Structural Development of the North Sea Basin

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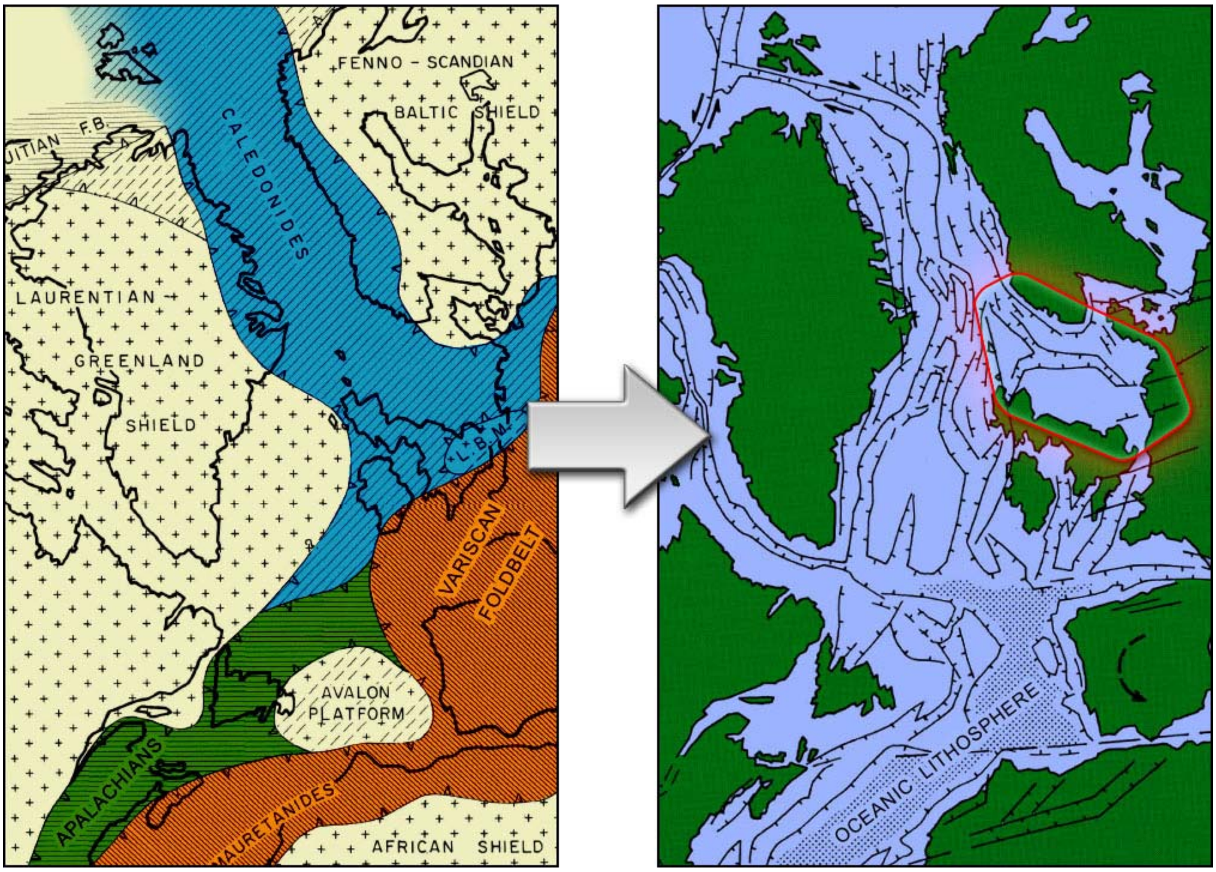

Fig. 1 An overview of the North Sea Area and the adjacent Northern Atlantic region during the Paleozoic (left) and Post Meozoic times (right). The tectonic complexity of this area becomes quite clear from this image as three different foldbelts are 'transformed' in an intensively rifted area. This process has happens in several different stages and is absolutely not spatially homogenous. The area encircled in red is the area of mainly focus on in this article; the North Sea Basin.

1 Introduction

As becomes clear from Fig. 1, the North Sea area must have experienced quite a complex tectonic history. The main process of transforming an area comprising of several massive mountain belts into an area of widespread rifting forms the main trend in this region. However, the overview depicted above is still very simple and leaves out many important details of the structural development of this area. For example, tectonics varied laterally, many different phases have followed each other through time and sedimentary cover has induced its own structural styles and has influenced tectonics. The latter mainly refers to salt tectonics which has been of prime importance for hydrocarbon accumulations in the South of the North Sea.

Furthermore Fig. 1 does not depict the final tectonic phase, which is one of inversion. This phase has been particularly important for the Southern North Sea and the Netherlands and was focused too locally to be depicted on the map of Fig. 1.

Here, the structural history of the North Sea Basin will be discussed and related to it's importance to hydrocarbon exploration and production. By no means has the North Sea Basin been in its current configuration throughout geological times. The overall form and configuration as we know it today was only achieved during the Tertiary and this article will discus the entire structural history from Pre Silesian times until present. Several palaeo basins and structural regimes have influenced the formation of the North Sea Basin as we know it today and these will be referred to with their commonly excepted names.

Also, because the entire tectonic and structural history can by no means be fully explained in a paper of this size only the most important elements and events have been picked out. A general trend and structural development will be depicted here and where possible be linked to hydrocarbon accumulations. These accumulations are usually linked to structural development by their trap type, but in some areas structural development has also been of prime importance for the deposition of source rock and off course for the maturation of this source rock.

