

**PS Variability in Syn-Rift Structural Style Associated with a Mobile Substrate and Implications for Trap Definition and Reservoir Distribution in Extensional Basins: A Subsurface Case Study from the South Viking Graben, Offshore Norway\***

**Christopher A-L. Jackson<sup>1</sup>, Karla Kane<sup>1</sup>, Eirik Larsen<sup>2</sup>, Elisabeth Evrard<sup>1</sup>, Gavin Elliott<sup>1</sup>, and Rob Gawthorpe<sup>3</sup>**

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**Abstract**

The South Viking Graben (SVG), northern North Sea, hosts many large hydrocarbon accumulations. In the Norwegian sector, the main reservoir-trap pairs are: (i) Middle Jurassic shallow marine sandstones in structural traps, and (ii) Palaeocene Deepwater sandstones in structural or combination traps. Upper Jurassic, syn-rift turbidite sandstones form reservoirs in several fields in the UK sector, but the equivalent succession in the Norwegian sector remains relatively unexplored due to difficulties in predicting reservoir distribution and trapping configurations. These difficulties reflect the control that rift-related normal faults and salt movement has on the deposition of Deepwater reservoir sandstones. In this study we use potential field, 3D seismic and well data to investigate how normal fault growth and movement of the evaporite-dominated Zechstein Supergroup control spatial variations in syn-rift structural style, trapping styles and reservoir distribution in the SVG. In the north of the basin, syn-rift deformation is dominated by listric faults that detach downwards into the underlying evaporites. These faults formed in response to tilting of the hangingwall and break-up of the supra-salt units, and halokinesis in this area is restricted to low-relief salt rollers in the immediate footwalls of the listric faults. In the central part of the basin, rift-related normal faults are basement-involved and only rarely propagated up through the Zechstein Supergroup. In this location fault-propagation folds, which are cored by low-relief salt pillows, developed in the supra-salt cover strata. The southern part of the basin is dominated by a series of ‘minibasins’ developed in response to the collapse of older Triassic-age salt diapirs; normal faulting is rare, and limited to low-displacement structures overlying the crests of salt diapirs and a few basement-involved faults that breach the Zechstein Supergroup. This study demonstrates that the Late Jurassic, syn-rift structural evolution of the SVG varied markedly over relatively short (i.e. <20 km) length-scales. We interpret this variability is related to mobile halite distribution within the Zechstein Supergroup; ‘halite-poor’ parts of the basin

are characterized by supra-salt, gravity-driven faults, whereas minibasins formed in 'halite-rich' parts of the basin. We conclude by demonstrating how these variations in structural style control the distribution and geometry of syn-rift reservoirs.

# Variability in Syn-Rift Structural Style Associated with a Mobile Substrate and Implications for Trap Definition and Reservoir Distribution in Extensional Basins: A Subsurface Case Study from the South Viking Graben, Offshore Norway

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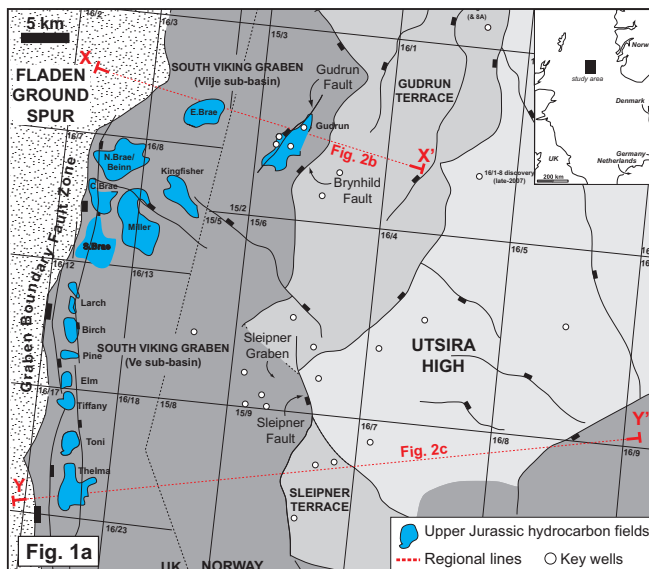
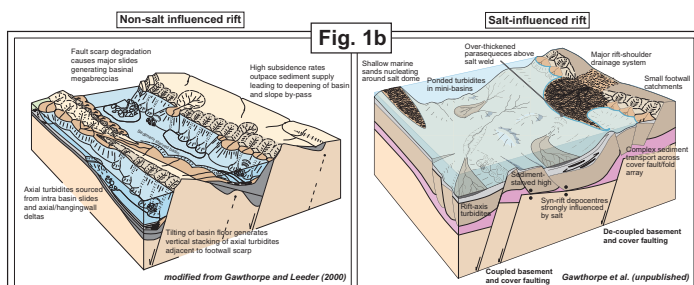
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## 1. Rationale

