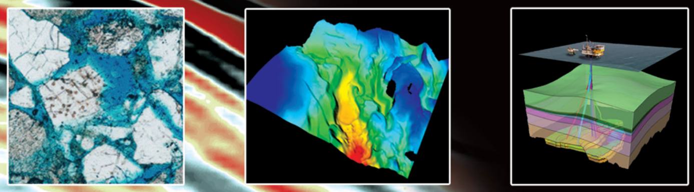

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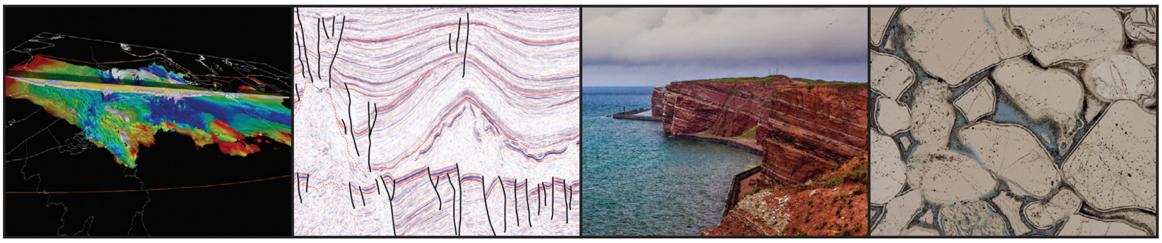
7-9 September 2016

Burlington House, Piccadilly, London



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Mesozoic Resource Potential in the Southern Permian Basin

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Mesozoic Resource Potential in the South Permian Basin

Geological Society of London, Petroleum Group
Burlington House, London, 7-9 September 2016

On behalf of the convenors, I would like to welcome you to this conference, which has been organised by the Petroleum Group of the Geological Society. In this booklet you will find the programme and abstracts for all of the talks and poster presentations given over the two days of the conference.

The Petroleum Group consists of a committee of experienced industry professionals and academics with a desire to promote education in energy matters and to organise 5 to 6 high quality conferences per year. For the past five years I have worked in different hydrocarbon exploration projects across the Southern Permian Basin. Although the largest historic volumes sit within the Palaeozoic interval, exciting new gas and oil discoveries have also been made within the Mesozoic. As the basin reaches its mature stages of conventional hydrocarbon exploitation I felt that there is a need to maximise our understanding of the post-Permian geology at all scales. It therefore seemed an exciting and obvious topic for a conference; a prolific hydrocarbon basin with a less-understood but economically attractive Mesozoic sequence and no previous specific meeting.

I personally, and the rest of the convening committee, see real excitement in gathering a group of interested colleagues across Europe to discuss the geological secrets of the Triassic, Jurassic and Cretaceous intervals. In particular, there is a significant opportunity to increase cross-border collaboration between the UK, Netherlands, Germany, Denmark and Poland. This can be absolutely key in finding further conventional hydrocarbon accumulations, but even more importantly can serve as the foundation for an increased interest in geothermal developments and unconventional exploration.

On behalf of the Petroleum Group Committee, I would like to thank and acknowledge my fellow convenors (below) for putting this conference together, their ideas on how to maximise its impact and for chairing the sessions. Our thanks also go to the Geological Society staff for their help and organisation. Our appreciation goes to the conference sponsors, Shell and EBN who made this meeting possible and, in addition, to ongoing corporate sponsors BP and Statoil. I must acknowledge the generosity and help of Howard Johnson (Imperial College), James Maynard (Exxon Mobil), Martin Wells (BP) and Gary Hampson (Imperial College) for giving up their personal time to organise our one day field trip. Finally, a big thank you to keynote volunteers and everyone who offered presentations and posters. We hope that the conference will be interesting, that you will learn something new, share ideas with professionals from different areas and, finally, enjoy the hospitality and surroundings of historic Burlington House.

Ben Kilhams

Petroleum Group Convenor, Geological Society of London

Convenors and session Chairs

Ben Kilhams, Shell
Peter Kukla, RWTH Aachen University
Stanislaw Mazur, Getech UK
Tom McKie, Shell
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Kees v. Ojik, Argo Geological Consultants/Engie
Robert Schöner, LBEG

Reference:
Abstracts of '*Mesozoic Resource Potential in the South Permian Basin'*, Petroleum Group of the Geologicl Society of London, Burlington House, London, UK, 7-9 September 2016

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Oral Presentation Abstracts
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Thursday 8 September

Session One

Mesozoic Resource Opportunities

Keynote Speaker: The Central European Basin system and its petroleum systems

Ralf Littke
Institute of Geology and Geochemistry of Petroleum and Coal, EMR Group, RWTH Aachen University

The differentiation between basins, highs and platforms in the Central European Basin system (CEBS) developed in response to global plate movement and responding changes in lithosphere structure and stress field (Maystrenko et al. 2008; Cloetingh & Ziegler 2007). The main tectonic events that affected the Netherlands, southern North Sea and NW-Germany comprise the Caledonian and Variscan orogenies due to amalgamation of Pangaea during the Paleozoic, Mesozoic rifting accompanying the breakup of Pangaea, the Alpine orogeny induced by the collision of Europe and Africa during the Upper Cretaceous/Lower Tertiary, and the Oligocene to recent rifting of the Rhine Graben system (van Wees et al., 2000; de Jager 2007; Senglaub et al., 2006). As a result multiple phases of uplift and basin inversion occurred in different parts of the study area (Littke et al., 2008).

Sedimentary basins in the CEBS contain numerous known hydrocarbon accumulations and represent potential targets for future shale gas/shale oil exploration due to the presence of Lower Cretaceous lacustrine and Jurassic (Posidonia Shale) organic-rich marlstones and shales as well as various Carboniferous black shales. The Lower Jurassic Posidonia Shale is the most important source rock for conventional oil exploration in this area, but is also one of the most promising candidates for unconventional shale gas/oil exploration. With respect to conventional hydrocarbon accumulations, a variety of compositions from dry gas to light and heavy oil exists. Also, gas accumulations differ widely with respect to hydrocarbon gas, molecular nitrogen and carbon dioxide contents. These compositional differences mainly reflect burial and temperature history, but also the presence of deep reaching faults and surface near degradation processes.

The Posidonia Shale is an excellent petroleum source rock which exists within the southern CEBS, i.e. the Lower Saxony basin, at maturity levels ranging from immature to dry gas window, i.e. vitrinite reflectance reaches values between less than 0.5 and greater than 5%. This fact makes this basin a natural laboratory in which the effects of temperature on petroleum generation can be ideally studied. For example mass balances on petroleum generation and expulsion have been developed, but also experimental studies on evolution of petrophysical properties (Ghanizadeh et al., 2014).

Numerous basin modeling studies have been published on this area in order to develop a quantitative understanding of burial, uplift, temperature and petroleum generation history, comprising mainly 1D and 2D modeling approaches. Recently high resolution 3D modeling studies were developed on specific sub-basins, allowing to model also petroleum migration and accumulation, but also porosity and permeability evolution and sorption over large areas (Bruns et al., 2016).

Quantification of the total storage capacity, including sorbed gas and free gas is a prerequisite for estimations of resource potential and technically recoverable amounts of gas at given reservoir conditions. In early exploration phases, 3D basin modelling with integrated sorption modules together with the simulation of the burial history, gas generation/expulsion and consideration of organic matter-hosted porosity is a valuable tool to reduce the exploration risk. In addition, an accurate reconstruction of the source rock maturation through geologic time and within the different basins is crucial for the assessment of petroleum generation and storage. First results on this new type of modelling are presented and discussed. At present day, the Posidonia Shale and the Wealden shales are undersaturated in thermally generated methane regarding the bulk adsorption capacity and the amount of gas which is actually present in an adsorbed phase. For the Posidonia Shale, the reduction in adsorbed gas content was caused by deep burial and high temperatures, leading to a reduction in adsorption capacity and subsequent desorption of gas volumes. For the Wealden shales, which did not reach burial depths similar to those of the Posidonia Shale, a reduction of adsorption capacity and hence adsorbed gas contents was caused by uplift during the Late Cretaceous basin inversion.*

***References**, p. 122*

NOTES

The economic importance of the Mesozoic in the Southern Permian Basin; paradigm shift in Mesozoic exploration: from the highs to the lows

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[2]*TNO, Geological Survey of the Netherlands, Utrecht, the Netherlands*

The Southern Permian Basin (SPB) is generally considered a mature basin in terms of oil and gas exploration. Although this is true for large parts of the basin, other parts remain underexplored. This can occur at a regional level, for instance in the case of the German offshore, but also by overlooking the potential of stratigraphic intervals.

The main play in the SPB is the Permian Rotliegend gas play. Runner up is the Mesozoic Triassic play, which accounts for a significant amount of reserves in the Dutch sector and about a quarter of production (Fig. 1). Other important Mesozoic reservoirs can be found in the Upper Jurassic – Lower Cretaceous clastic sedimentary sequence and Upper Cretaceous Chalk deposits, which are host to a prolific oil play in Denmark that is now experiencing a revival in the Dutch sector. Prospect portfolio's show a similar spread over the plays (Fig. 2). Mesozoic targets account for approximately 40% of the remaining exploration potential.

In the Netherlands the most prolific Triassic reservoir is the Middle Bunter sandstone, which is developed as a sheet sand. Gas is trapped in tilted fault blocks, turtle back structures, dip closures against salt walls or truncation traps. In general the reservoir section is relatively easy to identify on seismic if the structural configuration is not too complex. Additional Triassic reservoirs do exist, but their potential is often overlooked. An example of such a reservoir is the informally named Solling Fat Sand which was first encountered in 1993, when a Triassic Volpriehausen prospect was drilled in the Dutch offshore L9 block. Before reaching the target a surprisingly thick gas-bearing sandstone sequence was encountered not seen or recognized before. It was concluded that this sandstone is of Triassic age, now informally called the "Solling Fat Sand" and that it is only locally developed in incipient fault related salt withdrawal depressions (de Jager, 2012).

In the Netherlands, geothermal exploration and production is booming. Since 2006 13 doublets have been realized, 12 of which are in use for heating greenhouses. The target reservoirs of the geothermal wells are the same as the ones in oil and gas exploration and production; Upper Jurassic – Lower Cretaceous fluvial and marine sandstones, Triassic and Rotliegend sandstones and Dinantian carbonates. Data acquired in geothermal projects may therefore be of benefit to the E&P industry. An example is found in the West Netherlands Basin where the target reservoirs are Lower Cretaceous shallow marine sandstones and Upper Jurassic to Lower Cretaceous fluvial sandstones. In contrast with what is common in the oil and gas industry geothermal operators typically target structural lows. Wells drilled into these lows show that the amount of sandstones in these graben fills, is higher than on the horsts, helping de-risk oil and gas exploration in such reservoirs and settings. Another example of unexpected reservoir presence can be found in the Dutch northern offshore where well B13-02 found an anomalous thick Upper Jurassic sand in a depocentre created by a salt diapir related growth fault.

Stratigraphic traps are also underexplored. Many stratigraphic traps have been drilled in the Mesozoic in the UK, with a number of obvious successes such as the Buzzard field. 6% Of the fields and discoveries in the UK are in stratigraphic traps and that another 12% are in combination traps (DECC, 2014). In Germany, Netherlands and Denmark very few stratigraphic traps have been tested and it is not unlikely that many stratigraphic traps remain undrilled. Seismic studies show locally overthickened sections at various stratigraphic levels including the Triassic, Jurassic and Lower Cretaceous. Detailed well re-interpretation, seismic and geologic modelling may help de-risk reservoir development in depressions and stratigraphic trapping through shale-out.

In summary one can state that Mesozoic plays have been and are of significant economic importance. Oil and gas production figures and discovery rates clearly show that these plays are currently in a creaming mode; the relatively “easy” to find prospects in traditional plays have been harvested to a large extent. New insights suggest that significant potential remains in non-traditional traps and plays. As the examples of the Solling Fat Sand, the fluvial sandstones in the geothermal doublets and the Upper Jurassic overthickened wedge show, new opportunities may exist in lows with good sand development, combined with stratigraphic trapping.

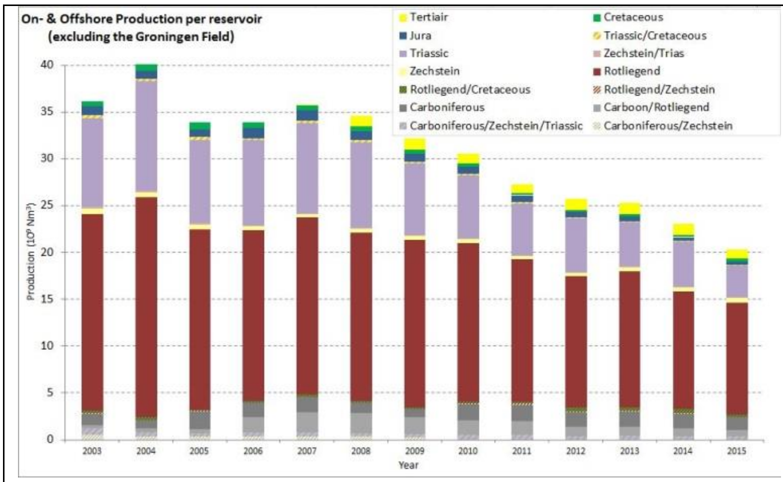

Fig. 1: Dutch yearly offshore gas production volumes by reservoir. (based on MEA 2015)

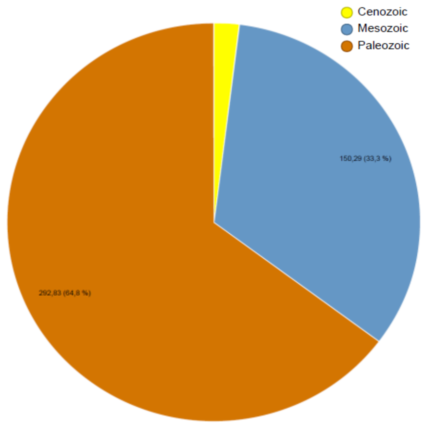

Fig. 2: Prospective risked resources in the Dutch on- and offshore (BCM Groningen equivalent) (source: EBN)

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Mesozoic sandstone reservoirs in NE Germany: From oil and gas exploration towards geothermal use and underground gas storage

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Oil and gas exploration in north-eastern Germany started in the 1950s. Different Late Palaeozoic (Devonian to Permian) and Mesozoic source and reservoir rocks have been investigated by numerous wells and seismic surveys until 1990. 38 small oil accumulations often accompanied by gas occurrences have been found in Stassfurt carbonates of the Zechstein in depths between 2000 m and 3000 m (Müller et al. 1993). The largest deposit with an area of 3 km^2, total oil in place of 4.25 million tons and total gas in place of 830 million m^3 was discovered at Lütow on the Baltic Sea island of Usedom in 1965 (Rasch et al. 1993). The total oil production between 1961 and 2015 was about 3.3 million tons. The gas production in the same period reached approximately 1.4 billion m^3. Besides, a large natural gas deposit with relatively low CH_4 content was discovered in Rotliegend sandstones near Salzwedel (Altmark) that produced more than 210 billion m^3 since 1969 (LBEG 2015).

The geological and geophysical data were the basis to characterize the evolution of the North German Basin (NGB), which contains up to 10 km of Permian to Cenozoic deposits in the eastern part, and the geothermal potential of Mesozoic sandstones (e.g. Feldrappe et al. 2008, Franz & Wolfgramm 2008). Best reservoirs for geothermal uses in NE Germany include the sandstones of the Rhaetian/Liassic aquifer complex, as well as sandstones of the Middle Buntsandstein, Middle Jurassic and Lower Cretaceous. Besides, the Rotliegend sandstones and the Schilfsandstein of the Middle Keuperian show locally good reservoir properties.

With only a few local exceptions, the Rhaetian/Liassic aquifer complex is distributed across the whole of the eastern part of the North German Basin. Sandstone aquifers in the Rhaetian are found in the Postera, Contorta and Triletes beds; they are often >10 m thick. Horizons used for geothermal heat production in Mecklenburg-Western Pomerania are the sandstones of the Upper Postera beds and the Contorta beds, respectively. The poorly cemented sandstones have porosities of 25-30 %, permeabilities of 500-1000 mD, and productivities of 50-150 m^3/h/MPa (Wolfgramm et al. 2008, 2009, Obst et al. 2009). The properties of the Liassic sandstones (Hettangian, Sinemurian, Pliensbachian) are comparable to those of the Rhaetian. The Middle Jurassic sediments in the North German Basin occur not basin-wide. Their distribution and thickness is influenced by differentiation processes and local salt movements. Suitable sandstones have been verified in the Aalenian as well as in the younger strata of the Bajocian/Bathonian and the Lower Callovian.

The Aalenian sandstones form aquifers with outstanding storage properties with calculated and testified productivities of 150-300 m^3/h/MPa. The Lower Cretaceous sandstones as well show porosities of around 30 % (25-37 %) with permeabilities averaging 250 mD, which create productivities of >100 m^3/h/MPa. The aquifers of the Middle Buntsandstein show good reservoir properties. Especially at the northern edge of the NGB, they have porosities of generally >20 % (Obst & Brandes 2011). Analogies with the productivities of the geothermal energy wells in Stralsund and Karlshagen indicate that the Detfurth Sandstone for example could have productivities of about 100 m^3/h/MPa. The Schilfsandstein (in particular the channel facies) of the Middle Keuperian, as well as the Rotliegend sandstones, could only be exploited locally as geothermal aquifers.

In the 1980s, 28 wells were drilled at 11 project locations in Mecklenburg-Western Pomerania and Brandenburg with the aim to use thermal waters from deep saline aquifers for district heating systems (Schneider 2007). The Geothermal Heating Plant in Waren started operations in 1984 as the first of its kind in Germany. It proves that a hydrothermal doublet system operates successfully even after 30 years. Starting in 1988 Germany's second Geothermal

Heating Plant in Neubrandenburg produced geothermal energy using the usual doublet technology for ten years. After conversion to store waste heat from a Combined Cycle Gas Turbine (CCGT) plant, it is now the world's largest heat storage system with a capacity of 3.0 to 3.5 MW (Obst & Wolfgramm 2010). The Neustadt-Glewe Geothermal Heating Plant, which has been operated since 1995, was converted in 2003 to a combined heat and power plant by installing an additional ORC system. With its installed electrical output of 230 kW, it could be seen as a pilot plant for the low enthalpy sector in Germany. Although the geothermal electricity production stopped in 2010, it demonstrated that an installation of this type could also be operated even at relatively low aquifer temperatures (Stober et al. 2013).

Data and information on the deep subsurface geology in Germany of interest for geothermal utilisation are provided by GeotIS, the geothermal information system (Agemar et al. 2014). They are available in the internet at www.geotis.de. The system provides, and continuously adds, geoscientific basic data as well as the latest findings and results. Users can choose from two modules: geothermal installations and geothermal potentials.

The Mesozoic reservoirs, which are suitable for geothermal use, are also in the focus of natural gas storage projects (Obst 2008). Potential reservoir (sandstones) and cap rocks (claystones and salt layers) were evaluated in the eastern part of the NGB within the national project Storage Catalogue of Germany (Bebiolka et al. 2010, Brandes & Obst 2010). First results suggest that the reservoir rock of the Middle Buntsandstein and the associated cap rock of the Upper Buntsandstein have storage potential at the northern margin of the NGB. The potential areas with thick sandstone reservoirs of Rhaetian/Liassic and associated barrier horizon of Toarcian age are only developed in the south-eastern part of the basin. Detailed seismic analyses, however, showed that the integrity of the cap rock is limited due to intense faulting and segmentation above the salt structure, e.g. near Hinrichshagen/Waren (Engelmann et al. 2012).*

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Mesozoic deep geothermal reservoirs of the North German Basin and their resource potential

Matthias Franz[1], Markus Wolfgramm[2], Gregor Barth[3], Kerstin Nowak[2], Jens Zimmermann[4],
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[2]*Geothermie Neubrandenburg GmbH, Neubrandenburg (Germany)*
[3] *Federal Institute for Geosciences and Natural Resources, Berlin (Germany)*
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The North German Basin (NGB), the Molasse Basin and the Upper Rhine Valley are the three large geotectonic units of Germany where deep geothermal reservoirs are under production. Among these, the NGB is commonly identified as the unit with the largest potential of geothermal energy. In the NGB, the exploration of deep geothermal reservoirs started in the early 1980ies with pilot projects of the former GDR. Some of these pilot projects proved successful and production started in Waren in the year 1984. Since, municipal energy suppliers of Neubrandenburg, Neustadt-Glewe, Waren and elsewhere are successfully exploiting geothermal resources, mainly from Rhaetian reservoirs. At Neustadt-Glewe for example, the so-called Contorta Sandstone, situated at about 2250 m depth, is under production since 1994 with an average annual production rate of about 17.7 GWh/a. From the up to 50 m thick sandstone reservoir, 97°C hot thermal waters are used for the production of heat in winters and electricity in summers.

Based on more than 30 years of experience in geothermal heat production, a potential deep geothermal reservoir should have: >20 m thickness, >20% porosity and >500mD permeability. However, in the past a number of projects unfortunately failed because thicknesses and/or permeabilities were unexpectedly to low. This demonstrated that the exploration risk at a certain locality in the NGB is still considerable high.

The deep geothermal resources of the NGB are commonly subdivided into petrothermal resources, mainly of Palaeozoic rocks, and hydrothermal resources of the Mesozoic. Intense exploration has identified numerous sandstone horizons that are grouped into the following Mesozoic deep geothermal reservoirs: (1) Lower Cretaceous, (2) Dogger, (3) Liassic, (4) Rhaetian, (5) Schilfsandstein and (6) Middle Buntsandstein (Fig. 1). Apart from principle stratigraphic and petrographic knowledge, detailed knowledge about the spatial distribution of individual reservoirs and their hydraulic properties is still missing.

In order to significantly reduce exploration risks, the six deep geothermal reservoirs of the NGB were and still are under evaluation by the R&D projects *Sandsteinfazies* and *GeoPoNDD*. The evaluation of the Schilfsandstein, Rhaetian and Dogger finished in 2015 (*Sandsteinfazies*); the evaluation of the Middle Buntsandstein, Liassic and Lower Cretaceous started in 2015 and will be finished by the end of 2018 (*GeoPoNDD*).

The **Schilfsandstein** was deposited in fluvio-deltaic to fluvial settings. In contrast to earlier reconstructions of exo-rheic drainage patterns, the Schilfsandstein originates from southern and northern source areas. Fluvial bypass and deposition from these sources to the basin centre advocates for endo-rheic drainage patterns. Subsurface mapping of the Lower and Upper Schilfsandstein show narrow meandering fluvio-deltaic to fluvial channels laterally associated to delta plains and floodplains. Sandy channel fills are on average 19 m (Lower Schilfsandstein) and 18 m thick (Upper Schilfsandstein) with a maximum of 35 m for both. Together with proximal overbank environments, for example crevasse splays, between 8 km and 17 km broad sandy belts were observed for the Lower Schilfsandstein and between 8 km and 12 km broad belts for the Upper Schilfsandstein. The fine to medium grained Schilfsandstein is mainly represented by matrix rich lithic arkoses and feldspathic litharenites. Average permeabilities of channel belts range between 143 mD and 3,058 mD for the Lower Schilfsandstein and between 354 mD and 2191 mD for the Upper Schilfsandstein. Frequent sheet flooding resulted in sheet sands with average permeabilities between 14 mD and 619 mD for the Lower Schilfsandstein and between 5 mD and 190 mD for the Upper Schilfsandstein. Thus, fluvio-deltaic to fluvial channel belts comprise a moderate reservoir potential, whereas the potential of overbank environments is considered low.

The **Rhaetian** reservoirs are subdivided into the terrestrial Postera Sandstone and the fluvio-deltaic Contorta Sandstone. The **Postera Sandstone** was deposited by a distributive fluvial system. Subsurface mapping revealed a distributive network of narrow sandy channels spreading across NE Germany. These channels are laterally associated to pedogenic playa-like overbank environments. Channel fills are on average about 20 m thick, locally thicknesses increase up to 85 m. Channel fills and proximal overbank environments form up to 35 km wide belts of predominating sandy lithology. The fine to medium grained Postera Sandstone is mainly represented by quartzarenites. Average permeabilities of channel belts range between 460 mD and 2,889 mD. Sheetsands, intercalated with playa-like shales, are less than 10 m thick and comprise average permeabilities ranging between 54 mD and 1,417 mD. The **Contorta Sandstone** was deposited by a fluvial-dominated delta. Subsurface mapping shows the successive delta formation resulting from delta progradation and lobe shifting. Sandy fills of distributary channels are on average 20 m thick, locally thicknesses increase up to 75 m. Distributaries and proximal overbank environments form up to 10 km wide sandy belts.

The fine to medium grained Contorta Sandstone is mainly represented by quartzarenites. Average permeabilities of channel belts range between 4 mD and 1,460 mD. Sheetsands, intercalated with delta plain fines, are less than 20 m thick and comprise average permeabilities between 21 mD and 2229 mD. As the channel belt facies of the Postera and Contorta sandstones are already under production at several localities in NE Germany the principal high reservoir potential is demonstrated. In contrast the wide-spread playa-like floodplains and delta plains have only moderate to low reservoir potentials.
The reservoir potential of the **Dogger** is detailed in a separate oral presentation by Zimmermann and co-authors.

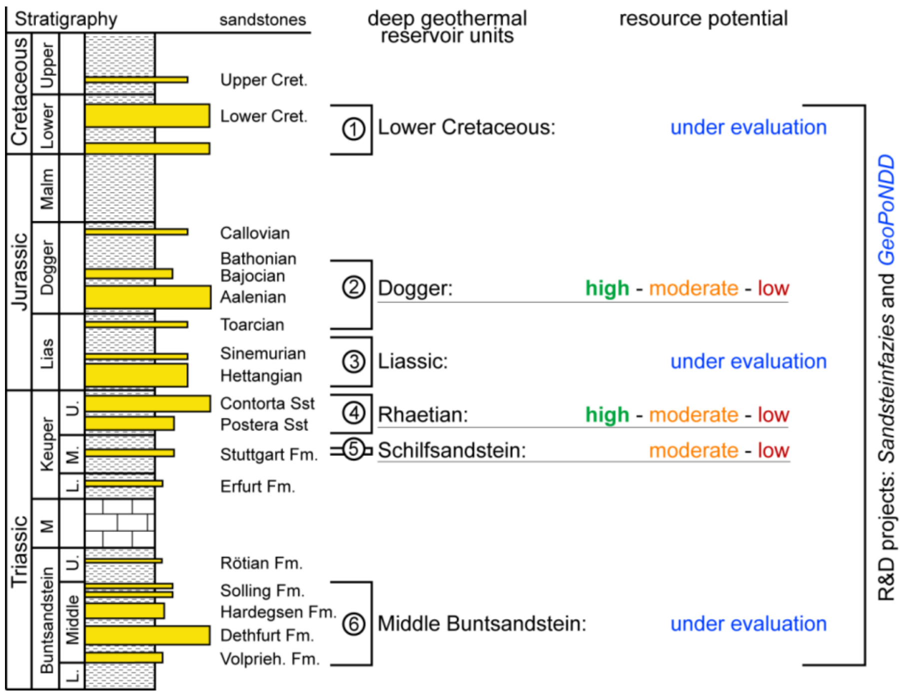

Fig. 1: Mesozoic sandstones and deep geothermal reservoirs of the North German Basin.

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Mesozoic petroleum systems of the northwestern German North Sea (Entenschnabel): A 3D basin and petroleum system modelling study

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To investigate the maturation and petroleum generation of assumed source rock units covering the northwestern German North Sea (Entenschnabel) a 3D basin modelling study has been carried out.

In the German North Sea only one oil field and one gas field were discovered in 1981 and 1974, so far. Source rocks that charged Chalk fields in the neighbouring sectors of the German North Sea are represented by the Upper Jurassic Kimmeridge Clay formation (Bo Member) and the Lower Jurassic Posidonia Shale. The Chalk Group is economically the most important reservoir unit within the Danish North Sea. In the German Central Graben area it is still an open question whether the Chalk Group hosts reservoirs of economic size.

The presented 3D model is a first model including petroleum system elements covering the Entenschnabel area (Fig. 1). The geological components of the 3D model are based on recently compiled maps and structural information of the Entenschnabel [Arfai et al. 2014]. These include thickness and depth maps of 14 prominent stratigraphic horizons as well as locations of faults and salt structures. The model contains Carboniferous, Permian, Mesozoic and Cenozoic sediment units. Accordingly, the main source rocks, such as the Upper Jurassic Kimmeridge Clay, the Posidonia Shale and the Carboniferous coal bearing sediments, and reservoir rocks such as the Rotliegend sandstones and chalk deposits of the Upper Cretaceous-Lower Palaeocene are present in the study area and integrated into the 3D model.

The time from the Late Palaeozoic to Present is characterised by three erosional phases related to large-scale tectonic events incorporated into the model: the Saalian (Late Carboniferous-Early Permian), the Late Kimmerian (Late Jurassic) and the Subhercynian inversion phase during the Late Cretaceous. Additionally, salt movements of salt diapirs and salt pillows are considered within the model. Temperature and maturity data from wells and published data covering the surrounding regions of the German North Sea are used for calibration.

