Indication of transpressional tectonics in the Gullfaks oil-field, northern North Sea

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New seismic data have provided important insights into the tectonic evolution of the Gullfaks area and the northern North Sea. Extensional tectonics, which predominate in the North Sea Basin, were accompanied by subordinate compressional deformation in the Gullfaks field involving the formation of thrust and reverse faults and compressional folds. The local compression is interpreted as a product of dextral strike–slip movement along the NE–SW trend of the Tampen Spur in Late Jurassic to Early Cretaceous times. In a regional context, the strike–slip movement may be related to dextral strike–slip movements along the Møre–Trøndelag Fault Zone further to the northeast.

Keywords: Gullfaks; North Sea; dextral strike–slip; local transpression

Introduction

The Gullfaks field in the North Sea is situated at the northern end of the Viking Graben *(Figure 1)*, within the highest part of a major fault block tilted to the west. Stratigraphically, the structure is characterized by a very marked late Kimmerian unconformity which separates extensively faulted Triassic to Upper Jurassic sands and shales from Upper Cretaceous marls, shales and limestones *(Figure 2)*. The structure has been described by Sæland and Simpson (1982) who interpreted it as a traditional extensional structure. Interpretation of the structure has been difficult due to the low resolution of the seismic data from the area. However, a new 3D survey (ST 8511) with a line spacing of 25 m has been shot over the Gullfaks structure, and the data quality has improved. Dipmeter data correlate very well with the dips seen on the seismic sections, and although the character of the seismic reflectors in the Jurassic sequence varies somewhat across the structure, the growing number of wells provides an important control on the seismic interpretation.

Stratigraphy

The Triassic to Paleocene sedimentary strata in the Gullfaks–Tampen area have been subdivided into the Hegre Group, the Statfjord Formation and the Dunlin, Brent, Viking, Cromer Knoll, Shetland and Rogaland Groups *(Figure 2)*.

The Hegre Group is dominated by interbedded white to red continental sandstone, red shale and claystone. A fluvial sand (the Lomvi Formation) was deposited during the Carnian, and causes a marked reflection on seismic lines in the Gullfaks area *(Figures 3, 4* and *5)*. The *Statfjord Formation* consists of sandstones deposited in a deltaic environment, diachronously overlain by marine shales and thin sands of the *Dunlin Group*. The Middle Jurassic *Brent Group* is dominated by a progradational delta-sequence of sands and minor shales. The *Viking Group* consists of shales (Heather Formation) overlain by a radioactive, organic-rich clay (Draupne Formation).

The sediments of the Viking Group were deposited during the late Kimmerian tectonic phase, which was the last important phase of extension recorded in the North Sea Basin. Deep erosion of the Jurassic and locally the Triassic occurred in large parts of the Tampen Spur *(Figure 2)*, though sedimentation may have been more continuous in the Viking Graben. Shales, marls and thin limestones of the Cromer Knoll Group and the overlying Shetland Group were deposited during Cretaceous basin subsidence, though only the uppermost part of the Cretaceous strata are present at the top of the Gullfaks structure *(Figures 3, 4* and *5)*. A marked reflection is commonly seen near top Paleocene in the shaly, Lower Tertiary Rogaland Group *(Figures 3, 4* and *5)*. A more detailed description of the stratigraphy has been presented by Vollset and Dore (1984).

Structural pattern

Faults in the Gullfaks field are generally sub-planar and easterly dipping, and the Triassic–Jurassic beds tend to dip *ca.* 15° to the west except in the eastern part of the area where they are sub-horizontal *(Figures 3, 4* and *5)*. Although many faults have been re-activated in the Cretaceous and even Lower Tertiary, displacements are considerable only in pre-Cretaceous rocks.

Structurally, the Gullfaks area may be divided into three sub-areas *(Figure 6)*. A southwestern sub-area (sub-area 1 in *Figure 6)* is influenced by extensional faults trending NE–SW. This trend may be connected to the major E–W fault which separates the Gullfaks and the Gullfaks Sør fields. A northern sub-area (sub-area 2 in *Figure 6)* is dominated by N–S trending planar faults with associated E–W adjustment faults.

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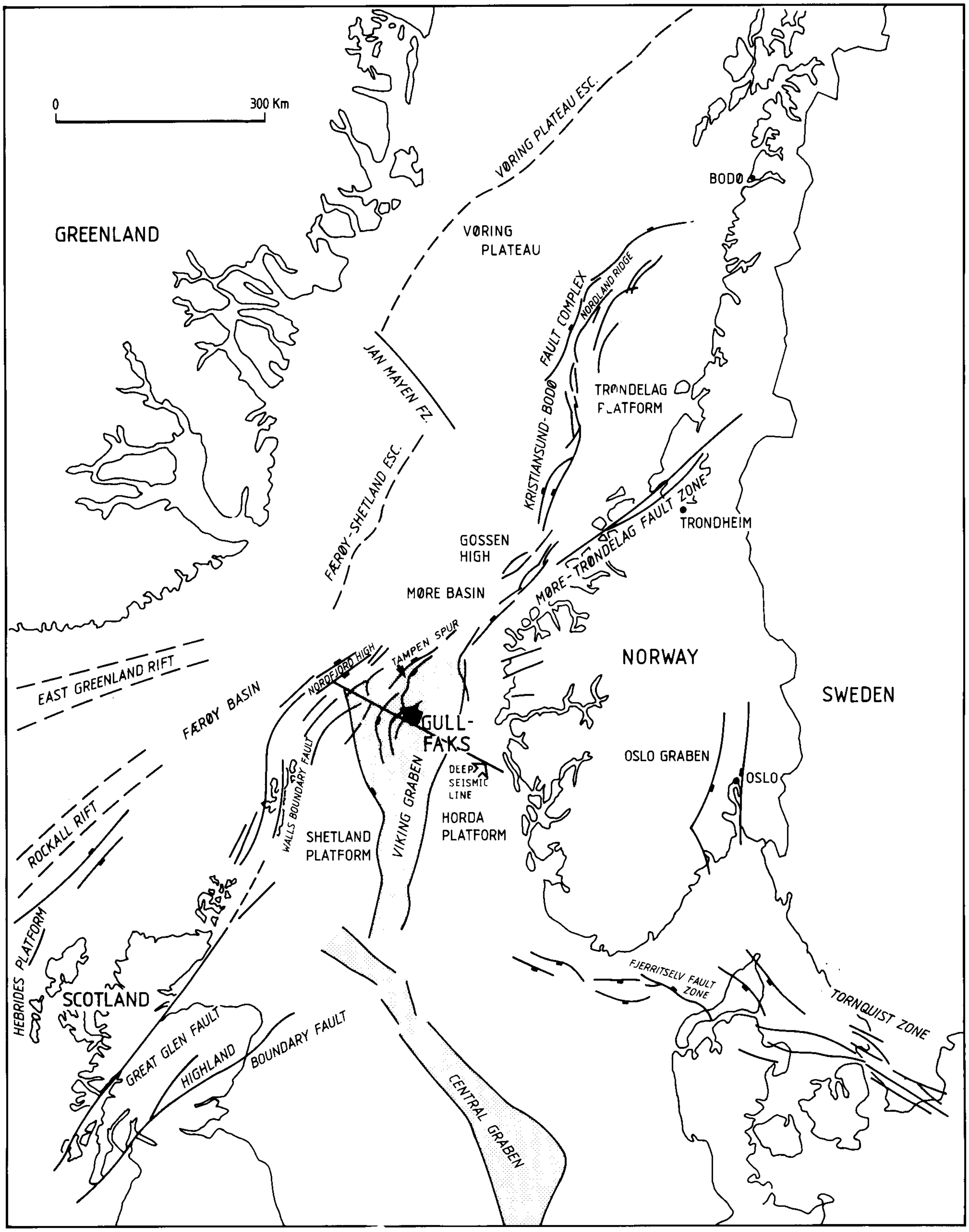


Figure 1 Regional tectonic setting and location of the Gullfaks field. Modified from Færseth (1984)

