Influence of Tectonic Inversion and Salt Mobility on Structural Styles and Reservoir Quality in the Norwegian Central Trough

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b) Mohr diagram for the scenario in a). In this schematic example, where $\mu=0.75$ and $P=0$ the rock may fail in accordance with the frictional sliding criterion (through reactivation of the pre-existing fault). Where $P>0$ the effective stress is reduced and brittle failure can occur more easily. Where $\mu=0.75$ and $P=P_f$, a new shear fracture may nucleate, or else reactivation may occur for any pre-existing faults within the shaded orientation range ($\theta_{\text{min}}<\theta<\theta_{\text{max}}$). (After Etheridge, 1986; Twiss and Moores, 1992)
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Regional extension creates room

Stairstep faulting above buried wall

Shallow thickening

Fan of normal faults

Deep thinning

Radial or sub-parallel faults

Monocline or thrust fault

Flap

Thinning, arching

Contact drag

Extrusive flange

Subtle thickness changes

REACTIVE

Extension creates room

ACTIVE

Diapir creates room

PASSIVE

No room problem

Figure 2.13: Cartoon diagram illustrating the three main modes of diapirism; reactive, active and passive. (From Dooley et al., 2005)
Figure 2.14: Schematic diagram illustrating how basement-cover relationships may vary along a fault strand due to spatial variation in salt layer thickness. The diagram is based on the Dowsing Fault Zone in the Southern North Sea. DFZ= Dowsing Fault Zone, DOGS= Dowsing Graben System. (From Stewart et al., 1996)
Figure 2.15: Schematic diagram illustrating how structural styles in the supra-salt sequence vary in accordance with salt thickness during Late Jurassic rift development in the Central North Sea area. 

a) Where salt is absent (e.g. Zechstein marginal facies) 'classic' half graben geometries evolve. 
b) Where salt is thin (<~30m) a complex array of cover faults develop over the basement fault scarp. 
c) Where a thick salt layer is present, early cover rafts separated by salt diapirs are draped across the evolving basement topography. 
d) More commonly in the Central North Sea, the salt is already structured due to the Triassic phase of minibasin subsidence (figure 2.12). Rotation of the fault blocks will give rise to further movements of these salt structures; whether they actively rise or fall will primarily depend on their position on the slope. (From Stewart and Clark, 1999)
Figure 2.16: Analogue experiments model salt behaviour in response to compression. a) Plan view of the model at maximum extension prior to compression. b) Serial sections demonstrate structural styles under extension. c) Plan view of the model after compression. d) Serial sections demonstrate structural styles of inversion and the role of salt. (From Del Ventisette et al., 2006)
Figure 2.17: Schematic illustration of inversion tectonics in a graben containing salt. Stage 1 is the pre-inversion setting, Stage 2 is post-inversion. 

a) Folds and short-cut faults develop in homogeneous strata above the inverted basement faults. 

b) Thrusts and folds are localized by pre-existing salt structures. 

c) Thrust and folds are localized by reactivation of basement faults. (From Letouzey et al., 1995)
Figure 2.18: Cartoon illustrating the geometric features of a salt diapir modified by compression. Features include an unusually thick lid of overburden strata up-domed above the diapir, evidence for continued upward movement of the diapir even when pinched-off from source, and concentric thrust faults localised at the diapir shoulders. (From Davison et al., 2000)
Figure 2.19: Location of the Norwegian Central Trough study area. a) Principal structural elements of the North Sea Permian-Cretaceous graben system (From Erratt et al., 1999). b) The study area is defined by the spatial extent of seismic data available to this project (After Megson and Tygesen, 2005; Petroleum Exploration Society of Great Britain, 2007)
Figure 2.20: Caledonian Orogeny in NW Europe. The Caledonian Orogeny is associated with closure of the Iapetus Ocean and the Tornquist Sea and involved three-way convergence between Laurentia, Baltica and Avalonia. (From Coward et al., 2003)
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**Figure 2.23:** Comparison of the Late Permian Zechstein development of the Northern and Southern Permian Basins. Halite and Anhydrite are the two most abundant salts within the Zechstein Group. Anhydrite is relatively immobile compared with halite, and the latter is the primary component of the Shearwater Salt Formation. *(From Glennie et al., 2003)*
Figure 2.24: The tectonically inverted basins of Western Europe. (After Ziegler, 1990; Nielsen and Hansen, 2000)
Figure 2.25: Summary diagram of the timings of tectonic inversion identified within the European Plate. (Stratigraphic columns modified from Ziegler et al., 1987)

Figure 2.26: Palaeotectonic reconstructions of NW Europe (From Coward et al., 2003)
Relative positions at 5my intervals

5 phases of motion:
- Fast 175my (Bajocian) - 140my (Early Valanginian)
- Almost Stationary 140my - 125my (Base Albian)
- Fast 125my - 75my (Campanian)
- Almost Stationary 75my - 45 my (Mid Eocene)
- Fast (slowing last 20my) - 45my to present

Smith attributes the first slow phase to the final emplacement of the H-D ophiolites and the second to the final emplacement of ophiolites in Turkey, Syria and Cyprus. "The duration of both episodes of slow motion can be interpreted as the time taken for subduction that has been terminated at one location to start up at another, and is about 15-20 Ma".

