GARAH GeoERA GEO-ENERGY

Geological Analysis and Resource Assessment of selected Hydrocarbon systems

Deliverable 1.6

Final Project Report

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EXECUTIVE REPORT SUMMARY

The main achievement of the GARAH project is a harmonized, scientifically based, geological analysis and assessment of the conventional and unconventional offshore hydrocarbon resources (Geological Analysis and Resource Assessment of selected Hydrocarbon systems (GARAH) – GeoERA). This contributes to sustainable and affordable energy resources and energy security. It also supports EU member states to address climate commitments and mitigation options on the path to net-zero GHG emissions. The analysis and assessment of hydrocarbons has focused on two areas:

(i) in Europe's major petroleum province – the North Sea a "Geological analysis and resource assessment of North Sea petroleum systems", Work Package 2.

This research includes the assessment of conventional and unconventional oil and gas resources in the most important hydrocarbon basin in Europe. The result enables the remaining resource to be better understood and managed and has identified options for multiple and alternative uses of the subsurface as producing conventional fields come off-line.

The assessment of the conventional resources is made quantitatively based on a harmonization of the national reserve and resource estimations for each country, and qualitatively following a play-based approach. In addition, the assessment of the unconventional resources is made following a Monte Carlo simulation approach known as the "EUOGA method".

The harmonization of the national conventional assessments shows that more than 14 billion cubic meter oil equivalents (o.e.) have been produced in the North Sea and that significant additional reserves and resources remain. The reserves amount to at least 2,900 x 10^6 m^3 o.e. and the contingent resources are estimated to be at least 1,500 x 10^6 m^3 Following the national agencies, it is estimated that the prospective *yet-to-find* resources are 1,900 x 10^6 m^3 o.e.

The qualitative assessment of the North Sea has resulted in the reconstruction of a total of 13 major conventional play maps that represent the first North Sea-wide mapping of the where hydrocarbon accumulations are likely to be located. The maps thus represent a major step in planning of the future use of the North Sea subsurface both in terms of licences rounds, and for alternative use and risking. The assessment of the unconventional *yet-to-find* resource potential show that there is a significant resource also within the unconventional plays. Ten potentially prolific oil plays in the North Sea have been identified with a *yet-to-find* resource potential (P50) of 6,648 x 10^6 m^3 oil and nine gas plays have a gas *yet-to-find* resource potential of 9,344 x 10^9 m^3 gas. This estimate includes the resource estimated for a 100 m thick Upper Jurassic - lowermost Cretaceous shale unit and thus excludes the resource base calculated in the >1 km thick shale interval in UK and Norway. The oil resource is mostly located in the Upper Jurassic-lowermost Cretaceous shales in the UK and Norwegian part of the North Sea owing to its vast regional coverage and thickness. The gas resource is dually distributed in the Carboniferous Bowland equivalent shales located in the Netherlands, and in the UK offshore area and in Jurassic shales in UK and in Norway.

Conventional and unconventional resources were additionally assessed in a 3D model. The basin and petroleum system model (BPSM) covers the Danish, German and Dutch Central Graben area. Based on the thermal history, maturation, generation, expulsion, and migration, the accumulation of hydrocarbons was calculated. Hydrocarbon generation from the three main source rocks of the study area were included in the model: the Upper Farsund marine source; the Middle Jurassic coals; and the Lower Jurassic Posidonia shale. Even though, some simplifications (for example, the heterogeneous permeability distribution within the Chalk Group) had to be made in such a large model, the BPSM results show reasonable migration flow paths from source areas to structural accumulations and the overall distribution of the known accumulations could be reproduced. The model serves as a pilot study and the harmonized datasets can be used in the future to act as a first-step 3D model to further assess the sedimentary record in space and time.

(ii) with a pan-European view, "Hydrate assessment in the European continental margin and related risks". Work Package 3.

The assessment of gas-hydrates resources in the European continental margin represents an information gap of pan-European interest. GARAH has improved the understanding of the potential role that gas-hydrates may play in the future EU energy mix, as the results constitute a base-line for future projects pertaining the improvement of the European model of the gas hydrate stability zone (GHSZ), related hazards, and potential for geological storage of CO_2. All the analytical data were generated to a common European Geological Data Infrastructure (EGDI) database. During the last years of the project, the main activities and results achieved in WP3 have been the (i) collection of available data focused on hydrate research in a pan-European area and (ii) the definition of the data model structure of the pan-European hydrate-related GIS. The main impact of this results has been to extend the existing EGDI structure to enable incorporation, maintenance, and dissemination of outcomes.

Alternative Use/Risk/Hazard

In addition to the regional analyses, a catalogue evaluating the multiple-use of hydrocarbon reservoirs, as integrated or alternative use of the subsurface, together with an appraisal on potential hazards, is presented. This catalogue includes options on CO_2 storage (CCS and CCUS), H_2 storage, underground natural gas storage, and geothermal energy. In addition, potential for conversion of oil & gas facilities for new natural habitats (“rigs-to-reefs"), windmill parks and energy islands are catalogued.

The hazards catalogue focuses on potential new risks and environmental impacts associated with continued exploitation of the subsurface for energy in the North Sea. This evaluation is based on a review of recent literature. We also examine gas hydrates and their geohazards.

TABLE OF CONTENTS

1 INTRODUCTION

The Geological Analysis and Resource Assessment of selected Hydrocarbon systems (GARAH) is a twofold project focussing on petroleum systems in the North Sea, Europe's prime hydrocarbon basin and gas hydrates beneath the European shelf (Geological Analysis and Resource Assessment of selected Hydrocarbon systems (GARAH) – GeoERA). For the North Sea the overall aim was to assess and evaluate the hydrocarbon (HC) resources across borders. The assessment of the conventional resources was carried out quantitatively based on a harmonization of the national reserve and resource estimations and qualitatively following a play-based approach. In addition, unconventional resources was assessed following a Monte Carlo simulation approach previously developed in the "EUOGA project" (EUOGA (europa.eu)) to asses onshore shale resources.

As one part of the overall objective of the GARAH project, a regional 3D basin and petroleum system model (BPSM) covering the Danish, German, and Dutch Central Graben area was constructed estimating petroleum resources. The 3D BPSM model is a pilot study to reconstruct the thermal history, maturity and petroleum generation of potential and proven source rocks. As a first step we modelled the unconventional resources, i.e., those retained in the source rocks that allow for comparison to the "EUOGA" approach.

The main objectives of the gas hydrate study (WP3) were: (i) to extend the existing European Geological Data Infrastructure (EGDI) structure to enable incorporation, maintenance, and dissemination of outcomes; (ii) to present the results in a GIS format at a scale and resolution suitable for integration with The European Marine Observation and Data Network (EMODnet) geological data; and (iii) to present a knowledge gap analysis of areas with limited or no data and to assess the uncertainty and sensitivity errors in critical oceanographic parameters such as geothermal gradient and seafloor temperature measurements.

The GARAH assessment on resources as wells as conventional and unconventional plays are important in terms of their potential contribution to: alternative energy security, for carbon capture (CCS, CCUS), hydrogen and other energy storage, and even for offshore geothermal energy. These later aspects are exemplified with a catalogue of the multiple-use (or sequential-use) potential and impacts of hydrocarbon reservoirs to further enable the European community to understand the most efficient, sustainable, and climate-friendly use of the subsurface. The alternative use catalogue is complimented by a risk and geohazard catalogue associated with the use of the subsurface (existing and to come) as well as with the gas hydrate resource mapped and assessed as part of the GARAH project. Also, the gas hydrates pose potential Geohazards related to its sensitive nature that can trick events such as tsunamis. In addition, as evidence mounts for sustained global warming, there is increased awareness of the relative importance of methane emitted to greenhouse warming. We know that the pressure/temperature conditions of the gas hydrate stability and the global distribution of gas hydrate make it susceptible to the key perturbations associated with global warming, namely relative changes in sea level (pressure) and increases in ocean temperatures. This is especially observed in several sites in the Arctic region and may also pose a long-term environment hazard within the GARAH study area.

2 PROJECT IDEA AND STRUCTURE OF GARAH

A variety of different evaluation methods have been employed to assess hydrocarbon resources in different offshore areas of the EU. Consistent evaluation methods and data processing on newly released and legacy data will help rationalize the resource estimates across the EU, allowing for improved planning for the exploration, development and closure of hydrocarbon reservoirs. Technological improvements may result in resources previously considered uneconomic (e.g., shale gas and methane hydrates) to be considered viable exploration targets in areas with little exploration history. The identification of these areas and quantification of resource will contribute to the development of planning strategies for member states in terms of licensing and policy development. A consistent estimation of hydrocarbon resource will be a first step in assessing and quantifying the hydrocarbon reserves in the main hydrocarbon basin in Europe. The GARAH project idea was the identification of new potential areas for hydrocarbon (HC) exploration, directly addressing the requirement for identifying secure energy HC sources.

GARAH aimed to give further information regarding basin development and evolution, and the HC resources will be systematically assessed. Outcomes will therefore feed into planning and policy (licensing of areas for exploration) by Member States, commercial exploration strategies and also highlight remaining knowledge gaps which may inform about further academic research or programmes of exploration sponsored by member states. The datasets generated also highlight areas of potential risks associated with exploitation of fossil fuels, alternative uses, and the closure of mature fields.

The assessment of gas-hydrates resources in the European continental margin represents an information gap of pan-European interest. The main objectives of this work-package have been: (i) to extend the existing European Geological Data Infrastructure (EGDI) structure to enable incorporation, maintenance, and dissemination of outcomes; (ii) to present the results in a GIS format at a scale and resolution suitable for integration with The European Marine Observation and Data Network (EMODnet) geological data; and (iii) to present a knowledge gap analysis of areas with limited or no data and to assess the uncertainty and sensitivity errors in critical oceanographic parameters such as geothermal gradient and seafloor temperature measurements. This has been achieved by (i) the development of a harmonized GIS-database for the pan-European hydrate data infrastructure storing hydrate evidences (both direct and indirect), oceanographic variables e.g. seafloor temperature, heat flow data, bathymetry, sedimentation rates, and Gas Hydrates Stability Zones (GHSZ) thickness. (ii) the definition of critical knowledge gaps of the related to hydrate related information stored in the GIS-data base. (iii) the susceptibility assessment of seafloor areas affected by hydrate dissociation and the potential role of CO_2-rich hydrates for the geological storage of CO_2.

The importance of the GARAH area in terms of alternative energy security; for carbon capture, hydrogen and other energy storage, and even offshore geothermal energy, is exemplified with a catalogue of the multiple-use (or sequential-use) potential and impacts of hydrocarbon reservoirs to further enable the European community to understand the most efficient, sustainable, and climate-friendly use of the subsurface. The alternative use catalogue is complimented by a risk and geohazard catalogue associated with the use of the subsurface (existing and to come) as well as with the gas hydrate resource mapped and assessed as part of the GARAH project.

Project Structure

The project was divided into four Work Package (WP1-4) each with several tasks identified:

WP1: Project management and coordination.

Tasks included were:

Task 1A: Administrative & Operational Management

Task 1 B: Project Data Management Plan

Task 1C: Communication

WP2 (North Sea Petroleum Systems) work objective was to define the range of petroleum systems in the North Sea and populate a North Sea-wide harmonized database detailing the oil and gas resource present in the UK, Dutch, German, Danish and Norwegian sectors. WP2 also demonstrated the advantages of 3D model assessment in a pilot study area. Within this work package a catalogue of the multiple-use (or sequential-use) potential and impacts of hydrocarbon reservoirs is made that will enable the European community to improve efficient, sustainable, and foster climate friendly use of the subsurface.

Tasks included were:

Task 2A: Methodology and data base

Task 28: Defining the North Sea petroleum systems

Task 2C: Resource assessment

Task 2D: 3D petroleum system modelling resource assessment

Task 2E: Multiple/alternative use of HC reservoirs (joint with WP2 and WP3 task)

WP3 (Addressing knowledge gaps in the hydrate assessment in the European continental) aim was to develop a harmonized model for a pan-European gas hydrate data infrastructure. A GIS-database has been developed that includes key gas hydrate observations.

