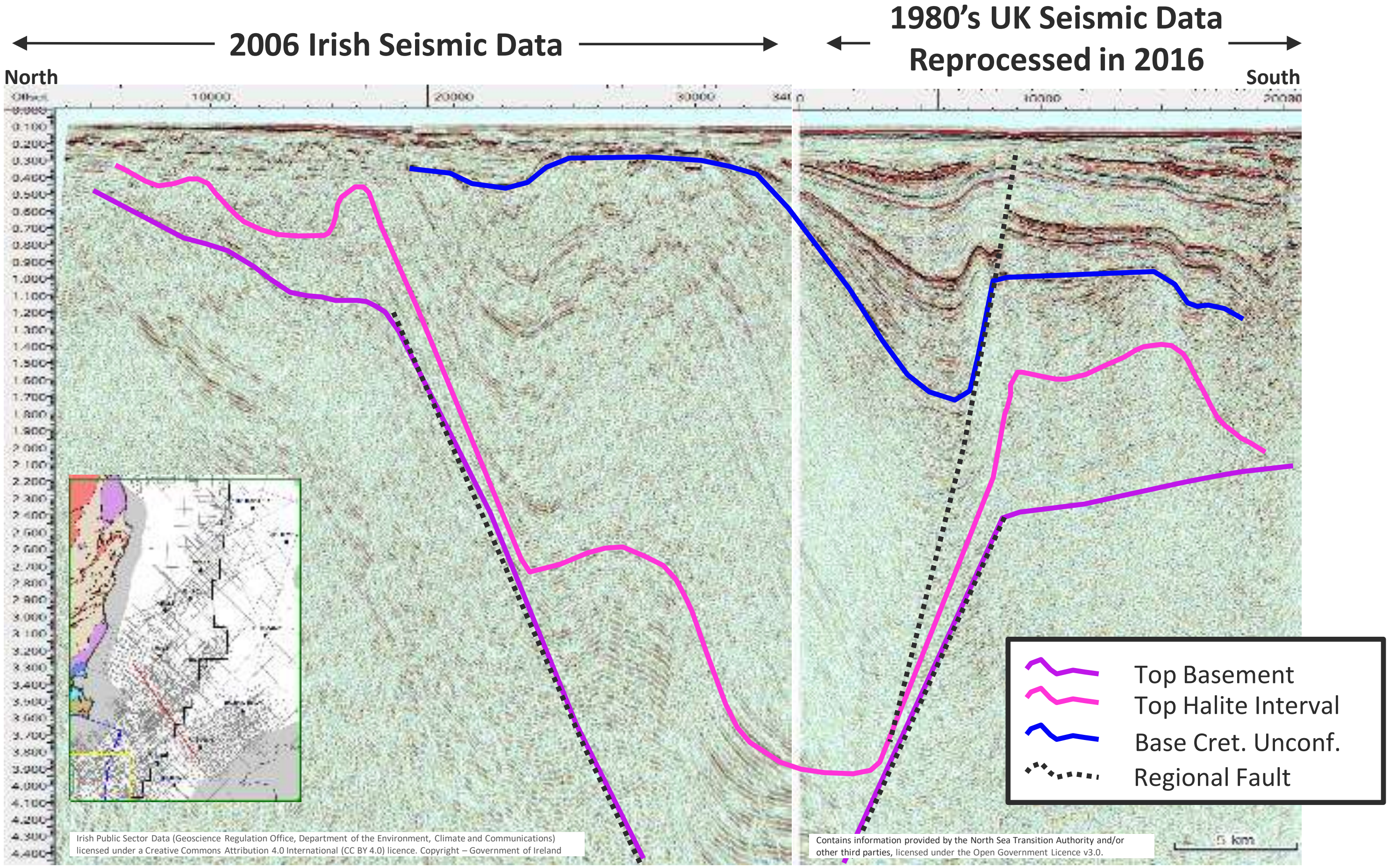

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Figure 12. Irish Sea Basins – example seismic lines, north to south, exhibiting best quality data available. Note the reprocessed vintage 1980's data in the UK is comparable with the 2006 Irish data, demonstrating the advantages of reprocessing older data.

Methodology

WP3-O1 & WP4-01 : Gridding

As the interpretation exists only where the 2D or 3D seismic data exists the interpretation was gridded to create a full 3D interpretation over the full extent of the Celtic Sea and Irish Sea Basins. As per WP2, 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.

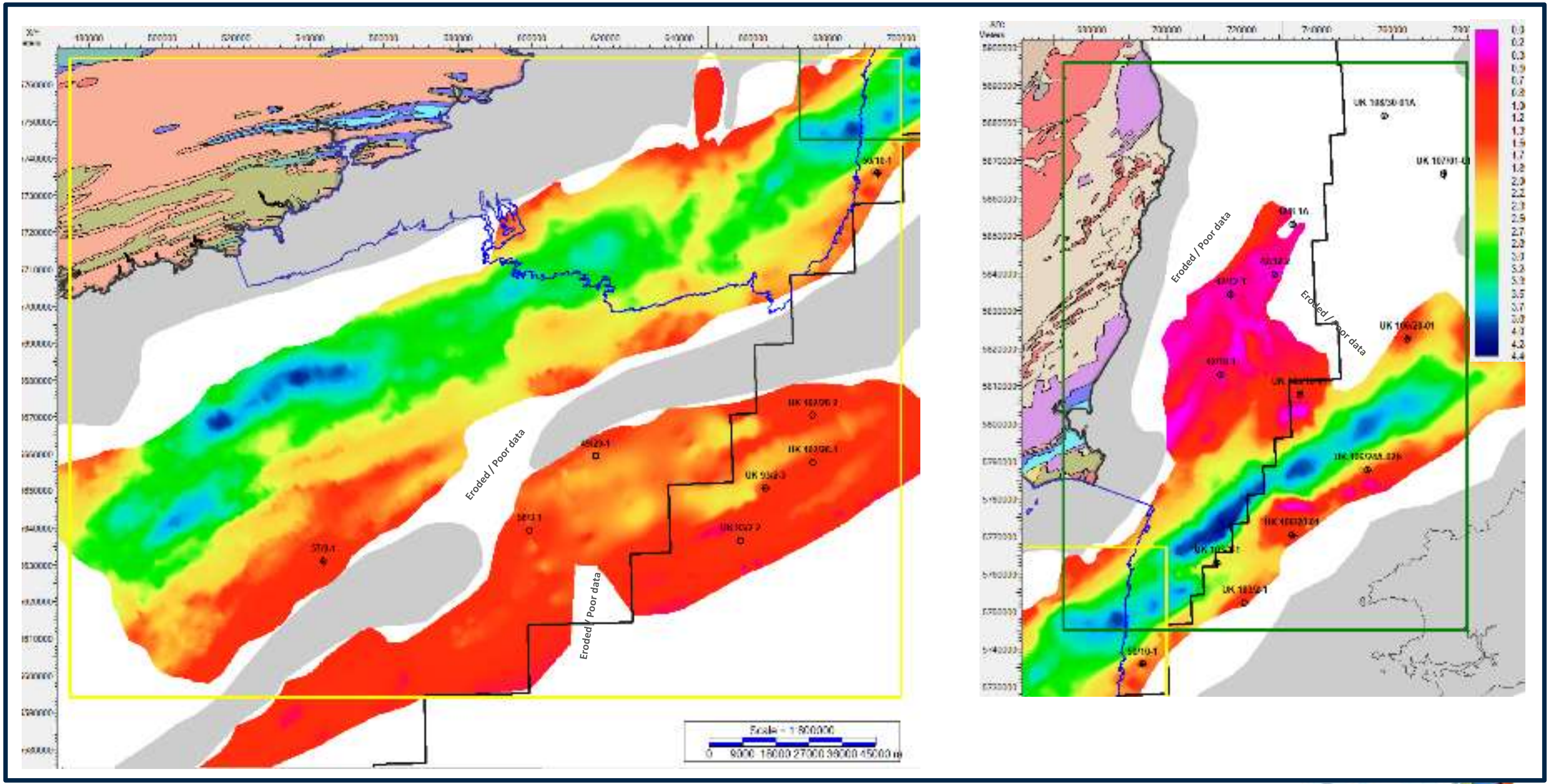

Figure 13. Feadóg/Warton and Preesall Halite interpretation in Time.

Methodology

WP3-O1 & WP4-01 : Gridding

As discussed earlier in this section, a lower halite section is encountered in the Irish Sea Basins (Mythop, Rossall, Flyde, which are also present in the Kish Basin) but the net thickness in the wells remains relatively constant at less than 50 meters thick, see well 42/12-2.

These halites are thus not considered to be sufficient for cavern development in the Irish Sea Basins area and there is no clear evidence of thickening of these units away from well control.

This interval is mapped on the seismic data where well control and seismic imaging is sufficient to provide a confident interpretation, though its extent is likely to be greater than currently mapped.

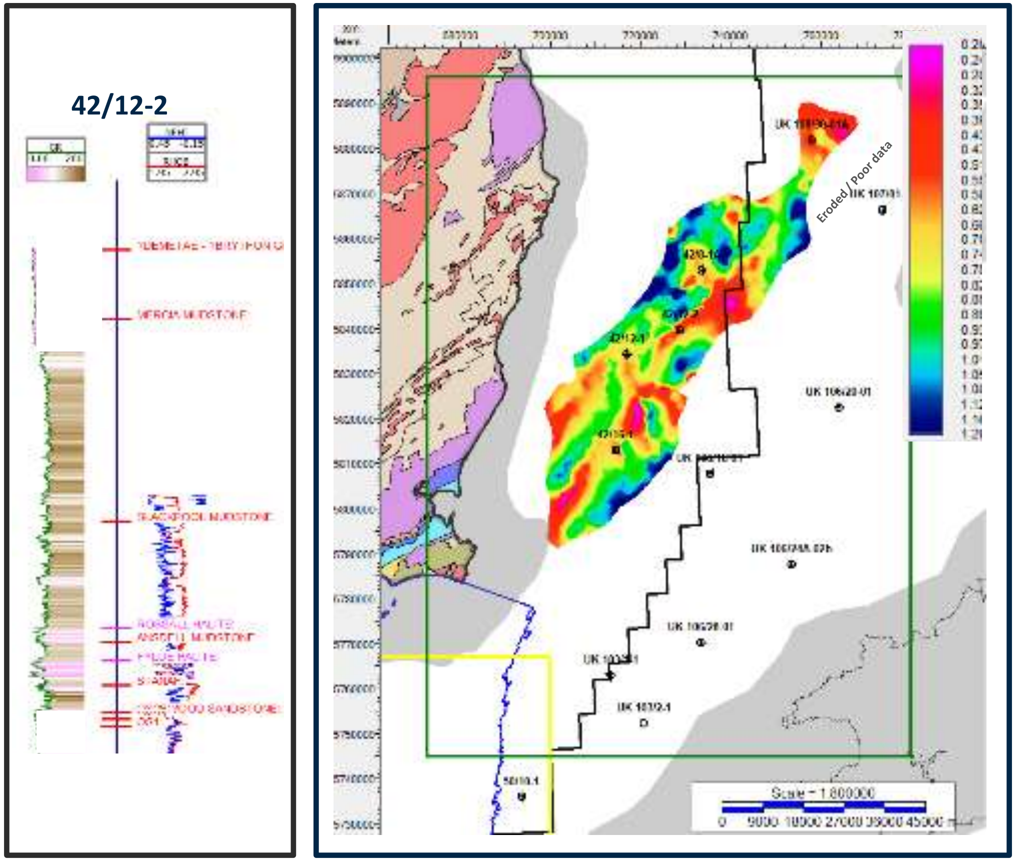

Figure 14. Mythop, Rossall and Flyde Halite in 42/12-2 well and the interpretation in Time.

Methodology

WP3-O1 & WP4-01: 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.

As there was sparse well control, and the interpretation spanned over 300km, a simple regional depth conversion was deemed to be appropriate. The time interpretation at each well (including the UK wells) and the corresponding halite depth was crossplotted and a simple linear relationship was defined between time and depth, Figure 15. The Time grids where thus converted to the depth domain using this relationship.

With only 8 Irish wells encountering halite, the expansion of the project scope to include the UK wells was once again critical in providing reliable data inputs to this study.

The apparent uncertainty in this simple depth conversion is considered to be +/- 200 meters and is considered acceptable for a regional depth product covering multiple geological basins, with differing structural histories and often poor seismic data imaging upon which to base the input interpretation.

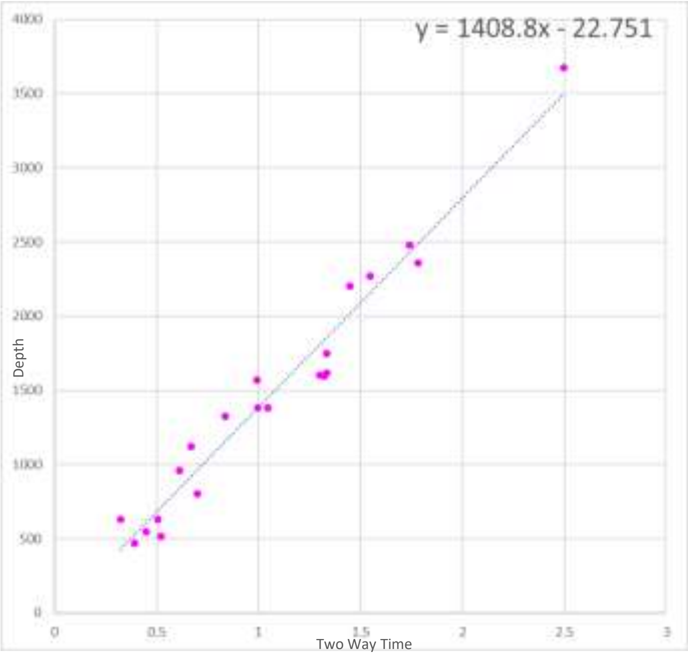

Figure 15. Crossplot of Time Interpretation v’s corresponding Depth in the wells, utilised to create a function to convert from time to depth.

Methodology

WP3-O1 & WP4-01 : Assessment of salt thickness and extent

The output from the depth conversion process was depth grids for the top salt within the Celtic Sea and Irish Sea Basins.

As discussed previously, the minimum salt thickness interpreted on the seismic data was chosen to be 50 meters, which agreed with the average thickness of halite units encountered in wells in the Irish Sea Basins. The salt thickness was increased where supported by well control and/or clear seismic data.

In the Celtic Sea and Irish Sea Basins the primary halite interval of interest is the Feadóg/Warton Halite and the underlying Presall halite, which ranges from 30m to 769m in Irish wells. The seismic data exhibits clear signs of halokinesis, specifically the development of localised salt pillows.

Based on a review of the well log character of Irish and UK wells it is interpreted that when the gross package of halite exceeds 150 meters in thickness the interval is likely to be predominantly halite with low proportions of interbedded shales. This is considered the cut-off point, where above this gross thickness, the halite is potentially suitable for salt cavern development.

For the Celtic Sea and Irish Sea Basin areas, to assess the potential of 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, with this range extended to 800m to 1700m to account for depth conversion uncertainty. As discussed above, a cut-off of 150m gross halite thickness has been chosen as the minimal salt thickness to be considered.

WP3-O1 & WP4-01: Feadóg Halite Maps

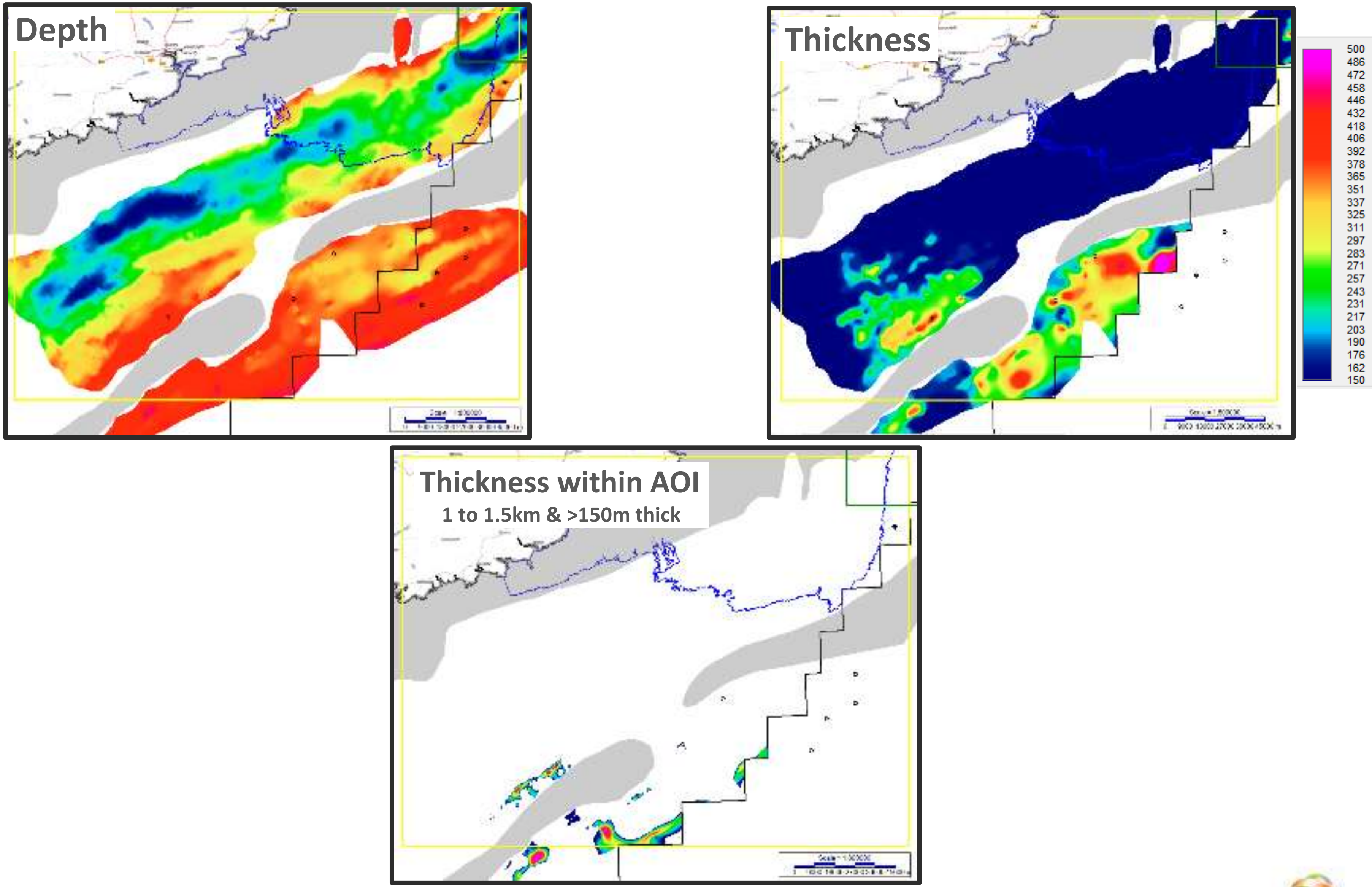

Figure 16. Feadóg halite Depth, Thickness and Areas of Interest.

WP3-O1 & WP4-01: Halite Maps

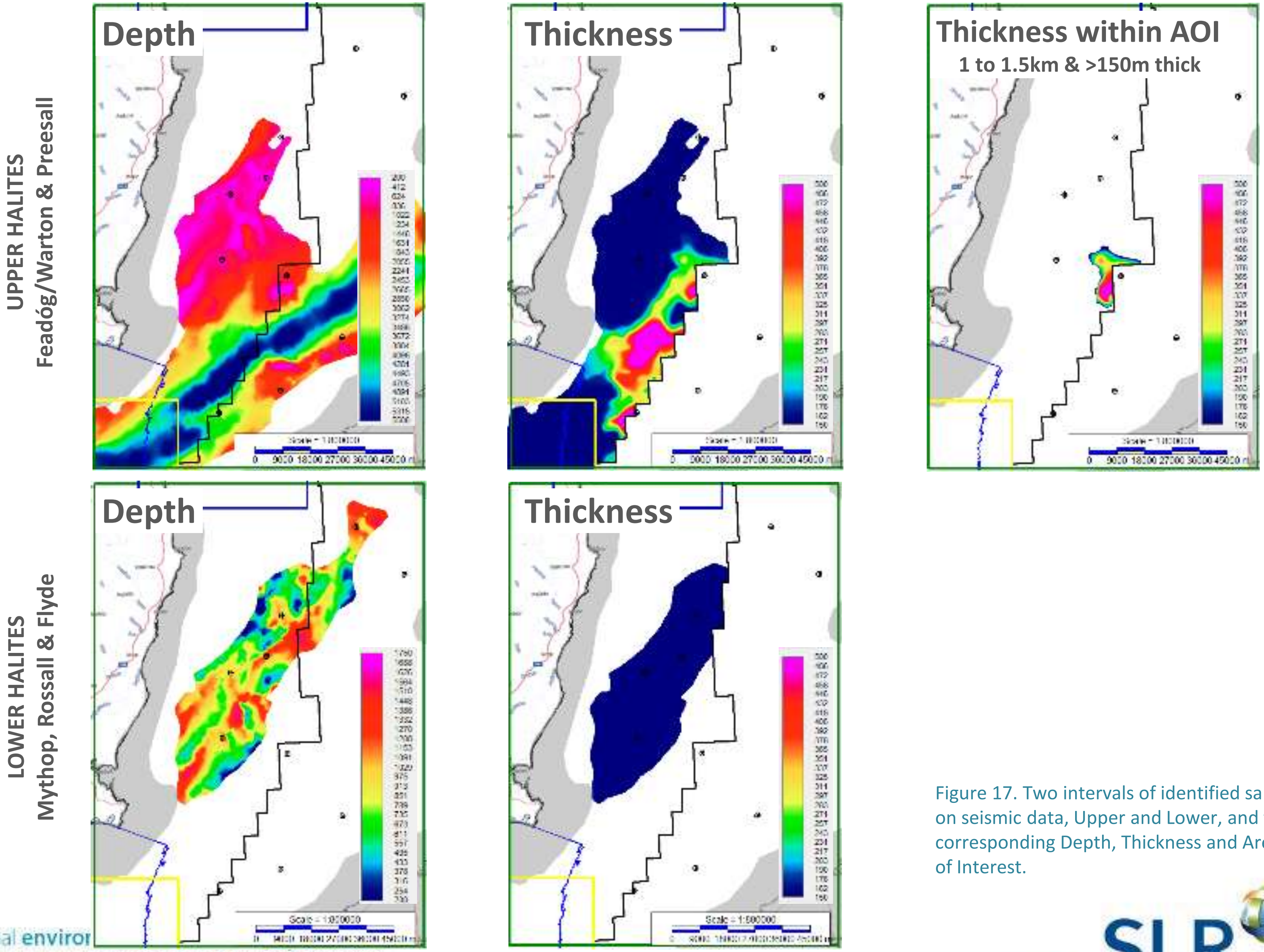

Figure 17. Two intervals of identified salt on seismic data, Upper and Lower, and the corresponding Depth, Thickness and Areas of Interest.

WP3-O1 & WP4-01: Seismic Line FNT2013_203 with interpreted halokinesis

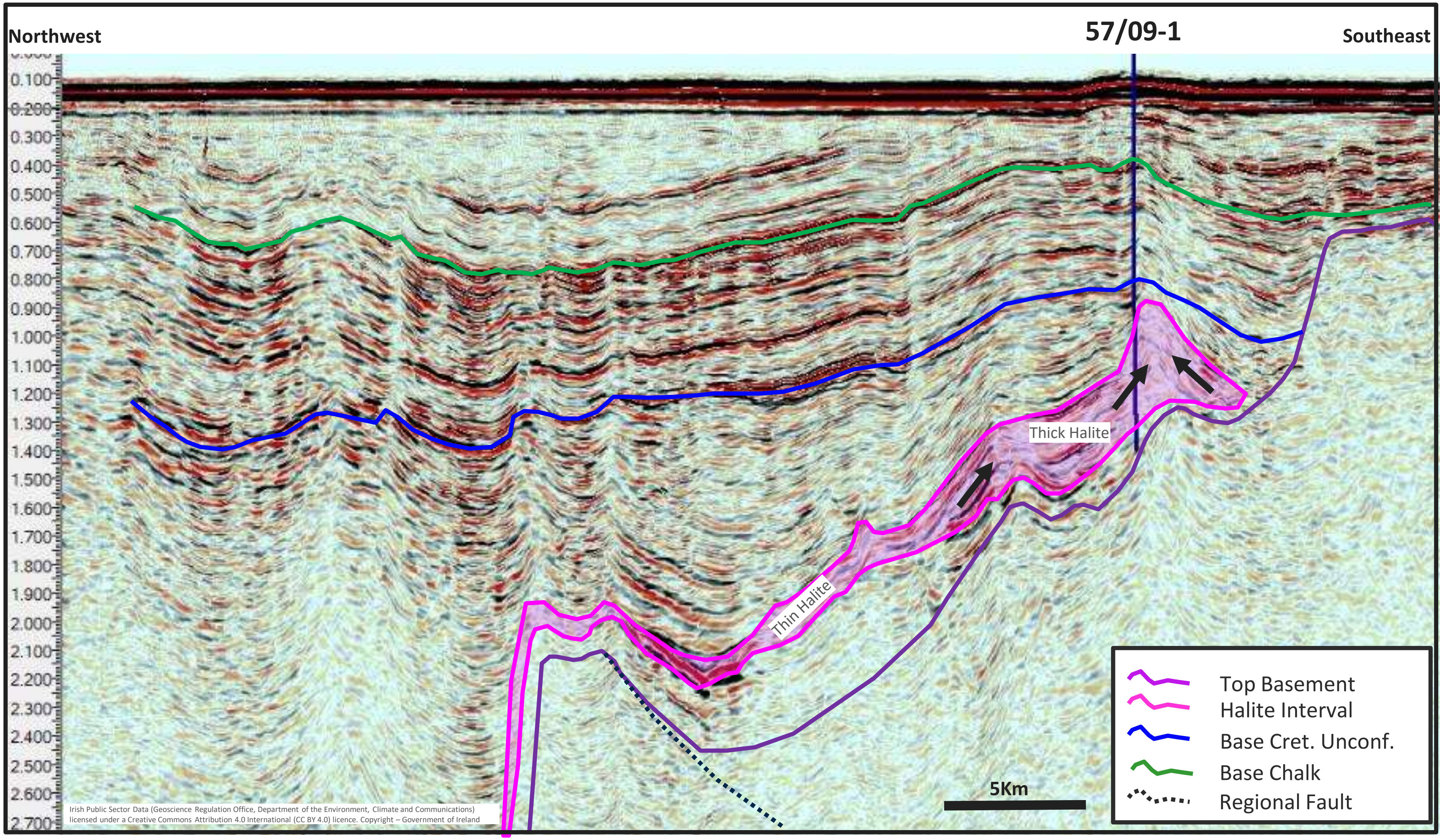

Figure 18. Seismic Line FNT2013_203 with interpreted salt movement / thickness changes.

Seismic Line OGA2016SWBWG162D-L141 with interpreted halokinesis

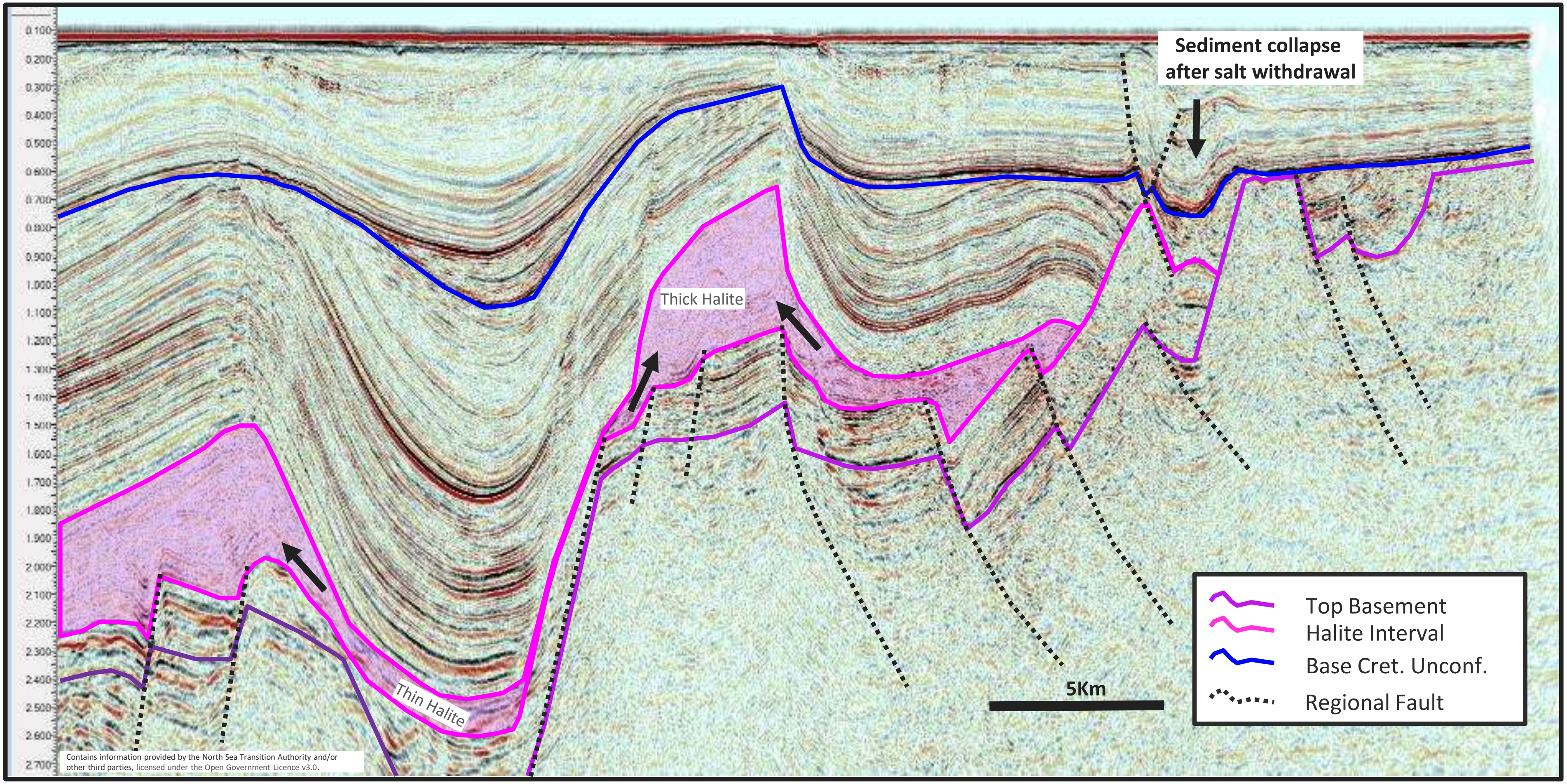

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Figure 19. Seismic Line OGA2016SWBWG162D-L141 with interpreted salt movement / thickness changes.

Seismic Line OGA2016SWBHB92-L31 with interpreted halokinesis

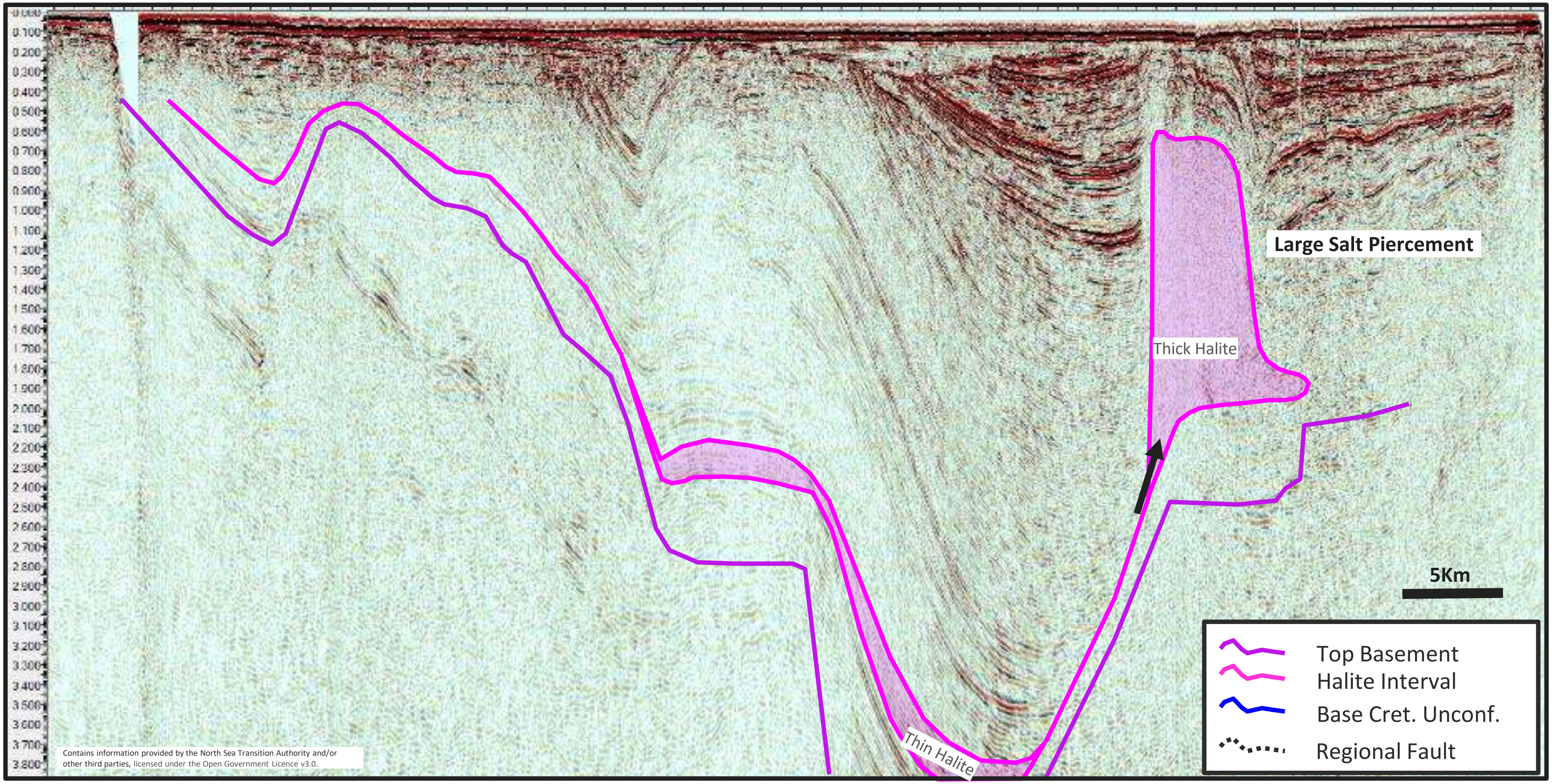


Figure 20. Seismic Line OGA2016SWBHB92-L31 with interpreted salt movement / thickness changes.

WP2-O1: Map of areas in Kish, Celtic Sea and Irish Sea Basins, with halite at a depth of 1,000m to 1,500m, and suitable thickness.

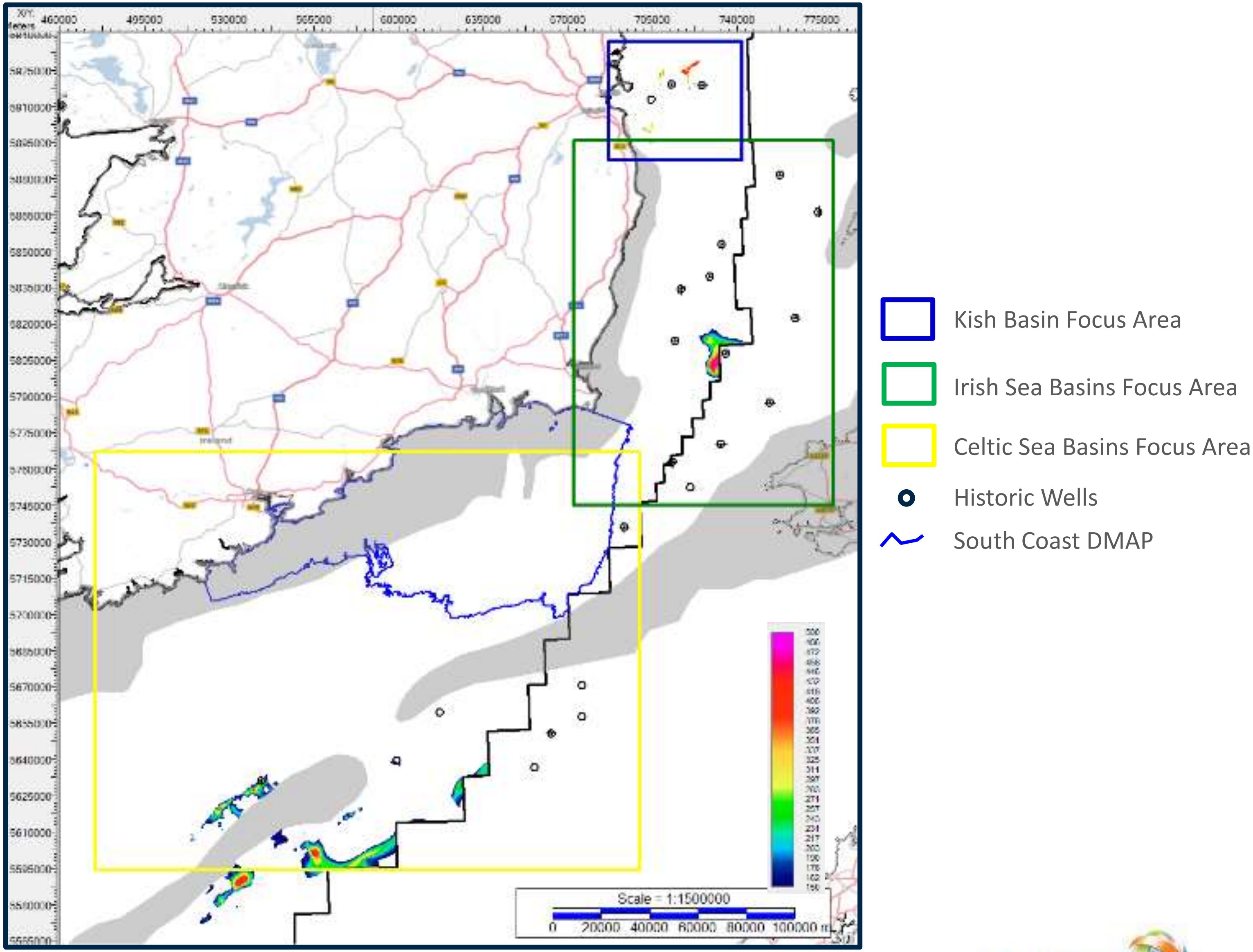


Figure 21. Map showing all focus areas on south and east coasts of Ireland and identified halite suitable for potential cavern development.

WP2-O4: 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 m3
- Cavern Working Gas Inventory (Low – Mid – High): 62.5 – 31.3 – 15.6 million Sm3
- Cavern Peak Gas rates (Low – Mid – High): 5.9 – 2.8 – 1.4 million Sm3/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.

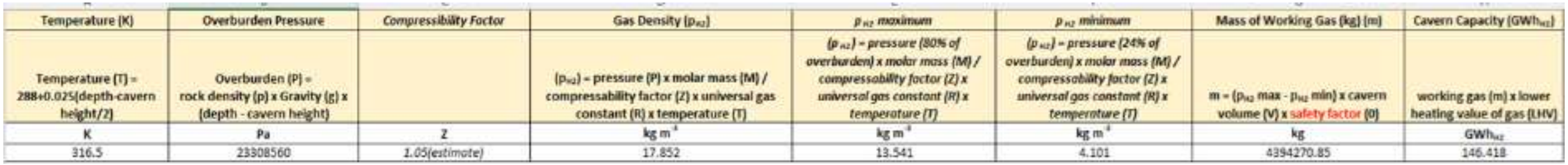
According to API 1170 (Design And Operation Of Solution-Mined Salt Caverns Used For Natural Gas Storage) cavern solution mining is accomplished by drilling a wellbore into a suitable salt formation, dissolving the salt by circulating fresh or low-salinity water into the wellbore and withdrawing or returning 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-O4: 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 m3 to 815,000 m3 as optimum.

