Maturation modelling of the Jan Mayen Micro Continent: quantifying the thermal influence of igneous activity associated with a dual rift system on a potential hydrocarbon system.

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Project Grant – New proposal
Detailed project description

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Introduction

We propose a thermal, fluid flow and petroleum system modelling study in collaboration with GeoModelling Solutions GmbH (GMS), Volcanic Basin Petroleum Research AS (VBPR), and the Iceland GeoSurvey (ÍSOR).

The project consists of an initial database compilation and project setup phase followed by the two main work packages:

WP1: Large scale thermal modelling, which aims to develop a regionally realistic thermal and subsidence model for the microcontinent throughout the Cenozoic incorporating the two known breakup cycles. This multi-scale model approach is necessary to address the complex temperature evolution of the JMMC (Fig. 1) and its effects on the potential petroleum system.

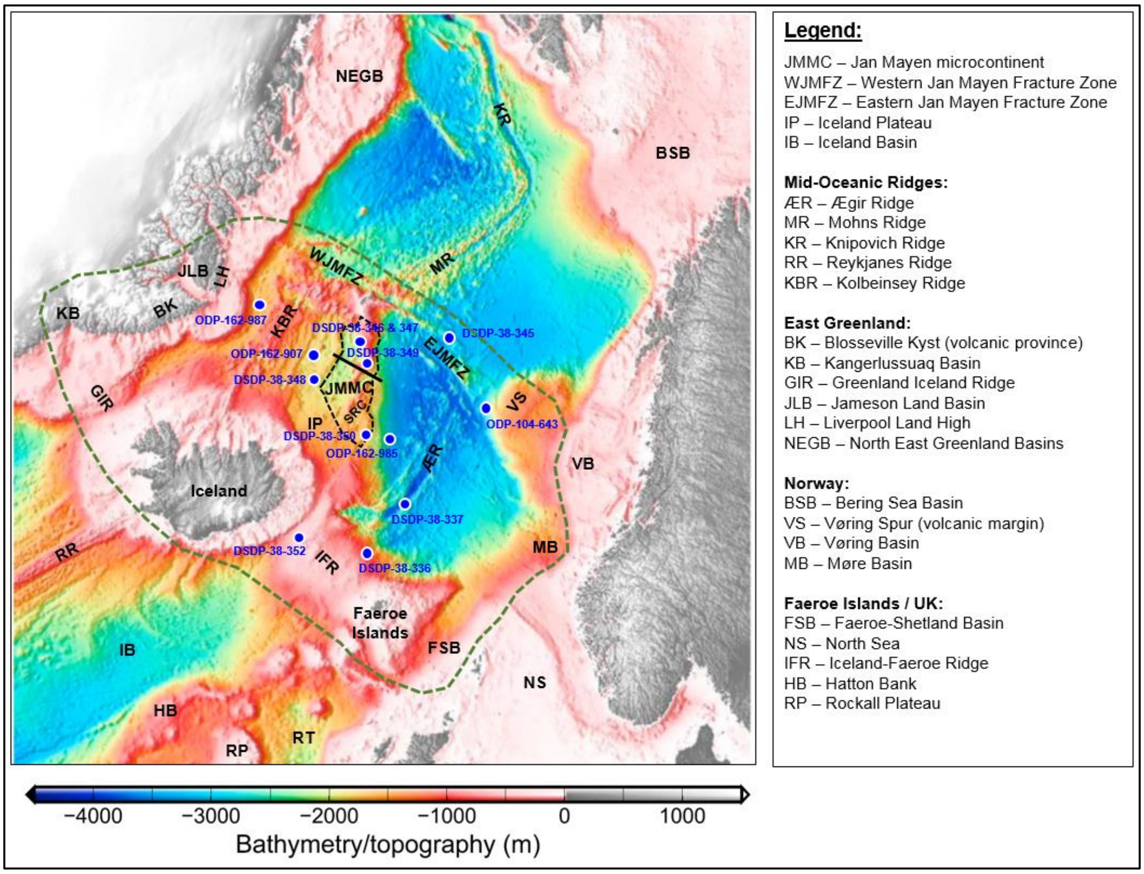

Figure 1. *Regional location map of the central NE Atlantic region based on ETOPO-2 bathymetry and topography (Smith & Sandwell 1997), and borehole locations in the central East Greenland – Jan Mayen micro-continent (JMMC, dashed black line) – Norwegian shelf corridor. The area of investigation (WP1) is marked with a dark green dashed line, and the target hydrocarbon model intersection (WP2) as a solid black line.*

