NEONOR
Neotectonics in Norway

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Summary:

Geodynamic modelling of the present crustal uplift indicates that the uplift of western Norway and northern Norway is partly due to other mechanisms that the glacioisostatic rebound. We have also deduced a new model based on the 'seismic pumping' mechanism to explain the observed correlation between land uplift and groundwater yield in Norway. Rock avalanches and landslides represent the most hazardous effects of earthquakes in Norway with its mountainous terrain, deep fjords and relatively large areas with unstable quick-clay. New seismic mini-arrays in the Ranafjord area and the northern North Sea have sharply defined zones of increased seismicity. A total of 350 earthquakes have been detected in the outer Ranafjord area during the project period (2½ years), with magnitudes up to 2.8. This is very high for onshore Baltic Shield areas. The return periods of magnitude 6 and 5 earthquakes have been estimated to 1500 and 130 years, respectively. The M6 earthquake in 1819 in Mo i Rana triggered several rockfalls and a landslide.

Existing neotectonic claims have been graded into five classes based upon careful field investigations wherever possible. After a critical evaluation of 64 neotectonic claims in Norway we have classified five claims as 'A - Almost certainly neotectonics' and another five as 'B - Probably neotectonics.' The majority of the claims can be attributed to effects other than tectonic. The present grade A claims include postglacial faults and earthquake swarms in northern Norway. The grade B claims include a potential postglacial fault and areas with large numbers of rock avalanches and other collapse structures in northern and western Norway. The Nordmannvikdalen fault in northern Troms and the Stuoragurra Fault in western Finnmark constitute the Norwegian part of the postglacial Lapland Fault Province. The former is a normal fault trending perpendicular to the extensive system of NE-SW trending reverse faults in northern Fennoscandia. The Stuoragurra Fault has an anomalous high content of water and CO_2. The gas may originate from the deep crust or the mantle. There are evidences of three separate large-magnitude earthquakes in the Finnmark-Troms area during the period 9,000-11,000 BP. Indications of large earthquakes have also been observed in western Norway. There are for example evidences of two separate events 2,000 and 7,000 years ago in Møre & Romsdal. The latter may be related to the triggering of the Storegga avalanche.

Detailed analysis of offshore 2D and 3D seismic data has not clearly indicated any neotectonic deformation (contrary to expectations). Several distortions in the Quaternary reflectors have, however, been mapped in the northern North Sea area. Some of the interpreted subtle features represent faults associated with gas leakage. There was most likely a major seismic pulse in mainland Fennoscandia and Scotland accompanying each of the deglaciations following the multiple glaciation cycles during the last 600,000 years. It is possible that the interaction of the contraction and dilation of fissures associated with these seismic cycles may have assisted in concentrating hydrocarbons from their source rocks and pumping them to reservoir formations or pockmarks at the sea floor. Neotectonic activity in the Etne, Rana, Masi and Kåfjord areas seems to have influenced the groundwater flow.

Keywords:	Geologi	Skred	Seismologi
	Geofysikk	Geologisk risiko	Forkastning
	Neotektonikk	Landhevning	Fagrapport

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Enclosure: Neotectonic map of Norway and adjacent areas, Scale 1: 3 million

i)   Preface

Even the average layman today is familiar with the concept of plate tectonics, implying that relatively stiff crustal plates move and interact in ways that are easily observable, even to the untrained eye (mountain chains, fault systems, earthquakes, volcanoes, etc.). In the interiors of plates, however, similar indications of recent crustal movements are less apparent, even though indications of major deformations in the geological past are easily seen in most places. From time to time we are reminded through earthquakes above 7 on the Richter's scale, that the plate interiors are not as rigid as first predicted by plate tectonic theory. A variety of more subtle indications of recent crustal movements in intra-plate areas are also noticeable, to the trained eye at least. Such indications of neotectonic activity and movements have been reported in Norway as 'claims' since the 1880's, increasing steadily in number. A few years ago it was realised that our understanding of these claims did not advance at pace with the increasing number, and the present research project on 'Neotectonics in Norway' (NEONOR) was proposed. Along with the aim to investigate in detail the various neotectonic claims, the project also defined a number of strategies for studying these problems, and to combine these studies through inter-disciplinary approaches.

The NEONOR project represents a national effort initiated by NGU, NORSAR, NPD and SK to investigate these phenomena through a multidisciplinary approach. Both the industry and the Norwegian Research Council have contributed with major financial support. One Dr. Scient fellowship at NORSAR/University of Oslo and one post-doctoral fellowship at NGU have been financed by the Norwegian Research Council. The work of these two research fellows has represented essential parts of the project. The NEONOR Project has also received financial support from the three petroleum companies BP-Amoco, Norsk Hydro and Phillips Petroleum and the Norwegian State hydro-power company Statkraft. Mark Shahly, Chris Dart, Robert Hunsdale (Philip J. Goldsmith until August 1998) and Ivar Hågensen were representatives of the four industrial partners in the steering committee. Dagfinn Rise (Statkraft), Per Christian Alsgaard (Amoco Norway) and Pål Haremo, Bjørn T. Larsen and Tor Harald Hanssen (Norsk Hydro) participated in the initial phase of the project. Dr. John Adams from the Geological Survey of Canada and Professor Arthur Sylvester from the University of California (Santa Barbara) visited NGU in February 1997 and August 1998, respectively, and contributed with valuable advice to the project.

The present document reports the main results from the activities that have been carried out by NGU, NORSAR, NPD, SK, NTNU, SINTEF, Rogaland Research, NTNU and the University of Oslo during the period 1997-1999. The activities have also been reported in the NEONOR annual technical reports all edited by Dehls & Olesen (1998, 1999, 2000) and a field excursion guide to Finnmark and Troms (Dehls *et al.* 1999). Chapters 1 and 2 of the present NEONOR Final Report deal with the onshore and offshore neotectonics, respectively, in Norway. Chapter 3 provides information on the present crustal stress, seismicity, seismotectonics and a geodynamic modelling of these data sets. The last chapter presents the neotectonic map of Norway and adjacent areas at a scale of 1:3 million (Dehls *et al.* this report). Parts of Chapters 1 & 3 will be published in a special neotectonics volume of Quaternary Science Reviews (Dehls *et al.* in press, Fjeldskaar *et al.* in press, Hicks *et al.* in press, Roberts in press). Olesen *et al.* (1999a) have reported a popular scientific paper on the project.

ii)   Technical summary

The main objectives of the NEONOR Project have been to systematically collect data, and to provide answers to the questions: 1) How can recent crustal deformation be characterised in time and space? 2) Which processes cause the neotectonic crustal deformations? 3) What are the implications for the migration and occurrence of fluids in bedrock and for geohazard related risk to the construction of sensitive installations such as pipelines, gas terminals and hydropower plants. We have within the project emphasised the quality analysis of existing neotectonic reports to establish a foundation for neotectonic research in Norway. Information on contemporary land uplift, seismicity and rock stress in addition to Neogene domes, depocentres and volcanic rocks and postglacial faults is compiled in a GIS (ArcInfo), which has founded the basis for the production of a 1: 3 million neotectonic map of Norway and adjacent areas. The map is enclosed in the present report, but is also accessible through the Internet. New geophysical, geodetic and geological data have been acquired to improve our knowledge of neotectonic deformation in Norway. These data sets include seismicity from mini-arrays, marine seismic profiling, multi-beam echo-sounding, ground-penetrating radar, precision levelling, *in situ* stress measurements, triangulation and GPS measurements. The shallow parts of 8 seismic 3D cubes (located in seismically active areas) have been studied to try to locate potential Quaternary deformation. The onshore geological studies include mapping, drilling, trenching and ^{14}C dating. Results from separate rock-avalanche projects in Troms and western Norway (NGU) and the Seabed Project (NORSAR/NGI/UiO/SINTEF) have been included. The present report therefore constitutes a synthesis of the combined knowledge on neotectonics in Norway today.

Sites with neotectonic deformations

Existing neotectonic reports have been graded according to the quality of the neotectonic claims into the classes: (A) Almost certainly neotectonics, (B) Probably neotectonics, (C) Possibly neotectonics, (D) Probably not neotectonics and (E) Very unlikely to be neotectonics. The most likely cause of the proposed neotectonic deformation has been identified, whenever possible; e.g. tectonic faults, gravity-induced faults, erosional phenomena, overburden draping of bedrock features and stress release features. After a critical evaluation of 64 neotectonic claims in Norway we have graded 5 claims in both of groups A and B. The present grade A claims include the postglacial faults in Masi and Kåfjord and the earthquake swarms in Steigen, Meløy and Sjona-Ranafjord. The grade B claims include possible movements along the Båsmoen Fault in Rana, gravitational spreading and faulting features (sackungen) on Kvasshaugen in Beiarn (Nordland) and Otrefjellet in Haram (Møre & Romsdal). A series of gravitational-fault systems and large rock avalanches in zones from Odda to Aurland (Hordaland and Sogn og Fjordane) and in northern Troms has been classified as grade B. The gravitational spreading, gravitational faults and large-scale rock avalanches are caused by

gravity collapse, but their spatial occurrence and the relative gentle slopes related to some of the features strongly indicate that another mechanism is necessary to trigger the features. This extra loading is most likely to have been caused by strong shaking from large-magnitude earthquakes.

Our work supports previous conclusions appealing to a major seismic 'pulse' (with several magnitude 7-8 earthquakes) following immediately after the deglaciation of northern Fennoscandia. The 80 km-long Stuoragurra Fault and 2 km-long Nordmannvikdalen fault constitute the Norwegian part of the Lapland Fault Province, which consists of nine NE-SW striking reverse faults and two NW-SE striking normal faults. Trenching of the Stuoragurra Fault in Masi has revealed that most of the 7 m-high scarp was formed in one seismic event (M7.4-7.7) during the very last part of the last deglaciation in Finnmark (i.e. c. 9,300 years BP) or shortly afterwards. There is good evidence for the Nordmannvikdalen postglacial fault being part of a conjugate set of normal faults perpendicular to the extensive system of NE-SW trending reverse faults in northern Fennoscandia. The Vaalajärvi Fault in northern Finland could also be part of this NW-SE trending system of normal faults. Earthquakes with magnitudes above 6 are usually associated with a surface rupture. The lengths and heights of fault scarps provide information on the magnitude of the accompanying earthquake. Small earthquakes, including a M4.0 earthquake near Masi on 21 January 1996, have been recorded within a 30 km-wide zone parallel to the Stuoragurra Fault, suggesting that the fault is active at depth. Focal mechanisms are consistent with a reverse faulting with a dip to the southeast. The Stuoragurra Fault is situated within the several km-wide regional Mierujavri-Sværholt fault zone, which constitutes a zone of weakness responding to the present-day stress field. Other faults within the postglacial Lapland Fault Province are also active at depth. This continuous fault failure could have been suppressed for as long as the last inland ice existed. The accumulation of tectonic strain energy beneath a large ice-sheet for 10,000 years or more could provide the energy source and explanation for the large-scale, late-glacial faulting in northern Fennoscandia. Alternatively, but less likely, the present seismicity along the postglacial faults could represent 'ghosts' or tectonic adjustments within the crust following the large-magnitude, deglaciation-induced earthquakes.

There have been earlier reports of contemporary movements along the Stuoragurra Fault as well as along faults in Yrkje and Ølen in southwestern Norway (from geodetic measurements). Repeated levellings within the NEONOR Project have, however, not provided any support for aseismic movements along any of these faults (Bockmann 1999, Sylvester 1999, Bockmann & Grimstveit 2000).

We have not found any conclusive evidence of postglacial faulting in southern Norway, even though the majority of the original neotectonic claims were reported from this area (30 out of a total of 50). A system of gravitational faults and rock avalanches along a NNE-SSW trending zone from Odda in Hardanger to Aurland in Sogn (Blikra *et al.* 2000a) and a collapsed mountain ridge in Haram, Møre & Romsdal (Anda *et al.* 2000) are difficult to explain in terms

of gravity alone. These features may indicate that there have been large earthquakes in postglacial time. In western Norway there is a general lack of Quaternary overburden and consequently few means of dating movements along the abundant bedrock scarps in the area. We can not rule out, therefore, the possibility of postglacial faulting in this region.

No analogues to the Lapland postglacial faults have yet been found in southern Finland and southern Sweden (Lagerbäck 1979, Kuivamäki *et al.* 1998). Postglacial faulting (cm/dm-scale) of the bedrock surface has, however, been observed in southern Finland (Kuivamäki et al. 1998). Mörner (1996) and Tröften and Mörner (1997) have reported seismotectonically disturbed varves and liquefaction structures which were formed immediately after the deglaciation of the Stockholm area. Some of these features may be related to large-magnitude earthquakes but no fault scarps have been found.

Offshore studies

One of the objectives of NEONOR was to screen large parts of the offshore area to try to identify possible neotectonic structures. NORSAR and NGI started the Seabed Project at almost the same time as the NEONOR Project was initiated, to study the sea floor stability along the continental slope and deep-water areas offshore Mid Norway. We have therefore concentrated our work in the shelf areas to avoid any overlap between the two projects. Fortunately, however, the findings of the Seabed Project are integrated into the present report. There has been an agreement for data exchange between the two projects.

A total of twelve pre-existing reports on possible offshore neotectonics were evaluated. In addition we have interpreted eight 3D seismic surveys which are located in the northeastern North Sea and the Nordland area where the present seismicity is relatively high. In-house, high-resolution, 2D seismics have been interpreted at IKU in addition to near-coast 2D surveys (KYST) at NPD. It has been necessary to collect multi-beam echo-sounding data in six areas to study in more detail indications of neotectonics from the 2D seismic profiles. We conclude that 2D seismic data do not provide sufficiently detailed information for defining neotectonic deformation with any high degree of confidence.

No postglacial faults with throws larger than a few metres have been observed on the Norwegian continental shelf. With a possible exception of the deep-water areas with poor seismic coverage, there are no offshore neotectonic faults of comparable size to the postglacial faults of the Lapland Fault Province. An evaluation of 19 offshore reports has resulted in a total of 3, 13 and 2 of grade C, D and E, respectively. One location has not been graded due to lack of data.

Three different types of possible neotectonic features have, however, been identified in the offshore area: 1) Fissures and lineaments correlated with areas of gas leakage (not obviously related to basement faults). 2) Subtle lineaments with possible fault throws identified on 3D

seismic data in the northeastern North Sea. 3) Probable reactivation of Miocene dome structures in the deep part of the Norwegian Sea. Contractional structures (large anticlines and synclines, reverse faults and inverted centres of deposition) were initiated during the Paleogene in the Vøring and Møre Basins. There are indications that some of these structures have been growing from the Eocene to the present, interrupted by an episode of more prominent deformation in the Miocene. In addition, submarine slides and/or gas leakage may be secondary effects of neotectonic activity in some areas.

An interesting feature is that there appears to be a rotation of the principal horizontal rock stress axes across the Møre-Trøndelag Fault Complex. These horizontal stress axes are oriented N-S/E-W to the northwest of the fault complex whereas to the southeast they are oriented NW-SE /NE-SW. There is also some earthquake activity along the Møre-Trøndelag Fault Complex, especially in its offshore extension to the southwest, indicating present tectonic activity along this fault complex.

The latest phase of deformation to affect the Baltic Shield appears to reflect the passive doming (approximately 1,000 metres amplitude) of South Norway and the Lofoten-Troms area (Riis 1996). The present elevation of Scandinavia is mostly a result of Neogene uplift. The combined effect of tectonic uplift of Fennoscandia and the onset of the northern hemisphere glaciation led to greatly increased erosion and sedimentation. More than 50% of the volume of Cenozoic sediments has been deposited during the last 2.6 m.y. Across the Norwegian continental margin the tectonic strain rate is probably at most in the order of 10^{-9} to 10^{-10} yr^{-1}, which is 3-4 magnitudes lower than that of an active plate margin but at least two orders of magnitude higher than within the Baltic Shield. Strain energy can accumulate over a very long period of time, and even regions with low strain rates can exhibit large earthquakes and often with more energy release per unit fault area because of generally higher stress drops. The seismicity of Norway and adjacent areas is intermediate in level, and even though it is the highest in northwestern Europe it is still lower than in many other stable continental (intraplate) regions. In a major seismic zonation study for Norway (NORSAR and NGI 1998), a M5 earthquake was estimated to occur every 9 years, a M6 earthquake every 96 years, and a M7 every 1072 years, on average. In comparison, and consistent with this, there were two M5+ earthquakes offshore western Norway in 1988 and 1989, one M5.4-5.6 earthquake in the Oslofjord region in 1904, while the largest known in historical times from the entire region is a M5.8-6.2 earthquake in the Rana region in 1819. This may indicate a current potential for larger earthquakes in Norway than is known from our short documented history. The return times for the largest earthquakes in intraplate region such as Fennoscandia could, however, be several thousand years. Paleoseismology will consequently be an important field of research in Norway. The distinct concentration of gravitational faults and slope failures in the Lyngen-Balsfjord area in Troms and in parts of Møre og Romsdal may indicate large magnitude prehistoric earthquakes in these areas. The Nordmannvikdalen postglacial fault of possible Younger Dryas age is situated in the former area. The distribution of rock avalanches and gravitational faults indicates that there could also have been another large earthquake of slightly younger age farther to the west. An

abundance of liquefaction structures in the postglacial overburden in the Ranafjord area also points to the occurrence of one or more large prehistoric earthquakes in this area. The results from onshore Norway should be compared with the large-scale offshore sliding features reported from along the Norwegian continental margin (e.g. the Storegga, Trænadjupet and Andøya slides). Age relations between the onshore and offshore slope failures contribute to a better understanding of the trigger mechanisms (e.g. large-magnitude earthquakes).

Geodynamic modelling of the present and postglacial uplift data shows that the bulk of the present uplift can be explained as a response to glacial unloading. The modelled uplift in three areas deviates, however, from the observed uplift: 1) a zone including northwestern Norway and part of eastern Norway, 2) the Lofoten-Troms area, and 3) the Bay of Bothnia area. The Bothnia area shows a negative deviation between the observed and calculated uplift whereas the two Norwegian areas show a positive deviation. The two areas in Norway also coincide partly with the Neogene domes in southern Norway and Lofoten-Troms, indicating that a long-term tectonic component is partly causing the present uplift. There is some evidence (e.g. Mangerud et al. 1981, Sejrup 1987) that the Norwegian coast may have been subject to tectonic uplift in the order 0.1-0.3 mm/yr during the Quaternary, in addition to postglacial uplift. Examination of recent seismicity in Scandinavia shows a pattern clearly not correlated with current uplift rates, but rather consistent with continued tilting of Norway and Sweden due to ridge push. A flexural hinge zone along the eastern border of the tilted Scandinavian block is represented with an area of increased seismicity. This zone continues through southern Sweden and along the western coast of the Bothnian Sea northwards to Finnmark in northern Norway. The postglacial Lapland Fault Province is situated along the northern part of this hinge zone. A flexural hinge with increased seismicity is also situated along the western border of the tilted Scandinavian block. Thus, Quaternary tilting of Fennoscandia due to ridge push or other mechanisms may also play a role in neotectonic activity in Norway.

Recent studies of uplifted Middle and Late Weichselian marine sediments (Olsen & Grøsfjeld 1999) do, however, show that the inland ice sheet fluctuated quite frequently during the interval 18,000-50,000 yr. BP. Repeated rapid ice retreat following heavy ice loading was the most likely mechanism for depositing marine sediments of both the same and different age intervals in several uplifted positions along the coast of Norway as well as in inland areas of southeastern Norway. This process can also explain the elevated Weichselian marine clay on Høg-Jæren and coastal caves above the maximum Holocene marine limit in western and northern Norway. These elevated caves have also been interpreted in terms of a Neogene tectonic uplift.

iii)   Implications and recommendations

Hazard

The results from the NEONOR Project support conclusions from previous neotectonic studies in Sweden and Finland that numerous magnitude 7-8 earthquakes coincided with the last deglaciation in northern Fennoscandia. Results from the NEONOR seismic mini-arrays in the Rana area have shown that the return period of magnitude 6 and 5 earthquakes in the Rana area is 1500 and 130 years, respectively. An earthquake with magnitude 5.8-6.2 occurred in this area in 1819 and triggered several rock avalanches and landslides. Such phenomena represent the most hazardous effects of earthquakes in Norway with its mountainous terrain, deep fjords and relatively large areas with unstable quick-clay. The enormous large Storegga slide at the continental margin occurred 7,200 years ago and was possibly triggered by a large earthquake. Recent mapping of rock avalanches and submarine debris flows within the Quaternary sediments may indicate that large earthquakes have occurred in the Møre og Romsdal area (Chapter 1.4). Similar studies in Troms county indicate large earthquakes before or during the Younger Dryas period (11,000-10,000 BP), possibly associated with the formation of the Nordmannvikdalen postglacial fault. Another slightly younger event seems to have been of an even larger magnitude. Several hundred large rock avalanches and landslides were triggered during these events. The collapse of mountainsides into the deep fjords of Troms would set up many metres high waves, which would be disastrous to the population along the shores. The slope failures in Troms county seem to be old (during and shortly after the deglaciation), and are likely related to the high seismic activity caused by the deglaciation. The large-scale rock avalanches in the Møre og Romsdal region are much younger, and the frequency seems to have increased during the second half of the Holocene period (5,000 years). The studies of the effects of the historical earthquakes evidence a high number of slope failures related to earthquake magnitude 6 and larger. Recurrence intervals of M7 earthquakes every 1,000 years as postulated by NORSAR and NGI (1998) means that large-scale slope failures onshore and offshore Norway needs to be taken into account when evaluating hazard. The highest risk onshore Norway is large bedrock failures along the steep fjords. Data of historical avalanche accidents in northeastern Norway demonstrate that 85% of all lives lost in the 20th century is due to tsunamis related to rock avalanches into fjords and lakes. The large consequences of tsunamis means that a recurrence interval of M7 earthquakes of 1,000 years represents a very high risk for several inhabited areas.