The 3D model reflects the burial history showing major subsidence and sedimentation events during the Late Permian-Early Triassic and the Late Triassic (Keuper) in the area of the present-day German Central Graben. Rapid subsidence occurred during the Late Jurassic. Upper Jurassic shales and minor sands are preserved within the John Graben a structural element within the German Central Graben reaching a maximum thickness of 2200 m.

The modelled thermal and maturity history includes a heat flow peak (88 mW/m²) during the Early Permian reflecting the beginning of graben formation and a second peak value of 65 mW/m² at 156 Ma during the Late Jurassic for the main phase of rifting within the German Central Graben. Heat flow is assumed to have been declining to a present-day value of 55 mW/m². The latter, represents a mean value adopted from publications of surrounding realms of the German Central Graben such as Beha et al. [2008; 52 mW/m²] from the Danish Horn Graben, Abdul Fattah et al. [2012] and Verweij et al. [2011; 55-58 mW/m²] from the northwestern Dutch offshore sector and the southern Dutch Central Graben and by Heim et al. [2013; 55-58 mW/m²] on the Schillgrund High.

First results of the 3D basin and petroleum system modelling indicate that the Upper Jurassic Kimmeridge Clay, a proven source rock in the North Sea Central Graben, started early oil generation during the Late Palaeogene and thus could have served as a source rock for chalk reservoirs in the German Central Graben.

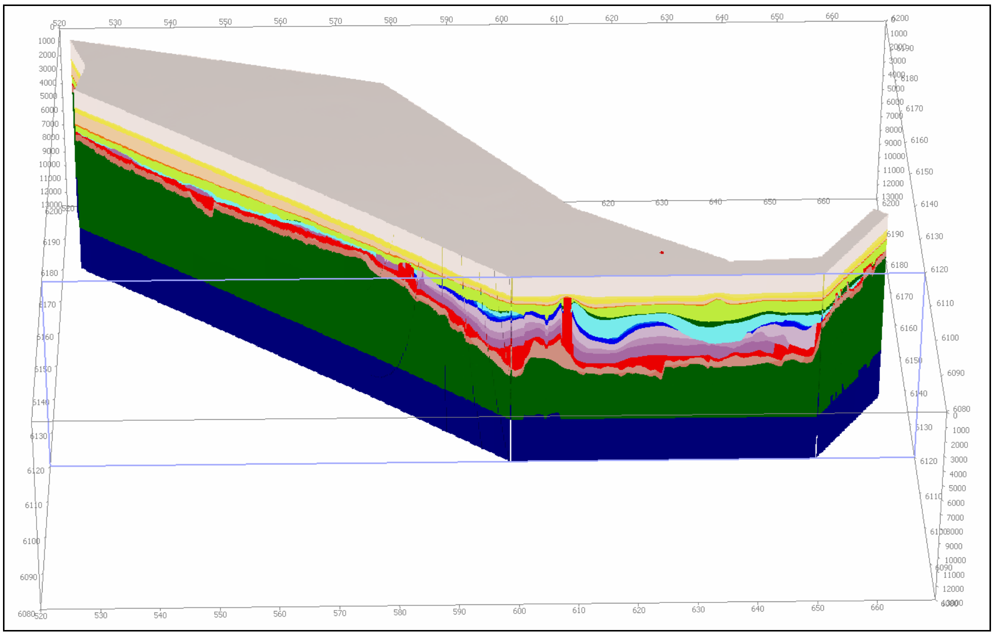

Fig. 1: 3D model Entenschnabel

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Thursday 8 September

Session Two

Tectonic Framework

Keynote Speaker: Mesozoic tectonosedimentary evolution of the Polish Basin - basin subsidence, salt tectonics and inversion

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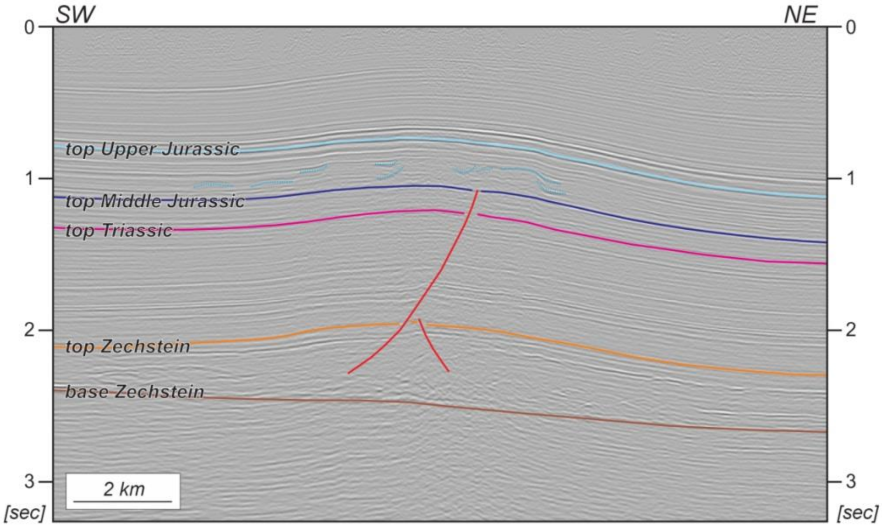
The Permian-Cretaceous Polish Basin belonged to the system of epicontinental depositional basins of Western and Central Europe and was filled with several kilometers of siliciclastics and carbonates. Sedimentary infill of the central and north parts of the basin includes also thick Zechstein (approximately Upper Permian) evaporites at its base that exerted a strong control on its tectonosedimentary evolution. The basin underwent three major pulses of increased subsidence during the Zechstein – Scythian, Oxfordian–Kimmeridgian and early Cenomanian, all of which were superimposed on an exponential thermal subsidence trend, and was fully inverted in the Late Cretaceous – Palaeocene. A wealth of the high-quality seismic data, including recently acquired regional deep seismic survey PolandSPAN, calibrated by deep exploration and research wells allows painting a comprehensive picture of the Polish Basin present-day structure and Mesozoic evolution. Salt started to move already in the latest Early Triassic (deposition of the Buntsandstein), reaching its climax in the Late Trassic when several salt diapirs rose to the surface forming submarine salt extrusions, subsequently covered by younger Triassic and Jurassic sediments. Late Jurassic growth of some of salt pillows was linked to the formation of the Oxfordian carbonate buildups (Figure). Similar buildups also formed within the south part of the basin, devoid of the Zechstein salt.



Oxfordian carbonate buildups developed above salt pillows

Late Creatceous compressional inversion of the Polish Basin was a complex and multi-phase process. Contrary to a model proposed by Nielsen et al. (*Plate-wide stress relaxation explains European Paleocene basin inversion. Nature, 435, 2005*), Late Cretaceous inversion of the Polish Basin could not be treated as a single event followed by deposition within the marginal troughs. Instead, it involved uplift of various basement blocks and compressional reactivation of salt structures. Growth of various inversion-related structures (salt and non-salt) resulted in modifications of the depositional systems characterized by localized thickness variations, development of progressive unconformities etc., the features creating a complex tectonosedimentary record of this basin-wide inversion phase. Strike-slip movements were also involved, including latest Cretaceous – Paleogene wrenching along the Grójec Fault Zone, rooted in deep Palaeozoic – Precambrian basement.

NOTES

Evolution of the Tornquist Fan fault systems along the north-eastern rim of the Southern Permian Basin

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On the basis of numerous 2D seismic lines and, to a lesser extent, borehole data acquired in the course of offshore oil and gas exploration in the southern Baltic Sea, the structural evolution of the north-eastern part of the Southern Permian Basin is characterized and visualized in a 3D model. This is a major goal of research conducted by the USO ("Untergrundmodell Südliche Ostsee") project working group. The USO is a cooperative project between the University of Greifswald and the Geological Survey of the German Federal State Mecklenburg-Western Pomerania, financially supported by Central European Petroleum Ltd. (CEP).

The project area is divided into a western and eastern part relative to the island of Rügen. The structural analysis within the USO East is based on the 2D reflection seismic imaging by the former organization PETROBALTIC (1970s-1980s). These lines were reprocessed in part during the SASO project ("Strukturatlas südliche Ostsee") in the 1990s and more recently by CEP. Additional lithological and geophysical data from on- and offshore wells, especially gamma ray and sonic logs were used for correlation with important seismic reflectors.

Besides modelling of seismic reflectors representing lithological (and stratigraphic) boundaries, major and minor faults in the area between the Tornquist Zone (subdivided into the Sorgenfrei-Tornquist Zone = STZ and the Tornquist-Tesseyre Zone = TTZ) and the TransEuropean Suture Zone (TESZ), named as the Tornquist Fan (Thybo, 2000), are analysed to characterise stress fields that initiated their formation and to evaluate their poly-phase evolution.

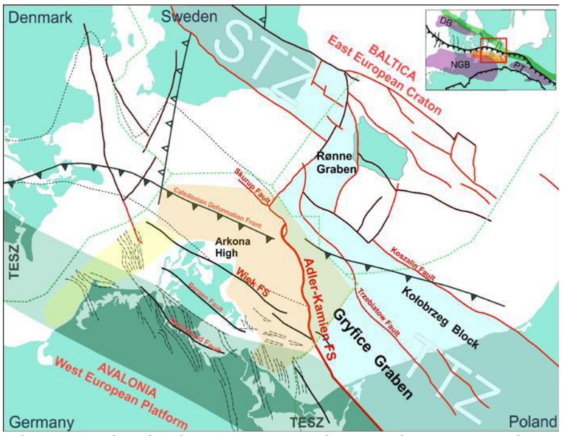

Fig. 1: Major fault systems at the north-eastern rim of the Southern Permian Basin. Working area of USO East is marked in orange and of USO West in yellow (based on Schlüter et al., 1997; Bayer et al., 1999; Krawczyk et al., 2002; Krauss & Mayer, 2004; Scheck-enderoth & Lamarche, 2005).

The software packages "SeisWare™" and MOVE™ (Midland Valley) were used to analyse fault systems of the Tornquist Fan cross the southern Baltic Sea mainly from NW to SE (Fig. 1). They are related to Palaeozoic extensional or compressional movements along the Tornquist Zone (e.g., the Adler-Kamien Fault System) or the TESZ (e.g., the Western-Pomerania Fault system). Formation of horst and graben structures and their structural inversion influenced the development of the Southern Permian Basin and controlled sedimentation processes therein (e.g., in the Gryfice Graben).

Restoration analysis of the NNW-SSE striking Adler-Kamien Fault System (AKFS, Figs. 1,2), which borders the TTZ to the west, suggests that Permian thermal destabilisation triggered subsidence. Continued E–W extension during the Triassic formed not only a large basin system in Central Europe but also minor graben structures like the Gryfice Graben (GG). This is shown by vertical displacements and differences in thickness of predominantly Mesozoic sediments along the AKFS. Compression in the NE–SW direction during the Late Cretaceous led to reactivation of faults and inversion of tectonic structures like the GG.

In contrast, the NW–SE striking Wiek Fault System (WSF; Fig. 2), which was also generated during a Mesozoic extensional phase, experienced transpression during the Late Cretaceous. This resulted in a complex seismic pattern, where normal faults are accompanied by reverse or thrust faults within a narrow zone.*

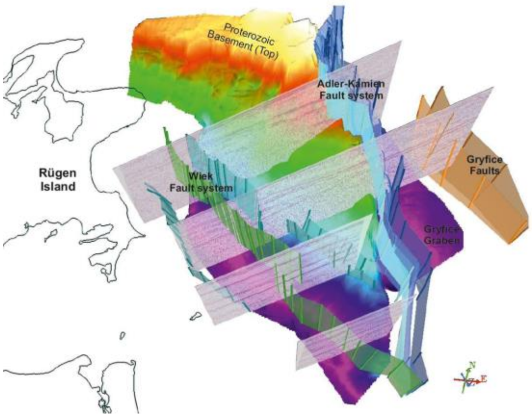

Fig. 2: 3D view of the study area (Gridded horizon: top of Proterozoic, Fault Systems: AKFS (blue), WFS (green) and Gryfice Faults (orange)).

***References, p. 123**

NOTES

Multiple phases of exhumation and inversion in the UK sector of the Southern Permian Basin revealed using AFTA: implications for hydrocarbon prospectivity

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Inversion of the Sole Pit Axis in the UK Southern North Sea has been recognised for many years, together with its importance to the hydrocarbon prospectivity of the region (e.g., Van Hoorn, 1989; Badley et al., 1989), while for many years the adjacent East Midlands Shelf was thought to have undergone modest Mesozoic subsidence and remained largely stable through Cenozoic times (e.g., Cope et al., 1992). Apatite fission track analysis (AFTA) and vitrinite reflectance (VR) data in samples from wells and onshore outcrops have changed this view, showing that a wide area across the offshore basin and the adjacent East Midlands Shelf (onshore and offshore through UK Quadrants 47, 48 and 49) underwent exhumation in the Early Cenozoic (Green, 1989; Green et al., 2001). Integration with sonic velocity data confirms a pattern of Cenozoic exhumation in which around 2 km or more of section has been removed along the Sole Pit Axis since ~60 Ma, with around 1 km removed from the onshore East Midland Shelf. Across the offshore East Midland Shelf, where the Late Cretaceous Chalk is preserved, around 700 metres of section was removed. This removed section must have been deposited after the youngest Chalk was laid down and prior to the onset of exhumation at ~60 Ma. While this interpretation was considered controversial when first mooted, more recent considerations of Cretaceous paleogeography have concluded that geological evidence is entirely compatible with this scenario (Cope, 2006). In some areas we also identify a discrete phase of Neogene exhumation, in which a significant proportion of the total Cenozoic exhumation took place.

Along the eastern flank of the Sole Pit Axis, Early to Mid-Cretaceous (120-95 Ma) exhumation appears to represent an early phase of inversion. This event correlates with a sub-Chalk unconformity which truncates underlying Jurassic and older units. Inversion within a similar time interval has been recognised from AFTA data in wells and outcrops samples within the Sorgenfrei-Tornquist Zone in Scandinavia (Japsen et al., 1997, 2015), and is interpreted to be a response to regional intra-plate tectonic stresses. Further east of the Sole Pit Axis, where a thicker Paleogene succession is preserved, results define a Neogene onset for Cenozoic exhumation, showing no evidence of the Paleocene event which dominates data over most of the region. Eastwards towards the central parts of the southern North Sea Basin Mesozoic sediments are at maximum burial today (except for local effects related to salt movements).

Southwards into Quads 53 and 54, the effects of Early Cenozoic exhumation decrease markedly and AFTA and VR data are largely dominated by the effects of Neogene inversion on the Hewett Fault. However, Neogene paleo-thermal effects in this region are not restricted to those expected purely from inversion-related exhumation, and the effects of heating due to hot fluids movements (presumably related to inversion) have been identified over a wide area. Where these effects are less pronounced, AFTA data also reveal evidence of Late Jurassic cooling from a paleo-thermal event involving both elevated heat flow and limited (though still km-scale) deeper burial. This episode is not recognised to the north in UK Quadrants 47 to 49.

The interplay between the various episodes of burial and exhumation has major implications for exploration, including higher than expected maturities due to formerly deeper burial, variation in the timing of peak maturation in relation to formation of structures, and potential for seal rupture during uplift and loss of charge during exhumation. In regions where burial has essentially continued throughout Mesozoic and Cenozoic times, maturation of Carboniferous source rocks has provided charge for structures of a range of ages formed during the various tectonic episodes defined from AFTA. But hydrocarbons generated during earlier phases of deeper burial prior to exhumation are likely to have been lost or remigrated. A detailed understanding of these various tectonic phases is therefore key to continued exploration success.*

References, p. 124

NOTES

New insights in salt tectonics in the northern Dutch offshore: A framework for exploration

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[3] *TNO – Geological Survey of the Netherlands, the Netherlands.*
[4] *Utrecht University, the Netherlands*

The northern Dutch offshore is an area that has seen less exploration drilling than other sectors of the Dutch on- and offshore. Recent acquisition of a regional 3D seismic dataset allowed for a re-evaluation of existing hydrocarbon play concepts and assessment of prospectivity in this area. The presence and movement of Upper Permian Zechstein evaporites had a major effect on the geological development of this area. Halokinesis has affected depositional patterns, structural development, hydrocarbon migration, trap formation and other aspects of plays in the northern Dutch offshore. This study looks specifically into salt tectonics in this area of the Dutch offshore, making use of high quality 3D seismic data.

Assessment of salt structure geometry, as well as associated depositional patterns and faults allowed to systematically investigate and categorise salt structures in a salt structure inventory. The results show that salt movement initiated in the Triassic and was most prominent during the Jurassic and Cretaceous. Timing of salt movement is not entirely consistent throughout the study area. A correlation can be seen between the location of salt structures within the structural elements, and the manner and timing of the development of salt structures.

To assess salt tectonic evolution within a structural context, a 2D structural restoration of the Elbow Spit Platform, Step Graben, Dutch Central Graben and Schill Grund Platform was performed using MOVE software (Midland Valley Exploration). Results provide a conceptual model allowing to better constrain the structural and depositional evolution of each structural province as well as to better quantify erosion and salt movements. It became evident that depositional patterns, distributions of salt structure types and timing of salt movement have to be regarded as the consequence of an interplay of salt movement and structural development of the Step Graben and Dutch Central Graben.

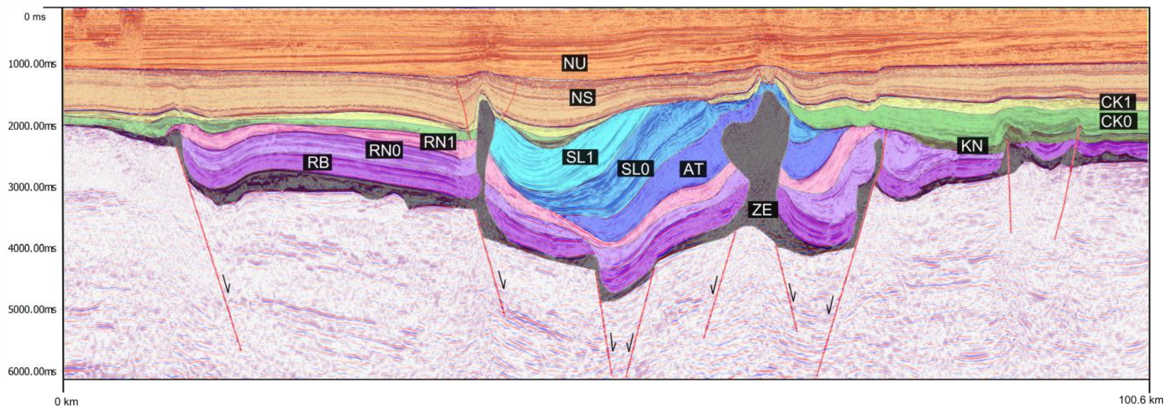

Fig. 2: The interpreted seismic section (TWT) that was structurally restored in this study, transecting the Dutch Central Graben and Step Graben and the margins of the Elbow Spit Platform and Schill Grund Platform. The location of this section is shown on ***Fig. 2****. Tertiary North Sea group (NS), Cretaceous Chalk group (CK), Jurassic Schieland group (SL) and Altena group (AT), Upper Germanic Trias group (RN) and Lower Germanic Trias group (RB), Permian Zechstein group including the salt (ZE)*

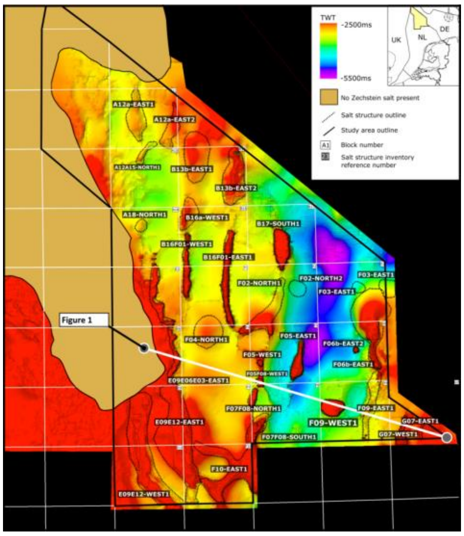

Fig. 3: Top Zechstein time structure (ms) map; all 30 identified salt structures are outlined (dotted black outlines) and referenced to the salt structure inventory, which was compiled in this study.

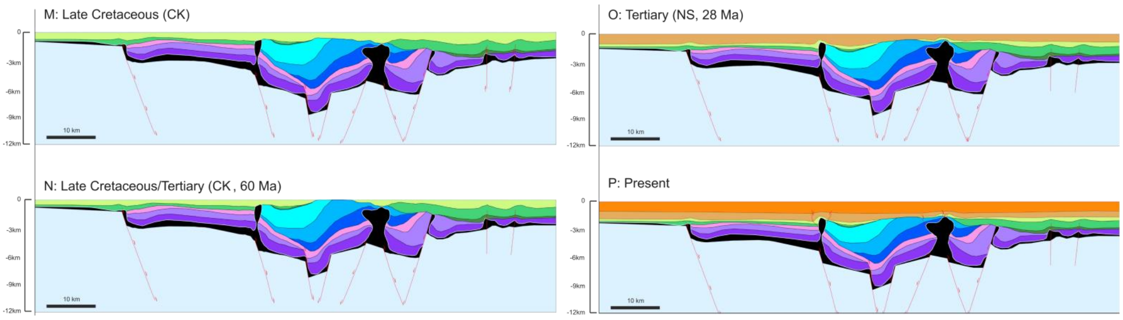

Fig. 4: Depth converted and structurally restored models of the seismic section shown in Fig. 1. These models show the Late Cretaceous to Present configurations, which represent four (4) out of in total sixteen (16) restoration steps presented in this study.

NOTES

Estimating masked deformation in basins influenced by halotectonics and structural inversion – the example of the Lower Saxony Basin.

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Structural restoration and balancing of basins influenced by halotectonics, multiphase rifting and structural inversion is not an easy task. The Central European Basin System (CEBS) comprises a number of such complexly structured basins, including the Broad Fourteens Basin, Mid-Polish Trough and Lower Saxony Basin (LSB). The LSB (Fig. 1) is a good example to explore the pitfalls of structural restoration and estimation of deformation in these settings. In this study, we focus on quantifying the last major deformation of the LSB during the Late Cretaceous (Coniacian to Campanian), when the entire basin was inverted due to a pulse of contraction resulting from Africa-Iberia-Europe convergence. Our study is based on approx. 100 geological profiles and structural description of the Geotectonic Atlas of NW-Germany (GTA). For analyses and mapping of results the software packages Move by Midland Valley and ESRI´s ArcGIS were used. We find that due to the challenges outlined above a quantification of strain can not be effectively tackled with 2D-restoration of geological profiles alone, and we thus present some specific workarounds for the LSB.

The LSB is located in the south of the North German basin (NGB), which is itself a segment of the CEBS. Including its uplifted parts the LSB is approx. 250 km long in a NW-SE direction and from 60 km to more than 100 km wide (Fig. 1A). Its structural and sedimentary evolution diverges from the rest of the NGB in the Late Jurassic to Early Cretaceous time. Besides increased subsidence of the entire LSB, several mostly ESE to SE trending grabens and half-grabens evolved and are connected by major fault systems which enclose most of the basin (e.g., Allertal Lineament). The central part of the LSB (Fig 1A; CLSB) shows little Late Jurassic to Early Cretaceous faulting. Late Cretaceous contraction of the LSB takes different forms in the Mesozoic basin fill (Fig. 1B), but NNE/NE dip-slip contraction is suggested by the majority of structures such as:

- A broad anticlinal inversion of the entire basin, with maximum uplift over the former centre of the LSB
- Major reactivation and inversion of grabens and faults along the borders of the LSB. Often entire grabens are upwarped while normal offsets on faults are preserved.
- Broad regional uplift in the hanging wall of the Osning Thrust
- Bulging of formerly flat-lying Upper Jurassic or Lower Cretaceous sub-basin fills
- Compressional overprinting of different forms of salt diapirs
- Formation of compressional salt-anticlines
- Subordinate formation of new thrust and reverse faults
- Indications for strike-slip faulting and strain partitioning along unfavourably oriented NNE striking lineaments (e.g., the Gifhorn-Braunschweig Fault Zone) but no clear evidence for NE/NNE dip-slip contraction.

Problems for the quantification of strain arise on different scales. For instance, due to strong uplift and erosion of the southern LSB (Fig. 1A; NWLS) constraints on the original extent of the basin and its structural and sedimentary evolution are scarce. Up to 7 kilometres of Triassic to Upper Cretaceous sedimentary strata may have been eroded. The uplift is related to the reactivation and inversion of the southern border fault system (Osning Lineament) of the LSB, but the strong erosion of its hanging-wall makes it difficult to quantify the contraction from structural data (Fig. 1B).

Compressional structures in the Mesozoic succession which show major erosion of syntectonic strata and the loss of other structural constraints, as well as disturbance by complex salt movement were classified as not balanceable for the purpose of this study. In general the superposition of different phenomena of structural reactivation and basin inversion makes it difficult to extract well-constrained estimates of contraction from cross-sections.

We attempted to circumvent these problems using different approaches. A first-order estimate of the maximum possible contraction is taken from the amount of Iberia-Europe convergence in plate reconstructions. The total amount of Late Cretaceous convergence exceeds shortening estimates of the Pyrenean orogen in the same time span by a few tens of kilometres. This extra contraction was presumably accommodated to a large extent on intra-plate structures of the CEBS, c. 1500 km northeast of the Pyrenean orogen. A central argument for our reconstruction is strain compatibility of structures and regions along the strike. To the southeast of the LSB, large basement faults and associated basement uplifts (Fig. 1A; e.g., the Harz Mountains) accumulated about 20 km of contraction. We infer that a similar amount was accommodated in the Lower Saxony Basin. On a smaller scale, the main NW-SE striking fault systems often seem to maintain a similar magnitude of deformation over long distances along their strike. This observation enables us to make consistent estimates for deformation magnitudes of complex structures on the basis of geological profiles crossing the same structural elements in a less disturbed situation. In other cases, contraction magnitudes were estimated by grouping similar structures according to structural style and determining minimum and maximum shortening values.

All derived estimates were used as input data for the final map-view balancing. In a map-view balance inconsistent strain estimates of individual structures clearly stand out in comparison with the overall context of all estimations. The broad anticlinal uplift of the entire basin and along the Osning thrust were constrained using data on Late Cretaceous erosion in the LSB. For a first-order estimate, these data were used to construct a reference surface to which forward-modelling of fault-controlled inversion was fitted.

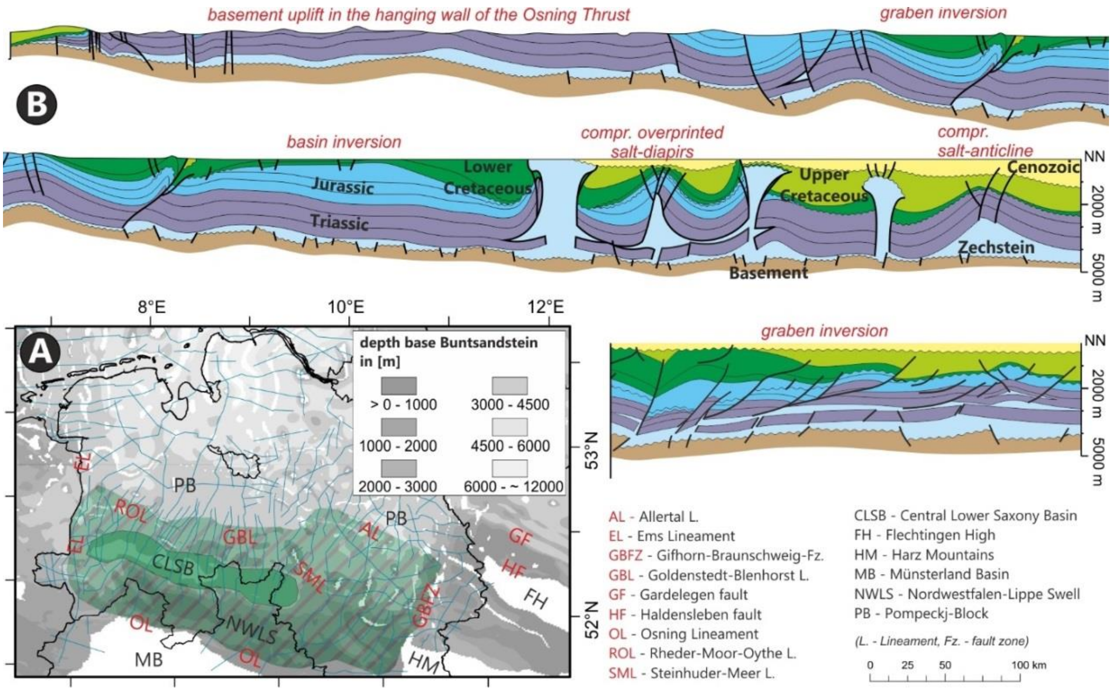

Fig.1: A.) Structural overview map of the LSB and surrounding areas. Additionally, the geological 2D-profiles of the GTA are plotted; B.) Exemplary geological profiles redrawn after the GTA. Typical structures with a Late Cretaceous contractional overprint within and along the borders of the LSB are highlighted.

