# CEED tectonic and basin modelling team:

***Integrated basin studies – linking plate tectonics, mantle dynamics and surface processes to basin evolution***

A major part of petroleum exploration is the evaluation of risks, which is typically performed by assessment of the six risk factors: (1) reservoir presence; (2) reservoir quality; (3) source rock presence; (4) petroleum charge (maturation and timing); (5) petroleum migration; (6) trap and seal (e.g. Baur et al., 2018). Basin and petroleum system modelling (BPSM) links geological and geophysical observations and predictive models of where to find hydrocarbons with long-term large-scale external processes, the geodynamic processes. Generally, factors that can be imaged, or drilled, are well constrained in BPSM. This is in part why the industry generally is successful in building predictive models of structure and presence of sediments with reservoir potential and source rocks. In contrast, taking geodynamic processes into account is limited to models existing at the time of analysis; and thus, this accounting is incomplete/uncertain. Furthermore, seal and petroleum charge/migration, the factors which are most affected by geodynamic processes, are believed to be the most common reasons for failure (dry wells) (Rayeva et al., 2014), a view that is recently confirmed for the Norwegian continental shelf (NCS) as well (NPD, 2018). Despite their importance, these factors have so far attracted surprisingly little attention in research compared to other risk factors such as reservoir presence/quality and traps which are imaged by seismic data (Baur et al., 2018; Curry, 2018; Hartz et al., 2018). This proposal aims to reduce risks in basin and petroleum system analyses by reducing uncertainties in the influence of geodynamic processes.

Geodynamic processes cannot be directly imaged, but still are of key importance. For example large-scale processes within the Earth's interior are linked to surface processes having impact on the vertical motion and temperature histories of sedimentary basins. At regional scales, plate tectonics (Fig. 1) play an important role and the associated paleogeography and paleoclimate have large impact on provenance and depositional environments (source-to-sink). Forces raised along plate boundaries and caused by lithosphere-mantle interaction lead to intraplate deformations and non-trivial stress patterns. Thus, improvements in understanding of geodynamic processes, and translating of these into BSPM have significant potential to reduce future well failures particularly when caused by lack of petroleum charge. A precondition for success with this is improved constraints for the vertical motion and temperature histories by integrating effects of mantle dynamics and plate tectonics. Furthermore, to evaluate seals improved understanding of strain related to intraplate stresses (both present and past) and pressure are needed.

The Centre for Earth Evolution and Dynamics (CEED) is a Centre of Excellence funded by the Research Council of Norway. A part of the main vision of CEED is to develop an Earth model that explains how mantle processes drive plate tectonics and control shallow, including crustal, processes. In the recent mid-term evaluation (RCN, 2017) the overall assessment by the international review panel was **exceptional**. They concluded that CEED is carrying out cutting-edge research and has assembled a world-renowned group of researchers, addressing first order questions concerning the internal dynamics of, and life on, planet Earth. Thus, CEED is a unique environment that can find links between large-scale long-term geodynamic processes with complex evolution of sedimentary basins and petroleum systems.

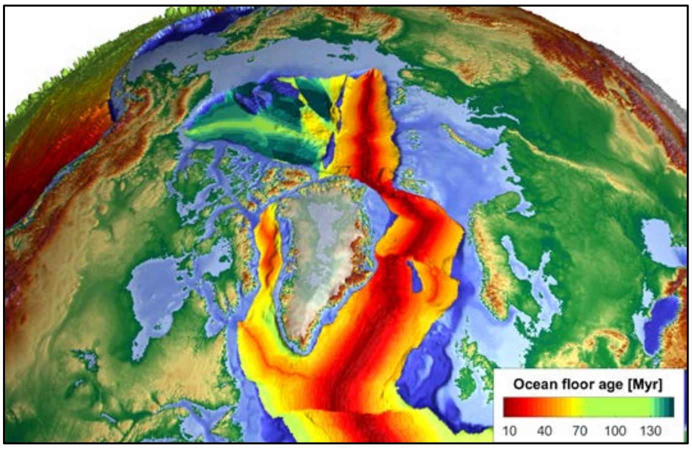



***Figure 1*** Age of the North Atlantic-Arctic ocean floor, bathymetry of shelf areas and topography of surrounding land masses.

We are seeking funding and scientific collaboration to establish an industry-academia consortium (CEED-MOD) with focus on quantitative tectonic/geodynamic and basin analyses. The overall goal is to increase our understanding of basin formation and evolution by combining key academic competences with industry long-term experience from basin and petroleum systems studies on the NCS. This will provide new and important knowledge for increasing production and reducing risk in exploration efforts on the NCS.

In this consortium we will integrate fundamental knowledge of geological structures and geodynamic processes into quantitative basin analyses for a better understanding of how sedimentary basins on the Norwegian continental shelf/margin have developed in time and space. By doing this we will establish an improved quantitative framework for future basin studies also having significant impact on BPSM carried out by industry. It is, as such, not our aim to perform BPSM but we aim to research the geodynamic input into future advanced BPSM. The proposed work is also an excellent example of how basic and applied research should be linked and how academic and industry can complement each other.

Below, we outline key enigmatic problems limiting our understanding of the NCS. Resolving these problems requires deep knowledge in many Earth science disciplines. CEED has key competences within all relevant research fields that we aim at integrating with theoretical and practical knowledge of the involved industrial partners.

## 1. Background

Understanding basin structure and evolution is a crucial task in the petroleum industry, which collectively has accumulated great experience in this field and uses advanced data acquisition, processing, and interpretation techniques. Yet, several aspects of basin structure and petroleum system analysis are largely overlooked and may be improved through close collaboration and integration with the more basic and theoretical approach of academia. We demonstrate such a framework here by emphasizing two aspects of basin modelling: (1) Basin and petroleum system modelling (BPSM) cannot be always treated by simplified models, the basis of the traditional BPSMs; and NCS presents examples of basin evolution that requires more complex approach. (2) Better understanding requires a multi-scale approach and often cannot be treated with traditional BPSMs which ignore the influence of large-scale mechanisms controlling the evolution and modern state of basins on the NCS.

Sedimentary basins on the NCS are dominantly extensional in origin. When doing quantitative basin analysis and petroleum system modelling it is therefore natural to use computer (numerical) tools based on a McKenzie-type model (Mckenzie, 1978) for basin formation and development/evolution. However, detailed mapping and analyses of many of these basins have shown that there are additional processes contributing to the vertical motion and temperature histories. For example, as an observed contrast to the classic McKenzie model is the fact that post-rift sequences are often considerably thicker than the syn-rift deposits in nature (Hartz et al., 2017). If we assume that lithosphere stretching/thinning is the main (or even only) mechanism driving subsidence we have to stretch the lithosphere excessively to fit the observed subsidence giving a basin scenario that is hotter than necessary. This example illustrates that isolating basins from deep Earth processes may result in inaccurate thermal evolution of the basin. Similarly, extensional basins associated with transform margins do not fit to a simple 2D description and require thorough 3D analysis (Le Pourhiet et al., 2017).

