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# Oblique rifting and sequential faulting in the Jurassic development of the northern North Sea

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**Abstract**—Jurassic structural development of the northern North Sea has characteristics of oblique rifting. This is interpreted to result from an obliquity between Jurassic NW–SE- to WNW–ESE-directed extension and a pre-existing N–S-trending zone of deformation related to Permo-Triassic rifting and thinning of the crust. The zone of maximum Jurassic extension, i.e. the Viking and Sogn grabens, defines a narrow (25–40 km) depression which trends diagonally (NNE–SSW) across a broader (130–150 km) Permo-Triassic basin. The Jurassic rift zone consists of a system of en échelon rift segments, with changing symmetry along strike, bounded by faults oblique to the overall graben envelope.

Sequential Jurassic fault development as well as the interference between N–S- and NE–SW-striking faults are explained within the context of oblique rifting. The early (Late Bajocian–Oxfordian) rift stage was dominated by reactivation of N–S-striking major faults, whereas a number of coeval but smaller faults have a NE–SW orientation. NE–SW-striking faults show increasing importance during the Jurassic stretching phase, and major faults defining this orientation accommodated most of the Kimmeridgian–Volgian extension. Faults striking NE–SW are observed to cross-cut earlier N–S-trending faults; they interfere with N–S-trending faults to define fault-blocks with rhombohedral shape; and they are associated with partial collapse of crestal areas of N–S-oriented fault-blocks to form structural terraces. © 1997 Elsevier Science Ltd.

## INTRODUCTION

The North Sea rift (Fig. 1) is related to a prolonged extensional history that started with Devonian extension of the thickened Caledonian crust. Subsequent intra-continental, Permo-Triassic and Jurassic phases of lithospheric extension followed by thermal cooling and subsidence produced the North Sea sedimentary basin. Sediment fill represented by Permian–Quaternary deposits exceeds 10 km in thickness in areas of maximum extension, where the basement substrate is thinned to some 10–12 km (Fichler and Hospers, 1990; Færseth *et al.*, 1995a; Odinsen *et al.*, in press).

At Mesozoic levels extension is manifest by normal faulting, and the northern North Sea as seen today is a *ca* 170–200 km wide basin, characterized by normal faults with predominant N–S, NE–SW and NW–SE orientation. The intra-basinal faults with several kilometres of throw define tilted fault-blocks some 15–50 km in width (Fig. 2), which result from Permo-Triassic and Jurassic extensional phases and form the fundamental morphological element of the rifted area (e.g. Færseth, 1996).

The prominent Viking Graben, representing part of a Jurassic triple rift system (Fig. 1), is generally referred to as a N–S-trending structural feature (e.g. Doré *et al.*, 1997). However, the zone representing maximum Jurassic extension ($\beta = 1.4$–$1.5$) within the northern North Sea, i.e. the Viking and Sogn grabens, trends diagonally NNE–SSW across a N–S-oriented and broader Permo-Triassic basin (Fig. 3). Like most rifts, the Viking Graben did not develop as a single, straight palaeotopographic feature, but as a system of discrete rift segments. They exhibit along-strike lengths of 50–70 km, and are

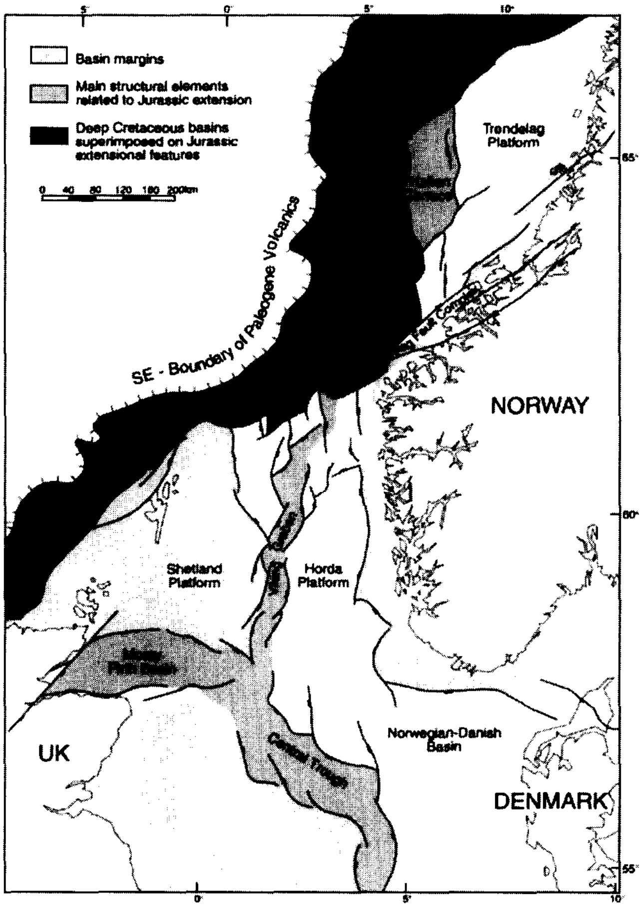

Fig. 1. Regional location map showing the main tectonic elements of the North Sea and southeasternmost Norwegian Sea (north of *ca* 62°N). The study area (58–62°N), flanked by the west Norwegian mainland and the Shetland Platform, is commonly referred to as the northern North Sea.

Fig. 2. Major structural elements associated with Jurassic extension in the northern North Sea. The location of fault-blocks referred to is as indicated. G, Gullfaks Fault-block; H, Huldra Fault-block; M, Magnus Fault-block; O, Oseberg Fault-block; S, Statfjord Fault-block; V, Visund Fault-block.

bounded by faults which are oblique to the overall graben envelope. There is a change from symmetrical to asymmetrical graben development along strike (Gabrielsen *et al.*, 1990; Marsden *et al.*, 1990; Færseth, 1996) with segments separated by accommodation zones. The different rift segments achieved their structural configuration, as seen today, at different stages of Jurassic development (Færseth, 1996).

A variety of Jurassic structural elements in the North Sea have been grouped together and referred to as 'Late Jurassic' structures, and kinematic models for the Jurassic North Sea rift system are generally based on the assumption that Jurassic faults can be ascribed to a uniform 'Late Jurassic' rift development. However, increasing evidence shows that Jurassic rifting affected the North Sea from late Middle Jurassic and in some areas it continued into the earliest Cretaceous, and there was diachronism both in the initiation and cessation of rifting in different areas of the basin (e.g. Graue *et al.*, 1987; Badley *et al.*, 1988; Helland-Hansen *et al.*, 1992; Johannesen *et al.*, 1995; Ravnås *et al.*, 1997). There is also evidence of deposition of the rift succession under conditions of increased extension, and accelerated fault-block rotation rate with the characteristics of a pulsed syn-rift sedimentation (Partington *et al.*, 1993; Rattey and Hayward, 1993; Færseth *et al.*, 1995b; Færseth and Ravnås, in press).

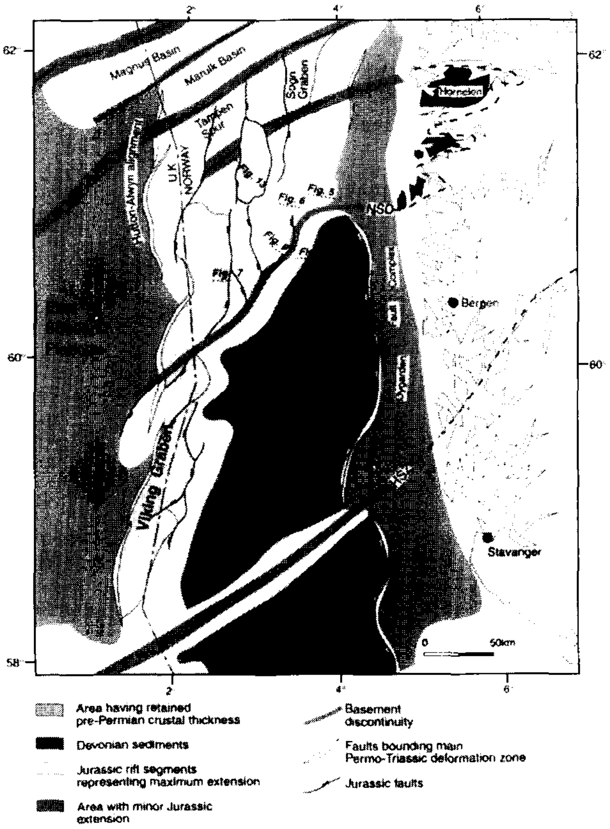

Fig. 3. Tectonic framework of the northern North Sea. Jurassic stretching affected primarily the northwestern half of the area under consideration, i.e. the area northwest of the Nordfjord–Sogn detachment (NSD). Jurassic rift segments representing maximum extension are aligned NNE–SSW across a broad N–S-oriented and fault-bounded basement depression resulting from Permo-Triassic extension. The location of basement discontinuities is based on interpretation of deep reflection profiles as well as commercial reflection seismic data in combination with gravity and magnetic data. HSZ, Hardangerfjord shear zone.

A significant strike-slip component within the rift system kinematics has been invoked (e.g. Gowers and Sæbøe, 1985; Beach *et al.*, 1987; Cartwright, 1987; Larsen, 1987), and elevated structures in the northern North Sea have been interpreted as results of transpression (e.g. Beach, 1985; Speksnijder, 1987; Fossen, 1989). There is an increasing tendency to explain Jurassic structures in the northern North Sea by extensional, dip-slip origin, although various kinematic models have been proposed:

(1) a reorientation of regional extension direction during evolution of the Jurassic rift, from E–W to NW–SE (e.g. Doré and Gage, 1987);

(2) a consistent E–W extension throughout the Jurassic rift phase (e.g. Speksnijder, 1987; Badley *et al.*, 1988; Roberts *et al.*, 1990; Stewart *et al.*, 1992; Bartholomew *et al.*, 1993; Brun and Tron, 1993);

(3) a consistent NW–SE extension throughout the Jurassic rift phase (e.g. Ziegler, 1990; Færseth, 1996).

