Lower Cretaceous clastic wedges – an under-explored play in the Arctic

Lower Cretaceous Basin studies in the Arctic (LoCrA)

A R&D proposal by the University of Stavanger (UiS) and the University Centre in Svalbard (UNIS) in cooperation with the University in Bergen (UiB); the University of Nebraska at Omaha (UNO), USA; the University of Texas at Austin, Institute for Geophysics (UTIG), USA; the Lomonosov Moscow State University (MSU); and the University of Oslo (UiO)

Main project goal

The main goal is to improve the basin configuration and fill of the Lower Cretaceous basins in the high Arctic as input to prediction of coarse grained siliciclastic wedges as plays on the Norwegian Continental Shelf. To meet this ambition, the project will aim for a better understanding of the basin evolution, stratigraphy, structural styles, depositional setting and paleogeography in the Greater Barents Sea including Svalbard, Franz Josef Land, the northern Norwegian Sea, and on- and offshore East Greenland and their relation to the North American arctic basins (Fig.1). To obtain a refined paleogeography of the Early Cretaceous basins and its coastlines, an improved plate tectonic reconstruction will be carried out.

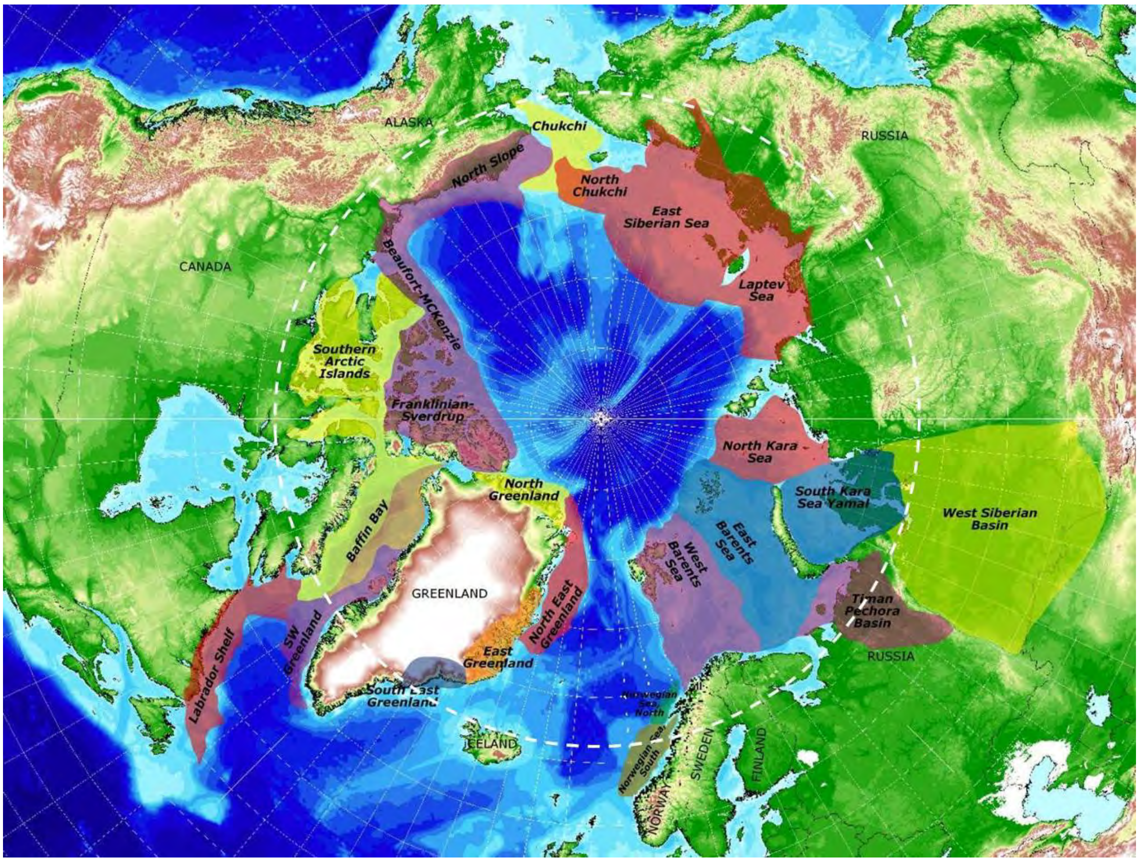


Figure 1. Map centred on the North Pole showing the location of main Arctic Basins: This study will initially focus on the Norwegian Sea, Barents Sea and eastern Greenland. Later on, the study will expand on other arctic basins. Stippled line is the Arctic Circle. Map after Olaussen & Steel (2011). The strata of the Mesozoic in westerly part of the Arctic is given in figure 2

Objectives

In this proposal, and as a first phase of this project, we request support for a regional study of the surface and subsurface of the Lower Cretaceous basins in the northern part of the Norwegian Sea, western margin and northern part of the Barents Sea, including Svalbard, Russian Barents Sea and optionally on- and offshore northeastern Greenland.

a) Construction of a regional geological database. The database will consist of all available data to the project from outcrop/field work information to maps generated from subsurface data. The database will be built into a geographic information system (GIS) that can be used by industry and academia.
b) Facies distribution and stratigraphy. Source to sink distribution of clastic sedimentation; by integrating field work (e.g. Svalbard) with subsurface interpretation (e.g. seismic and well data) we will analyze the sediment budget and depositional system distribution within the Cretaceous interval. Build up a "correlative" onshore offshore sequence and seismic stratigraphic framework.
c) Paleogeography and quantitative plate tectonic model and control in sedimentation and basin evolution. We will include modern quantitative plate tectonic models integrated with all available information using the GIS and serve as a template for paleogeography maps and understanding of the geologic processes that affected this region prior to the opening of the North Atlantic and the Canada basin.

In order to accomplish such objectives, collaboration between different institutions from countries in the Arctic will be established to incorporate all available data and different types of expertise. The project will be led by the University of Stavanger and the University Centre of Svalbard, and will build up strong collaboration from various institutions with knowledge in the region that include: the Institute for Geophysics at The University of Texas at Austin which have a large expertise in plate tectonic models of the region; The University of Bergen and Omaha University with knowledge in sedimentology and petrography of onshore Svalbard and the Barents Sea; the University of Oslo with expertise in provenance students in Svalbard and Greenland; and the Lomonosov Moscow State University with extensive knowledge on the Russian Barents Sea. At this stage, the Russian partner has shown interest in the project and we expect that the cooperation increases as the projects initiates.

We foresee this study as the beginning of a much larger study that will integrate more detailed analysis once the framework is established and can expand into the North American basin Arctic evolution, Greenland and the eastern Barents Sea and Kara Sea. A main motivation for this project is to contribute to better understanding of the geology of the Arctic and to successful exploration in the area that will secure the future of hydrocarbon production for the Norwegian government, Russia and other countries with ties to this region. Previous unification of models and geologic processes between the North American Arctic and the Norwegian-Russian have been limited to particular country boundaries and few knowledge about the neighbouring regions have been interchanged. This novel unification of a quantitative plate model, detailed arctic paleogeography and stratigraphy that includes surface and subsurface geology will serve as a basis for a sound basin evolution model, the structural styles and the present day distribution of different depocenters. This is paramount to develop an improved basinal framework that allows better understanding of the Cretaceous and its petroleum potential.

Motivation

Lower Cretaceous clastic wedges have been a successful play in the UK continental shelf (e.g. Moray Firth area). Only technical discoveries have been found in Post Valanginian Pre-Cenomanian units on the Norwegian North Sea Shelf and in the Norwegian Sea (Fig. 3). The majority of these discoveries have in addition been incidentally proven by drilling established Jurassic plays. Lack of economic discoveries is related to poor reservoir quality and insufficient trapping mechanism. On the contrary, mapped traps of Lower Cretaceous clastic wedges along the master faults or internal basin highs have been a target in the south-western Barents Sea where gas and oil technical discoveries have been proven as a valid play model. Here both deltaic/shoreline and submarine gravity flows have shown prolific sandstone bodies (Fig. 3). Even with some tested plays we claim that the Lower Cretaceous clastic wedges remain an under-explored play along the basin margins of the Norwegian Sea and the Barents Sea as most of the past and present focus has been into Jurassic and Triassic targets. In this proposal, we suggest that the Lower Cretaceous wedges are an important future target for the Barents Sea and offshore northeast Greenland.

We conclude that even within the hydrocarbon provinces in the Norwegian Sea, North and south-western Barents Sea Lower, the Lower Cretaceous clastic wedges are poorly tested and large or even giant discoveries are possible. Based on previous technical discoveries and outcrop on the conjugate margins, East Greenland, (see next section) following conclusion is given:

- Lower Cretaceous sandstone wedges are characterised by fine to very coarse grained fluvial, deltaic, estuarine, and shoreline facies deposited on narrow shelves on basin margins or banked onto intra basinal highs.
- The erosion of these narrow sand prone shelves has occasionally resulted in well sorted sandy gravity deposits.
- These sandstone wedges are limited to point source areas and occur down flank to strongly eroded highs.
- Prospect failures are suggested to be linked mainly to wrong prediction of prolific sandstone wedges.
- The wedges are either juxtaposed or situated above prolific Lower to Upper Jurassic source units (or above older source rocks in the Barents Sea) given moderate risk of hydrocarbon migration
- Efficient seal is probably one of the major risk parameters. Traps defined as combined stratigraphic and structural closures on the rim or on intra basinal highs might lower this risk.

After the newly discovered liquid petroleum system in the western margin of the Barents Sea (i.e. Skrugard and Havis) the link between the conjugate margin offshore north-eastern Greenland and the western Barents Sea becomes of particular interest. In addition, the northern boundary of the Barents Sea during the Cretaceous represents a key transition time in the evolution of the northern Arctic region which affected large areas of the Barents Sea, and was the time where most of the North American Arctic basins developed (Lawver et al., 2002). Plate tectonic models during this time are quite uncertain due to the lack of constrains (e.g. limited outcrop, difficult interpretation of magnetic anomalies, inconsistent biostratigraphy, limited amount of subsurface data, remote location, etc.), but the stratigraphy suggest that until the Late Jurassic/Early Cretaceous, most arctic basins seem to be related (Riis et al., 1986; Leith et al., 1990, Torsvik et al. 2002). Plate tectonic processes related to the formation of the Canadian basin, the Lomonosov ridge and the influence of the Icelandic plume are some of the geologic elements that seem to have modified the entire paleogeographic setting of the northern Barents Sea during Cretaceous time. This plume which might be the origin to HALIP and the precursor to the opening of the Canadian Basin in “mid” Cretaceous created a dome along the present-day northern boundary of the Barents Sea, which resulted in the observed south-east directed progradational deltaic wedge of Early Cretaceous age outcropping in Svalbard and Franz Josef Land. The complete subaerial exposure of Svalbard during the Late Cretaceous and uplift of structural highs in the western Barents Sea, (e.g. Loppa high and Stappen high) are just some of the geologic elements that reveal a complex plate interaction and basin evolution. To improve the understanding of the Lower Cretaceous on Norwegian Continental shelf some items should be focused;

- causes of uplift,
- the source of Lower Cretaceous clastic sediments in the Northern Norwegian Sea and Barents Sea
- the distribution of equivalent shelfal and deep water sediments in the Northern North Atlantic, Barents Sea and Early Cretaceous neighbouring terrains of Greenland and the Canadian basin.