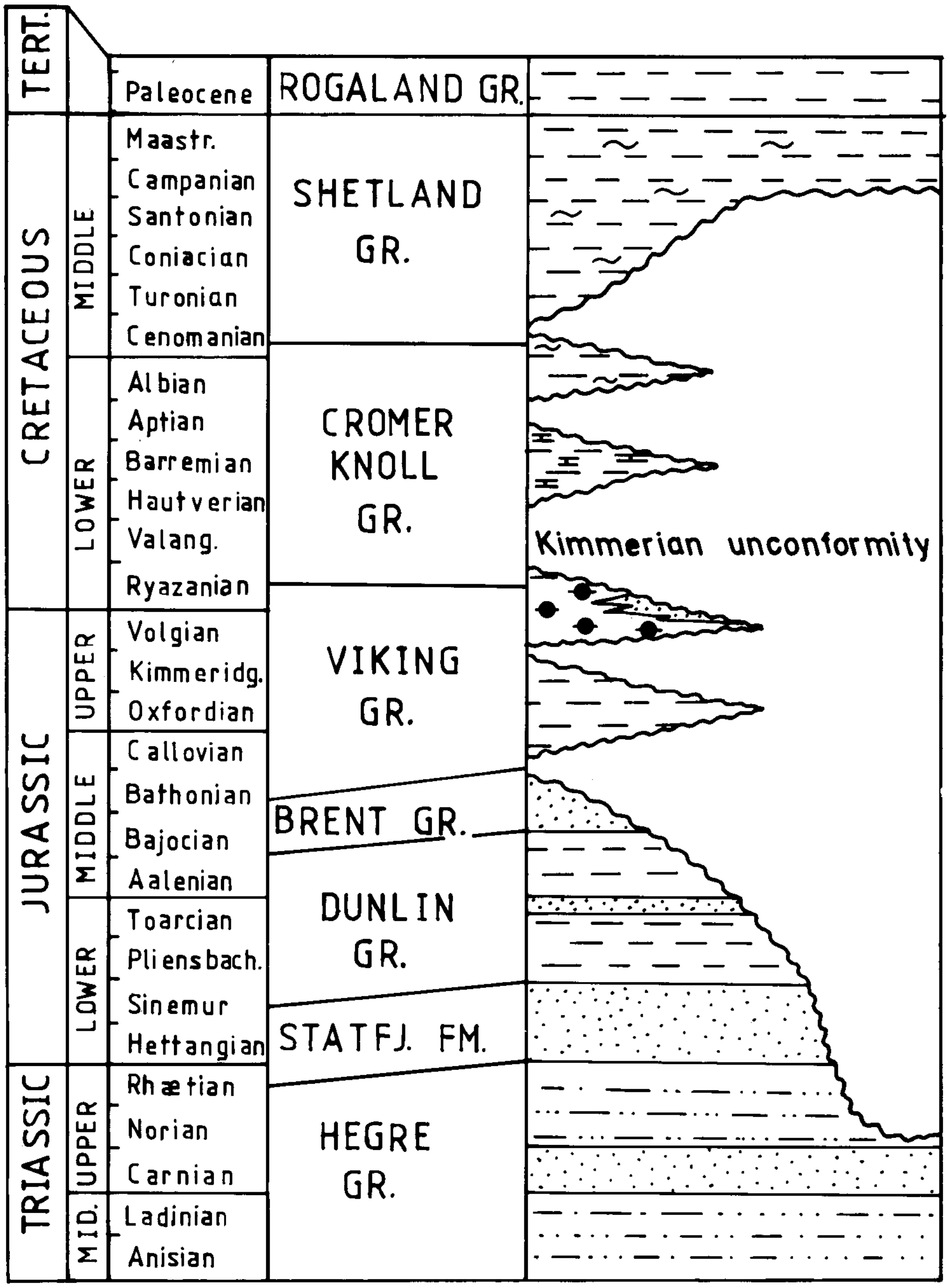


Figure 2 Stratigraphy of the Gullfaks area. White area marks erosion or non-deposition

To the east is a sub-area (sub-area 3 in *Figure 6)* which is characterized by a complex and generally deeply eroded horst structure. The horst is situated at the crest of the Gullfaks fault block, bounded by a major fault which may be traced down to the Moho (Beach 1986). Similar horsts are seen elsewhere along the eastern margin of the Tampen Spur, and may be explained by an irregular lower Triassic detachment zone beneath the horst *(Figure 7)*.

Indications of transpression

There are several indications that some form of transpressional deformation may have affected the sediments in the Gullfaks area:

(1) Major fault zones in the vicinity of the North Sea, e.g. the Møre-Trøndelag Fault Zone, the Great Glen Fault and the Tornquist Line *(Figure 1)*, indicate that strike–slip movements occurred during the Mesozoic development of the North Sea Basin.
(2) Seismic interpretation of new 3–D data from the Gullfaks structure shows elements (contractional faults and folds) with a nature and orientation which are not compatible with that of bulk pure extension. The structures indicate dextral transpression along a NE–SW lineament.
(3) A major fault zone immediately to the east of the Gullfaks field *(Figure 8)* is probably an important, crust-penetrative structure which is thought to have experienced the main movements within the basin. If there has been a strike–slip component along this fault zone, the curvature of faults in the zone around Gullfaks would make the Gullfaks area a location of transpressional deformation.
(4) An apparent inversion of the Gullfaks field is indicated as the area changed from being relatively low in the Middle Jurassic to become a high in the Cretaceous.