In this paper we present new data derived from industry seismic and well data indicating that Jurassic faults in the northern North Sea can be separated into generations that are related to stages of Jurassic rift development. The examples provided as figures are representative of interpretation of three-dimensional surveys and detailed mapping of a number of areas within the northern North Sea. We then argue that, in contrast with some previous hypotheses, the extension direction remained NW–SE-directed throughout the Jurassic rift phase. Our interpretation of Jurassic structural development is based on the assumption that regional extension direction in combination with pre-existing N–S and NE–SW structural grain were the main controlling factors.

## SEQUENTIAL FAULTING RELATED TO JURASSIC EXTENSION

Jurassic fault development, representing a period of some 30 Ma, exhibits characteristics of strike, vergence and timing of fault initiation and growth common to several study areas and indicative of systematic variations through time. We show below that:

(1) N–S-striking faults, representing an early stage of Jurassic rift development and characterized by a preferred dip-direction, are post-dated by parallel Jurassic faults with opposite dip;

(2) NE–SW-striking faults are increasingly important during Jurassic extension, and large NE–SW-striking faults post-date major N–S-oriented Jurassic faults.

### *N–S-striking and cross-cutting faults with opposite dips*

The dip direction of Jurassic faults with predominant N–S orientation differs, both spatially and temporally. Accordingly, it is possible to identify fault sets representing a specific Jurassic period, i.e. stage of rift development, which have a preferred direction of dip within a specific area.

The more obvious examples of sequential development of N–S-striking Jurassic faults in the northern North Sea are those showing opposite dip and cross-cutting relationship (Figs 4 & 5). Oppositely dipping faults with the same strike may represent a conjugate system or syn- and antithetic faults, i.e. they developed approximately contemporaneously. In the northern North Sea, where faults interfere at depth, one fault set was active over a long period to generate significant (100 m scale) throw. Subsequently, parallel and oppositely dipping faults became activated to displace the earlier faults, i.e. they represent different stages of Jurassic fault development. Fault segments representing the oldest fault set may be difficult to identify in footwalls of the younger faults, especially at depths where seismic resolution deteriorates. However, the diachronous development of oppositely dipping faults precludes the interpretation of such fault pairs as conjugate systems or syn- and antithetic faults.

### *Oppositely thickening of syn-rift Heather and Draupne formations across N–S-striking faults*

The Heather and Draupne formations represent Jurassic syn-rift succession in the northern North Sea. In some areas faults which bound half-grabens with a Heather Formation (Bathonian–Early Oxfordian) syn-rift fill were succeeded by oppositely dipping normal faults of a younger generation. This relationship has been established both with respect to faults representing boundaries of major graben segments and by smaller graben structures within large fault-blocks. Whereas the earliest set of faults generally terminate upwards within the Upper Jurassic sequence, the younger faults with opposite dip influence at base Cretaceous level, and are primarily associated with deposition of the Late Oxfordian–Ryazanian Draupne Formation. As a corollary, the Heather and Draupne formations may define syn-rift wedges, controlled by N–S-oriented boundary faults, which exhibit thickening in opposite directions. Such development may give the overall impression of a Jurassic symmetrical or full-graben, but is in fact the result of diachronous development of the graben-bounding faults (Fig. 6).

South of *ca* 61°N, the early rift stage represented primarily by the Heather Formation, resulted in fault-blocks tilted to the west and bounded by E-dipping faults (Figs 4 & 7). Further to the north, as in the Sogn Graben area (Fig. 8), the early rift activity and Heather Formation sedimentation appear to be associated with fault-blocks tilted to the east, and a subsequent reversal of tilt during deposition of the Draupne Formation. The switch in fault polarity during the Jurassic rift phase is possible to identify in most areas, although the recognition of faults of the first generation might be hampered due to the strong overprint exerted by major faults of the youngest generation, especially along the east flank of the Viking Graben (Fig. 7).

The N–S-striking central segment of the Viking Graben (60°20′–61°N) is a large-scale example of sequential development of graben-boundary faults. At present this graben segment, approximately 40 km in width (Figs 2 & 3), is symmetrical in profile at uppermost Jurassic–base Cretaceous levels. However, reflection seismic and well data indicate that the graben retained the asymmetry inherited from Permo-Triassic block tilting (Færseth, 1996) until the Late Jurassic. The syn-rift Heather Formation exhibits wedge-shaped geometries, thickening to the west against reactivated E-dipping major faults (Fig. 7). The large displacement faults, which at present delineate the central segment of the Viking Graben to the east, started to grow in the Early Bathonian (Færseth and Ravnås, in press). Whereas E-facing faults became inactive during late

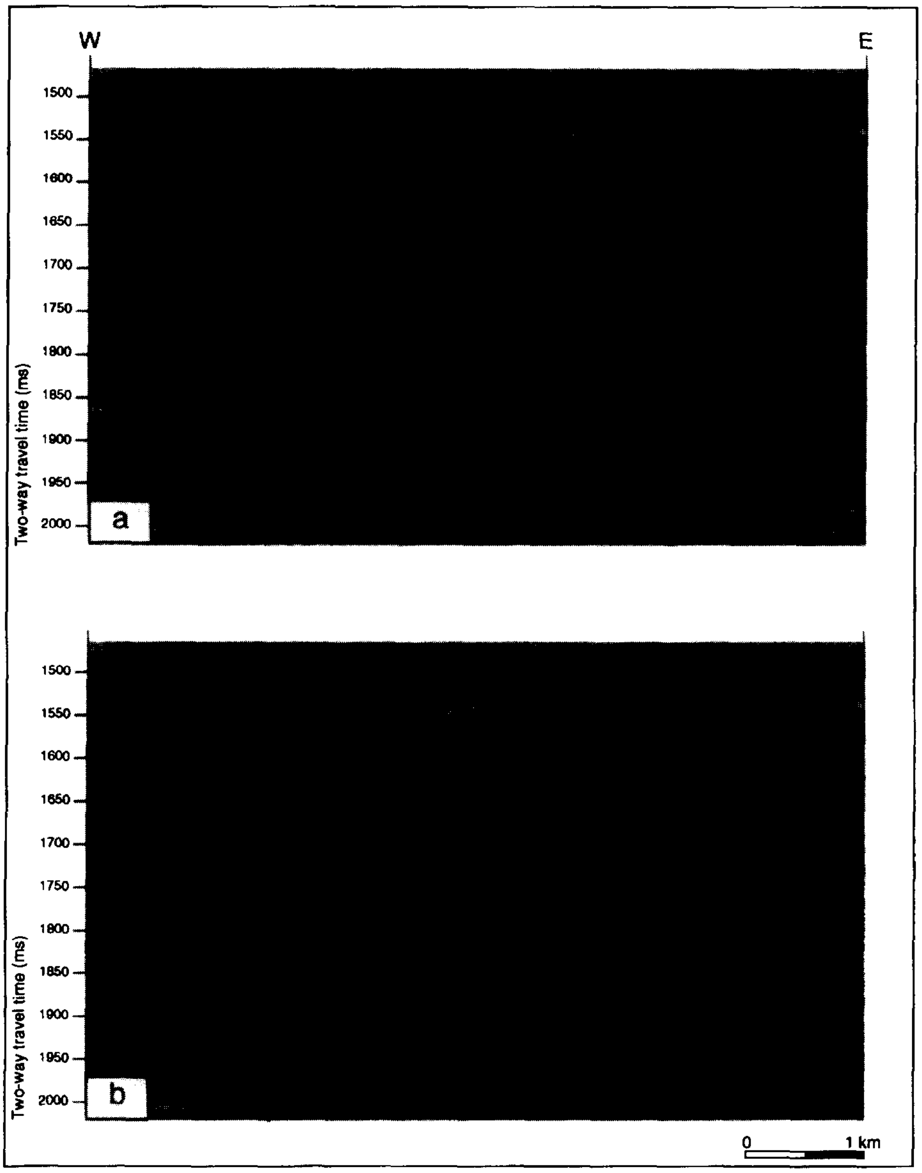

Fig. 4. Seismic section showing N–S-striking and oppositely dipping faults related to stages of Jurassic extension (see Fig. 3 for location). Top Brent Group reflector represents the base of the Jurassic syn-rift sequence. An E-dipping fault that was active in the Bathonian–Oxfordian is offset *ca* 100 m by a younger W-dipping fault.

Heather Formation (Oxfordian) time, the W-dipping faults remained active throughout the Jurassic (Fig. 7). A relatively thin, clay-rich Draupne Formation in the Viking Graben shows slight wedging and thickness increase to the east, i.e. opposite to the Heather Formation (Fig. 7), and was deposited in a then (Kimmeridgian–Volgian) full-graben segment characterized by significant relief.

## INTERFERENCE BETWEEN N–S- AND NE–SW-STRIKING FAULTS

The observations demonstrating interaction between N–S- and NE–SW-striking faults, related to Jurassic stretching, fall into three main groups:

(1) major NE–SW-striking faults cross-cut earlier N–S-striking faults to define fault-blocks with a present rhombohedral outline;

(2) NE–SW-striking faults developed within large fault-blocks bounded by N–S-striking faults;

(3) NE–SW-striking faults are associated with partial collapse of crestal areas of large N–S-oriented Jurassic fault-blocks to form structural terraces.

