Detachments and low-angle faults in the northern North Sea rift system

HAAKON FOSSEN,[1] TORE ODINSEN,[1]
ROALD B. FÆRSETH[2] & ROY H. GABRIELSEN[1]

[1] *Department of Geology, University of Bergen, Allégaten 41, N-5007 Bergen, Norway*
[2] *Norsk Hydro, 1321 Stabekk, Norway*

Abstract: Several master faults in the North Sea basin tend to flatten to give low dips at depth, and in this sense form detachments in the rift system. Such low angle faults are identified in the western flank of the Viking Graben (Tampen Spur area), where they occur as both intra- and supra-basement detachments. Interference between detachments and steeper faults results in ramp–flat–ramp geometries. In the eastern part of the Gullfaks fault block, a supra-basement detachment is probably associated with anomalously high late Jurassic extension in the Gullfaks Field area. The low-angle Gullfaks detachment also helps explain the presence of sets of parallel east-dipping faults (domino systems), a common feature in the collapsed hanging wall to low-angle detachments. Similar detachments probably exist beneath the Gullfaks Sør block and SE of the Visund fault block. All of these are interpreted as late Jurassic collapse structures directly related to active late Jurassic extensional tectonics. Strong indications of intra-basement detachments are also found in the Tampen Spur area. These detachments are formed by major normal faults that flatten in the basement, as seen beneath the Visund fault block. This geometry may to some extent be related to fault rotation during repeated phases of extension in the Palaeozoic–Early Mesozoic period. However, abrupt flattening of some of the faults in the basement indicates that the master faults follow some of the many pre-existing mechanically weak zones in the basement, primarily low-angle Devonian extensional shear zones or Caledonian thrusts.

The most common hydrocarbon trap types in the North Sea are controlled or influenced by faults, as delineating structures of rotated fault blocks, as synsedimentary structures controlling the distribution of source and reservoir rocks, or as barriers to fluid flow (Hardman & Booth 1991). Accordingly, fault geometry is important for understanding many oilfields and gas fields in this area.

Experimental modelling, kinematic considerations and field examples all indicate that faults in extended regions may be planar, non-planar (e.g. listric), high angle or low angle, or a combination of these (e.g. Wernicke & Burchfiel 1982; Gibbs 1984; Gabrielsen 1986; McClay & Ellis 1987; Fossen & Gabrielsen 1996). However, there has been a tendency in the literature to prefer one of these types of fault geometries when making interpretations. Faults shown as steep, sub-planar features dominate the literature, possibly because downward-flattening or low-angle structures are more difficult to detect seismically. However, extensive interpretation of listric fault geometries was favoured by some in the 1980s (e.g. Beach 1984; Gibbs 1984), and the discovery of low-angle faults in extended terranes (Armstrong 1972) also led to consideration of such structures in the same time period (e.g. Wernicke & Burchfiel 1982; Lister *et al.* 1986). In general, a large-scale rift system can be expected to contain elements of all of these types of fault geometries. We believe that this also holds true for the northern North Sea rift system.

In this paper we present observations primarily based on a combination of commercial 2D and 3D seismic data and a reprocessed deep seismic line across the northern North Sea (NSDP84-1) (Fig. 1). We will focus on the Gullfaks–Visund–Snorre region and on the non-planar and low-angle fault geometries revealed by the seismic data. Downward-flattening faults and detachment faults have been previously described south of the present study area, where extensional detachments tend to form along the Zechstein salt (Clausen & Korstgård 1996; Thomas & Coward 1996). Downward-flattening faults are also interpreted at deeper as well as higher levels in the North Sea (Beach 1984; Gibbs 1984; Speksnijder 1987; Gabrielsen 1988; Graue 1992; Platt 1995). In a complementary work to the present contribution, Odinsen *et al.* (2000) suggest that multiple levels of detachment, as well as composite fault geometries, are common in the northern North Sea.

From: NØTTVEDT, A. *et al.* (eds) *Dynamics of the Norwegian Margin*. Geological Society, London, Special Publications, **167**, 105–131. 1-86239-056-8/00/$15.00

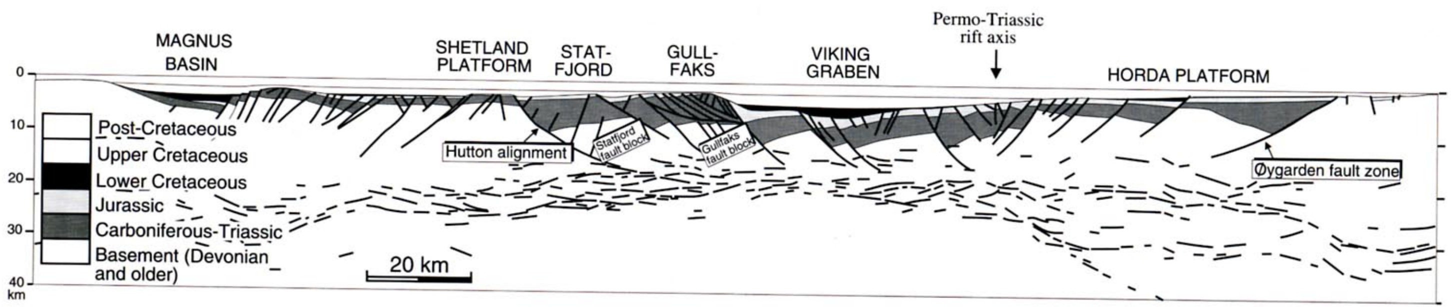


Fig. 1. Regional profile based on seismic line NSDP84-1. Modified from Christiansson *et al.* (1999).

We define the term detachment as: a low-angle (portion of a) fault or shear zone that separates rocks that show different amounts of extension and/or deformation styles. By low-angle fault we mean a fault with dip <30°. A listric fault is usually defined as a spoon-shaped fault in three dimensions, and appears as a curved, concave-upward fault on cross-sections. Faults with geometries different from both listric and planar faults are simply referred to as non-planar faults, with additional descriptive terms such as downward flattening. Below, we distinguish between supra-basement detachments occurring in the sedimentary sequence above the Caledonian basement, and intra-basement detachments, which partly or wholly are confined to basement rocks.

Regional geological development

The North Sea rift (Fig. 2) is a post-Caledonian graben system with a multiphase extensional history that started with Devonian extension of the thickened Caledonian crust. This extensional phase affected an area that extends far beyond the later (Permo-Triassic and Jurassic) margins of the North Sea rift system (Fossen & Rykkelid 1992; Fossen 1998). At least two important post-Devonian phases of rifting are recognized in the northern North Sea.

The first is a Permo-Triassic phase, which is not known in great detail but is thought to be of great importance, in terms of both extension and formation of a structural framework (Gabrielsen *et al.* 1990; Færseth *et al.* 1995*a*; Roberts *et al.* 1995). The Permo-Triassic extension appears to have affected a wider area than the Jurassic phase (Gabrielsen *et al.* 1990; Roberts *et al.* 1990, 1995; Færseth *et al.* 1995*a*; Odinsen *et al.* 2000*b*). The extensional faults defining the largest fault blocks in the North Sea rift are mostly of Permo-Triassic origin, although reactivated in Jurassic time. Thermal contraction and sediment loading prevailed throughout Triassic time, and around 2–4 km of Triassic sediments are deposited in the northern Viking Graben (e.g. Badley *et al.* 1988; Steel & Ryseth 1990). A major uplift (erosion) is recorded in the Lower–Middle Jurassic series of the central North Sea, where a major rift dome may have been located (e.g. Ziegler 1990). In the northern Viking Graben, doming-related regression led to the deposition of the Brent Group sandstones.

Although local fault activity is known for more or less the entire Jurassic time period, it is

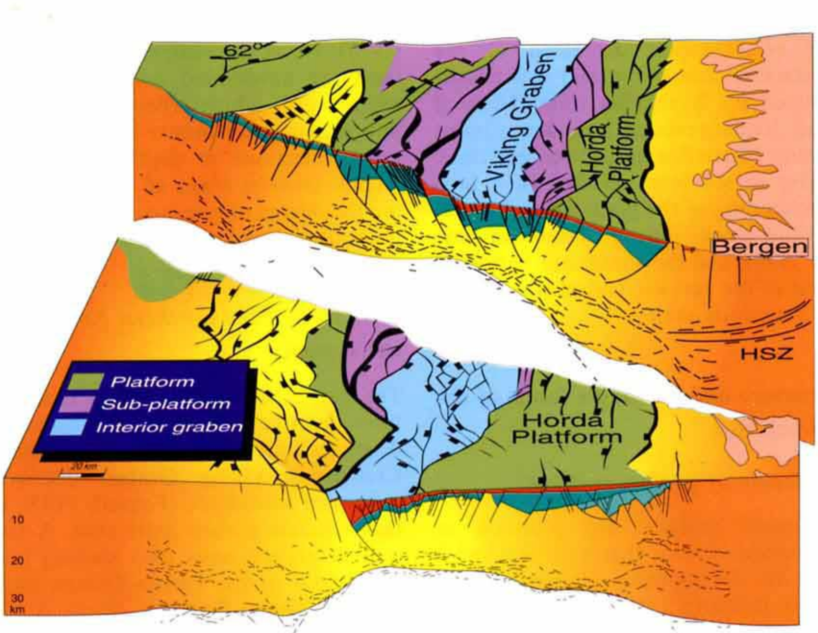


Fig. 2. Regional overview and internal subdivision of the northern North Sea rift system. Interpretations of lines NSDP84-1 and -2 are incorporated into the figure. It should be noted that colours on sections illustrate sedimentary sequences, whereas map areas are colour coded according to the topo-tectonic classification suggested by Gabrielsen (1986). HSZ, Hardangerfjord shear zone.

well established that most of the structural traps in the North Sea are the results of a late Mid- to Late Jurassic extension phase. The rate of crustal extension appears to have increased substantially from Mid- to Late Jurassic time. The Shetland Platform was formed, and differential subsidence was associated with the development and rotation of large fault blocks. Extensional structures related to this Jurassic phase are clearly imaged on seismic sections, and are therefore known in more detail than the Permo-Triassic ones. Stretching estimates vary from less than 15% in the platform/sub-platform areas to 40–50% in the interior part of the rift (Viking Graben) (Marsden *et al.* 1990; Roberts *et al.* 1993; Odinsen *et al.* 2000*b*). The fault blocks exhibit eroded crests, indicating that they were all at or near sea level during a late (Kimmeridgian) stage of the rifting history. Increased extension rate and accelerated fault movements resulted in increased water depth in late Kimmeridgian–Volgian time, and not until this time did the Viking Graben become the deepest structural–topographical element of the rift in the study area (Fig. 1) (Gabrielsen *et al.* 1990).

The Jurassic Viking Graben did not develop as a single, straight entity, but as a system of syn-rift units bounded by master faults. A system of graben segments formed, where the graben segments were linked through accommodation zones as described by Scott & Rosendahl (1989).

The rate of extension decreased at the Jurassic–Cretaceous transition, and was practically terminated by Ryazanian time. Thermal and sediment loading-related subsidence influenced the entire North Sea until Paleocene time. A general rise in sea level resulted in a progressive overstepping of the platform and burial of Jurassic fault blocks during Cretaceous time (e.g. Ziegler 1990), and the significant bathymetry at the end of the Jurassic period was infilled by marine Cretaceous shales.

General structure and low-angle faults of the northern North Sea

General structure of graben systems

Several structural features are common in extensional graben systems that have reached a certain stage of development (Johnson 1930; Robson 1971; Harding 1984). Several studies suggest that such features reflect the bulk geometry of the extending crust on a regional scale (Wernicke 1985; Coward 1986), and complex fault interaction at depth on the semi-regional and local scales (Wernicke & Burchfiel 1982).

On the basis of observations in the North Sea, Gabrielsen (1986) proposed a conceptual topotectonic model for extensional graben systems (Fig. 2). This model allows for non-rotating steep planar faults, rotating low-angle planar faults and listric faults to be developed at different stages of graben formation, and for such faults to be simultaneously active in different parts of the extending graben. Such relationships are also seen in analogue experimental models (Fossen & Gabrielsen 1996). In Gabrielsen's model, the extra-marginal fault system separates the area that has undergone stretching from its undeformed surrounding terrane. The extra-marginal faults, which may constitute a relatively small-scale horst-and-graben topography, are steep structures that were activated at the initial stage of the graben history. The platform, which commonly is separated from the extra-marginal fault system by a minor horst, represents a structural unit that is characterized by moderate fault activity and subsidence. Its width may vary considerably along the strike of the graben margin. On its graben-ward side, the platform is frequently bordered by a marginal platform high towards the heavily faulted sub-platform, which is characterized by an array of rotated fault blocks. The outer master fault system separates the margin from the interior graben.

Following Bosworth (1985) and Rosendahl (1987), we acknowledge that most graben systems are subdivided into separate units, the geometry of which reflects along-strike spatial interaction of the master fault systems and their interconnections at depth. Such relationships include transfer zones of different types, reflecting the degree of overlap and eventually shifting polarities between the fault segments.

Structure of the northern North Sea rift system

The North Sea basin displays most of the features described above, as illustrated in Fig. 2. Also, the interior graben of the late Jurassic–Cretaceous Viking Graben displays several centres of subsidence (Færseth 1983), indicating that separate graben units exist. A similar pattern of graben units with shifting polarities is recognized in the Permo-Triassic basin in the present Horda Platform (Scott & Rosendahl 1989; Gabrielsen *et al.* 1990; Færseth *et al.* 1995*a*). Finally, complex and composite fault geometries in the North Sea have been reported by several workers (Badley *et al.* 1984, 1988; Spekschnijder 1987). This has led to speculations about whether additional levels of detachment may have been active during its development (Gabrielsen 1988).