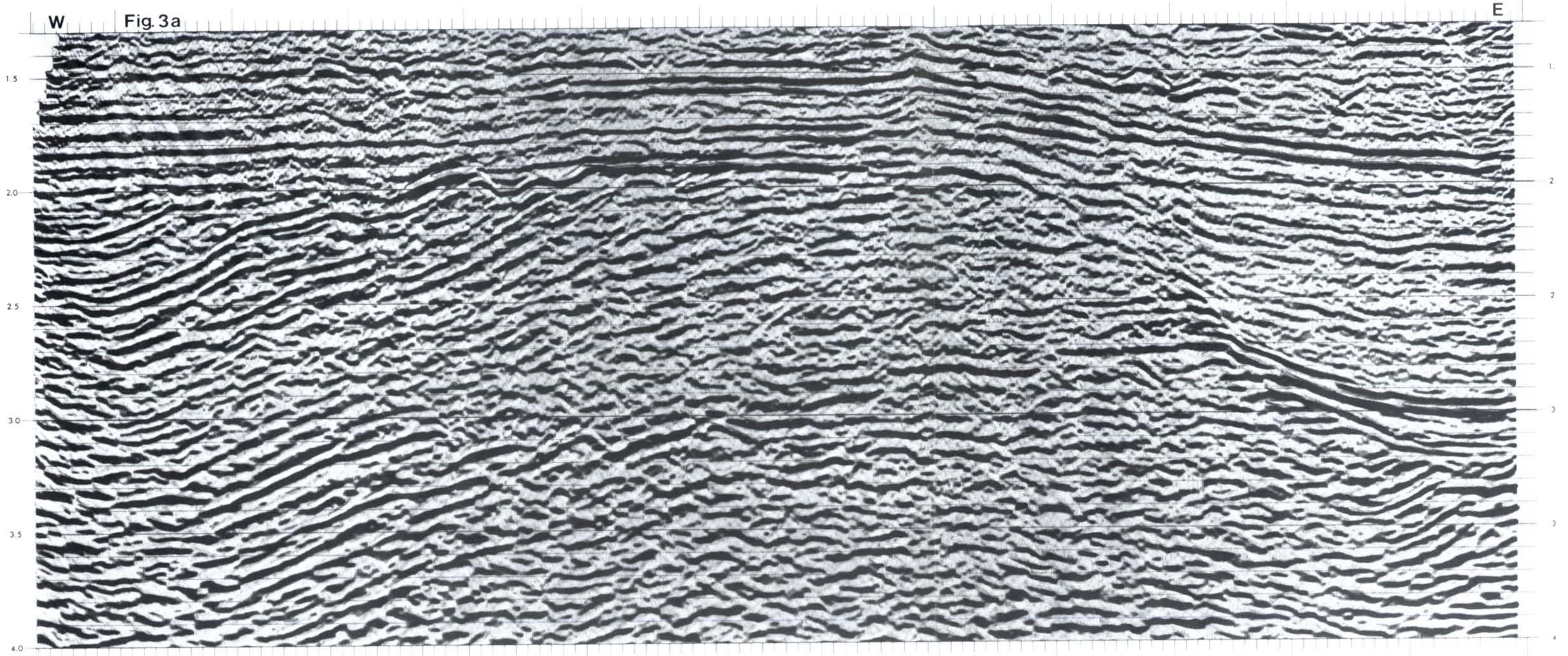
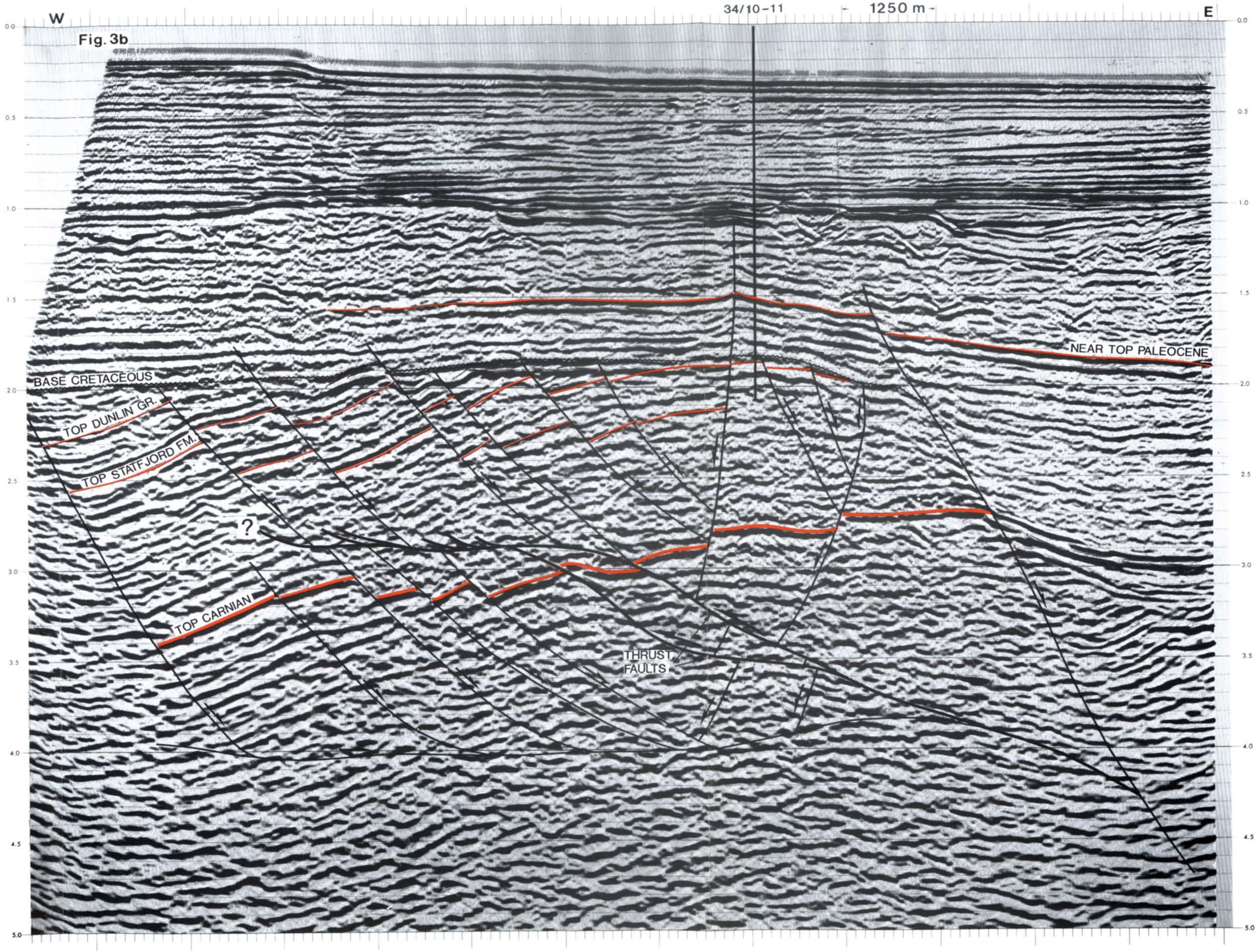
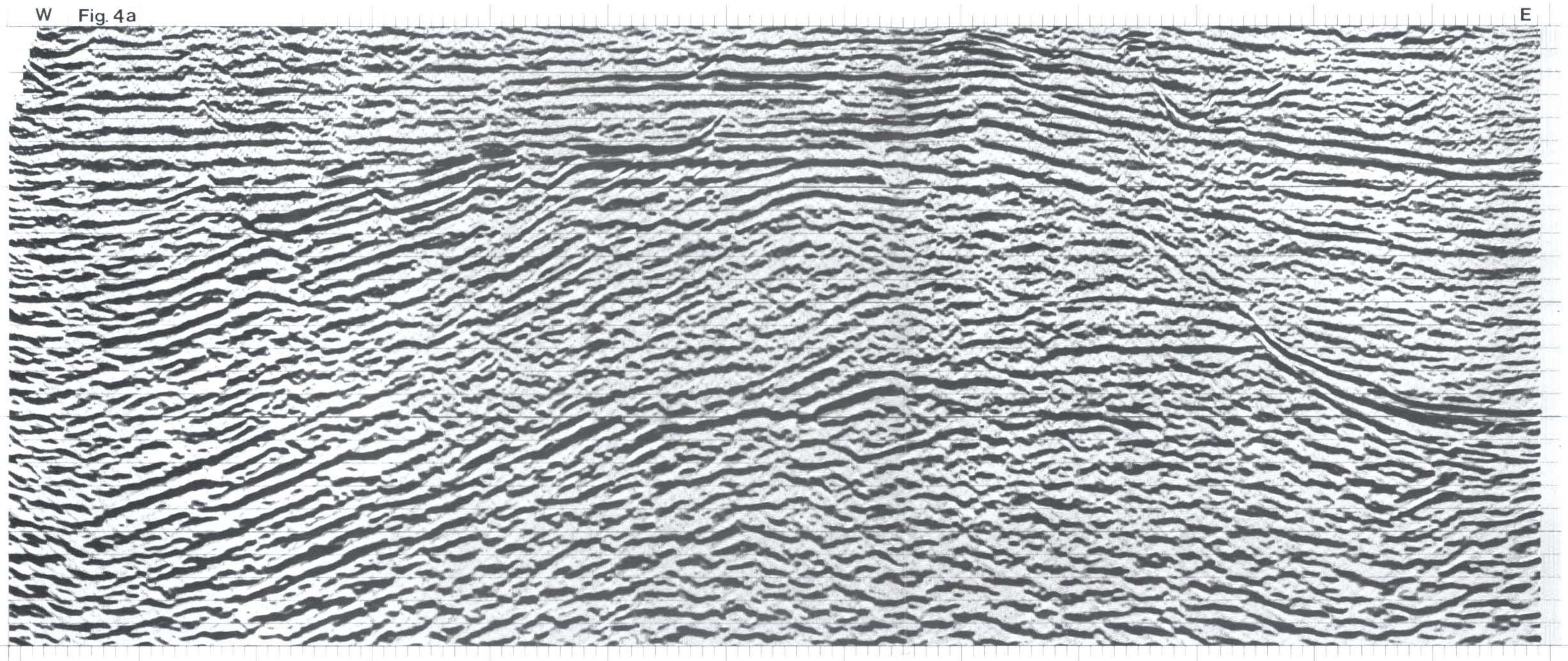


Figure 3 (a) Uninterpreted and (b) interpreted seismic profile from 3-D survey ST 8511 collected in 1985 from the Gullfaks field. Note stacking of intra Triassic (Carnian) reflectors by thrusting, and Tertiary reactivation of the steep faults which define the horst structure. For location, see *Figure 6*