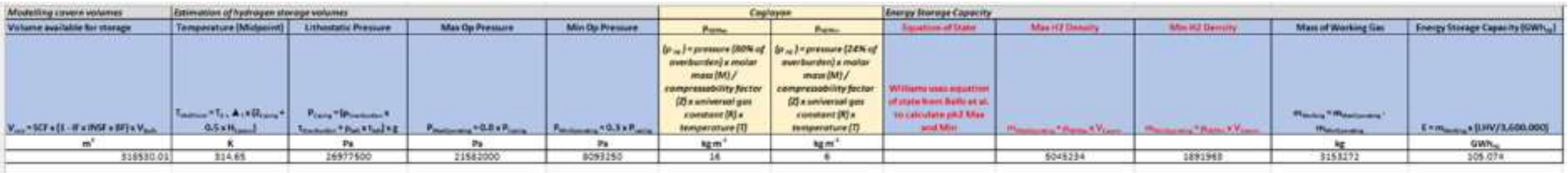
The calculations of cavern storage capacity were made using the methodology of Caglayan et al 2020 and Williams et al 2020. The results are shown in Table 1 and Table 2. There is a difference of 41 GWh_{H2} for a typical salt cavern at a depth of 1,200m with a height of 120m, diameter 84m and safety 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 Irish Sea and Celtic Sea Basins at the required depth of 1,000m and 200m thickness is such that several thousand salt caverns could be solution mined, sufficient for multi-seasonal hydrogen storage and storage for export. (see Figure 11).



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 (p) 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 (0)	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	[illegible]	[illegible]	Equation of State	Max H2 Density	Min H2 Density	Mass of Working Gas	Energy Storage Capacity (GWh_{H2})
[illegible]	[illegible]	[illegible]	[illegible]	[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]	[illegible]
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

WP3-O4: Map of Halite areas with potential salt cavern locations

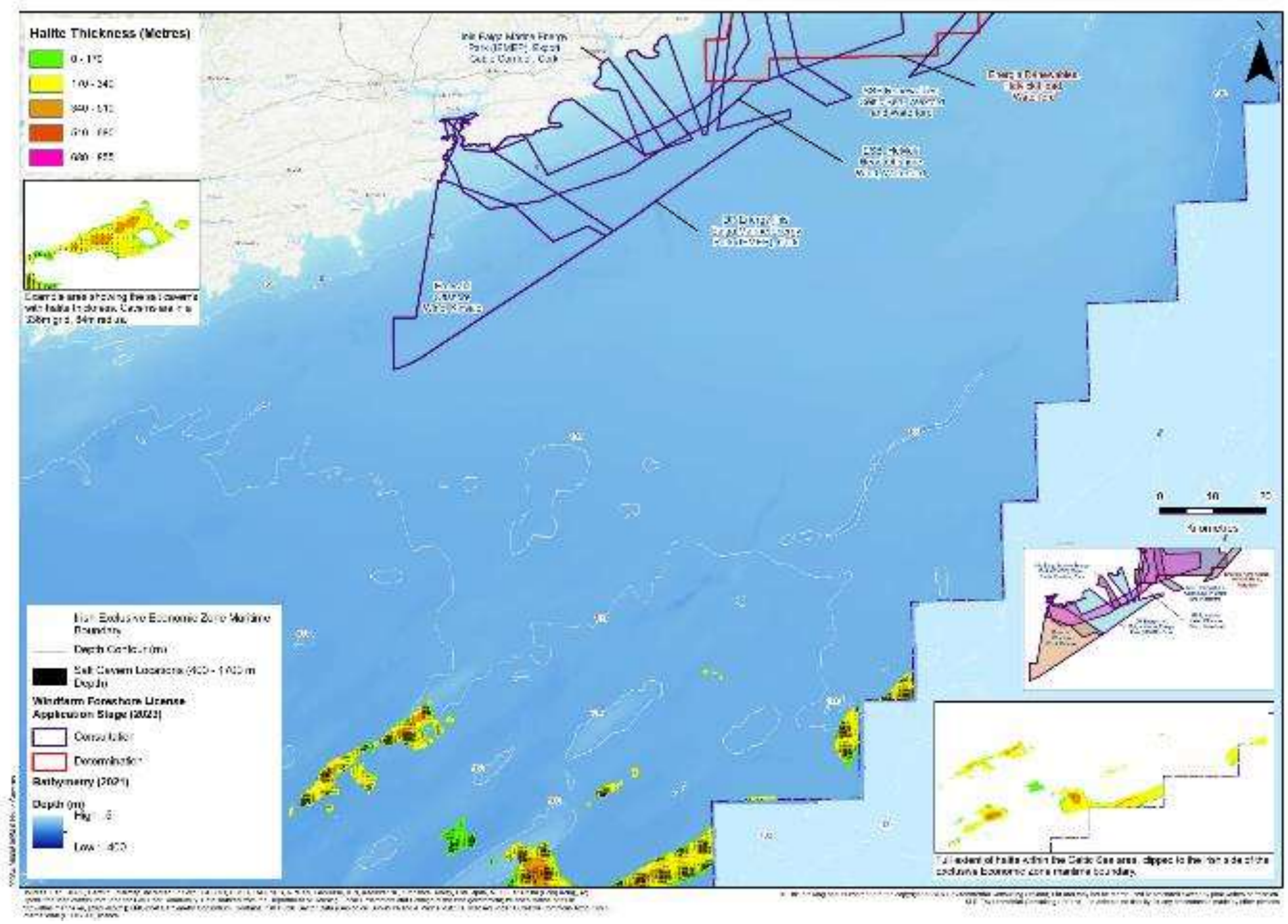


Figure 22 Celtic Sea Basins Halite Zone of Interest with potential cavern locations

This map shows the areas where the Halite Formations occur at depths of between 1,000m and 1,500m and is more than 150m thick, the optimum depth and thickness for salt cavern storage of gas. The Celtic Sea Basins have the potential for 5,237 standard size salt caverns for hydrogen storage. Just 1% of this potential is equivalent to approximately 7 TWh_{H2}.

WP4-O4: Map of Halite areas with potential salt cavern locations

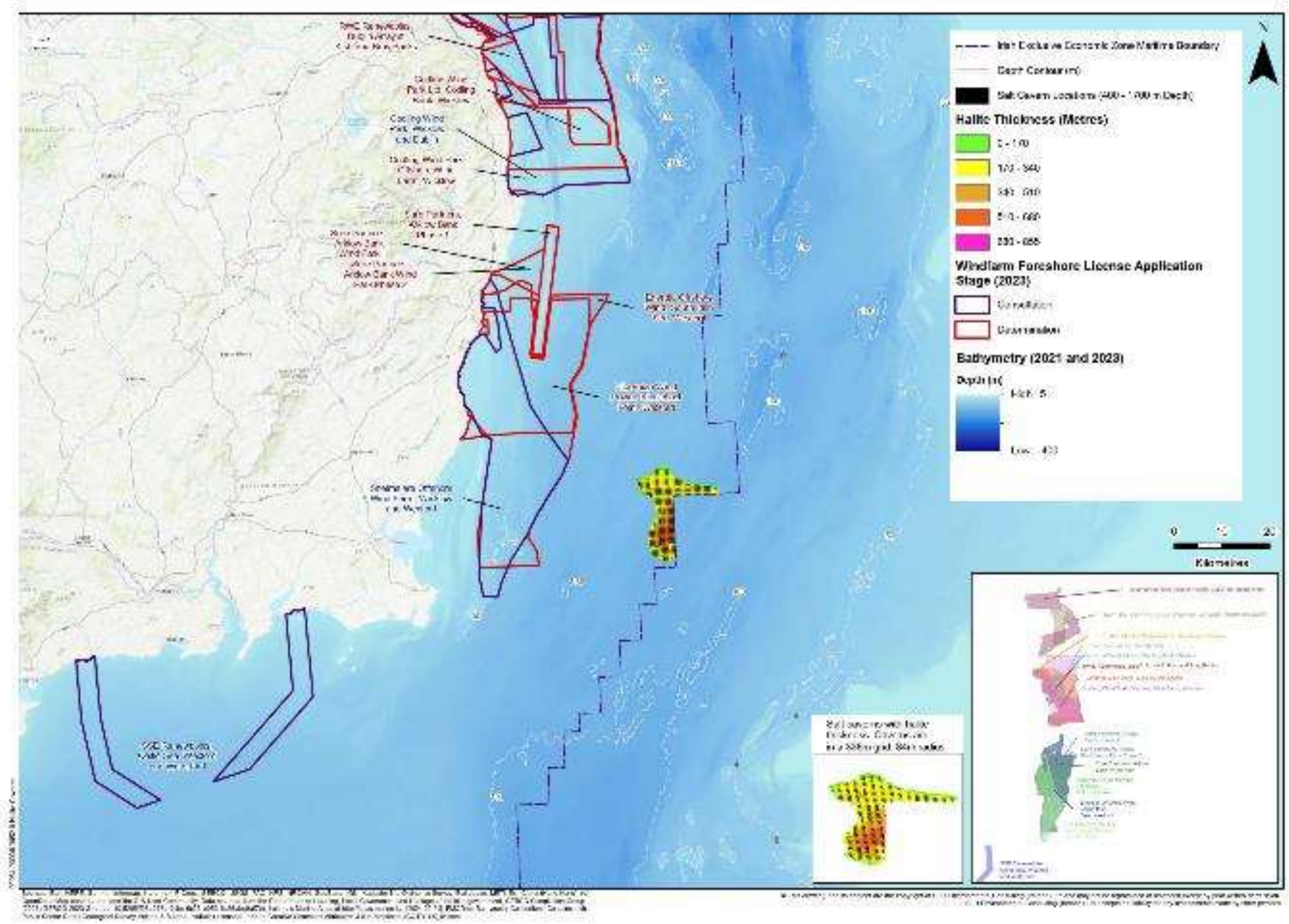


Figure 23 Irish Sea Basins Halite Zone of Interest with potential cavern locations

This map shows the areas where the Halite Formations occur at depths of between 1,000m and 1,500m and is more than 150m thick, the optimum depth and thickness for salt cavern storage of gas. The Celtic Sea Basins have the potential for 1,069 standard size salt caverns for hydrogen storage. Just 1% of this potential is equivalent to 1.5 TWh_{H2}.

WP3-O5 & WP4-05 : 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 South Irish Sea and Celtic Sea areas for 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, the currents are 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. In general areas with high stress result in high erosion and coarser sediment. This can be observed in the area outboard of the 12NM maritime limit in the deeper areas such as the Western Trough and St. Georges Channel. The area off Wexford where halite is present and has the potential for hydrogen storage is in a high stress environment. This needs to be mitigated against should any subsea infrastructure be put in place there.

The last glacial event to have affected the Irish and Celtic Seas (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 and Celtic Seas. In general, there is a lack of sufficient geotechnical and geophysical datasets to fully understand the complex glacial landscape that lies beneath the seabed. In areas where there has been data acquired the results has led to an evolved understanding of the effects and extent of the BIIS. This can pose as a potential hazard for the drilling of a salt solution mining borehole as well as any potential cable route or pipeline. Unfortunately, in the areas where halite has been identified the datasets are insufficient to fully comprehend the subsurface risks.

The Geoscience Regulation Office (GSRO) has a vast amount of geological and geophysical datasets that can provide additional benefit for offshore site investigations including legacy oil and gas datasets located offshore Ireland. Seismic and well velocities have been used to help quantify the geohazard risks in the Irish and Celtic Seas. 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 deeper part of the Jurassic in the Celtic Sea can be overpressured to some extent and at least two wells have had small kicks. Other wells have encountered high gas levels, and occasionally high mud weights have been used to reduce drilled and connection gas. The overpressure would appear to be predominantly in shales. The well control incidents have been infrequent, however, and have not resulted in any significant lost time.

Once a potential Hydrogen storage area has been identified, high quality data must be acquired over the site-specific area. This must include MBES bathymetry data, multi channel Sparker, CPT's, and a high resolution muti component 3D seismic survey. Once acquired the seismic will need to be brought through modern processing flows and a comprehensive seismic interpretation will need to be completed and integrated with the other project disciplines.

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, processing and integration of existing disparate datasets.

WP3-O5 & WP4-05 : 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.

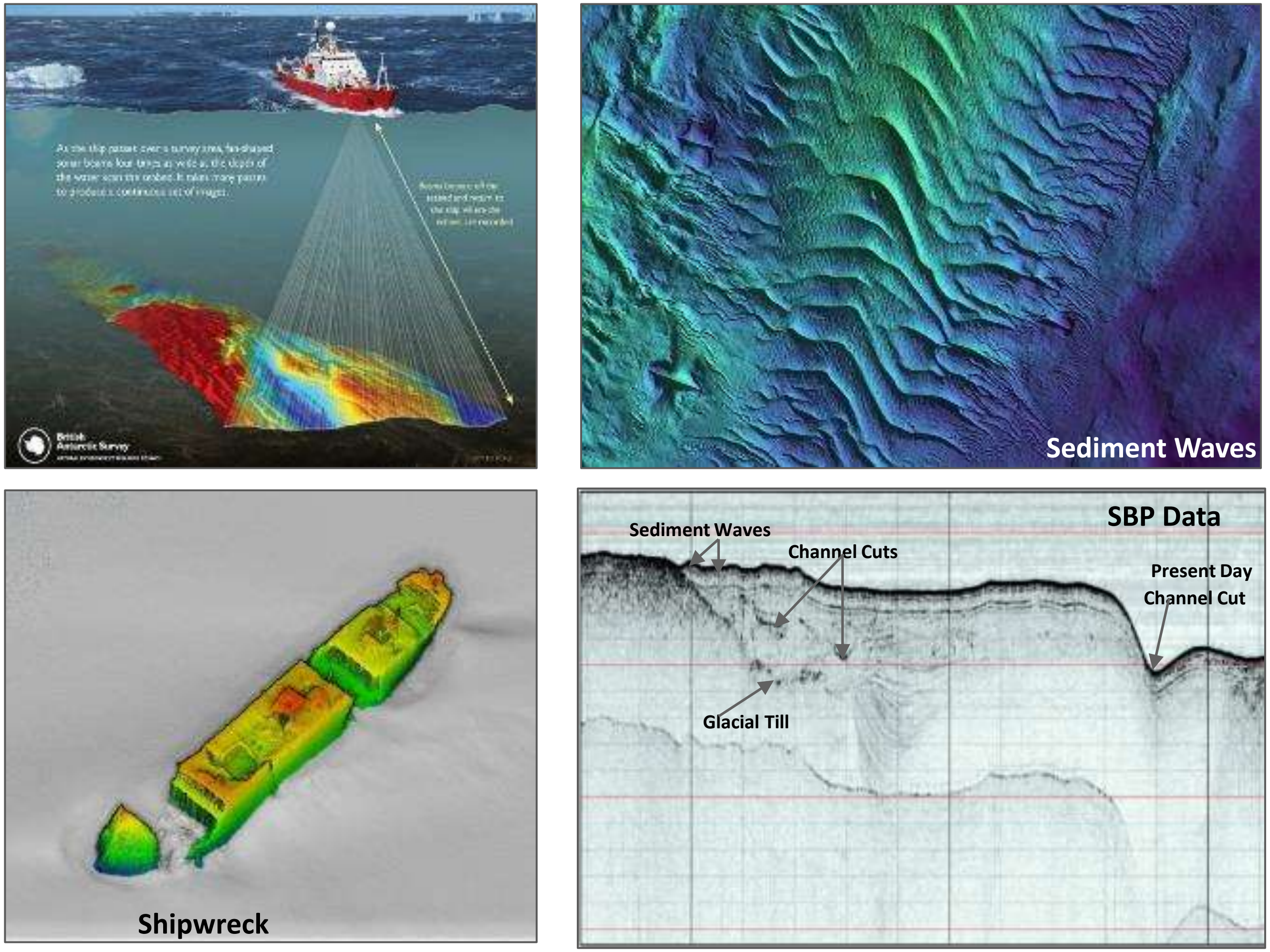


Figure 24 : Geophysical datasets and outputs.

WP3-O5 & WP4-05 : 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 bathymetric map 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.

The onshore geology varies from the granitic Wicklow mountains in the NW of the map to the thick-bedded grey-green and occasionally purple turbiditic greywacke sandstones interbedded with slaty mudstones found in the East. The many rivers in the area are eroding, transporting and depositing these sediments into the Irish sea, with many sand being the dominant sediment type close to the coast, forming distinct sedimentary features.

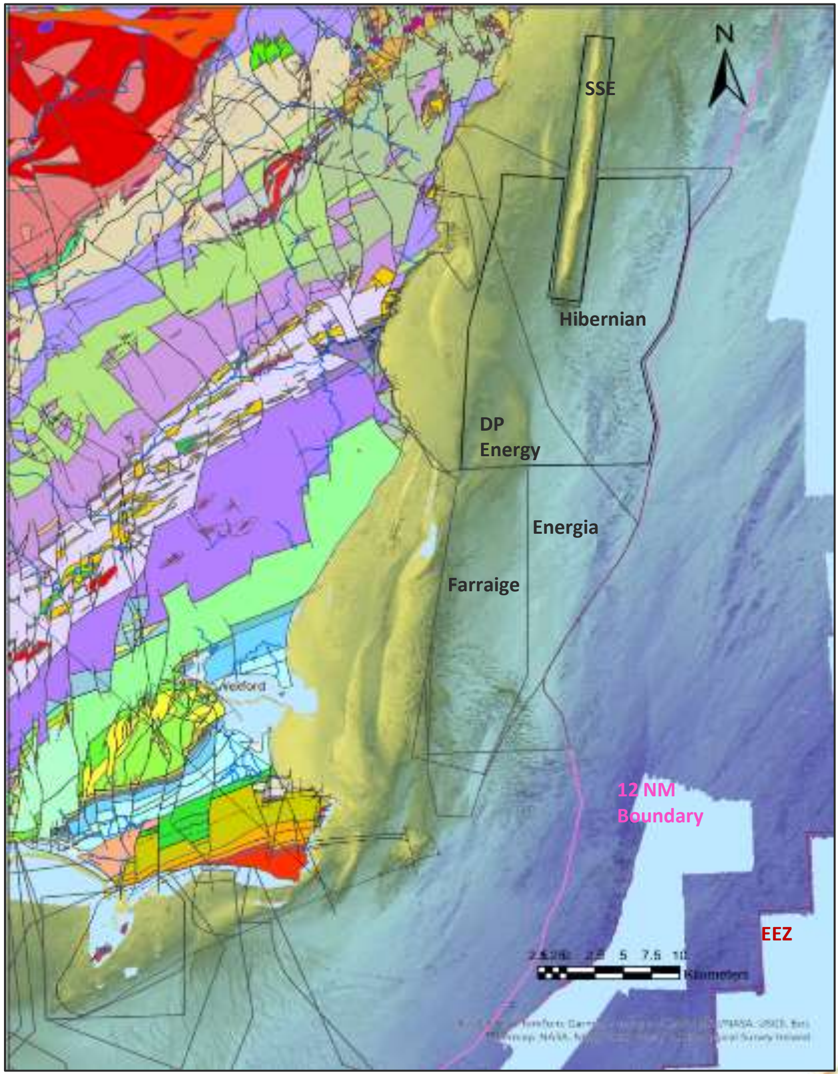
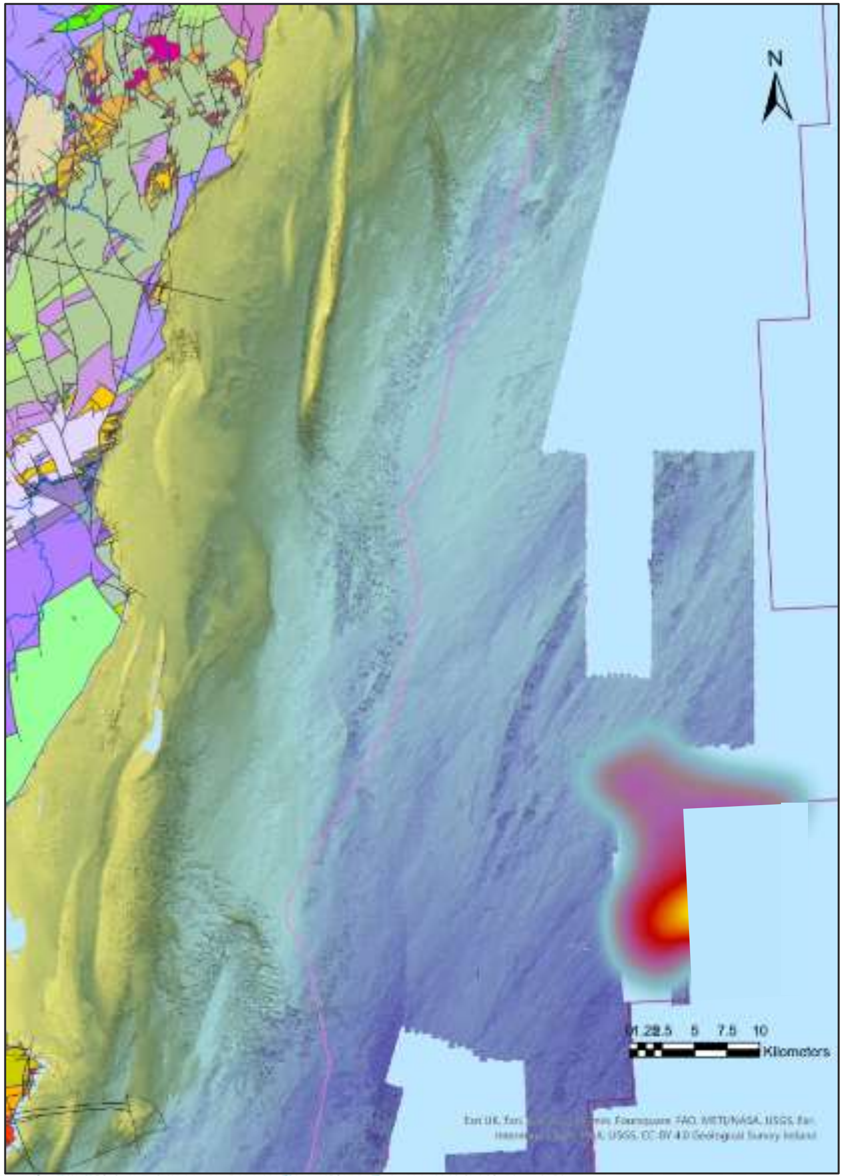


Figure 25 : Onshore Geology and Bathymetry Map.

WP3-O5 & WP4-05 : Regional geohazards study Southern Irish Sea – Bathymetric Data



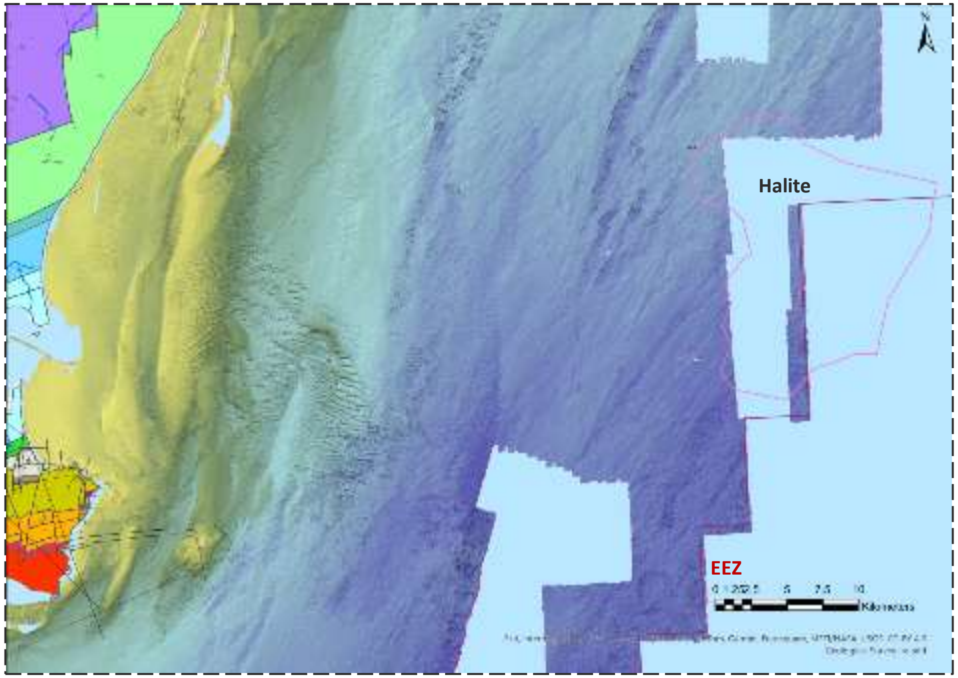


Figure 26 : INFOMAR Bathymetry Map over Halite Area of Interest.

The inshore area appears to have a lot of sand sequestered on the shelf. With many active sedimentological processes at play, notable features such as sand banks, sand bars, mega ripples and sediment waves highlighting the interplay between the onshore geology and the offshore metocean conditions.

As we move further offshore past the 12NM maritime boundary, the seabed appears to be more sediment starved with less depositional features and an increase in erosional features such as channels and canyons.

The Halite that has been mapped in this area sits primarily over an INFOMAR data acquisition gap, that will to be need to be filled before the programme ends in 2026.

WP3-O5 & WP4-05 : Regional geohazards study – INFOMAR Blue Scale Map Series

In November 2023, INFOMAR launched the Blue Scale Map Series; a collection of 18 high-resolution bathymetric maps of Ireland’s coastal waters. Developed by a dedicated team of hydrographers, data processors and cartographers, the maps highlight the topography of the coast in remarkable detail.

Wicklow Head in County Wicklow is the most easterly point in the Republic of Ireland. It is a designated a Special Protected Area (SPA) to conserve the kittiwakes that nest in the cliffs.

The Arklow bank is located 8km southeast of Wicklow Head and is one of a series of north-south orientated shallow sandbanks in the Irish Sea. These sandbanks have been the site of numerous shipwrecks over the years.

Irelands sole producing source of offshore wind is the Arklow Bank Wind Park. This is a 25-megawatt offshore wind farm generating electrical power for the Wicklow region in Ireland. It is the first offshore wind farm in Ireland, and the world's first erection of wind turbines rated over 3 MW. It is located on the Arklow Bank, a shallow water sandbank in the Irish Sea, around 10 kilometres off the coast of Arklow. It consists of seven wind turbines with a capacity of 25.2 MW. The turbines have a height of 73.5 metres and height to top of blade of 124 metres.

The blade length is 50.5 metres and each turbine has three blades and each turbine weighs 290 tonnes. They use steel monopile foundations driven in by a hydraulic hammer. They are spaced 600 metres apart. The generated electricity is fed to a distribution grid through the Arklow National Grid Substation. Phase 1 is owned and operated by GE Energy under a sublease to the foreshore lease and remains the first Turbines on the Arklow Bank and only operational offshore wind farm in Ireland.

Figure 27 : Blue Scale Map Series – Wicklow Head.

Figure 28 : Photograph of the Arklow Bank Wind Park, offshore wind turbines in the Irish Sea, 8km SW of Wicklow Head.

WP3-O5 & WP4-05 : Regional geohazards study – Tidal Currents and Sediment Mobility

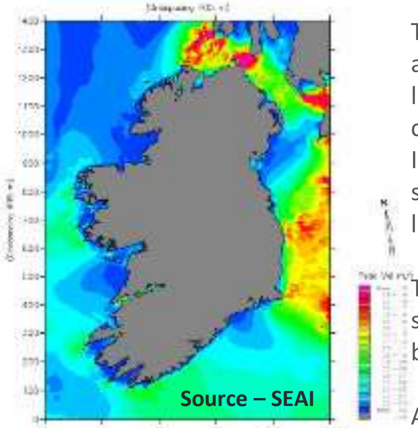


Figure 29 : Depth averaged Peak Spring Tidal Currents

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

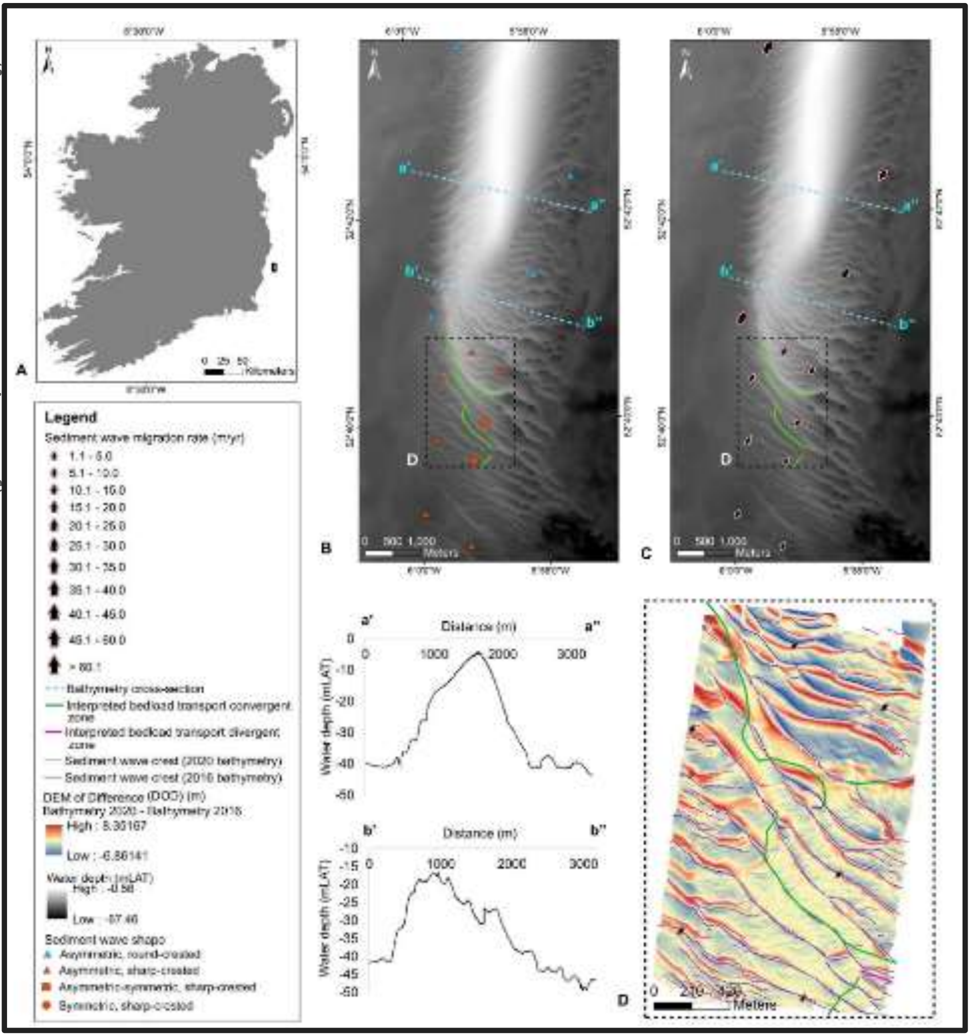


Figure 30 : Sediment wave translation rates & shapes at Arklow Bank, Irish Sea. Source Creane, Coughlan, O'Shea, Murphy 2022.

WP3-O5 & WP4-05: Regional geohazards study – Tidal Currents and Sediment Mobility

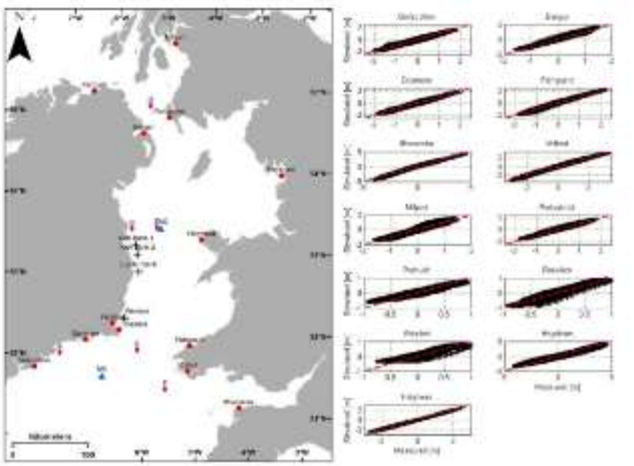
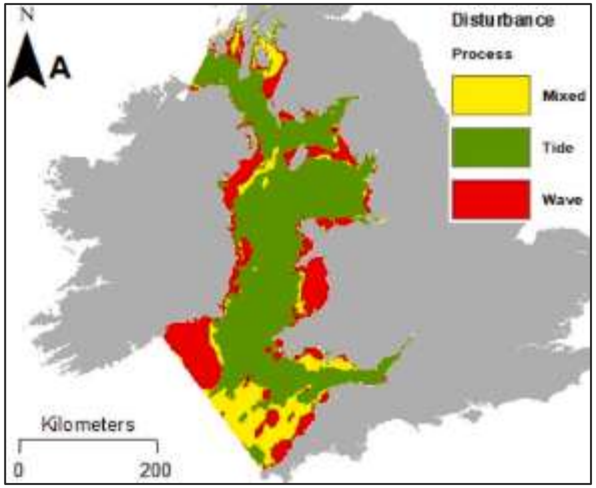
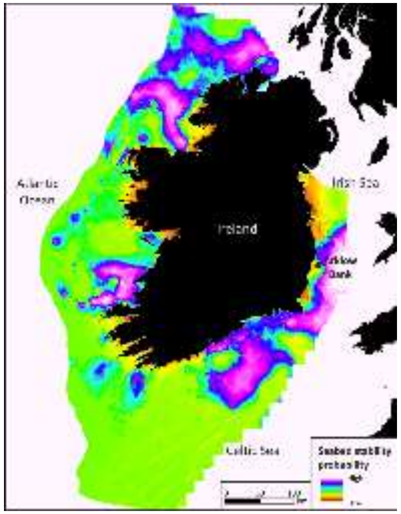


Fig. 2. Left panel: the locations of the tide gauge stations (red dots), offshore ADCPs (black crosses), grid points from the ERA5-ECMWF dataset (pink diamonds) and wave buoys (blue triangles) used in the model validation. Right panel: comparison between simulated and measured astronomical water level at various tide gauge stations.

A new seabed mobility index for the Irish Sea: Modelling seabed shear stress and classifying sediment mobilisation to help predict erosion, deposition, and sediment distribution. Coughlan et al 2021

As can be seem on the map to the right , there is a switch in sedimentological processes from tidal dominated to wave dominated processes once you turn the corner at Rosslare and enter the Celtic Sea.



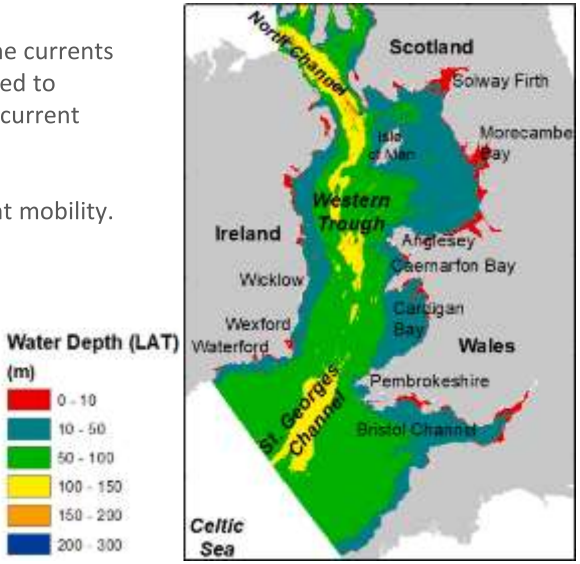


Peters et al 2020

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. Several research papers have published on this.

In general areas with high stress result in high erosion and coarser sediment. This can be observed in the area outboard of the 12NM maritime limit in the deeper areas such as the Western Trough and St. Georges Channel.
Low bed shear stress and residual flow sediment-transport are typically considered to be the hydrodynamic processes required for fine sediment deposition and retention in such systems (William, M E., et al., 2019). This can be seen in the Arklow bank and Carnsnore Point Areas.



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WP3-O5 & WP4-05 : Regional geohazards study – Tidal Currents and Sediment Mobility

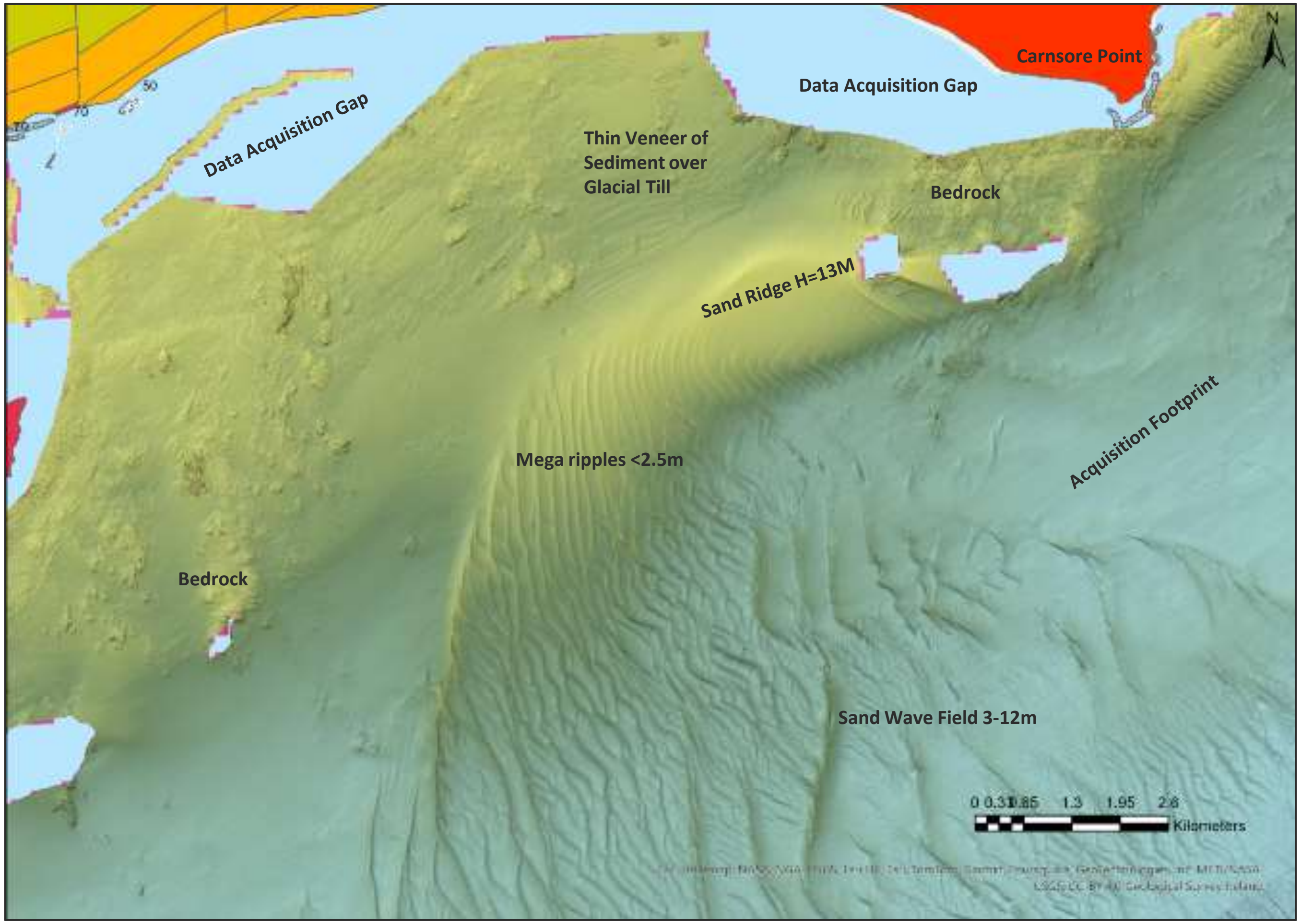


Figure 31: Bathymetry Map highlighting Seabed Features Offshore Wexford.