Anomalous tectonic subsidence has been observed both at rifted margins and within intra-cratonic settings. Several regional subsidence events covering wide areas and associated with limited or no faulting have affected the NCS since the Late Paleozoic. **The origin of anomalous tectonic subsidence (ATS)** of large intracontinental basins long after their most recent phase of extension and last thermal perturbation is the subject of a long-standing debate (e.g., Heine et al., 2008). ATS cannot be explained by a simple extension model and thus needs large-scale analysis of variety of tectonic features in the search of responsible mechanisms; for example, deep-Earth long-term processes such as sinking slabs and rising plumes may contribute to the subsidence of these tectonically stable basins. Testing this hypothesis requires modelling of how the deep Earth mantle affects lithosphere on the scale of hundreds to thousands km in both vertical and horizontal directions and through deep time.

Large-scale processes controlling basin architecture and petroleum systems in the NCS include **surface processes** which are especially active during Quaternary. Onshore erosion, offshore sediment accumulation, and periodical glacial loading/rebound lead to differential vertical motions of petroleum systems, depocenter relocations, and changes in drainage patterns. For example, Stoddart (2014) suggested that the load from large ice masses during past glaciation periods may have lead to significant periodic tilting of the Utsira High in the North Sea. The quantification of such processes requires analysis of surface-lithosphere interaction on the scale of hundreds to thousands km.

**Understanding paleo- and modern stresses** is also of major importance to the petroleum industry. The long-term stress evolution may explain the evolution of basins and thus lead to better understanding of basin architecture. Stress analysis is important for petroleum exploration in general as stresses are a major control of stability of wells, integrity of top and fault-seals, migration routes and drainage strategy. Exploration geologists will have access to all pressure data and most stress data from the NCS and adjacent shelves. Yet, when it comes to new exploration wells, all companies use empirical estimates despite accurate prediction is very important. Predicting the stress pattern requires accounting for areas, which are even larger than the ones discussed for the surface processes (e.g., Medvedev, 2016). For example, the North Sea realm is located on the border of two distinct dynamic systems (Gölke and Coblentz, 1996): the Central Europe province controlled by the Alps and the North Atlantic dynamic province, which includes the northernmost North Sea, the mid-Norwegian margin, and the SW Barents Sea and controlled by the active mid-oceanic ridge and the Iceland plume.

Paleo-stress may be considered as a link between global/regional tectonic events and local geological features and this way paleo-stress can constrain the timing of some local geological events (e.g., uplift, subsidence, trap formation) that are difficult to date by other means. Timing information is sometimes difficult to obtain because stratigraphic control is lacking. For example, in the Barents Sea it is notoriously difficult, say impossible, to date events younger than mid-Cretaceous because the entire region was uplifted and eroded in Cenozoic times (Henriksen et al., 2011).

In some areas of the NCS, understanding the basin evolution and estimation of the potential of particular petroleum system requires **understanding and quantification of an interaction of different mechanisms**. For example, the integrity of seals in the SW Barents Sea is regulated by a stress field controlled by the Iceland plume (e.g., Gac et al., 2016; Medvedev et al., 2016), this main stress field is periodically disturbed by ice sheet loads (e.g., Grollimund & Zoback, 2003) and active erosion (e.g., Medvedev et al., 2018), the resistance to the stress is controlled by 3D thermal field of this transform margin (Gac et al., 2016) and by some rheological characteristics inherited from the opening of the North Atlantic.

## 2. Proposed research

The proposed research does not intend to develop new basin modelling software, but rather to understand and quantify processes that control basin evolution still largely overlooked in the modern basin and petroleum system analysis. Key processes to integrate and address, which are closely interlinked, include: (1) Plate tectonics; (2) Mantle dynamics; (3) Intra-plate stress; (4) Surface processes; (5) Complex processes during basin evolution.

Such processes have different spatial and temporal characteristics (wavelength, amplitude, timing/duration), but all may contribute significantly to evolution of sedimentary basins. Analysis of these processes requires identification of effects of individual processes/mechanisms, quantification of their influence, and study of interplay between such.

The understanding of the early development, long-term evolution, and modern architecture of sedimentary basins usually requires the integration of data on the deep Earth, as well as quantifications by means of kinematic-sedimentological and thermomechanical modelling approaches coupling both surface and deep processes.

2D and 3D modelling tools are progressively developed to treat deep thermo-mechanical processes of the mantle and lithosphere, geomechanics of the upper crust and sediments (compaction, pressure-solution and fracturing of seals and reservoirs), basin-scale fluid and sediment transfers (development of overpressures, hydrocarbon generation and migration). The modelling approaches in these tools differ due to different time and spatial length scales and different physical processes addressed. Thus, the modelling can be rarely combined in a single tool and requires approach based on a combination of multiple expertises.

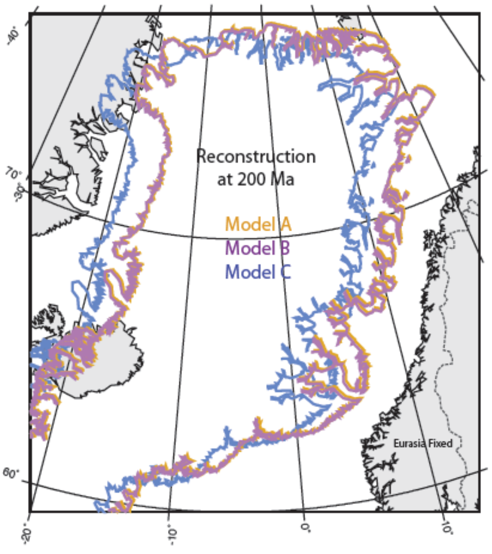
The following is the set of proposed directions, hypotheses, and available tools to treat the particular problems of basin modelling. One of the main aims of CEED, as a Norwegian Centre of Excellence, is to link the first two major topics below, plate tectonics and mantle dynamics, and thus separation in these themes is not really distinct.

### 2.1. Plate tectonics

The basin evolution must be linked to regional plate tectonics and to paleogeographic location; identifying and linking regional plate tectonics and basin formation/development on conjugate margins is especially important for NCS. The conjugate NE Atlantic margins experienced long-term post-Caledonian extension characterized by a number of stretching/thinning events prior to final continental breakup at the Paleocene-Eocene transition. This pre-drift extension/thinning has to be quantified and restored in order to obtain proper paleogeographic reconstructions (Fig. 2). In areas of oblique extension or strike-slip the opening gives rise to transtension and transpression that affect adjacent areas/margins.

In the plate reconstructions we have to consider all sides of Greenland and links to the Arctic plate tectonic evolution. This includes (1) restoring the Paleogene Eurekan-Spitsbergen fold-and-thrust belts, (2) improve the understanding of the Amerasia Basin breakup and evolution including its relation to Arctic magmatism (HALIP), (3) address potential continental blocks/fragments masked by HALIP magmatism, (4) linking Late Paleozoic-Mesozoic extension in the North Atlantic to the Sverdrup Basin in the Canadian Arctic.

