UiT THE ARCTIC UNIVERSITY OF NORWAY

Faculty of Science and Technology

Department of Geosciences

Quantification of the magnitude of net apparent erosion in the southwestern Barents Sea by using compaction trends in shales and sandstones – Implications for hydrocarbon exploration

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Dimitrios A. Ktenas

A dissertation for the degree of Philosophiae Doctor – January 2019

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‘I demolish my bridges behind me - then there is no choice but forward’

Fridtjof Nansen, Norwegian explorer and humanitarian

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PREFACE

The doctoral degree thesis entitled *''Quantification of the magnitude of net apparent erosion in the southwestern Barents Sea by using compaction trends in shales and sandstones – Implications for hydrocarbon exploration''* has been submitted to the Department of Geosciences – The Arctic University of Norway in agreement with the requirements for the degree of Philosophiae Doctor (Ph.D.). The research was carried out at the Research Centre of Arctic Petroleum Exploration (ARCEx) Department of Geosciences – The Arctic University of Norway, University of Tromsø, Norway (which is the degree-awarding institution), at North Energy Norge AS, Tromsø and Oslo, Norway, at the Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark and at First Geo AS, Oslo, Norway. The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement No 317217. The research forms part of the GLANAM (GLAciated North Atlantic Margins), www.glanam.org Initial Training Network. This also corresponds to a contribution to the Research Council of Norway funded project ''Research Centre for Arctic Petroleum Exploration'' (ARCEx) (Grant 228107).

The candidate has been supervised by Associate Professor Erik Henriksen, Department of Geosciences, UiT (Main supervisor), Professor Karin Andreassen, (Co-supervisor) Department of Geosciences, UiT, Dr. Jesper Kresten Nielsen (MOL Norge AS) (Co-supervisor) and Ivar Meisingset (First Geo AS), (Co-supervisor, as part of the Industrial PhD-scheme).

During my tenure at UiT, I had the opportunity through the Arctic Marine Geology and Geophysics research school (AMGG) to participate on various cruises aboard the R/V Helmer Hanssen; for example to the Vestnessa Ridge, Fram Strait, NW Svalbard and SW Barents Sea. In addition to marine expeditions, I attended several courses such as marine geophysics, 2D and 3D seismic interpretation in Petrel® software as well as advanced structural geology courses and training in 2D and 3D kinematic modelling, MOVE® software offered from Midland Valley. Additional training in basin modeling by using PetroMod® software was offered in-house, by North Energy ASA. During my secondment at First Geo in Oslo, I received training using the Geocap software, data and methods in order to carry out the compaction and velocity studies. During my short-term secondment at GEUS in Denmark, in the Geophysics department, I had the pleasure of collaborating with Dr. Peter Japsen in order to establish and improve my own Normal Compaction Trend (NCT) model in the SW Barents Sea benefiting from his long experience on the establishment of NCTs based on wells in the Danish North Sea. Furthermore, I was also able to participate in field trips studying outcrops (e.g. Møn, Denmark) that focused on better understanding the reservoir properties of chalk (Frykman 2001) related to the petroleum systems. I also participated at the various GLANAM project meetings and workshops and in national and international conferences, as it is enclosed in the Appendix, where I had the opportunity to present my work to a large scientific audience.

The research is mainly focused on the estimation of uplift and erosion in the southwestern Barents Sea by using compaction data. The main basis of the **first article** consisted of an interpretation of conventional 2D high-resolution seismic and well log data (sonic logs) which were used to quantify the net apparent erosion in the study area. Multi-client 2D seismic and well log data from Diskos data repository were provided from North Energy Norge ASA and controlled by the Norwegian Petroleum Directorate (NPD). In addition, TGS NOPEC, Spectrum and Searcher Seismic kindly provided 2D multi-channel seismic data. The dataset analysis results from the first article were used as input for the **second article**. Both, first and second articles were mainly carried out at First Geo in Oslo during my secondment. First Geo AS, kindly provided GEOCAP and AKGT data, software and methods. North Energy Norge AS mainly provided the employment and workplace in Tromsø and Oslo as well as access to the Geology and Geophysics (G&G) data and software (Petrel and PetroMod). A **third article** was also prepared at North Energy ASA, MOL Norge AS and at Shlumberger in Aachen, on petroleum systems modelling, carried out by running simulations on geological models in PetroMod software (1D and 2D) based on vitrinite reflectance data and compaction data. Furthermore, I was also involved as a co-author on a fourth article, 'Ice and its potential impact on temperature and pressure of petroleum systems: examples from the Norwegian Barents Sea' (Nielsen et al., in prep.) and a fifth article entitled 'The Finnmark Platform – Tectonostratigraphic elements, geological development and hydrocarbon potential' (Henriksen et al., in prep.).

This doctoral thesis consists of an introduction and three articles. The scientific articles presented are:

Article I

Ktenas, D., Henriksen, E., Meisingset, I., Nielsen, J.K., Andreassen, K., 2017. Quantification of the magnitude of net erosion in the southwest Barents Sea using sonic velocities and compaction trends in shales and sandstones. *Marine and Petroleum Geology*, 88, 826–844. DOI: https://doi.org/10.1016/j.marpetgeo.2017.09.019

Article II

Ktenas, D., Meisingset, I., Henriksen, E., Nielsen, J.K., in press. Estimation of net apparent erosion in the SW Barents Sea by applying velocity inversion analysis. *Petroleum Geoscience*. DOI: https://doi.org/10.1144/petgeo2018-002

Article III

Ktenas D., Nielsen J.K., Henriksen, E., Meisingset, I., Schenk, O., in prep. The effects of uplift and erosion on the petroleum systems in the southwestern Barents Sea: Insights from seismic data and petroleum systems modelling.

ACKNOWLEDGEMENTS

This doctoral thesis would not have been possible without the guidance, help and support from several individuals who in one way or another contributed to the preparation and completion of this PhD research.

I would first like to express my gratitude to my main supervisor Assoc. Prof. Erik Henriksen who accepted me for the PhD program. I thank him for mentoring me, for his commitment and for being there to support me in all stages of my research and throughout the process of preparing my publications. His knowledge of the Arctic petroleum geology and long experience as an exploration manager in major oil companies as well as his qualities as a person have positively influenced my PhD journey.

Special acknowledgements go to my co-supervisor and director of the Centre for Arctic Gas Hydrate, Environment and Climate (CAGE), Karin Andreassen for giving me the great opportunity to join the PhD program at UiT and for providing me all that was necessary for having a good start at the beginning of my studies.

I am indebted to Ivar Meisingset, exploration services manager at First Geo AS for his close collaboration in the first and second article. It has been a privilege to work with him under his tutelage. The compaction studies would not have been possible without his technical supervision and assistance in countless late-night tutoring and Geocap sessions. He had been several times critical of my work but had inspired me to think in an unconstrained manner when approaching geological processes by using rock physics and compaction studies. I really appreciate the time he took to review and comment upon the articles in the midst of his busy schedule at First Geo as well as from his family time.

I would like also to thank Olav Egeland for providing technical support in Geocap and encouraging me in developing new ideas through my research project. I have been really astounded by his talent in tackling complex technical issues in Geocap. Many thanks to

First Geo employees, Helge Nyrønning, Jørnar Hubred, Sigurd Eide, Steffen Storbakk and Ravan Gulmammadov for their technical support and discussions as well as all the good moments during my secondment in Oslo.

I am also indebted to my co-supervisor Dr. Jesper Kresten Nielsen, whose guidance, critical comments and knowledge of petroleum systems were invaluable to me and to this study. It has been a wonderful experience to work under his supervision and I greatly appreciate his calm manner and his willingness to help at all times. The fruitful discussions I had with him always prompted me to look at every research issue with a different perspective, which ended up in making some important scientific publications.

I would like to thank all my exceptional former colleagues at North Energy ASA in Tromsø, as well as in Alta, Stavanger and Oslo. The company's knowhow and experience on the Norwegian Continental Shelf and particularly in the Barents Sea was a very precious asset. In particular, this research has been additionally profited from discussions with Dr. Tommy Samuelsberg, Helge Ystborg, Inge Heika Hætta Eikelmann, Emil Husby, Stefan Paulsen, Evangelos Kaikas, Ketil Brauti, Dimitrios Konstantilieris, Dorthe Holm, Dr. Eig Karsten, Dr. Alexandra Henderson, Hilde Håland, Lajos Samu, Dr. Aris Stefatos, Prof. Jan Sverre Laberg, Prof. Jan Inge Faleide and Dr. Filippos Tsikalas.

Furthermore, I would like to express my gratitude to the CEO of North Energy ASA, Knut Sæberg and Exploration director Kristen Berli who kindly gave me the opportunity to use their facilities in order to complete my PhD studies. I thank also Rune Damn and Kari Olsen for their help and support as well as Bjørn Haugland and Thinh Vu for keeping my computer fit and running.

I would like to express my gratitude also to the Head of the Department of Geosciences Dr. Matthias Forwick, ARCEx director Prof. Alfred Hanssen, ARCEx coordinator Ellen Ingeborg Hætta, Hilde Beate Amundsen, Tine Hågensen, Inger Solheim, Kai Mortensen and Margrethe Lindquist for being always keen to guide me through the university's administrative system and for all practical matters. My friends and colleagues at the faculty have also been of immense support by giving some of their valuable time, for helping me with technical issues and discussing with me about various topics, related to my PhD. Many thanks to Dr. Alexandros Tasianas for his continuous advice during my PhD project, Andrea Barbolla, Rowan Romeyn, Dr. Jean-Baptiste (JB) Koehl, Espen Vålberg, Lina Alexandropoulou, Dr. Alexey Portnov and Dr. Amando Lasabuda among other outstanding PhD fellows at the Department of Geosciences.

The GLANAM network not only gave me the opportunity to meet high-ranked, well established and recognised scientists from all over Europe within my research field but also developed my skills at a professional as well as a personal level. Through the network I got lucky to know my very best friends Dr. Benjamin Bellwald and Dr. Oscar Fransner who gave me great fun during the GLANAM gathering locations and elsewhere. Furthermore, I thank them for the fruitful discussions we have had about the glaciated margins of the North Atlantic while writing my articles. Special thanks also go to my close friends Dr. Lukas Becker, Dr. Ben Manton and Dwarika Maharajan.

Finally, I would like to add a personal thanks to my parents Antonios and Katerina, my brother Nasos as well as to my dear Konstantina for their continuous encouragement and support through my difficult times.

Dimitrios Ktenas

INTRODUCTION

As indicated by the title of this PhD thesis 'Quantification of the magnitude of net apparent erosion in the southwestern Barents Sea by using compaction trends in shales and sandstones – implications for hydrocarbon exploration' the scope of the thesis is to concentrate on using compaction trends in shales and sandstones in order to quantify the magnitude of net apparent erosion in the study area.

It is important to first of all establish a concise and coherent terminology regarding terms relating to uplift and erosion (**Figure 1**). The shorthand often used for describing uplift and erosion is 'exhumation', which corresponds to the removal of material by any means from a basin in such a way that previously buried rocks are exposed (Doré, 2002).

More specifically, the term 'net erosion' is defined as the difference between maximum burial and the present day burial depth for a marker horizon. The differences between the notions of uplift, erosion and net erosion are further explained in Figure 1 below, using a pre-uplift and a post uplift situation to illustrate (Henriksen et al., 2011).

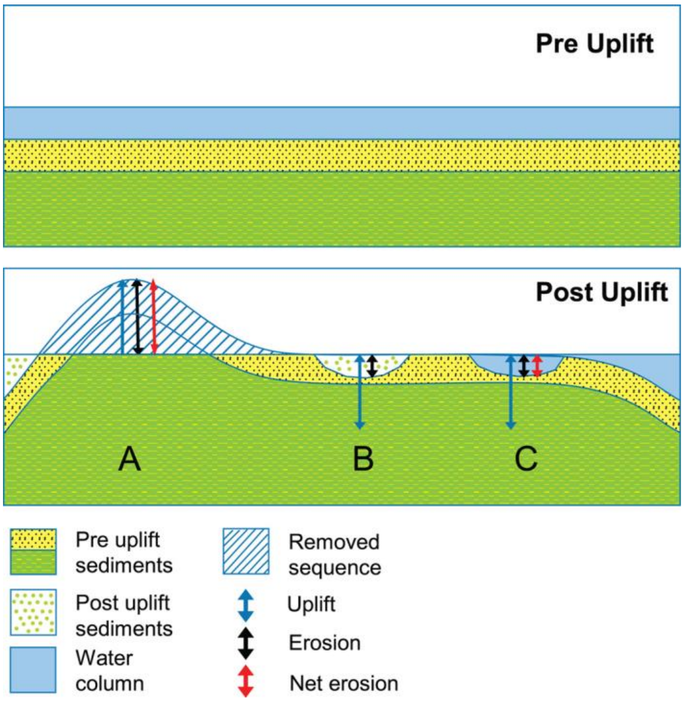

Figure 1. *Sketch showing the principal differences between the phenomena of uplift, erosion and net erosion how they affect sediments during different geological processes, a pre or post uplift phase (Henriksen et al., 2011).*

Uplift and erosion of sedimentary rocks as well as the magnitude of net exhumation estimates, have been studied offshore Norway using several methods (e.g. compaction trends such as porosity, bulk density and interval velocity (e.g. Richardsen et al., 1993; Novoselov et al., 2018), temperature data like vitrinite reflectance (e.g. Gac et al., 2018), apatite fission track analysis (Green and Duddy, 2010) or source-to-sink analysis/mass balance studies (Lasabuda et al., 2018)). Several studies focusing on uplift and net erosion using velocity data from well logs combined with NCT models also exist (Japsen et al., 2000; 2007, Henriksen et al., 2011). One of the major challenges is thus dealing with the large variations in net exhumation between methods and the uncertainty related to the individual methods. Compaction trends in shales and sandstones corresponds to the preferred method as from all the different methods. Net exhumation estimates from the shale compaction method seems to show the lowest standard deviation (Henriksen et al., 2011).

The erosion is known to be the most extensive in the western Barents Sea, and especially around the area in the north of Svalbard, where it has been suggested that more than 3000 m of rocks have been removed. However, in the southwestern Barents Sea (e.g. Hammerfest Basin), most current estimates of net exhumation are around 500-1500 m (Cavanagh et al., 2006).

As a contribution to the comprehensive and interdisciplinary main objectives of the GLANAM project, my PhD thesis aims to investigate the following:

- First of all the net apparent erosion in the southwestern Barents Sea,
- Secondly to determine the regional variation and magnitude of the net erosion by studying the compaction of selected stratigraphic layers.

In particular the main objectives of the thesis concern the following aspects:

- The development of a well log study; and the establishment of two baselines for the Cretaceous shales and the Lower Jurassic-Triassic coastal plain sediments by using reference wells from areas not subjected to uplift such as in the Norwegian

Sea (i.e. zero erosion reference wells in similar lithology and same age, e.g. Åre Formation).

- Calibration from wells to interpreted seismic profiles using calibrated velocities, adapting the baselines to give the same net apparent erosion estimates as from the wells. The profile study will provide a detailed investigation for layers suitable for net erosion.
- Application of this knowledge to velocity inversion in maps. We aim to select a series of maps following our interpreted main layers. In the west, the objective is to use the Top Paleogene and Base Tertiary structure maps to study the Paleogene section. In the central and eastern part of the study area, we aim to use the Base Tertiary and Base Cretaceous to follow the Cretaceous section and the Intra Lower Jurassic and Base Upper Triassic to follow the Lower Jurassic-Upper Triassic section.
- To integrate the results of the net apparent erosion estimates from the well log study and velocity inversion from maps (and profiles) to those from the vitrinite reflectance data. This corresponds to an important input for the basin modelling studies.

STUDY AREA

The Barents Sea occupies the northwestern corner of continental Eurasia (**Figure 2**). On the Norwegian Continental Shelf (NCS), the southwestern Barents Sea margin is one of the frontier areas that is currently open for oil and gas exploration. The Barents Sea corresponds to one of the widest continental shelves in the world and is confined by continental slopes both to the north and the west, by Novaya Zemlya to the east and by the Fennoscandian coast to the south. Between the Svalbard Platform and the Norwegian mainland there are several sub-basins and highs with more marked structural relief towards the west. The shelf has been exposed to major tectonic uplift episodes, in particular in the Cretaceous and Cenozoic time. The subsequent erosion during the Cenozoic removed sediments from Paleozoic-Neogene times along basin flanks. More of the younger formations were eroded in central basins and platforms.

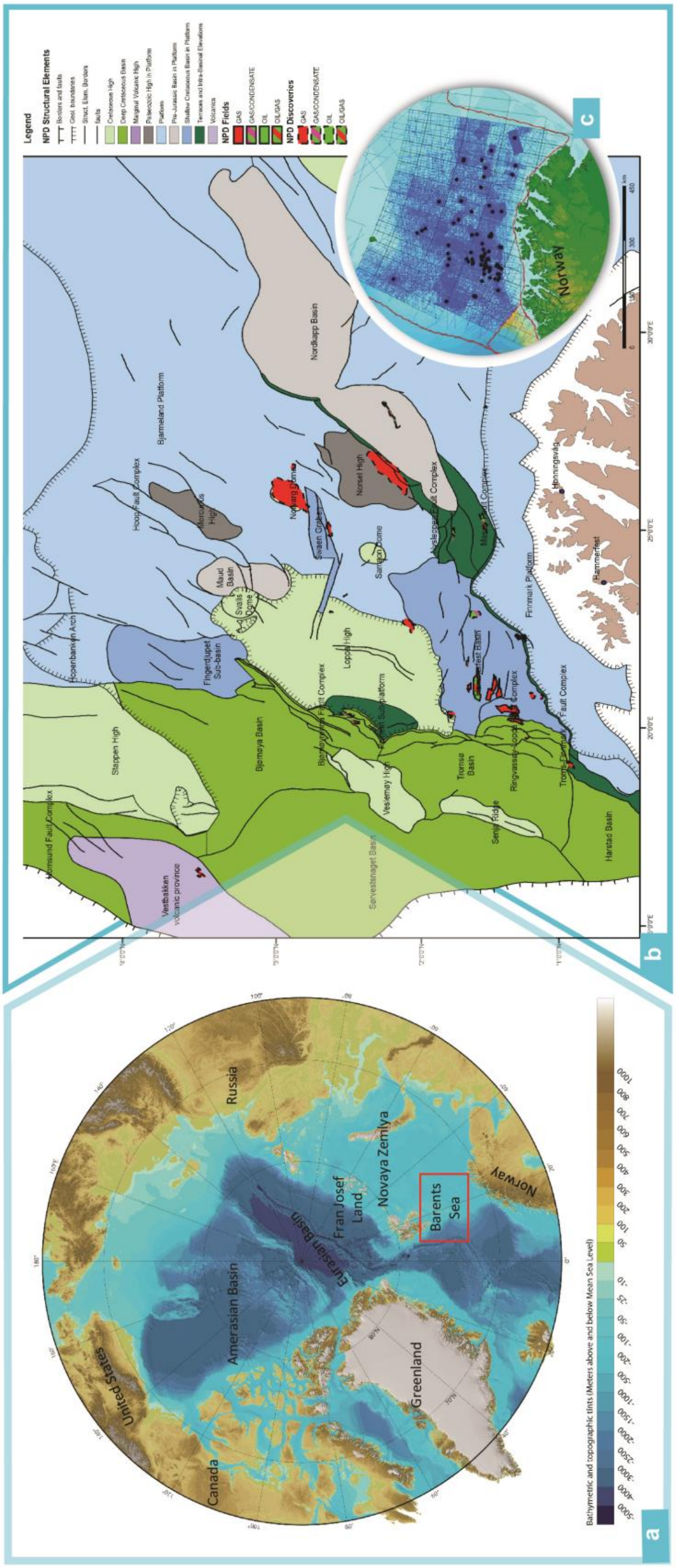

Figure 2. *a) International Bathymetric Chart of the Arctic Ocean (IBCAO; Jakobsson et al., 2008) with the approximate study area outlined in red; b) Tectonic map of the southwestern Barents Sea indicating oil-gas discoveries (NPD factpages); c) seismic and well-log data database from the Norwegian Barents Sea available in this thesis.*

The southwestern Barents Sea (**Figure 2**) is described by a complicated geological history accompanied by a geological evolution that dates back to the Paleozoic. It is furthermore characterized by several basins, highs and platforms (Faleide et al., 1993). The Barents Sea presents a petroleum province, which is characterized mainly by gas discoveries. The major petroleum systems that can be highlighted, consist of Paleozoic petroleum systems located in the eastern Barents Sea, the Early – Middle Triassic and the Late Jurassic petroleum systems that are most important in the southwestern Barents Sea (**Figure 3**).