### *NE–SW-striking faults cross-cutting N–S faults*

The number of NE–SW-striking faults of Jurassic origin increases northward and they bound major structural elements, e.g. Marulk, Magnus and Møre basins and the complementary footwall uplifts (Fig. 2). The Møre–Trøndelag Fault Complex, which controls the

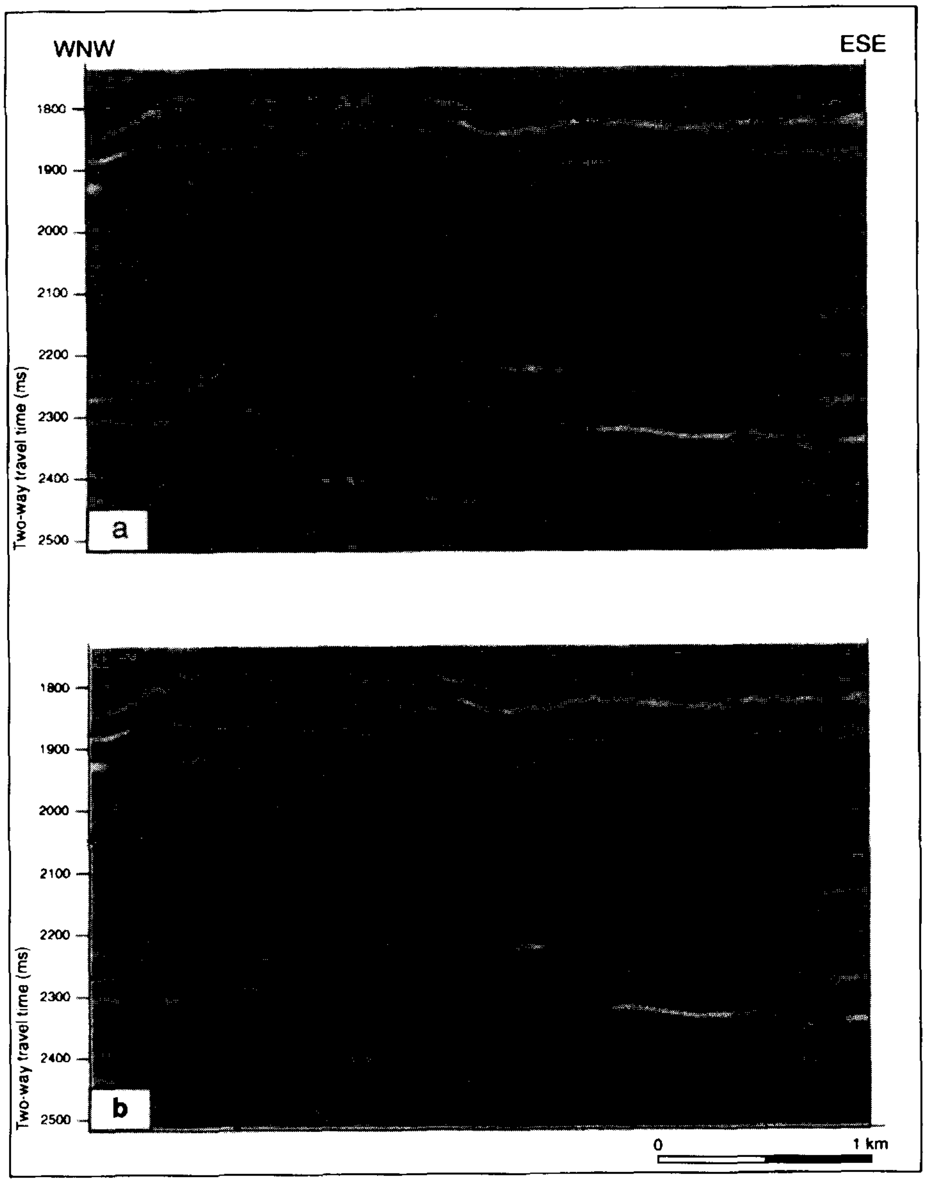

Fig. 5. Seismic section showing N–S-striking and oppositely dipping faults related to stages of Jurassic extension (see Fig. 3 for location). Top Brent Group reflector represents the base of the Jurassic syn-rift sequence. An E-dipping fault is offset *ca* 180 m by a younger W-dipping fault.

northwestern Norwegian coastline (Fig. 1) and encompasses a number of NE–SW-oriented structural features in the offshore area (Blystad *et al.*, 1995), forms a long-lived (Devonian–Tertiary) and fundamental crustal structure that extends from the mid Norwegian mainland, possibly to link with the West Shetland Basin to the southwest (e.g. Doré *et al.*, 1997).

Several large NE–SW-striking faults in the northern North Sea cut across N–S-trending Jurassic structural elements. The N–S-oriented ridge representing the footwall of the Magnus Fault-block (Fig. 2) became transected by NE–SW-striking faults which bound the Magnus Basin. Further east, N–S-trending structural elements of the Tampen Spur and the Sogn Graben are transected by NE–SW-striking faults of the Møre–Trøndelag Fault Complex (Fig. 2). Although overprinted by the prominent NE–SW structural trend, the N–S grain of the northern North Sea continues to the north (e.g. Cohen and Dunn, 1987; Blystad *et al.*, 1995; Doré *et al.*, 1997). As illustrated in Fig. 1, the Møre Basin and the Halten Terrace represent regional structural elements outlined by N–S- and NE–SW-striking faults.

Further south, and on a smaller scale, a number of faults striking N–S and related to Late Bajocian–Oxfordian stretching are cut by NE–SW-striking faults (Figs 9 & 10). Sequential Jurassic faulting is also demonstrated by oppositely thickening of Heather and Draupne rift wedges, controlled by N–S- and NE–SW-striking faults, respectively (Fig. 11).

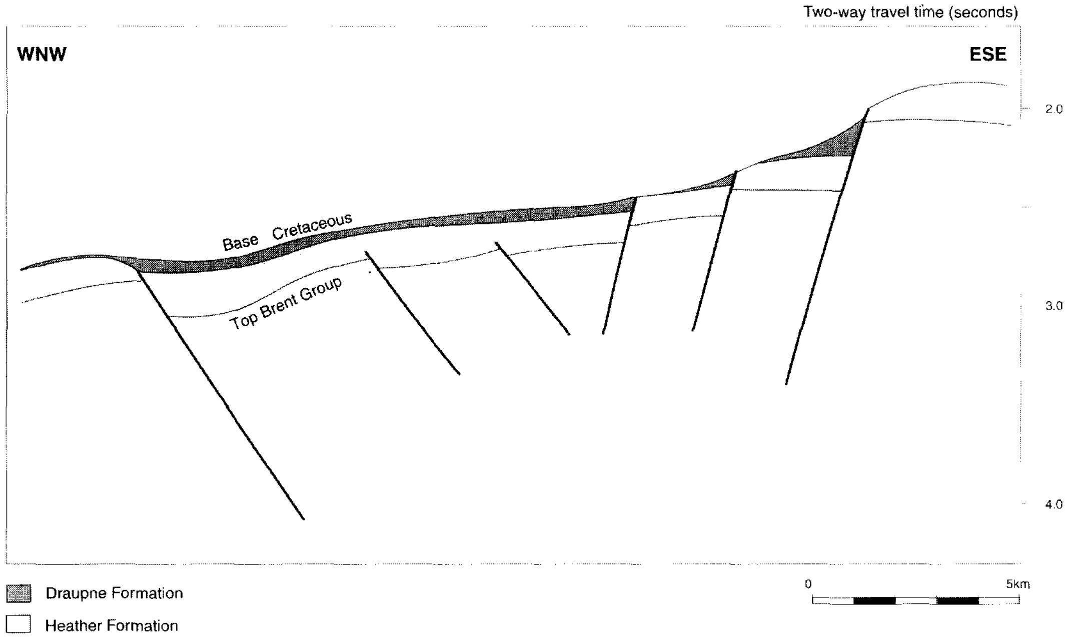

Fig. 6. Cross-section illustrating sequential Jurassic faulting (see Fig. 3 for location). E-dipping faults were associated with deposition of the Heather Formation (Bathonian–Oxfordian) syn-rift wedges. The younger W-dipping faults showed main activity during deposition of the Draupne Formation and they influence at base Cretaceous level. The switching of fault activity has created a symmetrical graben.

### *Fragmentation of major N–S-oriented fault blocks by NE–SW-striking faults*

The Oseberg and Huldra fault-blocks formed a single Jurassic structural element along the east flank of the central segment of the Viking Graben (Fig. 2). The N–S-striking fault, bounding the fault-blocks to the east, started to grow in the Bajocian (Ravnås and Bondevik, 1997). At a later (Kimmeridgian–Volgian) stage in the rift development, after *ca* 700 m of throw, activity along the N–S fault became negligible (Færseth and Ravnås, in press). However, during this stage of stretching, growth (*ca* 500 m) and footwall uplift were associated with the NE–SW-oriented fault located further to the south. This was also the time of separation of the Oseberg and Huldra fault-blocks by faults striking NE–SW (Fig. 2). A similar relationship between N–S- and NE–SW-oriented faults has been reported from the Magnus Fault-block (Fig. 2) (Young, 1992).

### *Obliquity between the Jurassic extensional direction and large N–S-trending Permo-Triassic faults*

Fault-bounded structural units, with predominant N–S orientation, may contain a set of internal faults characterized by an orientation (NE–SW) oblique to the borders (Fig. 12). The boundary faults of such areas, at Jurassic levels, lie on the trend of (but do not necessarily connect to) underlying basement-involved faults related to Permo-Triassic extension. The oblique block-internal faults which result from Jurassic nucleation and growth do not extend into basement. In the example shown in Fig. 12, the boundary faults and the block-internal faults are coeval and initiated during Early Bathonian stretching. The fault pattern may suggest an extension direction with a deviation from perpendicular to the N–S-oriented boundaries, i.e. that the block-internal faults are oriented orthogonal to a NW–SE extension direction. A similar fault pattern has been demonstrated in experiments performed with an obliquity between extensional direction and pre-existing grain (Tron and Brun, 1991; McClay, 1995).