The work in this direction is one of the trademarks of CEED. J.I. Faleide and C. Gaina has a strong record of detailed reconstruction of the North Atlantic opening and pre-opening evolution of the NCS. G. Shephard and C. Gaina will place the North Atlantic-Arctic evolution into the global framework using GPlates software, another trademark of CEED. The new features of GPlates, including deformable plates, will augment applicability of this software for regional applications planned within the project.



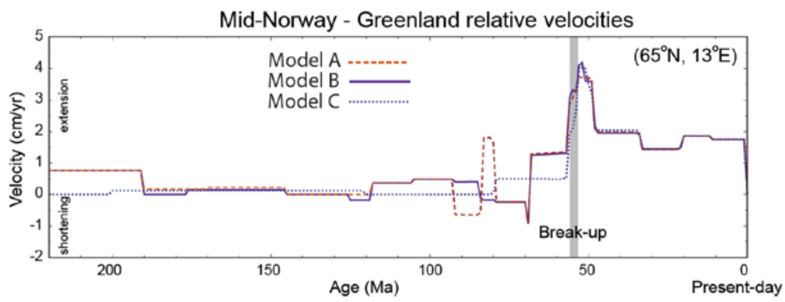




***Figure 2*** Comparison of three recent models: A = Seton et al. (2012), B = Torsvik et al. (2008), C = Müller et al. (2016). All models predict various periods and amounts of extension and compression, and periods of no motion. From Shephard et al (in prep.).

### 2.2. Mantle dynamics

One of the main directions of CEED research is linking deep mantle processes with shallow deformations. This effort explains and quantifies lithospheric deformations and topography evolution to help us understand the present topography, morphology and long-term evolution of continents. One example of a strong link between deep Earth and shallow processes is the phenomenon of dynamic topography, which is the deflection of Earth's surface by stresses from mantle flow. Up to about 1-2 km of dynamic topography is both observed at the Earth's surface and predicted by numerical models of present-day mantle flow (Steinberger et al., 2018). The time evolution of this dynamic topography can contribute to both destruction and creation of accommodation space in sedimentary basins. Two modes of deep and shallow processes interaction may be outlined depending on the mechanisms and timing involved.

#### *2.2.1 Plate mode*

This mechanism involves cooling of the oceanic lithosphere and its subduction into the mantle. Over time scales of 100 m.y., mantle flows associated with subducted slabs and other heterogeneity in the mantle induce deflections of the surface plates across wavelengths of ~1000 of km and longer. Such deflections, which can have 1-2 km amplitude, have been detected on continental margins of the present-day seafloor (Winterbourne et al. 2014). Based on seismic tomography, mantle flow models predict circum-Arctic dynamic topography (both negative/subsidence and positive/uplift) through time, as calculated by Shephard et al. (2014). Rates for such processes may be considered as rather minor, but their resulting amplitude is considerable. For the Barents Sea the model predicts dynamic subsidence (< 7 m/Myr, ~170-50 Ma) followed by dynamic uplift (< 6 m/Myr since 50 Ma). Thus, the study of long-term large-scale dynamic topography compliments traditional methods of plate kinematics and geological observations in studying vertical motions of the lithosphere and basin evolution. Note that the modelling of Shephard et al. (2014) requires detailed analysis of mantle of significant portion of the Earth, and that CEED has particularly relevant expertise for this type of modelling (e.g., Watkins & Conrad, 2018).

#### *2.2.2 Plume mode*

This mode is related to the influence of mantle plumes, including extreme cases such as the formation of Large Igneous Provinces (LIPs). The resulting dynamic topography evolves on shorter time scales (on the order of 10 m.y.) and gives rise to episodes of shorter-lived surface uplift and subsidence (at interregional scales seemingly unrelated to large-scale mantle flow of the plate mode).

The recent publication by Friedrich et al. (2018) presents geomorphological and stratigraphic features, which document the topographic response to plume ascent, arrival and lateral spreading (Fig. 3). The ascending plume head may produce a domal uplift of 1-2 km over a radius of ~1000 km. Plume-head impact at the base of the lithosphere is accompanied by dome build-up and collapse, narrow rifting, formation of giant dike swarms and the eruption of flood basalts. Many features of such plume-lithosphere interaction are observed in NCS and are related to modern and ancient plumes and LIPs (e.g., Torsvik et al., 2008; Minakov et al., 2018).

Basin evolution on the NCS may have been affected by at least four LIPs: North Atlantic Igneous Province - NAIP (in late Paleocene-earliest Eocene), High Arctic Large Igneous Province-HALIP (Early Cretaceous), Siberian Traps (latest Permian-earliest Triassic), and Skagerrak-Centered Large Igneous Province - SCLIP (latest Carboniferous-earliest Permian). The impact of LIPs on regional uplift and subsidence patterns may leave stratigraphic record recognizable in the basin architectures. Regional uplift is a typical pre-cursor to a LIP event and this may change the paleogeography creating new wide source areas subjected to uplift and erosion. Farther away from the LIP centre regional subsidence may occur affecting wide (basin) areas without significant complementary/associated faulting. Searching for such relationships, we have to integrate observations at basin, crustal and lithospheric scales (Faleide et al., 2018). Formation of large igneous provinces is also associated with widespread dyke-swarms and sill complexes intruding sedimentary basins, e.g. Barents Sea in the Early Cretaceous (Minakov et al., 2018) and the mid-Norwegian margin at the Paleocene-Eocene transition (Abdelmalak et al., 2016, 2017). The intrusive rocks may have a large impact on the temperature/maturation history and distribution of reservoir properties.

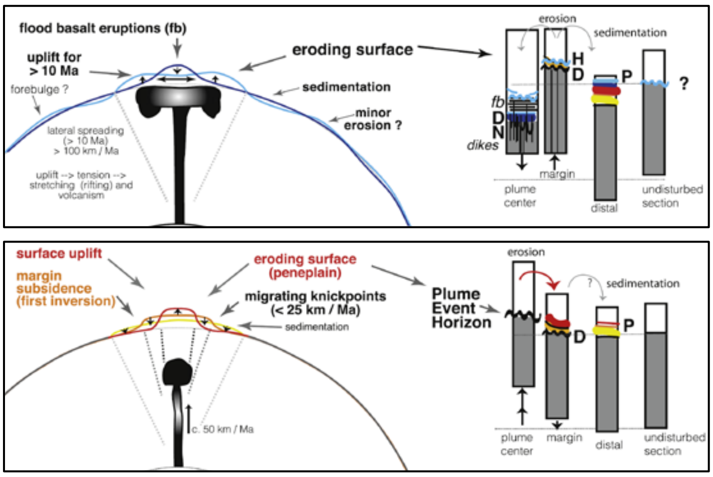



***Figure 3*** Two steps in the schematic model of Friedrich et al. (2018) showing the vertical surface motion in response to a mantle-plume event and the corresponding plume-stratigraphic record. Lower panel shows a rising plume head and significant uplift 10-20 m.y. before volcanism; Upper panel shows climax, collapse and incipient lateral spreading of plume head, and eruption of flood basalts.

