

Possible oblique-slip faulting in the Skagerrak Graben, as interpreted from high resolution seismic data

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A complex NE–SW-trending zone of deformation affecting Paleozoic sediments can be observed on high resolution seismic data in the Skagerrak. The fault zone corresponds to the northern margin of the Skagerrak Graben, as previously recognized on the basis of regional seismic data. However, rather than being a major fault with downthrow to the south, the apparent displacement on most lines is a downthrow to the north. In addition, in the west the sense of faulting is apparently normal, while to the east where the fault zone bends in an E–W trend it appears to be the reverse, with indications of compression. These observations lead to the interpretation that the deformed zone is the result of sinistral oblique-slip movements during the late Paleozoic. The observations appear to fit with the regional situation associated with the formation of the Oslo Graben in the late Carboniferous. East–west extension, which caused the normal faulting in the Oslo Graben, could have led to oblique-slip movements along an existing zone of weakness striking NE–SW where the movements would be sinistral.

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Introduction

In 1991, shallow seismic data covering about 1070 km were collected in the eastern Skagerrak area. The project was a continuation of a shallow seismic/shallow drilling project northeast of the Farsund Basin, and information and interpretation from this project could be transferred to the 1991 data. The aim of the Skagerrak project was primarily to investigate the Upper Paleozoic succession in the Farsund–Skagerrak area.

The seismic grid was located between 9° and 10° east, in the eastern part of the Skagerrak (Fig. 1), in an area known as the Skagerrak Graben (Ro et al. 1990). The data were acquired using a sleeve gun cluster, a 1200 m/80 channel streamer, and a 2.5 sec record length.

The Skagerrak Graben is thought to be part of the Oslo Rift System, the onshore parts of which, the Vestfold and Akerhus graben segments, are well described (e.g. Ramberg & Spjeldnæs 1978; Neumann et al. 1992). However, by contrast, the Skagerrak Graben is still in the early phases of investigation. The work that has been done so far is based largely on regional deep seismic data, and both the coverage and quality of the data limit definition of the structures present. The new high resolution seismic data provide an opportunity to investigate the northern boundary of the graben.

The Skagerrak Graben was named and described by Ro et al. (1990), based largely on the interpretation of Mobil Search Deep Seismic Line OG-7 (see also Huseby et al. 1988). The graben lies in a part of the Skagerrak that was largely unaffected by Mesozoic tectonics and was interpreted as an offshore continuation of the late Paleozoic Oslo Rift System. Paleozoic sediments have been recognized on the seismic data as dipping and