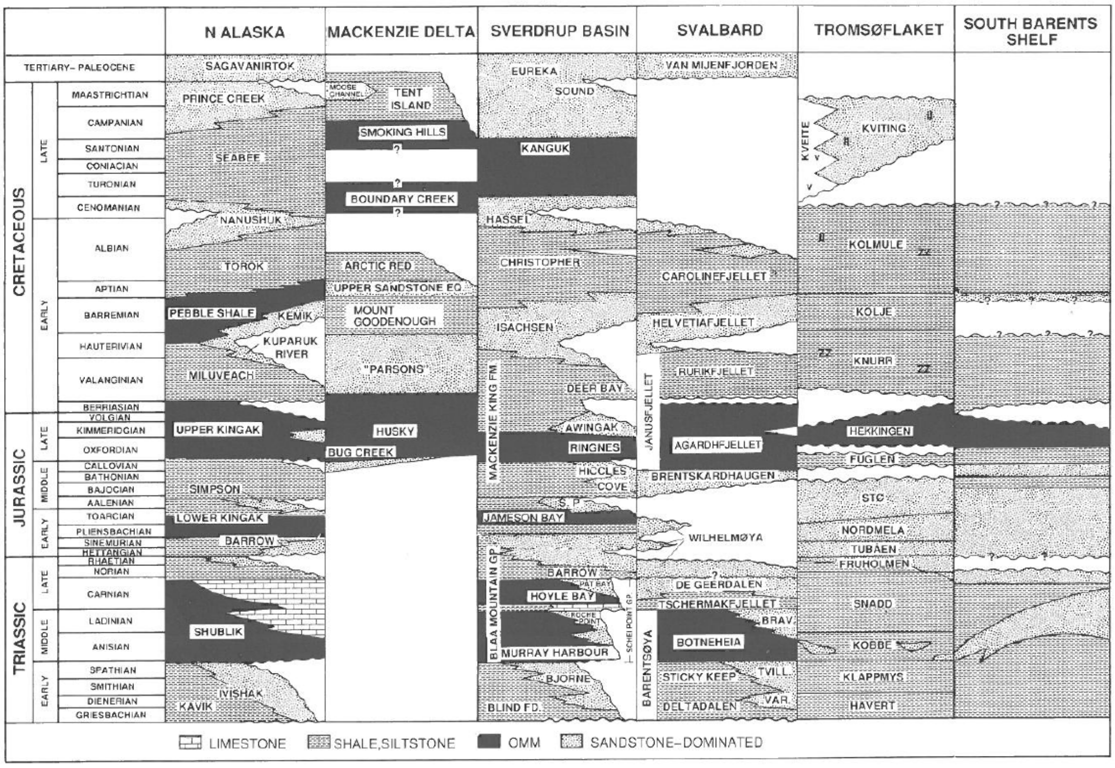


Figure 2. Simplified stratigraphic column showing the relation between the different arctic basins, from North Alaska to the Barents Sea (from Leith et al., 1990). Note also that the related basin to Barens Sea, the Sverdrup Basin has a source rock potential in the Cenomanian to Santonian Kanguak Formation. Similar units might occur in the preserved Upper Cretaceous section in the Western Margin of the Barents Sea.

In conclusion; we claim that better prediction of Lower Cretaceous clastic wedges are a valuable play concepts for increasing the resource potential (or resource estimates) on the Norwegian Continental shelf.

Lower Cretaceous examples for the Northern Atlantic, Barents Sea and Svalbard

Norwegian Sea, East Greenland

The Lower Cretaceous in the northernmost Atlantic can be subdivided into depositional sequences of the North Atlantic Valanginian to Early Cenomanian first order transgressive – regressive cycle (Jacquin et al., 1998). This cycle seems to be related to the beginning of sea floor spreading in the south and subsequent propagation northwards after the Late Jurassic extensional phase and post rift phase. It is proposed that shoulder uplifts caused by rapid subsidence of the old Jurassic rift axis resulted in clastic sedimentation into the basin axis. In addition renewed extensional and probably transtensional tectonic activities in Barremian created new accommodation space. The major T/R cycle and the related depositional sequences are recorded as point sourced clastic sand-prone wedges in the North Atlantic. East Greenland has several exposures of Lower Cretaceous costal and shallow marine sandstone bodies. Some of these bodies have thick and excellent net gross values (Fig. 3).

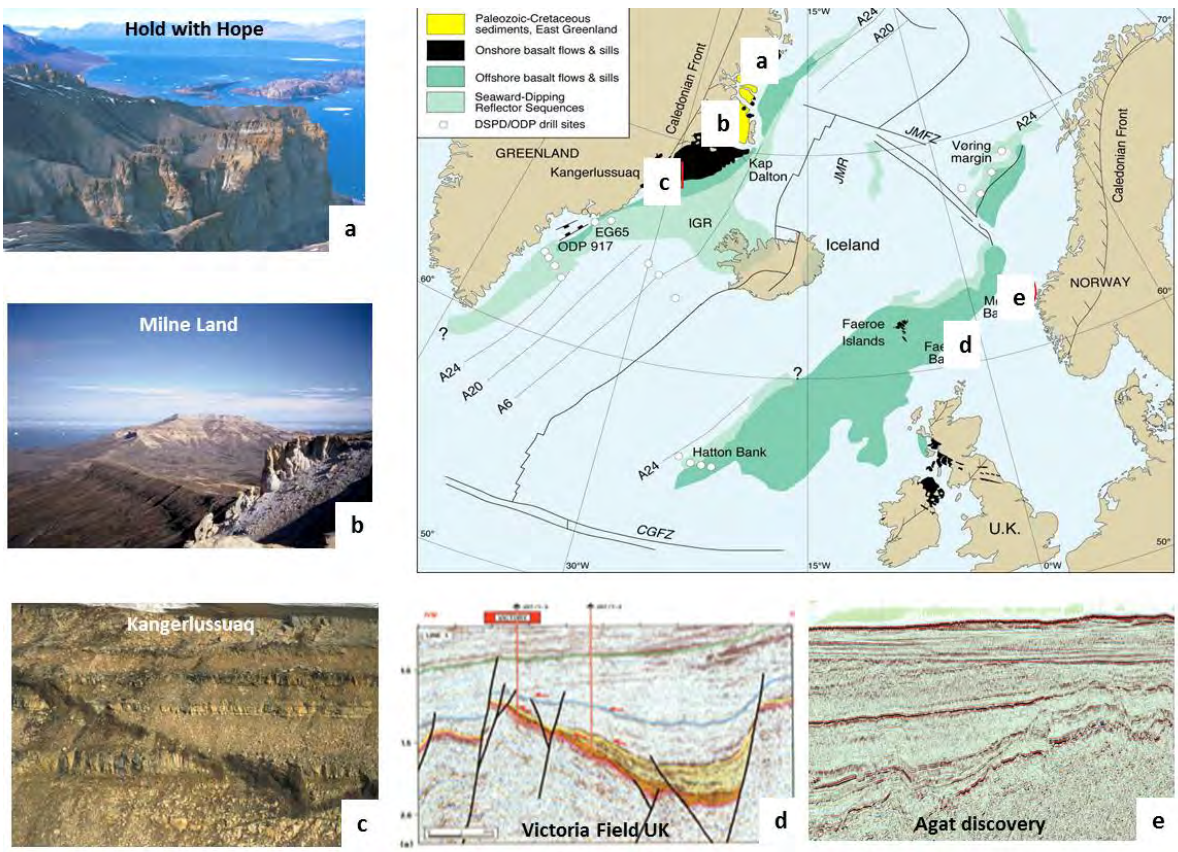


Figure 3. Examples of clastic wedges in the North Atlantic realm. a) 150m thick Albian shoreline and tidal deposited sandstone unit b) 200m thick unit of Valanginian to Hauterivian Shoreline to coastal plain deposited sandstones, c) 150m thick Aptian to Albian fluvial to estuarine deposited sandstones, d) Interpreted seismic section of the Victoria Field UK with Lower Cretaceous shallow marine sandstones as reservoir. e) East west seismic line (east to the right) showing Aptian Albian gravity (slope apron fan) as reservoir in the Agat gas discovery in west, down flank of Hauterivian shallow marine sandstone on the high to the east. All photos by M. Larsen. Map from Larsen & Olaussen (2004).

Lower Cretaceous sandstones are encountered on several wildcats in the Norwegian Sea (Fig. 4, left): The Hauterivian/Barremian unconformity is an important event on the western margin of the Fennoscandia Shield, but surprisingly seldom notified in publications from the Norwegian Continental shelf and in some cases previously misinterpreted as the Base Cretaceous Unconformity. It is well known on seismic dip lines (Fig. 4)

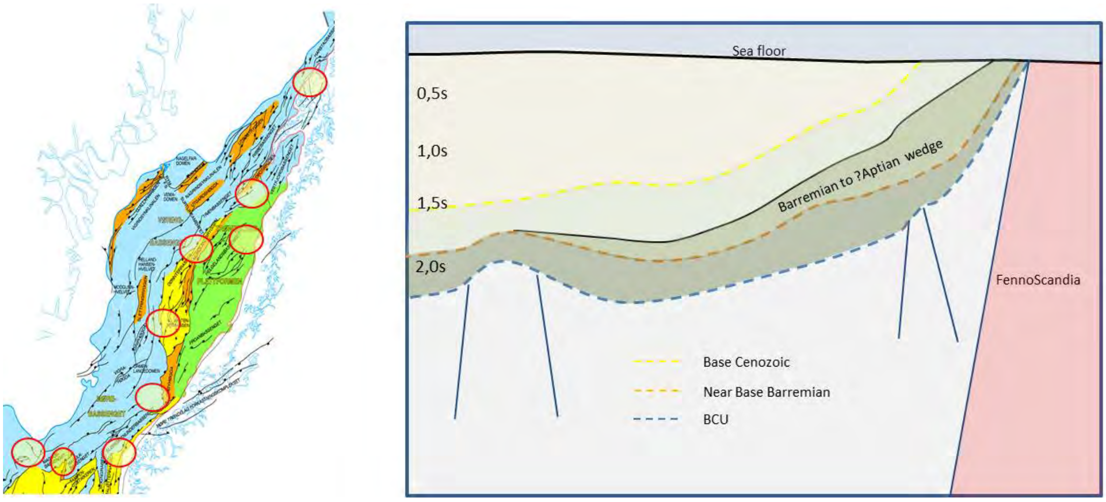


Figure 4. Left: Area of encountered Lower Cretaceous clastic wedges in the Norwegian Sea. Right: Simplified sketch from the eastern Margin of the Norwegian Sea. The Hauterivian/Barremian unconformity (stippled orange) is a regional important event along the western margin of Fennoscandia. Sketch is based on seismic dip lines.