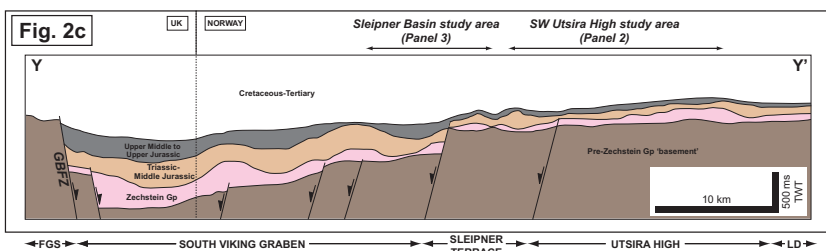
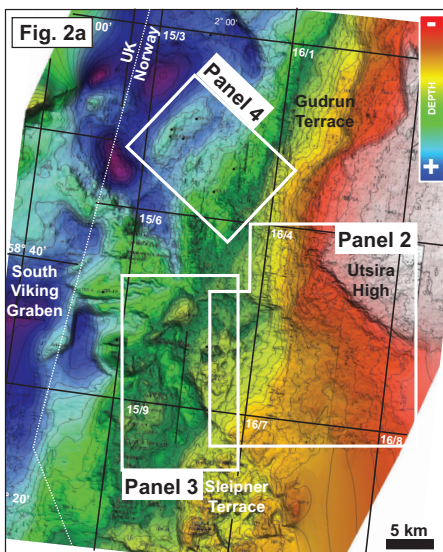
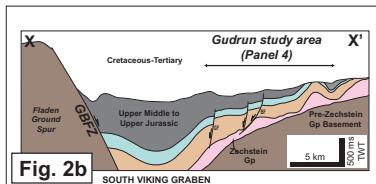
- Deep-water sands within the **Upper Jurassic syn-rift** succession form the reservoir for several hydrocarbon fields in the UK sector of the **South Viking Graben** but the equivalent succession in the **Norwegian sector remains relatively unexplored (Fig. 1a).**
- The prediction of **syn-rift reservoir distribution** requires an understanding of: (1) the control of salt lithology and thickness on normal faulting and folding; (2) the **impact of halokinesis and salt-influenced rifting** on trap development; and (3) the influence of faulting and halokinesis on **syn-rift sediment dispersal** during (Fig. 1b).



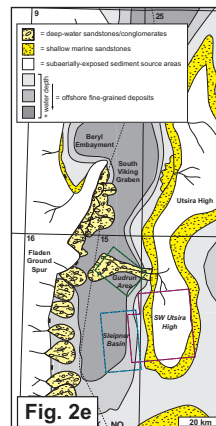
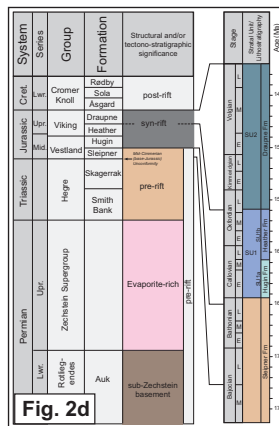
## 2. Study Area

### 2.1. Structural Setting

- The **South Viking Graben** is a half-graben located along the northern arm of the **Late Jurassic North Sea rift (Fig. 2a-c).**
- The **Graben Boundary Fault Zone (GBFZ)** bounds the South Viking Graben to the west (Fig. 2b-c).
- The case studies presented here are located on the **hangingwall dipslope** of the graben (Fig. 2a-c).



### 2.2. Stratigraphy and Palaeogeography

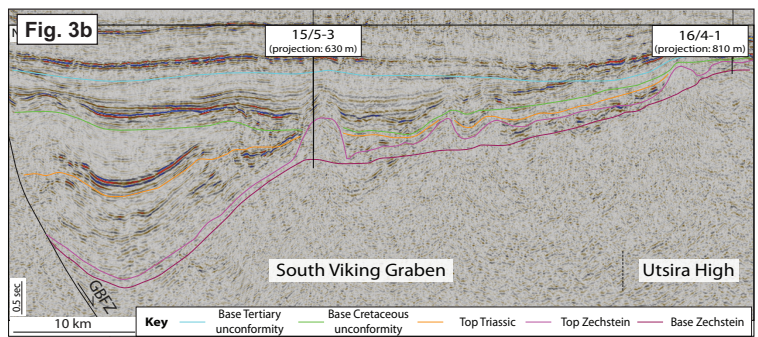
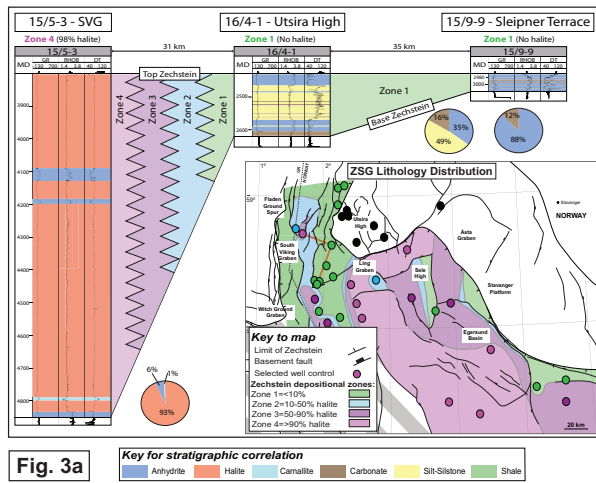


- The **pre-rift** succession contains the **Upper Permian Zechstein Supergroup evaporites**; these influenced the rift structural style (Fig. 2d).
- Triassic and early Middle Jurassic** units form pre-rift cover strata (Fig. 2d).
- Syn-rift** succession subdivided into:
  - SU1: early syn-rift**, late Callovian to late Oxfordian, **Hugin** (shallow-marine sandstone) and **Heather** (shelf mudstone) formations.
  - SU2: late syn-rift**, late Oxfordian to Volgian, **Draupne Formation** (deep-marine mudstone and turbidite sandstone) (Fig. 2e).





