Deep-water depositional systems of the Norwegian Sea; understanding the system evolution, depositional geometries and reservoir quality from subsurface data and field outcrops

Thesis submitted for the degree of
doctor philosophiae

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CONTENTS

Acknowledgement

This thesis is entitled “Deep-water depositional systems of the Norwegian Sea; understanding the system evolution, depositional geometries and reservoir quality from subsurface data and field outcrops”. It consists of eight published papers and a synthesis summarising and integrating the main results from the papers. Five of the papers document subsurface depositional systems in the Norwegian Sea, while three papers document outcrop analogues in western Ireland.

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Takk

Denne avhandlinga har tittel ’Avsetningssystem på djupt vatn i Norskehavet; forståing av system utvikling, avsetnings geometriar og reservoar kvalitet frå data av undergrunn og felt blotningar’. Den består av åtte publiserte artiklar og eit samandrag som oppsummerar og samanstiller hovudresultat frå artiklane. Fem av artiklane er om avsetningssystem i undergrunnen av Norskehavet medan 3 artiklar er om analoge avsetningssystem blotlagt på land i vest Irland.

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”Ondt ofte lider den Fiskermand, som ut maa fare.
Paa heim ei tenke, før Solen dale”

Synthesis

- Lien, T (2006): Deep-water depositional systems of the Norwegian Sea; understanding the system evolution, depositional geometries and reservoir quality from subsurface data and field outcrops. Thesis for the degree of doctor philosophiae. University of Bergen, Norway.

Publications

Subsurface deep-water depositional systems:

1. Lien. T. (2005): From rifting to drifting: effects on the development of deep-water hydrocarbon reservoirs in a passive margin setting, Norwegian Sea. *Norwegian Journal of Geology*, Vol. 85, pp. 319-332.

2. Færseth, R.B. & Lien, T. (2002): Cretaceous evolution in the Norwegian Sea – a period characterized by tectonic quiescence. *Marine and Petroleum Geology*, 19, 1005-1027.

3. Lien, T., Midtbø, R.E. & Martinsen, O.J. (2006): Depositional facies and reservoir quality of deep-marine sandstones in the Norwegian Sea. *Norwegian Journal of Geology*, Vol. 86, pp. 71-92.

4. Martinsen, O.J., Lien, T. & Jackson, C. (2005): Cretaceous and Palaeogene turbidite systems in the North Sea and Norwegian Sea basins: source, staging area and basin physiography controls on reservoir development. In: Dorè, A.G. & Vining, B.A. (eds) *Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference*, Geological Society, London, 1147-1164.

5. Fonneland, H.C., Lien, T., Martinsen, O.J., Pedersen, R.B. & Kosler, J. (2004): Detrial zircon ages: a key to understanding the deposition of deep marine sandstones in the Norwegian Sea. *Sedimentary Geology*, 164, 147-159.

Outcrop analogues of deep-water depositional systems:

6. Lien, T., Walker, R.G. & Martinsen, O.J. (2003): Turbidites in the Upper Carboniferous Ross Formation, western Ireland: reconstruction of a channel and spillover system. *Sedimentology*, 50, 113-148.

7. Martinsen, O.J., Lien, T., Walker, R.G. & Collinson, J.D. (2003): Facies and sequential organisation of a mudstone-dominated slope and basin floor succession: the Gull Island Formation, Shannon Basin, Western Ireland. *Marine and Petroleum Geology*, 20, 789-807.

8. Lien, T., Martinsen, O.J. & Walker, R.G. (in press): Ross Formation, Shannon Basin, Western Ireland. *American Association of Petroleum Geologists* (AAPG); Atlas of Deep Water Outcrops.