WP2: Detailed transect hydrocarbon maturation modelling, including the stratigraphic framework integration of previous work conducted on the microcontinent and closest analogue areas, such as the Jameson Land Basin (JLB, Fig. 1) of the central East Greenland coast and the area of the Faroe-Shetland Basin (FSB, Fig. 1), both associated petroleum prospective volcanic basins. The work package aim is a consistent hydrocarbon maturation transect model for the North Dreki area (black line of Fig. 1) within the central and most prospective area of the microcontinent, calibrated to the results of WP1.

Objective

The objective of this project is to quantify the thermal maturation state of potentially prospective areas of the JMMC frontier exploration area. A basin maturation model forms a fundamental requirement for any realistic petroleum systems analysis and should incorporate the major tectonic evolution episodes and heat fluctuations. The JMMC has a complex history including the combined effects of uplift and subsidence processes with time constrained crustal heating and cooling related to the rift jump and dual rift system development. By incorporating extensive regional knowledge and data for the evolution of the central Northeast Atlantic corridor region into state of the art custom built petroleum systems modelling software we propose to constrain a best estimate multi-scale maturation model for the JMMC.

The main goal of such a multi-phased model is to enable us to generate a frontier basin maturity model for the Jan Mayen microcontinent, specifically the northern Dreki exploration area. Thus establishing the basic tool of any hydrocarbon systems predictions for the exploration areas, and an important tool for future decision making of exploration activities for the North-Dreki area (Figure 1).

Key research tasks

Detailed analysis of offshore borehole-, existing geothermal- and heat-flow data, tied into a newly developed geodynamic tectonostratigraphic model (Blischke et al. 2015), will be used as input data for the multi-phased model, specifically for the JMMC area. In particular investigation of the relations to the Jan Mayen Island volcanic system, the Kolbeinsey Ridge system, the proto-Iceland igneous system that is related to the Iceland hotspot-track, the Aegir Ridge system, and the Iceland Plateau Rift system (Brandsdóttir et al. 2015). Key to any maturation modelling is the host rock properties of the basin and therefore selected data from key stratigraphic units collected during seafloor sampling (VBPR / TGS 2011) will be compiled with other regional data to inform best estimates and sensitivities for the modelling parameters.

The thermal effects of rifting and magmatism proximal to continental crust is a key area where this project will develop new knowledge. This impact relates to increased temperatures where the crust thins and mantle upwelling occurs resulting in melting, however, the presence of significant temperature fluctuations associated with transient uplift and variations in magma productivity during the evolution of the NAIP have been identified spanning ~60 Ma (Nadin et al, 1997; Parnell-Turner et al. 2014; Millett et al. 2015). As part of this project we will compile temporal estimates of temperature fluctuations and test the sensitivity of the thermal models to these fluctuations.

Impact & Originality

This study will address major questions in regards to the magmatic evolution for the southern extent of the JMMC, as they are poorly constrained, and the interplay of different rifting and magmatic episodes on the thermal state of the JMMC crust that remains unclear to date. In particular, information about the thermodynamic processes are lacking for that region, which are essential to model source rock expulsion behaviour. This study has an interdisciplinary approach that combines the tectonostratigraphic framework into a complex thermodynamic computerized model.