Tasks included were:

Task 3A: Collection of data sources to be implemented in the hydrate related GIS-database.

Task 3B: Definition of the data model structure and data loading.

Task 3C: Integration of results.

WP4 The objective of this work package is to lead the interactions with the GeoERA-IP project, to execute the parts of the Project Data Management Plan relating to IP and EDGI and to enable an efficient and consistent uptake and embedding of project results into the GeoERA-IP. WP4 was responsible for communicating the requirements of the project to GeoERA-IP and to ensure that the guidelines and standards provided by GeoERA-IP was implemented to ensure the maintenance, dissemination as well as the sustainability of the results in from the GARAH project.

Tasks included were:

Task 4A: Synthesis: Determination of requirements and standards and communication with EGDI team

Task 4B: Development: Preparing and creating the online platform

Task 4C: Implementation: Local data implementation, IP data implementation and prototyping, data validation and testing.

3 WORK PACKAGES

Below follows a brief summary of the objectives, approach and results of the technical work packages (WP2-4).

3.1 WP2 – North Sea Wide Assessment

3.1.1 Objectives

The North Sea Wide assessment aim was to assess and evaluate hydrocarbon (HC) resources across borders in Denmark, Germany, The Netherlands, The UK and Norway. The assessment of the conventional resources was made quantitatively based on a harmonization of the national reserve and resource estimation, and qualitatively following a play-based approach. The assessment of the unconventional resources was made following a Monte Carlo simulation approach known as the "EUOGA method".

3.1.2 Approach

The regional study follows the progress of tasks 2A, 2B and 2C in the GARAH project that culminated on the resource assessment of the unconventional as well as conventional hydrocarbons in the North Sea basin (D2.3). Collected data on the hydrocarbon resources from tasks 2A and 2B reported in GARAH Delivery Reports 2.1 and 2.2 are used in the assessment.

For the assessment of the conventional resources in the North Sea a two-step approach was followed. A quantitative assessment was made based on published information and reports from the respective countries. These were collected and the applied methods compared (see GARAH Deliverable Report 2.1 and 2.2). A qualitative assessment was made from harmonizing play maps across the North Sea. In this step, plays that were not included in the published assessments were identified, and collated to reveal cross-border issues. All plays were then classified into different categories, based on their assessment status as well as their maturity (mature, proven, new, conceptual). Finally, the published resource assessments were harmonized in terms of units and collated to cover the North Sea study area.

The assessment of the unconventional *yet-to-find* resource in the North Sea Basin is made as an extension of the mapping and assessment of European onshore unconventional resources made within the framework of the EU funded European Unconventional Oil and Gas Assessment (EUOGA) project completed in 2017. One outcome of the EUOGA project was the formulation of a scientifically based assessment methodology aimed to provide a consistent appraisal of this new resource base that can be used by relevant policy makers and society. In the GARAH project we have followed the EUOGA established method with minor modifications for adaption to the North Sea offshore setting.

3.1.3 Challenges/problems

The assessment of the national reserve and resource estimation and the subsequent harmonization faced challenges in synthesizing resource data which were produced using differing standards and units. We have made efforts to harmonize the national assessments, but we strongly recommend that a higher degree in alignment of reporting is made in countries bordering the North Sea to make more consistent regional assessments. In particular if all assessments could be converted into the same units while being calculated, this would remove errors propagating from differing standards of conversion factors such as gas to oil equivalent. While these conversions vary due to differences in physical properties of hydrocarbons across the North Sea (e.g. Groningen gas in the Netherlands compared to Norwegian crude), conversion during assessment would be most accurate.

The national assessments are not always linked to a specific geographical area. This can be seen for the UK, where reporting of reserves and contingent resources are published for the entire UK continental shelf rather than for sub-areas, as is done for prospective resources. Recognition of the North Sea as a unique hydrocarbon producing area would be most useful in any further cross-border estimates; its location bordering almost all hydrocarbon producing countries in northern Europe makes it an important area to analyse separately.
The uncertainties in actual reserves and resources relating to differences in reporting and methods, as well as a lack of detailed published estimates in some areas, hampers planning relating to conventional hydrocarbon extraction, as well as alternative uses in the GARAH North Sea area. Similarly, while play-based assessments better capture the geological reasoning behind hydrocarbon assessments, these are limited when influenced by the location of country borders and associated changes in detail and importance.

For the assessment of unconventional plays and resources then had to confront the issue that the shales were poorly characterized with specific capacity related parameters such as *Langmuir Volume,* and that mineralogy data were generally not available. Also, *in-situ* measurements from the source rock itself such as pressure, temperature and saturation (oil and gas) were not available for this study. Without such data a critical evaluation of the plays and the assessed resources cannot be made adequately, which results in overall larger uncertainties.

3.1.4 Results

The assessment of the conventional prospective resources is made quantitatively based on a harmonization of the national reserve and resource estimation and qualitatively following a play-based approach.

The harmonization of the national conventional assessment show that there are significant reserves, contingent resources and prospective resources left in the North Sea. More than 14 billion m^3 oil equivalents (o.e.) have been produced in the North Sea and additional reserves (2P) amount to least 2.9 x 10^9 m^3 o.e., and contingent resources (2C) of at least 1.5 x 10^9 m^3 o.e. Based on the national agencies it is estimated that the of *yet-to-find* resources amount to around 1.9 x 10^9 m^3 o.e.
The qualitative assessment of the North Sea has resulted in the construction of a total of 13 major conventional play maps (Figure 3-1). The play maps provide one of the first main North Sea-wide efforts to compile such maps from individual country interpretations, and thus represent a major step in planning of the use of the North Sea subsurface both in terms of future licences rounds, alternative use and risking.

The assessment of the yet-to-find resource associated with the unconventional plays in the North Sea Basin show that this resource is significant. Ten potentially prolific oil plays in the North Sea have been identified with a *yet-to-find* resource potential (P50) of 6,648 x 10^6 m^3 oil and nine gas plays have been identified with a gas yet-to-find resource potential of 9,344 x 10^9 m^3 gas (Figure 3-2). This estimate includes the resource estimated for a 100 m thick Upper Jurassic - lowermost Cretaceous shale unit and thus excludes the resource base calculated in the >1 km thick shale interval in UK and Norway. The oil resource is mostly located in the Upper Jurassic - lowermost Cretaceous shales in the UK and Norwegian part of the North Sea owing to its vast regional coverage and thickness. The gas resource is mainly distributed in the Carboniferous Bowland equivalent shales located in the Netherlands and in the UK offshore area and in Jurassic shales in UK and Norway.

The unconventional resource estimate is based on Monte Carlo simulations following the EUOGA method. The main parameters that contribute to the uncertainties are the saturation, porosity and thickness and the sorption parameters such as the Langmuir Volume.

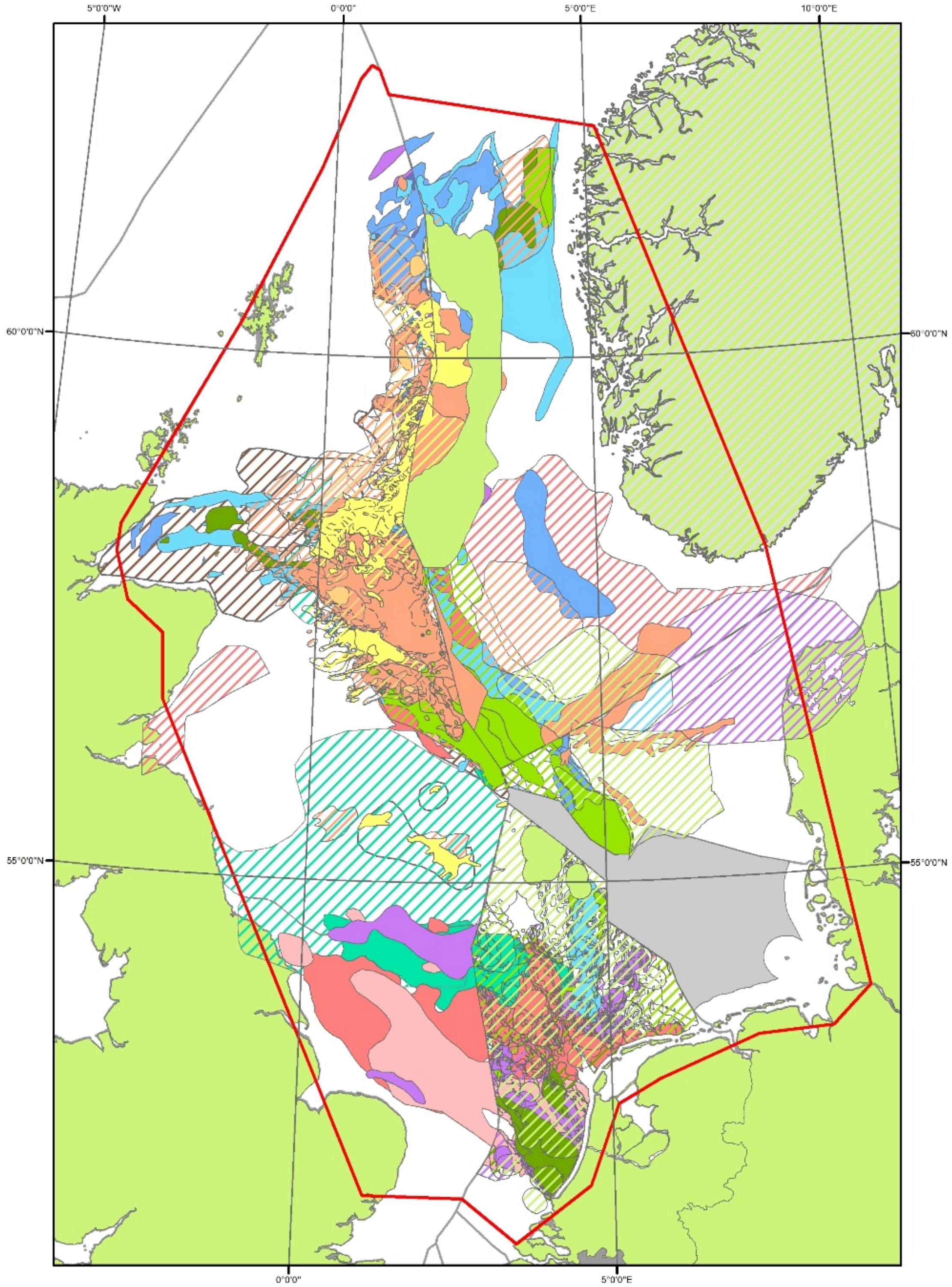

Figure 3-1 The GARAH North Sea study area (red outlines) and all harmonized conventional play outlines in GARAH GIS. Updated from GARAH Deliverable Report 2.2.