Hellenic Arc Subduction
Pindos Ocean Subduction
Northern Neo-Tethys Subduction
Latest Cretaceous – final emplacement of ophiolites in Turkey, Syria and Cyprus
Latest Jurassic – final closure of the Pindos ocean - obduction of the Hellenic-Dinaric ophiolites on to the Pelagonian continent

Figure 2.27: Motions of Africa relative to Eurasia (circles) and motions of Eurasia relative to Africa (diamonds) from 175 to 0 Ma (After Smith, 2006)
Figure 2.28: Summary illustration of the major Permian to Recent tectonic events affecting Western Europe. (After Ziegler, 1990; Glennie and Underhill, 1998)
Figure 3.1: Spatial extent of seismic reflection data used in this study. The data comprise two partially overlapping surveys (black rectangles). Red outline shows the actual area of seismic coverage. Small grey boxes are regions with no seismic coverage within the studied area; interpretation across these areas was by interpolation. Dotted black lines are international boundary lines. There are 43 wells in the project database.
Figure 3.2: Generalised stratigraphic column for sediments of the Norwegian Central Trough (after Erratt et al., 1999)
Figure 3.3: Time-Depth data for 43 wells in the Norwegian Central Trough (blue). The well data extend to ~4300 msec (5200m) but have been extrapolated to 6000 msec for depth conversion. See text for discussion.
Figure 4.1: Key to sections displayed in chapter 4
Relief over crest of Zechstein salt diapir may be attributed to: either salt uplift (e.g. due to Cenozoic compressional squeezing); to differential compaction effects; or to both processes. The contribution from differential compaction has been modelled in Ch6 (see figure 5.2).

There is a thick lid of locally elevated strata above the diapir, capped by pronounced onlap onto the top Hordaland surface, rather than a gradual upward reduction in fold amplitude. There is also the suggestion of thinning in the neck of the salt diapir, with upward-rotated onlaps of adjacent sediments. These observations suggest Cenozoic compressional squeezing has occurred (see figure 2.18).

The Zechstein diapir (Breiflabb South) is situated above a sub-salt extensional fault. From this single line interpretation it is not possible to determine whether the diapir's location is controlled by this fault, nor the extent to which the interpreted fault offset is real as opposed to being an artifact of velocity differences between the salt and non-salt layers. 3D interpretation has enabled the fault-salt relationship to be examined more thoroughly (see section 4.3.3 for discussion).

Reflections above top Humber are less asymmetric. They are typically concordant and indicative of passive infill not a thermally subsiding basin.

Figure 4.2a: Seismic cross section A-A’. Vertical scale is in TWTT but approximates to two times vertical exaggeration.
Norma! fault detaches on salt: evidence that salt presence influenced the extensional development of the NCT, and that salt movements were occurring at this time. (pre-Cretaceous time).

As with the diapir in figure 4.2a, there is a thick lid of locally elevated strata above the salt crest, suggestive of salt uplift. Prominent onlaps have been labelled within the Nordegg and Nordegg Groups: the timing difference with respect to the diapir in figure 4.2a is likely only partly explained by data uncertainty (see image above).

At Albuskjell a Lower Cretaceous thick forms a structural high and is capped by an Upper Cretaceous and Cenozoic section that is thinner than the regional average. This is indicative of Late Cretaceous- Early Cenozoic uplift (see figure 5.17 and Ch5 text for discussion).

Figure 4.2b: Seismic cross section B-B'. The localized Lower Cretaceous thick on the NE part of the section (labelled) is attributed to the collapse of a salt wall dividing two Triassic minibasins, creating accommodation space at this time (see also figure 2.12).
Figure 4.2c: Seismic cross section C-C'. Tommeliten Gamma and Ekofisk labels mark the locations of Chalk Group oil (and gas) fields.
The elevation of top Chalk strata at the Lindesnes Ridge, and further east near 2/8-2, can be attributed to the presence of underlying salt. Lindesnes Ridge, the amount of salt beneath this ridge varies along its strike. Fault and salt interaction at the Lindesnes Ridge is studied in more detail in Chapter 5 (see figures 5.9 to 5.16, and figure 5.16 in particular).