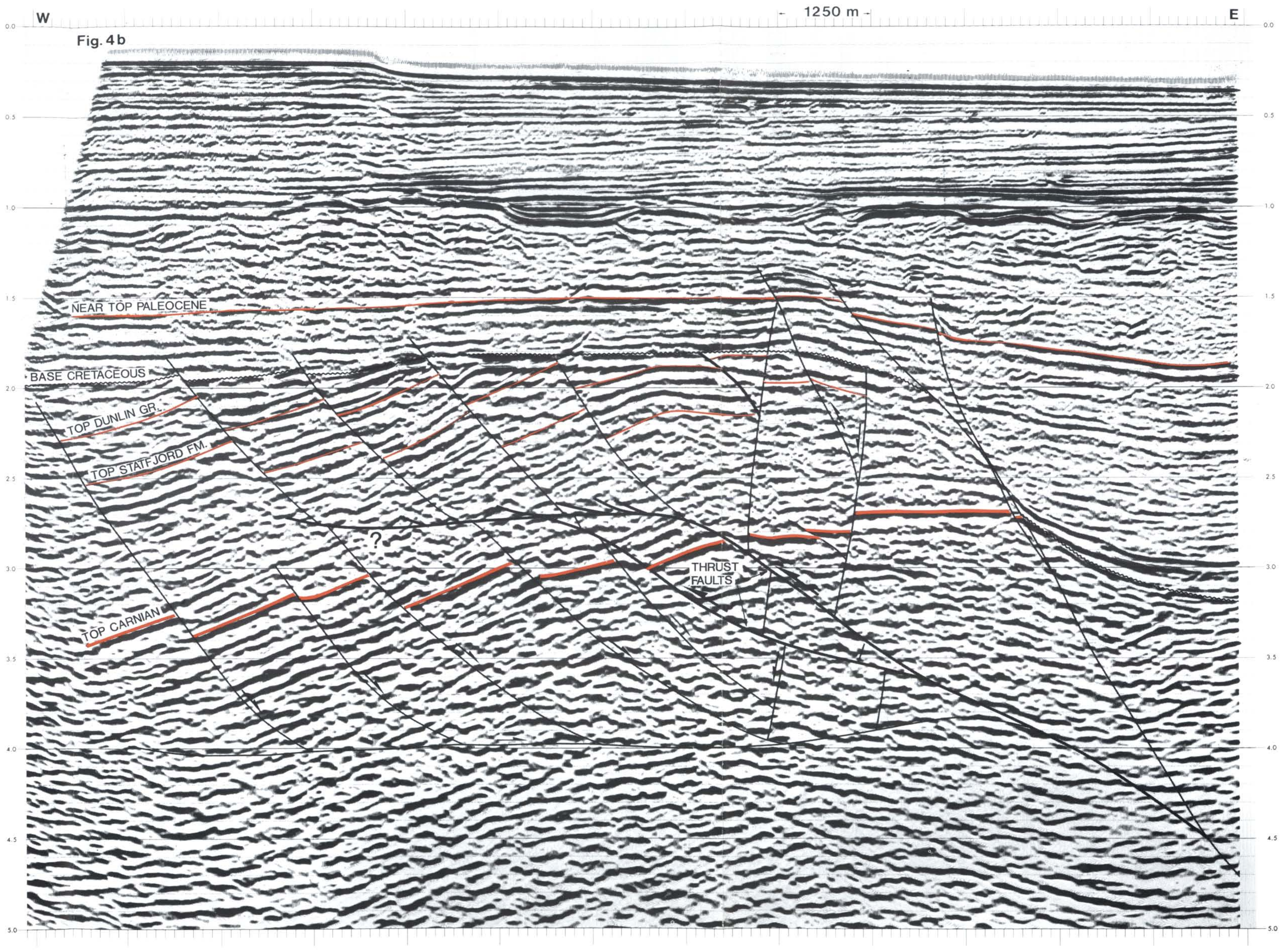
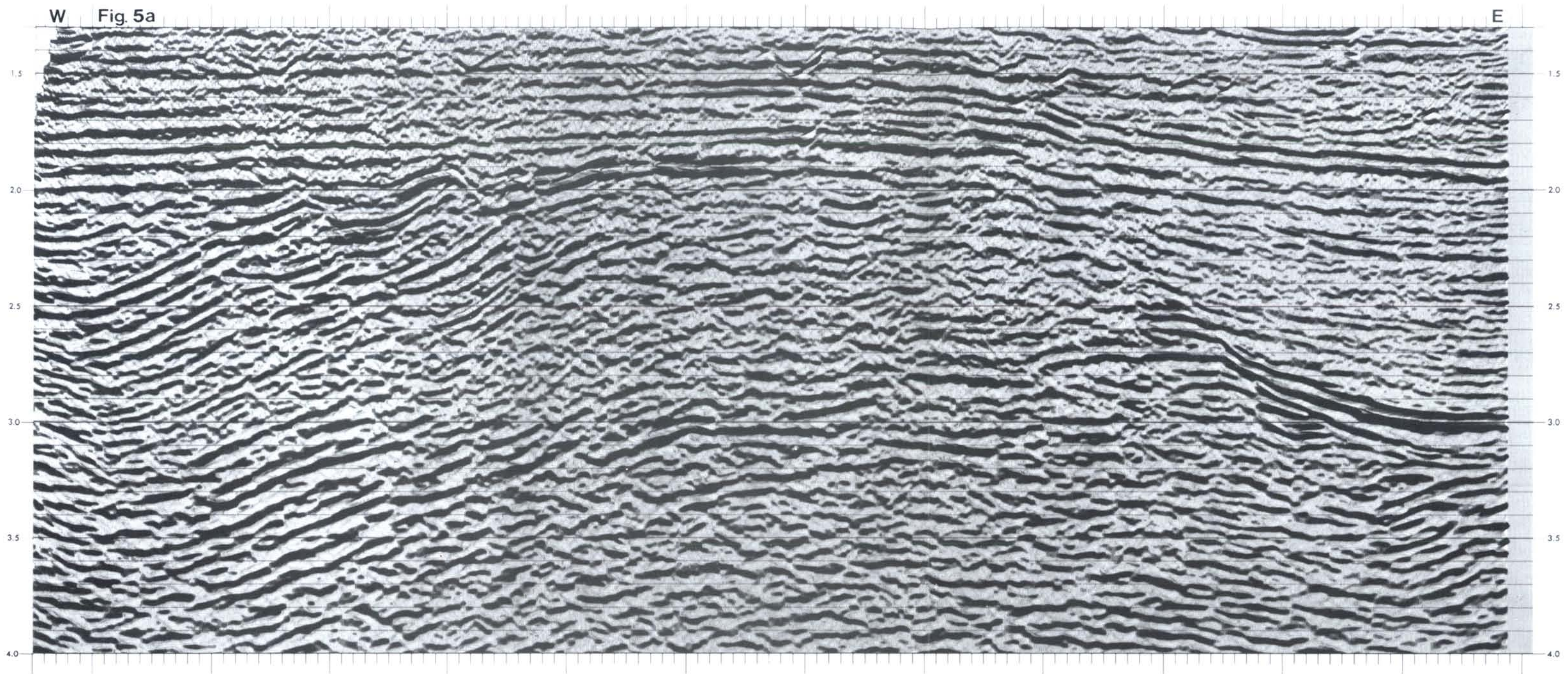


Figure 4 (a) Uninterpreted and (b) interpreted seismic profile from 3-D survey ST 8511 with reverse fault in the Jurassic. Large-scale kink-like fold to the west of the horst may be due to compression. For location, see *Figure 6*



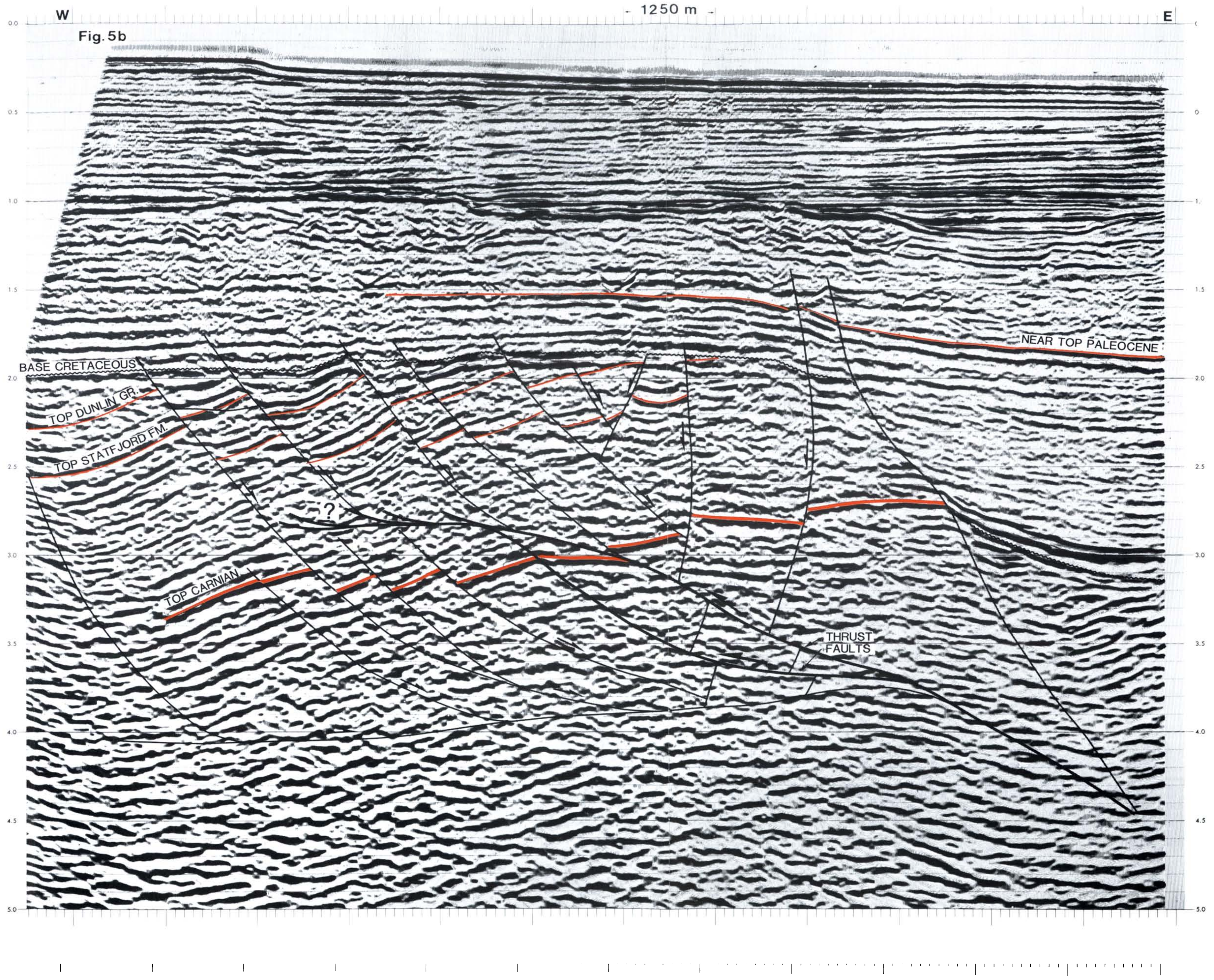


Figure 5 (a) Uninterpreted and (b) interpreted seismic line from 3-D survey ST 8511 showing thrusting of the Triassic and folding of the Jurassic to the east of the horst. For location, see *Figure 6*

