Understanding potential pressure regimes in undrilled Labrador deep water by use of global analogues

S. Green, Ikon Science Canada Ltd.
S. A. O'Connor, and A. P. Edwards, Ikon Science Ltd.
J. E. Carter, D. E. L. Cameron, and R. Wright, Nalcor Energy

Abstract

In recent years, new deepwater seismic-based exploration work has resulted in the revision of existing basin boundaries and identification of new, potentially oil-bearing basins in the deepwater Labrador region. The petroleum potential in this deepwater area has also been encouraged by the identification of slick and seepage locations using 2D seismic data and satellite imagery. The importance is that surface slicks possibly are related to subsurface hydrocarbon migration. Thus, all recent data collated together show strong evidence for an active petroleum system in deep water. Many of the wells in shallow water have been drilled with low mud weights, suggestive of low pore pressures. However, where thick shale packages are present, significant overpressure is observed by significant kicks. Clearly, there is a close association between thick (and deep) shale packages and high pore pressure. Thus, one of the key risks in developing the deepwater potential is to understand the pressure regime. The success of this approach has been highlighted recently by successful discoveries such as the presalt Lulu field onshore Brazil and associated discoveries in Gabon and Angola and postsalt discoveries that include Jubilee field offshore Ghana and the associated discovery of Zaedyus field in French Guiana. The deepwater Vøring Basin of the Mid-Norway North Sea and the Labrador slope and deep water share a similar passive margin setting to each other, similar facies associations, and structural development.

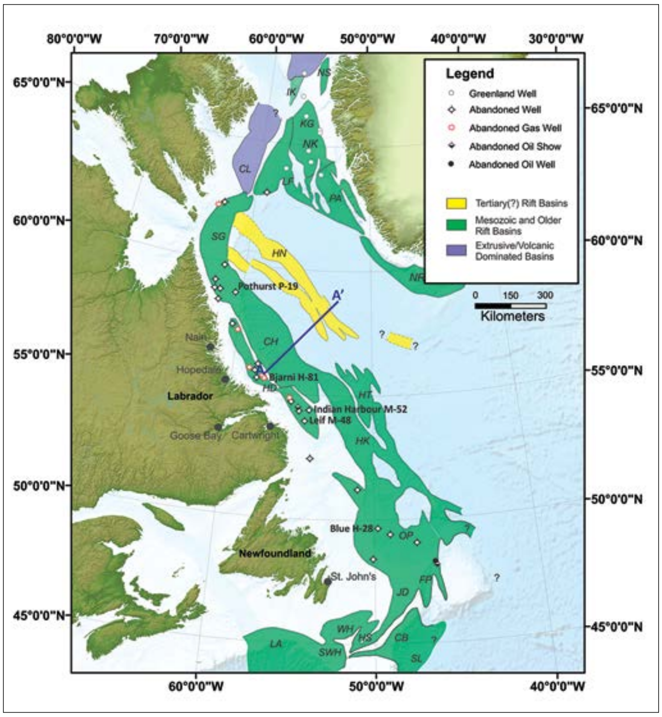


Figure 1. *Location map for the shelf and deepwater Labrador region extending south into Newfoundland. The latest interpretation of basin outlines is shown, including the newly identified deepwater basins — Henley (HN), Chidley (CH), and Holten (HT) — as well as the newly extended outlines of previously identified basins, e.g., Saglek (SG). Wells referred to in the article are highlighted, as is the regional cross section A-A' shown in Figure 3a.*

Introduction

The Labrador Shelf extends from the Davis Strait in the north through the Saglek Basin and down to the Hopedale Basin in the south and farther in the Orphan and Flemish Pass Basins of the Newfoundland coast, along the northeast margin of eastern Canada (Figure 1). In 1971, the first well, Leif E-38, was spudded in the Labrador Sea Complex, and drilling continued throughout the 1970s (Enachescu, 2008). Since the Bjarni H-81 discovery in 1973, four additional significant discoveries have been made in the Hopedale Basin and a single discovery in the Saglek Basin. Thus, a working petroleum system was proved; however, all wells to date have been drilled in shallow water, with a bias toward structurally elevated fault blocks.

In recent years, new deepwater seismic-based exploration work initiated by Nalcor Energy has resulted in the revision of existing basin boundaries and the identification of new, potentially oil-bearing basins in the deepwater Labrador region (Figure 1). The new basins are, from north to south, Henley Basin, Chidley Basin, and Holton Basin. The petroleum potential in this deepwater area has also been encouraged by identification of slick and seepage locations using 2D seismic data and satellite imagery. The importance is that surface slicks possibly are related to subsurface hydrocarbon migration. Thus, all recent data collated together show strong evidence for an active petroleum system in deep water as well as in shallower regions. Early seismic interpretation also indicates the presence of structural and stratigraphic trapping geometries (Carter et al., 2013).

Many of the wells in shallow water have been drilled with low mud weights, suggestive of low pore pressures. However, where thick shale packages are present, significant overpressure (pore pressure minus hydrostatic pressure) is evidenced by way of kicks experienced, e.g., 15,000 kPa (~ 2200 psi) above mud weight in Blue H-28 and 17,500 kPa (~ 2500 psi) above mud weight in Pothurst P-19. Those kicks also suggest that drilling has been underbalanced (pore pressure above mud weight) in several wells, e.g., Blue H-28 (Bjarni Formation), Snorri J-90 (Kenamu Formation and Cartwright Formation), and Indian Harbour M-52 (Cartwright Formation and Markland Formation). Pothurst

P-19 is a sand-rich well down to 300 m above the kick in the Lower Kenamu Formation, at which point mud weight is increased rapidly to kill the kick. Clearly, there is a close association between thick (and deep) shale packages and high pore pressure.

Thus, one of the key risks in developing the deepwater potential, where shale-rich lithology is more dominant from worldwide analogue experience, is to understand the pressure regime. To understand the controls on deepwater pressure regimes in Labrador, where there is no current well calibration, would be to use these global analogues. The success of this approach has been highlighted recently where successful discoveries have been made based on the understanding of conjugate margins, such as the presalt Lulu field onshore Brazil and associated discoveries in Gabon and Angola. Further examples include postsalt discoveries that include the Jubilee field offshore Ghana and the associated discovery of Zaedyus field in French Guiana (Borsato et al., 2012).

This article will feature analogue data from many basins worldwide; however, the primary focus is the relation of the deepwater Vøring Basin of the Mid-Norway North Sea to the Labrador slope and deep water. These regions share a similar passive margin setting, facies associations, and structural development. Whereas limited shelfal well penetrations leave the Labrador basins undersampled, the Vøring Basin benefits from many well penetrations that can be used to provide a direct analogue to the slope and deep water of Labrador.

Depositional and structural development of the Labrador Shelf

This section provides a brief geologic summary of depositional and structural episodes in shallow and deep water. These have been divided into prerift, synrift, and postrift. A generalized stratigraphy for Labrador is shown in Figure 2a.

Prerift. Crystalline basement rocks are drilled in several wells along the Labrador Shelf. The crystalline rocks are Precambrian (Grenville, Makkovik, and Nain orogenies) and consist of weathered and fractured metamorphic and igneous rocks (Ermanovics and Ryan, 1990). The oldest clastic sediments in the Labrador area are Ordovician carbonates that underlie all the Mesozoic-Tertiary successions. These sediments are largely localized to the southern extents of the Labrador Sea and north of the Labrador Sea Basin off Baffin Island (Balkwill et al., 1990), although it is possible that some remnant outliers exist throughout the margin.