Figure 4.2d: Seismic cross section D-D'.
Absence of Zechstein salt in well 2/9-3 on the Piggvar Terrace. Discordant, deformed seismic character in the vicinity of the well indicates halite removal (erosion, withdrawal) rather than non-deposition.

Figure 4.2e: Seismic cross section E-E'. Shows the location of two timeslices through the ga3d93 survey posted in figure 2.16.
Salt presence in the basin has led to greater structural amplitudes and shorter wavelengths than might otherwise have been observed (e.g. SE). Localized extension over salt diapir attributed to crease collapse; a mechanism for collapse would be the cessation of Cenozoic compression.

Salt thins to SE (onto Cromer Knoll): interpreted as non-deposition on Permian structural high. (Compare with salt absence on Piggya Terrace in figure 4.2e)

No clear evidence for rotated onlaps in the Late Cretaceous to top Hordaland section

Local thicks attributed to the infilling of Lower Cretaceous accommodation space by salt withdrawal at this time

Figure 4.2f: Seismic cross section F-F'
Late Cretaceous structural high at Albuskjell, first encountered on figure 4.2b, and considered further in Ch5 (see figure 5.17).

Salt thins onto Grensen Nose (as figure 4.2f).

Figure 4.2g: Seismic cross section G-G'
Thick lid of strata above salt and narrowed neck of diapir is suggestive of compressional squeezing. The thinning of Late Cretaceous and Early Cenozoic strata towards the salt dates movement to these times.

Early Cenozoic thick attributed to shifting of salt-controlled accommodation space.

Figure 4.2h: Seismic cross section H-H'
Salt diapir with folded overburden.

Top Hordaland

Triassic thick

2/9-1

Figure 4.2i: Seismic cross section l-l'.

Local absence of Lower Cretaceous section suggests salt had entirely withdrawn from the locality prior to Early Cretaceous times; there was no later creation of accommodation space through salt withdrawal. This observation points towards pre-Cretaceous establishment (emplacement) of the Balder diapir.

Salt thins to SE onto the Piggvar Terrace

Top Triassic

Balders diapir

Figure 4.2j: Seismic cross section l-l'.
Figure 4.3: Top Rotliegend Group TWTT horizon map. The top Rotliegend surface is offset by faults, as shown. The basin depocentre is laterally restricted in the SE, where it is bounded by the large offset NNW-SSE trending Skrubbe, Piggvar and Mandal faults. Elsewhere in the Norwegian Central Trough fault throws are much less and fault orientations more variable.
Figure 4.4: Top Zechstein Group TWTT horizon map (150ms contour interval). Line shading highlights areas of non-deposition and halite removal (erosion, dissolution).
Figure 4.5: Top Rotliegend to Top Zechstein (Zechstein Group) isochron map (50ms contour interval, truncated at 300ms). The location of wells that penetrate Zechstein and/or Rotliegend is shown. This map illustrates the location of named Zechstein Group thicks (salt walls and salt diapirs) relative to structure at Top Rotliegend level. Line shading highlights areas of non-deposition and halite removal (erosion, dissolution).
Area with strong evidence for Triassic minibasins, as demonstrated on the northern parts of 4.2 sections AA', BB', HH' and II'.

Area with poor evidence for Triassic minibasins, based on character of the top Triassic reflection.

Area with no evidence for Triassic minibasins due to lack of constraint on the top Triassic reflection.

Figure 4.6: Top Triassic (Tr50) TWTT interpretations across the study area. More complete interpretation including surface contouring was not possible due to the difficulty of tracing this seismic reflection away from Tr50 well pick locations. Dashed red line divides northern area with strong evidence for Triassic salt movements from southern area, where this evidence is less clear. Pink blobs are salt structures that pierce the top Humber surface.
Figure 4.7: Top Humber Group TWTT horizon map (50ms contour interval). Pink blobs are salt structures that pierce the top Humber surface.
Figure 4.8: Top Zechstein to Top Humber (Hegre and Humber Groups) isochron map. Top Humber salt piercements (pink) are superimposed; the Triassic-Jurassic time thickness in these areas is zero.
Figure 4.9: Top Cromer Knoll Group TWTT horizon map (50ms contour interval). Pink blobs are salt structures that pierce the top Cromer Knoll surface.
Figure 4.10: Top Humber to Top Cromer Knoll (Cromer Knoll Group) isochron map. Salt perecements are shaded pink.
Figure 4.11: Top Chalk Group TWTT horizon map (50ms contour interval). Pink blobs are salt structures that pierce the top Chalk surface.
Figure 4.12: Top Cromer Knoll to Top Chalk (Chalk Group) isochron map. Salt piercements are shaded pink.
Figure 4.13: Top Rogaland Group TWTT horizon map (50ms contour interval). Pink blobs are salt structures that pierce the top Rogaland surface.
Figure 4.14: Top Chalk to Top Rogaland (Rogaland Group) isochron map. Salt piercements are shaded pink.
Figure 4.15: Top Hordaland Group TWTT horizon map (50ms contour interval)
Figure 4.16: Top Rogaland to Top Hordaland (Hordaland Group) isochron map. Salt piercements are shaded pink.
Figure 4.17: Timeslices through part of the ga3d93 survey. 