Utilizing reprocessed deep reflection data, high-quality commercial seismic lines and gravimetric and magnetic data, the deep structure of the northern Viking Graben has recently been reinterpreted by Christiansson *et al.* (2000) and Odinsen *et al.* (2000). These studies support the view that the area is truncated by a principal east-dipping crustal-scale fault, which subcrops along the eastern margin of the East Shetland Basin and flattens in the highly reflective lower crust beneath the western border of the (Jurassic) Viking Graben. Intra-mantle eastward-dipping reflections mapped beneath the Horda Platform (also reported by Klemperer (1988)) may represent the continuation of this master fault. A shallower (intra-Triassic) detachment was postulated for the Gullfaks Field (Fossen 1989; Koestler *et al.* 1992) and for the Cormorant Field (Speksnijder 1987), and has been supported in the later work by Odinsen *et al.* (2000). A similar detachment was observed below the Horda Platform, which is dominated by antithetical and more planar faults. The present study concentrates on analysis of these detachments, and elaborates upon their complex geometries.

A transect across the northern North Sea (Fig. 1) reveals the asymmetrical geometry of the rift. This part of the North Sea basin is at present bound by downward flattening, marginal faults, called the Øygarden Fault Zone and Hutton alignment, respectively. These faults, as well as most master faults within the rift, are of Permo-Triassic origin, but were reactivated in Jurassic time.

Between these marginal faults, the strata are rotated and generally dip toward the margins,

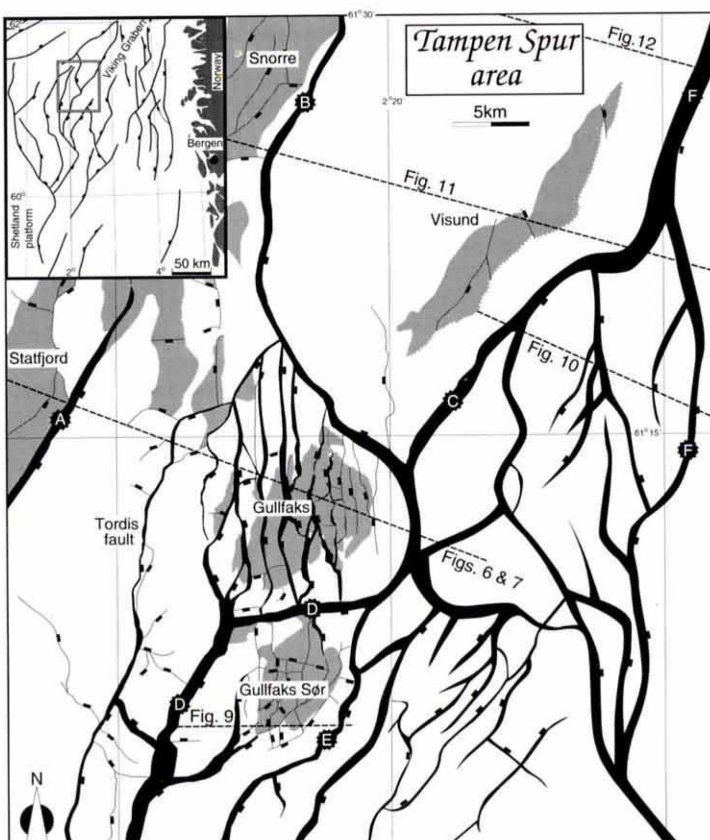


Fig. 3. Fault map of the Gullfaks–Visund–Snorre area, with profile locations. Faults at top Brent Group or base Cretaceous level (where the Brent Group is eroded).

away from the Permo-Triassic rift axis east of the Jurassic Viking Graben (Figs 1 and 2). Similarly, the main faults dip toward the Permo-Triassic rift axis, but somewhat more steeply on the eastern (Horda Platform) side. This difference in dip and the asymmetry of the system reflect that a larger portion of the extension accumulated on the western side of the Permo-Triassic rift axis than on the eastern side.

Low-angle faults are particularly related to the western margin of the Viking Graben proper (e.g. Swallow 1986; Harris & Fowler 1987; Cherry 1993; Færseth *et al.* 1995*b*; Platt 1995). Thus, the area west of the Hutton alignment represents the western footwall of the entire asymmetrical Jurassic graben system. However, low-angle faults of less regional significance also occur within the basin, and it may be useful to distinguish between marginal and intra-basin low-angle faults because of their different spatial and kinematic significance in rift systems.

The marginal faults to the northern North Sea rift exhibit steep upper parts (*c.* 55–60° for the Øygarden fault), and flatten downwards into the basement to locally form low-angle faults. It is possible that these faults are linked to low-angle or sub-horizontal ductile shear zones in the ductile middle to lower part of the crust, and in this sense are mechanically linked. The downward flattening of these marginal faults is reminiscent of that of simple extensional models where rigid footwalls require the marginal faults to be listric to develop sets of rotated (domino) fault blocks in their hanging walls (e.g. Wernicke & Burchfiel 1982, fig. 7). Rotation of the domino fault blocks is made possible by the non-planar geometry of the related marginal fault, and consequently, an abrupt change in dip is seen from the relatively horizontal beds in the footwall to rotated beds in the hanging wall. However, models that include (flexural–isostatic) footwall deformation (e.g. Kusznir *et al.* 1991) are not restricted by the same boundary conditions, and non-planar marginal faults are therefore not a necessity in rift systems.

The Tampen Spur area

Intra-basin low-angle faults or detachments are most common on the western side of the Viking Graben, particularly the Gullfaks–Visund–Snorre part of the Tampen Spur area (Fig. 3). The high density of oilfields and prospects has made the concentration of geological and geophysical data in this area remarkably high. Low-angle faults and detachments in that region will be the main focus of the rest of this paper.

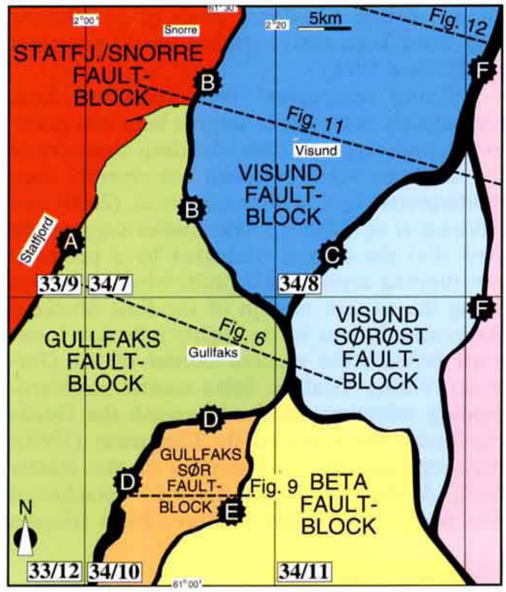


Fig. 4. Main fault blocks in the Gullfaks–Visund–Snorre area and the names applied in the text. A, the Statfjord fault; B, the Snorre fault; C, the Visund fault; D, the Gullfaks fault; E, the Gullfaks Sør fault; F, the Viking Graben boundary fault.

The most significant faults in the area are referred to as follows (Fig. 4): A, the Statfjord fault; B, the Snorre fault; C, the Visund fault; D, the Gullfaks fault; E, the Gullfaks Sør fault; F, the Viking Graben boundary fault. Similarly, the main fault blocks of the area (Fig. 4) are called the Statfjord, Gullfaks, Gullfaks Sør, Visund and Visund sørøst fault blocks. All these fault blocks are tilted so that the bedding is dipping gently to the west or northwest between the generally east- or southeast-dipping faults. We have found indications that several of these faults (A, B, C, D) have non-planar geometries, and that they form local basement-involved detachments in the area (Fig. 5). In addition, we see indications of a supra-basement detachment beneath the Gullfaks Field (Gullfaks detachment) and south and northeast of Gullfaks (Gullfaks Sør and Visund sørøst detachments; see below).

Supra-basement detachments

An example of supra-basement detachment is found beneath the Gullfaks oilfield (Petterson *et al.* 1990; Fossen & Hesthammer 1998), which occupies the eastern part of the Gullfaks fault

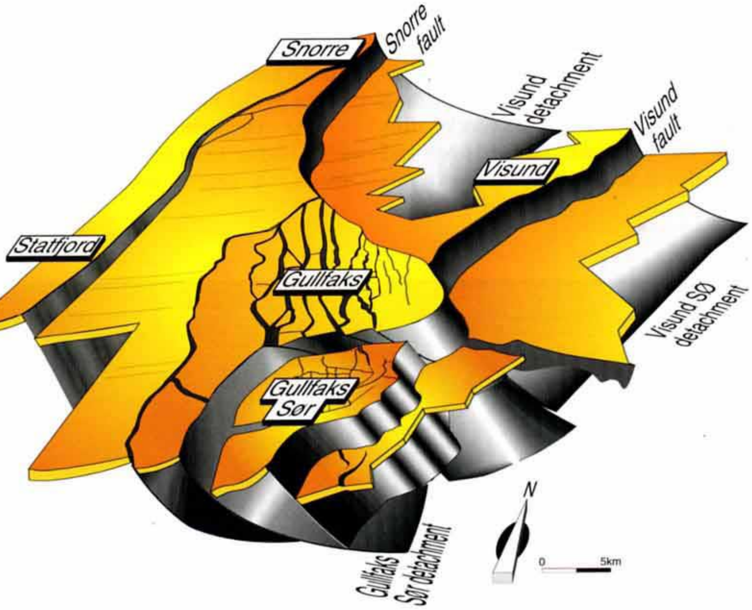


Fig. 5. Simplified 3D illustration of the Gullfaks–Visund–Snorre area. Layering at middle Jurassic level is indicated.

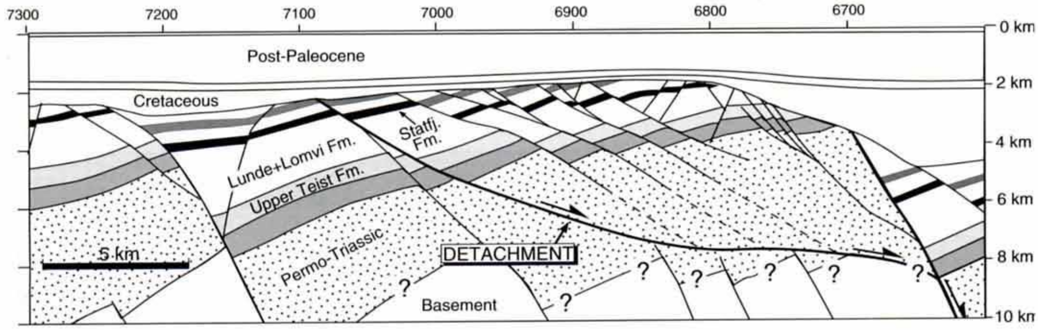


Fig. 6. Profile across the Gullfaks fault block, showing the presence of a low-angle detachment. Carefully interpreted 3D seismic data, well information and the deep seismic line shown in Fig. 7 form the basis for the interpretation. A standard 'lin-vel' depth conversion method with well data from the Gullfaks Field was applied and extended down to basement, which is assigned a constant velocity of $6.1\ \mathrm{km\,s^{-1}}$. Parameters used for interval sea floor–base Cretaceous: $V_0 1 = 1790\ \mathrm{m\,s^{-1}}$, $k = 0.2653$; base Cretaceous–top Statfjord Fm: $V_0 2 = 800\ \mathrm{m\,s^{-1}}$, $k = 0.8523$; base Cretaceous–top Triassic: $V_0 2 = 1000\ \mathrm{m\,s^{-1}}$, $k = 0.8523$. (See Fig. 3 for location.)

block (Fig. 4). Master faults with kilometre-scale displacements separate the Gullfaks fault block from the Statfjord fault block to the west (fault A) and the Visund–Gullfaks Sør area to the east (faults D and B Fig. 4). Among these, faults D and B form a highly non-planar structure that wraps around the Gullfaks Field in a very characteristic manner. This fault structure splays both to the south and north (faults D, E, B and C), and delineates the Gullfaks Sør and Visund fault blocks, respectively (Fig. 4).

Detailed knowledge about the structural geology of the Gullfaks Field has been gained through systematic analysis of exploration and production data (Fossen & Hesthammer 1998). In general terms, the western part of the Gullfaks fault block is dominated by a classical domino fault system. The domino faults are dipping about 30° to the east, whereas the bedding within the blocks exhibits more gentle dips (generally 10–18°) to the west. This distinct and geometrically uniform domino system extends from the Tordis fault in the west (Fig. 3) to a horst complex in the easternmost part of the Gullfaks fault block (Fig. 6), spanning about 10–15 km in the E–W direction and slightly more in the N–S direction.

