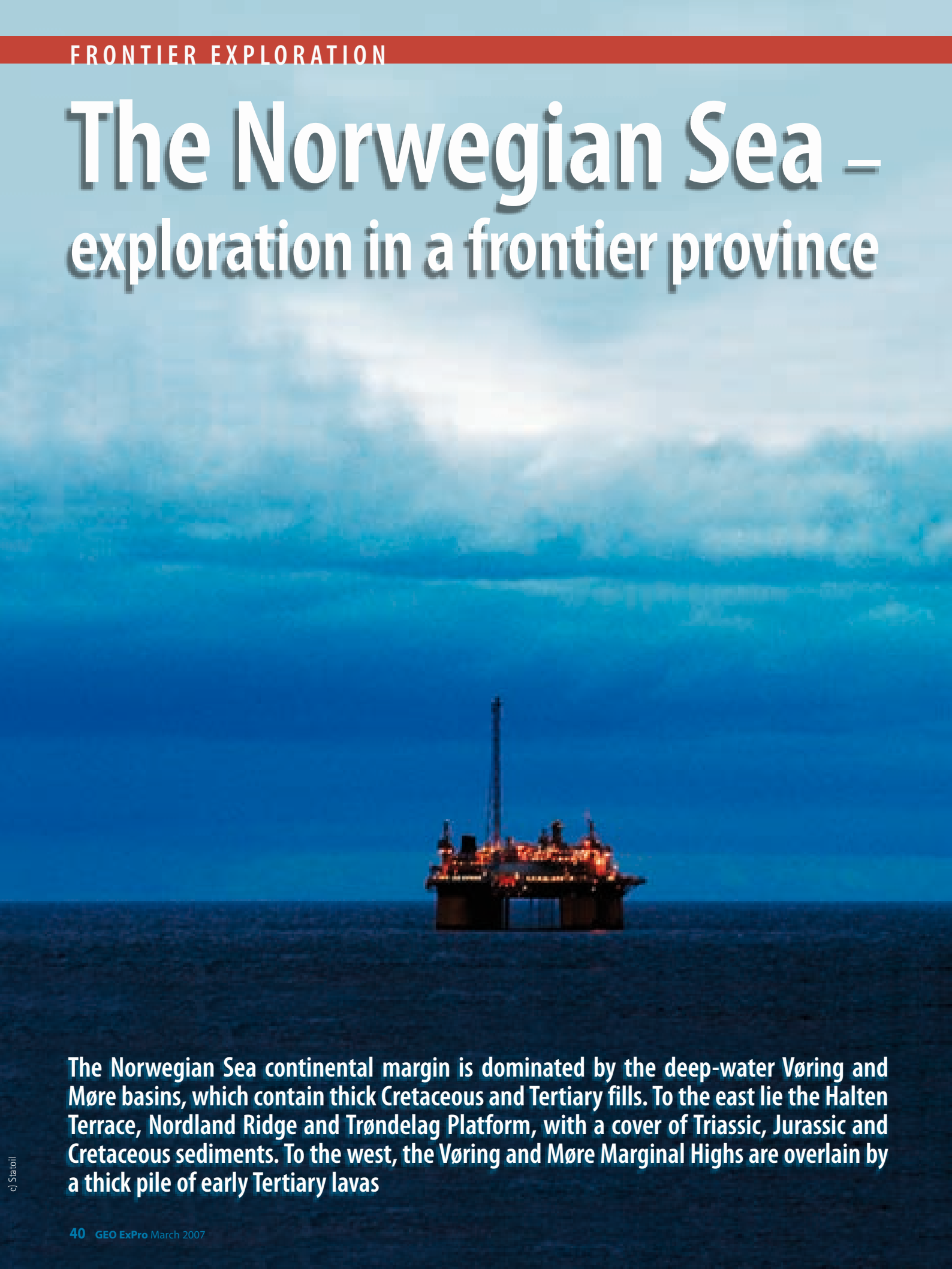
The Norwegian Sea – exploration in a frontier province



The Norwegian Sea continental margin is dominated by the deep-water Vøring and Møre basins, which contain thick Cretaceous and Tertiary fills. To the east lie the Halten Terrace, Nordland Ridge and Trøndelag Platform, with a cover of Triassic, Jurassic and Cretaceous sediments. To the west, the Vøring and Møre Marginal Highs are overlain by a thick pile of early Tertiary lavas

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Exploration in the Norwegian Sea in the 1980s and 1990s was concentrated on the Halten Terrace and along its faulted margins. This is the Haltenbank province, where more than 200 wells have been drilled, leading to some 50 discoveries, including the 15 Jurassic fields now in production.

