Dating and measuring of erosion, uplift and subsidence in Norway and the Norwegian shelf in glacial periods

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The large Plio-Pleistocene deposits off the coast of Norway and in the Barents Sea indicate a significant increase in erosion rates and in vertical movements in Norway and the Barents Sea in the last 2–3 Ma. This activity had impact on several hydrocarbon accumulations on the shelf. Results from ongoing research projects suggest that parts of the Norwegian mainland were also uplifted in the Paleogene. In South Norway, important vertical movements are indicated later than 1 Ma ago, causing tilting of Lower and Middle Pleistocene sediments along the eastern boundary of the Norwegian Channel.

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Results from petroleum exploration in the Norwegian part of the Barents Sea indicate that in most of the explored area, several hundreds of metres of Tertiary and older sediments have been removed by erosion (e.g. Nyland et al., in press). In the northern and western parts, the erosion cuts into older rocks, and data from Bjørnøya and Svalbard suggest removal of as much as 3000 m or more of overburden in the Tertiary (Manum & Throndsen 1978; Wood et al. 1990). Figure 1 is based mainly on well data. In the north, contours are extrapolated by using bathymetry and outcrop patterns.

Studies of the properties of reservoir liquids and gases show that this amount of erosion will have a great impact on the petroleum accumulated in traps (Skagen 1990). The effects related to uplift and erosion in the Barents Sea are therefore now the subject of study in many oil companies and in the Norwegian Petroleum Directorate. Some of these effects are summarized in Fig. 2.

Large amounts of Tertiary erosion also occurred in the western part of Fennoscandia, and the deposition of the erosional products took place along most of the Norwegian shelf (Riis & Fjeldskaar, in press).

Biostratigraphic studies of the uppermost clastic wedges off the coast of central Norway and in the western Barents Sea (Eidvin & Riis 1989, 1991; Eidvin et al. 1991) indicate that an important part of the erosion in the whole region took place in the Late Pliocene and Pleistocene, and was related to glaciation. Similar conclusions were reached by Nøttvedt et al. (1988) and Vorren et al. (1990), although the dating of some of the stratigraphic units has been disputed.

In addition to the clastic wedges which can be correlated to the period of glaciation, Paleocene to Eocene depocentres can be identified in the northern North Sea, off Møre, in the Lofoten area and in the area west of the Stappen High in the Barents Sea. These depocentres could be related to the Early Tertiary opening of the North Atlantic, high heat flows and tectonic movement (Sales, in press). The central parts of the North Sea have a differing geological history with a more continuous subsidence through the Tertiary and in particular a thick Miocene section was deposited.

Therefore, a model for the Tertiary uplift and erosion north of 62° should be divided into a Paleogene part, which can be modelled by plate tectonics, and a recent part which is related to glaciations in the last 2–3 Ma (Eidvin & Riis 1989; Jansen et al. 1988). South of 62°, the geological development may have been more complicated.

Riis & Fjeldskaar (in press), calculated the isostatic responses of erosion from the Barents Sea and Fennoscandia and the corresponding deposition on the shelves. Using maximum models for the amount of glacial erosion (Figs. 1 and 3), they concluded that there is a component of tectonic uplift in Fennoscandia which cannot be explained by the calculation. This is consistent with modelling work by other authors (Doré, in press). Similarly, the subsidence of the shelves seems to be larger than what the models predict. The part of the uplift which cannot be modelled seems to be greater in the onshore mountain areas and smaller in the Barents Sea.