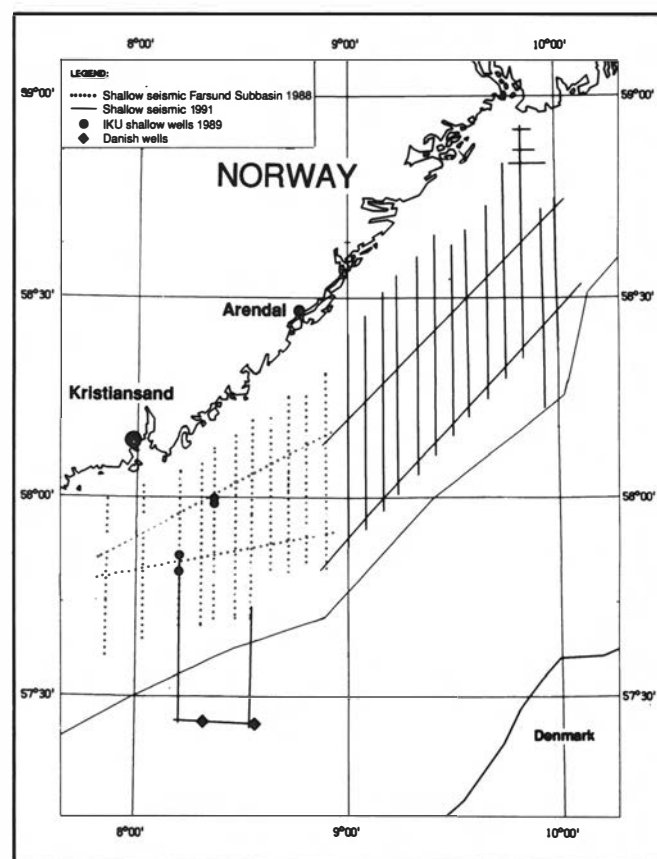


Fig. 1. Location of the 1991 seismic grid in the Skagerrak. Locations of 1989 seismic and shallow core holes in the Farsund Basin are also indicated.

faulted sediments unconformably truncated and overlain by flat-lying Mesozoic sediments. To the southwest the Skagerrak Graben is bounded by the NW–SE-trending

Sorgenfrei–Tornquist Zone, which extends from the Baltic through the Kattegat and into the Skagerrak area. In this zone Mesozoic sediments occur in a series of fault-bounded basins that developed during the Triassic to Cretaceous, but which were inverted in the latest Mesozoic and early Cenozoic. There is general agreement that the Sorgenfrei–Tornquist Zone was formed by dextral strike-slip movements in the late Paleozoic (Liboriussen et al. 1987) and that minor dextral movements continued throughout the Mesozoic (Mogensen & Jensen 1994).

Interpretation

The seismic data have been interpreted with the aim of identifying Upper Paleozoic units, and to locate areas where these rocks could be sampled by shallow coring. The main seismic feature on the data is a marked unconformity (TPZ) separating Mesozoic from Paleozoic rocks (Fig. 2). A total of five intra-Paleozoic horizons was interpreted, numbered upwards from 1 to 5. Horizons 1 to 3 are based on interpretation in the western part of the area (1988), during the shallow drilling project, and have been traced to the eastern part. Horizons 4 and 5 are identified in the eastern part, based on seismic character. On most of the N–S lines, however, a narrow disturbed zone made the correlation and interpretation of these horizons difficult. As neither the exact nature of the zone of deformation nor the position of individual faults is

apparent on the seismic data, we have shaded the area of disturbance on the seismic figures.

From the interpretation on the westernmost line (Fig. 2), there is an apparent displacement of about 600–700 ms twt down to the north of horizon 3, and normal faulting downthrowing to the north appears to be characteristic in this area. The zone can be observed on successive lines eastwards, and, occasionally, northward–downthrowing faults are seen to displace the Paleozoic–Mesozoic unconformity by small amounts, up to 100 ms (Fig. 3). In this part of the zone the Paleozoic reflectors are up-domed across the zone but the overall displacement is apparently small. Further to the east, the apparent displacement across the zone increases and the interpretation of southward-dipping faults implies a reversed sense of movement, with the southern (up-thrown) side showing signs of folding close to the zone (Fig. 4). Here the apparent displacement is considerable (>1500 ms?), but not well constrained. All these observations occur on the same NE–SW-trending fault zone (Fig. 5), with a consistent sense of displacement down to the north. Consequently, we appear to be seeing a situation where both extensional and compressional features are observed along the same trend. Even though the structure in Fig. 4 could be interpreted as a normal fault downthrowing to the north, we think the reversed sense of movement and the southward dip of the fault zone are the more likely interpretation. This is supported by the interpretation of the adjacent line to the west where the southward dip of the zone appears to be more tightly