The extension in the domino area is considerably higher than in the rest of the Gullfaks fault block. A recent map-view restoration of the

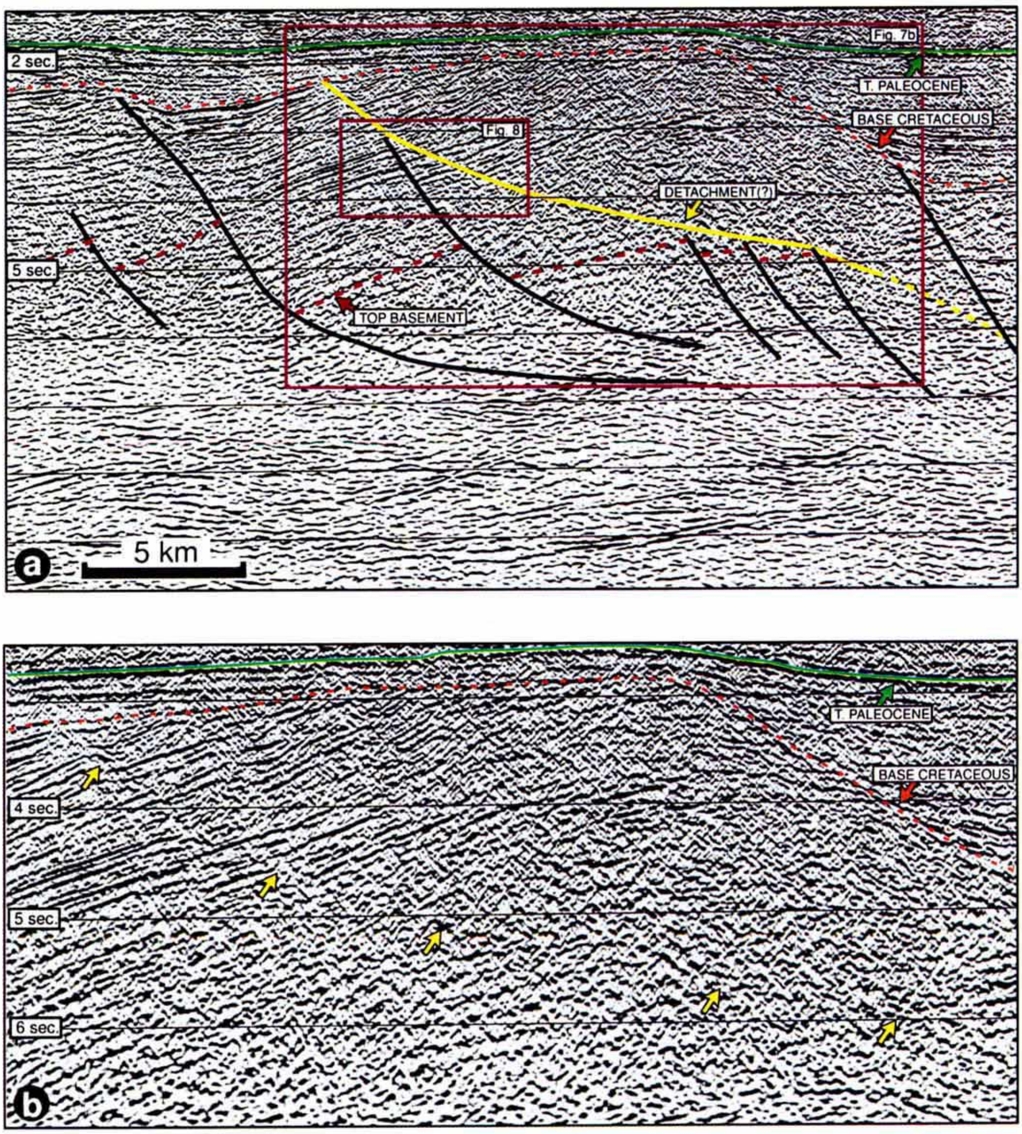


Fig. 7. (**a**) Part of the reprocessed deep seismic line NSDP-1 that traverses the Gullfaks fault block. The low-angle detachment is indicated together with some of the major basement-involving faults. The interpretation of faults within the basement is speculative and not well constrained. (See Fig. 3 for location.) (**b**) Close-up of the reflection interpreted as the Gullfaks detachment (arrows).

Gullfaks Field (Rouby *et al.* 1996) shows that the seismically resolvable Jurassic E–W extension across the field is of the order of 40–50% ($\beta = 1.4$–1.5). A similar estimate of the western part of the Gullfaks fault block gives only 10–15% extension ($\beta = 1.1$–1.15). Similar results can be obtained by summing the heaves of faults across E–W profile lines. There is good evidence that additional sub-seismic deformation is present in the domino system (Koestler *et al.* 1992; Fossen & Hesthammer 1998), possibly increasing the total extension to as much as 80% ($\beta = 1.8$).

The Gullfaks detachment

The presence of a low-angle, shallow detachment beneath the Gullfaks Field has been suggested by previous workers (Fossen 1989; Koestler *et al.* 1992), although no compelling evidence for its existence has been presented. Reprocessing of line NSDP84-1 has, however, revealed a gently E-dipping seismic event at about 3–5 s (Fig. 7). In the west the reflection appears to merge with a steeper fault. There are no similar reflectors shallower in the section, where the reflections are either sub-horizontal or westerly dipping. The reflection is therefore not a multiple of shallower reflections, and can be traced for a horizontal distance of more than 10 km. Considering the geometry, position and extent of the reflection, we interpret it as a low-angle fault (detachment) underlying the Gullfaks Field. A problem with this interpretation is that the possible detachment reflector cross-cuts a strong and continuous W-dipping signal in its western part (Fig. 8a). However, a simple restoration exercise (Fig. 8a–c) reveals that this continuous seismic signal can be explained as a coincidental alignment of two reflections from different stratigraphic levels on each side of the low-angle E-dipping reflection (detachment), a case that is familiar to most experienced seismic interpreters.

An interpreted geological section along this seismic line, based on both 2D and Gullfaks 3D seismic data and well information (Fig. 6), indicates that the detachment has a dip of 5–30°, and reaches a depth of about 7–8 km in the eastern part of the Gullfaks fault block. Gravity and magnetic data are consistent with the seismic interpretation of top basement beneath the Gullfaks Field as shown in Fig. 6 although a precise definition of top basement is difficult from any available dataset. According to our interpretation, the detachment soles out just above the basement–cover interface.

The contact relationship with the steeper and older (Permo-Triassic) master fault to the east (fault B–D) is not clear from the reflection seismic data. As no evidence is found for the detachment in the hanging wall to this fault, it is assumed that the detachment merges with fault B–D to form a ramp structure, similar to the Visund sørøst detachment (see below). In the west, the detachment appears to be connected to the Tordis fault, which therefore may have acted as the breakaway fault to the detached Gullfaks domino system.

The Gullfaks Sør detachment

Fault D (Fig. 4), which separates Gullfaks Sør from the Gullfaks fault block to the west, has a flattening-downward appearance on 3D seismic data (Fig. 9). Although the geometry is not well constrained in its eastern part, it appears that fault D flattens at depths of about 5.5–7 km to form a detachment at similar depth to the Gullfaks detachment. The entire Gullfaks Sør fault block rides on this detachment, which appears to join fault E east of Gullfaks Sør. Faults above the detachment are characterized by domino-style, sub-parallel E-dipping faults, similar to the style seen in the Gullfaks Field. The general interpretation of depth to basement in this area implies that the detachment is located within the Permo-Triassic sedimentary sequence. We therefore classify the Gullfaks Sør detachment as a supra-basement detachment.

The Visund sørøst detachment

Faults B and F formed the boundaries of the initial Visund mega fault block (combined area of the Visund and Visund sørøst fault blocks in Fig. 4). The upper part of fault F (Fig. 3) appears to be straight in cross-section. It is of Permo-Triassic origin (Færseth *et al.* 1995*b*), although the main throw is related to Jurassic extension, reaching a maximum of about 5 km at Middle Jurassic level.

The area at present bounded by faults C and F (Visund sørøst fault block in Fig. 4) was part of the initial Visund mega fault block, but was separated as a result of Volgian footwall collapse of the southeastern part of the mega-block (Færseth *et al.* 1995*b*). Fault C and some minor, east-dipping faults formed at this stage. The faults appear to converge and merge at depth (Fig. 10).

Depth conversion of fault C reveals a ramp–flat–ramp geometry with a present maximum

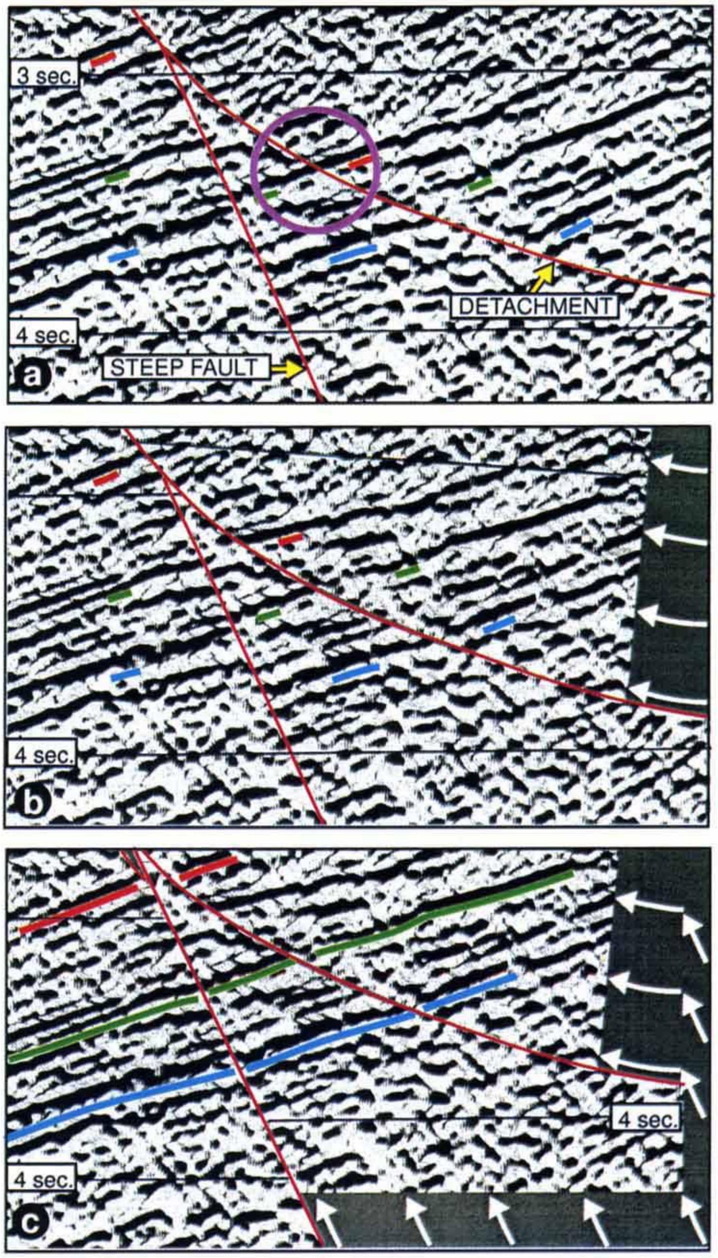


Fig. 8. Simple restoration of the portion of line NSDP84-1 where the detachment reflection merges with the steeper normal fault (see Fig. 7a for location). From (**a**) the detachment reflection appears to transect a continuous reflection (circled). The section was restored by rigid rotation of the hanging wall to the detachment (**b**) and subsequently by translation along the steep fault (**c**). In (**c**) the section is restored, after removal of an offset of a few hundred metres along the detachment. The rotation that was required is consistent with anti-clockwise rotation of the hanging wall of the detachment during deformation. The successful restoration shows that the continuous reflection may be the result of coincidental alignment of two different reflecting surfaces on each