Uplift and erosion in the period of glaciations

The results of the regional study by Riis and Fjeldskaar (in press) caused the Norwegian Petroleum Directorate

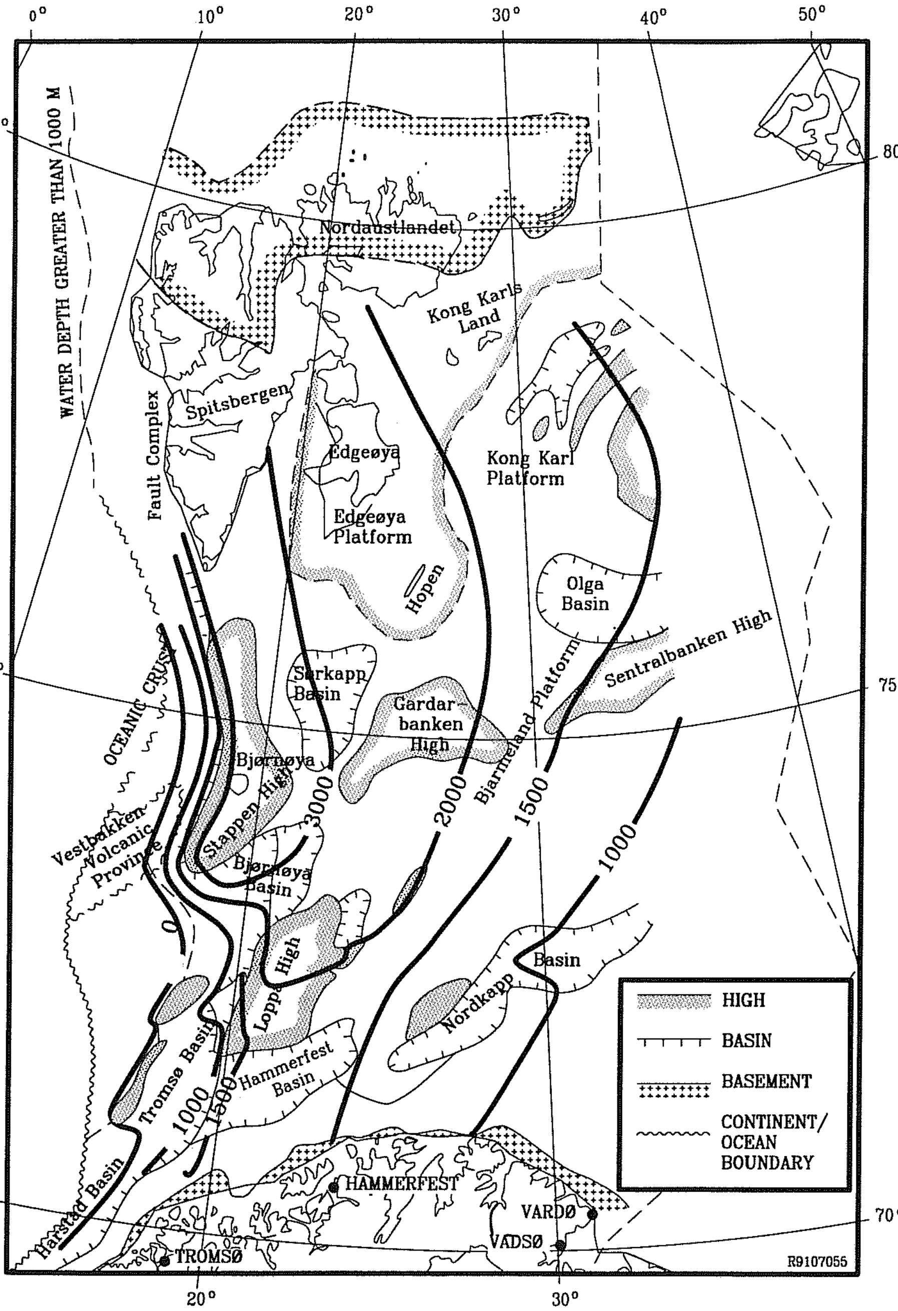


Fig. 1. Sketch map of the western part of the Barents Sea showing an interpretation of the amount of overburden which has been removed by erosion in the Tertiary and Quaternary. Contour interval 1000 m (500 m). The map is based mainly on geochemistry data from wells (vitrinite reflectance and pyrolysis T_{max} data) and on seismic interpretation of the reflector interpreted to represent the opal A to CT transformation. In the north there are few data points.

to concentrate its studies to the Norwegian Channel and southern-central Norway. The objective is to obtain more precise data on the timing and amounts of erosion, deposition and tectonic movements through the Late Pliocene and Pleistocene.