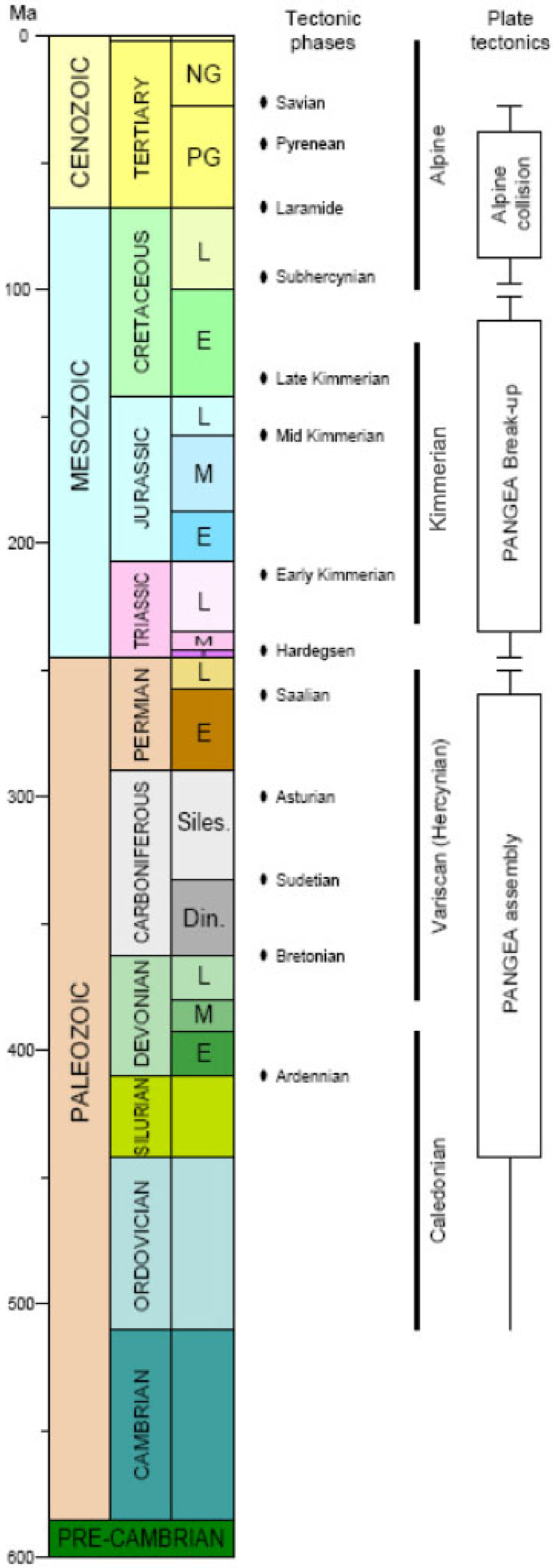

Fig. 2 An overview of the different tectonic phases and events active on the North Sea Area during the Paleozoic, Mesozoic and Cenozoic.

2 Structural Development

Because most geological times have been defined by looking at lithological differences, caused by many environmental factors like climate and sea level as well as tectonics a different subdivision is presented here. The structural development can best be appreciated when presented in relation to the mayor tectonic events, rather than being subdivided to fit in geological time units. Here a subdivision based on the four mayor tectonic events influencing the North Sea Basin is presented; the Caledonian, Variscan and Alpine compressional phases and the Kimmerian phase linked to the break up of Pangaea. In
Fig. 2 an overview of these different phases in shown.

2.1 *Caledonian Phase*

Although most wells in the North Sea do not reach deep enough depths to provide data of the basement of the North Sea Basin, onshore outcrops and some deep wells have allowed correlation of this basement to the Caledonian tectonic phase. These are mainly metamorphic and igneous rocks that have strongly been deformed by the Caledonian mountain building phase.

The Caledonian phase was active from about 510 Ma until approximately 390 Ma. It encompasses the entire Ordovician and Silurian and the Early Devonian in the north Sea Basin Area. Of course tectonic activity was not homogenous during that entire time and the most well developed phase during the Caledonian Orogony is referred to as the Scandian in Scandinavia, the Grampian in the British isles or the Ardenian on European mainland.

In essence the Caledonian phase encompasses a number of tectonic phases that are laterally diachronous. Rocks deposited during this time are commonly referred to as being of Pre Silesian age.

2.1.1 Plate Tectonic Setting

The Caledonians were he result of the collision between Laurentia, Baltica and Avalonia during the Pre Silesian. It was one of the first orogenies that would eventually be the result of the formation the super continent Pangaea.

In the Early Paleozoic almost all landmass was concentrated and united to form the supper continent Gondwana. Then, from 650 to 550 Ma the smaller continents of Baltica, Laurentia and Avalonia rifted to the north and the Iapetus Ocean developed in between these continents. These continents were now positioned around 30º on the Southern hemisphere and around 505 Ma the first proof of subsidence of the Iapetus Oceanic crust subsiding below Baltica was recorded in the rock record of Scandinavia (Finnmarkian phase). The tectonic-metamorphic evolution of the Finnmarkian phase are coeval with the intrusion of Alkaline igneous bodies of the Seiland Igneous Province (Sturt et al., 1978) . This phase thus probably reflects the collision of island arcs against Baltica, while the Iapetus ocean slowly closed. A second minor collision phase is reflected in the

Jammtlandian phase around 455 Ma. Similar collisional phases have been recorded on the Laurentia side of the iapetus where an island arc caused the Tactonic orogeny between 480 and 435 Ma.

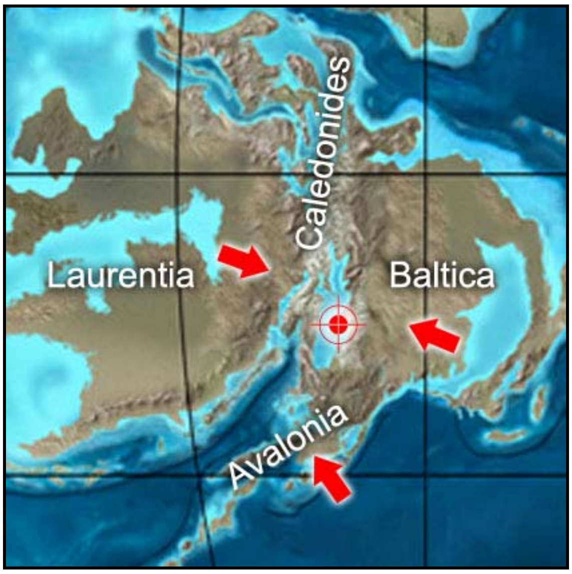

Fig. 3 Paleogaeographic reconstruction of the North Sea area and surrounding plates during the Caledonian phase. Red arrows depict general plate movements and the red dot shows the location of the North Sea.