Onshore/offshore north-east Greenland

Haman et al. (2005) show by scarce seismic data offshore north East Greenland occurrence of local rift basins in Lower Cretaceous with probably drainage from the surrounding highs (Fig. 5 and 6) whereas the northeastern onshore of Greenland seems to have a northern and westerly source (Røhr et al., 2010). Northeast Greenland represents together with Svalbard key localities for better understanding the basin evolution in the Arctic. This was also the time where most of the North American arctic basins developed (Lawver et al., 2002). Limited access to remote outcrops, poor and inconsistent biostratigraphy, limited amount of released seismic data will still give provide major challenge to sequence stratigraphic subdivision and correlative horizons for prediction of prolific sandstone units. However, Dypvik et al. (2002) shows that local knowledge of the lower Cretaceous stratigraphy on Svalbard (Fig. 6) may give reasonable correlation.

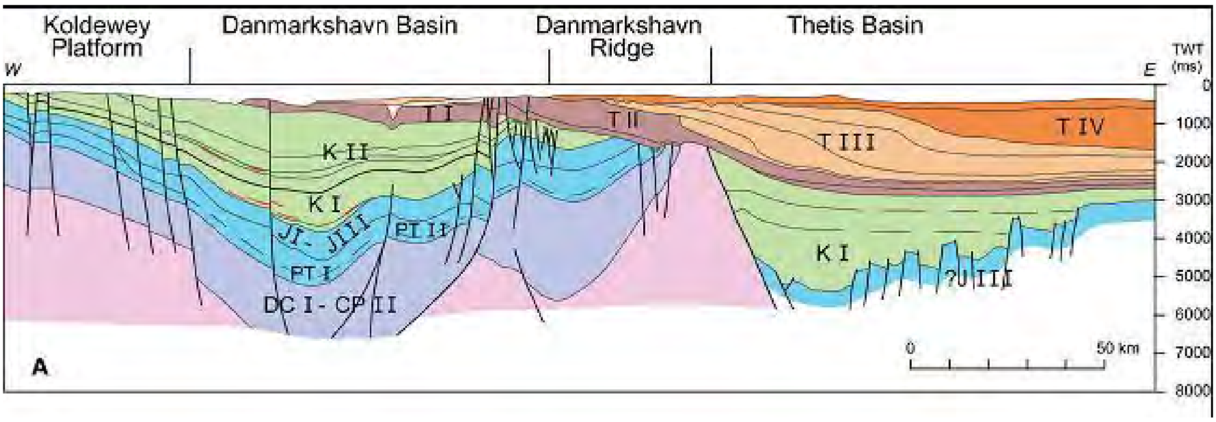


Figure 5. Interpreted seismic section from North East Greenland (see Mark *Fig. 4A* on figure 6 for location). Due to burial depth Cretaceous seems to be a valid play in north East Greenland. From Hamann et al. (2005).

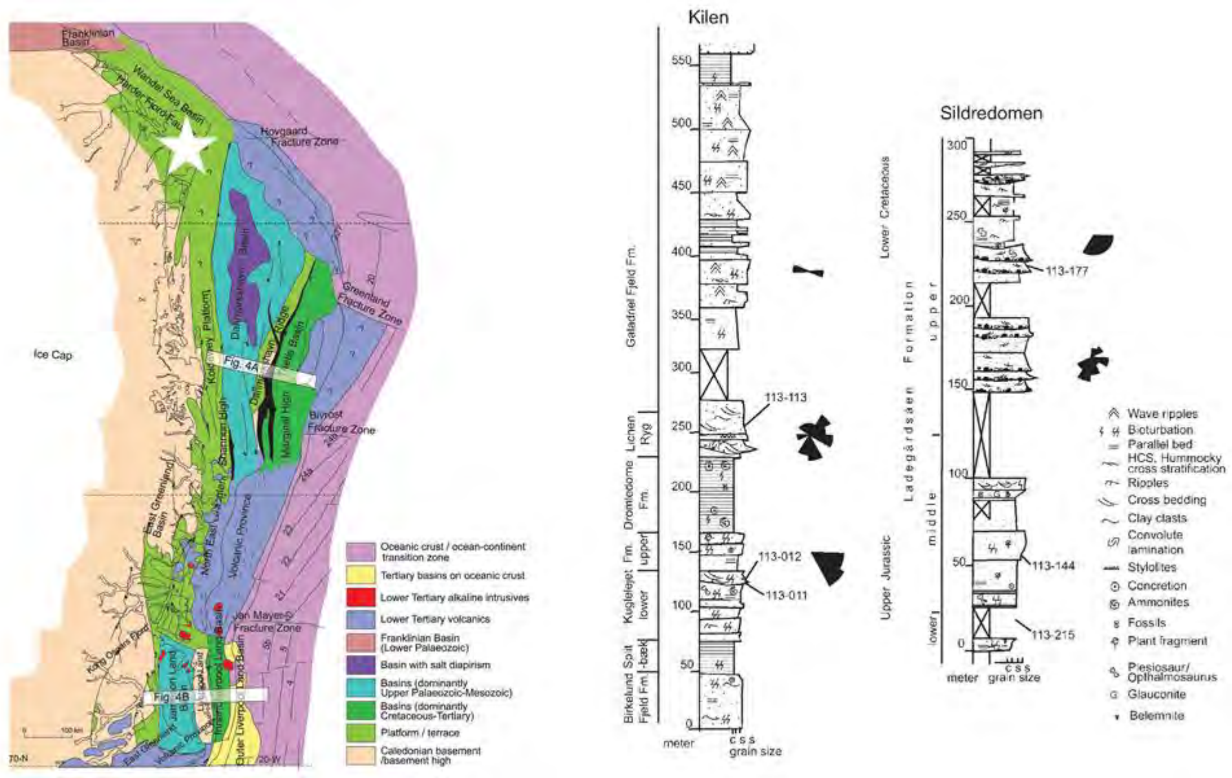


Figure 6. Structural elements of onshore offshore North East Greenland (From Hamman et al. 2005) and sedimentological log from Kilen (From Røhr et al. 2008) White star on the map show the location of the measure section.

South-western Barents Sea

Both the Norwegian Sea and more recently the south-western margin of the Barents Sea have been proven as efficient hydrocarbon provinces. However, as in the Norwegian Sea, the south-western Barents Sea accumulations have so far mainly been proven in the Triassic and Jurassic reservoirs. In the Southwest Barents Sea “economic” source rock is proven in two levels; lower/middle Triassic (Goliat) and Upper Jurassic while Lower Cretaceous is proven as a potential source rock west of the Loppa High (Ohm et al. 2008). Well defined lower Cretaceous clinoforms are observed in seismic on the southwestern Barents Sea and as shown on outcrops in Svalbard, the main progradational trend of these clinoforms is also directed southeastward (Fig. 7). Similar southward prograding clinoforms are observed in the northern Barents Sea Basin, south of Franz Josef Land (Klett and Pittmann, 2011). Current studies of the geometry and image of the clinoforms have shown the importance of recognizing coarser, sandstone prone, from fine grained clinothems by analyzing shoreline trajectory directions. A method which should be on great importance for prediction of both paleogeography and sandstone wedges in the Barents Sea (Fig. 8).

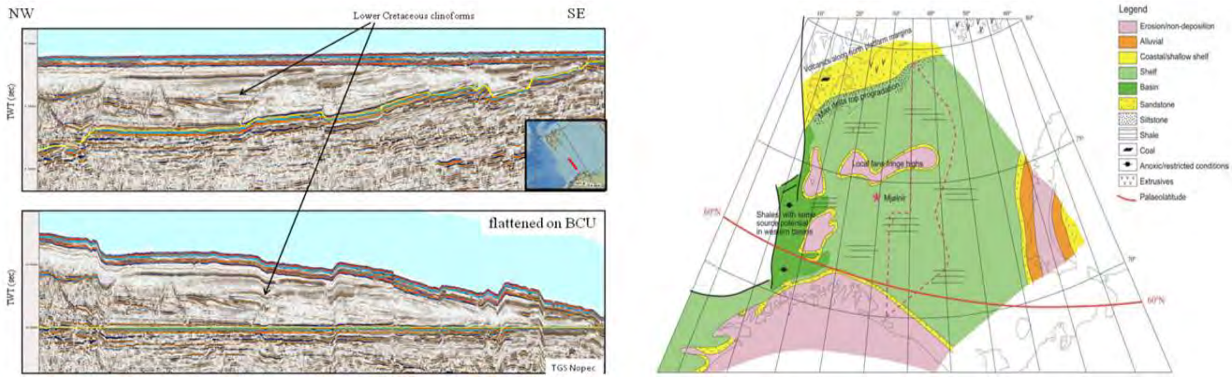


Figure 7. NW-SE seismic line showing south directed clinoforms in the central and southern parts of the Barents Sea in the Lower Cretaceous interval. The lower section is the same section as above but flattened on the Base Cretaceous unconformity (BCU) to highlight the clinoform shapes and original depositional setting. Seismic examples kindly provided by TGS Nopec. Figure to the right is a palaeographic reconstruction of the Barents Sea after Worsley (2008).