### *Footwall collapse along NE–SW-striking faults*

Depth-migration of seismic reflection profiles shows that most large faults in the northern North Sea have planar geometries, at least at Mesozoic levels (e.g. Nelson and Lamy, 1987; Yielding *et al.*, 1991). However, in some areas faults flatten downward to obtain low dips at depth, and examples of both supra-basement and intra-basement detachments have been demonstrated (Fossen *et al.*, in press). Faults which exhibit ramp–flat geometries are mainly related to crustal stretching and partial footwall collapse of larger N–S-oriented fault-blocks during a Kimmeridgian–Volgian/Ryazanian period of rifting. Footwall collapse typically took place along faults with a NE–SW orientation, and these faults tend to join large N–S-oriented faults of an earlier Jurassic origin at depth.

Færseth *et al.* (1995b) documented that the Visund Fault-block (Fig. 2), initially some 25 km wide, was bounded by N–S-oriented faults during Bathonian–Early Kimmeridgian rifting. This period of rifting was followed by accelerated fault-block tilting, and there was a partial footwall collapse and decoupling of the present southeast terrace from the present crestal area along a

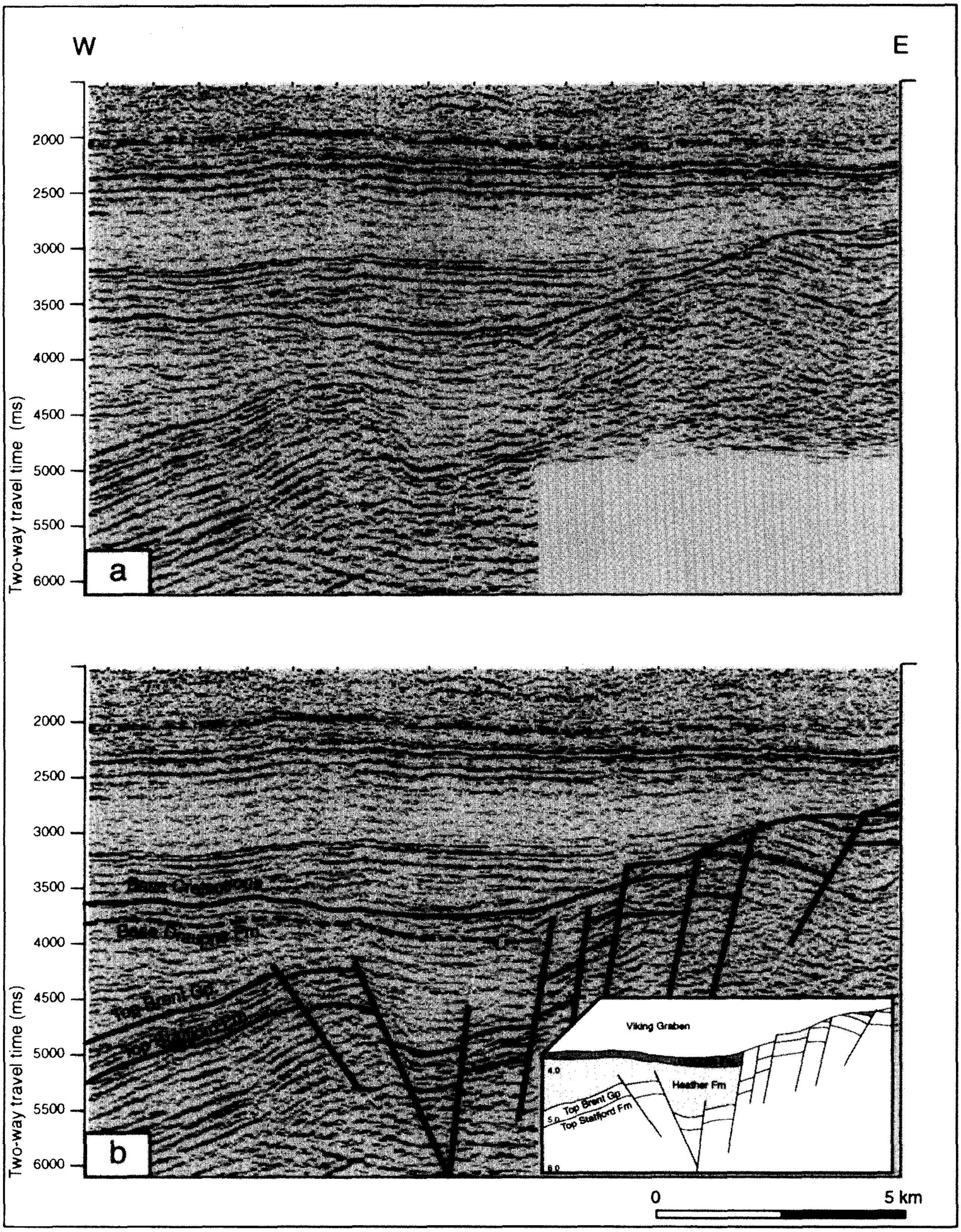

Fig. 7. Seismic section across the eastern margin of the central segment of the Viking Graben (see Fig. 3 for location). Top Brent Group reflector represents the base of the Jurassic syn-rift sequence. In the Viking Graben area the Heather Formation exhibits wedge-shaped geometries thickening to the west, controlled by E-dipping faults which terminate upward within this formation. The W-dipping faults are part of a fault zone representing the eastern boundary of the Viking Graben. These faults remained active throughout the latest Jurassic and there is a slight westerly thickening of the Draupne Formation.

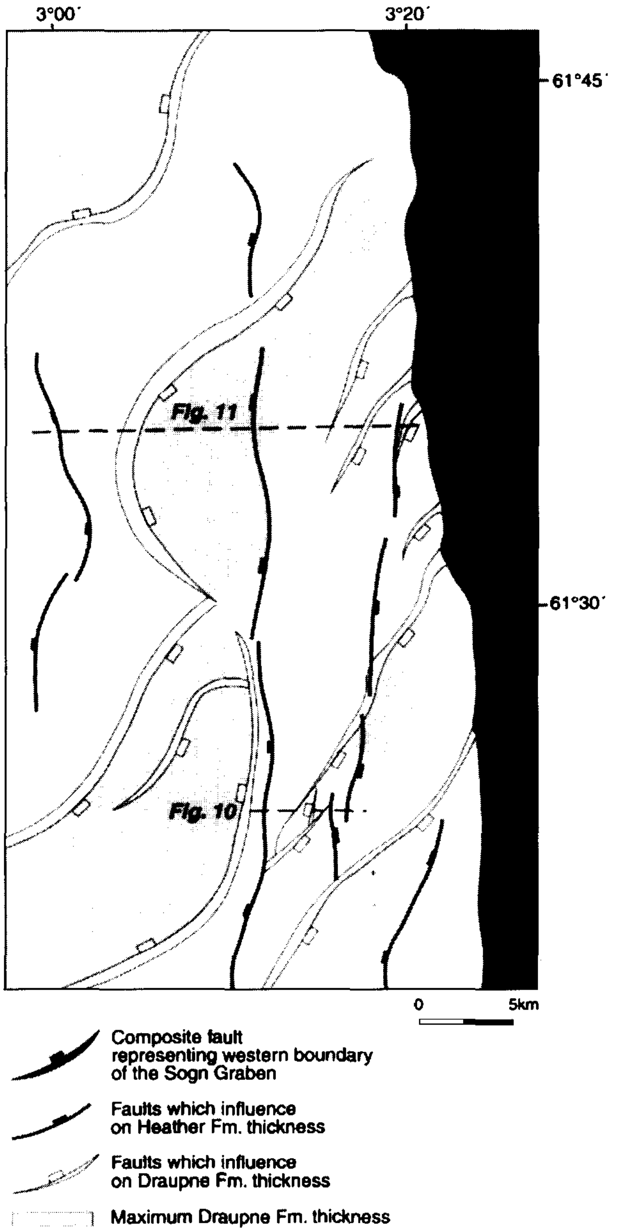

Fig. 8. Main structural features at Jurassic level west of the Sogn Graben (see Fig. 2 for location). In this area NE–SW-striking faults, which controlled depositional thickness of the Draupne Formation (Oxfordian–Volgian), post-dated Jurassic faults with a predominant N–S orientation. NE–SW-striking fault segments, oblique to faults representing the western boundary of the Sogn Graben, converge at depth and join N–S-striking major faults, as illustrated in Fig. 11.

major NE–SW-striking fault characterized by a more shallow dip below the collapsed footwall (Fig. 13).

The ridge bounding the Sogn Graben to the west is characterized by fault segments which are oblique (NE–SW) to the overall N–S-trending graben boundary fault (Fig. 8). The NE–SW-striking faults appear to converge at depth to join major N–S-striking faults (Fig. 11). These NE–SW-striking faults are generally associated with displacement at base Cretaceous level, indicating extended stretching and fault activity.

## EXTENSION DIRECTION, BASEMENT GRAIN AND FAULT ORIENTATION

Normal faults are generally considered to define a strike direction perpendicular to the least principal stress ($\sigma_3$). However, in areas characterized by pre-existing structural grain, it is not obvious that the principal stress orientation can be deduced from present geometric data. Pre-existing zones of weakness oriented at high angles to the largest horizontal principal stress can be reactivated as normal faults rather than new faults being generated at an optimal orientation (e.g. Morley, 1995; Higgins and Harris, 1997).

In the offshore area directions of slip on large faults are sparse and the extension direction in the northern North Sea is therefore difficult to unravel. In wells where major faults (100 m-scale displacement) have been drilled or even cored, interpretation of wireline logs or kinematic indicators, i.e. slickenside striations, indicate that faults are close to dip-slip. Rouby *et al.* (1996) reached a similar conclusion for large faults in the Gullfaks area (Fig. 2). Cores from Mesozoic intervals generally contain small (cm-scale displacement) faults (Gabrielsen and Koestler, 1987), and striations show predominantly dip-slip movements. Hence, our discussion and model on the kinematics are based on the assumption that main faults in the northern North Sea are dominantly dip-slip. Variations in slip direction are attributed to faults and fault segments which accommodated changes in geometry on major normal faults.