a) Location of the timeslice area relative to the Top Chalk Group TWTT map (figure 4.11). 

b) Timeslice at 2828msec (intersects mainly lower Hordaland reflections). 

c) Timeslice at 3250 msec (intersects mainly Chalk Group reflections). Salt piercements and the Mandal fault are visible on both slices. The shallower slice shows second order discontinuities not seen in the deeper slice: these features, seen most clearly over the Piggvar Terrace, are interpreted as polygonal faults and are attributed to the dewatering of shales associated with rapid deposition of the Hordaland section.
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<th>Compressional Style</th>
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| Faulting unrelated to salt mobility | • Halite absent, or present but isopachous; no detachment effect on faults  
• Contractional offset on a fault that is in net extension at depth  
• Uplifted syn-rift sediment wedge  
• Monoclinal folding of overburden (post-rift) | Example modified from section 4.2e (see also figures 2.1, 2.2)  
Onlap if as shown would date uplift as early Cenozoic, and indicates top Chalk palaeobathymetric high  
Fault shallows near tip, where it has a reverse offset (footwall cut-off, e.g. figure 2.4)  
Uplifted syn-rift sediment wedge causes asymmetry of the fold  
Zechstein salt is present locally, but does not detach the fault into supra- and sub-salt sections |
| Salt movement unrelated to fault movement | • Salt structures present, with rotated onlaps against the salt body. This is indicative of salt movement, but not necessarily compression  
• Thick lid of updomed strata over the salt body  
• Thinning in the neck of the salt body | Example from section 4.2b (see also figure 2.18)  
Thick lid of updomed strata over salt body attributed to compression  
Rotated onlaps are indicative of salt movement during sedimentation (may be due to compression)  
Thinned neck, attributed to squeezing under compressional stress regime |
| Fault and salt movement | • Salt structures present, with geometries often three-dimensionally complex (rather than simple diapirs or salt walls)  
• Uplifted syn-rift sediment wedge, spatially related to major sub-salt faults  
• Halite acting as fault detachment layer  
• Folding of overburden (post-rift) | Example from section 4.2c  
Erosional truncation below and onlap above surface indicates growth of structure at the time of deposition of this surface (Late Cretaceous)  
Uplifted syn-rift sediment wedge. The wedge may have formed due to earlier salt wall collapse rather than rifting sensu stricto, but the key observation is that the wedge has been uplifted subsequently  
Halite thick adjacent to major (top Rotliegend) fault which has both supra-salt and sub-salt components |

Figure 5.1: Seismic criteria for recognition of and discrimination between compressional structural styles in the salt-prone Norwegian Central Trough
The effects of compaction and isostasy, and faulting have been modelled for progressively older time steps. Parameters for decompaction and isostatic adjustment are recorded in the legend and justified in section 3.6. The same values were used for all shown restorations. Model layers are named and coloured according to their upper surface (a seismically mapped horizon). The $\beta$ (stretching) factor records the amount of extension at top Rotliegend level since late Permian times. It is not possible to measure any shortening because the magnitude of that shortening is significantly less than the magnitude of extension, and may have been substantially accommodated by salt movement. ‘Original’ Zechstein thickness was calculated under the assumptions of constant area (no salt movement perpendicular to the plane of section) and uniform initial thickness.
Figure 5.3: Structural restoration of seismic cross section C-C' (figure 4.2c) using 2dmove. Vertical and horizontal scales are equal.

The effects of compaction and isostasy, and faulting have been modelled for progressively older time steps. Legend records the parameters used for decompaction and isostatic adjustment. The β factor indicates 2.6% net extension since end Permian, and an original Zechstein thickness of 410m was calculated.
Figure 5.4: Structural restoration of seismic cross section E-E’ (figure 4.2e) using 2Dmove. Vertical and horizontal scales are equal.