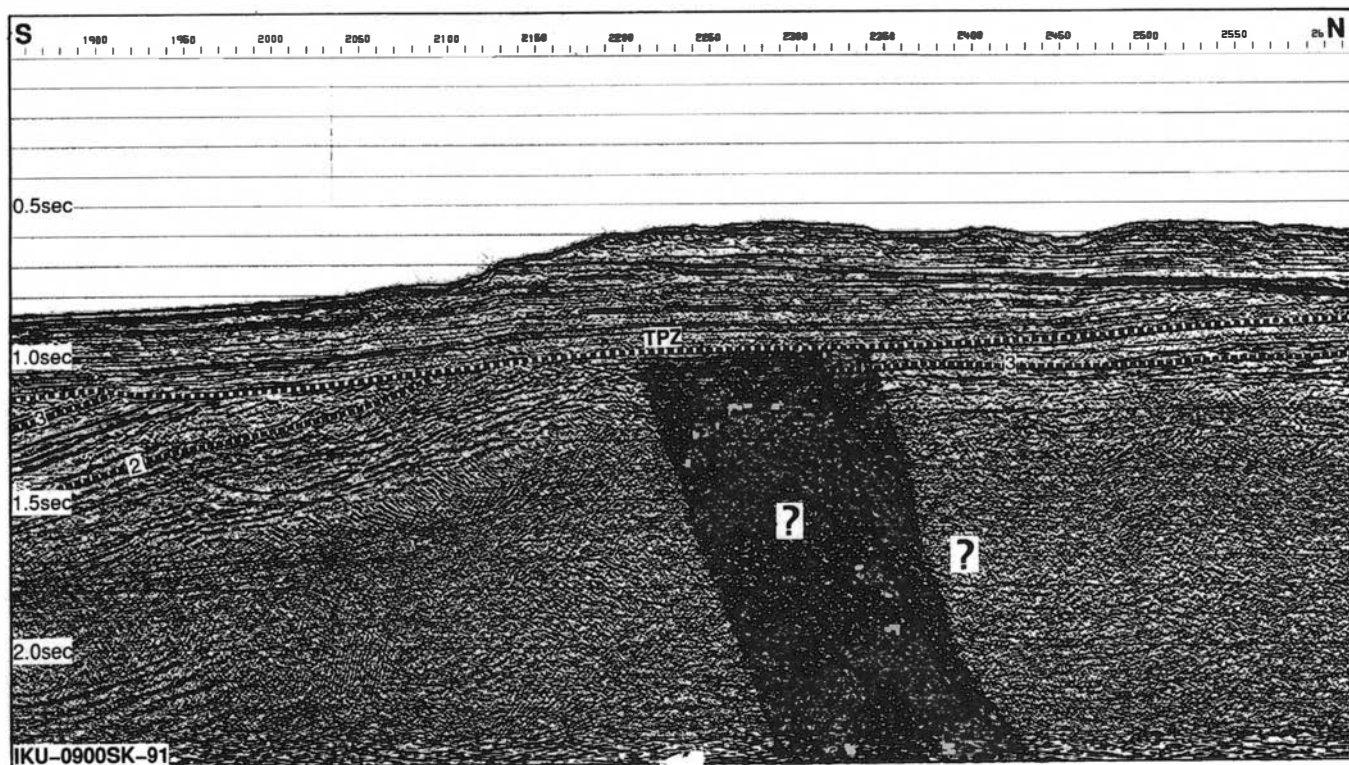


Fig. 2. Part of a seismic line from the Skagerrak survey (for location, see Fig. 5). Paleozoic rocks are separated from Mesozoic by the distinct unconformity 'TPZ' (Top Paleozoic). Numbers 2 and 3 refer to intra-Paleozoic horizons. The interpretation suggests that these horizons are displaced by about 600–700 ms twt down to the north across the 'disturbed zone'.