### *Influence of pre-existing grain on fault orientation*

In the northern North Sea multiple stretching affected a substrate which varies significantly across the basin with regard to both composition and grain (Færseth, 1996). The most prominent structural trends at basement level appear to be N–S and NE–SW, of which the N–S grain exerted a fundamental control during Permo-Triassic basin development (Færseth *et al.*, 1995a; Færseth, 1996). The Øygarden Fault Complex (Fig. 2), the most extensive (> 300 km) N–S-trending structural element offshore of western Norway, marks a sharp transition in pre-Mesozoic crustal thickness from the mainland to the adjacent sedimentary basin primarily as a result of Permo-Triassic stretching.

In southwest Norway, the NW-dipping Hardangerfjord shear zone and the W-dipping Nordfjord–Sogn detachment are examples of structures accommodating substantial, top-to-the-WNW ductile to semi-ductile Devonian extensional transport (Hossack, 1984; Norton, 1986; Fossen, 1992). Interpretation of deep reflection profiles as well as commercial reflection seismic data reveals that these Devonian shear zones can also be recognized in offshore areas (Hurich and Kristoffersen, 1988; Klemperer and Hurich, 1990; Færseth *et al.*, 1995a), and at upper crustal level they apparently trend NE–SW across the North Sea basin (Fig. 3) (Færseth, 1996; Doré *et al.*, 1997). These shear zones separate

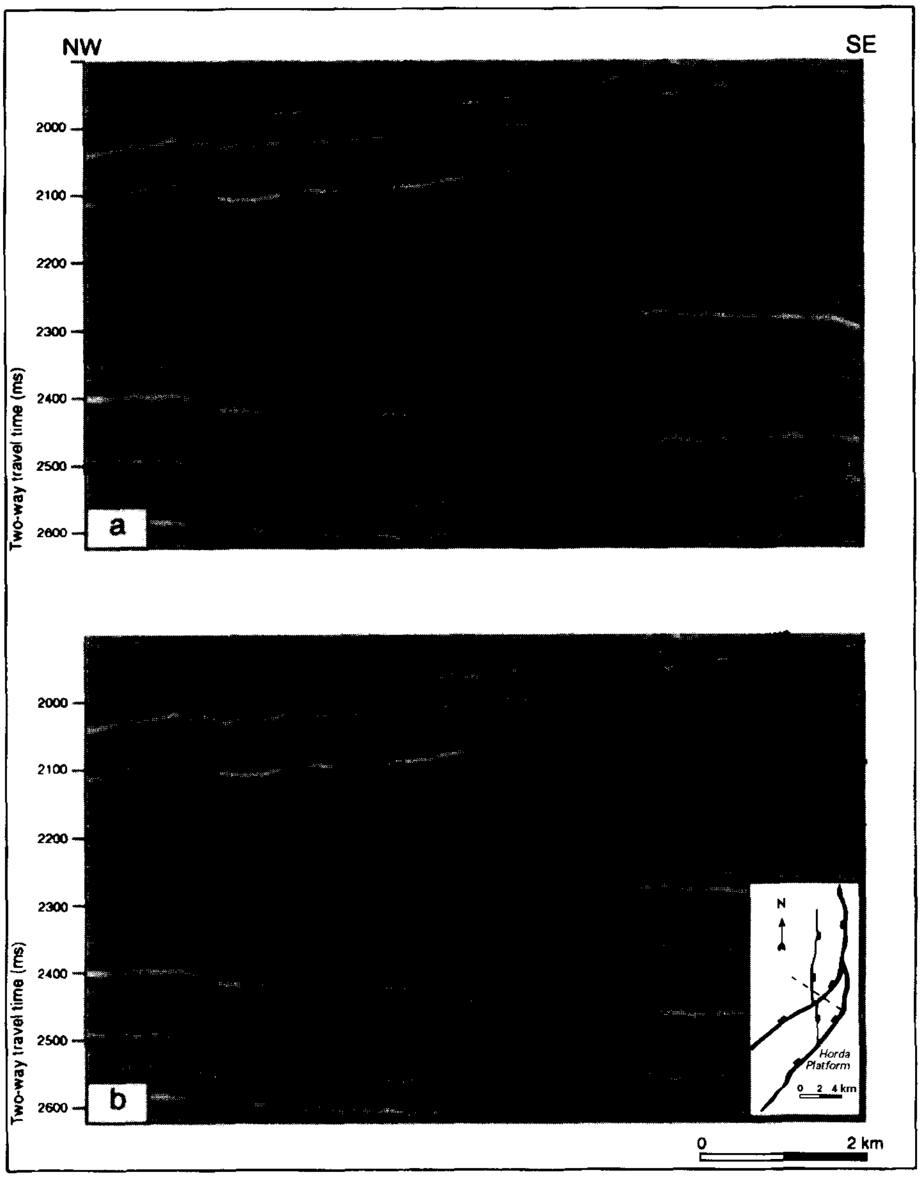

Fig. 9. Seismic section illustrating the intersection of N–S- and NE–SW-striking Jurassic faults along the northwestern margin of the Horda Platform (see Fig. 3 for location). Top Brent Group reflector represents the base of the Jurassic syn-rift sequence. The E-dipping fault was initiated in the latest Bajocian–earliest Bathonian, whereas the cross-cutting and NW-dipping fault that was initiated in Late Bathonian saw main activity from Late Oxfordian and remained active into the earliest Cretaceous.

contrasting basement units in onshore as well as offshore areas. In the offshore area, the Nordfjord–Sogn detachment also separates domains which at Mesozoic levels are characterized by contrasting structural configuration, following both Permo-Triassic and Jurassic extensional phases (Færseth *et al.*, 1995a).

Other NE–SW-striking zones interpreted as basement discontinuities, which influenced Late Permian–Late Jurassic basin configuration and fault orientation, are shown in Fig. 3. Faults and fault segments at Jurassic levels with a NE–SW orientation lie on the trend of basement discontinuities across the northern North Sea. The NE–SW-striking faults which delineate the Tampen Spur to the southeast (Fig. 2) form part of a lineament defined by Late Jurassic faults across a major part of the basin. Reflection seismic, gravity and magnetic data indicate that these faults lie on the trend of a basement anomaly. Near the eastern margin of the basin the anomaly is seen on seismic data as a zone of S-dipping basement reflections, and matches the offshore projection of the northern boundary of the Devonian Hornelen Basin of western Norway (Fig. 3).

### *Permo-Triassic extension direction*

Extension is generally assumed to have been E–W in the northern North Sea during the Permo-Triassic stretching phase (e.g. Doré and Gage, 1987; Roberts *et al.*, 1990; Ziegler, 1990; Færseth *et al.*, 1995a). Alkaline dykes of this generation intruded steep crustal-scale N- to

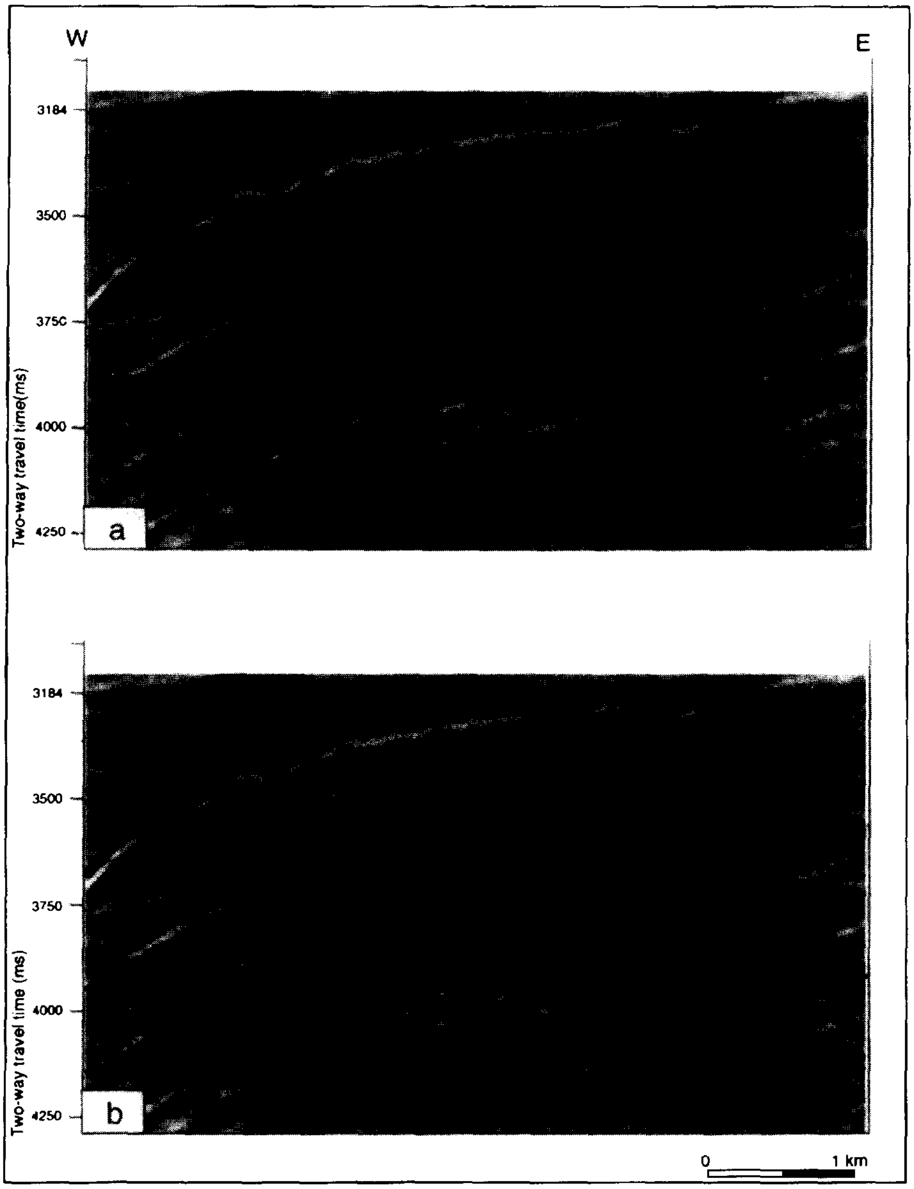

Fig. 10. Seismic section showing cross-cutting faults west of the Sogn Graben (see Fig. 8 for location). Top Brent Group reflector represents the base of the Jurassic syn-rift sequence. A W-dipping Jurassic fault with a throw of *ca* 100 m is offset *ca* 200 m by a younger (Late Jurassic) fault trending NE–SW which dips to the southeast.