A problem worth noting is that although the level of seismicity in Norway is stable, the level of vulnerability of society to earthquakes has increased enormously. One only has to compare the population (5,000) and infrastructure (very few roads, no industry and mostly one-storey wooden houses) of the Rana area of 1819 with the population (30,000) and infrastructure (railroad, hydropower plants, bridges, tunnels, smelters and tall buildings) of the same area
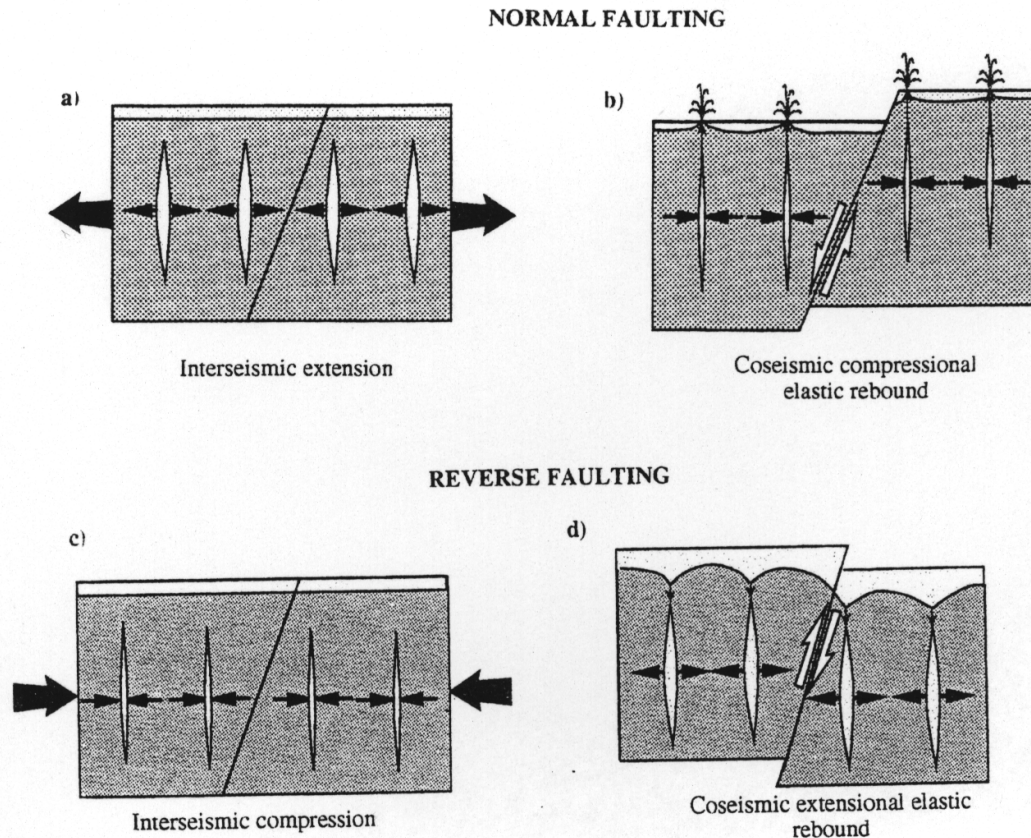
today to see how many more people and much more values are at risk. This is even more so taking into the account the seismic active areas in the northern North Sea and along the coast of western Norway with its many petroleum installations, tunnels, bridges and hydropower plants.

Hydrogeology - Seismic pumping of groundwater and hydrocarbons

The concept of 'seismic pumping' has been suggested earlier on the basis of outpourings of warm groundwater along fault traces following some magnitude 5-7 earthquakes (Sibson *et al.* 1975). We have concluded that large-scale earthquakes followed immediately after the last deglaciation of Fennoscandia. If similar earthquakes occurred after each of the numerous glaciations during the last 600,000 years the dilatation and closing of fissures in the surrounding bedrock could increase the migration of hydrocarbons from the relatively impermeable source rocks up into reservoir or to pockmarks at the sea floor (Hovland & Judd 1988, Muir Wood & King 1993, Olesen & Riis 1999). These seismic pulses associated with the glaciation-deglaciation cycles could also explain why the groundwater content in bedrock fractures is positively correlated with the present land uplift in Norway as reported by Rohr-Torp (1994) and Morland (1997). Repeated pulses of high-pressure groundwater through faults and fractures could prevent the continuous void spaces from being clogged by clay minerals. This model assumes that the largest earthquakes occurred where the inland ice was thickest. This assumption is reasonable since the accumulation of tectonic strain energy beneath the large ice-sheet most likely provides the energy source for the late-glacial faulting in Fennoscandia. Subglacial meltwater will cause additional flushing of relatively shallow aquifers during the glacial periods (Boulton *et al.* 1996) and assist in keeping fractures open in glaciated terrain. The magnitude of the hydraulic head will be directly dependent upon the thickness of the ice.

Gudmundsson (1999) has suggested an alternative mechanism to explain the observed correlation between land uplift and groundwater yield. Bedrock fractures are kept open due to doming-generated tensile stresses associated with the postglacial rebound. The tensile stresses at the surface would according to this model decrease in magnitude with distance from the centre of the dome and become compressive in the marginal parts of the uplifted crust. There is, however, not a clear correlation between observed *in situ* stress (Myrvang 1993) and distance from centre of uplift dome (see Chapter 3) in Norway.

NORMAL FAULTING

a)

Interseismic extension

b)

Coseismic compressional
elastic rebound

REVERSE FAULTING

c)

Interseismic compression

d)

Coseismic extensional elastic
rebound

Fig. 1   Simplified model for the accumulation and coseismic release of strain in extensional and compressional tectonic environment. (a) For extensional faulting, the interseismic period is associated with crack opening and increase of effective porosity. (b) At the time of the earthquake, cracks close and water is expelled. (c) For compressional faulting, the interseismic period is associated with crack closure and the expulsion of water. (d) At the time of the earthquake, cracks will open and water will be drawn in. Both mechanisms will contribute to an increased groundwater and hydrocarbon migration. From Muir Wood & King (1993).

Large amounts of water poured out of the Stuoragurra fault escarpment some time between the 21 January 1996 earthquake (magnitude 4.0) and August of that year. The water level in the Iesjåkka River, which drains the area where the earthquake occurred, was however reduced by 15-20 % during the first weeks after the earthquake. The water level stayed low during the months afterwards. Reduced water flow after large reverse fault earthquakes has also been reported from Alaska and Japan (Muir Wood & King 1993). Normal fault earthquakes, on the other hand, cause increased water flow (Fig. 1). The fault plane mechanism from the 1996 earthquake shows that it is a reverse fault earthquake. This pumping mechanism must occur regionally in the bedrock surrounding the fault zone. Several groundwater springs occur locally along the Stuoragurra Fault, and drilling through the fault (DH7 in Fig. 1.1.2) has revealed a groundwater yield among the highest ever recorded in Norway. The CO_2 content in the groundwater is 10-100 times higher than usual in hard rock aquifers (Klemetsrud & Hilmo 1999). Recent studies of the San Andreas Fault (Kharaka *et al.* 1999) show circulation of

meteoric water down to a depth of 6 km. This water has a high content of CO_2 originating from the mantle or the deep crust. These relative high fluxes of gas were found to generate lithostatic fluid pressures at depths larger than 6 km and thus weaken the fault to failure. Toutain & Baubron (1999) have also made a literature review on gas geochemistry and seismotectonics and concluded that CO_2-degassing from deep crust and mantle through active faults is a common phenomenon. Release of hydrocarbons and CO_2 during deglaciation-induced seismic pulses may explain the improved climate immediately after the deglaciation as a result of increased greenhouse effect. The greenhouse effect of CH_4 is 20 times higher than of CO_2.

In the Fidnajåkka area a spring occurs 20 metres to the west of the escarpment. Nothing but the flower Viscaria Alpina grows in a 25 m long and 3-5 m wide field downstream from the spring revealing that the ground water has a quite high content of heavy metals. Trenching of the Stuoragurra Fault shows that fault breccia had been injected from the fault zone and more than 12-14 m horizontally into the lower part of the glacial overburden. It is reasonable to assume that the fault breccia must be mixed with high-pressure groundwater to reach this transportation length in the consolidated till.

The Stuoragurra Fault has been studied by percussion drilling (DH4 in Fig. 1.1.2) and ground water was encountered at a depth of 35 m (2 m above the main fault zone). After penetration of the fault gouges at a depth of 37 m the ground water was drained but appeared again at a depth of 40 m. The fault gouges consequently caused a 'hanging' ground water surface above the main fault zone. We conclude that the fault gouges in the Stuoragurra Fault have sealing properties, even if the more than 10 m wide fault-zone is totally fractured and water-bearing at larger depths.

The hydrological effects of the magnitude 5.8-6.2 earthquake in 1819 in the outer Ranafjord area have been described: 'many streams were disturbed as though they had been mixed with milk, such that the water, smelling strongly of sulphur, remained undrinkable, even for animals, for three days' (Helzen 1834, Muir Wood 1989a). At Saltdal (150 km to the north of Ranafjord) the water emerging from two small springs at the foot of a mountain, 'became whitened with clay although there was no such material along the stream-banks' (Sommerfeldt 1827). Several pockmarks occur at the sea floor in the Lyngenfjord in Troms (Hovland & Judd 1988). Most of the locations are situated along the NW extension of the Nordmannvikdalen postglacial fault and the nearest pockmark is located only 5-6 km from the fault. It is possible that an earthquake associated with the formation of the postglacial fault has triggered the release of groundwater or gas. Karpuz *et al.* (1991) have also reported disturbed groundwater flow and formation of ponds after the M4.2 earthquake in Etne, Hordaland in 1989.

There are numerous reports of changed groundwater flow and active pockmarks after earthquakes in the western US and the Mediterranean (Clifton *et al.* 1971, Nardin & Henyey 1978, Field & Jennings 1987, Hovland & Judd 1988, Hasiotis *et al.* 1996). Some of the pockmarks in the North Sea do also seem to be formed during postglacial faulting (Chapter 2, Fig. 2.10).

Recommendation for further work

We have in the present study suggested that the 'seismic pumping' mechanism and flushing of subglacial meltwater through shallow aquifers can explain the observed correlation between land uplift and groundwater yield of hard rock wells in Norway. Gudmundsson (1999) has proposed an alternative model where this correlation is related to tensile stress caused by the postglacial rebound. There is a need to study which of the proposed models are the main cause of the observed phenomenon.

Within a new project on neotectonics and fluids in the upper crust, we would recommend a study of the Stuoragurra and Nordmannvikdalen faults at depth with deeper wells to investigate the chemistry (e.g. the gas- and metal-content) and temperature of the groundwater. The understanding of the *in situ* stress along these faults must also be improved. Results from these combined studies will throw light on the behaviour of fluids and gases in the upper crust and consequently on the future utility of thermal energy and groundwater. Improved knowledge of neotectonics and occurrence of gases in the crust could also assist in solving the paleo-climate puzzle. Release of hydrocarbons and CO_2 during deglaciation-induced seismic pulses could explain the improved climate immediately after the deglaciation as a result of greenhouse effect.

The steadily increasing number of tunnel-projects will also gain from an increased knowledge about the occurrence of water in the Norwegian bedrock. These investigations may in addition have implications for our understanding of migration of hydrocarbons through sediments and along fracture zones in the offshore areas.

A regional view of instability features with data of their spatial occurrence and dating of individual events is essential for palaeoseismic analysis. A program should be initiated in order to map large-scale gravitational-slope failures in Norway, both on land and in the fjords. A selection of detailed studies is needed, and especially important is dating of individual events. A dating program including rock avalanche and slope failures in fjords (coring) will be essential in order of comparing the instability trends with offshore data. The effect of future large earthquakes should be modelled and it should be considered to establish local seismic stations. A better coupling between data from offshore and onshore Norway may be important for the understanding of the palaeoseismic history and thus the evaluation of future seismic activity.

1. ONSHORE NEOTECTONICS

1.1 Quality assessment of reported neotectonic phenomena

By Odleiv Olesen, John. F. Dehls, Lars H. Blikra, Alvar Braathen, Lars Olsen & Leif Rise (NGU)

1.1.1 Introduction

There has been a surge in the number of neotectonic reports during the last twenty years. Almost 70% of the total 64 registered reports are published in the 1980's and 1990's. Within the NEONOR Project we have put significant effort into the quality analysis of all the neotectonic reports to establish a scientific foundation for neotectonic research in Norway. The new dataset of postglacial faults in Norway can be combined with other information on crustal deformation to achieve an improved understanding of the dynamic processes that are active in Norwegian regions. Such understanding is desirable from a scientific point of view, but also has practical implications, including various aspects of geological risks and occurrence of fluids in the bedrock.

Neotectonics are, according to the International Association for Quaternary Research (INQUA), defined as "Any earth movement or deformations of the geodetic reference level, their mechanisms, their geological origin (however old they may be), their implications for various practical purposes and their future extrapolations (INQUA 1982)." Neotectonic crustal deformations have been reported at a large number of locations in Norway (both on local and regional scales). Documentation of large scale postglacial faulting (with up to 150 km length and 30 m offset) in northern Fennoscandia (Fig. 1.1.1; Table 1.1.1) has justified a re-evaluation of the previously reported evidences of Quaternary deformation in Norway.

1.1.2 Classification criteria

The definition of postglacial faulting is tectonic faulting that has occurred since the end of the last glaciation. Criteria for identification of postglacial faulting have been presented earlier by Fenton (1991, 1994) and Muir Wood (1993):

1) Offset of an original continuous surface or sediment of postglacial or late glacial age.

2) Reasonably consistent direction and amount of slip along the length of the fault.

3) The ratio of displacement to overall length of the feature should be less than 1/1,000. For most faults this ratio is between 1/1,000 and 1/10,000.

4) Exclusion of gravity sliding as the driving mechanism of faults in areas of moderate to high relief.

5) No signs of glacial modification (such as striation or ice-plucking) of fault scarps especially those controlled by banding, bedding or schistosity.

6) Exclusion of mechanisms such as glaciotectonics (ice push features), collapse due to ice melting, differential compaction or deposition over a pre-existing erosional scarp being the cause of an apparent offset in overburden.

*Table 1.1.1. Summary of properties of the documented postglacial faults within the Lapland province. The major faults are NE-SW trending reverse faults and occur within a 400x400 km large area in northern Fennoscandia. The Nordmannvikdalen and Vaalajärvi faults are minor faults trending perpendicular to the reverse faults. The former is a normal fault and the latter is a potential normal fault. The scarp height/length ratio is generally less than 0.001. The Merasjärvi Fault has a scarp height/length ratio of 0.002. *Moment magnitudes calculated from fault offset and length utilising formulas by Wells and Coppersmith (1994).*

Fault	Country	Length (km)	Max. scarp height (m)	Height length ratio	Trend	Type	Moment magni-tude*	Comment	Reference
Suasselkä Fault	Finland	48	5	0.0001	NE-SW	Reverse	7.0		Kujansuu, 1964
Pasmajärvi-Venejärvi Fault	Finland	15	12	0.0008	NE-SW	Reverse	6.5	Two separate sections	Kujansuu, 1964
Vaalajärvi Fault	Finland	6	2	0.0003	NW-SE	??	6.1		Kujansuu, 1964
Pärve Fault	Sweden	150	13	0.0001	NE-SW	Reverse	7.6		Lundquist & Lagerbäck, 1976
Lainio-Suijavaara Fault	Sweden	55	30	0.0005	NE-SW	Reverse	7.1		Lagerbäck, 1979
Merasjärvi Fault	Sweden	9	18	0.002	NE-SW	Reverse	6.3		Lagerbäck, 1979
Pirttimys Fault	Sweden	18	2	0.0001	NE-SW	Reverse	6.5		Lagerbäck, 1979
Lansjärv Fault	Sweden	50	22	0.0004	NE-SW	Reverse	7.1		Lagerbäck, 1979
Burträsk-Bastuträsk Fault	Sweden	60	c. 10	0.0002	NE-SW N-S	??	7.1	Two separate sections	Lagerbäck, 1979
Stuoragurra Fault	Norway	80	7	0.0001	NE-SW	Reverse	7.3	Three separate sections	Olesen, 1988
Nordmannvik-dalen Fault	Norway	2	1	0.0005	NW-SE	Normal	6.0		Tolgensbakk & Sollid, 1988

Slight glacial modification of scarps suggests late glacial or interglacial age for a fault scarp. We can when applying these criteria, objectively rank neotectonic claims similar to the review of seismotectonics in Sweden by Muir Wood (1993). He classified the claims into five grades;

(A) Almost certainly neotectonics,

(B) Probably neotectonics,

(C) Possibly neotectonics,

(D) Probably not neotectonics

(E) Very unlikely to be neotectonics.
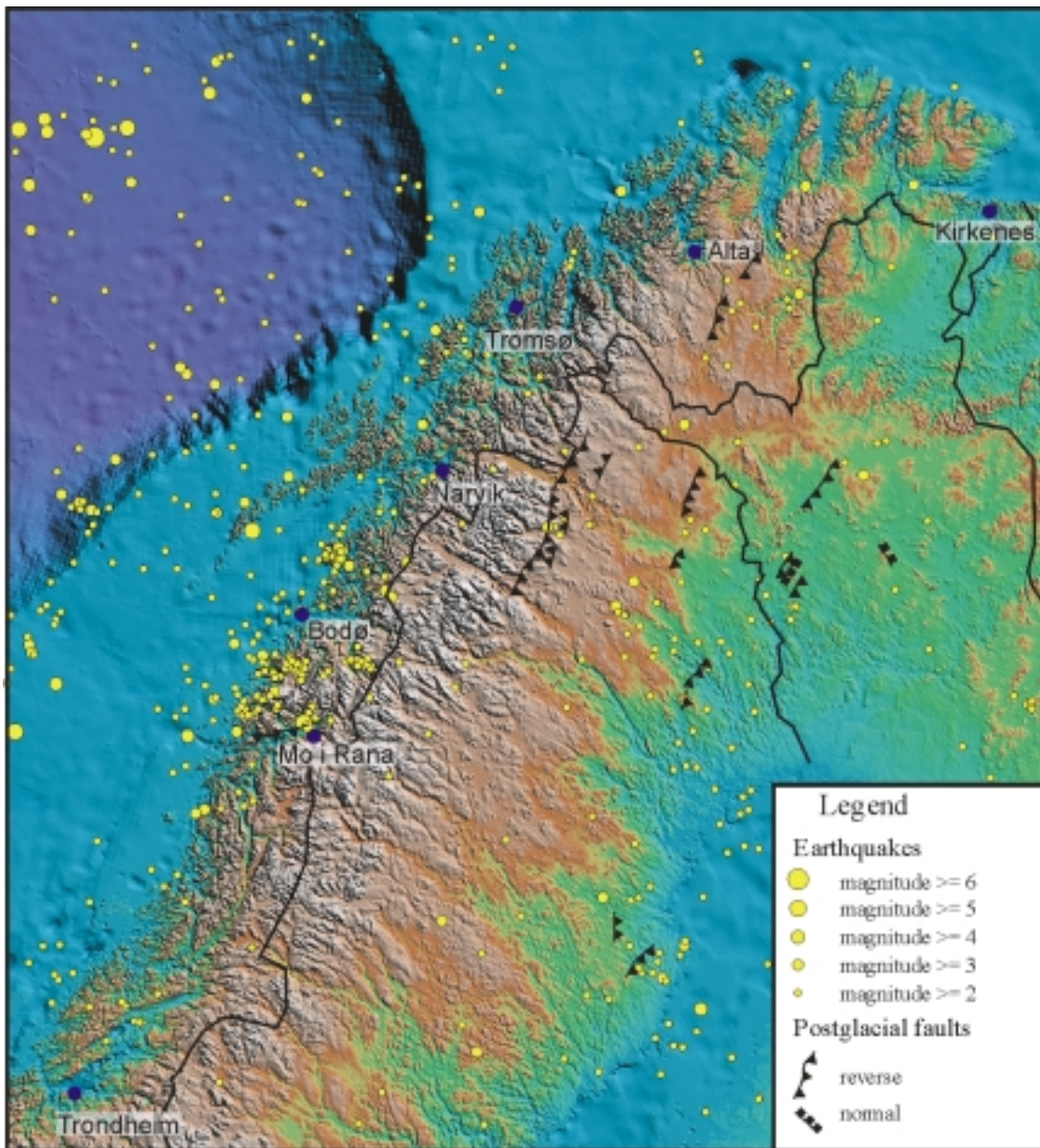
Fig. 1.1.1   Earthquakes during the period 1965-1998 and postglacial faults in northern Fennoscandia. The faults occur in areas with increased seismicity.