The study of the deep mantle interaction with the lithosphere, including both modes of interaction will benefit from expertise of Prof. Torsvik in paleogeography, Prof. Conrad in mantle dynamics, Dr. Shephard in integrating surface plate motion with mantle convection, and Dr. Minakov in geophysical aspects of LIPs.

### 2.3. Intra-plate stress

Stress analysis is important for petroleum exploration in general as stresses are a major control of stability of wells, integrity of top and fault-seals, migration routes and drainage patterns. Lithospheric stresses, modern and paleo, are also a major control of basin evolution. Understanding sources of stresses and their quantifications (including orientation) is a major problem in Earth Science. For example, fluid injection operations in critically stressed rocks are potentially hazardous as they can trigger induced seismicity and rock failure (e.g. Rozhko et al. 2007, Yarushina et al. 2017). Several aspects of this problem related to NCS are already under consideration in the modelling community, world-wide and within CEED. Understanding the regional/local stress field requires quantification of influence of several mechanisms, depending on lateral scales involved and duration of the processes.

We plan to constrain a base stress model (section 2.3.1), and then upgrade it by incorporating tectonics-induced stresses (sections 2.2.2, 2.3.2) and surface-induced stresses (section 2.4.2) at present-day and back in time. The results are to be tested using world stress map and well data.

#### *2.3.1 Geopotential stress: base stress model for NCS*

Intraplate stresses caused by gravitational potential energy (GPE) will be investigated to constrain the base model for stress analysis. Gradients in GPE arising from density heterogeneities and topographic variations in the lithosphere are considered as the main source for the lithospheric stresses (Medvedev, 2016; Schiffer et al., 2017). Iceland, the Mid-Atlantic Ridge, the Knipovich Ridge, and the Gakkel Ridge create regional geopotential stress fields that can disturb the NCS. Elevated continental structures, such as the Scandinavian Mountains, Svalbard, Novaya Zemlya surrounding the NCS, also contribute to the geopotential stress field.

Several modelling approaches are currently being tested at CEED. In the most traditional approach, the North-Atlantic realm will be modelled using 3D density models of lithosphere constrained by geophysical data and geological models. We plan to compare this model with newer, yet more controversial approaches based on the global geoid model and satellite gravimetric tensor data (Medvedev et al., 2016; Minakov & Medvedev, 2017).

The base model will be completed by applying models of tractions from the convecting mantle (Medvedev, 2016) and accounting for dynamic effects of the ascending Iceland plume (Schiffer & Nielsen, 2016; Schiffer et al., 2017). The model will be augmented from continued research on the theoretical aspects of sources and distribution of stresses in the lithosphere conducted by CEED researchers in world-wide collaboration (Medvedev, 2016; Schmalholz et al., submitted; Schmalholz et al., 2014)

#### *2.3.2 Intraplate stress and plate kinematics and paleo-orogens*

Intraplate stresses may originate from far-field forces at plate boundaries either by collision (e.g. Alps, Urals/Novaya Zemlya/Taimyr) (Gac et al., 2014; Indrevær et al., 2018) or by transpression with other plates along transform (strike-slip) plate boundaries (e.g. Spitsbergen). We will first investigate how much and how far horizontal stresses caused by North-Atlantic plate interactions can propagate laterally away from plate boundaries and how they change through time in the NCS (Fig. 4; Gac et al., in prep.).

North-Atlantic Cenozoic plate kinematics has different stages that are thought to have produced different intra-plate stress patterns in the NCS (Faleide et al., 2008; Gaina et al., 2009): (1) Pre-Cenozoic motion of Greenland causing contraction along the western margin of Svalbard. (2) Eocene breakup along the Norwegian margin and northern Barents Sea forcing Greenland to move towards NNE. This stage was accompanied with shearing along the western margin of the Barents Sea and transpression west of Svalbard. (3) At Oligocene times, sea-floor spreading ceased in the Labrador Sea leading Greenland to move westerly. Transpression ceased west of Svalbard.

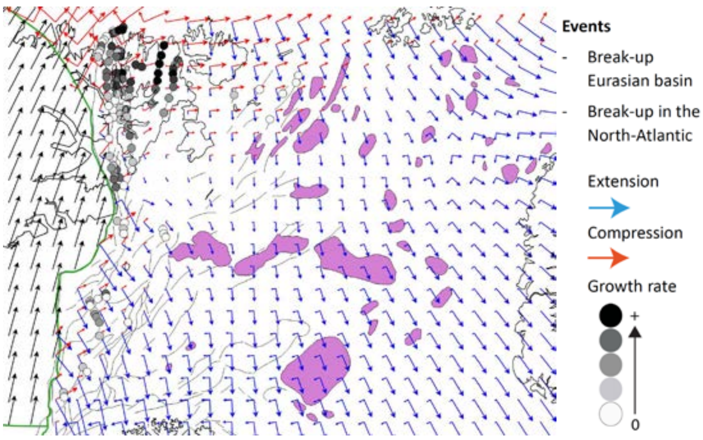


***Figure 4*** A plate kinematic model for the Cenozoic opening of the North Atlantic and Eurasia Basin, predicting early Eocene transpression along most of the western Barents Sea-Svalbard margin, is combined with a mechanical model of the lithosphere to quantify intraplate paleo-stress and associated deformation across the Barents Shelf. From Gac et al. (in prep.).

We will use a numerical modelling approach combining plate kinematic models of the North-Atlantic with a mechanical model of lithosphere to quantify intraplate paleo-stress in the NCS. Lithosphere plates are not homogeneous entities. Lateral variations in composition and temperature affect plates strength and hence stress distribution. For example the Eastern Barents Sea is colder and stronger than the Western Barents Sea (Gac et al., 2016; Klitzke et al., 2016). The effects of these heterogeneities in time and space on paleo-stress will be investigated.

#### *2.3.3 Effects on basin evolution and petroleum systems*

Intraplate stresses have effects on sedimentary basins and petroleum systems:

- Exact timing and mechanism of domes and trap formation is important for understanding petroleum system evolution, but this record is often hidden in the NCS. For example, in large parts of the Barents Sea the Late Cretaceous and Cenozoic sedimentary record has been erased during Cenozoic regional uplift and erosion events (Henriksen et al., 2011; Baig et al., 2016). The numerical modeling of paleo-stress and deformation offers an alternative way to provide key information on the timing and causes of formation of those contractional structures.
- Compressional stresses may trigger metamorphism of deeply buried sediments and make them indistinguishable from crystalline crust on seismic recordings, as is the case for the deep Bjørnøya Basin in the SW Barents Sea (Clark et al., 2013; Gac et al., 2018) and the Møre and Vøring basins on the mid-Norwegian margin (Theissen-Krah et al., 2017; Zastrozhnov et al., 2018). As a consequence data-based estimation of stretching factors, thermal history, and maturation of sediments may become biased. Metamorphism of deep sediments therefore needs to be accounted for in basin analysis.
- Quantification of stresses and their effects on seal stability and reservoir quality provide key information for reducing exploration risk.
- Wellbore stability depends crucially on stress amplitude and orientation. Background (large-scale, tectonic) stresses control which directions of well drilling are safe and which may lead to partial or even complete well collapse. Wellbore failure in the North Sea alone costs millions of NOK in additional expenses each year.