NNW-trending (N160–180°E) pre-existing fractures onshore western Norway (Færseth *et al.*, 1976; Færseth, 1978; Løvlie and Mitchell, 1982). A detailed investigation of dykes indicates a very precise E–W extension vector (Fossen, in press). Consequently, the Permo-Triassic basin boundaries (Fig. 3), as well as intra-basinal major faults of this generation, are characterized by an orientation close to orthogonal to the regional extension direction.

### *Jurassic extension direction*

In contrast to the widely distributed Permo-Triassic extension and basin development, the Jurassic extension in the northern North Sea was generally more localized (Fig. 3). The Nordfjord–Sogn detachment represents a divide between a wide area (*ca* 200 km) to the northwest affected by Jurassic stretching and faulting, and a southeastern area where extension was concentrated to the narrow south Viking Graben (Figs 2 & 3). Large Jurassic faults have predominant N–S, NE–SW and NW–SE orientations, i.e. they exhibit a larger spread in orientation than those resulting from Permo-Triassic extension (Færseth, 1996).

As stated above, authors who have explained regional Jurassic structures in the northern North Sea by extensional dip-slip origin have invoked various kinematic models. These include the following.

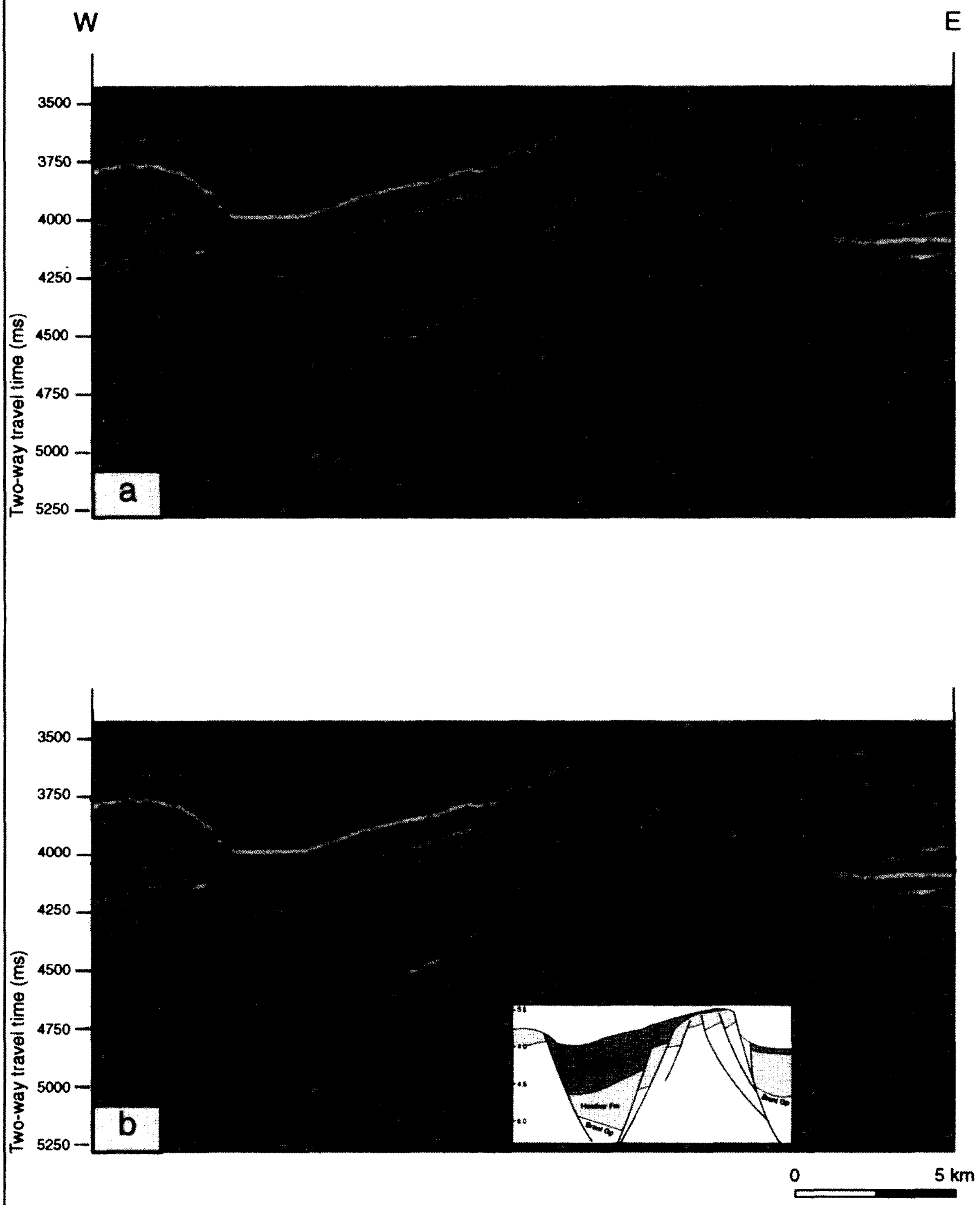

Fig. 11. Seismic section showing sequential Jurassic faulting and oppositely thickening syn-rift wedges west of the Sogn Graben (see Fig. 8 for location). Top Brent Group reflector represents the base of the Jurassic syn-rift sequence. W-dipping faults controlled the Heather Formation thicknesses, whereas a SE-dipping fault that represented the boundary of a large half-graben was active during deposition of the Draupne Formation.

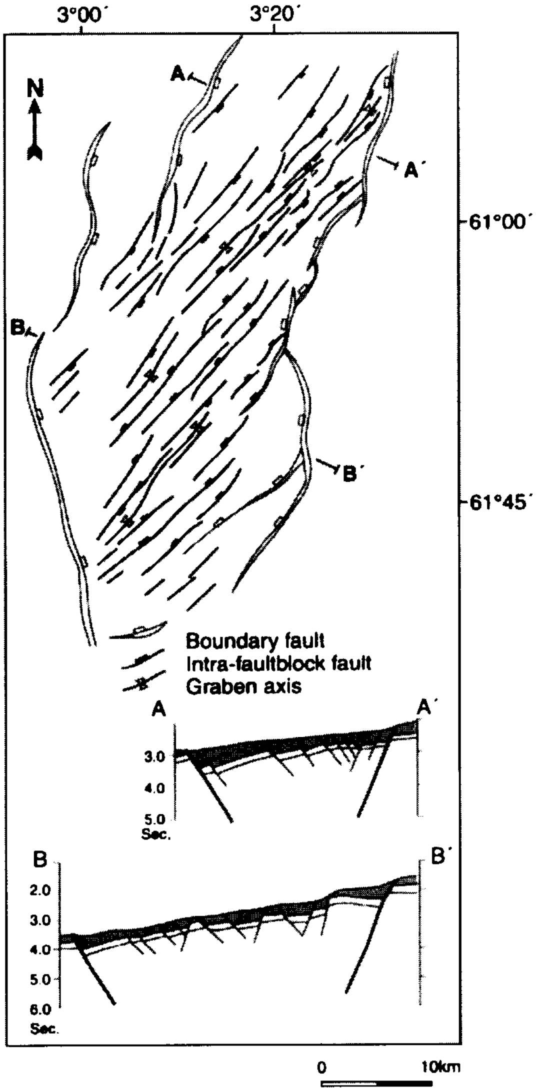

Fig. 12. Structural unit showing characteristics of oblique Jurassic extension (see Fig. 2 for location). The boundary faults are aligned along the trend of underlying major and basement-involved Permo-Triassic faults. Both N–S- and NE–SW-striking faults were initiated as a response to Bathonian extension. The NE–SW-striking faults are interpreted to have formed at approximately 90° to the direction of regional extension. Note the shift of the NE–SW-trending graben axes. The stippled interval in the cross-sections represents syn-rift (Bathonian–Volgian) Heather and Draupne formations.

*Reorientation of Jurassic extension direction.* A change in extension direction from an E–W to a NW–SE orientation at a late stage in the North Sea rift development is generally regarded as an effect of the opening of the Central Atlantic Ocean (e.g. Doré *et al.*, 1997). The increasing number of NE–SW-striking faults to the north is assumed to reflect a progressive strain concentration on the Atlantic rift system (e.g. Doré and Gage, 1987; Ziegler, 1990), and is regarded as being associated with a late stage of Jurassic rift development (Graue, 1992; Stewart *et al.*, 1992; Young, 1992; Rattey and Hayward, 1993).