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Thursday 8 September

Session Three

Triassic Resources

Keynote Speaker: Triassic depositional systems in NW Europe: an interplay of base level changes, tectonics and climate

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[1]Shell International, New Ventures, [2] Shell UK Exploration and Production

Over the last few decades detailed studies in NW Europe have resulted in new insights into tectonics and sedimentation during the Triassic. High-resolution stratigraphic log correlations have been carried out for the Permo-Triassic interval in the Southern Permian Basin (SPB) to consolidate the different stratigraphical frameworks in NW Europe, and to identify basin-wide potential reservoir units in the area between the United Kingdom in the west and Poland in the east. These correlations can also be tied, via limited biostratigraphy, to equivalent successions further afield in the North Sea region to develop an understanding of the regional palaeogeographic evolution in response to tectonics and climate.

Antecedent Caledonian, Variscan and Permian structures had great bearing on Triassic structures and deposition. The main controlling lineament is defined by the Iapetus Suture, the northern margin of the Caledonian collision. North of this line focussed rift tectonics prevailed, whereas to the south a wide extension zone existed in areas of Variscan-thickened crust. As a result the southern Permian basin is an amalgamation of several depocenters (Polish Trough, North German Basin, Sole Pit Basin). Gradual overstepping of highs around the basins occurred mainly in Middle to Late Triassic times (e.g. Paris Basin, onshore UK). Early to Middle Permian rifting resulted in widespread extrusive volcanic activity and the collapse of the Variscan Mountains by a series of grabens. The fault systems and inherited faults formed during this rifting form the backbone of the later Triassic graben systems. During the Triassic progressive modification by extensional tectonics occurred as a result of extension propagating from both the Boreal and Tethyan regions. From the Middle Triassic onwards, rifting concentrated mainly in the Central and Northern North Sea, Horn and Glückstadt graben, together with onshore graben in the UK and France.

Clastics were initially shed northwards from the Variscan foldbelt until Anisian (Middle Triassic) times; from the Ladinian/Carnian onwards a major reversal in sediment transport occurred, when Fennoscandia became the main source area. Fluvial fan, aeolian and playa facies alternate at a variety of scales, driven by high frequency fluctuations in catchment climate responding to Tethyan monsoon strength and higher latitude precipitation over Fennoscandia and Greenland. In general there appears to be a broad correlation between more pluvial episodes and volcanism, either from widespread peri-Tethyan activity or more pronounced episodes during the eruption of large igneous provinces. During short-lived extensional pulses, combined with aridity, the main rifts were the site of evaporitic precipitation and up to 4,500 m of salt accumulated. In periods of tectonic quiescence, particularly during more humid episodes, large fluvial fan and delta systems originating from the Fennoscandian Shield built out over the SPB. Marine influence in the Triassic succession is now thought to extend beyond simply the middle Triassic Muschelkalk flooding, and even in the continental Lower Triassic ‘Buntsandstein’ the deposits of brief but widespread flooding events are identified. Marine access was facilitated by the tectonic opening of “gates” within the Variscan chain, which created routes for Tethyan marine waters to access the SPB. Fill and spill of marine waters between partially linked basins allowed the precipitation of marine evaporites across the region, facilitated by aridity and tectonic barriers which provided the restriction to fully marine flooding.
A variety of natural resources occur in association with Triassic rocks in NW Europe, dominated by their suitability as hydrocarbon reservoirs. Source rocks are limited in these red-bed deposits, but higher TOC deposits occur in the Rhaetian (marine SR in Tethys), as coaly beds in offshore Denmark, NW Germany and The Netherlands. Oil and gas in Triassic reservoirs in the southern North Sea mainly occur in the Early Triassic, fluvial-aeolian Buntsandstein. In the Central and Northern North Sea more widespread fluvial reservoirs extend through the Middle and Late Triassic. In the East Irish Sea the fluvial-aeolian Ormskirk

Formation forms the main reservoir. In the Wessex basin the largely fluvial, Sherwood Sandstone forms the main reservoir in the Wytch Farm Field. Triassic reservoirs are further used for gas storage in Germany, both in depleted gas fields (Allmenhausen, Döttlingen, Kalle, Uelsen) and aquifers (Berlin, Bucholz). In NE Germany, geothermal energy is produced from Triassic rocks (Neubrandenburg). In the Polish part of the SPB no hydrocarbon accumulations have been encountered. Reservoirs rocks are present in the Lower Triassic, but charge and sealing remains an issue. Rock salt in the Röt, Muschelkalk and Keuper forms a major resource in NW Germany, The Netherlands and onshore Germany (Geluk et al., 2007), and locally in the Cheshire Basin in the UK.

Triassic salt is widespread and being exploited in the Eastern Netherlands and Germany by solution mining and in Cntral Germany by dry mining methods (Muschelkalk, Heilbronn).

NOTES

A 3D lithofacies model of the Buntsandstein in the central German North Sea

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The Federal Institute for Geosciences and Natural Resources (BGR) aims to enhance the understanding of the deep subsurface of the German North Sea sector especially regarding its storage potential. For this purpose, a basin scale geological 3D lithofacies model of the Lower Triassic Buntsandstein in the central part of the German North Sea sector was built. The area of the 3D model comprises approximately 20,000 km^2 in the German North Sea sector without its westernmost part, the so-called “Entenschnabel”. The different formations of the Buntsandstein are of particular interest as they may contain several complex interlocked layers of reservoir or barrier rocks.

In the area of investigation, two structural 3D models have been built (e.g. Bombien et al. 2012, Kaufmann et al. 2014) based on the “Geotectonic Atlas of NW-Germany” (Baldschuhn et al. 2001). These models are an indispensable database for further detailed volumetric modeling regarding the distribution of reservoir and barrier rocks. The 3D distribution of the lithologies is the key element for the evaluation of these topics. Lithofacies models in 3D are well established and tested on reservoir scale (e.g. Schetselaar 2013) rather than on regional or basin scale (e.g. Mathers et al. 2014, Stafleu et al. 2011). All these models tackle different challenges concerning the available data, used methods and uncertainties. Nevertheless, the development of 3D lithofacies models is a worthy goal because the regional lithology distribution gives a first idea of the palaeo-development of the area of interest and can be used to get a first impression of possible reservoir/barrier units in basin scale.

The presented basin-scale 3D model is based on the GSN 3D (“Generalisiertes, erweitertes Strukturmodell des zentralen deutschen Nordsee-Sektors” Kaufmann et al. 2014), a new dense 2D seismic reinterpretation of the Buntsandstein formations and 21 wells. The finished model consists of layers and contains 501,5660 rectangular grid cells, each measuring 1km² in the horizontal plane. Cell heights vary mostly between 5 m and 80 m, reaching a maximum in the western Horn Graben with 130 m for each cell. The modeling procedure involved a number of steps: The first step was a classification of the well descriptions using their lithological information (well reports, geophysical logs). In the second modeling step, the 3D structural model was constructed including the fault network and the salt structures. Furthermore, the base surfaces of the Buntsandstein formations were added from a new interpretation of the available seismic data set. As a last step, a parametrized 3D property model was obtained by extrapolating the lithological information from every well using the Sequential Indicator Simulation with the software Schlumberger Petrel.

The described steps resulted in the first 3D lithofacies property model for the Buntsandstein in the central German North Sea sector providing spatial distribution of the different Buntsandstein formations. Distinct features like fining upward cycles within the formations or evaporitic pattern can now be visualized and interpreted much more thoroughly, for example concerning possible marine transgression paths. This model provides valuable knowledge about the 3D spatial variation of the lithofacies (Fig. 1). Therefore, it represents an improvement compared to existing 2D maps. The basin-scale estimation of properties is always bound to the quantity and quality of the available data and the used methods. Issues like a strongly generalized structural model and several further steps of generalization of input data are necessary to build basin-wide models but these models led to a better understanding of the palaeo-development of the investigated area, which is necessary to isolate local areas providing a promising scope for further investigations in local scale. The results show that the basin-scale lithofacial 3D modeling method effectively provides a first-order 3D characterization of the geometry and spatial configuration among lithofacies units which is crucial for further detailed reservoir modelling approaches in this area.

In addition, the 3D lithofacies grid can be used with supplementing data or assumptions to develop further lithofacies-dependent geological properties, e.g. permeability or porosity. The 3D model provides a realistic lithofacies distribution in the area of investigation. Future work will focus on an improved 3D geometry based on further seismic interpretation, a refinement of lithological patterns in the Buntsandstein formations, a more detailed uncertainty analysis, a better understanding of the geological evolution, as well as the modeling of additional parameters. The lithofacial 3D model (Wolf et al. 2015), exemplary maps of lithology distribution for different Buntsandstein formations, and a technical report in German are accessible to the public at www.gpdn.de.*

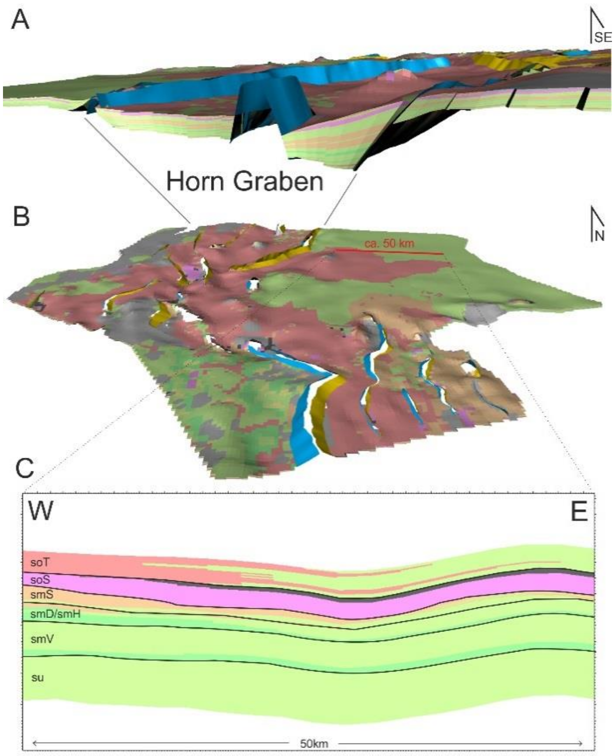

Fig 1. Different views on the final 3D model (no vertical exaggeration, part C shows a magnified part of the geological intersection). (A) Structure and lithological filling of the Horn Graben from a southeastern point of view. (B) Top view of the whole lithofacies 3D model including the used major fault system (blue and yellow). (C) Cross section of the Westschleswig Block. It indicates a base of undifferentiated fine-clastic rocks interrupted by coarser beds that represent the bases of the Volpriehausen and Detfurth/Hardegsen formations. Above them a fining westwards trend of the clastic sediments is visible, interrupted by the Röt-Salz Formation. The colour code for the different lithology classes is given in Wolf et al. (2015). Faults are represented by yellow or turquoise walls.

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NOTES

The Triassic Main Buntsandstein play – New prospectivity in the Dutch northern offshore

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The Early Triassic Main Buntsandstein (MBU) is an established hydrocarbon play in the Southern North Sea. Aeolian Volpriehausen sandstone forms the main reservoir rock. It is generally perceived that reservoir presence and abundance decrease towards the north and that prospectivity of the MBU play in the Dutch northern offshore is limited. Access to charge from the Carboniferous is often seen as an additional risk for this play. Consequently, few wells have tested Triassic reservoir and this part of the basin remains under-explored. A recent study has mapped the lithologic character and stratigraphic extent of the northern Triassic in detail and presents evidence of alternative reservoir provenance in the marginal Step Graben system. Numerous untested Triassic leads were identified and their prospectivity is being assessed.

The EBN evaluation of the MBU play in the Dutch northern offshore incorporates well and seismic data from the Dutch, German, Danish and British North Sea sectors. A thorough borehole review including well tops, reservoir development and post-mortem analysis, suggests that fluvial sands with (local) northern provenance may have been preserved in the north-western area of the Step Graben system (*Fig. 5*). Syn-tectonic strata in local depocentres may have been formed in this area due to early halokinesis in the Triassic, in analogy to the Central North Sea described in Smith et al. (1993). Olivarius et al. (2015) analyse provenance area for Early Triassic sandstones in the North German Basin (NGB). They identify a southern source of aeolian sands from the Variscan mountains and a northern – local – source of fluvial sands from the Ringkøbing High in the NGB. The distinct log character of well A15-01 and A05-01 in the marginal basin system of the northern Dutch Step Graben describes a series of sandstone beds that may also be subject to local sediment provenance (*Fig. 5*). The Danish Bertel-01 shows a similar log response (not shown).

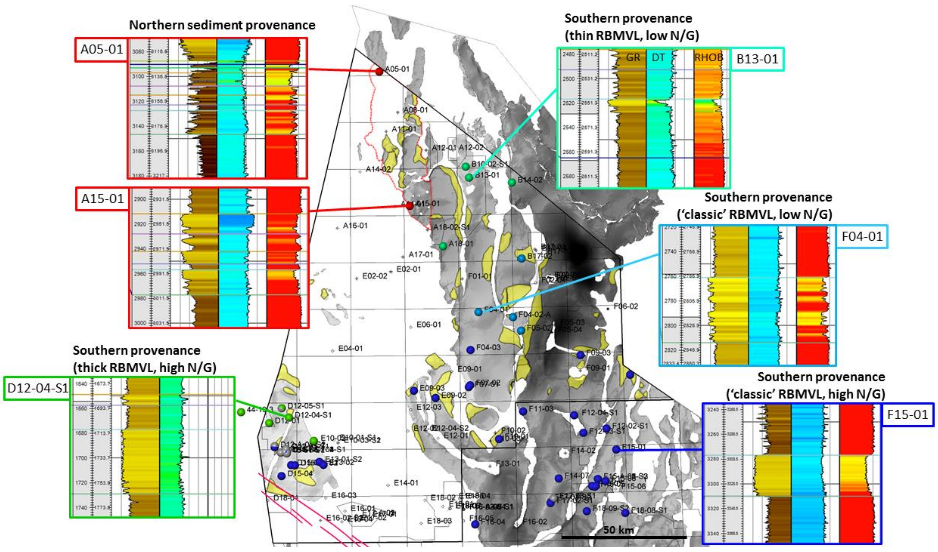

Fig. 5: Regional reservoir architecture – typical well log response for different types of Volpriehausen sandstone (RBMVL). Study area is outlined in solid black, yellow polygons indicate Triassic leads.

In both the A05-01 and Bertel-01 there is an age-dating uncertainty for the Triassic rocks. Analyses of biostratigraphy, heavy minerals, clay mineralogy, grain size distributions and quartz surface microtextures on cuttings and core material from the Dutch northern offshore are currently being performed to assist in understanding age, provenance and depositional environment of the Triassic in the study area.

Regional mapping of the Volpriehausen sandstone enabled us to identify more than 50 untested structures in the study area. These leads roughly cluster in three types and areas (*Fig. 6*): 1) 'classic' leads with proven types of trap, source, seal and reservoir, 2) leads which may be sourced with hydrocarbons via Tertiary volcanic dykes and 3) leads with reservoir provenance from the north. Un-risked P50 GIIP for 29 structures screened to date range between 1-9 BCM each and total 80 BCM.*

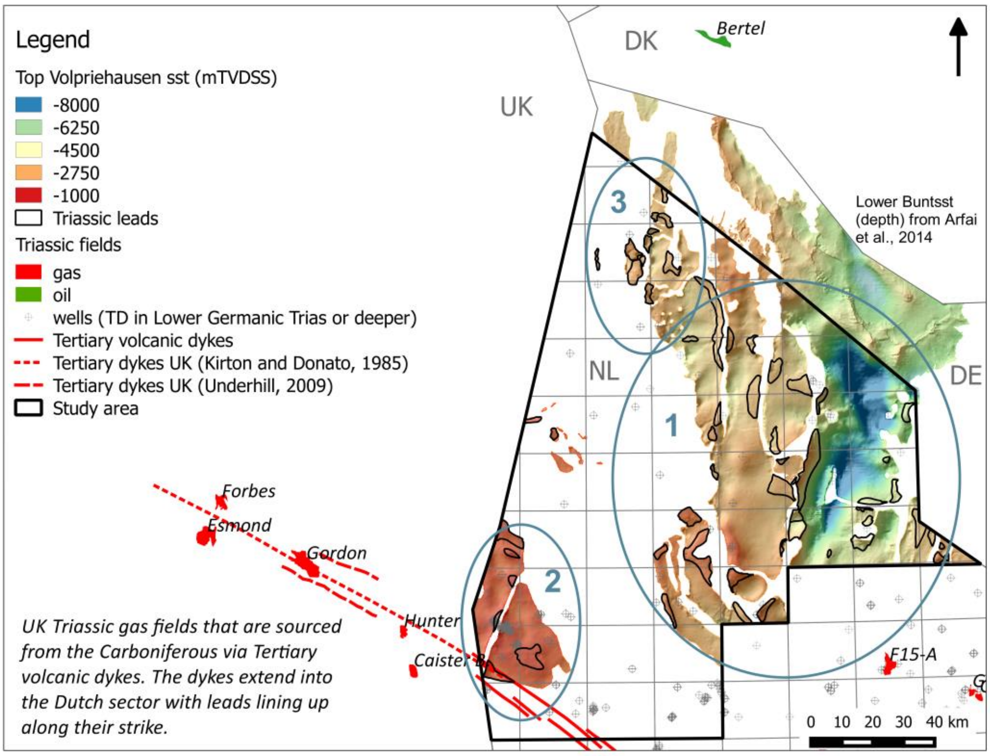

Fig. 6: Top Volpriehausen sandstone depth map in the study area. The identified leads are separated in three types (1- 'classic', 2- sourced via volcanic dykes, 3- northern reservoir provenance).

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NOTES

Towards better understanding of the highly overpressured Lower Triassic Bunter reservoir rocks in the Terschelling Basin

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Large lateral variations in pore fluid formation pressures and associated overpressures occur in the Lower Triassic Bunter reservoir rocks in the Terschelling Basin in the Dutch sector of the North Sea. This study describes in detail the main controlling factors on the distribution of these overpressures in the Terschelling basin by combining structural interpretations based on seismic data with pressure data. Insight in these controlling factors also makes it possible to estimate the pore fluid overpressures in the Bunter compartments that haven't been drilled (yet). Furthermore, this study aims to gain insight into the overpressure generating mechanisms. Additionally, a theory is presented to explain the occurrence of secondary salt cementation in the pores of the Lower Triassic Bunter reservoir rocks, which is a widespread phenomenon and an exploration risk for the Lower Triassic Bunter play in the Terschelling Basin.

Regarding the controlling factors on the distribution of overpressures in the Lower Triassic Bunter strata, it is found that the most important controlling factor is the presence of both lateral and vertical permeability barriers. Lateral permeability barriers are formed by Zechstein salt and faults. The most important vertical permeability barrier is the Upper Triassic Röt evaporite. In the Bunter compartments where the Röt evaporite is continuously present, high overpressures of around 30MPa and higher are observed. In areas where the Röt evaporite is absent due to Mid-Kimmerian uplift and subsequent erosion, overpressures are less than 15MPa. The timing of the formation of the lateral permeability barriers (Zechstein salt and faults) has been of great importance for the generation of the presently observed high pore fluid overpressures in the compartments, as overpressures could only have built up after hydraulic closure of the compartments. Based on structural interpretations, by making use of seismic data, it is concluded that the compartments where the Röt evaporite is continuously present became hydraulically restricted in three phases; starting with Middle Triassic faulting (phase 1) followed by the activity of Zechstein salt walls, diapirs and domes during the Middle and Late Triassic (phase 2). Subsequently, the compartments became fully hydraulically restricted during Late Jurassic and Early Cretaceous faulting (phase 3). Calculations show that the subsequent sedimentary loading during the Cretaceous and Cenozoic could largely explain the observed overpressures in the hydraulically restricted Lower Triassic Bunter reservoirs. Hence, it is concluded that sedimentary loading during the Cretaceous and Cenozoic is the main pressure generating mechanism for the Lower Triassic Bunter reservoir rocks in the Terschelling Basin. Additionally, the local presence of natural gas contributes to the pore fluid overpressures.

Regarding the distribution of secondary salt cementation in the pores of the Bunter reservoir rocks, it is suggested that this salt plugging originates from a regional fluid outflow event during Late Jurassic uplift. During this period, the Röt salt was eroded on the platforms towards the north and the south of the Terschelling Basin due to Mid-Kimmerian thermal uplift. Consequently, the pore fluids, likely to be already slightly overpressured at that time due to the continuous presence of the Röt salt and the N-S trending Zechstein salt walls, could have escaped during this period towards the north and the south. This escape of fluids would have lowered the pressure, consequently lowering the solubility of the fluids and causing precipitation of salt into the pores of the Lower Triassic Bunter reservoir rocks. Towards the end of the Jurassic and into the Cretaceous, normal faulting closed of the compartments in the Terschelling Basin towards the north and the south and overpressures could have built up (again). However, by this time the reservoir was already strongly affected by salt cementation. Over time, water could have percolated through the pores of the Triassic reservoir rocks at the platforms and the hydraulically more open compartments in the Terschelling Basin, whilst dissolving some of the cemented salt. This could explain why reservoir qualities in the hydraulically more open compartments of the Terschelling Basin are generally better compared to the hydraulically more closed (overpressured) compartments.

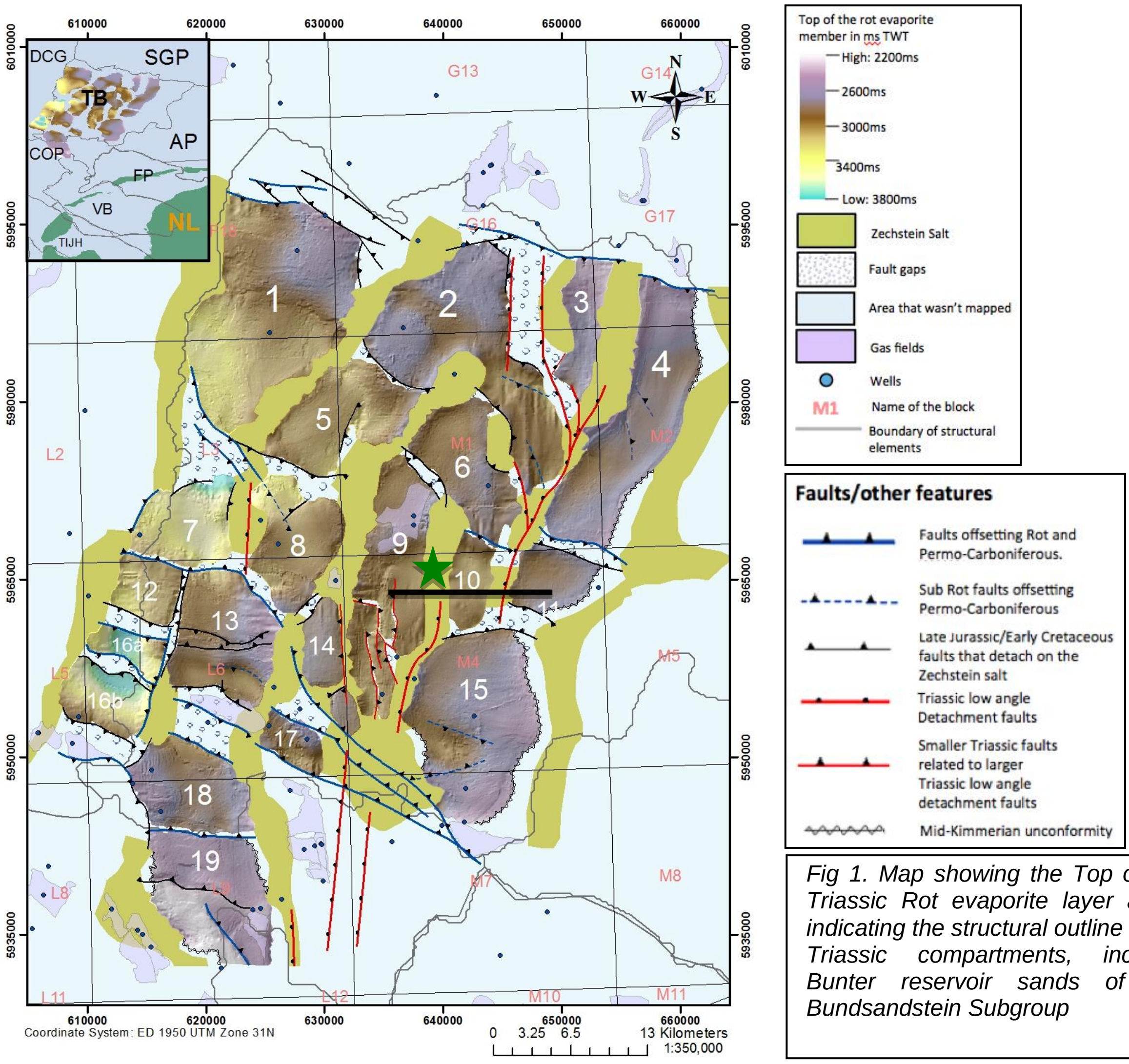

Fig 1. Map showing the Top of the Upper Triassic Rot evaporite layer and thereby indicating the structural outline of the Lower Triassic compartments, including the Bunter reservoir sands of the Main Bundsandstein Subgroup

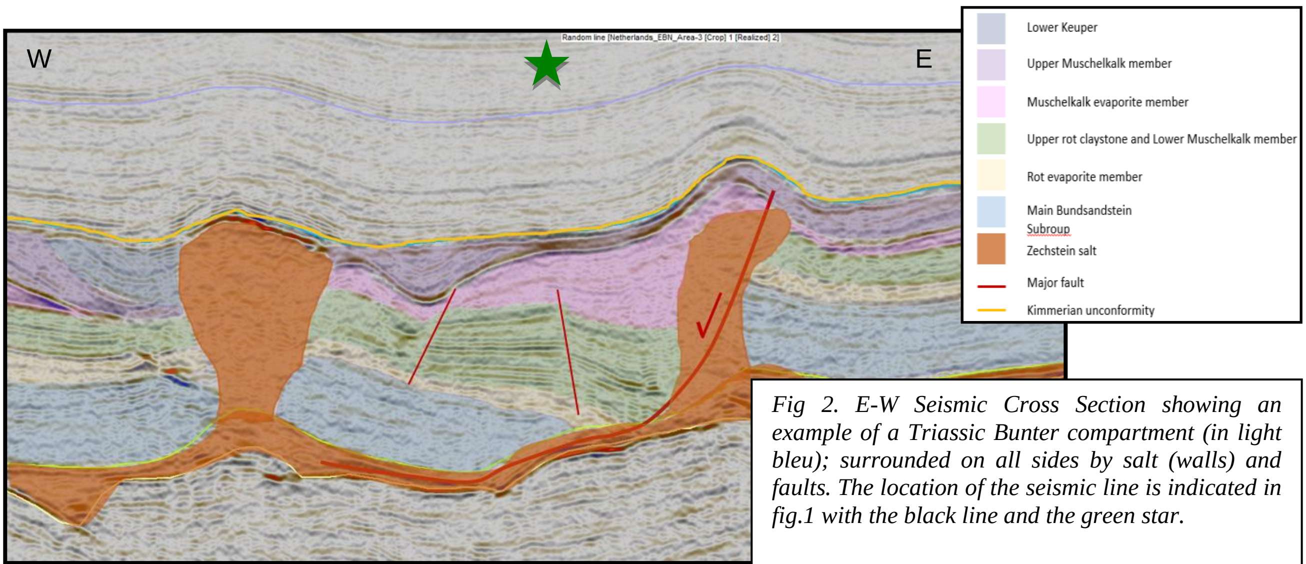

Fig 2. E-W Seismic Cross Section showing an example of a Triassic Bunter compartment (in light bleu); surrounded on all sides by salt (walls) and faults. The location of the seismic line is indicated in fig.1 with the black line and the green star.

NOTES

De Wijk gas recovery: Shell's first example of a successful enhanced gas recovery utilising Nitrogen displacement

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De Wijk Gas field, Eastern Onshore of the Netherlands, presented a geological setting and commercial opportunity, which encouraged NAM to apply nitrogen enhanced gas recovery for the first time. De Wijk is one of the oldest onshore natural gas fields in the Netherlands, producing 14.9 bcm (1.1.2014) high calorific gas with a natural N2 content of 5-11% for more than 60 years, bringing it close to the end of system life. Enhanced gas recovery would significantly increase the production life of this ageing onshore gas field. It has 35 wells that could not only be used as dedicated injectors and producers, but also allowed to understand the flow behaviour in the reservoirs better. The existing surface infrastructure was readily available to utilise different nitrogen enhanced recovery techniques. The nitrogen enhanced gas recovery technology is expected to extend the project's life by around 15 years, and ultimate gas recovery could rise from 73% to as much as 83%.