### 3. Thickness and lithology of the Zechstein Supergroup

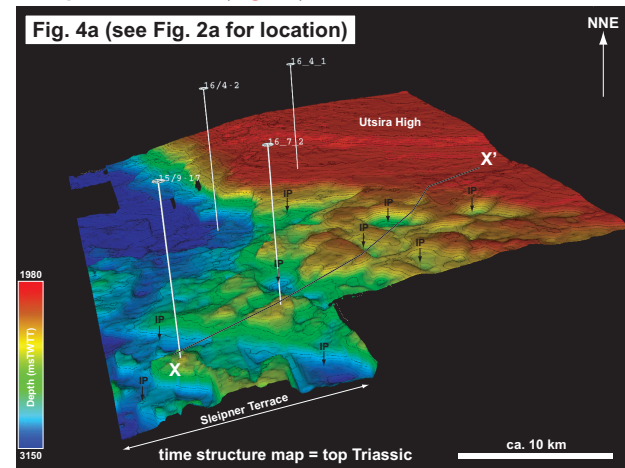


- The ZSG is dominated by halite, anhydrite and carbonates (Fig. 3a).
- Based on halite proportion, four depositional zones are identified (Fig. 3a).
- At the basin margins, the ZSG is relatively thick and dominated by anhydrite and carbonate; towards the basin centre the unit is relatively thick and halite-dominated (Fig. 3a-b).

### 4. Case Study 1: Minibasins on the SW margin of the Utsira High

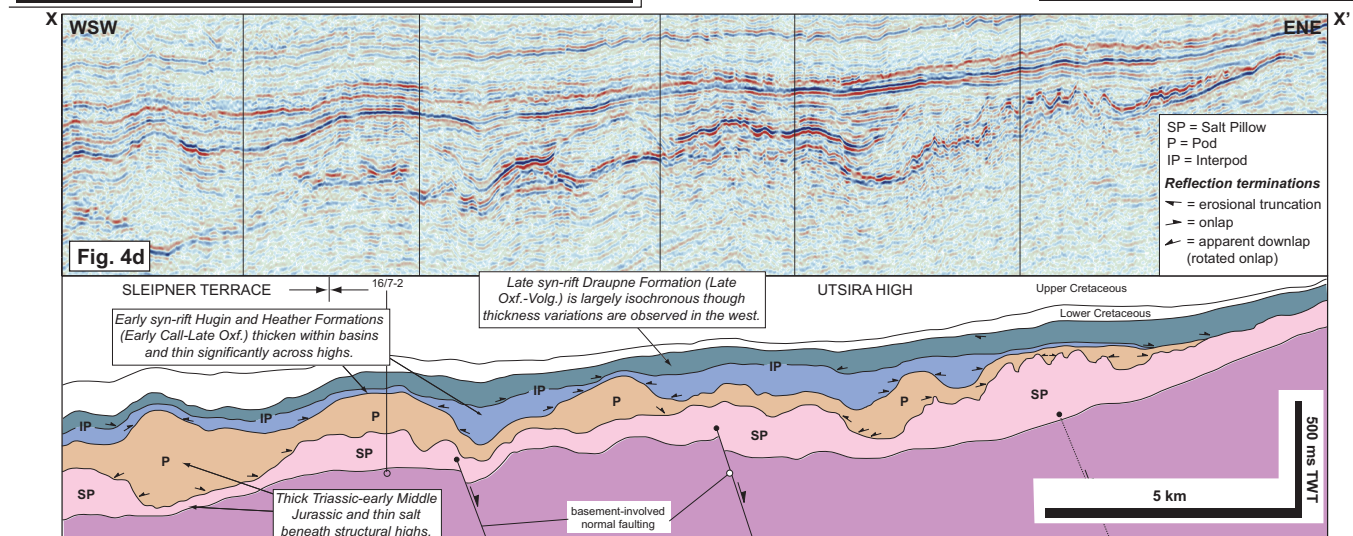
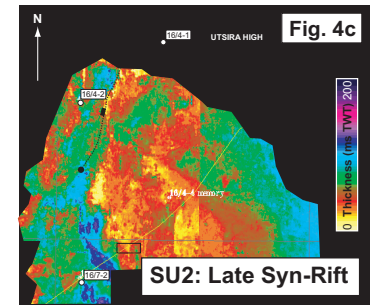
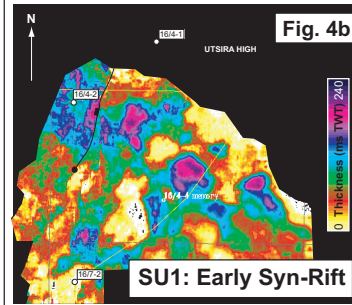
#### 4.1. Structural Style

- Minibasins are developed between the Utsira High and Sleipner Terrace (Fig. 4a & 4d).
- Minibasins are cored by thick Triassic successions, and early Middle Jurassic strata and Zechstein Supergroup evaporites are thin (Fig. 4d).