Synrift. Rifting dominated the Early Cretaceous, and hence the sedimentary sequences are exclusively intracontinental deposits. Basaltic lava flows and volcaniclastics that form the Alexis Formation were generated during that time. These volcanic sequences largely erupted from extensive fissure systems from the center of the basin, as identified by linear gravity lows (Chalmers and Pulvertaft, 2001), into a marine environment. The volcanism resulted in laterally and vertically overlapping volcanic extrusive deposits with

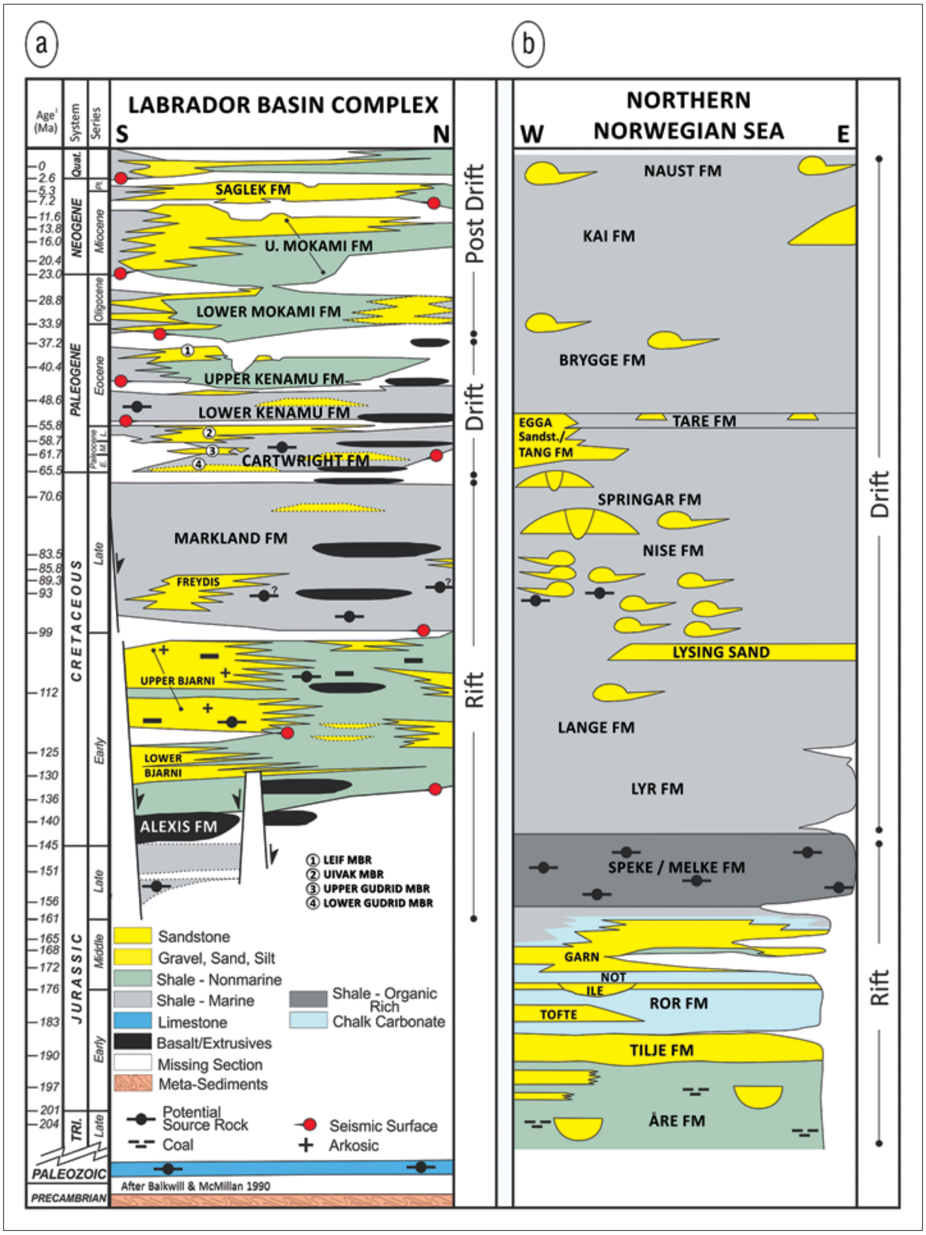


Figure 2. *General stratigraphy for (a) Labrador and (b) Mid-Norway. The Lower Cretaceous Bjarni represents synrift deposits comparable to the Jurassic and Triassic of Mid-Norway. The Upper Cretaceous Markland and Tertiary deposits of Labrador are similar to the Tertiary Nise and Egga Sandstones, the Brygge and Kai Shales, and the Cretaceous Lysing and Lange Formation in Mid-Norway.*

interbedded sequences of fluviatile and lacustrine sediments that form the Bjarni Formation.

The intercalation of sedimentary and igneous material is common in these types of environments, as exemplified by the Faroe-Shetland Basin (Naylor et al., 1999; Japsen et al., 2005). It is important to note that although they are not regionally extensive, basaltic flows interbed with clastic sediments throughout the Cretaceous and early Tertiary time frame in the northern extents of the study area (Balkwill et al., 1990).

The Markland Formation represents the transition from rifting to seafloor spreading and is interpreted to have been deposited in a late rift-stage subsiding basin (Chalmers, 1991; Chalmers and Pulvertaft, 2001). Recent biostratigraphic analysis in several wells along the margin has identified an unconformable transition from Maestrictian to Selandian time, highlighting the transition from rift to postrift (N. Ainsworth, personal communication, 2013).

Postrift and drift. The lower Tertiary is characterized by the Cartwright Formation, which is comprised of marine clays and siltstones that unconformably overlie the Markland Formation. The Cartwright Formation is a lateral equivalent to the Gudrid Member and is interpreted to comprise submarine sandstones. The Gudrid Sandstone is interpreted to represent redeposited eroded material from the Markland Delta (DeSilva, 1999).

The Kenamu Formation overlies the Cartwright Formation and consists of marine shales, siltstones, and localized sandstones. The top of the Kenamu Formation is characterized by fine-grained sandstones of the Lief Member. The Leif Member is interpreted as a shallow-marine sandstone deposited toward the latter stages of seafloor spreading (DeSilva, 1999; Chalmers and Pulvertaft, 2001).

After the cessation of seafloor spreading, a period of thermal subsidence commenced in the Oligocene-Miocene, during which the Mokami Formation and the Pliocene Saglek Formation were deposited. The Mokami Formation is comprised of marine siltstones and shales with localized sandstone intervals, whereas the Saglek Formation consists of fine to coarse-grained conglomerates and sandstones (DeSilva, 1999). These are overlain by unnamed glacial beds (Chalmers and Pulvertaft, 2001).

Characteristics of typical deepwater systems

Structural development. Passive margins mark the transition between oceanic crust and continental crust without an intervening plate boundary. Simplistically, these margins are formed by sedimentation above a paleorift, now marked by transitional crust. The sedimentation leads to heating and crustal thinning followed by continental breakup and the formation of new oceanic basins under an overall tensional stress regime. The new basin development is generally associated with the development of normal faulting, magma generation, vertical movements of uplift and subsidence, erosion, and sediment deposition (McKenzie, 1978). These margins can be either volcanic or amagmatic.

Using deep seismic-reflection transects of the Labrador Sea Basin conjugate margin, the structure of the margin has been described by several authors (Keen et al., 1994; Chian et al., 1995; Louden and Chian, 1999). The characteristic reflectivity interpretations shown are a basinwide band of very thin crust