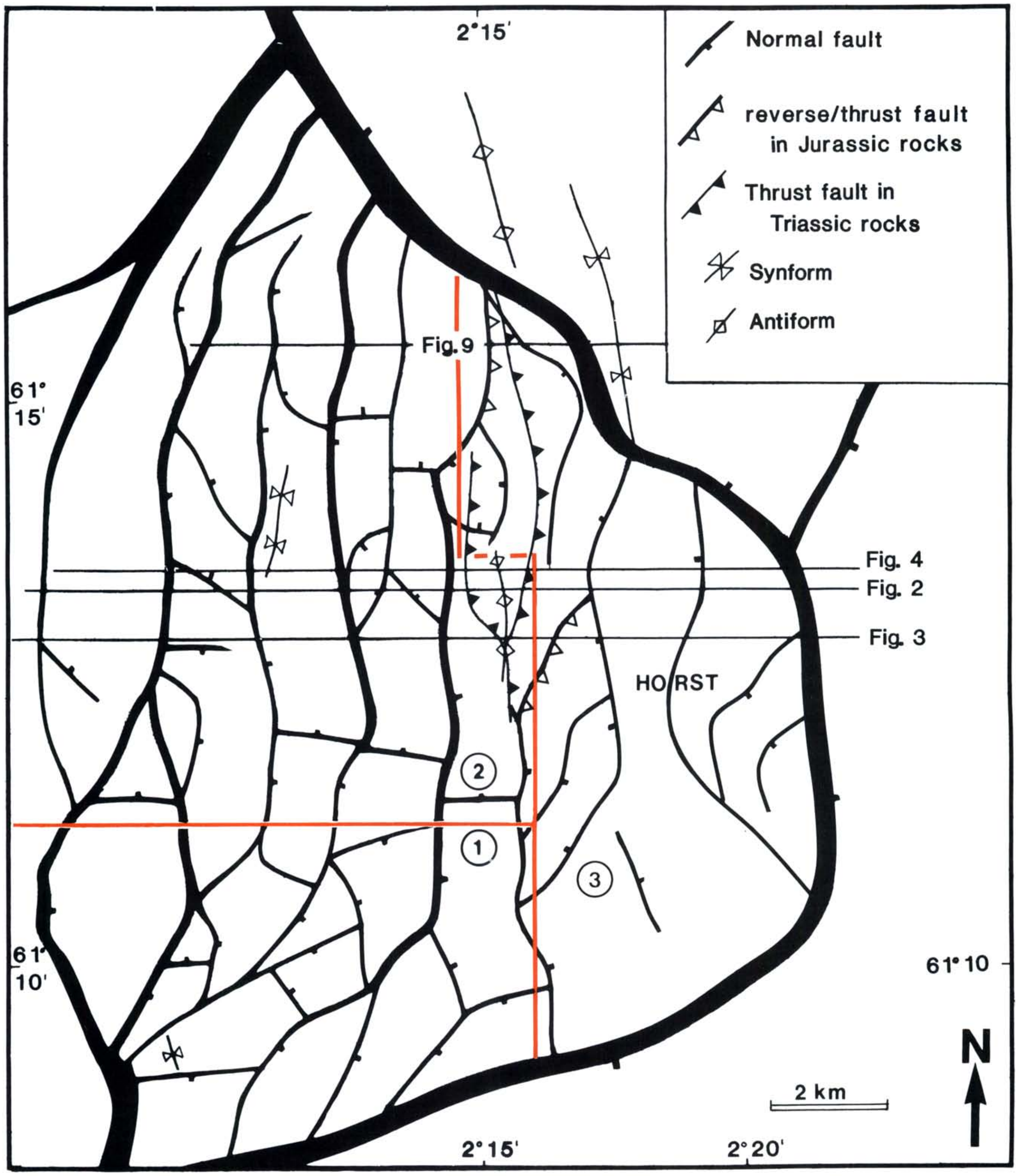


Figure 6 Structural elements in the Gullfaks area, top Dunlin Group. The main thrusts at the Carnian (Triassic) level are indicated. Numbers refer to sub-areas discussed in the text

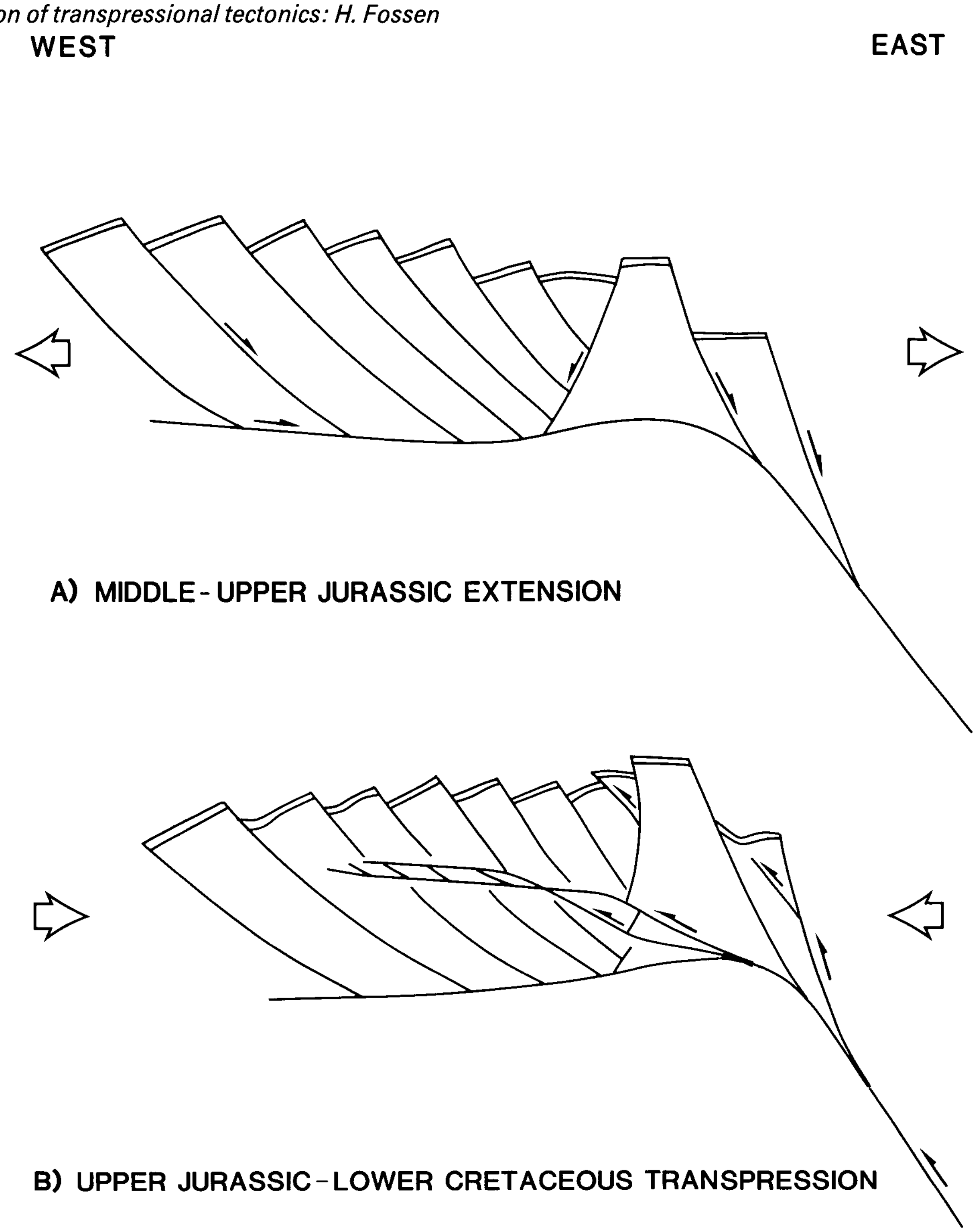
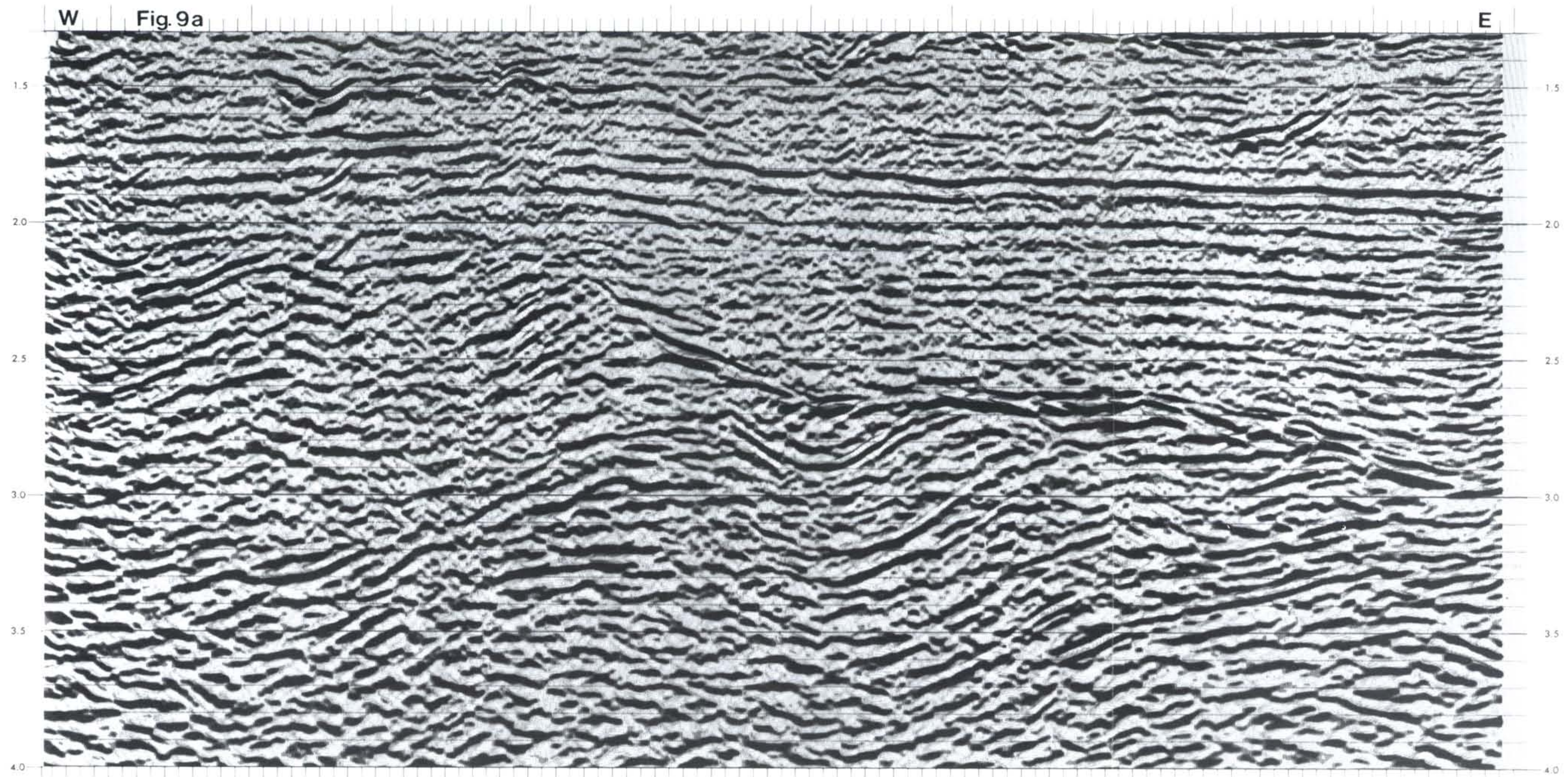