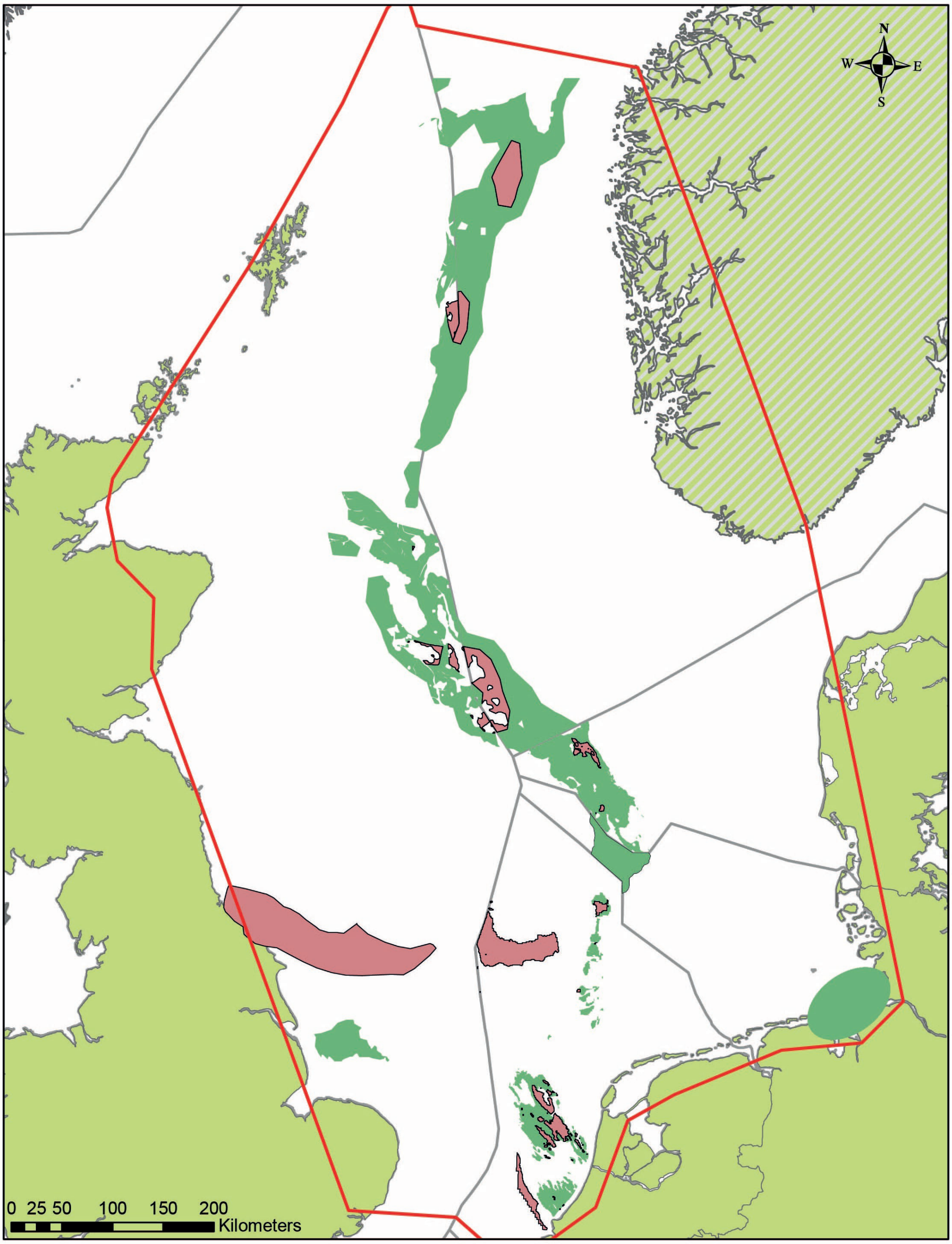

Figure 3-2 The GARAH North Sea study area (red outlines) and occurrence of the identified shale play (10 oil plays marked with green, and 9 gas plays marked with red) outlines in the unconventional GARAH GIS. From GARAH Deliverable Report 2.2. Note that some plays may be hidden below others.

3.1.5 Deliverables

Name	Short description, remarks	Link
D.2.1	*Database and harmonization report based on fill-in questionnaires*	Deliverable 2.1. Database and Harmonisation Report.
D.2.2	*Report on North Sea Petroleum System including conventional and unconventional plays in GIS format.*	Deliverable 2.2. Petroleum system report and GIS maps
D.2.3	*Resource assessment in the North Sea based on harmonized national assessment and the "EUOGA" method*	Deliverable 2.3. Updated assessment of the conventional and unconventional resources of the North Sea Basin

3.2 WP2 – 3D Pilot

3.2.1 Objectives

As one part of the overall objective of the GARAH project, a regional 3D basin and petroleum system model (BPSM) covering the Danish, German, and Dutch Central Graben area was constructed for estimating petroleum resources. The 3D BPSM model was a pilot study to reconstruct the thermal history, maturity and petroleum generation of potential and proven source rocks. As a first step we modelled the unconventional resources, i.e., those retained in the source rocks. This assessment has been described in report D2.4 (GARAH Deliverable report, 2.4 (Lutz et al., 2021)). The conventional resources were assessed and are reported in D2.5 (GARAH Deliverable report, 2.5 (Mathiesen et al., 2021)).

3.2.2 Approach

In close cooperation the GARAH and 3DGEO-EU projects' participants, we delineated the area of interest (AOI) and the stratigraphic framework for the 3D basin and petroleum system modelling study. The AOI comprises the cross-border area of the Danish, German, and Dutch Central Graben in the central North Sea. This area has been selected based on the geological, stratigraphical and geophysical data compilation, showing reasonable cross-border coverage as well as several potential and proven petroleum source rocks.

The construction of a single model of the pilot study area highlighted the different interpretations and stratigraphic concepts of each country. Nevertheless, we were able to harmonize the data across borders and reach a comprehensive volume model.

The 3D basin and petroleum systems model of the pilot study area allowed us to study the petroleum systems in the area and enabled the calculation of generated petroleum amounts. The simulations were carried out using the PetroMod software (v2019) (Figure 3-3). The 3D numerical model is a deterministic forward model, which reconstructs the burial history and all related processes from time of deposition towards present day, for example, sedimentation, erosion, compaction, radiogenic heat production, petroleum generation, migration and accumulation. Thus, the BPSM model allows for a comprehensive understanding of the petroleum systems in the AOI and enables the calculation of generated petroleum amounts within the proven source rocks and the amounts of hydrocarbons migrated and accumulated and trapped in structures. The model also provides information on timing, quantifies petroleum generation and migration and directs focus towards the parameters that affect simulation results the most. Variation of input parameters and their influence on the calculated volumes were assessed. Various output parameters in the cross-border area, for example, maturity of source rocks, transformation ratio and migration and trapping of hydrocarbons were also calculated (Figure 3-4).

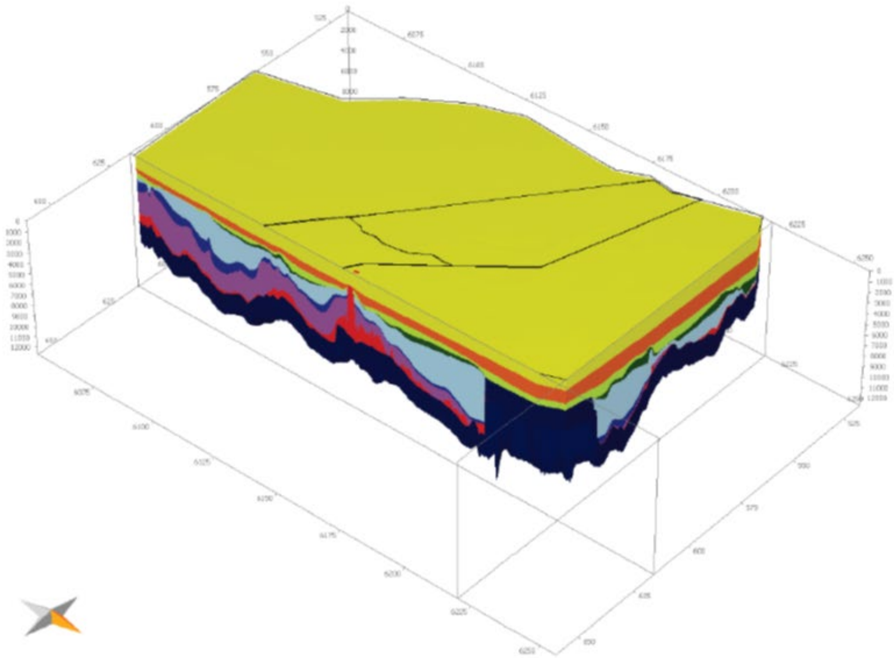

Figure 3-3 View from the NE into the 3D BPSM model. The eastern and northern sides are not shown to give a better view into the model. Red layer is Zechstein salt and light blue layer is Upper-Middle Jurassic strata.

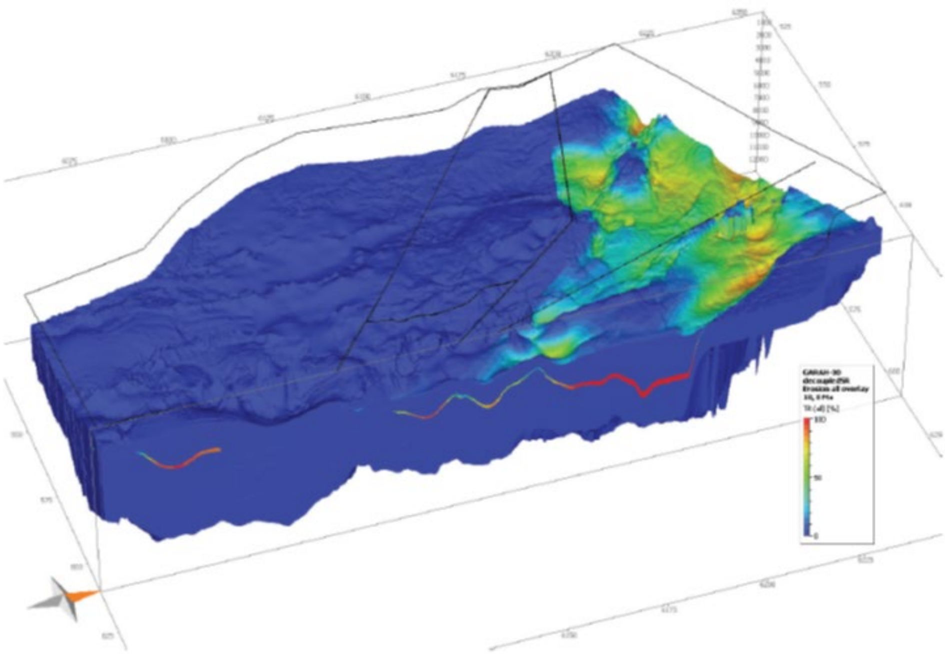

Figure 3-4 3D BPSM model result showing transformation ratio (TR) at the top of the Upper Jurassic source rock layer. The coloured line along the front of the model side represents deeper lying source rocks.

3.2.3 Challenges/problems

Combining the erosion models of the three countries was a challenge, because of the different structural evolution of the Central Graben in the study area. Each part experienced phases of uplift and erosion after the Jurassic rifting which varied across the area and during time. The apportionment of uplift and erosion to the three main erosion phases, the Mid-Cimmerian (Mid-Jurassic), the Late Cimmerian (Early Cretaceous) and the Subhercynian inversion (Late Cretaceous) was therefore adjusted in the model.

3.2.4 Results

One of the results is that maturity maps now can be extracted from the model without breaks at country borders (see Figure 3-4 and examples in GARAH Delivery Reports D2.4 and D2.5). Furthermore, unconventional resources were calculated for the main source rocks as well as conventional petroleum resources. Comparison of the resource estimates calculated from the 3D model with the estimates provided from the independent EUOGA method (GARAH Delivery Report D2.3) show good agreement. Also, the results for the Danish conventional resources are in good agreement with the previously published

Danish estimate (Table 3-1 shows a summary for the Danish Central Graben). For Germany and the Netherlands no published numbers are available for the study area.

Figure 3-5 and 3-6 show examples of expulsion, migration and accumulation extracted from the conventional 3D model. Notice how the generated gas is lost in the Dutch sector due to seal break (Figure 3-5). Figure 3-6 shows the distribution of oil and gas accumulations with reference to oil/gas fields. Furthermore, Figure 3-6 shows how the accumulations in selected reservoir layers in the Danish sector are related to various play type areas and the oil/gas fields.