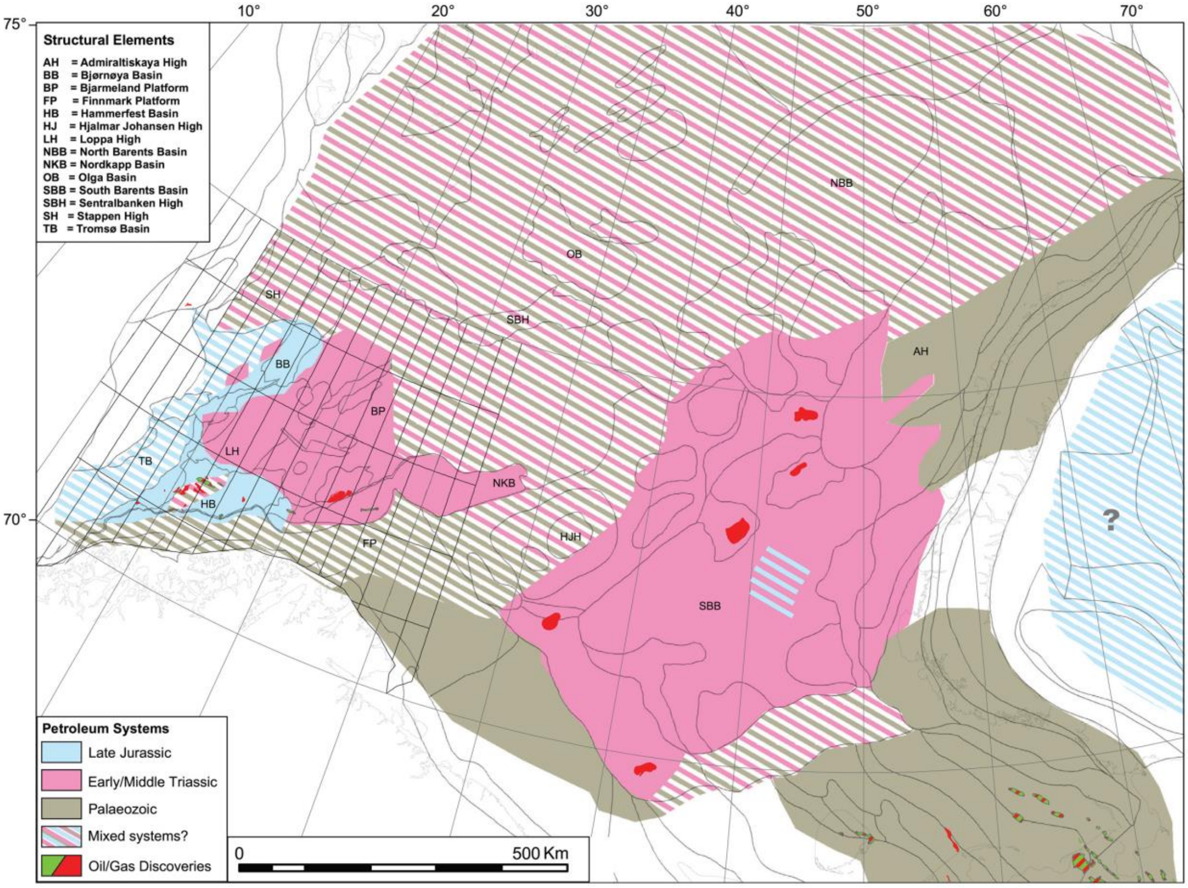

Figure 3. Map showing the *petroleum systems map of the Greater Barents Sea based on an inferred presence of source rocks and a modelled maturity of hydrocarbons in exploration wells in the Norwegian Barents Sea (Henriksen et al., 2011).*

SUMMARY OF THE ARTICLES AND SYNTHESIS

Article 1: *Quantification of the magnitude of net erosion in the southwest Barents Sea using sonic velocities and compaction trends in shales and sandstones. (Published in Marine and Petroleum Geology).*

Dimitrios Ktenas, Erik Henriksen, Ivar Meisingset, Jesper Kresten Nielsen and Karin Andreassen

The southwestern Barents Sea has been subjected to uplift and erosion in several areas as can be observed from the studied interpreted regional profiles. A new Normal Compaction Trend (NCT) for selected lithologies has been constructed based on sonic logs, calibrated to the corresponding lithologies in other locations e.g. the northern North Sea and Norwegian Sea but then applied to the context of the Barents Sea.

The new NCT model, allowed to estimate net apparent erosion in selected Barents Sea wells and create a net apparent erosion map of the study area, with an accuracy that is limited in areas with little well control. It has the advantage that it can address greater depths and provide a better representation of the younger shale stratigraphic intervals. Furthermore, this newly constructed NCT model can be used for accurate velocity analysis, depth conversion of seismic data, pore pressure prediction or basin and petroleum systems modelling.

We can clearly observe two regional trends which dominate the erosion pattern in the study area; an increasing amount of erosion towards the north and a sharp decrease of erosion westwards into the southwestern Barents Sea. Furthermore, these results have allowed to clarify the relationship between compaction, as measured by velocity, and the maximum depth of burial of the rocks. In addition, the establishment of this relationship has been utilized to understand how the state of compaction of an uplifted and eroded rock sequence can indicate the amount of erosion in a specific area.

Article 2: *Estimation of net apparent erosion in the SW Barents Sea by applying velocity inversion analysis. (Published in Petroleum Geoscience, in press.).*

Dimitrios Ktenas, Ivar Meisingset, Erik Henriksen and Jesper Kresten Nielsen

The processes of uplift and erosion that the SW Barents Sea has been subjected to during the Cenozoic, have had a significant impact on hydrocarbon exploration (maturation and migration) in the area. In this publication, we have created a map of net apparent erosion covering the entire SW Barents Sea area, showing regional trends consistent with deep-seated isostatic uplift of the crust in combination with glacial erosion as a driving mechanism for the process of erosion.

We find increased erosion along an axis stretching in a SE–NW orientation towards Svalbard, indicating major change in the crustal uplift pattern in the transition from the Norwegian mainland to the Barents Sea.

The method used in this study for accurate erosion estimations involved carrying out velocity inversion analysis in combination with a two-baseline normal compaction trend model. A high-quality regional velocity model and time structure maps were used in order to create a net apparent erosion map of high quality, covering a larger geographical area and which are consistent with similar previously published maps. The net apparent erosion map can also be used as input for petroleum migration studies as it indicates the area tilted during tectonic uplift, showing the direction of migration prior to uplift.

Article 3: *The effects of uplift and erosion on the petroleum systems in the southwestern Barents Sea: Insights from seismic data and petroleum systems modelling. (In prep.).*

Dimitrios Ktenas, Jesper Kresten Nielsen, Erik Henriksen, Ivar Meisingset and Oliver Schenk

In this paper, interpreted seismic horizons and stratigraphic forward modelling, were used to unravel the evolution along the regional 2D profile especially focusing on the Finnmark Platform area. The interpretations were based by focusing from the oldest to the youngest event, in order to assess petroleum systems in such frontier areas and thus provide the scientific community with a powerful tool for the assessment of petroleum systems in such areas.

The methodology used provides a best-fit realization of the basin-scale sedimentary filling from the post-rifting Jurassic times until the Last Glacial Maximum (LGM). The 1D and 2D models used, helped to depict the burial, thermal and maturity history at well locations of the study area, in the first case, while 2D modelling helped to reconstruct oil and gas generation, migration and accumulation along the 2D profile.

The results show that the influence of different scenarios related to tectonic and glacigenic uplift-erosion events does not really determine the timing and at what location the source rocks reach the appropriate depth which involves stages of oil and gas generation and expulsion. It actually determines the expulsion quality of the source rock by determining the amount of time that the source rock is retained at great depth and therefore the time for generating and expelling oil and gas from the deeper kitchen area, until the source rock is uplifted into a low temperature regime. With that in mind, re-definition of the Golden Zone, which is to be aligned with the magnitude and timing of the severe uplift and erosion events in the southwestern Barents Sea is important.

The expectations of future commercial discoveries are still high, although prospectivity varies considerably within the region. The existence of several working petroleum systems indicates that hydrocarbons were expelled over a long time span ranging from the Palaeozoic to late Cenozoic times. Furthermore, gas has been discovered in almost all reservoir intervals. During the last decade an increasing amount of oil was discovered i.e. Johan Castberg, Wisting, Alta and Gotha discoveries. Now the region is treated as an oil and gas province.

Having an understanding of maximum burial depth and uplift is an important element for promoting the understanding of the reservoir characteristics, the maturity of the source rocks timing of expulsion and the retainment of hydrocarbons in the traps. The basin modelling study shows that the classical Upper Jurassic source rock is immature to marginal mature in the central and eastern part of the Norwegian Barents Sea. Although not proven by commercial discoveries, there is evidence that the Permian Ørret Formation may be an important source rock in the eastern Norwegian Barents Sea. In those areas the exploration activities have to rely on the Triassic or Palaeozoic source rocks. An advantage for uplifted traps is the so called "pasteurization" effect of oil in shallow reservoirs, which is sheltered from biodegradation. It is also necessary to shift the depth and temperature interval for the Golden Zone in regions such as the Norwegian Barents Sea that have been heavily subjected to uplift and erosion events.

SYNTHESIS

Here the main findings of all papers contained in this PhD thesis are presented and discussed in a common context related to the title of the thesis.

By taking into account processes such as diagenesis and tectonic events, it was possible to predict compaction trends and associated seismic velocities in areas with more complex burial history involving both mechanical and chemical compaction, as well as uplift episodes and corresponding erosion.

Estimates of net erosion can be carried out in both drilled and undrilled areas. In this thesis net apparent erosion has been estimated for 28 wells in the southwestern Barents Sea leading to the creation of a regional map showing the amount and distribution of estimated erosion in the region.

Erosional products of the Cenozoic uplift are present in both the Paleogene and Neogene wedges (Ktenas et al., 2017). The sequence thickens westwards through the Hammerfest Basin and becomes even thicker towards the Sørvestsnaget Basin. The existence of normal faults allows for subsidence to occur and this in turn allows for more sediments to be deposited in certain parts. Faulting can also develop in a differential manner in the geological formations of the Bjørnoya Basin. The Cretaceous and Carboniferous sediments are slightly affected by faulting whereas the Triassic sediments, due to the nature of the lithology, are affected by faulting more extensively.

For estimating net erosion in undrilled areas, well log data based NCT models can be used and calibrated to other velocity data such as interval velocities in maps and seismic profiles from regional depth conversion.

The apparent net erosion (**Figure 4**) has been calculated from hiQbe™ stacking velocities which corresponds to data in the form of a regional velocity cube for the southwestern Barents Sea, for the Paleogene and Cretaceous layers. This model is based on the Normal Compaction Trend (NCT) calibrated to the Upper Cretaceous shales in Haltenbanken, Mid-Norway. It has been also verified that there is a match between the wells and the velocity cube. The model prediction is stable in the Hammerfest Basin and directly west of the Loppa High, indicated with red and green colours. In some places, the velocity indicates a difference in the lithology which doesn't match with the shale NCT baseline assumption.

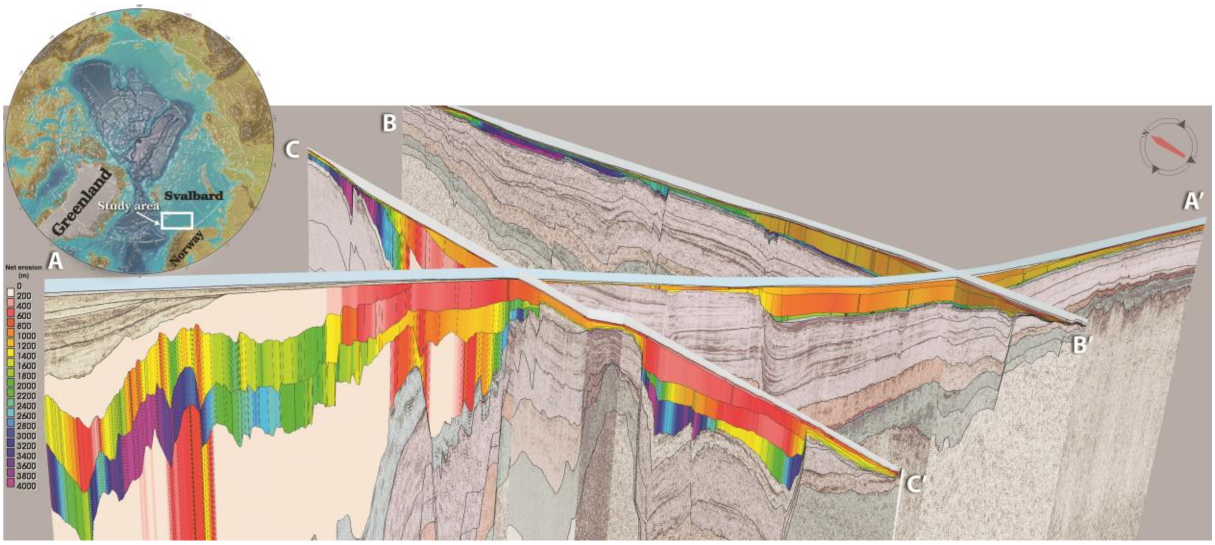

Figure 4. *Preliminary results of the regional inverted composite lines A-A', B-B' and C-C' in a 3D perspective illustrating an estimation of the net apparent erosion (indicated with colours) for the Paleogene and Cretaceous wedges in the southwestern Barents Sea. The final results of each of the inverted seismic profiles as well as the location of the regional profiles can be found in the original version of the corresponding paper (Ktenas et al., in press).*

Implications for hydrocarbon exploration

The processes related to uplift and erosion, for the different areas in the Barents Sea region, have important consequences for the petroleum systems. It is essential to understand the uplift and erosion history of a sedimentary basin in order to understand the hydrocarbon potential of the region. For example, reservoir quality, maturity of the source rocks and the migration of hydrocarbons are affected by these processes. Owing to changes in the PVT conditions in a hydrocarbon-filled structure, uplift and erosion increases the risk of leakage and expansion of the gas cap in a structure (Henriksen et al., 2011). Simulation results related to stratigraphic forward modelling, as presented in the paper by Ktenas et al. (in prep.), provide a powerful tool for the assessment of petroleum systems in frontier areas.

The Barents Sea is considered to have a high success rate in hydrocarbon exploration with most of the discoveries being gas prone (Ohm et al., 2009). Within the region the exploration activities have concentrated on the Mesozoic sandstone plays of the Hammerfest Basin. This has yielded abundant gas and less oil, which is typical of peripheral North Atlantic margin basins that have undergone Cenozoic exhumation (Cavanagh et al., 2006). The impact thus of Cenozoic exhumation on Arctic petroleum systems is something of primordial importance. Furthermore, better understanding of the timing of uplift and remigration of hydrocarbons is important in the exploration of the Barents Sea and in order to hold successful future exploration activities elsewhere. Consequently, in order to understand the remigration of hydrocarbons, assessing uplift and net erosion is crucial to exploration.

The expectations of future discoveries in the area are high and according to preliminary results by Ktenas et al. (in prep.) the highest potential for oil is expected in the western areas, while gas and gas-condensate will be dominant in most of the eastern areas of the Norwegian Barents Sea.

Petroleum systems can be subjected to glacial–interglacial ice sheet cycles. Furthermore, the hydrocarbons resident in these petroleum systems can be affected by extraordinary pressure oscillations related to ice sheet loading (Cavanagh et al., 2006). Further modelling work can thus be undertaken in order to pinpoint how the ice sheet loading and unloading can affect the resident hydrocarbons in these systems.

Once the actual uplift in a particular area has been estimated, we can then assess elements such as realistic porosity ranges for the relevant formations in a given exploration prospect (Henriksen et al., 2011). Any prediction of reservoir quality (porosity) should also take into account the maximum burial prior to uplift. Other important elements also exist and the relationship of uplift and net erosion to these elements affecting petroleum prospectivity can be summarized in the sentences below. In particular, uplift can affect the change of drainage pattern through time, the fracturing of the cap-rock and fault reactivation. Similarly, net erosion can affect reservoir quality, reduction in hydrocarbon generation rates, fracturing of the cap-rock, PVT changes in the reservoirs and fault reactivation (e.g. Henriksen et al., 2011).

This explains why significant research is therefore done to estimate the net erosion which in several studies, such as in basin modelling, is separated into several Cenozoic erosion episodes. The paper by Ktenas et al. (in prep.) contributes to this overall research objective by aiming to integrate different estimates of total net erosion (velocity inversion, sonic logs and vitrinite reflectance). This has led to the establishment of a consolidated net erosion estimate which then provided the necessary input to the discussion of the consequences on the subsidence and thermal history of sediments and maturity.

Effects on petroleum generation, migration and biodegradation

Severe uplift can cause hydrocarbon leakage from traps and cooling of source rocks (Doré and Jensen, 1996). It can alter reservoir quality and cause redistribution of hydrocarbons by changing migration pathways (Baig et al., 2016; Henriksen et al., 2011; Ohm et al., 2008).