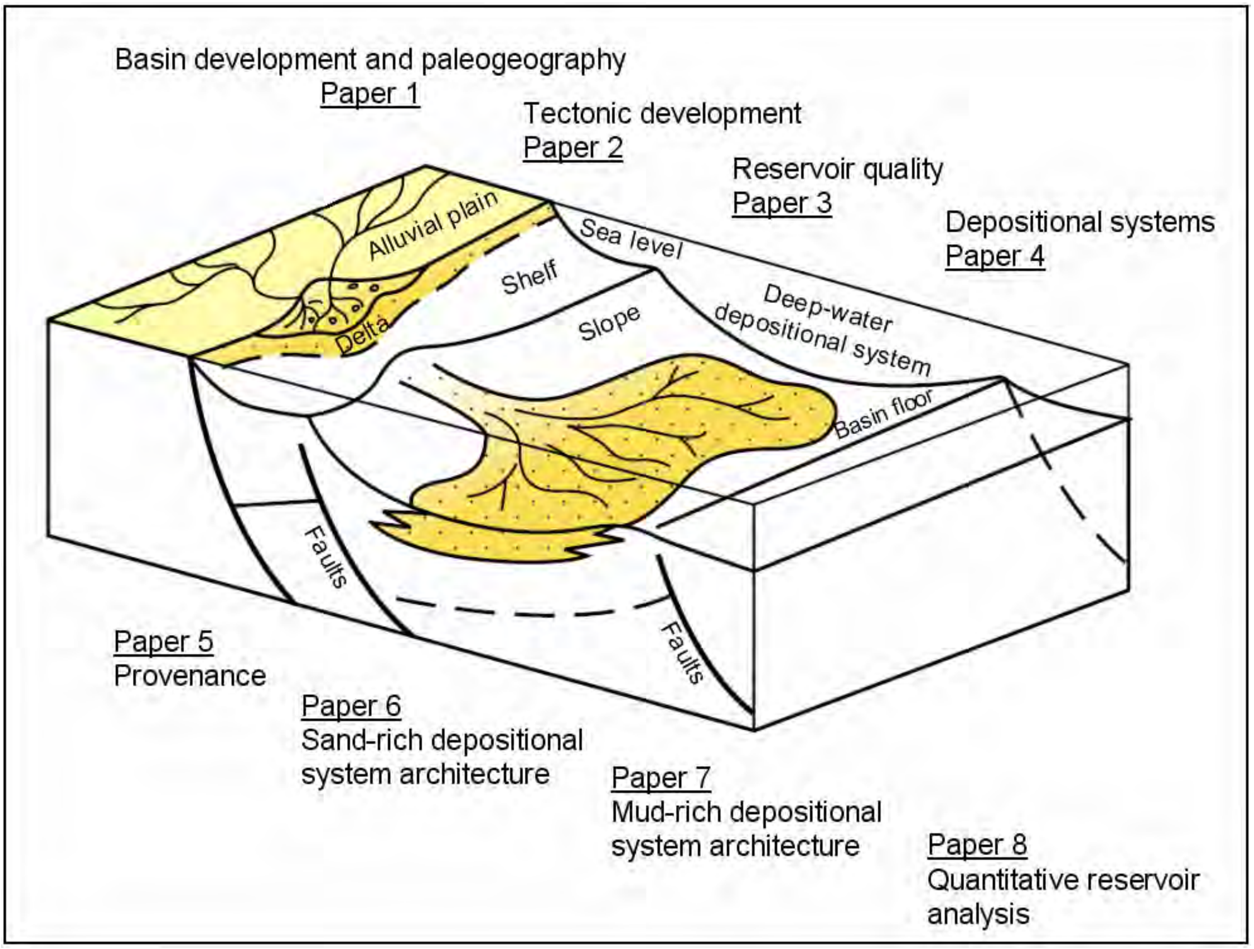

Figure 1 Levels of topics integrated in this thesis

Introduction

Understanding deep-water depositional systems is important in exploration and production of hydrocarbons in the Norwegian Sea. During the last 10 years, numerous exploration wells have been drilled in the Norwegian Sea, resulting in several discoveries in reservoirs of deep-water depositional environments. However, many of these exploration wells failed due to a lack of significant reservoir interval, or poor reservoir quality, highlighting the variable nature of deep-water systems. The successful development of hydrocarbon bearing, deep-water reservoirs (e.g. Ormen Lange) are also dependent on a detailed understanding of the internal reservoir architecture, sedimentology and spatial facies distribution.

Therefore, documenting the reservoir characteristics, and understanding the processes controlling reservoir deposition, distribution and preservation is vital for the future exploration and production of deep-water depositional systems in the Norwegian Sea.

This thesis aims to document deep-water depositional systems from the subsurface and outcrops to gain an insight into the processes controlling deep-water depositional systems. The results of this work are applicable to the exploration and production of deep-water reservoirs in the Norwegian Sea and analogue basins worldwide.

A total of eight published papers form the basis of this thesis (see page 2). Five papers (Papers 1-5) describe and discuss the subsurface deep-water depositional systems along the Norwegian shelf, while three papers (Papers 6-8) describe and discuss ancient outcropping deep-water systems.