Figure 31 is highlighting the complex interplay between deposition and erosion in the area. The effect of divergent tidal currents can explain the formation of the sand wave field, mega ripples and large sand ridge.
The effects of scouring of the seabed can be seen further to the West and North where exposed bedrock and glacial features are visible and pose a significant challenge for any infrastructure coming to shore.

WP3-O5 & WP4-05 : Regional geohazards study – INFOMAR Blue Scale Map Series

As we continue further South along the coast of the Irish Sea, we see further stunning examples of the seafloor and its geomorphological features being highlighted by the INFOMAR Blue Map Series.

Ireland’s coastline is approximately 3,171km in length and boasts some of the most unique & dynamic marine environments in Europe. County Wexford has a coastline of approximately 273km – and showcases some of the Ireland’s most unique coastal landscapes. The latest in the new map series are the Blue Scale bathymetric maps of Hook Head & Carnsore Point. The two maps reveal the brilliant marine geology and unique seafloor across the Wexford Coastline.

Carnsore Point is a headland in the southeast corner of County Wexford, Ireland. It marks the southernmost point of the Irish Sea, on the western side of St George's Channel. A large, offshore area wrapped around the Point is a marine protected area (MPA) for its reefs and species-rich underwater life.

The intertidal and offshore reefs are formed of Carnsore granite, a coarse pinkish-brown rock, and range from very exposed to moderately exposed to wave action. In water at depths of 11-30m there are excellent examples of sea squirt communities. Intricate sandbanks lie due east of the headland and North into the Irish Sea.

Hook Head is a headland in County Wexford, on the east side of the Three Sisters rivers Nore, Suir, Barrow). It is part of the Hook peninsula and is the location of Hook Lighthouse, the oldest working lighthouse in the world.

The Hook Peninsula is composed of many rock types including sedimentary limestone and sandstone. The outcrops around Hook Head consist of abundant exposures of Lower Carboniferous rocks in foreshore platforms, containing beautifully preserved crinoids, bryozoans, bivalves, corals and brachiopods.

CARNSORE POINT

HOOK HEAD

Figure 32 : Images of Carnsore Point and Hook Head from INFOMAR Blue Map Series

WP3-O5: Regional geohazards study – Tidal Currents and Sediment Mobility

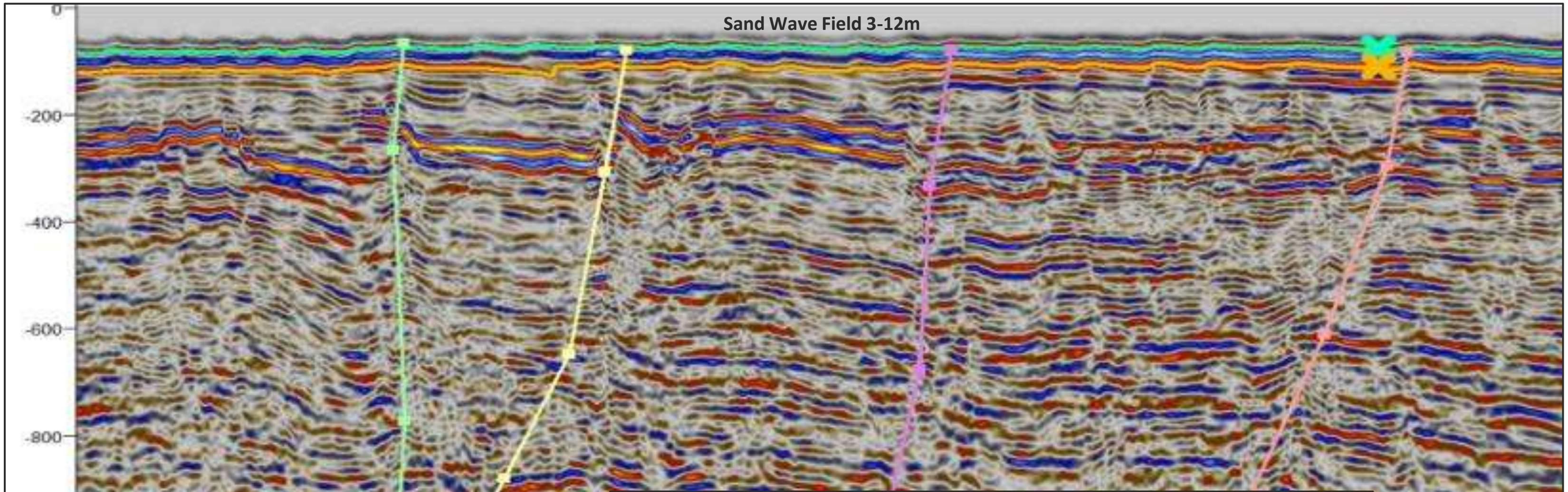


Figure 32: 2D Seismic Line Offshore Wexford .

Fig 32 highlights a 2D seismic dip line acquired offshore Wexford. The line is orientated perpendicular to the coast and highlights even with this low frequency data and at a zoomed-out scale that the large sediment waves are still prominent features that are visible across the area.

It's also worth noting the significant tectonic faults that are deep-rooted into the stratigraphy and sole out on the seafloor, indicating that they are still active.

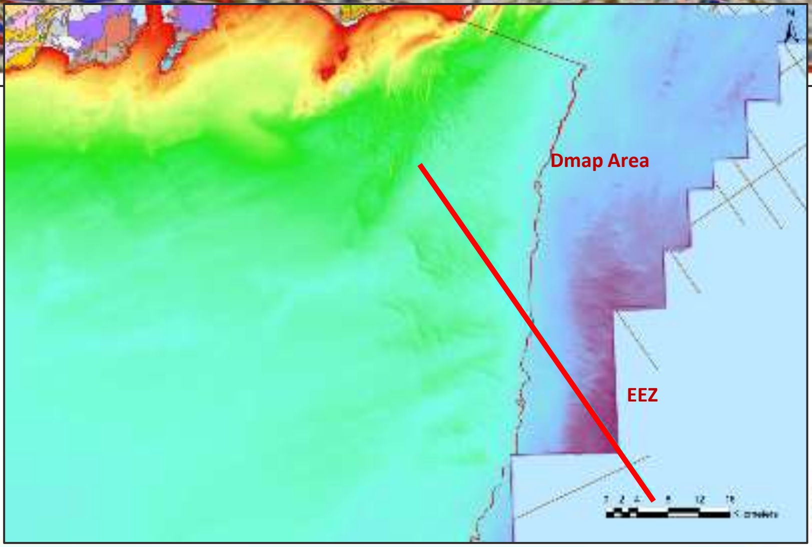
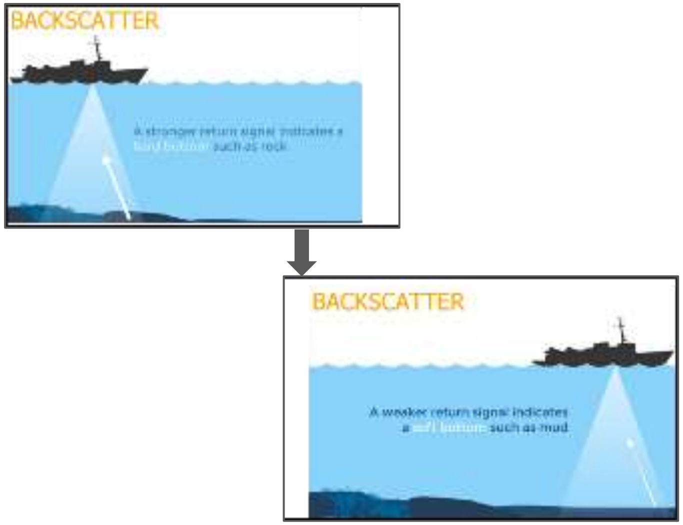


Figure 33: INFOMAR bathymetry map highlighting the location of the 2D seismic line offshore Wexford.

WP3-O5: Regional geohazards study – Backscatter



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. The low intensity values here are indicative of sand and there is a good correlation with the bathymetry MBES data to highlight the various depositional features in the area such as sand banks, sand bars and large-scale sediment waves which are dominating the seafloor landscape in the foreshore area.

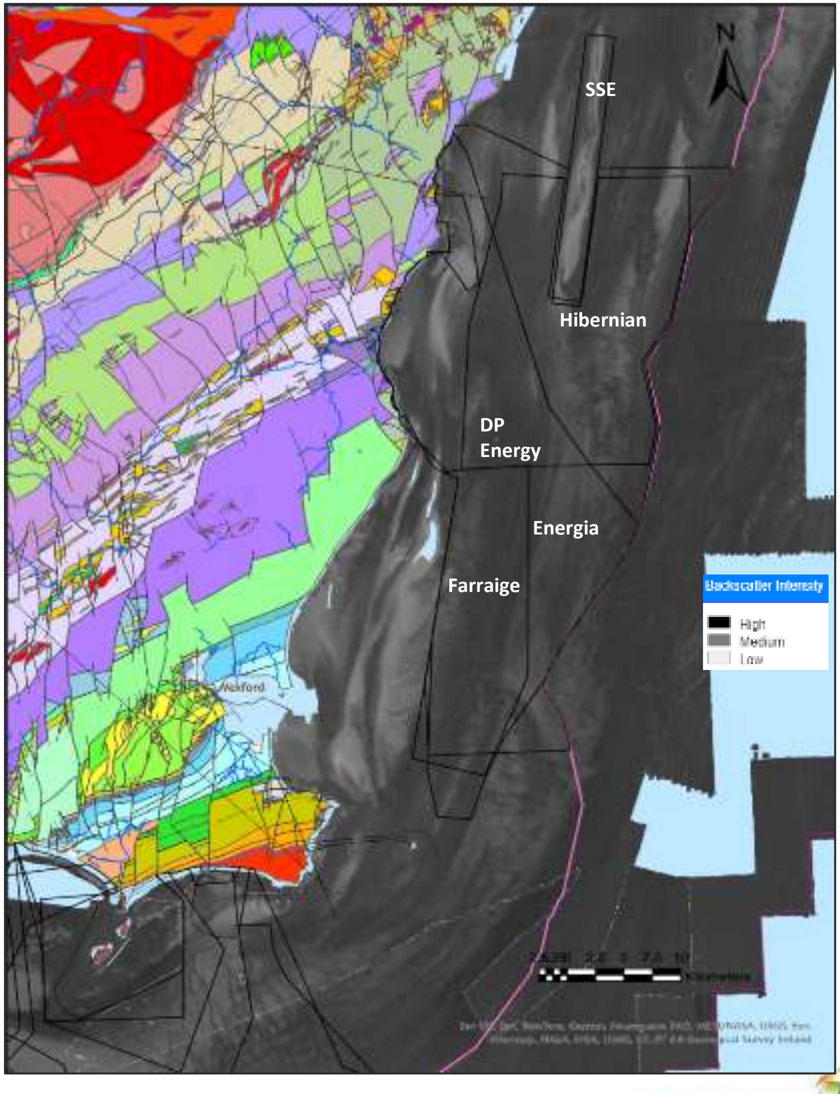


Figure 34: Onshore Geology and Backscatter Map.

WP3-O5: Regional geohazards study Irish Sea – Backscatter Data

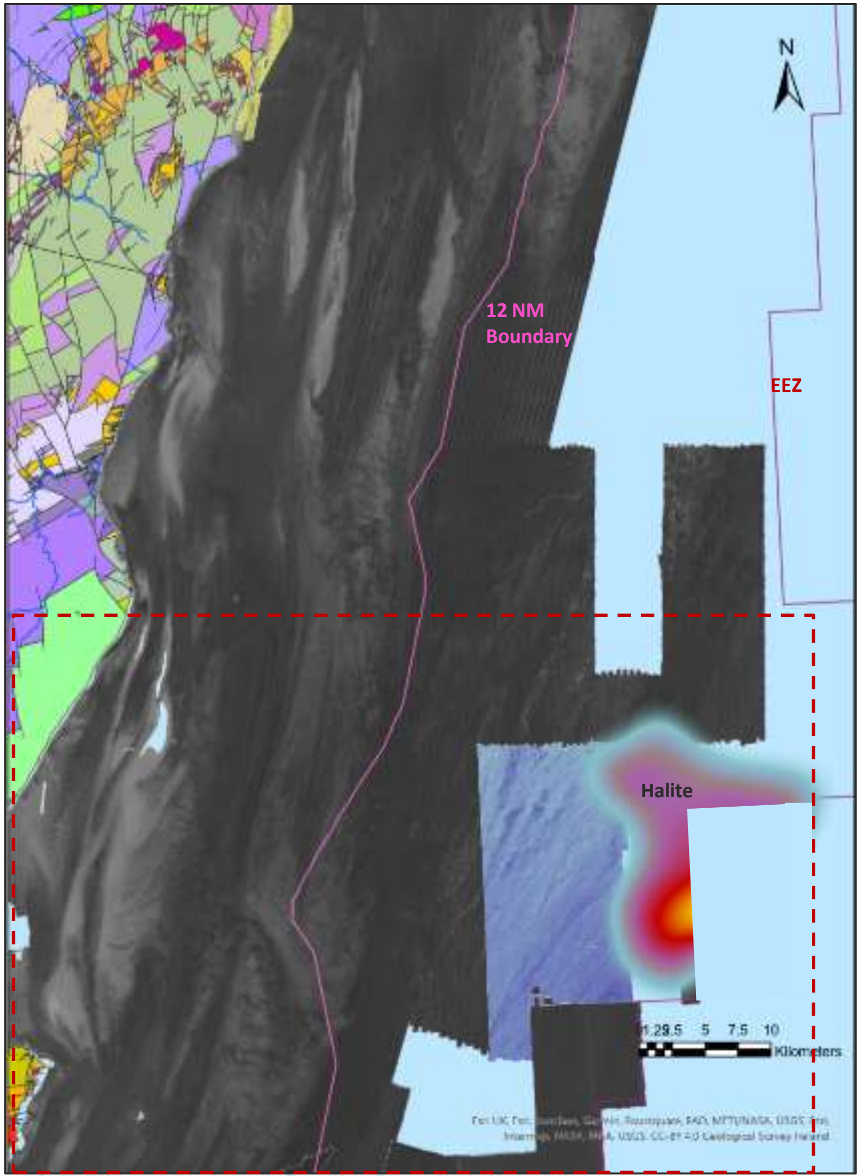
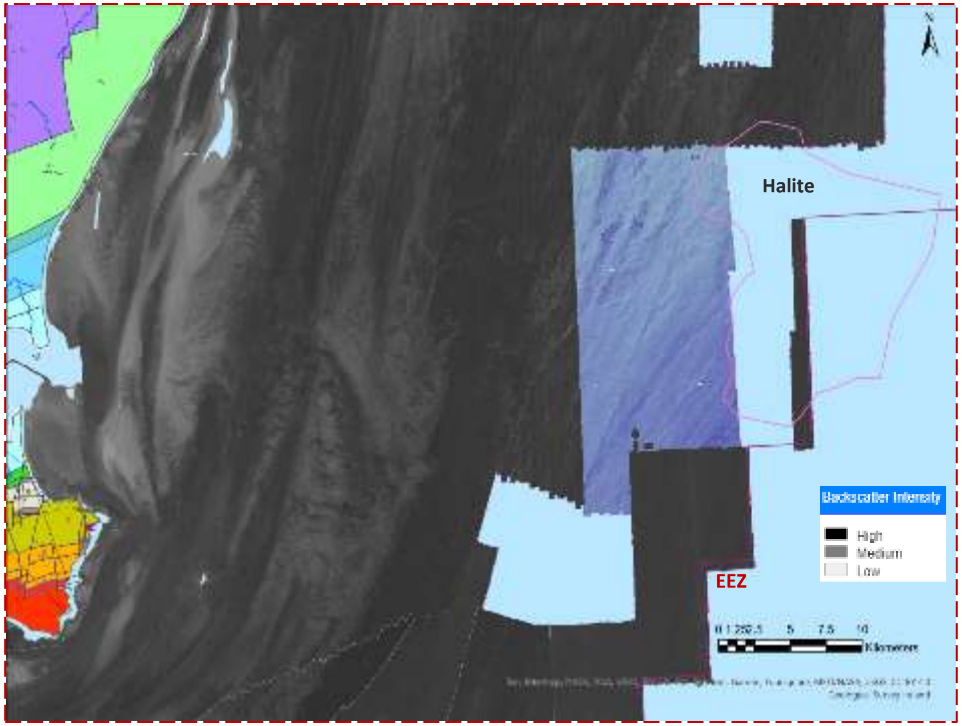


Figure 35: INFOMAR Backscatter Map over Halite Area.



The inshore area appears to have a lot of sand sequestered on the shelf. With many active sedimentological processes at play, notable features such as sand banks, sand bars, mega ripples and sediment waves highlighting the interplay between the onshore geology and the offshore metocean conditions.

As we move further offshore past the 12NM maritime boundary, the seabed appears to be more sediment starved with less depositional features and an increase in erosional features such as channels and canyons.

The Halite that has been mapped in this area sits primarily over an INFOMAR data acquisition gap, that needs to be filled before the programme ends in 2026.

WP3-O5: 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.

There is a complex relationship in the area between deposition and erosion, leading to a variation between high deposition of sands in areas like the Arklow bank and high amounts of erosion offshore Kilmore Quay and the Saltee Islands.

There are is large amounts of bedrock exposed at the seabed due to the scouring of the sediments by storms and tidal currents. Such areas will make it more difficult and expensive to install and maintain subsea infrastructure.

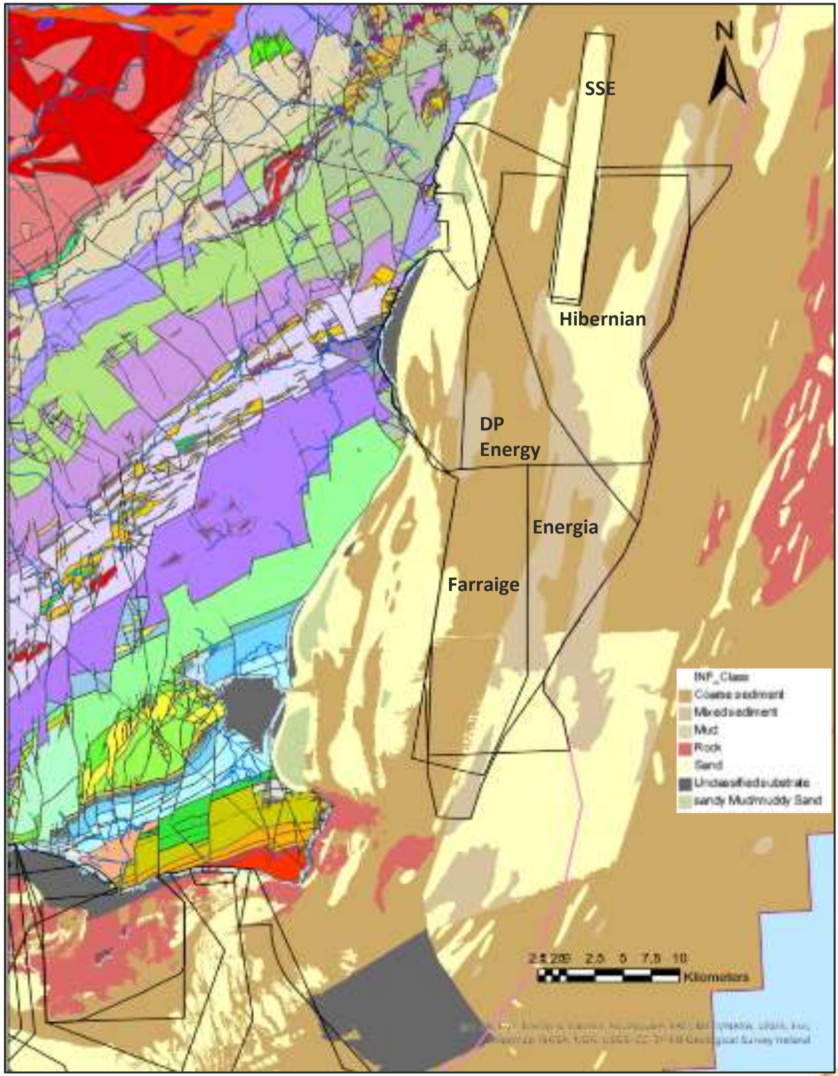


Figure 36: Onshore Geology and Seabed Sediment Classification.

WP3-O5 : Regional geohazards study Celtic Sea – Bathymetric Data

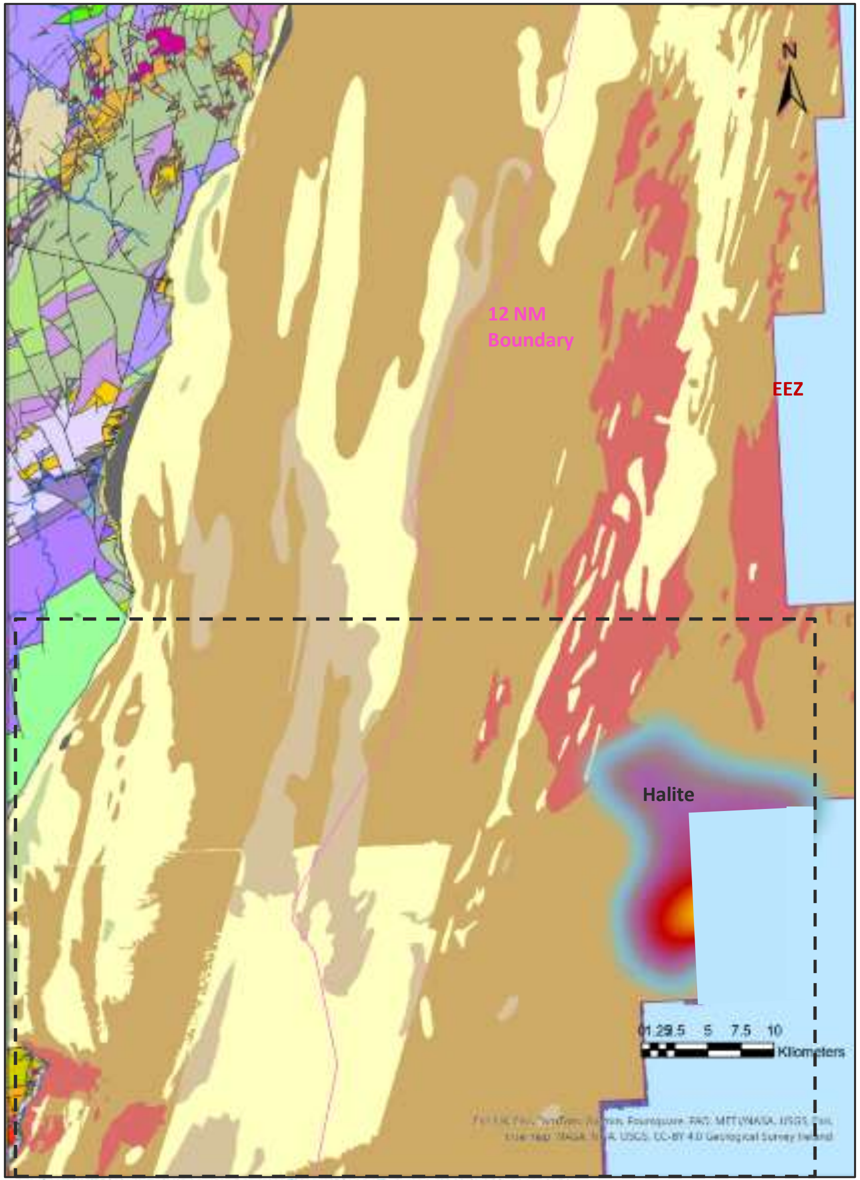
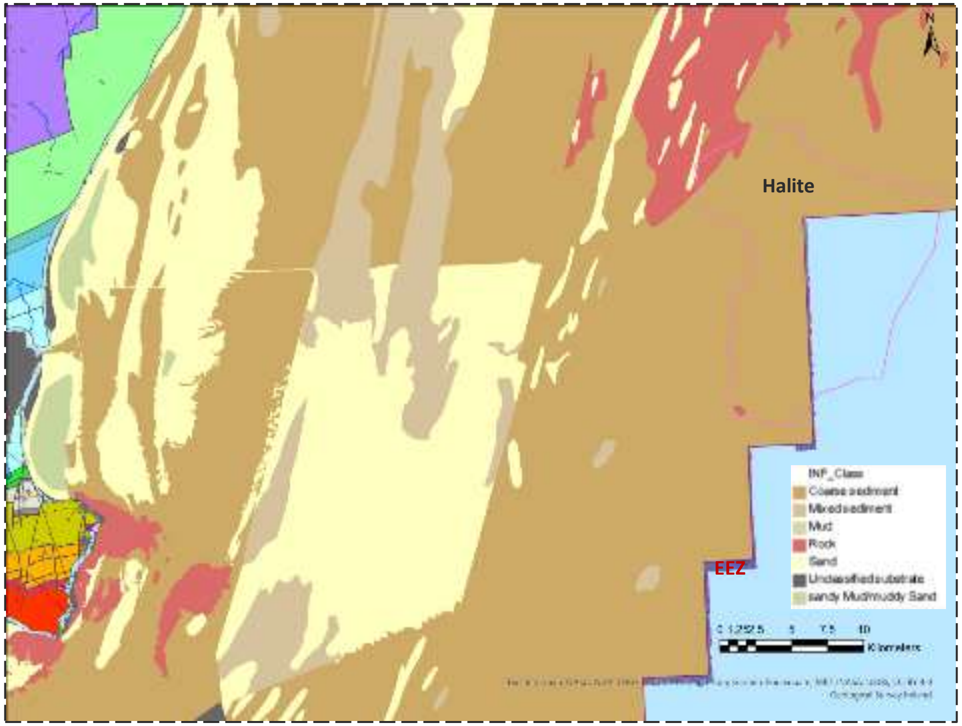


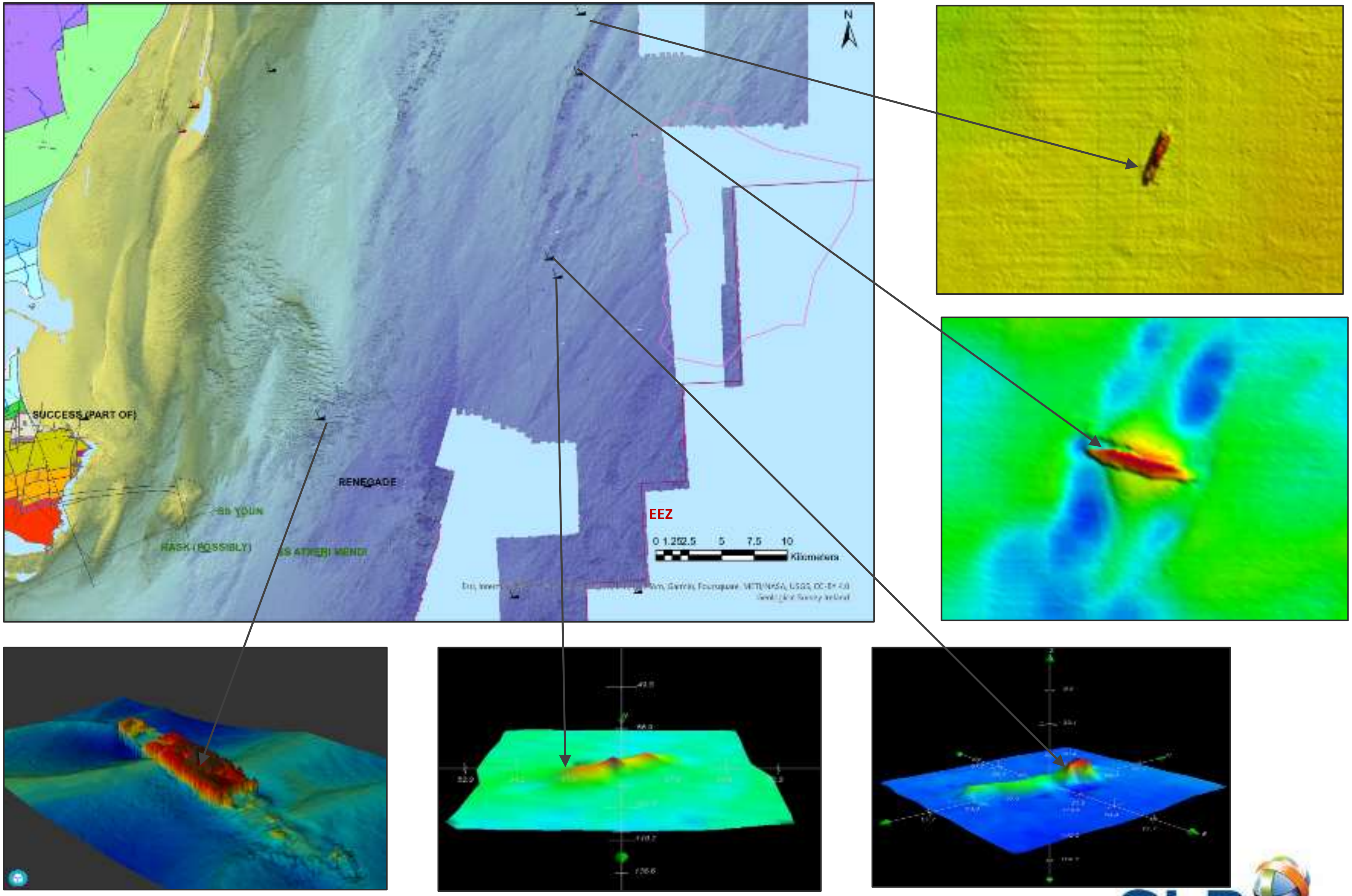
Figure 37: Seabed Sediment Classification Map over Halite Area.



The inshore area appears to have a lot of sand sequestered on the shelf. With many active sedimentological processes at play, notable features such as sand banks, sand bars, mega ripples and sediment waves highlighting the interplay between the onshore geology and the offshore metocean conditions.
As we move further offshore past the 12NM maritime boundary, the seabed appears to be more sediment starved with less depositional features and an increase in erosional features such as channels and canyons. Areas with high stress result in high erosion and coarser sediment, driven here by tidal current processes.

The Halite that has been mapped in this area sits primarily over an INFOMAR data acquisition gap, that needs to be filled before the programme ends in 2026.

WP3-O5: Regional geohazards study – Shipwrecks in the vicinity of the Halite.



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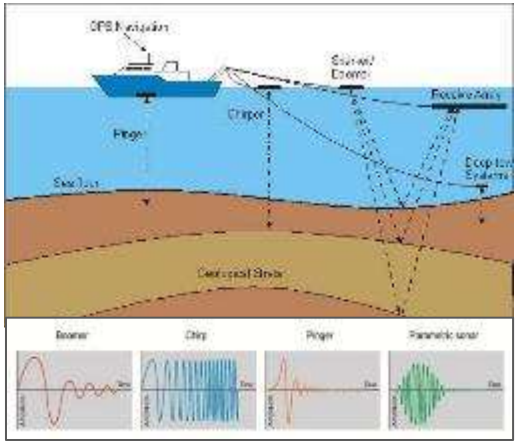
WP3-O5: Regional geohazards study – Survey Coverage & Vintages



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 pipleines.

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.

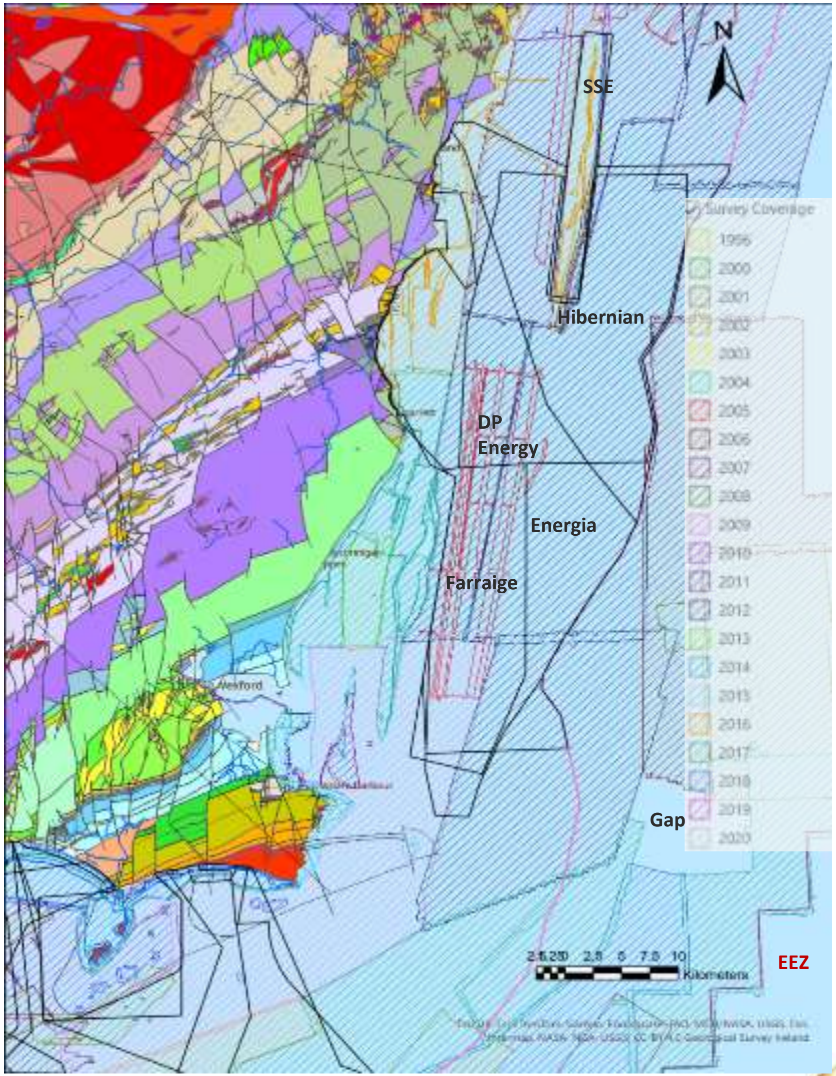


Figure 38: Onshore Geology and Survey Coverage.

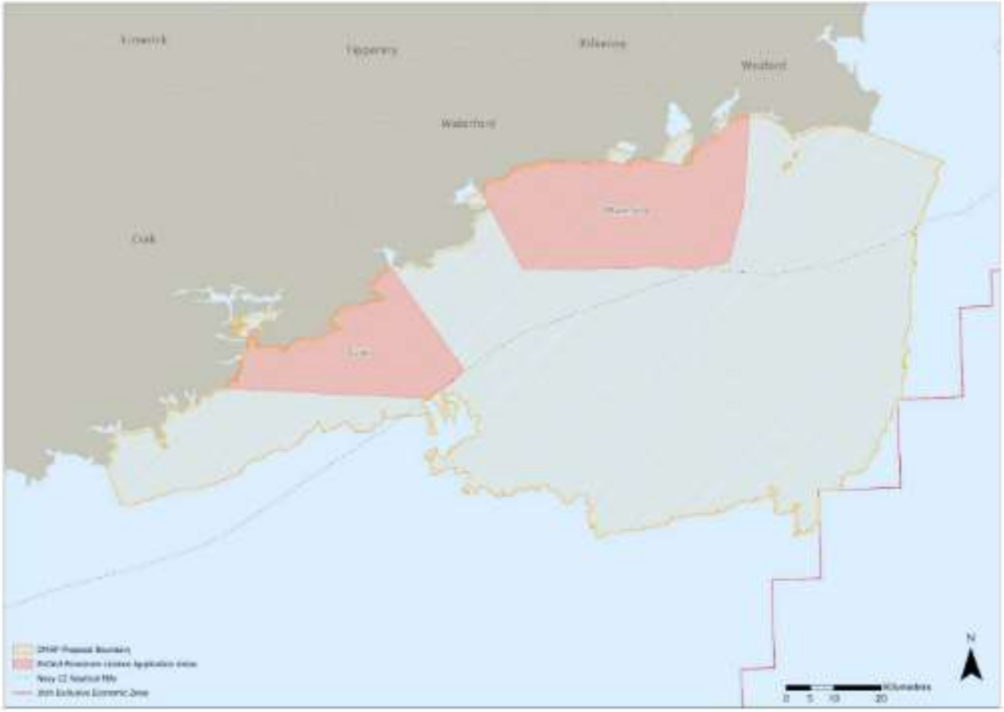
WP4-05 : Regional geohazards study Celtic Sea – Proposed DMAP Area

The National Marine Planning Framework (NMPF) was adopted by Government in May 2021 as Ireland’s first statutory maritime spatial plan. This framework applies to a maritime area of approximately 495,000 square kilometres. To facilitate sustainable maritime spatial planning, the NMPF commits Government to the use of sub-national forward spatial planning through the establishment of Designated Maritime Area Plans, or DMAPs.

Areas will be identified within these DMAPs for renewable energy deployment and this plan-led approach is a departure from what came before in what was known as the ‘Relevant Projects’ which was developer led and resulted in the successful auction of >3GW in the Offshore Renewable Energy Support Scheme (ORESS) 1.

The Maritime Area Planning (MAP) Act, enacted in December 2021 establishes a new marine planning regime and is guided by the NMPF and represents the biggest reform of marine governance since the foundation of the State. The MAP Act provides for a new licensing and development management regime, to be administered by a new government agency, the Maritime Area Regulatory Authority (MARA), in conjunction with An Bord Pleanála and the coastal planning authorities. This new marine planning system replaces existing State and development consent regimes and will streamline arrangements by introducing a single State consent, known as a Maritime Area Consent (MAC).

Figure 39: South Coast DMAP Proposed Geographical Area including Eirgrid Areas of Interest.



In July 2023, the Irish government published the South Coast Designated Maritime Area Plan (DMAP) Proposal. The Government will seek to procure up to 900 MW of offshore wind capacity within this maritime area via Ireland’s next competitive offshore wind auction, known as ORESS 2.1, which is proposed to commence in 2024. This will align with current available onshore grid capacity that is required to integrate offshore wind generation to the onshore grid.

This initial procurement is aimed at achieving the deployment of up to 900 MW of offshore wind capacity within an area or areas of this DMAP before 2030. At this point it is not intended to procure more than 900 MW within the area of this DMAP Proposal.
The current programme of deployment, aims to deliver 5 GW before 2030. It should be understood, however, that further programmes will take place within this DMAP area over the next decade through an orderly, strategic and managed process of development.