Different lines of approach have been used to obtain better data, and research carried out by several academic groups in Norway is essential for the project.

Precise dating within the Plio-Pleistocene section is important for correlation of major events between different parts of the shelf. Also, if the Neogene wedges can be divided into sedimentary packages of known age, a more detailed mass balance study can be made. The biostratigraphy (foraminifera) in the clastic wedges in the Northern North Sea, mid-Norway and Barents Sea was examined by Eidvin & Riis (1989, 1991) and Eidvin et al. (1991). In the Troll Field, core material allows dating of the complete Quaternary section in the Norwegian Channel (Sejrup et al. 1989; unpublished data).

The results indicate that the volume of late Pliocene sediments in the wedges exceeds the volume of Pleistocene sediments. In the Norwegian Channel, the basal glacial deposits are overlain by Lower to Middle Pleistocene marine clays and silts (Sejrup pers. comm.).

The calculations by Riis & Fjeldskaar (in press) were based on the assumption that it is possible to define

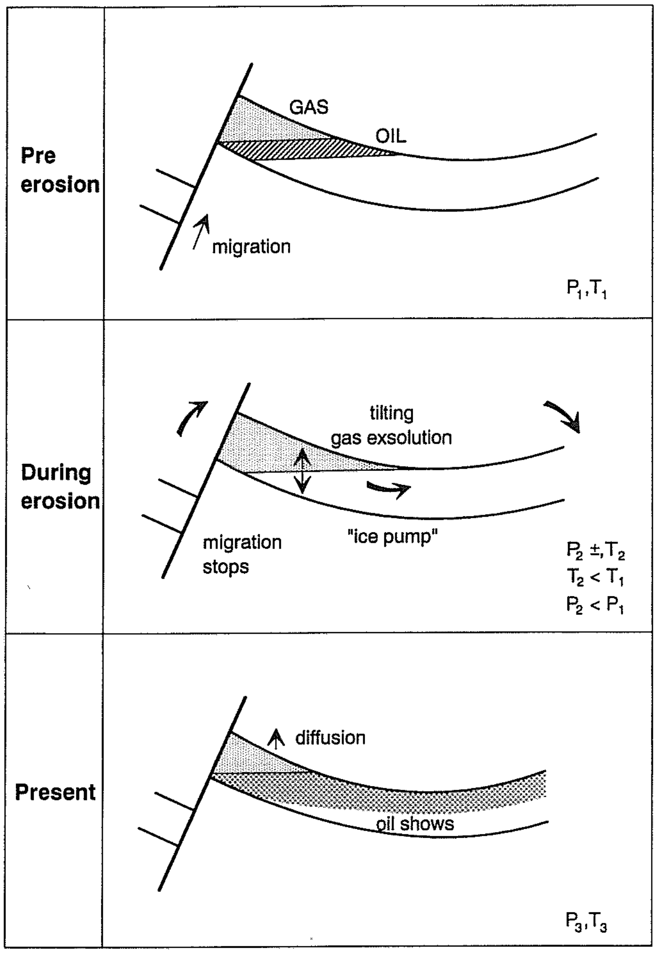


Fig. 2. Effects of erosion and uplift on hydrocarbon accumulations. If the cooling caused by erosion blocks the generation of hydrocarbons, oil will tend to be redistributed in the reservoir rock by the processes of gas expansion and gas exsolution caused by pressure and temperature drop. Tilting of the reservoir is an additional effect. It is also suggested that replacement of the water with a thick ice cap will result in hydrostatic pressures in excess below the ice. This would cause a free gas cap to contract, while it would expand when the ice melts. This is referred to as the 'ice pump' effect in the sketch.

certain morphological levels onshore which can be regarded as low relief plains formed relatively close to sea level. The erosion below these levels, and the deformation of the levels (Doré, this volume), will then give important information about the recent erosion and uplift. If the block fields as defined by Nesje et al. (1988) represent pre-glacial weathering surfaces, the block field level could represent such a marker surface. This level can be defined in the mountains of South Norway and North Norway (Thoresen 1990).