The individual topics integrated in this thesis are shown in Figure 1, and can be grouped in three main research areas:

1) Basin physiography and tectonic development (Papers 1, 2 and 5),
2) Depositional systems and reservoir quality (Papers 1, 3 and 4)
3) Outcrop analogues (Papers 6, 7 and 8)

Previously published papers of the deep-water succession in the Norwegian Sea have focused on single issues, or local areas within the Norwegian Sea. This thesis presents an integrated ‘source to sink’ study of the deep-water depositional systems of the Norwegian Sea by integrating research on tectonics, sedimentology and post-depositional evolution. Detailed field-based studies of deep-water outcrop analogues give additional understanding of the detailed reservoir architecture and the individual depositional elements of deep-water depositional systems.

Methods and database

Integration of data on the regional basin development, tectonic framework and depositional systems of the Norwegian margin provides an insight into the processes controlling deep-water deposition in a passive margin setting. This is achieved through the study of several topics (Fig. 1), from tectonic development (Paper 2), to sediment source area (Papers 4 and 5), transport systems (Papers 1 and 4), facies analysis (Paper 3), reservoir quality (Paper 3), depositional systems (Papers 1 and 4) and depositional system architecture (Papers 6, 7 and 8).

Subsurface interpretations are based on a combination of seismic data, well information, onshore outcrop studies and published literature from the ancient depositional systems of the Norwegian Sea and North Sea, and are combined with outcrop studies of ancient deep-water analogue systems in western Ireland. Combining subsurface and outcrop analogue data provides an insight into the link between depositional processes, large-scale geometries and detailed reservoir architecture.

The tectono-stratigraphic framework of the Norwegian Sea (Paper 2) is based on interpretation of regional seismic maps, selected regional and local seismic cross-section combined with well correlations of the Norwegian Sea. This framework was strengthened and updated using onshore field data collected from the Mesozoic and Cenozoic successions of East Greenland.

The sedimentological development and depositional environments were interpreted from a combination of well log and conventional core interpretations. All relevant wells of the Norwegian Sea are studied, and all the available cores from the deep-water successions are interpreted (Paper 3). Facies and depositional elements interpreted from core are integrated with well logs, well cross-sections and tied into the regional tectono-stratigrapic framework to interpret the different depositional environments (Papers 1 and 4).

The paleogeography was interpreted by integrating the tectonic framework with regional seismic thickness maps and the depositional models from the wells (Paper 1). In addition, provenance studies based on onshore field data (East Greenland and Norway) and samples from subsurface well data (Norwegian Sea and North Sea) were used to constrain the interpretation of the sediment source areas and sediment transport routes through time (Paper 5).

The interpretation of post depositional reservoir alteration is based on combining core analysis with studies of the post depositional basin development. The core analyses undertaken are detailed facies interpretation linked to core porosity and permeability and petrographic analyses (modal analyses of thin sections, and X-ray diffraction) of core plugs. These data are integrated with temperature data from wells and burial history plots to interpret the factors controlling the present day reservoir quality (Paper 5).

The onshore field data (Papers 6, 7 and 8) was all collected during fieldwork in County Clare, Western Ireland. Detailed sedimentological sections were measured with bed-to-bed logging combined with extensive paleocurrent measurements and photo mosaics. These measurements were used to correlate sections in order to reconstruct the depositional history and interpret the depositional facies, geometries and architecture as well as the controlling factors on depositional system development.

Synthesis: Deep-water depositional systems

This chapter presents a synthesis of the published papers of the studied subsurface deep-water depositional systems and the outcrop analogues.

The synthesis is grouped in three research areas:

1) Basin physiography and tectonic development
2) Depositional systems and reservoir quality
3) Outcrop analogue systems.

Basin physiography and tectonic development

Understanding of the basin physiography and tectonic framework is fundamental in interpretation of the development of the deep-water depositional systems in the Norwegian Sea.

Tectonic framework
In the Norwegian Sea basins, the Late Jurassic structural template controlled Early Cretaceous deep-water sedimentary systems in a manner similar to the North Sea Basin (Papers 2 and 4). In contrast, during the Late Cretaceous, onset of precursor tectonic activity to sea-floor spreading in the Norwegian Sea led to a different development than in the North Sea (Paper 2).