WP4-05 : Regional geohazards study Celtic Sea – Bathymetric Data

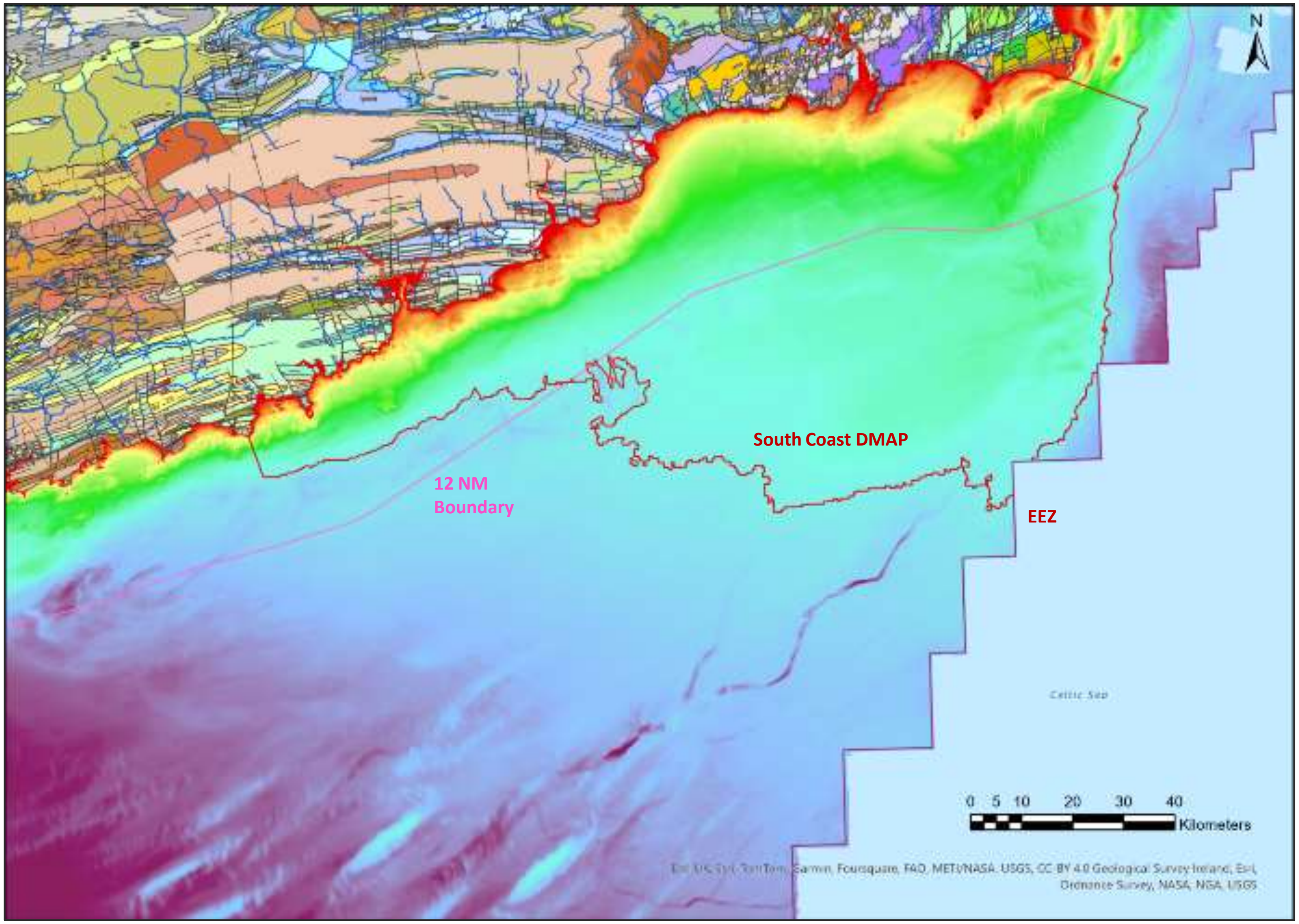


Figure 40: Onshore Geology and Bathymetry Map.

Included on the bathymetric map 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.

The onshore geology varies from Carnsore granite in the NW of the map to lower Carboniferous Limestone at Hook Head to Devonian Sandstone at the old head of Kinsale. The many rivers in the area are eroding, transporting and depositing these sediments into the Celtic Sea, with many sand being the dominant sediment type close to the coast, forming distinct sedimentary features.

Seabed canyons, channel cuts, sand banks, point bars mega ripples as well as exposed bedrock are some of the many features that are visible.

WP4-05 : Regional geohazards study Celtic Sea – INFOMAR Blue Scale Map Series

Tramore Bay is located in County Waterford on the Southeast coast of Ireland. A large sand spit divides the bay. Behind the spit lies a tidal lagoon known as the Backstrand. The dunes and backstrand area are a categorised as a Special Area of Conservation (SAC) and as such it would be difficult to develop any onshore connection points through either cabling or pipelines should infrastructure develop further offshore.

Many prominent subsea structures are visible on the map. The structural grain of the bedrock can be seen in stunning detail, particularly in the area offshore Brownstown Head. Bedrock, scour marks and sand ripple are juxtaposed against each other in the bay area.

Youghal Bay is located in Co. Cork and situated on the estuary of the River Blackwater. The Blue Scale map is highlighting in high definition the complex interplay between sediment deposition and erosion.

Winter storms have scoured the coastline of sediment, exposing bedrock on the seabed. The River Blackwater has eroded a pathway through this rock pavement and deposited sediment from the river in this outboard channel area.

It was this feature that was to play an important role in planning the landfall for the Celtic Interconnector between France and Ireland.

The Celtic Interconnector cable will enable the exchange of 700MW of electricity between the two countries. The electricity will move across a distance of 575km with 500km of the cable running subsea.

It is being developed with EirGrid and the French equivalent Réseau de Transport d'Electricité (RTE) and will be the first interconnector between Ireland and continental Europe.

The Celtic Interconnector will travel from east Cork to the north-west coast of Brittany. The project is co-funded by EirGrid and RTE. In 2019, it was awarded €530.7 million from the European Commission's Connecting Europe Facility (CEF).

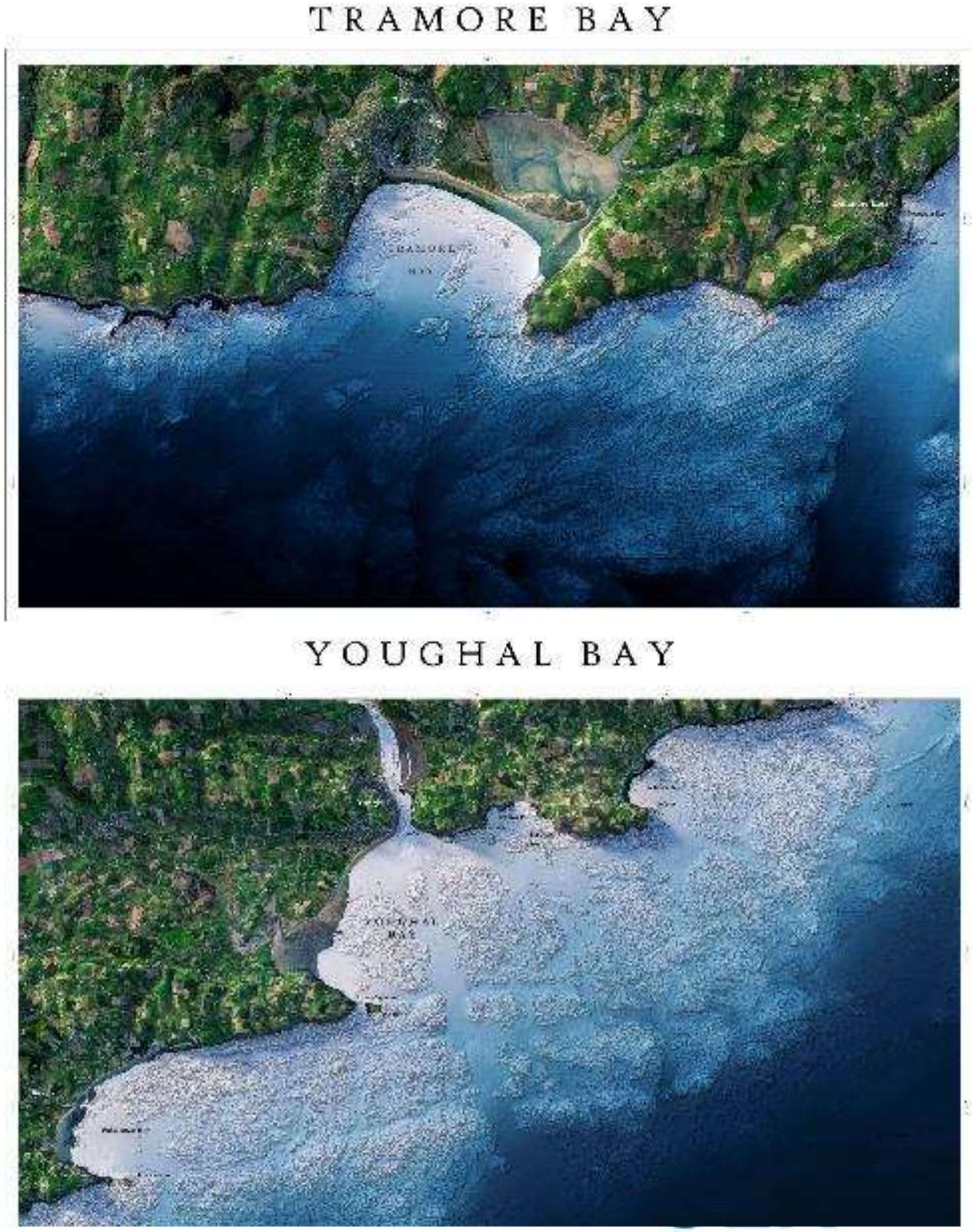


Figure 41: Images of Tramore and Youghal Bays from INFOMAR Blue Map Series

WP4-05 : Regional geohazards study Celtic Sea – Celtic Interconnector

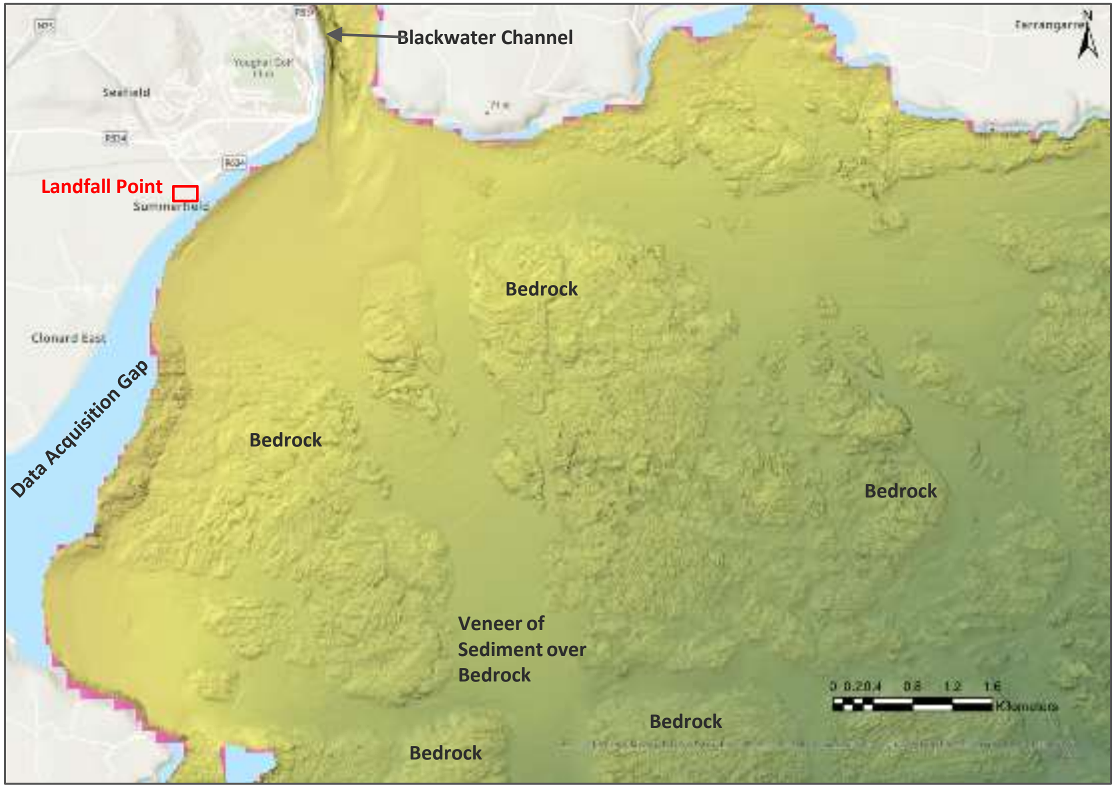


Figure 42: Bathymetry Map highlighting seabed features and interconnector landfall point .

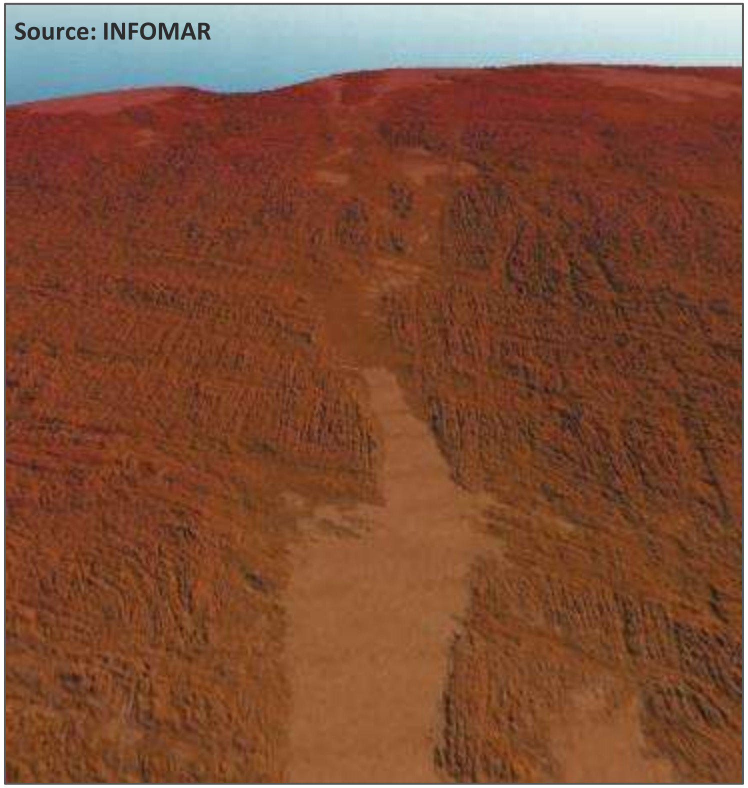


Figure 43: 3D Visualization of the seabed in the area.

In 2018 the RV Keary acquired data as part of INFOMAR's national inshore surveying programme. This data delivery was fast-tracked at the request of the Celtic Interconnector project so that it could be incorporated into assessments for potential landfall locations.

The study area consisted of extensive rock outcrop, featuring inclined and deformed bedding intercut by sediment filled channels and heavy faulting. A smooth veneer of sediment overlaying bedrock is the dominant seafloor characteristic to the west of the study area which highlighted the seafloor complexity which could prove challenging for marine infrastructural projects such as the Celtic Interconnector.

This data assisted the Celtic route development for the marine landfall which is now more favourable as an offshore installation solution compared to the original surveyed routes. It is estimated that this will deliver marine installation savings of approximately €8.5 million by avoiding 10-15km of rock cutting and remedial protection. It will also result in lower impacts to the environment as it avoided the use of specialist rock cutting tools and external cable protection.

WP4-05: Regional geohazards study Celtic Sea – Bathymetric Data

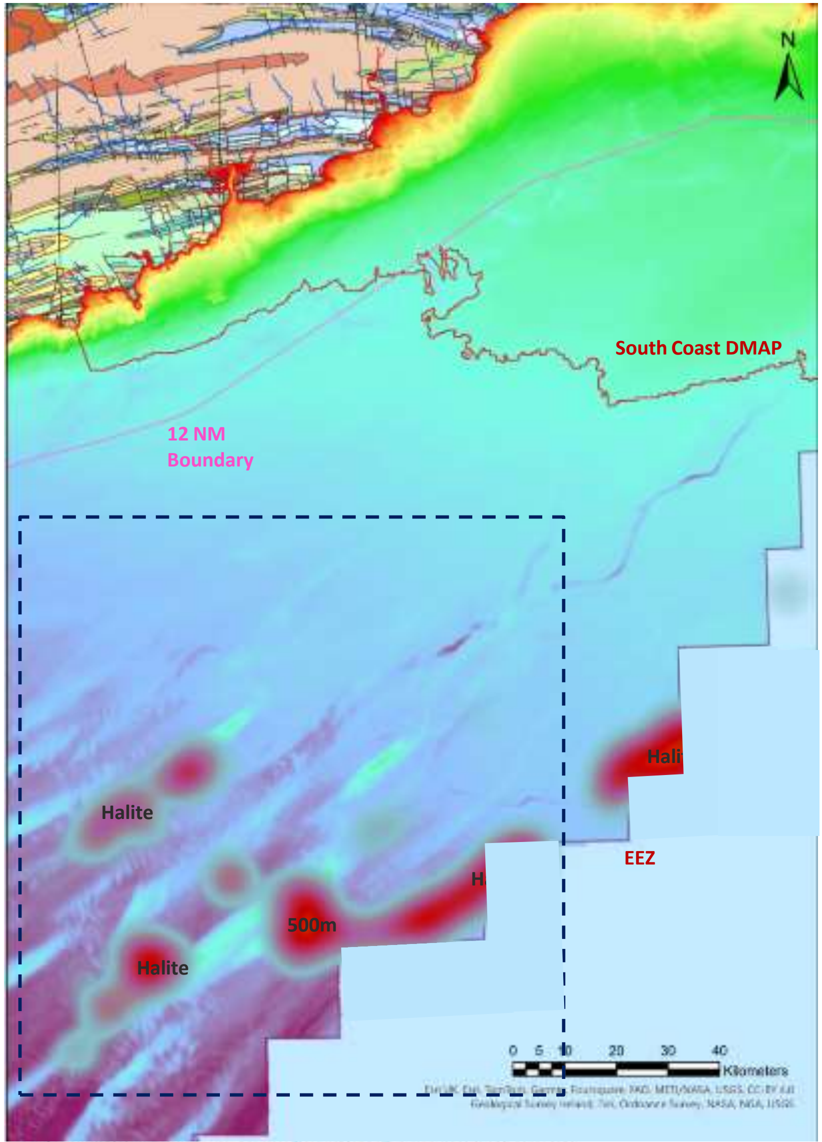
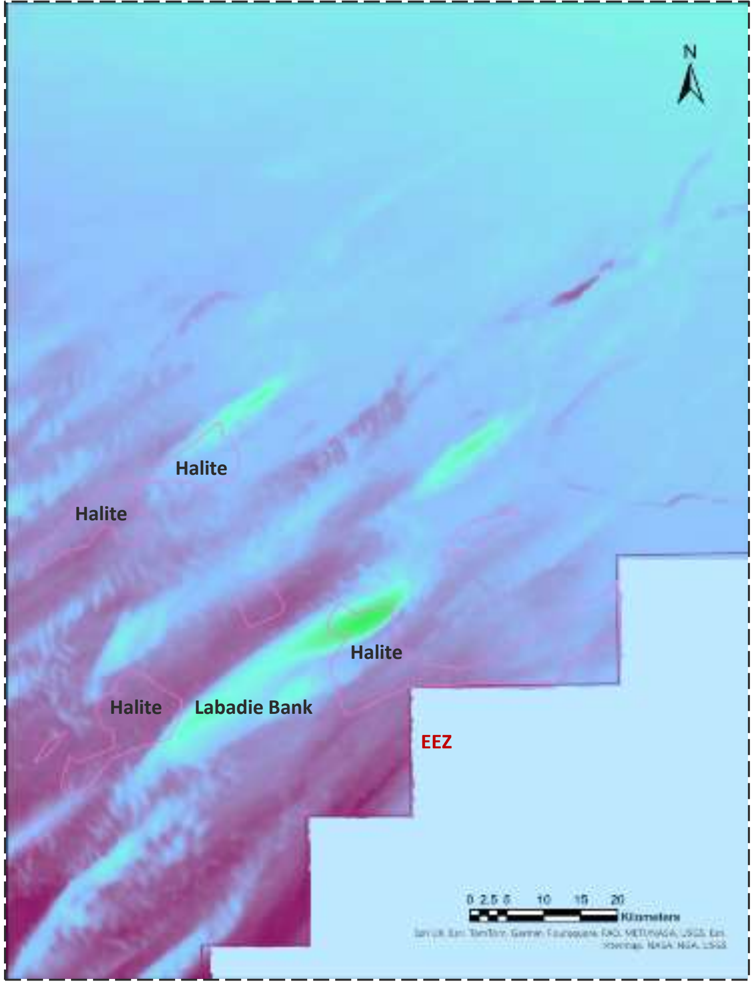


Figure 44: INFOMAR Bathymetry Map over Halite Area.



The bathymetry shallows to 62m in the area approximately around where the halite has been deposited subsurface . There are several sand banks in the vicinity as well as sediment waves seabed channels.

Given the shallow depths there could be the possibility to co-locate fixed foundation (Jackets) wind turbines.

WP4-05: Regional geohazards study Celtic Sea – Backscatter Data

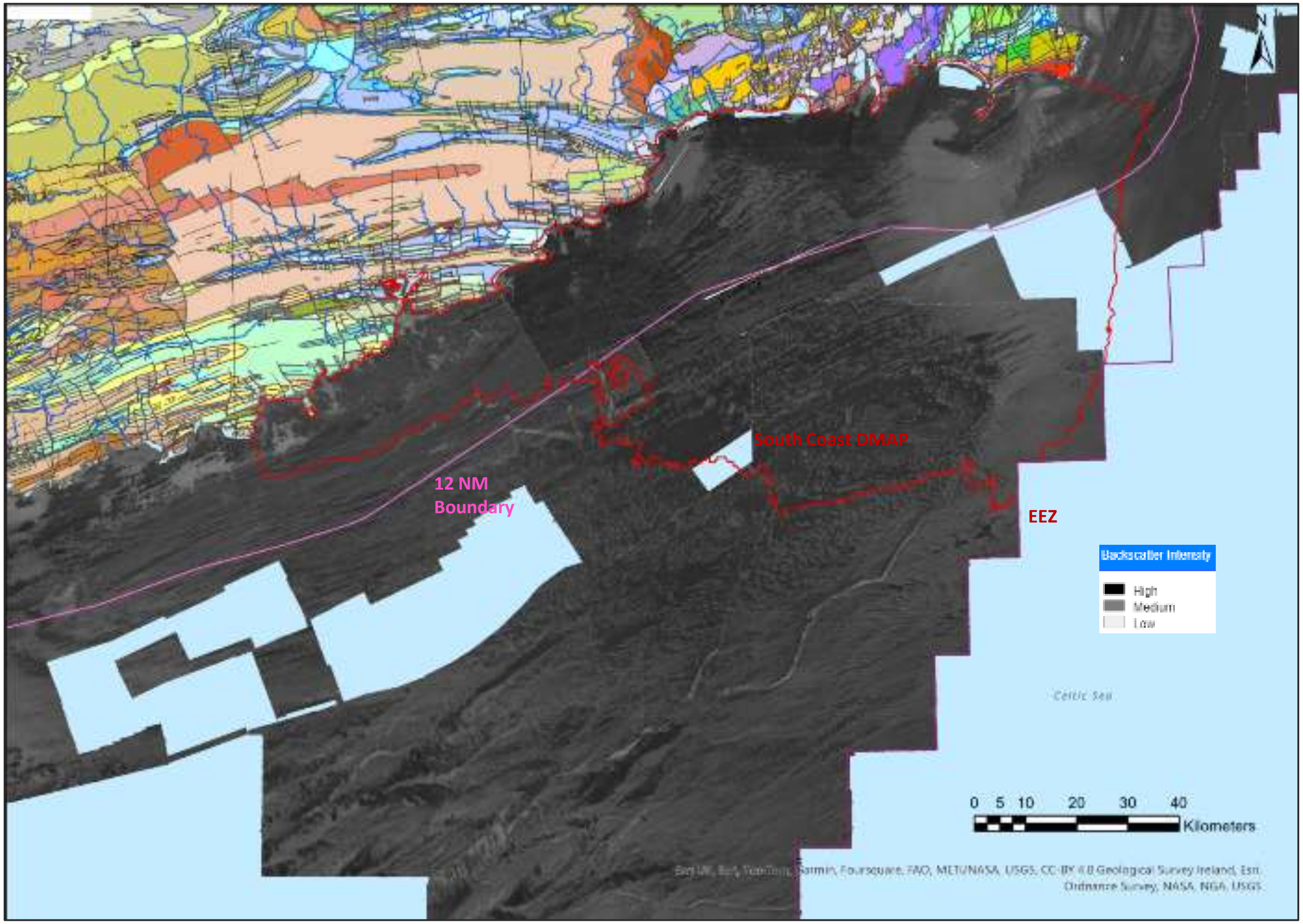


Figure 45: Onshore Geology and Backscatter Map.

The backscatter signal in this area varies across the region as does the onshore geology.

The low intensity values are indicative of sand and there is a good correlation with the bathymetry MBES data to highlight the various depositional features in the area such as sand banks, sand bars and large-scale sediment waves which are dominating the seafloor landscape in the centre of the Dmap area.

Further South there are many geomorphological features of interest such as seabed channels that appear to be infilled by sand.

However, there are many areas where the backscatter data has yet to be made available and there are significant data gaps in areas outboard of the 12 Nautical Mile maritime boundary.

WP4-05 : Regional geohazards study Celtic Sea – Backscatter Data

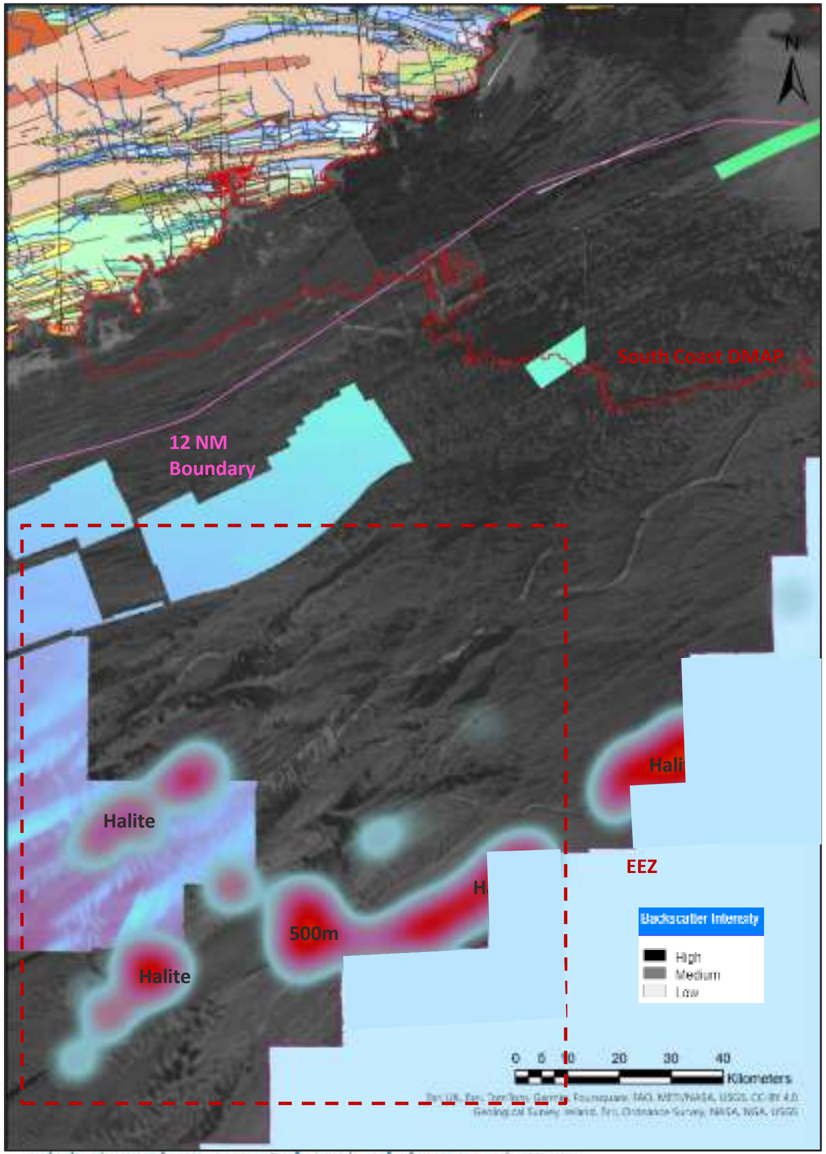
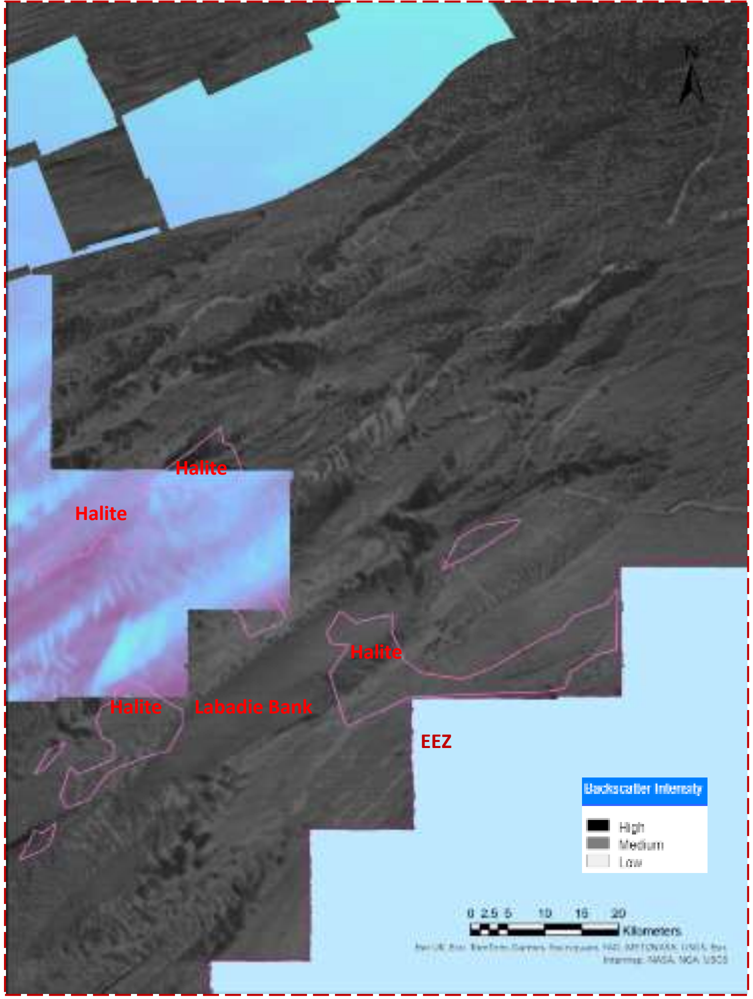


Figure 46: INFOMAR Bathymetry Map over Halite Area.



The backscatter data is highlighting several depositional features and has a good correlation to the MBES bathymetry data.

However, there are areas where the backscatter data has yet to be made available and there are significant data gaps in areas where there is Halite present subsurface.

WP4-O5: Regional geohazards study Celtic Sea – Seabed Sediment Classification

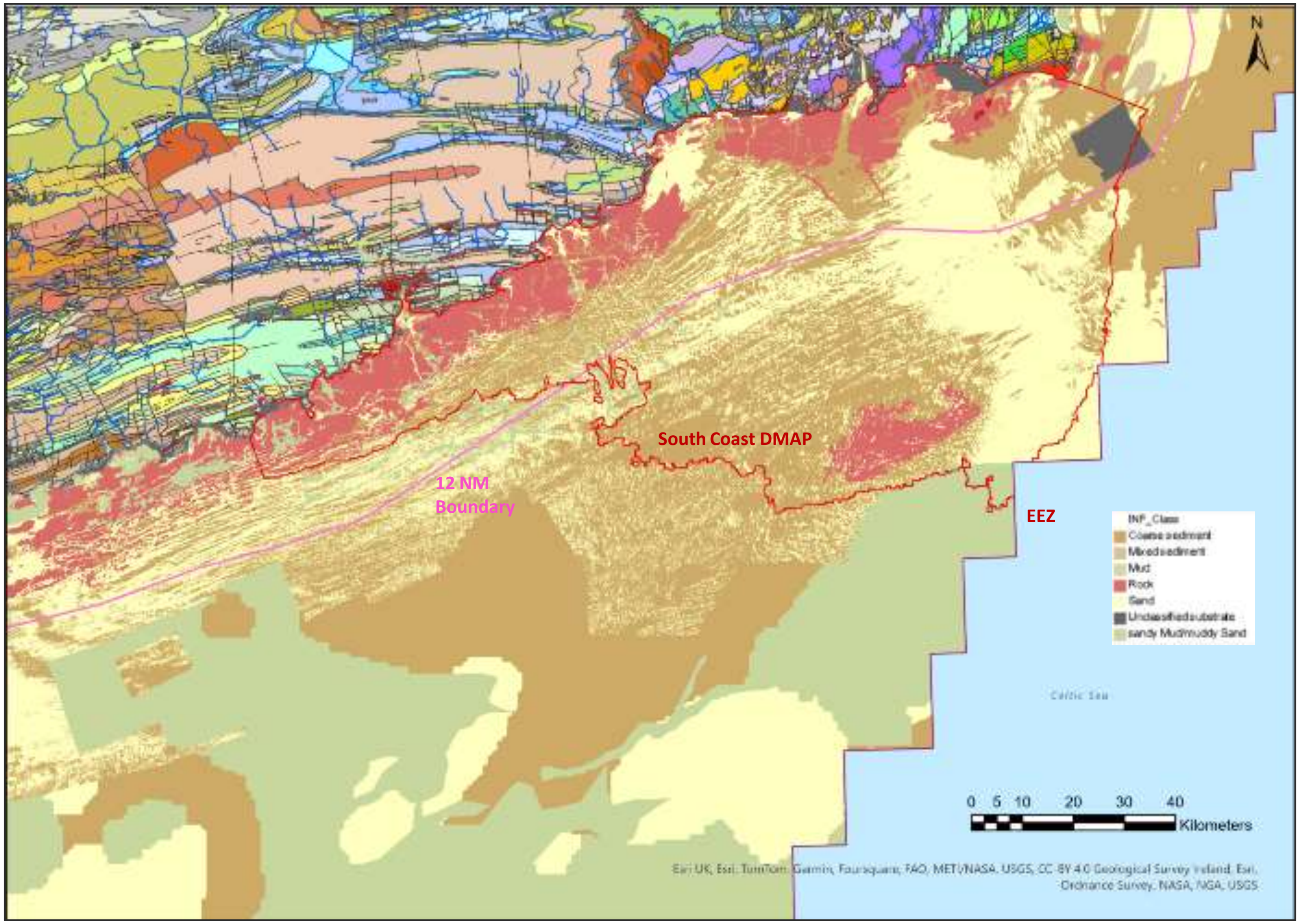


Figure 47: Onshore Geology and Seabed Sediment Classification Map.

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.

There is a complex relationship in the area between deposition and erosion, leading to a variation between high deposition of sands in areas like the SE of the Dmap and high erosion further to the West where there is a large area of rock exposed on the seabed surface.

Large amounts of bedrock are being exposed at the seabed primarily due to the scouring of the sediments by storms and tidal currents. This coupled with a thin sediment cover over the area means that it is essential to understand the geotechnical properties of both the sediments but also the underlying bedrock.

Areas with lots of rock and lack of sediment cover will make it more difficult and expensive to install and maintain subsea infrastructure.

WP4-O5: Regional geohazards study Celtic Sea – Seabed Sediment Classification

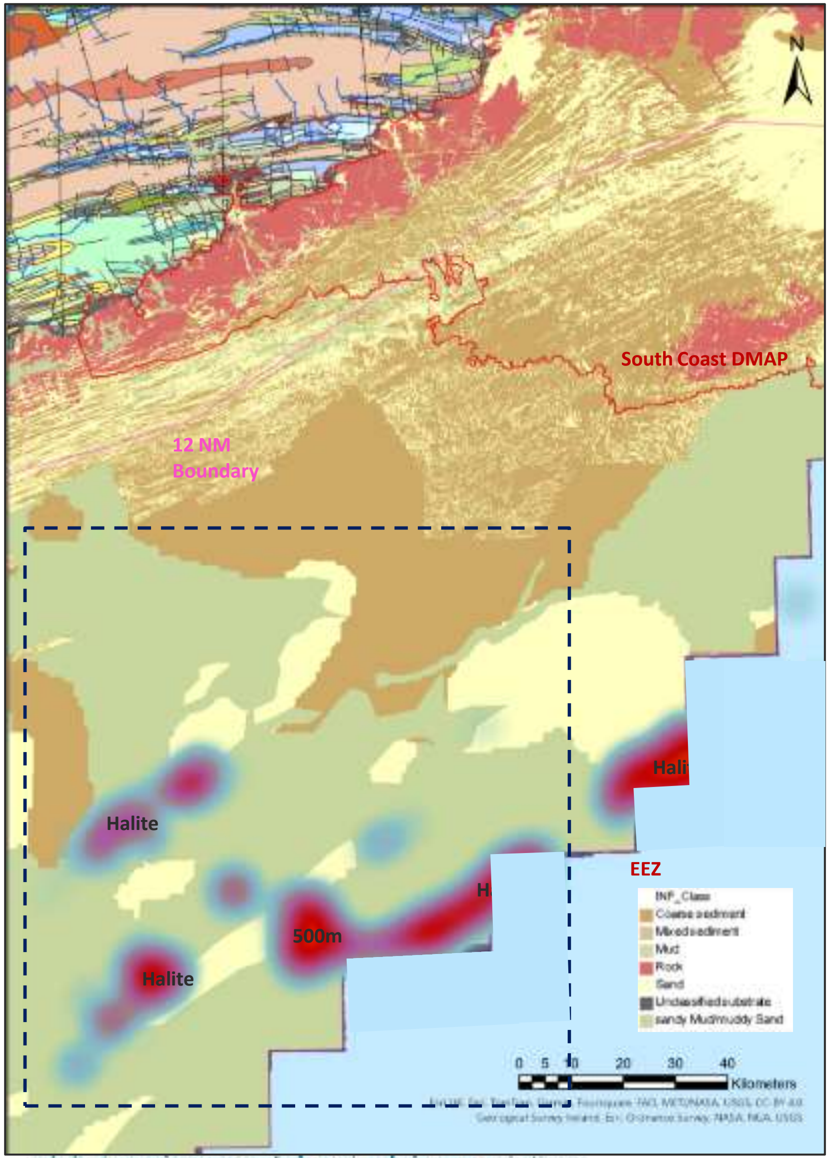
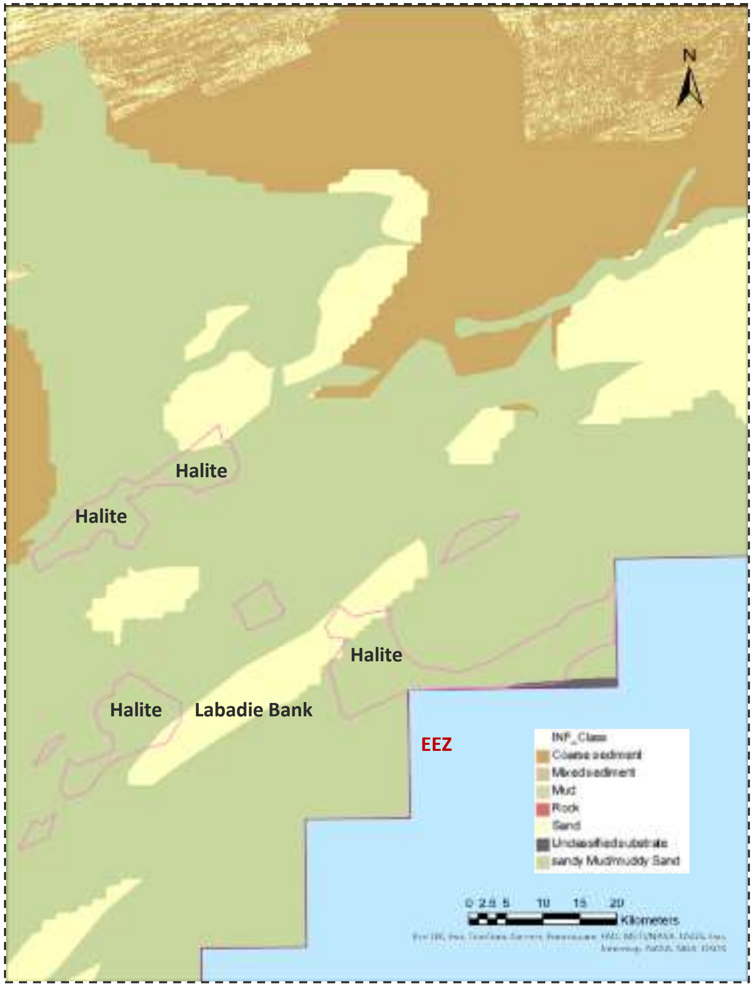


Figure 48: INFOMAR Seabed Sediment Classification over Halite Area.