Also, the topography of the paleic surface (Gjessing 1967) as mapped by Nesje (reported by Riis & Fjeldskaar, in press) contains important information. Nesje et al. (in press) calculated that the volume eroded below the paleic surface in the Sognefjord basin exceeds 7000 km^3, corresponding to an average erosion of more than 600 m in the drainage area of the Sognefjord. Using an average Quaternary thickness of 250 m in the Norwegian Channel, the eroded volume exceeds the sediment volume deposited in the Quaternary in the northern part of the Norwegian Channel between 61° and 62°30′.

This study therefore gives an impression that the paleic surface in the Sognefjord area could have existed prior to the major glaciations in the Quaternary. However, more exact volume comparison must await better data of the outer parts of the Plio-Pleistocene wedge off the Norwegian Channel where a large volume of Pleistocene sediments was deposited. As is indicated in Fig. 3, there is a great Pliocene–Pleistocene sediment volume in the wedge, so the mass balance method does not necessarily indicate a pre-glacial minimum age for the paleic surface in West Norway.

Another approach to the detailed study of the onshore uplift and erosion is to examine the cave deposits in the major caves in Nordland, Central Norway. Some of the larger caves show erosion levels which can be dated by speleothems, and ages back to at least 300,000 years have been reported (Lauritzen et al. 1990). These deposits are the oldest post-Cretaceous deposits recorded so far onshore in Norway. Since there are mountains rising more than 1000 m above the dated levels in the caves, these data suggest that a considerable relief existed far back in the Quaternary in Central Norway, and that the onshore uplift was not pronounced in the last few hundred thousand years in this area.