The onset of the Oligocene erosion in the Hammerfest Basin marks the end of hydrocarbon generation due to the cooling of the source rocks (Duran et al., 2013b). Furthermore, in the Pleistocene, the main loss of gaseous hydrocarbons is predicted to be associated to the glacial-interglacial cycles and concomitant erosion (Duran et al., 2013a).
The consequence of net erosion is that prospective areas are now shallower and at lower temperatures compared with basins without net erosion (Henriksen et al., 2011).

Net apparent Cenozoic erosion estimates

Although Cenozoic exhumation of the northeastern European margin (over an area including Svalbard, the Barents Sea, Scandinavia and the British Isles) is not very well understood (Mjelde et al., 2002), there is a general consensus regarding the net apparent Cenozoic erosion estimates for the Hammerfest Basin and especially for the Snøhvit area. In this area, a lot of work and consequently several publications have been made in order to assess the severity of erosion within the southwestern Barents Sea (**Table 1**) (Lasabuda, A., 2018).

Table 1. *Comparison of average net erosion (m) estimates from various recently published publications (modified after Lasabuda, A., 2018)*

Structural Elements	Well name	Lasabuda et al., 2018 + Laberg et al., 2012 Mass-Balance	Ktenas et al., 2017 Shale compaction (Sonic)	Baig et al., 2016 Shale compaction, Shot gathers, Vitrinite	Henriksen et al., 2011 Shale compaction (Sonic), Thermal Maturity, Apatite Fission-Track (AFT), Vitrinite	Ohm et al., 2008 Vitrinite	Riis and Fjeldskaar, 1992 Vitrinite, Pyrolysis T-Max, Opal A/CT
Hammerfest Basin	7121/5-1	1380-1480	1650	800-1400	1000-1200	700-1200	1000-1500
Finnmark Platform (banks area)	7128/4-1 and 7131/4-1	1200-1830	1450	1200-1400	800-1400	800-1400	800-1400
Finnmark Platform (troughs area)	7019/1-1	1700-2460	1800	1700	1400	750	1500
Sørvestsnaget Basin	7216/11-1	0	361	0	0	250	0
Vestbakken Volcanic Province	7316/5-1	0	800	0	350	1500	500-100
Loppa High	7120/2-1 and 7220/8-1	1760-2460	1750	1150-1950	1200-2000	1500-2200	1500-2000
Bjarmeland Platform	7324/10-1	1860-2280	2100	1250-2400	1400-2500	1400-2500	1400-2500
Nordkapp Basin	7228/2-1 and 7228-9-1	1200-1350	2000-2250	1400	1400-1600	900	1100

The average net erosion estimates have been obtained using methods such as shale and sandstone compaction estimation (sonic log and refraction velocity depth trends), mass-balance studies, thermal maturity, shot gathers, diagenesis of clay minerals, fluid inclusions, anomalous seismic velocities, seismic sequence geometries, volumetric mass balance studies, vitrinite reflectance and apatite fission track data as presented in (Cavanagh et al., 2006 and Linjordet & Grung-Olsen, 1992). In some cases even, as presented later on in the thesis, by utilising an NCT model and sonic log velocities, estimates of net apparent erosion in 28 selected Barents Sea wells were established (Ktenas et al., 2017).

The general consensus is that an exhumation of c. 1000 m, ±200 m, took place (**Table 1**). Most authors agree on the severity of the Cenozoic erosion and they converge to reach broadly similar estimates. However, there is a clear divergence of opinion regarding the timing of the Cenozoic erosion event. Amongst the various methods employed, it is the mass balance, geochemical data and seismic velocity independent methods that favoured a Pleistocene event (Cavanagh et al, 2006). This event coincides with ice sheet activity on the margin (Nyland et al. 1992; Riis & Fjeldskaar 1992; Richardsen et al. 1993).

Furthermore, any uncertainties that may exist in the methods applied can explain the existence of variations in the erosion estimates observed. For example, the erosion estimate varies between 400-600 m (e.g. in the Hammerfest Basin) according to the method applied; with the mass-balance technique providing one of the largest uncertainty ranges and producing estimates that differ by much from the other techniques (Lasabuda, A., 2018). In some other areas, discrepancies of up to ~200-600 m are observed due to uncertainties and differences in how the methods are estimating net erosion, which are based on the availability of input data.

If we look more closely on previous work carried out for the southwestern Barents Sea more specifically, we can observe that most authors also propose an erosion of c. 1000 m. It is in the northern part of the Barents Shelf that an uplift of in excess of 3000 m occurred (**Figure 5**) (Cavanagh et al, 2006). This more severe erosion was estimated to have occurred further north in areas such as the Stappen High and Svalis Dome.

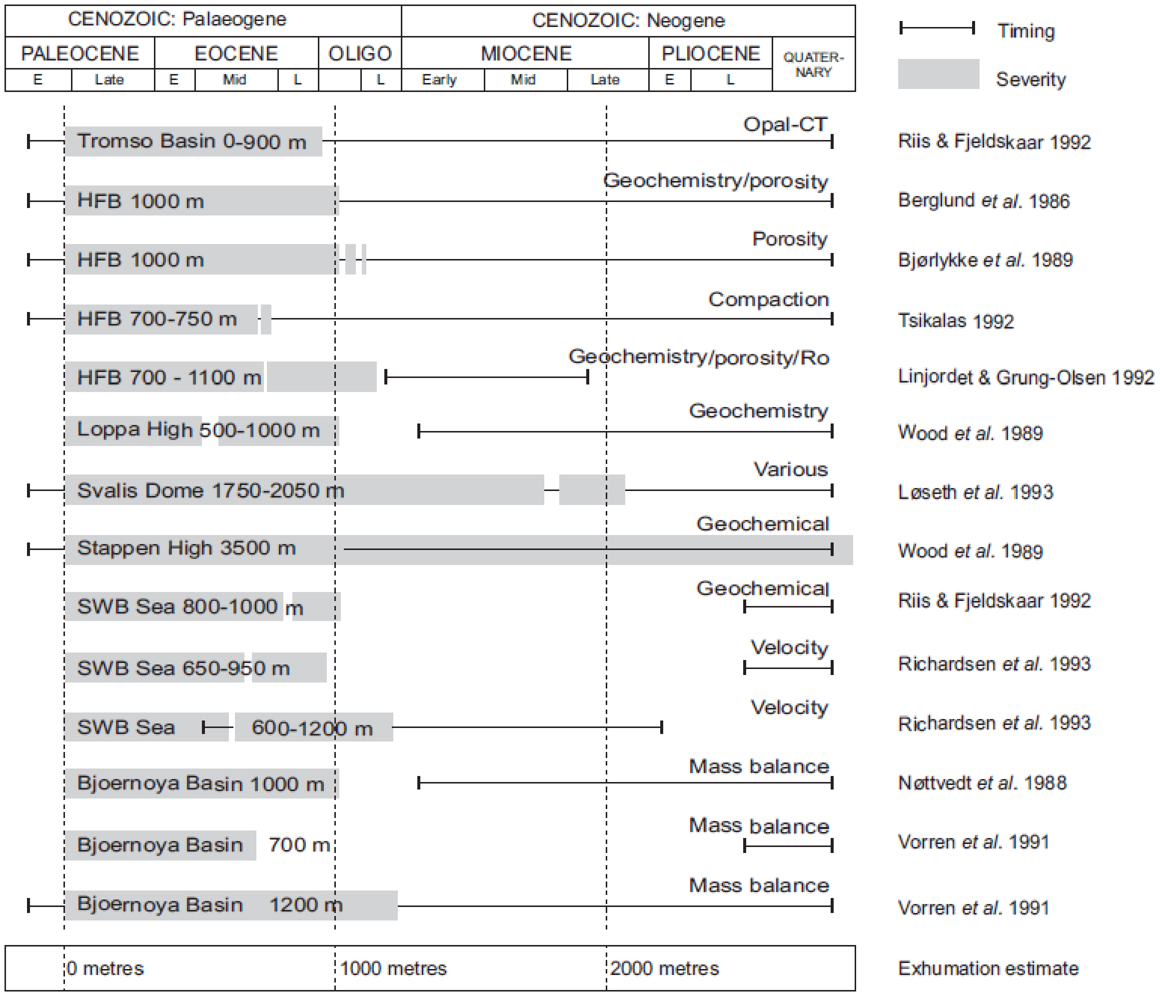

Figure 5. *Timing and severity of exhumation for the southwestern Barents Sea with the thick bars indicating erosion amount and the thin bars indicating wide variations in published timing estimates. HFB, Hammerfest Basin; SWB Sea, southwestern Barents Sea (Cavanagh et al., 2006).*

FUTURE WORK

Future work could involve using tools to carry out basin modelling in order to establish the sensitivity of the petroleum system to various scenarios of Cenozoic exhumation. Such modeling work can help to better understand how significant thermal disequilibrium in the different basins, platform and highs is at the present day and its link to Late Cenozoic exhumation.

More work should be carried out in order to establishing the Normal Compaction Trends (NCT) in shale and sandy intervals in different areas in the arctic region. In addition an establishment of a baseline in carbonate rocks in the southwestern Barents Sea could also bring additional information to those studies. Correlation between seismic velocity trends and maximum burial depth should be tested in several areas with high quality data available.

Furthermore, basin modelling could be undertaken along the seismic profiles covering the northern part of the Barents Sea. This approach would be based on the observed maturity, vitrinite reflectance and present-day temperature measurements. It would be thus important to take into account the variability of the heat flow, which has changed through time and burial history.

Furthermore, forward modelling of Pleistocene ice sheets could allow for an estimation of pressure and temperature fluctuations in response to glacial-interglacial cycles. The use of several methods allows for the standard deviation in net erosion estimates to be reduced. However, for obtaining more detailed estimations, more work needs to be carried out to further resolve the local variations that certainly exist along the shelf.

A way of reducing the uncertainties further and of resolving the local variations when calibrating an uplift map can be through the use of more correct estimations. This piece of future work would involve the use of a calibration process and a gridding approach based on sparse well data. In this analysis, the following aspects should be accurately investigated:

- The structure control on interpolation and extrapolation in between wells and away from the wells.
- Making a comparison with other gridding algorithms, especially *kriging with external drift*, as this is expected to give a better control on the calibration process and provide uncertainty estimates useful for carrying out the assessment.
- Making a final comparison with a published regional uplift map, e.g. Henriksen et al. (2011). This should be included in order to emphasize how these results differ from what has been thought before, and what this translates into in geological terms. This would mean that the analysis should be widened beyond just the pure gridding and geostatistics methods.

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Article I

Quantification of the magnitude of net erosion in the southwest Barents Sea using sonic velocities and compaction trends in shales and sandstones.

Dimitrios Ktenas, Erik Henriksen, Ivar Meisingset, Jesper Kresten Nielsen and
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Research paper

Quantification of the magnitude of net erosion in the southwest Barents Sea using sonic velocities and compaction trends in shales and sandstones

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ABSTRACT

During specific intervals within Mesozoic and Cenozoic times, several areas of the southwestern Barents Sea were subjected to uplift and erosion. Areas with missing shallow stratigraphic interval sections and major erosion can be seen at several places along interpreted regional profiles in the southwestern Barents Sea. A new Normal Compaction Trend (NCT) for two selected shale– and sandstone–dominated lithologies has been constructed based on sonic logs in the southwestern Barents Sea. The shale–dominated NCT is calibrated to the Cretaceous shales in the northern North Sea and Norwegian Sea and applied to the Cretaceous shales of the Barents Sea. The sandstone–dominated NCT is calibrated to the Lower Jurassic Åre Formation of the Norwegian Sea and applied to the Lower Jurassic–Upper Triassic coastal plain section in the Barents Sea. By utilising the NCT model, the study estimates net apparent erosion in 28 selected Barents Sea wells based on comparison of sonic log velocities. A net apparent erosion map of the study area was constructed by gridding of the well values. The accuracy of the map is limited in areas with little well control, such as in the northwest, where the east–west transition into the southwestern Barents Sea region is poorly constrained. With that in mind, the map clearly shows two regional trends which dominate the erosion pattern in the study area; an increasing amount of erosion towards the north and a sharp decrease of erosion westwards of the hinge zone into the southwestern Barents Sea. The highest erosion estimates are observed towards Svalbard, with values up to 2500 m. The results of this study can be further utilized in petroleum system studies in the eroded areas.

1. Introduction

As part of the Norwegian Continental Shelf (NCS), the southwestern Barents Sea is generally ice–free and more accessible than any other continental shelf in the Arctic. It also corresponds to one of the frontier areas that is currently open for hydrocarbon exploration. After drilling of the first exploration wells in the Barents Sea in the early 1980s, the issue of uplift and erosion has been much debated in academia and in the oil industry.

The southwestern Barents Sea area (Fig. 1) has been subjected to several phases of uplift and erosion during Mesozoic and Cenozoic times, resulting in a profound impact on the petroleum systems (Henriksen et al., 2011a). Along the southern flank of the Barents Sea, the Finnmark Platform is a characteristic example of an area that has undergone major uplift, this can be clearly seen on the seismic sections and regional interpreted profiles (Figs. 2 and 3). There is still a debate in academia and in the petroleum industry about the magnitude and timing of the erosional products

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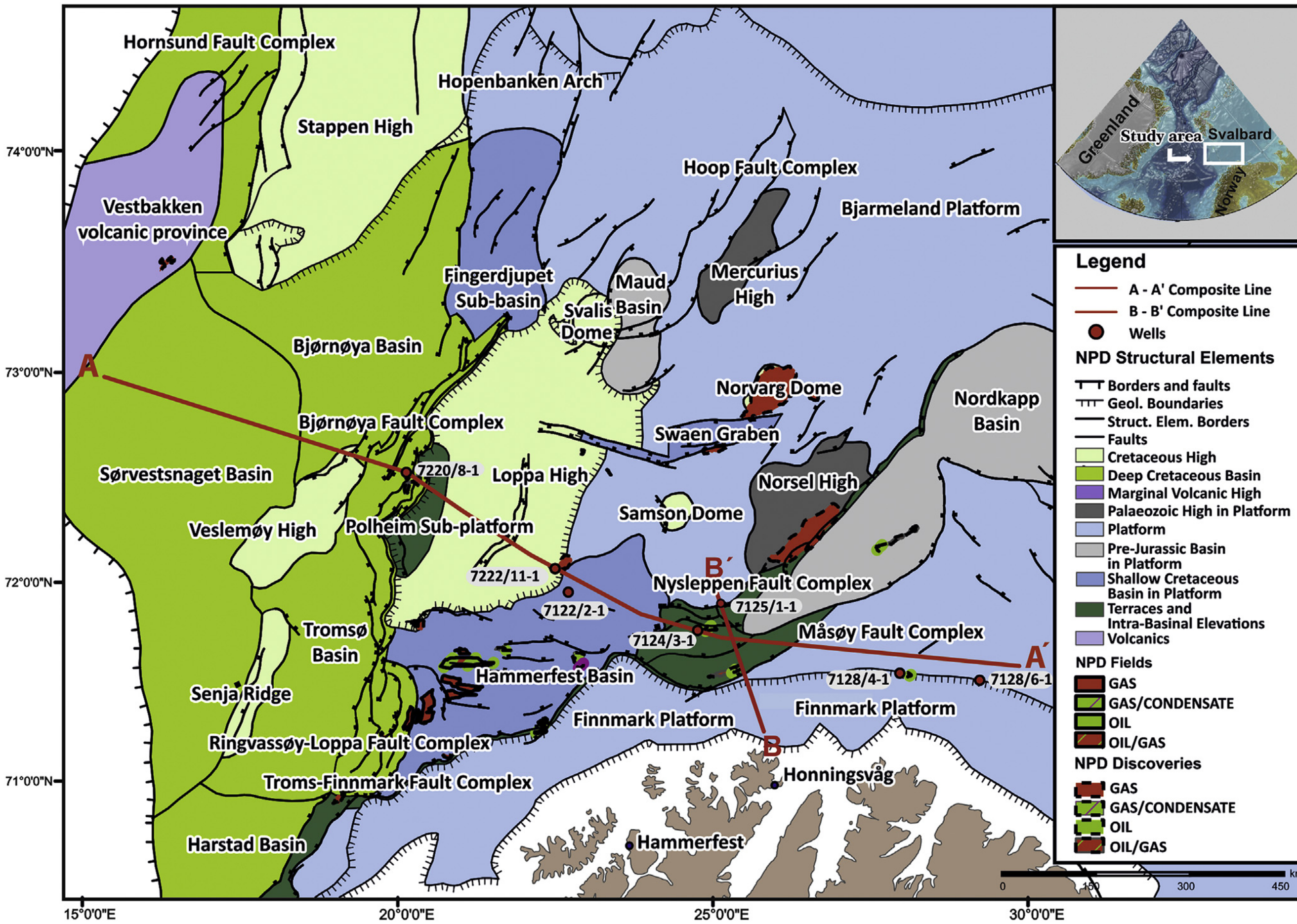

Fig. 1. Map of the southwestern Barents Sea showing the different structural elements and oil-gas discoveries. The regional profiles A-A′, and B-B′ and the wells studied along the lines are indicated with a red colour and red dots, respectively. The location of the study area is indicated in the inserted figure. Modified from the Norwegian Petroleum Directorate (NPD, 2014a, http://gis.npd.no/factmaps/html_20/) and Jakobsson et al. (2008). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

especially from the Cenozoic uplift. This is a research question of great importance for the petroleum industry with regards to play and prospect evaluation in undrilled areas.

The Norwegian explorer Fridtjof Nansen (1904) was the first to suggest that substantial uplift (of ~500 m) and deep erosion has occurred both onshore and offshore, on the Barents Shelf, during Cenozoic time. Later studies of the magnitude and timing of uplift and erosion have used many different methodologies, including compaction estimation (sonic log and refraction velocity depth trends), diagenesis of clay minerals, fluid inclusions, anomalous seismic velocities, seismic sequence geometries, volumetric mass balance studies, apatite fission track analysis, vitrinite reflectance and basin modelling (e.g. Vassmyr, 1989; Vorren et al., 1991; Nyland et al., 1992; Riis and Fjeldskaar, 1992; Eidvin et al., 1993; Løseth et al., 1993; Richardsen et al., 1993; Reemst et al., 1994; Sættem et al., 1994; Fiedler and Faleide, 1996; Rasmussen and Fjeldskaar, 1996; Lerche, 1997; Dimakis et al., 1998; Elverhøi et al., 1998; Butt et al., 2002; Cavanagh et al., 2006; Ohm et al., 2008; Green and Duddy, 2010; Henriksen et al., 2011a; Laberg et al., 2012; Duran et al., 2013; Nielsen et al. 2015; Baig et al., 2016; Zattin et al., 2016).