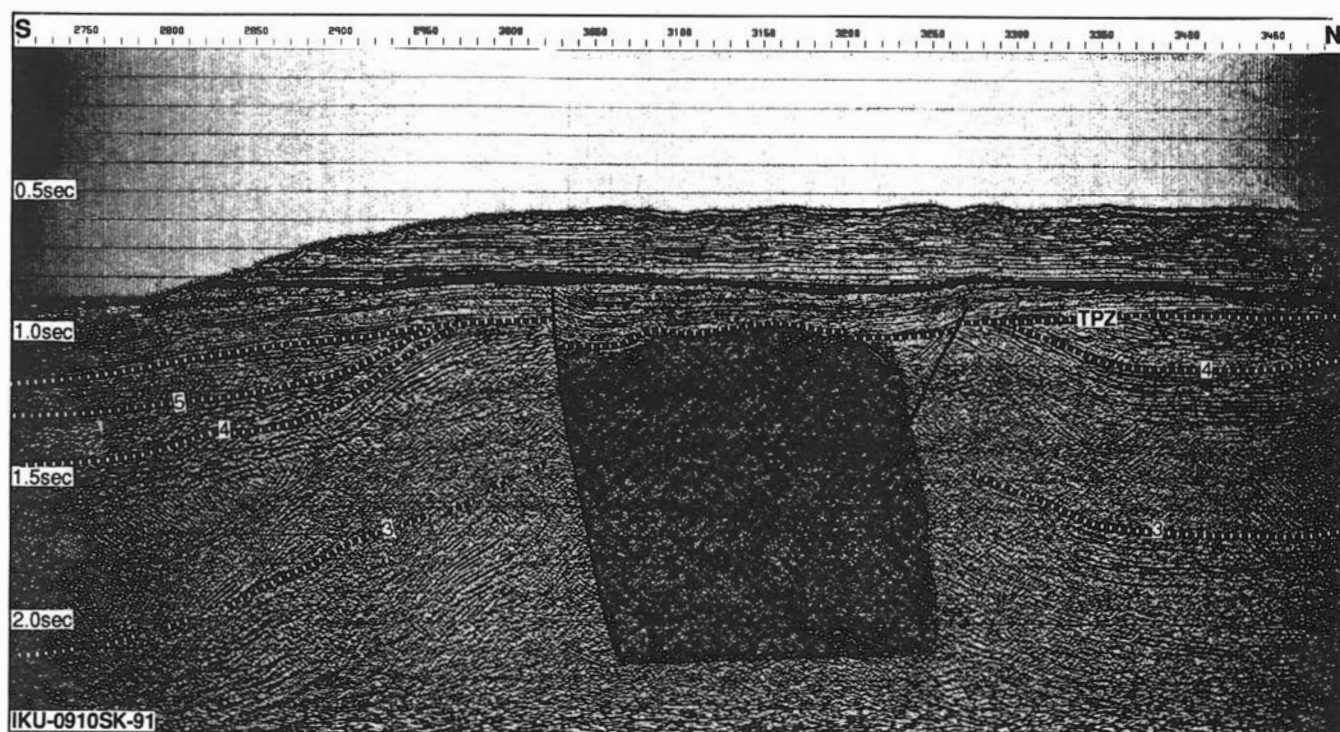


Fig. 3. Seismic example northeast of Fig. 2 (for location, see Fig. 5). Numbers 3, 4 and 5 refer to intra-Paleozoic horizons. Faulting affecting the Top Paleozoic unconformity (TPZ) has been reactivated in the Mesozoic. Note that the Paleozoic reflectors are upturned across the zone but that the overall apparent displacement is zero.

