SALT TECTONICS CONTROL ON RESERVOIR GEOMETRY, VOLVE FIELD, NORTH SEA

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Abstract

This study was undertaken to investigate mobile salt and its control on reservoir geometry in the Volve Field, North Sea by using 3D seismic and well data. During the Triassic – Cretaceous, structures and stratigraphy develop in the Volve Field, SW margins of Utsira High, North Sea, resulting in the formation of a minibasin and halokinesis of the Zechstein Supergroup. The subsequent continental, fluvial, deltaic and marine sediments were deposited into the accommodation space formed by salt movement. The movement of salt in combination with the rift-related fault system has complicated the distribution and geometry of the reservoirs. The Triassic minibasins developed because of the mobilization of Zechstein Supergroup, Upper Permian. Consequently, the series of Jurassic minibasins formed due to the collapse of the underlying salt ridges. Early Cretaceous reservoirs are slightly affected by salt withdrawal caused by high compaction. However, movement of salt was not related to the formation of Late Cretaceous reservoirs. The salt movement would have been related to: (a) the salt dissolution due to groundwater and changes in relative sea level, (b) differential erosion of salt bodies and Triassic-cored highs, (c) the salt withdrawal due to the extension resulting in high accommodation space and sediment loading leading to high compaction. The study gives the detailed insights into the structural evolution of the minibasin on the Volve Field and has implications for reservoir geometry and distribution of Zechstein salt within the North Sea rift systems and the development process of depositional system of reservoirs from Triassic to Cretaceous.

Keywords: Salt Tectonics, Volve Field, Zechstein Supergroup, Minibasin, Reservoir Geometry

1. Introduction

The Volve Field is an oil field, situated on a structural high within the Sleipner Terrance, west of Uitsira High and five kilometers north of the Sleipner East field with water depths of 80 meters in the block 15/9 that belongs to the southern part of the Viking Graben in offshore of Norway, North Sea. The Volve field has many geological similarities with the neighbouring structures Loke and Sleipner East (Figure 1). The current basis for the development of the Volve Field consists of the base case volume of the 4-way closure. The reservoirs from Triassic to Late Jurassic have fault-limited structure and formed as a result of salt movement and stretch during and after deposition of sediment. The deposition and deformation of evaporites has played an important role in reservoir distribution by the ability of salt to create structure closures, generation of salt related traps and forming a competent seal to fluid migration in this field.

To better understand the control of salt tectonics and its influence on syn- and post-kinematic sedimentation, this study focuses on the salt structures, distribution and its variations in thickness. In particular, the study aims to outline the influence of rift-related faulting and halokinesis on distribution and thickness of reservoirs. This is achieved through seismic-stratigraphic analysis of 3D seismic dataset tied to well data. As outlined below, it is critical to establish the relationship between the sediment deposition and timing and causes of salt movement. The results presented here demonstrate that salt movement and the phases of rifting were the primary control on the structural development of the Volve Field. The results compile useful information for solving poorly understood problems regarding to salt impact of structural history and play potential within the Volve Field. In addition to improving the general understanding of the tectono-stratigraphic evolution of Volve Field, this study also helps constrain depositional system development and reservoir geometry.

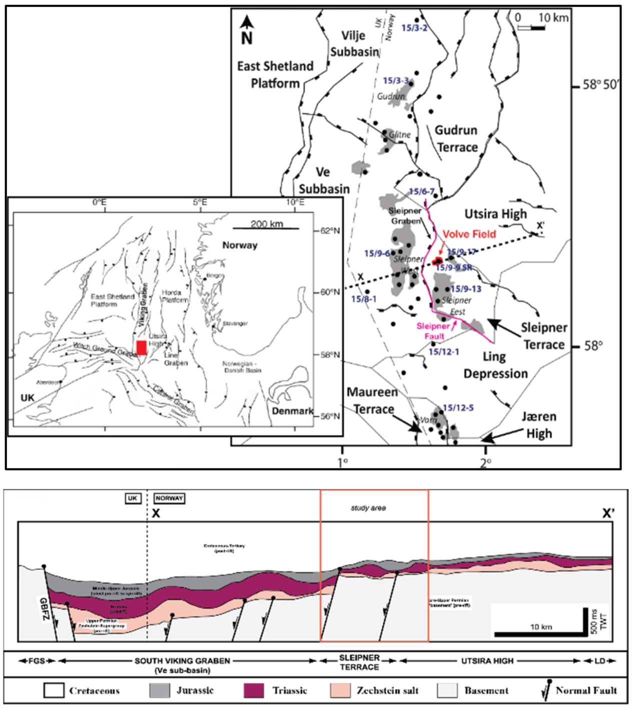

Figure 1: (a) Location of the study area (red), showing the structural elements and (b) cross-section of the South Viking Graben (SVG), northern North Sea. (Jackson, 2010).

2. Geological Framework

Permian - Triassic

During the late Carboniferous to Early Permian, strike-slip deformation and extensional tectonics due to thinning of the crust lead to formation and subsidence of South Viking Graben and Sleipner Terrance to form an embayment for the deposition of continental and evaporitic stratigraphic units. It was widespread across the study area (Lyngsie et al., 2006). Results in wells 15/9-9, 15/9-13, 15/9-16 and 15/9-17 in block 15/9 proved anhydritic Zechstein Supergroup in Upper Permian with carbonates and evaporites being underlain by the Rotliegendes Group in Lower (Figure 2) (Cocking et al., 1992). Dominant extension and rifting due to the initial uplift of North Sea Dome during Triassic time formed Viking Graben, normal faults and the movement of the underlying Zechstein Supergroup salt resulting in the differential subsidence and erosion. It caused the significant variations in present thickness of Triassic sediments, resulting in non-deposition and/or erosion at this time (Pegrum and Ljones, 1984). Continental conditions continued into the Triassic with lacustrine and alluvial deposition of Smith Bank and Skagerrak formations (Figure 2).