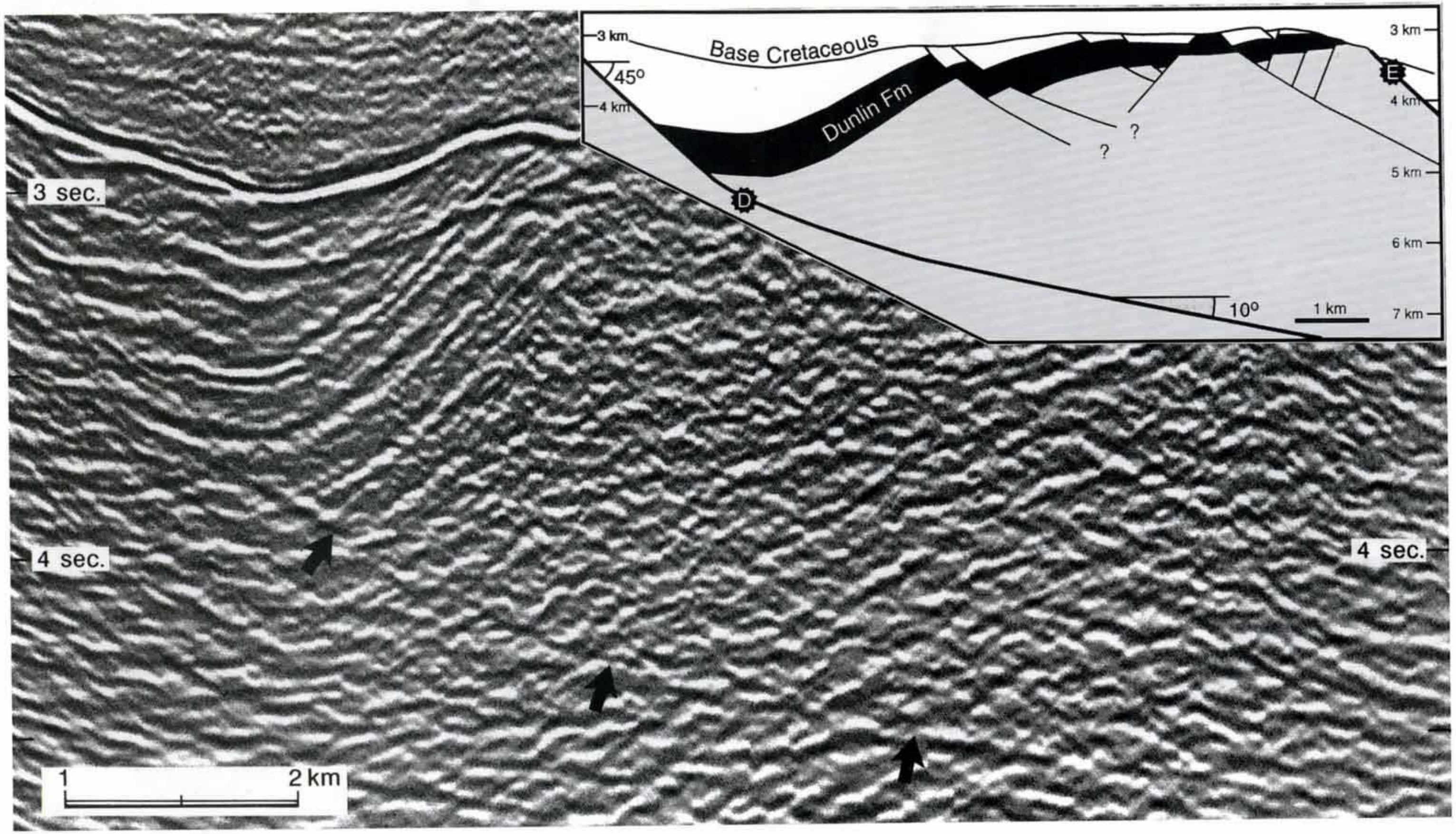
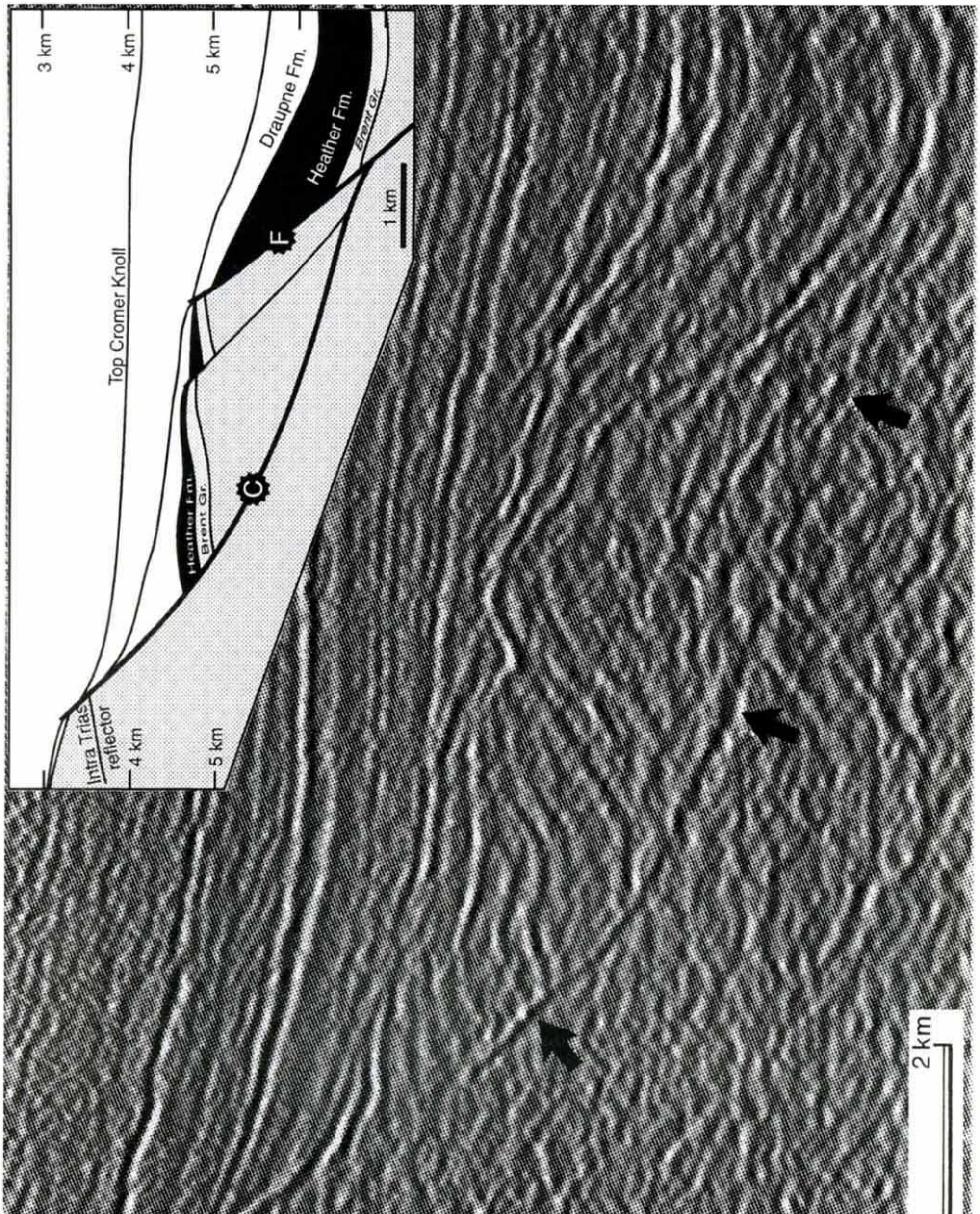


Fig. 9. Seismic profile through the Gullfaks Sør fault block, showing the downward-flattening geometry of fault D within the (Permo-?)Triassic sediments. Depth-converted version (no vertical exaggeration) is shown in the upper right corner. The low-angle part of fault D defines the Gullfaks Sør detachment.


3 km
4 km
5 km
Draupne Fm.
Heather Fm.
Brent Gr.
Top Cromer Knoll
F
C
1 km
Heather Fm.
Brent Gr.
Intra Trias
reflector
4 km
5 km
3 sec.
4 sec.
0
2 km

dip of 45–50°, decreasing towards 15° below the Visund sørøst fault block before merging with the steeper fault F (Fig. 10). The exact position of top basement is ambiguous from the seismic data, but from regional stratigraphic information it is likely that the fault detaches just above top basement. We therefore classify the fault as a supra-basement detachment similar to the Gullfaks detachment.

Detailed tectono-stratigraphic work by Færseth *et al.* (1995*b*) gives strong evidence that the Visund sørøst detachment (fault C) formed during latest Jurassic footwall collapse of the Visund fault block, which before this collapse was continuous with the Visund sørøst fault block.

Intra-basement detachments

The Visund detachment

The Snorre fault (B), which separates the Visund fault block from the Snorre Field, is well defined from fault-plane reflections and/or terminating reflectors in the hanging wall and footwall down to about 4 s on 2D lines (Figs 11 and 12) (see also Nelson & Lamy 1987). Below this depth the fault enters a zone of reduced reflectivity where the fault plane is not so clearly displayed. However, at lower depths (5–6.5 s) another reflector appears on the seismic line. This signal is much stronger than the surrounding reflections, and is gently east dipping (Fig. 12b) or locally sub-horizontal (Fig. 11b). It is clear from their strength and geometry that these reflections cannot be multiples from overlying events (they are overlain by a low-reflective zone below W-dipping reflections), and the fact that they generate unequivocal sea-bottom multiples (Figs 11b and c, and 12b and c) shows that they represent real physical structures in the crust. It is possible to correlate this signal from line to line, and a contoured map of the reflection is shown in Fig. 13. We suggest that the lower, strong reflection represents a low-angle fault within the basement, and that it is connected to the Snorre fault to define the Visund detachment. On some of the lines, a sub-horizontal reflection also appears to the west of the Snorre fault (e.g. Fig. 11), suggesting that the Visund detachment is part of a more extensive detachment system at about 6 s. Depth conversion of this detachment (see Fig. 15a, below) shows that the detachment remains sub-horizontal after depth conversion, and exists at a depth of about 14 km.

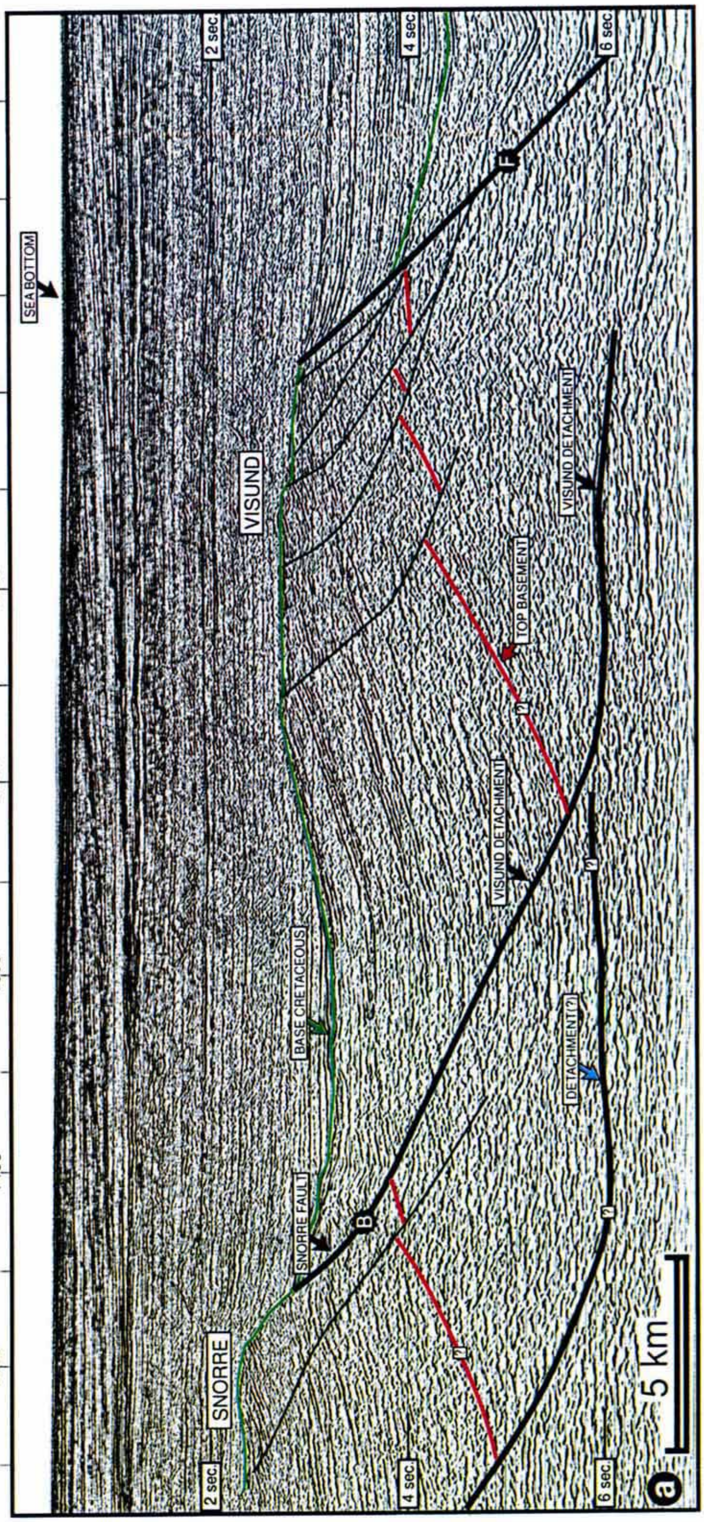
Gullfaks area

Interpretation of the deep seismic data across the Gullfaks Field, together with commercial 2D seismic lines, has resulted in the fault geometries shown in Fig. 14 (Odinsen *et al.* 2000*a*). The Statfjord fault (A) is here interpreted as a non-planar fault that becomes a low-angle detachment structure in the basement. A domino-style fault-block arrangement is tentatively interpreted to be situated above this detachment, similar to the Jurassic domino system above the overlying Gullfaks detachment. Hence, there are indications that two levels of detachments (a supra- and intra-basement detachment) may exist beneath the Gullfaks Field.

Evolution of the intra-basement detachments

Low-angle detachments of late to post-Caledonian age are known from both sides of the North Sea rift. The sub-horizontal décollement zone between Caledonian nappes and basement in southern Norway, the NW-dipping Hardangerfjord shear zone, and the Nordfjord–Sogn detachment are all well-exposed examples of low-angle structures accommodating substantial Devonian extension on the eastern side of the North Sea (Norton 1987; Séranne & Séguret 1987; Fossen 1992). Similarly, reactivation of Caledonian thrusts as low-angle extensional features is recognized in Scotland (McClay *et al.* 1986; White & Glasser 1987; Powell & Glendinning 1990). Some of these detachments continue under the North Sea and form zones of weakness in the crust. For mechanical reasons, these and similar low-angle structures of Caledonian or Devonian age were easily reactivated as detachments during the Permo-Triassic and Jurassic extension phases, especially in areas of high post-Devonian extension, and caused ramp–flat geometries of the type seen in Fig. 11. Reactivation of orogenic structures as low-angle extensional faults or shear zones is a common phenomenon in extended areas, such as in the western USA (Allmendinger *et al.* 1983; Coney & Harms 1984; Wernicke *et al.* 1987; Parrish *et al.* 1988; Constenius 1996). Assuming that this

Fig. 10. Seismic profile (from 3D data) across fault C (Visund sørøst detachment), which clearly appears as a downward-flattening fault on the seismic data. Depth-converted version (no vertical exaggeration) is shown in the upper right corner. (See Fig. 3 for location.)


a
SNORRE
VISUND
SEA BOTTOM
SNORRE FAULT
BASE CRETACEOUS
VISUND DETACHMENT
TOP BASEMENT
VISUND DETACHMENT
DETACHMENT(?)
B
F
2 sec.
4 sec.
6 sec.
5 km
1200
1400
1600
2800
3000
4200
4400
5500