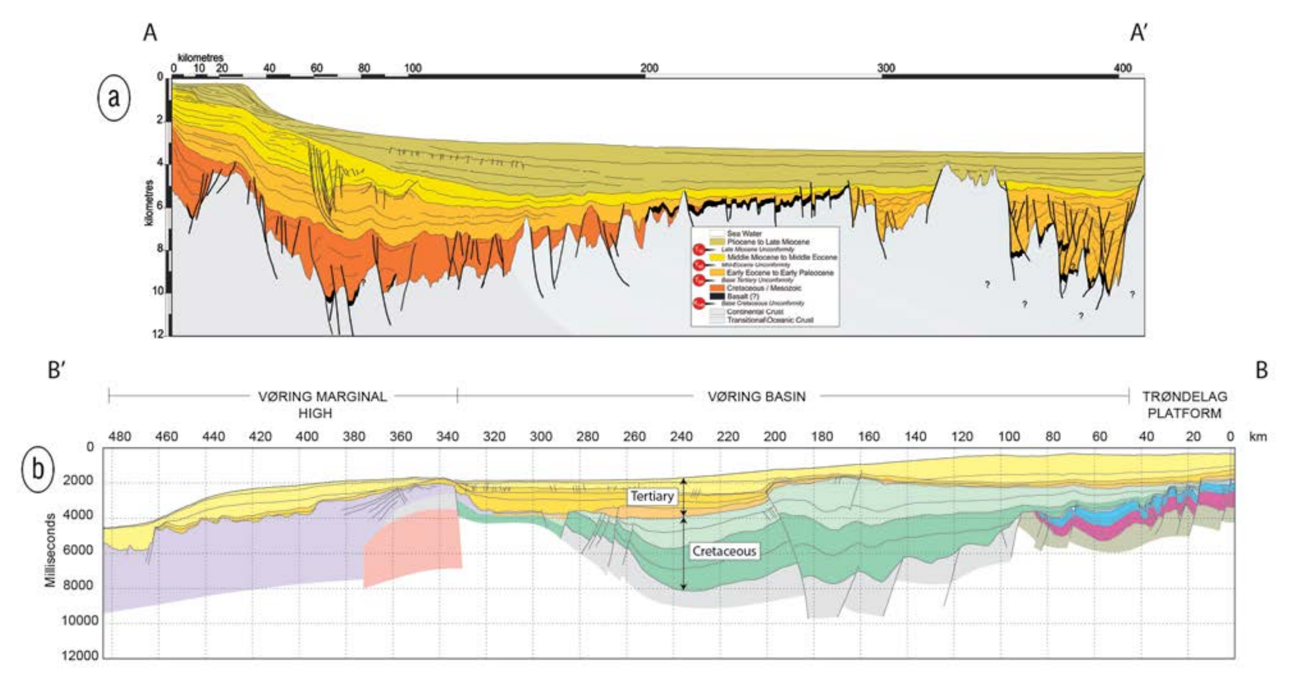


Figure 3. *(a) Section A-A′ is a schematic cross section of the Labrador sequence based on a 2D seismic line showing the main stratigraphic and structural relationships from shelf to deep water. The internal framework is based on well ties from the shelf. The line runs from the southern Hopedale Basin past the southern extent of the Henley Basin. (b) Section B-B′ is a schematic cross section of Mid-Norway showing the main stratigraphic and structural relationships from shelf to deep water (Blystad, et al., 1995).*

associated with lithospheric stretching, with faulting confined to the upper crust (Keen et al., 1994) (Figure 3). These data imply that the Labrador Basin is a nonvolcanic passive margin. However, basaltic lava flows and volcaniclastics are present in the Davis Strait and locally in the shelf along the central and northern Labrador margin (Balkwill et al., 1990; Chian et al., 1995; Chalmer and Pulvertaft, 2001; Keen et al., 2012).

The intercalation of sedimentary and igneous material is common in these types of environments, as exemplified by the Faeroe-Shetland Basin, for instance (Naylor et al., 1999; Japsen et al., 2005) and West Greenland (GEUS, 2002; Japsen et al., 2005). Deep water would be closer to the spreading ridge and source of magmatism, specifically in the northern extents of the study area.

Therefore, in conclusion, the Labrador margin might be transitional between the Scotian Shelf and Grand Banks regions to the south and the volcanic West Greenland area to the northeast (GEUS, 2002; Dalhoff et al., 2006).

In the deepwater well Gjoa G-37, in 1200 m of water, is a series of late Paleocene basalts. Direct pressure data within these sheets of basalt form hydrostatic-parallel fluid gradients, with only minimal pressure offset from sheet to sheet, implying that these are fractured and therefore in hydraulic communication. In well 214/27-2 in the Flett Subbasin, West of Shetland, the mid-Paleocene Kettla tuff (and associated T36 shale) has a pressure difference of 4450 kPa (650 psi) in the reservoirs above and below the Paleocene Vaila and Sullom Formations, respectively.

These volcanics are associated as sealing of accumulations such as Rosebank; however, evidence from Gjoa G-37 suggests that many volcanics are fractured. Therefore, any volcanics in the deep water of Labrador in the Kenamu, Cartwright, Markland, or Bjarni Formations might act as seals only if they are associated with thick shales. The heating caused by these intrusions might also have implications for the Bjarni Formation, identified recently as the main source rock in Labrador (Enachescu, 2008), and thus by analogue to other potential source-rock intervals of the Late Cretaceous to early Tertiary.

A characteristic of deep water that can be observed in Figure 3 is a general lack of faulting. This is a common feature of many deepwater settings worldwide. For instance, as can be observed in Figure 3b, faulting in the Vøring Basin sediments is minimal compared with that affecting the Jurassic and Triassic interval in the shallow-water shelf. The implications for Labrador of the worldwide observation of a general lack of faulting in deep water are little structural compartmentalization except for the synrift sediments of likely Cretaceous and potentially older age (Figure 2). Stratigraphic isolation (creating the opportunity for stratigraphic traps) will be common in deep water.

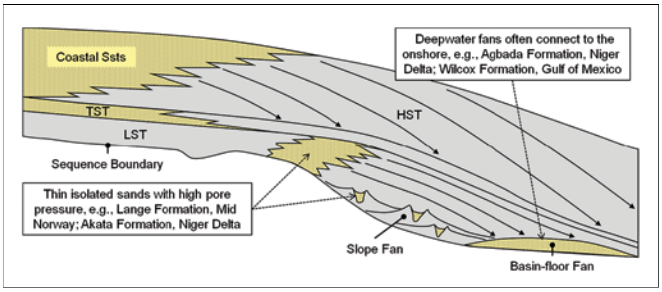


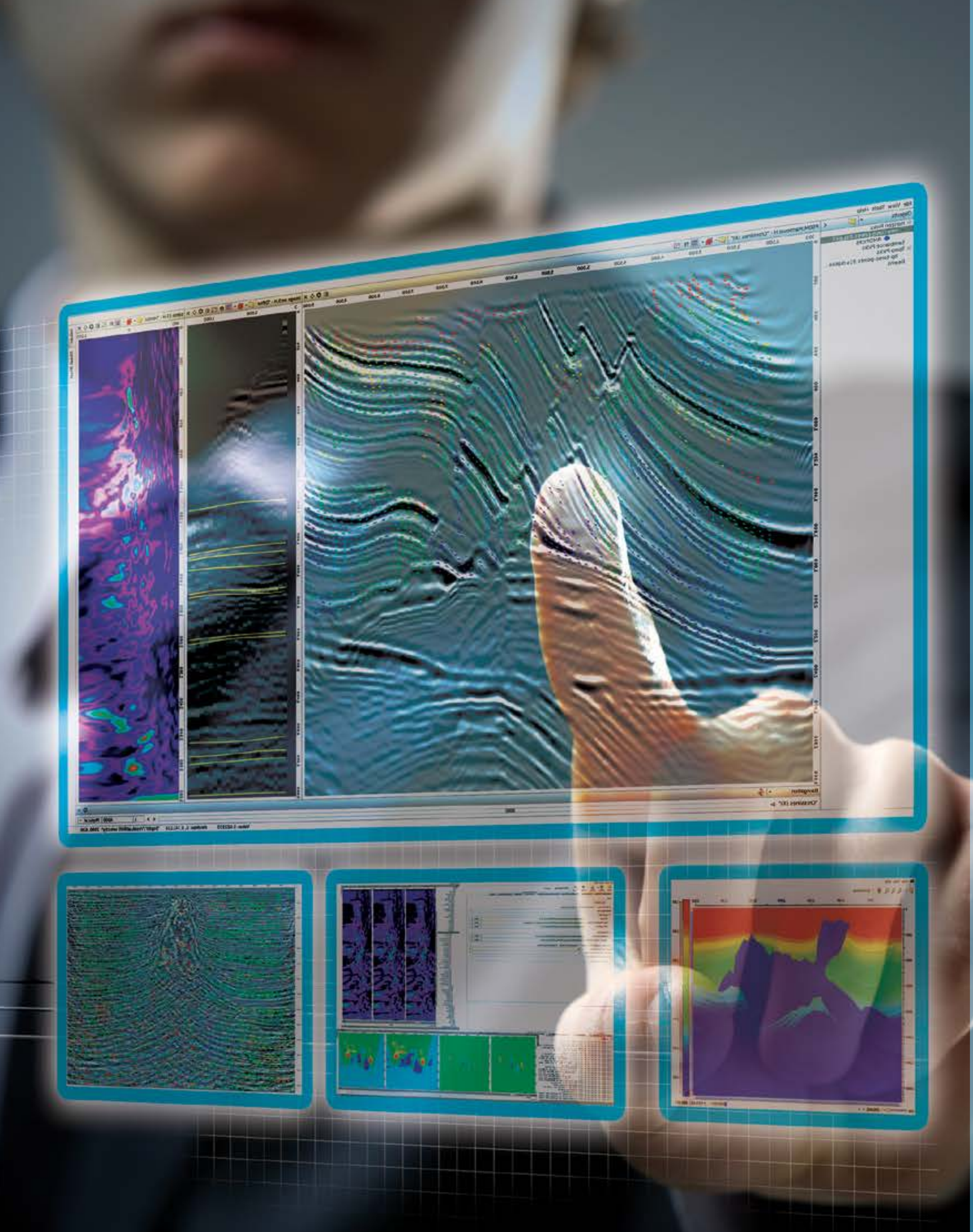
Figure 4. *Schematic cross section through a shelf to a deepwater depositional sequence. Highlighted are the typical sand deposits encountered, including basin-floor fans, slope fans, and isolated lowstand sands. The thick, regionally extensive basin-floor fans often can connect to the shelf via channel features (not shown), allowing fluids to drain, resulting in low-pressure deepwater sands. Conversely, thin and/or isolated sands cannot drain and maintain an overpressure in equilibrium with the surrounding sands. Where these sands are small (below seismic resolution), they present a potential kick hazard.*