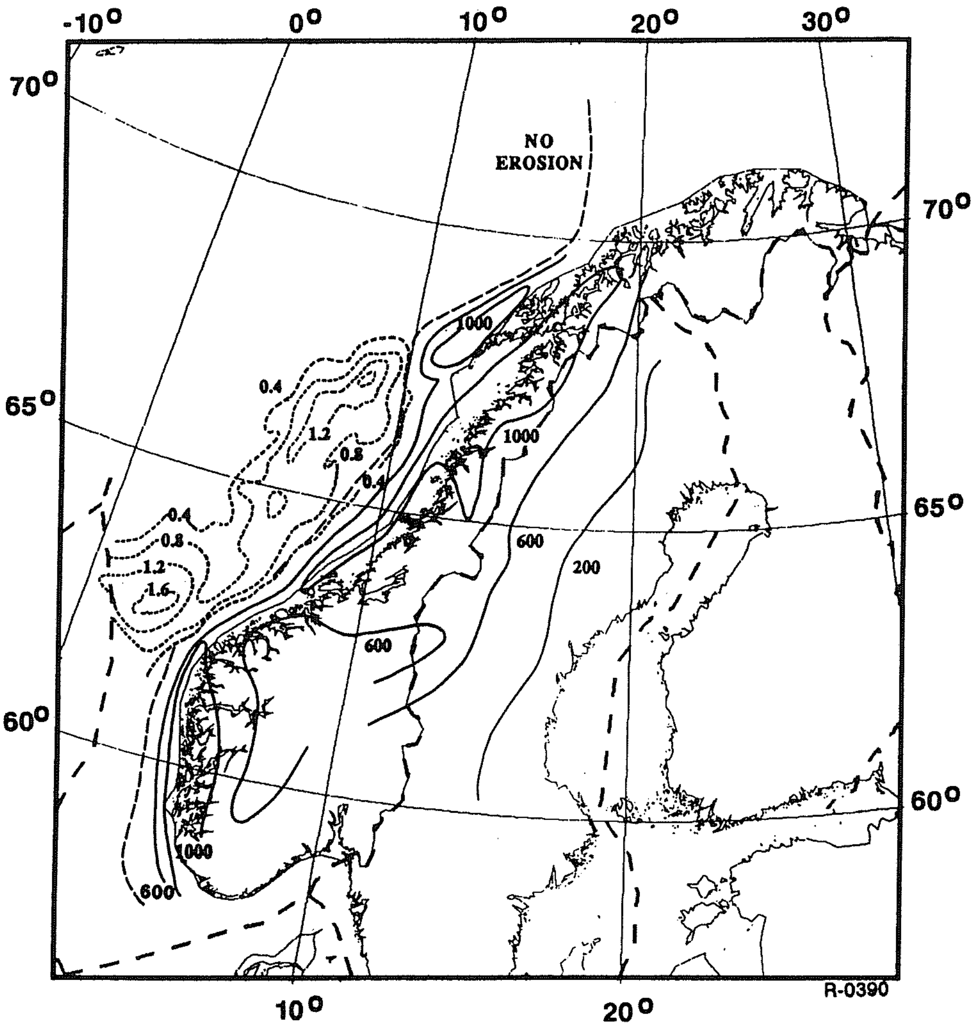
The study of neotectonics may also give relevant data on the uplift problem. Neotectonics in Norway is mainly related to the glacio-isostatic rebound. The present uplift rates seem to be fairly regular on a regional scale (Sørensen et al. 1987). However, detailed studies across fault zones indicate that differential movements may take place locally (Anundsen 1990; Olesen et al., in press).

The neotectonics is also strongly related to earthquake activity. The seismic activity of Norway is concentrated along some of the well known major fault zones and rifts (Bungum et al. 1990). Also, on the maps produced by Bungum et al. (1990), it can be noted that there is a concentration of epicenters along the west coast of Norway, in the area where the Tertiary and Quaternary erosion was at a maxium, and where Quaternary vertical movement took place along the Norwegian Channel as discussed below. Bungum et al. (1990) suggest that 'ridge push', sedimentary loading effects and postglacial uplift are important sources of stress.

Similarly, it is suggested here that the vertical movements observed today could have one short-term component related to glacio-isostasy and one component which is a response to forces and loads acting over longer periods of time.

Quaternary vertical movement along the coast of South Norway

In the platform areas along the coast, Mesozoic and Cenozoic strata have a regional dip away from the coast.



— — — — — SUBCROP OF WEDGE

······0.8······ THICKNESS OF PLIO-PLEISTOCENE WEDGE IN TWO WAY TIME

——1000—— EROSION IN METERS

Fig. 3. Composite map showing the averaged amount of overburden removed between the present surface and the summit level in Mid-Norway, as well as an isopach map in two-way time of the thickness of the Plio-Pleistocene wedge deposited off Mid-Norway.

In an outcrop map this results in a geometry where the different horizons parallel the coast (Rokoengen et al. 1988; Sigmond, in press). The tilted layers are truncated by the base of Quaternary unconformity (Fig. 4), suggesting a late Pliocene or early Quaternary phase of tilting.

However, seismic lines shot close to the coast of SW Norway may be interpreted to show tilting of even the Quaternary beds. The tilted area is located at the eastern flank of the Norwegian Channel, and only the deeper parts of the Quaternary section have been locally preserved from later erosion. Fig. 4 shows an interpretation of parts of two shallow seismic sections close to the island of Utsira (profiles AA′ and BB′). The seismics was acquired for IKU by Geoteam.