The timing of the several phases of uplift and erosion as well as the maximum burial of the sedimentary sequences represents a key factor in assessing the exploration potential of frontier areas (e.g. Green and Duddy, 2010). A series of papers (Vorren et al., 1991; Riis and Fjeldskaar, 1992; Eidvin et al., 1993; Løseth et al., 1993; Mørk and Duncan, 1993; Fiedler and Faleide, 1996; Hjelstuen et al., 1996; Laberg et al., 2012) suggests a dominant phase of Late Pliocene to Pleistocene exhumation. They describe the presence of Cenozoic clastic wedges of young glaciogenic sediments along the western margin of the Barents Sea and Svalbard, related to several phases of glacial erosion followed by isostatic compensation during the last ~2.7 Ma (Rasmussen and Fjeldskaar, 1996). In addition, Andreassen et al. (2007), Andreassen and Winsborrow (2009) documented in more detail the importance of glaciotectonism for the evolution of the Barents Shelf, and that erosion rates were higher where former glacial ice streams flowed. Studies from the North Slope of Alaska (Green and Duddy, 2010), the Western Canada Basin, the Sverdrup Basin (Arne et al., 2002), Svalbard (Blythe and Kleinspehn, 1998), West Greenland (Japsen et al., 2005) and East Greenland (Thomson et al., 1999; Hansen et al., 2001) describe regions subjected to significant Cenozoic exhumation similar to the Barents Sea.

The purpose of this study is to quantify the amount and regional variation of uplift and erosion in the southwest Barents Sea using best practice industry techniques. In order to avoid confusion concerning the terminology of uplift and erosion, it was proposed by Henriksen et al. (2011a) to use the term “net apparent erosion”. This is the difference between the maximum burial depth and present–day burial depth for a specific horizon. By adding the erosion value to the present depth, information about the

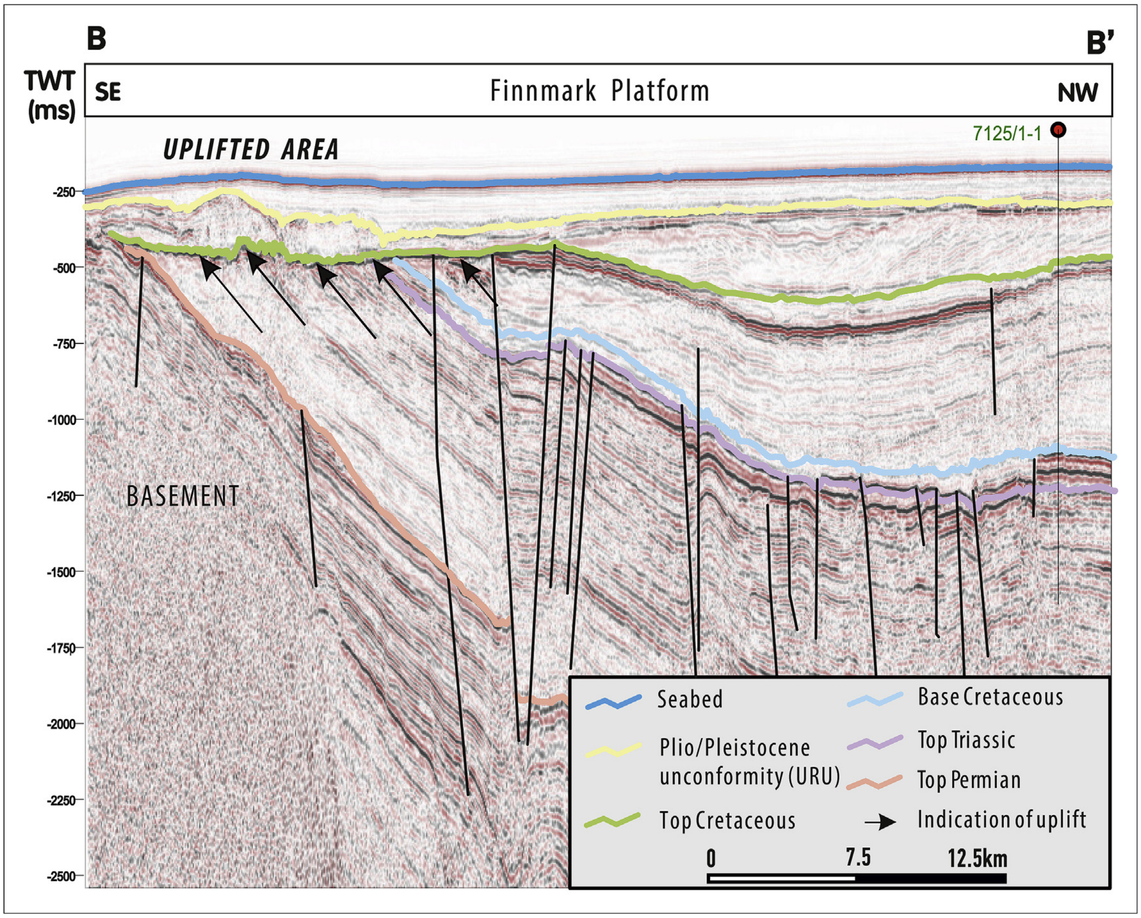

Fig. 2. North-south geoseismic profile B-B′ across the Finnmark Platform. This cross section shows thick Mesozoic strata below extensively truncated layers from the uplifted shelf to the south, left hand side of the profile. The box on the right corner shows the approximate age of the various units. For the location of the 2D line see Fig. 1.

maximum burial depth can be obtained.

The method used for the net apparent erosion estimates is based on shale and sandstone compaction. The study uses velocity data from 40 wells located on the Norwegian Continental Shelf (NCS), 28 in the southwestern Barents Sea study area and 12 reference wells in Norwegian Sea and North Sea. The reference wells were used to construct velocity depth-trends for shale– and sandstone–dominated sedimentary sequences. The interpretation of the velocity–depth trends has led to the construction of a new Normal Compaction Trend (NCT) model for the southwestern Barents Sea. The NCT model for shale– and sandstone–dominated lithologies was further used to estimate net apparent erosion from sonic logs in available wells.

2. Study area and geological setting

The main study area is located in the southwestern Barents Sea (Fig. 1). Well log data from other parts of the NCS were analysed in order to compare the Barents Sea with areas with little or no uplift (Norwegian Sea and North Sea). The Barents Sea is an epicontinental sea with an average depth of 230 m and a maximum depth reaching 500 m (Butt et al., 2002). It developed as an intra-cratonic basin from the Late Devonian, includes of a number of basins, platforms and basement highs and is underlain by Caledonian basement rocks (Fig. 4) (Faleide et al., 1993; Smelror et al., 2009). Evidence from a pseudo–gravity field in Finnmark County shows the extension of the Caledonian front (Henriksen et al., 2011b; Gernigon et al., 2014; Nasuti et al., 2015).

Following the Caledonian orogeny, the basement topography was covered by Devonian–Carboniferous strata. Faleide et al. (1993, 2008) divided the post–Caledonian history of the western Barents Sea into three significant extensional rift phases. The crustal extension during the Late Paleozoic led to the development of half–grabens (e.g. Hammerfest Basin) in the southwestern Barents Sea (Rønnevik and Jacobsen, 1984; Faleide et al., 1993; Worsley, 2008; Henriksen et al., 2011b). The onset of collision in the Uralian Orogeny during the Devonian and Carboniferous–Permian led to the subsequent uplift to the east of the Barents Sea and acted as a main source for Triassic sediments in the western Barents Sea (Ritzmann and Faleide, 2009; Henriksen et al., 2011b). To the west, major faults facilitated post–Permian subsidence and separated the Hammerfest Basin by major faults, from the Loppa High and the Finnmark Platform (Smelror et al., 2009) (Fig. 3).

Later extensional tectonics shifted westwards, with Late Jurassic rifting in the Hammerfest Basin, Cretaceous subsidence in basins along the western margin and Cenozoic subsidence due to the opening of the Norwegian-Greenland Sea during Paleocene-Eocene (Faleide et al., 1993; Tsikalas et al., 2012). The Cenozoic subsidence can be also seen in Fig. 3 towards the Sørvestsnaget Basin and Vestbakken Volcanic Province (Faleide et al., 1993; Henriksen et al., 2011b). These features are both bounded by oceanic crust developed during the Early Eocene (Henriksen et al., 2011b) – Oligocene,

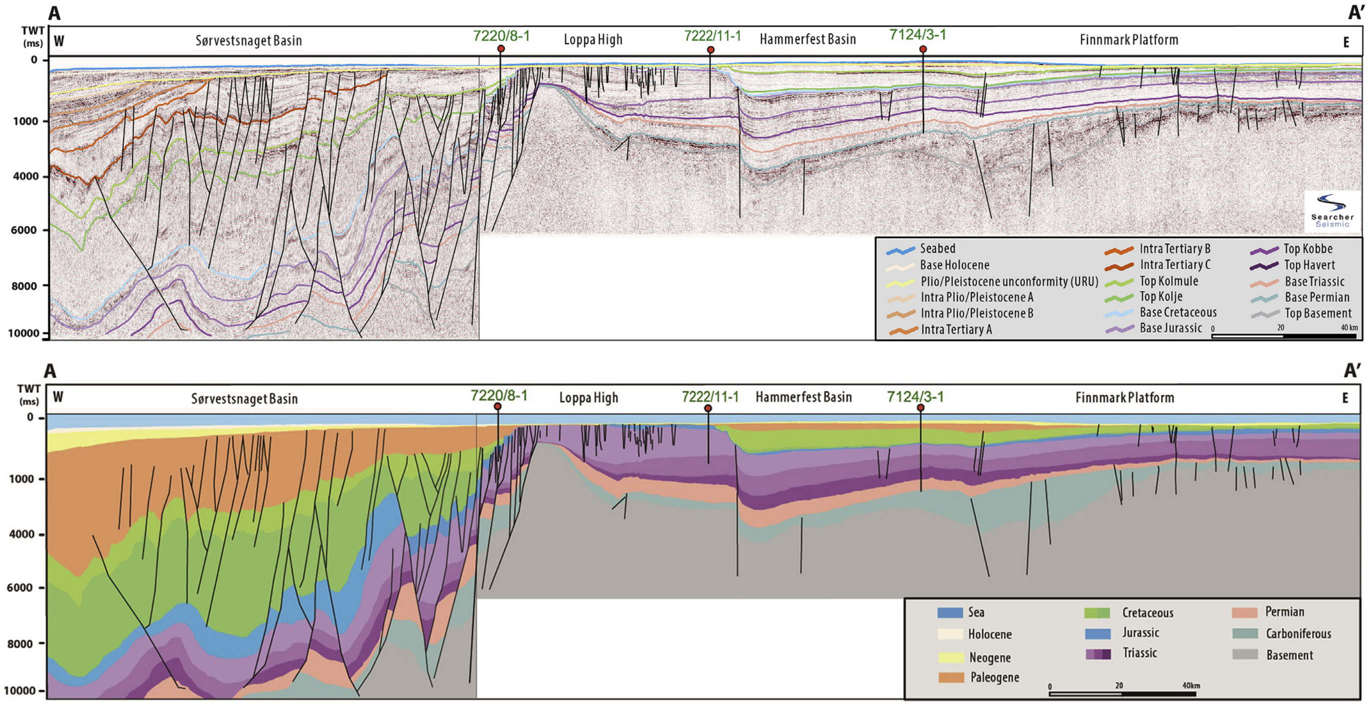

Fig. 3. Regional geoseismic profile A-A′ running from the southeast to the southwest. This cross-section illustrates the basin configuration, the changes in structural styles and geometries. Areas with missing sections and major erosion can be identified along the profile. For the location of the 2D line see Fig. 1.

leading to subsidence (Ryseth et al., 2003). Since then the area of the Barents Sea has been affected by repeated phases of uplift and erosion and the eroded sediments have been transported and deposited to the northern and western margins (Vorren et al., 1991; Faleide et al., 1996; Laberg et al., 2012; Baig et al., 2016).

The tectonostratigraphic evolution and paleogeographic changes since the Caledonian orogeny have been extensively described in detail by several authors (e.g. Henriksen et al., 2011b). The regional profile A-A′ illustrates the changes in structural style and geometries and the gross stratigraphy (Fig. 3). To the west, thick wedges of preserved Paleogene-Neogene deposits testify to the Cenozoic erosion of the Barents Sea, and are also linked to the opening of the Norwegian-Greenland Sea (e.g. Faleide et al., 1993). The Sørvestsnaget Basin, Bjørnøya Basin and other basins towards the western margin are characterized by thick Cretaceous units (Henriksen et al., 2011b).

In contrast, to the east in the Barents Sea, thick units of Paleozoic and Mesozoic strata with a dominant Base Cretaceous regional unconformity (BCU) can be mapped (Henriksen et al., 2011b). A prominent Upper Regional Unconformity (URU), representing the base of the Quaternary strata, can be mapped regionally (Fig. 3). This major unconformity is an outcome of the Paleogene uplift and erosion in the Greater Barents Sea to the east of the western margin (Riis and Fjeldskaar, 1992; Riis, 1996; Henriksen et al., 2011a, 2011b). The Plio-Pleistocene erosional products can be also seen along the profile A-A′ as described by several authors (e.g. Vorren et al., 1991; Richardsen et al., 1991; Ryseth et al., 2003) (Fig. 3).

3. Database

Forty (40) wells from three separate areas were analysed (Fig. 5): namely from the northern North Sea (3 wells), from the Norwegian Sea (9 wells) and from the main study area, the southwestern Barents Sea (28 wells). It was necessary to investigate areas that have not experienced uplift and erosion in order to establish a zero erosion reference point for the new NCT model and after that to investigate the southwestern Barents Sea area, which has been subjected to significant uplift and erosion. Fig. 6 shows the locations of the 28 studied wells covering a large part of the southwestern Barents Sea. The sediments in the studied wells are mainly of Paleogene to Triassic age and have been subjected to Cenozoic uplift and erosion (e.g. Nyland et al., 1992; Fiedler and Faleide, 1996; Dimakis et al., 1998; Henriksen et al., 2011a; Laberg et al., 2012; Baig et al., 2016).

Of the nine wells from offshore Mid Norway investigated in this study, two are located on the Sør High, six in the Haltenbanken area and one in the Møre Basin (Fig. 5). The northern North Sea wells added as supporting data. The tectonostratigraphic evolution of the Haltenbanken area has been summarized by Gage and Doré (1986), Dalland et al. (1988), Ehrenberg et al. (1992) and Blystad et al. (1995). The easternmost area of the Trøndelag Platform was subjected to Cenozoic uplift and erosion (e.g. Hansen, 1996). The Haltenbanken area has been separated into three different pressure regions. In general, the highest pressure areas are confined to the deeper western region (Karlsen et al., 2004; Storvoll et al., 2005; Van Balen and Skar, 2000; Borge, 2002; Lothe et al., 2004). The wells have penetrated sediments from Cenozoic to Mesozoic age and have been selected to represent a range of structural settings from shallow platform areas (Sør High and Horda Platform) to a deep basin (Møre Basin). The reference area wells have not been subjected to uplift because they are located geographically towards the west, far away from the Norwegian coastline.

The sonic logs from 40 exploration wells along the Norwegian shelf were imported and thoroughly quality checked (Figs. 5 and 6). The primary data sources (time-depth curve, well path, sonic logs (DT), well tops and well reports) were provided from the Norwegian Petroleum Directorate (NPD) web pages and Norwegian Diskos National Data Repository (Diskos) database. Any erroneous or low quality time-depth-velocity data were removed, in particular at the top and the bottom of each of the individual logging runs. Invalid

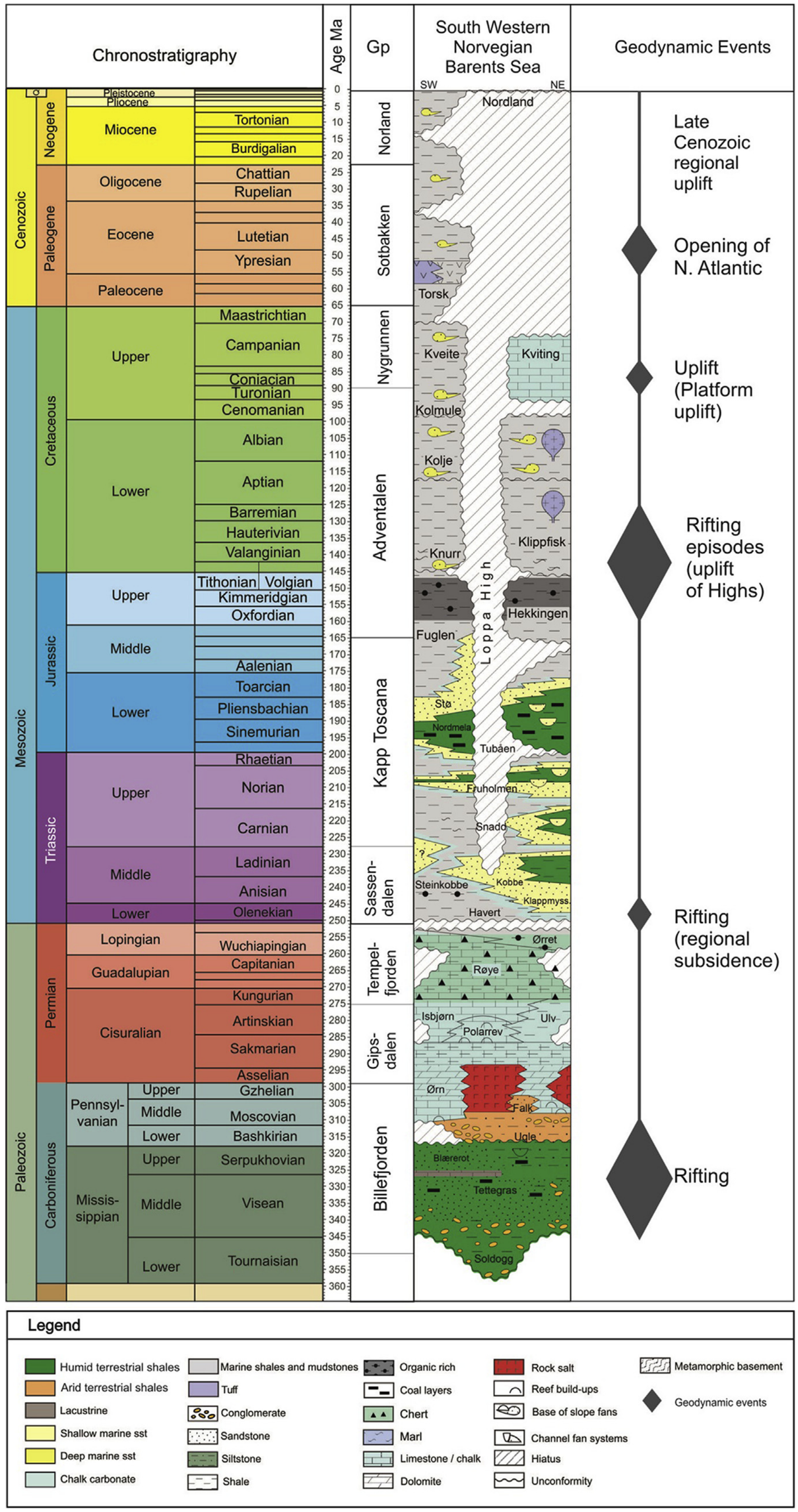

Fig. 4. Tectonostratigraphic chart from the southwestern Barents Sea, showing the general stratigraphy and the major tectonic events. Modified from Ohm et al. (2008) and Norwegian Interactive Offshore Stratigraphic Lexicon (NORLEX, http://www.nhm2.uio.no/norlex/).