In De Wijk field, reservoirs stretch from Carboniferous carbonates, Triassic clastics, to Tertiary tuffites. All the reservoirs are charged from the extensive Carboniferous coals by migration from the Carboniferous upwards. The enhanced gas recovery project consists of 4 phases, where in first phase the Triassic reservoir was used. Deposition of the Triassic reservoirs in the area occurred in an arid east-west trending closed continental basin. Repeated alternations of sandstone and claystone deposition marked cyclicity of the deposition, probably controlled by climatic changes. Interbeds of ooid lake margin and floodplain deposits are common during deposition of the Rogenstein. The Late Kimmerian event caused a regional uplift that reactivated older faults in the area. Salt pillowing was initiated and the Triassic and Jurassic sediments in the area were uplifted. The Triassic formations subcrop progressively, with the older strata in the west and the youngest Triassic strata in the east, below the Base Cretaceous Unconformity. Halokinesis, triggered from Late Jurassic times, continued and induced the present day closures at Lower Cretaceous and Tertiary level, forming the structural trap of the De Wijk field. Lower Cretaceous Vlieland shales form the top seal to the Triassic and Early Cretaceous reservoirs in the area. Diagenesis through leaching in the Late Jurassic - Early Cretaceous removed most of the cements and improved the reservoir properties.

De Wijk enhanced gas project applies two injection displacement processes; NERG (Nitrogen Enhanced Residual Gas) and NADD (Nitrogen Assisted Depletion Drive). The NERG process involved nitrogen injection which displaces residual gas in either watered out reservoirs (due to aquifer influx during primary production phase) or in water bearing reservoirs containing geological residual gas (trapped by capillary forces during geological migration or due to paleo imbibition in blown traps). For example, the upper part of Rogenstein is a watered out reservoir that shows strong aquifer support. The aim is to sweep the residual gas in these formations towards the producers. NADD uses nitrogen to displace remaining gas in a depleted (non-associated) gas reservoir. For example, in the lower part of the Rogenstein, consisting of alternating Oolitic/sandstone beds intercalated by claystone/siltstone, pressure has dropped to almost the economic and technical limit, leaving substantial amount of gas within the gas phase. Both NERG/ NADD sweep efficiency depends on reservoir architecture and structure geometry, chosen injector/producer configuration, and the amount of nitrogen that can be accommodated in the production after partial nitrogen breakthrough. Current field results confirm the dynamic models i.e. pressure increase and nitrogen breakthrough. Formation gas is expected in mid-2017. The first result from De Wijk pilot project demonstrates the feasibility of nitrogen enhanced gas recovery in this field, a learning that can be shared for application in similar mature fields.

NOTES

Critical elements for a dual hydrocarbon-geothermal energy play in the Boskoop field, NL

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The attractiveness of geothermal energy, a green and sustainable resource, is downgraded by high investment costs and current low fossil energy prices. A case study on the Roden gasfield (Peters et al., 2014) has shown an increase in gas production and recovery rate when both gas and geothermal energy are produced simultaneously. A study by van Wees et al. (2014) has shown the benefits of this synergy in monetary risk and reward.

The benefits of synergy can make geothermal energy more attractive. The problem is that it is still unknown whether or not the benefits of synergy will be the same in other fields with different reservoir properties. The objective of this study is to find out what critical elements determine whether or not synergy will be successful.

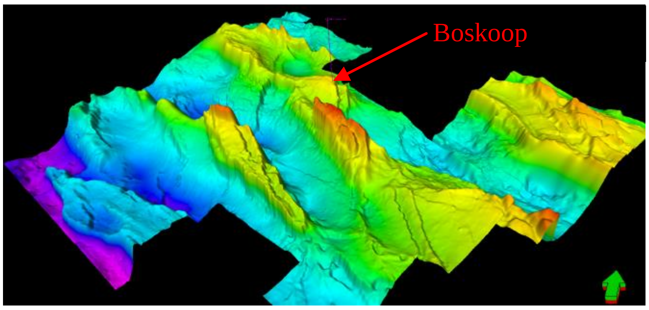

Fig. 1: Structure of the Boskoop field and surrounding area. Surface from seismic interpretation, base Altena.

This study evaluates the dual hydrocarbon-geothermal potential of the Boskoop stranded gasfield, a complex faulted field situated in the West Netherlands Basin (Fig. 1). Due to the low estimated gas reserves the field was considered to be uneconomic, but if the effect of combining gas and geothermal energy production will be profitable suggestions can be made to put forward a field development plan.

Two reservoir zones, the Triassic and Rotliegend, were analyzed and with the results of a petrophysical evaluation conclusions were drawn that only the Rotliegend reservoir is suitable for dynamic simulations. After building the structural reservoir model in Petrel different dynamic reservoir simulations were performed with Eclipse.

For the Boskoop field results show an insignificant increase of 0.19% in gas production in the synergy scenario; not enough to reconsider the field for production. To analyze what critical elements determine whether or not synergy will be successful simulations with different settings were done to compare the Boskoop field to the Roden case study.

First the reservoir model was populated with a higher permeability to adopt the good reservoir properties of the Roden field. This results in a higher cumulative gas production in a single gas production scenario. When a geothermal doublet is placed the ultimate gas recovery decreases with a negligible 0.5%. In a final simulation case the water production rate of the geothermal doublet is increased and total gas production decreases even slightly more with 0.6%.

In Fig. 2 the water production rates for different scenarios are presented. In a synergy scenario the water production in the gas well is lower than a regular single gas scenario. This means there is a delay in water breakthrough, and the mechanism behind synergy does seem to work.

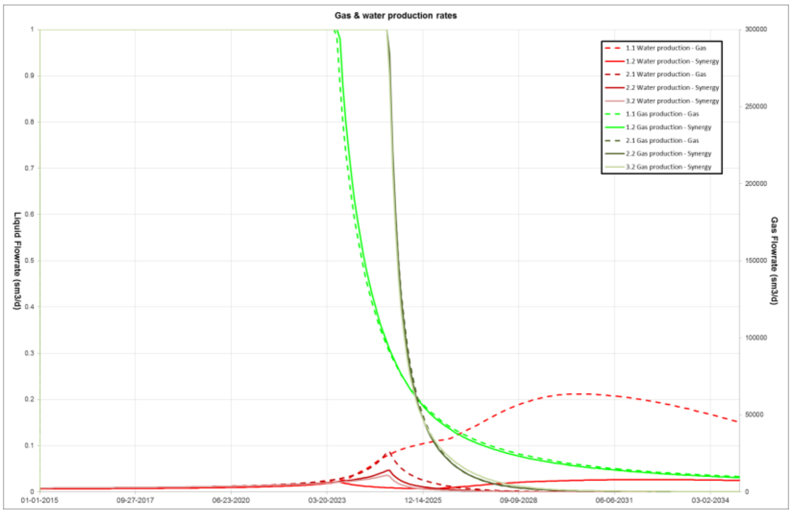

Fig. 2: Gas and water production rates of the gas well. Case 1: Boskoop properties, case 2: high permeability, case 3: high permeability and higher doublet rate.

Analysis of the pressure (re)distribution during production shows a trend for the different simulation cases. During gas production the reservoir pressure decreases and the ΔP at the geothermal production well cannot be maintained. Subsequently, the water production rate cannot be maintained in the synergy scenario (Fig. 3). The declining geothermal water production rate has a negative effect on the synergy benefits. To get the positive effect of synergy reservoir pressures must be maintained which is the case in the Roden field due to the presence of a large active aquifer.

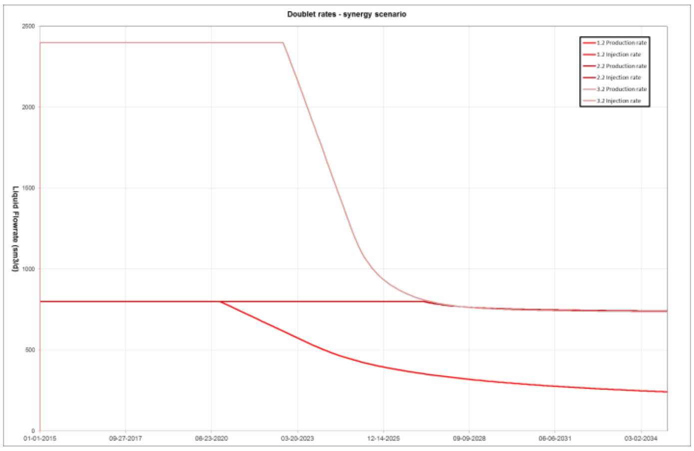

Fig. 3: During a synergy scenario the doublet rates cannot be maintained due to the declining reservoir pressure.

NOTES

Reservoir properties revisited: results of datamining in the Dutch Oil and Gas Portal www.nlog.nl

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The Dutch Oil and Gas Portal (**www.nlog.nl**) holds a wealth of data and information of the Dutch subsurface. For example about 200,000 core analysis measurements of porosity, permeability and grain density are available, as well as a litho-stratigraphic subdivision for almost all released wells. Additionally, for a considerable number of wells petrophysical evaluation results of different origin and vintage are available. Furthermore, regional reports on the geology, originating from the Dutch Geological Survey, are available through the portal as well as a bibliography of Dutch geological literature. Data gathering and first pass evaluation of this large dataset reveals illustrative results on well-known reservoir property trends for the different formations in the Dutch subsurface, on a regional to sub-regional scale. The benefit of these data analyses is that the results provide a solid reference framework for local reservoir quality analysis. For this paper the Triassic Lower Volpriehausen reservoir is chosen to illustrate the value of datamining on **nlog.nl**.

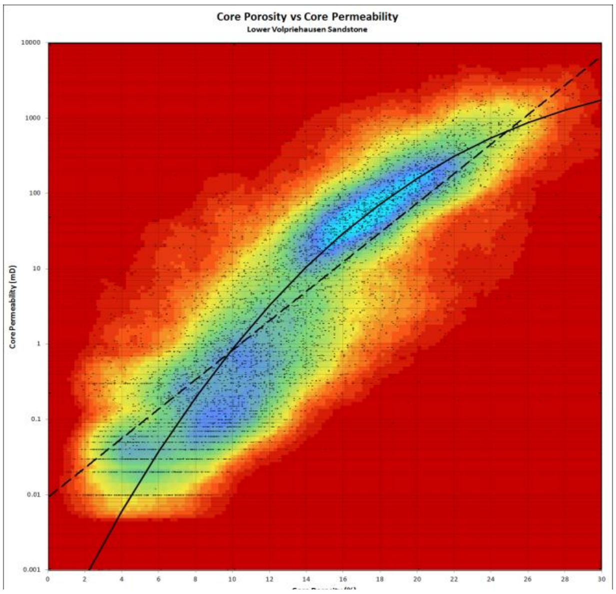

Fig. 1: Permeability vs porosity cross plot of core plug measurements of the Lower Volpriehausen Sst.

Classic porosity – permeability cross plots of the datasets pertaining to one litho-stratigraphic interval (Fig. 1) show invariably a curved data cloud. This trend is highlighted by gridding the data cloud using *Isatis*. On a subset of the data, or data pertaining to a single well, this curved relation may not be apparent. Using a linear correlation line on the Log(k)-porosity data set will generally overestimate the permeability in the low and the high porosity domain and underestimate the permeability in the medium porosity domain.

Plotting the same core plug porosity measurements versus True Vertical depth reveals an apparently undefined data cloud (Fig. 2a). The large spread in porosity values per depth interval can be attributed to facies variation and diagenetic alteration of the rock. Despite the amorphous nature of the cloud, there is a subtle trend in the upper (high porosity) envelop where maximum porosity reduces with depth. Apparent uplift or maximum burial estimates can be used to assign a max burial attribute to each core plug. Numerous reports on burial history and maximum burial depth / apparent uplift of various litho-stratigraphic units are publicly available, for instance van Dalfsen et al. (2005), Matev (2011) and Nelskamp et al. (2012). Plotting the core measurements in a max burial depth – porosity graph (Fig. 2b), the amorphous cloud changes in shape. The number of data points with low porosity at shallow depths reduces because they are transferred to greater depths. Gridding the data cloud reveals a clear trend: the shape of the density-cloud shows a decrease in porosity with greater depth. Averaging these porosity values per 200m depth interval also shows a decreasing porosity trend with depth. This matches with the generally accepted trend (see e.g. Bjørlykke (2010) and Ajdukiewicz (2010)). These observations are seen for all clastic Mesozoic reservoirs and the Rotliegend.

Fig. 3 shows the average porosity of the Triassic Main Buntsandstein in the West Netherlands Basin. It is a relatively small dataset based on publicly available petrophysical data. Parts of the West Netherlands Basin have been uplifted during the Late Cretaceous inversion events. Some average porosity values need to be shifted downward to be positioned at max burial along the depth axis. Although different in slope, the maximum envelope of porosity values clearly decreases. Unless no extraordinary geological circumstances are locally present the average reservoir porosity of the reservoir at a depth of 4 km is unlikely to exceed 6%.

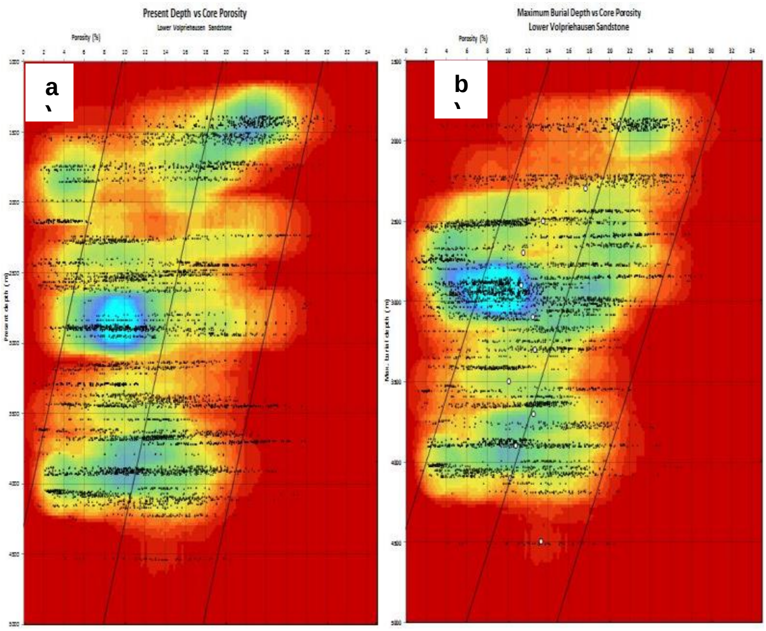

Fig. 2: Porosity - depth graph of the Lower Volpriehausen Sst Mbr. (a) core plug porosity values versus present day depth and (b).maximum burial depth. The open circles are the 200m depth interval averages

On ***nlog.nl*** detailed petrographical information on the reservoir can be found in the well files as for example for well GAG-5. Core porosities of this well plot at the low porosity side of the data cloud in a graph of Fig. 2. The reservoir interval lies at approx. 3500m depth (Fig. 3). From thin section analysis it may be inferred that the porosity degrading mechanism is due to cementation and compaction. It appears that long grain and concavo convex contacts are predominant over point contacts, suggesting significant compaction. Additionally, while visible porosity varies from 0.7 to 11.7%, the original porosity, (minus cement porosity), ranges from 6 to 25%. Pore occluding fractions comprise dolomite, anhydrite and quartz. These diagenetic components are more abundant in this well as compared to the Gaag-2-S1 well, which was buried less deep (Fig. 3). A more in depth evaluation of this and other available material can disclose the most likely argumentation for the prediction of local reservoir properties.

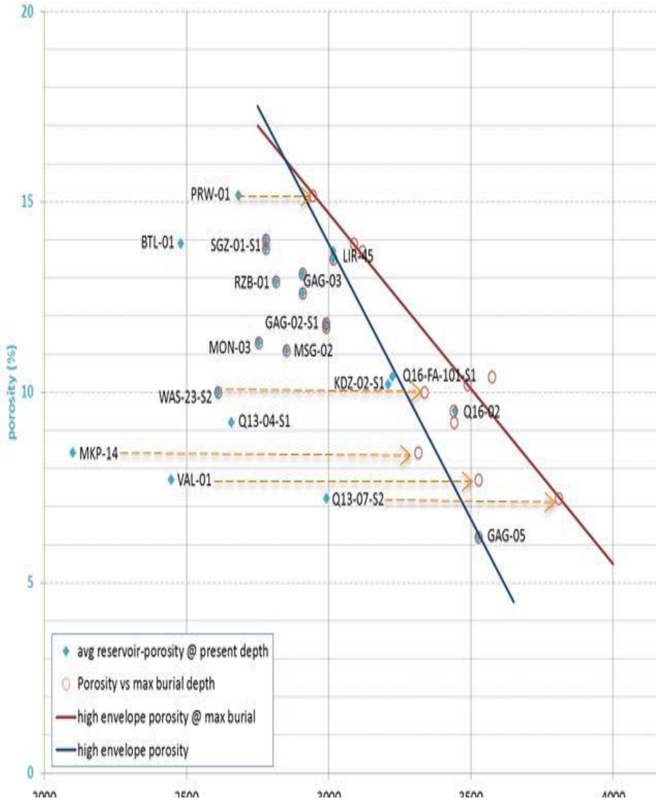

Fig. 3: Porosity depth trends. Porosity vs present depth, porosity vs max burial depth and suggestions for max porosity envelopes.

NOTES

Friday 9 September

Session One

Jurassoc Resources

Keynote Speaker: Jurassic of the Southern Permian Basin - an overview of tectonostratigraphic evolution and resource potential

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The Jurassic period was a time of marked global tectonic, environmental and biota turnovers, observed also in the area of the Southern Permian Basin (SPB) in Europe. The Pangea super-continent started to break up at the Triassic-Jurassic transition; this was also a time of giant volcanic activity in the Central Atlantic Magmatic Province, marked sea-level fall, and one of five big mass extinctions. Triassic and Early Jurassic westward propagation of the Neo-Tethys sea-floor spreading axis and accelerated crustal extension in the Central Atlantic culminated in the Mid Jurassic separation of Gondwana and Laurussia. The Early Jurassic depositional pattern was controlled by a regional transgression recorded across Central Europe and only minor coeval tectonic activity. Mid Jurassic thermal doming in the Central North Sea resulted in regional uplift of Mid-Central Europe. Jurassic uplift is observed also across much of northern Central Europe: south of the Sorgenfrei-Tornquist Zone across Denmark to northern Germany including the Ringkøbing-Fyn High and the southern part of the Danish Basin as well as the northern half of the North German Basin. On the other hand, sedimentary basins of South Central Europe experienced during the Jurassic their maximum extent. Late Jurassic northward propagation of the central Atlantic spreading centre exerted a major influence on the tectonic evolution of Central Europe leading to increased subsidence and deposition. The Jurassic depositional patterns within various sub-basins of the SPB, such as for example the North Sea, North German Basin and the Mid-Polish Trough, were to a different degree also controlled by lateral and vertical movements of the Zechstein salt.

Early Jurassic biota recovery resulted in the immense wealth of fossils throughout the whole Jurassic system. Stratigraphic subdivision of the Jurassic system into 11 stages (of which lower 7 have been ratified as GSSPs) is based on the precise ammonite biostratigraphy, supplemented by other biostratigraphic criteria, chemostratigraphy, magnetostratigraphy and sequence stratigraphy. The Jurassic varied marine, marginal-marine/deltaic and continental sediments of the SPB show strong cyclicity observed as sedimentary rhythms, in most cases controlled by sea-level changes and regional tectonics. Some marine successions represent continuous sedimentation for long periods and they can be used for astronomically calibrated timescale, as the periodicity of these microrhythms is consistent with orbital forcing due to the Milankovitch cyclicity. Cross-border facies corellations within a stratigraphic framework allow spatial correlation of different environments and creation of time-tuned paleogeographical maps.

One of useful tools to correlate marine with marginal and non-marine deposits is sequence stratigraphy. Reconstruction of sea-level changes, based on multidisciplinary sedimentological, petrological, paleontological and geochemical studies, show that sedimentation in the shallower marginal-marine settings of SPB was particularly sensitive to reflect changes in sea level; internally consistent sequence stratigraphic scheme (like that one of Poland, East Germany or Southern Sweden) can be compared with fossiliferous marine sediments of the Ligurian cycle of United Kingdom and France.

The subordinary sequences identified within the first-order Ligurian Cycle (Rhaetian-Aalenian) and North Sea Cycle (Aalenian-Tithonian) play a very important role in correlation as they can be recognised in the shallow, marginal basins (Fig. 1). Major episodes of sea-level rise occurred in the Early Hettangian, Early Sinemurian, Early Pliensbachian, Early Toarcian, Early and Late Bajocian, Middle Callovian and Late Oxfordian to Kimmeridgian.

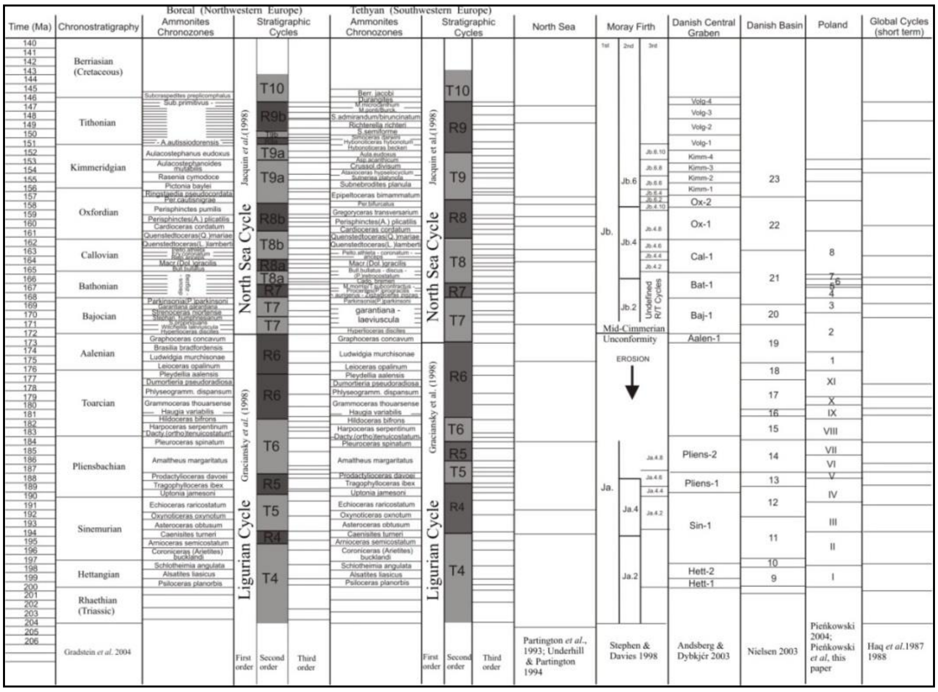

Fig. 1.Comparison of cycles and sequence stratigraphic key surfaces for the Jurassic in Central Europe. This sequence stratigraphy compilation is based on data from the SPB and the Paris Basin, the Eastern Aquitaine and the Subalpine Zone–Tethyan margin (after Pieńkowski, Schudack et al, 2008).

Transgressive trends were interrupted by episodes of stillstand and resulting progradation and hiatuses observed particularly in marginal areas, where they often correspond with erosion/non deposition stages at the sequence boundaries. A significant episode of rapid and very extensive regression took place at the end of the Triassic and in the Late Aalenian (Mid-Cimmerian unconformity), other episodes of notable regression occurred in the Late Pliensbachian, Late Oxfordian-Kimmeridgian and Tithonian and these were clearly of a regional extent, related to tectonic events in north-west Europe. Late Pliensbachian-Early Toarcian sea level changes might be connected with rapid climate changes, involving shifts from icehouse to greenhouse world. The Aalenian regression event in north-west Europe is related to thermal doming in the North Sea, which blocked passage that connected the equatorial Tethys Ocean to the Boreal Sea. This event resulted in abrupt earliest Middle Jurassic (~174 Ma) mid-latitude cooling of seawater by as much as 10 °C. In contrast, the gradual deflation of the central North Sea thermal uplift by the end of Mid-Jurassic times led to renewed marine incursions across this shallow basinal area, which resulted in broadly continuous sedimentation into the overlying marine-dominated Upper Jurassic successions. The tropical, warm, and equable climate of the Jurassic world has been challenged, especially since carbon and oxygen isotopes have been used to reconstruct the paleotemperature history. Mechanistic links between the occurrence of organic-rich black shales and sea level and climate are likely. High primary production was sustained by riverine input of nutrients under anoxic conditions. However, anoxia depended strongly on local paleoceanographic conditions and anoxic events were not always basin-wide and coeval. TOC content was controlled also by temperature-related decomposition of terrestrial organic matter on land areas – which was the case in the Polish Basin. The Oxford Clay and Kimmeridge Clay formation organic-rich mudstones and 'oil-shales' form the principal source rocks.

NOTES

X-border geology of the Jurassic: what can we learn from our neighbours?

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In the southern North Sea, the offshore sectors from five countries meet like the slices of a giant pizza (Fig. 1). Geology does not stop at the boundaries, but legislation, geological maps and stratigraphic nomenclatures often do. Geological atlases are ideally suited to cross the borders but cannot always provide the level of detail that is required in hydrocarbon exploration. By zooming out and constructing adequate cross-border correlations on the basis of integrated bio-stratigraphy and stable isotope stratigraphy, the drivers that control deposition can be identified and distinguished much better than would be the case if we would stick to our own backyard.

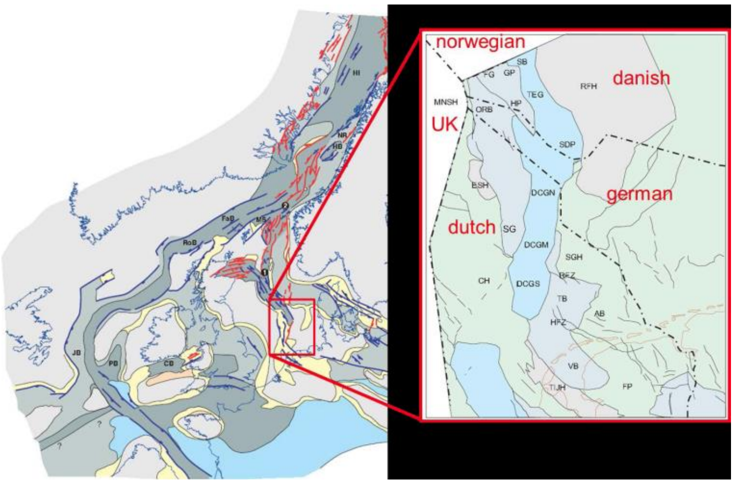

Fig. 1 The southern North Sea, an area where the offshore sectors of five countries meet. The Upper Jurassic paleogeographic map on the left is modified after Zanella and Coward, 2003.

In this paper, we present the cross-border geology of the Upper Jurassic to lowermost Cretaceous from the Danish, German and Dutch Central Graben area (see Fig. 1). A detailed correlation of the sedimentary records from these areas reveal interesting insights that illustrate the importance of cross-border geology with respect to hydrocarbon exploration. In Fig. 2 and 3 an example of such an insight is highlighted. In the Danish sector an organic mudstone (the Bo Member of the Farsund Formation) occurs in the Ryazanian. This mudstone correlates across the German and Dutch border, with the Scruff Greensand Formation, a glauconitic sandstone (Fig. 2 and 3). The trends in the wire-line logs of the Bo Member mimics that of the Scruff Greensand, indicating an aggradational nature of the sandstone. Yet, the base of the Scruff Greensand is often separated from the underlying sediments by a hiatus, reflecting vertical movements i.e. tectonic activity. This leaves us with an apparent contradiction: organic-rich, condensed sections on one side of the border, and erosive, tectonically induced sandstones on the other side. These contrasting depositional regimes may be explained by assuming a short-lived compressional phase, leading to very local uplift, in combination with a basin-wide transgression that pushed the margins of the basin, where coarse-grained deposits are trapped, far away. This gained insight provokes the thought of looking for sandy counterparts of the Scruff Greensand in other parts of the basin.

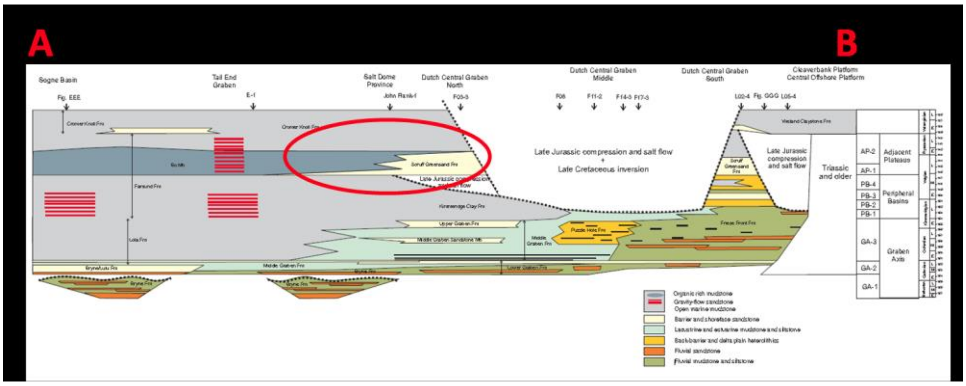

Fig. 2 Geologic cross section A-B from Denmark to the Netherlands, vertically scaled on absolute time. In the encircled area, the lateral transition is displayed from the organic-rich Bo Member of the Farsund Formation (Denmark) into the glauconitic sandstones of the Scruff Greensand Formation (The Netherlands).