The modelling of paleo-stress in the NCS combined with plate reconstructions will benefit from expertise of Drs. Gac, Medvedev and Minakov in stress modelling, Dr. Shephard in plate reconstruction and Profs. Faleide and Gaina in detailed reconstruction of the North Atlantic opening and the pre-opening evolution of NCS. Estimates of lithospheric basal traction from convective mantle flow will be based on various global mantle convection models, and the project will benefit from Prof. Conrad's expertise. The effects of stress on petroleum systems will benefit from expertise of Drs. Medvedev, Gac, and Minakov in this field.

### 2.4. Surface processes

Several aspects of surface processes, such as erosion, sediment accumulation and glaciation, may affect the basin evolution and petroleum system stability.

#### *2.4.1 Differential vertical motions caused by surface processes*

The main approach here considers mechanical loads controlled by mass redistribution during surface processes. Changes of the internal geometry caused by differential vertical motions are very important to understand basin architecture and the secondary migration into and outside petroleum fields. Our pilot studies (see also Medvedev & Hartz, 2015; Medvedev et al., 2008) showed that (1) glacial load and rebound, (2) the onshore localized erosion, and (3) offshore sediment accumulation, cause significant vertical motions and these motions may lead to considerable changes to basins architecture (Fig. 5). That includes not only absolute depth changes, but also tilting of basins and traps and shifting migration routes caused by differential vertical movements. We hypothesize that this mechanism affected number of petroleum provinces of NCS.

An important feature of lithospheric response to surface processes is that the local features of surface processes are smoothed by flexural rigidity of the lithosphere. Thus, the local (Airy) isostasy is not valid, especially for fast processes (like fjord carving and ice sheet loading). Regional-scale flexural isostatic models are necessary, and local applications require multiscale approach (Medvedev & Hartz, 2015; Medvedev et al., 2018; Medvedev et al., 2008; Medvedev et al., 2013).

#### *2.4.2 Stresses associated with surface processes*

Reconfiguration of the stress pattern caused by surface processes is another important aspect for understanding basin and, especially, petroleum system evolution. Several studies point to ice-induced stresses as an important mechanism controlling multiple periods of fault reactivation and potential hydrocarbon leakage in the hydrocarbon fields (e.g., Goffey et al., 2016; Grollimund and Zoback, 2003). The surface processes may change the stress pattern significantly, but this is often overlooked in modern exploration. These changes may be rapid considering glacial periodicity, but may take almost the entire Late Cenozoic if controlled by fjord carving and associated sedimentation. Thus, understanding the major mechanism leads to understanding the time-evolution of petroleum systems.

#### *2.4.3 Regional studies of erosion and sedimentation*

The entire Barents Sea was affected by several Cenozoic uplift and erosion events leading to an absence of Neogene and most of Paleogene sedimentary strata. Uplift and erosion may have crucial implications on petroleum systems. For example, the erosion of overburden rocks may result in hydrocarbon leakage causing emptying of the reservoir; uplift may change migration pathways; maturation of source rocks may cease because of reduced temperatures due to uplift; pressure release due to uplift/erosion could lead to gas expansion in reservoirs driving spill of oil laterally. Thus, understanding the causes and timing of uplift/erosion is crucial for exploration. Several models of erosion for the Barents Sea were analysed and pilot studies show need for rectification within the models.

These studies will be carried out by S. Medvedev using in-house software suite ProShell and in close collaboration with Drs. Gac and Minakov. The direction is benefited from the long-term close collaboration with Dr. E. Hartz (AkerBP).

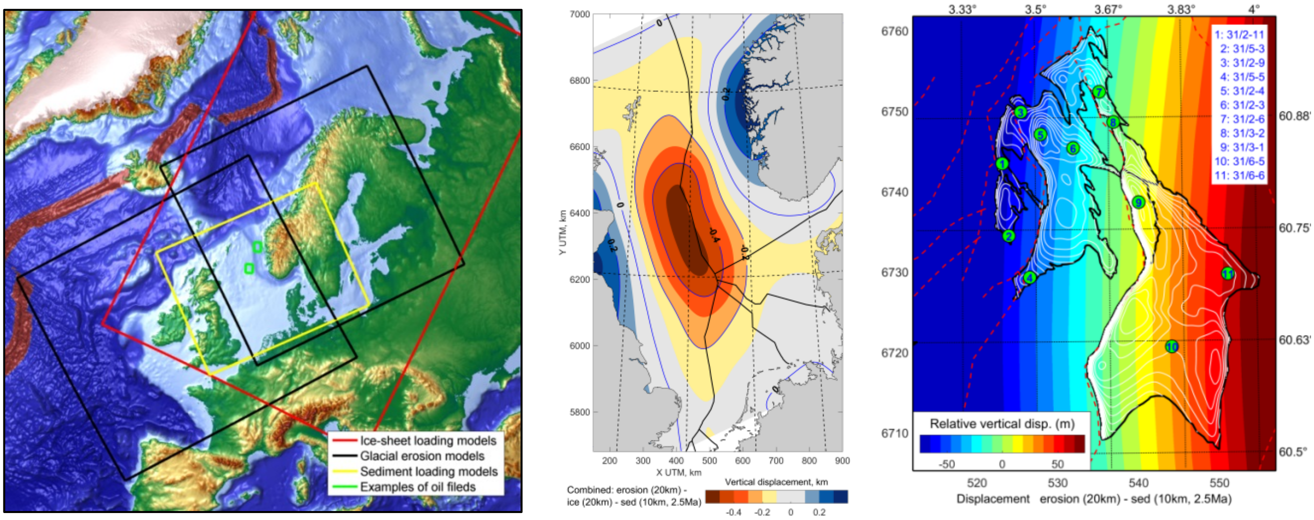



***Figure 5*** Several surface processes mechanisms were analyzed using >1000-km scale numerical models (left panel) to evaluate vertical displacements of the lithosphere in the North Sea (middle) and then Quaternary tilting of the Troll field and explain paleo-oil records in the wells, which are tens of km apart (right panel). Colors on the right panel indicate up to 150 m differential vertical displacement caused by on-shore glacial erosion and off-shore sediment accumulation. White contour lines present geometry of BCU (20 m intervals), a proxy for the top migration routes and seal. From Medvedev et al. (in prep.).