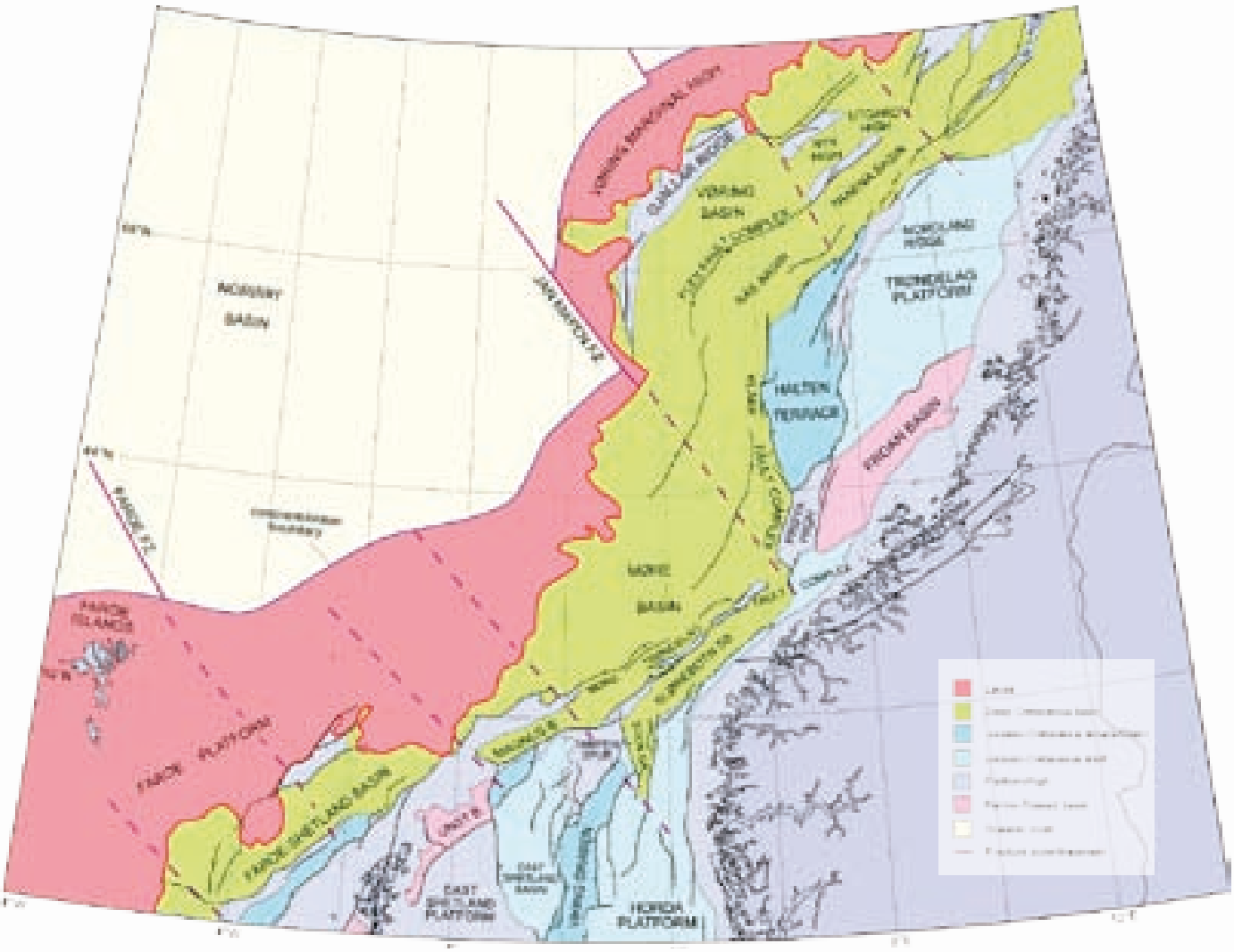
Drilling in the frontier Vøring and Møre basins did not start until 1997 and only 15 wells have been drilled so far. However, these have resulted in six discoveries, including Ellida, Stetind and the giant Ormen Lange gas field.