Faulting is not expected to be completely absent. A common localized structural feature of deepwater sediments is polygonal faulting, which tends to form in layer-bound, shale-dominated environments. Polygonal fault systems are also recognized in the fine-grained Miocene sediments of the Kai Formation. They occur extensively to the west of the Klakk Fault Complex (Berndt et al., 2003) and have been observed offshore Newfoundland and Labrador (Skuce, 1999). This type of faulting is characteristic of young, shale-rich intervals. The faults are typically layer bound. In the Ormen Lange field in Mid-Norway, polygonal faulting is present, which could have implications for the likely behavior of the field fluid dynamics. However, fault seal analysis undertaken by Stuevold et al. (2003) shows that the faults are unlikely to form juxtaposition seals except locally, particularly in lower reservoir units. Data in O'Connor et al. (2008) suggest that hydrodynamic flow is not affected by these faults.

Uplift effects will also be reduced or absent in deep water. Very low angle unconformities are common across the Greenland Shelf and much of the Labrador Basin and are thought to represent periods of nondeposition (Japsen et al., 2010); however, these could also represent periods of uplift.

Seismic sections from West Greenland, in particular through the Qulleq-1 well, show a distinct angular unconformity (Christiansen et al., 2001). Because Quelleq-1 is a deepwater well, with a water depth of approximately 1150 m, the interpreted uplift might provide supportive evidence for uplift in the deep water of Labrador, specifically in Saglek Basin. The amount of uplift is approximately 700 to 800 m. The timing of uplift was between middle to late Miocene and Early Eocene. In Saglek Basin, recent biostratigraphy (Pothurst P-19) has confirmed an unconformity at that time period. These hiatal boundaries could allow some pressure dissipation and might require the need for multiple compaction curves.

Depositional characteristics. Although the predominant lithology in deep water is shale, sands are often developed locally (turbidites) and semiregionally (basin-floor fans). The main control on deposition and facies development is the interplay between accommodation space and sediment supply. Accommodation space is controlled primarily by the rate of extension and fault development/subsidence along shelf margins and slope leading to along-strike variation in facies, sequence thickness, and stacking/packing. Fault-controlled accommodation is the key component in determining whether sediments are deposited in fault-bounded minibasins or bypass the local fault basin and instead are delivered through linked deepwater provinces, forming basin-floor fans.



Revolutionary Tomography and Depth Velocity Model Building Starts Here

Z-Terra Inc.
17171 Park Row, Suite 247 • Houston, TX 77084
281.945.0000 www.z-terra.com
Contact us today at sales@z-terra.com.

Z-TERRA

Z-Tomo should be an essential component of your workflow

Z-Terra Tomography Features

- Grid based tomography.
- VTI and TTI velocity updates.
- Single and multiple parameter residual velocity estimation.
- Wide azimuth backprojection updates.
- Selection of wide azimuth update geometry.
- Multiscale regularization tomography.
- Model preconditioning.
- Uses offset or angle gathers.
- Automatic residual velocity picking.
- Horizons and faults picking and visualization.
- Updates from topography.
- Automatically generated back-projection points.
- Use of horizons to constrain the velocity update.
- Layer freezing or global updates.
- Salt bodies insertion.
- Top and base salt horizon insertion.
- Salt flood model generation.
- Build complex overthrust and fault shadow velocity models.
- Global and local error visualization and QC.
- Residual error back-projection QC tools.
- Residual error smoothing along horizons.
- Ray coverage visualization and QC.
- Azimuth coverage visualization and QC.
- Checkpoint restart.
- Add and subtract nodes during runtime.
- Job monitoring.

Z-Terra has a wide range of velocity model building algorithms and workflows:

- Vertical and normal ray updates,
- Deregowski loop updates,
- Wide azimuth tomography using
  - offset gathers produced by Kirchhoff or Fast Beam Migration (FBM),
  - angle gathers produced by wave-equation migration,
  - angle gathers produced by Kirchhoff or FBM,
- Residual move-out gather-flattening and gather-fitting techniques,

The processing and visualization software is designed for rapid and accurate quality control and turnaround of the velocity iterations.

The architecture of deepwater fan systems is largely dependent on sediment supply, source terrain, and depositional setting. The controls strongly influence the character of clastic submarine fans such that mud-rich, mixed sand-mud, and sand-rich fans are generated. The connectivity or lack thereof of sand deposits will control the ability of sands to drain (low pressure) or be in equilibrium with the shale around the sand (Figure 4).

Where the net to gross is low, as in the case of mud-rich fans, thin isolated reservoirs are developed (Figure 5b). Because these reservoirs are low volume, their pressures are influenced by the encasing shale lithology, leading to high pore pressures (e.g., Lange Formation, Mid-Norway; Akata Formation, Niger Delta). There is some evidence from shale pressure prediction for these profiles on the shelf in Labrador, but there are few direct data to prove the profile.

By way of contrast, where net to gross is high, as in the case of sand-rich or amalgamated fans (Figure 5a), single thick sand reservoirs are present (e.g., Nise Formation, Mid-Norway; Agbada Formation, Niger Delta; Wilcox Formation, Gulf of Mexico). These sands can drain pressure toward onshore via feeder channels. In this case, the shales encasing the sands are more highly overpressured, and the sands become pressure sinks. The mixed-sand-mud case leads to thick sands that can be drained variably, i.e., certain portions of the fan can be normally pressured, whereas others are at shale pressure. There are multiple examples of such fluid drainage on the Labrador Shelf, e.g., Pothurst P-19, which is sand rich and therefore normally pressured over the first 3 km of section before transitioning into a shale-rich sequence leading to a 35,000-kPa overpressure kick.

In summary, through the potential use of seismic facies, the net to gross of these depositional fans might be determined in Labrador and their likely pressure characteristics inferred. Calculation of encasing shale pressure is also part of this analysis.

Other pressure characteristics of deepwater regimes. In this section, we highlight briefly the other likely characteristics of deep water in Labrador, based on experiences in other current deepwater basins or from sediments that were deposited in deep water but are now located in shallow water.