1.1.3 Reported neotectonic activity in Norway

Indications of neotectonic deformation have appeared in Norway since the 1880s. The number of reports during each decade afterwards has varied from 0 to 3 (with the exception of 8 during the 1920's) until the number surged in the 1980's with a number of 19 reports followed by 22 in the 1990's (not including the NEONOR and Seabed Reports). Muir Wood (1993, 1995) initiated the quality assessment of reported neotectonics in Norway and reported 13 claims, (6 on mainland Norway and 7 offshore). We have added 44 and 7 more accounts to form the onshore and offshore lists reported in Appendices A & B, respectively. Preliminary versions have been published in previous NEONOR Annual Technical Reports (Dehls & Olesen 1998, 1999). 14 of the claims are situated in the offshore area and the 50 others are located on mainland Norway (Fig. 1.1.3).

**STUORAGURRA POSTGLACIAL FAULT
PROFILE 807 FIDNAJÅKKA AREA**

LEGEND
- TILL AND GLACIOFLUVIAL DEPOSITS
- DIABASE
- REDDISH-GREY QUARTZITE
- DARK BANDED QUARTZITE
- INTENSE FRACTURING AND BRECCIATION
- INTENSE FRACTURING
- FRACTURING
- FOLDING
- CORE DRILL- HOLE DH 6
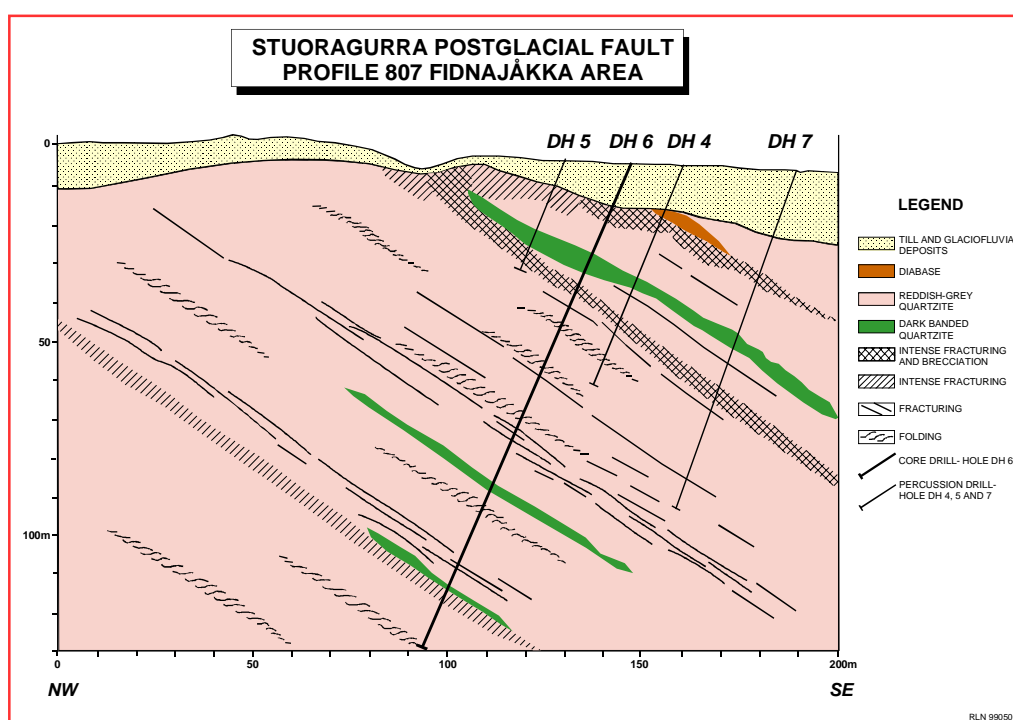- PERCUSSION DRILL- HOLE DH 4, 5 AND 7

Fig. 1.1.2   Interpretation bedrock-profile across the Stuoragurra Fault based on core (DH6) and percussion (DH4, 5 & 7) drilling and geophysical measurements. The mineralogy of the fault gauge (quartz, goethite and clay minerals) is described by Åm (1994). Fig. 1.2.3 illustrates the deformation of the Quaternary overburden.

A total of 22 locations were visited for closer geological and geophysical examination within the NEONOR Project (Dehls & Braathen 1998, Olesen & Dehls 1998 and Olesen *et al.* 2000): Ragnhildnuten (Sandnes), Mosvatnet (Suldal), Yrkje, Vindafjorden, Ulvegrovene (Forsand), Lygre (Fusa), Grytehorgi (Eidfjord), Geitura (Ulvik), Ytre Byrknesøy (Gulen), Gnedden (Sel), Rudihø (Heidal), Tron (Tynset), Båsmoen-Utskarpen (Rana), Austerdalsisen (Rana), Beiarn, Skjomen, Vassdalfjell (Narvik), Kåfjord (Troms), Nordreisa, Masi, Gæssajavri (Karasjok) and Skipskjølen (Varanger Peninsula). Longva *et al.* (1998) and Rise *et al.* (1999) have carried out an evaluation of neotectonic claims in Tjeldsundet and Hjeltefjorden-Gannsfjorden.
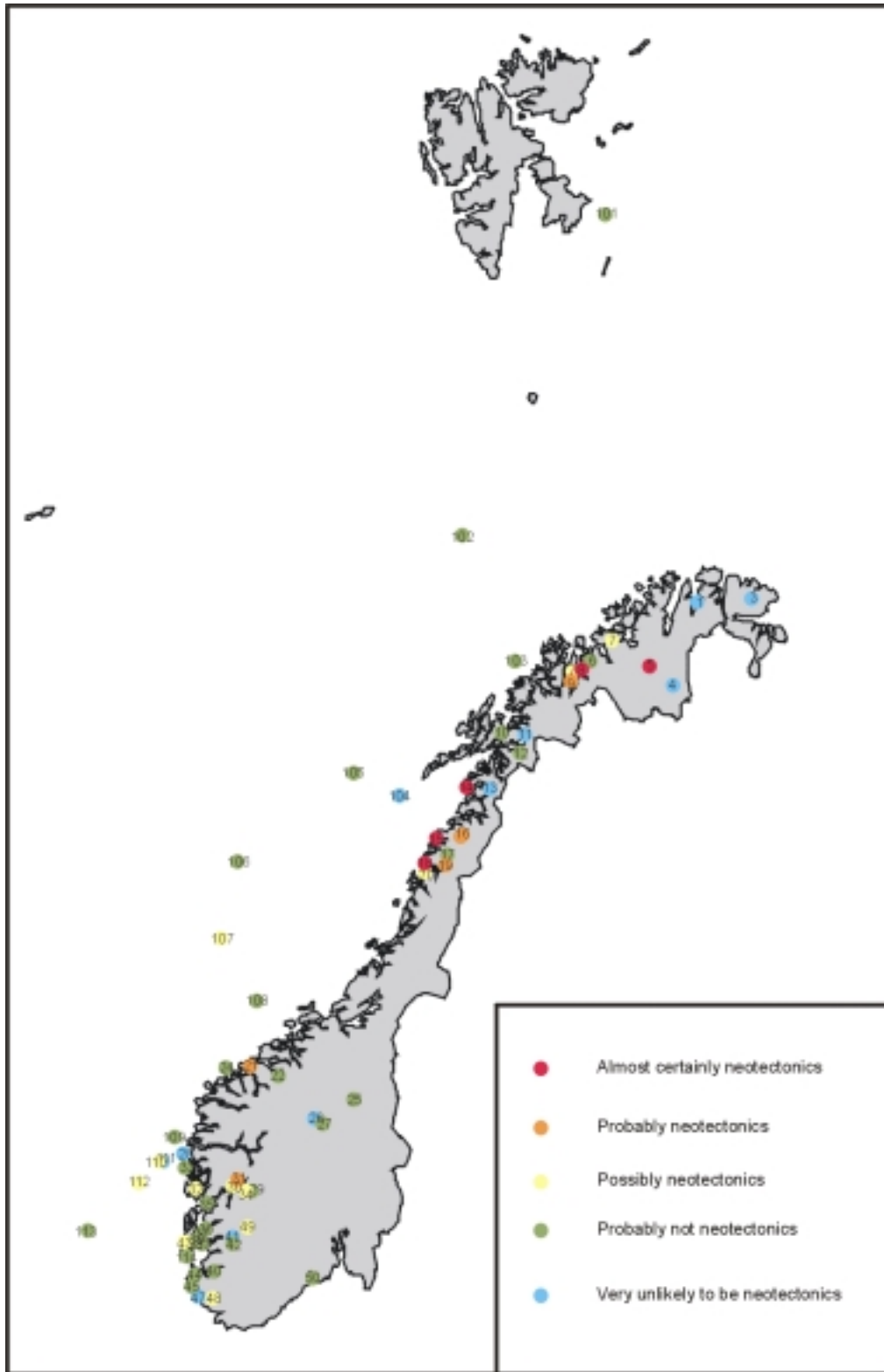
Fig. 1.1.3 Locations of the 50 onshore and 14 offshore locations that have been collocated and classified within the NEONOR Project. Five additional offshore reports in the Norwegian Sea have been evaluated within the Seabed Project (see Chapter 2). The colours refer to the quality grading, and the numbers on the map refer to the location numbers in Appendices A and B, which summarise the onshore and offshore classification. The Seabed locations are included in Appendix B (location 115-119) and displayed on Fig. 2.3.

A total of 7 and 10 claims were classified as grade A and B, respectively in the tentative onshore assessment included in the NEONOR Project proposal. At the end of the NEONOR Project the present status is 5 claims within each of the grade A and B groups. The present grade A claims include the postglacial faults in Masi (Figs. 1.1.2 & 1.2.2-5) and Kåfjord (Figs. 1.2.6 & 1.2.10) and the earthquake swarms in Steigen, Meløy and Sjona-Ranafjord (Fig. 1.3.1). Claims with grade C, D and E has increased in number from 12 to 39 and the numbers within each grade are 8, 21 and 10, respectively. Note that additional 20 onshore claims are added to the list. A majority of the neotectonic claims can consequently be attributed to other effects than tectonic. Gravity-induced sliding (Fig. 1.1.4) and glacial erosion along pre-existing faults and fractures (Fig. 1.1.5) are the dominant agents in forming the geomorphological features that were earlier claimed to be of neotectonic origin. At least three of the collapse structures are probably triggered by large earthquakes (in Beiarn, Haram and Ulvik). The ice-plucking features may, however, also indirectly be related to neotectonics. Bell & Eisbacher (1995) have shown that a moving glacier in the Canadian Cordillera tends to pluck bedrock along fractures parallel to the direction of maximum horizontal stress. An inland glacier would in an analogous way cause a higher degree of bedrock plucking along favourable oriented fractures in areas with highly anisotropic rock stress.
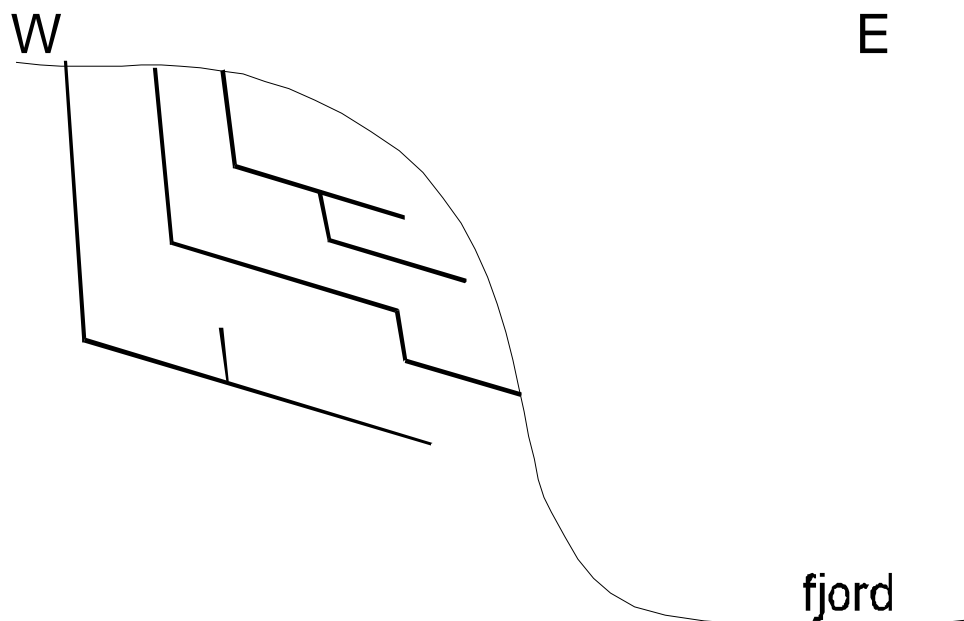
Fig. 1.1.4   Schematic diagram showing example of gravity induced faults at Ringja in Vindafjorden, Rogaland (Dehls & Braathen 1998). Large blocks slide along schistosity surfaces towards the fjord.
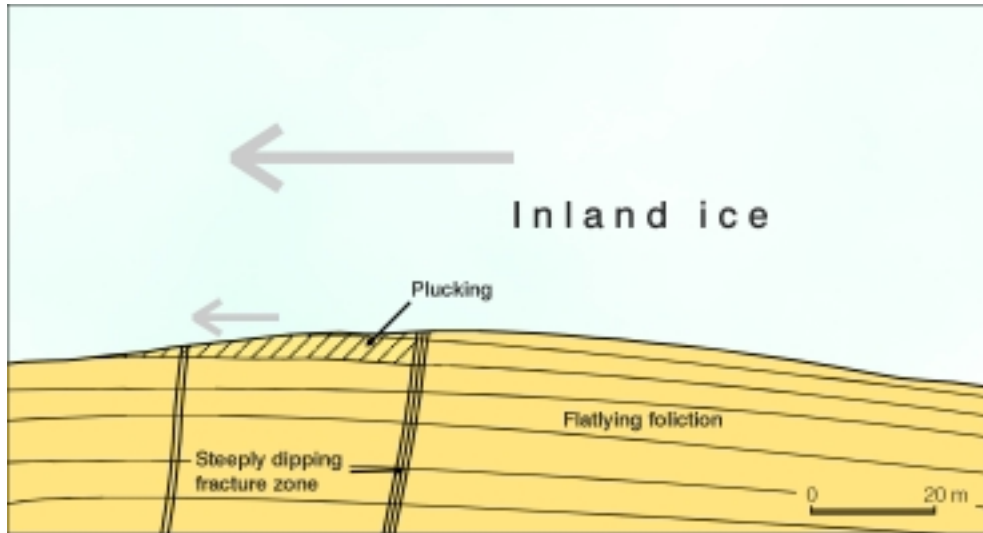
Fig. 1.1.5   Schematic diagram illustrating how scarps are formed by plucking from the moving inland ice. Blocks are removed along steeply dipping fracture zones and sub-horizontal foliation (Olesen et al. 2000).

An evaluation of 14 offshore reports has resulted in a total of 3, 9 and 2 of grade C, D and E, respectively (Appendix B). An evaluation of the offshore neotectonic claims is included in Chapter 2 (Offshore neotectonics). Four out of the five Seabed locations have been assigned grade D.

Sackungen structures occur along the crest of Kvasshaugen in Beiarn, Nordland. Up to 20 m wide and 10 m deep clefts occur along an approximately 5 km long NNE-SSW trending zone (Grønlie 1939). The large-scale faults are suggested to be of postglacial age since there is no sign of glacial sculpturing along the escarpments. The faults were classified by Muir Wood (1993) as some of the most reliable claims of neotectonic surface fault rupture in Scandinavia, but he pointed out that they may probably be of superficial character.

Similar sackungen structures consisting of double-crested ridges, upslope-facing scarps, linear troughs and downslope facing scarps occur in the Alps, Rocky Mountains and New Zealand (Zischinsky 1969, Varnes *et al.* 1989 and Beck 1968). These characteristic geomorphic forms are produced by gravitational spreading of steep-sided ridges (Varnes *et al.* 1989). Several different interpretations of the origin of the structures have been proposed. Whether initiation of movements is by strong shaking, faulting, long-term creep, or a combination of factors has long been a matter of debate (Jibson 1996). Varnes *et al.* (1989) and McCalpin & Irvine (1995) argue that the movement originates from long-term, gravity-driven creep but the former does not exclude tectonism as a possible contribution. Other investigations in New Zealand, Slovakia and Russia conclude that earthquake shaking was the most likely trigger of movement (Jibson 1996, Beck 1968, Jahn 1964) partly because the sackungen features occur in seismically active areas. The Kvasshaugen mountain is also situated in a seismically active

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area so earthquake shaking could be a triggering mechanism. Similar structures on Otrefjellet in Haram, Møre og Romsdal is also located in a seismically active area (Anda *et al.* 2000).

The 50 km long Båsmoen Fault (Olesen *et al.* 1994, 1995) occurring along the northern shore of Ranafjorden, is a possible postglacial fault (grade B in our classification system). Liquefaction structures in sand along the fault zone suggest that earthquake induced disruptions may have occurred during late-/postglacial time (Olesen *et al.* 1994, Olsen 1998). Trenching of the Båsmoen Fault at Båsmofjellet has revealed structures which indicate a reverse fault. The hanging-wall block of the faulted rock has penetrated up to 40-50 cm vertically through the till and sand cover of the lowermost part of the fault slope (Olsen *et al.* 1999). Observations of glacial striae on the hanging-wall block some 40 cm above ground surface have led us to conclude that the general postglacial vertical movement along the fault was no more than 30-40 cm. The evidence for postglacial faulting is, however, not as compelling as in the Kåfjord and Masi areas.

We have not found any conclusive evidence of postglacial faulting in southern Norway even though the majority of the original neotectonic claims were reported from this area (30 of a total of 50). There are, however, indications of large earthquakes along a NNE-SSW trending zone from Odda in Hardanger to Aurland in Sogn and at the coast of Møre og Romsdal where several large rock avalanches occur in relatively gentle dipping terrain (Blikra *et al.* 2000a,b, Anda *et al.* 2000). There a general lack of Quaternary overburden in western Norway and consequently few means to date movements along the abundant bedrock scarps in the area. We can not, therefore, rule out the possibility of postglacial faulting in the area.

No conclusive evidence has been found of postglacial faulting in southern Finland and southern Sweden (Muir Wood 1993, Kuivamäki *et al.* 1998). Mörner (1996) and Tröften and Mörner (1997) have, however, reported seismotectonically disturbed varves and liquefaction structures that were formed immediately after the deglaciation of southern Sweden. Fenton (1992) described more than 20 postglacial faults in the highlands of northwestern Scotland. The offset and length of these postglacial faults are 1-10 m and 1-10 km, which are significant smaller than the northern Fennoscandian faults.

1.1.4 Conclusions

Field checking of neotectonic reports and claims has shown that the majority of these can be attributed to effects other than tectonic faulting. In northern Norway there are now documented postglacial crustal deformation in Rana, Meløy, Beiarn, Kåfjord, Steigen and Masi. The extensional faults in Beiarn are, however, gravity-induced and classified as a sackung feature which has earlier been reported from mountainous areas in western US and Canada, Alps and New Zealand (Savage and Varnes, 1987). It is a matter of debate if these features are caused by slow creep or triggered by earthquake shaking. The normal NW-SE

trending fault in Kåfjord represents a normal fault perpendicular to the system of NE-SW trending reverse faults in northern Fennoscandia (Lapland postglacial faults).

Postglacial faulting seems to be rare or absent in southern Norway since no conclusive evidence has been found so far. There are, however, indications of large earthquakes in western Norway where several large rock avalanches occur in relatively gentle dipping terrain (Blikra *et al.* 2000b). There is generally a lack of Quaternary overburden in western Norway and consequently few means to date movements along the abundant bedrock scarps in the area. We can not therefore rule out the possibility of postglacial faulting in the area.

The present study of neotectonic claims on-land Norway suggest that they can be classified into five groups:

(1) Neotectonic faults (examples: Stuoragurra in Masi and Nordmannvikdalen in Kåfjord)

(2) Gravitationally induced faults (examples: Vassdalsfjell, Kvasshaugen, Rudihø, Ringja and Ulvegrovene)

(3) Erosional scarps along older zones of weakness (examples: Nordreisa, Skjomen, Austerdalsisen, Gnedden and Grytehorgi)

(4) Overburden draping of underlying bedrock features (example: Gæssagielas in Karasjok)

(5) Stress release features (examples: Lebesbye, Kobbelv and Ødegården).

Gravitationally sliding (Fig. 1.1.4) and glacial erosion (plucking) (Fig. 1.1.5) have been the most important agents to form scarps that have been misinterpreted as postglacial faults.