Early – Late Jurassic

A regional uplift during Early-Mid Jurassic in the central North Sea eroded high areas and Sleipner Terrance, resulting in large removal of sediments on the Sleipner Terrance and abundant deposition of sand on Sleipner Graben in Bathonian and Callovian, which is predominantly composed of sandstone and coal layers, from Triassic to Jurassic record the transition from continental to marine environments (Figure 2). The subsequent major phase of rifting due to collapse of the dome and reactivation of fault systems during the Middle to Late Jurassic led to rise of relative sea level (Davies et al., 2001). As a result, the deposition of shallow-marine clastic sediments of Hugin Formation in Callovian interfingers and replaces the coastal plain and coal swamp deposits of the Sleipner Formation, following by offshore mudstone of the Heather Formation. (Figure 2). Relative sea level continued to rise during the Late Jurassic due to fault-related subsidence (Cockings et al., 1992), which led to continued deepening of the basin and deposition of shelfal and deep marine deposition of Heather and Draupne Formations.

Cretaceous

Rift-related faults became inactive and a period of compression from the Late Jurassic to Early Cretaceous. The last tectonic event of importance for the study area occurred in the Mid Tertiary resulted in a regional compression (Phillips et al., 2018). During early Cretaceous-Jurassic extension ceased with the onset of passive thermal subsidence and the syn-rift topography was covered by transgressive sediments to develop the Base Cretaceous boundary. (Zanella & Coward 2003). Deep marine environment of the Cromer Knoll Supergroup was deposited with siliciclastic, mud-prone shelfal and marls in the study area and South Viking Graben (Figure 2). There was widespread chalk deposition in northwest Europe including over the entire study area during the Upper Cretaceous (Glennie, 1998).

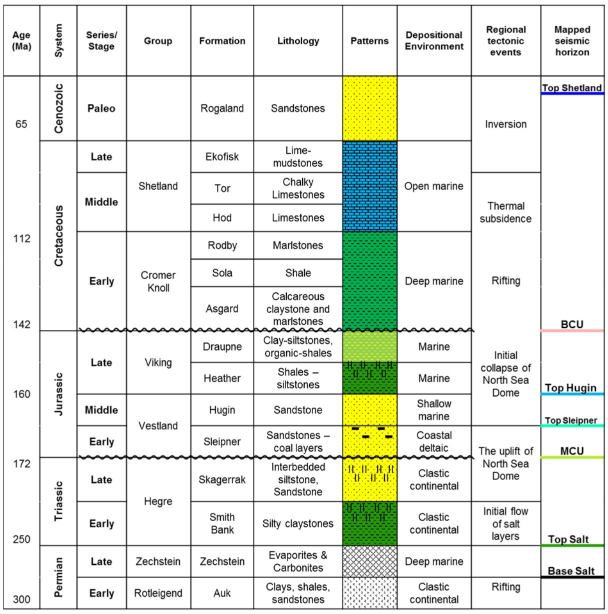

Figure 2: The tectono-stratigraphic column for the study area. It shows significant horizons for mapping, lithology, depositional environment and stratigraphic units (summarized from well reports, NPD, 2019).

3. Dataset and methods

This study used a post-stack time and depth-migrated 3D reflection seismic surveys covering 76.2 km^2 of Volve Field and a part of Loke Field (Figure 1) with normal polarity. The target interval for this study is from 2300ms to 3100ms TWT included Cretaceous Fm. to Upper Permian (Figure 2).

The selected wells (15/9-19A, 15/9-F1A, 15/9-F1B and 15/9-F4 are located on Volve field and 15/9-17 is located on Loke Field and 15/9-9 is located on Sleipner East) were used for stratigraphic calibration and well to seismic tie.

To observe the control of Zechstein salt layer on reservoir geometry in Volve Field, it is essential to be aware of the range of different configurations of Zechstein salt and thickness of reservoirs that occur in the study area by mapping key seismic horizons. The project was done using Petrel Software 2017. The seven key age-constrained stratigraphic surfaces are mapped at top of formations as in figure 2.

4. Structure and thickness of the reservoirs.

The change of thickness in both thickening and thinning through time of multiple geological intervals of reservoirs is observed to understand the influence of salt movement in the Volve Field

There are two stretching phases Permo-Triassic and Jurassic to Early Cretaceous, accompanying thermal cooling and subsidence in the Volve Field. (Færseth, 1996). The first phase of extension affected not only North Sea but also the study area resulting in the formation of Viking Graben, and occurred at the Sleipner Fault as the main western boundary of the Volve Field as well as Zechstein salt layers.

The evolution and deposition of the Triassic stratigraphic interval began with creation of primary salt-related minibasins (or “pods”), the sequence is marked from the base of Triassic to the more reflective wedge in the middle of Triassic. Generally, the salt diapirs have controlled the deposition of Triassic interval with thinning on the top of salt structures and thickening in depocentres. Consequently, the salt walls have collapsed. Rifting continued into earliest Triassic time and the Triassic to Middle Jurassic succession reflects a pattern of repeated outbuilding of clastic wedges from Utsira High. There was still considerable sediment supply from hinterlands. A similar geometry of sequences in both continental Triassic and marine Jurassic successions was related to variations of subsidence rate. Differential subsidence across faults throughout Triassic and Jurassic time is illustrated by various thickness of sediment on hanging wall and foot wall (Figure 3, 4). The high sedimentation rate is enough to keep up with the subsidence and variations in thickness resulted in forming diapirs of the underlying Permian salt (Figure 4a). During Triassic – earliest Jurassic, the uplift of North Sea Dome and fall of sea level causes the erosion of Triassic sediment at the top of structures and formation of fault-bounded high structures around the Volve Field (Figure 3, 4).

The second phase of rifting was primarily strengthened along the axis of Viking Graben associated with much more localized activity during Jurassic. Therefore, rift zone is wider and depended on depth and thickness of formations. As a corollary, the structure of Volve field has a series of down stepping faults due to gradual salt subsidence at the east flank and a more segmented west flank (Figure 3, 4).