### 2.5. Complex processes during basin evolution

This activity aims to compile and link the other aforementioned activities to particular features of basin evolution and petroleum systems. This part may be considered as a main bridge between modelling-loaded academic research and practical implications.

CEED already has experience of basin modelling beyond the McKenzie (1978) model. Accounting for mineral phase transitions, additional heating from dissipative deformations, dynamic pressure, and mantle flows shows effects that should not be ignored. These effects were quantified on a theoretical level by Hartz et al. (2017) and in a more applied subsidence modelling at rifted margins (Minakov et al., 2012; Minakov & Podladchikov, 2012) and internal basins of the Barents Sea (Clark et al., 2014; Gac et al., 2012, 2013, 2014, 2018). We aim to combine already available experience of CEED basin modelling with effects discussed in the previous sections to make an essential step towards truly dynamic basin modelling.

This work package will be performed by the key personnel of the project, Prof. Faleide and Drs. Medvedev, Gac, and Minakov, who will be involved in more or less all activities presented above.

## 3. Organization of the consortium

The industry consortium will fund two researchers, Dr. Sergei Medvedev and Dr. Sebastien Gac, who have been key personnel in much of the geodynamic and basin modelling carried out at the University of Oslo during recent years (see reference list). Both researchers have academic background in quantitative research, and have interest and experience in applied basin and petroleum research. Thus, the natural way to keep these researchers as part of the team is through industry funding. Two additional researchers (Dr. Grace Shephard and Dr. Alexander Minakov) presently employed by CEED can partially contribute with their expertise/competence. Their direct participation in the project can be considered as project develops.

CEED senior staff including Prof. Jan Inge Faleide (regional geology and basin analysis), Prof. Trond H. Torsvik (plate reconstructions and paleogeography), Prof. Carmen Gaina (marine geophysics and plate reconstructions; also director of CEED), Prof. Clint Conrad (mantle dynamics) will assist with their respective expertise. Several postdoc/PhD fellows from the Department of Geosciences working with related topics, e.g. Dr. Irfan Baig (funded by NFR Petromaks) and Muhammad Hassaan (funded by ARCEx) will be affiliated with the consortium.

Jan Inge Faleide will act as the leader and coordinator of the consortium building on his long-term experience with basin/margin studies and close collaboration with industry. A steering committee, including one representative for each industry partner, will govern strategic directions and financial engagements of the consortium.

The consortium will organize a yearly workshop for all partners where we present and discuss recent work and results. The results will later be presented at scientific meetings/conferences and finally published in scientific papers. Partners are also encouraged to contact CEED personnel for informal discussions and advice on key questions of special interest to individual companies. Upon mutual interest, the consortium may also organize smaller workshops to cover particular topics of research.

The consortium will also apply for funds from the RCN. We plan to apply for 1-2 Petromaks projects during the consortium activity. The funds will bring PhD student(s) and additional funds, which can be used either to increase work forces of the consortium or ease financial contribution of the industrial partners (can be decided by steering committee). In 2017, Faleide and Medvedev in collaboration with AkerBP applied to Petromaks with a proposal entitled "Stress and tilt effects on the petroleum system dynamics of the North Sea". The proposal received good marks last year, and its resubmission will be boosted by having larger industrial support this year.

### 3.1. Duration and budget of project

The consortium is planned for 3 years with a potential extension of 2 years until the termination of CEED. To finance the salary of 2-2.5 researchers (Medvedev and Gac, and partially Minakov) in addition to running costs, we need in the order of 3.5-4 MNOK per year. We hope to recruit between 4 and 8 industry partners in the consortium, each contributing with 600-800 kNOK per year. A more detailed budget will be made when we see the response to the proposal, and it will be approved by the steering committee.

## 4. Summary of proposed research topics/tasks

The directions listed in section 2 present ambitious multi-disciplinary multi-level research which cannot be fulfilled completely within a single project. This section is designed to choose priority directions, which will be governed by the steering committee. The summary can also be extended upon request of industry partners. A kick-off meeting will be arranged to develop more detailed research plans and priorities.

| | | |
|---|---|---|
| **1.** | **Plate tectonics** | Reconstructing the plate evolution |
| 1.1 | Quantification and restoration of North Atlantic pre-drift extension | Constraining amount and direction of extension |
| 1.2 | Paleogeography | Linking plate reconstructions and source-to-sink evolution |
| 1.3 | Arctic plate reconstructions | Large uncertainties still exist – increasing amount of new data/constraints have to be implemented |
| **2.** | **Mantle dynamics** | Linking deep and shallow processes, influence of LIPs and dynamic topography on basin evolution. |
| 2.1 | Understanding wavelengths and amplitudes | The variations of length- and time-scales involved in this study requires multi-level studies |
| 2.2 | LIPs and plumes and their relation to vertical movements in NCS | P-Tr transition (Siberian Traps), Early Cretaceous (HALIP), Late Paleocene (Iceland) |
| 2.3 | Iceland plume and modern mantle flow and dynamic topography | The Iceland plume controls many features in the North Atlantic, including thermal, kinematic, and stress patterns. |
| 2.4 | Contractional deformation – both in Barents Sea and conjugate Atlantic margins | Linking shallow/inverted and deep structures – address timing and potential causes and implications |
| **3.** | **Intraplate stresses** | Digital maps of stresses and their orientation |
| 3.1 | Understanding general features of modern | Constraining reliable base model, which may explain large-scale |

| | | |
|---|---|---|
| | stress pattern in NCS | features of the stresses in NCS |
| 3.2 | Establishing modern stress pattern: timing, causes, implications | Rectifying the base model adding more mechanisms including local features. |
| 3.3 | Stresses caused by plate tectonics | Continent collision (Alps, Urals/NZ/Taimyr) and shear/transpression (Spitsbergen) |
| **4.** | **Surface processes** | Sediment accumulation, erosion, and ice sheets loading. These processes were especially active during Late Cenozoic |
| 4.1 | Maps of vertical movements caused by surface processes | Mass redistribution by surface processes causes lithosphere vertical motions |
| 4.2 | Tilting of petroleum systems in NCS | Spatial variations of the vertical motion result in tilting of petroleum systems, changing migration paths. |
| 4.3 | Stresses caused by surface processes | Surface processes load and unload lithosphere and may result in significant changes in the stress pattern |
| **5.** | **Complex basin evolution studies** | Integration of studies from the other parts of the project into particular aspects of basin evolution and petroleum systems |
| 5.1 | Source-to-sink studies | Provenance, sediment transport and depositional systems, facies distribution. |
| 5.2 | Some mechanisms affecting burial history | Compaction, mechanical and chemical; metamorphosed meta-sediments; some aspects of temperature history; mineral phase transitions |

## References

*Key participants of the project (emphasised by bold) are co-authoring 22 related papers published and prepared during last three years (2016-2018)*


Abdelmalak, M.M., Planke, S., **Faleide, J.I.**, Jerram, D.A., Zastrozhnov, D., Eide, S. & R. Myklebust, 2016, The development of volcanic sequences at rifted margins: New insights from the structure and morphology of the Vøring Escarpment, mid-Norwegian Margin, J. Geophys. Res. Solid Earth, 121, 5212–5236.