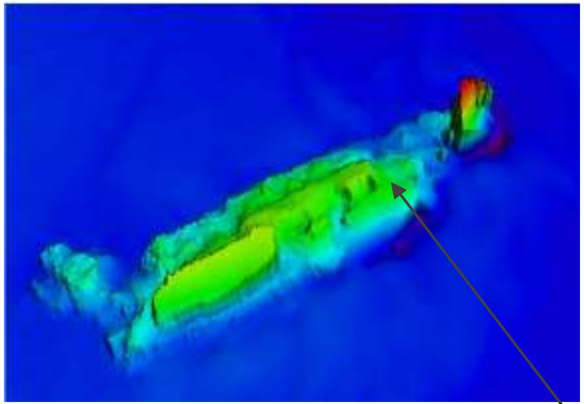


The Seabed Sediment Classification Map is correlating the various MBES datasets with the grab samples that have been acquired in the area. Many of the depositional features such as the Labadie bank have been classified as having sand whereas the deeper intervals either side have mud.

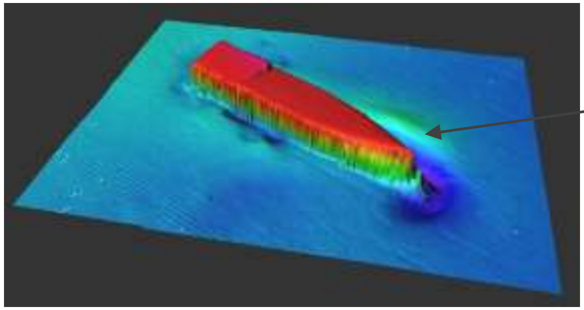
It will be important to understand the shear strengths of these sediments and a full geotechnical assessment including CPTs would be required.

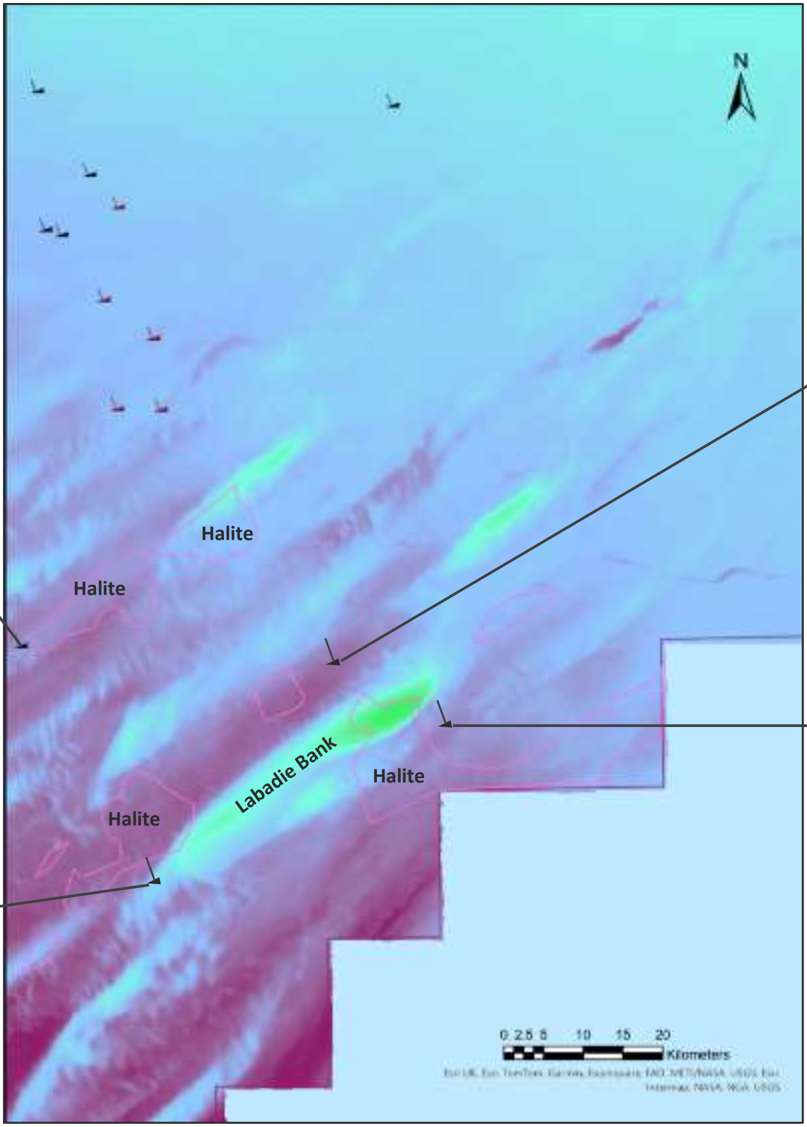
WP4-O5: Regional geohazards study – Shipwrecks

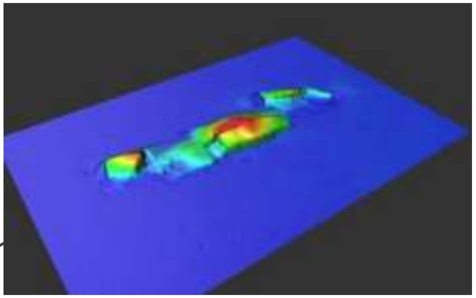
INFOMAR have over 400 wrecks mapped throughout Irish coastal waters.



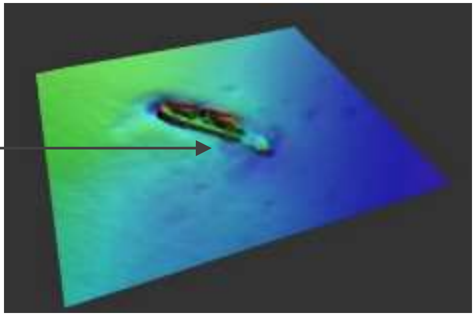
Geomorphological features have proven hazardous throughout history for various maritime vessels. The sand banks and sediment waves coupled with the strong currents and varying water depths have proven to be challenging obstacles for many mariners.







Various 3D models, wreck reports and publications are available from the INFOMAR website.



The MBES data illustrates the interplay between the seabed sedimentological processes and anthropogenic activity as highlighted above.

WP4-O5: Regional geohazards study Celtic Sea – Survey Coverage & Vintages

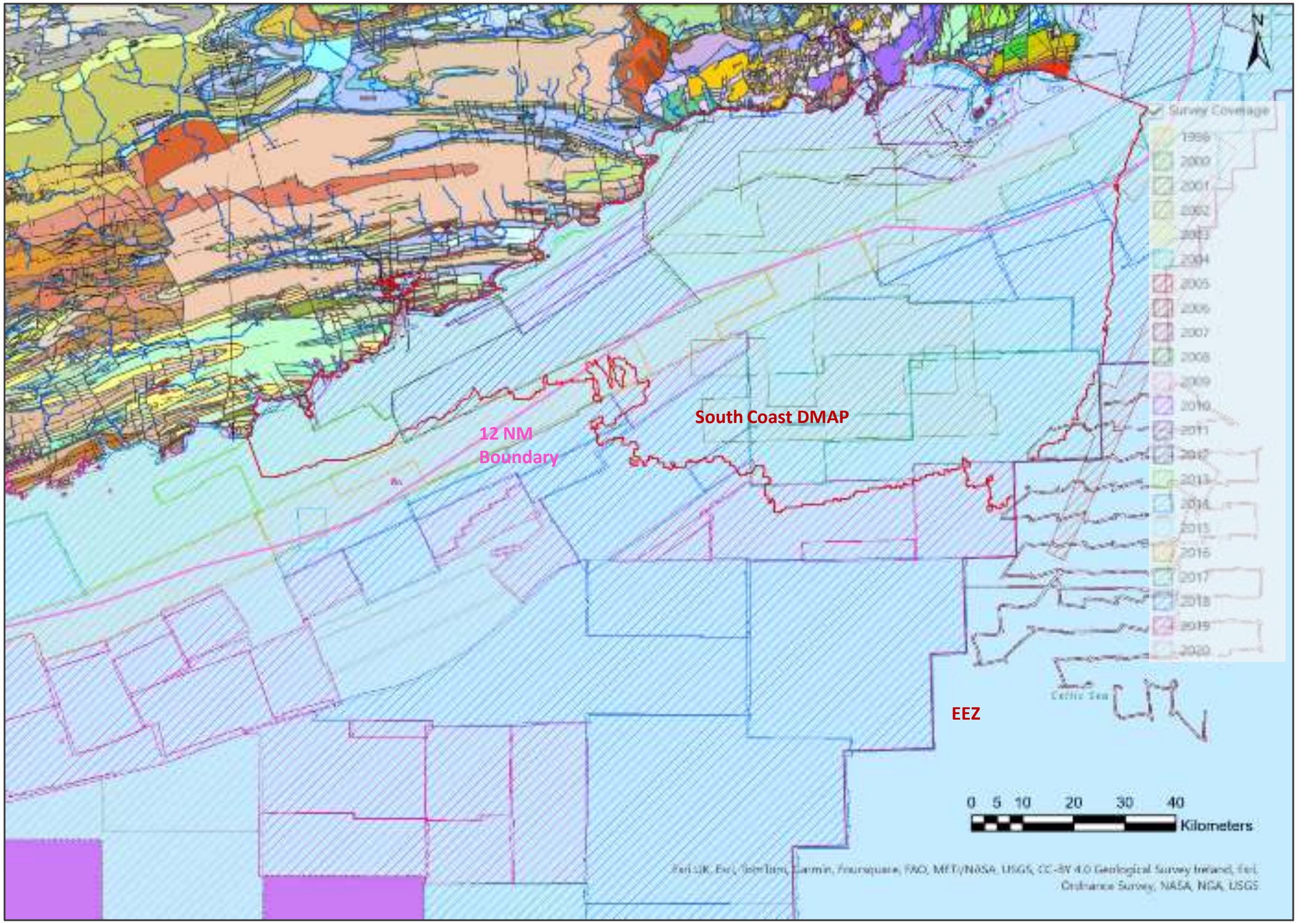


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Figure 49: Onshore Geology and INFOMAR Survey Coverage.

There are many vintages of marine surveys that have been acquired over the years.

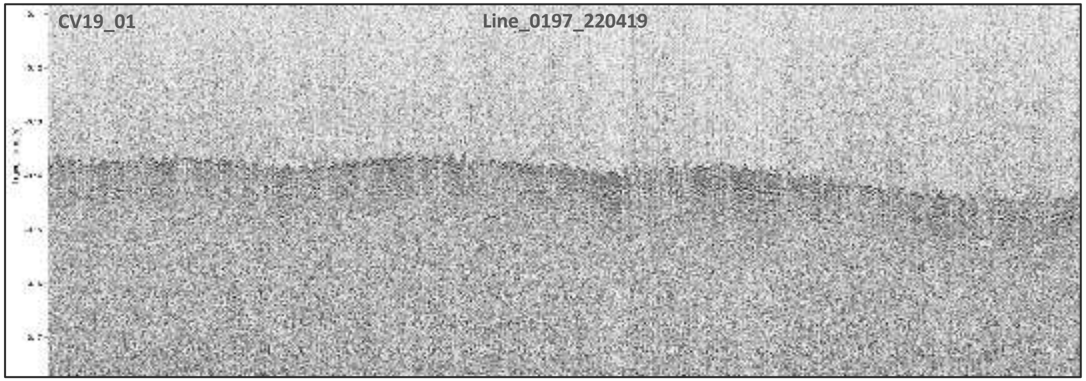
Ireland has undertaken hydrographic and geophysical survey operations to designate its maritime territory since 1996.

Originally conducted by Ireland's Petroleum Affairs Division on behalf of the Government of Ireland, the findings reinforced the need for a comprehensive assessment of the entire Irish seabed.

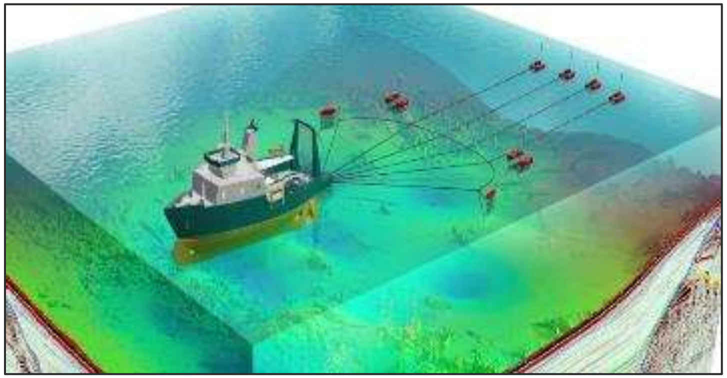
The Geological Survey Ireland (GSI) managed Irish National Seabed Survey (INSS, 2000-2006) followed, an ambitious but successful programme to survey Ireland's entire deep-water territory beyond 200m water depth.

INFOMAR evolved as the follow-on national seabed survey initiative as a joint venture between Geological Survey Ireland and the Marine Institute. INFOMAR was initiated to survey the remaining shelf and coastal waters between 2006 to 2026 and to deliver a baseline bathymetry data set to underpin the future management of Ireland's marine resource.

WP4-O5: Regional geohazards study – Data Quality and Quantity



Poor quality Pinger line from the Celtic Sea



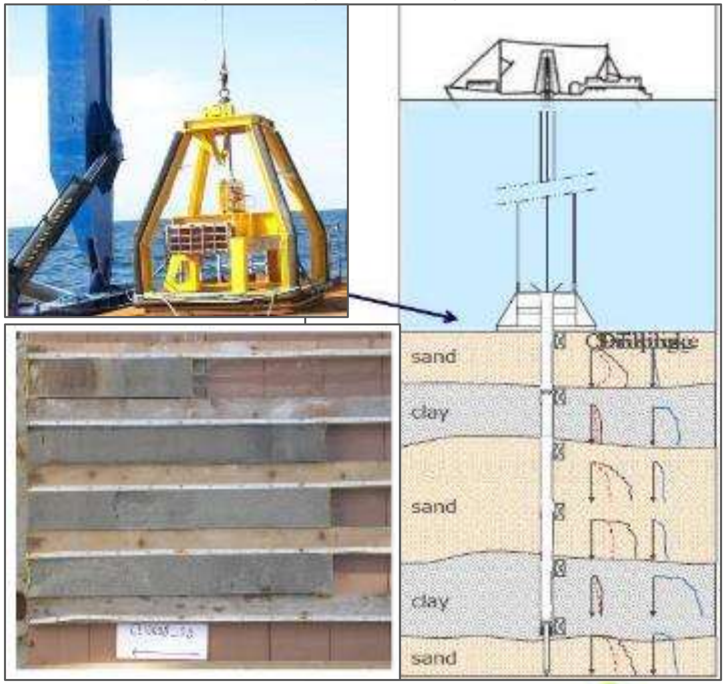
High quality 3D site specific surveys

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.

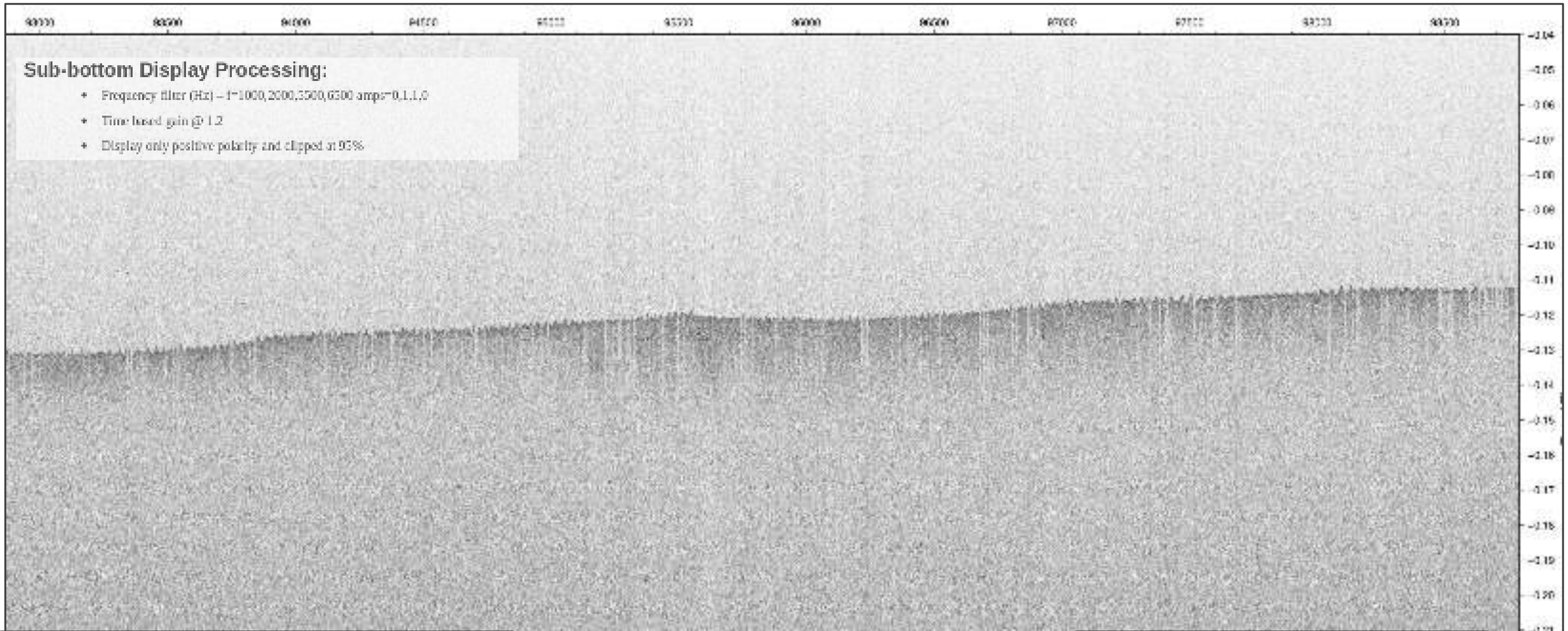
Additional site-specific geophysical surveys will need to be undertaken and carried out prior to any construction or installation in the Irish Sea and Celtic Sea areas. Time lapse (4D) bathymetric surveys will be required to understand if the sediments in a specified area have moved over time and if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



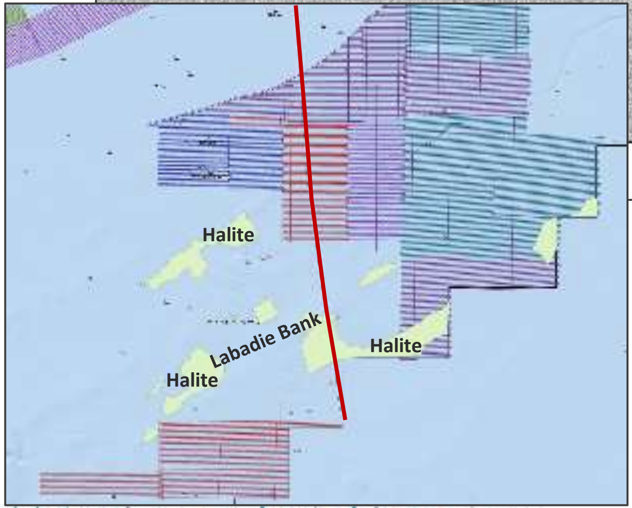
Cone Penetration Test (CPT)

WP4-O5: Regional geohazards study Celtic Sea – SBP Data (CV19_02)



Sub-bottom Display Processing:

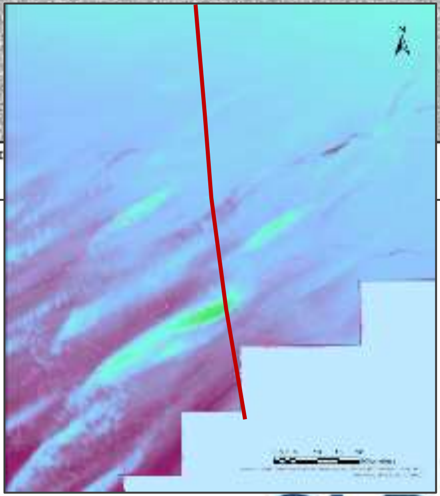
- Frequency filter (Hz) – f=1000,2000,3500,6300 amps=0,1,1,0
- Time based gain @ 1.2
- Display only positive polarity and clipped at 93%



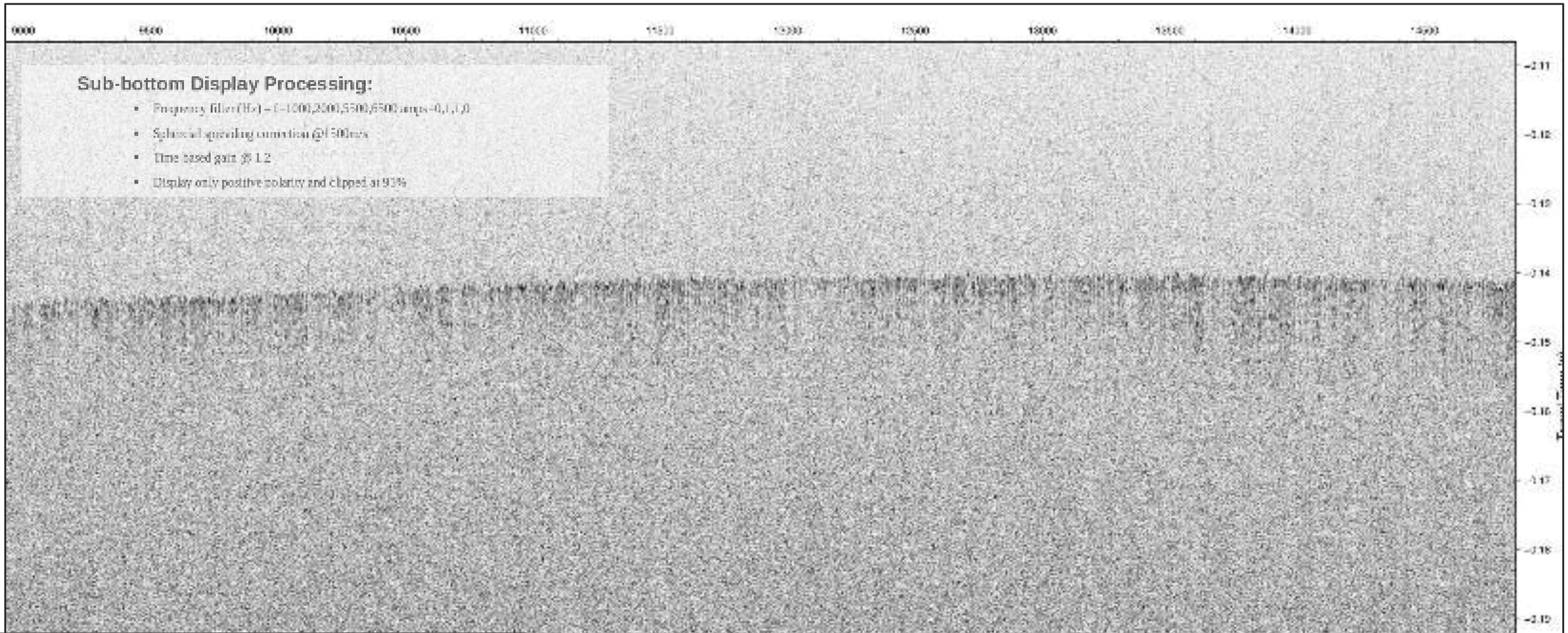
The SBP line above highlights the sparsity of the sub bottom datasets in the area where halite has been mapped in the Celtic Sea.

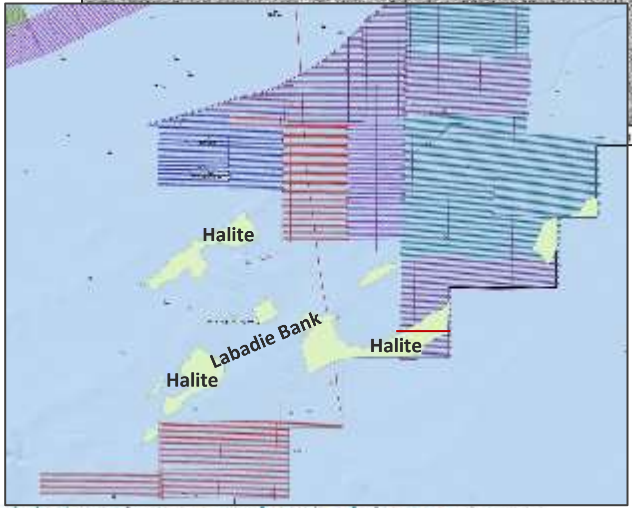
The above is an example from the CV19_02 survey where just one Pinger line was acquired over the Labadie Bank area.

The SBP data is of poor quality and contains many dead traces. A stronger source would be needed to highlight the near surface geology.



WP4-O5: Regional geohazards study Celtic Sea – SBP Data (CV18_03) Purple Corner

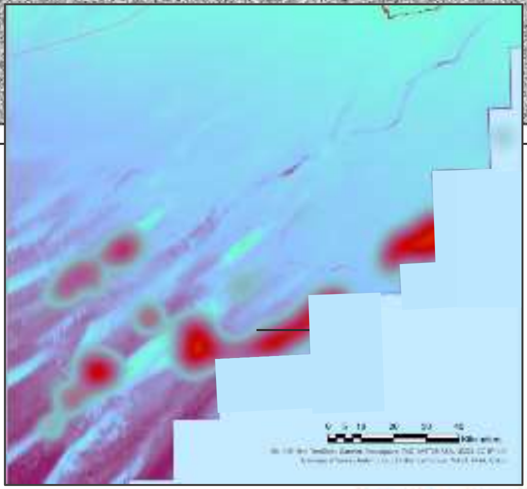




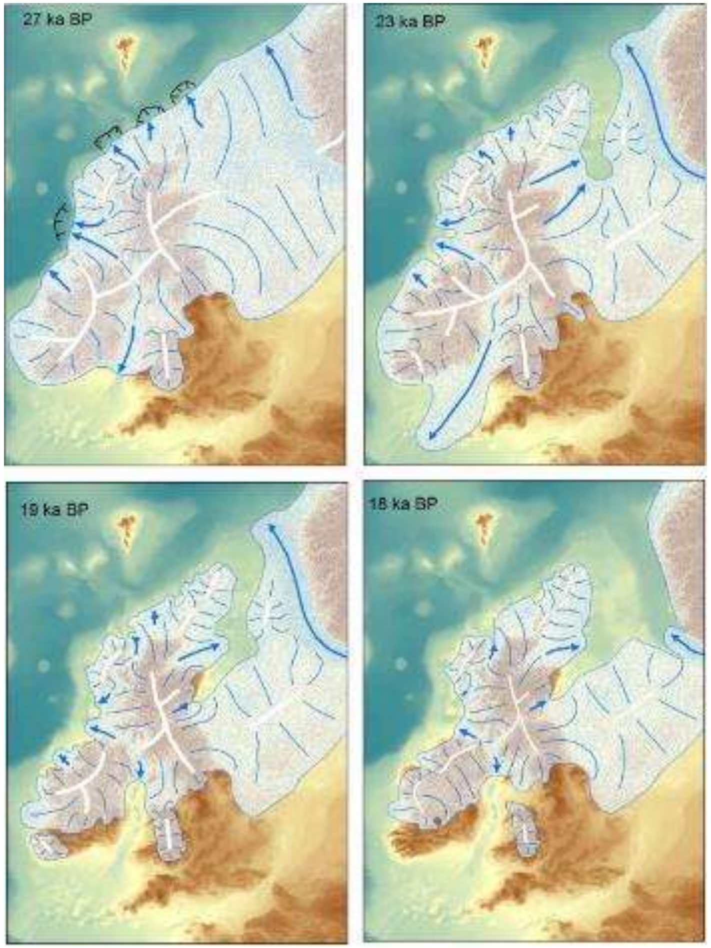
The above is an example from the CV18_03 survey where a limited number of Pinger lines were acquired in the Halite area.

The SBP data is of poor quality and contains many dead traces. A stronger source would be needed to highlight the near surface geology.

A Sparker or Boomer geophysical array would be the minimum equipment required to penetrate suffciently.



WP3-05 & WP4-05: Regional geohazards study – What lies beneath?



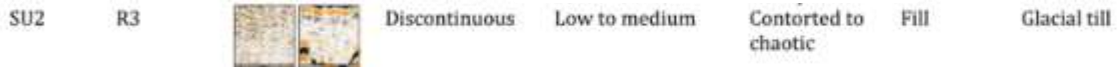
Clark et al 2020

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 **Toth et al 2019**. in the North Celtic Sea area calibrated Multichannel Sparker data to provide a litho-seismic description for varies units including a Glacial Till formation.



SU2	R3		Discontinuous	Low to medium	Contorted to chaotic	Fill	Glacial till

WP4-05: Regional geohazards study Celtic Sea – Multichannel Sparker Data

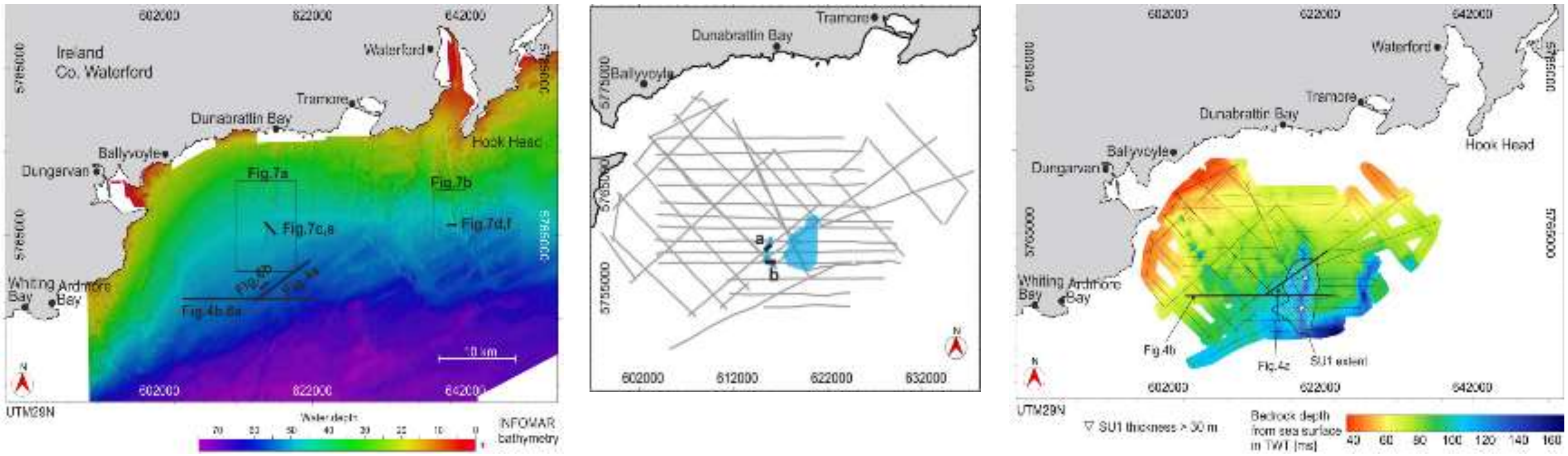


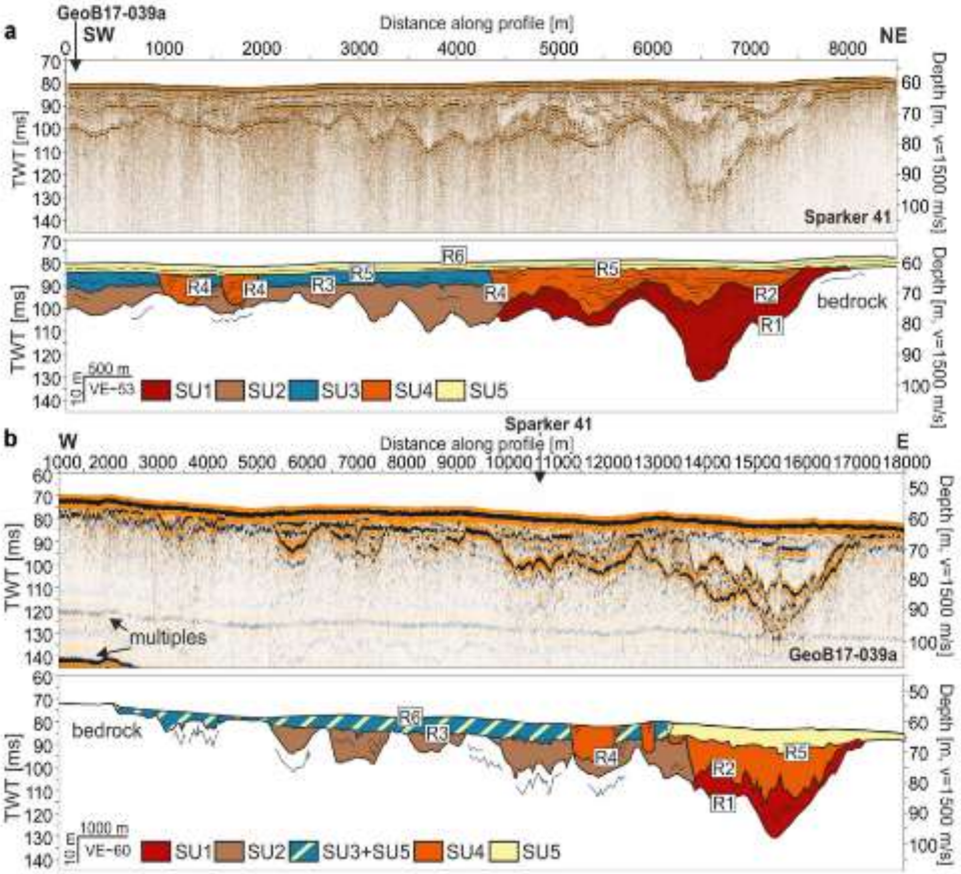
Figure 50: Maps Highlighting Bathymetry, Multi-Channel Sparker Seismic Lines and Depth to Bedrock. Toth et al 2020

There is a paucity of good quality multi-channel Sparker data available offshore Ireland. However high resolution bathymetric and multichannel sparker data was acquired, processed and interpretated offshore Waterford and is described in **'Geomorphological and seismostratigraphic evidence for multidirectional polyphase glaciation of the northern Celtic Sea'** Toth et al 2020.

The datasets vary in vintage and type. An initial Sparker survey was carried out in September 2012 with the R/V Celtic Voyager (Dorschel et al., 2012) and investigated the area between Dungarvan and the Saltee Islands in the Celtic Sea. The survey was a collaborative research project undertaken by University College Cork and INFOMAR. Acoustic sub-bottom data were acquired using a Geo-Source 400 Sparker system.

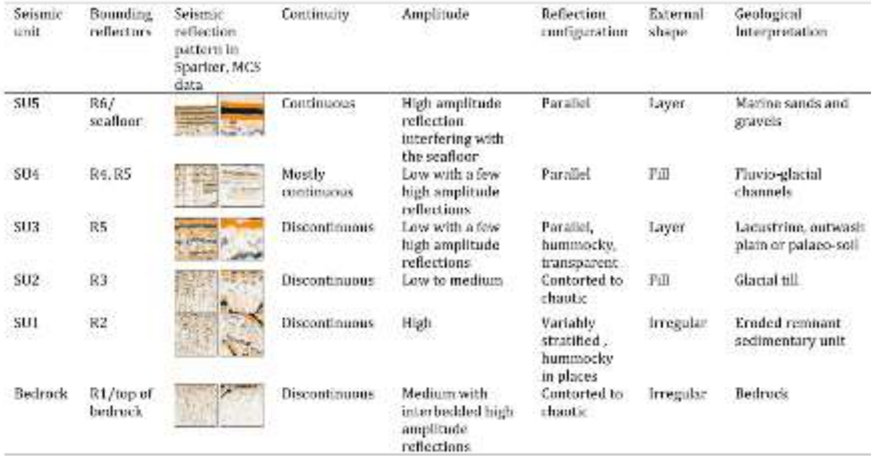
The site was revisited in 2017 with the R/V Celtic Voyager (Wheeler et al., 2017). Multichannel seismic data were acquired using the high-resolution seismic system of the University of Bremen, Germany. A 96-channel Teledyne streamer with an active length of ~220 m was used for acquisition and a Sercel micro G.I. gun was employed as the seismic source, using two chambers of 0.1 litre volume each. The frequency content of the data is between 80 and 500 Hz with a main frequency of ~200 Hz, yielding a vertical resolution of ~2–4 m. Data penetration into the sub-seafloor is usually several hundreds of metres in marine sediments, although probably due to the coarse grain size of seabed sediments and the shallow geological basement in the study area, signal penetration is generally lower than 200 m.

WP4-O5: Regional geohazards study Celtic Sea – Multichannel Sparker Data



A typical Sparker profile (a) and multichannel profile (b) from the study area revealing reflectors (R1–R5) that bound seismic units (SU1–SU5).

Once the Multi-Channel Sparker Data was acquired and processed several seismostratigraphic units where defined and described.



Seismic unit	Bounding reflectors	Seismic reflection pattern in Sparker, MCS data	Continuity	Amplitude	Reflection configuration	External shape	Geological interpretation
SU5	R6/ seafloor		Continuous	High amplitude reflection interfering with the seafloor	Parallel	Layer	Marine sands and gravels
SU4	R4, R5		Mostly continuous	Low with a few high amplitude reflections	Parallel	Fill	Fluvio-glacial channels
SU3	R5		Discontinuous	Low with a few high amplitude reflections	Parallel, hummocky, transparent	Layer	Lacustrine, outwash plain or palaeo-soil
SU2	R3		Discontinuous	Low to medium	Contorted to chaotic	Fill	Glacial till
SU1	R2		Discontinuous	High	Variably stratified , hummocky in places	Irregular	Eroded remnant sedimentary unit
Bedrock	R1/top of bedrock		Discontinuous	Medium with interbedded high amplitude reflections	Contorted to chaotic	Irregular	Bedrock

Figure 51: highlights the various seismic units and their associated seismic signature. Toth et al 2020

The R1 reflector defines the top of Bedrock; it is a ‚high-amplitude boundary that reaches up to the seafloor in places where bedrock outcrops. The internal bedrock structure is generally poorly imaged and characterized by discontinuous reflectors.

SU1 (R2) is characterized by a variety of high-amplitude reflection patterns: in some places hummocky to chaotic, and in others clearly stratified.