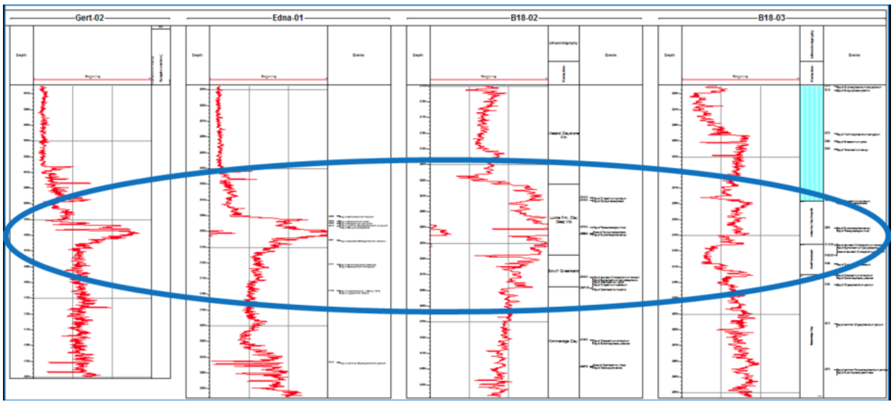

Fig. 3 Blow up of the lateral transition of the Bo Member into the Scruff Greensand Formation. Note that the trends in the wireline logs can be correlated.

NOTES

Tectono-stratigraphic evolution of active basin margins during the Late Jurassic and Early Cretaceous in the Dutch Central Graben and Terschelling Basin, Dutch offshore.

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Recent discoveries of Upper Jurassic reservoirs sands in the vicinity of basin margins in the Dutch offshore show that thick and good quality sands locally accumulated along active marginal areas. This research investigates the structural and paleogeographic controls on the deposition of continental and shallow marine depositional systems along the southern margin of the Terschelling Basin (L5 block, Fig. 1) and the eastern margin of the Dutch Central Graben (F6 block, Fig. 2).

During the Upper Jurassic-Early Cretaceous the region was subject to active rifting and salt tectonics. The distribution, nature, thickness and preservation potential of Upper Jurassic and Lower Cretaceous strata varied due to the syn-depositional tectonic activity. The study includes stratigraphic, biostratigraphic analysis and seismic interpretation, including amplitude mapping and stratal termination analysis of several key horizons and intervals. The stratigraphic analysis focused on several sand-rich stratigraphic intervals ranging from continental to lower offshore settings, including the Callovian Lower Graben Formation, the Oxfordian Middle and Upper Graben Formations, the Early Tithonian Terschelling Sandstone Member and the Late Tithonian - Berriasian
cruff Greensand Formation.

The tectono-stratigraphic analysis shows that syn -depositional faults, as well as autochthonous and allochthonous salt bodies were increasingly active along the basin margins in the Dutch Central Graben and the Terschelling Basin during the Upper Jurassic and Early Cretaceous. The differential subsidence associated with these active structures greatly affected the physiography of the basin margins by modifying the local slopes and affecting the sediment pathways, distribution confinement and preservation. These topographic features affected the geometry and distribution of fluvialdeltaic (including channels and crevasses) and shallow marine (debris flows) geobodies, creating heterogeneous stratigraphy along the basin margins. Several laterally stacked deltas and their associated channels systems are observed within the Upper Graben Formation (Figures 2B) in the Dutch Central Graben. The sediment transport direction during this period is from the east to the west. On the basin margin the channels are confined due to reduced accommodation (increased gradient and the growth of a salt diapir) and are less confined when reaching the axial zone of the Graben. A 300 m wide meandering channel is observed in the upper part of the Lower Graben Formation (Fig. 2C) and displays a different trend on the basin margin (from E to W with sharp meanders) and in the basin axis (from S to N and large and smooth meanders).

This tectono-stratigraphic study gives new insights on the complex interplay between active structures and depositional systems by empirically relating measurable external control parameters (e.g. differential subsidence) to stratigraphic heterogeneities and decreasing uncertainties in basin margin reservoir characterization. This study also highlights the potential for combined stratigraphic/structural traps in the Dutch offshore.

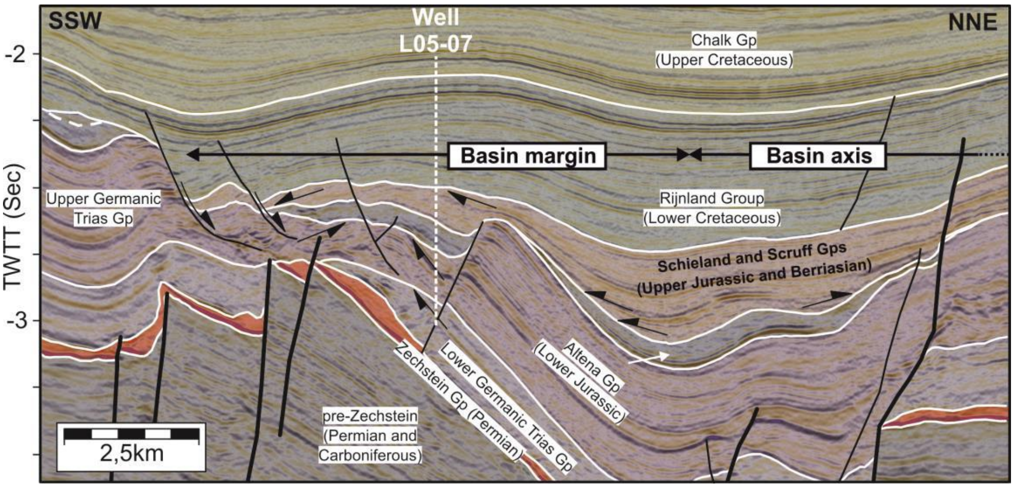

Fig. 1. Interpreted seismic section in the Terschelling Basin (block L5) showing the southern basin margin. Black arrows show truncation and stratal onlaps.

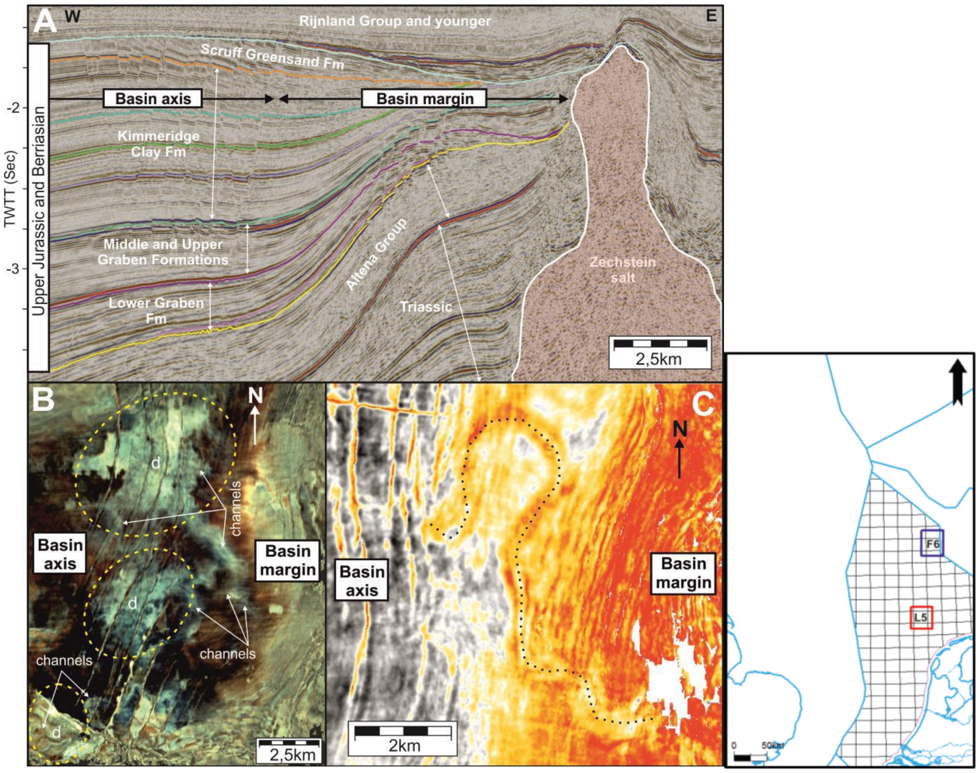

Fig. 2. Interpreted seismic section in the Dutch Central Graben (block F6) (A), spectral decomposition of the upper part of the Upper Graben Formation (B) and sweetness attribute of the upper part of the Lower Graben Formation (C) along the eastern margin of the Dutch Central Graben (block F06). Small laterally offset deltas (d) and associated channels are observed in Fig. 2B.

NOTES

Liassic and Upper Jurassic organic-rich shales in the Southern Permian Basin area. Possible targets for conventional and unconventional oil & gas exploration

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Imperial College London, South Kensington, London

The extent and geochemical quality of Liassic and uppermost Jurassic (Purbeck) organic-rich shales at the Tethys and Atlantic boundaries of Europe was studied in various locations. Samples from southern England, western England, southern Germany and central France were collected and analysed for their geochemical characteristics. These results are compared with published geochemical measurements of similar-age rocks. The Liassic organic-rich shales extend across central and southern Europe, under different names: Blue Lias (UK), Schistes carton (France), Posidonienschiefer (Germany, Austria, Switzerland), Posidonia Shales (Italy, Balkans). These rocks were deposited during the Early Jurassic, especially from the Sinemurian to Toarcian. The Blue Lias organic-rich shales charge the largest onshore oilfield in Europe, the Witch Farm field in southern UK. Upper Jurassic, lagoonal shales and carbonates outcrop in southern England and eastern France.

The Liassic organic-rich shales are found along an onshore fairway extending from the Lusitania Basin of Portugal to the Ionian Basin of NW Greece, via northern Spain, southern and central Britain, central and eastern France, Germany, Austria and Italy. Their geochemistry indicates deposition within a strongly anoxic marine environment. An important observation is that the general geochemical and sedimentary characteristics of the Liassic shales remain constant throughout their depositional fairway, which indicates an affinity in their depositional environment. The current model of deposition, involving deposition in semiisolated small basins at the north-western edge of the Lower Jurassic Tethys Ocean is, therefore, put to question. The Liassic shales are often interbedded with limestones, an indication of varying seabed topography and oxygenation. The lack of oxygen in the deeper marine water layers may be explained by local formation of wind-induced oxygen-minimum layers, or by anoxic conditions created by deep water isolation. An additional reason for the Liassic anoxic sea beds in the Tethys Ocean may be the large distance from oxygenreplenishment areas (i.e. the poles). The quality of the Liassic shales makes them an excellent candidate for shale gas & shale oil exploration. High-quality Upper Jurassic-Early Cretaceous shales and carbonates were deposited within hypersaline lagoons across the Southern Permian Basin and may create valid petroleum systems.

NOTES

Evolution of Lower and Middle Jurassic deltaic systems of the North German Basin – allogenic and autogenic controls on delta formation

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Depositional systems like deltas are influenced by external (allogenic) and internal (autogenic) controls. Allogenic controls include all tectonic processes (subsidence or uplift) of both, the basin and the hinterland, climatic processes and sea-level changes. Autogenic controls comprise basin-internal processes such as lateral shifting as result of differential compaction or avulsion. Although each of these processes influence depositional systems, intensities of individual processes may vary significantly. The assessment of allogenic and autogenic controls is crucial, for example in basin analysis or reservoir exploration.

Within a basin-scale subsurface study on Lower and Middle Jurassic (Toarcian to Bajocian) deep geothermal reservoirs, lithofacies analysis of 15 cored wells was combined with lithofacies interpretations of more than 450 wireline logs of the North German Basin (NGB). Based on this intense dataset and high-resolution ammonite biostratigraphy, the evolution of Toarcian to Bajocian deltaic systems could be reconstructed with respect to allogenic and autogenic controls. The subsurface mapping enabled for the first time the detailed morphological description of Toarcian elongate river-dominated deltas, Aalenian lobate mixed river-dominated deltas and Bajocian cuspate mixed wave-dominated and river-influenced deltas.

In the Toarcian, a delta plain of up to 20,000 km² prograded from northern basin margins up to the Pomeranian region. Meandering and anastomosing distributary channel belts of 0.8 to 8 km width formed a distributive network of an elongate river-dominated delta type. Between distributaries, bays formed subaqueous environments at the lower delta plain, whereas wetlands formed subaqueous to subaerial environments at the upper delta plain. At the lower delta plain, a marine influence can be recognized, for example by the occurrence of marine palynomorphs. Overtopping and crevassing during flood stages contributed to sheet flooding, the dominant process at the upper delta plain, and subsequent filling up of interdistributary bays. The distributary channels were fringed by lobe-like distributary mouth bar complexes representing the delta front. These complexes include terminal distributaries and mouth bars with bar-finger-sand architecture. In the Upper Aalenian, the delta plain prograded towards the South and West. Resulting from this, the delta plain enlaged to about 40,000 km² and covered larger parts of NE and NW Germany. Meandering channel belts of 1 to 10 km width formed a lobate mixed river-dominated and wave-influenced delta type. Distributaries were separated by wide interdistributary bays. The delta front was formed by thick and large progradational distributary mouth bar complexes. An increasing influence of wave action can be concluded from redeposition of sand in longshore direction, in particular in the Pomeranian region. In the Upper Bajocian, the about 30,000 km² large delta plain shifted towards the West. The cuspate mixed wave-dominated and river-influenced delta was fed by only one main active channel belt system fringed by progradational distributary mouth bar complexes. Lateral to distributary mouth bar complexes, ooid bar developed on top of shoals. These shoals protected smaller and larger lagoons, for example in the Pomeranian region. The overall cuspate shape of the delta, lagoons and ooid-bearing shoals demonstrate the predominance of wave action on delta formation.

Delta formation and progradation are related to sea-level falls and lowstands. Changes of subsidence of the NGB or hinterland uplift (Fennoscandia) can be excluded based on constant deposition rates and sandstone petrography. Thus, delta size and sediment volume are allogenically controlled, mainly by the sea-level. The change from the fluvial-dominated delta type of the Toarcian to the wave-dominated delta type of the Bajocian is considered to result from basin reorganisation. Opening of a new gate in South Poland connected the eastern CEB with the NW Tethyan relam and triggered the transition from a semi-enclosed inland sea in the Early Jurassic to a continental shelf sea in the late Middle Jurassic. The subsequent westwards shift of the entire deltaic system from the Toarcian towards the Bajocian is explained by autogenic response to differential compaction of delta plain sands and prodelta mud.

NOTES

The Liassic Posidonia Shale as target for oil exploration in the Gifhorn Trough, northwest Germany – Insights from organic geochemical analysis of oil samples and 3D petroleum systems modeling

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Within the Central European Basin System (CEBS) the Liassic Posidonia Shale is well known as one of the most important source rocks for oil and gas. Together with the Lower Cretaceous Wealden Shales, Carboniferous black shales and coals, it is a source rock for the majority of oil and gas reservoirs within the area. We present geochemical analyses of oils sourced by the Posidonia Shale from the North-Eastern Lower Saxony Basin, the Gifhorn Trough and the Pompeckj Block (Fig. 1). Methyl-phenantrene (MPI) and Methyl-dibenzothiophene (MDR) indices reveal that oil maturity is equivalent to 0.8-1.1 % VRr. This suggests a differential oil expulsion at slightly higher maturities than peak oil. The oil maturity itself can vary by quite a high degree, especially in structures like the Gifhorn Trough, where source rock and oil maturities are lower in the center (Schwarzkopf & Leythaeuser, 1988) as compared to the flanks of the structure. While undegraded oil from conventional reservoirs within the Lower Saxony Basin, Gifhorn Trough and Pompeckj Block is generally of high quality, possessing low sulfur contents (<1 wt.-%) and high API values (> 30°), biodegradation, especially in shallower reservoirs, can lead to a decrease in API values and has to be considered for prediction of oil properties.

Petroleum system modeling using the software PetroMod® was used to create a high-resolution 3D model of the study area. Geochemical analyses results, including TOC-, Rock-Eval Pyrolysis, and source rock phase kinetics measurements were used for the assessment of the petroleum potential, and, together with sorption properties used for predicting expulsion properties of the source rock. Calibration of the model was conducted using tectonic and thermal history from high number of calibration wells in combination with petrographical results from analogue samples of Posidonia Shale. Variable scenarios of erosional amount and burial history were used to calculate different scenarios of petroleum generation.*

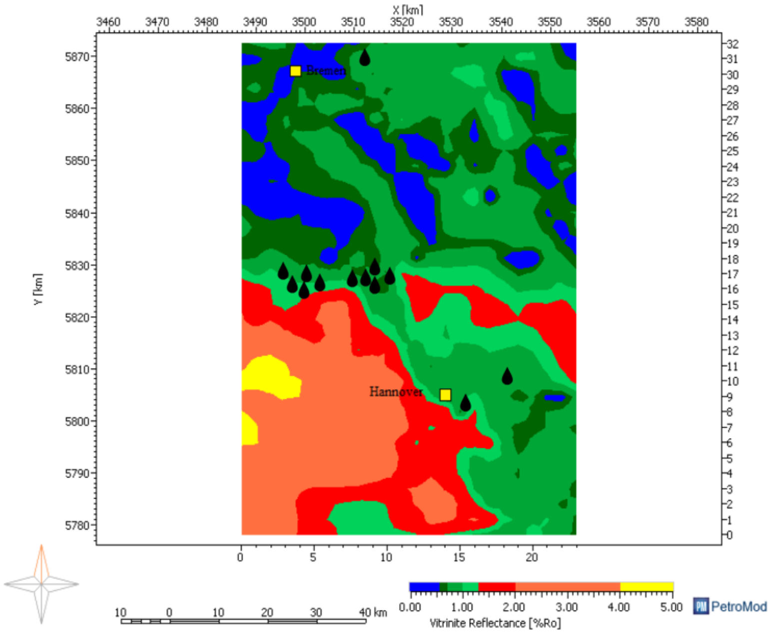

Fig. 1 - Thermal maturity map of the Posidonia Shale for parts of the LSB, Gifhorn Trough and Pompeckj Block showing the location of the analysed oil samples, modified after Bruns et al. (2014).

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NOTES

Evolution of Salt Structures and Post-Permian Depocenters in the Broad Fourteens Basin, Southern North Sea: Implications for Triassic-Jurassic Reservoir Potential.

Matthew Payne[1], Jürgen Adam, Nicola Scarselli & Steve Morse
[1] *Royal Holloway, University of London*

The Broad Fourteens Basin is a NW-SE trending positively inverted intracontinental rift basin in the Southern North Sea. The Southern North Sea was part of the Southern Permian Basin with characterized by a Zechstein megahalite succession. Consequently, salt tectonic processes strongly influenced the Post-Permian basin evolution and HC prospectivity.

This study focusses on the regional basin evolution and salt tectonic history of the Northern Broad Fourteens Basin and Cleaver Bank High. Hydrocarbon exploration in the Broad Fourteens is dominated by a Sub-Zechstein Rotliegend gas fields. However, additional prospective reservoirs are in the Post-Zechstein section, including Lower Triassic Bunter Sands, Late Jurassic Schieland Sandstone and Lower Cretaceous Vieland Sandstones. Preserved within the Broad Fourteens Basin, Mid-Jurassic Posidonia shales have the potential as an oil prone source rock (Verweij *et al.,* 2003).

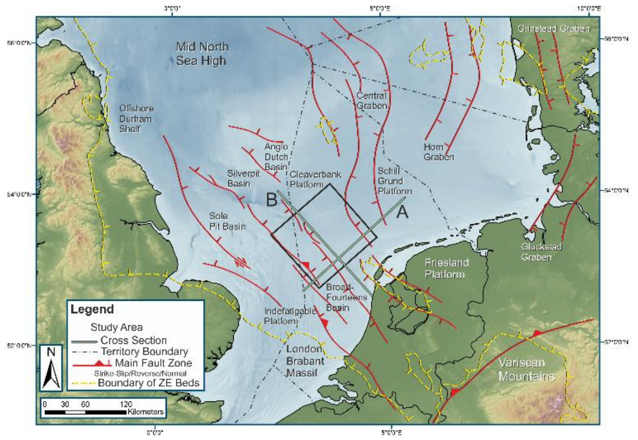

Fig.1: Study area and regional map including the main structural elements within the Southern North Sea.

Structural and seismic-stratigraphic analysis of a basin-scale 3D seismic dataset allowed: (1) refinement of the existing regional tectonostratigraphic models, specifically for the Broad Fourteen Basin with its complex thick-skinned and thin-skinned structural history. (2) Correlation of salt tectonic processes with major regional tectonic events. (3) Assessing the hydrocarbon potential of supra-salt plays.

A better understanding of the Post-Zechstein basin evolution is not only important for improving the tectonostratigraphic and kinematic models, but to investigate the potential migration pathways from sub-salt sources to supra-salt reservoirs. The presence and critical timing of petroleum elements is investigated for the key stages of thick and thin-skinned deformation with particular focus on the evaluation of the potential hydrocarbon prospectivity of the Triassic and Jurassic basin fill.

The Post-Permian evolution of the Broad Fourteens study area has been affected by:

- Saalian-Hercynian Orogenic stage (Late-Permian-Mid Triassic) which form intracontinental rift basins with salt depocenters, of the Southern Permian Basin.
- Cimmerian extensional rift phase associated with Atlantic spreading (Jurassic), with reactivation of Caledonian basement fabrics and large amounts of syn-rift deposition,and triggers reactive intra-basin salt structures.
- Post-Rift phase (Early Cretaceous) indicated by a regional erosional unconformitiy and overlying post-rift sedimentary packages during a phase of regional thermal subsidence.
- Strong inversion caused by the Alpine Subhercynian and Laramide Orogenic stages (Late Cretaceous) with inversion of basement faults with fault block rotations, marginal low-angled fault reactivations and contractional reactivation and growth of salt diapiric walls on the adjacent Broad Fourteens Platforms.
- Post Inversion Stage (Late Cenozoic-present day), continues to deform stratigraphic sections through thin-skinned gravity driven processes, forming extensional reactive diapiric structures and salt welds in areas of greatest salt displacement.

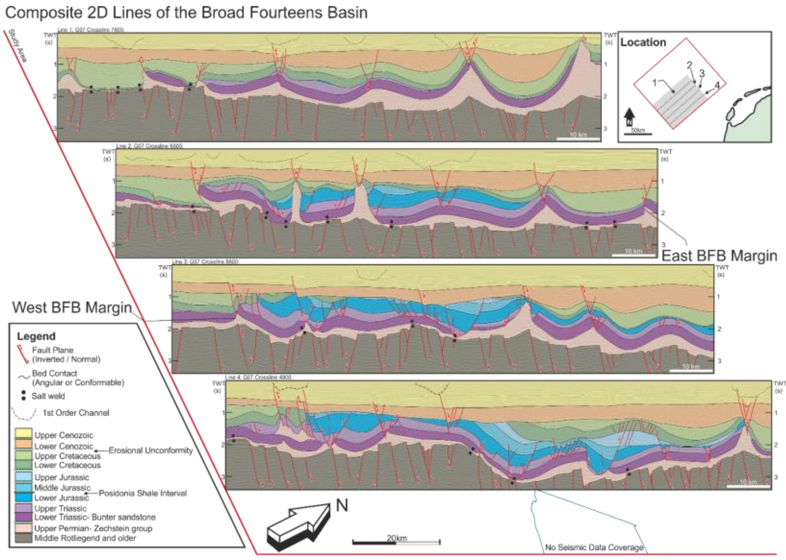

Fig.2: Composite parallel fence diagram displaying the spatial evolution of the Broad Fourteens Basin, Southern North Sea, in the SW-NE orientation. (Red line: perimeter of study area, Blue Line: Perimeter of 3D seismic coverage)

A series of conceptual restored regional sections of the Broad Fourteens Basin and Platform have been integrated into a 4D tectonostratigraphic model. The correlation of sub-salt and supra-salt structural geometries by composite structural maps have identified areas of hard-linked and soft-linked structures.

Furthermore, the Broad Fourteens Basin and Platform show very contrasting structural configurations. In the Broad Fourteens Basin, potential hydrocarbon plays include 4-way/3-way dip closures and salt juxtaposed trap geometries with potential charge from Posidonia Shale and Carboniferous Coal sources. Many of these potential traps formed during inversion in the Late Cretaceous. Upper Jurassic deep reservoir intervals are preserved within the basin center. Below, Lower Triassic Bunter-Sands have a greater area of preservation and coverage across the basin. Oil and gas migration from sub-salt sources may percolate through salt welds, up-dip through carrier beds and through fault systems. Welds formed from the Mid-Cretaceous to present due to salt withdrawal beneath subsiding depocenters and inversion-related diapir growth.

The Broad Fourteens Platform gas plays may include the similar trap geometries within salt confined minibasins, with gas charge through salt welds into Lower Triassic sands. This production model is analogous to other oil discoveries and gas fields in the Northern Broad Fourteens Platform area. Total inversion of the Broad Fourteens in the Late Cretaceous increases the risk that pre-inversion formed reservoirs are eroded or destroyed by biodegradation during meteoric water infiltration. Petrophysical and attribute analysis may be utilized to produce viable leads.

Friday 9 September

Session Two

Cretaceous Resources

Keynote Speaker: Cretaceous tectonic evolution of the Southern Permian Basin

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The Cretaceous evolution of the Southern Permian Basin (SPB) is governed by two contrasting tectonic regimes: (1) Approximately SW-NE-directed extension leading to differential subsidence of several sub-basins and (2) contraction, directed SSW-NNE, inducing basin inversion and sometimes reactivation of normal faults. The extensional episode started in Late Jurassic time and continued until the Early Late Cretaceous. Most of the inversion phase is bracketed between 90 and 70 Ma, but it is commonly viewed to be part of a long-lasting Late Cretaceous-Paleogene contraction regime comprising several distinct events. The two-phase deformation affecting a stratigraphic succession which contains several evaporitic levels in Permian and Triassic strata has often created structures of bewildering complexity when studied in detail. However, thin-skinned deformation on a large scale has not been documented, and neither the bulk extension nor the contraction accommodated across the SPB exceed a few tens of kilometers or ca. 5% strain.

Since the pioneering work of Ziegler (e.g., 1987), the Meso-Cenozoic intraplate deformation of west-central Europe was interpreted to be linked to the opening of the Atlantic Ocean and the evolution of the Mediterranean realm. In particular the inversion episode is thought to be caused by (micro-)continent convergence and collision. However, the European intraplate deformation is episodic in time and fluctuates in space, probably much more so than ocean spreading or orogenic deformation whose driving mechanisms are linked to large-scale mantle convection and therefore unlikely to proceed in stop-and-go mode. Episodic and shifting deformation characterizes both the extensional and the contractional periods. For instance, the onset of the Late Jurassic-Early Cretaceous extension regime coincided with a rotation in the extension direction from ca. W-E to SW-NE, and with a shift of main subsidence centres to sub-basins on the southern border of the SPB (e.g., Lower Saxony and Broad Fourteens). At the same time, substantial parts of the SPB ceased to subside (e.g., Pompeckj Block to western Poland), whereas other structural elements remained active (Central Graben). Similarly, basin inversion in Late Cretaceous time affected the area from Poland to the North Sea but was absent or much weaker farther southwest. The opposite appears to hold for Cenozoic contraction.

Intraplate contraction and inversion are traditionally viewed as reactions to changes in the adjacent orogens, particularly the transition from subduction to continental collision. However, improved kinematic and timing constraints on plate motions and the tectonic evolution of the Alpine mountain belts and intraplate structures reveal a lack of synchronicity. The global plate reorganization event that started the convergence of Africa and Europe is now interpreted to have occurred at 105-100 Ma (Matthews et al. 2012). This matches 100-90 Ma HP metamorphism in Austroalpine units (Froitzheim et al. 2008) but pre-dates most intraplate shortening. The main, Late Cretaceous phase of central European intraplate shortening between about 90 and 70 Ma does not seem to correlate with any clearly identifiable event in the Alpine orogens. Its onset overlaps in time with oblique spreading in the Valais Basin. Spatially it is centered on a ca. 600 km wide swath along the southwestern border of the Baltic shield, while the Helvetic shelf remains undeformed except for some areas in the external Alps of southern France. Iberia shows no sign of intraplate deformation at that time, although the Pyrenees have entered their first stage of growth. Conversely, the Eocene peak of orogeny in the Pyrenees and Alps has very little or no correlative intraplate deformation in central Europe, but shortening is recorded in the Channel area and southern Britain. Intraplate deformation of that age also creates the inversion structures of the Iberian Ranges. The Neogene stages of the Alpine orogeny have not created any major intraplate shortening structures.

An alternative view of orogeny and broadly coeval intraplate deformation is therefore one of no simple cause-and-effect relationship. Rather, both phenomena should be driven by the same, relatively continuous plate motions. The episodic nature of deformation must be strongly modulated by rheology varying in space and over time. For orogens, such variations may be due to different types of crust entering the subduction zone, for intraplate areas due to rifts that go from initial weakening to slow cooling and strengthening. Without invoking time-dependent rheology it is difficult to understand why Iberia deformed little in Late Cretaceous time but strongly in the Eocene, or vice versa in central Europe.