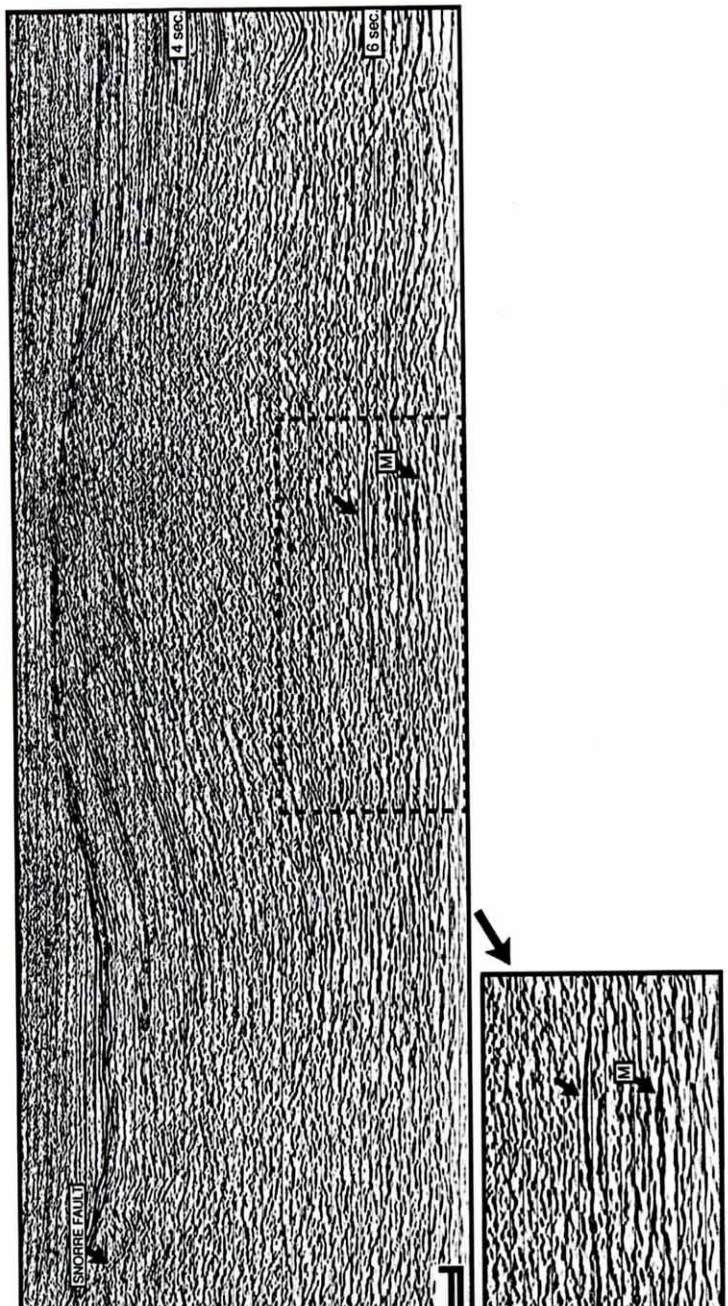
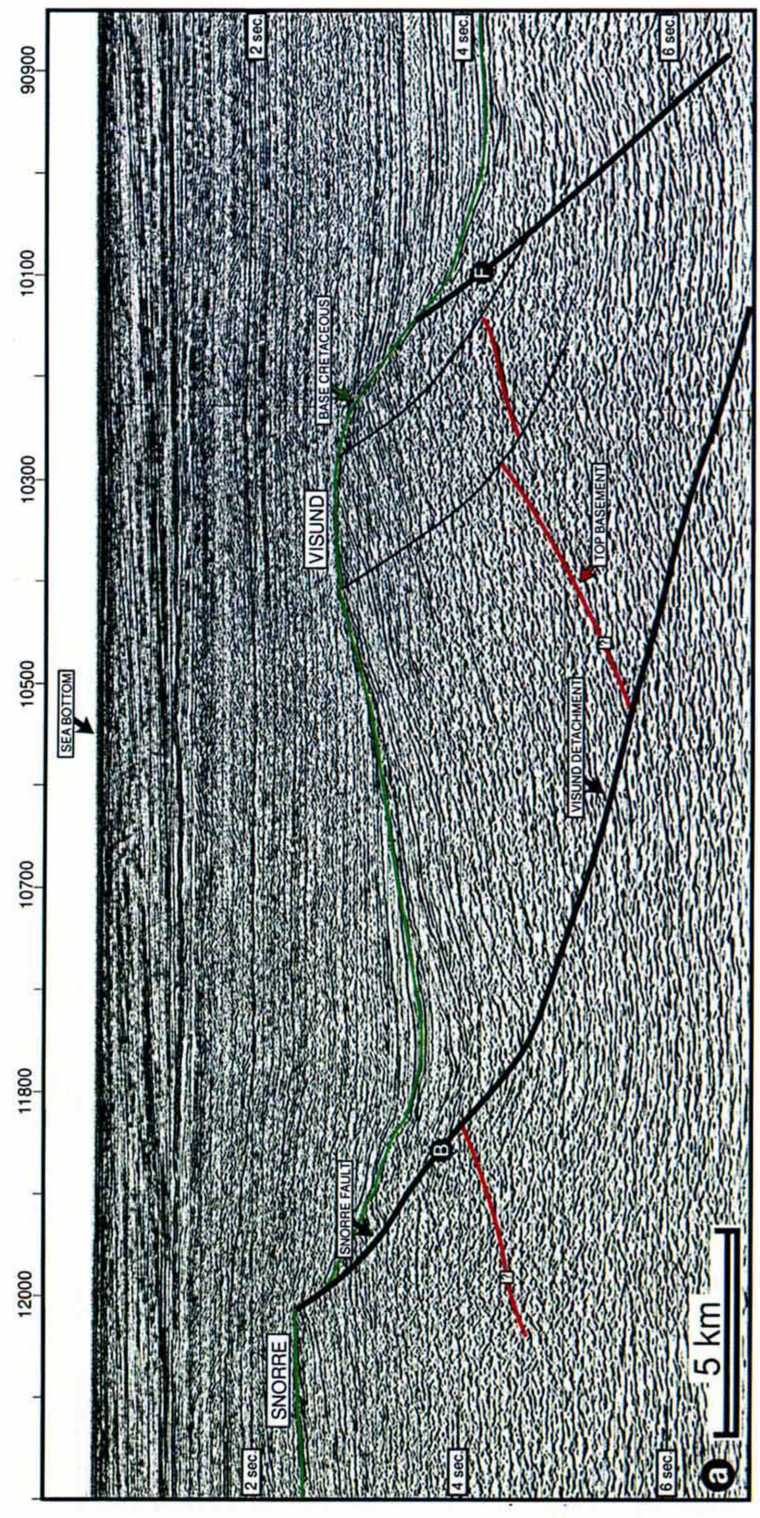


Fig. 11. **(a)** Seismic line NVGT-88-08 across the Visund fault block, showing how the Snorre fault flattens beneath the Visund fault block to form an intra-basement detachment (Visund detachment) at about 6 s. **(b)** Uninterpreted version of **(a)**. The upper part of the Snorre fault is clearly visible as a downward-flattening reflection, and a sub-horizontal reflection is interpreted as a low-angle detachment. **(c)** Close-up of the strong sub-horizontal reflection and its multiple. (See Fig. 3 for location.)


90900
10100
10300
10500
10700
11800
12000
SEA BOTTOM
2 sec
4 sec
6 sec
BASE CRETACEOUS
VISUND
TOP BASEMENT
VISUND DETACHMENT
SNORRE FAULT
SNORRE
F
B
5 km
a

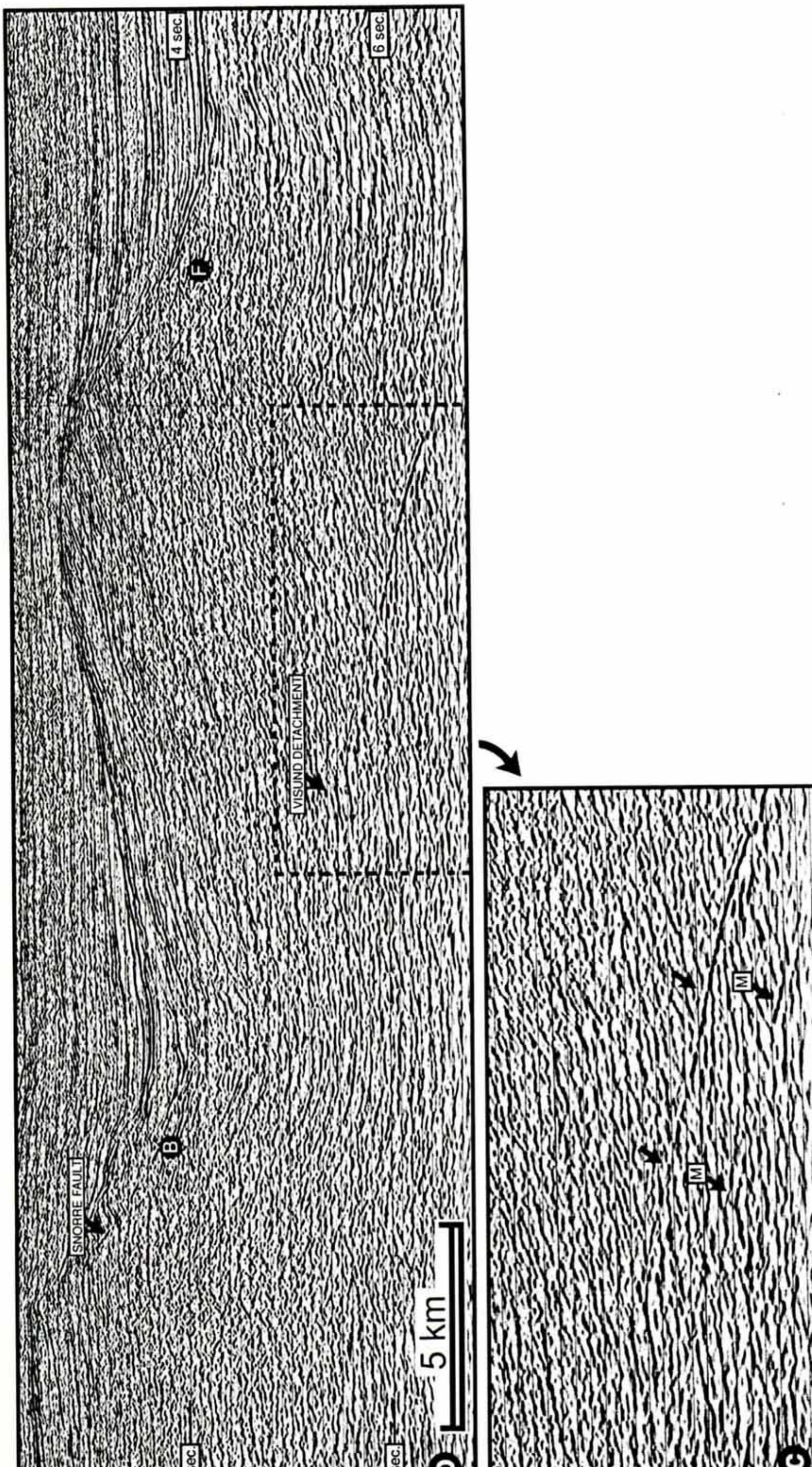


Fig. 12. **(a)** Seismic section NVGT-88-09 shows how the low-angle Visund detachment is somewhat steeper than in Fig. 11. **(b)** Uninterpreted version of **(a)**. The Visund detachment is clearly visible as a multiple-generating reflection in the basement **(c)**. (See Fig. 3 for location).

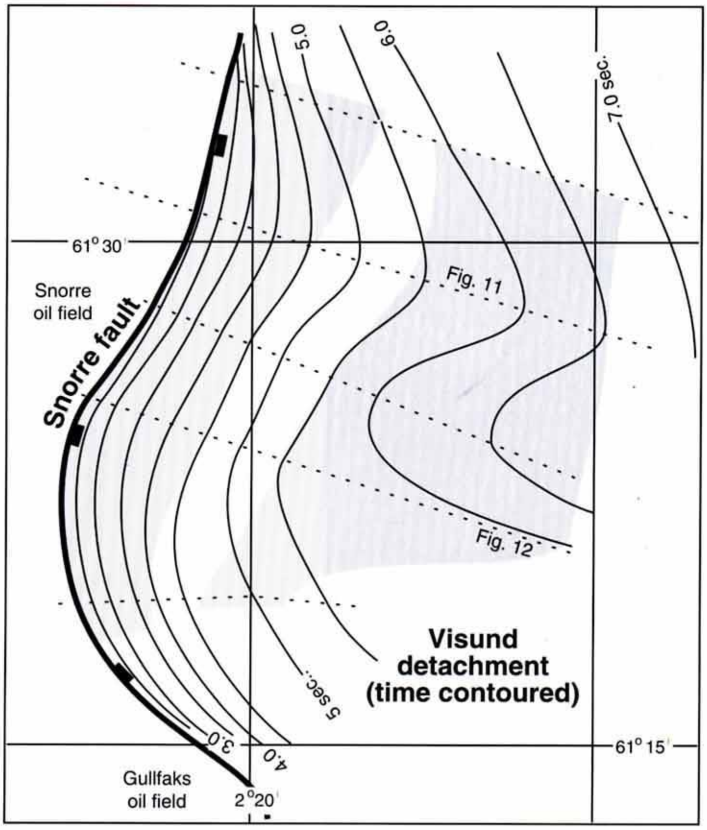


Fig. 13. Time-contoured map of the Visund detachment (Snorre fault) based on 2D seismic lines (stippled lines). Grey area indicates area where the fault-plane reflection is visible, or where terminating reflectors define the fault plane.

development also holds for the North Sea, the easterly dip of low-angle intra-basin faults or detachments in the Tampen area may indicate that the Caledonian suture zone is located east of the Tampen area, beneath the Viking Graben or close to the Permo-Triassic rift axis.