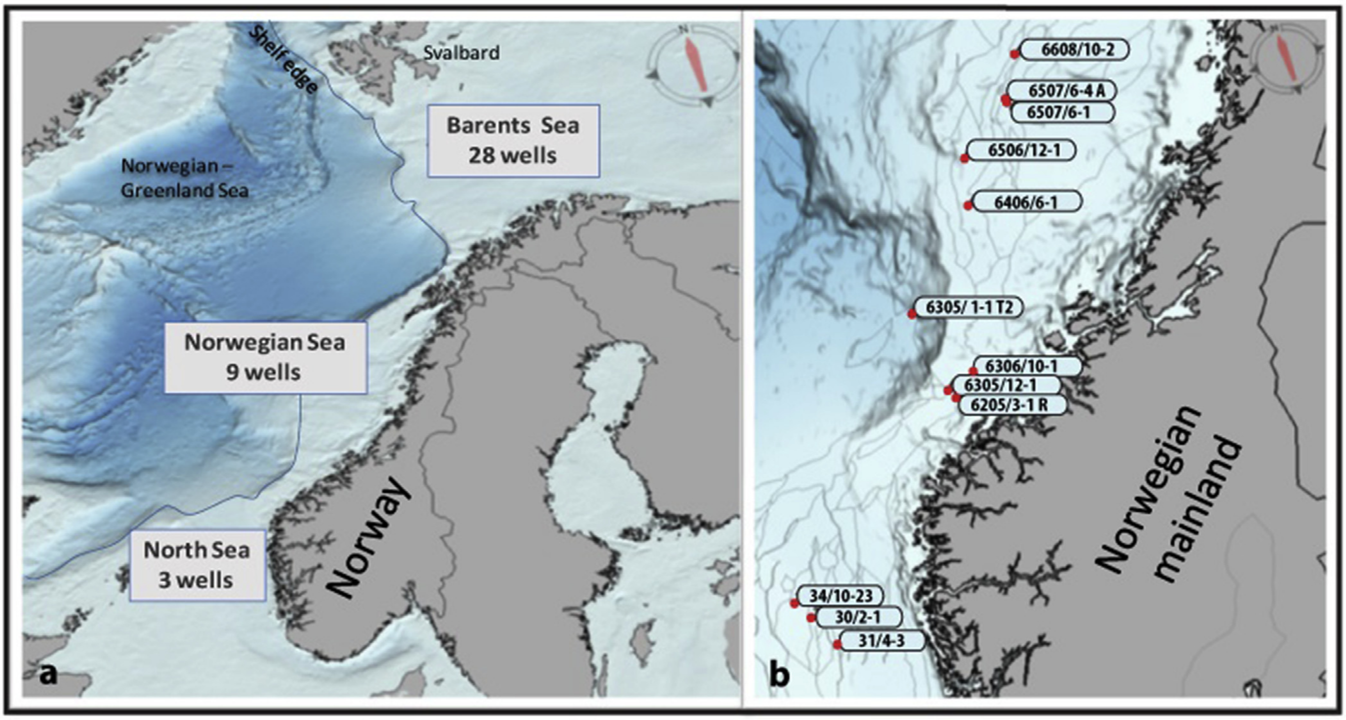

Fig. 5. (a) Location map showing the studied wells (40) from the Norwegian Continental Shelf (NCS). (b) The location of the reference wells with no erosion in the Norwegian Sea and North Sea areas used in this study, are marked by red dots along with the well name according to the Norwegian Petroleum Directorate (NPD FactPages 2014b, http://factpages.npd.no/factpages/). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

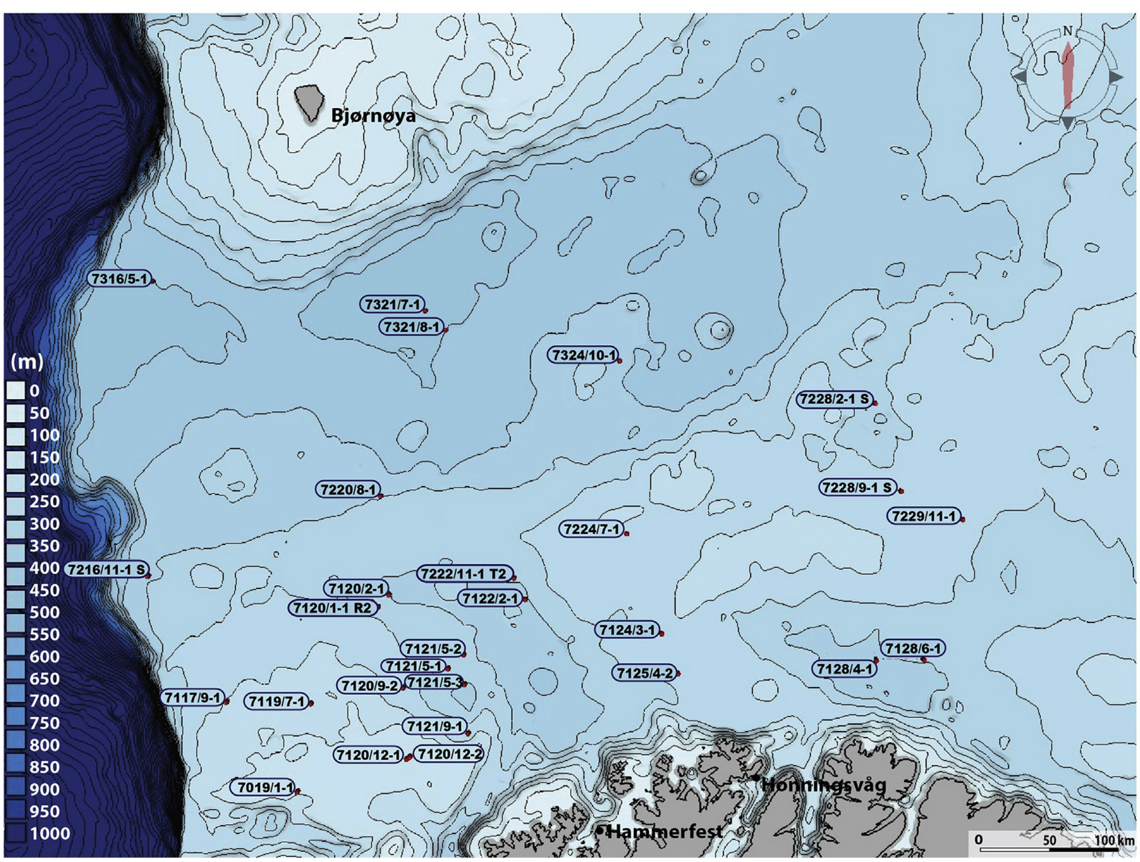

Fig. 6. Bathymetric map of the southwestern Barents Sea, showing the location of the wells used in the study area.

curve data recorded due to logging operations within borehole casing, were also removed. Deviated wells were converted to True Vertical Depth Sub Seabed (TVDSS). As shown in Table 1, there is an abbreviated list of the well tops from NPD used for the velocity vs. depth plots in the Norwegian Continental Shelf. This was needed to set up well tops as a set of common names that could be consistent for the whole NCS.

In addition to the quantitative evaluation of the net apparent erosion by studying the compaction trends of the well logs, regional seismic profiles A-A′ and B-B′ have been interpreted. The composite 2D lines were constructed from different 2D seismic surveys that are partly public from NPD Diskos database. Well log data from wells located in the vicinity of the 2D seismic lines were also integrated (Figs. 2 and 3, for the location of the profiles and tied–to–seismic wells see Fig. 1). In the wells, information on formation tops for a well–to–seismic tie was important for the seismic interpretation in order to identify and delineate the stratigraphy. This also helped to gain understanding of the lithological variation, fluid content and geophysical characteristics of the subsurface.

4. Method

4.1. Establishment of a new NCT model

Defining normal compaction trends using sonic velocity vs. depth base lines, is an established exploration geophysical method, and several mathematical formulations have been introduced to describe the increase of velocity with depth, in a manner similar to porosity (e.g. Wyllie et al., 1956, 1958; Athy, 1930). Many authors have published exponential equations or other linear trends to define compaction trends for shale or other lithologies (Hottmann and Johnson, 1965; Magara, 1976; Scherbaum, 1982; Sclater and Christie, 1980; Baldwin and Butler, 1985; Bulat and Stoker, 1987; Wells, 1990; Issler, 1992; Hillis, 1995; Japsen, 1993, 2000; Hansen, 1996; Heasler and Kharitonova, 1996; Storvoll et al., 2005; Japsen et al., 2007; Mondol, 2009; Tassone et al., 2014; Baig et al., 2016).

Two sets of NCT curves which have been tested extensively with many rock types in basins worldwide are from Japsen (2000), Japsen et al. (2007) and First Geo (unpublished, based on Gardner et al., 1974). They are based on different data, and as shown in Fig. 7 they look quite different. Whereas Gardner et al. (1974) based his curves on clean sands and shales picked from well logs in young sedimentary basins (Gulf of Mexico area), Japsen (2000), Japsen et al. (2007) used interval velocities from consolidated Jurassic and Triassic shale- and sandstone-dominated formations from wells in the UK and Danish North Sea Basin. Fig. 8 shows the Japsen and First Geo NCT models plotted together with reference wells 31/4-3 from the northern North Sea well and 6305/1-1 T2 from the Norwegian Sea. The former is from a shallow platform with thick Triassic, the latter from a deep basin (Møre Basin) with an ultra-thick Cretaceous sequence. The First Geo "Gardner" shale baseline gives a reasonable fit to well 6305/1-1 T2, except for the (Tertiary) diatomite sections where the velocities are extremely low. The "Japsen" sand line gives a reasonable fit to the Jurassic-Triassic section in well 31/4-3. This demonstrates the difficulty of making one NCT model which fits all wells and lithologies and illustrates the need to develop a new, independent NCT model for use in the southwestern Barents Sea.

The velocity depth-trend or baseline (Japsen et al., 2007), (synonym of NCT used in this study) describe how the velocity increases with depth in a formation, with relative homogeneous brine saturated sedimentary formation when the porosity is reduced during normal compaction (mechanical or chemical). The NCT model referred to in this study corresponds to a set of curves, whereby a NCT is a curve or a straight line that is used as a trend line against a log curve (two in this study). Comparison between the NCT model and the actual compaction trend also allows identification of zones of overcompaction and undercompaction (e.g. Heasler and Kharitonova, 1996; Japsen 2000). The existence of such zones will also give information on the amount of removed overburden (e.g. Bulat and Stoker, 1987; Corcoran and Doré, 2005), on estimating overpressure due to undercompaction (e.g. Japsen, 1998, 1999, 2000), on depth conversion of seismic data (Al-Chalabi, 1997), on stratigraphic velocity interpretation (Peikert, 1985) and on amplitude variations with offset (AVO) on seismic data (e.g. Smith and Sondergeld, 2001).

A new NCT model has been developed for the southwestern Barents Sea. Well logs from this study have been used to establish the calibration curves which describe the NCT model for a given rock type as a function of depth. The workflow for establishing a new NCT model and a net apparent erosion map is shown in Fig. 9. All the information from the wells in the southwestern Barents Sea was gathered and reference wells from the North Sea and Norwegian Sea with zero net erosion were carefully studied. As a first approach, based on a review of published and unpublished baselines, these were applied to the reference wells. While matching the baselines against the well logs in the Norwegian Sea, the same baselines using deep wells for the Paleogene and Cretaceous shale layers were applied to the southwestern Barents Sea. Then, after the adjustment of the baselines, these baselines were extended deeper, down to the Lower Jurassic and Triassic sections in the southwestern Barents Sea. When a good match between the baselines for shale and sandstone had been obtained, a new NCT model was constructed (Fig. 10). In this study, these two baselines will be called "Dikte NCT model" calibrated for the Cretaceous shale (CretShale) and Lower Jurassic–Triassic (LJurTrias) sequences which correspond to mixed sand-shale lithologies. The baselines in the combined set work together, and represent the normal compaction of a multi-lithology system.

Table 1
Abbreviation of the well tops from NPD used for the velocity vs. depth plots of wells on the Norwegian Continental Shelf.

Well Tops	Abbreviation
Water depth + Kelly bushing	Seabed
Paleogene (Sotbakken/Hordaland Group)	Paleogene
Top Cretaceous (Nygrunnen/Shetland Group)	TC
Adventdalen/Cromer Knoll Group	Cromer
Base Cretaceous (Viking Group/Hekkingen formation)	BC
Base Jurassic (Kapp Toscana Group/"Gray Beds")	BJ
Intra Base Triassic (Sassendalen Group)	InBTr
Base Triassic (Sassendalen Group)	BTr
Base Permian (Gipsdalen Group)	BPerm
Base Carboniferous (Billefjorden Group)	BCarb

4.2. Interpretation of the net apparent erosion

In general, a porous rock will compact as a result of the effective stress and will therefore have an appropriate normal compaction trend line. A deviation from normal compaction, for a given lithology, can be interpreted as a measurement of net apparent erosion (Fig. 11). The result of the process of aligning the wells with the zero net erosion baselines has the effect of adjusting the depth of the wells to maximum depth of burial while keeping the baseline fixed.

After establishing a NCT model based on well log data, three main stages were followed to establish a net apparent erosion map:

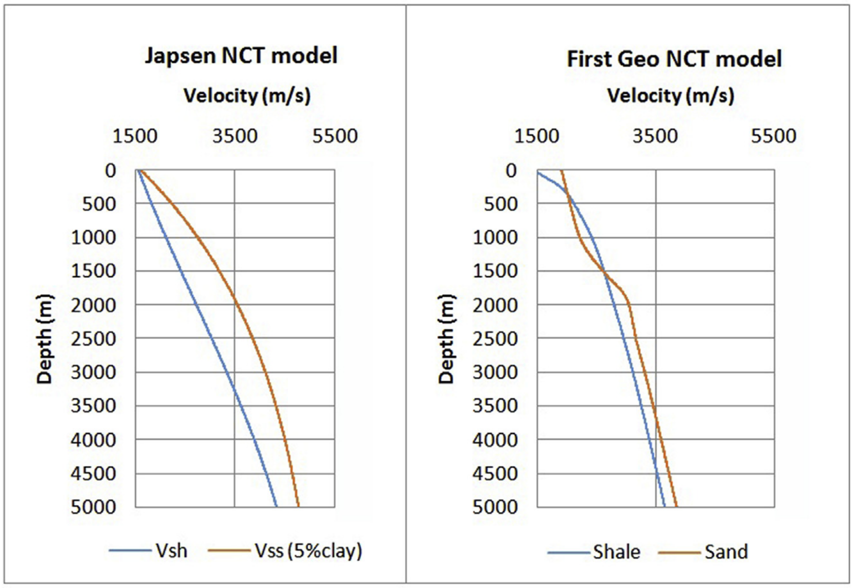

Fig. 7. Different Normal Compaction Trend (NCT) models for shale and for in-situ sands containing different fluids from First Geo (modified from Gardner et al., 1974) and Japsen (2000), Japsen et al. (2007).

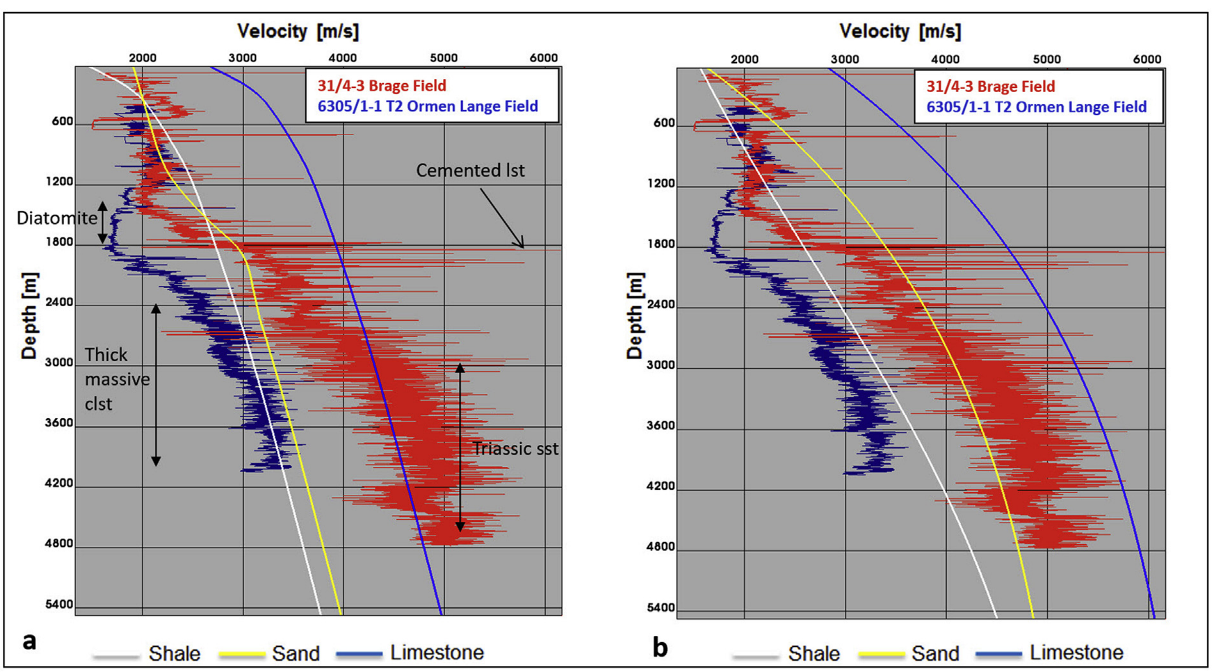

Fig. 8. Example from the North Sea well 31/4-3 and Norwegian Sea well 6305/1-1 applying different Normal Compaction Trend models for shale, sandstone and limestone. (a) The NCT model of First Geo (modified from Gardner et al., 1974) and (b) the NCT model of Japsen (2000), Japsen et al. (2007). Both wells are undercompacted (overpressure) and have the same pattern with different lithology. Geological factors that affect the sonic velocity are shown with black arrows. sst: sandstone, clst: claystone. For the location of the studied wells see Fig. 5. As shown, it is a challenge to make one single NCT model which works for both of these wells.

1) A stratigraphic layer was selected as a basis for the analysis (shale or other lithologies).
2) Net apparent erosion was estimated in the wells, following the method shown in Fig. 11.
3) The well estimates were gridded and contoured. Conflicting values in neighbouring wells were investigated and reinterpreted to achieve a consistent and geologically reasonable pattern of uplift and erosion.