The concept of tectonic inversion as an uplift mechanism has sometimes been overplayed. The evidence for several discrete pulses of Late Cretaceous to Cenozoic inversion (the Subhercynian, Laramide, Pyrenean and Savian phases) is primarily stratigraphic, not structural. Attention should be paid to the specific mechanisms capable of inducing uplift and erosion of characteristic magnitude and wavelength or areal extent. These mechanisms are: (1) Thrusting and folding producing localized uplift of some km to a few tens of km wavelength. Uplifting areas are tied to structures and interspersed with subsiding basins. The magnitude of uplift can attain many km. (2) Folding of the lithosphere has been modelled to produce long-wavelength subsidence and uplift. In central Europe, lithospheric folds of 270 km wavelength and 1.5 km amplitude have been interpreted (Bourgeois et al. 2007). (3) Thinning of the mantle lithosphere can lead to uplift on similar wavelengths as lithospheric folding. In a simple isostatic model the lithospheric mantle must thin by many tens of km to create 1 km of uplift. However, (4) dynamic topography resulting from upwelling mantle can also contribute to uplift. Only mechanisms (1) and (2) fit the definition of inversion, i.e. uplifting an extensional basin after a change to a contractional regime.

In Europe, thrusting and folding account for much of the Late Cretaceous uplift which was widespread but localized and created strong structural relief. By comparison, all later phases are subdued and appear to uniformly uplift larger areas. Discrete structures associated with them are scarce. For instance, the Paleocene Laramide phase coincides with the termination of chalk deposition and the emergence of large stretches of west-central Europe. These changes occur indiscriminately across Mesozoic grabens and inversion structures. It is hard to see how this could have been caused by mechanisms (1) or (2) above. Nevertheless, the Laramide phase is commonly considered a tectonic event comprising regional uplift and inversion (e.g. Doornenbal & Stevenson 2010), and interpreted to be the strongest inversion event in some Dutch basins (de Jager 2007). In analyzing the tectonic evolution of the SPB it is useful to separate inversion events associated with discrete structures from unconformity-creating events whose lengthscales and patterns neither match thrust-related uplift nor lithospheric folding. It is probable that at least some of the latter events reflect upwelling in the upper mantle and/or thermal erosion of the mantle lithosphere. These processes can even coexist with inversion: Some areas of Late Cretaceous intraplate shortening exhibit superimposed coeval, long-wavelength uplift and exhumation, an effect that cannot be attributed to the insignificant increase in crustal thickness caused by the contraction of small magnitude.

NOTES

Vlieland sandstone distribution in the G&M blocks offshore the Netherlands: New insights in the distribution away from the known areas

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Early Cretaceous strata are target for oil and gas exploration in the Dutch on- and offshore. The Vlieland sandstone formation (KNNS) of Early Cretaceous age is a proven reservoir in Netherlands. The distribution of the Vlieland sandstone is spread over several different basins (and highs) in the Netherlands, and it is often assumed that the Terschelling basin defines the northern extend of the KNNS. On the Schill Grund High (SGH) however, there are several wells that have encountered the Vlieland sandstone. Most wells show a thickness of a few meters of sand at the base of the Vlieland shales. In general, the KNNS shales out towards the north into the Vlieland Claystone formation (KNNC).

This study shows that the presence of this basal transgressive sandstone of the KNNS extents further towards the north than shown in earlier studies. Jeremiah (2011) shows a northern extend of the sandier facies belt into the Vlieland basin in the late Ryazanian age. However, in the G7-2 well at the Schill Grund High, a thick section of fine sandstone and siltstone is found at the base of the Vlieland Claystone. The well aimed at a deeper target and was found to be dry and no valid structure is present at Vlieland sandstone level. Besides this well, a number of wells in the Terschelling basin and the Schill Grund High have encountered up to tens of meters of this transgressional sands at the base of the Vlieland claystone formation, suggesting localized deposition away from the main depocenters (Fig. 1).

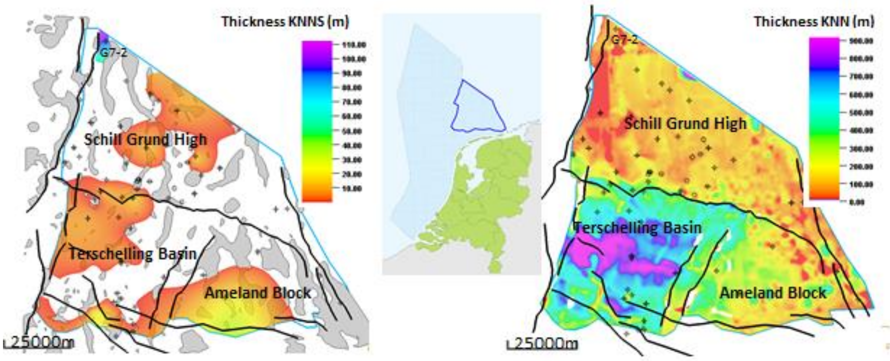

Fig. 1a: Vlieland Sandstone thickness, based on well data only(*). Grey outlines are salt structures. (The thickness is often below seismic resolution and therefore very difficult to pick on seismic).*

Fig. 1b. Lower Cretaceous Vlieland subgroup thickness.

The subcropping sediments may have an impact on the paleo topography during the lower Cretaceous and therefore on the distribution of the KNNS. Fig. 2 shows the Base Cretaceous Unconformity (BCU) subcrop map. Salt tectonics play an important role in the depositional history of the area and it is likely that salt withdrawal has created local accommodation space for the transgressive Vlieland sandstones. The large thickness of the Vlieland sandstone encountered in the Northern part of the Dutch Schill Grund High in well G7-2, suggests that there might also be a Northern provenance for the sediment supply; the Ringkøbing-Fyn high is a likely candidate as a source for the sediments.

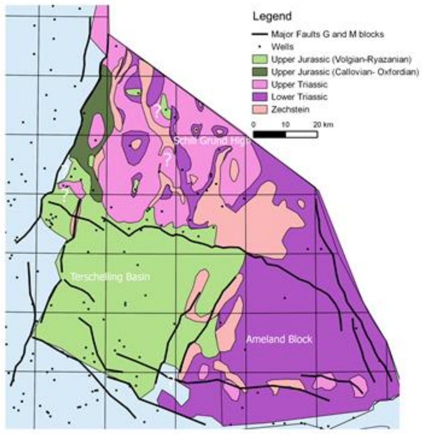

Fig.2: Subcrop map of the Base Cretacous unconformity

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The sedimentology of the English Wealden (Lower Cretaceous) and implications on potential fluvial reservoir quality

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The Lower Cretaceous Wealden sediments in England are mainly sandstones, siltstones, mudstones, and ironstones and were deposited in predominantly fresh water environments with some lagoonal and tidal influences. The sedimentary facies show that deposition occurred in both braided and meandering river systems although meandering facies are more prominent in the lower Ashdown Formation. Petrographic analysis on the arenaceous facies within the Ashdown and Wadhurst Clay Formations reveal that the sandstones and siltstones are quartz arenites and quartzose siltstones composed mainly of quartz grains. Porosity and permeability of the Wealden outcrop samples were measured using pycnometry and gas permeametry methods respectively. Porosity in the sandstones ranges between 6.3% and 13.2% with an average of 9.9% while permeability ranges from 0.4mD to 11.9mD with an average of 3.1mD. The prominent Cliff End Sandstone with the highest porosity and permeability has the best quality, followed by the Top Ashdown Sandstone, the Ashdown Sandstone at Haddock's Cottages and by the sandstones at Rock-a-Nore in the lower part of the Ashdown Formation with generally low porosity and permeability. The main controls on porosity and permeability in these sandstones are grain sizes, grain shapes, and sorting which are intimately linked to their depositional environments. The potential of these sandstones and siltstones as possible analogue for fluvial reservoirs and their usefulness for regional correlation are reviewed. This study provides useful data on the porosity and permeability of the English Wealden sandstones and lays the foundation for advanced assessments, which can fully access their potential as possible analogues for fluvial reservoirs.

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The Bentheimer Sandstone revisited: a new sedimentological interpretation of the massive sands.

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Background

The Lower Cretaceous Bentheimer Sandstone is one of the best known rocks in the world. It is quarried in and around the village of Bad Bentheim in Germany close to the German-Netherlands border. The Bentheimer Sandstone was frequently used as a building stone (Dubelaar and Nijland, 2014) predominantly in Germany and the Netherlands. The sandstone also features in numerous geomechanical, petrophysical and flow experiments (e.g. Wolf et al., 2015; Reyer & Philip, 2014). One of the prime qualities of the Bentheimer Sandstone is its textural and mineralogical homogeneity. The sandstone is often massive and classified as fine to medium grained quartz arenite. It is very well sorted and the grains are sub- to well-rounded (Kemper 1976; Wolf et al., 2015). Excellent outcrops of the massive sandstones are found in quarries near Bad Bentheim. There is general agreement that the sands were deposited in a relatively shallow marine environment. Kemper (1976) suggests water depths in the order of 10 to 20 m. Wonham et al. (1996) describe the massive beds as gutter or channel-fill facies. During field trips the massive sandstone beds have been interpreted as either upper shoreface sands, washover sandstones, mass flow deposits or storm sands. We will focus on the detailed description of the massive sandstone beds and propose a novel depositional mechanism for these sandstones.

Observations

The massive sandstone beds of the Bentheimer sandstone in the Bentheim area are one to four meters thick and invariably have a sharp, flat base (Figure. 1). They generally overlie dm-thick beds of thoroughly bioturbated fine-grained to silty argillaceous sandstones. In the basal part of the beds horizontal to low-angle lamination is vaguely visible. The lamination is defined by subtle textural differences and occasionally highlighted by alignment of flat elongated to slightly curved oversized pores interpreted as dissolution holes and moulds of shell hash. Apart from this, significant grading is absent. Locally, vertical burrows interpreted as escape burrows are found in the base of the massive beds, indicating rapid burial. The middle part of the beds is structureless. It generally constitutes the main part of the bed. The top bed boundary is either undulating, curved or shows V-shaped indentations interpreted as plastic deformation structures (Fig. 2). The top 0.1-0.2 m is burrowed and contains, amongst others, frequent *Ophiomorpha* burrows, indicating post-sedimentation quiescence. On the upper surface of the bed locally large ichnofossils interpreted as *Rhizocorallium* are found. In outcrop, mostly 2D-cuts, the beds are lenticular, pinching out to the east and the west over several 10's, often 100's of meters. They beds have an erosive base and locally cut into the underlying set of massive sands. This is evidenced by the erosional truncation of the fine-grained silty sand which can be followed laterally to a sand-sand contact lined with clast moulds and finally to a subtle "weld" line. It appears that the lenticular shape is asymmetrical: a more gradual thinning towards the east with respect to the west.

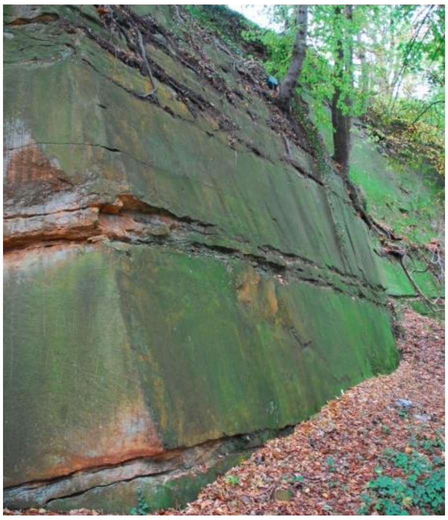

Fig. 1: Example of the Massive beds (Schlüters Kuhle, Bentheim)

Fig. 2: Irregular top surface of a massive bed (Freilichtbühne, Bentheim).

Depositional mechanism

Our new interpretation of the origin of these massive sandstones is inspired by the depositional and palaeogeographical interpretation of the Paleogene Brussels Sandstone as presented in Houthuys (2011). The massive beds of the Brussels Sandstone are, facies wise, similar to the massive sandstone beds of the Bentheimer Sandstone. Additionally other facies such as the cross-bedded sandstone sequence under the Bentheim Castle (Wonham 1996) has its equivalent in the Brussels Sandstone in the Bierbeek Quarry. The working hypothesis is that there is analogy in the facies architecture and depositional environment between the Brussels and Bentheimer sands.

The Brussels sands are interpreted to be deposits originating from a series of breaching events, or “controlled” channel bank or channel slope collapses and their resultant “sustained gravity mass flows” (Van den Berg & Mastbergen, 2002). This corresponds well with the indications for channelized tidal flow in the central part of the Bentheimer sandstone near Bentheim Castle (Wonham 1996) (see also Houthuys, 2011).

Future work

In order to substantiate the interpretation of the massive sand beds, the larger scale sedimentary environment needs reinterpretation for the entire nearshore Bentheimer Sandstone succession by reconstructing the detailed paleogeography. This can be done by mapping the geometry of individual beds, measuring the palaeo-flow directions and integrating the observations in a 3D model.*

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Tectonic control on deposition of the Early Cretaceous Bentheim Sandstone Member in the Schoonebeek oil field, the Netherlands

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The Bentheim Sandstone Member is the reservoir interval of the Schoonebeek oil field – one of the largest onshore oil fields in Europe. It was recently redeveloped, and its extensive well data and a high-resolution seismic survey were used in this study. Recent production problems ask for an improved understanding of reservoir continuity. This is determined not only by structural compartmentalization, but also for a considerable part by factors controlling accommodation, palaeogeographical development, and sedimentary facies distribution. Complex differential subsidence of the German/Dutch Lower Saxony Basin played a major role in the deposition of the sands comprised in the Early Valanginian Bentheim Sst Mb. But sedimentological variations of this shallow marine deposit are nevertheless minor over a large area (> 120 km).

The objective of our study was to evaluate the extent and mode of tectonic control on the deposition of the Bentheim Sst Mb in the Schoonebeek oil field. The main issues addressed in this presentation are the structural style of the Schoonebeek area, the deformation history of the Bentheim Sst Mb, and the extent to which local fault movement affected the present-day thickness differences of the Bentheim Sst Mb. To this end, detailed 3D seismic interpretation of local fault patterns as well as interpretation of key horizons were undertaken. Palinspastic reconstructions of several parallel sections illustrate the pre-deformational state of the Bentheim Sst Mb. Well-data were used to map the local thickness variation of the Bentheim Sst Mb. Sub-regional seismic sections were interpreted to analyse the structural evolution of the larger Schoonebeek area.

Local thickness changes of the Bentheim Sst Mb were found to be gradual, and without correlation to the closely spaced fault patterns, nor to the major faults of the complex Schoonebeek structure. Instead, it is hypothesized that the Bentheim Sst Mb and the encompassing Early Valanginian to Barremian Vlieland Subgroup were deposited on an unstable, changing palaeo-topography. Crucial elements controlling deposition in the larger Schoonebeek area during the Valanginian were halokinesis and thin-skinned folding. The development of Bentheim Sst Mb depocenters was controlled by development of Late Cimmerian synclines combined with Zechstein salt withdrawal into the cores of anticlines (Fig. 1). This structural style resulted in wedge-shaped depositional geometries and a multitude of low-angle internal unconformities. The development of a transpressional pop-up structure resulted in local erosion of the Bentheim Sst Mb unit shortly after its deposition (Fig. 2). Subsequent Albian peneplanation of the area was preceded by an episode of normal faulting that locally protected the Vlieland Subgroup deposits from erosion on downthrown blocks.

This study clearly demonstrates the importance of regional studies in the understanding of field-scale phenomena. It is concluded that major controls on deposition of the Bentheim Sst Mb were dominated by far-field tectonic forces with pre-existing fault structures resulting in variable local expression. Since no evidence was found in Schoonebeek for syn-depositional faulting related to a tectonically enhanced rift valley during deposition of the Bentheim Sst Mb, an alternative model is put forward. It involves syn-depositional folding and/or halokinesis to produce wedge-shaped depositional architecture in the Vlieland Subgroup. This model better explains the observations of gradual thickness changes, broad sedimentary facies belts, the paucity of onlaps and spatially variable preservation of the Bentheim Sst Mb.

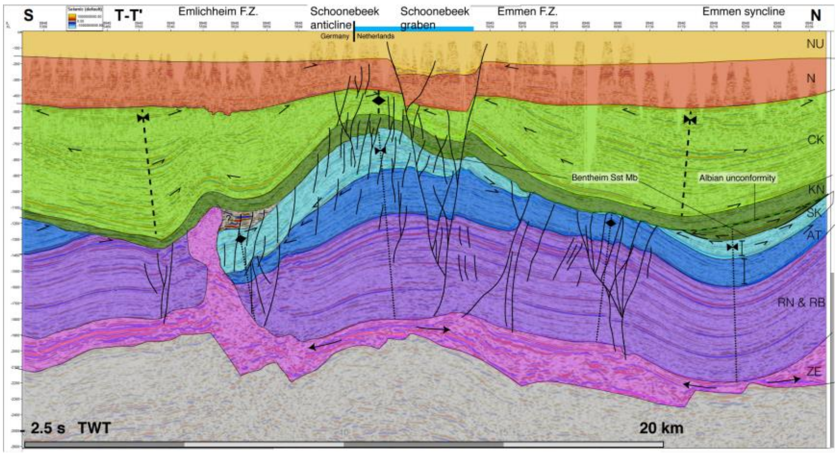

Fig. 1, N-S seismic section showing the extent of the Schoonebeek redevelopment area in blue at surface level. The Bentheim Sandstone Member is present near the base of the Early Cretaceous (KN, i.e. Rijnland Group, dark green). Note its substantial preservation in the core of the Emmen syncline, as well as the clear expression of the Albian angular unconformity (indicated by a dashed line). This unconformity is present in the Schoonebeek structure as well, but is less pronounced. Two generations of folding with different wavelengths can be distinguished: Cimmerian and Alpine folds (indicated with coarsely dashed and finely dashed axial trace, respectively). During Late Cimmerian tectonics, Zechstein salt withdrew from below the synclines towards the anticlines in which crestal faults developed. Albian peneplanation concluded this episode. The Sub-Hercynian basin inversion superimposed a second set of folds that were accompanied with new crestal faults of the Schoonebeek structure.

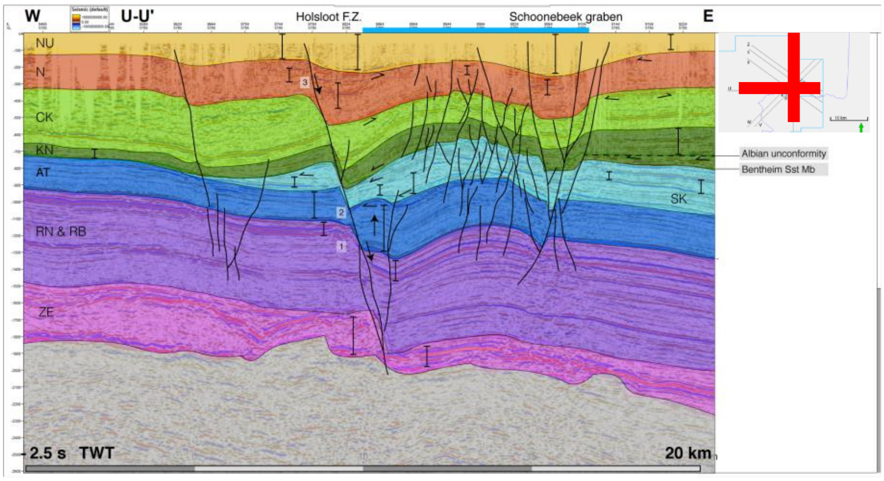

Fig. 2, E-W section which strikes parallel to the Schoonebeek anticline hinge line with the East Netherlands High to the west and the Lower Saxony Basin to the east. The pre-Variscan Holsloot fault zone (trending N-S) also played an important role in the Mesozoic development during which it was reactivated multiple times. First as a normal fault during the Late Triassic and Early Jurassic (1), that was reversed into a pop-up structure (2) during the Late Jurassic to Early Cretaceous Late Cimmerian tectonics. Continuous reverse movement of this pop-up structure resulted in the onlap of Early Jurassic Niedersachsen Gp (light blue). During later movements, the top of the Niedersachsen Gp was eroded, as was the Bentheim Sandstone Member shortly after its deposition which consequently resulted in the Schoonebeek reservoir western pinch-out. This fault was activated again during the Paleogene and Neogene as a normal fault (3), downthrowing all previous structures.

NOTES

The impact of heterogeneity in clastic shallow-marine shelf reservoirs: the importance of geological understanding in waterflood developments.

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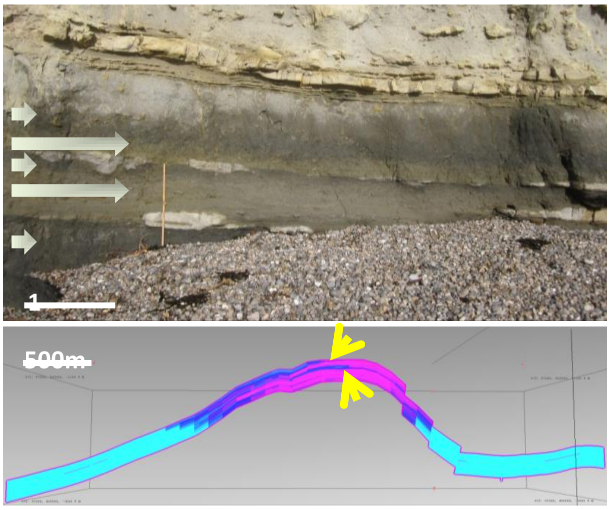
A solid geological understanding to the way fluids flow through a reservoir is crucial when considering waterflood developments in heterogeneous reservoirs. Recent integrated production geoscience and reservoir engineering studies on the Holland Greensand oil reservoir (Aptian) of the Rotterdam field in the West Netherlands Basin, are used to illustrate the geological controls on fluid flow in a clastic shelf depositional environment.

An integrated understanding of the sub-surface has been gained through core, log and production data analysis. Analogous Early Cretaceous coastal exposures in south-west England have been used to gauge the scale of lateral and vertical heterogeneity, and its impact on hydrocarbon and water flow paths. This has been used to steer static reservoir model construction and subsequent simulation. Results from field testing by production logging tool analysis, fully support the geological concepts developed and the modelling approach used. This work has major implications for defining the approach for future reservoir management and re-development, in particular the well type and configuration and completion strategies post-reservoir flooding. The application of such methodologies is recommended for similar waterflood developments.



Top: Upper Greensand Formation, Hooken Cliffs, Devon, UK, displaying interbedded argillaceous sandstones and arenaceous mudstones, analogous to the Rotterdam field Holland Greensand oil reservoir. Sandstones in the Rotterdam field are believed to be laterally extensive, with those of higher permeability acting as the main conduits for fluid movement.
Bottom: Upscaled saturation model of the Holland Greensand reservoir, Rotterdam field, after 28 years of water injection. Arrows indicate layers of higher permeability with high water saturation (oil = pink, water = blue).

NOTES

Risk reduction of geothermal energy projects: Case study of the Delft Sandstone

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Since the first deep geothermal doublet was realised in 2007 in the West Netherlands Basin (WNB), 13 more geothermal doublets were drilled, of which six targeted the Delft Sandstone of the Nieuwerkerk Formation (Late Jurassic – Early Cretaceous). The energy generated by the doublets is currently exclusively used for greenhouse heating.
Prerequisite for the optimal placement of a geothermal doublet is the availability of a detailed reservoir model in which the size, shape, spatial distribution and connectivity of the geothermal aquifers are captured. Our current knowledge of the aquifers in the WNB is from hydrocarbon exploration. Vintage 2D and 3D seismic data, oil and gas wells that are all located on structural highs, and lithostratigraphical well-to-well correlations all contribute to the currently used subsurface model. Extrapolation of subsurface data from the structural highs to the lows, where the geothermal targets are located, results in increased geological uncertainty and economic risk for the lows.

The Delft Sandstone is interpreted as massive, stacked distributary-channel complex in a coastal-plain setting. It occurs in different sub-basins of the WNB showing variations in development, wells in the same sub-basin show major differences in the characteristics of the Delft Sandstone. The NW-SE elongated fluvial trend is constrained by syn-sedimentary rift fault activity. The depositional setting contributes to the reservoir heterogeneity and uncertainty about aquifer connectivity.

In this paper an improved stratigraphic correlation and depositional model of the Delft Sandstone are presented, based on newly-acquired biostratigraphy data from geothermal wells in combination with well-log correlation, 3D seismic, and sequence stratigraphic concepts. The model will be important in reducing the risks when planning future geothermal doublets. and preventing interference between adjacent projects.

NOTES

Facies reconstruction and aquifer properties of Lower Cretaceous sandstones in the Lower Saxony Basin (North Germany) - a geothermal perspective

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Numerous clastic aquifer complexes with a potential for geothermal applications are expected in the North German Basin. This study focusses on Lower Cretaceous sandstone units in the Lower Saxony Basin (LSB), which form the shallowest Mesozoic aquifer complex. It consists of the so-called “Valendis-Sandstone” of Valanginian age and the sandstones of the Isterberg Formation (“German Wealden”) of Berriasian age. Both units are widely present in the LSB and can be found at depths up to about 1700 m. The E-W striking LSB is around 300 km long and 65 km wide and can be subdivided into three sub-basins with different depositional developments. In general, the western part of the basin is mainly filled with claystones with some carbonate intercalations and subordinate sandstones at the basin margins, whereas the central and eastern sub-basins consists of claystones and intercalated fluvial to deltaic sandstones (Röhling et al., 2013).

Facies changes were analyzed on well sections using Gamma Ray and Spontaneous Potential logs, core description and thin section analysis. For each well a Volume of shale (VSH) model was established to differentiate between sand and clay, and to determine the sandstone thickness. Aquifer properties like porosity was calculated from logs and permeability is derived from calculated porosity in the wells. Existing porosity and permeability measurements from conventional core plugs analyses were used to quality-control the log derived values. A lithostratigraphic correlation was established to map the major sandstone units.

The Valanginian comprises a sandstone belt (“Valendis-Sandstone”) along the northern margin of the basin, deposited in a shallow marine environment. This relatively narrow belt pinches out to the basin centre, were clay-rich deposits dominate. The “Valendis-Sandstone” is a relative homogenous, structureless, fine- to medium-grained sandstone and reaches a maximum thickness of around 70 m. Large sections of this sandstone consist of poorly consolidated sand with high porosities, and only a few well-cemented zones were recorded.

The Isterberg-Formation is characterized by a variety of depositional environments. The northern and southern margin of the LSB is dominated by fluvial to deltaic-estuarine deposits with an alternating sequence of thin sandstone layers (up to max. 10m), thick claystones and local coal layers (Pelzer, 1998). In the central part of the basin two sandstone units can be determined. Both units are intercalated in clay-rich deposits. The cumulative thickness of these sandstones reaches up to 45 m, however single sandstone units are commonly not greater than 20 m. The sandstones are fine- to medium-grained, partly well sorted, and typically homogenous. However, the porosity is partly reduced due to massive cementation.

The “Valendis-Sandstone” is a well-known oil reservoir in the LSB (Boigk, 1981). According to the transmissivities determined in the present study, this sandstone unit could be a primary target for geothermal use. On a regional scale, the sandstone units of the Isterberg Formation in the central part of the LSB barely meet the minimum requirements for geothermal use. Nevertheless, suitable aquifer conditions may be developed on a local scale.

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F17-Chalk: New Insights in the Tectonic History of the Dutch Central Graben

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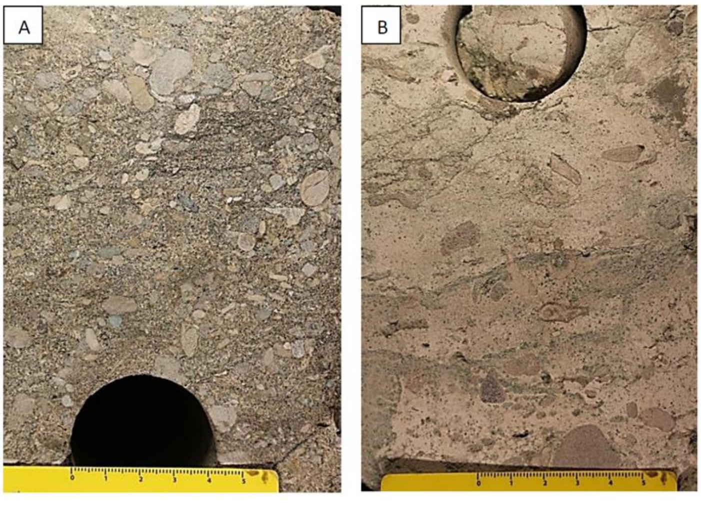
Between 2012 and 2015 Wintershall Noordzee BV discovered oil in two Chalk closures in Dutch offshore block F17 at the southern end of the Dutch Central Graben. Previous published maps of this area showed the Chalk to be absent due to erosion by inversion tectonics.

The entire Chalk section (<100m) has been cored at these discoveries. Sedimentological and biostratigraphical analysis of the cores resulted in new insights in the geological and tectonic history of the Dutch Central Graben. The geological analysis and 3D seismic interpretation of the Chalk interval proved that the main tectonic inversion of the Dutch Central Graben is related to the early-mid Campanian Sub-Hercynian tectonic phase and not to the Paleocene Laramide phase, as often assumed in literature.