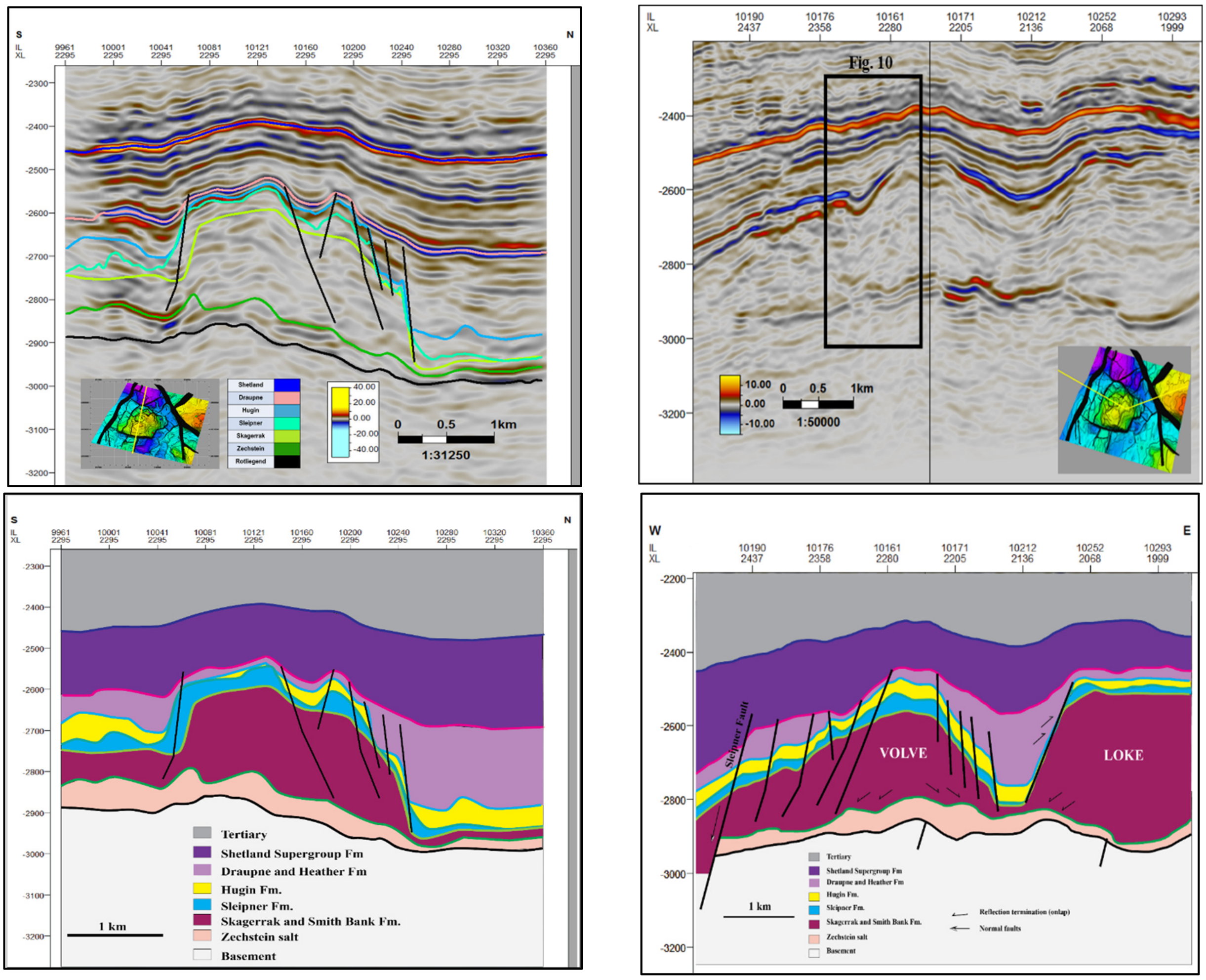

Figure 3: (a). Regional seismic line along XL 2295. (b). E–W trending seismic lines and corresponding geoseismic sections across the study area. Some of the key seismic-stratigraphic relationships (i.e. onlap, (apparent) downlap, erosional truncation) is shown.

During the Early Jurassic, impingement of a mantle plume at the base of the lithosphere led to the formation of the North Sea Dome (NSD) (Underhill and Partington, 1993) together with subsequent uplift of the SVG and the development of an unconformity at the base of the Jurassic succession. Sediment derived from the NSD and high structures prograded northwards through the Volve Field and into the SVG (Figure 4d). During the Middle Jurassic (Callovian), marine transgression associated with collapse of the NSD and the reactivation of the Sleipner Fault Zone (Thomas and Coward, 1996) led to deposition of the shallow-marine Hugin Formation. The initiation of rift-related normal faults influenced thickness and facies variations within these early syn-rift deposits (Figure 4c). During the latest Jurassic, an increase in fault- driven subsidence rates combined with the rise in relative sea-level, led to further continuous deepening of the minibasin and deposition of mudstone Heather formation and the deep marine organic-rich shale Draupne Formation (Figure 2, 4b).

Top Shetland Supergroup Formation is the upper boundary of Cretaceous age reservoir. At the crest of the high structure, time and depth values shows a domed geometry of the field. The western part of the area due primarily to crustal cooling caused subsidence after the Jurassic rifting (Bjorlykke et al., 2016). It has been given rise to eastward directed output of sedimentation witnessed a greater thickness than eastern part.

5. Estimation of salt distribution and thickness through time

A primary challenge for making geometrically corrected evolutionary models in a salt basin is the description of changes in thickness and volume of mobile layers.

For the calculation of salt volumes, it is assumed that base of salt layer will not change through time. The calculation of salt volume is based on the top salt at time A and base salt. The top of salt at time A is calculated by subtracting thickness between time A and top salt from the flatten surface at time A (Figure 5). Due to rough shape of salt layer, the Petrel software is utilized to divide the salt layer into small cells to determine the salt volume.

The total volume decreases forward in time to present day. Salt volumes for each period were estimated in the area from salt isopachs. As shown in figure 6, the salt volume generally decreases through time, rapidly from Triassic to Cretaceous and more slowly after that, ending with around 83% less than the Mesozoic values. Some anomalies need to be discussed through time.