Figure 7 Cartoon illustrating the structural evolution of the Gullfaks area in the Middle Jurassic–Early Cretaceous as interpreted in this work. The length of the cartoon approximately corresponds to the length of the seismic sections in *Figures 3, 4* and *5*

It is widely accepted that extensional tectonics controlled the development of the North Sea. However, it is also accepted that strike–slip movements accompanied the extension (Hay, 1978; Ziegler, 1981; McQuillin *et al.*, 1982; Hamar and Hjelle, 1984; Pegrum and Ljones, 1984; Pegrum, 1984; Bøen *et al.*, 1984; Bucovis *et al.*, 1984; Gibbs, 1986; Speksnijder, 1987; Beach *et al;* 1987; Frost, 1987; Larsen, 1987) and generally occurred along fundamental fault zones. The most important of these are the possible extension of the Tornquist Zone *(Figure 1)* into the North Sea south of Gullfaks (Pegrum and Ljones, 1984; Pegrum, 1984), the Great Glen Fault (Kennedy, 1946; Smidt and Watson, 1983) to the west, and the Møre–Trøndelag Fault Zone (Gabrielsen et al., 1984) to the northeast *(Figure 1)*. The fault zones have different orientations and each zone has experienced different types of deformation through time.

The NE–SW trending Møre–Trøndelag Fault Zone is probably the most important zone in this regard, extending from the Trondheimsfjord area in Central Norway to the Tampen Spur and Gullfaks area *(Figure 1)*. Work in progress by Grønlie and Roberts (1987, and in preparation) shows that the onshore part of this fault zone functioned as a dextral strike–slip system during the Late Jurassic to Early Cretaceous, as previously indicated by Aanstad *et al.* (1981) and Rindstad and Grønlie (1986). Dextral shear along a NE–SW trend is also recognized offshore in the Kristiansund–Bodø Fault Complex *(Figure 1)* (Gabrielsen *et al.*, 1984). Evidence favouring dextral strike–slip shear was



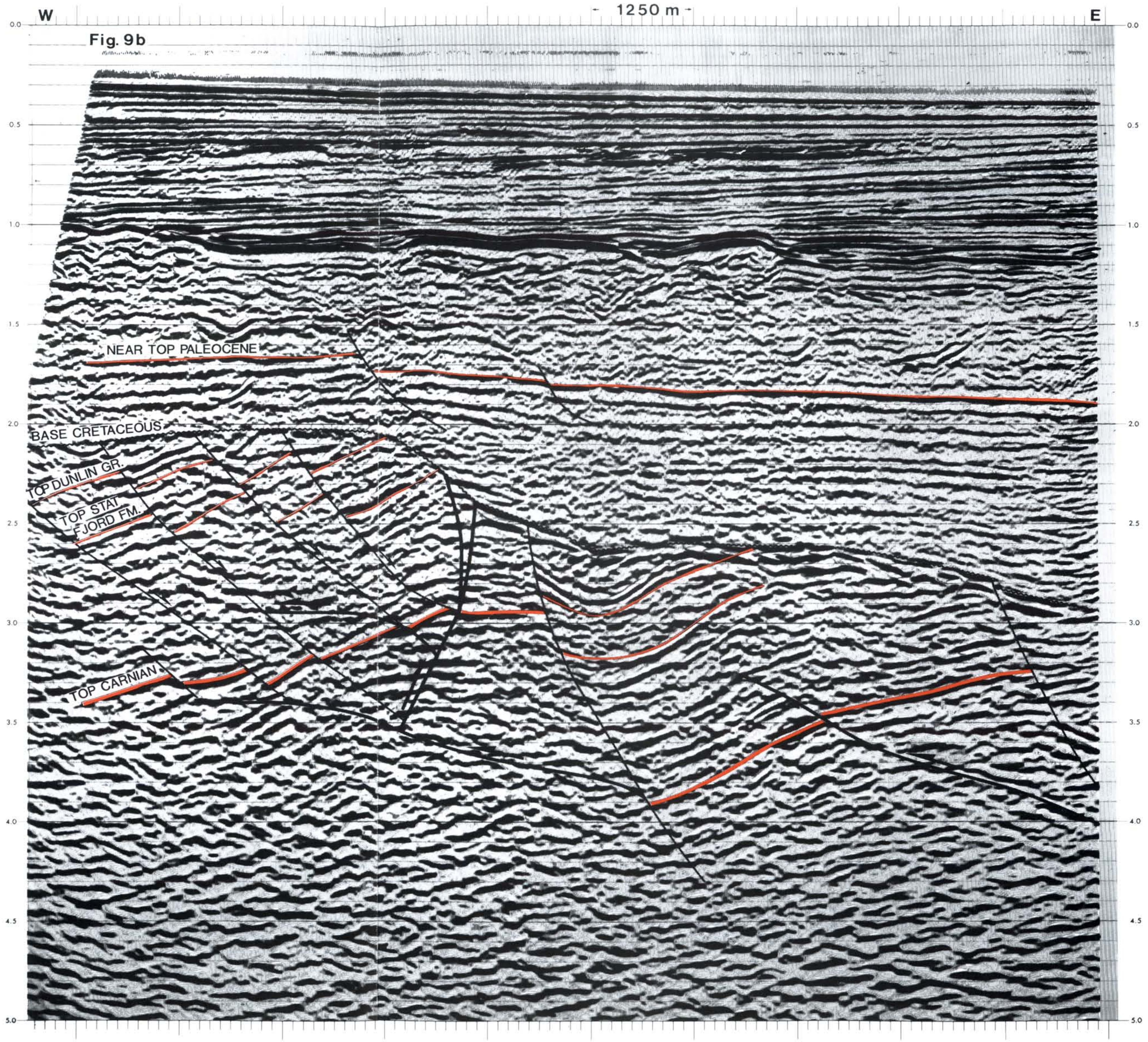


Figure 9 (a) Uninterpreted and (b) interpreted seismic line from 3-D survey ST 8511 from the northern part of the Gullfaks field, showing compressional folding to the east of the main fault and the deeply eroded horst. For location, see *Figure 6*