Abdelmalak, M. M., **Faleide, J. I.**, Planke, S., Gernigon, L., Zastrozhnov, D., **Shephard, G. E.**, & Myklebust, R., 2017, The T-Reflection and the deep crustal structure of the Vøring Margin, offshore mid-Norway. Tectonics, 36, 2497–2523.

Baig, I., **Faleide, J.I.**, Jahren, J. & Mondol, N.H., 2016, Cenozoic exhumation on the southwestern Barents Shelf: estimates and uncertainties constrained from compaction and thermal maturity analyses. Marine and Petroleum Geology, 73, 105-130.

Baur, F., Hosford Scheirer, A. & Peters, K.E., 2018, Past, present, and future of basin and petroleum system modeling. AAPG Bulletin, 102, 549–561.

Clark, S. A., **Faleide, J. I.**, Hauser, J., Ritzmann, O., Mjelde, R., Ebbing, J., Thybo, H. & Flüh, E., 2013, Stochastic velocity inversion of seismic reflection/refraction traveltime data for rift structure of the southwest Barents Sea: Tectonophysics, v. 593, p. 135-150.

Clark, S.A., Glørstad-Clark, E., **Faleide, J.I.**, Schmid, D., Hartz, E.H. & Fjeldskaar, W., 2014, Southwest Barents Sea rift basin evolution: comparing results from backstripping and time-forward modelling. Basin Research, 26, 550-566.

Curry, D.J., 2018, Future directions in basin and petroleum systems modeling: Building more useful models a survey of the community. AAPG Bulletin, doi:10.1306/1208171615217152.

**Faleide, J. I.**, Tsikalas, F., Breivik, A. J., Mjelde, R., Ritzmann, O., Engen, O., Wilson, J. & Eldholm, O., 2008, Structure and evolution of the continental margin off Norway and the Barents Sea: Episodes, v. 31, no. 1, p. 82-91.

**Faleide, J.I.**, Pease, V., Curtis, M., Klitzke, P., **Minakov, A.**, Scheck-Wenderoth, M., Kostyuchenko, S. & Zayonchek, A., 2017, Tectonic implications of the lithospheric structure across the Barents and Kara shelves. *In* Pease, V. and Coakley, B. (eds) Circum Arctic Lithosphere Evolution, Geological Society of London Special Publication, 460, 285-314.

Friedrich, A. M., Bunge, H.-P., Rieger, S. M., Colli, L., Ghelichkhan, S. & Nerlich, R., 2018, Stratigraphic framework for the plume mode of mantle convection and the analysis of interregional unconformities on geological maps: Gondwana Research, v. 53, p. 159-188.

**Gac, S.**, Huismans, R., Podladchikov, Y. & **Faleide, J.I.**, 2012, On the origin of the ultra deep East Barents Sea basin. Journal of Geophysical Research, 117, B04401.

**Gac, S.**, Huismans, R.H., Simon, N.S.C., Podladchikov, Yu.Yu. & **Faleide, J.I.**, 2013, Formation of intracratonic basins by lithospheric shortening and phase changes: a case study from the ultra-deep East Barents Sea basin. Terra Nova, doi: 10.1111/ter.12057

**Gac, S.**, Huismans, R.S., Simon, N.S.C., **Faleide, J.I.** & Podladchikov, Y.Y., 2014, Effects of lithosphere buckling on subsidence and hydrocarbon maturation: A case-study from the ultra-deep East Barents Sea basin: Earth and Planetary Science Letters, v. 407, p. 123-133.

**Gac, S**., Klitzke, P., **Minakov, A., Faleide, J. I**. & Scheck-Wenderoth, M., 2016, Lithospheric strength and elastic thickness of the Barents Sea and Kara Sea region: Tectonophysics, v. 691, p. 120-132.

**Gac, S**., Hansford, P. A. & **Faleide, J. I.**, 2018, Basin modelling of the SW Barents Sea: Marine and Petroleum Geology, 95, 167-187.

**Gaina, C.**, Gernigon, L. & Ball, P., 2009, Palaeocene–Recent plate boundaries in the NE Atlantic and the formation of the Jan

Mayen microcontinent. Journal of the Geological Society, London, 166, 601–616.

Goffey, G., Attree, M., Curtis, P., Goodfellow, F., Lynch, J., Mackertich, D., Orife, T. & Tyrrell, W., 2016, New exploration discoveries in a mature basin: offshore Denmark, *in* Proceedings Geological Society, London, Petroleum Geology Conference series, Volume 8, Geological Society of London, p. PGC8. 1.

Grollimund, B. & Zoback, M. D., 2003, Impact of glacially induced stress changes on fault-seal integrity offshore Norway: AAPG bulletin, v. 87, no. 3, p. 493-506.

Gölke, M. & Coblentz, D., 1996, Origins of the European regional stress field: Tectonophysics, v. 266, no. 1, p. 11-24.

Hartz, E. H., **Medvedev, S.** & Schmid, D. W., 2017, Development of sedimentary basins: differential stretching, phase transitions, shear heating and tectonic pressure: Basin Research, v. 29, no. 5, p. 591-604.

Hartz, E.H., **Medvedev, S.**, Schmid, D., **Faleide, J.I.**, Iyer, K., Hosford Scheirer, A. & Hartwig, A., 2018, Geodynamic Gamechangers in Petroleum System Models. 80th EAGE Conference & Exhibition, Copenhagen, 11-14 June 2018, A15 09.

Henriksen, E., Bjørnseth, H., Hals, T., Heide, T., Kiryukhina, T., Kløvjan, O., Larssen, G., Ryseth, A., Rønning, K. & Sollid, K., 2011, Uplift and erosion of the greater Barents Sea: impact on prospectivity and petroleum systems: Geological Society, London, Memoirs, v. 35, no. 1, p. 271-281.

Indrevær, K., **Gac, S.,** Gabrielsen, R. H. & **Faleide, J. I**., 2018, Crustal-scale subsidence and uplift caused by metamorphic phase changes in the lower crust: a model for the evolution of the Loppa High area, SW Barents Sea from late Paleozoic to Present: Journal of the Geological Society, v. 175, no. 3, p. 497-508.

Klitzke, P., Sippel, J., **Faleide, J. I.**, & Scheck-Wenderoth, M., 2016, A 3D gravity and thermal model for the Barents Sea and Kara Sea: Tectonophysics, v. 684, p. 131-147.

Le Pourhiet, L., May, D.A., Huille, L., Watremez, L. & Leroy, S., 2017, A genetic link between transform and hyper-extended margins. Earth and Planetary Science Letters, 465, pp.184-192.

Mckenzie, D., 1978, Some Remarks on Development of Sedimentary Basins: Earth and Planetary Science Letters, v. 40, no. 1, p. 25-32.