The deep-water systems of the Norwegian Sea were deposited during four main tectonic stages from continental rifting to oceanic drift (Paper 2):

1) Late Jurassic - Early Cretaceous continental rifting
2) Early - Late Cretaceous post-rift subsidence
3) Late Cretaceous - Paleocene continental rifting
4) Post Paleocene oceanic drift stage

The mode of reservoir deposition changed significantly between these four stages, where the variation and dominance of three main factors; 1) sediment source area, 2) sediment transport system and 3) geometry of the receiving basin, had a large control of the reservoir geometry, quality and spatial reservoir distribution (Papers 1 and 4).

Source area
Variations in the sediment source (drainage) area appear to have had a major control over the overall volume of sand deposited (Papers 1, 4 and 5). Generally small and poorly developed drainage systems developed in early post-rift stages and resulted in the development of mud-rich systems. Sand-rich systems sourced from a relatively large hinterland and shallow marine staging area developed during the rift-stages. A lack of sand deposition dominated the drift stage as the sediment source area was progressively drowned. The sediment source area is mainly controlled by a complex interaction of relative tectonic subsidence or uplift; induced by rift extension, variation in hot-spot activity or basin-margin flexural uplift related to sediment loading. In addition, variations in eustatic sea level and climatic conditions may have had an additional control (Papers 1 and 4).

Transport systems
The link between the source area and the depositional sink is very important to understand for correct prediction of reservoirs. Variation in the complexity of the sediment transport routes from source to basin plays a major control on the location of reservoir intervals (Papers 1 and 5). Thick sand successions were deposited along the inner basin margin, and mud in the basin centre during the early post-rift and late rift stages. In contrast, sands were transported to the basin centre during the late post-rift stage when the transport route across the basin margin shelf was simple (Paper 1). Narrow shelf-width increases the potential for finding sands in the down-flank basin caused by the short transport distance and proximity of the sediment source (Paper 4). The complexity in the sediment transport route varies according to the tectonic stage and is controlled by the relation between subsidence and sedimentation rate (Paper 1).

Depositional system and reservoir quality

Depositional geometry
The receiving basin geometry and topography had a major control on the geometry, architecture and quality of the depositional systems (Papers 1 and 4). The initial rift stage is characterised by moderate basin topography and is dominated by aggrading confined sand-rich systems (i.e. Nise, Springar and Tang Formations). Thinner, widely distributed semi-confined sheet-like sand- to mud-rich deposits (i.e. Lysing Formation) dominates during the late post-rift stage when the basin topography is low (Paper 1). The early post-rift stage with high basin topography is characterised by mud-dominated slope systems which onlap, basin margins (i.e. Lange Formation, Paper 4).

From seismic, the deep-water depositional systems have an apparently sheet-like internal architecture. However, sand filled channels less than 15m thick are commonly recognised from core within both sand-rich and mud-rich systems. This difference is due to seismic resolution and quality.

Facies and depositional processes
High- and low-density turbidity currents were the dominant transportation processes of the deep-

water sands deposited in the Norwegian Sea, but debris flow deposits and cross-laminated sediments deposited by sustained sea floor currents occur (Paper 3). Depositional transport processes (in addition to sediment source area) control grain size and total clay content of the deposited sediments and had major influences on the reservoir quality. The high-energy transport processes (high-density turbidity currents and strong sustained sea floor currents) deposited the coarsest and cleanest, clay poor sediments with the best reservoir quality (Paper 3).

Reservoir quality

The reservoir quality of the deep-water reservoirs of the Norwegian Sea is variable and difficult to predict because of variations in facies, burial depth and temperature history (Paper 3). The grain size and total clay content have a major influence on the reservoir quality, where reservoirs deposited by turbidity currents have the coarsest and most clay-poor sediments, and the highest porosity and permeability.

Superimposed on the facies related reservoir quality trends, is a general trend of decreasing porosity and permeability with increasing burial depth. Given similar facies and similar burial depth, variation in the temperature and burial history results in completely different reservoir quality. High heat flow and late structural uplift resulted in anomalously poor reservoir quality at present burial depth (Paper 3).

Reservoir quality variations across the Norwegian Sea reflect the complex interplay of sandstone composition and texture (controlled by depositional processes and source area) and tectonic history (temperature and burial depth history) in controlling reservoir quality. By considering all these factors, regional reservoir quality studies can both aid in the prediction of sweet spots with high-quality reservoir sandstones, and help identify areas with anomalous temperature or burial history.