1) Narrow-margin drilling (NMD) is a common feature of deepwater environments. Because the facies is likely shale dominated in deepwater Labrador (and has lower permeability), the top of overpressure will be shallower, and pore-pressure profiles will build parallel to the overburden by a process called disequilibrium compaction (Swarbrick and Osborne, 1998). Narrow-margin drilling is observed in the deepwater Gulf of Mexico as well as in the Nile and Niger Deltas and the Central North Sea (Tertiary interval). The drilling window (the relationship of pore pressure to fracture pressure) will be small for the majority of the duration of the well, thus requiring more casing strings for safe drilling.
2) Once the shales become diagenetically altered or enter the gas window, pore-pressure profiles will converge with the overburden, and additional pressure-generation mechanisms might be present. However, data in Hauser et al. (2013), from the deepwater Gulf of Mexico, suggest that even at temperatures of 120°C, a single compaction model can be used. Therefore, it is likely that a single compaction model could be used in the deepwater Labrador area (certainly to the depths of the 120°C isotherm at least and where disequilibrium compaction is the dominant mechanism of overpressure generation). The exact form of the compaction curve will depend on sediment source and type, i.e., proportion of smectite, illite, and kaolinite.
3) Hjelstuen et al. (1999) provide evidence from their analysis of the Cenozoic evolution of the northern Vøring margin of Norway for glacial sediments in deep water. Using foraminifera, palynomorph, and stable isotopes from cores of the Northern Labrador Sea, glacial-interglacial oxygen isotopes, ^{18}O values, are similar in magnitude to those reported from the Norwegian and Greenland seas (Aksu et

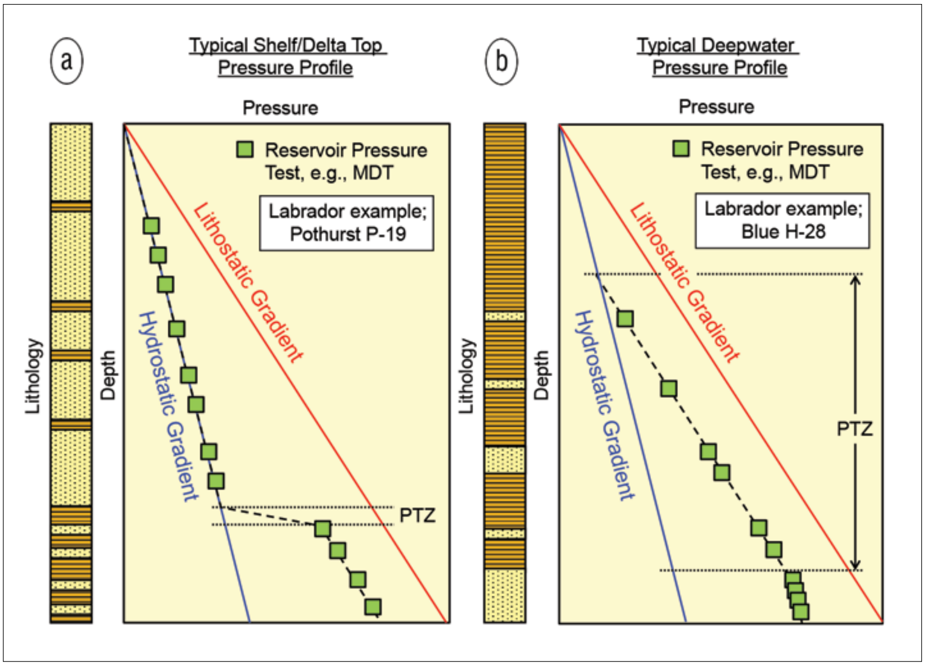


Figure 5. *(a) Schematic pressure-depth plot consistent with a sand-rich sequence overlying a deep shale (see associated lithology column); such a sequence is typical for shelfal wells (e.g., Pothurst P-19). The sand-rich sequence cannot retain any overpressure. However, any thin isolated sands within the deep shale will be overpressured, leading to a rapid change in pressure (PTZ = pressure transition zone) and a significant potential for kicks. (b) Shale-rich sequence down to total depth; such a sequence is typical for deepwater settings. The pressure-depth plot shows a constant trend of increasing overpressure with increasing depth within sands, assuming all sands are isolated.*


CLARITY

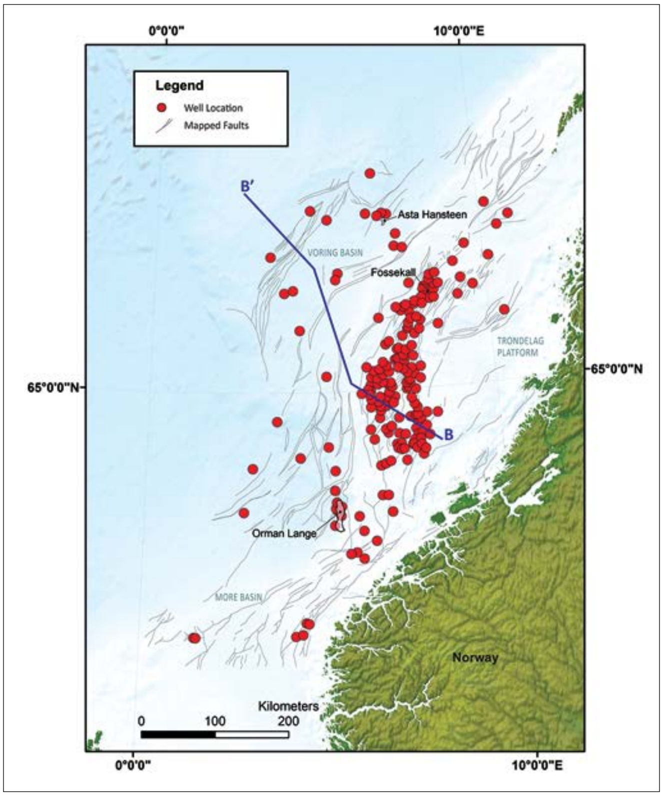


Figure 6. *Location map for Mid-Norway showing the regional structural framework, including the Trøndleg Platform, Vøring Basin, and Møre Basin; locations of all exploration and appraisal wells drilled to date (red dots; sourced from the Norwegian Petroleum Directorate); and locations of key fields, as referred to in the article. Section line B-B' refers to Figure 3b.*

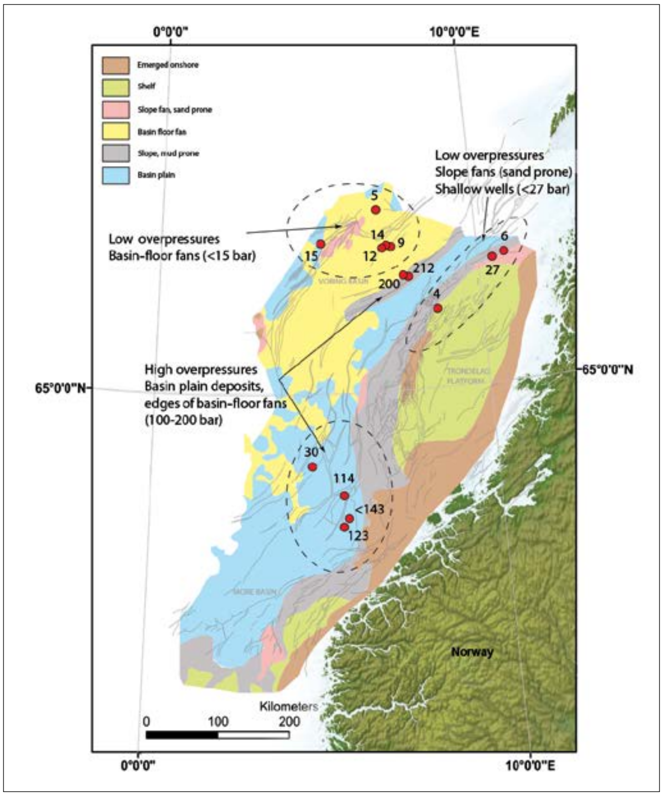


Figure 7. *Regional distribution of facies for the Nise Formation. The values shown are reservoir overpressure values recorded in bars (10 bar = 1000 kPa). Low overpressure values correlated to regionally connected and therefore drained sands, whereas high overpressure values correlate to isolated sands, either basin-plain or mud-prone deposits. After Vergara et al. (2001), Figure(s) 11.*

al, 1988; Rasmussen et al., 2003). Therefore, this might provide evidence for glacial sediments to be present in Labrador deepwater basins. The presence of these tills produces a high-density layer at the seabed; the layer can be more than 1.0 km thick. For example, using data from Mid-Norway, the Neogene interval has an upper 1.0 km of increasing density from 2.1 to 2.3 g/c^3; the next 1.0 km has a constant density of 2.1 g/c^3.