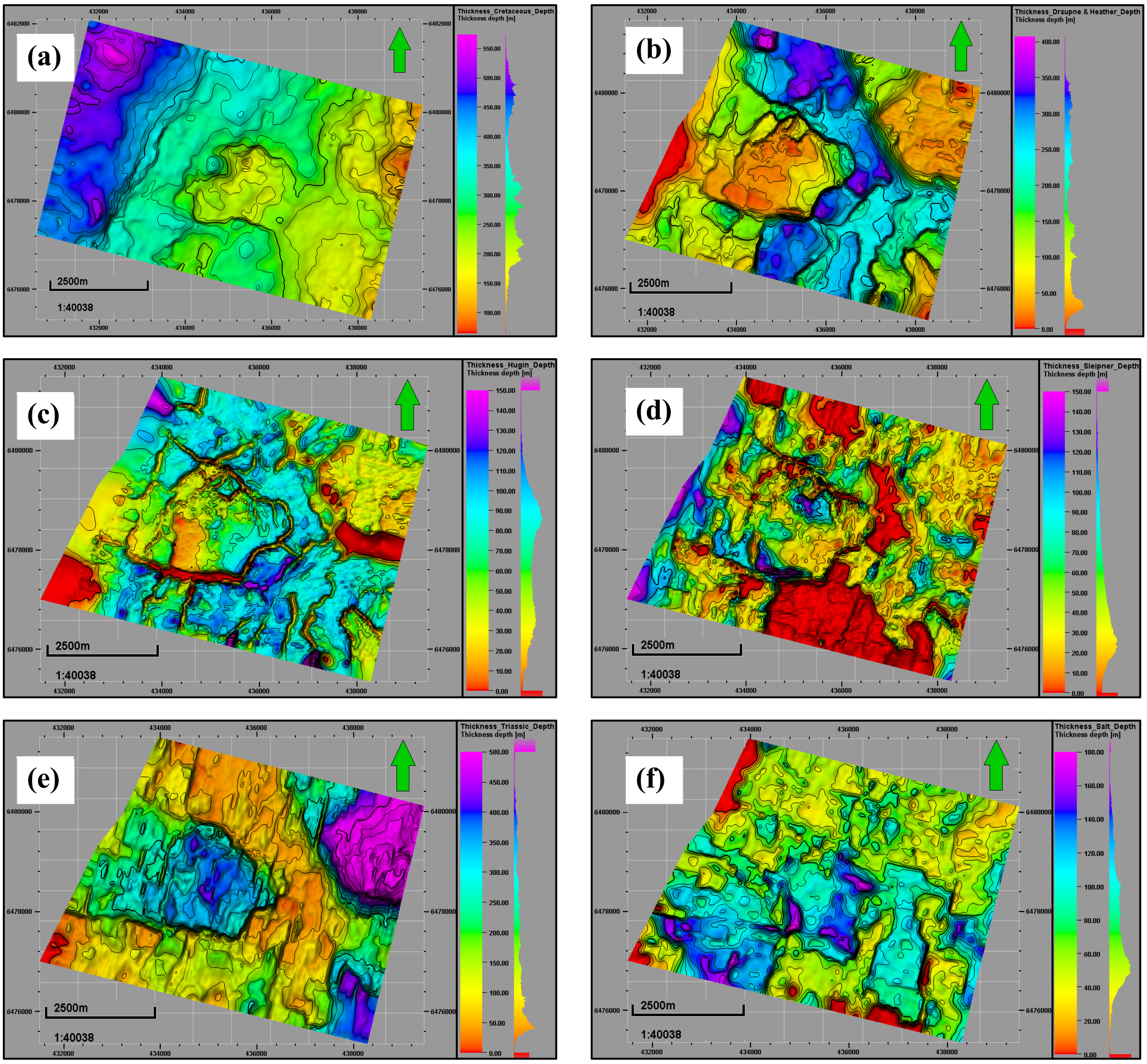

Figure 4: Depth thickness isopach maps of formations. Pronounced thickness variations are related to salt movement and tectonic activities. (a) Cretaceous Shetland Supergroup. (b) Late Jurassic (Volgian) Draupne and Heather Formation. (c) Middle Jurassic (Callovian) Hugin Formation. (d) Early Jurassic (Bathonian) Sleipner Formation. (e) Triassic Skagerrak Formation. (f) Upper Permian Zechstein Formation (Salt Layer).

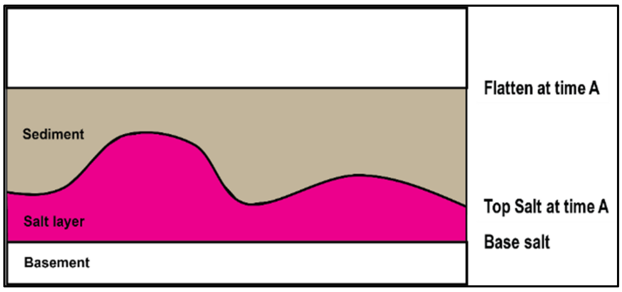

Figure 5. Concept model for calculation of salt volume and build top salt through time.

First of all, salt volume for oldest step are mostly higher than the corresponding values of the later time steps in entire area. The most likely explanation for this is that high sediment supply rate is deposited and resulted in the formation of salt ridge and depocenters or Triassic minibasin. Observation in Figure 7a shows that the salt ridges formed between Loke Field and Volve Field. The volume of salt is highest in end of Triassic period above present Jurassic minibasin due to movement up and formation of salt ridge. However, volume of salt below the Triassic minibasin is significantly decreased compared with previous time due to high deposition of Triassic sediment to form Triassic minibasin with the large thickness of present Triassic succession (Fig. 4e).

During middle Jurassic to latest Jurassic, rate of salt volume that moved out of area is highest at approximately $0.25x10^9m^3/Ma$ (Figure 6). It is affected by compaction of mudstone in the Draupne and Heather Formation, high sediment supply rate, the collapse of North Sea Dome associated with rise of sea level. The uplift and related events may have formed dissolution of salt from flowing underground freshwater (Groetzner, 1996) resulting in formation of large accommodation space, which resulted in deposition of thick sediments (Figure 4c). As a result, high compaction and subsidence of the Jurassic minibasin above salt ridges is evidence of a high decrease of salt volume.