In these seismic sections, the older part of the Quaternary section dips to the west, and there are at least two erosional events (tentatively correlated with major phases of glaciation) in the upper part of the section.

Obviously, care must be taken to distinguish dips due to progradation and dips due to draping over pre-existing topography from tectonic tilting of the layers. The suggested tectonic tilt is based on the following description of the sections.

The base of the Quaternary section (BQ, Fig. 4) is an angular discordance which truncates dipping Mesozoic and Tertiary sediments. This unconformity is close to horizontal in the Norwegian Channel, but along a coast parallel line, this horizontal attitude changes to a pronounced dip towards the channel. The dip is apparently not related to lithological changes in the underlying sediments (Fig. 4, profile AA′).

The section overlying the unconformity is interpreted as a Lower Pleistocene basal till succeeded by marine sediments which in the lower part are older than 0.7 Ma (Sejrup pers. comm.). These marine sediments are well developed with a consistent reflection pattern in the northern part of the Norwegian channel. In general they

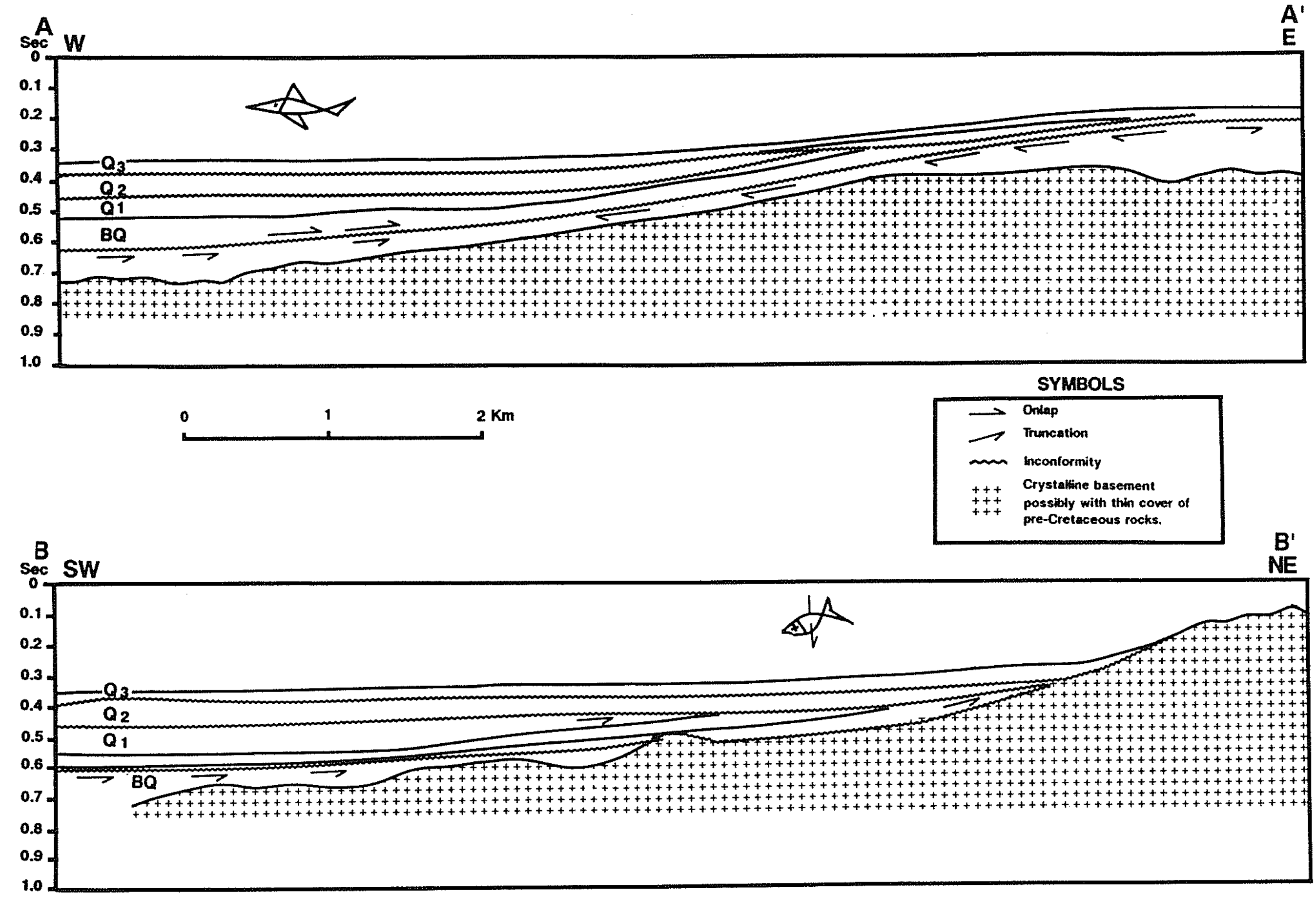


Fig. 4. Two geoseismic sections in the Utsira area, southwest Norway. The interpretation is based on seismics collected by IKU in 1988. Onlaps and truncations are indicated by arrows.

are parallel to the basal unconformity, but in the western flank of the channel, they onlap the base of the channel. However, on the eastern flank, which at present has a much more pronounced topography, these reflectors continue to be parallel with the basal unconformity even in the dipping part of the section. Onlaps can be defined only in a small area in the deepest part of the channel. Farther updip, there is little change in thickness in the dipping lower Quaternary section (Fig. 4).