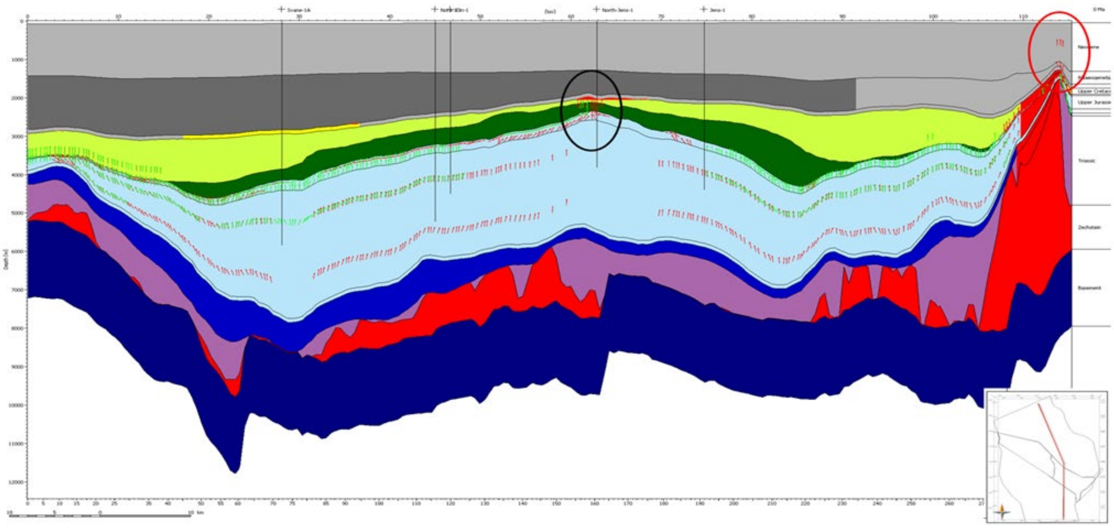

Figure 3-5 2D cross section extracted from the 3D BPSM (see inset in lower right corner). The cross section shows the sedimentary layers with overburden layers in grey colors, Cretaceous layers in green colors and the salt diapirs in red colors. Notice the accumulation of gas and oil around the North Jens-1 well location (black circle), and that gas is lost to the surface (red circle) in the southern part of the section within the Dutch sector.

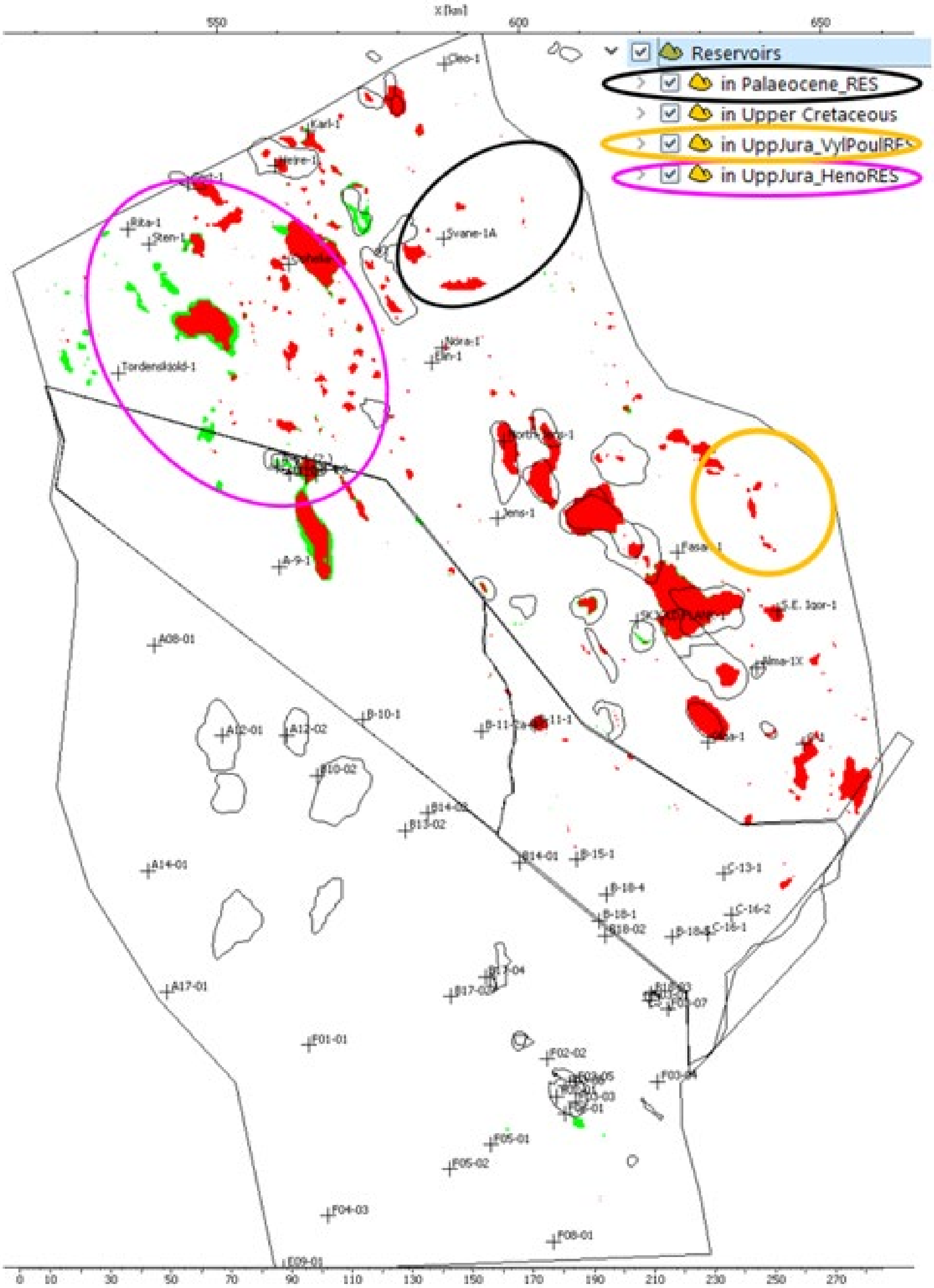

Figure 3-6 3D BPSM model result showing the distribution of oil (green colored spots) and gas (red colored spots) accumulations. The colored circles mark areas where the model predict HC accumulation within none chalk reservoirs (shown in the upper right corner). See also Table 3-1 and 3-2.

Table 3-1 Summary of estimated reserves and resource in Denmark pr. 1/1-2021 from the Danish Energy Agency (top). GEUS resources for *yet-to-find* is from Schovsbo et al. 2020; bottom).

PT No.	Play Type	Proven Discoveries			Yet-To-Find			
		Category 1 (mill m^3 oe)			Category 2+3 (mill m^3 oe)			
		Discoveries	P50	Prospects and Leads	P50 (non-risked)	Posibble extra resources	P50 (risked)	Posibble extra resources
1	Neogene	1	10	5	65		18	
2	Paleogene	3	21	2	3		0	
3	Upper Cretaceous (Ekofisk & Tor Fms)			12	223	25	45	2,2
4	Upper Cretaceous (Hidra & Kraka Fms)	4	25	4	41		4	
5	Lower Cretaceous (Tuxen & Sola Fms)	1	29	3	41		19	
6	Upper Jurassic (Upper Farsund Sst)			9	189		30	
7	Upper Jurassic (Intra Farsund Sst)	1	44	4	81	20	27	2
8	Upper Jurassic (Outer Rough Sst)			3	44		7	
9	Upper Jurassic (Heno Fm)	5	78	15	102		21	
10	Mid Jurassic Sandstone	6	39	11	38	15	9	1,5
11	Pre-Jurassic			4	30		4	
	Total	21	246	72	857	60	184	5,7
					917		189,7	

Summary Resources and Reserves (1/1 2021) *Danish Central Graben (DCG)*	Gas 10^9 Nm^3	Oil 10^6 m^3	Oil eq 10^6 m^3			
Produced	183	447				
Reserves	29	65				
Contingent resources	45	80				
Technological resources	1	15				
Exploration	6	22				
Discoveries (P50)			246			
Prospects and leads (catagory 2+3) - Unrisked (P50)			857			
Prospects and leads (catagory 2+3) - Risked (P50)			184			
Possible additional resources - Unrisked (P50)			60	Cat..(1+2+3)	1163	unrisked
Possible additional resources - Risked (P50)			6	Cat..(1+2+3)	436	risked

The Danish petroleum resources range between 917 and 1,163 million m^3 oil equivalents (o.e.) as given by the Danish Energy Agency and Schovsbo et al. (2020), respectively. In the 3D BPSM study, the calculated oil and gas resources amount to 1,998 million m^3 o.e. (Table 3-2), which is roughly twice the previous estimate. Considering the large study area, which includes three countries, and that the calculated resources are summed up for the whole reservoir layer, then this is in quite good agreement. The total estimate also includes tiny accumulations, which are probably partially artefacts caused by geometrical inaccuracies. Furthermore, some of the modelled accumulations are larger than the actual fields, which is likely a result of the simplified regional migration model.

Table 3-2 shows one result of the calculated accumulated conventional resource. The model scenario is the same as shown in Figure 3-6 and shows the calculated resources for selected plays (first two columns for gas (red column) and oil (green column)), in the last column the total amounts are converted to x10^6 m^3 o.e. Notice that not all the play types are implemented into the 3D BPSM model (grey rows, Play type No. 4, 5, 8). In the model the Upper Cretaceous Chalk reservoir receives most of the migrated and accumulated HCs which is in agreement with the known distribution.

PT No.	Play Type	Reservoir / Carrier	GIIP Accumulated volumes (From PetroReport) (10^6 t)	OIIP Accumulated volumes (From PetroReport) (10^6 t)	Total eo Accumulated Unrisked (10^6 m^3 oe)
2	Paleogene	Paleocene_RES	0,08	12,65	13
3	Upper Cret. Chalk (Ekofisk & Tor Fms)	Upper Creteceous	896,02	1101,69	1998
4	Upper Cret. Chalk (Hidra & Kraka Fms)				
5	Lower Cret. (Tuxen & Sola Fms)				
6-7	Upper Jura. (Upper Farsund Sst)	Upp_Jura_VylPoulRES	0,02	4,64	5
8	Upper Jura. (Outer Rough Sst)				
9	Upper Jura. (Heno Fm)	UppJura_HenoRES	71,27	3,79	75
10	Mid Jurassic Sandstone	(Lower-)Mid JurassicRES	0,00	0,00	0

3.2.5 Deliverables

Name	Short description, remarks	Link
D.2.4	*Assessment of the unconventional resources in the main source rocks within the 3D pilot study area*	Deliverable 2.4. 3D Pilot Study - Unconventionals
D.2.5	*Assessment of the conventional resources within the 3D pilot study area*	Deliverable 2.5. 3D Pilot Study - Conventionals

3.3 WP2 and 3 Alternatives use of the subsurface

3.3.1 Objectives

The objective of the catalogue of the alternative or multiple-use (or sequential-use) of the subsurface was to present the options for the subsurface that further enable the European community to understand the most efficient, sustainable, and climate-friendly use. Offshore technologies for carbon capture, hydrogen and other energy storage, and even offshore geothermal energy, could contribute to achieve the greenhouse gas (GHG) reduction commitments of the North-Sea bordering states and the "net-zero" target for 2050. We used a case-based approach and focused on most recent developments and projects that are on-going or planned for the North Sea.

Marine gas hydrates are crystalline solids forming ice-like marine deposits composed of water molecules surrounding light hydrocarbon gases such as methane (the most common), ethane and propane, in cage-like lattices. Although mapping the marine gas hydrate distribution along the European continental margin is ongoing, an awareness of potential geohazards of marine gas hydrates remains critical, especially with the potential for destructive tsunamigenic events. In addition, as evidence mounts for sustained global warming, there is increased concern that widespread disintegration of marine gas hydrates may lead to excess methane emissions and enhanced global warming. This project presents for the first time on the whole of the European margins and adjacent areas, a geohazard assessment (susceptibility analysis) of the presence of marine gas hydrates. It also assesses the main knowledge gaps of hydrate-related information with a pan-European scope, and analyses their impact on the uncertainty of susceptibility inference.

3.3.2 Approach

The approach followed the catalogue presenting potential alternative usages, synergies and competitions of a mature offshore area and associated infrastructure. Additionally, a catalogue of potential environmental hazards and risks accompanying the use of the subsurface has been compiled. The task is a joint task between WP2 and WP3 of the GARAH project and reports on the work related to Task 2E: Multiple/alternative use of HC reservoirs, as reported in GARAH Report 2.6.