1.2 Neotectonics in Troms and Finnmark, northern Norway

By John F. Dehls, Odleiv Olesen, Lars Olsen, Lars Harald Blikra, (NGU) & Lars Bockmann (SK)

1.2.1 Introduction

Together, Troms and Finnmark account for 10 accounts of neotectonic activity investigated during the course of this project. All but three have been ruled as unlikely to be of neotectonic origin. One occurrence, the high concentration of landslides and gravitational faults in the Balsfjord-Lyngen area, is discussed in a separate chapter in this volume (Chapter 1.4). In this chapter, we focus on two postglacial faults in northern Norway (Fig. 1.2.1) that appear to have a tectonic origin. One fault, the Stuoragurra Fault, is a large reverse fault in Finnmark County. The other fault, the Nordmannvikdalen fault, is a much smaller normal fault in Troms County.
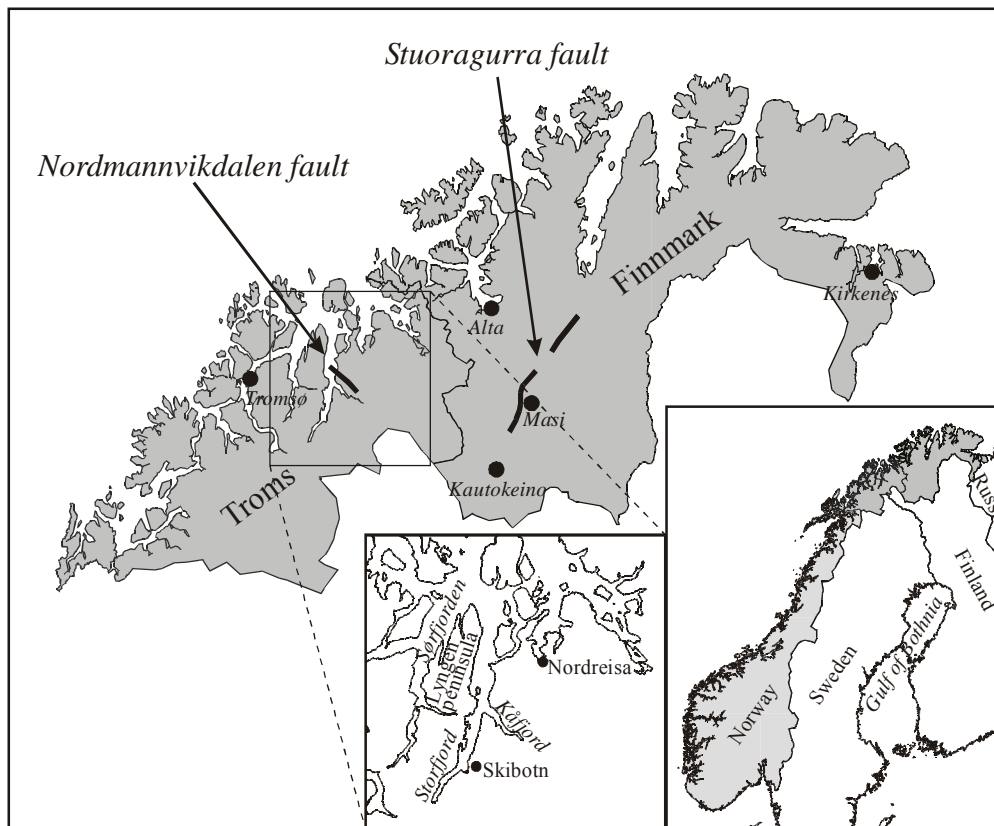

Fig. 1.2.1   Location of the Nordmannvikdalen and Stuoragurra postglacial faults in northern Norway.

Deglaciation and uplift

The last glaciation in northern Fennoscandia occurred during the Late Pleistocene epoch. The Late Weichselian substage lasted from approximately 25,000 ^{14}C-yr BP to 10,000 ^{14}C-yr BP

(Donner 1995). The Fennoscandian inland ice sheet retreated from the coast of Finnmark county c. 10,000 ^{14}C-yr BP. During this initial ice recessional phase the ice thickness was still several hundred meter over Finnmarksvidda in the south. The ice margin retreated generally towards the S and SW, and finally, the ice disappeared from Finnmarksvidda in the SW prior to 9,000 ^{14}C-yr BP (Göttlich *et al.* 1983) and probably c. 9,200 ^{14}C-yr BP (Olsen *et al.* 1996). This implies an ice retreat over a distance of at least c. 150-200 km in c. 800 ^{14}C-yr, giving an average ice retreat rate of c. 190-250 m per year.

A huge ice volume had consequently to be removed in this process, which of course included a considerable weight release on the ground surface during a very short time interval. Fennoscandia is still experiencing crustal uplift due to the melting of the Late Weichselian ice sheet. In the northern part of the Gulf of Bothnia, for example, the present apparent rate of land uplift is approximately 9 mm/yr. The present apparent rate of uplift near the Stuoragurra Fault is approximately 2.5 mm/yr. Along the coast of Troms county, the rate is 1-1.5 mm/yr.

1.2.2   Stuoragurra Fault

Initial studies

The Stuoragurra Fault was identified in 1983 during the course of a collaborative project between the Geological Surveys of Norway and Sweden. Details on the Stuoragurra Fault have been reported by Olesen (1988), Muir Wood (1989b), Olesen *et al.* (1992a, 1992b) and Roberts *et al.* (1997). Bungum & Lindholm (1997) carried out a detailed seismotectonic study. The southernmost part of the Stuoragurra Fault has also been included in the Masi bedrock map at the scale 1:50,000 by Solli (1988).

The fault, located within the Mierujav'ri Sværholt Fault Zone (MSFZ), is an 80 km long fault zone that contains three main eastward dipping (30-60o) segments, with up to 10 m of reverse displacement and a 7 m high escarpment (Fig. 2.2.2). Each of the three main segments, Fidnajåkka-Biggevarri (south), Masi-Stuoragurra (central) and Iesjavri-Lævnjasjåkka (north), is composed of sub-parallel segments which are often located in an en echelon pattern. The postglacial fault segments follow to a large extent older fault zones represented by lithified breccias and contacts of albite diabases. These intrusions within the Mierujavri-Sværholt fault zone occur as both dykes and sills and are 1815 ± 24 Ma (Krill *et al.* 1985). They are locally strongly foliated after intrusion.

Fig. 1.2.2   Aerial photograph of the Stuoragurra Fault as it crosses Finnmarksvidda. Photo taken from the west. Large amounts of groundwater poured out of the escarpment to the right sometime between the earthquake on Jan. 21, 1996 and Aug. 1996.

The Stuoragurra Fault cross-cuts glaciofluvial deposits northeast of Iešjav'ri (Olesen 1988) and an esker northeast of Masi and is consequently younger than 9,300 years BP (Olesen *et al.* 1992b). The postglacial fault coincides locally with a 5-10 m wide zone of lithified breccia and is composed of several thin (a few cm wide) zones of fault gouge within a couple of metres wide zone. The southernmost segment of the fault is listric with a dip of ~ 50° close to the surface and ~ 30° at a depth of 40 m. The fault typically has an offset/length ratio of approximately 1/10,000, which is one of the criteria generally applied for the classification of neotectonic faults.

Roberts (in press) has reported an E-W directed maximum horizontal stress in Finnmark. This stress orientation could explain a possible dextral component (1-2 metres) in the offset of the dominantly reverse Stuoragurra Fault. Indication of a dextral component exist from an apparent offset of an esker in Stuoragurra to the northwest of Masi (Olesen *et al.* 1992b) and a sag pond located between two overlapping fault segments in the Fidnajåkka area (Dehls *et al.* 1999).

Seismicity

On January 21, 1996, a magnitude 4.0 earthquake occurred to the east of the Sturoagurra Fault. Earthquakes of magnitude 3.3 and 3.0 had occurred previously, in July and October of 1995. Bungum and Lindholm (1997) studied the microseismicity around the Stuoragurra Fault. They found a clear SW-NE trend in the earthquake locations, with the majority of the events

occurring in a 20-30 km wide cluster to the east of the fault. They interpreted this spatial correlation as reflecting a broad zone of weakness that is responding to the present day stress field. Focal mechanism solutions are consistent with oblique reverse faulting with a dip to the southeast (Bungum & Lindholm 1997).

Trenching

The interpretation of the character and age of the Stuoragurra Fault has been based, up to 1998, mainly on airphoto-interpretation and geophysics. In August 1998, we excavated the overburden in two 25 metre long trenches across this fault at Fidnajohka, between Masi and Kautokeino in Finnmark. In this way, we were able to see, for the first time, deformational structures in the loose deposits covering the fault escarpment.

Fig. 1.2.3 shows an interpretation of the northern trench. Within the excavations, the vertical fault height is c. 7.2 m, which corresponds well with the c. 7.0 - 7.5 m height of the fault escarpment as it appears on the ground surface. The reference level in the deformed overburden is the c. 3°-sloping boundary between a basal till and the overlying deglaciation material, consisting of glaciofluvial sediments, with diamict zones included. The boundary zone appears to be mainly undeformed, with nearly the same dip in the easternmost and westernmost parts of the trench.
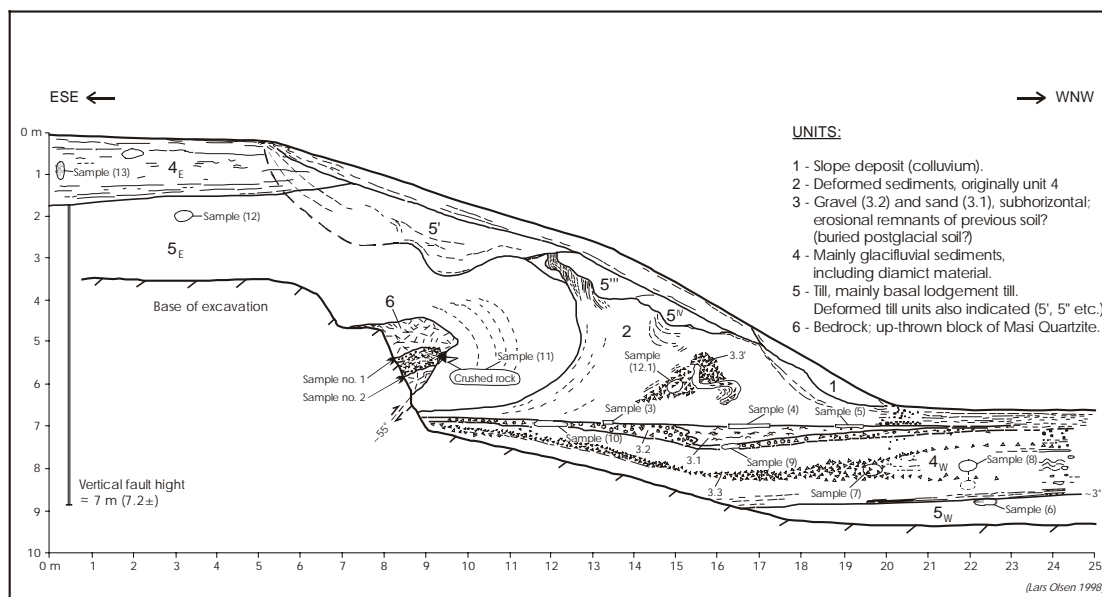
Fig. 1.2.3   Outline of the first trench at Fidnajohka. The orientation of the section is normal to the fault. The nose of the up-thrown block of bedrock (6) is buried by deformed basal till (5E) and glaciofluvial gravel and sand (2, 3 & 4), with colluvial slope deposits (1) on top.

The nose of the up-thrown hanging wall block of bedrock was well exposed below 3 m of overburden in the trench in the upper part of the escarpment (Fig. 1.2.4). The hanging wall has

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a dip of 55°, which confirms previous estimates of the dip of the fault plane, based on drilling and ground geophysics (Olesen *et al.* 1992a). The loose deposits in front of the hanging wall block have been bulldozed and folded during the fault process, producing a blind thrust. Abundant liquefaction structures and other deformations, such as convolutions, diapirism, squeezing, injections etc., are recorded in the sections (Fig. 1.2.5). The ability of glacial sediments to deform in a ductile manner during the rapid strain associated with an earthquake has been demonstrated by Cetin (1998). The high moisture content indicated by the liquefaction structures would have increased the ductility of the sediments.
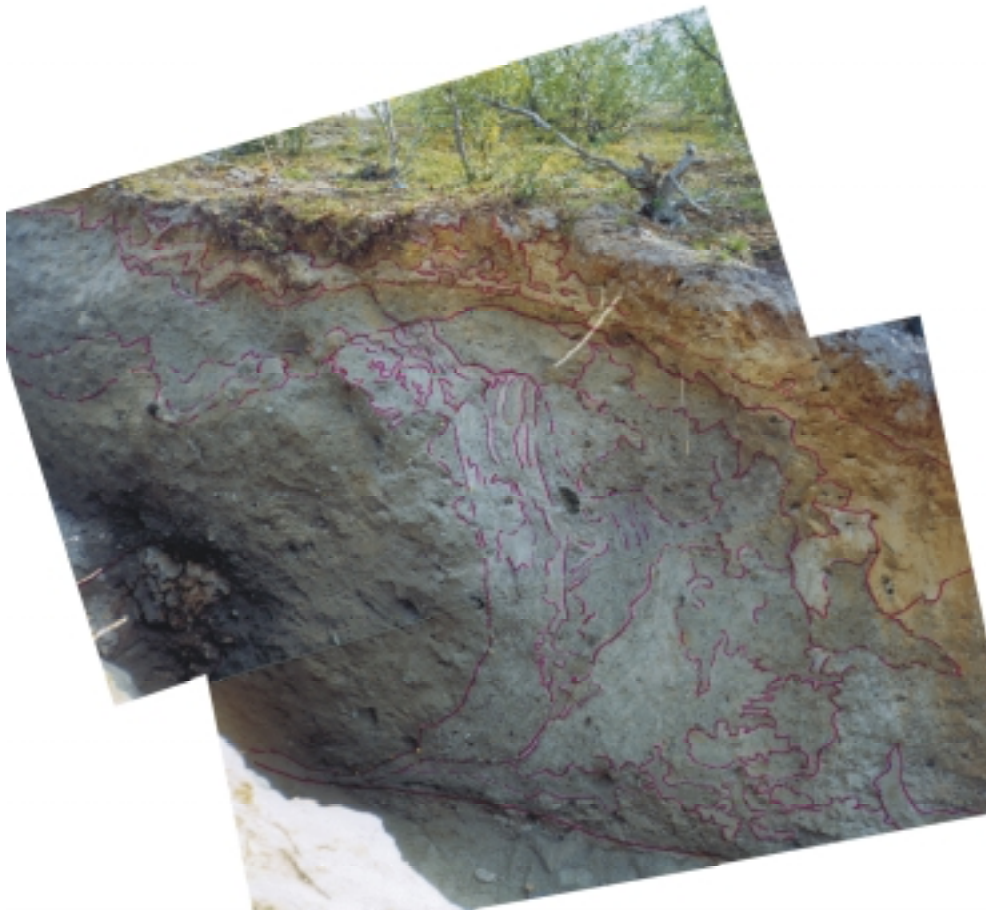
Fig. 1.2.4   Deformed basal till can be seen in front of the nose of the hanging wall block. On top lie undeformed glaciofluvial and colluvial deposits.

A sub-horizontal unit of gravel and sand may include remnants of the previous soil, which therefore may be buried in the fault escarpment. The sand facies of this horizon includes organic-bearing material that may represent either such a buried soil or secondary input of dissolved or particulate organic matter through groundwater transportation. This is not yet fully evaluated. However, in any case the fault-derived deformation of the sediments appears to have moved out from the fault zone towards the northwest with the possible buried soil as a décollement plane.

Some of the most striking deformation structures observed in the lower part of the main section are injections of clast-supported gravel of the local bedrock lithology. These gravely injections which start at the hanging wall - sediment interface, wedge out towards the west, but may be followed at least to the lower break of the escarpment, i.e. 12-14 m from the fault. Analyses of roundness and lithology of the gravels (Dehls *et al.* in press) support strongly our interpretation of a tectonic origin of these wedges. The sharp-edged and almost 100% - Masi Quartzite derived lithology of the gravels in the injections indicate a distinctly different genesis compared to the pebbles and cobbles in the other, mainly glacially derived sediments in this area. We interpret the sharp-edged gravel injections simply to be injections of fault breccia (e.g. Carver & McCalpin 1996).
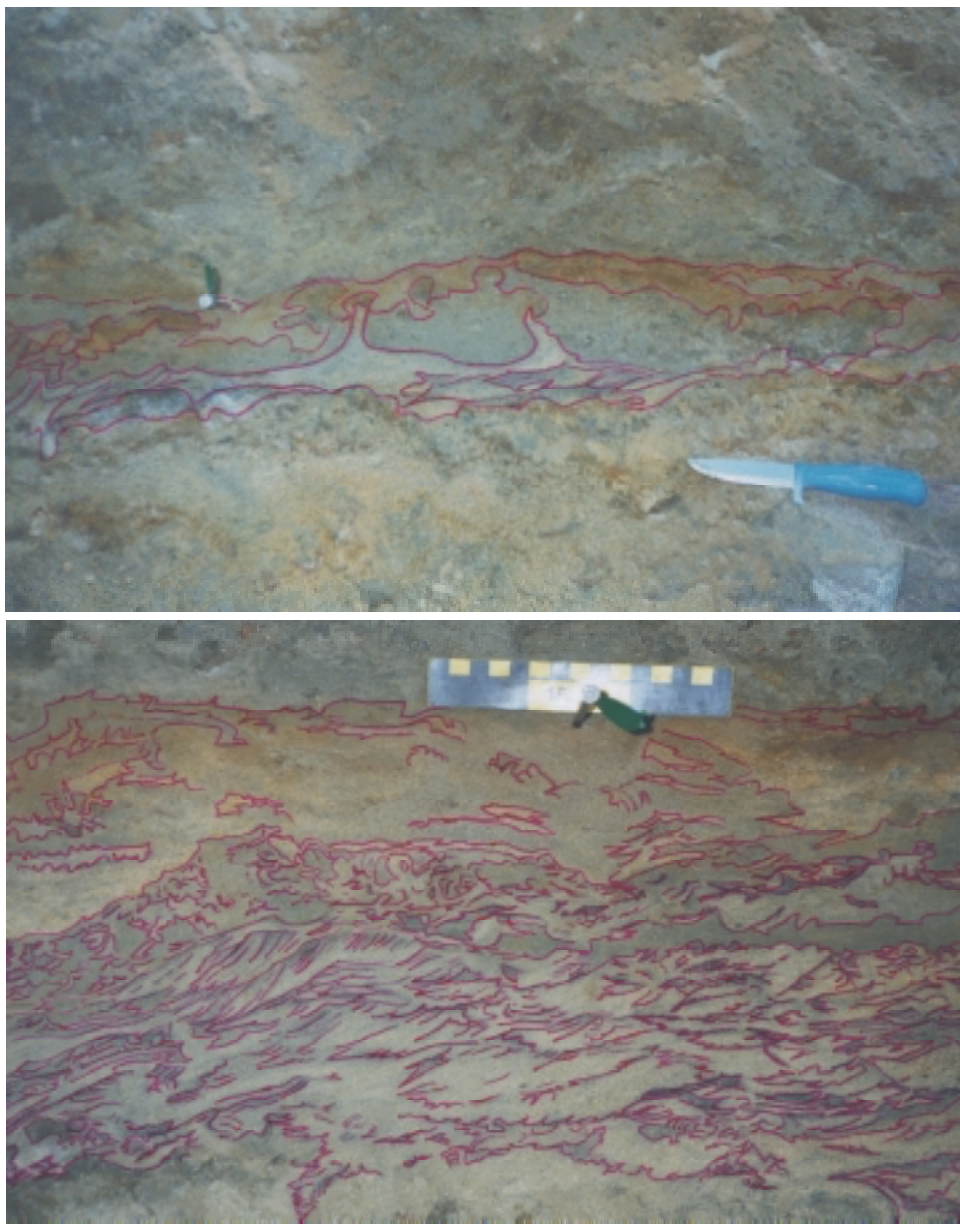
Fig. 1.2.5   Photographs of convolutions and other disturbances in the glaciofluvial sediments.

As parts of the fault escarpment appear with two distinct steps in the slope, it has been speculated that this may indicate that the fault developed as a result of two distinct tectonic events, separated in time. However, the deformation structures observed in the excavated sections do not support this hypothesis. All deformational structures seen may be explained as a result of one major fault event, and the bump in the slope profile represents simply the crest of a pressure ridge located in the head of the major fold structure. The length and vertical one-step displacement of the Stuoragurra Fault indicate that this structure was a result of a tectonic event with an associated earthquake of magnitude c. 7.3. This is based on a comparison with analogous data from recent active fault zones (cf. Wells & Coppersmith 1994). Bungum & Lindholm (1997) estimated the magnitude of the accompanying earthquake to the Stuoragurra Fault to be 7.7 on the assumption that it was created by one single event.

Two additional trenches dug in 1999, three kilometres north of Masi, support the above conclusions.

1.2.3 Nordmannvikdalen fault

The Nordmannvikdalen postglacial fault (Fig. 1.2.6) was first reported by Tolgensbakk & Sollid (1988). It is a normal fault, with an escarpment of up to 1 metre height. The fault scarp branches locally into 2-3 sub-parallel scarps causing an anastomosing appearance. The fault is situated along the gradients of parallel gravity and magnetic anomalies, which are interpreted to represent structures in the underlying Proterozoic basement that is situated at a depth of c. 3 km in this area (Olesen *et al.* 1990). The fault also coincides with a NNW-SSE trending gradient in the depth to the Precambrian basement surface, which increases from a depth of 1-2 km in the Reisa area to more than 3 km in the Lyngen area to the west.

The fault is exposed for approximately 2 km parallel to the valley floor. The terrain slope of 10-12º suggests that a gravitational explanation for the Nordmannvikdalen fault is unlikely, nonetheless, it cannot be ruled out on that basis alone.

Ground Penetrating Radar

Ground penetrating radar (GPR) profiles made during the summer of 1997 revealed a pair of prominent reflectors in the bedrock, dipping to the northeast (Mauring *et al.* 1998). Measurements were made using a pulseEKKO 100 GPR system. Transmitter frequency and voltage were 50 MHz and 1,000 V respectively. The antennae separation was 1 m and the station interval was 0.5 m. Common mid-point (CMP) measurements were carried out for velocity analysis. The CMP stacking velocity was determined to be approximately 0.11 m/ns. This velocity was used for depth conversion of the radar profiles.