During Early Cretaceous, activity of North Sea Dome and tectonics are still remaining and gradually decreased, so new and older (Jurassic) accommodation space are available due to an increase in relative sea level. The variations in thickness map of Cretaceous (figure 4a) shows that the process of sedimentation into the place of previous Jurassic minibasin is slow, stable and widespread, thus the compaction of overburden on Zechstein Supergroup is continued and equally force on older sediment and salt layers. In Cretaceous, volume of salt that moved out of areas is still diminished but at a higher rate than later time steps (Figure 9). However, high withdrawal of salt volume is caused by large sediment supply of Cretaceous carbonate.

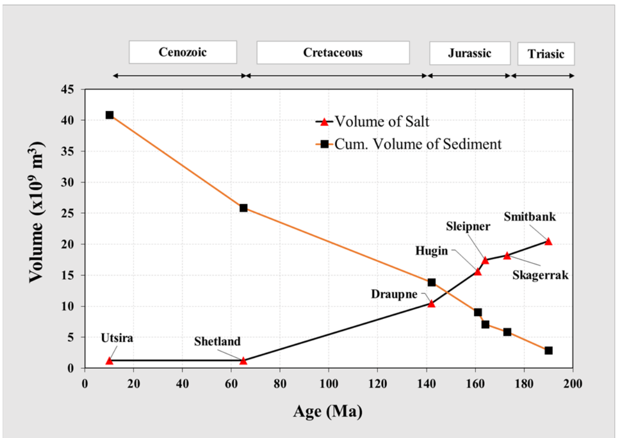

Figure 6: Plot showing salt volume change implied by the restoration through time. Final volume is 83% less than the initial volume. Overall, volume of salt significantly decreases during Jurassic to Cretaceous. The largest decline rate is in Jurassic (aroound 0.250x109m3/Ma).

During Cenozoic and Tertiary, salt volumes do not change, even though high sediment is deposited (Figure 6). All of the events related to tectonics have mainly ceased except for widespread deposition of sediment. The sediment covers the entire study area, so the compaction above salt is almost equal in everywhere. Top salt at end of Cretaceous and present day is generally the same. (Figure 7e, f).

6. Discussion

6.1 Reservoir Geometry Through Time

The spatial various amount and rate of deposition of lacustrine shale in Early Triassic Smith Bank Formation have caused difference of overburden sediment loading that can trigger and drive the movement of Zechstein salt layer.

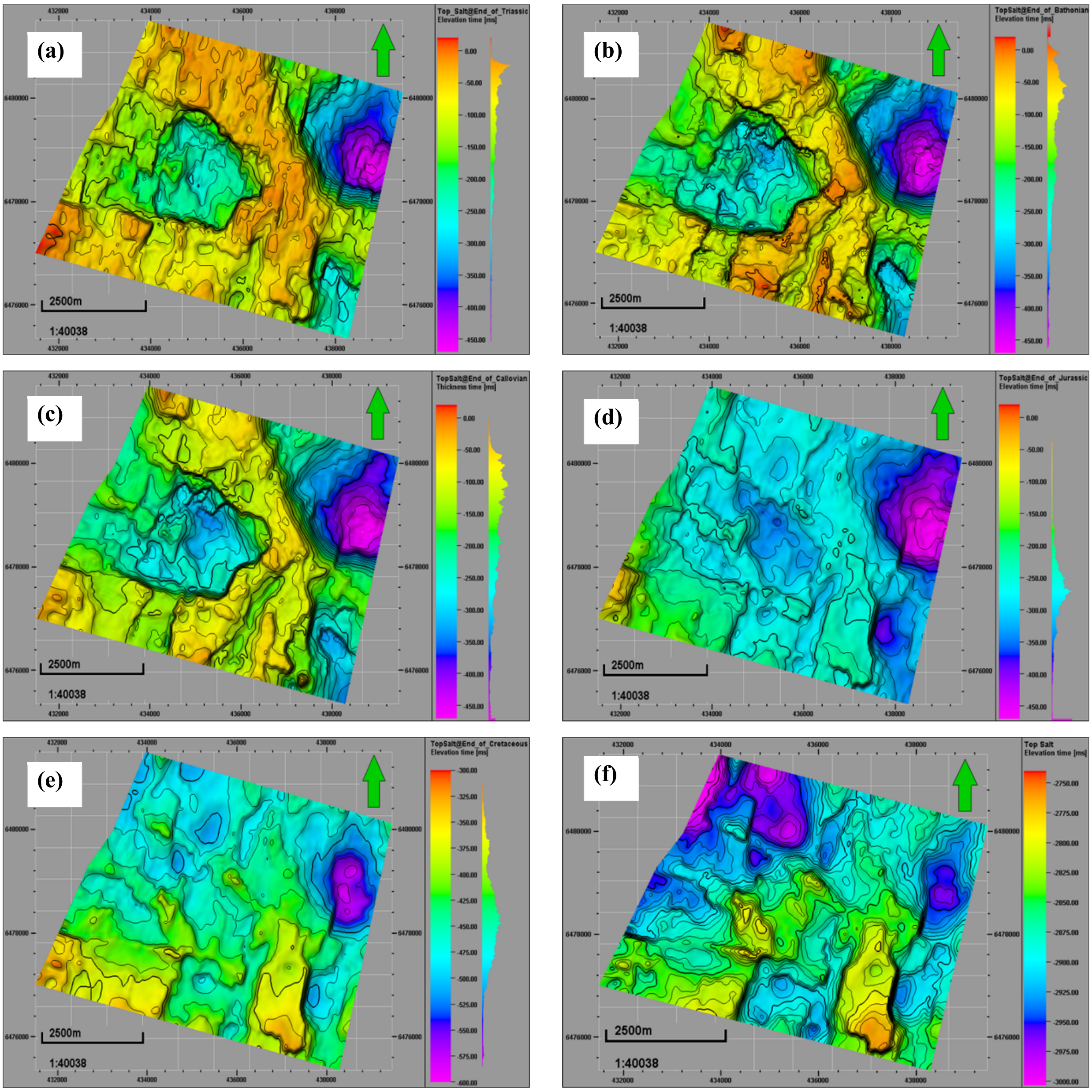

Figure 7: The maps show the evolution of top salt from Late Triassic to present. (a) End of Triassic. (b) End of Bathonian (Early Jurassic). (c) End of Callovian age (Middle Jurassic). (d) End of Volgian (Late Jurassic). (e) End of Cretaceous. (f) At present day