**Medvedev, S**., 2016, Understanding lithospheric stresses: systematic analysis of controlling mechanisms with applications to the African Plate: Geophysical Journal International, v. 207, no. 1, p. 393-413.

**Medvedev, S.** & Hartz, E. H., 2015, Evolution of topography of post-Devonian Scandinavia: Effects and rates of erosion: Geomorphology, v. 231, p. 229-245.

**Medvedev, S**., Hartz, E. H. & **Faleide, J. I**., 2018, Erosion-driven vertical motions of the circum Arctic: Comparative analysis of modern topography: Journal of Geodynamics.

**Medvedev, S**., Hartz, E. H. & Podladchikov, Y. Y., 2008, Vertical motions of the fjord regions of central East Greenland: Impact of glacial erosion, deposition, and isostasy: Geology, v. 36, no. 7, p. 539-542.

**Medvedev, S**., Hartz, E. H., Schmid, D. W., Zakariassen, E. & Varhaug, P., in prep., Glacial effects: A key trigger of the North Sea petroleum systems: Geological Society Special Publications.

**Medvedev, S., Minakov, A**., Lebedeva-Ivanova, N. & **Gaina, C**., 2016, Understanding lithospheric stresses in Arctic: constraints and models, *in* Proceedings EGU Gen. Assembly2016, Volume 18, p. 8377.

**Medvedev, S**., Souche, A. & Hartz, E. H., 2013, Influence of ice sheet and glacial erosion on passive margins of Greenland: Geomorphology, v. 193, p. 36-46.

**Minakov, A.** & **Medvedev, S**., 2017, Analysis of Lithospheric Stresses Using Satellite Gravimetry: Hypotheses and Applications to North Atlantic, *in* Proceedings AGU Fall Meeting Abstracts.

**Minakov, A**., Yarushina, V., **Faleide, J. I**., Krupnova, N., Sakoulina, T., Dergunov, N. & Glebovsky, V., 2018, Dyke emplacement and crustal structure within a continental large igneous province, northern Barents Sea: Geological Society, London, Special Publications, v. 460, no. 1, p. 371-395.

**Minakov, A.N**. & Podladchikov, Y.Y., 2012, Tectonic subsidence of the Lomonosov Ridge. Geology, 40(2), pp.99-102.

**Minakov, A., Faleide, J.I.,** Glebovsky, V.Y. & Mjelde, R., 2012, Structure and evolution of the northern Barents-Kara Sea continental margin from integrated analysis of potential fields, bathymetry and sparse seismic data. Geophysical Journal International, 188(1), pp.79-102.

NPD, 2018, Petroleum resources on the Norwegian continental shelf. Norwegian Petroleum Directorate, http://www.npd.no/en/Publications/Resource-Reports/2018/

Rayeva, N., Kosnazarova, N., Arykbayeva, Z. & Shaikhina, D., 2014, Petroleum systems modeling and exploration risk assessment for the eastern margin of the Precaspian Basin: SPE Annual Caspian Technical Conference and Exhibition, Astana, Kazakhstan, November12–14, 2014, SPE-172332-MS, 12 p.,doi:10.2118/172332-MS.

RCN, 2018, Midterm Evaluation of Thirteen Centres of Excellence (SFF-III). The Research Council of Norway, https://www.forskningsradet.no/servlet/Satellite?pagename=ForskningsradetNorsk%2FHovedsidemal&cid=1212565796096&c=InnholdsKontainer&p=122078826490 3&querystring=Midterm+Evaluation+of+Thirteen+Centres+of+Excellence+%28SFF-III%29&sortby=Aar&sortorder=desc&hits=30&publicationType=ALLE

Rozhko, A.Y., Podladchikov, Y.Y. & Renard, F., 2007, Failure patterns caused by localized rise in pore-fluid overpressure and effective strength of rocks. Geophysical Research Letters, 34(22).

Schiffer, C. & Nielsen, S., 2016, Implications for anomalous mantle pressure and dynamic topography from lithospheric stress patterns in the North Atlantic Realm: Journal of Geodynamics, v. 98, p. 53-69.

Schiffer, C., Tegner, C., Schaeffer, A. J., Pease, V. & Nielsen, S. B., 2017, High Arctic geopotential stress field and implications for geodynamic evolution: Geological Society, London, Special Publications, v. 460, p. SP460. 466.

Schmalholz, S. M., Duretz, T., Heteneyi, G. & **Medvedev, S.,** submitted, Distribution and magnitude of membrane and bending stresses due to lateral variation of gravitational potential energy between India and Tibetan plateau: Geophys J Int.

Schmalholz, S. M., **Medvedev, S**., Lechmann, S. M. & Podladchikov, Y., 2014, Relationship between tectonic overpressure, deviatoric stress, driving force, isostasy and gravitational potential energy: Geophysical Journal International, v. 197, no. 2, p. 680-696.

**Shephard, G.E.,** Flament, N., Williams, S., Seton, M., Gurnis, M. & Müller, R.D., 2014, Circum-Arctic mantle structure and long-wavelength topography since the Jurassic: Journal of Geophysical Research, v. 119, p. 7889-7908.

Steinberger, B., **Conrad, C.P**., Osei Tutu, A. & Hoggard M. J., 2018, On the amplitude of dynamic topography at spherical harmonic degree two: Tectonophysics, in press, doi:10.1016/j.tecto.2017.11.032.

Stoddart, D., Recent glacial events in the Norwegian North Sea-implications towards a better understanding of charging-leakage of oil fields and its impact oil exploration, *in* Proceedings EGU Gen. Assembly2014, Volume 16, p. 1370.

Theissen-Krah, S., Zastrozhnov, D., Abdelmalak, M.M., Schmid, D.W., **Faleide, J.I.** & Gernigon, L., 2017, Tectonic evolution and extension at the Møre Margin – Offshore mid-Norway, Tectonophysics, 721, 227–238.

Watkins, C. E. & **Conrad, C. P.**, 2018, Constraints on dynamic topography from asymmetric subsidence of the mid-ocean ridges, *Earth and Planetary Science Letters*, *484*, 264-275, doi:10.1016/j.epsl.2017.12.028.

Winterbourne, J., White, N. & Crosby, A., 2014, Accurate measurements of residual topography from the oceanic realm, *Tectonics*, *33*(6), 982-1015, doi:10.1002/2013TC003372.

Yarushina, V.M., Podladchikov, Y.Y., **Minakov, A.** & Räss, L., 2017, On the Mechanisms of Stress-Triggered Seismic Events during Fluid Injection. In Poromechanics VI (pp. 795-800).

Zastrozhnov, D., Gernigon, L., Gogin, I., Abdelmalak, M.M., Planke, S., **Faleide, J.I.**, Eide, S. & Myklebust, R., 2018, Cretaceous-Paleocene Evolution and Crustal Structure of the Northern Vøring Margin (Offshore Mid-Norway): Results from Integrated Geological and Geophysical Study. Tectonics, 37 (2)