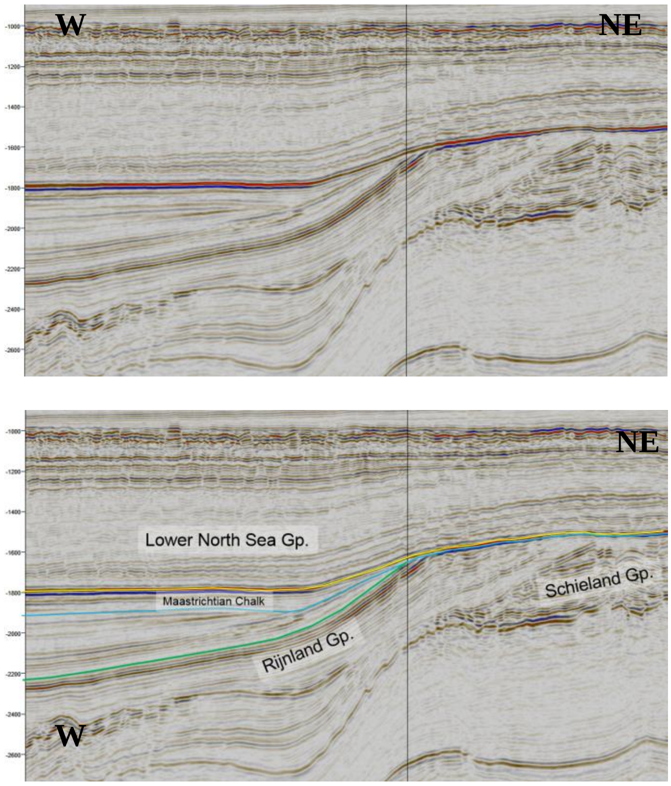
Clastic intervals found above the Sub-Hercynian unconformity document the presence of an eroding island in the Chalk sea after the Sub-Hercynian inversion, which was largely submerged again during the Maastrichtian. The clastic intervals, time equivalent to the Vaals Formation in the south of the Netherlands, are erosion products of the underlying Schieland, Scruff, Rijnland and older Chalk formations. The clastic material is deposited as shallow marine glauconitic sandstones, often with a high carbonate content, which originated from eroded older Chalk. In addition to the sandstones, pebble size clasts are found floating in Chalk matrix, most likely deposited by submarine debris flows.

The overlying Maastrichtian Chalk is characterized by a cleaning and deepening upwards of the section. The lower part of the Maastrichtian Chalk contains more than 10% siliciclastic grains, which reduces to a few percent in the upper part of the Maastrichtian. This is thought to be due to a transgression of the Chalk sea, largely covering the island, thereby reducing the erosion area available for clastic input.

The Maastrichtian Chalk is disconformably overlain by Paleocene (Selandian to Thanetian) marine claystones. The uppermost part of the Maastrichtian, the Danian and the lowermost part of the Selandian are missing at this location. The cored disconformity surface shows a marine hard-ground development with burrows into the underlying Chalk. The Laramide phase is here mainly a period of non-deposition and not of major erosion and tectonic activity.



*Well F17-11: Mid-Campanian conglomerate with Chalk matrix.
A: clast supported, B: matrix supported*



Seismic section Dutch offshore blocks L1 and L2, western flank of inverted Central Graben. Un-interpreted and interpreted section. Thin Maastrichtian Chalk is present over inverted Central Graben. Yellow: Top (Maastrichtian) Chalk, Blue: Sub-Hercynian Unconformity (note phase change) and Green: Base Texel Chalk.

NOTES

Poster Presentation Abstracts

Lower Jurassic transgressive-regressive cycles in NE Germany and W Poland - lithofacies analysis and faunal distribution

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The North German Basin (NGB) and the western part of the Mid-Polish Trough (MPT) are large geotectonic structures of the Central European Basin (CEB) with a high potential for geological use of the deeper underground, i.e. geothermal heat production, storage of gas and fluids. Main reservoir units are within the (1) Middle Buntsandstein, (2) Stuttgart Formation, (3) Rhaetian, (4) Lower Jurassic, (5) Middle Jurassic and (6) Lower Cretaceous. Although former studies have investigated these intervals, the knowledge is rather preliminary, in particular about spatial distribution of reservoirs and their properties (porosity, permeability).

In cooperation with the TU Bergakademie Freiberg, the University Göttingen, the Polish Geological Survey (PGI) and the Federal Institute for Geosciences and Natural Resources (BGR) the projects *Sandsteinfazies*, *GeoPoNDD* and *GEOPOLD* were established a refined cross-border biostratigraphic and sequence stratigraphic framework for NE Germany (Mecklenburg-Vorpommern, Brandenburg) and NW to W Poland.

In this study, we focus on the Lower Jurassic of E Germany and W Poland. Following significant environmental perturbations around the Triassic/Jurassic boundary, the Early Jurassic in the NGB was characterized by alternating marine transgressions and regressions. Marine transgressions entered the NGB from the North-West and South and expanded stepwise towards the East, culminating with the entire flooding of the NGB and the MPT in the Early Pliensbachian and Early Toarcian. The marine basin extended from onshore UK via NW Germany, NE Germany and Pomerania up to the Holy Cross Mountains region. Although marine influence (marine palynomorphs) is already evident in the Rhaetian, fully marine ammonite fauna initially entered the NGB in the Early Hettangian. Enhanced ammonite migration towards the East occurred in the Early Pliensbachian.

Based on a combined approach of biostratigraphy and sedimentary architecture, an ammonite calibrated sequence stratigraphic framework of the Lower and Middle Jurassic of the NGB was developed (Fig. 1). Time-constrained mapping of biofaunal dispersal reveal repeated shifts of shorelines resulting in pronounced strata pattern architectures of basinal and costal sediments. Lithofacies and biofacies maps were constructed for ten biostratigraphically constrained intervals showing the spatial dispersal of marine, brackish-marine, brackish-aquatic and terrestrial conditions. This framework can be further correlated with Western Poland (Pieńkowski, 2004). In a further step, the spatial dispersal of lithofacies associations, that were interpreted on cored and logged wells, will display the paleogeography of the Early Jurassic in the NGB and western Poland.

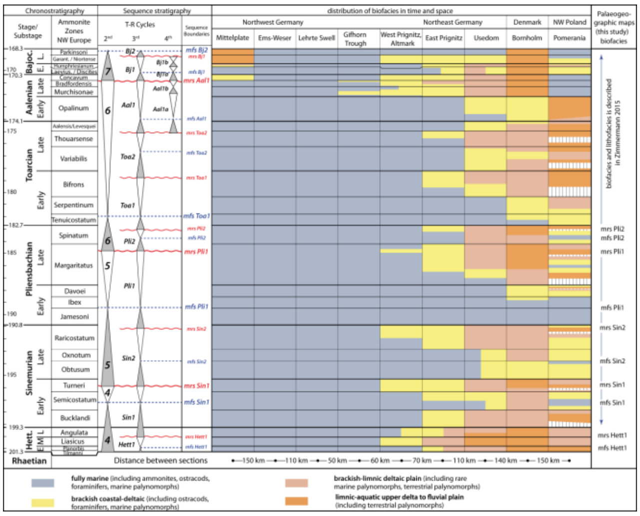

Fig. 1: Stratigraphic column showing Lower and Middle Jurassic ammonite zones together with T-R cycles and the levels of paleo biofacies maps constructed in this study. Table compiled from data by Zimmermann et al. (2015) and Barth et al. (in review).

Source rocks, thermal maturity and unconventionals in the Weald Basin

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The Weald Basin in southeast England is a well-known target for oil and gas, however these deposits often prove to be limited in extent. Despite over four hundred exploration wells being drilled in the Weald there has been limited success due to a lack of understanding of the structural geology and sedimentary sequences in the basin. Four potential source rocks have been identified in this basin including Jurassic marine clays such as the Lias, Oxford and Kimmeridge as well as the Early Cretaceous terrestrial Weald Clay. In the context of the Weald Clay as a viable source rock there are two significant unknowns, which are the lateral and vertical distribution of organic matter throughout the unit and the thermal maturity of the clay. Preliminary total organic carbon (TOC) values indicate generally low values throughout the Weald Clay but with localised high TOC peaks. Vitrinite reflectance studies reveal that high palaeogeothermal gradients were present and that the lowest part of the Weald Clay often has a ‘dog leg’ with much steeper temperature gradients. The current data illustrates that the Weald Basin has a complex history in both the structural and sedimentary geology which needs to be fully understood to uncover the true hydrocarbon potential of the basin.

Determining the source rock properties of the Weald Clay will be achieved by studying the TOC values and vitrinite reflectance of cuttings and core samples from commercially released wells. High TOC peaks will then be tied to wireline log data, correlated across the basin and then palynologically calibrated. Organic matter that has been isolated from high TOC peaks will be typed using transmitted and incident light microscopy. These results will then be used to produce a detailed understanding of the thermal history of the Weald Basin and associated source rocks as well as a map of the location and stratigraphic level of the optimal source rock within the Weald Clay.

Kinematic Analyses and Structural Restoration of the Schillgrund Fault as Eastern Boundary of the German Central Graben

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The Central Graben is one of the most prominent Mesozoic rift-structures within the Central European Basin system and a major hydrocarbon province in the North Sea. In Germany, the Central Graben crosses the westernmost part of the German North Sea sector (Entenschnabel; Fig. 1a), where it shows a pronounced half-graben character. Its eastern flank is represented by a major fault structure (Schillgrund fault, also named Coffee Soil fault in the Danish sector), whereas its western flank forms a broad, low amplitude anticline, dissected into several minor horst and graben structures (Step Graben system; Fig. 1b).

The highly complex structural and sedimentary evolution of the Central Graben was investigated by numerous studies. However, previous research interests were mostly confined to prospective hydrocarbon areas in the Norwegian, Danish and Dutch parts of the Central Graben, whereas its German part is comparatively under-explored and investigated in an overview scale only. Although reviewing structural styles and features, none of the previous studies dealt with kinematic analysis, structural restoration, detailed quantification of Mesozoic graben subsidence or quantification of strain in detail.

As a consequence, the study presented here, as part of the project TUNB ("Subsurface Potentials for Storage and Economic Use in the North German Basin"), intends to better constrain the structural evolution of the Eastern German Central Graben. To do so, we carried out detailed seismic interpretation of Triassic to Cenozoic intervals along seismic lines approx. perpendicular to the Schillgrund fault (Fig. 1c). In subsequent steps we will perform retro-deformation and decompaction analyses along lines using MOVE software (Midland Valley Exploration) aiming to: (i) investigate the subsidence history of the German Central Graben area by determining the individual subsidence processes and deciphering their contribution to total subsidence observed; (ii) better constrain the timing of deformation along the Schillgrund fault during Mesozoic extension/rifting and contraction/inversion; (iii) investigate the influence of Zechstein salt mobilisation on the deformation style in the Post-Permian strata; (iv) derive constraints for future static and dynamic volumetric modelling studies (e.g. petroleum system and lithofacies modelling, fluid migration modelling).

Although structural restoration and kinematic analysis have not been completed yet, we can draw based on seismic interpretation and interim modelling results, the following preliminary conclusions:

The Schillgrund fault can be subdivided into several sub-parallel, steep normal faults with probably oblique components, which are connected by steep transfer structures and relay-ramps, wherefore we prefer the name Schillgrund fault system (SFS) instead of Schillgrund fault. With regard to the base Zechstein, the total visible fault-offset across the SFS vary from 2000 m - 3000 m and shows only moderate horizontal proportion. However, major rollover structures (Fig. 1c) in the Mesozoic overburden suggest a considerably higher amount of extension.

Concerning the base Zechstein, the German part of the Central Graben forms a 'structural high' compared to its Danish and Dutch counterparts. This might be related to a higher amount of displacement during Late Cretaceous inversion tectonics as compared to the adjacent Dutch and Danish Central Graben area. Thrusting along the SFS related to Late Cretaceous reactivation and structural inversion also resulted in the development of a foreland basin on the eastern graben flank, which was filled by thick Upper Cretaceous sediments.

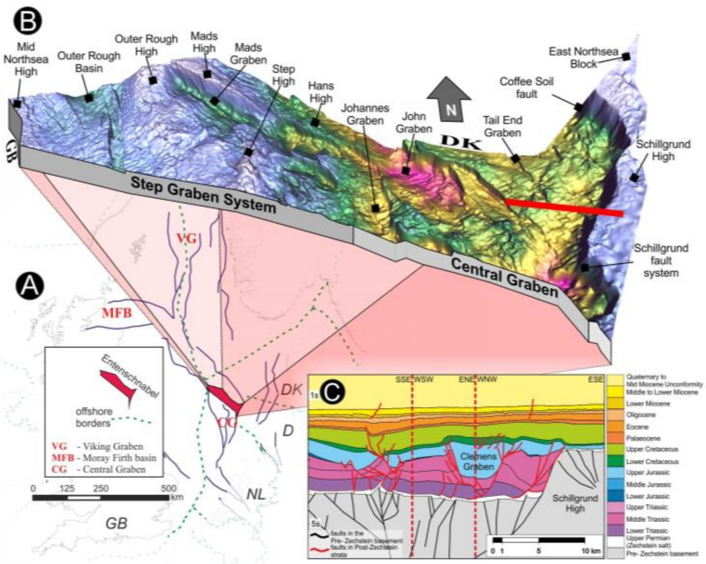

Fig. 1: a) Overview map of the North Sea region with location of the study area (Entenschnabel) and the main graben systems; b) 3D view of the Top Pre-Zechstein (blue to green colours indicate structural highs; pink to yellow colours show structural lows); c) cross-section with structural interpretation across the Schillgrund fault; line of section is highlighted as red line in b).

Structure and evolution of the Western Pomeranian Fault System in NE-Germany and its continuation towards Denmark and Sweden across the southern Baltic Sea

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The subsurface of the southern Baltic Sea area was the subject of oil and gas exploration by the former Petrobaltic organization in the 1980s. Based on these activities several re-processed seismic lines west of Rügen Island give new insights in style and evolution of fault zones. These investigations are the goal of the joint research project USO (Untergrundmodell Südliche Ostsee) of the Geological Survey of Mecklenburg-Western Pomerania and the University of Greifswald.

The investigation area USO West is located at the northern margin of the North German Basin (NGB) as part of the Southern Permian Basin. The structural evolution of this area is characterized by different tectonic phases that resulted in formation of fault zones of varying orientation and structure. The major NW–SE trending faults of the Tornquist Zone as well as the Tornquist Fan were generated by late Paleozoic extensional movements (Berthelsen 1992, Thybo 2000, Graversen 2009). Nearly at the same time the formation of the Northern and Southern Permian basins started. The initial phase of rift volcanism was followed by the major subsidence phase. The ongoing basin evolution during the Mesozoic was accompanied by transtensional movements (Cimmerian tectonics), especially above the TransEuropean Suture Zone (TESZ), where Baltica collided with Avalonia during the Mid-European Caledonian orogeny. Thus, the NW to NNW trending Western Pomeranian Fault System (= Vorpommern-Störungssystem) developed. These faults border graben and halfgraben structures in NE Germany and adjacent offshore areas (Krauss & Mayer 2004). Compressional tectonics during late Cretaceous to early Tertiary times led to inversion of structures, e.g. the Grimmen anticline (Jubitz 1981, Krull 2004).

The reprocessed seismic data west of Rügen Island offer the opportunity to distinguish between several fault systems and to discuss their northwards continuation into known fault systems of Denmark and Sweden as mentioned earlier by Dadlez (1993), Krauss (1994), Vejbaek (1997) and Schlüter et al. (1998). At least four major fault systems occur within the study area (Fig. 1). The WNW oriented Wiek fault crosses the northern part of Rügen Island. Based on well data and onshore 2D seismic it has the highest vertical offset of about 3000 m. Ordovician rocks deformed by the Caledonian orogeny in the north are displaced versus Carboniferous strata in the south, whereas Mesozoic units are not affected. East of Rügen reactivation of the fault is suggested by a fault system of similar orientation, which shows offsets within the Mesozoic deposits (Seidel et al. 2015). West of Rügen, the NW–SE striking Wiek fault can be extended to the Odense fault in Denmark.

The northern part of the investigation area is crossed by the very complex NNW–SSE trending Agricola Fault System that belongs to the Western Pomeranian Fault System according to Krauss & Mayer (2004). Two major faults can be determined. The Plantagenet fault shows an offset of about 500 m at the base of Upper Permian. Thickness differences of Upper Triassic deposits suggest formation during the Late Cimmerian tectonic phase. A continuation of this fault into the Öresund Fault System is suggested by Håkansson & Pedersen (1992), Krauss (1994) and Schlüter et al. (1998). The second major fault, which was also generated by Late Cimmerian movements, is named Agricola fault (sensu stricto). It trends nearly N–S, and might rather be connected with the Svedala fault (Thomas et al. 1993, Krauss 1994 and Schlüter et al. 1998). Even recent seismic surveys show a nearly N–S trending fault in Triassic deposits (Hübscher et al. 2010), which could be interpreted as the link between the Svedala and Agricola faults.

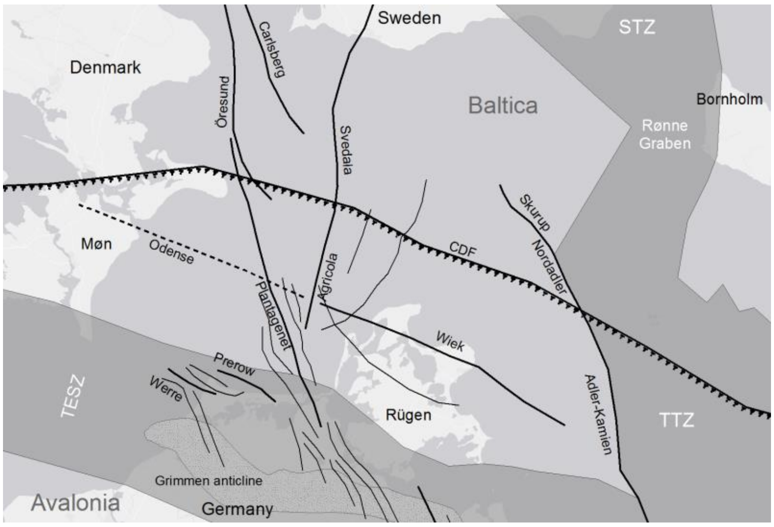

Fig 1: Major fault systems in the southern Baltic Sea between NE Germany, Denmark and southern Sweden. TESZ: Trans-European Suture Zone, STZ: Sorgenfrei-Tornquist Zone, TTZ: Teisseyre-Tornquist Zone (after Graversen 2009, Thybo 2000, Krauss 1994, Thomas et al. 1993)

Paleogeography and facies architecture of the North Sea Chalk: implications for hydrocarbon exploration

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Spectrum Geo Ltd. (UK)

The North Sea Chalk is Upper Cretaceous-Paleocene limestone, characteristic of medium to shallow water and pelagic environments. Its evolution started with a widespread carbonate platform, including also anoxic shales and mudstones, which are regionally distributed and related to the Cenomanian transgression. Carbonate facies formed by erosion and re-sedimentation processes are well known, “allochthonous chalk”, frequently associated to mass transport and deep water channelized systems.
Regional 2D seismic data currently allows the mapping of the sedimentary patterns within the chalk, which can be related to different sequences and depositional environments. The interpretation is challenged by the lateral continuity of the seismic horizons and the seismic facies. Stratigraphic terminations and paleo-morphological reliefs can be highlighted at distances of tens or hundreds of kilometres. Three paleogeographic domains have been identified, laterally and vertically juxtaposed, extended in the entire southern North Sea and part of the central sector: 1) persistent carbonate platform (Cenomanian-Maastrichtian), 2) diachronous carbonate shelf/ramp (Turonian?-Danian), 3) slope to basin (Maastrichtian-Danian) (Fig. 1).

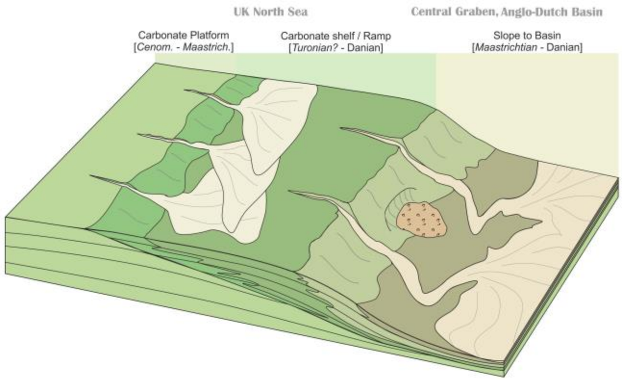

Fig. 1 Sketch representing the paleogeographic domains distinguished in the chalk.

The paleogeographic evolution of the North Sea chalk has been compared to other back-stepping carbonate system. A peculiarity is in the low angle relief of the shelfs and the ramps, eventually associated to differences in the bathymetry, and not related to any absolute value of paleo water depth.
The chalk underlies a previous morphology controlled by Lower Cretaceous deltaic systems and the salt movement of the Zechstein evaporites. Halokinesis and tectonic structures were present during the chalk deposition, particularly in the areas of the Central Graben and in the Anglo-Dutch Basin (Figure1), controlling the local thickness and the facies. 3D seismic interpretation highlighted the lateral and vertical homogeneity of the platform in the UK sectors (Quad. 20-21) and the complexity of the shelfal and pelagic domains in the Central Graben and in the offshore Netherlands, overall where the halokinesis was more active.

The chalk is a successful target for the hydrocarbon exploration, with significant discoveries and fields in production. Fields include: Ekofisk, South East Tor, Eldfisk, Valhall and Hod in Norway, Joanne, Banff, in UK and Kraka, Dan, Gorm, Tyra and Skjord in Denmark. The exploration case-history suggests that the paleogeographic setting influenced the diagenetic processes, the hydrocarbon migration, and finally the reservoir properties. Reservoir conditions tend to be associated with more pelagic chalk, overall if re-sedimented (Norwegian fields), while most of the failures concentrate within the platform (UK sector). In the UK North Sea, thermogenic hydrocarbons, of Jurassic source rocks, are present in the Eocene clastic deposits, conformably above the chalk, suggesting preferential migration paths oriented laterally along the platform shelfs and up-dip in the overlying units.

Sedimentology, palynology and heavy mineral analysis of the Triassic Skagerrak Formation of the Central North Sea: An integrated approach

Roger Burgess, Ewan Gray, **Iain Greig**[1]
[1]*University of Aberdeen*

The Mid-Late Triassic, Skagerrak Formation of the Central North Sea is a dryland continental succession, comprising alternating fluvial sandstone and lacustrine-palustrine mudstone dominated members, with significant exploration potential within a mature petroleum basin.

This study, with initial focus on UK quads 22/29/30, integrates sedimentological, palynological and heavy mineral analyses, and aims to provide a deeper understanding of the stratigraphic framework, regional Triassic palaeogeography and resultant facies distribution north of the Mid-North Sea High.

Although Skagerrak deposits in this region are commonly perceived to be laterally homogeneous, previous studies have recognised lateral facies changes and significant diachroneity between lithostratigraphic members. Sand-prone intervals in the form of the Judy, Joanne and Josephine Sandstone Members, which provide reservoir intervals to several CNS fields, represent deposition of a fluvial and terminal fluvial system with multiple sediment sources, primarily Scottish Highland and Fennoscandian upland areas.

Core-identified depositional facies from the fluvial and terminal fluvial Skagerrak integrated with heavy mineral provenance data can be used to suggest the proportionality of lateral to axial dominated systems. These core facies can be matched quantitatively to wireline log data to produce a wireline facies signature. This signature can be utilised to interpret facies proportion changes in various intervals within the Skagerrak Formation across the CNS, thus allowing regional depositional models to be produced.

Although palynology has long been used for age determination and environmental reconstruction, Triassic sediments have previously yielded poor recovery due to a combination of PDC drilling techniques, oil based muds, poor preservation and the heavily oxidised nature of the Skagerrak. Utilising state of the art palynology processing techniques to maximise and concentrate the sporomorph content within drillcore and well cuttings, a robust age model can be constructed along with paleo-environmental interpretation providing a chronostratigraphic framework.
The combination of palynological and sedimentological environmental reconstructions allows for a composite reconstruction from two independent data sources, with sediment sources constrained by heavy mineral provenance.
The preliminary results of this integrated regional study are presented.

Dry well analysis for the Triassic play of the German and Danish Horn Graben: source rock presence, charge timing and complex salt movements.

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[1] Shell Exploration and Production Deutschland.
[2] Shell Projects and Technology, Rijswijk

The Horn Graben is a significant late Carboniferous to Late Triassic extensional system formed at the meld between the Avalonia and Baltica tectonic plates (present day offshore areas of Germany and Denmark). Late Carboniferous dextral shear and its interaction with existing basement blocks generated a series of rotated basement structures and dissecting lows (Horn Graben, Rynkobing Fyn High and Gluckstadt Graben). During the Carboniferous and Permian periods the stratigraphy and tectonics affecting this area appears to have been consistent with other areas of the basin with likely Carboniferous coal-rich deltas, a period of inversion resulting in erosion, deposition of dryland and evaporitic systems during the Rotliegend and large-scale evaporite development during the Zechstein period. However, in the Triassic, greatly increased heat flow (related to the re-organisation of Pangaea) across the Horn and Gluckstadt grabens led to significant extension and the deposition of 3.5 to 6 km of Triassic sediments. As in much of northern Germany and the Netherlands, large sections of the Jurassic are missing due to a period of inversion. The sequences here are completed by Cretaceous chalks and Tertiary mixed clastic systems.

The presence of the Horn Graben as a deep (up to 9 km) extensional basin has, and continues to be, of interest to the hydrocarbon industry. A number of well penetrations have reached the Lower Triassic “Buntsandstein” equivalents, targeting salt-generated rollover structures. All have been considered dry. Beha et al. (2008) proposed that these dry holes can be explained in two ways:

1. Any Carboniferous coals were eroded during the early Permian inversion phase and, therefore, no gas generating source rock is present (no well penetrations within this interval).
2. Charge has occurred but has not reached the Triassic because of the sealing Zechstein salt interval.

Here we present an alternative explanation based on new seismic interpretation and basin modelling. It is possible that no Carboniferous coals are present but a number of bright seismic reflectors below the Base Permian Unconformity may hint at source rock preservation. The Zechstein thickness is also highly variable representing the transition from Upper Permian basin to platform facies. As such, it is suggested that any gas charge could have reached the Triassic interval. Instead we suggest that the timing of possible charge was prior to, and feasibly during, the main halokinetic phase. Therefore, any Triassic rollover structures are likely to have formed too late or carry a serious risk of underfilling. It is felt that the Triassic could offer further potential in longer-lived traps (e.g. against bounding faults). The presence of salt diapirs also gives the possibility that subtle thermal effects allowed for small pockets of delayed gas generation.

With no pre-Triassic well penetrations this new basin model understandably carries significant uncertainties particularly in terms of crustal thickness, heat flow, source rock facies and the amount of Jurassic erosion. However, the timing of peak expulsion seems relatively robust relative to the timing of halokinesis. The authors would welcome further insights with regards to model inputs and implications.

Tackling petroleum systems in the German North Sea with 3D basin and petroleum system modelling

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The German North Sea covers an area of around 35,000 km² and hosts about 80 exploration wells. Its northwestern most part, the so-called Entenschnabel has a size of approximately 4000 km² and contains ~28 exploration wells. The German North Sea is bordered to the North by Denmark, to the South by the Netherlands and to the West by the United Kingdom. North of the central German North Sea, in Denmark only few wells were drilled, which targeted the Horn Graben and did not encounter petroleum. South of the central German North Sea, in the Netherlands numerous wells were drilled and discovered economic gas reservoirs. These gas reservoirs, situated in Rotliegend sandstones, are sourced by Upper Carboniferous coals. The same petroleum system extends into the German North Sea but the amount of nitrogen increases from the Netherlands into Germany rendering all reservoirs, found until present, uneconomic. To date the reason of the increasing nitrogen amount is not fully understood. The Entenschnabel area in the northwest looks much more promising. It contains a producing gas field (A6-A) which is sourced by Carboniferous coals. Farther, to the northwest in the UK offshore two oil fields exist within reservoirs in Upper Jurassic sandstones. In Denmark to the north numerous oil fields are exploited which have their reservoirs in Upper Cretaceous-Palaeogene Chalk sediments. There, the main source rock is represented by the Kimmeridge Clay Formation with the Bo Member. In the Netherlands to the south the Posidonia Shale is the source rock for two more oil fields in the Central Graben structure. Additionally, the presence of a Lower Carboniferous source rock in the study area is likely. Therefore, we created several freely available basin and petroleum system models to study the maturation of source rocks, their petroleum generation and migration in this part of the Southern North Sea. The models incorporate structural data published in recent years and additional literature data. They represent one realization of the existing data and can be further refined and modified to address specific topics of petroleum generation or other geological questions.