In essence, convergence and closure of the Iapetus happened between about 520 to 425 Ma after which Baltica collided with Laurentia and mayor uplift and mountain building occurred. This final stage, the Scandian phase, occurred from 425 to 395 Ma and commenced in the North and slowly progressed to the South, closing the Iapetus ocean like a scissor.

While Baltica and Avalonia converged in the South, the third continent, Avalonia, moved towards the North. During the Ordovician, around 450 Ma the collision of Avalonia and Baltica started and is shown in Fig. 3. The Southeastern part of the Iapetus, the Tornquist Sea subsided beneath Eastern Avalonia and a suture formed, now referred to as the Tornquist line, running under the North Sea, through Southern Denmark into Poland. Eventually also Laurentia collides with the West of Avalonia and the Acadian Orogeny (part of the present day Appalachians) is formed. Due to this final suture the Western part of the supercontinent Laurasia is born.

2.1.2 Geological Setting

The Caledonians formed a mountain chain that ran from North to South right where the current North Sea is situated. It extended North along the coast of Greenland and Norway. In the South, the mountain range sprang of to the South West and, to a lesser extent, to the North East around where currently the Netherlands is positioned. This triple junction was formed due to the later collision with the small continent of Avalonia. In the center of this triple junction the London Brabant massif developed , that would maintain a structural high during most of the Paleozoic.

In the Southern North Sea the Rocks of pre Silesian age can be subdivided in two groups. The oldest comprises of slightly metamorphosed and deformed rocks of Precambrian to Silurian age. There is little known about this rock unit due to it’s deep burial and it’s irrelevance to hydrocarbon exploration. The second group lays unconform atop the first and comprises of Middle Devonian to Early Carboniferous siliciclastics and carbonates (Wong, 2007).

Due to the position, just south of the equator, of Laurentia, Baltica and Avalonia the area had an arid climate. This caused high erosion rates as flash floods could wear down the barren mountain slopes very fast. The deposits caused by this erosion are commonly referred to as the Old Red Sandstones (primarily outcropping in Northern U.K.). These deposits of red fluvial and deltaic deposits can reach thicknesses of 11 km in places and were laid down over a large area from about 408 to 370 Ma. The continent that formed after the suture of Laurentia, Baltica and Avalonia is therefore also referred to as the ‘Old Red Sandstone Continent’.

In the North Sea area the large siliciclastic input was confined by a horst and graben structure. Basinal deeper marine deposits were deposited in the hanging wall blocks and fluvial deposits were concentrated on the footwall blocks. It is suggested that these grabens were caused by back-arc rifting during the Devonian. The Campine basin, in the South of the Netherlands is an example of this. Most basins formed by this pre Silesian rifting followed a NW to SE trend and were later overprinted by Variscan tectonic events.

2.1.3 Structural development

Overal, the area of the North Sea was dominated by a compressional regime during the Caledonian phase. A East to West copressional setting can be discovered in the metamorphic and igneous rocks deformed in the Caledonian. This East to west compression was bordered by a T-junction to the South (Fig. 1), off which the London-Brabant massif formed the centre point. The London Brabant massif remained a structural high during most of the late Paleozoic, while other areas were heavily eroded and formed basins towards the end of the Devonian.

Palaeo magnetic studies have also shown a large transpressive system was active along the Western flank of the Caledonians. A long fault system, of which the a major element is formed by the Great Glen fault in Scotland, had an overall lateral displacement of 1000 to 2600 km Ziegler (1978). At the end of the Caledonian phase a postorogenic collapse of the North Atlantic Caledonian foldbelt created large intermontane basins like the Orcadian Old Red basin in Scotland (Ziegler, 1977). Some of the fault systems formed during the Caledonian phase may have been reactivated during later phases, but a lot of the structures formed in this phase have little to no implications for the petroleum systems of the North Sea. Therefore a detailed analysis of the mayor faults and structures formed here is beyond the scope of this paper and a more information can be acquired in Ziegler (1977), Ziegler (1978) and Sturt et al. (1978).

2.1.4 Associated traps & plays

Not a lot of traps relevant to hydrocarbon exploration where formed during the Caledonian phase. Some deep rooted faults that were later reactivated formed during this time, but no direct traps resulted. Off course this has more to do with the fact that no source rock has been deposited in the area before the Caledonian phase. Furthermore, the uplift of the mountain range and it's subsequent erosion has left mainly metamorphic rock as a remnant of this time. This is also why the Caledonian or Pre Silesian rocks are usually considered basement for the North Sea.

In recent years interest has shifted towards some Pre Silesian play levels as most of the younger levels have reached a high exploration maturity. Structures sought after of Pre Silesian age are mainly siliclastic reservoirs deposited in the graben structures that formed at the end of the Caledonian phase. Charge could be through lateral migration from younger source rocks after juxtaposition due to later faulting. As of now no large economic accumulation has been found, but the Pre Silesian play still has potential.

2.2 Variscan (Hercynian) Phase

The Variscan phase occurred during the late Paleozoic from late Devonian times to the End of the Permian (380 to 250 Ma). A gigantic mountain range was produced by the suture of Gondwanaland and Laurussia and this resulted in a new super continent, Pangaea. It's an important tectonic phase for the North Seas hydrocarbon potential, especially in the South. This is because the Variscan phase marks the beginning of very important sedimentary infill into the basins underlying the current North Sea.