Haltenbanken is now an established hydrocarbon-producing province with continuing high levels of exploration and development activity following announcement of APA 2007. In contrast, the Norwegian Petroleum Directorate (NPD) has postponed the start of the 20th licensing round until 2008 to allow more time for companies to develop a better understanding of the geology and plays of the frontier province.

Strategy for exploration in a frontier province

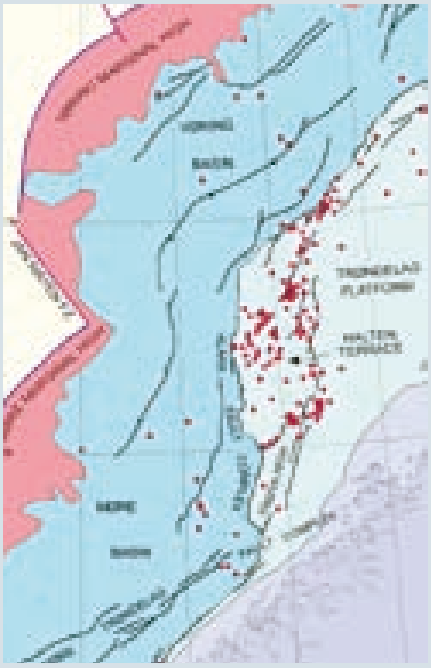
This article looks at how play prospectivity and exploration risk can be most effectively evaluated in the largely unexplored Vøring and Møre basins, where there is only limited well and seismic data. In these basins the main plays are slope and basin fan sandstones of the Cretaceous and Palaeocene. The Jurassic is deeply buried and not considered an exploration target at the present time. The key regional risk parameters are reservoir presence and hydrocarbon charge. Topseal is considered a secondary risk because of the likely presence of deep-water reservoirs encased in mudstones that will provide regional seal.

To persuade oil companies to spend money on frontier exploration, they need to be convinced that both reservoir and hydrocarbon charge are likely to be present, preferably at several stratigraphic horizons. Drilling in Haltenbanken has provided well data relevant to the Cretaceous and

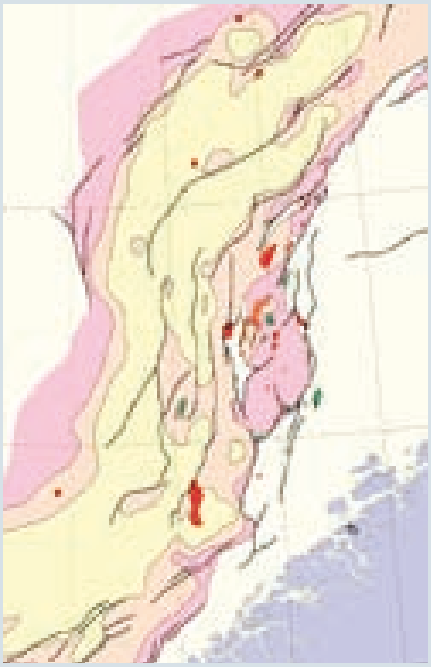


Tectonic Elements of the Norwegian Sea, Faroe-Shetlands and Northern North Sea

The Norwegian Sea, Faroe-Shetlands and northern North Sea are major hydrocarbon provinces located along the northeast Atlantic margin. Structural maps of the three areas have been integrated to help understand the geological history of this passive margin, which is bounded to the west by oceanic crust of post-Palaeocene age. The margin contains a series of linked NE-SW Cretaceous-Tertiary basins that overprint older Permo-Triassic and Jurassic rift systems with dominantly N-S and NNE-SSW trends. The basin trend is cut by a series of NW-SE lineaments that acted as transfer zones during extension. The most prominent of these is the Jan Mayen Lineament, which forms the boundary between the Vøring and Møre basins. The Norwegian Sea basins are separated from the Viking Graben rift system of the northern North Sea by the Møre-Trøndelag Fault Complex, which also forms the eastern margin of the Faroe-Shetland Basin. The western seaboard of the Cretaceous-Tertiary basin system is covered with a thick pile of lavas extruded prior to the start of sea-floor spreading in the northeast Atlantic during the Eocene.



Exploration Provinces and Well Database
The Norwegian Sea contains two exploration provinces. Most wells, shown in red, have been drilled in Haltenbanken, on the Halten Terrace and western part of the Trøndelag Platform (light blue). The western frontier province comprising the Vøring and Møre basins has only sparse well coverage (dark blue). To the west, these basins are separated from oceanic crust by a zone of thick Tertiary lavas.