The effects of compaction and isostasy, and faulting have been modelled for progressively older time steps. Legend records the parameters used for decompaction and isostatic adjustment. The β factor indicates 12.2% net extension since end Permian, including a small but measurable component attributed to the Early Cretaceous (assuming the Early Cretaceous asymmetric infill was due to extension rather than salt withdrawal). An original Zechstein thickness of 225m was calculated.
**Figure 5.5:** Structural restoration of seismic cross section G-G' (figure 4.2g) using 2dmove. Vertical and horizontal scales are equal.

The effects of compaction and isostasy, and faulting have been modelled for progressively older time steps. Legend records the parameters used for decompaction and isostatic adjustment. The $\beta$ factor indicates 12.9% net extension since end Permian, and an original Zechstein thickness of 275m was calculated.
Figure 5.6: Structural restoration of seismic cross section 1-1' (figure 4.2i) using 2dmove. Vertical and horizontal scales are equal.

The effects of compaction and isostasy, and faulting have been modeled for progressively older time steps.

Legend records the parameters used for decompaction and isostatic adjustment. The $\beta$ factor indicates 2.7% net extension since end Permian, and an original Zechstein thickness of 330m was calculated.
Figure 5.7: Key to sections discussed in chapter 5. Section 3C3C is shown in chapter 4, as section EE.
Offset on the reverse fault, and asymmetry of the domed sequence, is most pronounced where salt is least involved. Discrete doming within the top Rogaland to top Hordaland interval interpreted as an Eocene-Oligocene pulse of compressional uplift, and as an asymmetry of the domed sequence, is less pronounced where salt is most involved. Salt thick adjacent to fault, but low in amplitude relative to present day.

Figure 5.8: Serial sections 2A2A', 2B2B', 2C2C', and 2D2D'. The top Chalk high is the structural trap for the Tor field and has been drilled at 2/5-1. Geometries within the Chalk Group vary in relation to the underlying fault and presence of Zechstein halite. Moving westwards from section 2A2A' to 2D2D', salt involvement increases, Chalk Group onlaps become more pronounced and occur at later times. Vertical scale in TWTT corresponds approximately to two times vertical exaggeration.

Salt thick with associated End Albian relief (justified by onlaps onto this surface in the present day section), but low in amplitude relative to present day.
Figure 5.9: Section 3A3A'

Early Cretaceous salt withdrawal beneath Lower Cretaceous thick; major phase of salt withdrawal into the hangingwall diapir at this time. Subsequent topography over salt diapir due to combination of: differential compaction; salt squeeze and consequent uplift; and tectonic inversion

Pattern of onlap onto the Mid-Miocene unconformity is regionally consistent, indicative of a basin-wide down-to-the-east rotation rather than a pattern of localised onlap over the top Chalk highs, which would indicate a compressive pulse

Minor inversion of Early Cretaceous infill due to Late Cretaceous contractional reactivation of earlier normal fault (Piggvar fault)

Pattern of onlap within Late Cretaceous section (Santonian/ Campanian); compressive pulse at this time

Onlap within post-Paleocene to Mid-Miocene section (~Late Eocene/ Early Oligocene); compressive pulse at this time

Locus of maximum graben extension moves eastwards (towards the Piggvar fault) at the time associated with this unconformity (assumed Late Jurassic given its location within the post-Permian, pre-Cretaceous sediment pile)
Early Cenozoic onlaps onto the Lindesnes Ridge (not shown)

Upper Cretaceous onlaps onto structural high in the immediate hanging wall to the Skrubbe Fault, especially within the top Hod to top Chalk (upper) part of the Chalk Group

Absence of salt from the Piggvar Terrace due to halite removal (erosion/dissolution) rather than non-deposition (see also figure 4.2e)

In the case of salt absence, relief at top Chalk is lower, with the fold axis more closely aligned to the underlying fault axis

Postulated appearance of Lindesnes Ridge in the case of salt absence from the immediate hangingwall to the Skrubbe fault

Less thickness variation in the pre-Chalk section because no salt movements: this translates into less structural variety in the post-salt section

Figure 5.10: Serial section 3B3B’. In the case of salt absence from the immediate hangingwall to the Skrubbe fault, top Chalk geometries can be predicted to be lower in amplitude, and more asymmetric.
Area of salt present in the hangingwall to the Skrubbe Fault differs significantly from that in sections 3A3'A and 3B3'B (figures 5.9 and 5.10). Geometry at top Chalk also differs markedly. Along strike variability in salt involvement at the Skrubbe Fault is examined in figure 5.16.

Harpoon-shaped geometry of the top Cromer Knoll is indicative of Cretaceous compression.