2.2.1 Plate Tectonic Setting

During the Variscan phase the Variscan mountain range was created as is shown in

Fig. 4. This mountain range was quite extensive and must have been similar in structure as the current Himalayas. At the end of the Devonian Gondwanaland started colliding with Laurussia in the North. The area of the North Sea was now located just above the equator around 10º latitude. The end of the Variscan phase would finally produce the supercontinent Pangea but this suture can be subdivided into several phases.

At the end of the Early Devonian Laurussia was assembled and the cratons of Siberia and China had started merging with it in the East. In the Late Devonian and the Beginning of the Carboniferous the small archipelago of Armorica collided with the South of Laurussia. This marked the beginning of the Variscan phase and caused mountains to form just East of the pre-existing Caledonians.

The Variscan orogony was the result of a series of smaller collisions between Laurussia and smaller continental plates moving northwards. Due to this complex nature it is very difficult to grasp the exact geological history of the fold belt. Also because both the Caledonian and Variscan orogeny are closely related, as they both were the result of the formation of the supercontinent Pangea, and the Caledonian phase slowly grades into the Variscan phase it is very difficult to distinguish between the two in some areas.

In the Late Carboniferous the final collision took place between the supercontinent Gondwanaland and Laurussia. This formed a mountain range of which remains can be found in the US al the way to Eastern China. At the same time Siberia approached Laurussia from the east and created the Ural mountain range. The supercontinent of Pangea had been created, although the Paleotethys sill separated Laurussia from Gondwanaland in the East.

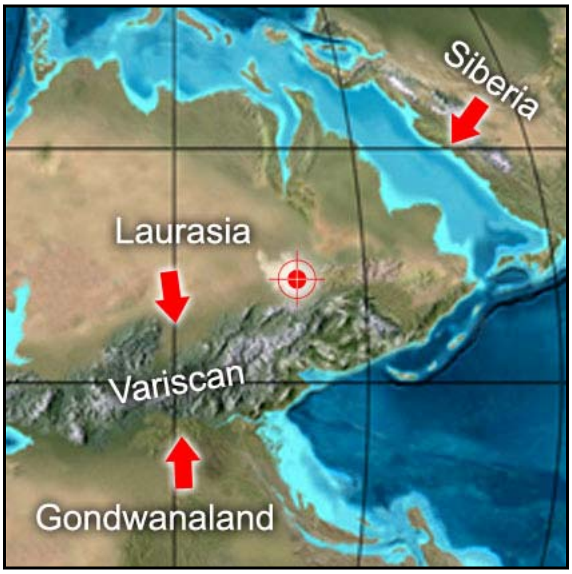

Fig. 4 Paleogaeographic reconstruction of the North Sea area and surrounding plates during the Variscan phase. Red arrows depict general plate movements and the red dot shows the location of the North Sea.

2.2.2 Geological Setting

During the Variscan phase the area of the North Sea had moved North and was subjected to a tropical climate. The Caledonian Mountain range had been heavily eroded and in the Carboniferous most of the North Sea formed a flat low-lying coastal plain. This forms the first mayor unconformity in the North Sea basin. Towards the South the Variscan mountain range was trusted up and it's erosion supplied a lot of sediment into the new formed basin. During the Carboniferous the area was subject to a strong cyclicity in subsidence and the Carboniferous is characterised by mudstones during transgressions and deltaic sediments when river sediment reclaimed the sea. After this, Lycopod forests sprang up on the coastal plains and a phase of peat formation followed. This succession was repeated many times and would later form the important Westphalian coal source rock that is interbedded with the fluvial and marine deposits.

The lower Carboniferous is also characterised by volcanic activity, primarily in the Northern north Sea.

Here many basaltic lavas, tuffs, plugs, sills, dykes and laccoliths can be found. Also around the Corboniferous-Permian boundary postorogenic volcanism can be found far North from the Variscan range (Ziegler, 1977).

By the end of the Permian the area had shifted even more to the North and was now in arid desert condition s. The important aeolian and fluvial deposits of the Rotliegendes were the result, followed by the Zechstein salt of late Permian times.

During the Permian two basins developed, the North Permian basin and the South Permian basin. They were separated by a high located around the position of central Denmark, the Mid North Sea-Ringkøbing-Fyn-Møn trend. Both basins were elongated and followed an East to West trend.

Although an intricate fault pattern developed most tectonic activity in the North Sea area was limited to slow and cyclic subsidence due to sedimentary loading and loading of the Variscan mountain range. The North Sea area was a foreland basin at this time and while Variscan thrustsheets were thrusted northwards and loaded the underlying slab, the land subsided and was filled by sediment from the high mountain range to the South.

2.2.3 Structural development

Although there is no reported evidence that the Variscan compression reached farther north that the Netherlands many of the structures formed during this time are related to the Variscan orogeny.

Many of the currently visible faults at the Rotliegend level are a remnant from the late Carboniferous fault patterns that were caused by the movements of the Variscan orogeny (Dirkzwager et al., 2000). They follow a general NNW-SSE trend that can be linked with the Middle Devonian to Early Carboniferous grabens, opening up a seaway across Eastern Netherlands. The start of the Variscan phase is characterised by the collapse of the Caledonian orogeny and a general extensional regime, causing a depression that could be filled with sediment.

During the Variscan phase four tectonic phases can be distinguished in these structures although the first, the Bretonian, is primarily reflected in changes in sediment input and the reactivation of a south-plunging subduction zone. This was associated with a sudden tectonic pulse caused by the collision of Gondwana derived continental fragments.

The second phase, the Sudetian, was primarily of a volcanic nature and extrusive and igneous rocks can be found in Eastern Netherlands. Also the uplift of the Texel-IJselmeer high, the Malvern High and mild folding of the Irish and Scottish grabens may have been the result of foreland inversion tectonics during this phase.

The Asturian tectonic phase near the end of the Carboniferous and is expressed in a rather complex fault system of conjugate shear faults and secondary extensional faults. These faults cause fragmentation of the Variscans and it's foreland.