We use a case-based approach describing these technologies and focused on most recent developments and projects that are on-going or planned for the North Sea. Our examples employed the current scientific literature as well as project-based data and reporting. We discussed the current roadmap and strategy situation, technological needs to achieve the current emission targets, time and spatial constraints as well as give a view on the public perception discussion by comparing the onshore versus offshore situation. We also discuss hazards associated with gas hydrates and their impact on alternative sea floor uses.

3.3.3 Challenges/problems

One of the initial ideas of the GARAH project was to link GIS database features to corresponding hazards and thereby map areas where these hazards might be encountered. However, during the course of the GARAH project it became evident that the level of detail of the available information was not sufficient to provide this in a basin-wide context. Many of these hazards are local, and strongly dependent on reservoir-scale aspects (e.g., induced seismicity – see discussion in Buijze et al., 2020). Where possible, we have referenced relevant GIS layers in the list of hazards. However, this is not a comprehensive overview and should only be regarded as a first pass in identifying potential hazards.

3.3.4 Results

The "alternative use" catalogue groups the different use objectives into CO_2 Storage, Energy Storage (Hydrogen Storage, Underground Natural Gas Storage and others), Geothermal Energy, re-use of existing infrastructure and other area restrictions. These are further subcategorized by their potential geological subsurface targets/reservoirs in the GARAH report D2.6.

The second part of the report focusses on the identification and description of hazards related to subsurface use, either through conventional hydrocarbon related activities or from alternative energy applications. A general overview of these hazards is given and a general discussion whether any of the new technologies require a re-evaluation of the known risks and hazards.

The presence of gas hydrates in marine sediments is a geohazard that has not yet been evaluated along the whole European continental margin. This study, analyses the geological hazard by means of the susceptibility assessment. The term ''susceptibility'' is employed here to define the likelihood of occurrence of hydrates in the sediment column, and subsequently the likelihood of them being affected by dissociation processes resulting from natural or human induced activities (liquefaction, explosions, collapse, crater-like depressions or submarine landslides).

Most of the technologies that are using the subsurface can benefit (financially or technologically) from synergies or re-use of infrastructure and knowledge from other technologies. At the same time, however, several of these technologies are also utilizing similar structures or subsurface environments, which will result in competing interests (see Figure 3-7) as well as potential additional hazards. In the third part of the report these potential synergies as well as competitions or competing interests are identified for the described technologies.

The summary of technologies that use the subsurface for energy generation and storage, as well as the list of associated hazards compiled in this report, can be used for planning policy-making (particularly for licensing of areas for exploration), and commercial exploration strategies by EU Member States.

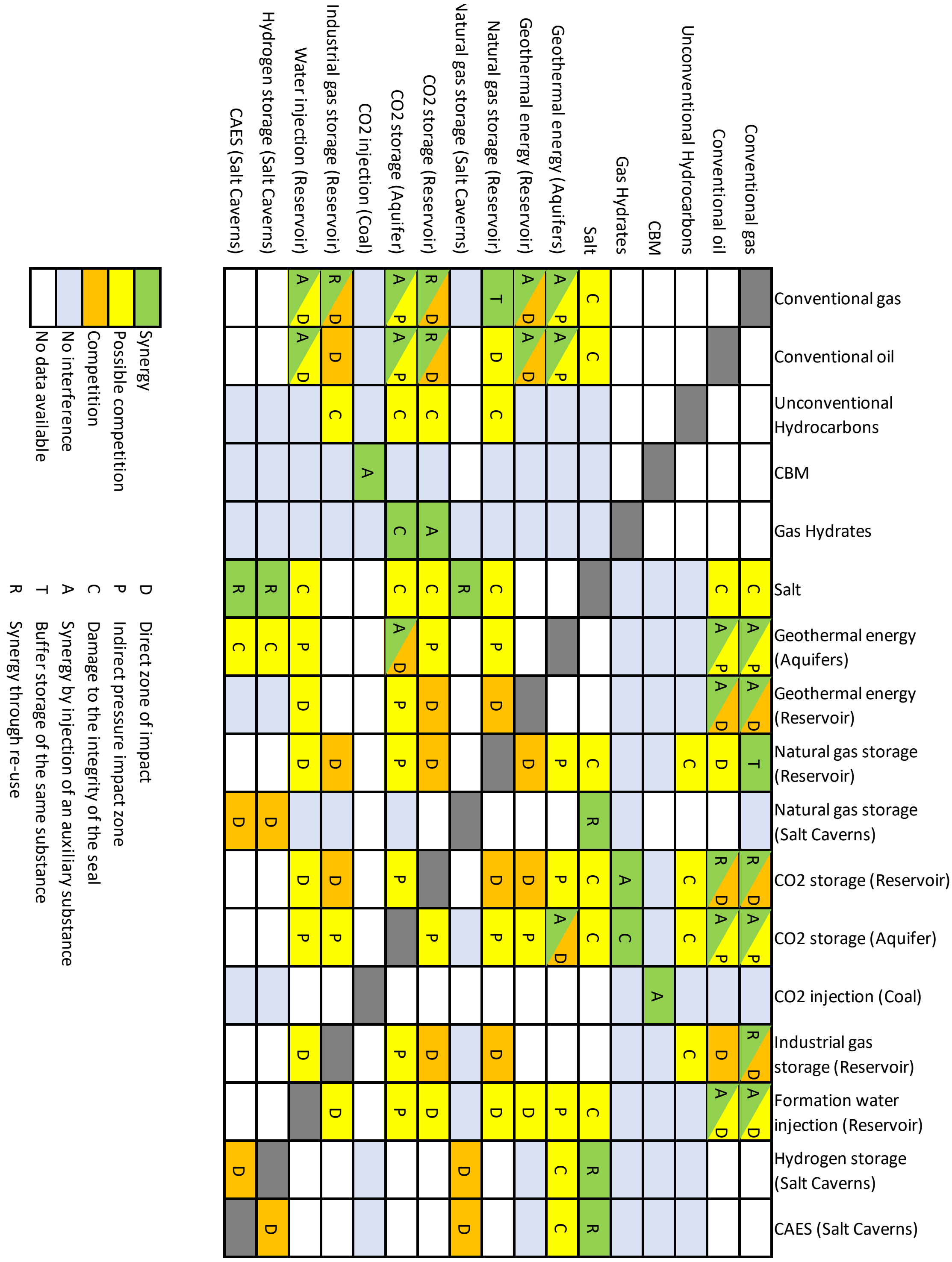

Figure 3-7 Overview of potential synergies and competitions in subsurface use between different technologies (modified from Le Guenan and Gravaud, 2016).

3.3.5 Deliverables

Name	Short description, remarks	Link
D.2.6	*Catalogue of Alternative use, Risks and Syn-energies*	Deliverable 2.6 Alternative use and risks

3.4 WP3. Addressing knowledge gaps in the hydrate assessment in the European continental margins

3.4.1 Objectives

The study area of WP3 involves the geographical area of the European Marine Observatory Data Network (EMODnet) Bathymetry (Fig. 3-8a): 85ºN, 25ºN, 43ºE and 30ºW, limits north, south, east and west respectively. However, because hydrate data for the neighbouring area were stored in the databases collected in this project (PERGAMON, MIGRATE and EMODnet), we extended the GIS database to western Greenland (Fig. 3-8b) and the Barents Sea (Fig. 3-8c).

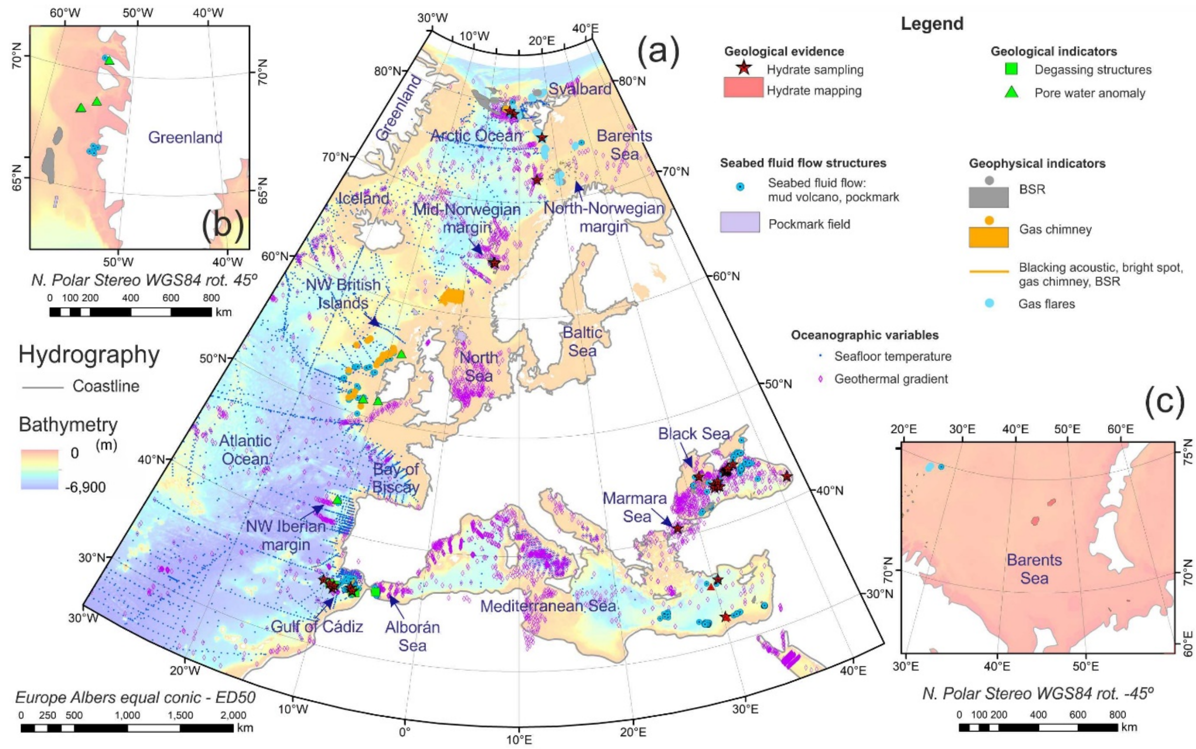

Figure 3-8 Study area of GARAH gas hydrate assessment (WP3).

The main objectives of this work-package have been: (i) to extend the existing European Geological Data Infrastructure (EGDI) structure to enable incorporation, maintenance, and dissemination of outcomes; (ii) to present the results in a GIS format at a scale and resolution suitable for integration with The European Marine Observation and Data Network (EMODnet) geological data; and (iii) to present a knowledge gap analysis of areas with limited or no data and to assess the uncertainty and sensitivity errors in critical oceanographic parameters such as geothermal gradient and seafloor temperature measurements.

In order to reach these objectives, the following actions have been carried out: (i) the development of a harmonized GIS-database for the pan-European hydrate data infrastructure storing hydrate evidences (both direct and indirect), oceanographic variables e.g. seafloor temperature, heat flow data, bathymetry, sedimentation rates, and Gas Hydrates Stability Zones (GHSZ) thickness. (ii) the definition of critical knowledge gaps of the related to hydrate related information stored in the GIS-data base. (iii) the susceptibility assessment of seafloor areas affected by hydrate dissociation and the potential role of CO_2-rich hydrates for the geological storage of CO_2.

3.4.2 Results

3.4.2.1 Hydrate GIS-database

The hydrate-related information of GIS of GARAH WP3 is structured in four levels: (i) geological and geochemical evidence and indicators, (ii) geophysical indicators, (iii) sea-bed fluid flow structures, and (iv) oceanographic variables (Fig. 3-8). Four types of items describe the information: location items, property metadata, geo-descriptors and references/comments. Location items describe the geographical location (coordinates, geological setting, etc.). Property-reference metadata store the owner of the data and contact information. Geo-descriptors describe the geological, geochemical and geophysical characteristics of the evidence or indicator. Finally, references/comments store bibliographic references and other comments of interest of each item of evidence or indicator.