On the other hand, it is possible that the detachments were initially steeper faults that rotated to become low-angle structures during the Permo-Triassic and Jurassic extensional phases. A maximum estimate of the original (pre basin-fill) dip of the detachments is obtained from the dip of the top-basement surface in the footwall of the detachment faults. This estimate is valid only for rigid block rotation without significant internal, small-scale deformation. In the case of the Visund detachment, the top basement surface in the footwall is dipping about 25° to the west (Fig. 15a). Top basement restoration by predominantly rigid block rotations and translations would result in original dip of detachment of the same order (Fig. 15c). If additional small-scale deformation is allowed for (e.g. inclined shear, not shown in Fig. 15), original fault dips may be found to have been lower than 25°. Lowering of fault dips throughout the extensional history of the North Sea Rift is thus possible, but only to a limited extent (maximum 20–30°). Hence, faults that are currently dipping 30° to the east may have exhibited dips up to 50–60° in Permian time. It is possible that some of the faults developed into low-angle structures after repeated phases of extension, and acted as low-angle faults or detachments only during the Late Jurassic extension phase.

The above discussion relates to the model envisaged by Yielding *et al.* (1991). This model suggests that the downward shallowing of master faults in the North Sea is a result of multiple episodes of deformation. An early, Permo-Triassic phase of extension caused the formation and subsequent rotation of the faults in the

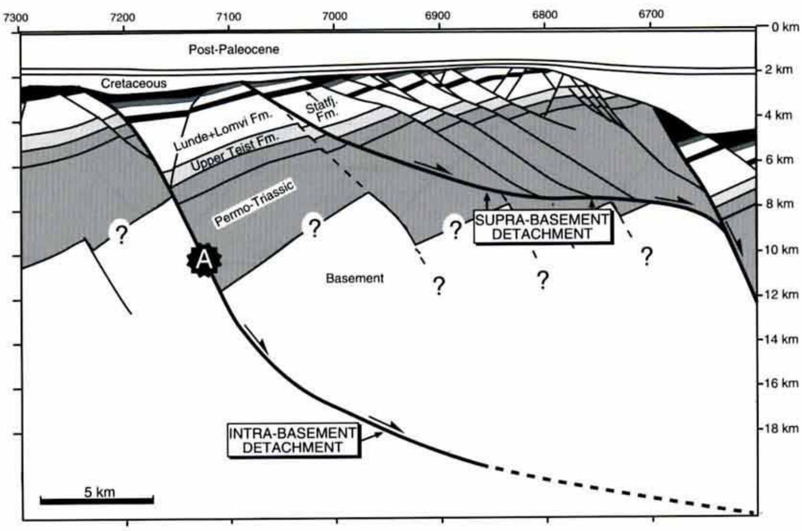


Fig. 14. Depth profile across the Gullfaks fault block, showing the interpretation of fault A as downward flattening, forming an intra-basement detachment underneath the Gullfaks supra-basement detachment. The interpretation on this line is based on a combination of line NSDP84-1 (Fig. 7), the Gullfaks 3D seismic data and well information, and conventional 2D seismic data from the area.

basement, whereas Jurassic extension caused the faults to grow into the Jurassic sequence with steeper dips. Faults with a lower (Permo-Triassic level), low-angle segment and an upper (Jurassic level), steeper segment would result from this model. However, examples such as Fig. 11, where the ramp–flat transition is located within the basement, demonstrate that the model of Yielding *et al.* (1991) cannot account for all of the fault geometries related to low-angle faults in the northern North Sea. We think that both the multiple-deformation model and the control of older (Devonian or Caledonian) shear zones in the anisotropic basement influenced the occurrence of low-angle fault movements in Mesozoic time.

Evolution of the supra-basement detachment

From the discussion above, we conclude that most of the intra-basement detachments have a history that goes back at least to the Permo-Triassic extension phase, and probably to the Devonian extensional and/or Caledonian contractional events. The supra-basement detachments are clearly of younger age, because they occur in rocks of (late) Triassic age. They are therefore likely to be partly or wholly related to the late Jurassic extension phase, as discussed below.

This is particularly clear for the Visund sørøst detachment, which has recently been shown to be a collapse structure that formed during late Jurassic rotation of the Visund fault block. This collapse occurred in the southeastern and highest portion of the original Visund mega-fault block. The initiation of the collapse can be dated to mid–late Kimmeridgian time, but the main activity is believed to have been in the Volgian period (Færseth *et al.* 1995*b*). These constraints show that supra-basement detachments formed at a relatively late stage in the late Jurassic extension phase and after the main faults were established.

The nearby Gullfaks Field is located on a bend in the Gullfaks fault block, which occurs between the southern tip of fault B and the northern termination of fault D. The characteristic 'Gullfaks bend' may be interpreted as an accommodation zone (family 3 case G′) between faults B and D according to the scheme of Rosendahl (1987) (Fig. 16). Throw variation data (Fig. 17) for faults B and D indicate a significant decrease in throw for both faults towards the apex of the 'Gullfaks bend'. This is consistent with a model in which these faults grew towards the Gullfaks field, where they finally intersected to form the Gullfaks bend accommodation zone. During this process, the Gullfaks Field area became an elevated part of the rotating Gullfaks fault block. Any elevated

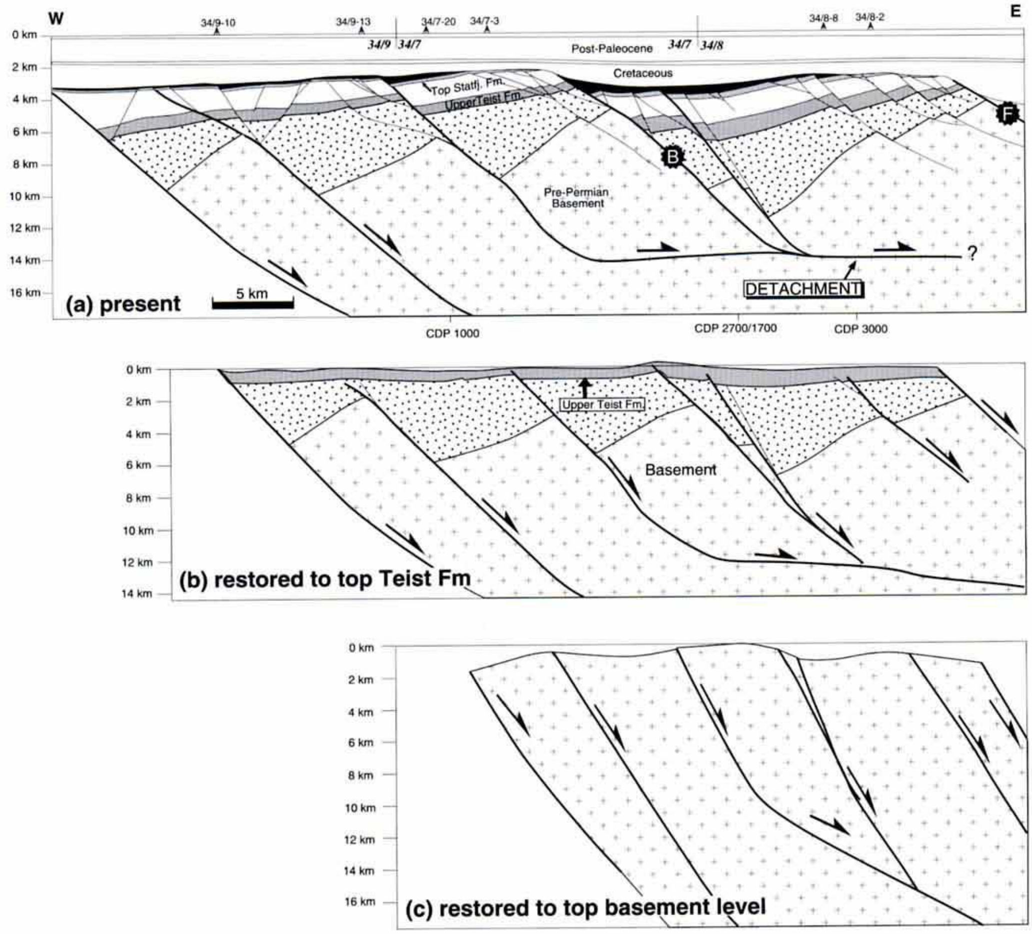


Fig. 15. (**a**) Depth-converted version of Fig. 11, showing that the detachment occurs at about 12–14 km depth. It should be noted that the change in dip of the master faults occurs well within the basement. The lin-vel depth conversion method based on well data from the Gullfaks Field is applied down to basement, where a constant velocity of 6.1 km s^{-1} is applied. (See text for discussion.) (**b**) Simple restoration to the Triassic top Teist Fm level. (**c**) Restoration of the top basement surface. (Note change in dip of the detachment fault.) The balancing performed here restores the section by making the marker horizon approximately horizontal. Rigid-body rotation and minor amounts of vertical shear are applied. Compaction-related effects are not considered. Vertical shear with no rigid body rotation gives a similar result.

part of a large fault block in a rift system is the potential object of extensional collapse, and it appears that the high portion of the Gullfaks fault block collapsed above the Gullfaks detachment. This process was probably dynamic rather than strictly sequential, so that the gradual uplift of the Gullfaks area led to formation of the Gullfaks detachment and repeated slip along the detachment as faults B and D grew.

The presence of a detachment beneath the Gullfaks Field explains several of the characteristics of the area. First, it provides a sound explanation for the presence of the domino system. All the main faults in the Gullfaks Field (i.e. in the upper plate of the Gullfaks detachment) dip to the east, antithetical to bedding, except for the marginal horst complex at its eastern edge (Fig. 6, sp. 6800). The formation of such uniformly dipping sets of faults is favoured if a dipping basement or detachment exists underneath the parallel fault system. In that case, the faults in the upper block may easily develop domino-style fault blocks with faults dipping synthetically to the detachment or basement. This has been demonstrated by extensional experiments performed with tilted

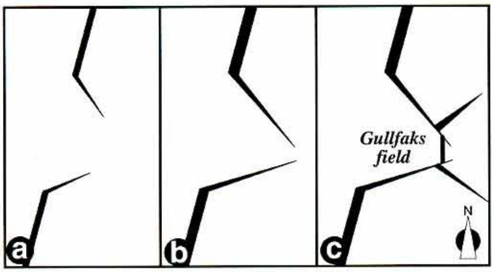


Fig. 16. Model for the development of the Gullfaks spur. The Snorre and Gullfaks Sør faults (faults D and B in Fig. 4) are thought to have defined half-grabens with a geometry similar to that described by Rosendahl (1987) (**a**). As they grew (**b**), the faults approached one another, and as they crossed (**c**), the Gullfaks spur was defined. It is possible that part of the complex fault pattern mapped to the east of the Gullfaks Field (see Fig. 3) is a result of simultaneous movement on faults D and B.

sandboxes (McClay & Ellis 1987; Vendeville *et al.* 1987) (Fig. 18), and is also characteristic for the upper-plate deformation above detachments in the western USA (e.g. Wernicke 1985; Lister & Davis 1989). Domino systems may also develop in untilted sand models, but rarely with the consistency and number of fault blocks as seen in the Gullfaks Field (Fig. 6). A similar argument can be made for the existence of a gently east-dipping detachment underneath Gullfaks Sør during development of the upper-block faults.

A Gullfaks detachment also helps explain the unusually large extensions in the Gullfaks Field (domino system) as compared with the rest of the Gullfaks fault block. Rouby *et al.* (1996) used a numerical map-view restoration method to show that the Late Jurassic E–W extension is much higher in the Gullfaks Field (*c.* 40%) than in the Gullfaks block in general (*c.* 15%). This observation fits well with a detachment model, where the upper plate can collapse and extend independently from the lower and western part of the block. In a similar way, the Gullfaks Sør block showed high extension (33%) compared with the area to the west, which can be explained by an underlying Gullfaks Sør detachment.

Insights from plaster experiments

The observations from the Gullfaks Field and physical modelling suggest that the geometries and interaction between master faults are crucial for the final result of the extensional deformation. Three basic relationships exist between supra-basement detachments and the steeper master fault associated with the basement scarp (ramp). In the first case (Fig. 19a), the detachment is older than the steep fault and is therefore offset by the latter. In the second example (Fig. 19b) the detachment is the younger structure, and accordingly cross-cuts and offsets the steep fault. Finally, if the two are active at the same time (Fig. 19c), they may join and merge into a single structure in the ramp region.

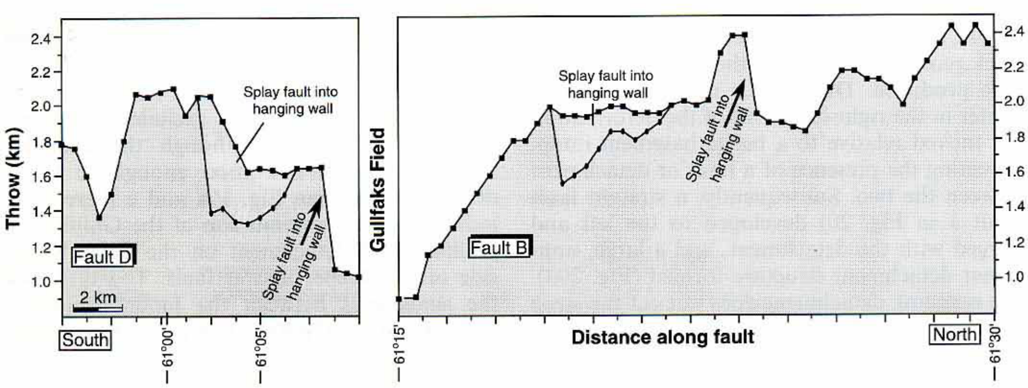


Fig. 17. Throw-variation diagrams for faults D and B (Fig. 4) at top Brent Group level. Fault D shows a maximum at about 61°00′, and a decrease in throw is recorded towards the Gullfaks Field. Similarly, fault B has maximum throw values north of the Gullfaks Field (north of 61°30′), and shows a decrease in throw to the south towards Gullfaks. These data indicate that faults D and B grew towards the Gullfaks Field, where they eventually met, as suggested in Fig. 16.