Unfaulting, unfolding and unconformities in the Schoonebeek Oil Field, the Netherlands -- clarifying the stratigraphy

Kees W. Rutten[1], Willem Smoor[2]
[1]*Slokkert Consultancy*
[2] *VU University Amsterdam*

We have applied the Landmark ezValidator software on the 2005 NAM high-resolution seismic survey of the Schoonebeek oil field to clarify the stratigraphic relationships of the Early Cretaceous Bentheim Sandstone Member reservoir unit to its underlying and overlying successions. ezValidator (www.slokkert.nl) provides a view of the seismic after restoration, i.e. unbroken by faults, and unfolded on one or more horizons. Unconformities can be shown as gaps representing missing section.

The original seismic survey was post-processed using a Structural Oriented Filter for noise reduction (Fig. 1). Three major unconformities are shown in the restored section (Fig. 2). The unconformity gaps are determined by the unfolding of seven horizons, using a top and a base horizon for each unconformity. This display can be interpreted like a Wheeler diagram.

The deepest, Late Jurassic unconformity (Weiteveen-C; Atlantic break-up) shows little missing section in the center and major erosion on the sides. The center part apparently subsided prior to the unconformity, protecting the sediments locally. In addition, there might be several other unconformities just above and below the mapped Weiteveen-C level.

The base-Bentheim unconformity shows substantial erosion of the underlying Coevorden Formation towards the NE side and limited erosion on the SW flank. The Coevorden Formation was protected by subsidence on the SW flank prior to unconformity time. On the NE side, above the unconformity, sediment formed a wedge onlapping onto the unconformity.

Two complementary displays provide more detail of the base-Bentheim unconformity. The first display (Fig. 3) highlights the paleostructure by unfolding the unconformity itself, assuming that the unconformity peneplenated the underlying succession. This shows the paleostructure of the subsided SW flank of the Coevorden Formation. The second display (Fig. 4) highlights the interaction of the stratigraphy by unfolding on a horizon above and a horizon below, while the unconformity itself is shown as a gap determined by the unfolding space requirements. This shows the onlapping wedge on the NE side really well. By mapping thickness variations and seismic reflection terminations in these structural and stratigraphic displays the relative timing and onlap/offlap/erosion relationships of the sediments above and below the unconformity can be defined.

The Paleocene unconformity (Fig. 1) shows the Late Cretaceous uplift and Early Tertiary erosion in the center. Towards both flanks the earlier sediments were protected. The bowl-shaped unconformity gap is the opposite of the butterfly-shaped gap of the Weiteveen-C unconformity.

Using ezValidator helps to provide insight into the complex relations between faulting, folding and erosion/onlap at unconformities as shown here in overview and in detail. By restoring the seismic at an unconformity the seismic below it can be read as paleostructure. Alternatively, by restoring the seismic at multiple levels and showing gaps at unconformities, the resulting seismic can be read as a Wheeler diagram.

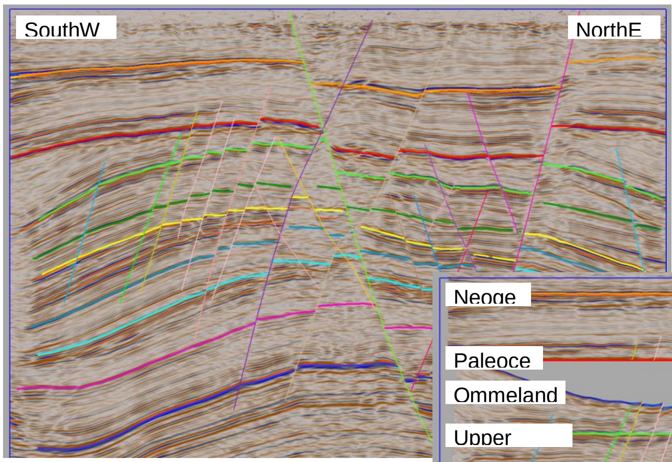

Fig. 1: Original seismic Landmark SOF 9x9x15

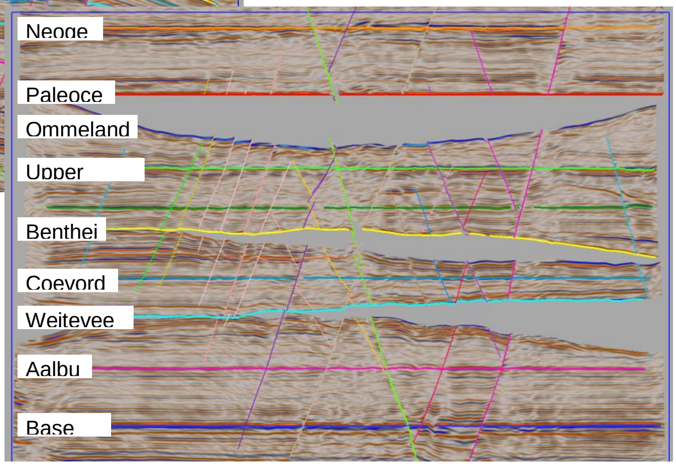

Fig. 2: Seismic unfaulted and unfolded on seven horizons. Stratigraphic display with gaps for three unconformities.

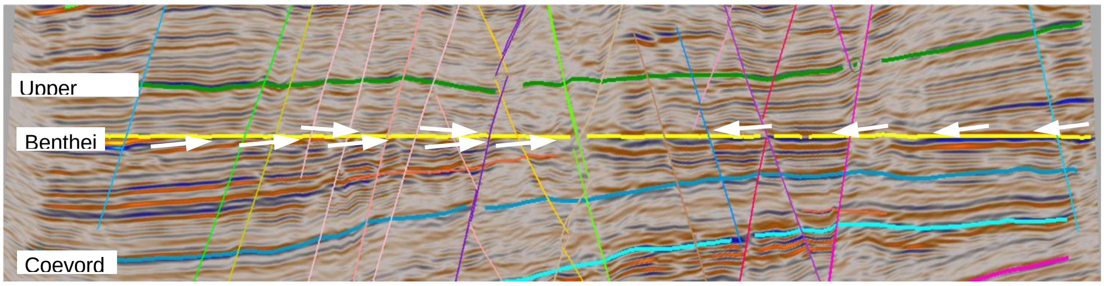

Fig. 3: Structural display unfolded on base-Bentheim unconformity. White arrows for seismic reflection terminations (approx.).

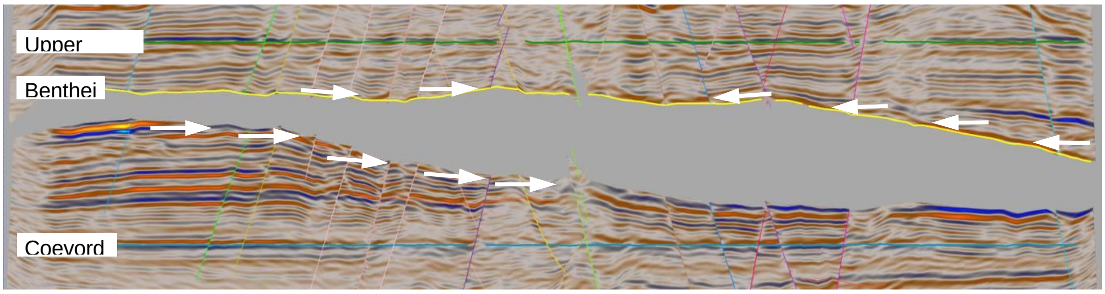

Fig. 4: Stratigraphic display with unconformity gap at base-Bentheim unconformity. Unfolded on horizons above and below the unconformity. White arrows for seismic reflection terminations (approx.).

Thick vs thin-skinned deformation of the Sole Pit High (UK Southern North Sea Basin) and its impact on the evolution of supra-salt prospectivity

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The Southern North Sea Basin (SNSB) has produced 48 Tcf gas (DECC, 2014). With only 10% of this production coming from post-Permian supra-salt plays (DECC 2010), Mesozoic strata remains relatively underexplored. We investigate the post-Permian basin evolution of the Sole Pit High area (UKCS Quadrant 49) based on seismic analysis and structural modelling of a regional 3D seismic data set provided by Petroleum Geo-Services (PGS). The aim of this study is the kinematic analysis of thick-skinned and thin-skinned deformation processes with a particular focus on the interaction and coupling of sub-salt and supra-salt deformation processes and their implication for supra-salt prospectivity.

The post-Permian evolution of the SNSB was controlled by a combination of regional tectonic processes (thick-skinned tectonics) and gravity-driven salt tectonic processes (thin-skinned tectonics). The basin is bound to the southwest by the Dowsing-South Hewett Fault Zone (DSHFZ) and to the northeast by the North Dogger Fault Zone (NDFZ) and the Dutch Central Graben (Van Hoorn, 1987).

Rift flank uplift associated with Early Triassic rifting in the Central Graben initially tilted the basin to the southwest enabling the deposition of a thick sedimentary succession in the hanging wall of the DSHFZ (Sole Pit Trough). This regional tilting caused supra-salt strata overlying the thick Zechstein megahalite sequence to experience gravity sliding from the basin margins to the basin centre. Post-rift thermal subsidence in the Central Graben combined with inversion of the DSHFZ reversed the tilt of the basin to the northwest during the Late Cretaceous and Cenozoic. This reversal uplifted the Sole Pit Trough to its current position as the Sole Pit High, partially eroded the thick Triassic to Jurassic sequence, and shifted the basin centre to the Cleaver Bank High area, depositing up to 1,000 m of Cenozoic sediments (Cameron et al., 1992; Stewart and Coward, 1995). Trap formation primarily took place during Late Cretaceous inversion, prior to Carboniferous source rocks reaching maturity from the Late Cretaceous onwards (Pritchard, 1991). Upper Liassic shales may also have reached the early oil window in the pre-inversion Sole Pit Trough (Glennie, 1998). However, the results of this study show only limited connectivity of Mesozoic sources with potential reservoirs.

In the Sole Pit High study area, four main stages of post-Permian deformation have been identified. Early Triassic tectonic quiescence is evidenced by an un-faulted Lower Triassic section. The onset of halokinesis in the Late Triassic is marked by the development of Upper Triassic depocentres between salt structures. Thickening of Upper Triassic sediments towards the Sole Pit High indicates that halokinesis was driven by regional south-westerly basin tilt.

Ongoing thin-skinned deformation during Jurassic times is documented by the formation of salt-cored buckle folds and adjacent salt-withdrawal depocentres. Extensional faulting within the Sole Pit High Collapse Zone (SPHCZ) is recorded by Jurassic growth strata. Observed extension of supra-salt faults (Top Winterton Formation) is significantly larger than sub-salt fault-related extension (Rotliegend Formation), suggesting that thick-skinned and thin-skinned extension were mostly decoupled. Kinematic results from the sequentially restored regional cross sections provide quantitative evidence that a significant portion of post-salt extension was controlled by gravity gliding on the Zechstein megahalite succession.

Thick-skinned inversion of the DSHFZ and uplift of the Sole Pit High is indicated by north-westerly thickening Cretaceous sediments. Cretaceous growth strata in the hangingwall of extensional faults of the SPHCZ suggest ongoing thin-skinned extension as a result of Cretaceous inversion and uplift. In the Cleaver Bank High area, Cretaceous depocentres between salt diapirs mark the onset of thin-skinned amplification of existing salt structures. Stratal geometries of Upper Cretaceous and Palaeogene sediments date the formation of salt welds suggesting that deformation of supra-salt sediments was partly coupled with regional tectonic processes in the sub-salt basement from Late Cretaceous times onwards.

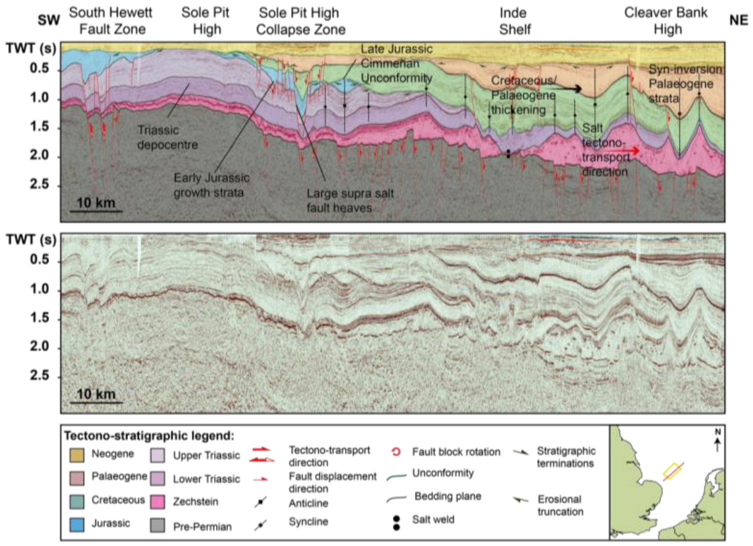

Fig. *1. Regional cross section of the UK SNSB highlighting key structural features discussed*

In order to assess the prospectivity of the Mesozoic basin fill, the location, extent and timing of numerous salt welds have been mapped. These welds may form potential hydrocarbon migration pathways from Carboniferous source rocks and/ or Rotliegend fields into potential Mesozoic supra-salt reservoirs. Potential Mesozoic reservoir formations are the Lower Triassic Bunter Sandstone and speculatively, the Cretaceous Chalk Group. Amplitude extractions indicate potential reservoir intervals in Lower Triassic depocentres. Potential traps include 4-way dip closures in salt-cored anticlines and 3-way dip closures in salt- and fault-juxtaposed carrier beds.

Correlation of location and timing of migration pathways, and reservoir and trap presence shows that Mesozoic prospectivity exists within undrilled areas of UKCS Q49, albeit to date with low expected commercial value.

Evolution of Salt Diapirs and Related Depocenters in the Southern Danish North Sea

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The Southern Danish North Sea was part of the Southern Permian Basin and is characterised by the presence of mature salt structures with variable geometries which formed during several Mesozoic and Cenozoic regional tectonic stages and halokinetic phases of salt mobilisation. This area is also known as Salt Dome Province and forms the SE end of the Danish Central Graben and includes sequences from Paleozoic to Cenozoic. The area can be defined as a half graben which is restricted by the Coffee Soil Fault to the E that developed due to Jurassic rifting. The Late Cretaceous stage was influenced by inversion of extensional rift faults. Inversion continued until the Mid-Miocene and was followed by regional subsidence in Late Cenozoic. All of these tectonic events contributed to mobilisation and growth of 8 mature salt structures in the study area including 7 diapirs and 1 pillow, with the names of: John, Kraka pillow, Central, Tove, Regnar, Vagn, B-15 and C-13. The development of the North Sea Dome in Mid Jurassic times, resulted in a tectonic hiatus; as well as thinning and erosion of Early Jurassic cover above salt diapirs, which helped the initation of salt mobilisation with progressing rifting. A pillow stage in early phases was common for all salt structures and it was followed by passive piercement. Occurrence of rim synclines around salt diapirs can be associated with the erosion of Early Jurassic strata and withdrawal of Zechstein salt adjacent to rising diapirs. Migrating salt contributed to diapir growth, down-building and increased subsidence rates of mini basins. Extreme subsidence and occurrence of welded basins such as along the mapped mock-turtle structure and mini basins, determined the migration pathways of salt during the Mesozoic. Once all the salt had flowed into the diapirs in Early – Mid Cretaceous time the burial phase has started for Tove, Vagn, Regnar, B-15 and C-13 diapirs. John & Central diapirs which are aligned in NW-SE direction, have not been influenced by burial, due to the remaining salt ridge on which they sit. Continued growth of these diapirs was accompanied by deposition of wedge and hook shaped halokinetic sequences. Their growth lasted until they were cut off from the salt ridge by vertical salt welds occured due to inversion and changed their shape into tear-drop diapirs in Late Cenozoic. Absence of feeder salt resulted in burial of these diapirs by younger Quaternary strata. Therefore, 3 families of salt structures have been identified in the study area by considering their different present day geometries such as; i) tear-drop shaped diapirs (John & Central) ii) buried diapirs and iii) pillow (Kraka). All Zechstein salt in the study area except the salt ridge, flowed into growing diapirs and they are inactive today. Thus, the salt ridge can be determined as the only part, which still has the potential to be mobilised. Zechstein salt in the study area also determined reservoir's geometry, timing of trap formation and timing of generation of hydrocarbons which was considered as Late Tertiary. Therefore, very young structural traps can be expected along salt structures. On the other hand mock-turtle anticline might bear potential for the older strata. The Rotliegend Group also exists in the study area which can be considered as a pre-salt play.

Diapir collapse features in the Upper Jurassic from the Dutch offshore

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In the northern part of the Dutch offshore Zechstein salt structures are abundant. In some cases, these structures are capped by a predominantly clastic, heterolithic layer, consisting of breccia, sandstones, shales and sulphates (Fig. 1). The coarse nature of the sediments provides good reservoir characteristics, but the lateral continuity is difficult to predict. The hotchpotch of lithologies is the result of subrosion and dissolution of the salt that occurred during the Late Jurassic rift phase. Large angular clasts point to an *in-situ* origin of the caprock. Palynological analyses on these successions reveal the presence of excellently preserved Permian pollen in combination with Late Jurassic dinoflagellate cysts and pollen and spores (Fig. 2). The Late Jurassic palynomorphs provide information on the timing of the diapir collapse, while the perfect preservation of the Permian palynomorphs indicates the very local provenance of the sediments. The cause for collapse of the salt structures is related to flooding by sea water. The base of the caprock succession of well F15-06 for example, can be dated as latest Callovian and correlates with the J46 regional maximum flooding surface '*Lamberti'* of Partington et al (1993). Interestingly, well 15-06 is situated on the Schill Grund Plateau, an area where Jurassic rocks are normally absent. Apparently, the subrosion and dissolution created a mini-basin in which the sediments were preserved and protected from subsequent regression and erosion in the Oxfordian.

Fig. 1 The base of the caprock succession of well F15-06. Dark mudstones with angular clasts overlie Zechtstein evaporates and grade upwards into sandtones with matrix supported clasts.

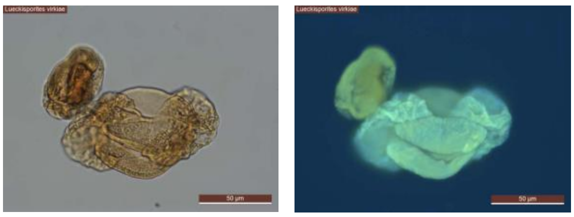

Fig. 2 Well preserved specimen of the Late Permian pollen type Lueckisporites virkiae. On the left, the specimen is displayed under normal transmitted light, on the right under incident ultraviolet light, displaying extremely bright fluorescence.

Subrosion at the Late Cimmerian Unconformity and its impact on the barrier potential of the Lower Cretaceous - an example from the central German North Sea.

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The Federal Institute for Geosciences and Natural Resources (BGR) aims to enhance the understanding of the deep subsurface of the central German North Sea especially regarding potential storage or barrier formations (Jähne et al. 2014). The validation of barrier potential in the deeper subsurface is crucial for many objectives as e.g. storage of CO_2 in saline aquifers, or the evaluation of hydrocarbon potentials. Potential barrier rocks in the German North Sea sector comprise fine clastic rocks and evaporates. The latter occur mostly in Permian and Triassic formations (Upper Rotliegend, Zechstein, Buntsandstein, Muschelkalk or Keuper). Dissolution of evaporitic strata (e.g. along unconformities) is quite common in the North Sea as several examples have shown (Clark et al. 1999, Jenyon 1984). It is commonly investigated using seismic data (e.g. Bertoni & Cartwright 2005).

The prevalent unconformity in the German North Sea is the Late Cimmerian Unconformity (Kockel 1995). This mostly angular unconformity usually marks the erosion of underlying Jurassic and Triassic sediments. In most cases it is covered by Lower Cretaceous clays. The erosional cut down along this unconformity and its descent to evaporitic layers facilitated a downward percolation of solvent water. This led to leaching and subrosion of evaporites, mainly the halite, and possibly the anhydrite, and as a result to a collapse of the Lower Cretaceous sequences above (Jenyon 1984). These collapse features formed narrow, only a few hundred meters wide, channel-like synforms in the palaeo-topography of the erosional surface clearly recognizable in seismic sections. The hanging wall of this subrosional sinks can show fault structures. If so, having impact on the barrier potential of the Lower Cretaceous clay-formation in many ways (e.g. erosion, thickening, faulting, sub-seismic deformation). The evaporitic formations themselves are often identified as excellent barriers. An erosion of parts of these units affects the barrier potential. In particular the evaporitic units Röt-Salt, Middle Muschelkalk and Middle Keuper are affected the most by this erosion and subrosion along the inner border of rim synclines of salt structures where the Triassic sediments are tilted. The overlying sediments of the Lower Cretaceous filled the collapsed structures, thus causing a thickening of possible barrier rocks. However Fig. 1 shows that these collapse structures have partially steep flanks, that are bounded by normal faults, causing possible migration pathways (Jenyon 1988). These faults, again, could have a negative impact on the properties of potential barriers in the overlying strata.

A generalized mapping study of the locations of subrosion structures at the Late Cimmerian Unconformity in the central German North Sea is shown in Fig. 2. In the area of the German North Sea the distribution of subrosion structures is reserved to inner flanks of salt structure rim synclines. Especially the Horn Graben area and the western and southern part of the German

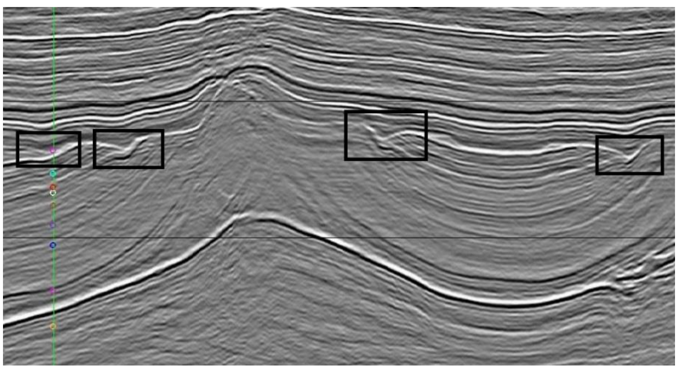

Fig. 1 Subrosional sinks of Triassic evaporites below the Late Cimmerian unconformity (c. Base Lower Cretaceous) near the German border in the NL part of the North Sea.

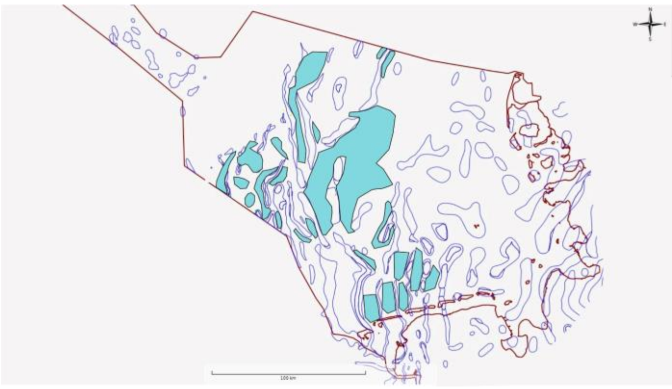

Fig. 2 Schematic distribution of mapped subrosion at the Late Cimmerian unconformity in the central German North Sea sector marked as blue regions. Additionally the main salt structures after Reinhold et al. (2008) are displayed to show the relationship between the subrosion and the salt rim synclines.

North Sea are affected. Additionally, the interpretation of subrosional features can give hints to seismostratigraphic concepts in areas with only a few wells and less constrained assumptions of lithological composition. If the underlying strata is not well defined, the topological behavior of unconformities on different underlying rocks and changes in seismic characteristics give indications about their lithologies and therefore their possible stratigraphic units. Only the above described evaporitic formations show the subrosion, helping in the assignment of reflectors to stratigraphic units.

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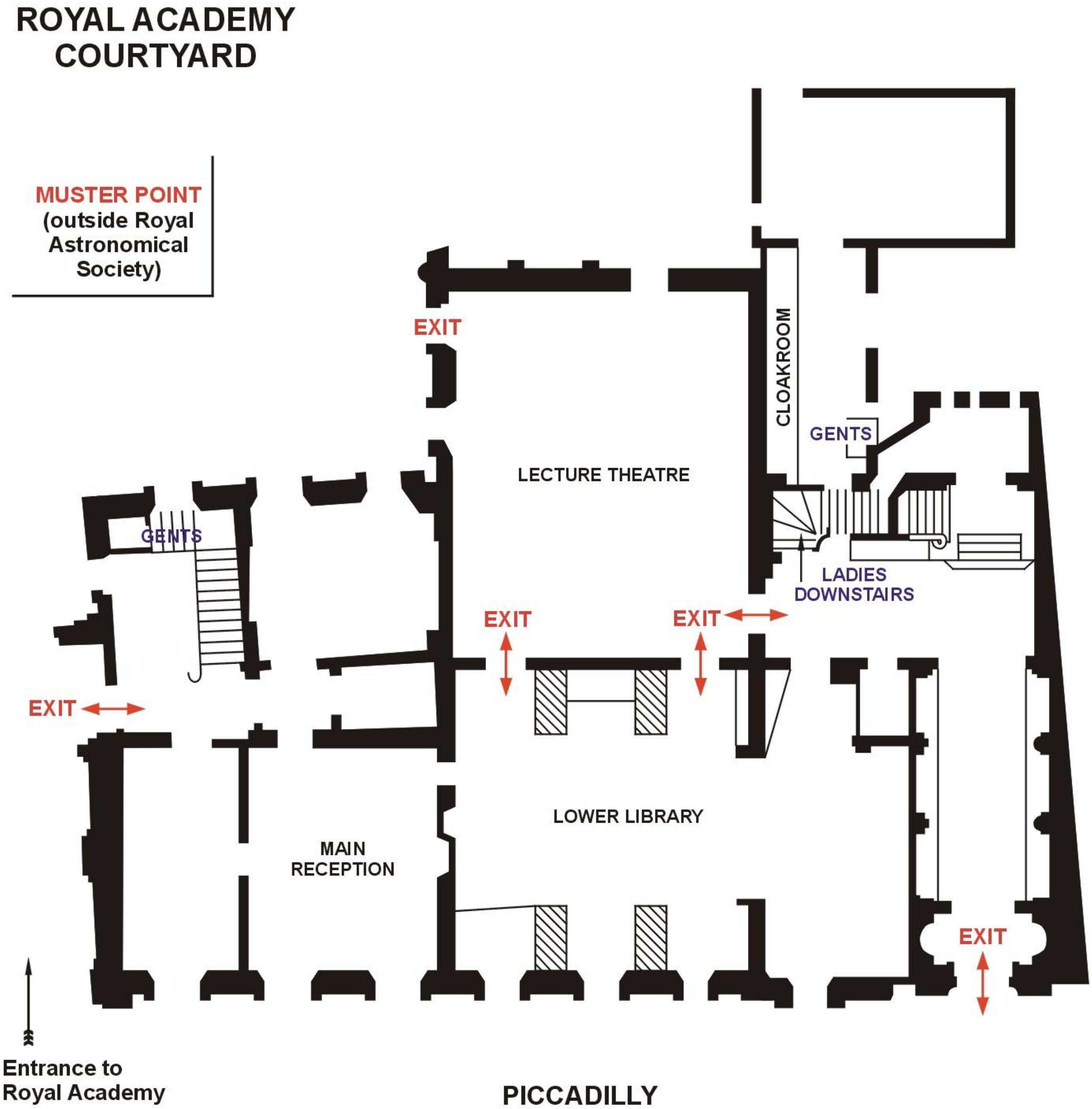

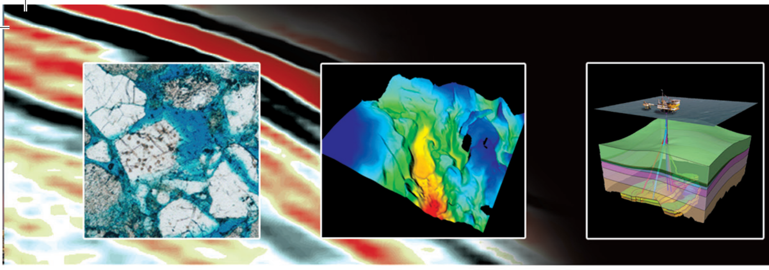

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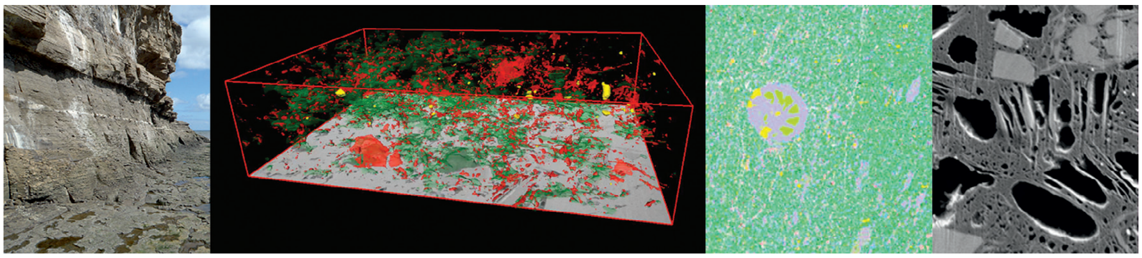

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