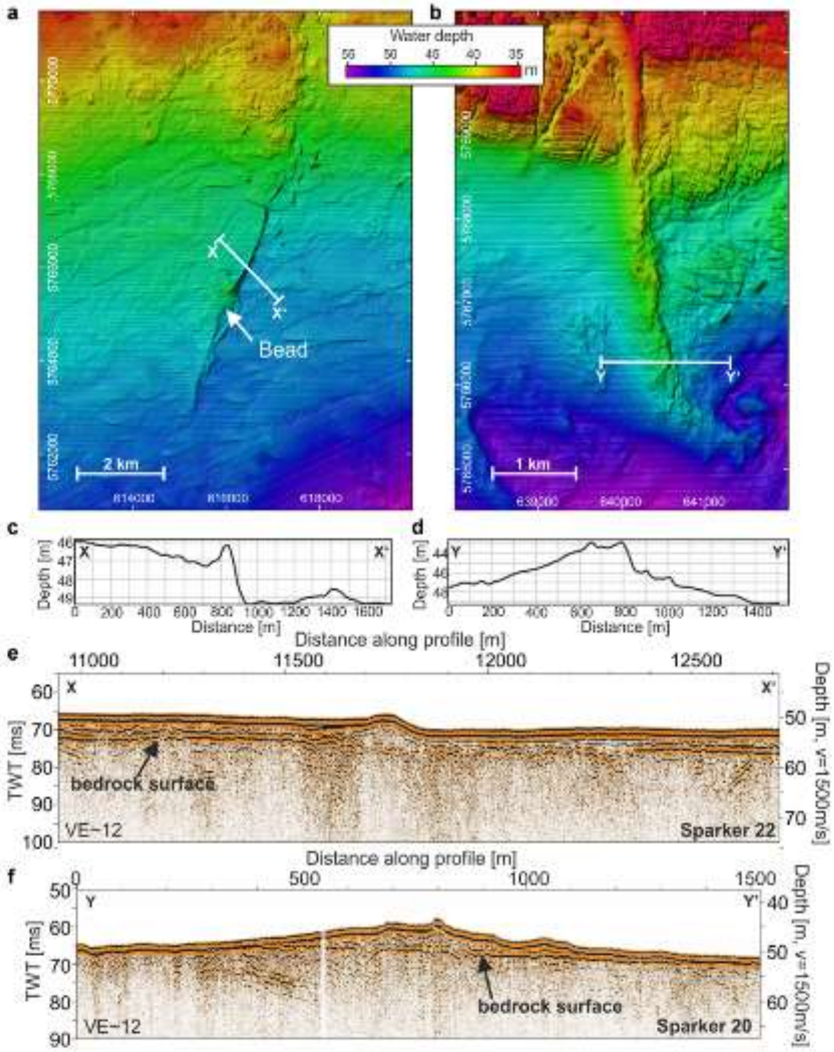
The top of SU2 (R3) is relatively smooth, horizontal and of low to medium amplitude, can be seismically transparent in places.

SU3 is bounded by both R4 and R5. R5 defines most of the unit, which is relatively flat, smooth and of a lower amplitude than the underlying R3 reflector.

SU1–SU3 are incised by a series of well-defined channels filled by SU4, the bases of which are defined by R4.The channels vary in width from 300 to 1000 m and have a maximum depth of 12 m. SU4 is characterized by low-amplitude reflections.

SU5 is a relatively thin layer at the seabed In the Sparker and seismic dataset it appears as a high-amplitude reflection at the seafloor.

WP4-O5: Regional geohazards study Celtic Sea – Multichannel Sparker Data



(a,b) Multibeam bathymetry showing two generally N–S-oriented seafloor ridges which extend across bedrock exposed at the seabed and onto the deeper water seabed underlain by a sub-seafloor sedimentary unit offshore south-east Ireland.

(c) Two cross-profiles across the ridges with recent seabed sediment accumulations on their western sides consistent with local longshore tidal current regimes.

(d,e) Sparker profiles running orthogonally across the ridges showing bedrock below and the R5 reflector partially onlapped by SU5.TWT, two-way travel time.

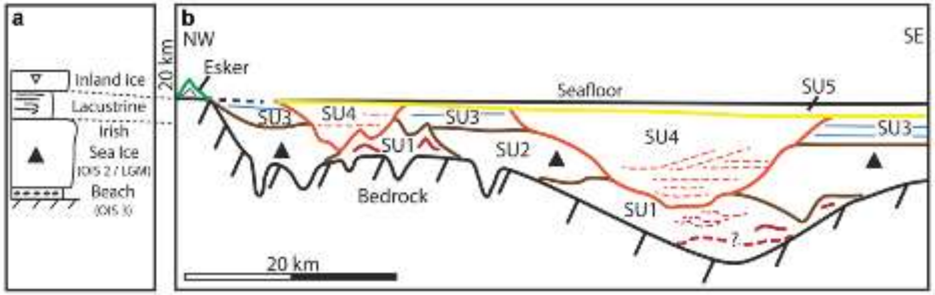


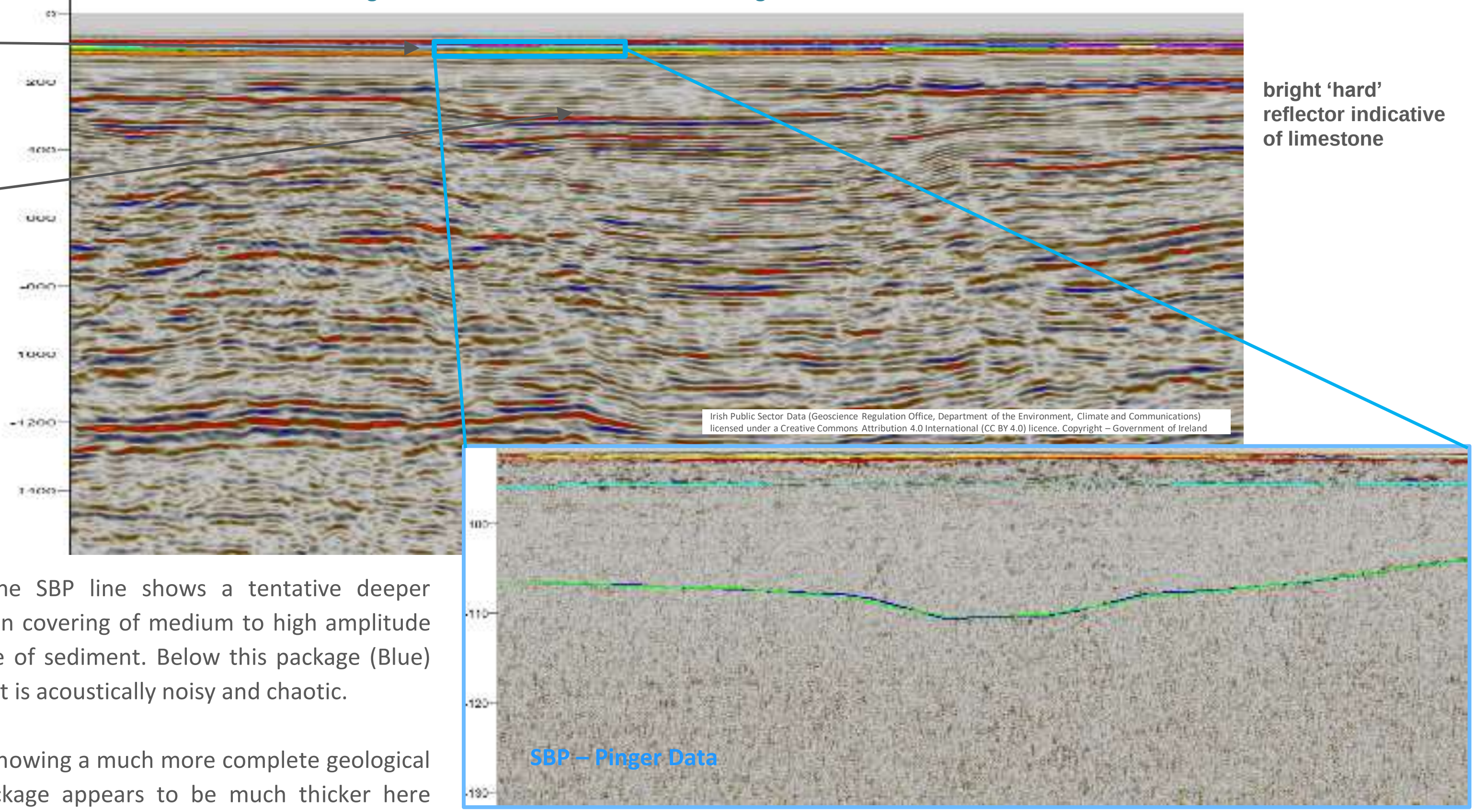
Figure 52: Cross-section of interpreted seismic stratigraphy of the northern Celtic Sea related to a generalized onshore coastal stratigraphy, Toth et al 2020.

Studies of the Quaternary sequences preserved on the Irish continental shelf have been very limited due to a paucity of high-resolution shallow seismostratigraphic data. This new seismic dataset, used in combination with high-resolution bathymetric data, reveals the Quaternary seismostratigraphy of an area off south-eastern Ireland in the northern Celtic Sea. There is a complex history of ice sheet sector interplay during and post-dating the last glacial period.

Six seismostratigraphic units record a sequence of erosion and deposition events. The offshore extension from the BIIS across modern Co. Waterford is proposed as the last major ice sheet event to have occurred in the area, post-dating eastward withdrawal of the ISIS.

WP4-O5: Regional geohazards study – Integrating various datasets

Figure 53: SBP and 2D Seismic Line Integration



SBP Horizons

Large channel cut infilled by soft sediments?

bright ‘hard’ reflector indicative of limestone

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When taken in isolation the SBP line shows a tentative deeper subsurface canyon and a thin covering of medium to high amplitude reflectors that are indicative of sediment. Below this package (Blue) there a transparent zone that is acoustically noisy and chaotic.

The 2D deep seismic line is showing a much more complete geological story. The sedimentary package appears to be much thicker here compared to the SBP line and there are much better-defined units

The SBP line penetrates approx. 50 milliseconds (approx.37 meters) beneath the seabed, whereas the 2D seismic line is penetrating over 2 seconds (approx. 1500 metres).

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.

WP4-O5: Regional geohazards study – An Example of UHR Data from Norway

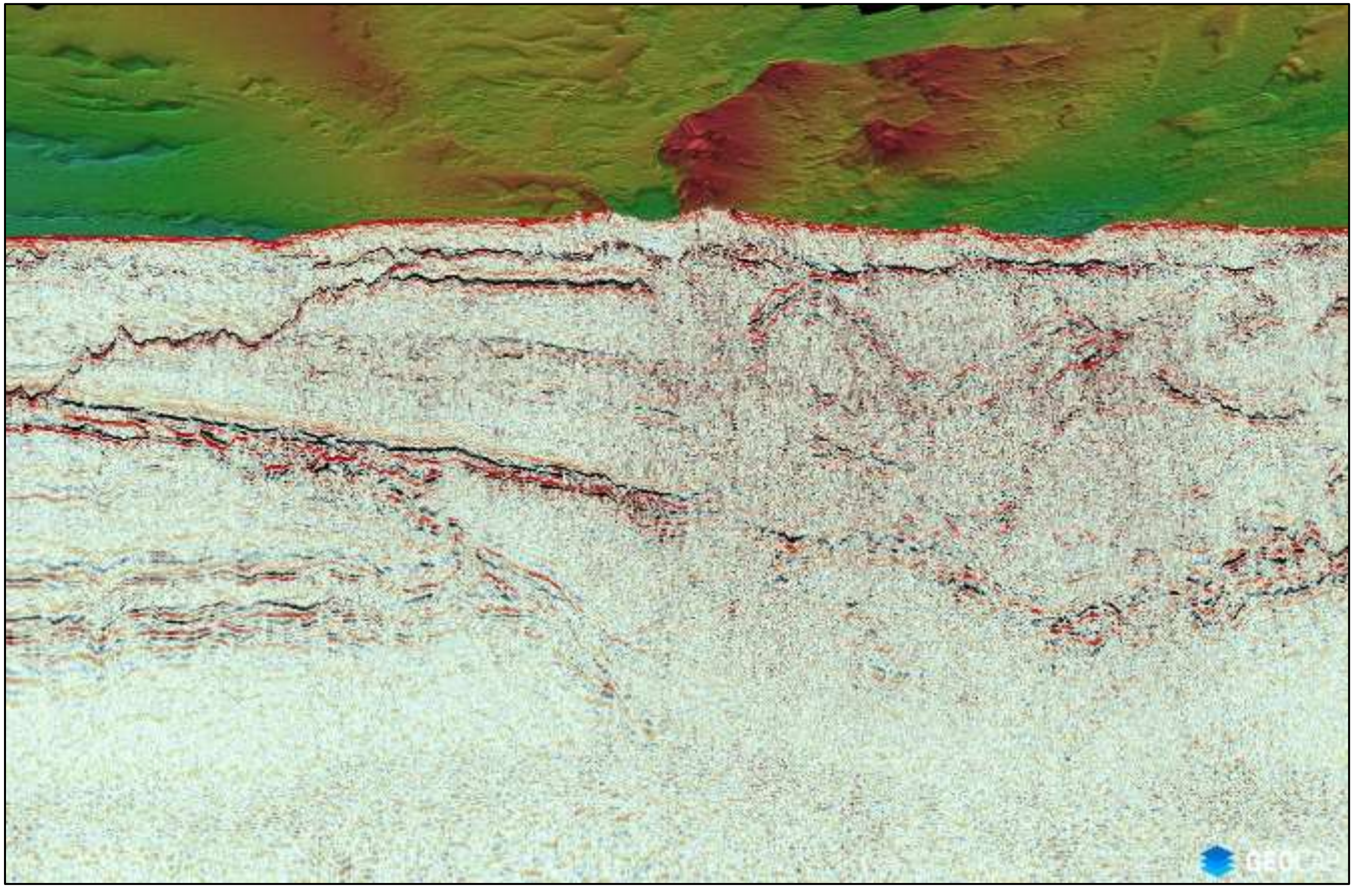


Figure 54: Multi Channel Sparker Data and Bathymetry Map.

2D Ultra-High-Resolution (UHR) multi-channel seismic acquired in 2022 displayed together with multibeam bathymetry data from part of the Norwegian offshore wind round area - Sørlige Nordsjø II (Southern North Sea II).
Note that the bathymetry data is draped on the seismic data and we can see the correlation between subsurface and seabed expressions.
Data courtesy of the Norwegian Offshore Directorate and GEOCAP and Peter Croker 2024.

WP4-O5: Regional geohazards study Celtic Sea – Legacy Well Data

The Geoscience Regulation Office (GSRO) has a vast amount of geological and geophysical datasets that can provide additional benefit for offshore site investigations including legacy oil and gas datasets located offshore Ireland.

Well 50/30-3 was drilled on the South Coast, offshore Wexford and contains several different reports and files including a site clearance survey report.
A site survey was undertaken and completed from 27/04/1991 – 03/05/1991 prior to the rig moving on to the final drilling location on the 30th of May 1991. The exploration well was spudded on 3rd June 1991 and the rig was released and moved off location after the well was plugged and abandoned on 1st July 1991. The well encountered some oil and numerous gas shows indicating an active petroleum system in the area, however it was deemed to be a dry hole having found no commercial amounts of hydrocarbons.

Water depths range from 53.5m-72m across the survey area and are recorded as 64.6m (212ft) at the final drilling location. The velocity of the seawater was found to be 1491 metres per second.

The seafloor exhibited distinct outcropping of bedrock in the NE quadrant of the survey. The sidescan sonar data reveal a seafloor of low relief and low sonar reflectivity, which is indicative of fine-grained sediments. A number of low amplitude sediment waves and dunes are visible and are orientated in a NW-SE pattern. The sediment waves are typically asymmetrically, being steeper on the SW sides and range in height from 2-5m. Their overall geometry suggests a predominate ocean current flow from the NE to SW.

The extensive sand wave pattern alludes to active/mobile sediments in the area. The report recommends that scour resistant foundation designs need to be considered for drilling operations and any platform design.
The only other features of note on the seabed are trawl scars from fishing activities in the area.

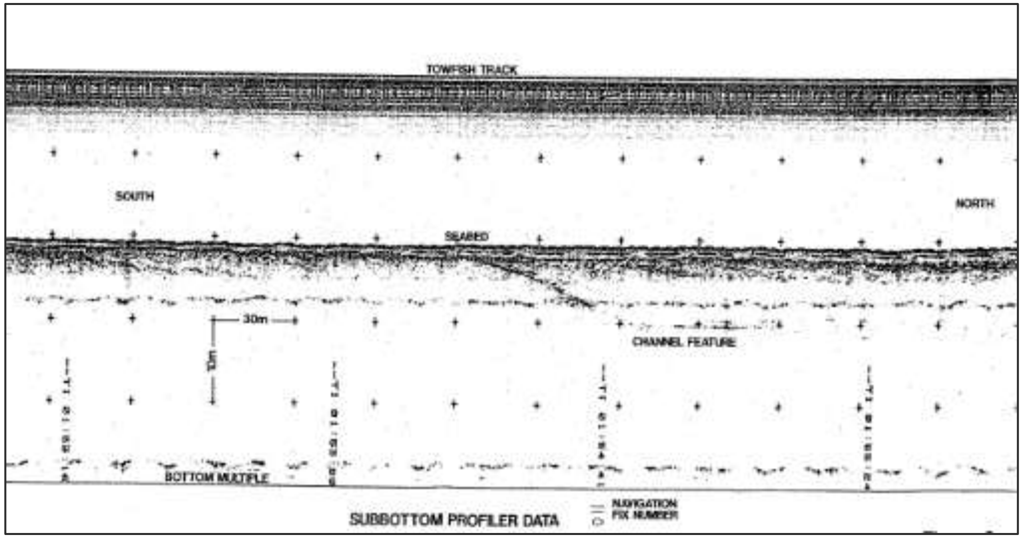


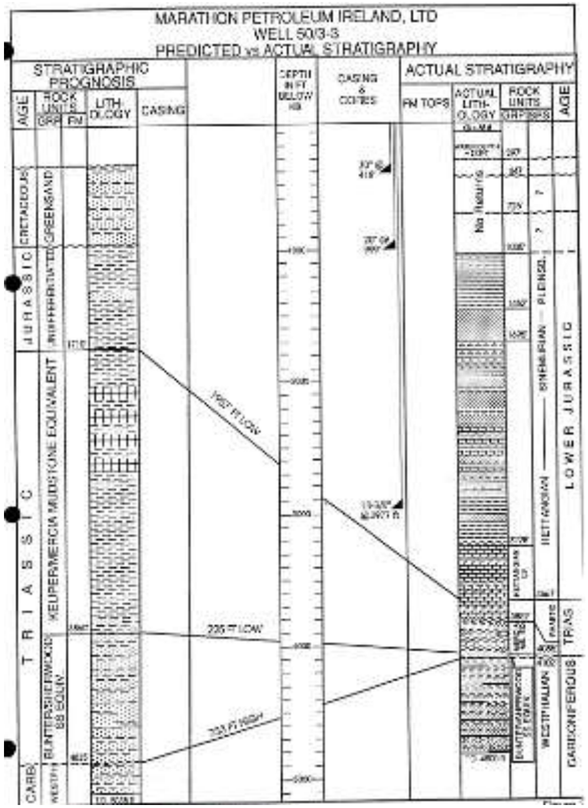
Figure 55: Annotated cross section from the Sub Bottom Profiler Data.

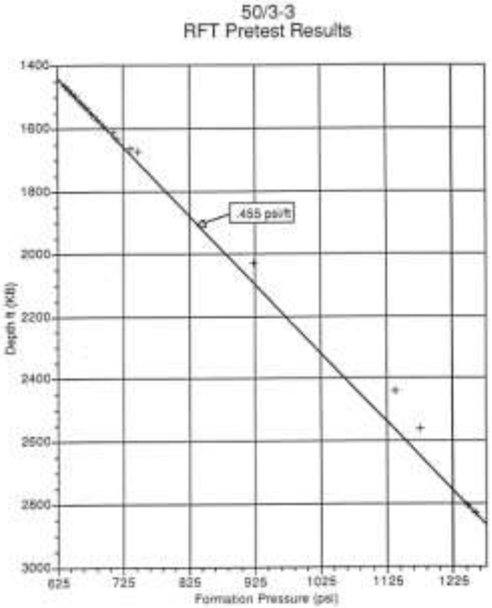
The sub-bottom profiler (boomer/sparker) data set provided most of the information on the shallow geology immediately below the seabed.
The whole site is covered by fine to coarse grained sand deposition, the sub surface information is generally limited to the upper 6-7 metres below the seabed.
In several areas due to the formation of subsurface channels the sediment thickness can be as thick as 17-19m. Fig XX illustrates one of these channels.

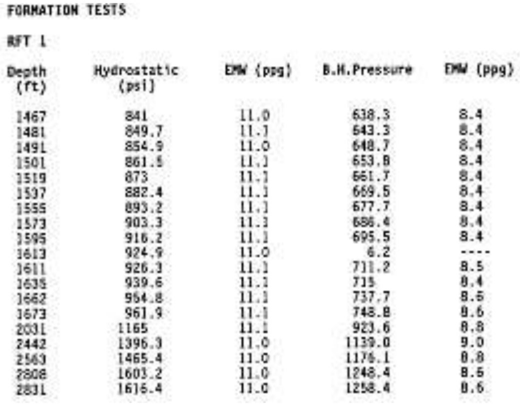
The maximum observed depth of the major channel feature is approximately 19m below the present seabed. This channel is now infilled and exhibits no seafloor expression. This channel infill is anticipated to be the equivalent to basal sands and gravels but no samples are available to verify this. Variations in bearing, strength and other geotechnical properties may exist between the channel fill and adjacent Tertiary sandstones.

In 3 distinct areas on the acquired SBP data the signal was attenuated to such a degree that it was almost impossible to identify completely any sub surface features. This may be caused by an underlying hard unit acting as a barrier to the sound wave penetrating deeper.

WP4-O5: Regional geohazards study Celtic Sea – Legacy Well Data







FORMATION TESTS

RFT 1

Depth (ft)	Hydrostatic (psi)	EMW (ppg)	B.H.Pressure	EMW (ppg)
1467	841	11.0	638.3	8.4
1481	849.7	11.1	643.3	8.4
1491	854.9	11.0	648.7	8.4
1501	861.5	11.1	653.8	8.4
1519	873	11.1	661.7	8.4
1537	882.4	11.1	669.5	8.4
1555	893.2	11.1	677.7	8.4
1573	903.3	11.1	686.4	8.4
1595	916.2	11.1	695.5	8.4
1613	924.9	11.0	6.2	----
1611	926.3	11.1	711.2	8.5
1635	939.6	11.1	715	8.4
1662	954.8	11.1	737.7	8.5
1673	961.9	11.1	748.8	8.6
2031	1165	11.1	923.6	8.8
2442	1396.3	11.0	1139.0	9.0
2563	1465.4	11.0	1176.1	8.8
2808	1603.2	11.0	1248.4	8.5
2831	1616.4	11.0	1258.4	8.6

Irish Public Sector Data (Geoscience Regulation Office, Department of the Environment, Climate and Communications)

In the stratigraphic summary highlighting prognosed v actual above it is notable that there are no lithological descriptions for the shallow geology as there were no rock or sediment returns to the rigfloor for this interval immediately beneath the seabed.

The well had several gas shows and from reviewing offset 2D seismic and well data in the area there is the potential for shallow gas to occur in places, particularly in areas with deep rooted faults close to the seabed.

Repeat Formation Tests (RFT) confirming the well was normally pressured.

The well 50/30-3 was spudded on the 3rd June 1991 in 212ft of water. Hole problems attributed to unconsolidated gravel, the size of the gravel varied from pea to walnut size. The gravels were presumed to be of glacial origin.

Initially it was believed that Cretaceous rock was immediately beneath the seabed and it was surprising to encounter 132ft (40m) of younger sediments. This may have implications for depth to bedrock in the Celtic Sea.
As evidenced from the site survey and drilling operations the sediment thickness varies on the South Coast, with subsurface channelised features offering a greater depth to bedrock than at other parts of the site.
However, the base of these channels did cause some drilling complications as they were unprepared for the gravels they encountered close to the seabed.
Rock outcropping at the seabed was also noted in the NE quadrant of the site survey.

WP4-O5: Regional geohazards study – Geopressure

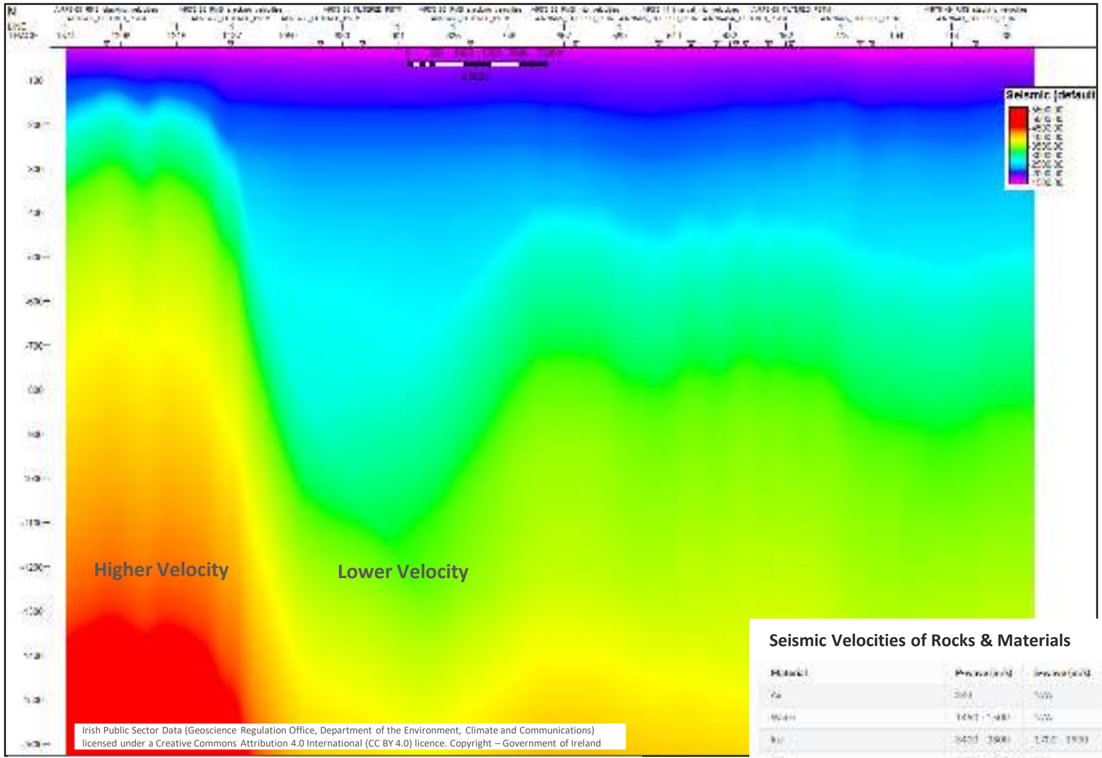
Pore pressure prediction is used to develop a subsurface model for the pressure regime and it is a critical property towards an effective geohazard mitigation. A quantitative predrill prediction of pore pressure is required and can be obtained from elastic wave velocities using a velocity-to-pore-pressure 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.



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PRESDM Seismic Velocities from a 2D Seismic Line.

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.

Seismic Velocities of Rocks & Materials

Material	P-wave (m/s)	S-wave (m/s)
Air	343	N/A
Water	1450 - 1498	N/A
Ice	3400 - 3800	1700 - 1900
Oil	1200 - 1250	N/A
Vegetal Soil	300 - 700	100 - 300
Dry Sands	400 - 1200	100 - 500
Wet Sands	1500 - 2000	400 - 600
Saturated Shales and Clays	1100 - 2500	200 - 800
Porous and Saturated Sandstones	2000 - 3500	800 - 1800
Marls	2000 - 3000	750 - 1500
Chalk	2300 - 2600	1100 - 1300
Coal	2200 - 2700	1000 - 1400
Salt	4500 - 5500	2500 - 3100
Anhydrites	4000 - 5500	2200 - 3100
Limestones	3500 - 6000	2000 - 3300
Dolomites	3500 - 6500	1900 - 3600
Granite	4500 - 6000	2500 - 3300
Basalt	5000 - 6000	2800 - 3400
Gneiss	4400 - 5200	2700 - 3200

WP4-O5: Regional geohazards study Celtic Sea – Geopressure

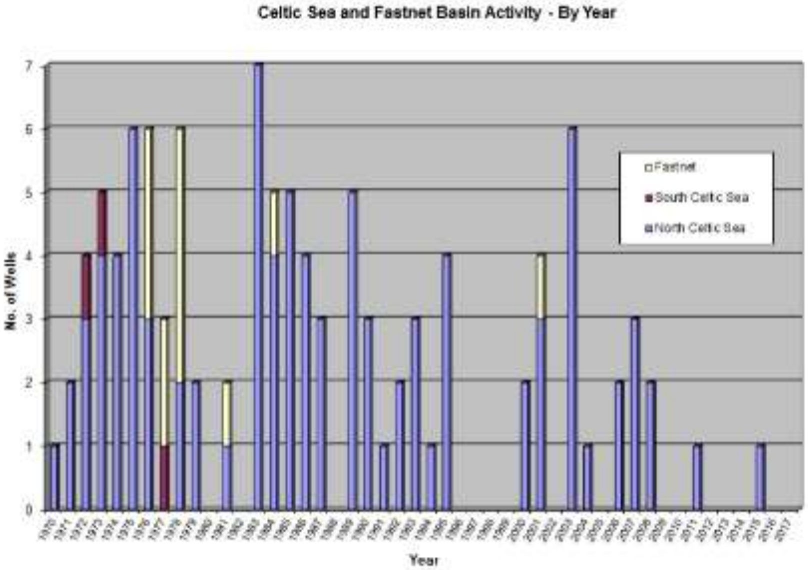
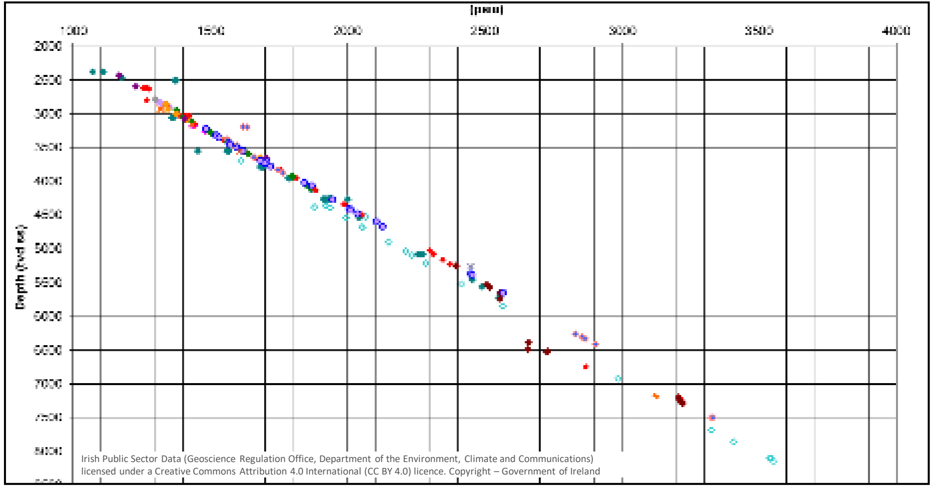
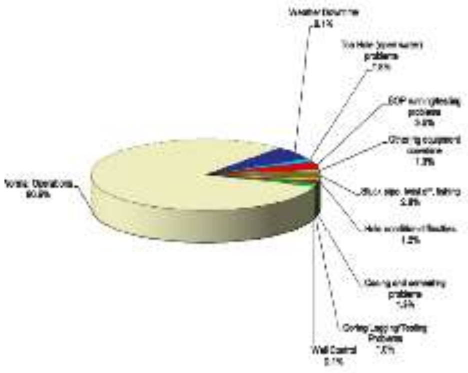

Celtic Sea and Fastnet Basin Activity - By Year

Figure 56: Celtic Sea Wells RFT Data.



Source: Petroleum Infrastructure Programme



Celtic Sea and Fastnet - Downtime Distribution

The North Celtic Sea Basin is the most explored area within Irish waters, with more than half of all Irish offshore wells in this basin. The South Celtic Sea basin has been relatively unexplored, with only 3 wells drilled, and a further 12 wells drilled in the Fastnet Basin.

All three areas share similar geology. Prospective reservoirs generally are in Cretaceous or Jurassic sandstones. The North Celtic Sea tends to have very little Recent or Tertiary Sediments overlying the Cretaceous Chalk whereas wells in the Fastnet Basin have encountered Chalk around 1000 metres. Seabed conditions do vary significantly
Well total depth ranges from less than 1,000m to over 3750 m.
All oil or gas bearing reservoirs drilled in the area have been close to normally pressured. There does appear to be an overpressuring within the Jurassic shales however, and this has frequently resulted in high gas peaks and hole instability problems, especially in some of the deeper North Celtic Sea wells.

The deeper part of the Jurassic in the Celtic Sea can be overpressured to some extent and at least two wells have had small kicks. Other wells have encountered high gas levels, and occasionally quite high mud weights have been used to reduce drilled and connection gas. The overpressure would appear to be predominantly in shales. The well control incidents have been infrequent, however, and have not resulted in any significant lost time.

WP4-O5: Regional geohazards study Celtic Sea – Geopressure

From reviewing oil and gas exploration industry internal reports Late Upper Jurassic Reservoirs Late Kimmeridgian to Portlandian strata has been identified as a gas/condensate prone source rock of optimum maturity for wet gas generation, due to presence of terrestrial kerogens (Marathon 49/19-1 Geochemistry Report). Argillaceous limestones are present in thin beds as are well-cemented sandstones, and the frequency of these sequences increases shelfward (e.g. well 50/3-2) although thin sands remain present in basinal wells such as 48/24-3 and 48/25-1.

There is uncertainty in the depositional environment of Late Upper Jurassic low energy sediments as few studies have been carried out on spatial distribution of facies types. Cores and sidewall cores are rare due to operational limitations imposed by risks from overpressured zones, which also imposed a necessity to drill over-balanced and thus possibly incur formation damage. Little separation of shallow and deep resistivity curves is observed, suggesting that low porosity and permeability has resulted in low mud invasion – rare sidewall cores support this. However, “sweet spots” have been observed in some Upper Jurassic sands of well 49/19-1. The improved porosity may be due to the effect of formation overpressure that can reduce burial overburden and burial diagenesis in some of the thicker, upward fining, fluvial channel sands. Over-pressuring is likely to have been generated by sediment dewatering as a result of rapid sedimentation, burial and hydrocarbon expulsion from source rocks prior to and/or during Tertiary inversion.

While fractures are seen in sidewall cores from the Upper Jurassic, where carrier beds and fractures are absent, gas has accumulated in situ in micro-porosity associated with shale and porous sandstones. Fractures in shale are seen in Upper Jurassic core in 48/25-1 between 10,811 and 10,840 ft, up to 8 cm in width and cemented with secondary calcite fill. High pressure gas bleeds and flows of between 7 and 10 barrels of oil were discovered in this well, with connection gas kicks of up to 24%, apparently in non-reservoir sections – these are associated with natural fracture systems generated by pore pressure build-up and the resultant hydraulic fracturing. Varying competencies of thinly bedded shale, cemented sandstone and argillaceous and recrystallized limestone would have assisted this process. Calcite cementation may be of early origin and relating to dissolution and precipitation of carbonate minerals in interbedded limestones.

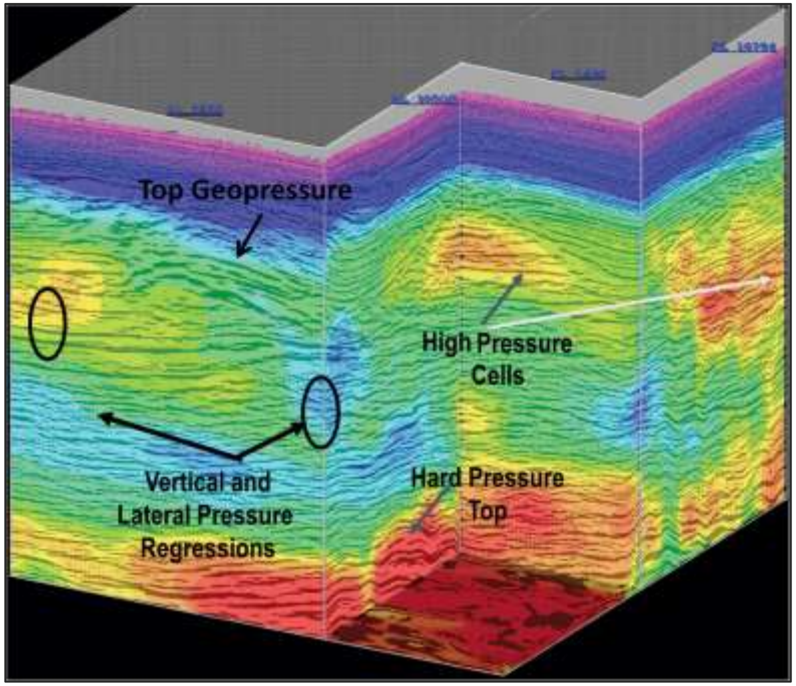


Figure 57: Highlights the use of 3D seismic velocities for geopressure prediction. Source Dutta et al 2021

An understanding of this diagenetic history will inform evaluation of preserved fracture porosity. Fractures resulting from over-pressuring generally have lower permeabilities than tectonically-derived fractures. They can, however, contribute porosity to low porosity formations. Here, tectonic-related fracturing may have occurred due to late Jurassic extensional faulting and Tertiary basin inversion.