Case study: Vøring Basin, Mid-Norway

The Halten Terrace of Mid-Norway, North Sea (Figures 3 and 6) has been an active area for exploration for several decades; it contains large fields such as Kristen and Smorbukk, which are predominantly in shallow water. During the last decade, the deepwater Vøring Basin, which has wells with water depths as great as 1.5 km, has seen an exploration focus, particularly in areas such as the Gjallar Ridge and Nyk High. Discoveries such as the Luva (6707/10-1) are in this basin, with the Nise Formation the target. The Luva discovery is now the Aasta Hansteen field. Other discoveries include 6608/10-14S (Fossekall) in 2010. Another example of an accumulation in deep water, although in the Møre Basin rather than Vøring, is the Ormen Lange field, in Paleocene reservoirs.

Applicability to deepwater Labrador. Figure 3 highlights the similarity in basin structure between the Halten Terrace and Vøring Basin in Mid-Norway and Labrador. Stratigraphically, these basins are similar as well. In Figure 2, the Lower Cretaceous Bjarni represents synrift deposits comparable to the shallow-water Jurassic and Triassic of Mid-Norway. In Mid-Norway, these Jurassic and Triassic deposits are heavily fault-compartmentalized and form isolated overpressure cells.

The Bjarni Formation would be expected to similarly form isolated, overpressured cells, with this formation expected to be present at toe of slope to deepwater transition and gradually thinning toward the center of the Labrador Sea (see Figure 3). Within the overpressure cells, the pore-pressure profiles are expected to be hydrostat parallel, whereby gas generation creates fractures, allowing the interval to communicate hydraulically. It would also be expected that a hydrostat-parallel profile would form through the Bjarni Formation if the transition from early synrift to late-rift sedimentation were marked by an unconformity, which appears likely (Figure 2).

In the North Sea, e.g., Central North Sea Jurassic and Triassic intervals, the same transition is marked by a 30- to 40-Ma hiatus, allowing any pressures to bleed off, prior to reburial and renewed sedimentation and gas generation.

The Upper Cretaceous Markland and Tertiary deposits of Labrador are similar to the Tertiary deepwater Nise and Egga Sandstones, the Brygge and Kai Shales, and the Cretaceous Lysing and Lange Formation. The sediments in Mid-Norway are turbidites (Lange and Lysing Formations) and deep-sea fan deposits (Nise, Egga Sandstone Member). The Lange

Formation consists of turbidites of restricted extent and, as such, is likely to have the same overpressure as the encasing Lange shales. The Lysing Formation contains sands that connect over several tens of kilometers, and within each of these sand bodies, overpressure is the same and a hydrostat-parallel gradient is present. The sands are still stratigraphically isolated despite some small regional extent. These isolated sands will form good stratigraphic targets, with proven tight seals, and are exploration targets in Mid-Norway.

The Upper Cretaceous Nise Formation is a deep-sea fan complex, consisting of stacked, amalgamated sand bodies that have few internal seals. Similar facies define the lower Tertiary Wilcox play in the Gulf of Mexico, for instance, where sands can be 330 m thick ("Whopper Sand"). Well 6706/10-1, the Luva discovery, has a Nise section more than 900 m thick that communicates vertically.

Figure 7 shows a paleogeographic reconstruction of the Nise Formation and age-equivalent strata. Note that overpressure data are plotted in bars (10 bar = 1000 kPa [145 psi]). There is a strong correlation between high magnitudes of overpressure shale-rich facies, e.g., basin-plain deposits. In contrast, the sand units of the Nise Formation have only low overpressure and are interpreted as basin-floor fans, slope feeder channels that exit on the shelf. In parts, where data are sufficiently abundant, systematic changes in reservoir overpressure are observed, relating to hydrodynamic flow.

Figure 8 displays all the deepwater reservoir data within Mid-Norway and highlights the facies control mentioned previously. Where reservoirs can connect to the seabed and/or onshore, their overpressures are low. Where stratigraphic isolation occurs, the reservoirs have the same overpressure as the surrounding shales, and pore-pressure profiles build up parallel to the overburden. Note that Figure 8 contains an average overburden because water depth varies from 500 to 1700 m. Data from Knitvos, Nise, Springar, and Egga Sandstone Formations are displayed in Figure 8.

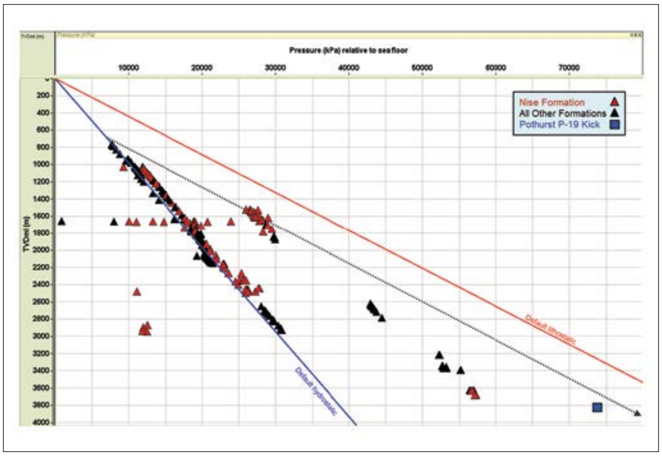


Figure 8. *Pressure-depth plot for all available data in the Mid-Norway deepwater area. Water depths range from 500 m to 1700 m. Data shown in red are from the Nise Formation. The blue square shows the approximate location of the kick taken from Pothurst P-19. The dashed black arrow represents an approximate overburden-parallel trend in reservoir data. These reservoirs are inferred to be at the same pressure as the encasing shales. Note: The overburden (red line) is an average of all water depths. The reservoir data that are normally or near normally pressured belong to a series of deep-sea fans (including the Nise Formation), where pressure has dissipated. Data are sourced from a nonproprietary regional pressure study by Ikon Science.*

Conclusions

In the absence of well penetrations, analogues can be a useful method for establishing exploration potential and risk. In a largely unexplored region, the main tool for exploration is high-resolution imaging of the structure and stratigraphy using combined seismic, gravity, and magnetic data. Tullow Oil made the Zaedyus discovery in offshore French Guiana in 2011 using these data and the analogy from equatorial African discoveries.

Deepwater settings generally have a series of common features, which include being shale prone, having less faulting, and having less uplift. Evidence for additional mechanisms of overpressure generation rather than disequilibrium compaction is less. All these features impact the pressure regime; for instance, likely pore-pressure regimes in deep water are overburden parallel.

Seismic data from Nalcor Energy has resulted in the identification of new, potentially oil-bearing basins in the deepwater Labrador region. These seismic data have also revealed the similarity between Labrador and basins such as Vøring Basin in Mid-Norway. In Vøring Basin, shale lithology dominates, and many reservoirs form stratigraphic traps, where sands have the same pressure as shales. Regional pressure trends can be defined.

Deep-sea fans are also visible on the seismic. In the case of the latter, the feeder channel acts as a pressure-release valve, allowing the sands to depressurize, creating a mobile aquifer. Similar deepwater hydrodynamic fan systems are reported in the Tertiary of the Central North Sea, although current water depths are shallow. Here, hydrodynamic trapping results in tilted fluid contacts. Enhanced seal capacity is also a feature, as is primary migration out of source rocks. TLE