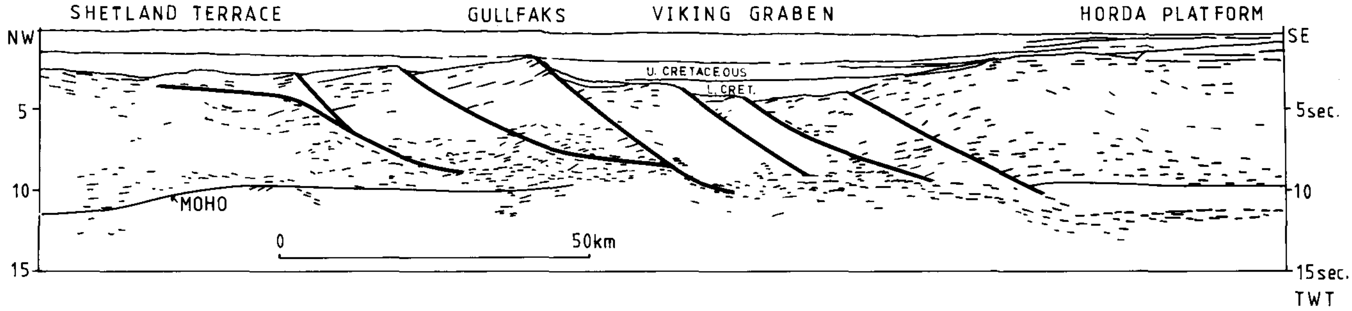


Figure 8 Profile from deep seismic line across the northern North Sea. For location, see *Figure 1*. Redrawn from Beach (1986). See also Beach *et al.*, 1987, Fig. 6

also found by Price and Rattey (1984) in the vicinity of the Møre–Trøndelag Fault Zone; they interpreted the strike–slip to be of Mid-Cretaceous age. There are also indications of uppermost Jurassic–Cretaceous transpression and transtension in the southwestern offshore extension of the Møre-Trøndelag Fault Zone, and compressional structures have been interpreted in the area of the Tampen Spur to the north of the Gullfaks field (Hamar and Hjelle, 1984). Hence, a strike–slip system which involved at least local transpression is strongly indicated between the Tampen Spur and the Trondheimsfjord area *(Figure 1)*.

There is also evidence of dextral Mesozoic displacements on the Great Glen Fault in the order of some tens of kilometres (Flinn, 1975; Speight and Michell, 1979; McQuillin *et al.*, 1981). The movement has not been accurately dated, but it may be related to the Late Jurassic to Cretaceous shear event along the Møre–Trøndelag Fault Zone. The Tornquist Zone experienced sinistral transpression during this particular period (Pegrum 1984).

The Møre–Trøndelag Fault Zone continues to the southwest towards the Tampen Spur and the Gullfaks area *(Figure 1)*. In the Gullfaks field, structures have been mapped which are at variance with the extensional deformation which otherwise dominates the area. These structures are contractional faults and folds which are generally found in the north-eastern part of the Gullfaks area *(Figure 6)*.

Thrust faults (low-angle reverse-faults) are indicated by intra-Triassic reflectors near top Carnian which show local imbrication *(Figures 3, 4* and *5)*. The thrusts generally have a N–S orientation, and may be followed for several kilometres along strike. A reverse fault with a NE–SW strike has also been traced in the Middle Jurassic. In Upper Cretaceous to Lower Tertiary sediments only minor indications of compression are found, related to the horst-bounding steep faults. From the seismic data it can be seen that the extension is greater for the Jurassic than for the Carnian *(Figures 3, 4* and *5)*. The thrusts are interpreted as branches of the major fault occurring immediately to the east of the Gullfaks field. Such a configuration is comparable with those generally associated with strike–slip fault zones (e.g., flower structures, Harding and Lowell, 1979) where contractional faults tend to have flatter dips than the normal faults.

An alternative interpretation may be that the Triassic structural features represent pre-Jurassic horsts and grabens, being separated from the Jurassic system by an extensional detachment. This interpretation is considered less likely, however, because the Jurassic and Triassic offsets seen on the seismic lines generally appear to be linked by continuous faults in the western part of the Gullfaks area showing roughly the same amount of extension in the Jurassic and the Triassic. Furthermore, the horst system in the east (sub-area 3 in *Figure 6)* is similarly developed in the Jurassic and the Triassic layers *(Figures 3, 4* and *5)*. The horst is therefore mainly a post-Middle Jurassic feature.

Compressional folds are present in the Gullfaks structure in a zone immediately west of the horst system *(Figure 6)*. The fold axes here generally trend N–S and are sub-horizontal. Compression of the Middle to Upper Jurassic sediments may be related to a component of E–W compression which nearly or partly overturned the horst. Compressional folds are also common in the footwall to the Gullfaks fault block, particularly to the northeast *(Figure 9)* where the axes strike nearly N–S *(Figure 6)*. These folds have been recognized previously (Karlsson, 1986, Fig. 9), but have not been ascribed to compressional tectonics. Folds similar to these may form by bulk extension depending on the geometry of the fault surface. If this is the case in the Gullfaks area, the geometry of the folds points to an abruptly downward steepening of the fault surface. Although differential compaction makes geometric calculations uncertain (Gibbs 1983), such a fault surface is at variance with the relatively steep, sub-planar fault trace indicated on the seismic profiles.

The orientation of the fold axes relative to the strike of the associated faults also indicates that the folds are perhaps not simply related to extension. If they were of extensile origin, e.g., reverse drag structures, then the axial trend of the fold would closely parallel the trend of the fault (Hamblin, 1965). This is not the case in the Gullfaks area, where there is a difference between the trends of folds and faults immediately to the north of the Gullfaks oil field *(Figure 10)*.

The interpretation of contractional faults and folds from the new seismic data in the Gullfaks field is difficult to explain in terms of extension alone. The generally N–S orientation of contractional structural elements in the area suggests E–W orientated axes of compression. In the light of the regional tectonics, a phase of simple E–W compression is hardly likely. The compressional elements are rather related to strike–slip movements along the NE–SW oriented fault system along the Tampen Spur. The major fault system near Gullfaks may thus be linked with the Møre–Trøndelag Fault Zone to the NE and probably experienced similar strike–slip movements.

The marked curvature of the major fault around Gullfaks would have caused local compression (transpression). The N–S trend of contractional structures in the Gullfaks area is suggestive of dextral transpression (e.g. Sanderson and Marchini, 1984) along the NE–SW lineament *(Figure 11)*. A dextral strike–slip shear would also explain the close relationship between the location of deeply eroded high structures and the curvature of the generally NE–SW faults which separate the Tampen Spur from the Viking Graben system. Where the NE–SW faults curve anticlockwise, the sediments are in their structurally highest position (and erosion is deepest). The interpreted strain ellipse during the strike-slip phase is shown in *Figure 11*.

There appears to be an inversion of the Brent Group in several places in the North Sea, and to various degrees this has been related to some component of strike-slip tectonics (e.g. Hancock, 1986; Larsen, 1987). The Gullfaks structure was close to sea level during deposition of the Brent Group, and the relatively higher source area is considered to have been to the south-west (Karlsson, 1986). The occurrence of marine shales of the Viking Group in the Gullfaks area indicates at least local marine conditions in the Upper Jurassic. The absence of Lower–Middle Cretaceous sediments and the presence of the very thin Upper Cretaceous sequence is obvious in the Gullfaks field. This indicates that the Gullfaks area changed from being relatively low in the Middle Jurassic to being a high which suffered extensive erosion in most of the interval Upper Jurassic to Middle–Upper Cretaceous. Even today the Gullfaks field is structurally high compared with the level of the Shetland and Horda Platforms, which may be considered as the margins of the northern North Sea Basin (Fig. 8, Beach, 1986; Beach *et al.*, 1987), especially if the deep erosion of the Gullfaks structure is considered. The inversion of the Gullfaks structure may be an indication of transpressional tectonics.