The level of information “geological and geochemical evidence and indicators” stores evidence (e.g. crystals of gas hydrates) and indicators (e.g. degassing structures and pore water anomalies) of gas hydrates acquired by direct sampling. The level “geophysical indicators” stores seismic or electric features of gas hydrate presence in the sediment column, such as high resistivity, BSR levels, bright spots, acoustic blanking facies and gas chimneys. The level “seabed fluid flow structures” stores structures related to fluid migration in areas where evidence or indicators of marine gas hydrates have been observed. Finally, the level “oceanographic variables” stores information about seafloor temperature, geothermal gradient and bathymetry.

3.4.2.2 Critical knowledge gaps

The available public hydrate related information stored in the GIS-database shows a non-homogeneous continuity along the European continental margins. This issue is especially critical for understanding the behaviour of the GHSZ or making predictions or calculations on it. We therefore assessed the critical knowledge gaps in the geological and geophysical evidence and indicators and the oceanographic key parameters of hydrate nucleation/dissociation. This assessment was carried using density maps (Fig. 3-9).

Evidence of marine methane hydrates has been reported in eight main regions (Fig. 3-9a): offshore Greenland and Svalbard, the Norwegian margin, offshore the northern British Islands, the southern Iberian and northwest African margins (the Gulf of Cádiz and Alborán Sea), and the Black, Marmara and eastern Mediterranean seas. These areas show a high density of high-quality data. The reliability of the lack of evidence outside the limits of these areas is controversial. Although the majority of European continental margins have been prospected for the oil industry, some deep ocean basin areas have not. Therefore, some areas with lack of evidence (possibly located in deep ocean basins) could be treated as information gaps resulting from lack of prospection or scientific fluid flow research.

Seafloor temperature and marine geothermal data show a heterogeneous distribution. Marine geothermal data appear concentrated with high density in some of the above-mentioned eight main regions (Fig. 3-9b). Seafloor temperature data (Fig. 3-9c) are especially concentrated in the Black Sea and on the eastern Atlantic continental shelf. For the two above datasets, areas with less than 1 record per 100,000 km^2 were selected as knowledge gaps. These knowledge gaps are especially critical (i) in areas where direct hydrate samples have been recovered, (ii) in the vicinity of the up-dip limit of the GHSZ, and (iii) in areas where seabed fluid flow structures have been detected. The critical knowledge gaps for geothermal gradient data are east of Greenland, Svalbard–Barents Sea, the White Sea, northwest of the British Islands and the south-eastern Mediterranean Sea; and for sea-floor temperature they are east

Greenland, the western Barents and White seas, the north-ern Black Sea and the south-eastern Mediterranean Sea (north of Libya).

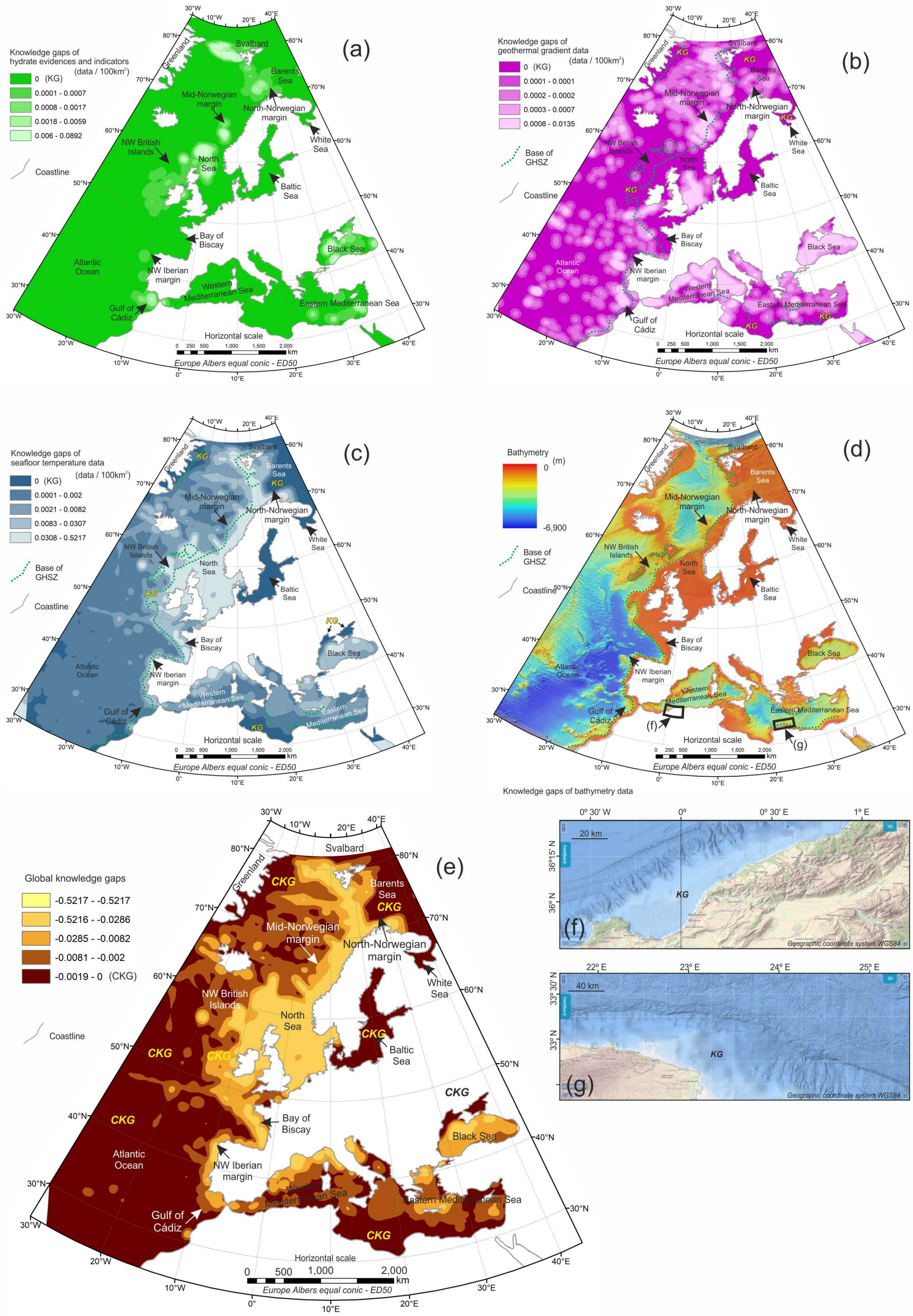

Figure 3-9 (previous page) Knowledge gaps assessment based on density kernel algorithm of ArcGIS®. Pixel value, number of hydrate evidences and indicators per 100,000 km^2. Parameters: population field, none; cell size, 5000; radius, 178,415 meters; areal units, square kilometres; method, geodesic. Knowledge gaps assessment of hydrate evidences and indicators (**a**), geothermal gradient (**b**), seafloor temperature (**c**) and bathymetry (**d**). (**e**) Global knowledge gap assessment. (**f**) Detail of knowledge gap in the Algerian margin. (**g**) Detail of knowledge gap in the Libyan margin. KG, knowledge gag; CKG, critical knowledge gap.

In general, the publicly available bathymetry data collected (EMODnet Bathymetry and IBCAO) have a quite acceptable quality and have been very useful for the objectives of this hydrate-related pan-European study. The original grid has a cell size of 100 x 100 m and the inference was calculated with a cell size of 5 x 5 km (Fig. 3-9).

3.4.2.3 Susceptibility assessment of seafloor areas affected by hydrate dissociation

The term ‘‘susceptibility’’ is employed here to define the likelihood of occurrence of hydrates in the sediment column, and subsequently the likelihood of them being affected by dissociation processes resulting from natural or human induced activities (liquefaction, explosions, collapse, crater-like depressions or submarine landslides). Gas hydrate dissociation can take place, driving large-scale natural gas release with potentially profound impacts, generating landslides, pockmarks, collapses, seafloor explosions and gas release.

In the susceptibility assessment, factors such as marine gas hydrate evidence, seismic indicators, seabed fluid flow structures and thickness of the GHSZ were taken into account. Each geological and geophysical item of evidence and indicator was weighted according to the confidence/certainty of finding hydrates at the site. The maximum weight (weight = 1) was given to recovered samples of gas hydrates or evidence of hydrate dissociation, such as degassing or liquation structures in gravity cores. Seismic indicators of the presence of gas hydrates or hydrocarbon seabed fluid flow in the vicinity of the GHSZ were weighted with a lower value (weight between 0.8 and 0.9).

Regarding the theoretical GHSZ, the seafloor was weighted in three categories: (i) sea-floor areas outside the theoretical GHSZ were excluded as not likely to be affected by hydrate dissociation processes; (ii) any location inside the GHSZ was selected as theoretically likely to suffer dissociation processes, and (iii). A strip at the up-dip limit of the GHSZ (50 m in thickness) was a critical area for these dissociation processes.

The susceptibility assessment was performed by map algebra, taking into account the control maps of density of hydrate evidence and indicators and the weighted map of the GHSZ on the seafloor (Fig. 3-10).

In order to assess the reliability of the susceptibility inference, a qualitative value of uncertainty (very high, high, middle, low and very low) was established as a function of the data density taken into account in the susceptibility calculation (Fig. 3-10). The reliability (u) is thus equal to the sum of the density maps of geothermal gradient (ρ_{gr}), seafloor temperature (ρ_{st}) and hydrate evidence and indicators (ρ_{hy}), $u = \rho_{gr} + \rho_{st} + \rho_{hy}$.

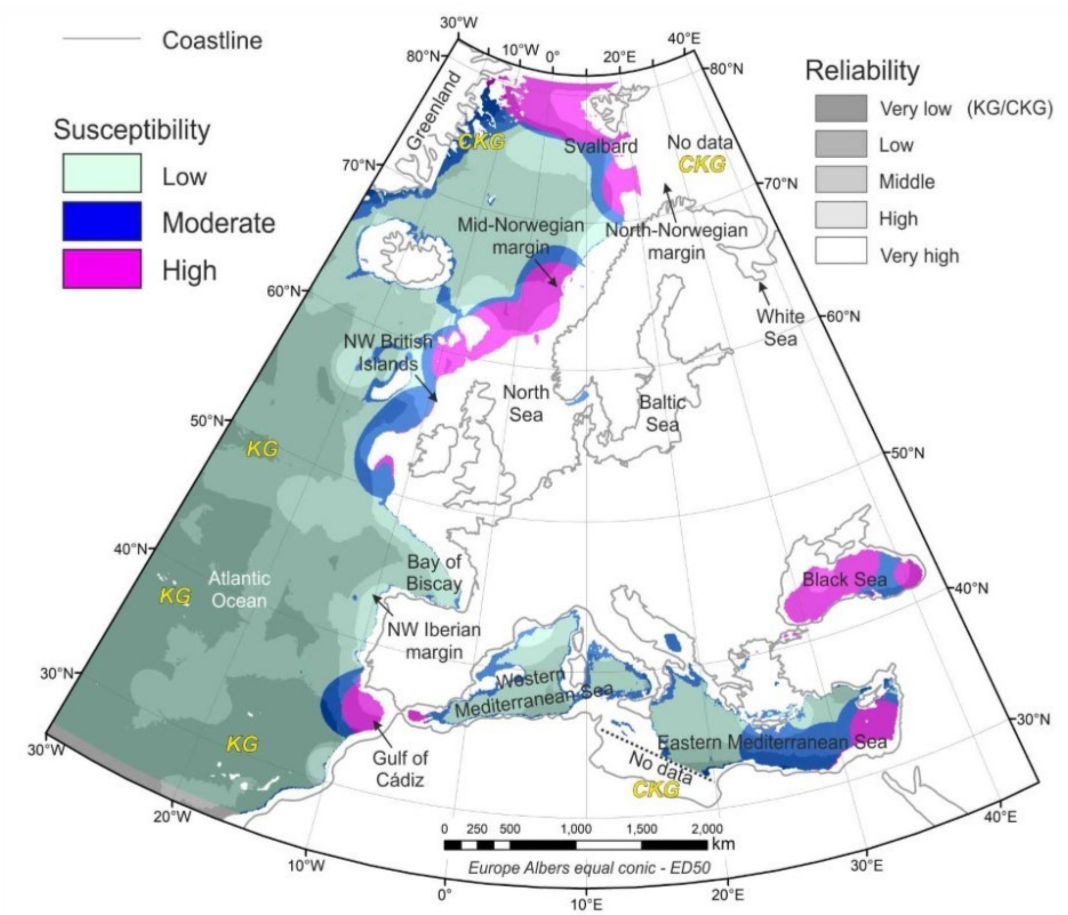

Figure 3-10 Susceptibility assessment of hydrate presence on the European continental margins and reliability of this prediction. KG, knowledge gap; CKG, critical knowledge gap.