Various developments of accommodation space and differential overburden are started by the formation of random surface topography. The Zechstein salt moved laterally to create a series of salt walls (Figure 8a, b) (Warren, 2016). Movement and growth of salt body and the deepen minibasin above the area of salt withdrawal were during the Late Triassic resulting in thick deposition of the Skagerrak Formation. It supplies the high sedimentation rates together in non-marine settings. The accommodation space was rapidly filled, thus forming significant thick Triassic minibasin. However, the uplift and development of North Sea Dome have led to the interruption of Triassic minibasin development and also the drop of sea level leading to formation of the Mid-Cimmerian Unconformity (MCU) during Bathonian.

Based on seismic data, Jurassic minibasin was obviously formed by salt-driven subsidence compared to the previous Triassic phase of minibasin development (Figure 3, 4). Salt-cored structures, resulted in low accommodation with deposition of relatively thin Triassic succession. The movement of the salt from salt-cored structures resulted in places of accommodation and resulting minibasin during Jurassic. The apparent withdrawal and collapse of salt walls deformed internally earlier-generated Triassic minibasin. The margins of Jurassic succession are turned downward and onlap on MCU (top of Triassic minibasin). The development of clinoforms in Triassic succession is a primary depositional features as downlap relationship. The tectonic-stratigraphic model illustrates the sediment widespread patterns resulting in the reservoir distribution between Loke Field and Volve Field (Figure 3, 4). During Early Jurassic, fluvial systems of Sleipner Formation from Utsira high may flow from North to North-West direction along Jurassic minibasin and spill across salt ridges or high structures of Triassic (Jackson, 2010). Consequently, rise of relative sea level during Middle –Early Jurassic is flooded on minibasin terrain on Loke Field and Volve Field and deposited a series of shallow marine sediments from Utsira High and crest of Triassic-cored pods. All of these sandstone reservoirs are complex because of pre-existing and syn-existing movement of salt and fault-related tectonic activity (Figure 3, 4, 5 and 6). Furthermore, reservoir distribution and geometry is more complicated due to the various processes of sediment supply, transport and types of deposition such as wave, tide and rivers. Continuous rise of sea level during Late Jurassic resulted in more flooding of the study area and immersion of the preceding Early Jurassic Succession. As a result, subtle topography and complicated seabed bathymetry of the study are present. Sand-rich gravity currents in Heather and Draupne Formation may flow across the bathymetry and become the ponded and deflected structures (Figure 3, 4, 5b and 6b).

The latter stages of deposition in Cretaceous, the sediment transport would have been more broadly expansive throughout the Viking Graben with thickening westward. The control of Cretaceous reservoir on contemporaneous deep-water deposition is the process of filling and spilling rather than influence of salt movement.

Due to the large extent of fault systems during Permo-Triassic, it suggests that the series of large faults also control basin geometry as well as extension, subsidence and sedimentation patterns. A North to NE-trending Sleipner Fault bounds the limit of thick Triassic sediment to west and also becomes the western boundary of Jurassic sediments. Generally, the Jurassic extension in Viking Graben was localized. Additionally, the collapse of North Sea Dome at this time enhanced the complicated formation of fault systems. As a result, eastern and northern flank of the field formed by many stepping faults and is divided into blocks (Figure 4).

6.2 Salt Stages

By the observation of sediment thickness variation and the reconstruction of top salt through time in the study area, it can be concluded that initial stage of Triassic minibasin and formation of salt wall happened in Late Permian – Early Triassic. Minibasin deepening and salt wall growth was because of continued sediment loading until Late Triassic. Salt diapirism continued until middle Jurassic. It caused the increase in thickness of the succession into salt diapirs.

The early Triassic was the main stage of salt wall because this sequence displays large sediment thickness variation with thickness decreasing in the direction of salt high structure. Triassic sediments are also draped with sediments displaying a gentle dip along the flanks of salt structures. Significant withdrawal of salt from the source towards salt structures created large anticlines. There is a presence of on-stepping halokinetic sequence stacking. It is related to the diapir contraction. At the end of the period, the rate and amount of salt withdrawal was decreased in high sediment loading and increased in formation of salt walls with thin thickness of sediment. (Figure 5, 8a).

In Middle Triassic, minibasin deepening and salt wall growth occurred due to continued sediment loading. Late Triassic–Early Jurassic, the many events such as regional Early Jurassic uplift to form fault systems around minibasin and fall of relative sea level resulted in the initiation of collapse of overburden to create Jurassic minibasin and subterranean dissolution of Zechstein salts. The dashed line in figure 10b show the initial location of top salt. Dissolution-related subsidence may be locally raised by differential erosion of Triassic minibasins and salt-cored highs by Sleipner Formation fluvial systems. Moreover, due to the dropping of sea level caused by uplift, the Mid-Cimmerian Unconformity (MCU) was formed associated with the main differential erosion of Triassic minibasin and adjacent areas leading to creation of Jurassic minibasin above salt-cored highs.

Middle–Late Jurassic, the minibasins were filled in the preceding sites of Triassic subsidence and salt dissolution. Note that the filling of minibasin in east is earlier than that of west because of either the stopping of subsidence on Triassic or a high sediment supply to the areas. Moreover, the formation of South Viking Graben may have caused deepening westward that brings sediment from Utsira High into the study area associated with the flowing of groundwater resulting in augmentation of salt dissolution. In the central parts, minibasins were continuously subsided in latest Jurassic, resulting in thicker sediments than above high structure of Volve Field and Loke Field (figure 5b). With high sediment supply of deep marine shale of Draupne and Heather Formation, the compaction of overburden above salt diapirs happened resulting in rapid withdraw of Zechstein Supergroup.