N-trending structural elements can be recognized in the Halten Terrace area, as well as below the deep Cretaceous Møre Basin (Fig. 1), and Jurassic extension affected these areas at least as early as the Bathonian (e.g. Blystad *et al.*, 1995; Jongepier *et al.*, 1996). We interpret the increased influence of NE–SW-striking faults to the north not merely as a result of proximity to the Atlantic margin, but to reflect a higher intensity of NE–SW-oriented zones at basement level to the north (Figs 1 & 2).

In regions where a single extensional phase reactivated pre-existing zones of weakness, sets of faults in the sedimentary cover with different strike may be easily confused with structures resulting from two or more phases of crustal extension with different orientations of maximum extension direction (Higgins and Harris, 1997). In the northern North Sea, as well as further north, the N–S- and NE–SW-trending faults were coeval and developed throughout the Jurassic rift phase. Accordingly, as suggested by Roberts *et al.* (1990), we see the Møre Basin like the Halten Terrace area as a contiguous part of the northern North Sea Jurassic rift system, with a temporal and kinematic link between these areas.

*Consistent E–W extension throughout the Jurassic rift phase.* Roberts *et al.* (1990) suggested that the simplest kinematic assessment of the northern North Sea involved an orthogonal E–W extension on major extensional faults, which they claimed to strike N–S. However, faults striking NE–SW interfere with the N–S trend and, as demonstrated above, they appear to be equally important in the development of the Jurassic rift system. Brun and Tron (1993), with reference to laboratory modelling (Tron and Brun, 1991), interpreted the Viking Graben development in the context of oblique extension. They concluded that there was an obliquity (60°) between an E–W Jurassic extension and the NNE–SSW orientation of the Viking Graben. We feel, however, that these models do not satisfactorily account for the importance of NE–SW-striking faults throughout the Jurassic rift phase.

An E–W Jurassic extension vector would imply a tectonic setting similar to that recorded for the Permo-Triassic stretching phase. Although Jurassic stretching reactivated several large N–S-oriented faults of Permo-Triassic heritage, a number of faults with an orientation disparate from the predominant Permo-Triassic N–S grain also formed. Unlike the Jurassic rift phase, Permo-Triassic extension did not significantly activate NE–SW-oriented basement shear zones, and N–S-striking Permo-Triassic faults have, in fact, been demonstrated to transect the NE–SW basement grain (Færseth *et al.*, 1995a). It has also been demonstrated that the Horda Platform, which had been the site of maximum Permo-Triassic stretching and fault activity, is almost unaffected by Jurassic extension (Fig. 3) (Færseth *et al.*, 1995a; Roberts *et al.*, 1995; Odinsen *et al.*, in press). Consequently, the Jurassic stress distribution and fault pattern are significantly different from that related to the Permo-Triassic extension, both spatially and with regard

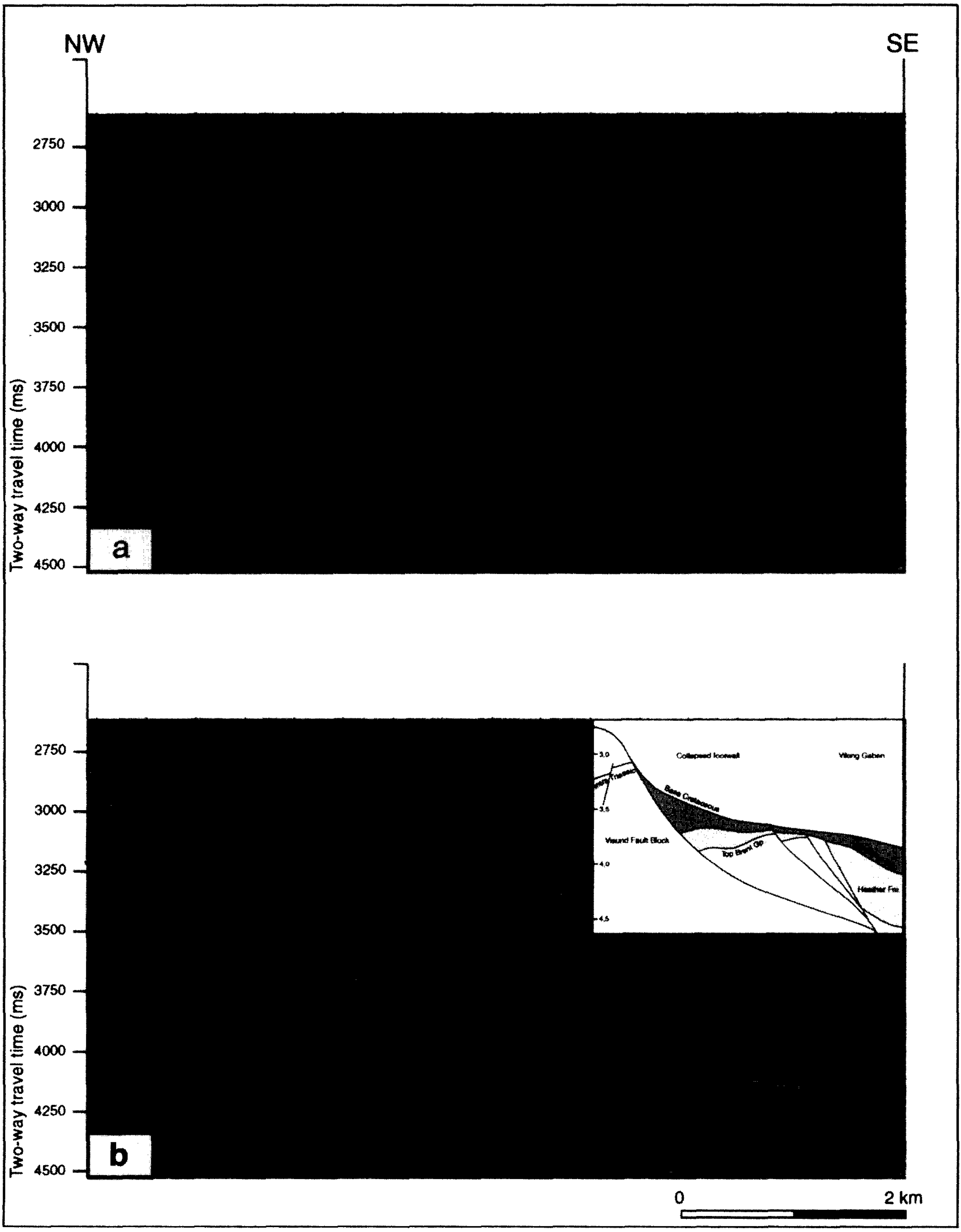

Fig. 13. Seismic section representing the transition from the Visund Fault-block into the Viking Graben (see Fig. 3 for location). Top Brent Group reflector represents the base of the Jurassic syn-rift sequence. The easternmost fault, with a maximum throw of some 5 km at Jurassic level, strikes N–S and represented the boundary between the Visund Fault-block and the Viking Graben proper during Bathonian–Early Kimmeridgian extension (observe the thick syn-rift Heather Formation in the hangingwall of this fault). From this stage activity along the fault to the left, which strikes NE–SW, resulted in partial footwall collapse to give a terrace separated from the present uplifted and deeply eroded crestal area to the west. Note the Draupne Formation (Late Oxfordian–Volgian) syn-rift wedge in the hangingwall of this fault.

to the strike and dip directions of large faults. We thus conclude that the orientation of Jurassic minimum principal stress ($\sigma_3$) was different to the Permo-Triassic E–W direction.

*Consistent NW–SE extension throughout the Jurassic rift phase.* This kinematic model appears to acknowledge both the sequential development of Jurassic faults in the northern North Sea and the influence of NE–SW-striking faults at all stages of Jurassic stretching. Assuming that NE–SW-striking faults formed orthogonal to the least principal stress ($\sigma_3$), the Jurassic extension direction was NW–SE (N135°E). If the graben envelope containing the rift segments (Figs 2 & 3), i.e. areas undergoing maximum Jurassic stretching, lie perpendicular to the regional extension it would have been approximately N120°E. Hence, we suggest that extension in the northern North Sea was between N120°E and N135°E throughout the Jurassic stretching phase.

## JURASSIC DEVELOPMENT OF THE NORTHERN NORTH SEA IN THE CONTEXT OF OBLIQUE RIFTING

Our interpretation of Jurassic structural development in the northern North Sea is based on the assumption that underlying structural grain, in combination with the regional extension direction, exerted a first-order control.

(1) Prior to Jurassic rifting the northern North Sea was a linear N–S-trending and extended zone, some 100 km wide, following Permo-Triassic stretching. This zone was characterized by significantly thinned basement crust, as compared to *ca* 35 km in the basin margins, and was assumed to represent the unstretched pre-Permian thickness of the North Sea region. The N–S-oriented borders of the basement depression were represented by major faults, i.e. the Øygarden Fault Complex to the east and the Hutton-Alwyn alignment–East Shetland Platform to the west (Fig. 3). This broad graben feature was filled with 5–7 km of sediment when the basin became subjected to Jurassic extension *ca* 70 Ma after the cessation of Permo-Triassic rifting.

(2) The northern North Sea appears to cross over the Laurentia–Baltica plate boundary (Iapetus Suture) (Klemperer and Hurich, 1990). Consequently, the rift zone representing maximum Jurassic extension (Fig. 3), on a gross scale, may follow the supposed NNE–SSW trend of the Caledonian-age Iapetus Suture (e.g. Watson, 1985; Ziegler, 1990; Færseth *et al.*, 1995a).

(3) An extension direction in the range N120–135°E implies an obliquity (45–60°) between the Jurassic least principal stress ($\sigma_3$) and the N–S-oriented boundaries of the Permo-Triassic structural depression.