One of the reflectors, when extrapolated to the surface, coincided with the surface scarp of the fault (Fig. 1.2.7). The reflector could be seen in three parallel GPR profiles. In two of the profiles, it dipped approximately 40º. However, in the third profile, it had a more shallow dip,

indicating a possible gravitational origin. Further GPR profiles made in 1998 failed to resolve the issue.

Field studies

The main purpose of the field studies was twofold. First, to check the possibility of the scarp being the top of a gravitational slump. Second, to check the possibility that the parallel reflectors visible in the GPR profiles were bedding or foliation planes.

Fig. 1.2.6   The Nordmannvikdalen fault. Top: view from the west. The trace of the fault scarp is shown by the dashed, white line. Bottom: view from the east. The fault scarp runs parallel to the valley floor. The surface slope is at most 15-20º.
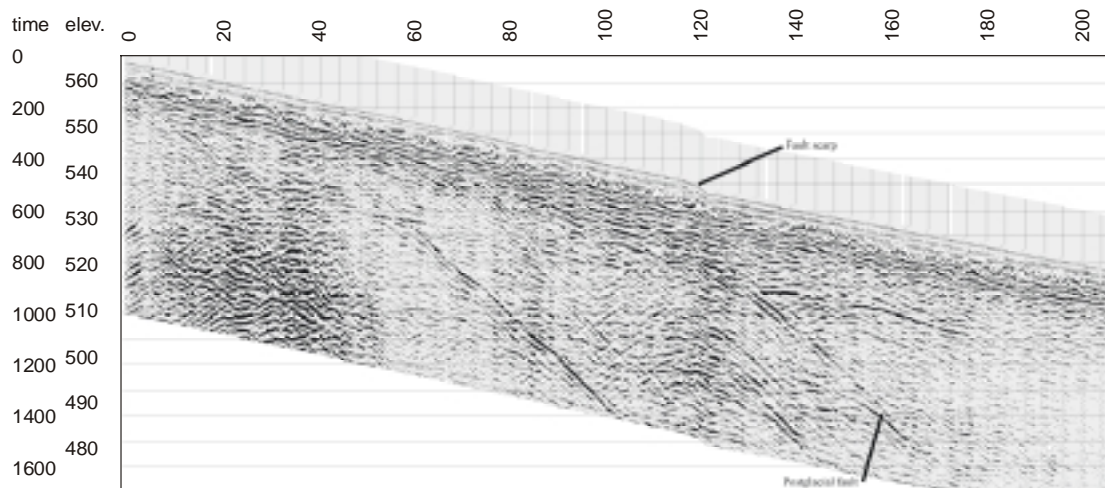
Fig. 1.2.7   GPR profile perpendicular to the Nordmannvikdalen fault. Two prominent reflectors can be seen. The northern reflector can be extrapolated to the surface location of the fault scarp.

Evidence for gravitational slumping

If the scarp in Nordmannvikdalen represented the head of a gravitational slump feature, we would expect to see several things. First, the scarp should be somewhat arcuate in shape. This is not the case. The curvature seen in map view is due to the topography (see below). Second, we should see some sort of accommodation structures along the sides. The western end of the scarp terminates against a large rock flow. Due to the large size of the blocks, it is impossible to determine the relative ages of the two features. It is possible that the rock flow conceals the original side of a slump, however there is no evidence pointing towards this. The eastern end of the scarp terminates against the edge of a mountain (Fig. 1.2.8). Here, there is clearly no evidence for slumping. Third, we should see the foot of the slump along the valley floor. Although there are numerous small terraces between the scarp and the valley floor, there is no feature that could be interpreted as the toe of a slump.

Regional bedding and foliation

Measurements of bedding and foliation throughout Nordmannvikdalen showed that both surfaces dip to the southwest. This is the opposite direction to the reflectors seen in the GPR profiles. The fault scarp is cut by two streambeds near the eastern end. Within the bedrock exposed in these streambeds, the bedding and foliation surfaces are quite variable. In places, they dip towards the northeast, but they are highly folded and generally dip to the southwest (Dehls 1999). The dipping reflectors seen in the GPR profiles must represent discrete fracture/fault surfaces.

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Fig. 1.2.8   The east end of the Nordmannvikdalen fault terminates against the foot of a mountain.

Digital Elevation Model

The fault scarp in Nordmannvikdalen runs over two gentle hills and is cut by two streambeds. It was thought that a digital elevation model (DEM) would allow us to estimate the dip of the fault by standard geometrical techniques. A DEM, and accompanying orthophoto, were produced (Fig. 1.2.9). The traces of both the bottom and the top of the fault scarp were digitised. The x, y, and z values of the DEM along the traces were then used to fit an optimum plane through the points. A least-squares algorithm was used. The resulting plane has a dip of 28º to the north-northeast (Fig. 1.2.10). This is obviously shallower than the reflectors seen in the GPR. There are two possible sources of error that may account for this discrepancy. The determination of the dip of the fractures in the GPR is based upon an estimated velocity. If this velocity is too high, then the calculated dip is too high. This is unlikely, as a velocity equivalent to that in peat would have to be used to produce such a shallow dip. The second source of error is the assumption that the digitised fault scarp is in fact one scarp. In fact, however, the scarp has several segments, sometimes en echelon, sometimes subparallel. In either case, it seems that the dip of the fault is shallower than expected for a normal fault. It seems likely, therefore, that the present scarp has been formed by reactivation of an existing (possibly reverse) fault.

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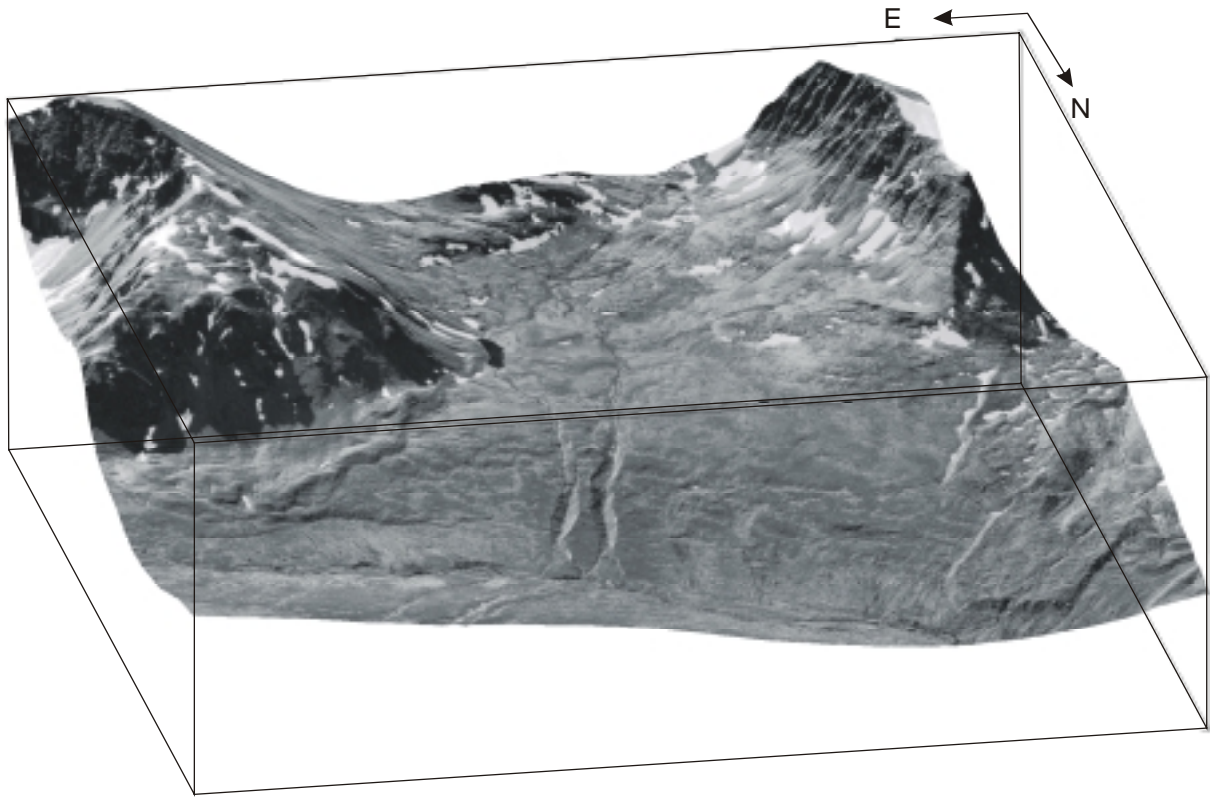
Fig. 1.2.9   An orthophoto draped upon a digital elevation model (DEM). These were used to calculate the apparent orientation of the fault at the surface, based upon the curvature of the fault scarp across the hills and streambeds.

Summary

Detailed field mapping, GPR imaging and terrain analysis rule out the possibility that the Nordmannvikdalen fault is a gravitational fault. In the absence of a gravitational explanation for the origin of the fault, we propose that the fault is a tectonically driven normal fault, possibly formed shortly after the last deglaciation of northern Norway.
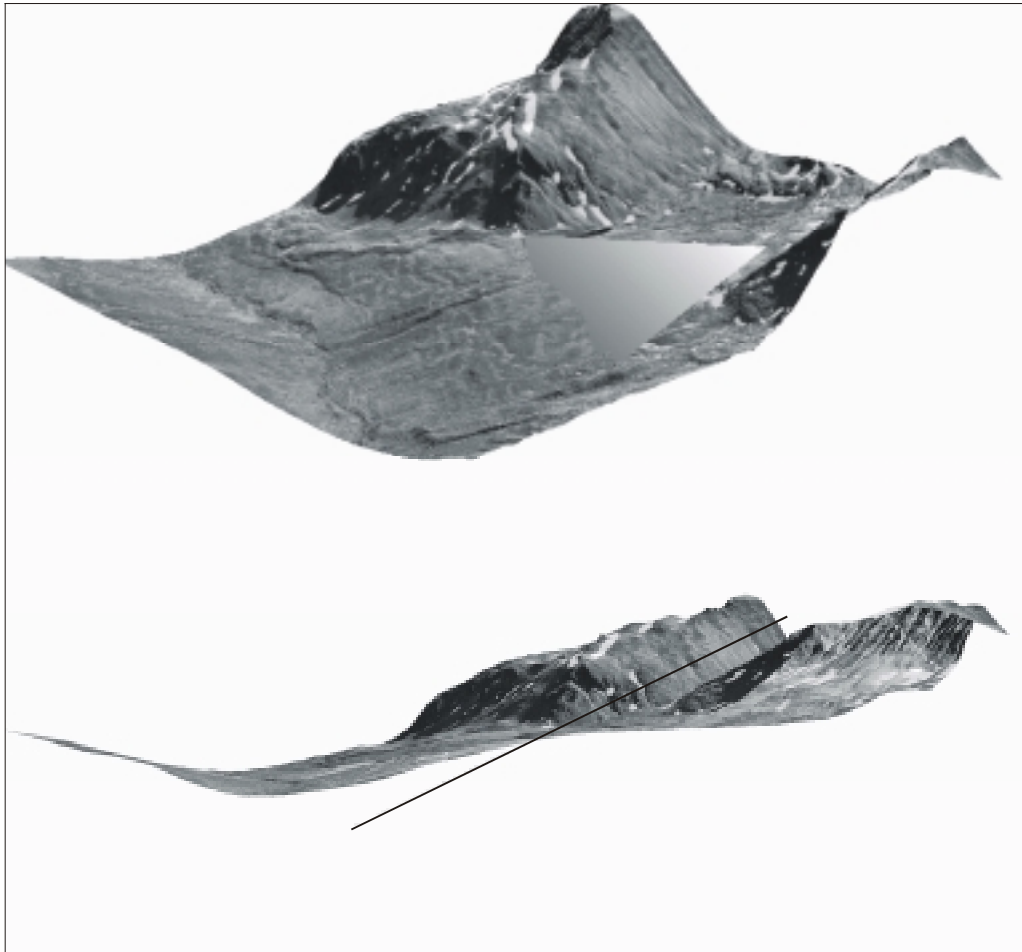
Fig. 1.2.10   The best fit plane through the fault scarp is shown in three dimensions. The plane dips 28º to the north-northeast. Top: oblique view from the northwest. Bottom: along strike view from the west.

1.2.4   Geodetic measurements

Levelling

At Stuoragurra, the elevation difference DH between bench marks on both sides of the fault has been measured by precise levelling. Sundsby (1996) reported the results of levellings at the Stuoragurra fault 1987, 1990, 1991, and 1996. All these levellings were done using Wild N3 precision spirit levels. The 9th of July 1999 another relevelling was done, using two digital levels Zeiss DiNi11, simultaneously. Weather was very favourable for precise measuring work. 40 series of observations were performed, from 9.30 am to 4.30 pm. Each instrument was used on both sides of the fault. The precession of this series of measurements is expected to be roughly 0.1 mm.

After having analysed the results, we cannot conclude that any significant change of elevation difference across the Stuoragurra fault in Masi has occurred since 1996.

Earlier conclusions about a vertical displacement of 2.3 mm between 1987 and 1991, are reconsidered due to scepticism of the quality of the data from 1987. Further discussions are given in the annual technical report for 1999 (Bockmann 1999, Sylvester 1999, Bockmann & Grimstveit 2000).

GPS network

GPS measurements at Masi have so far been completed only once, and therefore no information is yet available concerning significant deformation. Indications of deformation will only begin to emerge once additional observations and computations are completed. The planned observations in 1999 were dropped due to higher priority of measurements in the GPS network of Mo i Rana. To achieve the original goal, all GPS-nets involved in the project have to be remeasured in a new future project. Further description of the GPS campaign and computations are given in the Annual Technical Reports 1998 and 1999 (Bockmann 1999, Bockmann & Grimstveit 2000). The data and a list of point description as well as picture documentation are kept at The Norwegian Mapping Authority, Geodetic Department.

1.2.5   Discussion

Lagerbäck (1990) argues that the Lansjärv postglacial fault in northern Sweden was formed during one major event shortly after the deglaciation of the area. Neither of the events that formed the Stuoragurra and Nordmannvikdalen faults has been precisely dated yet, although both must have occurred after the Weichselian deglaciation.

The timing of neotectonic faulting in northern Fennoscandia suggests that it is closely related to the stresses of post-glacial isostatic uplift. The current rate of uplift near the Stuoragurra fault, for example, is approximately 2.5 mm/yr. At the time of deglaciation, this rate would have been much higher. Nonetheless, postglacial rebound is not the only factor that must be considered.

There is some evidence (e.g. Mangerud *et al.* 1981, Sejrup 1987) that the Norwegian coast may have been subject to tectonic uplift in the order 0.1-0.3 mm/yr during the Quaternary, in addition to postglacial uplift. Examination of recent seismicity in Scandinavia (Fig. 1.2.11) shows a pattern clearly not correlated with current uplift rates, but rather consistent with continued tilting of Norway and Sweden due to ridge push. A flexural hinge zone along the eastern border of the tilted Scandinavian block is represented with an area of increased seismicity. This zone continues through southern Sweden and along the western coast of the Bothnian Sea northwards to Finnmark in northern Norway. The postglacial Lapland Fault Province is situated along the northern part of this hinge zone. A flexural hinge with increased seismicity is also situated along the western border of the tilted Scandinavian block. Thus,

Quaternary tilting of Fennoscandia due to ridge push and/or other mechanisms may also play a role in neotectonic activity in Norway.
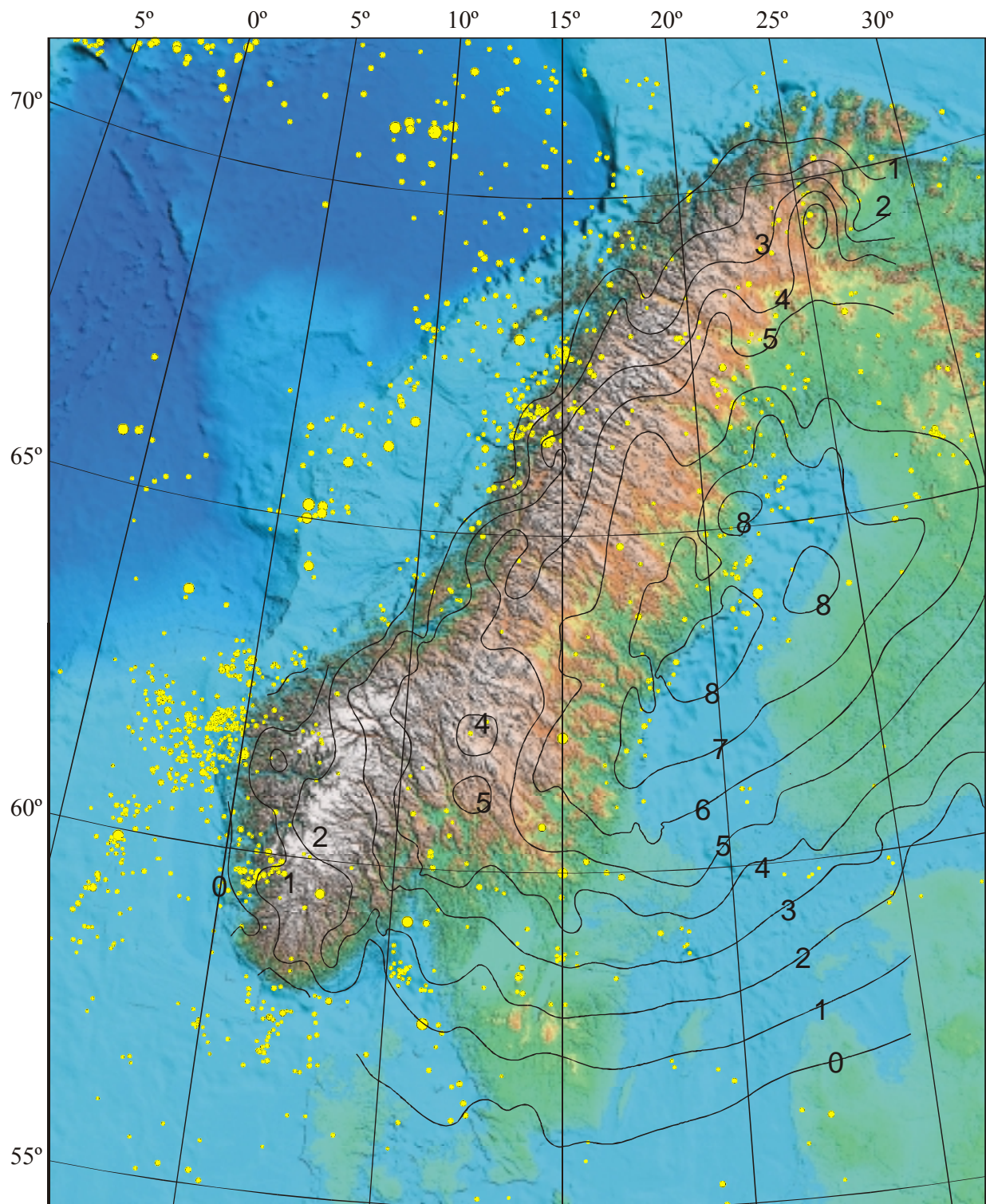
Fig. 1.2.11   A shaded relief map of Fennoscandia, showing the current apparent uplift rates (in mm/yr) as well as the locations of earthquakes with magnitudes greater than 3.0 since 1965.

1.3 Neotectonics in Nordland, northern Norway

By Erik Hick, Hilmar Bungum, Conrad Lindholm (NORSAR), Odleiv Olesen, Lars Olsen, John F. Dehls (NGU) & Lars Bockmann (SK)

1.3.1 Introduction

The Nordland area in northern Norway is an interesting area from a neotectonic point of view, especially since the northern parts of the coast exhibit high levels of seismic activity, including shallow earthquake swarms at different locations. From this region are also known a number of other and earlier reports of neotectonic observations, of which the Båsmoen fault running parallel to the Rana fjord has been considered potentially the most interesting one. All of these aspects have been studied thoroughly in this project, by means of field evaluation of neotectonic claims, Quaternary geological studies, a new seismic network and GPS measurements in the Rana area. The conclusion from this scrutiny is that the only phenomena with probable neotectonic causes are three areas of shallow swarm activity, one of which was discovered using the new seismic network, and possible indications of postglacial activity on the Båsmoen Fault. There does not, however, appear to be any contemporary seismic activity in conjunction with the fault itself.

1.3.2 Geological framework

The bedrock geology of mainland Nordland is dominated by Caledonian nappe complexes situated on a Precambrian basement (Roberts & Gee 1985). Mesozoic sedimentary basins and structural high are situated on the attenuated continental shelf to the west (Blystad *et al.* 1995). The Precambrian continental-scale Protogin Zone is trending in a N-S direction below the Caledonian Nappes in Nordland (Olesen *et al.* 1997). The NW-SE trending Bivrost Lineament may represent a Mesozoic reactivation of the Protogin Zone.

The regional Vestfjorden-Vanna Fault Complex (Andresen & Forslund 1987) bounds the Vestfjorden Basin and continues through the western Hinnøya-Tjeldsundet area in the northern part of Nordland. There is evidence of both Late Paleozoic and Mesozoic activity along the fault complex (Andresen & Forslund 1987, Olesen *et al.* 1997). The Trøndelag Platform terminates along Nordland Ridge, which changes in orientation from NNE-SSW to almost E-W immediately offshore the Meløy area. The Ylvingen Fault Zone along the southern margin of the Mesozoic Helgeland Basin may have a northeastward continuation into the Rana area.