<u>*Outcrop analogues*</u>

Outcropping deep-water depositional systems from the Shannon Basin, western Ireland are studied as analogues to the deep-water depositional systems of the Norwegian Sea. Combining subsurface and outcrop analogue data obtains a better link between depositional processes, large-scale geometries and detailed reservoir architecture.

The Upper Carboniferous deep-water rocks of the Shannon Group were deposited in the extensional Shannon Basin of County Clare in western Ireland, and are superbly exposed in sea cliffs along the Shannon Estuary. Carboniferous Limestone floors the basin, and the basin fill succession begins with the deep water Clare Shales. These shales are overlain by various turbidite facies of the Ross Formation (Paper 6) and the Gull Island Formation (Paper 7). The type of turbidite system, scale of turbidite sandstone bodies, and the overall character of the stratigraphic succession, make the Ross and Gull Island Formations well suited as an analogue for sand-rich and mud-rich turbidite plays in the Norwegian Sea and in passive margin basins around the world.

Depositional geometry and architecture of a sand-rich depositional system

The Upper Carboniferous Ross Formation, Western Ireland (Papers 6 and 8) is an unusually well exposed sand-rich deep-water depositional system, which can be reconstructed in three dimensions. The reconstruction suggests that it should form an excellent outcrop analogue for sandy, low sinuosity channel systems with sandy spillover deposits but no large muddy levees.

The Ross Formation is a 460 m thick deep-water depositional system deposited within a confined extensional sag basin (Paper 6). The succession shows an overall sandier up-ward trend with an average sand- to mud-ratio of 60 percent.

The lower Ross Formation is extensive tabular turbidites with no channels, and no small-scale succession trends. Channels, thickening-upward packages, and slump/slide horizons characterize the upper Ross Formation (Paper 6). The depositional setting, confinement, thickness, facies and sand- to mud-ratio are analogue to the sand-rich Upper Cretaceous (Nise and Springar Formations) and Paleocene (Tang Formation) depositional systems in the Norwegian Sea (Papers 1 and 4). Detailed studies of the Ross Formation provide a better understanding of the depositional geometries and internal architecture of the sand-rich systems in the Norwegian Sea.

Channels in the Ross Formation are 100 to 200 m wide and have fills 5 - 10 m thick (Paper 8).

Facies relationships suggest that channel filling began with deposition of lateral accretion deposits on the "point bar" of the channel, with simultaneous erosion on the "cut bank" side, and spill of mud and thin turbidites onto the overbank side of the cut bank side. Followed by a phase of vertical accretion, with deposition of thick amalgamated sandstones. As the channel filled, more and more sand spilled overbank, particularly on the cut bank side, forming channel margin thick-bedded sandstones with megaflutes. These beds can be traced laterally from the channels into thin beds and thick amalgamated turbidites that form thickening-upward packages (Paper 6).

The thickening-upward packages (Paper 8) are commonly 2 - 4 m thick consisting from base to top of mudstones, thin-bedded turbidites, thick-bedded amalgamated turbidites and a sharp uppermost surface that is commonly scoured and with megaflutes. The packages are interpreted to have formed during progressive lateral shifting of channels (Paper 6).

A stack of four or five channels and packages up to 30 m thick define a sinuous channel belt (Paper 6). An individual channel-package system may be a little over 4 km wide, and the stack of such channels may form a channel belt of the order of 5 km wide.

Depositional geometry and architecture of a mud-rich depositional system

Lower Cretaceous Lange and Rødby Formations and the Upper Cretaceous Lysing and Kyrre Formations in the North Sea and Norwegian Sea are deposited on basin margin slopes, onlaping the basin margins (Papers 1 and 4). These mudstone-dominated turbidite systems provide a challenge to hydrocarbon exploration because their potential reservoir sandstones are relatively thin, commonly challenging to detect on seismic, with unknown internal architecture and unpredictable stratigraphic position.

The Carboniferous Gull Island Formation in western Ireland (Paper 7) is well exposed, and forms an excellent outcrop analogue for mud-rich turbidite systems with thin reservoirs units consisting of channels sheets but no large muddy levees.

The Gull Island Formation is a 550 m thick mudstone-rich turbidite-bearing succession, which onlaps basin margins (lower Gull Island Formation) and a mudstone-dominated prograding slope succession (upper Gull Island Formation).