Figure 5.11: Serial section 3D3D'. Relative absence of salt against the Skrubbe fault coincides with low top Chalk relief on the Lindesnes Ridge.
Salt presence in the immediate hangingwall to the Skrubbe fault is minimal (compared with figures 5.9 and 5.10). A candidate explanation is salt withdrawal into the Mode diapir.

Salt is absent in the footwall to the Skrubbe fault (Grensefjord). A candidate explanation is salt withdrawal into the Mode diapir.

Figure 5.12: Serial section 3E3E'. Caption illustrates pattern of faulting in lowermost Rogaland sediments over crest of salt structure.
Figure 5.13: Serial section 3F3F '. Caption illustrates quality of cnsmerge seismic data on which interpretation of salt-fault interaction beneath the Lindesnes Ridge is based.

Post-Zechstein, pre-Cretaceous sediments rotated by Triassic-Jurassic salt movements
Figure 5.14: Serial section 3G3G'. Caption illustrates quality of cnsmerge seismic data on which interpretation of salt-fault interaction beneath the Lindesnes Ridge is based.

Strong impedance contrast associated with top Rotliegend surface

That concordant reflections can be traced towards the SW almost to the Skrubbe Fault indicates an absence of salt in much of the hangingwall.
Break in reflection continuity defines fault location

Strong impedance contrast associated with top Rotliegend surface

Seismic transparency due to salt presence in hangingwall to Skrubbe fault. The fault position has been interpreted from detailed 3D mapping. (While there is positional uncertainty on any given section, this uncertainty reduces significantly when individual interpretations are iteratively adjusted.)

Figure 5.15: Serial section 3H3H'. Caption illustrates quality of cnsmerge seismic data on which interpretation of salt-fault interaction beneath the Lindesnes Ridge is based.
Figure 5.16: Along-strike variability in fault displacement (blue) and salt-involvement (pink) at the Skrubbe fault (Lindesnes Ridge) and how these parameters influence top Chalk Group relief (green). Along-strike variations in salt presence affect structural geometries and fault displacement-length profiles. See text for discussion.
Figure 5.17: Serial sections 4A4A', 4B4B' and 4C4C'. The top Chalk high that has been drilled in each section corresponds to the Albuskjell oilfield. The observed geometry in 4B4B' is interpreted to be an inverted graben; the graben most likely formed in response to an Early Cretaceous phase of salt withdrawal/salt wall collapse (see also figure 4.2b).

Vertical scale in TWTT corresponds approximately to two times vertical exaggeration.
Figure 5.18: Summary map shows locations where structural inversion has been identified in the Norwegian Central Trough. The areas exhibiting compression are superimposed onto the Zechstein isochron (as figure 4.5) and the top Rotliegend fault interpretation (figure 4.3).
Figure 6.1: Illustration of Chalk Group deposition in NW Europe. Eustatic sea level rise and associated marine transgression severely restricted clastic input to the North Sea area, giving rise to a thick sequence of mostly pelagic marine deposits. Chalk thicknesses were as much as 2 km in the basin interior. (After Surlyk et al 2003)
Figure 6.2: Detailed stratigraphic column for the Chalk Group. Seismic reflection data (red is positive amplitude, black negative), gamma ray (GR) and sonic (DT) log signatures are from well 2/7-15. The scale for the GR is API units, and the scale for the DT is microseconds/ft. Lower GR values are indicative of lower shale content. Lower DT values (higher interval velocities) are indicative of lower porosities, but can be strongly influenced by other factors such as fluid pressure and fracturing (Rider, 2000). The eustatic sea level curves are based on Haq et al., 1988 and biostratigraphic constraints are those defined by Bramwell et al., 1999.
Figure 6.3: Summary illustration of the relationship between Chalk Group lithofacies and depositional environment. Greyscale shading highlights the environments associated with a particular lithofacies type; darker shades indicate a stronger association. (After Surlyk, 1979; Bramwell et al., 1999)
Figure 6.4: Sedimentary structures within the Chalk Group, as photographed at Etretat, Normandy. a) Chalk 'mounds' and erosive channel features. b) Reverse fault in lithified chalk, with associated soft-sediment reworking in the overlying strata. c) Soft-sediment deformation within a horizontally bedded sequence. d) Slump fold within an apparently horizontally bedded sequence.
Figure 6.5: Introduction to the Norwegian Central Trough Chalk Group oilfields. a) Location of Chalk Group oilfields in the Central North Sea. b) Chalk fields of the Norwegian Central Trough. c) Production data from Chalk fields referred to in this study (Data from the Norwegian Petroleum Directorate, 2007)
Figure 6.6: Schematic diagram summarising factors that affect porosity preservation during chalk burial. Porosity differences attributed to the primary sedimentology tend to be preserved or even accentuated during the burial process. (From Megson and Hardman, 2001; based on the original figure by Brasher and Vagle, 1996)
Thin deposits along the emerging Lindesnes Ridge (thinnest to the south); allochthonous flow into the Feda Graben.