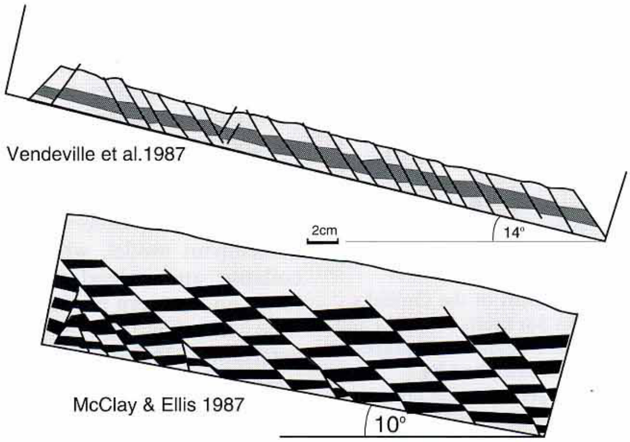


Fig. 18. Results of sandbox experiments above an inclined base. Redrawn from McClay & Ellis (1987) and Vendeville *et al.* (1987). In both cases a prominent domino-style fault pattern was produced, similar to the style seen above the Gullfaks supra-basement detachment.

However, if the displacement along the detachment is large, the upper part of the steep master fault is likely to become deactivated as it is transported towards the graben center. In this case, a new steep fault typically forms above the ramp in the footwall to the former fault (Fig. 19c).

It is possible to model supra-basement detachments and ramp–flat–ramp geometries experimentally with sand, clay or plaster. In such models, the temporal development of faulting and fault interaction can be studied in detail. Plaster experiments of the type described by Fossen & Gabrielsen (1996) have been found to be useful, particularly if wet plaster is extended together with a stronger, ductile basement of wet barite powder. In one of their experiments (run 1), a supra-basement detachment and fault-block geometries similar to the Gullfaks example were produced. During this run (Fig. 20), the plaster in the right-hand end of the deformation box moved relative to a barite basement ramp, indicating the presence of a fault or detachment between the two. Subsequently, a straight fault (fault 3 in Fig. 20) developed to the left and merged with the detachment, and a large, non-planar detachment structure formed (Fig. 20d). The resulting detachment does not cut the steep faults formed at an earlier point, but together these structures form a kinematically coherent system similar to Fig. 19c. Geometrically, this ramp bears similarities to the master fault east of the Gullfaks detachment (Fig. 6 except that the Gullfaks master fault continues downward).

In a different experiment, two steep master faults (1 and 2 in Fig. 21b) formed in a volume of wet plaster under plane strain extension. A new, listric fault (5 in Fig. 21c) grew from the free surface of the previously undeformed footwall, flattened out at about one-third of the total height of the model, and eventually cut across fault 1 to join fault 3 (Fig. 21d). Fault 1 was consequently deactivated and offset, and the resulting geometry and deformation history is an example of the case shown in Fig. 19b.

The two plaster experiments described here illustrate how two different situations can occur during a single plane strain extension history. For natural examples of supra-basement detachments, such as the Gullfaks and Gullfaks Sør detachments discussed above, the geometric relationships in the ramp zone (as illustrated in Fig. 19) should be examined. The apparent continuity of the relatively steep master fault that transects the basement and the sedimentary cover on the seismic data excludes the model shown in Fig. 19b. Although the available seismic data are not good enough to safely distinguish between Fig. 19a and c there is no indication of a continuation of the Gullfaks or Gullfaks Sør detachment on the downthrown side of the steeper master fault. Together with the similarities between the model shown in Fig. 20 and the Gullfaks Field (basement ramp, marginal horst), this supports the model shown in Fig. 19c, although the model shown in Fig. 19a was suggested by Koestler *et al.* (1992). As far as the Visund area is concerned, the age constraints discussed above (Færseth *et al.* 1995*b*) show that the Visund sørøst detachment is clearly younger than the steep master fault to the

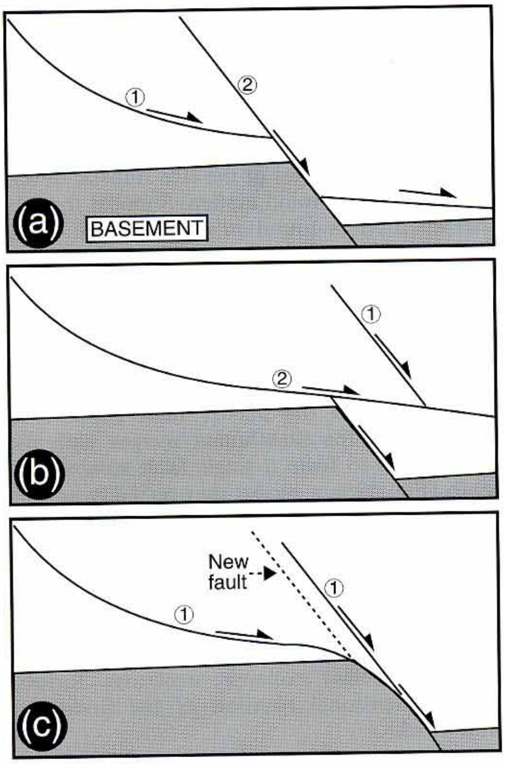


Fig. 19. The three possible relationships between detachments and steeper master faults above a basement escarpment. Numbers indicate relative timing. In (**a**) the steep fault post-dates the detachment, whereas in (**b**) the timing is opposite. In (**c**) the detachment and the steep fault are active simultaneously. If the displacement along the detachment is significant, the steep fault is transported across the ramp, and a new fault forms in its footwall (stippled). The result can be a complex fault zone above the ramp.

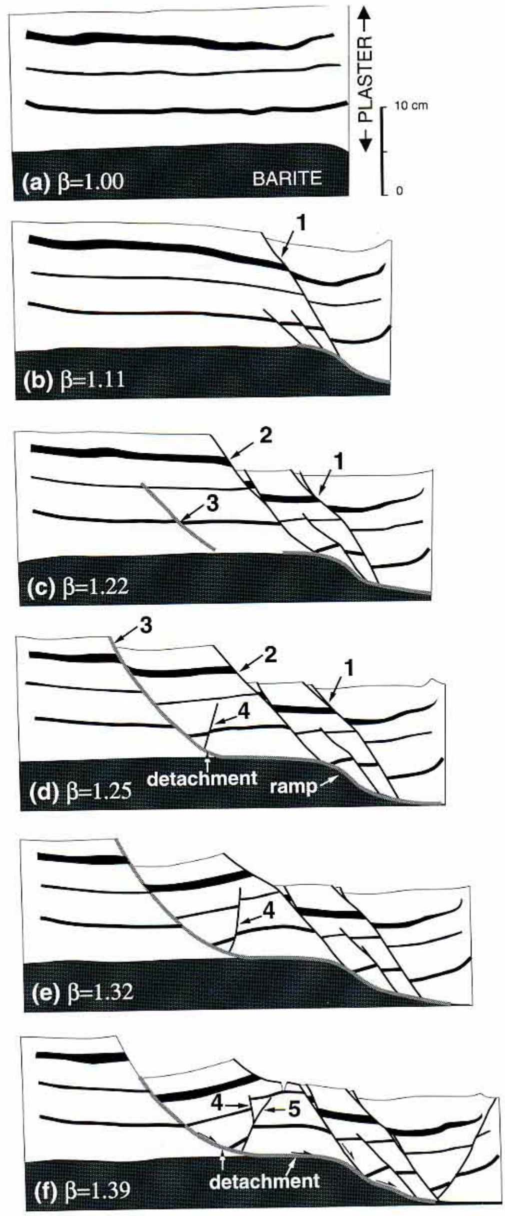


Fig. 20. Temporal development of plaster model, where the barite basement is stiffer than the overlying plaster, and therefore forms a ramp as the right-hand wall is pulled to the right. Fault 3 develops into a downward-flattening fault, which forms a detachment towards the end of the run. Modified from Fossen & Gabrielsen (1996).

east, but that they moved simultaneously in latest Jurassic time. Hence, the model shown in Fig. 19c also applies to this detachment system.

Conclusions

Some of the master faults on the western flank of the Viking Graben exhibit low dips in the basement, and acted as intra-basement detachments during the late Jurassic stretching phase. Some of these detachment faults might have had higher initial dips and rotated into less steep orientations through block rotations and internal deformation during pre-Jurassic rifting phases. In this model, faults that were originally intermediate or high angle rotated to form low-angle faults, which acted as detachments in Jurassic time. However, some faults are seen to flatten *within* the basement, indicating that they follow pre-existing E-dipping weak zones that

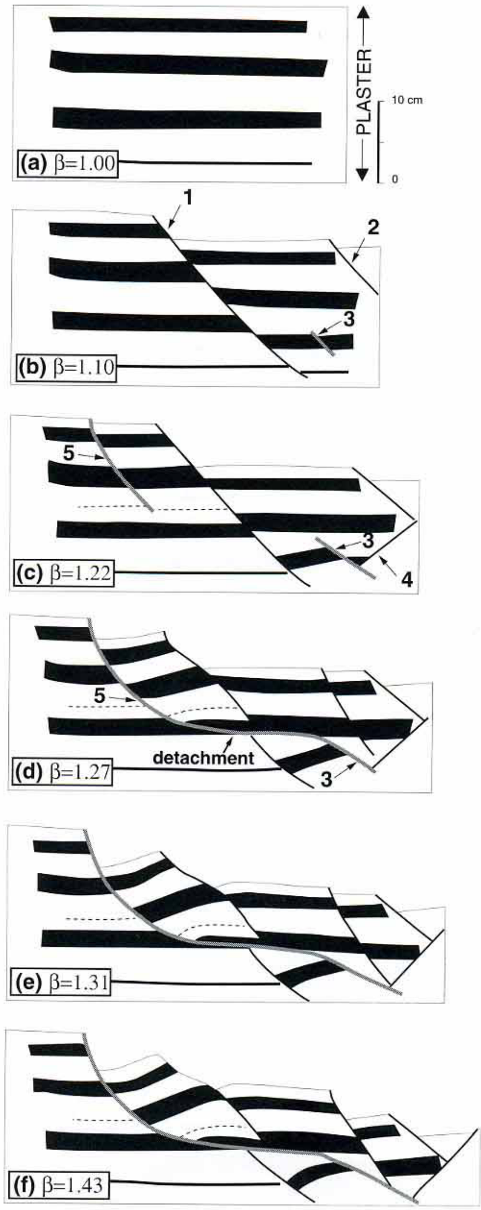


Fig. 21. Sequential development of plane strain extensional plaster model carried out at the 1992 TSGS meeting, Bergen. No basement is introduced, and a low-angle detachment develops and cuts earlier steep faults. (See Fossen & Gabrielsen (1996) for description of the experimental method.)

most likely are Devonian extensional shear zones and/or reactivated Caledonian thrusts.

Supra-basement detachment is identified in Triassic sediments beneath the Gullfaks Field, SE of the Visund fault block and underneath Gullfaks Sør. These detachments are therefore not reactivated Devonian extensional detachments or Caledonian thrusts. The development of a classical domino system on Gullfaks (consistent fault dip polarity) indicates that the detachment existed as an active, E-dipping slip surface at early stages of the late Jurassic development of the domino system. Support for this interpretation is found in experimental work, where such domino systems are found to develop more easily if the basal plate of the experiment is tilted. The Gullfaks detachment model also provides a sound explanation for the unusually high extension recorded in its hanging wall. Contemporaneous movement along the detachment and the master fault supports a model where the detachment merges with the master fault to form a single fault structure at depth (Fig. 19c), a model that certainly applies to the Visund sørøst detachment and probably also to the Gullfaks Sør detachment.

All of the three supra-basement detachments occur in the high parts of rotated, first-order fault blocks in the Triassic–Jurassic sequence of the Tampen area. This suggests that they are gravity-controlled collapse structures formed during extensional rotation of the first-order fault blocks.

Both supra- and intra-basement detachments may have a significant influence on the development of upper-crustal structures. A better mapping and understanding of these low-angle structures is important for improved understanding of the upper-crustal development of the North Sea rift system.

This paper has benefited from comments by J. Akselsen, N. Platt, M. Séranne, J. Walsh and D. Couturier.

References

ALLMENDINGER, R. *et al.* 1983. Cenozoic and Mesozoic structure of the eastern Basin and Range province, Utah, from COCORP seismic reflection data. *Geology*, **11**, 532–536.

ARMSTRONG, R. L. 1972. Low angle (denudation) faults, hinterland of the Sevier Orogenic Belt, Eastern Nevada and Western Utah. *Geological Society of America Bulletin*, **83**, 1729–1754.

BADLEY, M. E., EGEBERG, T. & NIPEN, O. 1984. Development of rift basins illustrated by the structural evolution of the Oseberg structure, Block 30/6, offshore Norway. *Journal of the Geological Society, London*, **141**, 639–649.

——, PRICE, J. D., DAHL, C. R. & AGDESTEIN, T. 1988. The structural evolution of the northern Viking Graben and its bearing upon extensional modes of basin formation. *Journal of the Geological Society, London*, **145**, 455–472.

BEACH, A. 1984. Structural evolution of the Witch Ground Graben. *Journal of the Geological Society, London*, **141**, 621–628.

BOSWORTH, W. 1985. Geometry of propagating continental rifts. *Nature*, **316**, 625–627.

CHERRY, S. T. J. 1993. The interaction of structure and sedimentary process controlling deposition of the Upper Jurassic Brae Formation Conglomerate, Block 16/17, North Sea. *In*: PARKER, J. R. (ed.) *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. Geological Society, London, 387–400.