Five levels of reliability were established. The reliability is considered “very low” with values from 0 to 36 data per 100,000 km^2, approximately less than ca. 1 datum per 50 km in mean; and “low”, “middle”, “high” and “very high” from 36 to 144, from 144 to 648, from 648 to 3,149, and from 3,149 to 15,218 data per 100,000 km^2, respectively. These levels were defined by the geometrical segmentation of u-value, except “very low” and “low”, which were defined by expert criteria. Very low reliability areas were catalogued as global knowledge gaps (KG in Figure 3-10) that are critical (CKG) in the vicinity of the up-dip limit of the GHSZ and hydrocarbon seabed fluid flow structures.

3.4.2.4 Potential safe geological storage of CO_2 as mixed gas hydrates: the "deep offshore" storage option

A "deep offshore" storage option is the trapping of CO_2 in onshore and offshore storage options. In this storage option, the CO_2-rich fluid (CO_2 and associated impurities) may be liquid and denser than seawater. In that case, the injected liquid CO_2 may be gravitationally trapped in the deep-sea sediments, either in the liquid state or in a solid state as gas hydrates.

The safety of "deep offshore" CO_2 storage will depend on the density of the injected CO_2 (including any impurities). Assuming 3.6 mol% of nitrogen in CO_2 stream (Table 3-3), the liquid density of this CO_2-rich fluid is higher than seawater below about 4,000 m water depth (Fig. 3-11). The bottom water temperature along the continental rise and the abyssal plain is almost constant (e.g. the mean value in the French EEZ is around 2.5°C). The seawater density is calculated by the 1980 International Equation of State (EOS-80) assuming that the salinity is almost constant along the vertical profile (e.g. S = 34.92 in the French EEZ).

Table 3-3 Pure CO_2 (CO_2-100) and CO2-96 stream compositions. Total volume for all non-condensable gases together (N_2, Ar, H_2, CH_4, CO, O_2) is recommended to be less than 4% (volume fraction) in CO_2 for carbon capture and storage.

Mole fraction (%)	CO_2-100 (Pure CO_2)	CO_2-96
CO_2	100	96.4
N_2	0	3.6

In this case, below about 4000 m water depth, the injected CO_2 may be therefore gravitationally trapped in the deep-sea sediments, either in the liquid state or in the solid state as gas hydrate. The ice-like hydrate phase can even clog pore space and cement grains, therefore reducing the permeability and forming a mechanically strong "self-sealing" cap in the overburden. Consequently, there is no need in that storage option of an overlying "cap rock", but only the need of sufficient high permeable sediments in deep-sea regions.

A study case for the potential safe ***CO_2 deep offshore storage capacity in the French and Spanish EEZs*** has been developed. Three safety criteria were defined in order to delimite a potential interesting zone for a safe deep offshore CO_2 storage: (i) a water column depth higher than 4,000 m to ensure that the density of the injected fluid is higher than the seawater density; (ii) a seafloor dip angle lower than 4° to avoid the risk of slumps coming from the continental slope; and (iii) a sediment thickness of at less 800 m.

Figure 3-11 Map of the area of the Bay of Biscay and Galicia Plateau showing locations of both CO_2 storage zones in the French EEZ (in green) and in the Spanish EEZ (in pink) after applying the three safety criteria (see text). Also shown are some boreholes (e.g. L400) and other data (e.g. BD9) physiographic features of interest in the studied area: (1) Trevelyan Escarpment, (2) Gascogne Knoll, (3) Jovellanos Seamount, (4) Charcot Seamounts and (5) Galicia Plateau.

The Generic Mapping Tool (GMT) has been used to apply these three criteria and to calculate the storage surfaces in both zones, i.e. 55,443 km^2 in the French EEZ and 107,289 km^2 in the Spanish EEZ (Table 3-4). By definition, the theoretical storage volume is the total physical porous volume that may host the CO_2-rich phase (gas hydrate or liquid). It assumes that the entire volume is accessible and utilized to its full capacity to store in the pore space. It represents therefore a maximum upper limit to a storage volume estimate GMT has also been used to calculate the theoretical storage volumes in both zones; the theoretical storage volume is the product of the three parameters (surface, thickness and porosity).

The French EEZ storage volume estimate of 3,422 km^3 is of the same order of magnitude as the total storage volume in the Spanish EEZ estimate of 3,700 km^3 (Table 3-4). There is, however, a big difference resulting from the seafloor depth: in the French case, almost all the stored volume is occupied by gas hydrates, whereas in the Spanish case, about the half (1,728 km^3) is occupied by CO_2 in hydrate phase and the other half (1,972 km^3) by liquid CO_2 (Table 3-4).

Table 3-4 *CO_2 storage capacity in the French EEZ and in the Spanish EEZ.*

		Surface[a] (km^2)	Mean thickness[b] (m)	Mean porosity	Theoretical storage volume (km^3)
French EEZ (CO_2-100)	Liquid	55,443	1213	0.3	20,173
French EEZ (CO_2-96)	Gas hydrate	55,442	115	0.53	3,422
Spanish EEZ (CO_2-96)	Gas hydrate	70,569	52	0.45	1,728
	Liquid	36,720	153	0.39	1,972

[a] Surface of CO_2-96 storage as gas hydrates is the subdomain where NBZ is included in GHSZ, and surface of CO_2-96 storage as a liquid is the subdomain where GHSZ is included in NBZ.

[b] Vertical thickness of the CO_2-96 storage volume, either in the liquid state or as gas hydrate: as a liquid, the thickness is twice the depth difference between the neutral buoyancy level and the gas hydrate formation level as gas hydrate, the thickness is the difference between the hydrate formation level and the neutral buoyancy level.

3.4.3 Lessons learned: recommendations on data collection and areas of interest

Two main lessons have been learned in the WP3: (i) recommendations on how future data should be collected and stored to be fully interoperable, and (ii) the identification of areas of interest for future projects.

Regarding recommendations on how future data should be collected, a lesson learned relates to the data model structure of the GIS-data base and the standards applied in order to improve their interoperability. Future hydrate-related information should be collected and stored compliant to the data model structure of the hydrate GIS-data base of GARAH project. Particularly, the four groups of items (location, property metadata, geo-descriptors and references) should be filled according to the standards as set forth in this project.

High susceptibility areas of gas hydrate dissociation are located in areas with a high density of evidence and indicators. The majority of gas hydrate evidence stored in the database was recovered in focused seabed fluid flow structures such as mud volcanoes or pockmarks. This is especially significant on the southern European margins in the Gulf of Cádiz and the eastern Mediterranean and Black seas. In these cases, gas hydrates are circumscribed to the feeder systems of the hydrocarbon fluid migration structures, which, subject to certain exceptions, do not exceed 0.1 to 1 km and 4 km in diameter for pockmarks and

mud volcanoes, respectively. In these areas, there is therefore no continuous spatial variation in the presence of hydrates.
There is still a need for a precise description of the physical and chemical behaviour of the injected fluid (liquid mixture of CO_2 and different impurities like H_2S) in the high pressure range (between 40 and 60 MPa) with respect to the geological matrix. In particularly, the variable fraction of clay in the deep-sea sediments on the gas hydrates formation may play an important role for the injectivity and the effective storage capacity. Large uncertainties remain with regard to the effective storage capacity due to the lack of knowledge of the influence of the sediment composition on the mixed gas hydrates formation kinetics and on the saturation level in the deep-offshore conditions. Molecular dynamics simulation may offer insights into atomic level mechanisms in high pressure conditions (40–60 MPa) that are not easily observable from an experimental point of view, for instance to study the influence of different types of clay surfaces on CO_2 hydrates formation kinetics. Thus, more experimental and modelling works still need to be done for a better understanding of the potential roles of gas hydrates for CO_2 geological storage.

Finally, taking into account the critical knowledge gaps, the theoretical thickness of the GHSZ and the density of records of hydrate evidence and indicators, oceanographic parameters (geothermal gradient, seafloor temperature and salinity) and seabed fluid flow structures, nine areas of interest for future scientific projects were defined: east Greenland and Svalbard, the west Barents and White seas, the northwest Norwegian margin, the northwest British Islands, the Bay of Biscay and the northwest Iberian margin, the southern Iberian and northern Moroccan margins, the Tunisian and Libyan margins, the eastern Mediterranean, and the Black and Marmara seas.

3.4.4 Deliverables

Name	Short description, remarks	Link
D.3.1	*List of the available hydrate related-data in a pan-European scope of interest to be incorporated into the GIS-database.*	Deliverable 3.1. Available hydrate related data in the European Continental Margins.
D.3.2	*Hydrate related GIS-database.*	Deliverable 3.2. Hydrates GIS-dataset
D.3.3	*Gas Hydrate overview report: knowledge gaps, possible areas of interest, geohazard assessment, potential role of CO_2-rich hydrates for the geological storage of CO_2*	Deliverable 3.3. Gas Hydrate overview report

3.5 WP4 GIS

3.5.1 Objectives

The objective of this work package is to lead the interactions with the GeoERA-IP project, to execute the parts of the Project Data Management Plan relating to IP and EDGI and to enable an efficient and consistent uptake and embedding of project results into the GeoERA-IP. WP4 is also responsible for communicating the requirements of the project to GeoERA-IP and vice versa ensure that the guidelines and standards provided by GeoERA-IP are properly implemented in the WP's 2 and 3 processes.

3.5.2 Results

The GeoERA Information Platform consist of several modules all of which the GARAH project has profited. The modules are:

- A web portal
- A project web site
- Web map services and web feature services
- A metadata database
- A digital archive for reports and unstructured data
- Multilingual keyword thesauri
- Code list repositories

In addition, the GARAH project also has added functionality that shows bibliographic references for a given feature.

By using the modules provided by the GeoERA Information Platform the GARAH project implemented the standards set by the GeoERA-IP. The result is that the data provided and their presentation by GARAH can easily be used by external partners, particularly by other projects that use the platform. The functionality that handles bibliographic references can - with a few adaptions - also be used by other projects. Future projects that use the GeoERA-IP web portal will also profit from the added functionality and testing done in projects like GARAH, as well as the collaboration that these projects had with the GeoERA-IP project.

The URL for the GARAH web portal is:
https://geusegdi01.geus.dk/egdi/?mapname=garah_preview

The information stored in the other modules (the metadata database, the archive for unstructured data, codelists etc.) are all accessible through this web portal.