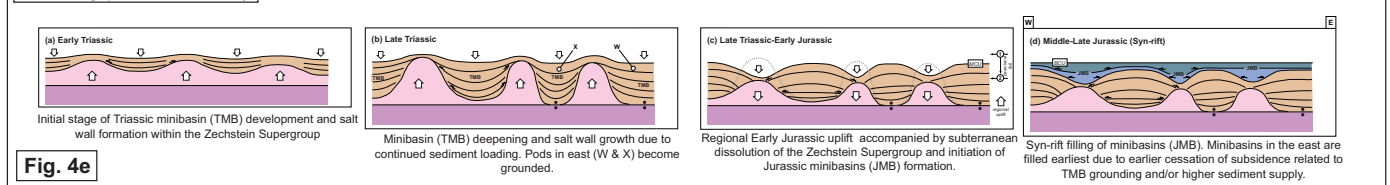


#### 4.2. Tectono-stratigraphic evolution

- The early syn-rift (early Callovian to Late Oxfordian) Hugin and Heather formations were deposited across the slope but were thickest in the basins (Fig. 4b & 4d).
- The late syn-rift (Late Oxfordian to Volgian) Draupne Formation were largely restricted to the western slope; thickness variations on the eastern slope are subtle because relief had been filled by early syn-rift deposits (Fig. 4c & 4d).
- Topography/bathymetry associated with flow of the ZSG during the Triassic-early Middle Jurassic and later collapse of salt structures during the late Middle and Late Jurassic (Fig. 4e).



Tectono-stratigraphic model for Case Study 1

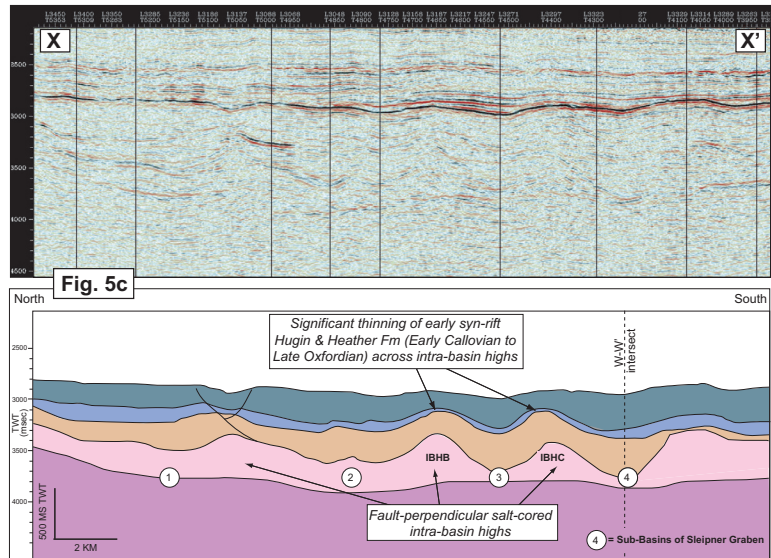
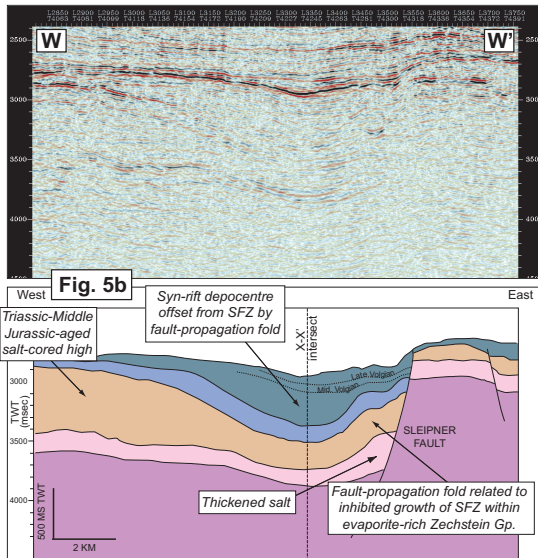
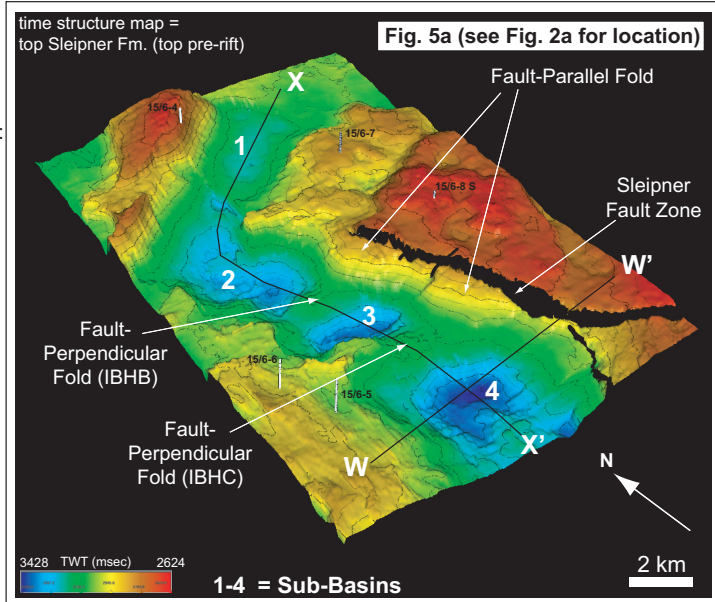