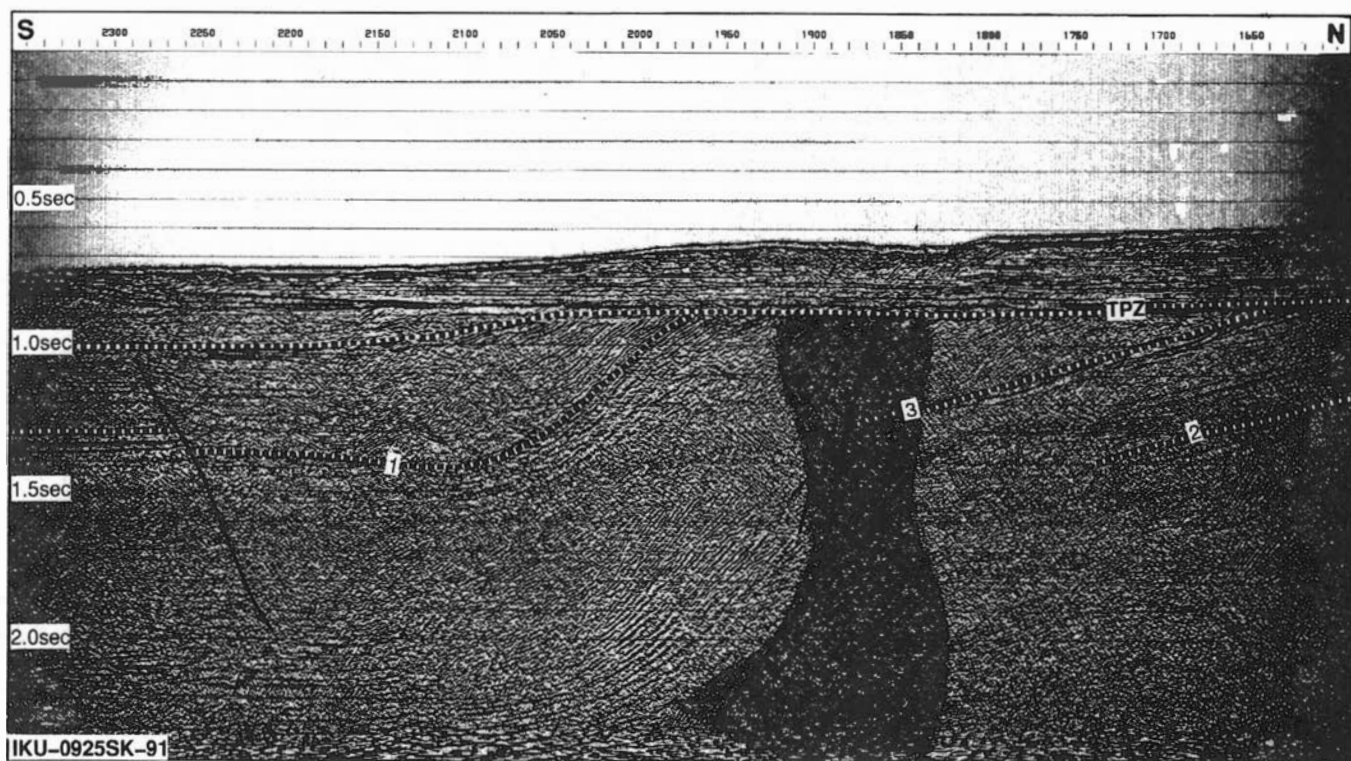


Fig. 4. Seismic line at the northeast end of the fault zone (for location, see Fig. 5). Numbers 1, 2 and 3 refer to intra-Paleozoic horizons. The vertical displacement across the fault zone appears to be considerable, and strong folding can be seen on the southern side. The fault is interpreted as southward-dipping, giving an apparent reverse sense of displacement.