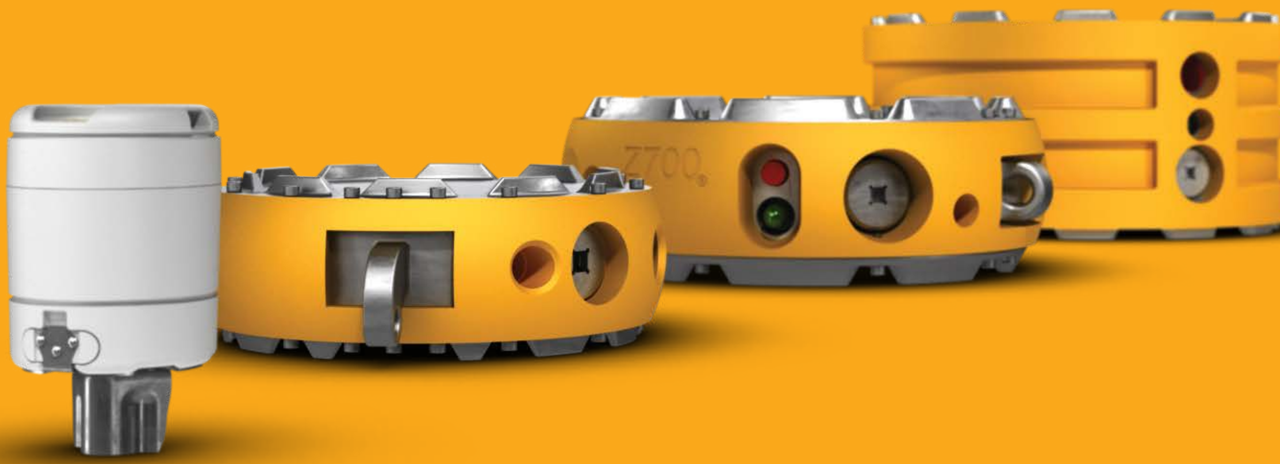
References

Aksu, A. E., P. J. Mudie, A. Macko, and A. de Vernal, 1988, Upper Cenozoic history of the Labrador Sea, Baffin Bay, and the Arctic Ocean: A paleoclimatic and paleoceanographic summary: Paleoceanography, **3**, no. 5, 519–538, http://dx.doi.org/1029/PA003i005p00519.

Balkwill, H. R., N. J. McMillan, B. Maclean, G. L. Williams, and S. P. Srivastave, 1990, Geology of the Labrador Shelf, Baffin Bay, and Davis Strait, *in* M. J. Keen and G. L. Williams, eds., Geology of the continental margin of eastern Canada: Geological Survey of Canada, Geology of Canada Series No. 2, 293–348, http://dx.doi.org/10.4095/132690.

Berndt, C., S. Bunz, and J. Mienert, 2003, Polygonal fault systems on the mid-Norwegian margin: A long-term source for fluid flow, *in* P. Van Rensbergen, R. R. Hillis, A. J. Maltman, and C. K. Morley, eds., Subsurface sediment mobilization: Geological Society [London] Special Publication 216, Polygonal faults and sediment mobilization, 283–290, http://dx.doi.org/10.1144/GSL.SP.2003.216.01.19.

Blystad, P., H. Brekke, R. B. Færseth, B. T. Larsen, J. Skogseid, and B. Tørudbakken, 1995, Structural elements of the Norwegian continental shelf: Part II: The Norwegian Sea region: Norwegian Petroleum Directorate Bulletin, **8**.


Z700

Borsato, R., J. Greenhalgh, M. Martin, T. Ziegler, P. Markwick, and A. Quallington, 2012, Conjugate margins: An exploration strategy: GeoConvention 2012: Vision, Canadian Society of Petroleum Geologists, oral poster presentation.

Carter, J. E., D. Cameron, R. Wright, and E. Gillis, 2013, New insights on the slope and deep water region of the Labrador Sea, Canada: 75th Conference and Exhibition, EAGE, Extended Abstracts, http://dx.doi.org/10.3997/2214-4609.20130447.

Chalmers, J. A., 1991, New evidence on the structure of the Labrador Sea/Greenland continental margin: Journal of the Geological Society, **148**, no. 5, 899–908, http://dx.doi.org/10.1144/gsjgs.148.5.0899.

Chalmers, J. A., and T. C. R. Pulvertaft, 2001, Development of the continental margins of the Labrador Sea: A review, *in* R. C. L. Wilson, R. B. Whitmarsh, B. Taylor, and N. Froitzheim, eds., Non-volcanic rifting of continental margins: A comparison of evidence from land and sea: Geological Society [London] Special Publication 187, Part 2: Margin overviews, 77–105, http://dx./doi.org/10.1144/GSL.SP.2001.187.01.05.

Chian, D., K. E. Louden, and I. Reid, 1995, Crustal structure of the Labrador Sea conjugate margin and implications for the formation of nonvolcanic continental margins: Journal of Geophysical Research: Solid Earth, **100**, no. B12, 24239–24253, http://dx.doi.org/10.1029/95JB02162.

Christiansen, F. G., J. A. Bojesen-Koefoed, J. A. Chalmers, F. Dalhoff, A. Mathiesen, M. Sønderholm, G. Dam, U. Gregersen, C. Marcussen, H. Nøhr-Hansen, S. Piasecki, T. Preuss, C. R. Pulvertarft, J. A. Rasmussen, and E. Sheldon, 2001, Petroleum geological activities in West Greenland in 2000: Geology of Greenland Survey Bulletin, **149**, 24–33.

Dalhoff, F., L. M. Larsen, J. R. Ineson, S. Stouge, J. A. Bojesen-Koefoed, S. Lassen, A. Kuijpers, J. A. Rasmussen, and H. Nøhr-Hansen, 2006, Continental crust in the Davis Strait: New evidence from seabed sampling: Geological Survey of Denmark and Greenland Bulletin, **10**, 33–36.

DeSilva, N. R., 1999, Sedimentary basins and petroleum systems offshore Newfoundland and Labrador, *in* A. J. Fleet and S. A. R. Boldy, eds., Petroleum geology of northwest Europe: Proceedings of the Fifth Conference: Geological Society [London], 501–515, http://dx.doi.org/10.1144/0050501.

Enachescu, M. E., 2008, Call for bids NL07-2, Labrador Shelf offshore region: Government of Newfoundland and Labrador, Department of Natural Resources, 1–54.

Ermanovics, I., and B. Ryan, 1990, Early Proterozoic orogenic activity adjacent to the Hopedale block of southern Nain Province: Geoscience Canada: Journal of the Geological Association of Canada, **17**, no. 4, 293–297.

GEUS, 2002, West Greenland play types: Geological Survey of Denmark and Greenland.

Hauser, M. R., T. Petitclerc, N. R. Braunsdorf, and C. D. Winker, 2013, Pressure prediction implications of a Miocene pressure regression: The Leading Edge, no. 1, 100–109, http://dx.doi.org/10.1190/tle32010100.1.

Hjelstuen, B. O., O. Eldholm, and J. Skogseid, 1999, Cenozoic evolution of the northern Vøring margin: Bulletin of the Geological Society of America, **111**, no. 12, 1792–1807, http://dx.doi.org/10.1130/0016-7606(1999)111<1792:CEOTNV>2.3.CO;2.

Japsen, P., P. F. Green, and J. A. Chalmers, 2005, Separating Palaeogene and Neogene uplift on Nuussuaq, West Greenland: Journal of the Geological Society, **162**, no. 2, 299–314, http://dx.doi.org/10.1144/0016-764904-038.

Japsen, P., P. F. Green, J. M. Bonow, E. S. Rasmussen, J. A. Chalmers, and T. Kjennerud, 2010, Episodic uplift and exhumation along North Atlantic passive margins: Implications for hydrocarbon prospectivity, *in* B. A. Vining and S. C. Pickering, eds., From mature basins to new frontiers — Proceedings of the Seventh Petroleum Geology Conference, Passive margins: Geological Society [London], 979–1004, http://dx.doi.org/10.1144/0070979.

Keen, C. E., K. Dickie, and S. A. Dehler, 2012, The volcanic margins of the northern Labrador Sea: Insights to the rifting process: Tectonics, **31**, no. 1, http://dx.doi.org/10.1029/2011TC002985.

Keen, C. E., P. Potter, and S. P. Srivastava, 1994, Deep seismic reflection data across the conjugate margins of the Labrador Sea: Canadian Journal of Earth Sciences, **31**, no. 1, 192–205, http://dx.doi.org/10.1139/e94-016.

Louden, K. E., and D. Chian, 1999, The deep structure of non-volcanic rifted continental margins: Philosophical Transactions of the Royal Society of London: Series A, 357, 767–804, http://dx.doi.org/10.1098/rsta.1999.0352.

McKenzie, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, **40**, no. 1, 25–32.

Naylor, P. H., B. R. Bell, D. W. Jolley, P. Durnall, and R. Fredsted, 1999, Palaeogene magmatism in the Faereo-Shetland Basin: Influences on uplift history and sedimentation, *in* A. J. Fleet and S. A. R. Boldy, eds., Petroleum geology of northwest Europe: Proceedings of the Fifth Conference: Geological Society [London], 545–558, http://dx.doi.org/10.1144/0050545.