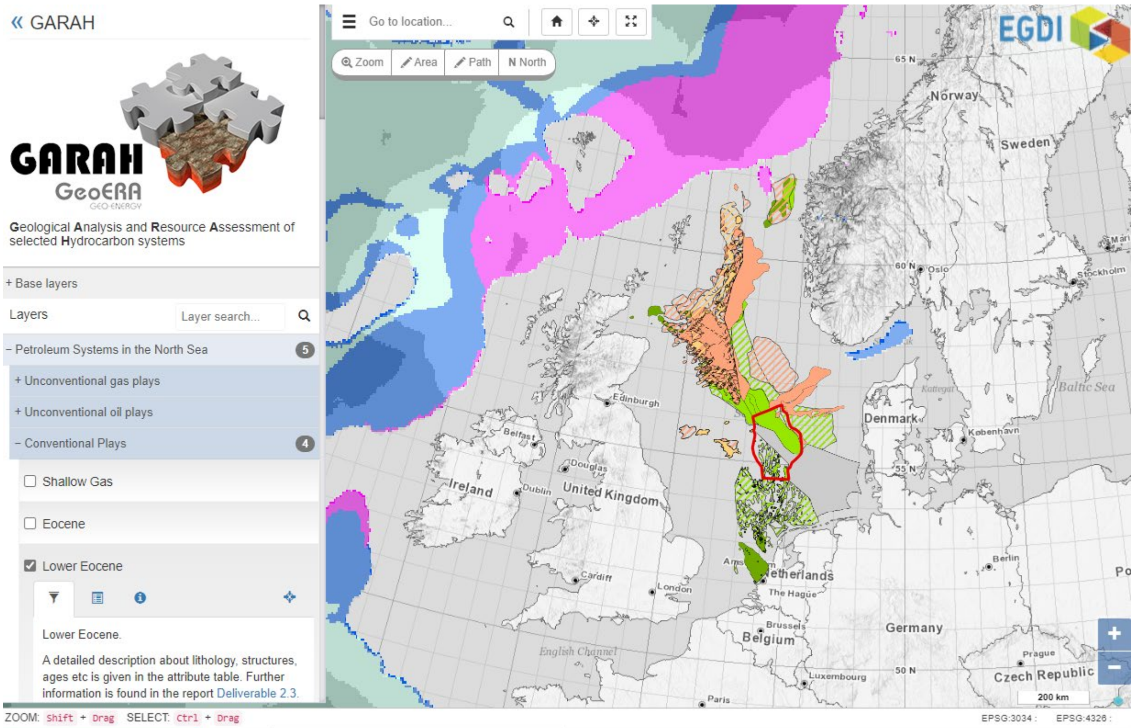

Figure 3-12 Screen dump from the GARAH web portal. The map shows layers that represent the main tasks of the GARAH project: 1) Conventional plays in the North Sea and their status (WP2); 2) The red line encircles the study area of the 3D basin and petroleum system modelling (also WP2); 3) The likelihood of gas hydrates in the sediment along the continental margins (WP3).

3.5.3 Deliverables

Name	Short description, remarks	Link
D.4.1	*Data selection and preparation*	Deliverable 4.1. Preliminary Data Selection to Provide Relevant Information in Assessing Hydrocarbon Resources in Subsurface
D.4.2	*Determination of requirements and standards - External communication with EGDI team*	Deliverable 4.2. Description of the work done on EGDI, guidelines for uploading updating and consulting information.
D.4.3	*Description of layers, metadata*	Deliverable 4.3. Assist in hydrocarbon ressource planning.
D.4.4	*Description of on-line EDGI GIS portal with GARAH online available results*	Deliverable 4.4. Online available results in GIS

4 FINAL REMARKS

4.1 Suggested or recommended workflows

The EUOGA method has been adopted from previous EU project and was developed for the onshore area. We here have extended it to the offshore as well. For future applications of this method we recommend including the calculation of absorbed oil as well as free oil to allow the calculation of OIIP. This feature is included in the basin modelling assessment (D.2.4) that shows that this is a significant component. We also recommend to include petrophysical descriptions to the workflow in order to address the saturations. The main added value of the 3D model is that the uncertainties following the EUOGA assessment approach are reduced as the definitions of the shale volumes are more accurate. For the conventional assessment the main advantage of using the 3D pilot model is the ability to examine and report the resources in a play-based manner that also allow different migration scenarios to be analyzed. However, the actual resources estimate depends on many different aspects and cannot be compared directly to the yet-to-find resource estimated based on a prospects and lead inventory.

The 3D BPSM model is the first publicly presented 3D basin and petroleum system model across the Danish, German and Dutch Central Graben area and serves as a pilot study to identify cross-border issues on horizon correlation. The conventional and unconventional resources could be assessed with this model and are in good agreement with the values found with the EUOGA method assessment and the official Danish resources published. Uncertainties in the BPSM model are, however, not evenly distributed, basically due to varying data coverage and density in the three modelled sectors of Denmark, Netherlands and Germany. However, in the future, the 3D BPSM model can be further refined for more detailed studies with higher model resolution e.g., by including faults and fault bounded structures using the HIKE dataset, with focus on smaller structural areas or on specific source rock layers or with focus towards resource assessment within specific play type areas. Thus, the harmonized dataset used for 3D BPSM model is a good starting point for more detailed yet-to-find assessments and may focus interest towards areas which at present are underexplored and need further assessment.

The gas hydrate data model structure of the GIS database has been designed based on the experience acquired from previous European hydrates initiatives (e.g. MIGRATE and PERGAMON COST actions). This data model structure should be taken into account as a standard in the workflows for future projects in the collection and storage of gas hydrate related information. In particular, for their interoperability and reutilization.

Until now, several pan-European hydrate related databases existed in different institutions and companies but were not harmonized and hat limited interoperability. The collection and harmonization of this information in a modern

GIS database have allowed establishing a new frame as a baseline with a pan-European scope for future hydrate scientific projects and recommendations for alternative seafloor uses. It is necessary to acquire further data in order to better understand these hydrate systems. In addition, WP3 has established standards of how future data should be collected and stored, as well as seafloor areas classified critical in respect to knowledge gaps, liable to store CO2 or susceptible to be affected by hydrates dissociation processes.
The workflows applied in the susceptibility assessment for seafloor area of gas hydrate dissociation are suggested for other pan-European regional assessments. This susceptibility assessment workflow is recommended for regional assessments where data appear scarce and scattered, and subsequently a detailed geohazard, vulnerability or risk assessment is unfeasible.

4.2 Outlook

The GARAH assessment of selected hydrocarbon systems and its reported total resource base, and especially the new unconventional resource estimate, may extend field life and postpone abandonment phase as the unconventional plays occur typically where production is already taking place. Understanding the current and potential resource may also support the shift from coal to domestic gas and should feed into planning and policy (particularly licensing of areas for exploration) by member states, as well as commercial exploration strategies. Our mapping of remaining knowledge gaps can inform academic research or programs of exploration sponsored by member states. The combined assessment of the resource base also has value for decarbonising energy in the subsurface of North Sea, with potential for providing carbon and other energy storage and production (e.g. blue hydrogen).

The construction of a Sigle **3D BPSM model** of the pilot study area highlighted the different interpretations and stratigraphic concepts of each country. The harmonized and comprehensive volume model allows now to show calculated results across country borders without interpolation and extrapolation artefacts caused by cross-border misalignments of geological features. Furthermore, the conventional and unconventional resources were calculated for the 3D model allowing for resource planning as well as spatial planning of the subsurface. Additionally, the 3D model can be used for planning of alternative usages e.g., storage of CO2 and other gases.

The GARAH gas hydrate study has demonstrated that gas hydrates in the European continental margins have been insufficiently studied from a global scope. There are critical knowledge gaps to be solved in the short-to -medium term. So far, WP3 has built an infrastructure of knowledge to be used as a baseline in future scientific projects. Understanding gas hydrates constitutes a unique scientific project with new data acquisition and a pan-European scope to tackle important issues such as:

I. what is the actual volume of gas hydrates beneath the European continental shelf?
II. what is the real fysical state of the hydrate systems on the European continental margins?
III. what will be the state (and the dynamic) of the European hydrate systems in the frame the global change in projected climate scenarios for the next 25, 50 and 100 years?
IV. Regarding the above scenarios, what will be real the impact of the dynamic of the gas hydrate systems on the sediment transference, fragile extremophile ecosystems, CO_2 storage, global change and human infrastructures?

Regarding hydrate related information, several issues remain open in order to understand the dynamic of hydrate system in the European continental margins. In this way, two groups of critical knowledge gaps are present, one focused in the spatial distribution of hydrates, and other concerning the parameters for nucleation/dissociation.

The main gap regarding the spatial distribution of hydrates, concerns the lack of:

(i) a continuous 3D geological model along the European continental margins
(ii) detailed and harmonized 3D model of the European hydrate systems.

Regarding parameters for nucleation/dissociation, some furtherquestions remain open concerning a continuous model and detailed values sedimentation rate, porosity, permeability, capillary pressure model, thermal conductivity (wet/dry & composite), heat flow and geothermal gradient, sediment density, gas hydrate composition and saturation, water activity (~salinity) and the presence of others inhibitor species, as well as the ocean primary production over seafloor.

5 GARAH PUBLICATION LIST

Peer-reviewed journals:

León, R., Llorente, M., Giménez-Moreno, C.J., 2021a. Marine Gas Hydrate Geohazard Assessment on the European Continental Margins. The Impact of Critical Knowledge Gaps. Applied Sciences 11. https://doi.org/10.3390/app11062865.

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Conference proceedings:

Arfai, J., Lutz, R., den Dulk, M., Jakobsen, F.C., Nelskamp, S., Ladage, S., Britze, P., 2019. 3D basin and petroleum system modelling in the North Sea Central Graben: a cross-border Dutch, German and Danish pilot study, GeoMünster 2019, Münster, Germany. http://www.geomuenster2019.de/assets/geomuenster_book_of_abstracts.pdf

León, R., Rochelle, C., Burnol, A., Giménez- Moreno, C.J., Nielsen, T., Hopper, J., Reguera, I., Mata, P., Thinon, I., Stewart, M.A., Aochi, H., Cervel, S., Nuñez-Varela, E., 2020a. A pan-European GIS focused on hydrate. A research base-line in geohazads and storage of CO2, EGU - General Assembly 2020, Vienna, Austria. https://doi.org/10.5194/egusphere-egu2020-4861.

León, R., Rochelle, C., Burnol, A., Giménez- Moreno, C.J., Nielsen, T., Hopper, J., Reguera, I., Mata, P., Thinon, I., Stewart, M.A., Aochi, H., Cervel, S., Nuñez-Varela, E., 2021b. Susceptibility assessment of gas hydrate dissociation occurrence along European continental margins and adjacent areas. GARAH project (GeoERA), EGU General Assembly 2021, vEGU21. https://doi.org/10.5194/egusphere-egu21-6407.

León, R., Rochelle, C., Burnol, A., Giménez-Moreno, C.J., Nielsen, T., Hopper, J., Reguera, I., Mata, P., Stewart, M.A., Cervel, S., 2020b. A pan-European GIS focused on gas hydrates: a research base-line in geohazards and geological storage of CO2 EGU General Assembly 2020, online. https://doi.org/10.5194/egusphere-egu2020-4861.

León, R., Rochelle, C., Burnol, A., Giménez-Moreno, C.J., Nielsen, T., Hopper, J., Reguera, I., Mata, P., Stewart, M.A., Cervel, S., 2021c. GARAHydrates: a research base-line in submarine geohazards and geological storage of CO2, X Congreso Nacional de Geología, Vitoria-Gasteiz, Spain, p. 755. https://sociedadgeologica.org/publicaciones/geotemas/geo-temas-18/

Lutz, R., Arfai, J., Nelskamp, S., Mathiesen, A., Schovsbo, N.H., Ladage, S., Britze, P., Stewart, M.A., 2020. 3D basin and petroleum system modelling in the North Sea Central Graben - a Dutch, German, Danish cross-border study, EGU - General Assembly 2020, Vienna, Austria. https://doi.org/10.5194/egusphere-egu2020-6873

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Nuñez-Varela, E., 2020. Cálculo del campo teórico de la zona de estabilidad de los hidratos de gas natural biogénico en los márgenes continentales europeos, Departamento de Ingeniería Geológica y Minera. Universidad

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None peer reviewed reports:

Schovsbo, N., Jakobsen, F., Britze, P., 2020a. Hydrocarbon Play Maps in the Danish Central Graben. GEUS. https://doi.org/10.13140/RG.2.2.28594.84169