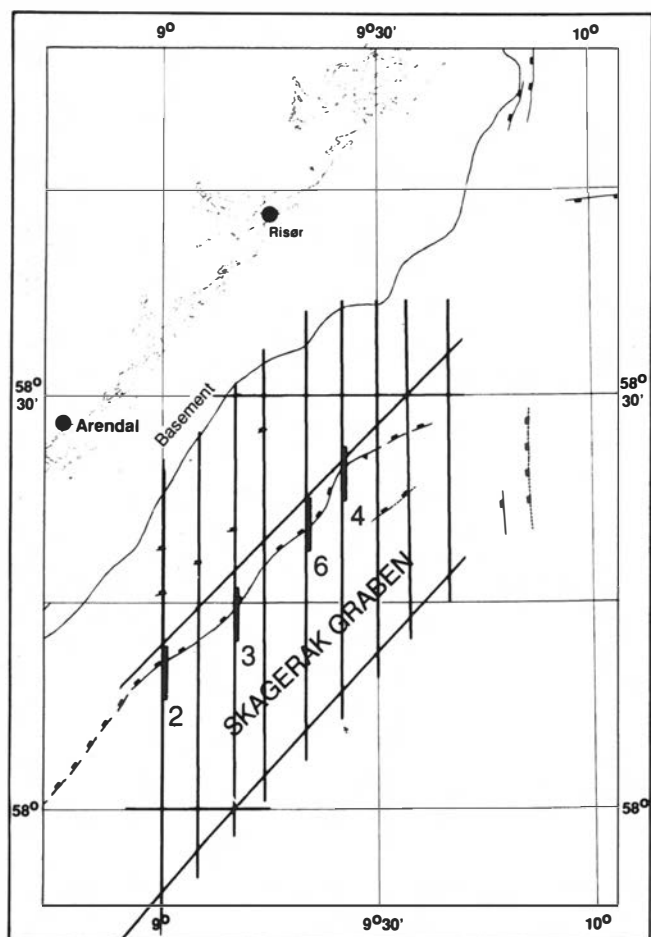


Fig. 5. Structural map of the study area showing the fault zone and other structural features. Part of the survey grid is superimposed (see Fig. 1). Positions of the seismic line figures are indicated by numbers.

constrained (Fig. 6). In conclusion, the most likely explanation for these observations is that we are observing a fault zone with an important component of strike-slip movement (i.e. an oblique-slip fault zone). Furthermore, the apparent vertical displacement seems to vary considerably, from several hundreds of metres to zero, along the strike.

Discussion

We believe that the proposed suggestion of an oblique-slip fault zone is the most likely explanation for the observed features; however, other explanations may be considered: for instance, it is possible that the disturbed zone is the result of igneous intrusions within the Paleozoic sediments. Permian intrusions are abundant in the Oslo Graben and it may be possible to identify them on the basis of geophysical anomalies in the Skagerrak area. However, intrusions will normally be seen on seismic data as high amplitude, discontinuous reflections. Such features have not been observed on any of the lines crossing the disturbed zone. In addition, magnetic and gravity anomaly maps (Hospers & Rathore 1984; Hos-

pers et al. 1985) show no anomalies that could be interpreted as intrusions occurring in the area of the fault zone. Likewise, salt intrusions are an unlikely possibility, as no salt is known from the Paleozoic sequences of the area.

From the map shown in Fig. 7, we can summarize the main characteristics of the fault zone: in the southwest it consists of several apparent normal faults, downthrowing to the north. In the centre is an area of little or no apparent displacement of the Paleozoic reflectors, although they are highly disturbed and updomed across the zone. To the northeast the zone turns eastwards in trend and has an apparent reverse displacement with folding in the hanging wall block. East of this point no clear indications of the zone can be observed, limiting its mapped length to approximately 45 km.

From geometric considerations (eastward bending of the fault zone) in the area where the possible compression and reversed faulting are observed, a sinistral sense of movement may be inferred (Fig. 7). In Fig. 7, a set of N-S-trending normal faults is shown. The relationship of these faults to the fault zone is uncertain but they may control its segmentation into areas of different displacements.

The faulting affects all the observed Paleozoic rocks, and, apart from the examples seen on one line (Fig. 3), does not extend into the Mesozoic. Therefore, a late Paleozoic age is attributed to the event or events which formed the fault zone. These could be coeval with the rifting events in the Oslo Graben, where a generally east-west extension caused normal faulting (Ramberg & Spjeldnæs 1987). However, in such a stress regime it is quite possible for oblique-slip movements to take place along existing fault zones or zones of weakness. With east-west extension, oblique slip will be sinistral along NE-SW trends, as inferred on the northern margin of the Skagerrak Graben (Fig. 8), and dextral along NW-SE trends, as reported from the Tornquist Zone (Mogensen & Jensen 1994).