Present-Day Upper Jurassic Maturity
The coloured area shows the present-day Upper Jurassic source rock kitchen. Yellow indicates overmature, areas of gas generation are shown in orange and oil generation in red. The oil, gas and condensate fields and discoveries are also shown.

Palaeocene plays, but for a more confident evaluation, the Norwegian Sea needs to be placed in its wider geological context as part of the northeast Atlantic margin. This region includes the northern North Sea and Faroe-Shetland basins, which are major hydrocarbon producers, together with the poorly explored Rockall and Porcupine basins, which also contain proven hydrocarbon systems.

The Northeast Atlantic depositional province

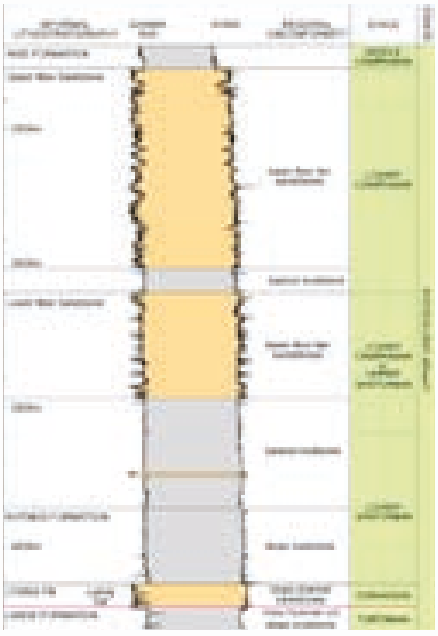
The Northeast Atlantic basins share a common plate tectonic history and were affected by the same extensional and thermal events. Basin development was associated with Jurassic rifting overprinted by deep Cretaceous subsidence and late Cretaceous/early Tertiary uplift and volcanism. As a result, the basins contain a similar suite of Mesozoic and Tertiary plays. So our knowledge of reservoir and source rock distribution is significantly enhanced by looking at the Norwegian Sea as part of a single geological province. Plate reconstruction has led to a better understanding of the tectonic and thermal controls on the evolution of basin architecture and depositional facies development. It has also provided evidence for the location and timing of clastic input into the Vøring and Møre basins from Greenland and the Norwegian margin during the Jurassic, Cretaceous and Tertiary.

The development of a common stratigraphic framework for the Norwegian Sea, Faroe-Shetland and northern North Sea basins has highlighted the similarities in age and depositional facies of the main reservoir and source rock horizons. For example, the late Triassic/early Jurassic transition from fluvial and coal-bearing sediments to transgressive marine sandstones and mudstones is seen in both the Åre-Tilje-Ror succession in Haltenbanken and the Statfjord-Nansen-Drake sequence in the Viking Graben. Similarities in facies are also seen in the Cretaceous and Lower Tertiary successions of the Faroe-Shetland, Vøring and Møre basins, e.g. the Sullom and Egga sandstones.

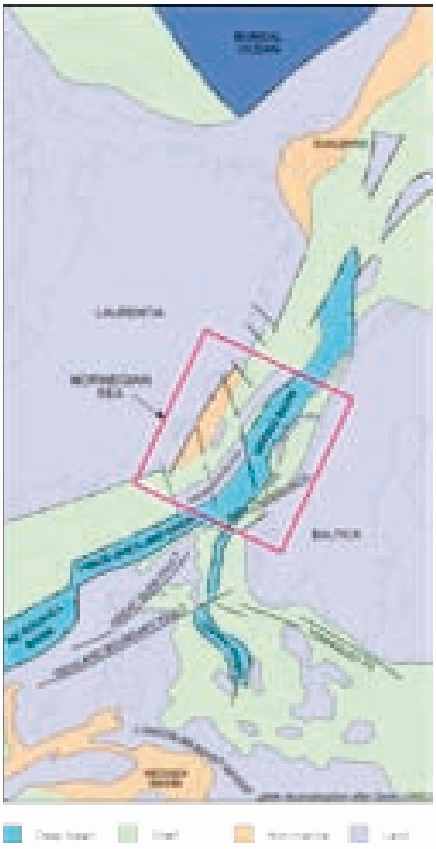
Finally, mapping across the artificial barrier of latitude 62°00'N gives a much clearer picture of the structure of the Møre-Trøndelag Fault Complex, its continuation as the West Shetland Spine Fault, and its relationship to the Slørebotn, Magnus and West Shetland basins.