The unconformities Q1 and Q2 (Fig. 4) which are interpreted as erosive events in the channel, do not tend to erode into the dipping part of the section, rather these unconformities also show dips indicating a progressive tilting taking place.

The difference in elevation of the base of Quaternary across the structure in Fig. 4 is in the order of 350 m, and it is thought that an important part of this differential uplift must be explained by tectonic movements.

Similar observations can be made in selected localities also along the coast of Jæren (Fugelli & Riis, in press) and north to Møre. In Fig. 5, the coastal hinge zone has not been drawn continuously to the north because of erosion of the key area close to the coast. Onshore, the Quaternary geology of Jæren suggests important vertical movements as recent as approximately 100,000 years (Fugelli & Riis, in press).

In conclusions, it is suggested that relative vertical motion in the order of several hundred metres could have taken place in the Quaternary along a gentle monoclinal structure (hinge zone) parallelling the west coast of southern Norway. The hinge zone cannot be mapped in detail, because the older Quaternary sections are too deeply eroded in many localities. However, the hinge zone seems to parallel more or less the bathymetrical eastern slope of the Norwegian Channel. It parallels the boundary of outcropping basement, and it has a trend similar to the major faults separating the Triassic-Jurassic fault blocks of the Horda Platform from the uplifted basement block of the continent. However, these faults are situated to the west of the hinge zone (Fig. 5).

If this interpretation is correct, it will be important for the modelling of the tectonic events since the motion was more rapid than previously anticipated. Also, our understanding of the tilting and migration of hydrocarbons into the Troll Field reservoir will be affected, since the Troll Field is within the zone of tilted Tertiary strata and fairly close to the Quaternary hinge zone (Fig. 5).