The fault zone described in this article coincides with the northern limit of the Skagerrak Graben, as defined by earlier authors (Huseby et al. 1988; Ro et al. 1990), as a large, down-to-the-south normal fault that cuts the Paleozoic succession. From our interpretation of the high resolution seismic data, it appears that this is not the case in the study area. We observe that thick sequences of Paleozoic rocks are present in the area north of the fault zone, extending northwards to the boundary of the basement close to the Norwegian coast (Fig. 5). There are several possible reasons for the previous interpretations of the fault: first, the data coverage and quality were insufficient for detailed mapping; second, the northern boundary of the Skagerrak Graben is overlain by thick, possibly glacial sediments that obscure the proper interpretation of the underlying reflectors; and third, steep dips may be interpreted as faults on squash plots of the regional deep seismic data. It now appears that the tectonics of the Skagerrak Graben are not simple, but

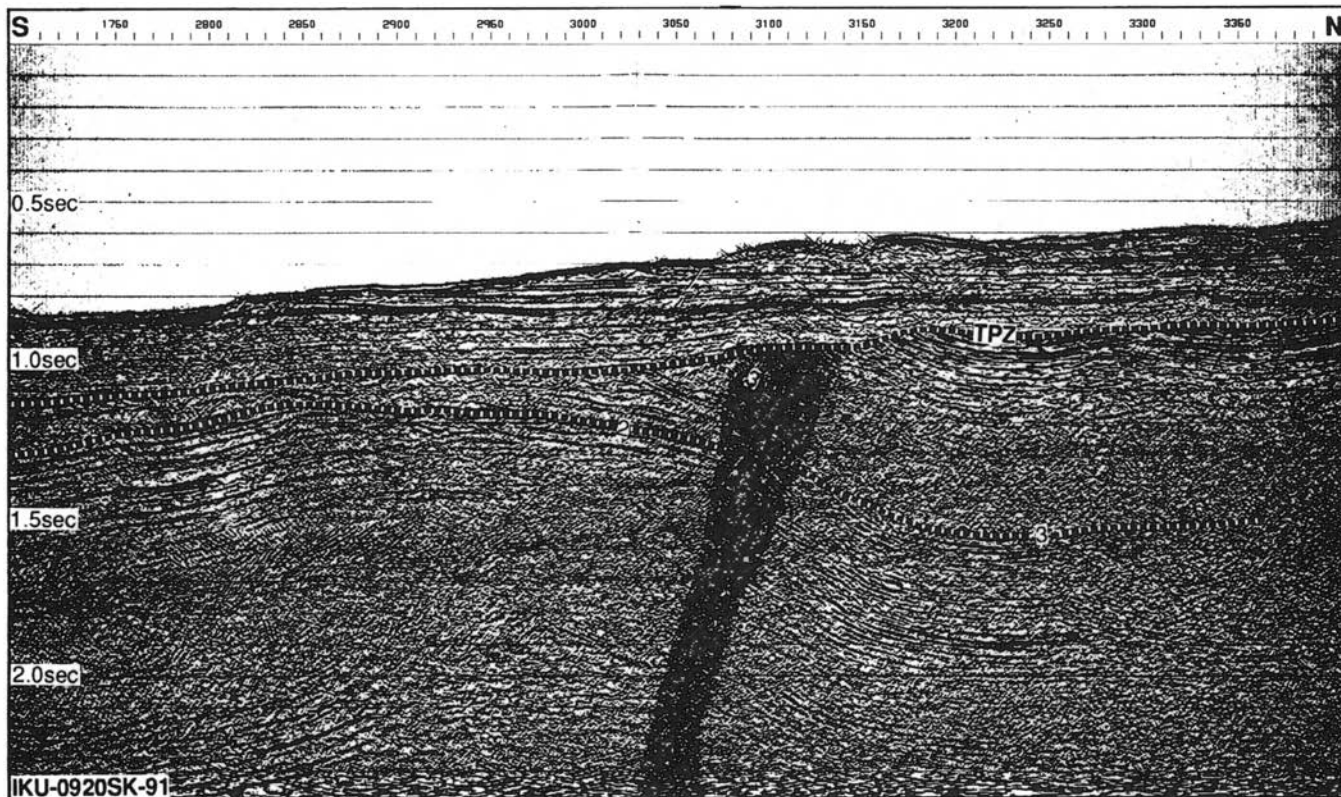


Fig. 6. Seismic example from the adjacent line to the west of Fig. 4. A southward-dipping fault zone and a reverse sense of movement are indicated.