The final tectonic phase, referred to as the Stephanian or Saalian in a broader sense, caused the majority of deformation and faulting, primarily expressed in wrench faults. This wrench faulting can sometimes be associated with magmatism and the swells formed by this can bee seen on the Westphalian subcrop map, marking the base Permian unconformity. This subcrop pattern clearly shows the shapes of the younger West Netherlands and the Lower Saxony basin and the Lauwerszee trough (Ziegler, 1977) .

Towards the end of the Variscan phase two basins had developed, the North Permian and the South Permian basin. These basins were associated with the largely extensional nature at the end of the Permian, the Permo-Triassic Variscan Foreland Collapse. This was in contrast with the mainly compressional setting during the earlier Variscan phases. The differential subsidence of two mayor cratonic blocks, together with a mayor NW SE trending fault system gave rise to two different basins that were separated by the effusion of widespread volcanics along the margins of major stable blocks. This formed the Mid North Sea-Ringkøbing-Fyn-Møn trend separating the Northern Permian Basin from the Southern.

2.2.4 Associated traps & plays

Although not a lot of structural traps are directly related to the Variscan tectonic phase it has been very important for hydrocarbon accumulations in the North Sea. This is primarily due to the basin that was formed by this tectonic phase. The foreland basin that developed slowly subsided and was not disturbed a lot by tectonics. This slow subsiding nature led to wide spread coal deposits as Lycopod forest could strive on these flat plains. Tectonic uplift of the Variscan mountain range shed enough sediment through erosion to keep up with the created accommodation space. This caused good burial of the Westphallian coals and later provided a good reservoir in the Rotliegendes sandstones. The Zechstein salt cap provides the last required factor for this textbook petroleum system.

The gas accumulations of this play are mainly concentrated in structures formed by later tectonic phases and are mostly related to horst blocks caused by rifting or popup and other inversion tectonic related structures. Variscan fault trends may have caused weak points along which these later structures could form. But, in general Carboniferous, Rotliegend or Zechstein play levels are not associated with traps formed during the Variscan.

2.3 Kimmerian Phases

The Kimmerian phase marked the beginning of the breakup of Pangaea and the creation of the continental configuration as we know it today. It is a phase of mayor rifting and produced small confined oceanic basins ideal for hydrocarbon accumulation due to anoxic conditions. Organic rich deposits, primarily the Kimmeridge clays, were widely deposited during this phase and it is of mayor importance, especially in the Northern North Sea. The Kimmerian phase lasted most of the Mesozoic and stretches from the Late Triassic to the Early Cretaceous

(240 to 120 Ma). It is generally subdivided in an Early, Mid and Late Kimmerian phase.

2.3.1 Plate Tectonic Setting

The onset of the breakup of Pangea started in the Triassic as the Rockal–Faerde Rift started developing along the Greenland coast and the Biscay Rift developed to the West of England and France. Minor rifting occurred in the north sea, but this did not develop fully yet. Towards the south the Tethys ocean had developed as Africa moved Southward and North America rotated clockwise causing an East to West trending ocean to develop. This ocean formed a seaway running along northern Africa and then Southwards along the coast of North America as depicted in

Fig. 5.

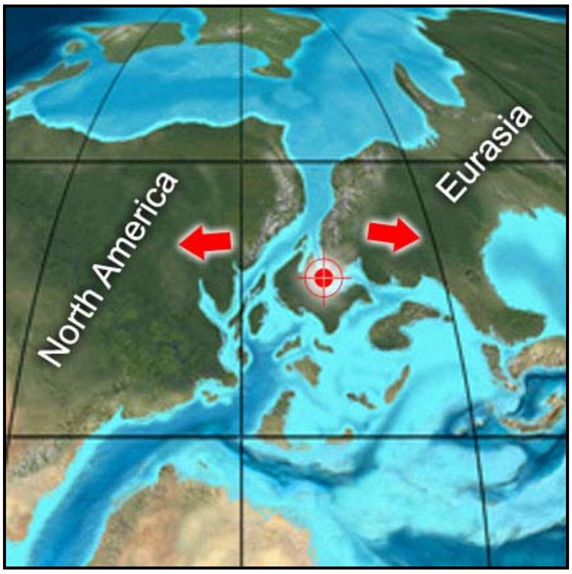

Fig. 5 Paleogaeographic reconstruction of the North Sea area and surrounding plates during the Kimmerian phase. Red arrows depict general plate movements and the red dot shows the location of the North Sea.

During the Jurassic rifting activity reached its peak and North America moved away from Eurasia. This rift first developed in the North and slowly spread southwards. At the beginning of the Jurassic the Panama straight was still closed causing the Tethys ocean and many of its branches to contain rather stagnant stratified seawater.

Only during the Cretaceous the Panama straight would open up causing a oceanic current to develop from East to West It was also during the Cretaceous that the Southern part of the newly formed Atlantic ocean opened up between Africa and South America. At the end of the Mesozoic the North Sea area had almost reached it's current position.

2.3.2 Geological Setting

The Kimmerian phase in the North Sea area is characterised by a failed rift system. During the Triassic the area was covered by a widespread, shallow and warm sea. Not a lot of tectonic activity occurred and deposits are rather widespread and homogenous in thickness. The Bundsandstein, Musschelkalk and Keuper formations were deposited during this time and although they form a mayor part of the North Sea sedimentary succession, they do are generally devoid of both source rock and good reservoir. These thick deposits did however cause substantial diapirism of the underlying Permian Zechstein salt. Diapirs formed swells and depressions and many Triassic sediments are no contained in pods 'floating' in-between salt diapirs.

Towards the end of the Triassic minor rifting had developed and the Viking Graben developed in the Northern North Sea area. Also during this time a mantle plume had developed under what would later become a triple rift junction, just West of Scotland. This mantle plume caused regional uplift and tilt of Triassic and underlying sediment. Throughout the Triassic some tectonic phase can be recognised and some minor unconformities are present, but overall, tectonic activity was low.