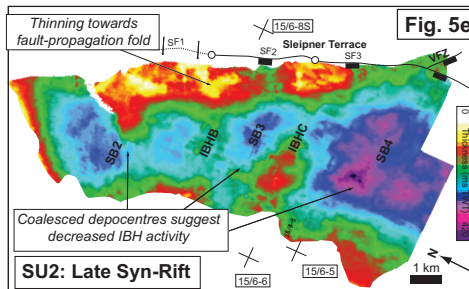
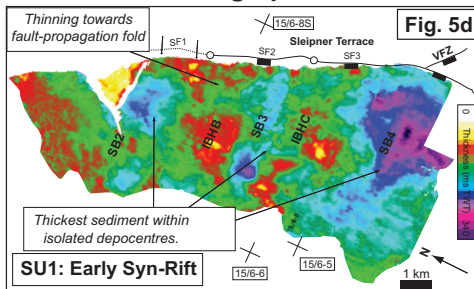
## 5. Case Study 2: Salt-influenced fault-related folding in the Sleipner Basin

### 5.1. Structural Style

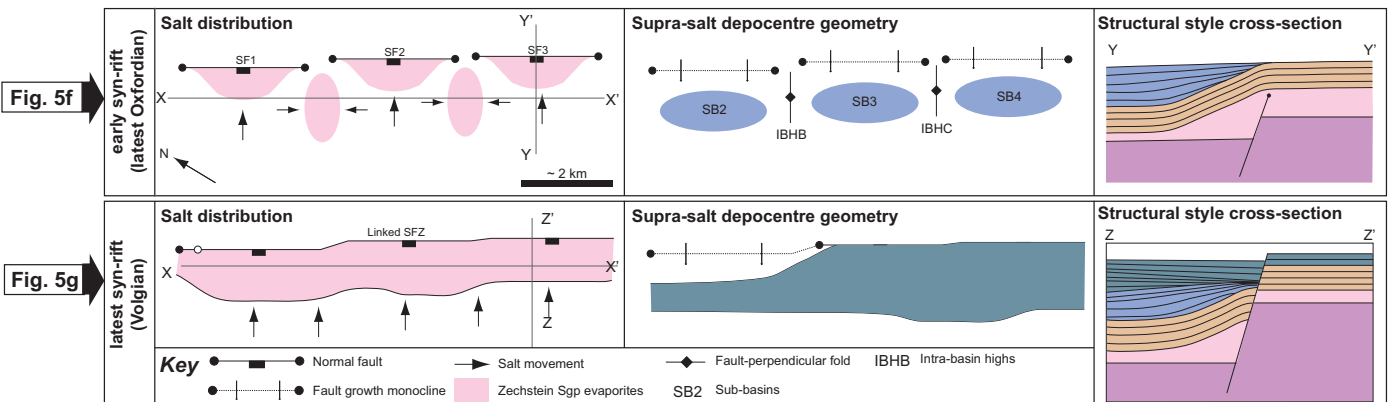
- The **Sleipner Basin** is bound to the east by a segmented extensional fault (**Sleipner Fault Zone - SFZ**) and to the west by a large salt-cored high (**Fig. 5a & 5b**).
- Fault and salt-related fold structures** are identified in the basin:
  - Fault-Parallel Fold** - A fault-parallel monocline underlain by thickened salt is identified in the immediate hangingwall of the SFZ (**W-W'** in **Fig. 5a & 5b**). This structure is interpreted as a **fault-propagation fold** (extensional forced fold) which formed through the inhibited growth of the Sleipner Fault within the ductile Zechstein Group (**Fig. 5a & 5b**).
  - Fault-Perpendicular Folds** - Three fault-perpendicular, salt-cored anticlines or intra-basin highs (IBH) compartmentalise the basin into four sub-basins (**X-X'** in **Fig. 5a & 5b**). These intra-basin highs are located adjacent to areas of fault segment overlap.
- Seismic isochron mapping** (**Fig. 5d & 5e**) provide insights into the temporal and spatial development of the SFZ and the Sleipner Graben and these allow proposal of a **tectono-stratigraphic model** (**Fig. 5f**).