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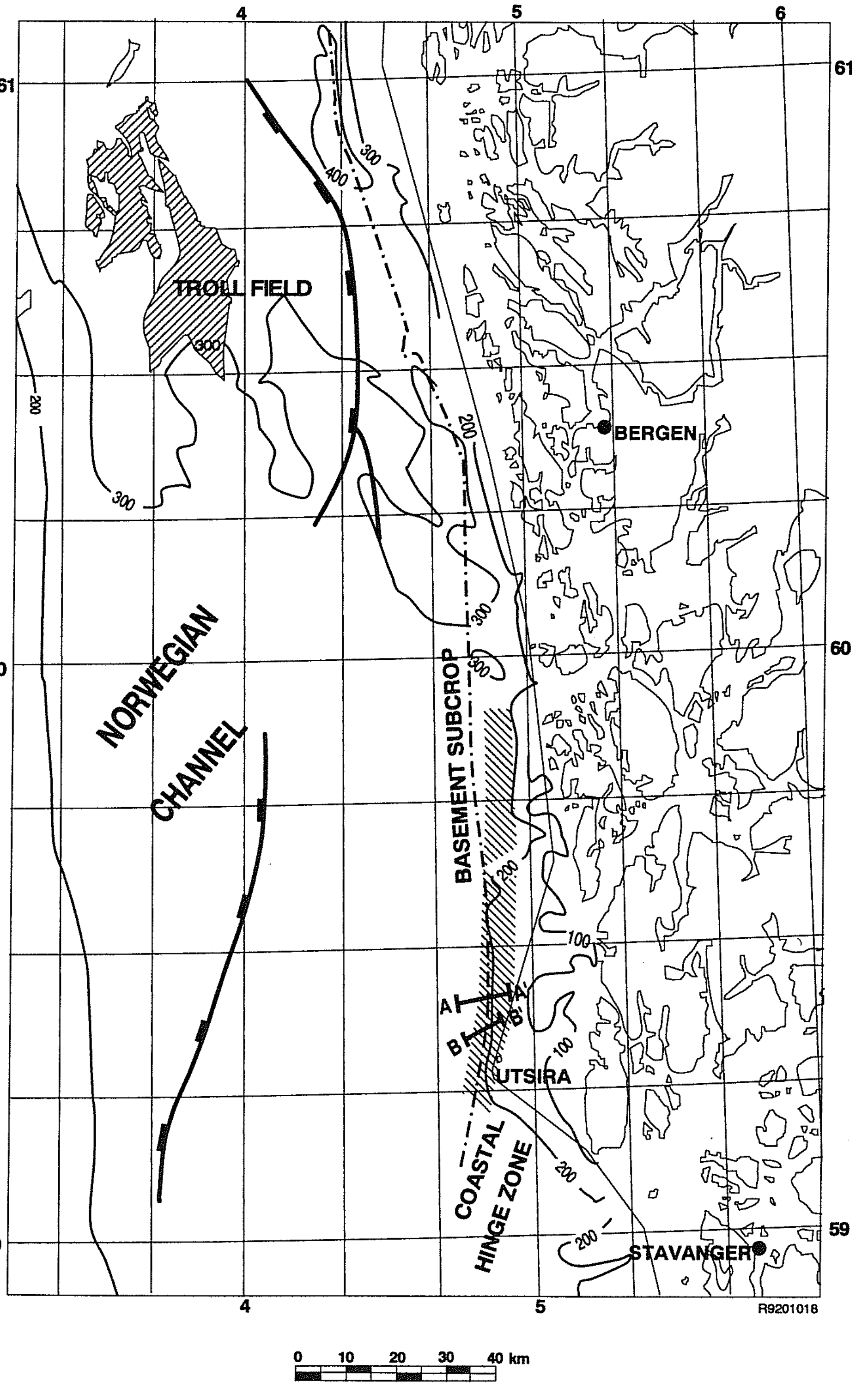

Fig. 5. Tectonic map of a part of the Norwegian Channel, showing bathymetry (contour interval 100 m), locations of the profiles AA′ and BB′, as well as the main faults and the basement subcrop below the Quaternary, modified from Brekke et al. 1992. The faults are mapped at the Base Cretaceous level, and they separate the faulted Triassic basins to the west from the upthrown crystalline basement to the east. The coastal hinge zone indicates the area where Quaternary layers are dipping. This zone probably continues to the north, but is difficult to map due to lack of data and deep erosion into the older parts of the Quaternary section.

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