The Jurassic was a mayor phase of rifting in the North Sea. Rifting initially began in the late Triassic in the North and slowly spread southwards. In the Middle Jurassic this rift had developed into the Viking Graben in the North, between Norway and Greenland. Near the East coast of Scotland a West trending branch sprang off called the Moray Firth. Towards the South the Central Graben developed creating a triple junction right where the mantle plume had been focused during the start of the Jurassic. The main fault trends and rift morphology is shown schematically in

Fig. 6.

The rifting produced many narrow and isolated basins, with each an distinct sedimentary succession. Also, due to the many deep small basins and due to the fact that the Tethys ocean was rather stagnant and did not harbour an oceanic current stagnant waters developed. Algae and plankton bloomed in the surface waters but was not decomposed when settling down due to anoxic conditions. This produced a rich oil source rock known as the Kimmeridge clays. Along the rift edges faulting caused differential loading and enhanced diapirism of the Zechstein salt. In some cases footwall uplift caused exhumed ridges and many alluvial fans and deltas filled the rift valleys. Rivers flowed through the valley during low sealevels and delta's prograded northwards. The Staffjord sands of the Viking Graben are an important reservoir horizon of this kind.

In the Cretaceous most of the rifting has seized and the rifting had failed to produce oceanic crust. At this time the North Sea lay in a dry warm climate. Sediment input was rather low and a thick calcareous succession were deposited, that can now be observed along the coast of Dover, UK. In some isolated basins, like the West Netherlands basin and the Broad Fourteens basin sedimentary infill was mainly deltaic.

2.3.3 Structural development

In the Triassic the Permian structural framework was overprinted by a early North South trending rift system. This Hardegsen phase was the first indication of rift movement and caused a regional unconformity during deposition of the Bunter (W.H. Ziegler, 1975). In the North the Viking graben started to develop and in the South the Ringkøbing-Fyn-Møn trend was breached. Rifting initially started in the East, close to the current Norwegian coastline. In successive steps the rift moved Westwards and became more narrow. During this rifting small faults developed and slowly became connected by stepover points and accommodation zones. Other depressions also developed during the Triassic like the Emsland Graben, the Glückstadt and the Hessian depression. In some areas subsidence was so intense that over 3000m of Triassic redbeds were deposited (Egersund basin & Danish Embayment) (Ziegler, 1994).

At the end of the Triassic the Early Kimmerian phase caused increased accentuation of the rift elements and a 1000km long rift system developed in the North, the Viking Graben. Some of the smaller stages during this rifting can be correlated to phases in the Northern Atlantic. Rifting caused footwall uplift and some of these blocks were exhumed above sealevel. On these ridges slumps developed causing a secondary structure important for reservoir connectivity in several blocks.

At the same time the mantle plume developing under the triple junction had caused regional uplift and tilt. This tilt can be observed in several minor unconformities and may have alos induced gravity sliding on the underlying Zechstein salts. The Sole Pit high may have acquired it's intensely folded and architecture from being the toe-thrust of a large scale gravity slide (*Stewart et al., 1994*).

By the End of the Middle Jurrassic, during the Mid Kimmerian phase volcanism concentrated itself in the rift triple junction. At the same time uplift of the Ringkøbing-Fyn-Møn trend again resulted in two separate basins. It was also during this time that the important Kimmeridge clays were deposited. These clays were deposited rather wide spread but lose their source rock potential just South of the Egersund basin.

Around the Jurassic-Cretaceous boundary a third and last mayor rifting phase occurred, the late Kimmerian phase. This phase affected the entire north Sea rift system and produced a mayor unconformity. In the Viking graben this tectonic phase accentuated the already existing topography and produced a relief of 2000 to 3000m. Towards the South in the Central Graben this expression was reduced by the presence of the Zechstein salts, in effect, damping movements. At the same time the Ringkøbing-Fyn-Møn trend was further uplifted, as well as the London-Brabant Massif. Some marginal depressions like the West Netherlands, Broad Fourteenth and Lower Saxony basin further deepened. Most of these basins developed in the early Jurrassic and had a NW-SE trending morphology (Ziegler, 1994)..

Simultaneously a mayor transgression caused flooding of most highs and sediment input was greatly reduced. Due to this, lower Cretaceous sands can primarily be found in the Moray Firth, the West Netherlands basin and Broad Fourteenth basin and the Dutch parts of the Central Graben. In most other areas the Cretaceous is characterised by thick chalk deposits (Wong, 2007).

During the rest of the Cretaceous rifting slowly came to a halt and the rift of the North Sea became to be a failed rift. In fact, the last rifting stage coincides greatly with the onset of rifting in the North Atlantic, suggesting regional stresses had shifted. At that moment regional subsidence that may still be active today has influenced the region and has created accommodation space for sediment to fill. This subsidence may be due to the mantle plume, or low-velocity rift pillow (Illies, 1970) that was slowly absorbed by the mantle during the Cretaceous and Tertiary ages.

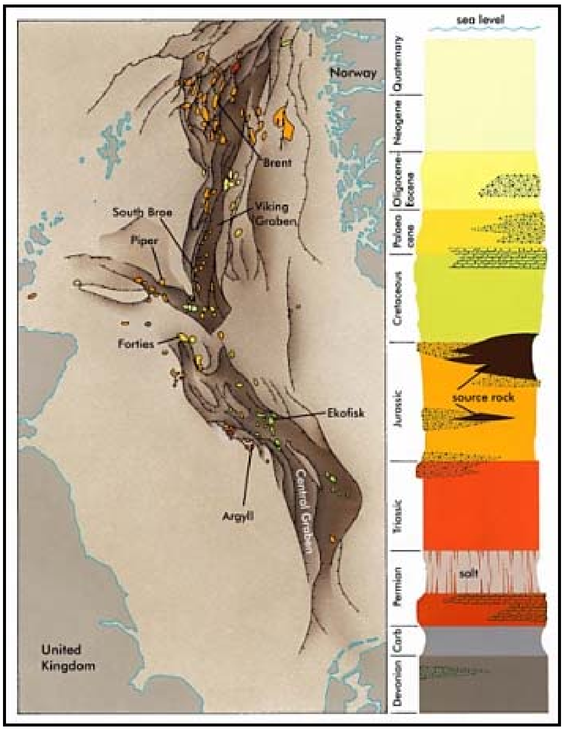

Fig. 6 Schematic representation of the rift morphology in the North Sea at the near the end of the Cretaceous. The main oil and gas fields are also depicted. Image from Oil & Gas UK.