A proven hydrocarbon system

The hydrocarbon system in Haltenbanken is now well understood. For the Jurassic plays in this province there is charge contribution from two source rock horizons: principally oil and gas from anoxic marine mudstones of the Upper Jurassic Spekk Formation, but also gas from coals of the Lower Jurassic Åre Formation. The presence of an active hydrocarbon system in the frontier province has also been demonstrated by a number of gas and oil discoveries in Cretaceous and Palaeocene sandstones. Depositional environment mapping suggests that Upper Jurassic source rocks are present throughout the Norwegian Sea region. The depth to the Base Cretaceous unconformity shows that although deeper parts of the Vøring and Møre basins are overmature, there is significant potential for mature Spekk Formation on the western flanks of both basins. Mature source rocks are also predicted to be present on Jurassic intra-basinal highs such as the Utgard High, Grip High and Vigra High, and along parts



Reference Well for Cretaceous Plays
Thick Upper Cretaceous sandstones have been drilled in wells in the Vøring Basin. Lysing sandstones were laid down in a slope channel setting, whilst the Nise sandstones represent basin-floor fan deposits. This well is located adjacent to the Nyk High and it is likely that the sands were sourced from this structural feature during episodes of late Cretaceous uplift and erosion. Hydrocarbons have been discovered in both sandstone intervals in the Vøring Basin, and the Lysing and Nise plays are predicted to have significant prospectivity in the frontier province.



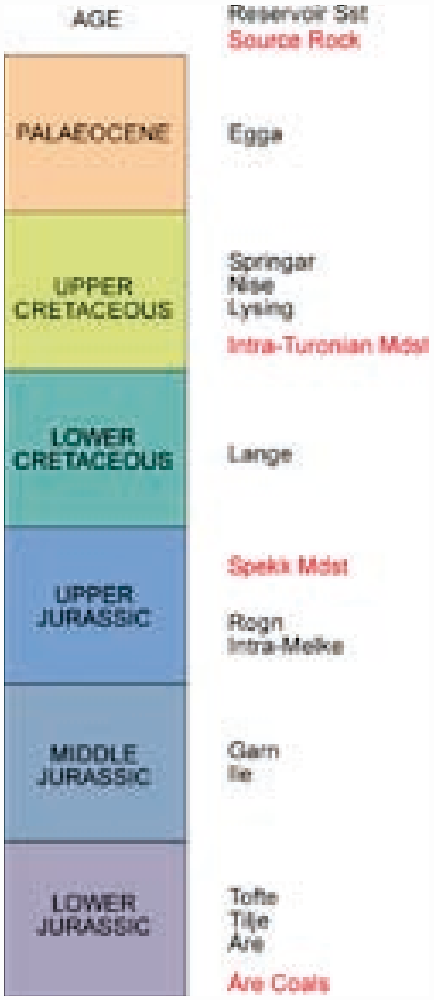
Cretaceous Palaeogeography, Northeast Atlantic
The Cretaceous depositional history of the northeast Atlantic was dominated by the presence of a seaway connecting the Atlantic and Arctic oceans. The area of the Norwegian Sea is outlined in red. The Vøring and Møre basins formed part of this seaway. Sands were shed into these basins during episodes of uplift and erosion along the Norwegian margin to the east, and from Greenland and smaller continental blocks, e.g. Jan Mayen, to the west. This seaway eventually became the locus of continental breakup and sea-floor spreading during the early Eocene.

of the footwall of the Fles Fault Complex. It is interesting to note the association of Cretaceous discoveries with some of these structural features. However, the origin of these hydrocarbons is still poorly understood and additional sources may be present, for example, shallower Cenomanian-Turonian 'hot shale' horizons in the Upper Cretaceous interval.