WP2-O5: Regional geohazards study – Assessing the Containment Risk

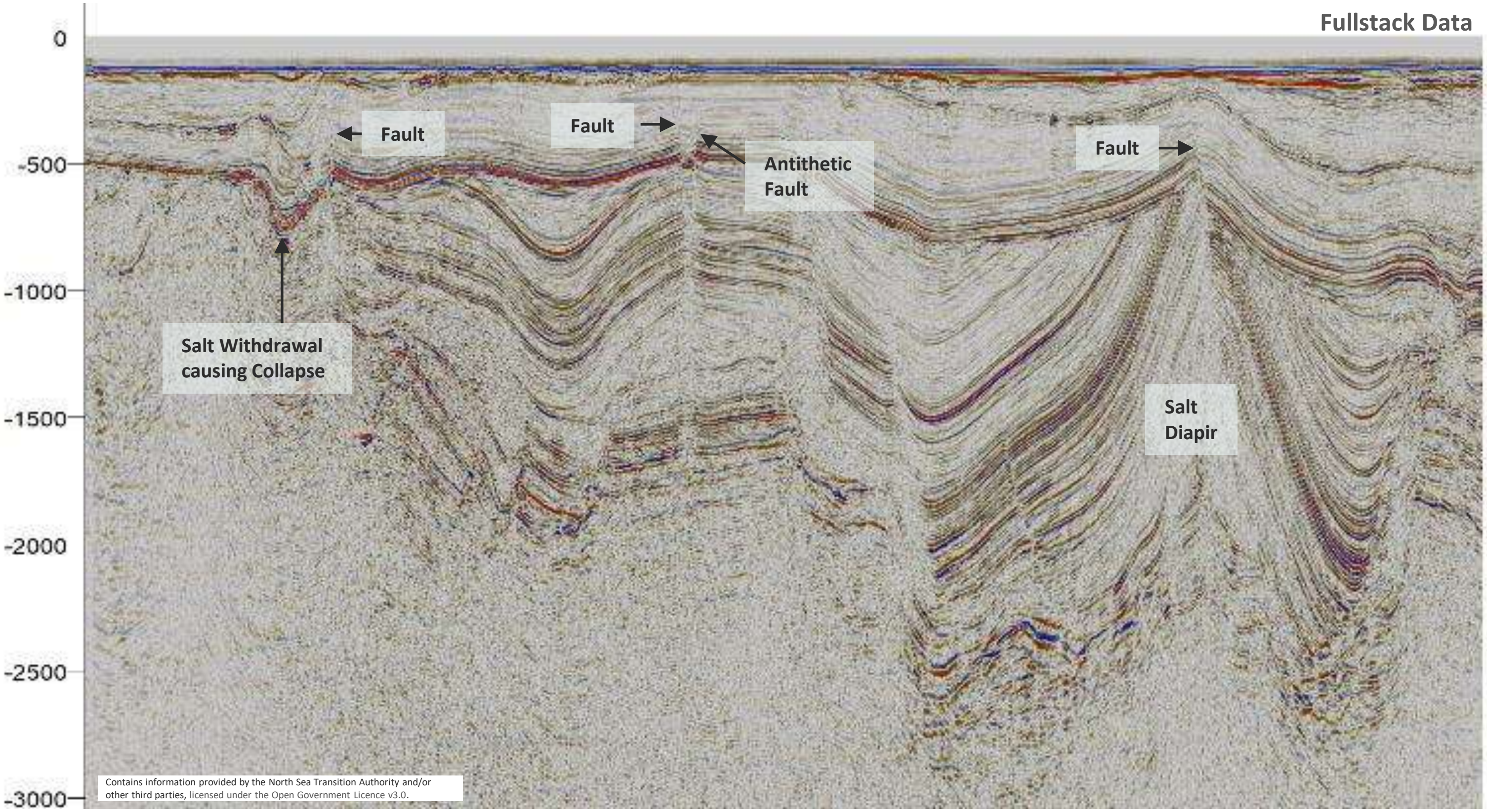


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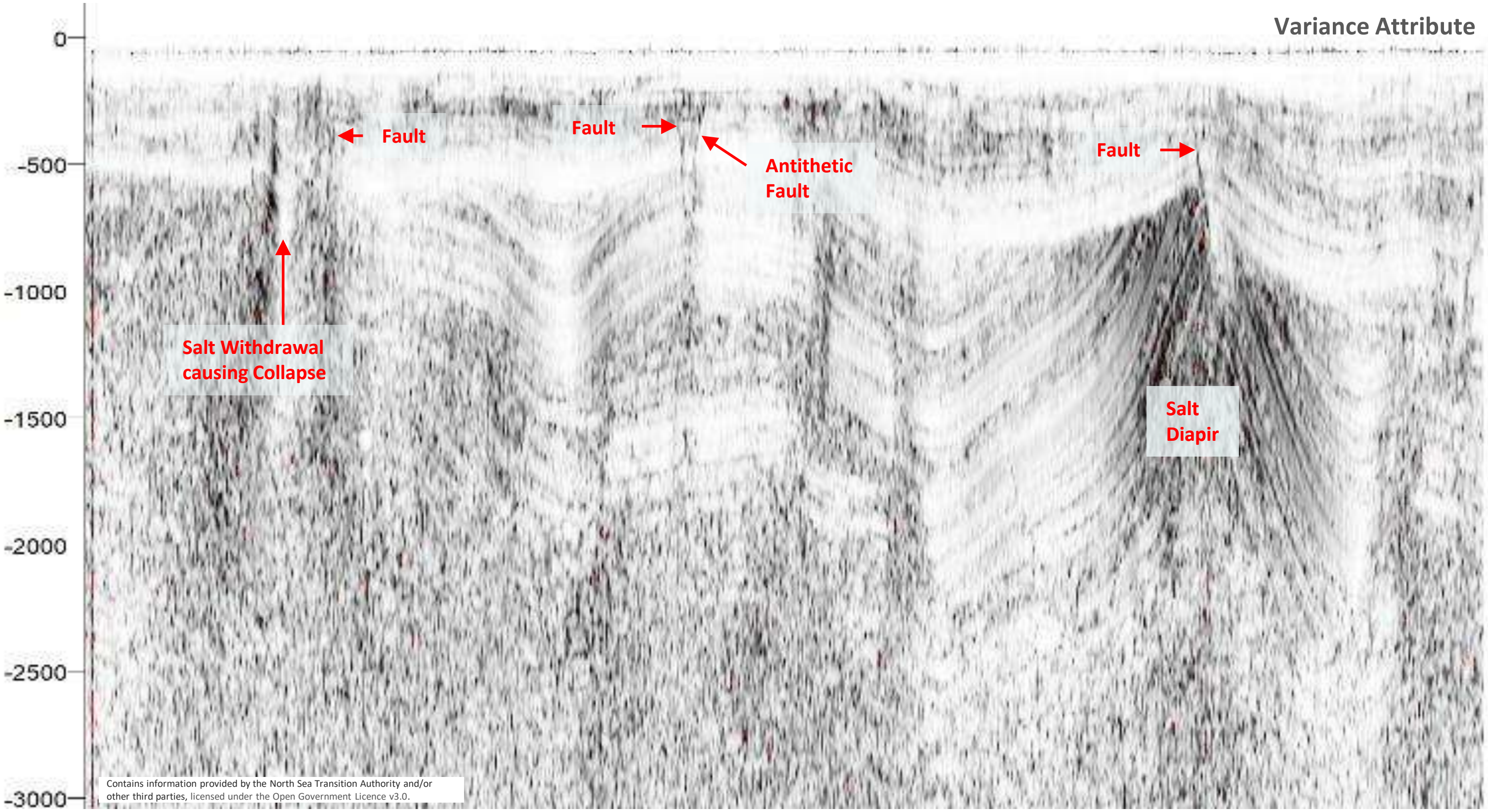
Figure 58: 2D seismic line highlighting Salt Diapirism in the South Celtic Sea and the containment risk posed by the faults in the area.

Halokinesis is clearly visible on the seismic line above, with the halite thickening to the North (right) and thinning to the South (left).
A salt diapir is visible on the North of this seismic line, this is causing disruption to the stratigraphy that directly overlies it.
From the 2D seismic line above there appears to be a large-scale fault that is terminating close to the seabed.
Movement of the halite is causing salt withdrawal on the South of the seismic line leading to collapse of the overlying stratigraphy.
It is essential to acquire, process and interpret a high-resolution 3D survey over this area to understand the containment risk posed by the salt tectonics in the South Celtic Sea.

WP2-O5: Regional geohazards study – Assessing the Containment Risk



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WP2-O5: Regional geohazards study – Assessing the Containment Risk

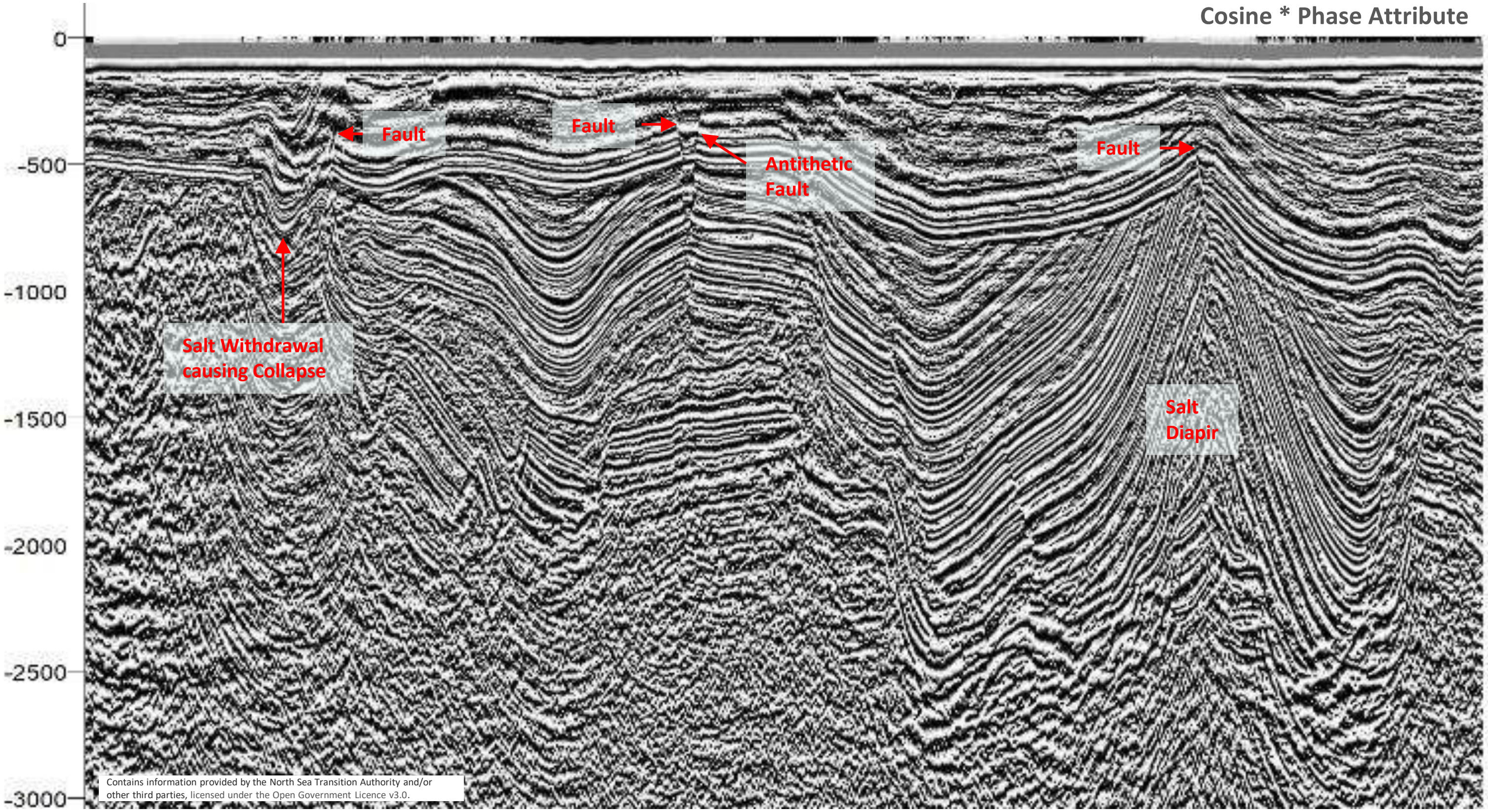

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Figure 60: 2D seismic line highlighting Salt Diapirism in the South Celtic Sea and the containment risk posed by the faults in the area.

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It is essential to acquire, process and interpret a high-resolution 3D survey over this area to understand the containment risk posed by the salt tectonics in the South Celtic Sea.

WP4-O5: Regional geohazards study – Assessing the Containment Risk

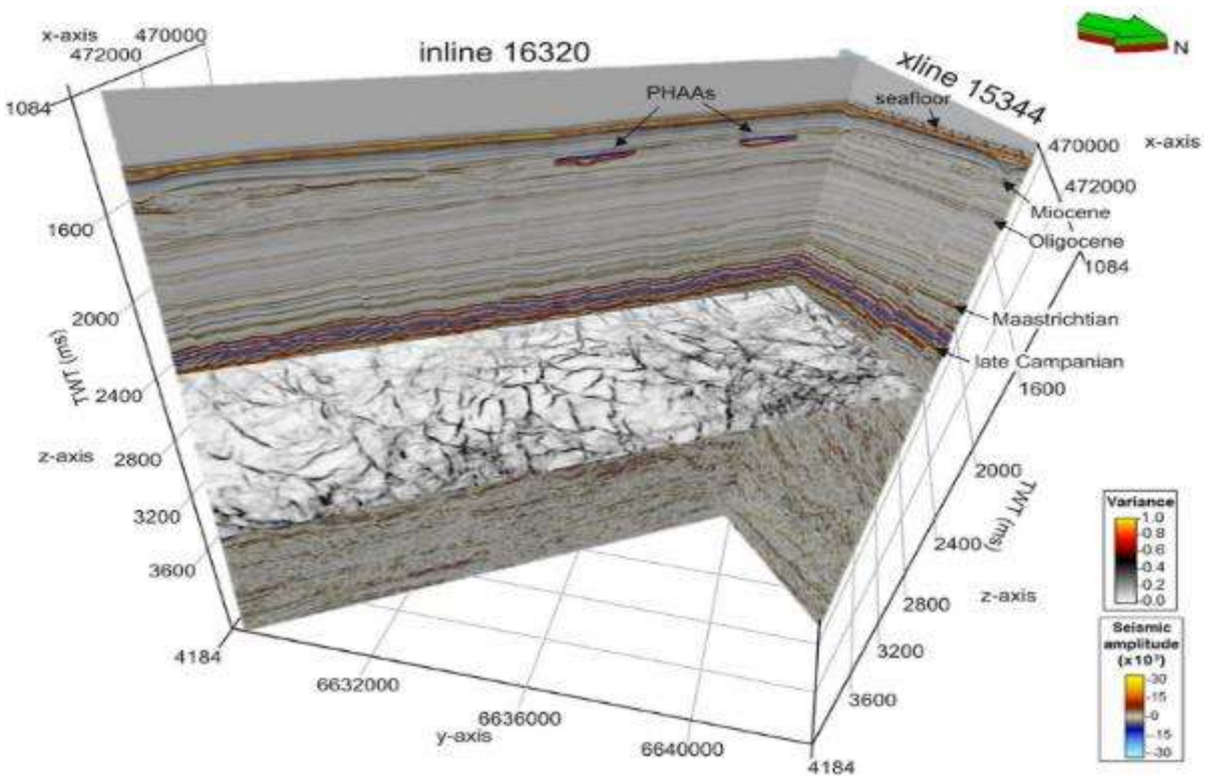


Figure 61: 3D seismic can be a useful tool to understand the fault trends and predict potential containment risks. Maduna et al 2023.

The quality of the geophysical datasets in the South Irish Sea and Celtic Sea are highly variable and there is a paucity of high-quality geotechnical and geophysical data over the areas identified that contain halite.

Once a potential Hydrogen storage area has been identified, high quality data must be acquired over the site-specific area.

This must include MBES bathymetry data, Multi-Channel Sparker, CPT’s, and a high resolution muti component 3D seismic survey.

To ensure the best possible survey is acquired an illumination study should be undertaken beforehand to understand what is the optimal azimuth for the survey to be acquired in to image the subsurface correctly.

Once acquired the seismic will need to be brought through modern processing flows including Q compensation, 3D SRME, FWI and iterations of velocity model building.

Finally, a comprehensive seismic interpretation will need to be completed and integrated with the other project disciplines.

WP3-O6 & WP4-06: Study of maritime traffic (shipping, fisheries, leisure), archaeological sites or other maritime/surface constraints

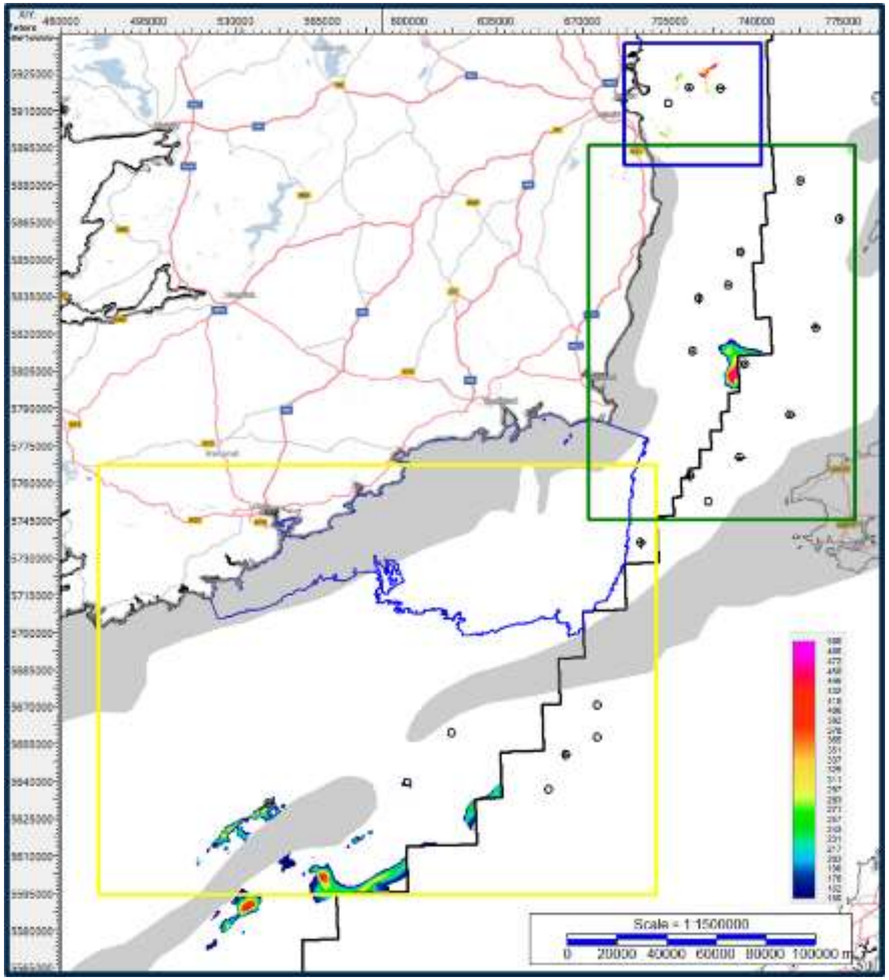


Figure 62 Map of areas with sufficient halite thickness, at a depth of 1,000m to 1,500m

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 62). GIS data relating to surface constraints for the development of an Offshore Green Hydrogen Production Facility (Fig 5) 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, 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 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 the Irish Sea and Celtic Sea Basins associated with offshore wind farms.

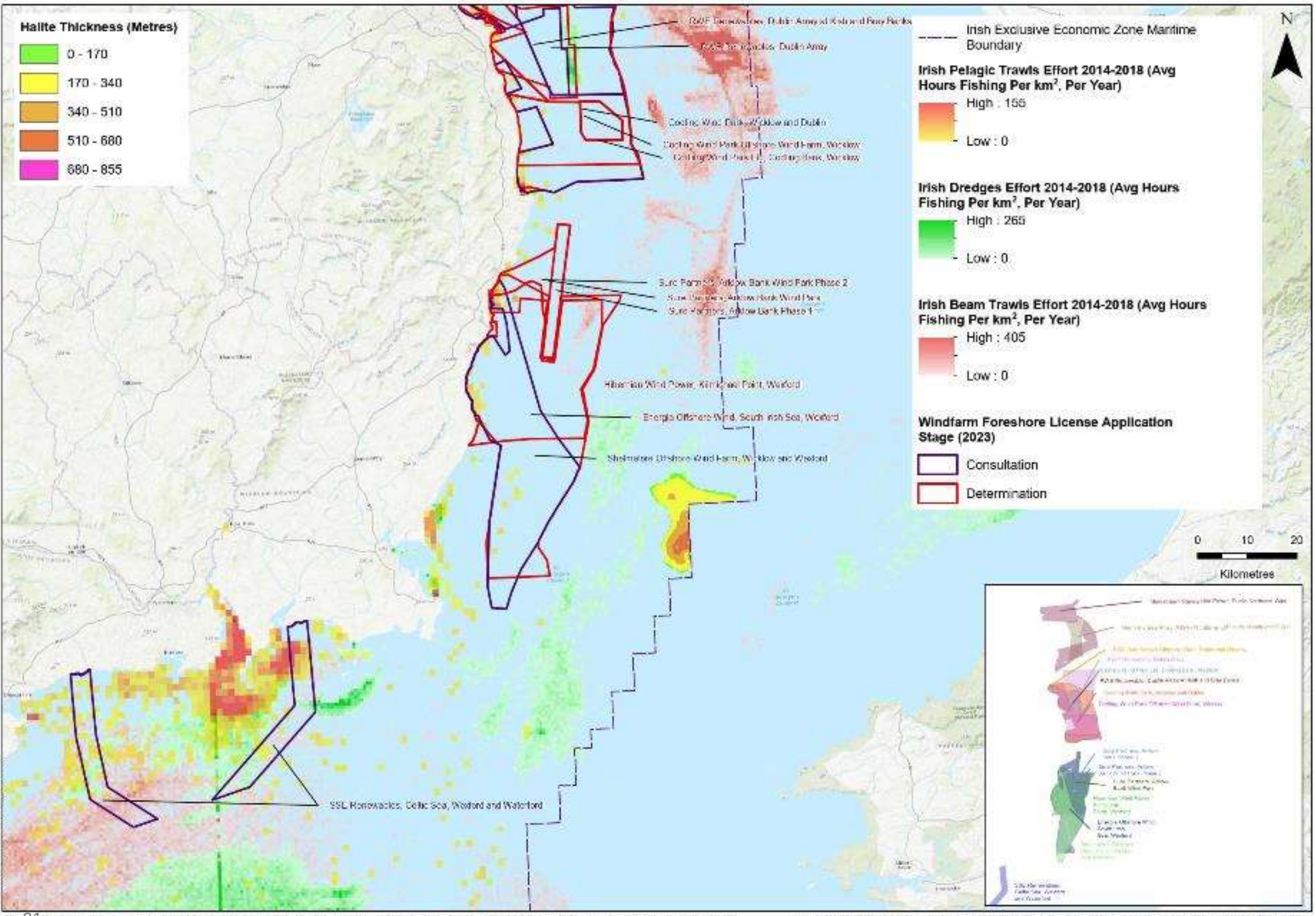
WP2-O6: Study of maritime traffic (shipping, fisheries, leisure), archaeological sites or other maritime/surface constraints

Maps 1a to 6 highlight constraints associated with fishing, shipwrecks, SAC, birds, dumping at sea, shipping, seabed substrate and telecommunications cables within the Irish Sea Basin Area. The areas where halite is of sufficient thickness and depth for solution mining of salt caverns are shown. There are no shipwrecks in the area of interest in the Irish Sea to constrain the anchoring of floating offshore structures, although coarse seabed substrate may hinder anchoring. The EXA North and South telecommunications cable runs through the area of interest which will also constrain the seabed anchoring for offshore floating platforms. The area of interest is removed from any intense fishing activity, seabird breeding areas and SACs. However, there is a high density of shipping passing either side of the area of interest. 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, though there is already successful implementation of traffic separation in the area.

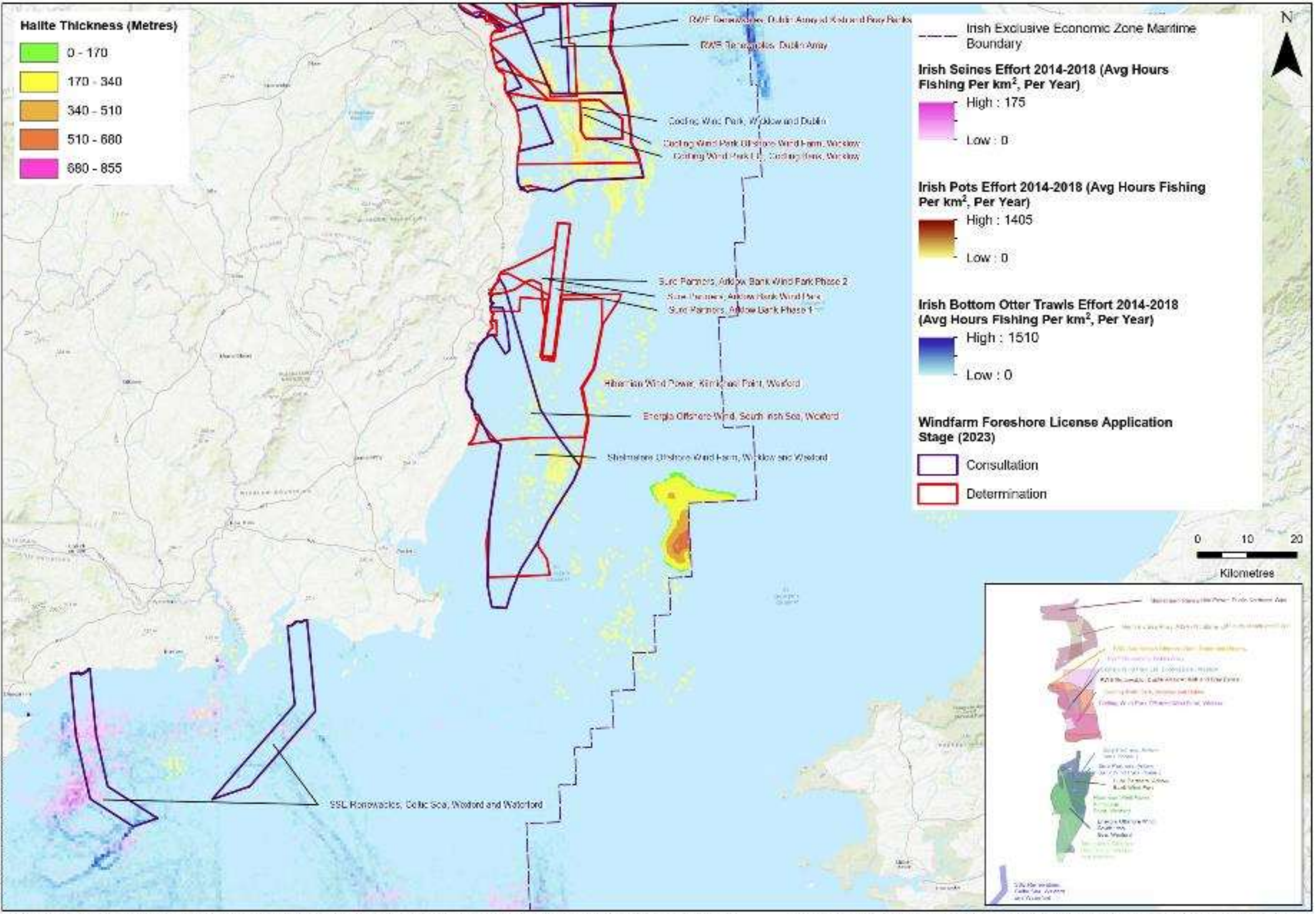
Maps 7a to 12 highlight constraints associated with fishing, shipwrecks, SAC, birds, dumping at sea, shipping, seabed substrate and telecommunications cables within the Celtic Sea Basin Area. The areas where halite is of sufficient thickness and depth for solution mining of salt caverns are shown. The large, relatively shallow, Labadie Bank sand bank is adjacent to identified an area of potential salt cavern development and is an attractive location for fixed bottom foundation structures for green hydrogen production from offshore wind. The area has some fishing activity. The seabed substrate is hard packed, semi-consolidated and heavily scoured, indicating high currents which will constrain the siting of subsea foundations. The areas of interests are well removed from SACs. There are no shipwrecks in the areas of interest. However, the area of interest is traversed by a submarine communication cable. There are no major shipping lanes passing through the areas of interest.

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 fishing activity, telecommunications cables and seabed conditions including high currents. This is reflected in the following Tables 3 to 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.

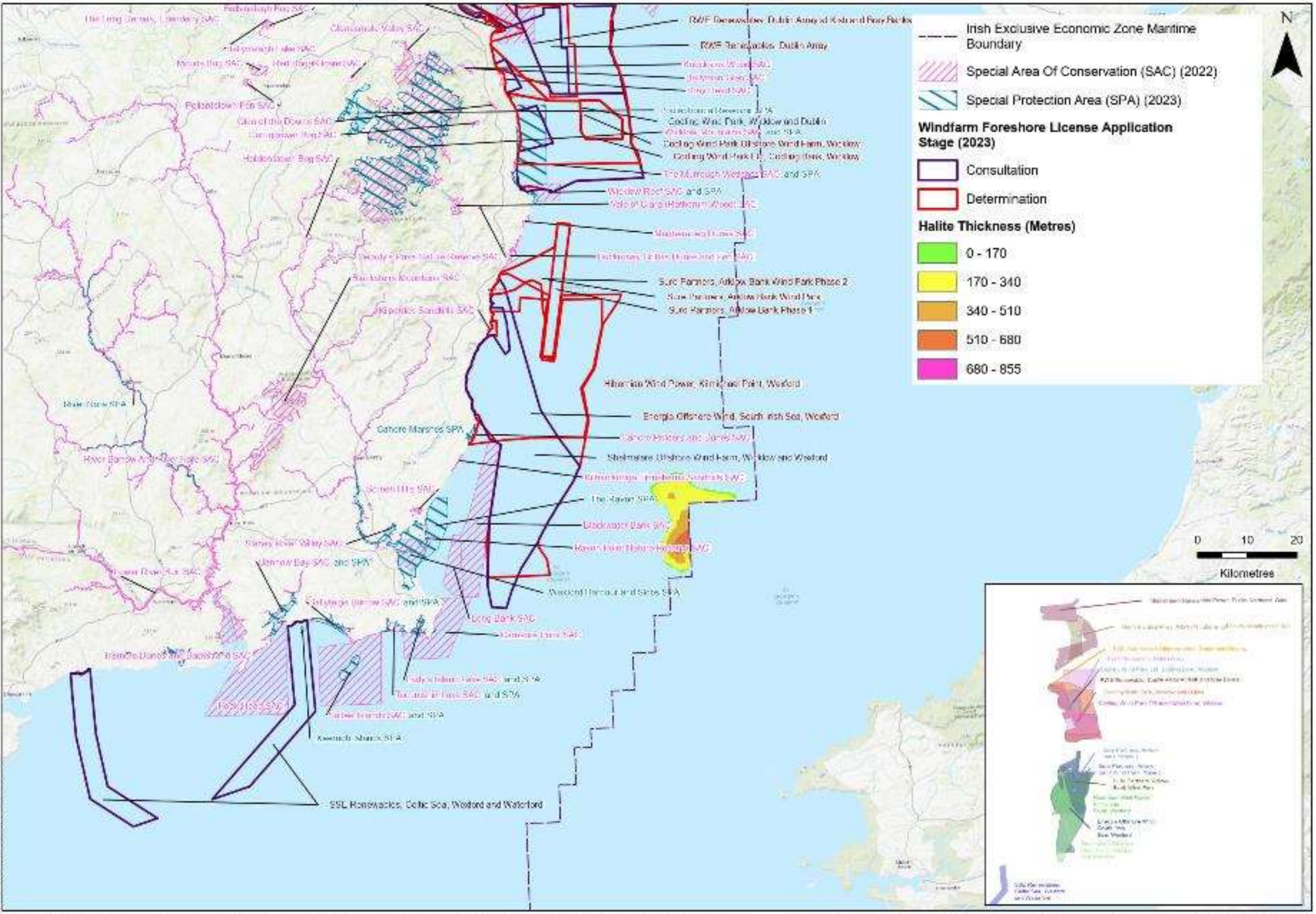
Constraints Map 1a – Fishing Effort – Pelagic, Dredge & Beam



Constraints Map 1b – Fishing Effort – Seines, Pots & Otter

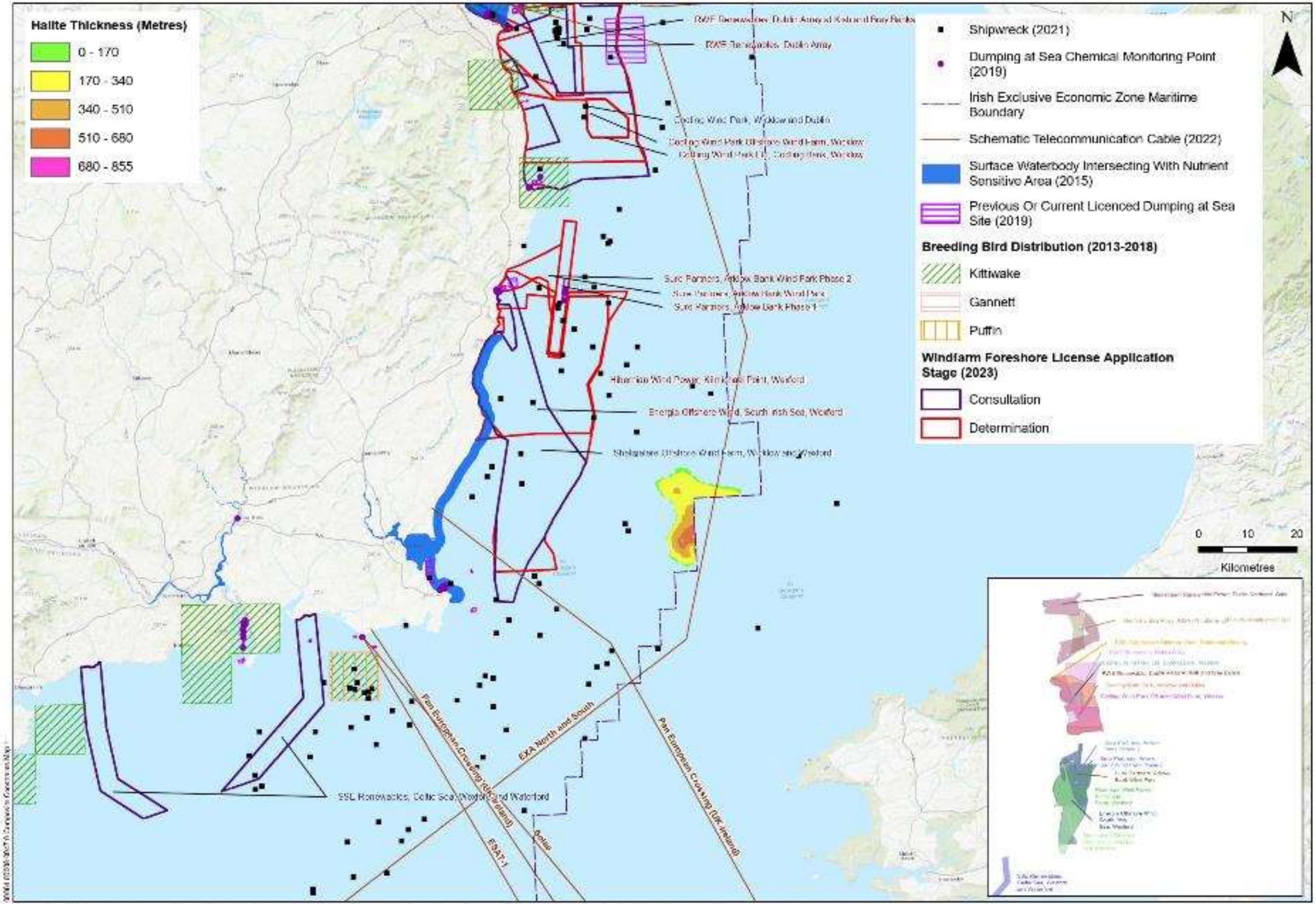


Constraints Map 2 – SAC / SPA



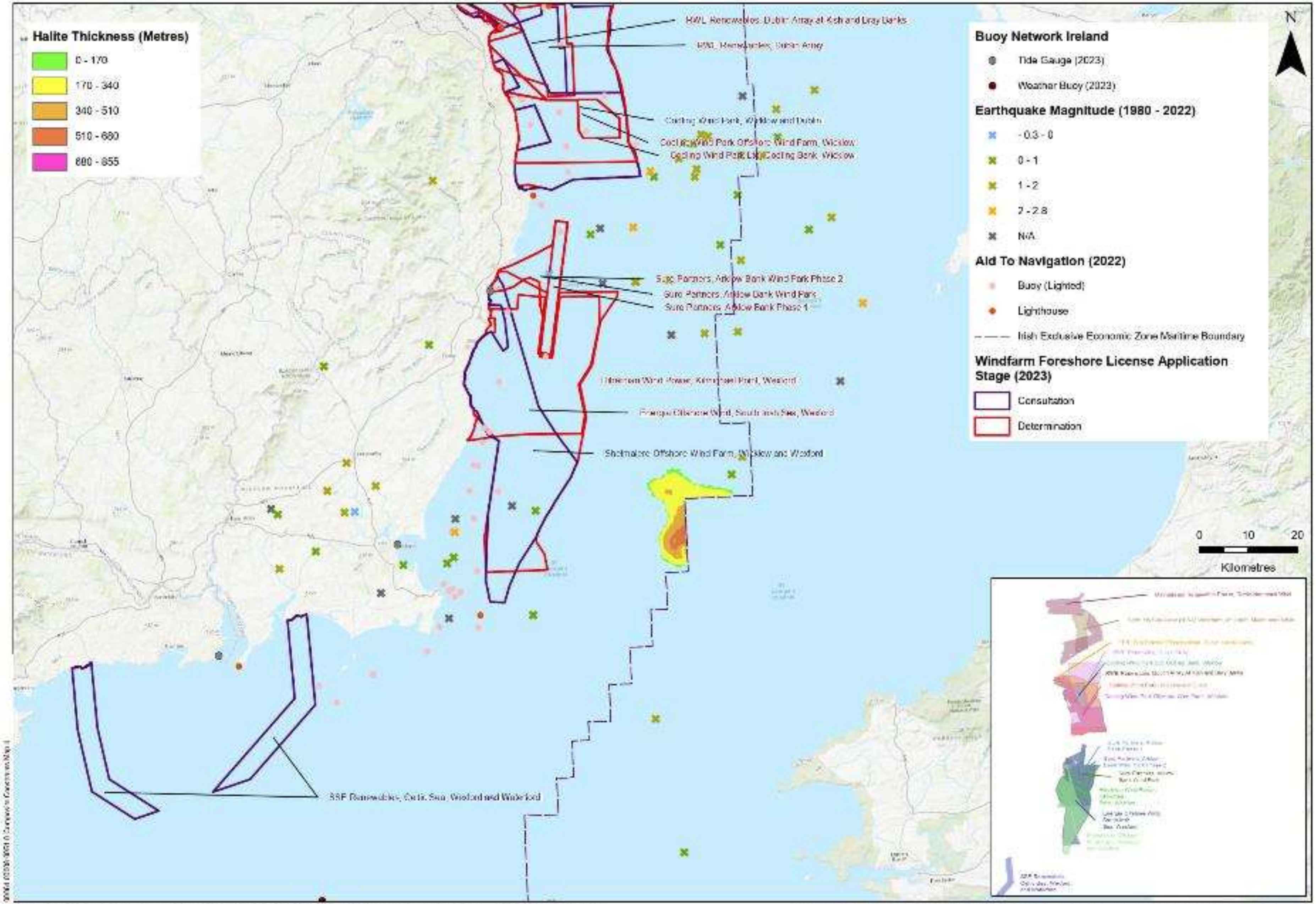
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community. Data sourced from the National Parks and Wildlife Service, Department of Arts, Heritage, Regional, Rural and Gaeltacht Affairs, previously of the Department of Housing, Local Government and Heritage of the Irish government. Data from Ireland's Marine Atlas at http://atlas.marine.ie/, [2024-02-[illegible]]

Constraints Map 3 – Shipwrecks, Telecoms, Dumping at Sea, Breeding Bird Distribution

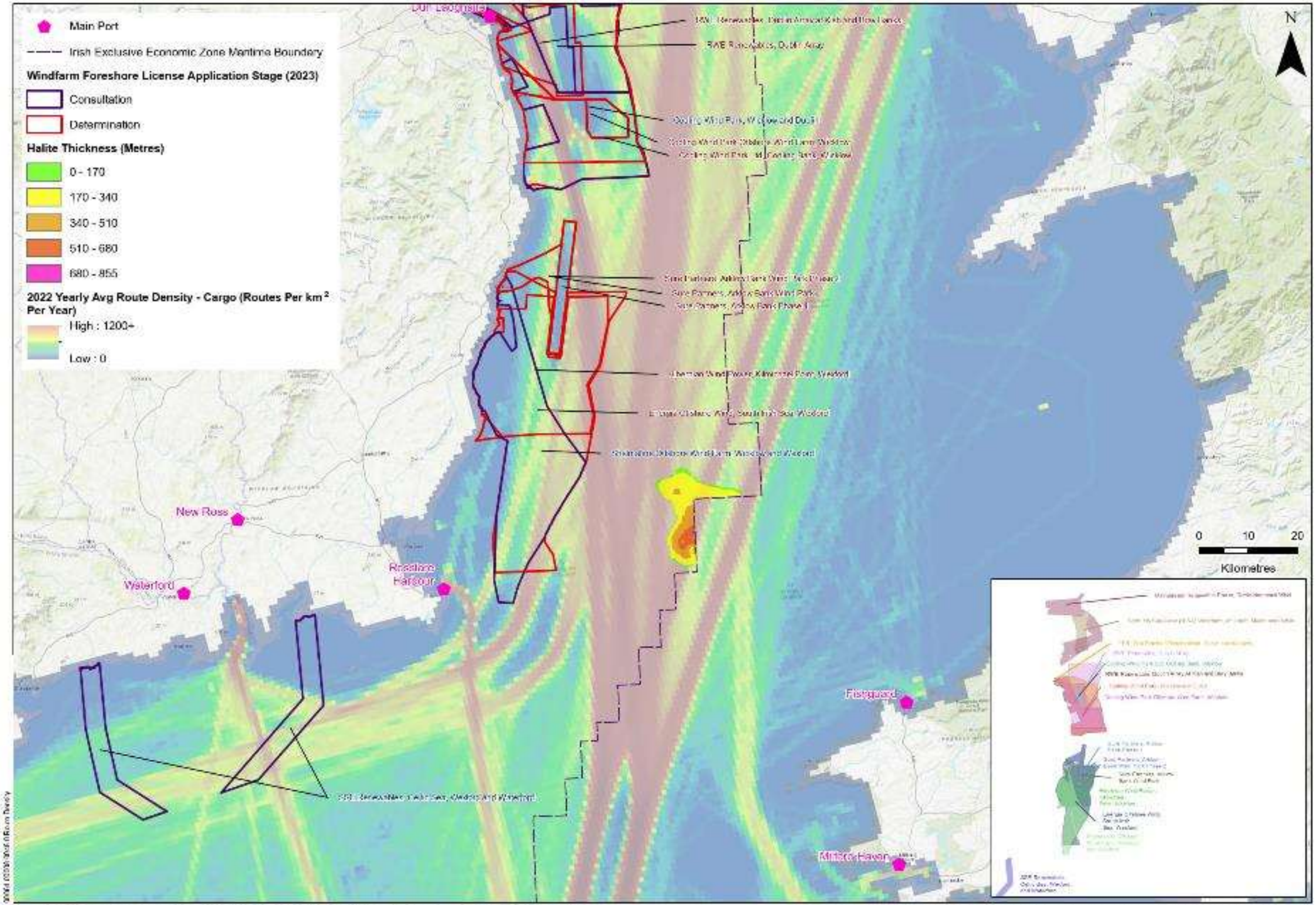


Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community. Contains Irish Public Sector Data (Geological Survey Ireland; Marine Institute). Data sourced from Integrated Mapping FOr the Sustainable Development of Ireland's Marine Resource (INFOMAR) and the Irish National Seabed Survey (INSS). [illegible] Department of Housing, Local Government, and Heritage of the Irish government. Data from Ireland's Marine Atlas at http://atlas.marine.ie/. [2024-02-21].