Movement of salt finally diminished during the latest Jurassic and Early Jurassic and then ceased completely on Late Cretaceous. The variation in structures of base (top Jurassic) and top Cretaceous as well as relatively consistent Cretaceous reservoirs indicate that early Cretaceous units are driven by differential compaction across the underlying Jurassic minibasin. The waning impact of salt movement during Cretaceous can reflect the final geometry of mainly Triassic minibasin and depleted location of the Zechstein Supergroup. In addition, the cover of the salt-related topography by permeability reduction of Heather and Draupne mudstones Formation could restrict the aggrading dissolution-related collapse of Zechstein salts.

6.3 Mechanisms of Salt Movement

(a) Salt Dissolution

Based on tectonic-stratigraphic seismic data, the dissolution process of Zechstein Supergroup in study area may have been driven by subsidence, groundwater and the formation of minibasin.

The flow of ground water or undersaturated evaporite pore water superjacent, along, underneath or within salt (Warren, 2016) may have formed the karst features in which Triassic sediment gradually collapsed. The mechanism of superjacent dissolution of Zechstein salt requires places of salt bodies located at or near depositional or erosional surface during the formation of Triassic minibasin (Jackson, 2010).

The observation of top salt through time and tectonic activity in the study area suggests that the uplift and erosion in Late Triassic – Early Triassic may have led to expose the salt ridges on surface (figure 8b). Moreover, thin and absent thickness of Early Jurassic above salt ridges (Figure 4) have been evidenced to account for strong erosion into Triassic minibasin to reach the top salt. The subsidence of Jurassic minibasin would have been formed by the dissolution mechanism.

Circle collapse features or sinkhole in the study area indicates that there is dissolution mechanism related to groundwater flow (Figure 9) (Clark, et al, 1999). Top of the buried salt layer is dissolved by circulation of phreatic waters through sediment and compaction-driven flow of pore waters (Warren, 2016). Zechstein Supergroup with interbedded salt and soluble rock such as carbonate, gypsum, dolomite and anhydrite (NPD, 2019) can cause failure and collapse of the overlying rocks resulting in the formation of sinkholes and fractures. During Late Permian – Early Jurassic, Zechstein evaporites may have been dissolved and exposed to groundwater circulation in the Lacustrine Smith Bank Formation resulting in formation of evaporite karst. The Smith Bank Formation were intruded by the downbuilt of Skaggerak Formation resulting in the top of salt close to depositional surface.

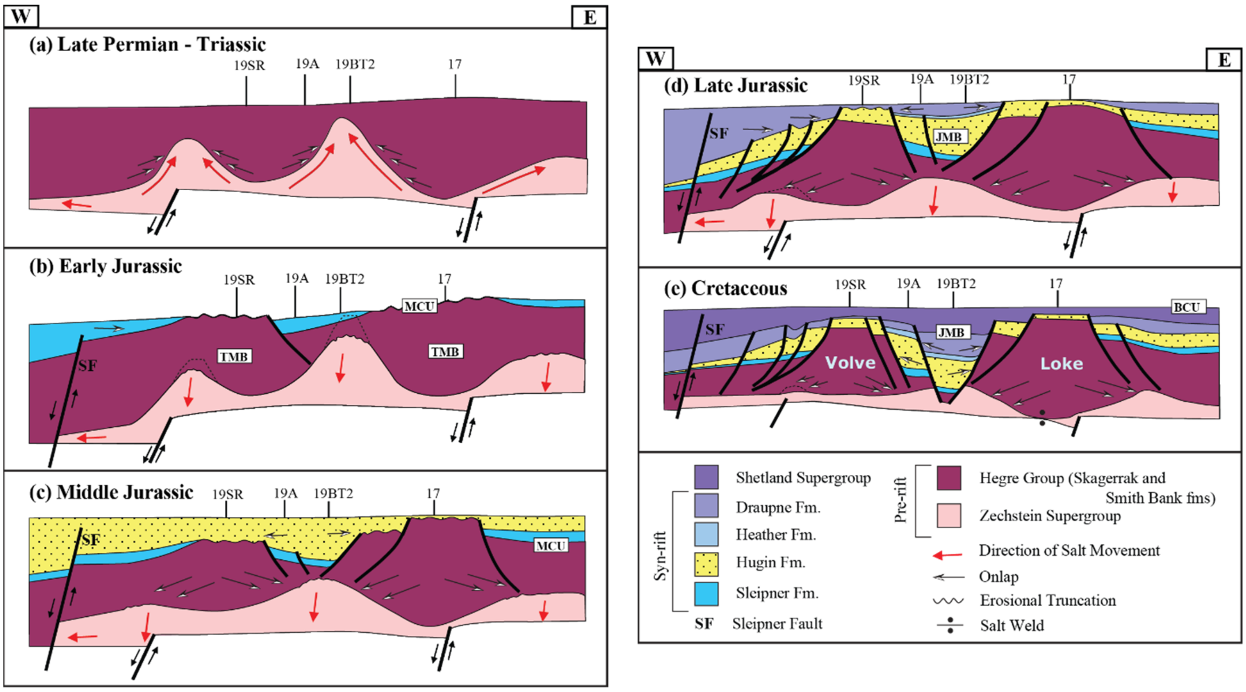

Figure 8: Schematic illustration of the evolution of the Volve Field. In the illustrations the three exploration wells (NO 15/9-19 SR, NO 15/9-19 A and NO 15/9-19 BT2) on the Volve structure and the one exploration wells (NO 15/9-17) on the Loke structure are shown. (a). Late Permian – Triassic: Deposition of Zechstein Salt and Deposition of Smith Bank and Skagerrak Fm. loaded the salt to extent that it started to move resulting in formation of Triassic minibasin. (b, c, d). Jurassic: Salt movements created depocenters (Jurassic minibasin) in areas of withdrawal and salt ridges and diapirs in adjacent areas. (b). Early Jurassic (Bathonian): Sleipner Fm. is deposited in the Jurassic minibasin. Regional uplift and relative fall of salt and creation of Mid-Cimmerian Unconformity (MCU) (c). Middle Jurassic (Callovian): Continued salt movements and deposition of Hugin Fm. thicker in subsiding areas and thinner on highs. (d). Late Jurassic (Oxfordian – Volgian): Depostion of Heather and Draupne Fm.and filling of Jurassic minibasin. (e). Cretaceous: Deposition of Shetland Supergroup. (Modified from well reports, NPD, 2019).