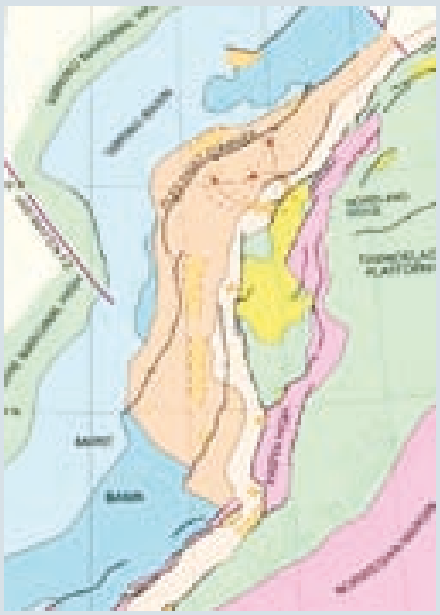
Reservoir distribution

Five reservoir intervals of Cretaceous to Palaeocene age can be correlated in wells drilled on the Halten Terrace, and in the Ormen Lange area and Slørebotn Subbasin. These are the Lange, Lysing, Nise, Springar and Egga sandstones. Sandstones of similar age also occur in wells in the Vøring and Møre basins; however away from well control, their presence remains unproven. In order to model the distribution of sandstones in the Norwegian Sea, gross depositional environment maps have been produced for each reservoir interval. These show the likely distribution of shelf, slope and basin environments and predict the location of sand-prone fairways.

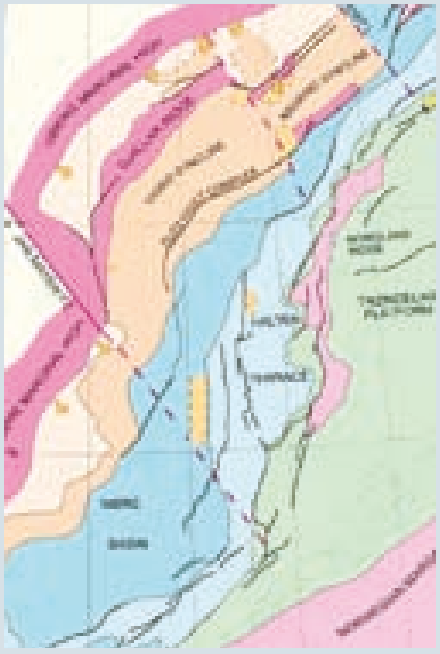
Construction of these maps is based on interpretation of northeast Atlantic palaeogeography for a series of time slices during the Mesozoic and Tertiary, and incorporates reservoir mapping from the northern North Sea and Faroe-Shetland basins. Regional seismic structure and isochron mapping of key Cretaceous and



Norwegian Sea Stratigraphy and Plays
Twelve hydrocarbon-bearing plays have been mapped in the Norwegian Sea. Most of the fields and discoveries are of Jurassic age and are located in Haltenbanken. However, the proven presence of reservoir and hydrocarbon charge in the frontier province together with the Ormen Lange gas discovery is very encouraging for future exploration, with the prospect of more giant fields being found.



Upper Cretaceous Lysing Gross Depositional Environments
This map shows gross depositional environments for the Upper Cretaceous Lysing play, based on a wider interpretation of northeast Atlantic palaeogeography and tectonic elements. Shelf, slope and basin environments are shown in shades of green and blue; areas of sand-prone deposition in yellow and orange. Zones of uplift and potential clastic sourcing are shown in pink. The asymmetrical nature of sand input into the Vøring and Møre basins during the Turonian and Coniacian is clearly seen.



Upper Cretaceous Nise Gross Depositional Environments
A major switch in clastic sourcing to the western margins of the Vøring and Møre basins took place during the Campanian. Large-scale block faulting accompanied uplift of the marginal highs with Nise sands being shed eastwards into the basin system and deposited in slope and basin channels and fans. Sand input from the east ceased and there was passive onlap of the Norwegian margin.