Figure 6.7: Time thickness map for the Maastrichtian to Early Palaeocene section of the Chalk Group (Tor and Ekofisk Formations), annotated to show allochthonous chalk movements off the uplifting Lindesnes Ridge and into the NE Feda Graben. Top Chalk salt piercements (pink) are superimposed on to the figure. There are thick Tor and Ekofisk sequences immediately adjacent to some of the diapirs (e.g. Trud) and these thick are indicative of salt movements (withdrawal and squeezing) synchronous with Tor and Ekofisk Formation deposition.
Figure 6.8: Types of fracture observed in Chalk core a) Tectonic fractures from Eldfisk field well 2/7-18A b) Stylolite-associated fractures from Eldfisk field well 2/7-13B (Images courtesy of ConocoPhillips)
Radial fractures.

Concentric (typically axis-parallel) fractures

Monocline axis

Striping artefact due to insufficient density of interpretation on the gas data

Figure 6.9: Top Chalk Group dip-azimuth map and accompanying annotations.

a) Dip-azimuth map. See text for discussion. Salt structures that pierce the top Chalk surface are shown in pink, and areas without data are shown in blue. The sub-salt fault network (from figure 4.3); top Chalk relief is related to these lineaments, but is also affected by the distribution of salt structures. c) Idealised pattern of radial and concentric tectonic fractures predicted for an inversion monocline (e.g. Brevlabb basin localities) d) Pattern of radial and concentric tectonic fractures predicted for the crest of a salt diapir (e.g. West Feda Graben localities). Fracture patterns associated with the Lindesnes Ridge are most likely include combinations of types in c) and d)
Figure 7.1: Location map of the Uinta Mountains, NE Utah/ NW Colorado (Modified from Gregson and Chure, 2003). In addition to the major (named) tectonic lineaments there are numerous minor faults and associated monoclines, including; Island park (IP), Mitten Park (MP), Yampa, Wolf Creek (WC), Willow Creek (WLC) and Rangely. Borehole constraints have been derived from the Husky 7-3 Clay Basin well (HCB), the McMorran-Freeport 43-2A well (MMF), the Champlin 31-19 Bear Springs well (CBS), the ARCO Willow Creek #1 well (AWC) and the Celsius 1 Cliff Ridge well (CCR). Red dot shows location of figure 7.4 and red box shows location of the South flank study area, as illustrated in figure 7.5. Section A-A' is shown in figure 7.3.
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Figure 7.2: Simplified stratigraphic column for the Eastern Uinta Mountains. Cambrian to Jurassic stratigraphic thicknesses are appropriate for the area of the Southern flank shown in figure 7.5 and are based on field observations and data from Hansen et al. (1983) and Gregson and Erslev (1997). Significant thicknesses of Cretaceous and younger deposits are exposed in the Uinta Basin to the south of the studied area (e.g. Hefner and Barrow, 1992).
Figure 7.3: North-South cross section through the Eastern Uinta Mountains (longitude 108°52′30″).

a) The Precambrian synrift was inverted during Late Cretaceous to Early Tertiary thick-skinned 'Laramide' compression. The large-scale geometry of the Southern flank is constrained by seismic data, such as that from the Rangely oilfield. (After Hansen 1986)