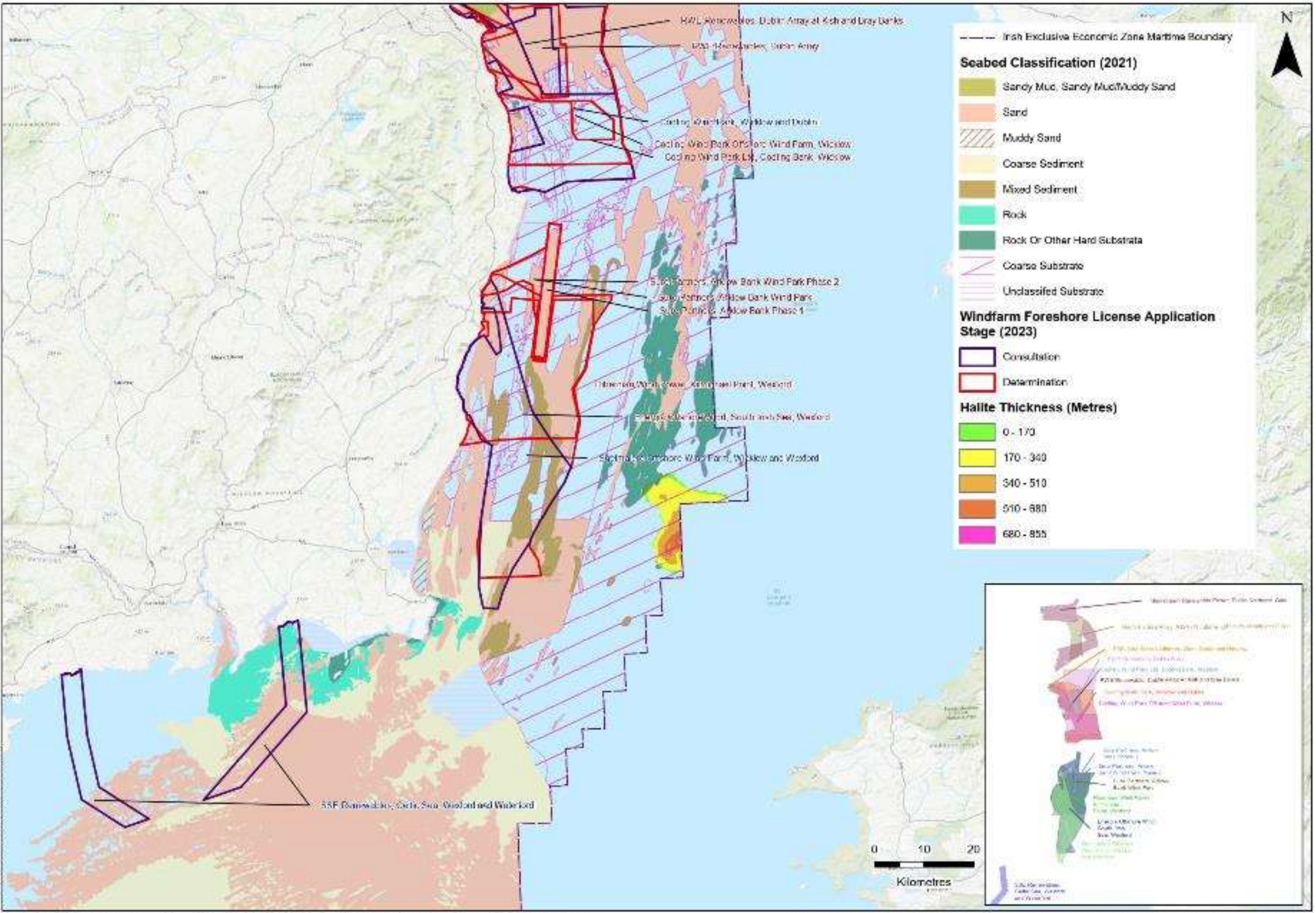
Constraints Map 4 – Marine Buoys, Historic Earthquakes



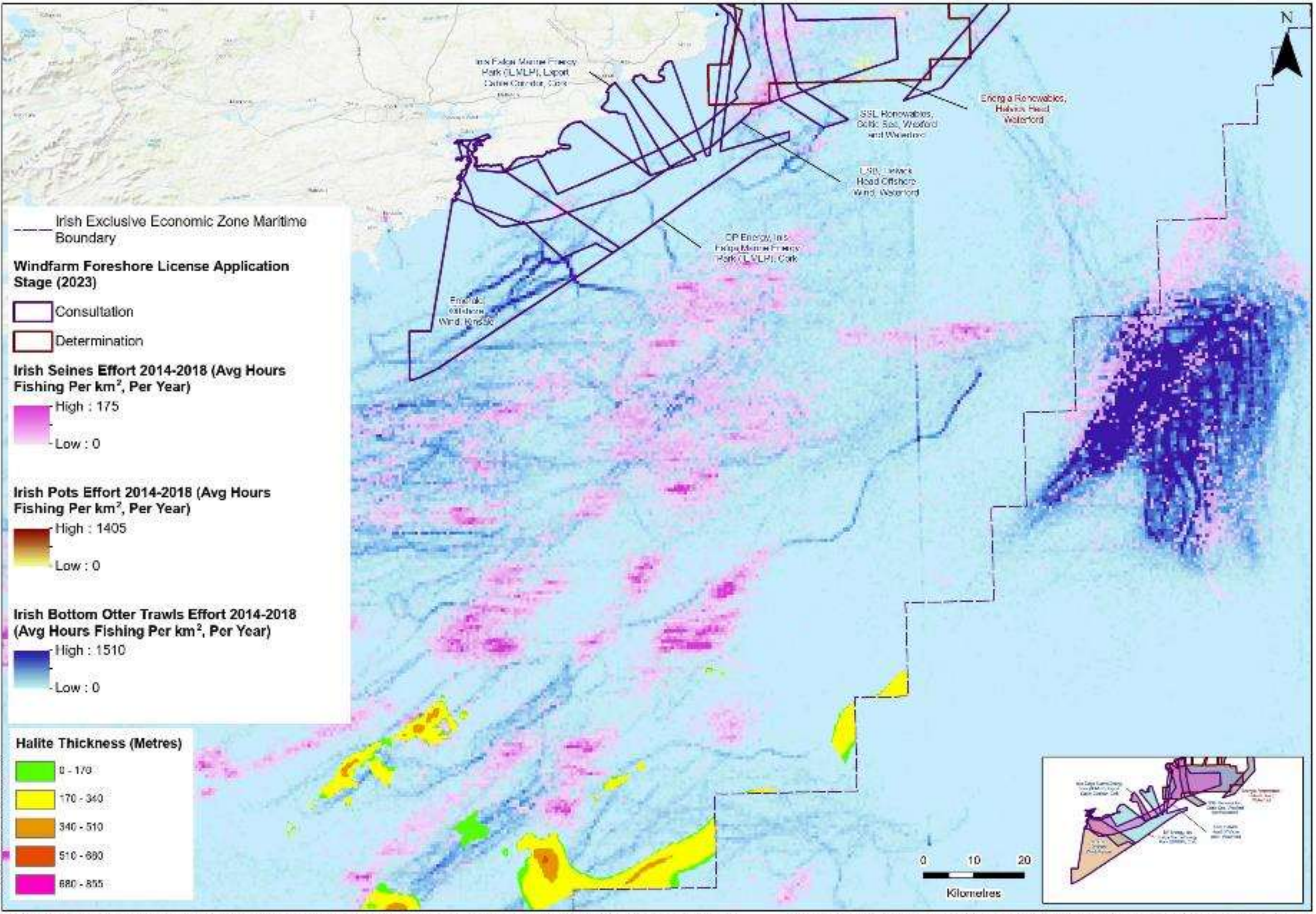
Constraints Map 5 – Shipping - All Types



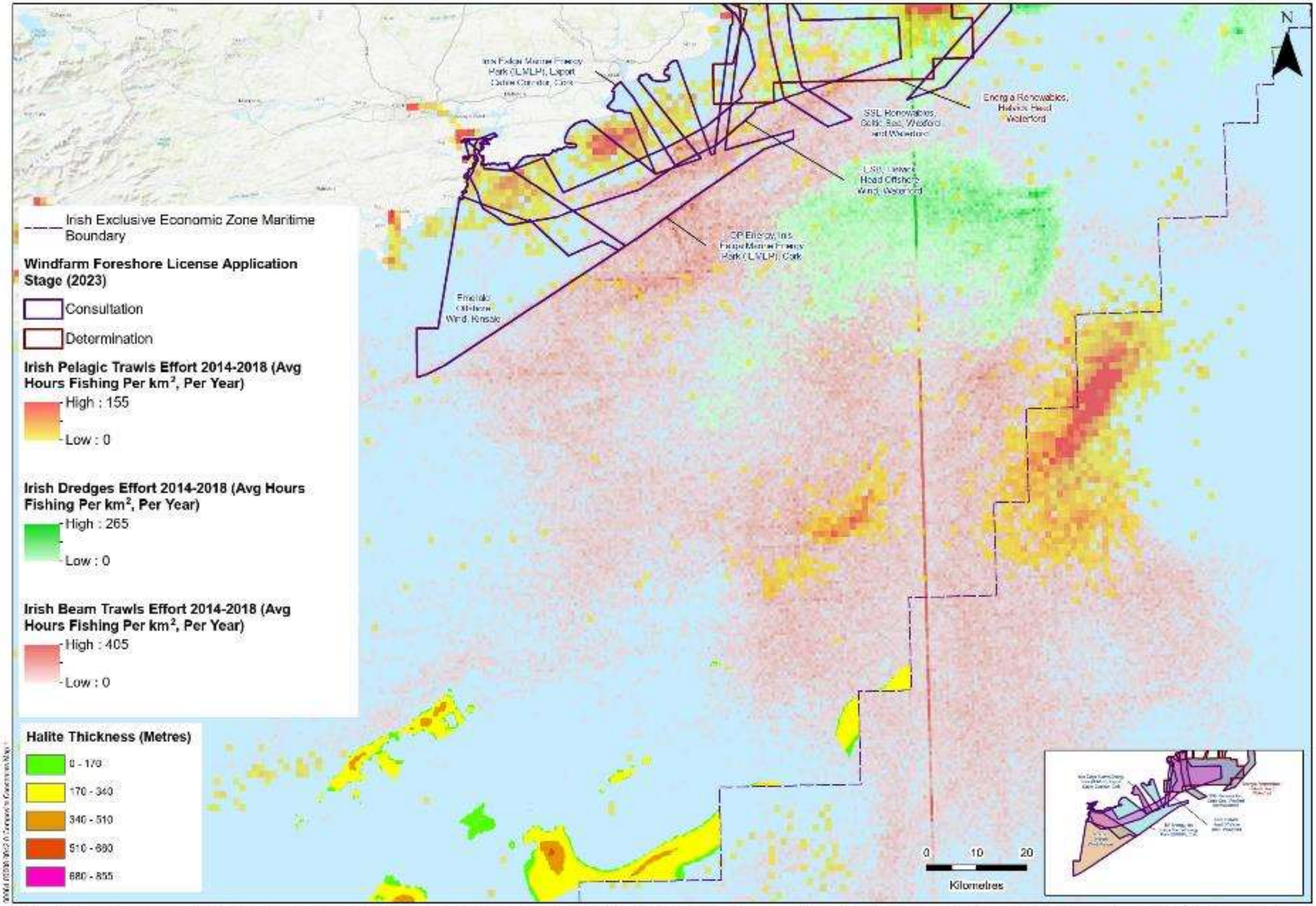
Constraints Map 6 – Seabed Substrate



Constraints Map 7a – Fishing Effort – Seines, Pots, Bottom Otter

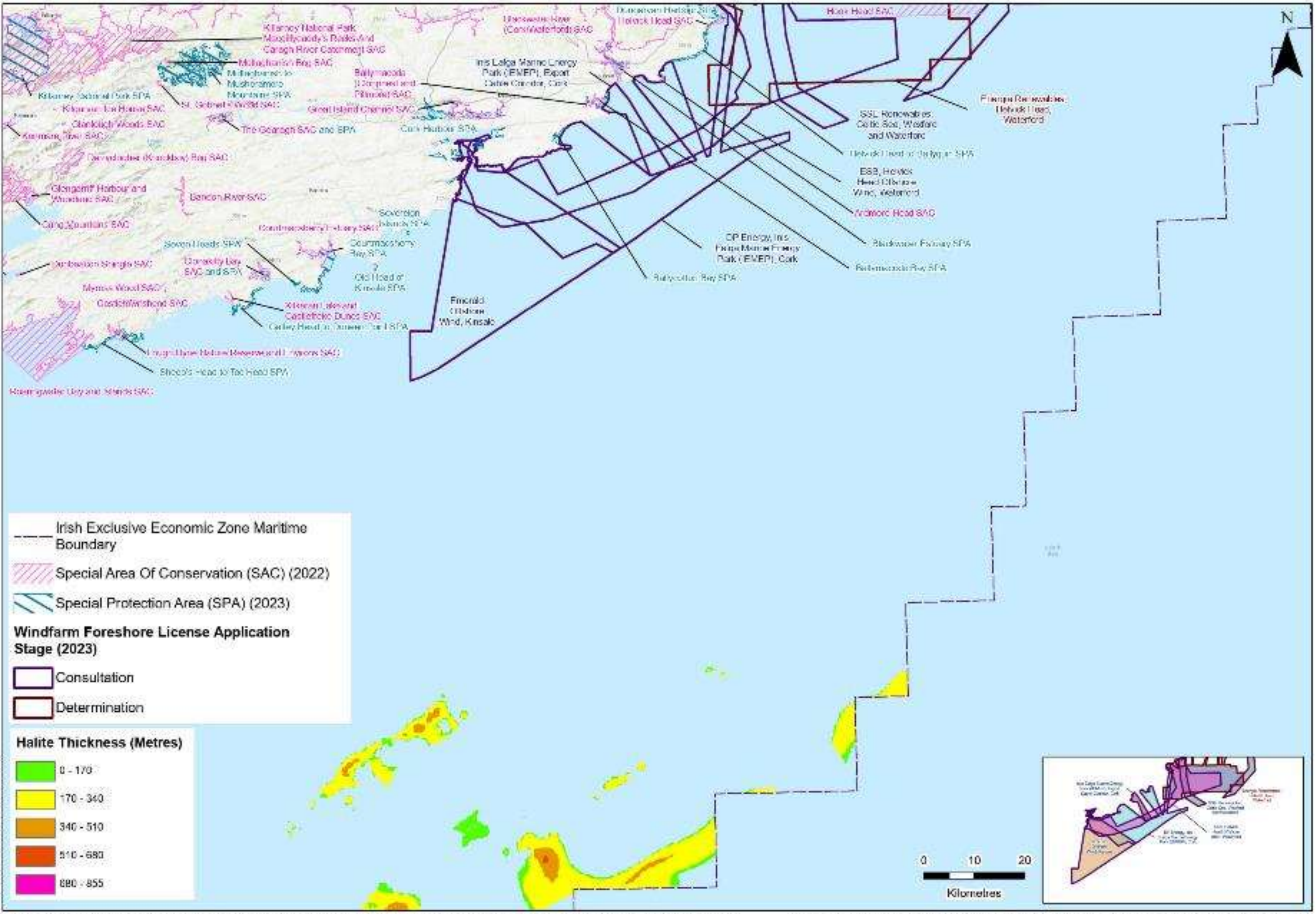


Constraints Map 7b – Fishing Effort – Pelagic, Dredge & Beam



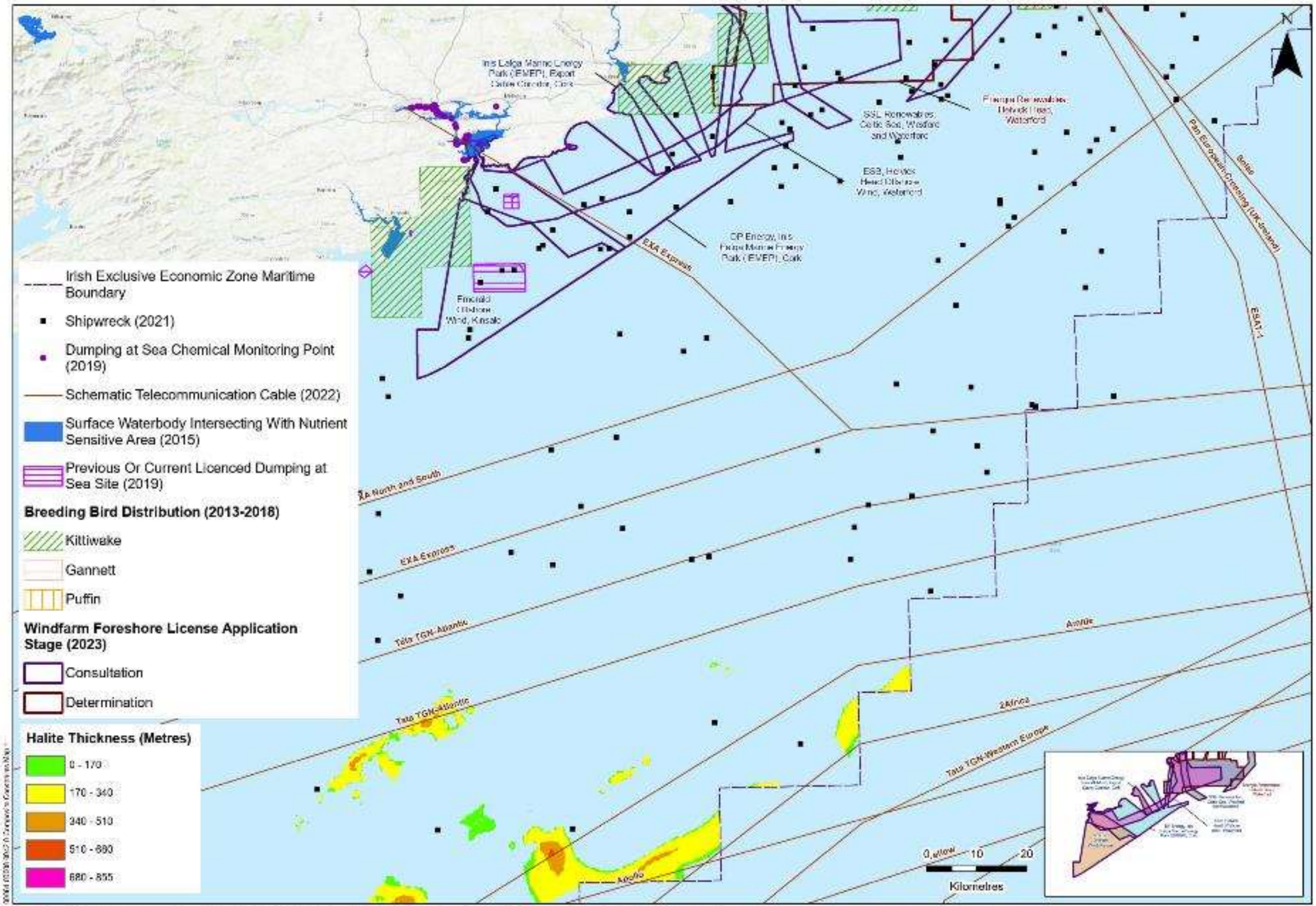
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community. Data sourced from Marine Institute of Ireland. Fishing Activity theme accessed through Ireland's Marine Atlas at http://atlas.marine.ie

Constraints Map 8 – SAC's / SPA's



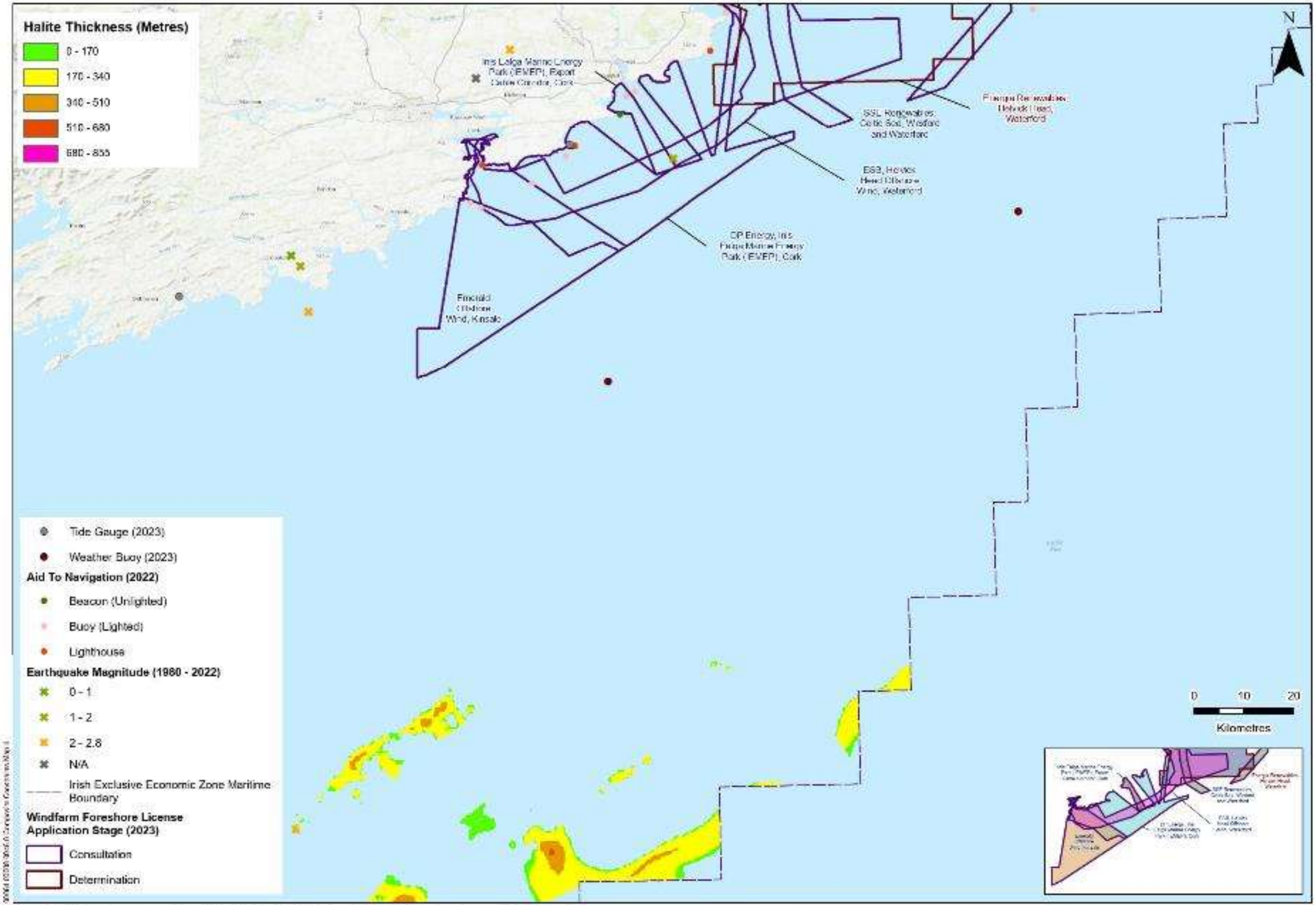
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community. Data sourced from the National Parks and Wildlife Service, Department of Arts, Heritage, Regional, Rural and Gaeltacht Affairs, previously of the Department of Housing, Local Government and Heritage of the Irish government.

Constraints Map 9 – Shipwrecks, Telecoms, Dumping at Sea, Breeding Bird Distribution



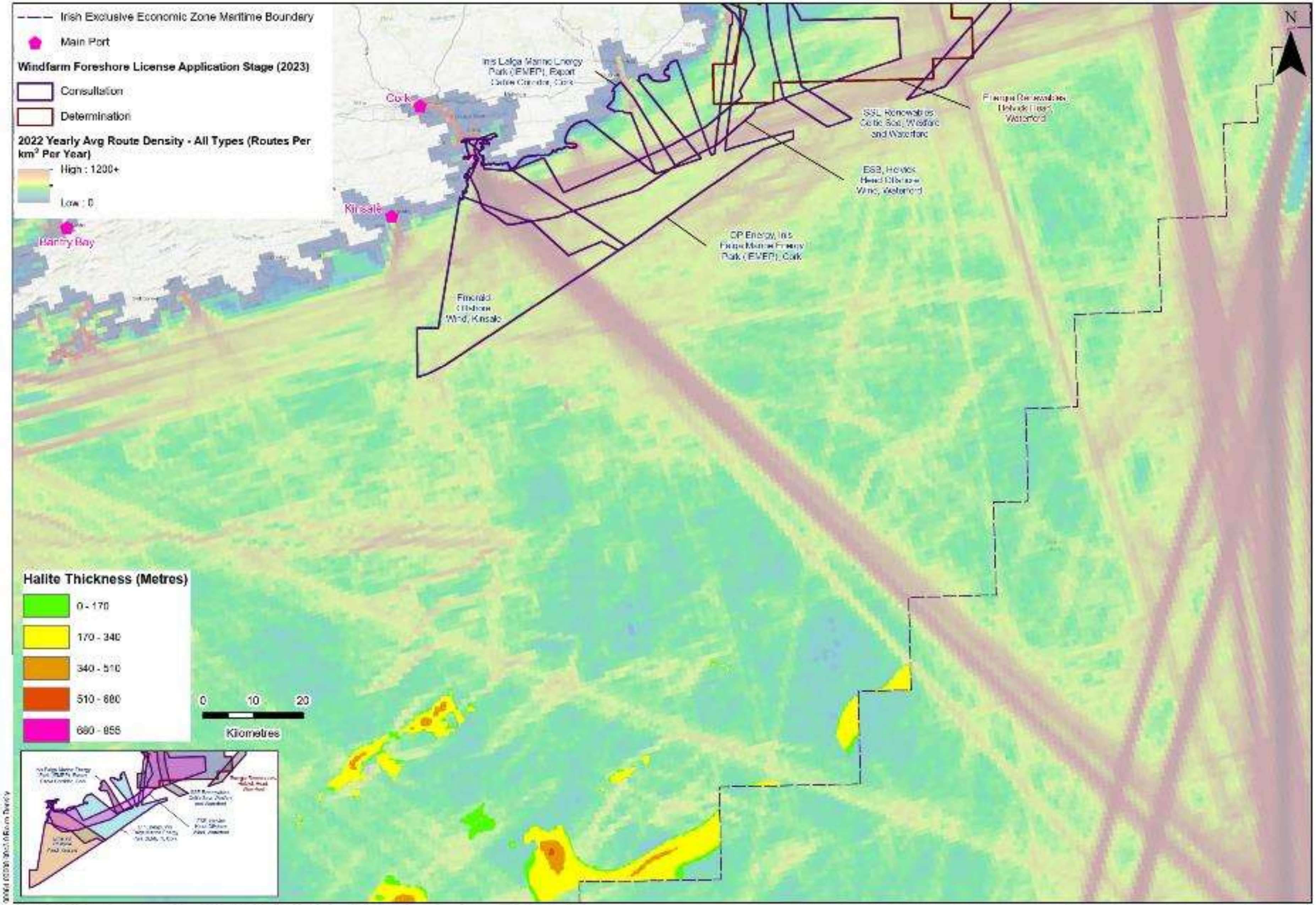
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community. Contains Irish Public Sector Data (Geological Survey Ireland; Marine Institute). Data sourced from: Integrated Mapping FOr the Sustainable Development of Ireland's Marine Resource (INFOMAR) and the Irish National Seabed Survey (INSS) [illegible] Heritage, Regional, Rural and Gaeltacht Affairs, previously of the Department of Housing, Local Government and Heritage of the Irish government.

Constraints Map 10 – Marine Buoys, Historic Earthquakes



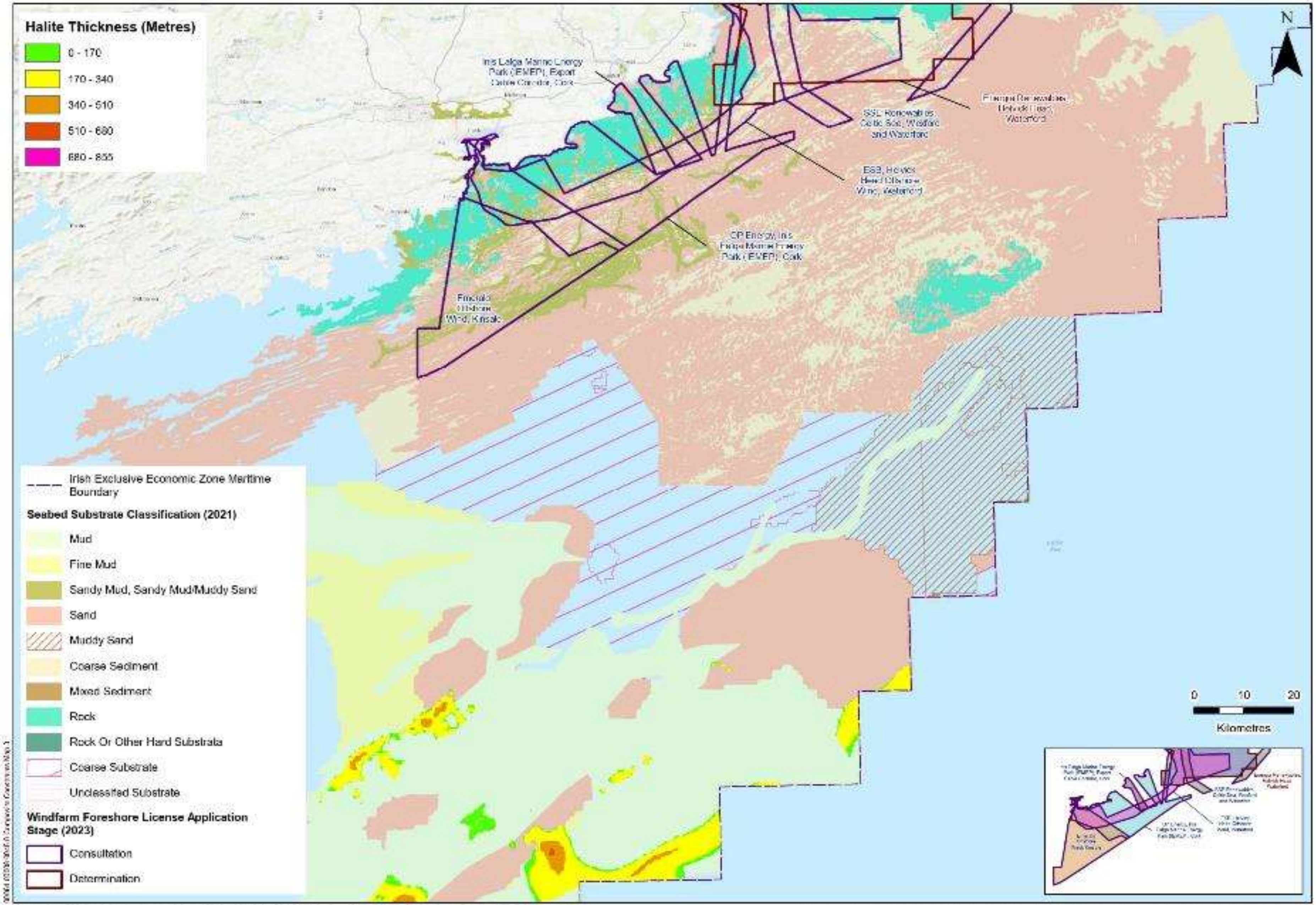
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community. Data sources: From the Commissioners of Irish Lights, the Irish National Seismic Network, [illegible]

Constraints Map 11 – Shipping – All Types



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community. Data sourced from EMODnet - Human Activities and European Maritime Safety Agency (EMSA). [illegible]

Constraints Map 12 – Seabed Substrate



WP3-07 & WP4-07 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 13).

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

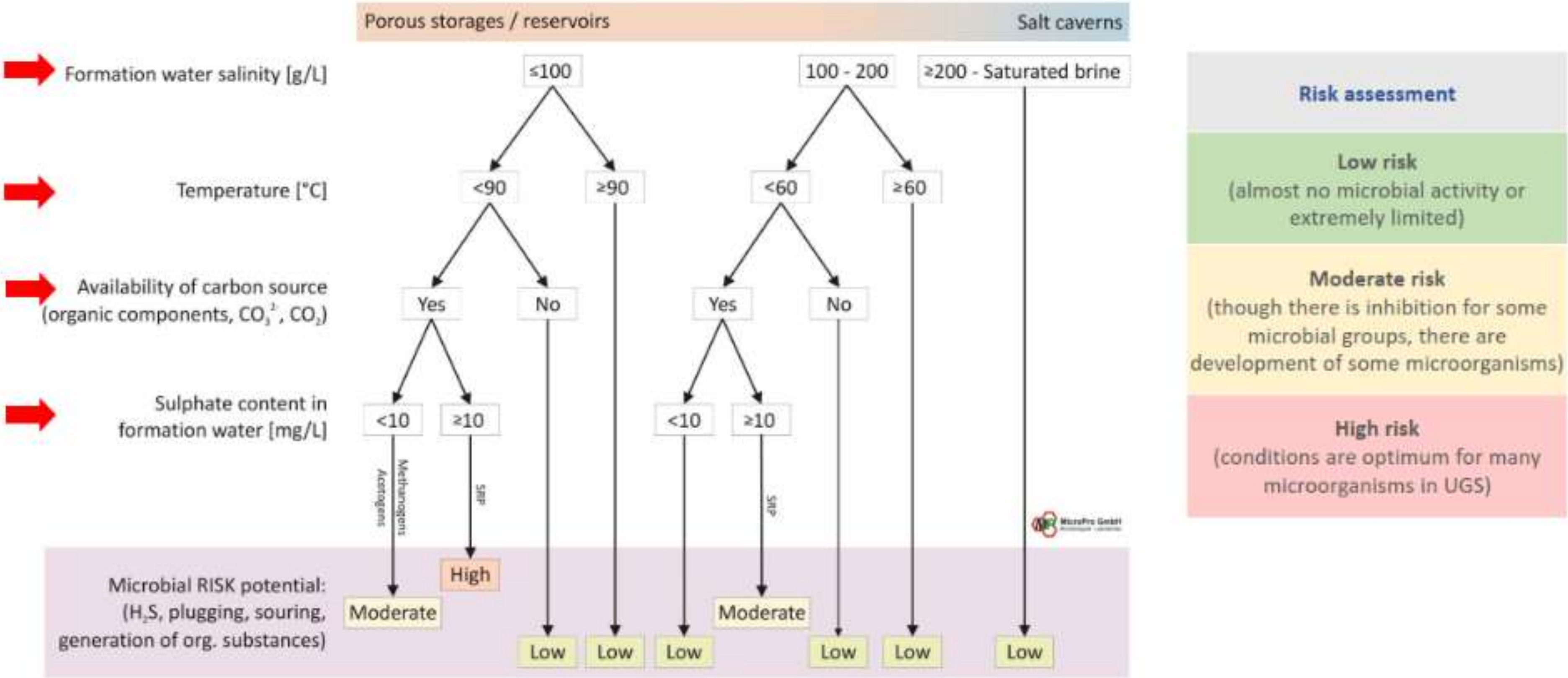


Figure 63 Simplified chart for the assessment of microbial risks (Hystories Project 2023)

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

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

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 Irish Sea Basin is a NE-SW trending graben located between the Kish bank Basin and the St George's Channel and Cardigan Basin to the SE. (Shannon et al, 2001). Water depths are less than 100m. Exploration wells in these basins have encountered salt in the Triassic Mercia Mudstone Group. There is evidence of salt migration in the St Georges Channel Basin and a massive salt wall (55kms long, 3km wide) has developed along the St. George's Fault. The new seismic interpretation from this study identified salt movement, particularly in the UK sector with the development of thick salt pillows, ideal for salt cavern solution. The ENE-WSW trending North and South Celtic Sea Basins lie in relatively shallow water (100m to 200m). A narrow belt of salt is encountered in wells at the southern margin of the North Celtic Sea while thick Triassic salt is encountered in the South Celtic Sea Basin in the UK sector (Naylor and Shannon 2011).

Based on seismic interpretation of legacy oil and gas data, maps of the Irish Sea and Celtic Sea Basins have been produced showing the areas where the halite formations occur at depths greater than 1,000m and are more than 150m thick, the optimum depth and thickness for salt cavern storage of gas. In a zone of interest beneath the Labadie Bank more than 100 standard size salt caverns can be developed for hydrogen storage. This is equivalent to approximately 10 TWh_{H2}.

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 Irish Sea and Celtic Sea Basins is extensive in localised areas 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 shallow gas, near surface glacial channel complexes, tectonically active faults and protruding Cretaceous rocks at or near the seafloor. 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 Irish Sea and Celtic Sea Basins.
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 Irish Sea and Celtic Sea Basin is sufficient to meet 100% of the predicted Irish storage requirements in 2050.
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 Irish Sea and Celtic Sea areas.
6. The regulatory risk to the development of a hydrogen storage project offshore Ireland 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 Ireland 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 Ireland.
4. Support the development of a regional hydrogen cluster or hub in the SE Area, to include a joint UK/Irish strategy to integrate all available datasets and agree extent of the salt.
5. Acquire additional high quality geophysical and geotechnical information to high grade areas for infrastructure development, to include high-definition 3D to define salt extent and highlight subsurface architecture and reduce containment risk.
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.

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