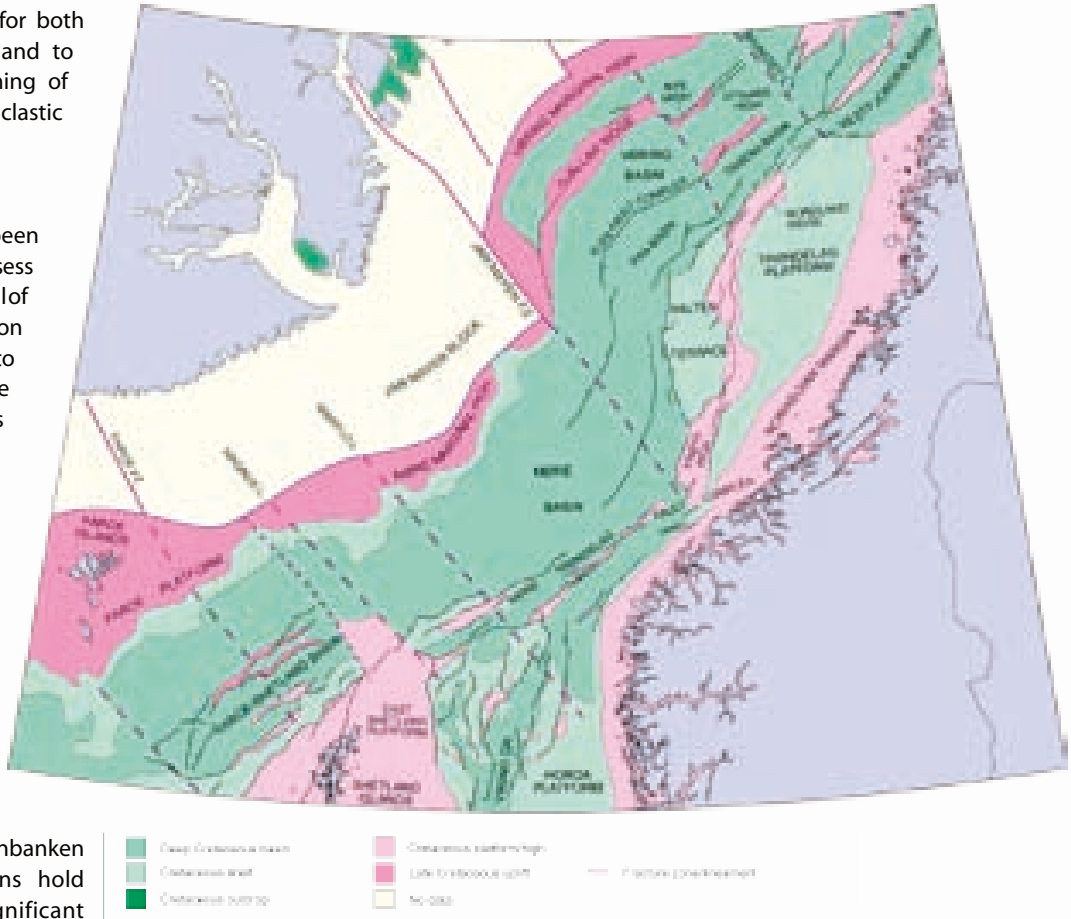
Tertiary horizons has been used for both source rock maturity modelling and to determine basin architecture, timing of uplift and the likely location of clastic source areas.

The way forward

Regional play analysis has been successfully used by Ternan to assess the remaining hydrocarbon potential of basins in various stages of exploration and development from mature to frontier. In the Norwegian Sea, the prospectivity of individual plays has been evaluated by combining the distributions of reservoir and hydrocarbon charge. This approach highlights extensive areas of play fairway at Jurassic, Cretaceous and Tertiary stratigraphic levels, where regional risk is predicted to be low. Blocks within these fairways can then be high-graded for detailed seismic interpretation, leading to the identification of potential leads and prospects.

Both the under-explored Haltenbanken province and the frontier basins hold substantial potential for significant discoveries in the future.

Ternan (*www.ternan.com*) is a wholly owned subsidiary of PGL, the Banchory-based subsurface consultancy (*www.pglweb.com*).



Cretaceous Structural Setting, Norwegian Sea-Faroe-Shetlands-Northern North Sea
Plate reconstruction shows the deep Cretaceous basin system in dark green extending through the Norwegian Sea, Faroe-Shetlands and northern North Sea. Understanding the regional uplift history of this province is the key to locating clastic source areas for the different reservoir intervals. The pink areas along the eastern margin of the basin system were sites of intermittent uplift and erosion for most of the Cretaceous. They include the Shetland Platform, Frøya High and Nordland Ridge. During the late Cretaceous there was a major palaeogeographic reorganisation with tectonic and thermal uplift of the western margin prior to extensive volcanism and plate separation during the Eocene. The Gjallar Ridge and other highs shown in red were formed at this time.

About the authors

David Mudge *(dmudge@ternan.com)* is Technical Director of Ternan. He has developed a consistent approach to regional play evaluation that uses stratigraphic and basin analysis to map and assess the hydrocarbon potential of basins of the North Atlantic and Arctic provinces, including offshore Norway, eastern Canada and Greenland.

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Katrine Holdoway *(kholdoway@ternan.com)* is Managing Director of Ternan. She is an exploration geologist with extensive experience in regional studies, licensing round assessment and asset evaluation.

David Mudge (right), Malcolm Gall and Katrine Holdoway with Dan Mander (centre left), who joined Ternan at the end of 2006