O'Connor, S. A., and R. E. Swarbrick, 2008, Pressure regression, fluid drainage and a hydrodynamically controlled fluid contact in the North Sea, Lower Cretaceous, Britannia Sandstone Formation: Petroleum Geoscience, **14**, no. 2, 115–126, http://dx.doi.org/10.1144/1354-079308-737.

Rasmussen, T. L., D. W. Oppo, E. Thomsen, and S. J. Lehman, 2003, Deep sea records from the southeast Labrador Sea: Ocean circulation changes and ice-rafting events during the last 160,000 years: Paleoceanography, **18**, no. 1, 1–15, http://dx.doi.org/10.1029/2001PA000736.

Skuce, A. G., 1999, Layer-bound compaction faulting: Applications for exploration in the South Caspian Basin: International Conference: Geodynamics of the Black Sea — Caspian segment of the Alpine folded belt and prospects of search for economic minerals: Geological Institute of Azerbaijan Academy of Sciences, Extended Abstract.

Stuevold, L. M., R. B. Færseth, L. Arnesen, J. Cartwright, and N. Möller, 2003, Polygonal faults in the Ormen Lange field, Møre Basin, offshore Mid Norway, *in* P. Van Rensbergen, R. R. Hillis, A. J. Maltman, and C. K. Morley, eds., Subsurface sediment mobilization: Geological Society [London] Special Publication 216, Polygonal faults and sediment mobilization, 263–281, http://dx.doi.org/10.1144/GSL.SP.2003.216.01.17.

Swarbrick, R. E., and M. J. Osborne, 1998, Mechanisms that generate abnormal pressures: An overview, *in* B. E. Law, G. F. Ulmishek, and V. I. Slavin, eds., Abnormal pressures in hydrocarbon environments: AAPG Memoir 70, Chapter 2, 13–34.

Vergara, L., I. Wreglesworth, M. Trayfoot, and G. Richardson, 2001, The distribution of Cretaceous and Paleocene deep-water reservoirs in the Norwegian Sea basins: Petroleum Geoscience, **7**, no. 4, 395–408, http://dx.doi.org/10.1144/petgeo.7.4.395.

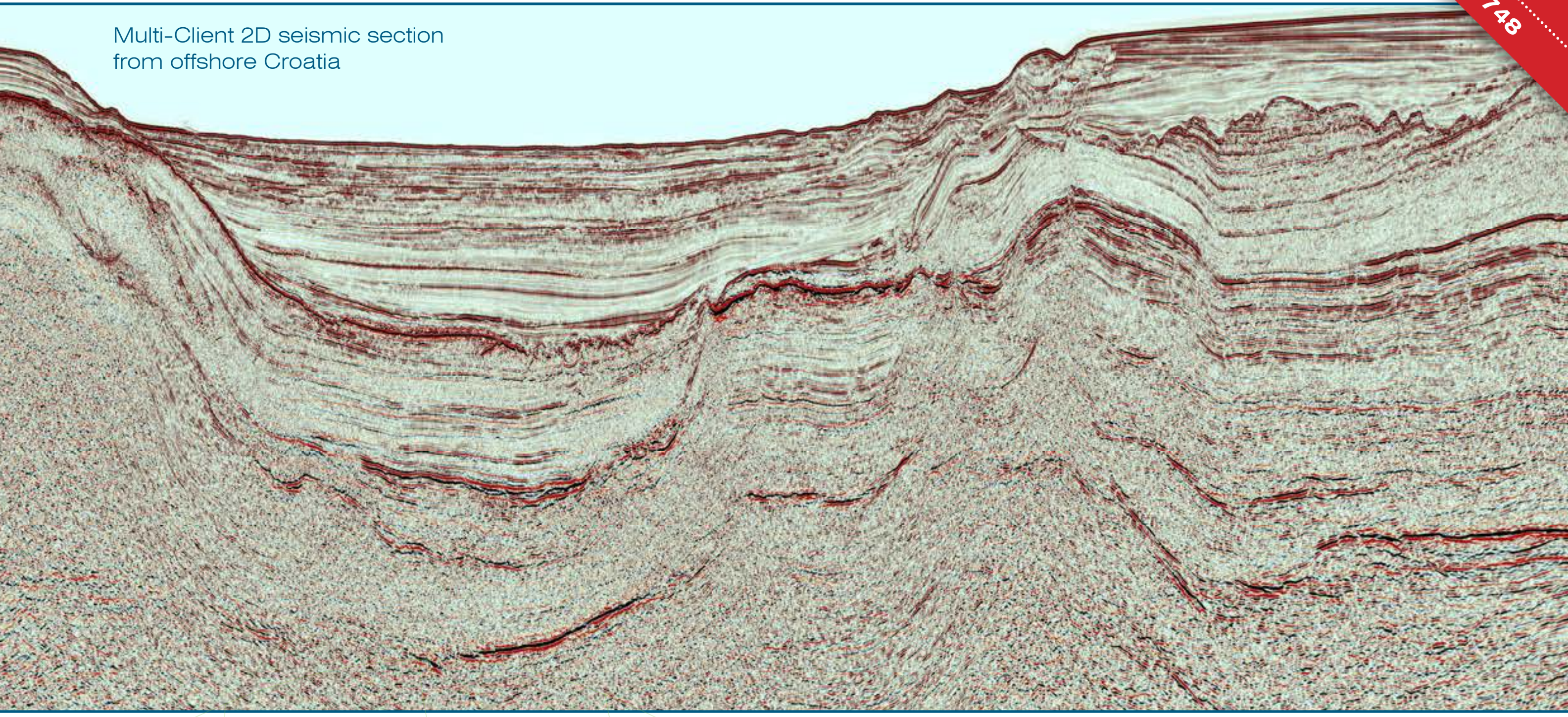
Acknowledgments: The authors would like to thank Nalcor Energy and PGS/TGS for supporting this study and supplying all the data used.

Corresponding author: sgreen@ikonscience.com

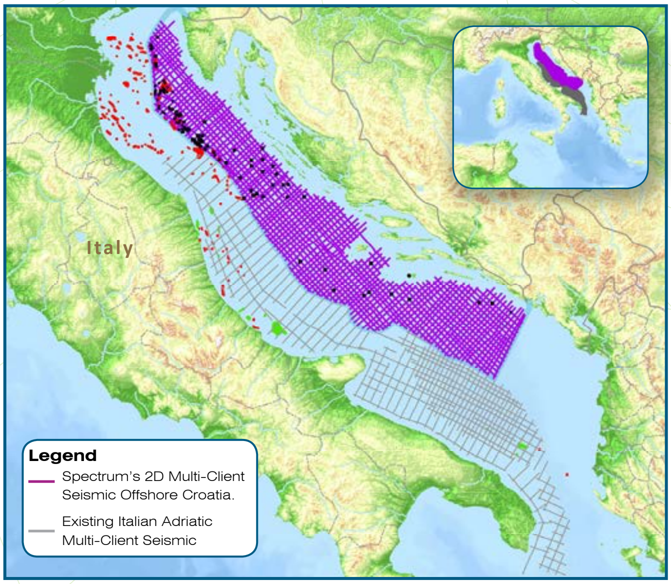
Offshore Croatia

A New Oil Province at the Heart of Europe

visit us at the
AAPG
Annual Convention
booth #1233
and AAPG International Pavilion #748



Multi-Client 2D seismic section
from offshore Croatia



Spectrum has acquired a truly unique Multi-Client seismic survey offshore Croatia. This is the only seismic data available to license in this hugely underexplored region which expects to see its first offshore licensing round this year.

The survey, acquired under contract to the Ministry of the Economy in Croatia, covers approximately 14,700 kilometres of long offset seismic data with a 5 km x 5 km grid. It extends across most of the Croatian Adriatic Sea and connects with Spectrum's reprocessed seismic data covering the Italian Adriatic Sea.

Final PSTM data has now been delivered and all processed data will be available in early April. The Government of Croatia plans to hold a licensing round over the country's offshore continental shelf in 2014.

Spectrum

☎ +44 (0)1483 730201
@ mc-uk@spectrumasa.com
www.spectrum**asa**.com