4.3. Geological constraints on the net erosion estimates

There are two fundamental geological constraints on the shale

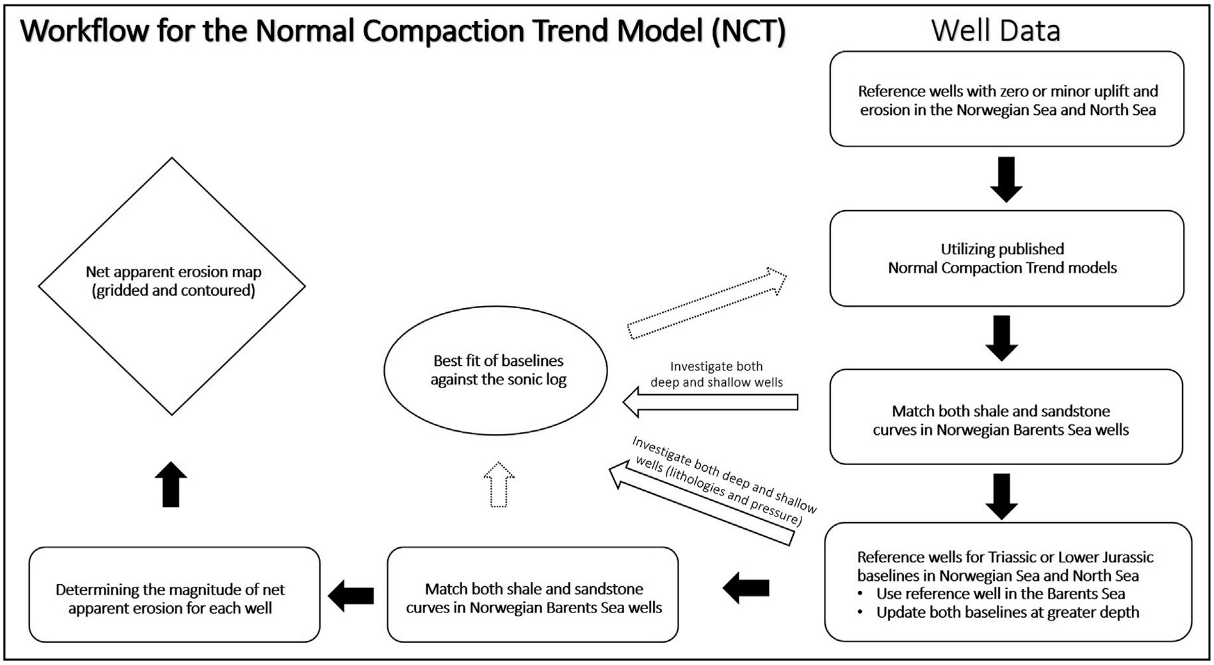

Fig. 9. Schematic overview of the workflow for establishing the Normal Compaction Trend model and a net erosion map based on well log data.

compaction method. The first is that the reference wells must have zero net apparent erosion. The second is that the net apparent erosion must be estimated from the compaction of the same type of rock in the reference and study areas.

In this study, the reference wells in the northern North Sea and in the Norwegian Sea did not have zero net apparent erosion. There was a small amount of glacial erosion of the seabed, with bearing seabed topography and one well that was affected by the Storegga slide. We decided to estimate the amount of these erosions and to compensate for them. In the Norwegian Sea and in the northern North Sea areas we assumed that a pre-glacial erosion seabed had existed as a flat surface 100 m below present-day sea level. This suggested value is compatible to what has been published by several workers (e.g. Sejrup et al., 2003), assuming that the terrain west of the Norwegian trench was formed by the effects of the glacial fluvial erosion processes during the late Cenozoic. In the Storegga slide area we used a reconstructed slide seabed (First Geo, unpublished). The difference in each well, between the present-day water depth and this estimated pre-glacial water depth was added as a net apparent erosion correction. This had the effect of eliminating the topographic variation in water depth from well-to-well due to the eroded seabed landscape. There is some uncertainty related to the 100 m pre-glacial water depth assumption, but this is small compared to the general uncertainty of the southwestern Barents Sea net apparent erosion estimates.

The Cretaceous shales in the Norwegian Sea and the southwestern Barents Sea are thought to be of the same litho-facies type and to be very suitable for net apparent erosion estimates. On closer inspection, we found that these shales in the Norwegian Sea, and the northern North Sea display a small amount of compaction disequilibrium. This is evident from comparison of the Upper Cretaceous thick massive claystones in well 6305/1-1 T2 (Fig. 8), with the shale baselines of "Japsen" and First Geo "Gardner" NCT models. These NCT models have been widely used, and the general relationship between shale baselines and compaction disequilibrium is well known (First Geo; Japsen P., pers. com.). A degree of compaction disequilibrium, and perhaps a moderate disequilibrium overpressure, is typical for massive shale units in active sedimentary basins worldwide. In our assumption, that the Norwegian Sea wells are good reference wells for the southwestern Barents Sea, there in an implicit assumption that the state of compaction disequilibrium in the southwest Barents Sea wells, at the onset of the uplift and erosion, was identical to the state of disequilibrium compaction in the Norwegian Sea wells at the present day. There is no way to know if this was actually the case, however we considered these assumptions to be reasonable since the geological history of these areas at these times was reasonable similar. The compaction disequilibrium in the Norwegian Sea today is moderate. If it was not similar to the Barents Sea during the onset of the uplift, then it is more likely to have been larger than smaller especially in the western most part of the Barents Sea where the shale units are thicker. A larger compaction disequilibrium means lower compaction relative to depth of burial and lower velocity. The shale compaction method will therefore underestimate the net apparent erosion in wells where this has occurred.

The sand-dominated Triassic sections which exist in thick deposits in the Barents Sea, Norwegian Sea and northern North Sea areas have similar proportions of clay and sand, but the compaction behaviour is very different. When we plotted the data we found them to group together on the basis of their depositional environment. The Lower Jurassic-Upper Triassic of the southwest Barents Sea was deposited in a coastal plain environment with some marine influence. A typical formation is the Fruholmen Formation (Norian to Rhaetian age). A typical formation of the Norwegian Sea area is the Åre Formation (Rhaetian-Pliensbachian). This is also a coastal to plain deposit. These coastal plain deposits from the Norwegian Sea and the Barents Sea seems to follow the same velocity vs. depth relationship and the same NCT baseline. The Triassic sections of the Norwegian Sea and the northern North Sea were deposited in a desert environment and are shown with higher velocity with respect to the depth of burial. These were investigated as possible references for the Triassic for the

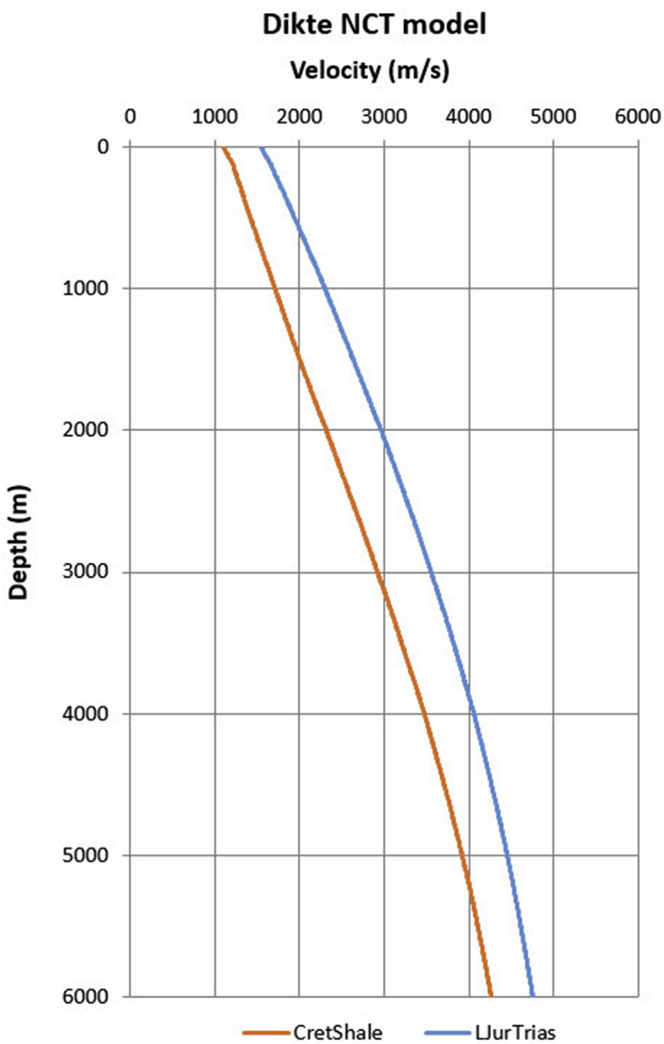

Fig. 10. The new calibrated "Dikte NCT model" constructed in this study for the Cretaceous shale (CretShale) and Lower Jurassic-Triassic (LJurTrias) units, which are mixed sand-shale lithologies deposited in a coastal plain to shallow marine environment. The Y axis corresponds to the depth below the ground surface (or seabed) and the X axis represent the corresponding velocity for the baselines.

southwest Barents Sea but had to be rejected. It seems that "sand" or "sand dominated" are not sufficient criteria for grouping lithologies for uplift and erosion studies. It is also necessary to have similar depositional environments.

5. Results and discussion

5.1. Net apparent erosion estimates from reference areas

Fig. 12 shows the primary reference wells from the Norwegian Sea and one well from the northern North Sea that have been calibrated to zero erosion for specific stratigraphic units; the shale-dominated Cretaceous lithologies and the sandstone-dominated Lower Jurassic. The correction value for the glacial/Storegga Slide erosion is given in the upper right corner of each well plot. Fig. 12 shows the NCT base lines from Fig. 10 plotted together with sonic velocity against maximum depth of burial. The objective of the reference well study was to obtain a best possible fit of zero erosion NCT base lines against the selected lithologies.

The primary NCT base line from the Norwegian Sea wells is the shale base line. This aligns very well with thick Cretaceous shale sections in all three Norwegian Sea wells in Fig. 12. In well 6406/6-1, the alignment is very good from near Top Cretaceous (TC) through Top Cromer Knoll (Cromer). The uppermost Cretaceous has a lower velocity than the base line, grading upwards into the Lower Tertiary where there is a velocity inversion. This inversion is typical for the Norwegian Sea as well as for the North Sea, and it makes the Tertiary section difficult to use as a reference section for erosion studies. The upper part of the Tertiary, which lies on the sandstone base line, is the prograding, glacially derived Pleistocene section. In well 6506/12-1 the log pattern is very similar, but the velocity variation in the Upper Cretaceous is slightly more variable and the fit to the base line is not quite as good. Both of these wells have mixed sand-shale lithologies in the Upper Cretaceous, but the dominating lithology is shale. Well 6305/1-1 T2 from the Møre Basin has a much thicker Cretaceous section with "cleaner shales". The BC horizon plotted at the base of the log is at Total Depth (TD), indicating that the age of the unit above TD is Cretaceous. This well shows a very good match with the shale base line and shows that the same base line works for wells with medium and very large stratigraphic thickness in the Cretaceous. Well 30/2-1 from the northern North Sea does not give a good match. There is a partial match to a shale unit within the Upper Cretaceous and the lowermost Tertiary Lista Formation. The Uppermost part of the Cretaceous (Maastrichtian) in this well has some sandstone and siltstone, which is a distal equivalent to the Maastrictian limestones which developed further south and southeast in the northern North Sea. This is indicated by a velocity increase as seen in Fig. 12. This well matches the shale baseline in the Lower Jurassic Drake Formation. This is different from how the Jurassic shales behave in the Norwegian Sea area.

It was required for the sandstone NCT baseline to support the same net apparent erosion estimate in the southwestern Barents Sea wells as it was done by the shale NCT base line. Therefore, the determination of the sandstone NCT baseline was based on both, the southwestern Barents Sea wells as well as the Norwegian Sea wells. It was found that the Lower Jurassic–Upper Triassic section in the Barents Sea followed the same NCT baseline for the Lower Jurassic section in the Norwegian Sea area, and in particular the Åre Formation.

Well 6506/12-1 is the primary reference well for the Lower Jurassic sandstone NCT base line in the Norwegian Sea area. It has a thick Åre Formation from about 4300 m to 4800 m maximum burial depth at the base of the well, to which the sandstone NCT base line gives a very good match. A very good match between the sandstone NCT baseline and the Åre Formation has also been identified in well 6608/10-2 from about 2700 m to 3500 m and in well 6507/6-4A from about 900 m to 1100 m maximum burial depth. Well 7120/9-2 was our key well for calibration of the sandstone NCT baseline in the southwestern Barents Sea (Fig. 13). This well has a thick Lower Jurassic–Upper Triassic section from about 3500 m to 5000 m of maximum depth of burial.

5.2. Net apparent erosion estimates in the southwestern Barents Sea

Fig. 13 shows the new Dikte NCT model developed for the southwestern Barents Sea applied to the sonic logs against the maximum burial depth. The interpretation on the net apparent erosion estimates is based on the Cretaceous shales and Lower Jurassic-Upper Triassic sections and the values are given in the upper right corner in Fig. 13. The primary NCT baseline for the determination of the net apparent erosion in the southwestern Barents Sea wells was the shale NCT baseline. The shale NCT baseline was established with great confidence from the closest

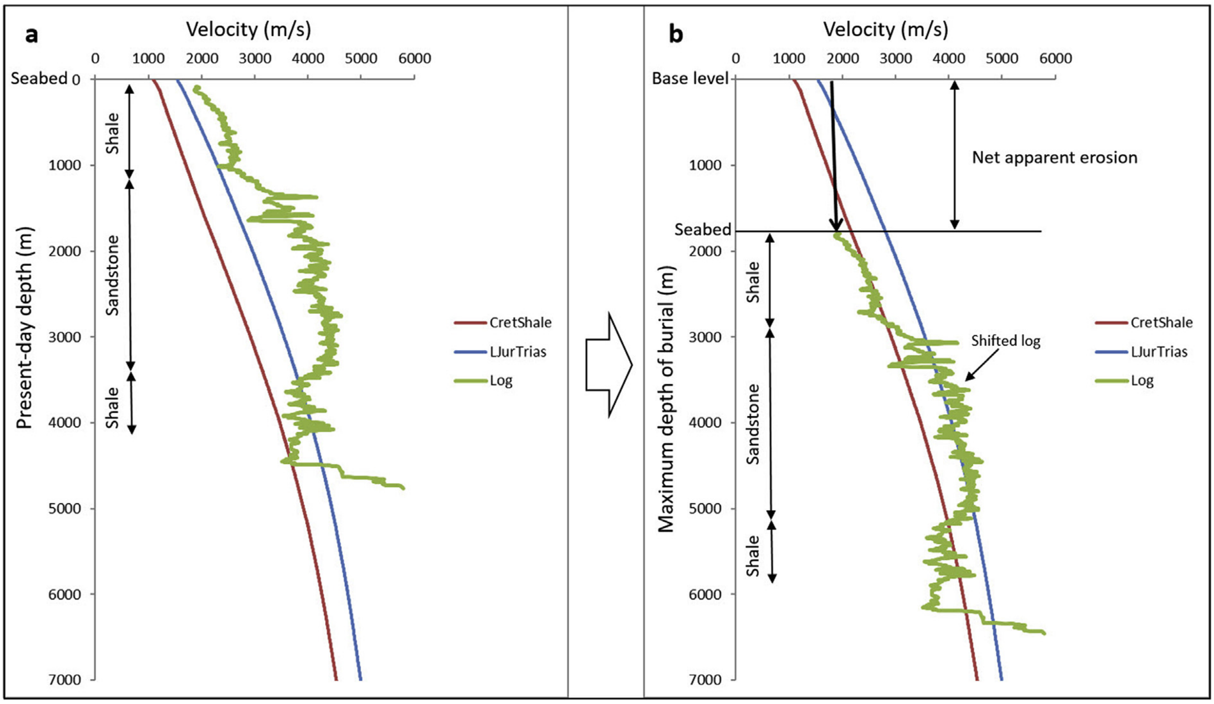

Fig. 11. Conceptual figure of the Dikte NCT model illustrates how the net apparent erosion is unravelled by matching by best fit the sonic log against the shale and sandstone curves. (a) Initially, the NCTs for shale and sandstone do not fit with the log. (b) Matching of the wells against the zero net erosion baselines requires a shift of the log curve downwards representing the amount of net apparent erosion; i.e. the amount of erosion is determined from the distance between the seabed at present day and the base level of the maximum burial axis.

reference area wells in the Norwegian Sea as well as in the northern North Sea. Therefore, many wells in the southwestern Barents Sea could be determined from the shale NCT baseline (e.g. well 7121/5-3, Fig. 13).

Among the 28 wells studied in the southwestern Barents Sea, the wells 7129/9-2, 7121/5-1 and 7121/5-3 were some of the good representatives using the shale NCT baseline for estimating the net apparent erosion for the southwestern Barents Sea (Fig. 13). The same wells were also helpful to define the alignment position of the sandstone NCT baseline. Well 7321/7-1 has a thinner stratigraphic section of Cretaceous shales compared to the other wells. The lithofacies development in the Cretaceous section is showing a poor match with the shale NCT baseline. In this well the net erosion estimate is mainly based on the sandstone NCT baseline. However, the Dikte NCT model has always been considered to work as a consistent set of baselines working together and the wells were inspected to look for good alignment either for thick or thin lithofacies.

There is no other Triassic section in the NCS which is quite similar to the southwestern Barents Sea. Hence, it was not easy to determine a sandstone baseline in the southwestern Barents Sea. However, we were more confident about the determined shale baseline in the Norwegian Sea where there is geological similarity to the southwestern Barents Sea Cretaceous shales. When we interpret the amount of net apparent erosion in each of the Barents Sea wells the first step is to use the established shale NCT baseline where the thick Cretaceous shales are present. It is well known that the Triassic section in the southwestern Barents Sea is more extensive compared to the Cretaceous section at the same area (e.g. see Profile A-A′, Fig. 3). Thus, the next step was to investigate many other wells whereas the net apparent erosion values were measured from Triassic sections against the sandstone NCT baseline (e.g. 7324/10-1, 7229/11-1, 7222/11-1 T2 and 7321/7-1, Table 3).

The sandstone NCT baseline gives a good match with the Lower Jurassic-Upper Triassic sections in all the four wells as shown in Fig. 13. In well 7120/9-2 there is a good alignment with the sandstone NCT baseline from Base Cretaceous (BC) through (InBTr). In well 7121/5-1 the sandstone NCT baseline shows a good match with the sonic velocity from 3600 m to 4500 m maximum burial depth. Similar quality of the match is shown in well 7121/5-3 from Lower Jurassic through to Intra Base Triassic (InBTr). Furthermore, the well 7321/7-1 shows a good fit with the sandstone NCT baseline from the Lower Jurassic to the Lower Triassic. From the overall alignment of the well logs studied in the southwestern Barents Sea it was concluded that the sandstone NCT baseline is efficient for silty-sandy lithologies.