Along the faults, due to differential loading, often salt diapirs developed. In some cases diapirism was so intense that it kept up with deposition and in some areas Triassic sediment is contained in pods bordered by salt. Salt played an important roles in the Southern North Sea and all salt tectonics associated structures like, turtle back anticlines, crestal collapse structures, doming, rim sinclines, etc. can be observed here.

2.3.4 Associated traps & plays

The Jurassic is probably the most important geological time for hydrocarbon exploration in the North Sea. Many accumulations are in Jurassic reservoir, the Kimmeridge clay is considered the most important source rock and structures formed during rifting form excellent traps.

In the first place rifting was responsible for the deposition of organic rich source rock due to anoxic conditions in the deep isolated rift basins. It also produced enough relief to a low submarine fans, turbidites and fluvial system to develop. These deposits all make excellent reservoirs.

Of course rifting also resulted in the creation of some very important traps. Many crests of tilted footwall blocks now form excellent structural traps. In some cases these are fragmented by secondary slumping that occurred when these ridges were exhumed above sealevel. The Brent field is such a reservoir. Other successful accumulations have been found in hangingwall blocks and their roll over anticlines or collapse structures.

Salt tectonics was also triggered by the rifting activity and many salt diapirs follow the rift axis and fault traces in the south. Many successful accumulations are associated with these salt diapirs. This salt was Zechstein salt deposited in the late Permian and actually only covered the Southern North Sea; almost around the same latitude where the Kimmeridge clay loses its source rock potential. This Zechstein salt acts as a perfect seal and together with Rotliegend reservoir rock and Westphallian gas source rock provides an excellent petroleum system. Some of the traps that currently hold gas accumulations were created during the Kimmerian rift phase. Many horst and graben blocks developed below this salt layer. In some cases these structures were reactivated Variscan deep rooted faults, such as might have been the case in the Broad Fourteenth basin. Also, many faults can not be followed above the Zechstein as their displacement is accommodated by the ductile salt.

Another important effect of the rifting was the creation of accommodation space which was quickly filled with sediment. This sediment provided enough overburden to cause early maturation. Outside the rift only in the Tertiary enough overburden was deposited to allow for source rock maturation. This had important implications for timing and needs to be taken into account during exploration.

2.4 Alpine Phase

In the late Cretaceous around 100 Ma the Alpine phase commenced. This last tectonic phase is still active today and has formed Europe as we currently know it. of most small plates in the Mediterranean area. During this phase the North Sea acquired its current configuration. Subsidence rates were still high and the Tertiary succession is about 2500m thick. Sediment deposited during this time have little to no source rock potential and also mayor reservoirs are still to be discovered. The structures formed during this time are of prime importance though. In most cases the now compressional setting caused by tectonic activity in the South caused inversion tectonics of most pre-Tertiary structures.

2.4.1 Plate Tectonic Setting

By the late Cretaceous the North Sea area had moved to about 60º N and rifting activity had almost stopped in the area. At the same time North America was moving Westwards as the Atlantic Ocean opened up. Also towards the South, South America was rifting away from Africa, while the later rotated anti-clockwise and started moving North as shown in Fig. 7.

This movement slowly closed the Tethys ocean and finally formed the confided inland sea of the Mediterranean around 30 Ma. During the Alpine compression a series of smaller phases have been discovered, like the Subhercynean, Laramide, Pyrenean and Savian phases. These phases are usually associated with more localized stresses caused by smaller continents colliding with Eurasia. Overall the main stress regimes were North to South as Africa rotated and progressed Northwards. Still a lot of research is done today to precisely decipher this activity. In the North Sea area tectonic activity was low, but several Alpine phases left their footprint in the structures in and around the North Sea area.

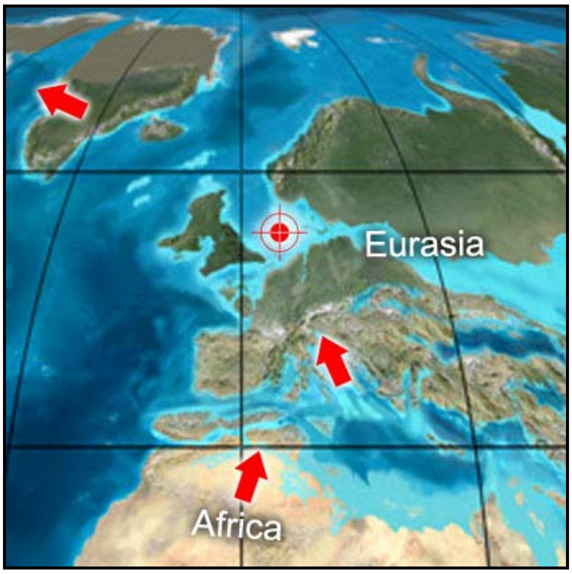

Fig. 7 Paleogaeographic reconstruction of the North Sea area and surrounding plates during the Alpine phase. Red arrows depict general plate movements and the red dot shows the location of the North Sea.

2.4.2 Geological Setting

During the Late Cretaceous the most of the North Sea was covered by a shallow warm sea and thick chalk deposits accumulated. This period was characterised with a rather quiescence of tectonic activity. In the Viking and Central Graben subsidence continued and reached depths of up to 1200 m and would slowly fade out to entirely stop after the Laramide phase in the Early Tertiary. This tectonic quiescence was interrupted by the Subhercynian phase as this caused some subregional disconformities. Subsidence continued on a whole and the Upper Cretaceous reached thicknesses of 200 to 300 m on most rift flanks and most of the rift was completely filled in.