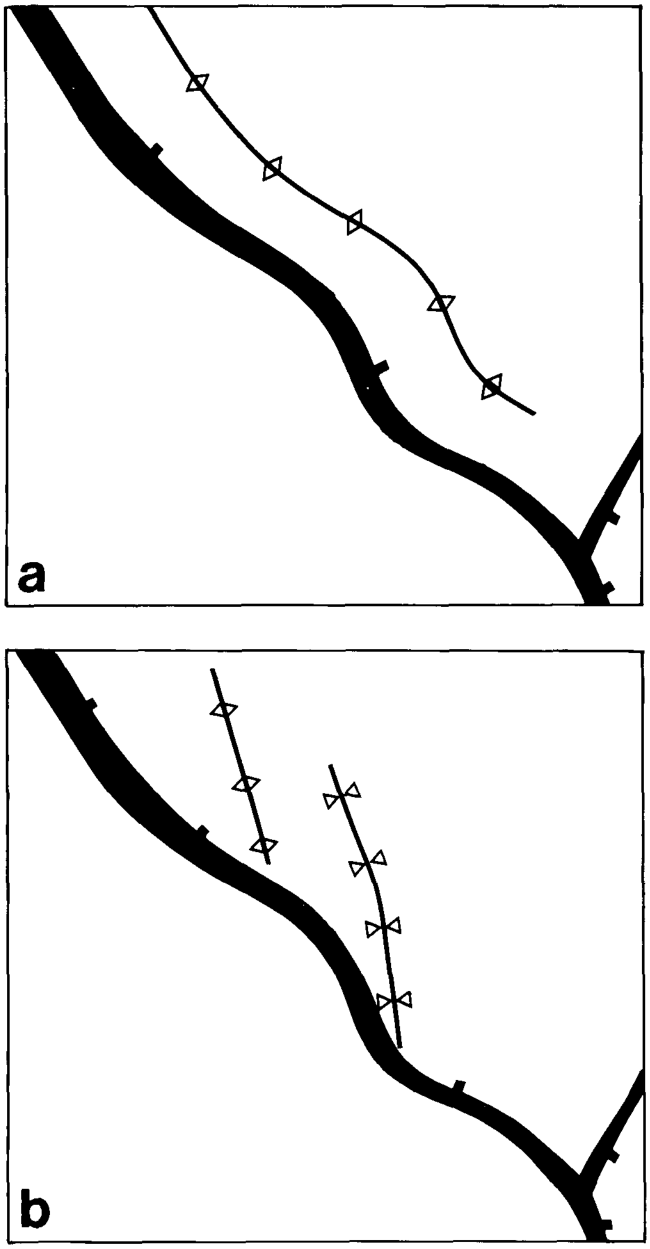


Figure 10 (a) Expected orientation of fold axis if due to simple extension. (b) Observed orientation of fold axes from the seismic data. Note angle between the fault and the fold axes

Timing of the transpression

The inversion of the Gullfaks and the Tampen Spur was predated by deposition of the Brent Group, and transpressional and possible transpressional structures are generally found in rocks older than the Upper Cretaceous sediments draping the structure. The Viking Group, and partly also the Cromer Knoll Group, are locally preserved on the structure, so it would seem that the deposition of the Upper Jurassic sediments predates at least part of the transpression. Several wells on the Tampen Spur show a hiatus in the Triassic–Barremian. This is not compatible with the well-known global rise in sea level at this time, unless the Tampen Spur was penecontemporaneously inverted. An Upper Jurassic–Lower Cretaceous date is in concordance with the timing of dextral strike–slip movements in the Møre–Trøndelag Fault Zone and the Kristiansund–Bodø Fault Complex (Grønlie and Roberts, 1987, and in preparation; Gabrielsen and Robinson, 1984). Late Jurassic to Early Cretaceous sinistral strike–slip movements along the Tornquist Zone (Fjerritselv Zone) and in the Norwegian block 15/9 (Pegrum, 1984) may or may not be complementary to these dextral movements.

Although most compressional tectonics probably occurred during the Malmian–Neocomian interval (Larsen, 1987), later Cretaceous to Tertiary strike–slip movements and associated inversions have also been proposed in the Southern North Sea (Bøen *et al.*, 1984), e.g., in the Gamma field (15/9) to the south (Pegrum and Ljones, 1984) and the Sele High (Hesjedal and Hamar, 1982) becoming gradually more pronounced towards the Alpine front. Weak Early Tertiary tectonics in Gullfaks *(Figures 4* and *5)* may be related to Tertiary movements with a strike–slip component. However, the limited amount of Tertiary structures in Gullfaks has made structural interpretations difficult, and no conclusions may yet be drawn about these features.

Conclusions

Seismic, structural and sedimentological features appear to indicate a transpressional event in the Gullfaks area after deposition of the Brent Group and prior to deposition of Upper Cretaceous sediments. Based on the orientation of structural elements in the area, the deformation is explained by dextral transpression along the NE–SW fault system defining the northeastern margin of the Tampen Spur. This

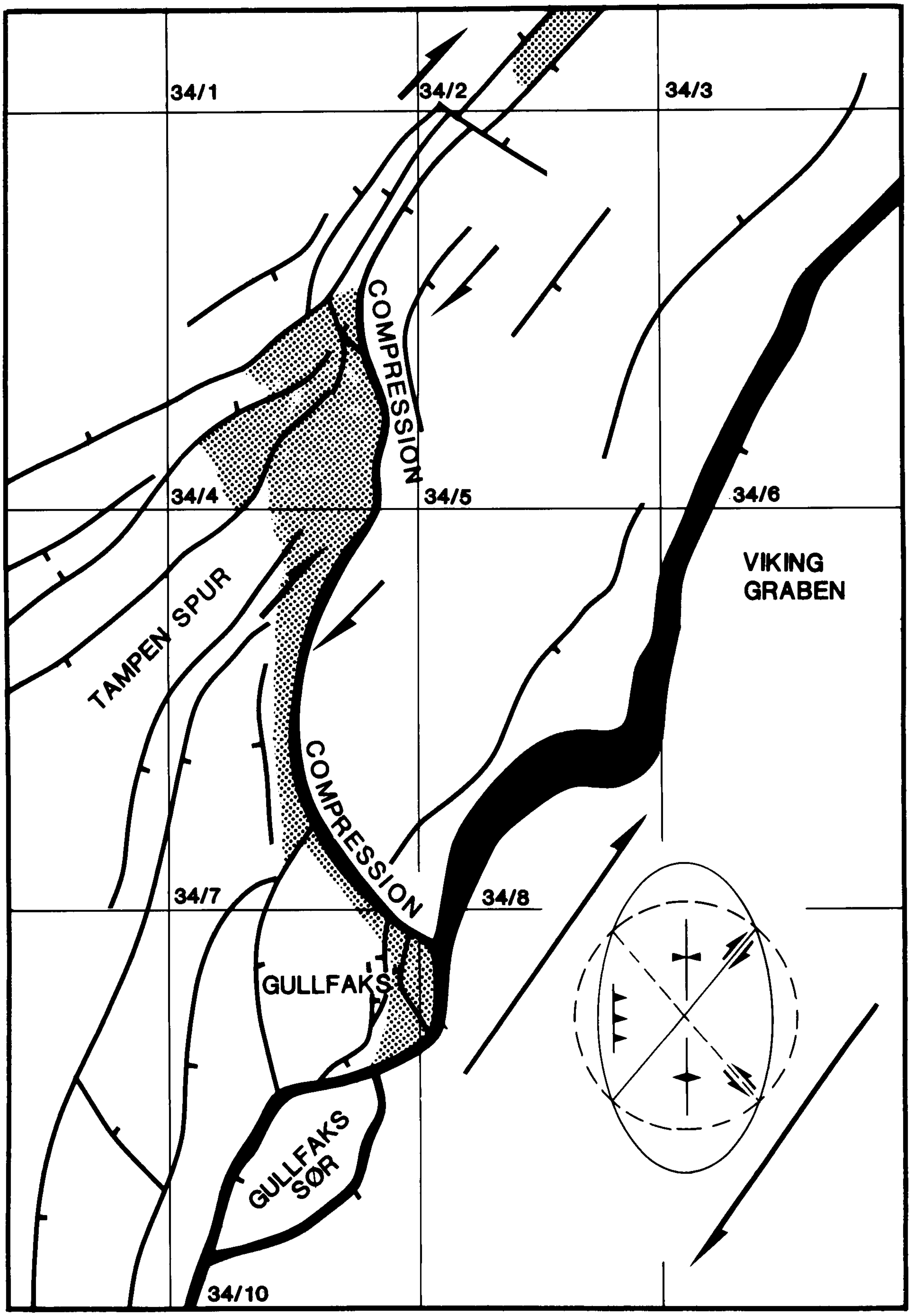


Figure 11 Simplified map showing the relationship between fault curvatures and erosion in the Tampen area. Shaded area: Statfjord Formation eroded. A strain ellipsoid is indicated, related to dextral shear along the NE–SW fault trend

deformation is interpreted as the southwesternmost expression of NE–SW dextral strike–slip movements along the Møre–Trøndelag Fault Zone and the Kristiansund–Bodø Fault Complex as indicated by Hamar and Hjelle (1984). A latest Jurassic to Early Cretaceous age for the major part of the transpression is confirmed, but a precise dating is difficult.

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