During the interpretation of the net apparent erosion some of the studied wells proved to be problematic. For example, in the westernmost area in the Barents Sea the wells 7316/5-1 and 7216/11-1S were more complicated. There are both not deep wells and the Tertiary section could not give a good match against the Dikte NCT model. Therefore, for the well 7216/11-1S the net erosion estimate provided in Table 3 corresponds to the present water depth which is 361 m. This estimate is also based on the assumption of previous works (e.g. Butt et al., 2002), that the water depth in the southwestern Barents Sea prior to the onset of glaciations was ~0 m below the present sea level.

Fig. 14 shows the sonic velocity measurements vs. maximum depth of burial for the deep exploration wells 7128/6-1 and 7128/4-1 on the Finnmark Platform. In well 7128/6-1 a relative good match between the sandstone NCT with the sonic log has been identified from 2300 m to 2800 m of maximum depth of burial. The net erosion estimate has been picked from the Lower part of the Triassic section. The InBTr is a horizon that represents the base of the Triassic section that matches the sandstone NCT baseline. Similar alignment with the sandstone NCT has been identified in

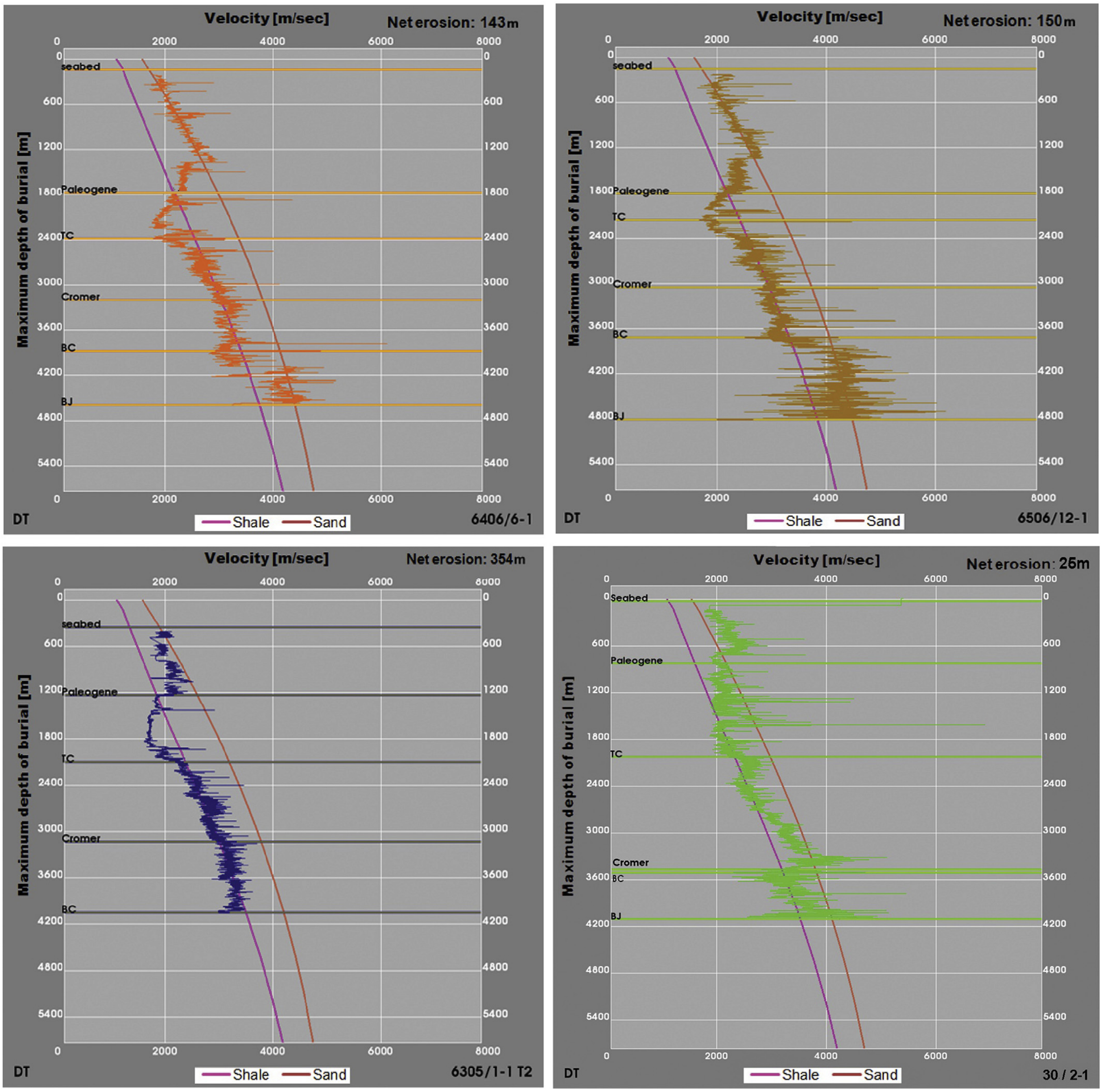

Fig. 12. The established NCT model for shale and sandstone calibrated to reference wells with no net erosion in the North Sea and Norwegian Sea (for the well top abbreviations see Table 1 and for the location of the wells see Fig. 5b). In wells with no net erosion, the present water depth is shown.

well 7128/4-1 from 1800 m to 2300 m of maximum depth of burial. It is typical in the structural high of the Barents Sea that the top of the Triassic is close to the seabed which has been eroded later/or recently. Our study supports the idea that the Triassic section in these areas is related to the maximum depth of burial prior to the latest erosion as we cannot see differences in the net apparent erosion between the Late Jurassic horsts and grabens. Several studies have shown that carbonates can also be used for uplift and erosion estimates (e.g. Schmoker and Halley, 1982).

The amount of net apparent erosion decreases towards the continental margin and is outlined at around ~300 m in the western part of the Barents Sea. The highest erosion values are observed towards Svalbard with values reaching ~2500 m. The present seabed topography (Fig. 6) seems to reflect the degree of erosion. The areas on the platform with least water depth correspond approximately to areas with the highest net apparent erosion (Fig. 15). Two different trends of net apparent erosion are observed; an increase along a south to north direction and a decrease from southeast to northwest. In the northwestern part of the study area, the rate of change of net erosion is much faster due to the close spacing of the isopachs. Due to the lack of well data, there is uncertainty in the net apparent erosion values in areas with total absence of well information, (e.g. in the northeastern part of the Barents Sea study area).

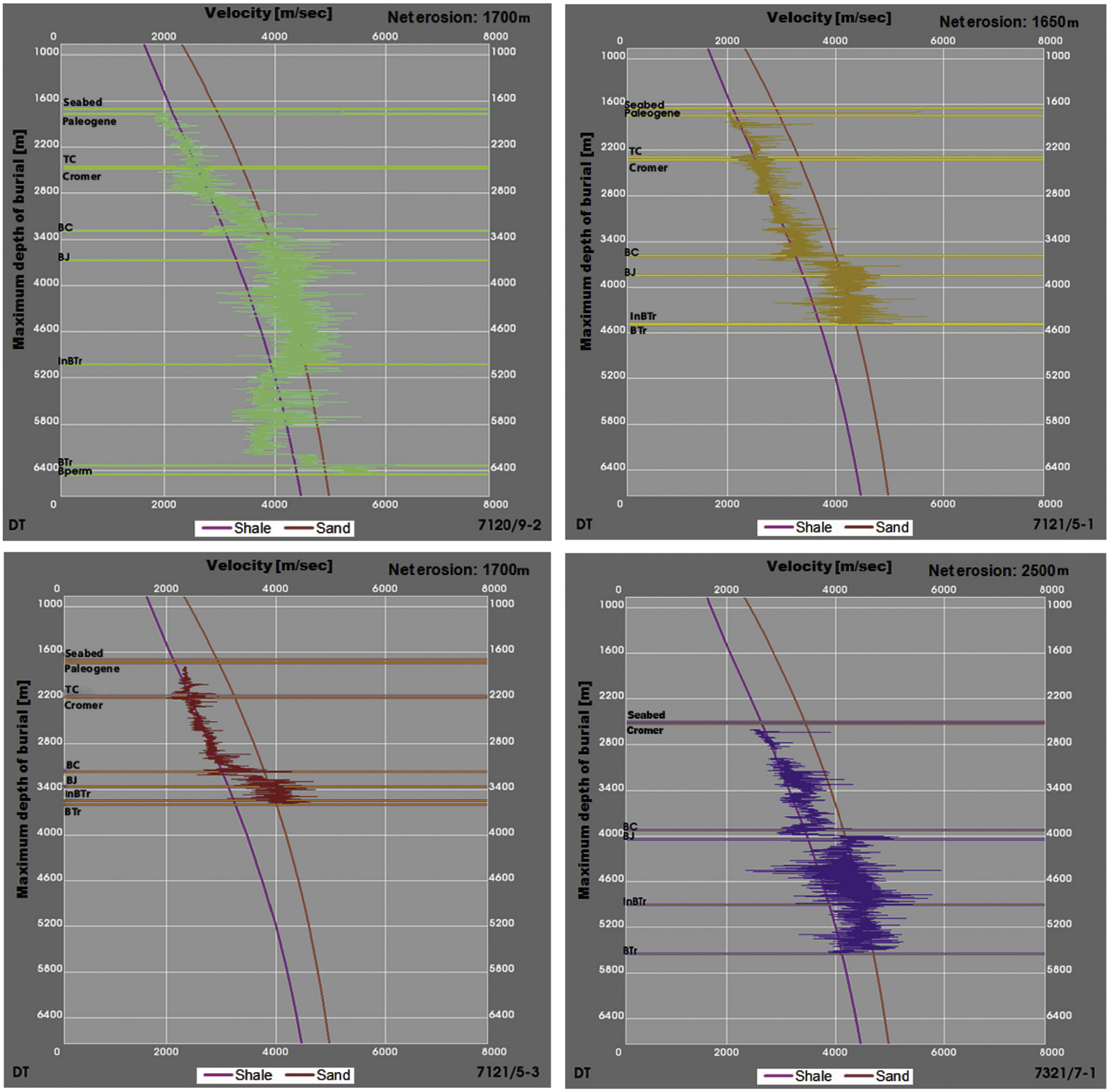

Fig. 13. Sonic velocity measurements vs. maximum depth of burial from the studied wells in the southwestern Barents Sea. The estimation of net erosion observed in the wells is based on the NCT model established in this study. For the well top abbreviations see Table 1 and for the location of the wells Fig. 6.

The erosion map from Nyland et al. (1992) (Fig. 16) showed that about 1200 m of uplift and corresponding erosion had occurred in the southwestern Barents Sea, while a thickness of about 3100 m of sediment had been removed from the Svalbard drainage area. Their studies were based on a map of the Upper Regional Unconformity (URU) (see also Fig. 3), combined with bathymetric maps and a drainage system map of the Barents Shelf, together with volumetric calculations of the western fans. Doré and Jensen (1996) calculated that 0–500 m of overburden have been removed from the Hammerfest Basin, Senja Ridge and Tromsø Basin, 100–1500 m from the remaining Hammerfest Basin and Loppa High, 1500–2000 m from the Finnmark Platform and over 2000–3000 m from the Stappen High area. For the southwestern Barents Sea sedimentary basins, Henriksen et al. (2011a) suggested net erosion magnitudes between 900 and 1400 m and further to the west minor or zero net erosion. In the Hammerfest Basin and Nordkapp Basin, the erosion reached magnitudes between 1000 and 1400 m and for the northernmost well in the Bjarmeland Platform ~1700 m. Baig et al. (2016) based on different methods (three data sources), including sonic well logs, constructed a net exhumation map and suggested an average of ~0–2400 m of uplift and erosion. The same authors suggested net erosion estimates that range from ~800 to 1400 m in the Hammerfest Basin, ~1150–1590 m on the Loppa High, ~1200–1400 m on the Finnmark Platform and ~1250–2400 m on the Bjarmeland

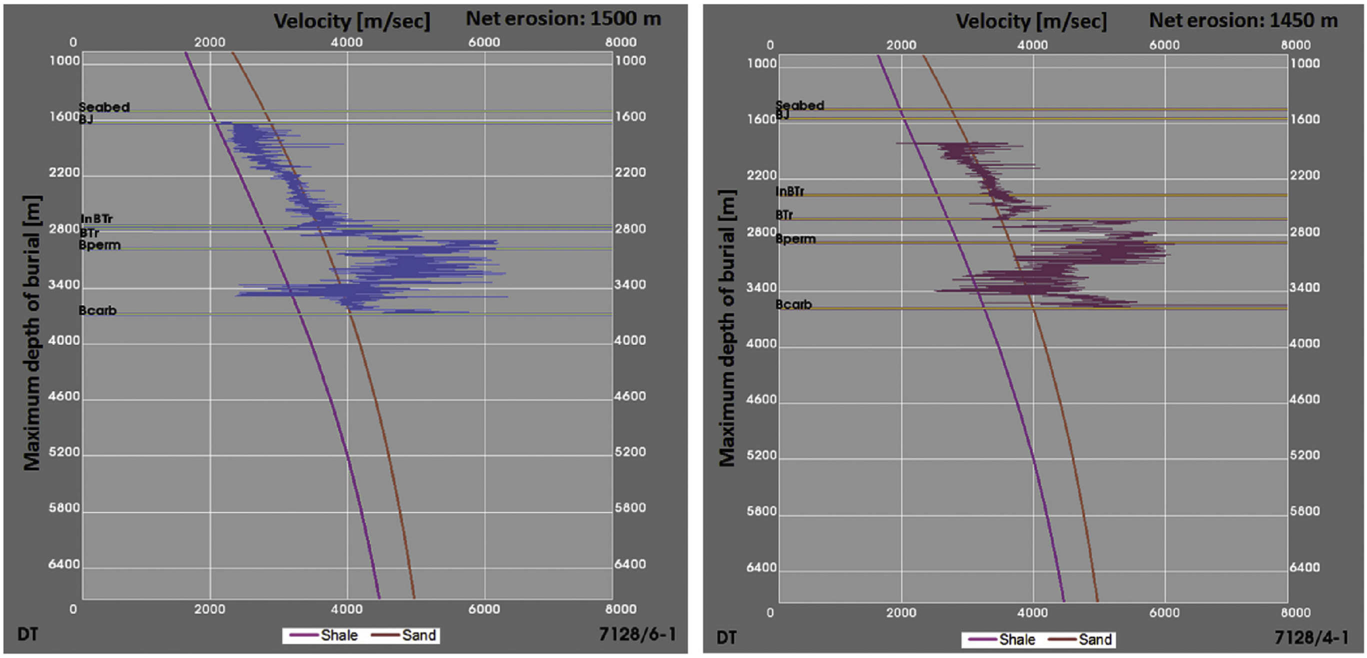

Fig. 14. Sonic velocity measurements vs. maximum depth of burial from the exploration wells 7128/6-1 and 7128/4-1 in the Finnmark Platform, southern Barents Sea.

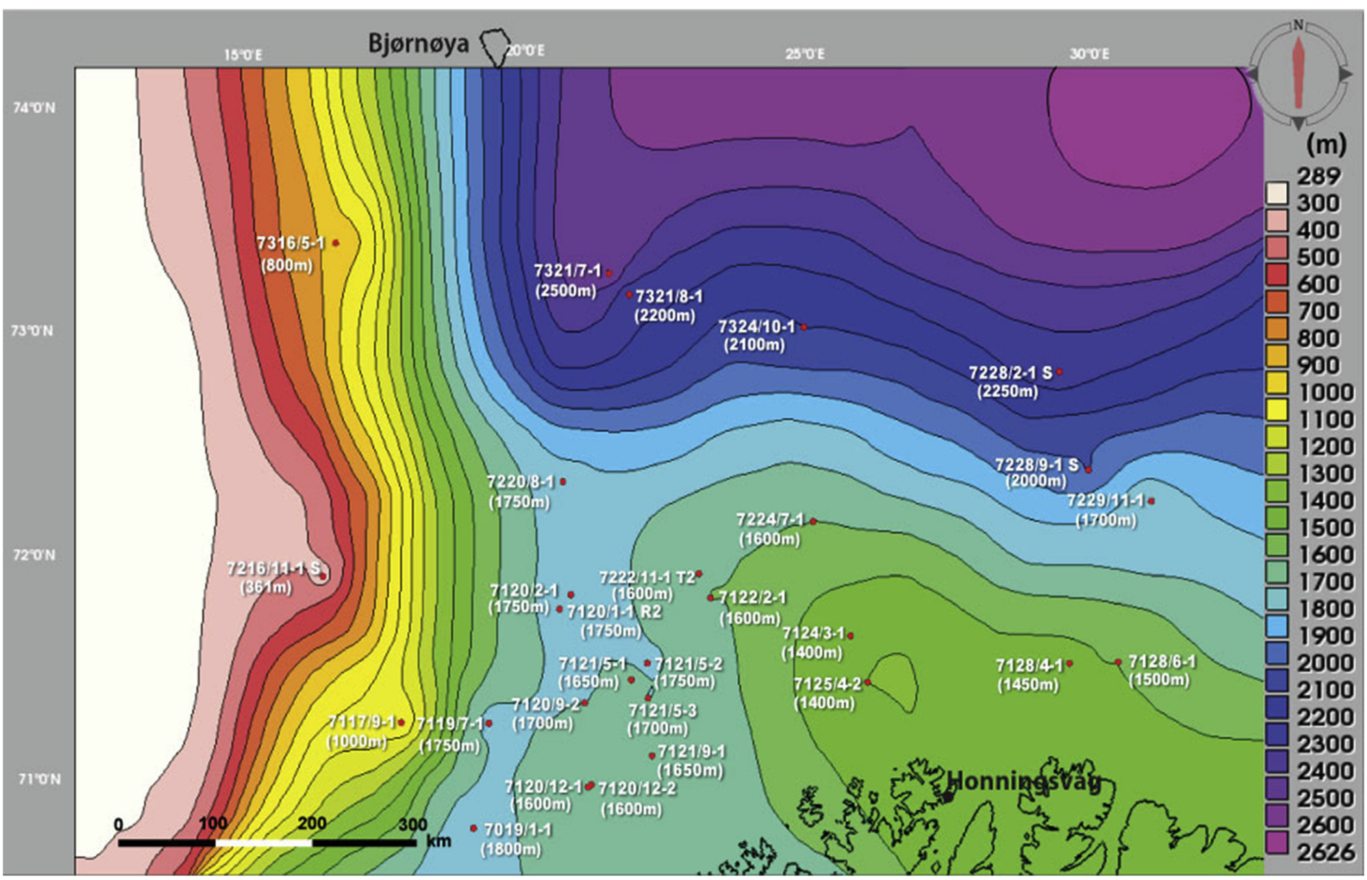

Fig. 15. Regional map illustrating the estimated net erosion for the southwestern Barents Sea, based on sonic log data. In areas that there is no well control, seismic data have been studied to complete the map (see also Table 3).