*Early rift stage (Late Bajocian–Early Oxfordian)*

The early rift stage coincides approximately with deposition of the mud-rich, shallow-marine Heather Formation, but may also encompass the uppermost Brent Group represented by deltaic sediments of Late Bajocian age (e.g. Graue *et al.*, 1987; Helland-Hansen *et al.*, 1992; Johannesen *et al.*, 1995; Ravnås *et al.*, 1997). The kinematic model favoured in this study implies that faults striking N–S, which accommodated most of the stretching during the early rift stage, developed with an oblique orientation (45–60°) to the regional extension direction. A predominant N–S fault trend at this stage, reflects mainly the reactivation of large Permo-Triassic faults (Færseth, 1996).

The Jurassic stretching affected primarily the northwestern half of the northern North Sea (Figs 2 & 3). In this context, it is noteworthy that the Sogn Graben, a site of maximum Jurassic extension in the northernmost part of the North Sea (Roberts *et al.*, 1993b; Færseth, 1996), is located to the north of the almost unstretched Horda Platform (Fig. 3). Extension was relayed from the Sogn Graben area and southwestward to the central segment of the Viking Graben through a set of generally short N–S- to NE–SW-striking faults representing the northeastern edge of the Horda Platform. These faults lie en échelon on the trend of the basement-involved Nordfjord–Sogn detachment (Fig. 3).

Jurassic extension initiated a broad zone of diffuse faulting, and there was both reactivation of pre-existing N–S faults and nucleation and growth of new fault sets. Faults representing initial Jurassic stretching (Late Bajocian–Early Bathonian) reveal generally close (2–3 km) fault spacing and dip polarities which may be in contrast to the asymmetry and tilt pattern of major Jurassic fault-blocks seen today. Oppositely dipping Jurassic faults within major fault-blocks may exhibit one set with a steeper dip, indicating that the block-internal faults have rotated due to the tilting of large fault-blocks at a late stage of Jurassic development (Figs 6 & 10). The earliest faults define domains characterized either by fault-blocks having a consistent tilt direction (domino style), or a narrow graben flanked by elongated fault-blocks tilted away from the graben axis (Figs 6 & 12). Many of these early faults, as well as the subsidiary graben axes, trend NE–SW, and are suggested to have formed at a high angle to the regional extension direction (Fig. 12). These observations demonstrate the early initiation of NE–SW-striking faults and, accordingly, that N–S- and NE–SW-striking faults are coeval and related to the same extension direction. There is, in fact, a striking similarity between the N–S and NE–SW fault pattern, as seen in the smaller area illustrated in Fig. 12, and having the characteristics of oblique rifting, compared to the regional fault pattern of the northern North Sea (Fig. 2).

In the Bathonian the main basin controlling element, i.e. the large half-grabens, were established and controlled by boundary faults with a predominant N–S orientation. The rift wedges represented by the Heather Formation are generally bounded by E-dipping faults, i.e. thickening to the west (Fig. 7). Faults of the same generation, but having a westerly dip, are most frequent in the area west of the Sogn Graben (Figs 8 & 11). The palaeoslope may have influenced fault initiation as well as the preferred dip direction. Major parts of the northern North Sea had a palaeoslope with a westerly dip component, which was generated during Permo-Triassic rifting and accentuated by Jurassic stretching and faulting (Færseth, 1996). It is likely that this palaeoslope triggered W-facing, i.e. downslope, normal faults during Jurassic rifting, of which some may have developed into major faults. It is noteable that W-facing Jurassic faults are frequent across long-wavelength flexures representing the east flank of asymmetric segments of the Viking Graben (Fig. 7) (Færseth and Ravnås, in press). The influence of palaeoslope on fault-dip pattern has been reproduced in sandbox models (e.g. McClay and Ellis, 1987; Vendeville *et al.*, 1987). When the sediments were inclined (tilted) during extension practically all faults dip downslope, whereas equal numbers of faults with opposite vergence appeared when extension affected sediments which were kept horizontal.

Higgins and Harris (1997) demonstrated that synthetic faults in the sedimentary cover above basement faults often display more offset than oppositely dipping faults which cause a rotation of the intervening graben block, i.e. to give an asymmetric graben profile. Assuming that the Jurassic Viking Graben follows the trend of the Iapetus Suture, opposite vergence of reactivated basement-involved thrust/fault surfaces located east and west of the suture may have contributed to the asymmetry of graben features envisaged at Mesozoic levels.

A characteristic feature of the early rift stage is that major fault-blocks exhibit modest (1–3°) tilt at pre-rift level after some 15–20 Ma of stretching, and there was an overall balance between accommodation space and sedimentation. The rate of displacement on major faults was generally small compared to the succeeding main rift stage (e.g. Færseth *et al.*, 1995b).

### *Main rift stage (Late Oxfordian–Volgian/Ryazanian)*

The structural development of the northern North Sea, at this stage, was associated with accelerated fault-block rotation (Graue, 1992; Stewart *et al.*, 1992; Young, 1992; Rattey and Hayward, 1993; Færseth *et al.*, 1995b; Færseth and Ravnås, in press), and the tilt at the pre-rift level within fault-blocks increased to more than 10° in the latest Jurassic–earliest Cretaceous. The clay-rich Draupne Formation was deposited in sediment-starved rift basins, i.e. when there was significant relief within the deeper parts of the northern North Sea.

As extension proceeded relatively few faults in the northern North Sea accommodated most of the extension, and rifting became more focused. NE–SW-striking faults developed into major faults and Jurassic rift segments, aligned NNE–SSW, became accentuated to give the characteristic en échelon sub-basin development (Fig. 3).

There are numerous examples of N–S-striking faults which terminate upwards within the syn-rift sequence (Figs 6 & 7), i.e. faults became dormant during Late Jurassic stretching. Such faults are post-dated and, in places, cross-cut by Jurassic faults, striking both N–S (Figs 4, 5 & 7) and NE–SW (Figs 9–11), which controlled rift wedges represented by the Draupne Formation. This may imply that the increased stretching rate in the Late Jurassic was strong enough to overcome the influence of a pre-existing N–S fabric and to result in an increased importance of faults with a more favourable (NE–SW) orientation relative to the regional Jurassic extension direction.

The accelerated tilting of fault-blocks, followed by partial crestal collapse, was associated with activity on NE–SW-oriented faults (Figs 11 & 13). An E–W transect across the Tampen Spur and the adjoining Viking Graben (Fig. 2) reveals that major fault-blocks, initially bordered by N–S-oriented faults, have eroded crests indicating that at an Early Kimmeridgian stage of the rifting period they were still at approximately the same topographic level and at, or near, sea level. Footwall collapse in the Late Kimmeridgian and decoupling of parts of the crestal area (e.g. Gullfaks, Statfjord and Visund fault-blocks) (Fig. 2) resulted in structural terraces at an intermediate structural level between the present crest and an adjoining deep graben structure (Roberts *et al.*, 1993a; Færseth *et al.*, 1995b; Fossen *et al.*, in press) (Fig. 13).

Faults striking NE–SW and associated with footwall collapse are particularly related to the eastern Tampen Spur (Færseth *et al.*, 1995b; Fossen *et al.*, in press), the Beryl Embayment (Swallow, 1986; Platt, 1995) and the Fladen Ground Spur (Harris and Fowler, 1987; Cherry, 1993), i.e. areas (Fig. 2) representing footwalls of asymmetric graben segments. Graue (1992) reported giant Late Jurassic–earliest Cretaceous footwall collapse associated with NE–SW-striking, low-angle, detachments along the northwestern frontal part of the Manet Ridge facing the Møre Basin to the northwest (Fig. 2). The locations showing footwall collapse represent sites of increased Jurassic fault-block tilting, footwall uplift and a considerable Late Jurassic fault-scarp topography. Hence, faulting and decoupling of parts of the footwall may be associated with crustal stretching and collapse of the unsupported flanks of large fault-blocks which bordered deep basins in the Late Jurassic.

## SUMMARY

(1) Jurassic structural development of the northern North Sea has characteristics of oblique rifting. This is interpreted to result from an obliquity between Jurassic

regional extension, which was directed in the range N120–135°E, and a pre-existing N–S-trending zone of deformation related to Permo-Triassic stretching and thinning of basement crust.

(2) Jurassic stretching and faulting affected primarily the northwestern half of the northern North Sea. Extension was relayed from the Sogn Graben area and southwestward to the central segment of the Viking Graben through a set of short N–S- to NE–SW-striking faults representing the northern edge of the Horda Platform. These faults lie en échelon on the trend of the basement-involved Nordfjord–Sogn detachment, which is a Devonian shear zone crossing the North Sea basin.

(3) The rift zone representing maximum Jurassic extension, i.e. the Viking and Sogn grabens, defines a narrow depression which runs diagonally (NNE–SSW) across the broader Permo-Triassic basin. The rift zone consists of a system of en échelon rift segments, the symmetry of which changes along strike, and they are bounded by faults which are oblique to the overall graben trend.

(4) Faults striking N–S and NE–SW have been generated throughout the Jurassic stretching phase. Consequently, the two fault trends are coeval and related to the same extension direction. Major N–S-striking faults, mostly of Permo-Triassic heritage, represented the block boundaries and controlled the basin geometry during the early (Late Bajocian–Early Oxfordian) rift stage. At the same time new block-internal faults developed oblique (NE–SW) to N–S-striking structural features, and at a high angle to the direction of regional extension.

(5) Major NE–SW-striking faults accommodated most of the Kimmeridgian–Volgian extension, whereas a number of N–S-striking faults became dormant during this period. Faults striking NE–SW occur within the total area of the northern North Sea affected by Jurassic stretching. However, there is an increase in fault frequency to the north, which is mainly ascribed to a higher intensity of NE–SW-oriented inhomogenities at basement level to the north.

(6) Large faults striking NE–SW may cross-cut Jurassic N–S-trending faults of an earlier generation; they separate earlier N–S-striking major fault-blocks to define blocks with a present rhombohedral outline; and they are associated with the partial collapse of crestal areas of large fault-blocks to form structural terraces.

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