1.3.3   Geology

Investigations of reported Neotectonic phenomena

A total of six previous reports of neotectonic activity in Nordland were available at the start of the project (Fig. 1.3.1), all of which have been re-evaluated as part of the present neotectonic mapping. Five of the reports (Vassdalfjellet, Reinneset, Tysfjord-Kobbelv, Kvasshaugen and Austerdalsisen) have been classified as having non-tectonic origins (gravitational sliding, erosional plucking etc.).
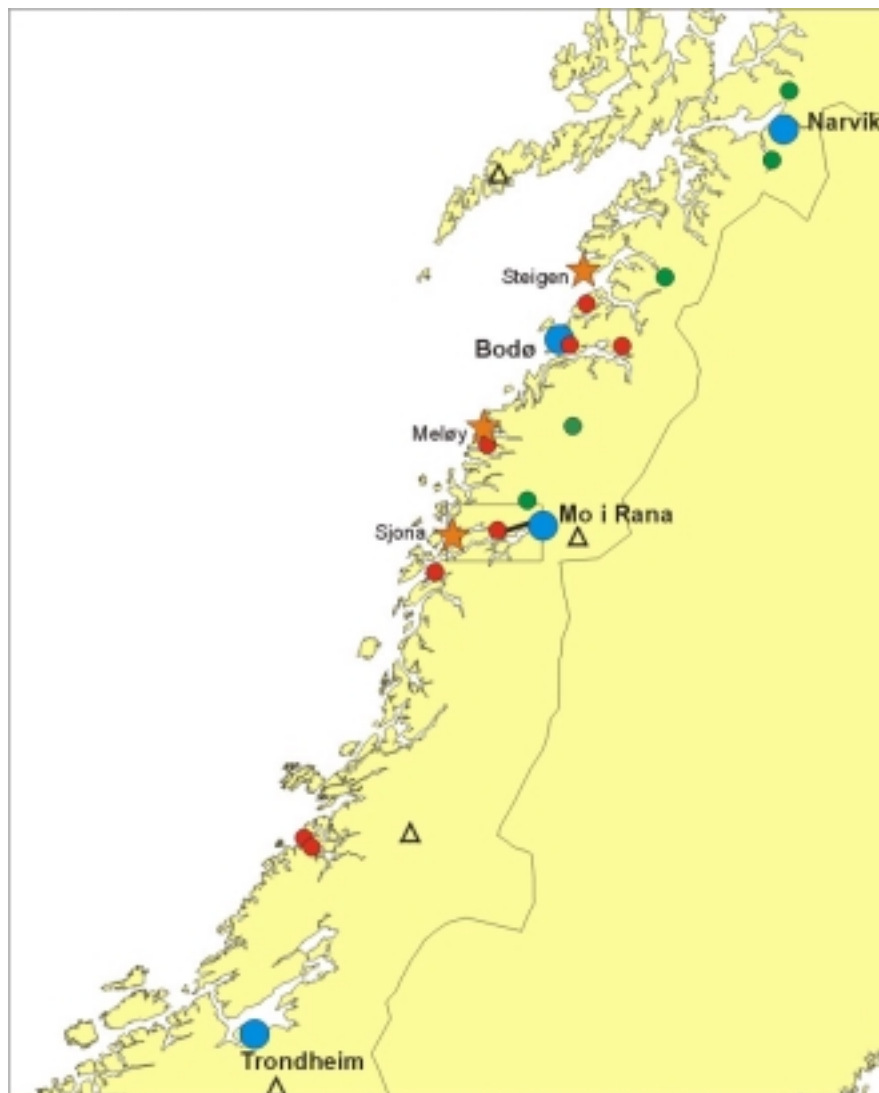
Fig. 1.3.1   Map of the areas of interest in the Nordland region. The red dots represent the eight locations where sand deformation structures with probable earthquake origins were found, while the green dots represent the locations of the four previous reports of neotectonic phenomena that have been evaluated and attributed to other sources. The Båsmoen fault is indicated by the thick black line west of Mo i Rana. The black rectangle shows the region of the new seismic network, and the red stars represent earthquake swarms. Permanent seismic stations are shown by triangles.

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Sackungen structures occur along the crest of Kvasshaugen in Beiarn, Nordland. Up to 20 m wide and 10 m deep clefts occur along an approximately 5 km long NNE-SSW trending zone (Grønlie 1939, Johnsen 1981, Muir Wood 1993, Olesen & Dehls 1998). The large-scale faults are suggested to be of postglacial age since there is no sign of glacial sculpturing along the escarpments.

The extensional faults in Beiarn are gravity-induced and classified as a sackung feature which has earlier been reported from mountainous areas in western US and Canada, Alps and New Zealand (Savage and Varnes 1987). Investigations in New Zealand, Slovakia and Russia conclude that earthquake shaking was the most likely trigger of movement (Jibson 1996, Beck 1968, Jahn 1964) partly because the sackungen features occur in seismically active areas.

The remaining potential neotectonic phenomena is the 50 km long Båsmoen Fault (Olesen *et al.* 1994, 1995) running parallel to the Rana fjord. There is still some uncertainty concerning this fault, even though it has been subject to extensive scrutiny. It is graded B in our classification system. Liquefaction structures in sand along the fault zone suggest that earthquake induced disruptions may have occurred during late-/postglacial time (Olesen *et al.* 1994, Olsen 1998). Trenching of the Båsmoen Fault at Båsmofjellet has revealed structures which indicate a reverse fault were the hanging wall block of the faulted rock has penetrated up to some 40-50 cm vertically through the till and sand cover of the lowermost part of the fault slope (Olsen 2000). In spite of indications of postglacial movement along the fault (Olsen 1998, 2000), conclusive evidence as to its neotectonic significance has not been found.

Quaternary studies

The Quaternary in Fennoscandia was characterised by repeated periods of ice growth followed by ice retreat. The glacial isostasy during these alternations had a considerable influence on ground stability. This was particularly well expressed during deglaciation periods, which were characterised by frequently occurring earthquakes and faulting in many areas (Kujansuu 1964, Lundqvist & Lagerbäck 1976, Olesen 1988). The last deglaciation is dated to 9,200 – 9,500 ^{14}C-yr BP in the area around Mo i Rana (Fig. 1.3.1) (Blake & Olsen 1999).

Deformation structures were studied at several localities in the Nordland region, and structures of a type that would be reasonable to associate with earthquake activity were found at a total of eight locations, including one locality near Utskarpen close to the Båsmoen Fault. It is not known for certain whether the Båsmoen Fault (Olesen *et al.* 1994, 1995) was active during the last deglaciation, but some liquefaction structures in sand along the fault zone suggest that earthquake induced disruptions may have occurred during late-/postglacial time (Olesen *et al.* 1994, Olsen 1998).

Excavations with trenching of the Båsmoen Fault at Båsmofjellet in 1995 revealed structures which indicate a reverse fault were the hanging wall block of the faulted rock has penetrated

up to some 40-50 cm vertically through the till and sand cover of the lowermost part of the fault slope (Fig. 1.3.2). Observations of glacial striae on the hanging wall block some 40 cm above ground surface along the fault some km west of Båsmofjellet, have led us to conclude that the general postglacial vertical movement along the fault was no more than 30-40 cm.

In 1995 it was suggested that the colluvial sand complex both on the upslope and downslope sides of the exposed hanging wall block might have been produced by postglacial slope processes (gravity mass movements) during severe climatic conditions (heavy rain storms, rapid and repeated freezing-thawing cycles, etc.). A re-evaluation of the deformation structures observed in 1995, followed by additional data from a new excavation in 1999 (Figs. 1.3.2 & 1.3.3), conclude that at least the oldest part of the colluvium, which is characterised by rip-up clasts of till matrix, was most likely induced by the last significant tectonic vertical movement of the fault.

The Båsmoen Fault, Båsmofjellet
- Section from excavation 1995

SSE

NNW

Colluvial sand

Dislocated lens of till (rip-off clast)

Hangblock of faulted rock
(weathered / crushed)

Till

Colluvial sand complex

A: Peat*

Peat

Glacial striation ?

Bedrock

Glaciofluvial / fluvial sand

Till

1 m

1 m

* Sampled for ^{14}C-dating
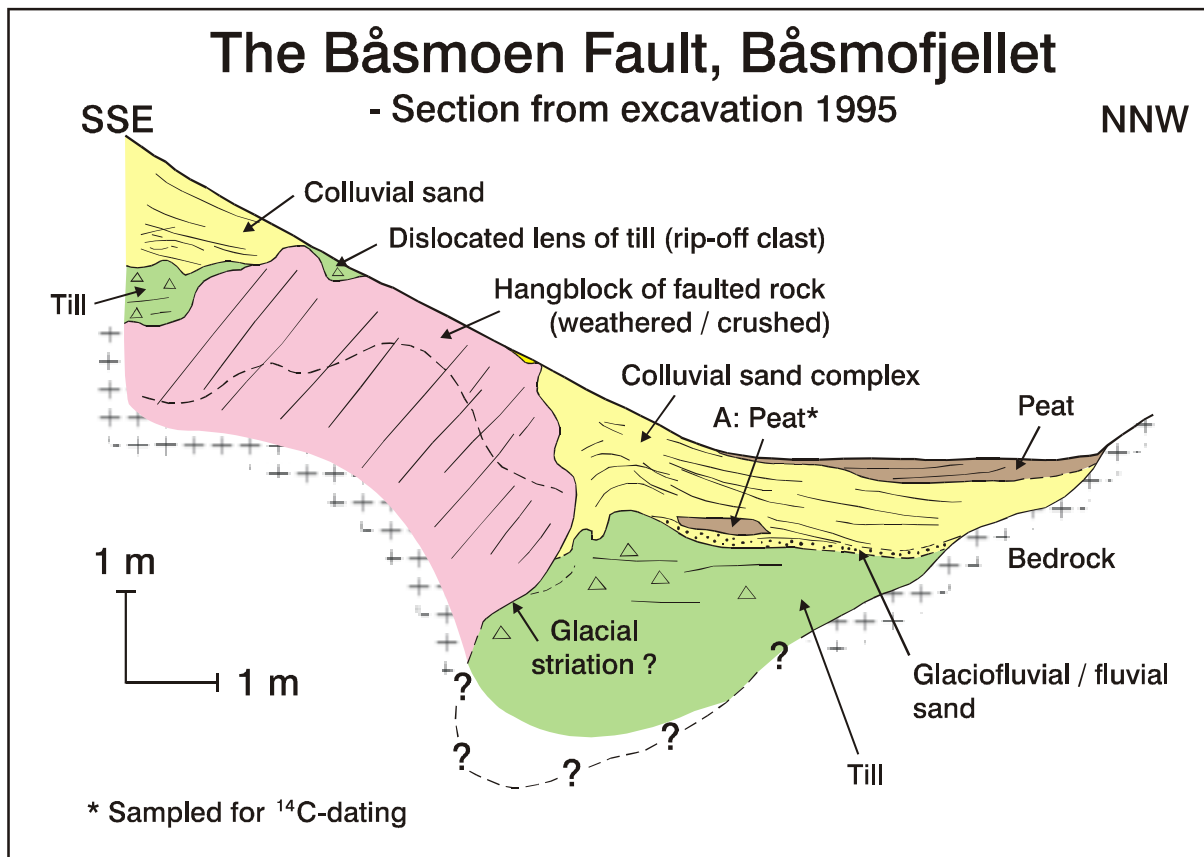
Fig. 1.3.2   Simplified sketch of the main section of excavation transverse to the Båsmoen Fault, 1995 (from Olsen 2000).
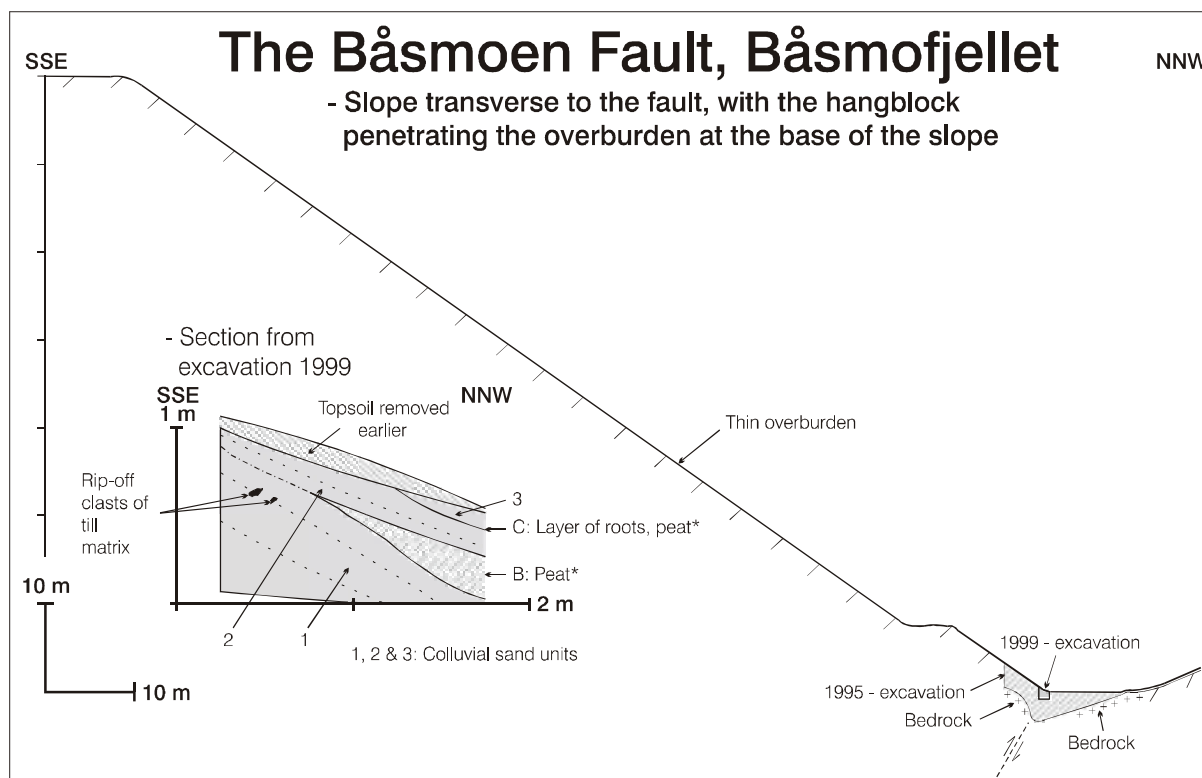
Fig. 1.3.3   Simplified sketch of a vertical profile transverse to the Båsmoen Fault at Båsmofjellet, including positions of the trenching through the fault in 1995 and 1999. A sketch of a vertical section from 1999 transverse to the fault is also included (from Olsen 2000).

C-14 dating of the Båsmoen Fault

The oldest part of the colluvial sand complex is underlain by gyttja A (Fig. 1.3.2) and overlain by gyttja B (Fig. 1.3.3). Samples of these gyttja units yield ^{14}C-ages of 8780 (±80) and 3880 (±75) years BP, which should correspond to the maximum and minimum ^{14}C-ages of the oldest part of the colluvium, and consequently the approximate age of the tectonic fault activity.

Marine geologic studies

A seismic survey was performed by NGU in the Rana and Sjona fjords to investigate if sedimentary structures indicating neotectonic faulting or neotectonic related slides could be seen (Longva *et al.* 1998). A number of young sediment slides and liquefaction within layered sediments were visible in areas where standing waves were reported during the 1819 earthquake, but no other evidence of neotectonic displacement of sediments were observed.

1.3.4 Seismology

Historical and recent earthquakes

The Nordland area has quite a varying and therefore an interesting pattern of seismic activity (Byrkjeland *et al.* in press). The southern parts exhibit only smaller earthquakes, including the region of the Møre-Trøndelag fault zone, while there is significant activity from the Rana area and northwards. The Rana area is also the location of the largest onshore earthquake in historic time in Fennoscandia, with a MS magnitude of 5.8-6.2. The earthquake was felt over most of Scandinavia, and caused numerous rockfalls and standing waves in the Rana area, and also a landslide at Utskarpen (Muir Wood, 1989a). The causative fault has not been found (surface rupture is possible, but should not be expected, at this magnitude), but the reported effects indicate a location in the north-eastern parts of the Ranafjord area. The locations of the various reported effects are shown in Fig. 1.3.4.

Two significant earthquake swarms are documented in Nordland in recent years, the Meløy swarm in 1978 (Bungum *et al.* 1979) in which several thousand earthquakes with magnitudes up to M_L 3.2 occurred over a ten-week period, and the Steigen swarm which consisted of several hundred earthquakes in several pulses during 1992 (Atakan *et al.* 1994). The earthquakes in these swarms were all shallow, with hypocenter depths in the upper part of the crust, mostly less than 8 km. These swarms, the latter in particular, bear many similarities to the activity observed using the local network in the Ranafjord since July 1997.

Contemporary seismic activity

A six-station seismic network was installed in June, 1997, in the Ranafjord area by NORSAR as part of the NEONOR project, initially aimed at monitoring possible seismic activity along the Båsmoen Fault. Since then, around 450 seismic events have been located, of which close to 350 are earthquakes within or close to the network. The main part of the activity, approximately 250 earthquakes, occurred in the western parts of the network, the same area in which many of the effects from the 1819 quake were reported. These earthquakes have an interesting spatio-temporal distribution, as they occur as swarms (clustered in time) and well confined in time and space. Five major swarms consisting of between 20 and 70 quakes have been identified, in addition to three smaller swarms with less than 15 quakes. All five major swarms exhibit the same NW-SE trend in the hypocenter locations. The two largest earthquakes during the period of operation, with magnitudes of M_L 2.8 and 2.7 occurred in two of the swarms in this area.
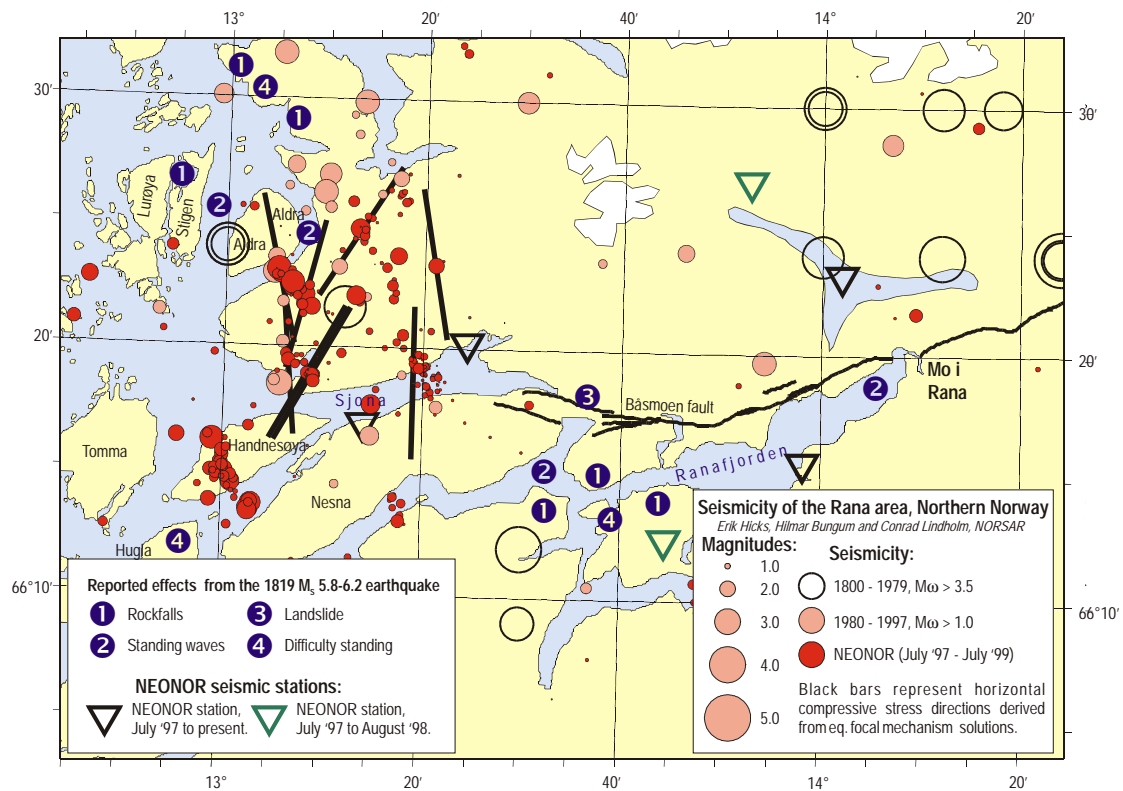
Fig. 1.3.4   Historic (open circles), recent instrumental (pink circles) and new (red circles) seismic data in the Rana area. Reported effects from the 1819 earthquake are shown by the numbered circles. Horizontal compressive stress directions from the eight earthquake focal mechanism solutions in this area are shown by the black bars. The NEONOR stations are shown as inverted triangles. The Båsmoen Fault is also shown, running more or less parallel to the north of the Rana fjord.

A total of ten new earthquake focal mechanism solutions have been determined with the help of the local network. The eight solutions within the most active areas in the outer parts of the Rana fjord all show an approximately 90º rotation of the direction of main compressive stress, as compared to the regional NW-SE trend. Fig. 1.3.4 shows the seismic activity in the Rana area, with the data determined using the new network as dense red circles, along with recent earthquakes (pale red circles) and historical earthquakes with much higher uncertainty (open circles). The directions of maximum horizontal compressive stress (σ_{Hmax}) for the eight focal mechanism solutions within the network are also shown, as black bars. Seismic data are also plotted in Fig. 1.3.4 for the entire Nordland area.