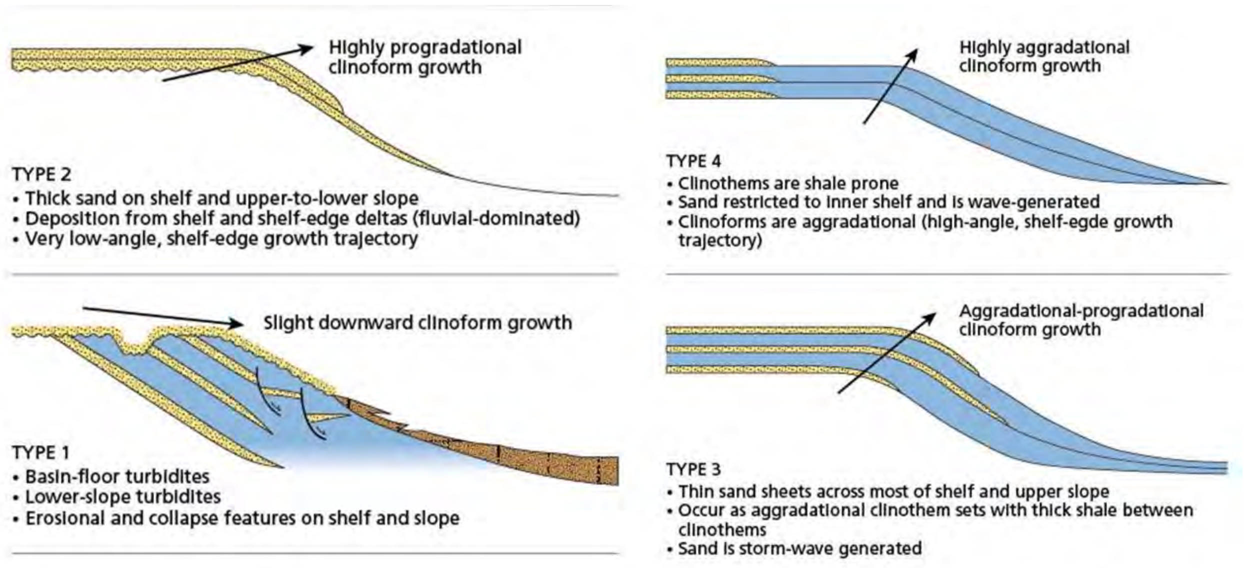


Figure 8. Conceptual model of dip oriented clinoforms and the likelihood of sandstone wedges related to the shoreline trajectories (From Deibert et al., 2003)

In addition to the south directed clastic wedges interpreted from outcrop geology in Svalbard and in the southwestern Barents Sea (Figs. 7 and 13), time coeval point sourced clastic wedges banked to the master faults and basinal highs in the western Barents Sea are quite important. Continued movement after the Jurassic rifting led to subsidence along major boundary faults with deposition of gravity flows into the basin from uplifted and eroded basin margins in Hammerfest, Tromsø and Bjørnøya basins (Seldal, 2003). On the Loppa High well known canyons and erosional features have been previously mapped (Fig. 9) with the presence of well sorted gravity deposited sandstone suggesting an extensive shoreline along the various basin highs (e.g. Loppa High). These wedges are possible exploration targets. In this setting prolific sandstone beds are proven in the southwestern part of the margin (Fig. 10). Due to Late Cretaceous, Paleocene and Neocene uplift the typical post rift subsidence as observed in the Northern North Sea is missing in the basin margins and on the platform. Only occasionally the shallow marine counterparts are observed (7122/2-1) and only a thin cover of Cretaceous units is seen in the Platform (Fig. 10).

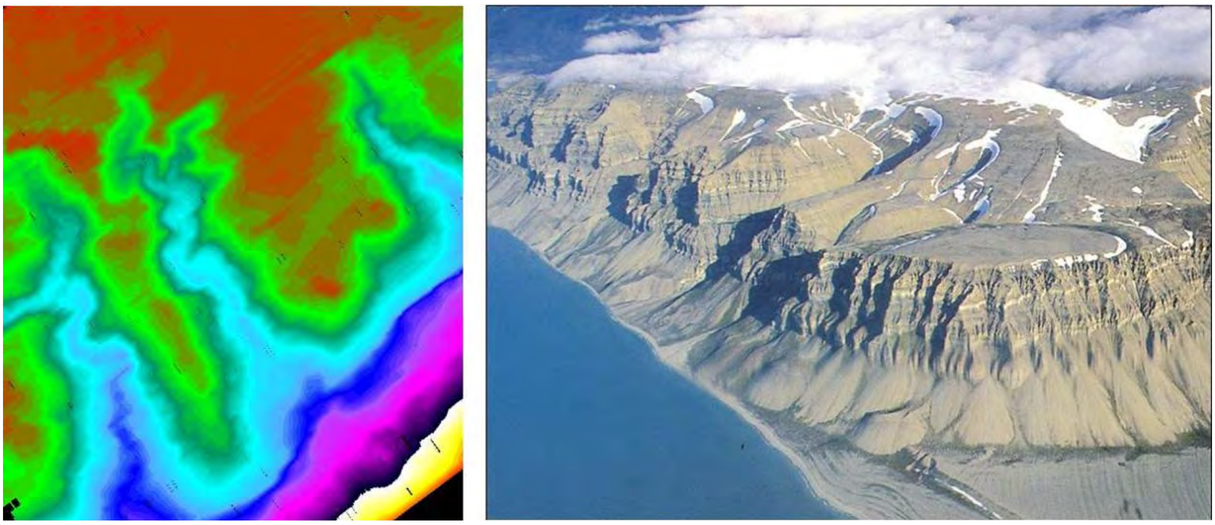


Figure 9. Left figure (deliberately blurred) shows a structural map showing Lower Cretaceous canyons on the south-eastern part of the Loppa High. Figure to the right shows an analogue example in Tertiary strata in Svalbard Isfjorden Svalbard indicating large amounts of clastics are deposited in the fjords

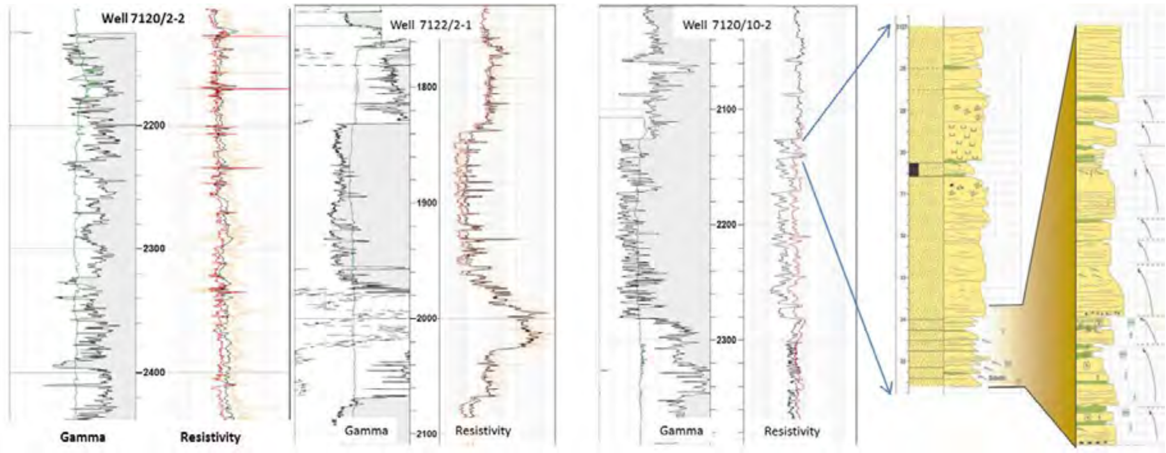
Svalbard

Figure 11 shows a compiled stratigraphic column from Spitsbergen. Up to 1000m thick Lower Cretaceous sediments are exposed on Svalbard (Fig . 11) The section from Hauterivian to Early Aptian is partly well dated and can be described as a regressive transgressive mega cycle (Gjelberg & Steel 1995, Midtkandal & Nystuen 2009). The Barremian fluvial deltaic unit at Svalbard (Figs. 11 and 12) belongs to a large southeast directed progradational costal wedge (Fig. 13). The upper part of the lower Cretaceous Carolinefjellet Formation in Svalbard is less known and is poorly dated but it is suggested to cover the Early Aptian to Late Albian (Fig. 11). The section is more than 600m thick and up to 100 m thick sandstone prone units of thick shallow marine to inner shelf origin are probably time equivalent to the mudstone dominated Kolmule Formation in the South-western Barents Sea.

A change in sandstone composition is seen in the middle part of the Barremian delta with income of plagioclase and volcanic clastic grains (Edwards, 1979, Maher et al. 2004). This change in sandstone petrology and the extrusive in eastern part of Svalbard and Franz Josef Land are related to High Arctic Large Igneous Province (HALIP; Tarduno, 1998).

Also some major geological events with proposed correlative seismic reflectors are given in Svalbard and the Barents Sea West Margin. In Svalbard and its offshore platform area, Franz Josef Land and offshore North East Barents Sea intrusive and extrusive volcanic rocks are an important constitute of the strata. This volcanism have been reported with very variable radiometric ages, probably caused by different methods, but are generally suggested to be within the Barremian to Aptian periods.

A.



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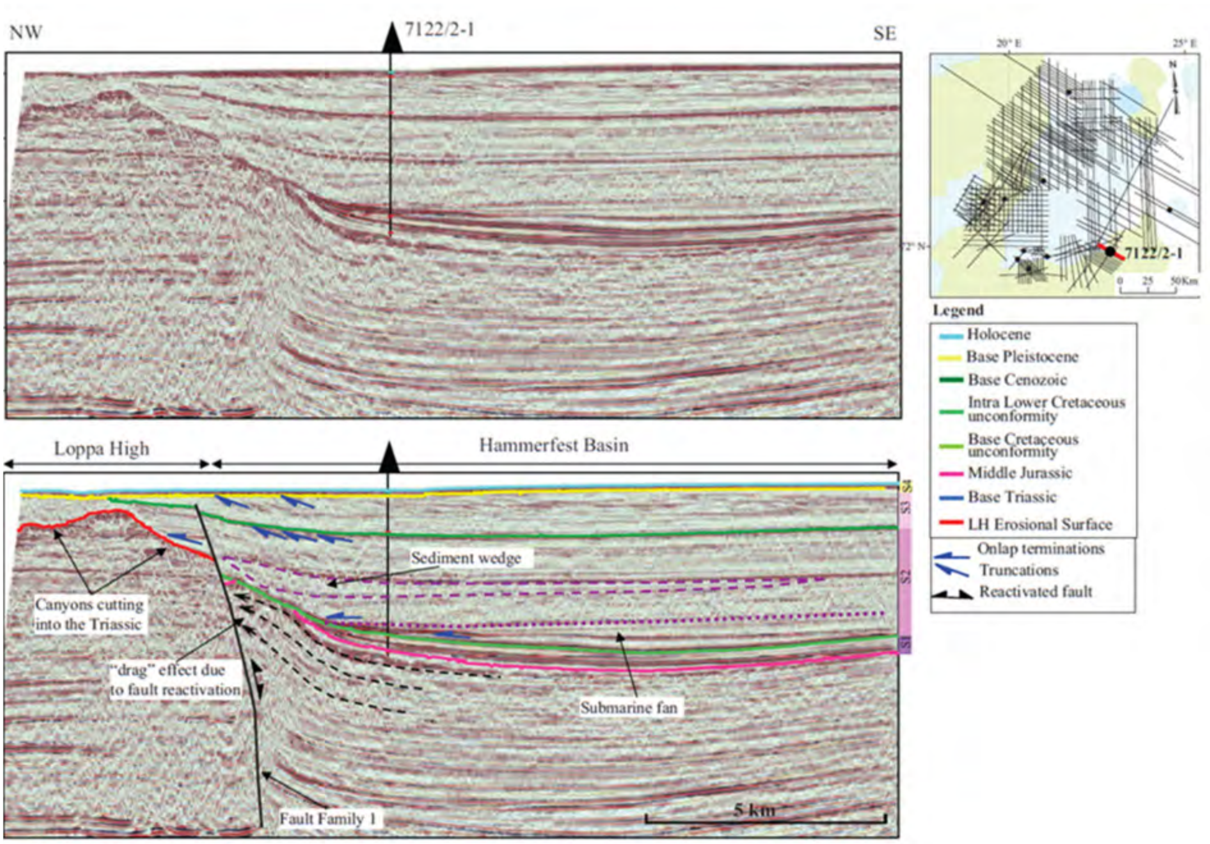