Geological background and present day knowledge

The JMMC is a distinct structural entity located between the volcanic complex of the Jan Mayen Island (Svellingen & Pedersen 2003), which is part of the Jan Mayen Fracture Zone system, and the NE coastal shelf area of Iceland, in between the Norway Basin to the East and the Iceland Plateau to the south-southwest. Based on a large quantity studies since the 1970´s (e.g. Vogt et al. 1970; Talwani an Eldholm 1977; Gunnarsson et al. 1989; Johansen 1992; Doré et al. 1999; Lundin et al. 2002; Scott et al. 2005; Gaina et al. 2009; Blischke et al. 2011; Peron-Pinvidic et al. 2012ab; Gernigon et al. 2012) the JMMC has been interpreted as a fragment of continental origin. The boundaries of the micro-continent itself have been defined based on magnetic, gravity, refraction and reflection seismic data (Talwani & Eldholm 1977; Johansen 1992; Gaina et al.

2009; Peron-Pinvidic et al. 2012a). The micro-continent is interpreted as a ~100 km wide crustal fragment of the East Greenland central coast-line (Gaina et al. 2009), with stratigraphic and crustal structures corresponding to the conjugate central East Greenland coast. The southern extent of the micro-continent is underexplored, due to poor data coverage, seismic data quality and – processing issues.

The JMMC contains several major unconformities and structures, such as listric faults, rotated fault blocks, volcanic passive margins, and small-scale revers faults. These structures appear to be related to the complex opening processes on either side of the micro-continent. The opening process comprises several major events, which started with the opening of the Ægir Ridge, east of the micro-continent during the first primary phase of extensional processes (rift to drift) affecting the JMMC during Early Eocene (Ypresian 55.9 – 47.9 Ma). This process was not gradual and coincided with major volcanic activity forming a distinct volcanic margin (Blischke et al. 2015) with igneous complexes and sill intrusions that are recorded in particular along the eastern flank and close to the ridge crests, primarily intruded into Eocene to Early Oligocene sediment strata (Peron-Pinvidic et al. 2012a; Blischke et al., 2014). The second main phase is described as a rifting transition and uplift along the southeastern and southern flanks of the micro-continent from the Mid-Eocene to Early Miocene Oligocene. However, very little is known for that stage of transition. The third, and final stage is associated with the formation of the Kolbeinsey Ridge system along the western flank of the micro-continent during the Early Miocene, separating the JMMC from East Greenland (Gunnarsson et al. 1989). During that stage the youngest large-scale igneous event is identified as a flat laying, opaque reflection seismic marker, the so called "F-Reflector" (Gunnarsson et al. 1989), covering an area of approximately 18400 km^2 of the "low-lands" between the micro-continent´s ridges, along the western and southern flank of the Jan Mayen Ridges, and within the Jan Mayen Trough area, west of the Jan Mayen Southern Ridge Complex (SRC, Figure 1). However the actual age and composition of those igneous formations are not known, as geophysical records can only give indirect evidence of the igneous activity. The igneous formations were most likely emplaced during the period of the JMMC - Mid-East-Greenland breakup volcanism (~C7-C6) and the establishment of the Kolbeinsey Ridge system. The evolution of the micro-continent appears to be controlled by deep structures, which are interpreted to be linked to the development of the GIFID, a part of the NAIP (Hopper et al. 2014), forming a complex WNW-ESE striking ridge structure, including the Greenland-Iceland Ridge (GIR), the entire Iceland shelf, and the Iceland-Faeroe Ridge (IFR), which resulted from increased magmatic activity of the Iceland plume (Morgan 1981; Holbrook & Keleman 1993; Lawver & Müller 1994; Torsvik et al. 2001).

Present state of knowledge in the field

We have a well-developed understanding of the tectonostratigraphic settings of the JMMC from breakup time to present. However the thermodynamic and uplift history has not been investigated in detail. The specific settings of the microcontinent can be described as the following.