1.3.5   Geodesy

GPS deformation measurements

A GPS campaign based on a grid of 18 points was conducted by NTNU in the Ranafjord area i 1994, covering three profiles across the Rana and Sjona fjords. This net was re-measured in

1997 by NTNU (Skogseth 2000), and was re-measured again in 1999 by the Norwegian Mapping Authority (Bockmann & Grimstveit 2000). The 1999 network was extended with two additional points in the Sjona area, in order to improve the possibilities for capturing significant deformation in the areas of the highest seismic activity.

The current results from the GPS campaigns in the Rana area do not show any measurable deformation, possibly related to a quality problem with the first two campaigns. However, the 1999 campaign by the Norwegian Mapping Authority (Bockmann 2000) using state-of-the-art instrumentation will provide a high-quality benchmark for further GPS measurements in the Rana area in years to come, thereby improving the chances for providing more conclusive answers with respect to ongoing deformations in the Rana area.

Postglacial rebound

A review of all available uplift rate data for Norway (Chapter 4.3) compiled under the NEONOR project shows, as demonstrated in Fig. 1.3.5, that the uplift patterns for Nordland are not as uniform as previously indicated by published uplift maps, which invariably have been strongly smoothed. Anomalies of fairly large magnitudes (up to several mm/yr) and of relatively short wavelengths (< 100 km) are present in these uplift data, when compiled from various sources.

1.3.6   Combined interpretation

The only firmly confirmed occurrences of neotectonic activity in Nordland are the three earthquake swarm areas of Sjona-Rana, Meløy and Steigen. These do not correspond with any known faults with surface manifestation, but appear to be connected to shallow (< 8 km) weakness zones in the crust. The conclusion regarding the Båsmoen Fault along the Rana fjord is still uncertain, however, in spite of the fact that a re-evaluation of the field studies by NGU concludes that postglacial movements of the fault of the order of 30-40 cm are possible (Olsen 2000).

The postglacial uplift gradient in Nordland closely follows the coast (and hereby the seismic activity north of 66ºN), leading Hicks *et al.* (in press) to conclude that postglacial uplift is most likely a major factor in explaining the seismic activity, although more local sources must also be considered, given the swarm-like nature of the seismic activity. Fig. 1.3.5 shows that the areas that exhibit significant seismic activity are also areas of high elevations and steep topography, indicating a possible connection.
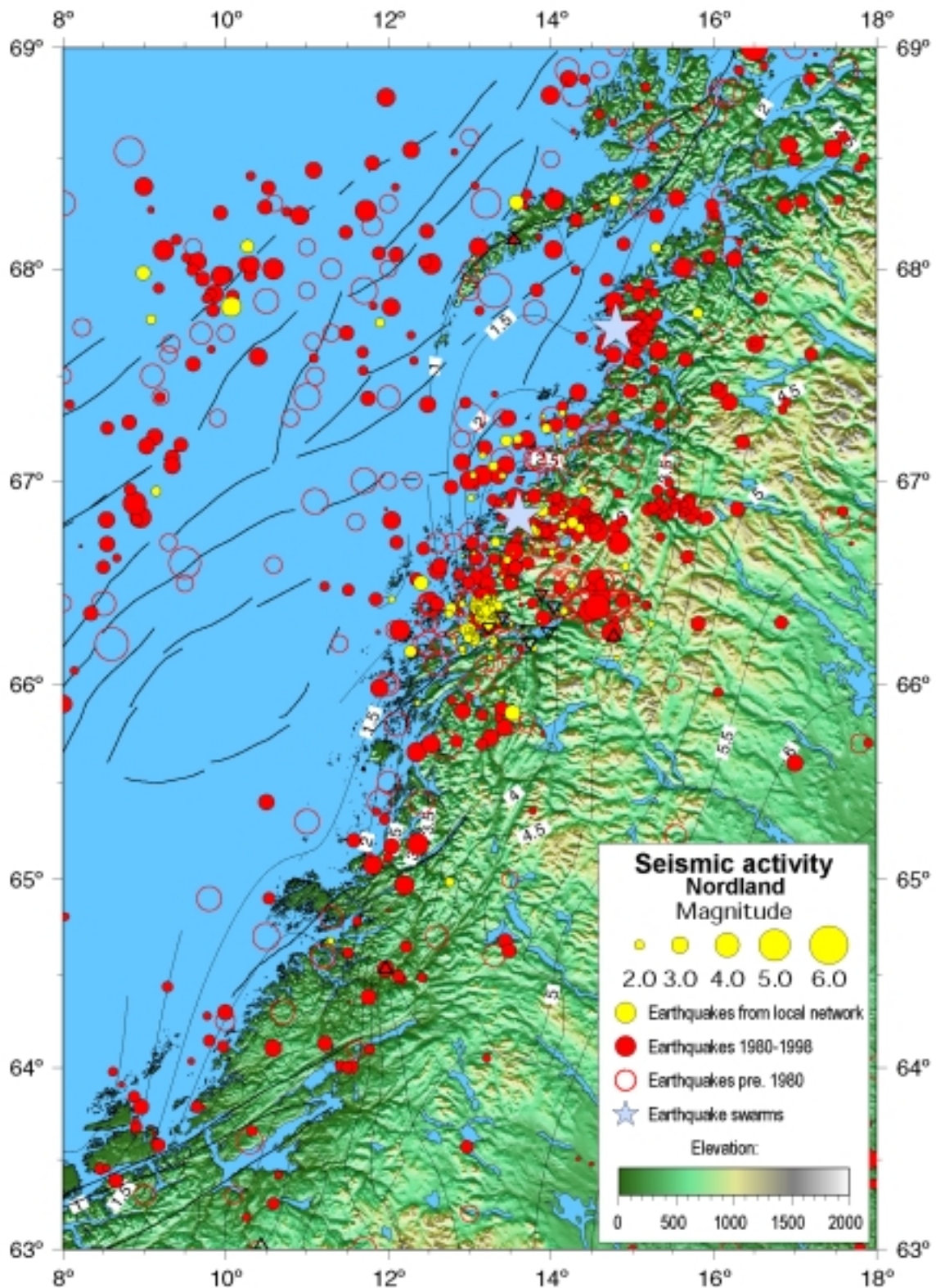
Fig. 1.3.5.   Seismic activity, contemporary uplift rates and topography in the Nordland region. Yellow circles are earthquakes located by the NEONOR network, filled red circles are instrumentally located earthquakes, 1980-1998, and open red circles are earthquakes from before 1980, including macro-seismically located ones. Uplift rates (black contours) are in mm/yr. Main structural elements from Blystad et al. (1995).

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1.4 Palaeoseismic activity and gravitational-slope failures

By Lars H. Blikra, Oddvar Longva & Kari Sletten (NGU)

It is known from studies of the effects of historical earthquakes that many of these trigger different types of debris and rock failures (Keefer 1984, Jibson 1996). The spatial occurrence and dating of individual events can thus be used for palaeoseismic analysis. The review made by Jibson (1996) indicates that the triggering of large rock avalanches requires a minimum earthquake magnitude of about 6.0, and he also concludes that large rock avalanches are the type of avalanche activity with greatest potential in palaeoseismic studies.
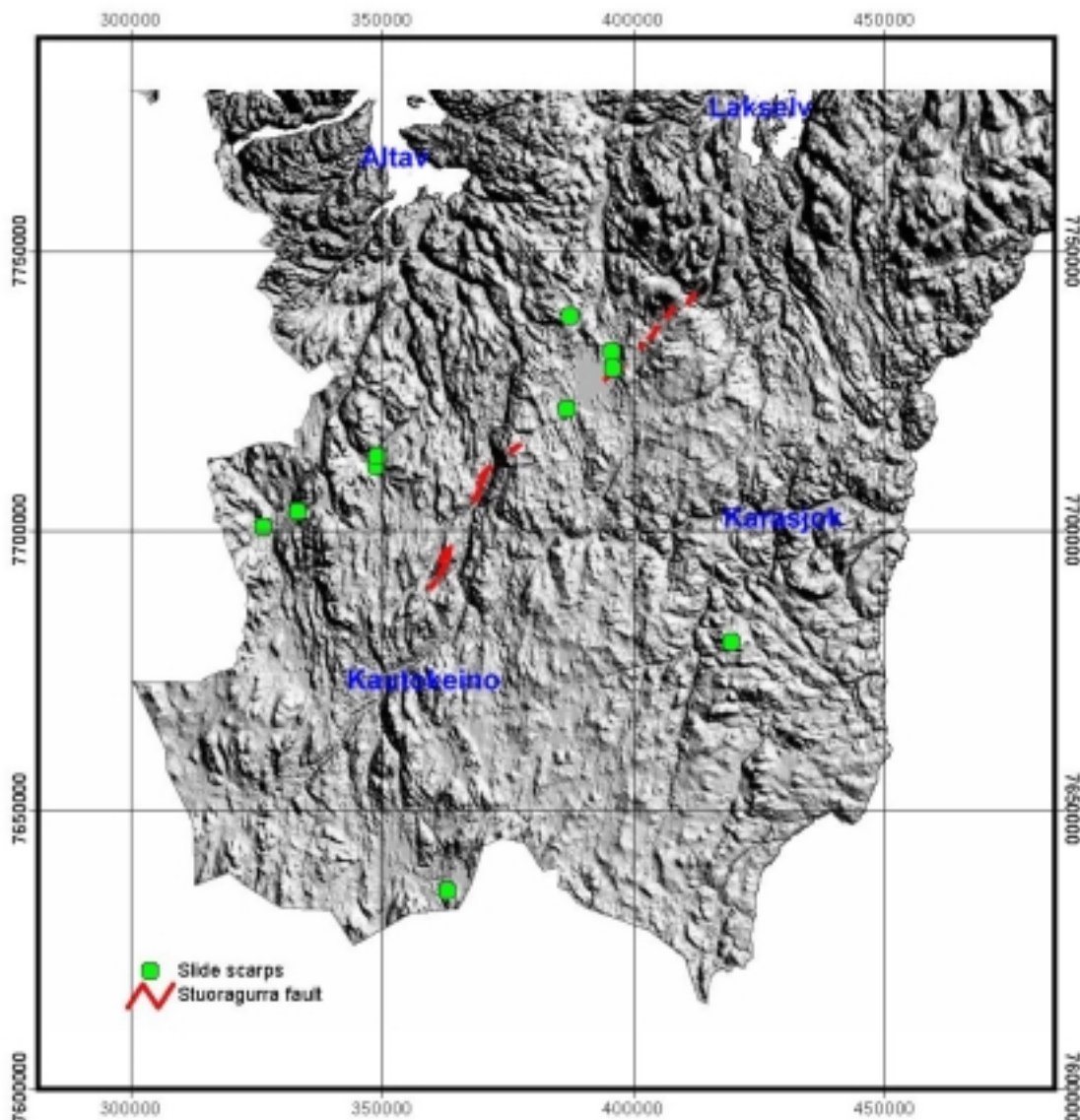
Fig. 1.4.1 Locations of slide scarps in parts of Finnmark, northern Norway. The line spacing of the UTM-grid is 50 km.

Geological mapping and studies of rock avalanches and other gravitational-slope failures are parts of two NGU projects in Troms and Møre & Romsdal counties. The data of potential interest for the NEONOR project will be presented here, and have also been reported in the annual NEONOR reports (Blikra 1998, Anda *et al.* 2000, Blikra & Longva 2000). Furthermore, some areas in Finnmark and in western Norway are studied on aerial photos in order to find areas characterised by gravitational-slope failures (Blikra 2000; Sletten 2000). The present report gives an overview of the regional occurrence of gravitational-slope failures in the studied areas in Troms and Møre & Romsdal, in parts of Finnmark and in a c. 20 km wide zone extending from Odda in Hardanger to Aurland in Sogn.

1.4.1   Finnmark, northern Norway

A reconnaissance study based on interpretations of aerial photos in 40% of the Finnmarksvidda area reveals a total of 10 slide-scarp features (Sletten 2000) (Fig. 1.4.1). They occur in glacial tills with relatively gentle slopes. Many of them are close to the Stuoragurra Fault and they may have been triggered by large earthquakes. Large-scale slides and debrisflows have also been mapped close to the postglacial faults in northern Sweden (Lagerbäck 1992).

1.4.2   Troms, northern Norway

Numerous gravitational faults and slope failures occur in certain regions in Troms county (Blikra & Longva 2000; Fig. 1.4.2). The most frequent features are large-scale rock avalanches and rock glaciers of rock-avalanche origin. More than 150 such features have been mapped in the Balsfjord-Lyngen-Kåfjord region covering an area of c. 7,000 km^2. The rock avalanches that probably have been modified by rock-glacier processes are concentrated to the Kåfjord area, but the spatial distribution is influenced of the fact that glaciers covered large parts south of this area during the period of formation. Rock glaciers need permafrost conditions to evolve and the only actual period for this is the cold Younger Dryas, ca. 11,000 to 10,000 radiocarbon years BP. The rock-avalanche events leading the rock-glacier formations need to have occurred before or during the Younger Dryas phase, and are restricted to areas outside the Younger Dryas ice margin or to nunataks within the ice sheet. The ice margin during the Younger Dryas are thought to be located at the city of Tromsø, and some 15 to 20 km north of Kåfjorden. The inner parts of the fjords was deglaciated after 10,000 BP. The bulk of the rock avalanches in this region has not been modified by rock glaciers (Fig. 1.4.2). Some of these events have been dated and seem to be triggered shortly after the deglaciation, ca 10,000 – 9500 radiocarbon years BP.

There are many areas characterised by gravitational faults and fractures in bedrock in the same region (see Fig. 1.4.2). They often occur in connection with large rock avalanches. Some of the mountain plateaux are highly fractured and flanked by gravitational faults and rock avalanches, for example in an area between Grøtsundet and Ullsfjorden, Northeast of Tromsø

(Fig. 1.4.3). Large-scale failures of the glacial till with the development of extensive debrisflows have occurred on the western side of the plateau.

A series of gravitational faults occur on the eastern side of Lyngen and Storfjorden (Fig. 1.4.2), with the southernmost failure south of Skibotn (Fig. 1.4.4). Detailed mapping on Nordnesfjellet, north of Skibotn, show that the basal shear planes of the failures seem to follow the low-angle foliation, with dips in the range of 10-15°. Normally a gradient of ca. 30° is needed for failures in bedrock to occur.
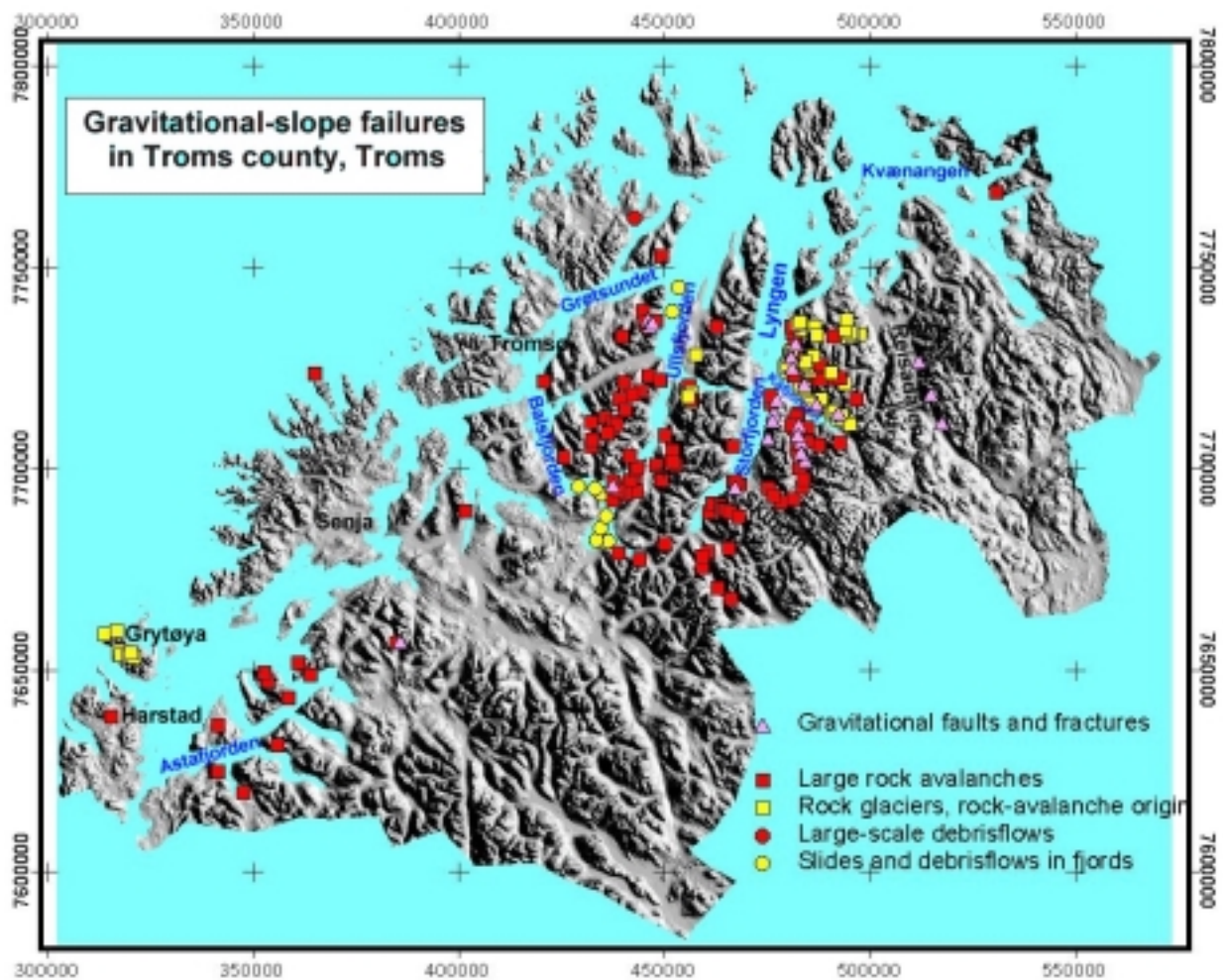
Fig. 1.4.2 Gravitational slope failures in Troms county, northern Norway. The northeastern part (Kvænangen area) has not yet been mapped. The line spacing of the UTM-grid is 50 km.

There are also large-scale collapse features of fine-grained fjord sediments along the fjord margins in Balsfjorden (Fig. 1.4.2), with a corresponding massive seismic unit in the deeper basin. The general stratigraphy indicates that the collapse event occurred shortly after the deglaciation (Fig. 1.4.5). A high number of failures occur also in the same stratigraphical position on both margins of Ullsfjorden.

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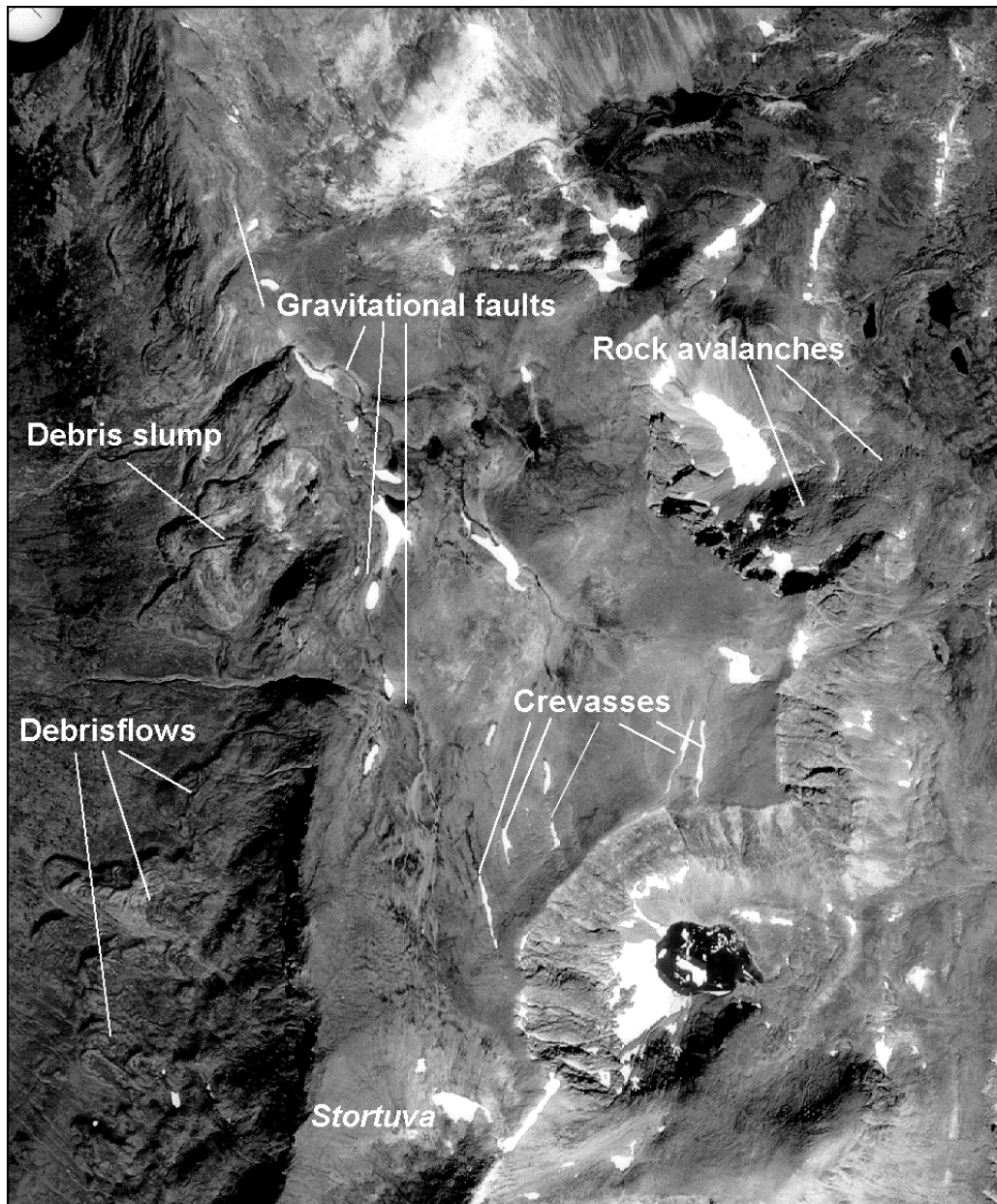
Fig. 1.4.3 Gravitational-slope failures on a mountain plateau Northeast of Tromsø. Note also prominent crevasses in the middle part. The aerial photo covers an area of ca 3.5 km x 4 km.