b) Rangely: the largest oilfield in the Rocky Mountain region (cumulative oil production >1,000 MMBO). An inversion-induced structural trap, comprising a doubly-plunging, south-verging hanging wall anticline above a north-dipping thrust fault. Vertical exaggeration is 2.5. The North flank dips at ~4° and the South flank at up to 30°. (After Stone 1989)
Figure 7.4: The Uinta Fault defines the northern margin of the Uinta Mountains uplift. It is visible in outcrop at Sheep Creek canyon (location shown in figure 7.1). Quartzites of the Precambrian Uinta Mountain Group are juxtaposed against limestone and cross-bedded sandstones of the Mississippian Madison Limestone Formation. a) Schematic illustration of the structural position. b) Photograph of the Uinta Fault viewed towards the WNW across Sheep Creek canyon. c) Field sketch clarifying the character of overturn in proximity to the Uinta fault. The area outside the photograph was not visible from a single vantage point due to obstruction by trees at the base of the canyon.
Figure 7.5: Aerial view of the southern Uintas study area (location shown in figure 7.1). The map is annotated to show the spatial extent of Palaeozoic outcrop, of which the major constituent is aeolian sandstone of the Pennsylvanian Weber Formation. SM= Split Mountain, RP= Ruple Point, IP= Island Park, MP= Mitten Park, CR= Cliff Ridge, BM= Blue Mountain, WC= Wolf Creek, and SC= Skull Creek. The fold, fault and fracture characteristics of the area were examined along the four transects labelled B-B', C-C', D-D' and E-E'.
Figure 7.6: Aerial photograph of locality F, viewed towards the southwest. The monoclinal character of folding is clearly visible. At river level, the Mitten Park fault juxtaposes Pennsylvanian Round Valley Limestone against quartzites of the Precambrian Uinta Mountain Group, but this offset passes into a monocline in the cliffs 200m above the river. (Photograph obtained courtesy of William Mitchum)
Figure 7.7: Serial cross sections through forced folds of the southern Uinta Mountains. The pronounced variability in fold amplitude and geometry is attributed to major lateral (along-strike) variations in fault throw. An outcrop photograph of the Mitten Park faulted monocline (red box in section EE') is shown in figure 7.8.
Figure 7.8: Outcrop photograph of the Mitten Park faulted monocline (locality F), viewed towards the northeast (compare with figure 7.6). See text for discussion. River rafters for scale.
Figure 7.9: Fracture and bedding orientation data as measured from outcrops within the SE Uintas study area. Strike and dip data were collected for bedding (red), joints (black), and deformation bands (blue). The number of measurements at each fracture locality is shown ($n$). Measurements are tabulated in Appendix 2. See text for discussion.
Figure 7.10: Location map and field photograph of Chalk in outcrop, South Dorset. a) Simplified geological map of the Chaldon Down area, showing the extent of coastal outcrop of Chalk and the location of the study area. b) Near-vertical dipping exposures of the Upper Chalk Group, looking West from Durdle Door.
Figure 7.11: Mesoscale fracture patterns in the Chalk Group of Swyre Head, Dorset. Vertical Bedding here is defined by flints. Fractures occur as a conjugate set.
Figure 7.12: Mesoscale fracture patterns in the Chalk Group of Bat's Head, Dorset.

a) Bat's Head pictured from the East. Hikers for scale
b) Fracture interpretation (After Bevan, 1985)
c) Schematic illustration of the stress conditions affecting the Chalks of Swyre and Bat's Heads
Figure 8.1: Summary illustration of the major Permian to Recent tectonic events affecting Western Europe, including timings and relative intensity of halokinesis and inversion tectonics in the Norwegian Central Trough. 1) Triassic minibasin formation 2) Active diapirism during Late Jurassic rifting 3) Continued growth of salt structures through passive downbuilding 4) Salt movements associated with Upper Cretaceous compression 5) Salt movements associated with Cenozoic compression; squeezing of diapirs 6) Sedimentation outpaces growth by passive downbuilding 7) Late Cretaceous inversion initiates during Turonian-Santonian; peaks during Maastrichtian-Earliest Palaeocene 8) Cenozoic compression
No halite (basin fill hard-linked to basement)  
Halite not mobilised during extension  
(and supra-salt section soft-linked to basement)  
Halite mobilised during extension  
(and supra-salt section soft-linked to basement)

a)  
Pre-inversion

post rift
upper syn-rift
lower syn-rift
basement

b)  
post rift
supra-salt syn-rift
halite
basement

c)  
post rift
supra-salt syn-rift
halite
basement

It has been illustrated elsewhere that the manner in which salt mobilizes is not straightforward (see also figure 8.3). In this example, a salt diapir has developed in the immediate hangingwall to the fault with the largest throw (c.f. Skrubbe fault examples presented in chapter 5).

d)  
Post-inversion

inverted post rift
upper syn-rift
lower syn-rift
basement

Classic 'harpoon' shaped inversion monoclines. The inverted faults may be accompanied by development of short-cut thrusts, as observed in the Uintas (e.g. Mitten Park fault), but not in the Norwegian Central Trough.

e)  
inverted
post rift
supra-salt syn-rift
halite
basement

f)  
inverted
post rift
supra-salt syn-rift
halite
basement

Uplift tends to be broader and greater in amplitude where a salt thick is situated beneath an inverting hangingwall.

Figure 8.2: Influence of halite on tectonic inversion geometry. The presence of halite within a graben infill sequence will affect the response of that graben to subsequent compression.
a) The location of basement faults governs whether a salt wall is preserved in the hangingwall or footwall.

Cover fault soft-linked to basement

Salt thick in footwall

Cover fault hard-linked to basement

Salt thick in hangingwall

Figure 8.3: Schematic illustration of how the location of salt thicks in relation to fault lineaments influences the structural style during compression. (Figure a) is modified from Stewart et al., 1996)