(1) During the uppermost *Paleocene to Middle Eocene*, tremendous igneous activities affected the JMMC, forming escarpments, sills, larger-scale intrusive sections, especially along the East Ridge Flank of the JMMC (Gunnarsson et al. 1989). Several stages of activity along the SE edges of the micro-continent during the separation from the Norwegian margin can be described, including observations in two key wells (DSDP 38-348 & 350; Figure 1) that reached through the entire overlying sediment cover into the basalt section, also considered as "acoustic basement". Well DSDP 38-350 reaches through the Tertiary sediment section into an Eocene basalt sill intrusion. Still, this single well data control is of poor quality, as the geological age for the Eocene basalt intrusion ranges from 33 to 50 Ma, making an accurate tie to the geo-chronological model not possible.

(2) The geological period from the *Late Eocene to Early Oligocene* is associated with an intensive magmatic activity along the flanks of the JMMC, with numerous sills, larger scale intrusive sections, and probably large-scale lava flows (F-Marker). The origin of the large-scale lava flows are unknown. One hypothesis postulates that these lava flows were originally coming from and elevated area to the south of the JMMC, as results of a major volcanic eruption, or a series of eruptions that coats large stretches of the land into the low areas between the elevated ridges of the JMMC (Blischke et al. 2015). However, only indirect data exists (refraction-/reflection seismic, gravity, and magnetic data) for this hypothesis, and the observed igneous activities in the strata can only be described with no direct compositional or available age data.

(3) Between the *Early to Middle Miocene*, shallow and regional extensive intrusions are emplaced along and over the western and southwestern areas of the micro-continent, which occurred most likely simultaneous as the opening of the Kolbeinsey Ridge. This sub-region of the JMMC margin also includes a calibration well, DSDP 38-348, as a borehole that reached through the Neogene sediment section into the Miocene basalt cover, but has not been analysed for its reported tephra layers. The majority of the offshore cores, located west of the micro-continent, include tephra layers of Miocene age. Here a connection of igneous activities in age can be observed along the easternmost edge of the Blosseville Kyst (Larsen et al. 2013).

Research plan and methology

The following summarises the sub-division of the project into two main work packages: WP1: *Large scale thermal model* and WP2: *Detailed transect modelling*. This multi-scale model approach is necessary to address the complex temperature evolution of the JMMC and its potential petroleum system.

The building of such a 2-dimensional maturation model involves the combination of a large scale thermal model with a specified transection across an area of most interest to obtain a scientific data based outcome. Therefore the project will be conducted within 2 stages.

WP1: Large Scale Thermal Model

The goal of this work package consists of developing a large scale thermal model that deals with ridges, transforms, and the Iceland hot-spot influences of the adjacent Greenland-Iceland-Faroe igneous province (GIFIC, Hjartarson et al. 2014) that have affected all flanks of the JMMC with a specific chronostratigraphic order (Blischke et al. 2014). The input data required are:

- Detailed spreading rates through time
- Ridge jump and architecture
- Temperature calibration data

Based on this we develop the kinematics of the model. Special focus has to lie on the shallow sections of the spreading system, as this would have had a major influence on the state of temperature in the sediment succession and crustal blocks in the vicinity see example case in (**Error! Reference source not found.**).

Building up on such a tailored 3D finite element method model, we can create more realistic boundary conditions for the maturation model. Boundaries that lie across the East Greenland – JMMC – Norway margin corridor, with its northern boundary, the Jan Mayen Fracture Zone & Mohn´s mid-oceanic rift system, and its southern boundary condition, the Greenland – Iceland - Faroe Ridge igneous complex (GIFIC).

Furthermore are material property distributions for the stratigraphic framework included, which calibrate the static model properties utilized from analogue areas, such as the central East Greenland coast and the Faroe-Shetland basin.

WP2: Detailed Transect Modelling

This work package focuses on the development of a detailed model for the thermal and hydrocarbon maturation evolution of a representative transect across Jan Mayen (**Error! Reference source not found.**). Required input includes depth converted, interpreted seismic, rock properties, ages, and temperature calibration data (temperature, heatflow, vitrinite, AFT), and seafloor sampling data. Horizons must include the oldest source rocks and at least one horizon per start and end of the various rift phases. The transect model will account for the thermo-tectono-stratigraphic evolution of the JMMC. In addition, WP2 is linked together with the thermal model that is developed in WP1. The two models will be iteratively improved to obtain the range of realistic scenarios and the best fit scenario. Detailed fault modelling is not considered here.