The lower part of the Gull Island Formation contains three principal facies associations: (a) turbidite channels and sheets representing channel-margin and levee deposits, (b) mud-rich slumps, and (c) less than 1m thick, rare, hemipelagic shales (Paper 7). The turbidites record transport along the axis of the basin, while slumps were derived from the unstable lateral slope and transported transversely into the basin. The lower part of the Gull Island Formation is interpreted to record progressive fill of a deep basin controlled by local, deep-water accommodation with onlap/sidelap of the basin margin. The instability and slumps are related to pronounced differential subsidence between basin margin and basin axis, thus sustaining an above-grade slope (Paper 7).

The upper part of the Gull Island Formation is entirely dominated by mudstones, which grade upwards into siltstones (Paper 7). It contains rare, up to 15 m thick, isolated channels filled by turbidites. The upper part records progradation of a deep-water slope controlled by regional accommodation, which was genetically tied to overlying deltaic deposits (Paper 7).

The contrast between the lower and upper parts of the Gull Island Formation show that onlapping/sidelapping turbidite successions have reservoir potential near basin axes, but that prograding deep-water slopes are less prone to have reservoir potential of significance. A suggested regional downlap surface between the two parts is a significant break and marker in terms of reservoir potential.

Integration of results

The papers presented in this thesis show that the interpretation of both the large-scale processes as well as the details are fundamental in the understanding of the deep-water systems of the Norwegian Sea.

Paper 1 discusses basin development, paleogeography and places the deep-water depositional systems within the tectonic frame presented in Paper 2. The paleogeographic reconstructions are constrained by provenance studies in Paper 5, which is a key in understanding the temporal and spatial influence from the different basin margins.

The types and variation of deep-water depositional systems, which developed related to the evolving basin history, are discussed in Paper 4 and 1.

The depositional facies and related reservoir quality of these depositional systems controlled by depositional and post depositional processes are discussed in Paper 3. The present day reservoir quality of the deposited sandstones is described controlled by the combination of depositional processes and the later diagenetic processes. The diagenetic processes are themselves controlled by the depositional facies (Paper 3), depositional environments (Papers 1 and 4) and the temperature history, which is controlled by the tectonic development (Paper 2).

The controls on the detailed geometry, system architecture and facies relations in the subsurface data is limited by the data available and the crudeness of the database. The seismic resolution/quality and one to two-dimensional well data limit detailed interpretation of subsurface data. Outcrops of ancient systems give commonly a detailed two- to three dimensional view and are used to better understand the architecture of subsurface depositional systems.

The vertical and lateral characteristics of the Ross Formation (Papers 6 and 8) are a good analogue to several sand-rich deep-water systems in the Norwegian Sea like the Upper Cretaceous systems in the Vøring Basin and the Ormen Lange reservoir (Papers 1 and 4).

The characteristics of the mud-rich Gull Island Formation (Paper 7), with sandy channels within a mud-rich succession influenced by slope remobilisation, serve in aspects as an analogue to the Lower Cretaceous deep-water systems in the North Sea and Norwegian Sea (Papers 1 and 4).

General significance of thesis

The results of this thesis provide an insight into, and contribute to, the understanding of deep-water systems in basins like the Norwegian Sea. Through a better understanding of the factors controlling the deposition of the deep-water sandy systems (Papers 1, 2, 4 and 5), we can better predict the stratigraphic and geographic distribution of deep-water reservoirs. This will improve future exploration in the Norwegian Sea, but the concepts are also relevant for the North Sea and rift margins worldwide.

Based on concepts derived from literature and outcrop analogues, interpretations from core and well logs can with more confidence be used to interpret lateral to vertical facies variations and reservoir architecture. This is important in both volumetric estimates as well as in production. For exploration purposes, a thorough understanding of the facies variation, geometries and spatial distribution of depositional elements is important to better predict reservoir presence and quality based on the subsurface data.

The understanding of the factors controlling preserved reservoir quality during burial (paper 3) is important in exploration to best predict the reservoir parameters both for volumetric estimates and estimates of potential hydrocarbon recovery.

For production issues, a good understanding of the internal geometry and architecture of the reservoir units (lateral and vertical barriers and heterogeneities) is important (Papers 6, 7 and 8) Likewise, integrated facies analysis and petrography (Paper 3) provides a better understanding of lateral, vertical and in-depth permeability variability within the reservoir and are crucial in estimation of hydrocarbon production efficiency.