### 5.2. Tectono-stratigraphic evolution

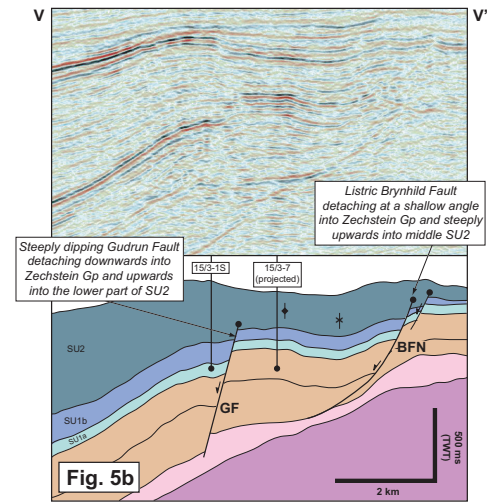
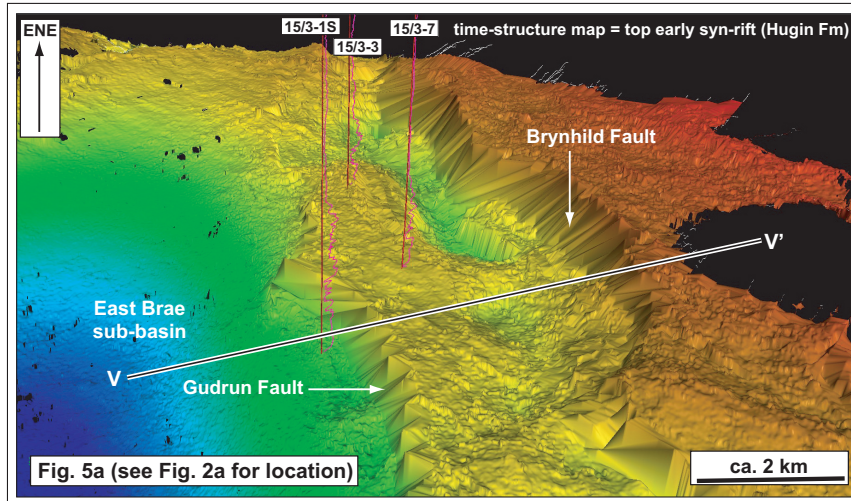


- Early syn-rift (SU1)** - growth of fault-perpendicular (IBH) and fault-parallel folds formed a compartmentalised depocentre and influenced syn-rift sediment distribution (**Fig. 5b-d**).
- Late syn-rift (SU2)** - diminished influence of fault-perpendicular folds and formation of a larger, linked depocentre; eventual breaching of fault-parallel fold (**Fig. 5b-c and e**).

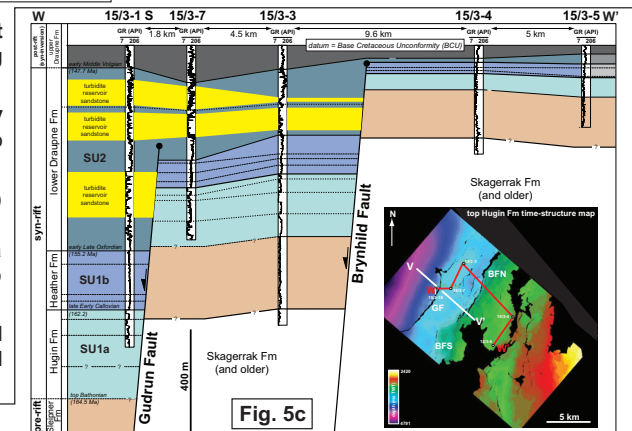


# 6. Case Study 3: Thin-skinned gravity-driven extension in the Gudrun area

## 6.1. Structural Style

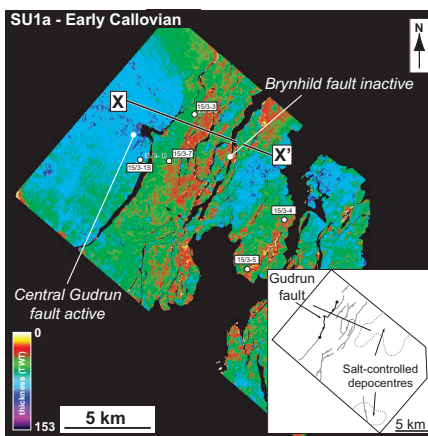


- In the Gudrun area the ZSG formed a detachment for a thin-skinned fault array that developed due to progressive westward hangingwall tilting towards the GBFZ (Fig. 5a & 5b)
- The Gudrun Fault is 17 km long, planar in cross-section and dips steeply to the NW. The fault tips out downwards into the ZSG and upwards into the lower part of the Draupne Fm (SU2) (Fig. 5a & 5b).
- The Brynhild Fault occurs 5 km to the NE (i.e. up the hangingwall dipslope) of the Gudrun Fault. It is 15 km long and is divided into a southern (BFS) and northern (BFN) segment. Both are listric in geometry, detaching at a shallow angle into the Zechstein Gp and tipping out steeply upwards into SU2. A rollover anticline is developed in its hangingwall (Fig. 5a & 5b).
- Biostratigraphically-constrained stratigraphic correlations (Fig. 5c) and seismic isochron mapping (Fig. 5d-f) document the temporal and spatial evolution of the Gudrun fault array (Fig. 5gi-iii).