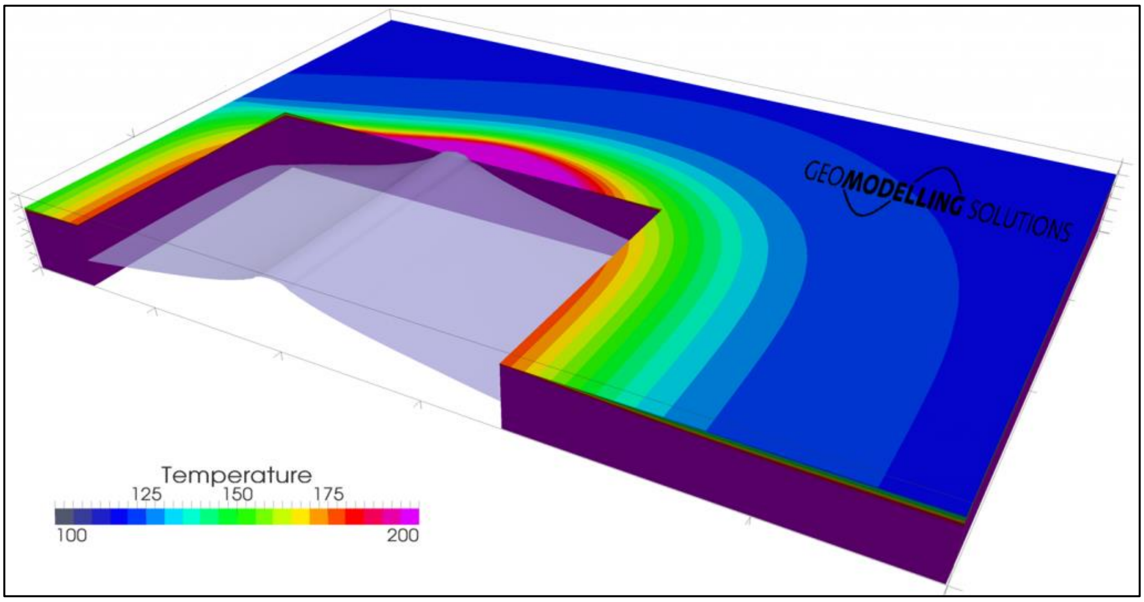

Figure 2. *Thermal influence of a moving ridge on nearby sedimentary basins. Important for breakup and transform systems. 3D finite element model.*