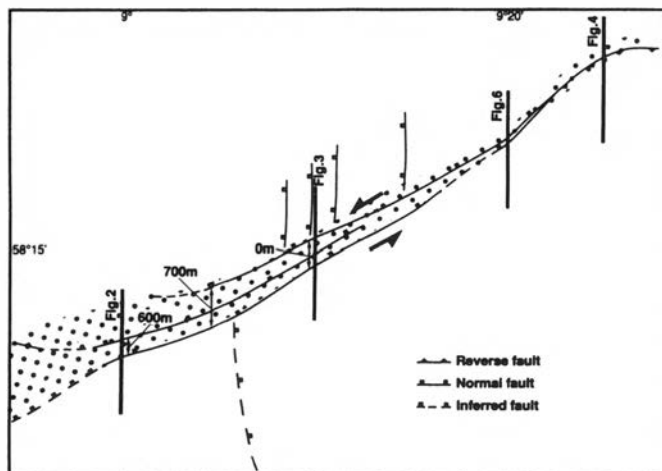


Fig. 7. A detailed map of the fault zone made from the high resolution seismic data. Note that the zone is widest in the southwest and narrows to the northeast where it bends to a more E-W trend in the area of Fig. 4. Note also the set of N-S faults that may be associated with the fault zone and that seems to influence the displacement across it (magnitudes of apparent displacement in metres are indicated).

may consist of several types of structural styles, of which the oblique-slip movements are an important element.

Conclusions

From regional considerations and observations on high resolution seismic data, it seems possible that complex

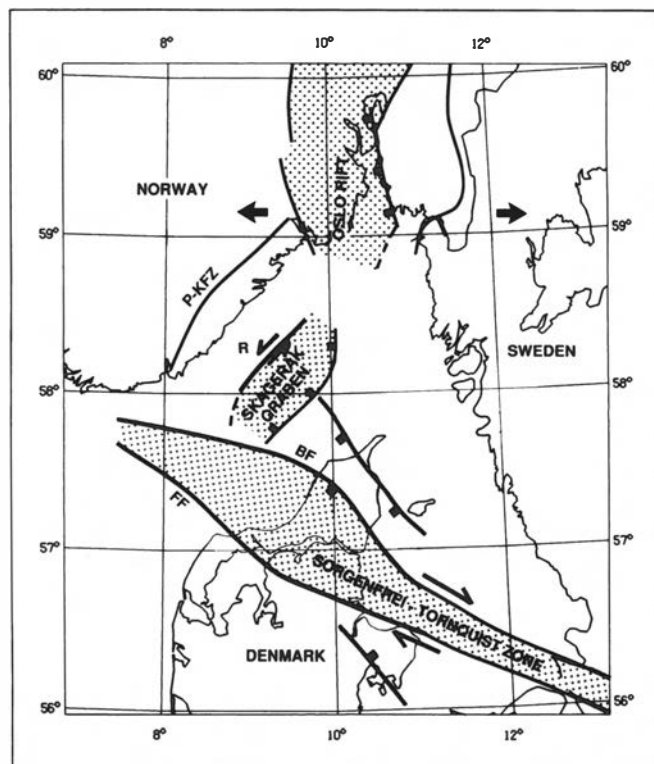


Fig. 8. Regional tectonic map showing the relationship between the Oslo Rift, the Skagerrak Graben and the Sorgenfrei-Tornquist Zone (modified after Ro et al. 1990).

but largely sinistral oblique-slip movements have taken place along a 45 km-long fault zone in the Skagerrak.

This feature forms the northern margin of the Skagerrak Graben and calls into question previous interpretation of this structure as a major normal fault downthrowing to the south or southeast.

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