During Latest Triassic to Early Jurassic, the formation of North Sea Dome and falling of relative sea level causes the uplift and erosion of Triassic minibasin and Zechstein salt due to fresh flowing water directed from Utsira High to Viking Graben. Moreover, mantling of low-permeability formation, late Jurassic – Early Cretaceous mudstones have restricted superjacent dissolution. The marine transgression during this period formed a new flow of waters, albeit marine, resulting in reactivation of dissolution of Zechstein supergroup in salt walls. It can cause subsidence and formation of circular features as in Figure 8.

b) Salt Withdrawal

A common mechanism for minibasin formations is salt withdrawal and remigration due to regional extension and differential loading. (Figure 8). Complex fault systems and a lot of normal faults in Triassic and Jurassic minibasin show the strong supra-salt extension and powerful tectonic activity as a major driver for salt wall subsidence and withdrawal. One of mechanisms for triggering salt movement is differential overburden associated with various sediment supply rates. As discussed above, the action of NSD, the two phases of extension and variation in relative sea level form the large accommodation space filled by a huge sediment source derived from Utsira High with high depositional rate. It forced the salt to move out of study area from North East to South West.

Moreover, Sleipner Graben on west is deeper than Utsira High on east. It suggests that the gravity sliding of salt also occurs due to sloping configuration supported to salt movement. In figure 4f, the thickness of salt layer on N-E beneath Loke Field is smaller than that of S-E below Volve Field.

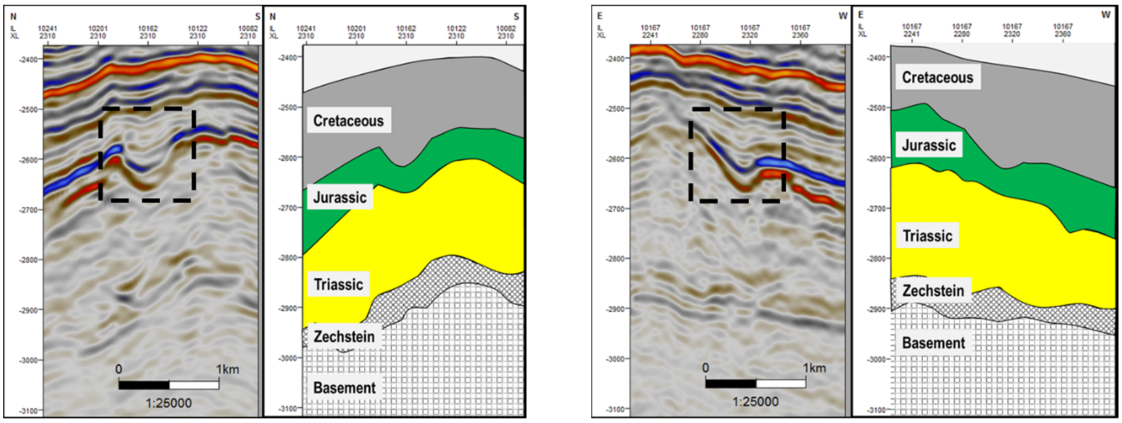

Figure 9: Schematic illustration of circular collapse features (dash black box) or sinkhole indicates the salt dissolution caused by hydrogeology.

As salt moves from NE to the SW, the larger thickness of salt layers allows the salt buoyancy to reduce the strength of the overburden to move upwards. Therefore, gravity sliding of salt layer may have supported the common trigging mechanism of salt movement caused by differential loading.

(c) Differential erosion

During Latest Triassic to Early Jurassic, the differential erosion of Triassic salt-cored highs and adjacent areas was caused by the uplift and falling of relative sea level. It is also expected to be combined with the dissolution mechanism (figure 10b). This coupled process remained until early Callovian resulting in erosion into Triassic minibasin, with an absence of Sleipner Formation and exposed salt ridges. The Triassic salt-cored highs would have formed in the less erodible topographic highs. As a corollary, the superimposition of Jurassic formations on preceding Triassic structural highs (figure 4, 8).

7. Conclusions

During the period of Upper Permian to End of Cretaceous, the study area experienced two different rift phases: Triassic to Early Jurassic and Middle Jurassic to early Cretaceous. The two extension phases are important for formation of the minibasin and salt movement.

In Triassic – Early Jurassic, Triassic minibasins were formed by the mobilization of Zechstein Supergroup Salt (upper Permian). The movement of salt was related to dissolution, various sediment supply and loading by the Smith Bank and Skagerrak formation. The geometry of Triassic minibasin was also configured by first phase of rifting.

In Middle Jurassic to Early Cretaceous, Jurassic minibasins were developed as the salt wall collapsed and dissolved. With large accommodation space created from previous Triassic and phases of rifting, it caused the great thickness of reservoirs resulting in high withdrawal of salt volume.

In Late Cretaceous, the salt movement generally does not influence the geometry of reservoir except for tectonic activity.

The influx of fluvial channel systems (Skagerrak and Smith Bank Formations), geometry of shallow marine depocentres (Sleipner and Hugin Formation) and flows of submarine sediment (Draupne and Heather) was affected by the formation of Triassic and Jurassic minibasin.

The trigger mechanisms of salt movement in the study area are withdrawal caused by differential loading associated with support of gravity sliding, salt dissolution and differential erosion.

The tectonic events formed the complexity of fault blocks in the Volve Field. A series of down stepping faults at the east flank and detachment faults at west flank were developed. In addition, the larger Sleipner graben fault defined the west bounding fault of the field.

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