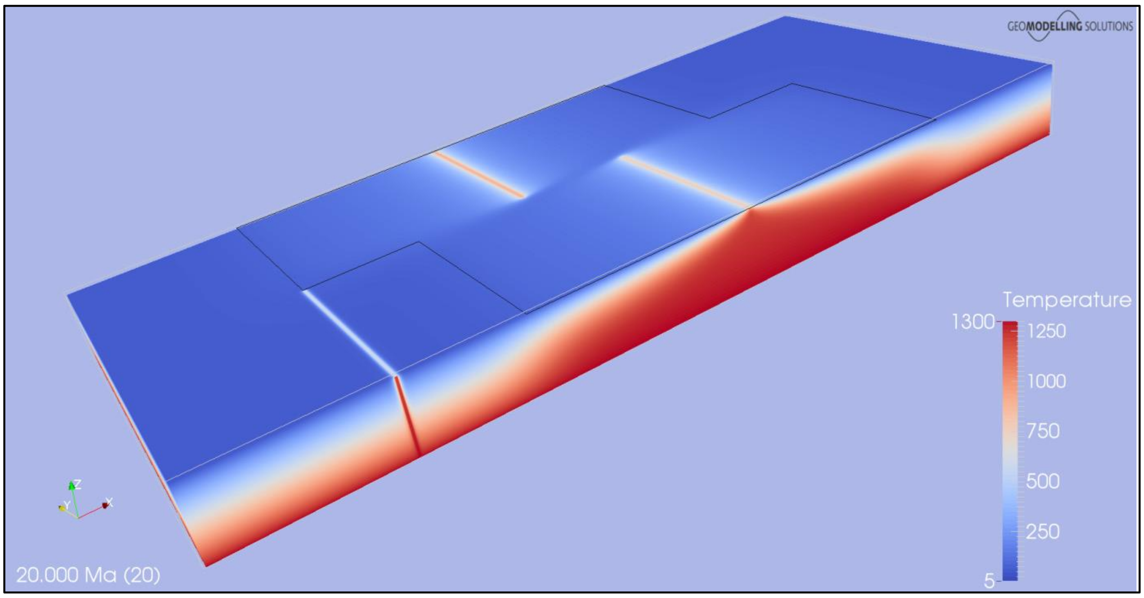

Figure 3. *Temperature state in the Ægir and Kolbeinsey Ridge system, where ridge jumps occur. The primary thermal anomaly of the Iceland shelf is necessary to include to this system.*

GMS has experience with both types of models that we can build upon in this project. Regarding the large scale thermal model we are in the fortunate position that we have previously worked on a related project for *Det norske oljeselskap,* which could serve as the basis for more refined models and with permission to publish the results. Figure **3**2 and Figure 3 show the temperature influence of a moving ridge and the temperature state in this system that includes transforms as well as ridge jumps.

Project timeframe

Project start date : September 2016

Project end date: September 2017

Year	2016				2017			
Quarter	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Project startup meeting in Oslo				M				
Model input database completed								
Tectonostratigraphic input JMMC				x	x			
Source rock data compilation				x	x			
Heatflow, or geothermal gradient data compilation				x	x			
Analogue area (JLB, FSB, central Norwegian Shelf) data compilation				x	x			
Project status meeting in Iceland					M			
Large scale thermal model complete								
Data implementation and process setup				x				
Model build and iterations					x			
Project update meeting in Oslo						M		
Detailed model for the thermal and hydrocarbon maturation evolution complete								
Setup and implementing Tectono-stratigraphy, and analogue source rock property data						x		
Hydrocarbon modelling and iterations						x	x	
Final project presentation in Iceland								M
Submit final project report							x	x

Milestones

Milestones	Date
Model input database completed	December 2016
Project status meeting in Iceland	January 2017
Large scale thermal model complete	April 2017
Project update meeting in Oslo	April 2017
Detailed model for the thermal and hydrocarbon maturation evolution complete	August 2017
Final project presentation in Iceland	September 2017
Submit final project report	September 2017

Deliverables

- Model input database:
  - Contribute selected TOC, Ro% and organic litho-facies data for key age intervals from the VBPR and TGS seafloor sampling project (2011) as input data for the project modelling full analytic data set collected during project phase (as electronic version).

- Compilation of a mantle potential temperature curve estimate for beneath the JMMC from breakup to present based on available literature data as input for the basin model.

- Adding regional analogue case information to the modelling parameter setup and data compilation.

- Large scale thermal model across the East Greenland – JMMC – Norway margin for defining the boundary conditions.
- Detailed transect model defining the hydrocarbon maturation process for the main hydrocarbon target exploration area for the microcontinent.
- Intermediate and final project presentations
- Final project report and summary.

Team members

Anett Blischke (ÍSOR, geologist-geophysicist, PhD student with the University of Iceland); expertise: structural geology and geophysics, in particular structural modelling and geophysical data interpretation to constrain tectonic evolutions though time; long experience working with the JMMC within the tectonic evolution of the NAIP. She will coordinate the collaboration with NAGTEC and the Dreki area exploration project, and implement the new constrain about provenance and age of the magmatic features into the geo-tectonic evolution model of the JMMC.