Figure 10. A) Examples of prolific Lower Cretaceous sandstone bodies along the master faults in the South-western Barents Sea. Well 7120/2-2, close to the Asterias fault complex shows an Aptian unit with a heterogenetic facies development. Core description and interpretation suggest costal deposits suggest with tidal and wave dominated shoreline. Well 7120/2-1 shows a Lower Cretaceous coarsening upward unit of thick well sorted sandstone unit. From 2125 to 2280m in well7120/10-2 which is located of the flanks if the Troms Finnmark fault complex, 160m thick sandstone with a high net gross value was penetrated. Core description in well 7120/10 -2 (figure to the right) show dm to m scale fining upward units, with scour marks and water escape structures suggesting deposition from density currents (e.g. Bouma units) probably deposited in a basin floor or slope apron fan. Logs modified from NPD Facta pages. B) Non interpreted and interpreted seismic line in the SW flank of the Loppa High showing the Lower Cretaceous wedge and location of well 7122/2-1 (Nazarova, 2009).

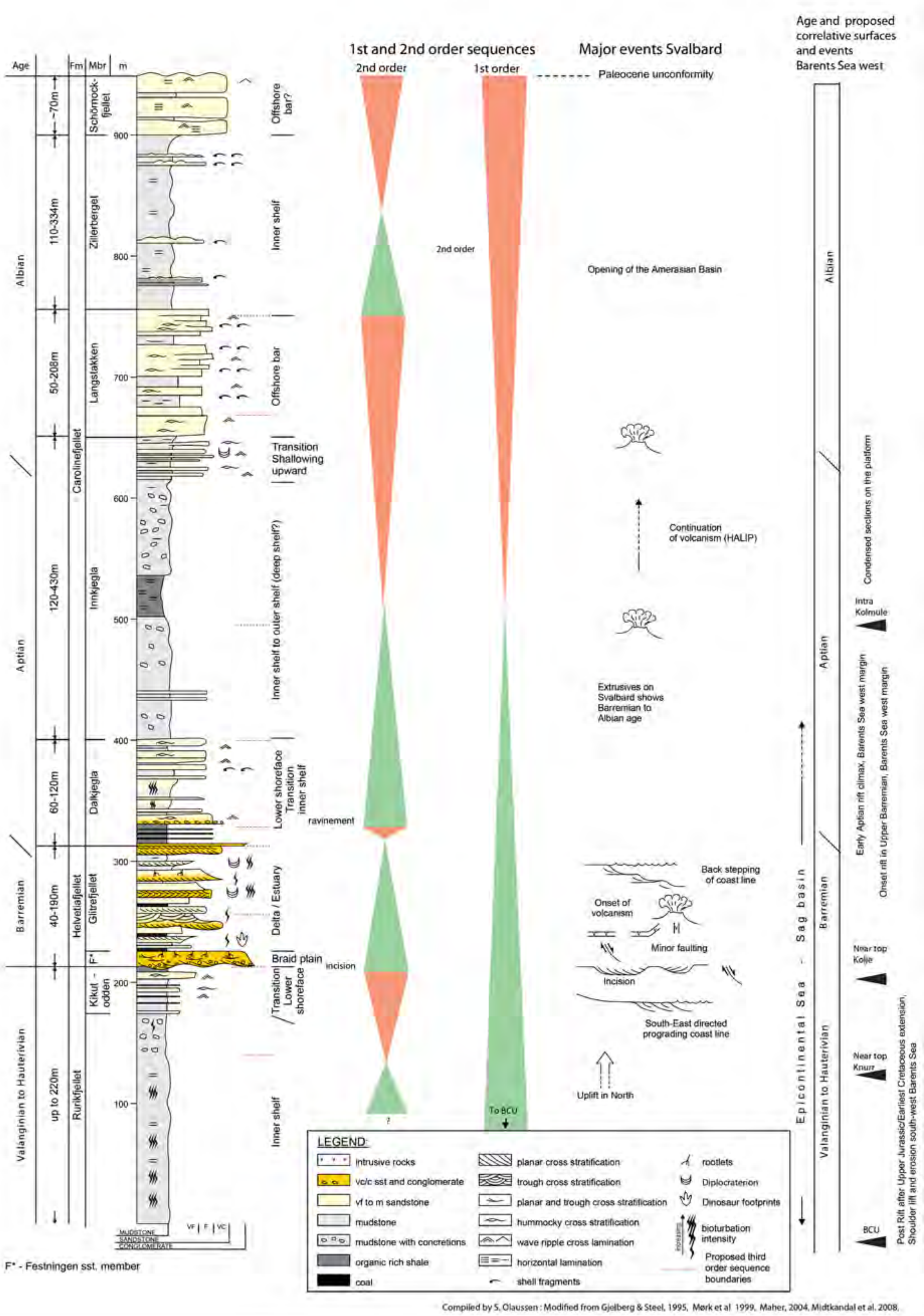

Figure 11. Composite stratigraphic section of the Lower Cretaceous on Spitsbergen.. Green and orange bars are T/R sequences. Green; transgressive , orange regressive .

Figure 12. Exposed lower Cretaceous clastic wedge at Ullaberget, Spitsbergen. Logged profile is from Midtkandal et al. (2008) and photo courtesy of E. Siggerud.

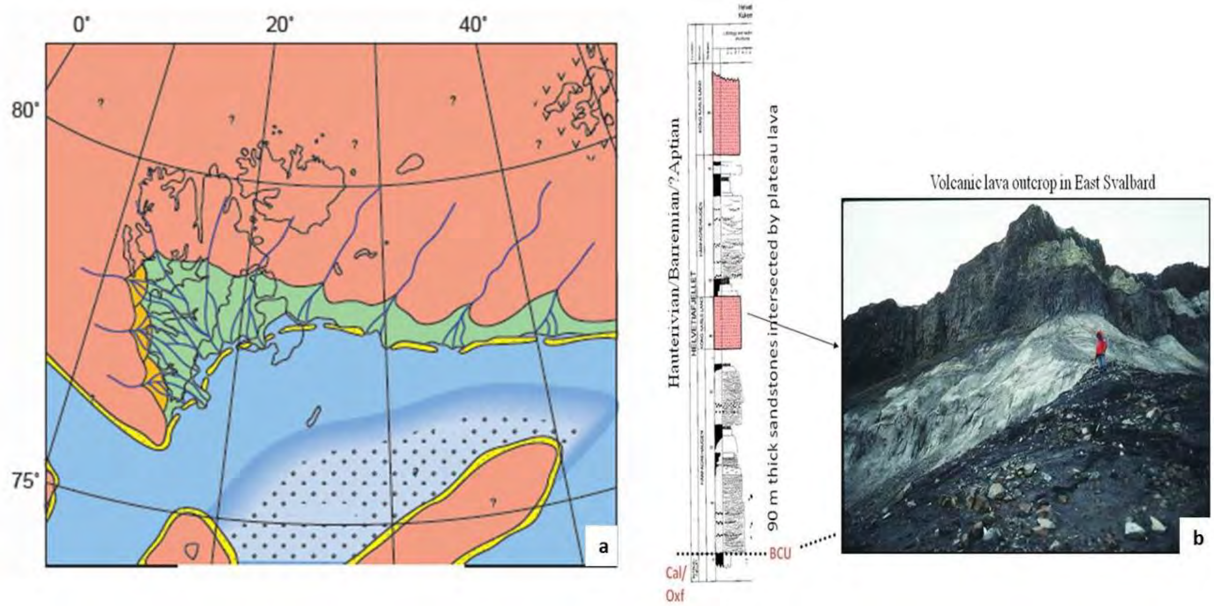

Figure 13. Suggested Palaeography of the Barremian onshore offshore Svalbard (Larssen et al. in prep) and stratigraphic section and outcrop photo showing Lower Cretaceous volcanic lava interbedded with Barremian paralic and deltaic sediments. The volcanic rocks are interpreted to be part of the HALIP event (From Larssen et al., 1993).

Additional background aspects relating to the research project

The Late Jurassic-Cretaceous evolution of the Arctic region is marked by initial rifting that led to formation of the present configuration, including the Early Cretaceous Canada basin, the formation of oceanic ridges such as the Alpha and Mendeleev ridges, development of the North Slope foreland basin and uplift of Svalbard and Franz Josef Land (Fig. 14). The Early Paleogene saw the opening of the Eurasia Basin that separated the continental Lomonosov Ridge from the Barents and Kara shelves. Plate tectonic models by Lawver et al. (2002) and Golonka et al. (2003) reveal a complex transpressional/transtensional motion of blocks during the Late Jurassic and Cretaceous that may have been initiated by convergence between western North America and the northeastern Pacific Rim. As a result, the Upper Jurassic/Early Cretaceous boundary represents a major change in the paleogeography of the northern Barents Sea, characterized by lowering of sea levels that resulted in open shelf conditions and the development of a large south directed progradational deltaic wedge that outcrops today in Svalbard and Franz Josef Land. By the end of the Cretaceous, and prior to the opening of the North Atlantic and the Eurasia basin in the Tertiary, uplift characterized large areas of the Barents Sea including the Svalbard archipelago and the basement structural highs on the western Barents Sea, such as the Loppa High and the Stappen High. There is as yet a poor understanding of the causes of uplift, the distribution of deep water equivalents of the deltaic clastic wedges, and the relation of equivalent stratigraphy in the neighboring terrains of Greenland and the North American Arctic.