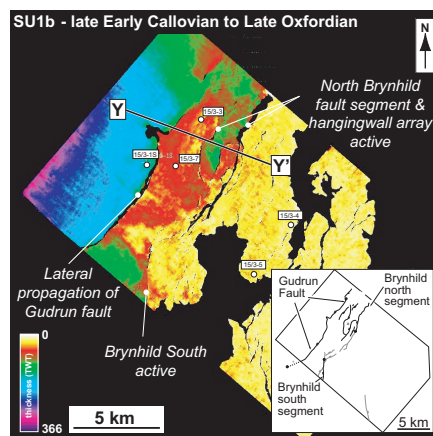


## 6.2. Tectono-Stratigraphic Evolution

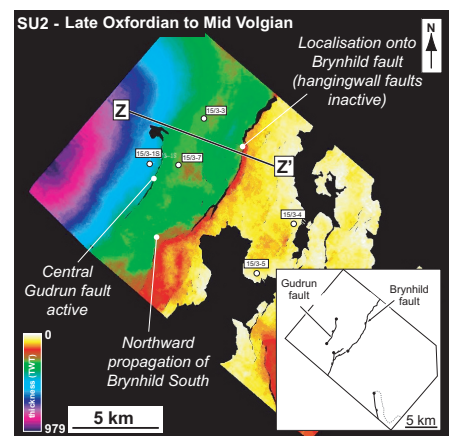
SU1a: Early Syn-Rift (Fig. 5d)



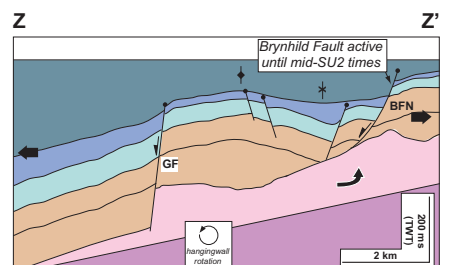
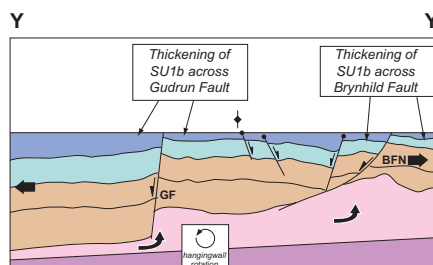
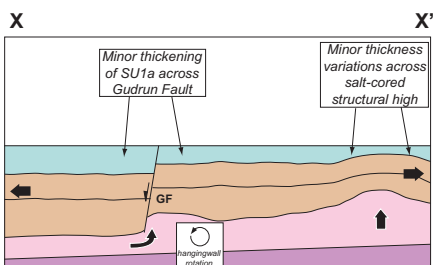
SU1b: Middle Syn-Rift (Fig. 5e)



SU2: Late Syn-Rift (Fig. 5f)