CHRISTIANSSON, P., FALEIDE, J. I. & BERGE, A. M. 1999. Crustal structure in the northern North Sea; an integrated geophysical study. *This volume*.

CLAUSEN, O. R. & KORSTGÅRD, J. A. 1996. Planar detachment faults in the southern Horn Graben, Danish North Sea. *Marine and Petroleum Geology*, **13**, 537–548.

CONEY, P. J. & HARMS, T. A. 1984. Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression. *Geology*, **12**, 550–554.

CONSTENIUS, K. N. 1996. Late Paleogene extensional collapse of the Cordilleran foreland fold and thrust belt. *Geological Society of America Bulletin*, **108**, 20–39.

COWARD, M. P. 1986. Heterogeneous stretching, simple shear and basin development. *Earth and Planetary Science Letters*, **80**, 325–326.

FOSSEN, H. 1989. Indication of transpressional tectonics in the Gullfaks Oil Field, northern North Sea. *Marine and Petroleum Geology*, **6**, 22–30.

——1992. The role of extensional tectonics in the Caledonides of South Norway. *Journal of Structural Geology*, **14**, 1033–1046.

——1998. Advances in understanding the post-Caledonian structural evolution of the Bergen area, West Norway. *Norsk Geologisk Tidsskrift*, **78**, 33–46.

—— & GABRIELSEN, R. H. 1996. Experimental modeling of extensional fault systems. *Journal of Structural Geology*, **18**, 673–687.

—— & HESTHAMMER, J. 1998. Structural geology of the Gullfaks Field. *In:* COWARD, M. P., JOHNSON, H. & DALTABAN, T. S. (eds) *Structural Geology in Reservoir Characterization and Field Development*. Geological Society, London, Special Publications, **127**, 231–261.

—— & RYKKELID, E. 1992. Post-collisional extension of the Caledonide orogen in Scandinavia: structural expressions and tectonic significance. *Geology*, **20**, 737–740.

FÆRSETH, R. B. 1983. *Tectonic map showing: northern North Sea and west Norwegian mainland*. Norsk Hydro, a.s., Stabekk.

——, GABRIELSEN, R. H. & HURICH, C. A. 1995*a*. Infuence on basement in structuring of the North Sea basin, offshore southwest Norway. *Norsk Geologisk Tidsskrift*, **75**, 105–119.

——, SJØBLOM, T. S., STEEL, R. J., LILJEDAHL, T., SAUAR, B. E. & TJELLAND, T. 1995*b*. Tectonic controls on Bathonian–Volgian syn-rift successions on the Visund fault block, northern North Sea. *In*: STEEL, R. J. (ed.) *Sequence Stratigraphy on the Northwest European Margin*. Norwegian Petroleum Society, Special Publication, **5**, 325–346.

GABRIELSEN, R. H. 1986. Structural elements in graben systems and their influence on hydrocarbon trap types. *In*: SPENCER, A. M. *et al.* (eds) *Habitat of Hydrocarbons on the Norwegian Continental Shelf*. Graham and Trotman, London, 55–60.

——1988. Reactivation of faults on the Norwegian continental shelf and its implications for earthquake occurence. *In*: GREGERSEN, S. & BASHAM, P. (eds) *Causes and Effects of Earthquakes at Passive Margins and in Areas with Post-glacial Rebound on both Sides of the North Atlantic*. Elsevier, Amsterdam, 69–92.

——, FÆRSETH, R. B., STEEL, R. J., IDIL, S. & KLØVJAN, O. S. 1990. Architectural styles of basin fill in the northern Viking Graben. *In*: BLUNDELL, D. J. &. GIBBS, A. D. (eds) *Tectonic Evolution of the North Sea Rifts*. Clarendon, Oxford, 158–183.

GIBBS, A. D. 1984. Structural evolution of extensional basin margins. *Journal of the Geological Society, London*, **141**, 609–620.

GRAUE, K. 1992. Extensional tectonics in the northernmost North Sea: rifting, uplift, erosion and footwall collapse in Late Jurassic to Early Cretaceous times. *In*: SPENCER, A. M. (ed.) *Generation, Accumulation and Production of Europe's Hydrocarbons II*. Springer, Berlin, 23–34.

HARDING, T. P. 1984. Graben hydrocarbon occurences and structural styles. *AAPG Bulletin*, **68**, 333–362.

HARDMAN, R. F. P. & BOOTH, J. E. 1991. The significance of normal faults in the exploration and production of North Sea hydrocarbons. *In*: ROBERTS, A. M., YIELDING, G. & FREEMAN, B. (eds) *The Geometry of Normal Faults*. Geological Society, London, Special Publications, **56**, 1–13.

HARRIS, J. P. & FOWLER, R. M. 1987. Enhanced prospectivity of the mid–late Jurassic sediments of the south Viking Graben, northern North Sea. *In*: BROOKS, J. & GLENNIE, K. W. (eds) *Petroleum Geology of North West Europe*. Graham and Trotman, London, 879–898.

JOHNSON, D. 1930. Geomorphic aspects of rift valleys. *Proceedings 15th International Geological Congress*, **2**, 354–373.

KLEMPERER, S. L. 1988. Crustal thinning and nature of extension in the northern North Sea from deep seismic reflection profiling. *Tectonics*, **7**, 803–821.

KOESTLER, A. G., MILNES, A. G. & STORLI, A. 1992. Complex hanging-wall deformation above an extensional detachment – example: Gullfaks Field, northern North Sea. *In:* LARSEN, R. M., BREKKE, H., LARSEN, B. T. & TALLERAAS, E. (eds) *Tectonic Modelling and its Application to Petroleum Geology*. Norwegian Petroleum Society, Special Publication, **1**, 243–251.

KUSZNIR, N. J., MARSDEN, G. & EGAN, S. S. 1991. A flexural–cantilever simple-shear/pure-shear model of continental lithosphere extension: applications to the Jeanne d'Arc Basin, Grand Banks and Viking Graben, North Sea. *In*: ROBERTS, A. M., YIELDING, G. & FREEMAN, B. (eds) *The Geometry of Normal Faults*. Geological Society, London, Special Publications, **56**, 41–60.

LISTER, G. S. & DAVIS, G. A. 1989. The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado river region, USA *Journal of Structural Geology*, **11**, 65–94.

——, ETHERIDGE, M. A. & SYMONDS, P. A. 1986. Detachment faulting and the evolution of passive continental margins. *Geology*, **14**, 246–250.

MARSDEN, G., YIELDING, G., ROBERTS, A. M. & KUSZNIR, N. J. 1990. Application of a flexural cantilever simple-shear/pure shear model of continental lithosphere extension to the formation of the northern North Sea basin. *In*: BLUNDELL, D. J. & GIBBS, A. D. (eds) *Tectonic Evolution of the North Sea Rifts*. Clarendon Press, Oxford, 241–261.

MCCLAY, K. R. & ELLIS, P. G. 1987. Geometries of extensional fault systems developed in model experiments. *Geology*, **15**, 341–344.

——, NORTON, M. G., CONEY, P. & DAVIS, G. H. 1986. Collapse of the Caledonian orogen and the Old Red Sandstone. *Nature*, **323**, 147–149.

NELSON, P. H. H. & LAMY, J.-M. 1987. The Møre–West Shetlands area: a review. *In*: BROOKS, J. &. GLENNIE, K. (eds) *Petroleum Geology of North West Europe*. Graham and Trotman, London, 775–784.

NORTON, M. 1987. The Nordfjord–Sogn Detachment, W. Norway. *Norsk Geologisk Tidsskrift*, **67**, 93–106.

ODINSEN, T., CHRISTIANSSON, P., GABRIELSEN, R. H., FALEIDE, J. I. & BERGE, A. 2000*a*. The geometries and steep structures of the northern North Sea rift system. *Norsk Geologisk Tidsskrift*.

——, REEMST, P., VAN DER BEEK, P., FALEIDE, J. I. & GABRIELSEN, R. H. 2000*b*. Permo-Triassic and Jurassic extension in the northern North Sea: results from tectonostratigraphic forward modelling. *This volume*.

PARRISH, R. R., CARR, S. D. & PARKINSON, D. L. 1988. Eocene extensional tectonics and geochronology of the southern Omineca belt, British Columbia and Washington. *Tectonics*, **7**, 181–212.

PETTERSON, O., STORLI, A., LJOSLAND, E. & MASSIE, I. 1990. The Gullfaks Field: geology and reservoir development. *In*: *North Sea Oil and Gas Reservoirs – II*. Graham and Trotman, London, 67–90.

PLATT, N. H. 1995. Structure and tectonics of the northern North Sea: new insights from deep penetration regional seismic data. *In*: LAMBIASE, J. J. (ed.) *Hydrocarbon Habitat in Rift Basins*. Geological Society, London, Special Publications, **80**, 103–113.

POWELL, D. & GLENDINNING, N. R. W. 1990. Late Caledonian extensional reactivation of a ductile thrust in NW Scotland. *Journal of the Geological Society, London*, **147**, 979–987.

ROBERTS, A. M., YIELDING, G. & BADLEY, M. E. 1990. A kinematic model for the orthogonal opening of the late Jurassic North Sea rift system, Denmark–Mid Norway. *In*: BLUNDELL, D. J. & GIBBS, A. D. (eds) *Tectonic Evolution of the North Sea Rifts*. Clarendon, Oxford, 180–199.

——, ——, KUSZNIR, N. J., WALKER, I. & DORN-LOPEZ, D. 1993. Mesozoic extension in the North Sea: constraints from flexural backstripping, forward modelling and fault populations. *In*: PARKER, J. R. (ed.) *Petroleum Geology of Northwest Europe. Proceedings of the 4th Conference*. Geological Society, London, 1123–1136.

——, ——, ——, —— & ——1995. Quantitative analysis of Triassic extension in the northern Viking Graben. *Journal of the Geological Society, London*, **152**, 15–26.

ROBSON, D. A. 1971. The structure of the Gulf of Suez (Clysmic) rift with special reference to the eastern side. *Journal of the Geological Society, London*, **127**, 247–276.

ROSENDAHL, B. R. 1987. Architecture of continental rifts with special reference to East Africa. *Annual Review of Earth and Planetary Sciences*, **15**, 445–503.

ROUBY, D., FOSSEN, H. & COBBOLD, P. R. 1996. Extension, displacements and block rotations in the larger Gullfaks area, northern North Sea, as determined from plan view restoration. *AAPG Bulletin*, **80**, 875–890.

SCOTT, D. L. & ROSENDAHL, B. R. 1989. North Viking Graben: an East African perspective. *AAPG Bulletin*, **73**, 155–165.

SÉRANNE, M. & SÉGURET, M. 1987. The Devonian basins of western Norway: tectonics and kinematics of an extending crust. *In*: COWARD, M. P., DEWEY, J. F. & HANCOCK, P. L. (eds) *Continental Extensional Tectonics*. Geological Society, London, Special Publications, **28**, 537–548.

SPEKSNIJDER, A. 1987. The structural configuration of Cormorant Block IV in context of the northern Viking Graben structural framework. *Geologie en Mijnbouw*, **65**, 357–379.

STEEL, R. & RYSETH, A. 1990. The Triassic–Early Jurassic succession in the northern North Sea: megasequence stratigraphy and intra-Triassic tectonics. *In*: HARDMAN, R. F. P. & BROOKS, J. (eds) *Tectonic Events Responsible for Britain's Oil and Gas Reserves*. Geological Society, London, Special Publications, **55**, 139–168.

SWALLOW, J. L. 1986. The seismic expression of a low angle detachment (sole fault) from the Beryl Embayment, central Viking Graben. *Scottish Journal of Geology*, **22**, 315–324.

THOMAS, D. W. & COWARD, M. P. 1996. Mesozoic regional tectonics and South Viking Graben formation: evidence for localized thin-skinned detachments during rift development and inversion. *Marine and Petroleum Geology*, **13**, 149–177.

VENDEVILLE, B., COBBOLD, P. R., DAVY, P., BRUN, J. P. & CHOUKROUNE, P. 1987. Physical models of extensional tectonics at various scales. *In*: COWARD, M. P., DEWEY, J. F. & HANCOCK, P. L. (eds) *Continental Extensional Tectonics*. Geological Society, London, Special Publications, **28**, 95–107.

WERNICKE, B. 1985. Uniform-sense normal simple-shear of the continental lithosphere. *Canadian Journal of Earth Science*, **22**, 108–125.

—— & BURCHFIEL, B. C. 1982. Modes of extensional tectonics. *Journal of Structural Geology*, **4**, 105–115.

——, CHRISTIANSEN, R. L., ENGLAND, P. C. & SONDER, L. J. 1987. Tectonomagmatic evolution of Cenozoic extension in the North American Cordillera. *In*: COWARD, M. P., DEWEY, J. F. & HANCOCK, P. L. (eds) *Continental Extensional Tectonics*. Geological Society, London, Special Publications, **28**, 203–221.

WHITE, S. H. & GLASSER, J. 1987. The outer Hebrides Fault Zone: evidence for normal movements. *In*: PARK, R. G. & TARNEY, J. (eds) *Evolution of the Lewisian and Comparable Precambrian High Grade Terrains*. Geological Society, London, Special Publications, **27**, 175–183.

ZIEGLER, P. A. 1990. Tectonic and palaeogeographic development of the North Sea rift system. *In*: BLUNDELL, D. J. & GIBBS, A. D. (eds) *Tectonic Evolution of the North Sea Rifts*. Clarendon, Oxford, 1–36.

YIELDING, G., BADLEY, M. E. & FREEMAN, B. 1991. Seismic reflections from normal faults in the North Sea. *In*: ROBERTS, A. M., YIELDING, G. & FREEMAN, B. (eds) *The Geometry of Normal Faults*. Geological Society, London, Special Publications, **56**, 79–89.