Guðni Axelsson (ÍSOR, senior geophysicist, Director Geothermal Training, project advisor); has worked at ÍSOR, and its predecessor Orkustofnun, since 1985. He specializes in geothermal reservoir physics, including testing, monitoring and modelling of geothermal reservoirs, as well having long experience in geothermal resource management, including reinjection, tracer tests and sustainable utilization. He has e.g. worked on geothermal projects in Iceland, China, The Philippines, Turkey, Kenya, Central-America and Europe. Gudni has been involved in world-wide geothermal training and technology transfer for more than 25 years, in particular through the United Nations University Geothermal Training Programme. He is a member of the editorial board of Geothermics, a member of the Science Academy of the GEORG Geothermal Research Group, as well as the alternate member for Iceland in the Geothermal Implementing Agreement of the IEA. Gudni is first author of about 50 international publications, co-author of numerous others as well as author or co-author of more than 250 technical reports

Dr. Daniel W. Schmid (GMS co-founder, research scientist, co-proposer); is a co-founder of GeoModelling Solutions with a background in structural geology and numerical modelling. Over the last 15 years, he has developed commercial basin modelling tools, worked on a large number of commissioned research projects and performed petroleum system studies worldwide. Dani also developed a 3D temperature model that investigates ridge jump and transforms that the project with ISOR will build upon. With regards to the project, Dani will refine and adapt the large scale 3D thermal model to capture the actual first-order Cenozoic evolution of Jan Mayen. The results from the model will be benchmarked data from the study area. Dani will also contribute to the development and execution of the basin model using the detailed transect and interface the two models and scales.

Dr. Karthik Herman Iyer (GMS, research scientist, collaborator); has a background in fluid-rock interaction which he has complemented with hydrothermal system modelling. His previous work relates to the development of fluid flow models that incorporate fluid-rock chemical interactions at divergent and convergent plate boundaries. His current work also includes the quantification of sill intrusion effects with regard to metamorphism, source rock maturation, hydrocarbon migration and its impact on the paleoclimate. Over the last two years, he has been working for GeoModelling Solutions where he expanded his skillset to include petroleum system and basin modelling. His experience covers the entire Norwegian Continental Shelf. Karthik's contribution to the project will include the construction, execution and analysis of the basin model for detailed transect analysis. This work will also cover benchmarking model results against the available data (heat flow, temperature, sea floor sampling). Furthermore, Karthik will develop a comprehensive petroleum system model to investigate likely hydrocarbon maturation in the study area.

Dr. Lars Rüpke (GMS, research scientist, collaborator); is a partner at GeoModelling Solutions with a background in geophysics and numerical modelling. Lars is professor of seafloor modelling at the Helmholtz Centre for Ocean Research Kiel, GEOMAR. His project based consulting work for GeoModelling Solutions has its main focus on the temperature reconstruction in sedimentary basins. Combining his expertise with large scale (mantle) systems, mid-ocean ridges, hydrothermal systems and sedimentary basins makes him one of the leading experts in the field. Lars will be in charge of quality control for the basin and flow models developed by the other team members and to analyse and derive the conditions required such that the models comply with the available information for the studied system.

Dr. John Millett (VBPR, research scientist, co-proposer); is a full time geologist at Volcanic Basin Petroleum Research AS (VBPR AS), and has been focusing on coordinating and developing the VMAPP (Volcanic Margins and Petroleum Prospectivity) multi-client project, which provides training and research on all aspects of the petroleum system within volcanic basins. He also holds a Honorary Research Fellow position with the University of Aberdeen, and his research covers a wide range of disciplines relating to the study of Large Igneous Province volcanism including stratigraphy, geochemistry, pertrophysics and volcanology.

Dr. Sverre Planke (VBPR CEO, research scientist, project liaison); is the CEO and co-founder of VBPR and holds a Professor II (20% position) at the Centre for Earth Evolution and Dynamics (CEED) Centre of Excellence, University of Oslo. He has over 20 year's research experience focusing on seismic imaging of volcanic constructions and understanding of tectono-magmatic continental breakup processes specializing in the North Atlantic. Also co-founder of the Norway based P-Cable seismic acquisition company and involved in seafloor sampling around the North Atlantic Basins including the JMMC in a joint project with TGS in 2011.

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