Platform.

Several net apparent erosion estimates from previous studies are summarized in Fig. 16. They all suggest a general trend of increase of uplift and net erosion towards the East and Northeast and less uplift across the basins. When comparing Figs. 15 and 16, we notice that the overall mapped trends appear to be the same,

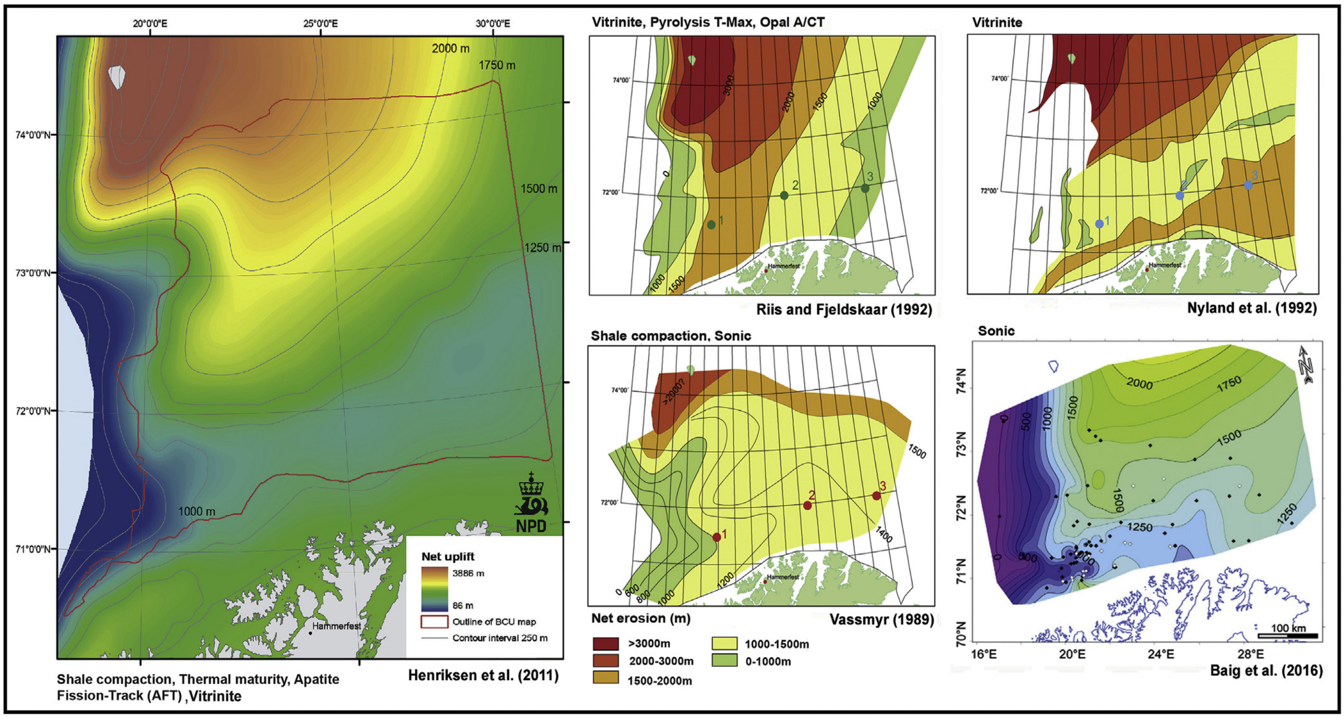

Fig. 16. Previous uplift and net erosion maps for the Barents Sea indicating a general trend of uplift and net erosion increasing towards the East and North. In some areas rather large differences in the estimates can be observed.

but also that there are quantitative differences, plus an apparent lack of differentiation in the northern Barents Sea between the Stappen High and areas farther east. However, due to the lack of well data points in that direction, uncertainties on the parabolic gridding have been also seen (Fig. 15). In some areas discrepancies up to ~200–600 m are observed due to uncertainties and differences in how the methods are estimating net erosion (Fig. 16), based on the availability of input data.

Net apparent erosion “alignment uncertainty” estimates for each of the wells are listed in Table 3. The average uncertainty is 126 m, with a maximum of 300 m. This uncertainty is related to the similarity of the lithologies between the reference area wells and the wells in the study area. In particular, uncertainties related to vertical and lateral facies variations in the Cretaceous shales and the degree of disequilibrium prior to the uplift and erosion. The shale compaction method depends on the assumption that the state of compaction has not been changed since the uplift and erosion had started. Furthermore, the velocity was not altered since that time. The same assumption applies to the Triassic sandstones as it will create a bias on the uplift estimates. Thus, the net erosion uncertainties have been minimized using the best possible reference wells from the closest areas (Norwegian and North Sea) where no uplift and a similar geology are present. Another uncertainty in the net erosion estimates could be related to measurement errors such as the quality of the well log data and the accuracy of the sonic log as a measurement of the velocity. Another source of uncertainty lies in the choice of zero uplift reference wells and (the slope of the) base lines. This would come as a change of the absolute values and will not change the shape of the net apparent erosion map.

By combining the net erosion estimates with sub-crop and truncational events interpreted in the regional seismic profiles A-A′ and B-B′, accuracy was optimized and the areal extent of net apparent erosion map was better constrained. The main reflectors that have been interpreted in Fig. 2, were identified from well log data ranging from the seabed to the Permian. Major sub-vertical faults cutting through the Mesozoic stratigraphy define the main tectonic activity. At between 270 and 400 ms, an erosional surface is observed and is interpreted as the Upper Regional Unconformity (URU, Fig. 2). The Cenozoic strata below the URU prograde towards the south-southeast. On the southeast of the Finnmark Platform an uplifted area of Cenozoic strata is observed. The lowest level affected by the uplift is approximately at 260 ms. The erosional surface can also be identified from the erosional contact that exists between Cenozoic strata and Mesozoic-Paleozoic strata. Mesozoic and Paleozoic strata were deposited on basement and thus develop a steep inclination towards the center of the Finnmark Platform (eastern part of B-B′ cross section, Fig. 2).

On the regional profile A-A′ (Fig. 3) the interpreted reflectors range from the seabed to the Basement. To the east, the URU is observed at 150 ms whereas along the western margin the unconformity can be observed at depths ~700 ms. On the Loppa High missing sections of a Paleogene to Carboniferous strata can be observed. The sedimentary successions on the eastern side of the Loppa High becomes thinner away from this geological structure towards the east. The fault zone variation between the Finnmark Platform and the Sørvestsnaget Basin indicates basin extension and larger accommodation space being created for deposited sediments in the Sørvestsnaget Basin. On the flanks of the Loppa High the thickening of the sedimentary succession suggests basin opening/extension and more accommodation space for deposition (Fig. 3).

6. Conclusions

Net apparent erosion has been estimated in 28 wells in the southwestern Barents Sea (Table 3) and a computer contoured map (Fig. 15) shows two main regional trends of erosional pattern; an increasing amount of erosion towards the north and a sharp decrease of erosion westwards of the hinge zone into the western

Table 2
Normal Compaction Trend (baselines) for the Cretaceous shale and Lower Jurassic-Triassic units in the southwestern Barents Sea.

Cretaceous Shale		L.Jurassic-Triassic	
Velocity (Vsh, m/s)	Depth (m)	Velocity (Vsh, m/s)	Depth (m)
1098.154	0	1543.154	0
1099.289	1.313	1549.06	6.833
1099.289	1.313	1549.06	6.833
1103.679	6.392	1551.799	10.002
1103.679	6.392	1551.799	10.002
1106.158	9.261	1556.995	15.545
1106.158	9.261	1556.995	15.545
1106.799	10.002	1561.175	20.004
1106.799	10.002	1561.175	20.004
1108.015	11.299	1570.023	29.443
1108.015	11.299	1570.023	29.443
1116.175	20.004	1570.551	30.006
1116.175	20.004	1570.551	30.006
1121.043	25.197	1571.906	31.452
1121.043	25.197	1571.906	31.452
1125.551	30.006	1579.927	40.008
1125.551	30.006	1579.927	40.008
1134.071	39.095	1583.051	43.341
1134.071	39.095	1583.051	43.341
1134.927	40.008	1589.302	50.01
1134.927	40.008	1589.302	50.01
1137.124	42.352	1596.079	57.239
1137.124	42.352	1596.079	57.239
1144.302	50.01	1598.678	60.012
1144.302	50.01	1598.678	60.012
1147.099	52.993	1605.351	67.142
1147.099	52.993	1605.351	67.142
1153.678	60.012	1608.039	70.014
1153.678	60.012	1608.039	70.014
1160.112	66.887	1609.06	71.123
1160.112	66.887	1609.06	71.123
1163.039	70.014	1617.246	80.016
1163.039	70.014	1617.246	80.016
1170.569	78.194	1621.764	84.924

The remaining part of this large table is enclosed as “Appendix A. Supplementary data”.

Barents Sea.

A clear empirical relationship between compaction, as measured by velocity, and the maximum depth of burial of the rocks can be obtained. From theory and empirical observation, rocks are known to become more compact as a consequence of burial and effective vertical stress. The state of compaction of an uplifted and eroded rock sequence can therefore be used to indicate the amount of erosion. Sonic velocity values from the studied wells show that general velocity-depth trends develop as a function of shale and sand compaction processes, lithology, burial depth history and compaction disequilibrium.

It is still not known whether there was compaction disequilibrium in the Barents Sea during the onset of the uplift and erosion. In this study, it is suggested, for the first time, that the Cretaceous shales were in a situation of a compaction disequilibrium, similar to that seen in the Haltenbanken area, Norwegian Sea. Our aim was to study the compaction and acquire information about the maximum burial depth. However, the amount of the compaction disequilibrium is uncertain and the results must be regarded in this light.

In this study, the calculated net erosion estimates are based from an assumption that the NCS was flat prior to the Quaternary glacial erosions that created the present day seabed relief. In the references area, a 100 m pre-glacial water depth is assumed, which means that the flat area was 100 m deeper than the present day. In the southwestern Barents Sea, it is assumed that this had been at 0 m. These different values of the pre-glacial water depth could change, but these values were not the primary goal of this study. The degree of uncertainty is not significant and adjustments to pre-glacial water depth are only likely to comprise a few tens of meters.

Based on the available well log data, a new NCT model for the southwestern Barents Sea was developed and a net apparent erosion map was constructed. In this new “Dikte NCT model” (Fig. 10, Table 2), the calibrated baselines for the southwestern Barents Sea match the Cretaceous shales in the reference wells and also the Lower Jurassic-Triassic units which represent mixed sand-shale lithology deposited in a coastal plain to shallow marine

Table 3
Apparent net erosion estimates for the studied southwestern Barents Sea wells. For the location of the wells see Fig. 6.

X coordinates	Y coordinates	Net erosion (m)	Uncertainty (±m)	Well name
429692	7869590	1800	300	7019/1-1
390813	7922856	1000	50	7117/9-1
437872	7922575	1750	100	7119-7-1
475817	7980020	1750	100	7120/1-1 R2
491170	7890289	1600	50	7120/12-1
492969	7891571	1600	50	7120/12-2
481924	7987306	1750	150	7120/2-1
489425	7932810	1700	200	7120/9-2
514307	7944422	1650	100	7121/5-1
523051	7952738	1750	100	7121/5-2
523421	7935227	1700	100	7121/5-3
525525	7906075	1650	100	7121/9-1
556833	7985596	1600	200	7122/2-1
632001	7966518	1400	50	7124/3-1
641392	7943214	1400	100	7125/4-2
749765	7952606	1450	150	7128/4-1
775927	7953278	1500	100	7128/6-1
348693	7996429	361	–	7216/11-1 S
477634	8044086	1750	100	7220/8-1
550640	7997835	1600	200	7222/11-1 T2
612059	8024028	1600	100	7224/7-1
744329	8099458	2250	100	7228/2-1 S
759926	8050128	2000	100	7228/9-1 S
793702	8034371	1700	200	7229/11-1
355518	8164236	800	100	7316/5-1
502403	8148910	2500	200	7321/7-1
513312	8138308	2200	100	7321/8-1
607068	8121933	2100	200	7324/10-1

environment. The new "Dikte NCT model" corresponds to a better representative for the younger shale stratigraphic intervals and can address greater depths (e.g. within the Triassic) compared with other published compactions trends.

In the calibration step, comparing the baselines in the south-western Barents Sea and the reference areas, it was concluded that it is not correct only to determine a baseline based on the age of sand-dominated rock. The depositional environment must also be considered. Similar baselines can be obtained where we have similar lithofacies and depositional environments. The new baselines match for strata from coastal environments and not (for example) "desert" environments typical of the North Sea. This study also reveals that general baselines for shale, sandstone and other lithologies (e.g. carbonates, see Fig. 14) can be generated using velocity data from well logs following the suggested work flow for establishing a NCT model (Fig. 9).

Taking into account uncertainties related with the well data and the NCT model assumptions, the quality of this work with compaction is solid and the shape of the map is reliable. The work process is mainly based on an interaction of single estimates and map displays, where at the end a regionally consistent multi-well interpretation of net apparent erosion map is calculated. The absolute values of the net erosion estimates are critically dependent on the calibration to the reference wells and the gradient of the NCTs. Different net erosion estimates from other studies illustrate the uncertainties between different methods (Fig. 16).

The well log based NCT model can be calibrated to other velocity data such as interval velocities in maps and seismic profiles from regional depth conversion. This can be used to estimate net erosion in undrilled areas. This can be done to support the mapping of net erosion from our well study, or to continue the mapping of net erosion into areas that have not yet been drilled. This also reveals that this NCT model that was constrained can be used for accurate velocity analysis such as seismic inversion and depth conversion of seismic data, pore pressure prediction, or basin and petroleum systems modelling. Basin modelling could be undertaken along the seismic profiles based on the observed maturity, vitrinite reflectance and present-day temperature measurements, taking into account the variability of the heat flow, which has been changed through time and the maximum burial depth.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.marpetgeo.2017.09.019.

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Article II

Estimation of net apparent erosion in the SW Barents Sea by applying velocity inversion analysis.

Dimitrios Ktenas, Ivar Meisingset, Erik Henriksen and Jesper Kresten Nielsen

In press, Petroleum Geoscience

Article III

The effects of uplift and erosion on the petroleum systems in the southwestern Barents Sea: Insights from seismic data and petroleum systems modelling

Dimitrios Ktenas, Jesper Kresten Nielsen, Erik Henriksen, Ivar Meisingset and Oliver Schenk

In preparation

APPENDIX

Conferenses, workshops and meetings

Oral presentations:

- Dimitrios Ktenas, 2017. Quantification of the magnitude of net erosion in the southwestern Barents Sea using sonic velocities and compaction trends in shales and sandstones. First Geo seminar, Oslo, Norway, 5 December.
- Dimitrios Ktenas and Erik Henriksen, 2016. Quantification of the magnitude of net apparent erosion in the southwestern Barents Sea using sonic velocities and compaction trends in shales and sandstones. Uplift and Erosion workshop, ARCEx, Tromsø, Norway, 26 October.
- Dimitrios Ktenas, 2016. Estimation of net apparent erosion in the SW Barents Sea by using compaction trends and sonic logs. 4th Annual Workshop of Glaciated North Atlantic Margins (GLANAM), Coleraine, Northern Ireland, 6-10 June.
- Dimitrios Ktenas, 2015. Quantification of magnitude of erosion in the SW Barents Sea using sonic velocities - First results. 3rd Annual Workshop of Glaciated North Atlantic Margins (GLANAM), Longyearbyen, Svalbard, 12-19 June.
- Dimitrios Ktenas, 2014. Quantification and timing of uplift and erosion in the SW Barents Sea– Implications for hydrocarbon exploration. 2nd Annual Workshop of Glaciated North Atlantic Margins (GLANAM), Durham, UK, 12-15 September.
- Dimitrios Ktenas, 2014. Quantification and timing of uplift and erosion in the SW Barents Sea-Implications for hydrocarbon exploration. AMGG workshop, Tromsø, Norway, 12 June.

Poster presentations:

- Dimitrios Ktenas, Jesper Kresten Nielsen, Erik Henriksen and Ivar Meisingset, 2019. Assesment of the Golden Zone for the Norwegian Barents Sea through erossion estimations and petroleum sysntems modelling. Celebrating the life of Chris Cornford (1948-2017): Petroleum Systems Analysis 'Science or Art?', The Geological Society (Burlington House), London, UK, 24-25 April.
- Dimitrios Ktenas, Erik Henriksen, Ivar Meisingset, Jesper Kresten Nielsen and Karin Andreassen, 2016. Quantification of the magnitude of net erosion in the SW

Barents Sea using sonic velocities and compaction trends in shales and sandstones. AGU Fall meeting, San Francisco, 12-16 December.

- Dimitrios Ktenas, Erik Henriksen, Jesper Kresten Nielsen, Tommy Samuelsberg and Karin Andreassen, 2015. Uplift and Erosion in the SW Barents Sea-The effects on the Petroleum Systems. 3P Arctic: The Polar Petroleum Potential Conference and Exhibition, American Association of Petroleum Geologists (AAPG), Stavanger, Norway, September 29-1 October.
- Jesper Kresten Nielsen, Dimitrios Ktenas, Erik Henriksen, Dorthe Holm, Evangelos Kaikas, Lajos Samu and Tommy Samuelsberg, 2015. Impact of Ice ages and tectonic activity on petroleum systems on the western Barents Sea. 3P Arctic: The Polar Petroleum Potential Conference and Exhibition, American Association of Petroleum Geologists (AAPG). Stavanger, Norway, September 29-1 October.
- Dimitrios Ktenas, Erik Henriksen, Jesper Kresten Nielsen and Karin Andreassen, 2015. Quantification and timing of uplift and erosion in the SW Barents Sea – Implications for hydrocarbon exploration. GLANAM (Glaciated North Atlantic Margins) Mid-Term Review Meeting, Copenhagen, Denmark, February 19-20.
- Dimitrios Ktenas, Erik Henriksen, Jesper Kresten Nielsen, Tommy Samuelsberg, Karin Andreassen and Mike Bentley, 2014. Uplift and Erosion in the SW Barents Sea – The effects on the Petroleum Systems. Arctic Conference Days, Norsk Geologisk Forening (NGF), Tromsø, Norway, 2-6 June.

Scientific cruises:

R/V Helmer Hanssen, Greenland Sea area and Vestnessa Ridge, offshore NW Svalbard, June 2014. 3D seismic data acquisition and sediment coring.

List of other articles involved:

- Nielsen, J.K., Schenk, O., Ktenas, D., Henriksen E., Joppen, T., Koronfu, N., Ma, F. (in prep.). Ice and its potential impact on temperature and pressure of petroleum systems: examples from the Norwegian Barents Sea.
- Henriksen, E., Ktenas, D. and Nielsen, J.K. (in prep.). Finnmark Platform – Tectonostratigraphic elements, geological development and hydrocarbon potential.