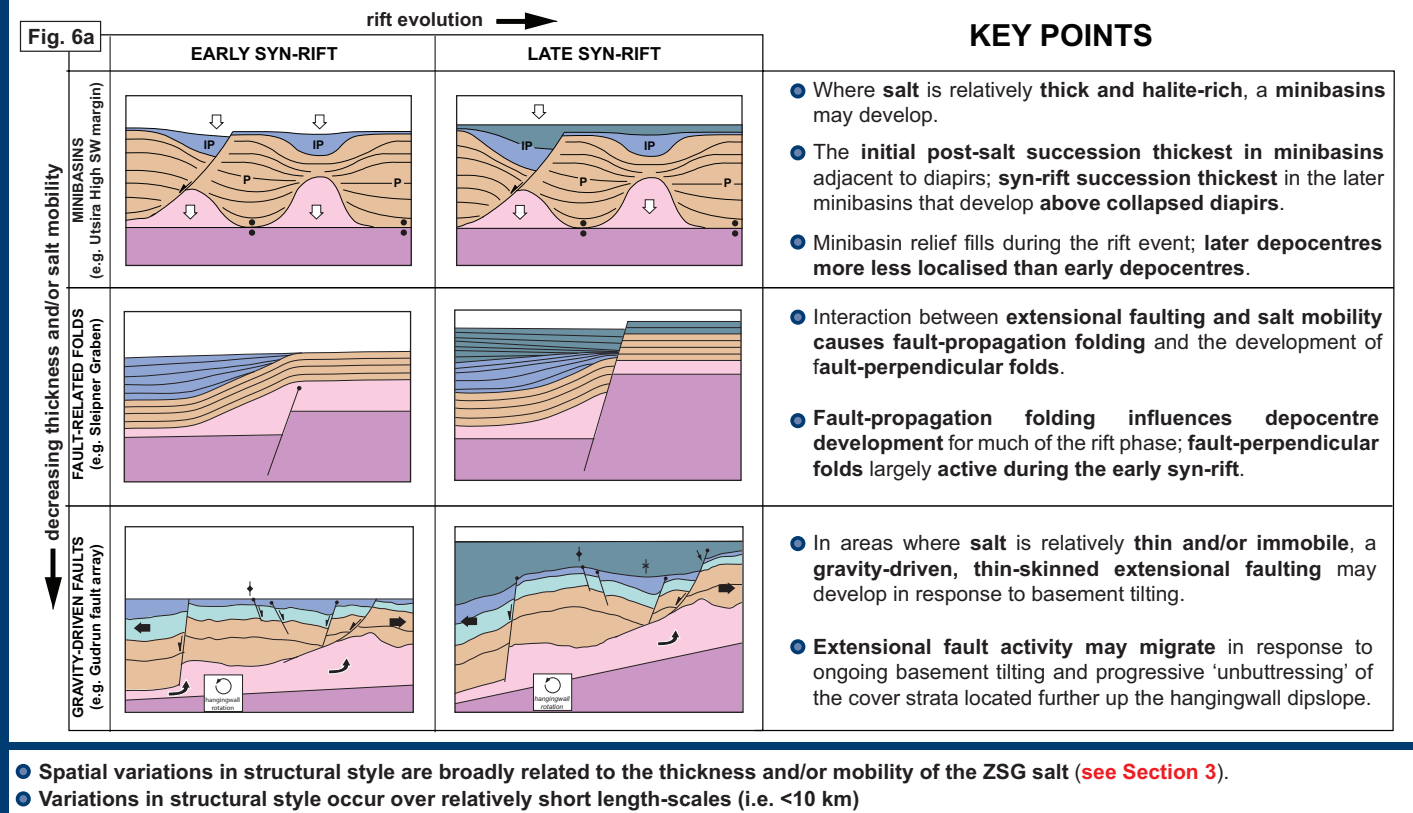


- The central part of the Gudrun Fault active and the Brynhild Fault inactive.
- Initiation of the Gudrun Fault associated with activity on the GBFZ, westward tilting of the hangingwall, and extension of Triassic to Lower Middle Jurassic units above the Zechstein Gp.
- Lateral growth of the Gudrun Fault and initiation of activity on the Brynhild North and South fault segments.
- Formation of a rollover anticline due to the listric geometry of the Brynhild Fault.
- Salt migration and formation of salt rollers in fault footwalls.
- Reduced activity and death of the Gudrun Fault and lateral propagation and overlap of the Brynhild Fault segments.
- Upslope migration of strain is interpreted to reflect progressive "unbuttressing" and extensional faulting of supra-salt strata.
- Eventual fault death during the latest Jurassic

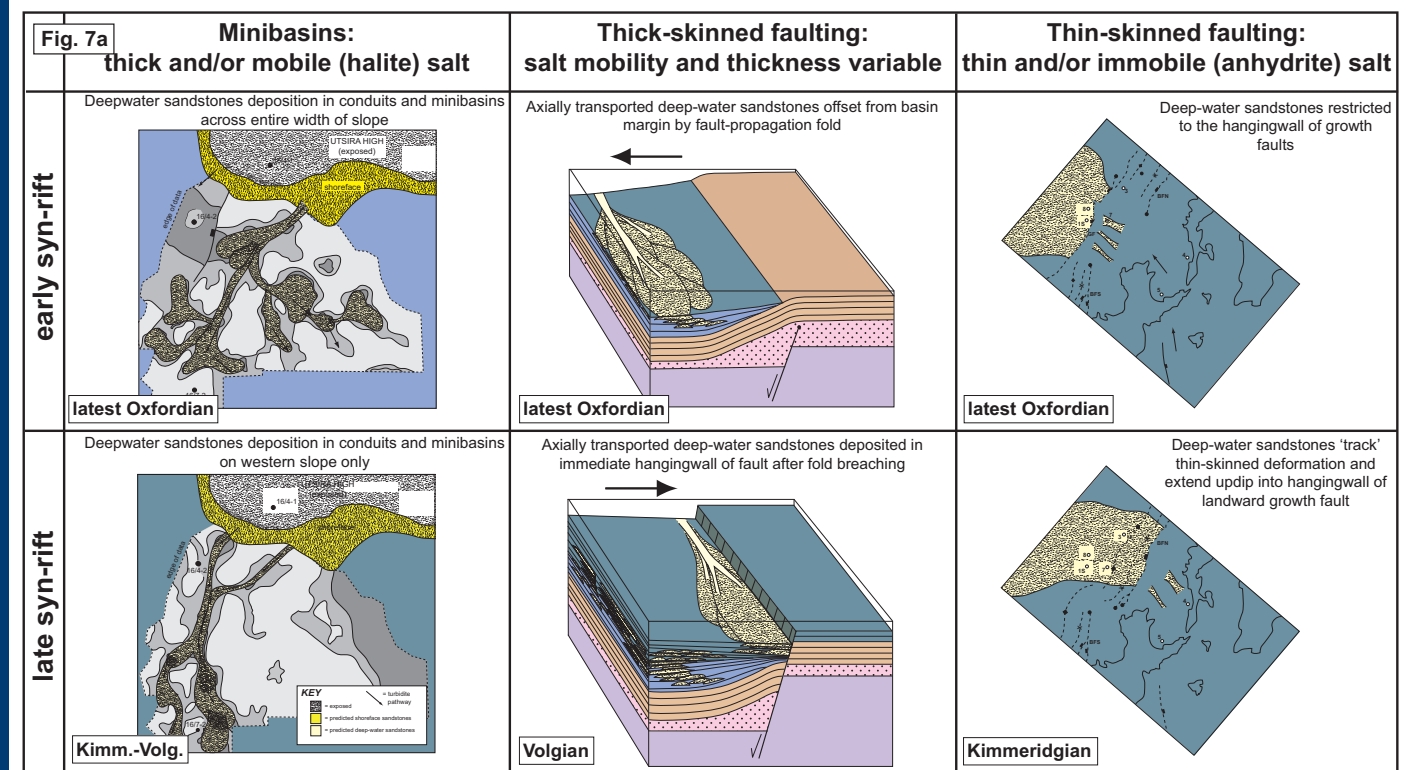




## 6. Summary of salt-influenced rift structural styles



## 7. Implications for reservoir distribution in salt-influenced rift basins



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