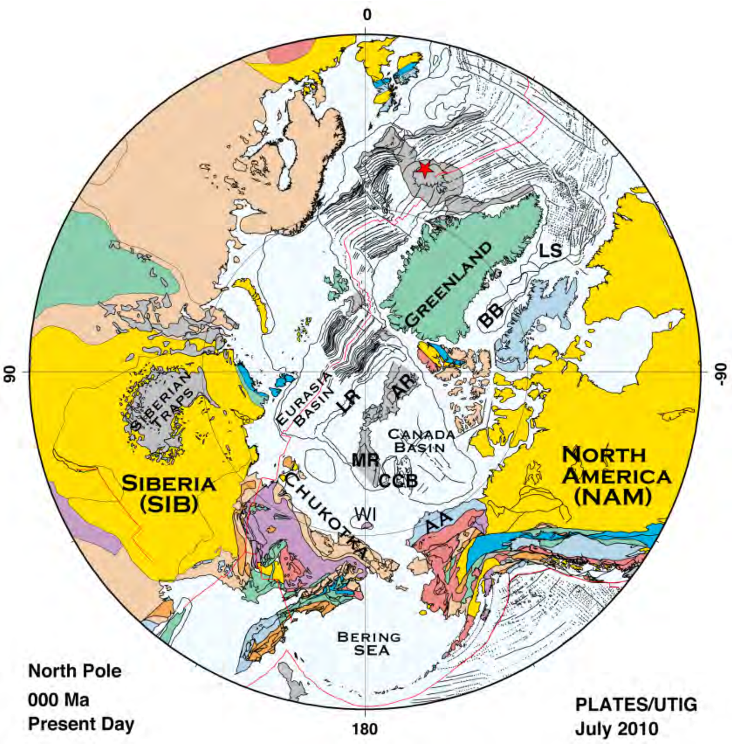

Figure 14. Present-day plate tectonic framework showing the main geological elements. Red start indicates the location of the Icelandic plume. LR (Lomonosov ridge); BB (Baffin Bay), AR (Alpha Ridge), AA (Arctic Alaska), WI (Wrangell island), CCB (Chukchi Continental borderland), MR (Mendeleev Ridge), LS (Labrador Sea). Modified from Lawver et al. (2002).

As part of this large scale plate tectonic setting during the Late Jurassic – Early Cretaceous, plate tectonic models (Fig. 15) predict a large dextral motion of the North American Arctic relative to the Norwegian-Russian Arctic, resulting in the following development (Lawver et al., 2002; Lundin and Dore, 2002):

1) Opening of the Canadian Basin as Chukota rotated counter clockwise away from the Canadian Arctic islands with a pole of rotation near the Mackenzie delta area;

2) Rifting of the Lomonosov ridge from the Barents Shelf, with the development of a large transform fault to accommodate the opening of the Canadian basin;

3) Uplift of the Brooks Range in Alaska;

4) Uplift of the northern Barents Sea and basement highs in the central Barents Sea;

5) Basaltic intrusions [HALIP-High Arctic Large Igneous Province] from western Siberia, Svalbard and northern Canada possibly related to the Icelandic hotspot.

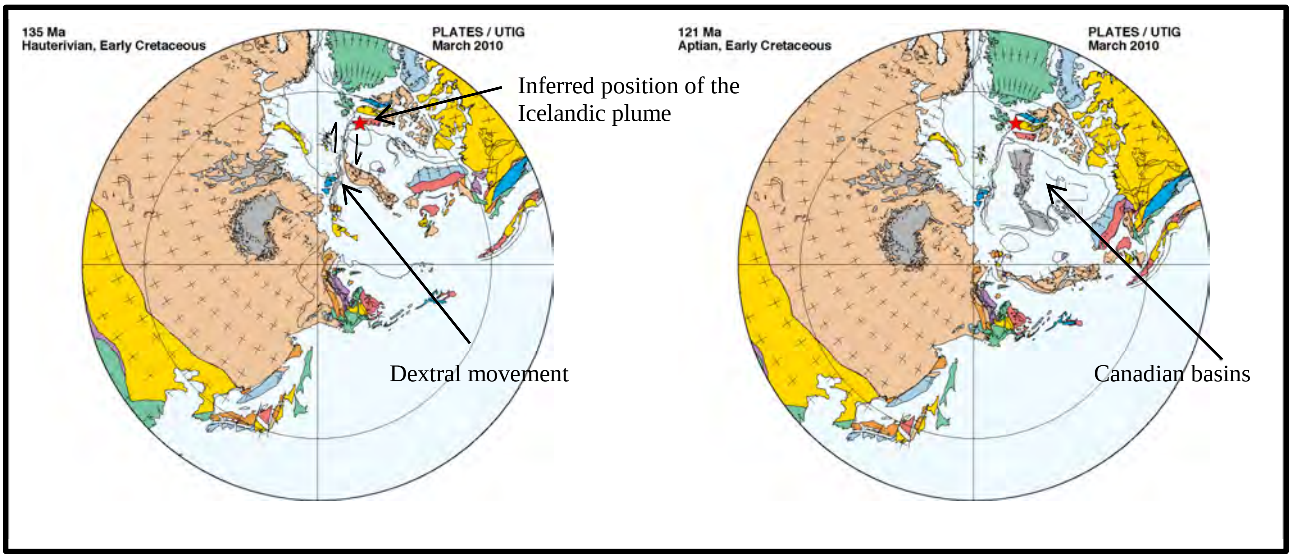

Figure 15. Plate tectonic reconstructions at 135 ma and 121 Ma respectively highlighting the development of the Canadian basins by dextral movement and the location of the Icelandic plume, north of the Svalbard Archipelago (modified from Lawver et al., 2002 and the Plate project at the Institute for Geophysics at the University of Texas at Austin).

Much work has been done since the late 1970's, but scarce surface and subsurface data availability at the public domain and good understanding of the plate tectonic evolution of the different Arctic blocks and their implications remains a major limitation. Unsolved questions related to these changes and their precise ages, basin evolution and impact on the petroleum system include the following:

- ***Processes for progressive Cretaceous uplift of the northern Barents Sea***: During the Late Jurassic-Early Cretaceous, shelf sedimentation dominated most of the Barents Sea, except in the north, where south-directed deltaic sedimentation took place (Worsley, 2006). This clastic sedimentation in the Svalbard-Franz Josef Land area suggest that uplifted terrains towards the north occurred and acted as a major clastic source (Worsley, 2006; Lundin and Dore, 2002). It has been postulated that the source of sedimentation was the uplifting Lomonosov ridge that formed as a micro-continent caused by dextral shearing during the Early Cretaceous along the Barents shelf prior to the formation of the Canadian basins (Faleide et al., 1993). Seismic data and field observations in the northern Barents Sea indicate a Cretaceous compressive phase (Gustavsen et al., 1997). In the Alaska region, this event coincides with a change in the direction of deposition from a south facing passive margin to a north facing foreland basin as the Brooks Range uplifts towards the north (Weber and Sweeney, 1990; Lawver et al., 2002) (Fig. 16).

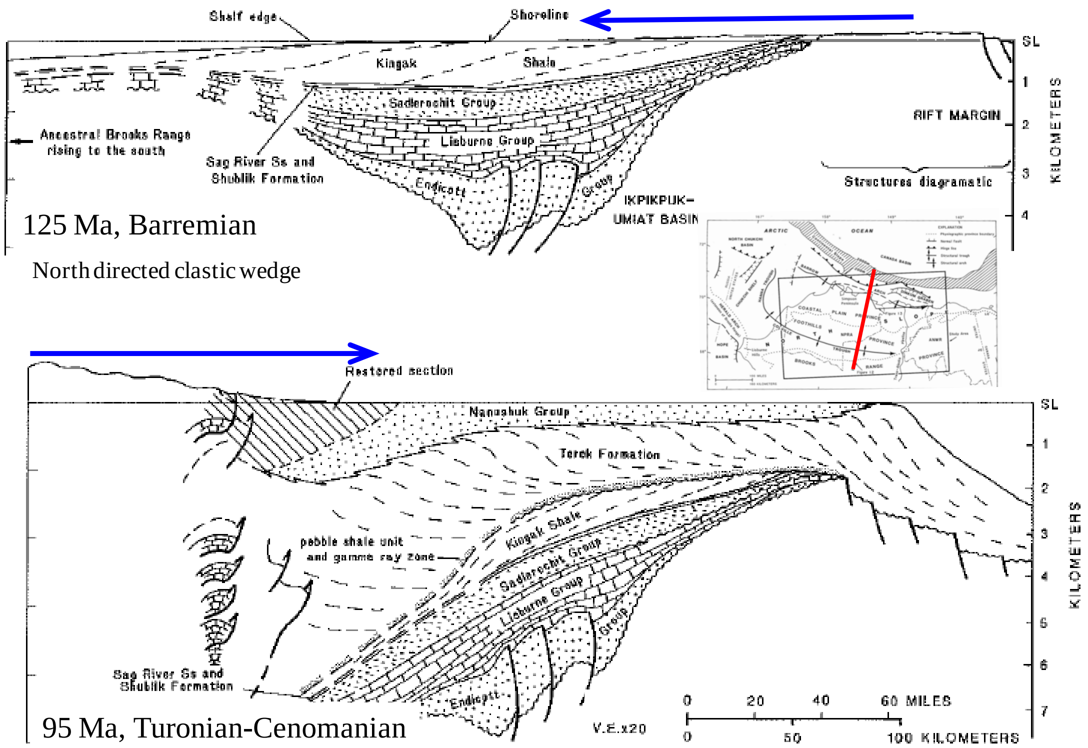

Figure. 16. N-S crossection in the north slope indicating the shift in depositions from south directed in the Barremian to north directed in the Turonian-Cenomanian.Taken from Lawver et al., 2010, Original from Bird (1987).

Another plausible explanation is migration of the Icelandic hotspot and related thermal effect along the northern margin of the northern Barents Sea and the Canadian basin (Lawver and Muller, 1994), resulting in doming and extrusive volcanism, in addition to lower eustatic sea levels (Fig. 14). Early Cretaceous magmatism is pronounced in the Sverdrup basin and the northern Barents Sea indicating a possible connection. It is generally accepted that opening of the Canadian basin occurred during the Early Cretaceous by counter clockwise rotation of eastern Siberia, formed by sea floor spreading. This opening coincides with the break-up unconformity in the Sverdrup basin, and also with uplift of the northern Barents Sea during the Late Cretaceous and volcanism (e.g. Lavas in Svalbard, Fig. 13). A question remaining relates to the style of deformation, which has a major impact in the petroleum system and basin evolution:

- 1) uplift caused by dextral transpression forming compressional structures along the sheared margin;
- 2) by transtension, resulting in shoulder uplift of the rifted margins as the Amerasia Basin opened.
- 3) Uplift caused by thermal effect of the Icelandic plume

- ***Evaluation of the causes of reactivation and sub aerial exposure of structural highs in the western Barents Sea***: in the western Barents Sea, reactivation of Jurassic structures was renewed during the Cretaceous. The Loppa high (Early Cretaceous) and Stappen high (Late Cretaceous) were inverted and truncated, acting as large positive areas. These highs acted as a main source of clastic sediments that deposited clastic wedges and large submarine fans in the flanks of adjacent basins (e.g. Bjørnøya and Hammerfest basins) (Faleide et al., 1993) (e.g. Loppa High, Fig. 9).