In the beginning of the Tertiary the Laramide phase caused rapid subsidence in the rifts for the last time and due to palaeogeographic changes also resulted in erosion on the rift flanks. At the same time uplift of the Shetlands Platform, probably due to increased mantle activity below this region, caused exhumation and erosion to take place. This eroded material was quickly transported Eastwards and was deposited in the outer Moray Firth. Slope failures of these fans caused turbidity currents to deposit sands in the Viking Graben and the Northern Central Graben.

Both during the Subhercynian and the Laramide phase inversion tectonics was active in some of the marginal troughs like the Southern Central Graben, the Broad Fourteenth and the West Netherland basin. This inversion led to the erosion of most of the Cretaceous deposits in these basins. Structures formed during this inversion form important traps and in some cases have hampered hydrocarbon exploration and thus are very important to understand.

During the remainder of the Tertiary two more phases are recognized, the Pyrenean and Savian phase, but these have influenced the North Sea basins structure to a lesser extent. Mainly uplift and erosion, especially in the Broad Fourteenth basin was the result of these phases. Overall, subsidence continued during the Tertiary and the basin was filled by a thick succession of muds and sands. Sediment input was primarily from the East from the Eridanos river system. During the Ice ages this river system drained the massive glaciers and shed a lot of sediment in the basin. Some turbidites resulted from these quick sedimentary inputs and these are now good reservoirs in some places.

Also salt diapirism continued during the Tertiary and formed some structures to develop. Furthermore the maturation of the important Kimmeridge Clays depends greatly on the thickness of the overlying Tertiary sediment in most places.

2.4.3 Structural development

The structural development during the Alpine Phase is one of reactivation of pre existing faults and structures. Many of the existing rifts and basins were inverted during the Tertairy. In many ways the Mesozoic troughs acted as spear pins in a rather rigid platform at which stresses exerted by the Alpine foreland could manifest themselves.

Because most Mesozoic rifts had developed in a North-South trend and the stressed formed by the Alpine diastrophism had a similar trend many rifts and structures experienced transpression or transtension. Primarily in the South and in some Marginal Troughs the effects of this inversion have been well developed.

Zechstein salt also played a mayor role in these areas as it functioned as a buffer or detachment layer separating two structural regimes. For instance, in the Broad Fourteenth basin Laramide inversion caused Post Zechstein rock to form a large thrust floating on the Zechstein salt. This thrust may have been uplifted to more than 1000m.

Below the Zechstein salt the Rotliegend and Carboniferous rocks show an intricate fault structure. Here existing Variscan deep-rooted faults, modified during the Kimmerian rifting have developed popup structures. These structures, also referred to as flower structures show no continuation above the salt in some cases, indicating the role of the salt as a buffer.

During most of these inversion overall subsidence continued and although there was a reversal of relief in generally there has always been deposition during the Alpine phase. An exception to this is the Broad Fourteenth basin, the West Netherlands and the Southern Central Graben. Here most of the Cretaceous has been eroded forming regional unconformities. Once inverted most basins became inactive and slowly followed the regional subsidence trend.

Salt tectonics remained active as Tertiary sediments were deposited and in some place Tertiary sediments have been penetrated by diapirs. Off course these diapirs were in most cases continuations of pre existing salt bulges or diapirs formed during the Kimmerian rifting phase. In many cases crest collapse structures developed above the diapirs.

2.4.4 Associated traps & plays

The Alpine phase has primarily reactivated and inverted old faults and in a way, thus complicated many structures and has created problems with investigating timing and leakage.

In the Broad Fourteenth basin this inversion has led to high uplift and erosion of Cretaceous and some Jurrassic rock. In total maybe 2000m of sediment has been removed and possible hydrocarbon accumulations have thus been lost. The source rock will now have to be reburied to a deeper depth before the source rock will further mature and start charging overlying traps. A similar thing happened in the West Netherlands basin where now only the South has producible accumulations in Tertiary sediments.

But apart from complicating hydrocarbon exploration the Alpine inversions have also produced some new structures that have proven to be perfect traps. Especially on the Rotliegend level in the Netherlands Alpine transpression and transtension has caused popup structures to form. These provide excellent traps below the impermeable Zechstein seal. In other places flower structures developed and fault blocks may have been moved to cause better sealing capacity, through better juxtaposition or more clay smear. Of course also the opposite can be true. Some sealing fault may have become leaking during the Tertiary inversions.

During the Tertiary sediment deposition also continued and this had effects on salt diapirs and source rock maturation. Diapirs in some cases penetrate Tertiary layers and may form traps. Other structures may also have developed due to further migration of the salt, such as turtle structures and rim synclines. These develop after piercing of the overlying rock due to the pressure on the salt becoming too great.

3 Conclusions

Overal the North Sea basin has experienced a quite complex geological history. But, due to the large amount of hydrocarbon accumulations it has been well studied. In this paper only a brief history has been portrayed.

Probably the most important tectonic phase in the North Sea has been the one of rifting, the Kimmerian phases. Not only has the depression caused by the rifting ensured the deposition of a very rich source rock, it has also produced adequate structures to function as traps.

Towards the south, primarily in the Netherlands the Variscan phase and it's associated foreland has produce a rich gas province. This was not so much due to the structures that developed during that tectonic phase, but rather due to the nature of the foreland basin which has created an almost perfect source-reservoir-seal succession. The final stage, the Alpine phase has in many ways complicated the structures in the Southern North Sea and has had some negative implications for timing and leakage. But, it has also caused ne structures to form that became excellent traps.

Because the North Sea is very mature, exploration wise, new discoveries should be sought in tight oil and gas and in play levels that have not been well explored. The Pre Sillesian may have potential although not a lot of commercial accumulations have been found. Tertiary delta sequences and their possible sedimentary traps may also prove successful if studied in detail.

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