- ***Configuration of depositional patterns of outer shelf, slope and deep basin deposits equivalent to terrestrial Early Cretaceous sediments in northern Svalbard***: During the Cretaceous, fluvio-deltaic prograding wedges and shallow marine sedimentation of Hauterivian-Barremian and Aptian-Albian age were deposited along the northern margin of the Barents Sea, localized basins in the southern Barents Sea, along the margins of eastern Greenland and Norway, and in the North Slope of Alaska (Fig. 14). Furthermore, south directed clinoforms are clearly interpreted in the seismic data in many areas of the Barents Sea (Fig. 7). The Svalbard prograding wedge is sourced from uplifted terrains located to the north along the sheared margin between the North American and the Barents Sea margin, and maybe related to the same wedges observed in the subsurface in the central and southern part of the basin suggesting a more complex paleogeography and basin evolution. It remains unclear if the same source of sediments is responsible for the prograding basin fill observed in the North Slope during the Lower Cretaceous (Fig. 16).

As discussed in the previous section, renewed uplift of the Loppa high during the Early Cretaceous produced localized sedimentation of clastic wedges and deep water turbidities along the flanks and adjacent basin depocenters as evidenced from regional seismic data and tested by wells (Figs. 10).

In summary, outcrop distribution of Lower Cretaceous wedges shown in Figure 17 represents a key area of interest for hydrocarbon exploration and the understanding of the basin evolution in the arctic region

Figure 17. Topography/bathymetry map of the Northern most North Atlantic showing outcrops with continental to shallow marine sandstone bodies: The depositional environment varies from fluvial to wave dominated shoreline, delta, estuarine and to inner shelf and offshore bar sandstones. Map from Jacobsson et al. 2000

Project plan

The project is proposed for an initial duration of 4 years, with the following general activities in each year of the project:

Year 1: Compilation of data and construction of project database, preliminary subsurface interpretation and initial plate tectonics and kinematic models. Begin field campaign in Svalbard. A main goal during this year is to build an integrated database that includes Greenland, and both the Norwegian and Russian Barents Sea sectors.

Year 2: Project database continuation, seismic interpretation continuation, and preliminary maps of the area, refine plate tectonic models and preliminary basin evolution models of areas with best geologic control. Continue field campaign in Svalbard.

Year 3: Construction of preliminary paleogeography maps and revision of interpretation and integration of different types of data.

Year 4: Construction of final evolutionary models, paleogeography controlled by plate tectonic model, quantification of deformation and structural styles, petroleum system characterization. Discussion to extend project scope.

Following proposal of work is given below:

A detailed project plan will be provided before initiation of the project, conditional on sponsor support.

This will include detailed plan for localities to be visited timing for field work the two first years. The participating companies will be invited to join the field work. On request field excursions in Svalbard is possible; an optional possibility, but not budgeted. Plan for analysis of rock samples will be planned and expected products given. We will provide a list of all surveys and wells which will be incorporated in the project. Plan for seismic interpretation with proposed reflectors will be provided together with planned maps. Special seismic workshops will be arranged.

Below we give a glimpse of the work to be executed.

Fieldwork

We will include sampling for biostratigraphy, geochemistry, provenance studies, petrology, petrophysics, sediementological logging, mapping and structural analysis. Most of this work will be provided by Master/PhD students and post doc together with supervisors from UNIS/UiB/UiO staff. Figure 18 shows outcrop areas which are planned for field work

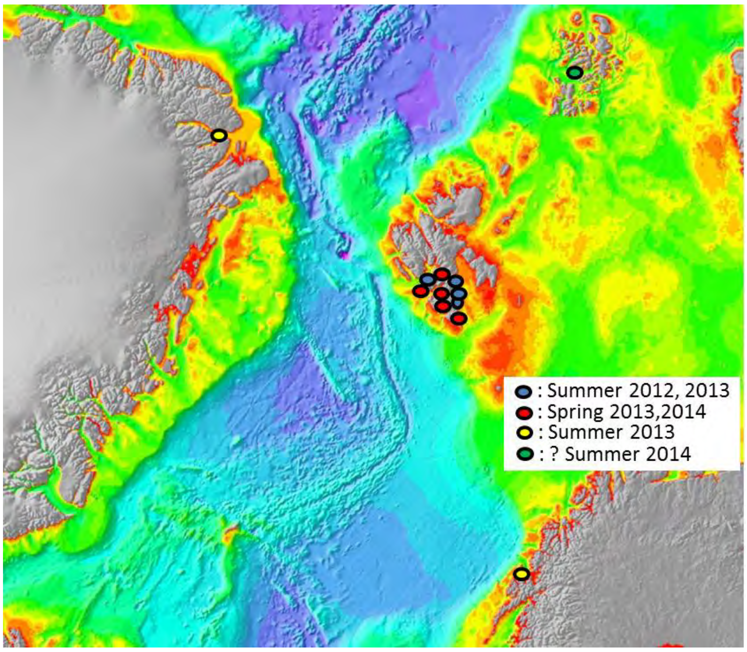

Figure 18. Proposed area for field work; this summer Shønrockfjellet, SE Spitsbergen will be visited for vertebrates research and staff from UNIS will join this small expedition and use the opportunity to log the section in this very remote area and within a Nature Reserve. Map from Jacobsson et al. 2000

Regional mapping of 2D seismic and available 3D volumes tied to available well data and outcrop data:

Norwegian academic institutions have access to the Norwegian Petrobank where data is available for the southwestern Barents Sea, south of Bjørnøya. In order to cover other areas, we may also have access to NPD north of Bjørnøya and east of Svalbard and our USA and Russian partners will collaborate with data from their respective arctic areas that will increase the project data coverage and give a better regional picture of the region. Figure 19 shows a base map of different types of seismic data existing in the Barents Sea region. The black dashed polygon shows the area of interest where the research group will attempt to get a coarse grid with good coverage to perform the study. The main target areas in the first phase (2012/2013) are Barents Sea north and west.

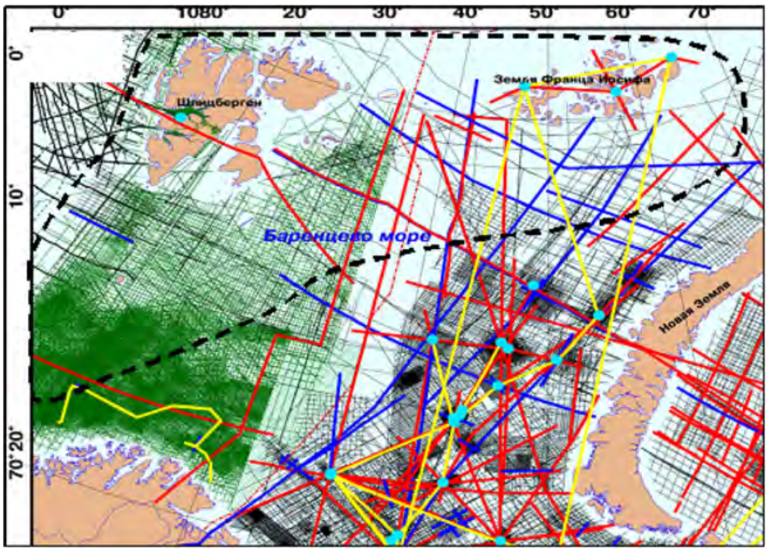

Figure 19. A map over available seismic in the Barents Sea provided by Russians colleagues.

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All conventional drilling in Svalbard is in the process of being released this summer. We aim to construct a Landmark full openworks projects with all available data (wells and seismic), and a smooth link between Petrel and Landmark (Fig. 20). A key point will be to try to integrate MAGE and others data to the Petrobank data. Apart from seismic data on- and offshore in Svalbard, the seismic north of Bjørnøya are restricted and any use of this data in figures, maps etc. are dependent on permission from NPD, which is a challenge within the project.

Plate tectonic reconstructions and paleogeography models:

New quantitative plate tectonic reconstruction softwares integrated with GIS database provide a better integration of data and analysis of displacement vectors and the exact location of control points such as facies, seismic, well, etc. (e.g. Paelogis; http://www.paleogis.com/DotNetNuke/). Construction of quantitative plate tectonic framework will serve as a template for paleogeographic maps and understanding of the different deformation styles. A particular focus is to evaluate the motion of the Barents Sea relative to the Icelandic hot spot proposed by Lawver et al. (2002) and the relative motion of other arctic blocks. This will provide insights on the radius of impact of the hotspot and the prediction of deformation styles that can lead to a better indication of uplifted areas. Information from the plate model will be used in all other parts of the project.

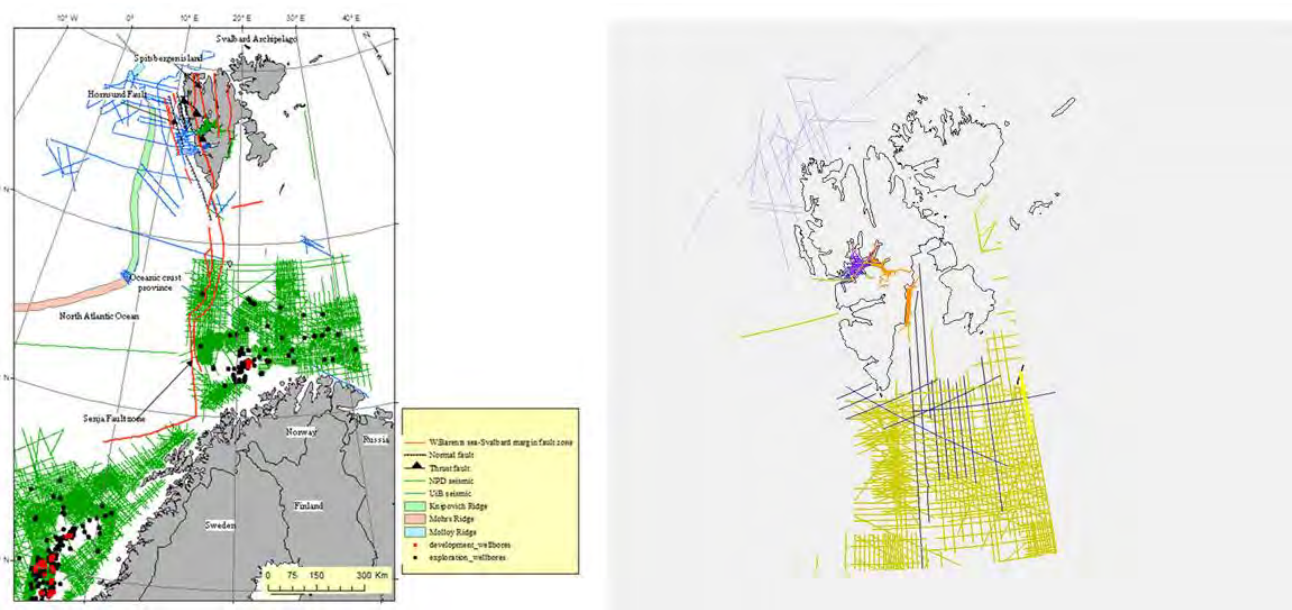


Figure 20 Left; current loaded seismic at UiS. Right; current loaded seismic north of Bjørnøya at UNIS

Financial support and budget proposal

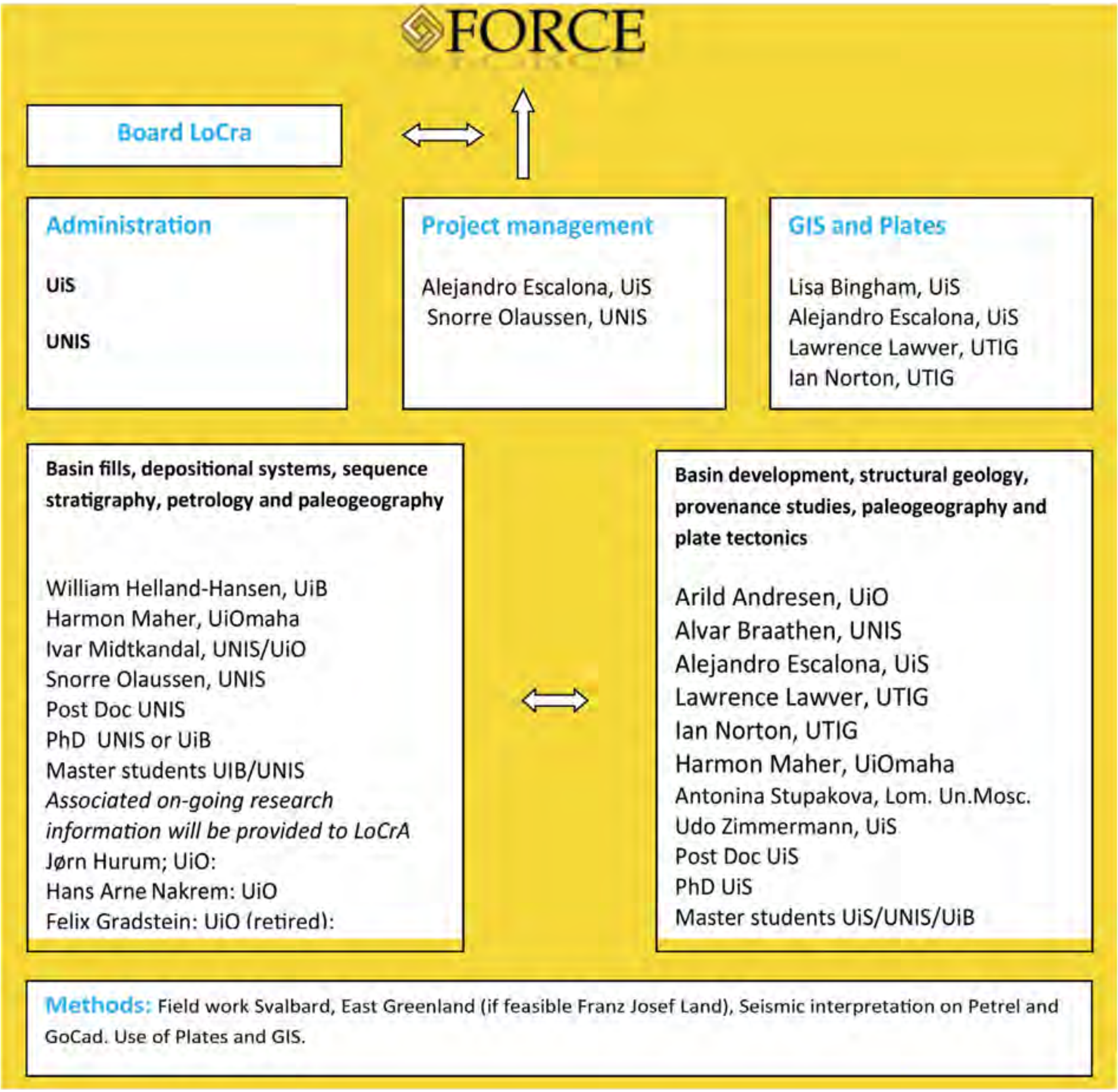
The project is intended to be supported by oil companies interested in the region. The Norwegian partners (UNIS and UiS) aim to have at least 10 companies interested in the project that could provide 2 MMNOK for the 4 years project, to make a total of 21,6 MMNOK. We will also apply to petromaks for research funds to support additional PhD and postdoctoral personnel. In addition, each research group has to contribute to existing data in the region in order to provide a good integrated database and look for further sources of funding in their home countries via industry or research agencies. Upon final budget, the project activities will be planned.

BUGET PROPOSAL LoCra 2012 to 2016						
	Year					
	2012	2013	2014	2015	2016	
Post Doc UIS		1,1	1,1	1,1		
Post Doc UNIS		1,1	1,1	1,1		
PhD UiS		1	1	1		
PhD UNIS/UIB		1	1	1		
Master students UiS		0,1	0,1	0,1		
Master students UNIS/UiB	0,1	0,2	0,2	0,2		
UTIG modelling		0,4	0,4	0,6	0,6	
GIS	0,1	0,5	0,6	0,5		
Field work Svalbard/East Greenland	0,3	0,6	0,6	0,5		
Laboratory Provenance	0,1	0,2	0,1	0,1		
Computer/software/storage seismic	0,1	0,2	0,2			
Travel cost USA Russia, Norway	0,1	0,4	0,4	0,1		
Conferences			0,1	0,1	0,1	
Yearly cost and total sum	**0,8**	**6,8**	**6,9**	**6,4**	**0,7**	**21,6**

Amounts in million Norwegian kroner

Project management, organisation and cooperation

All institutions personnel will collaborate closely on all aspects of the project and to faculty personnel. The team is composed of highly qualified persons in critical scientific areas ranging from the observational to the theoretical. The team has members with both academic and industry experience in regional studies and petroleum systems. Success depends on integration of the group effort and we plan to have several meetings a year to integrate research activities, review progress and also plan exchange research periods between Norway, USA and Russia. The University of Stavanger will act as the main administration and both UiS and UNIS will be the technical leaders of the project (co-PI Alejandro Escalona at UiS and co-PI Snorre Olaussen at UNIS)



Comments on postdocs and students: Because the scope of the project is very ample and challenging, including several geo-disciplines, we propose support for the following research staff

University of Stavanger: 1 PhD, 1 postdoctoral researcher and several M.Sc. students

In order to promote cooperation, we suggest that the PhD position at UiS could be offered to a Russian student from the collaborating university.

UNIS: 1 PhD, 1 postdoctoral researcher and several M.Sc. students.

The PhD position at UNIS will be within the topic sedimentology sequence stratigraphy and in cooperation with UiB, alternatively placed in UiB. The post doc position at UNIS will be announced as a geophysical/seismic interpreter position.

Meetings:

We plan to conduct two meetings a year to exchange ideas and updates between the different groups in a type of 2-3 days seminars. Also, exchange of personnel, from researchers to students will vary depending of the scope of the project which may vary from 2 weeks to several months. Collaboration between the USA and Russian partners will be done by week long visits of researchers and even longer visits for PhD students and postdocs

Field campaigns

Two main field campaigns are plan that include Svalbard and Greenland. Logistics will be managed and led by UNIS. Field campaigns will be 1-2 months long upon weather conditions. Special transportation is required such as helicopter, boat or plane rental.

Equipment:

- 5 Workstations with specialized software for subsurface interpretation and plate modeling
- Disk space and server
- Licenses: Because the project is research oriented, most licenses are free or have academic discounts. The main costs of licenses is for Paleogis
- Field campaign equipment
- Data analysis: Thin sections and provenance analysis

HSE

The project should be carried out without adverse events or injuries contributing personnel and environment, and without the emission of harmful substances to the nature /environment

Field work run by will be carried out accordingly to UNIS safety requirements and standards.

Participants in field work led by UNIS shall participate in UNIS own safety training – mandatory.

UNIS is responsible, among other things, to make sure that the fieldwork/excursion preparations and implementations follow instructions and guidelines given in the area of interest (e.g. Svalbard, East Greenland).

In addition participants from industry in the field are responsible for following their own company rules. (E.g. permission to carry gun, have helicopter lift with one engine or one pilot.)

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General Project plan

The project is proposed for an initial duration of 4 years, with the following general activities in each year of the project:

Year 1: Compilation of data and construction of project database, preliminary subsurface interpretation, which includes seismic mapping, core description and interpretation, wireline log motifs compilation, deposition models and sequence stratigraphy model. Execute initial plate tectonics and kinematic models. Begin field campaign in Svalbard. A main goal during this year is to build an integrated database that includes Greenland, and both the Norwegian and Russian Barents Sea sectors. Cosntructu preliminary paleogeographic maps

Year 2: Project database continuation, subsurface seismic interpretation continuation, and preliminary maps of the area, refine plate tectonic models and preliminary basin evolution models of areas with best geologic control. Continue field campaign in Svalbard.

Year 3: Construction of preliminary paleogeography maps and revision of interpretation and integration of different types of data.

Year 4: Construction of final evolutionary models, paleogeography controlled by plate tectonic model, quantification of deformation and structural styles, petroleum system characterization. Discussion to extend project scope.

Deliverables

- GIS database that includes all data used in the project
- Paleogis plate tectonic model for the study area
- Interpretations from data used in the project:
- Maps generated from surface and subsurface data (e.g. structural, thickness, paleogeography, etc)
- Correlations and cross-sections from field and subsurface data
- All presentations, thesis and publications made by the project researchers and students
- Two annual meetings will be held where progress and products will be presented to the members of the consortium
- A final project report in the form of an Atlas will be provided in year 4. Upon progress, annual project reports may be provided at the end of each project year.

Funding

The estimated project costs are 21.6 MMNOK for the four year project. We aim for at least 10 companies to support the project.

Financial support of the sponsorship is NOK 2 000 000 for the 4 year project. Payment can be divided four payments of NOK 500 000. We estimate that we can invoice on January 1 of each year from 2013-2016. A late fee of NOK 100 000 may be assessed for companies joining late or paying late.

Depending on the total amount of sponsors, the project activities will be modified