The distinct spatial distribution of different gravitational-slope failures in the Balsfjord-Lyngen-Kåfjord region strongly indicates that large earthquakes could be the triggering mechanism. The individual dates of events point also in the same direction. All available dates and fjord stratigraphy suggest formation shortly after the deglaciation. Keefer (1984) studied 30 historical earthquakes and drew boundaries around all reported landslide locations. If we compare his area versus earthquake magnitude plot with the areas of mapped large-scale gravitational-slope features in Troms, it indicates that the potential large earthquakes could have magnitudes in the order of M 6.5 to 7.5.

Fig. 1.4.4 Rotational slide in bedrock from Falsnestind, south of Skibotn. The slide is ca. 100 m long.
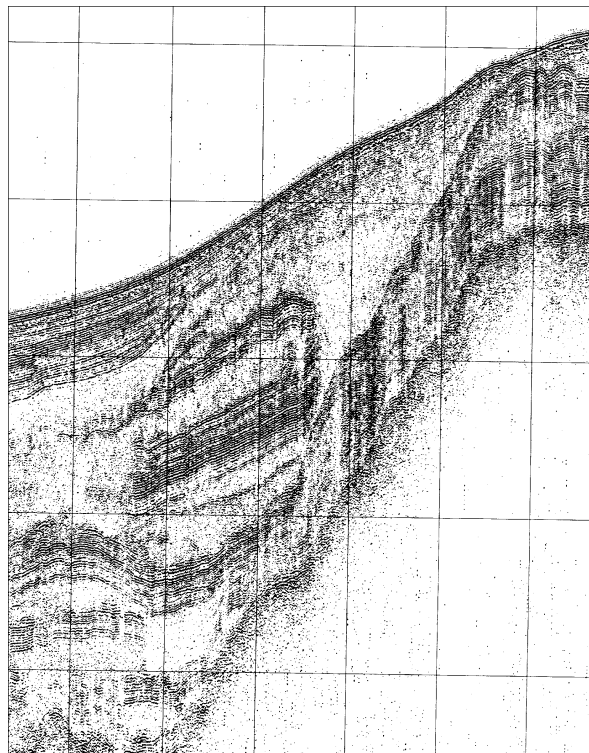
Fig. 1.4.5 Large collapse features on the fjord margins in Balsfjord. This event seems to have occurred shortly after the deglaciation of the area. There is 150 m between the vertical lines and ca. 10 between the horizontal lines.

A less pronounced grouping of rock avalanches also occurs east of Harstad, along Astafjorden (Fig. 1.4.2). The largest of them has a volume of more than 100 mill. m^3 and is one of the largest observed rock avalanche in Norway and Europe. Two events from this area have been

radiocarbon dated and they both indicate that the failures occurred shortly after the deglaciation, c. 10,000 BP.

1.4.3   Møre & Romsdal, western Norway

The mapping of large rock avalanches in Møre & Romsdal shows two regions with distinct concentrations of events, in the Romsdalen and Tafjorden area (Blikra 1998; Anda *et al.* 2000), see Fig. 1.4.6. New data from the fjords in Tafjorden-Stranda area demonstrates that large rock avalanches have been very frequent in certain portions of the fjords (Fig. 1.4.7) (Blikra *et al.* 1999). Preliminary interpretation of the seismic data indicates that some of the events are contemporaneous. There is no clear evidence of any palaeoseismic triggering mechanism for avalanche episodes, but it can obviously not be excluded that large earthquakes might be the cause for the spatial distribution pattern of large rock avalanches in the Møre & Romsdal county.
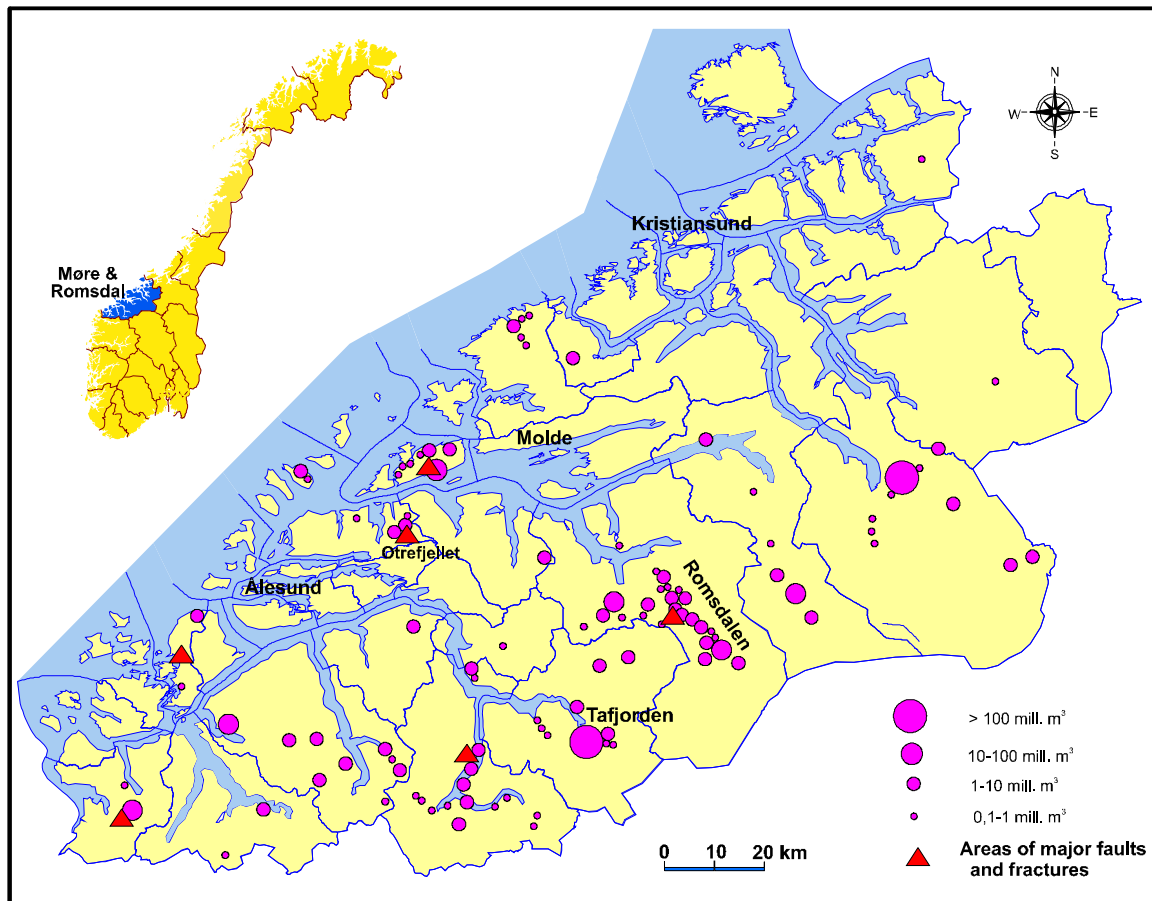
Fig. 1.4.6. Locations of large rock avalanches with volume estimates in Møre & Romsdal. Locations of some large areas of major gravitational faults and fractures are also shown.

Several mountain areas in Møre & Romsdal are characterised by gravitational spreading and faulting (Fig. 1.4.6). One of the localities is situated in Haram kommune (Otrefjellet). A two

kilometre long mountain ridge is heavily fractured and the bedrock are locally crushed within a 500 m wide zone (Anda *et al.* 2000). Large rock avalanches have been triggered on both sides of the ridge. The slope of the mountain Otrefjellet is probably too gentle to create slope failures due to gravitation alone. Severe earthquakes are a very plausible explanation for the features observed on Otrefjellet.

Fig. 1.4.7 Large rock avalanches in Tafjorden, Møre & Romsdal. The shaded-relief map covers ca. 8 km of the fjord.

A seismic survey in Voldafjorden has demonstrated that large parts of the fjord margins collapsed during three distinct events (Fig. 1.4.8; Anda *et al.* 2000). The regional slump events developed debris flows, which probably transformed into turbidites. A well-dated core from Voldafjorden shows three distinct turbidites within the Holocene unit (Grøsfjeld *et al.* 1999), probably correlative to the debris flow events. The middle turbidite is dated to ca. 7,000 BP and correlates with the tsunami formed by the Storegga slide (Bondevik *et al.* 1997). It is possible that the regional collapse of the fjord margins was triggered by an earthquake.
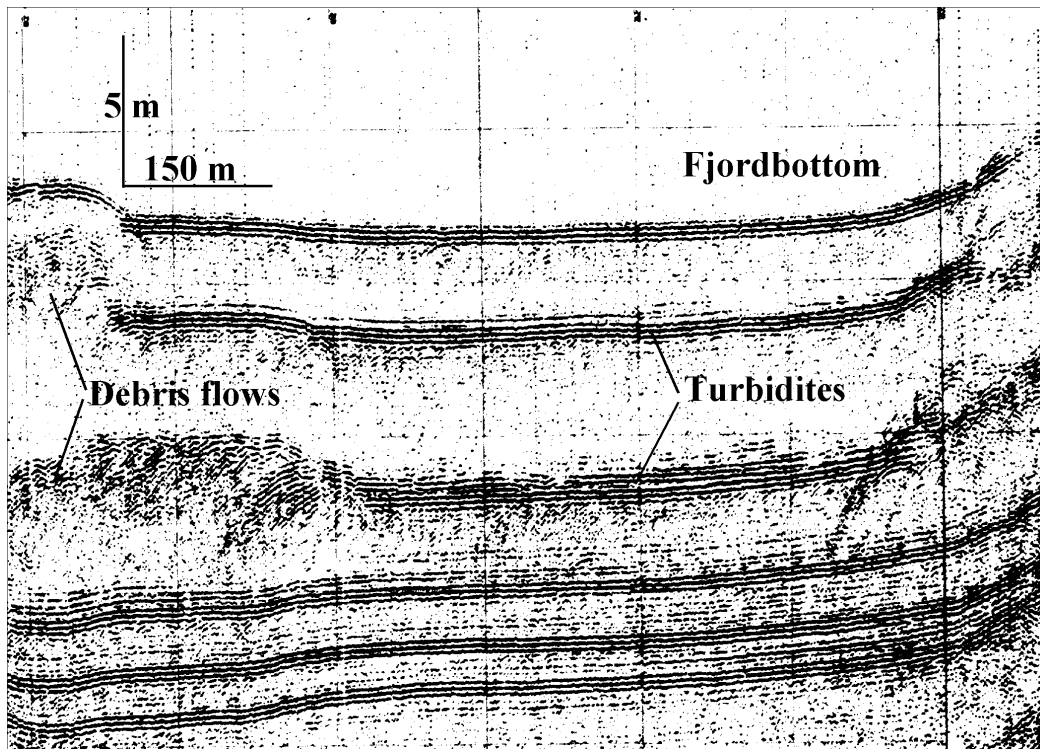
Fig. 1.4.8 High resolution seismic cross profile in the outer part of Voldafjorden.

1.4.4 Odda-Aurland, western Norway

A reconnaissance study based on interpretations of aerial photos in a 20 km wide zone from Odda in Hardanger to Aurland in Sogn shows more than 20 areas characterised by gravitational faults and/or large rock avalanches (Figs. 1.4.9 & 1.4.10). These features are oriented along a SSW-NNE line trending from Odda to Aurland (Fig. 1.4.10). This specific spatial distribution pattern might be a result of seismic activity.

1.4.5 Possible seismic triggering

The distribution pattern of different types of large gravitational-slope failures in the studied areas indicates that palaeoseismic activity could be the triggering mechanism for some of these. A series of slide scarps in gentle sloped glacial-till terrain on Finnmarksvidda, close to the Stuoragurra Fault, are thought to be the result of a large earthquake (Fig. 1.4.1). The area in northern Troms from Balsfjord to Kåfjord is characterised by a high number of large-scale slope failures (Fig. 1.4.2). We tentatively propose that the triggering mechanisms for the observed features are tectonic movements and high-magnitude seismic shocks. This is due to their specific geographic distribution, the high number of large-scale events, their limited time-span and the low-angle sliding surface of the gravitational-bedrock faults. The northernmost area is also situated close to a postglacial normal fault (Nordmannvikdalen fault). The events seem to have occurred at least two times, one event before or during the Younger Dryas and one shortly after.

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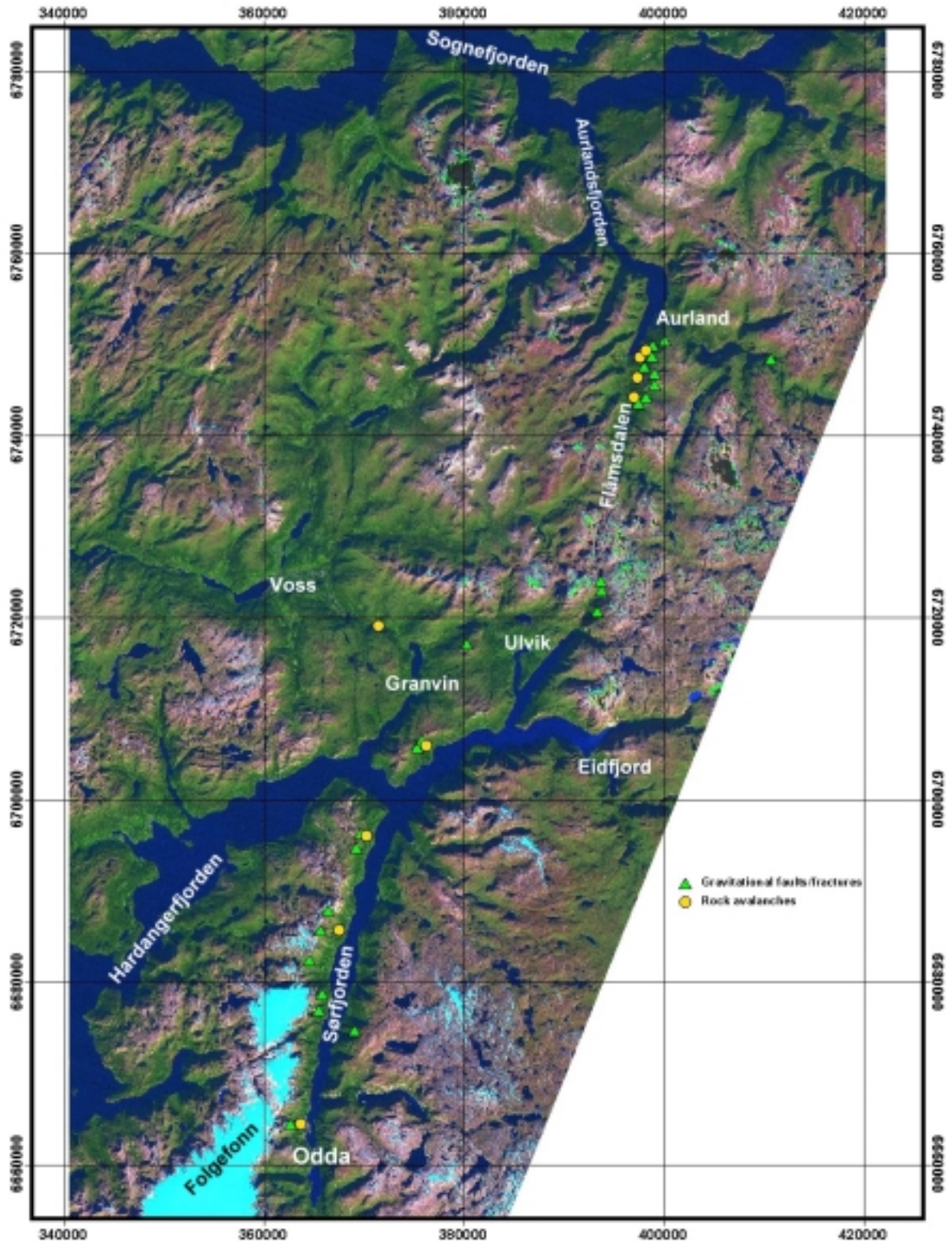
Fig. 1.4.9   A satellite image showing locations of gravitational-slope failures in an area from Odda in Hardanger to Aurland in Sogn. An interpretation of aerial photos has been done in a 20 km wide area from Odda to Aurland. The line spacing is 20 km.
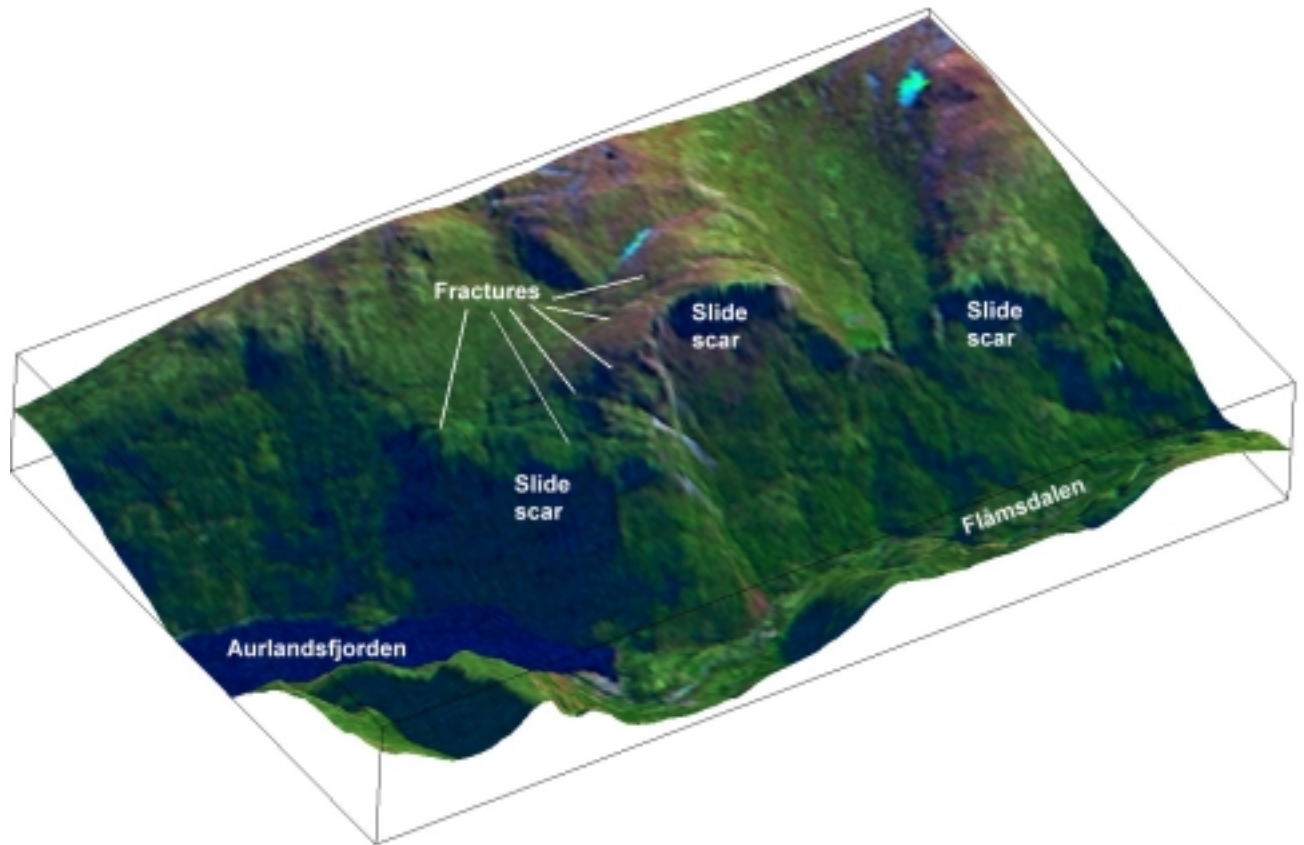
Fig. 1.4.10   A 3D model of satellite and topographic data showing the gravitational faults and fractures in Flåmsdalen, south of Aurland. View towards southeast.

The occurrence of gravitational spreading features and gravitational faults and crevasses in gentle sloping terrain in several areas in Norway may well be formed due to palaeoseismic activity. These include localities in Møre & Romsdal (Fig. 1.4.6) and a series of features lining up between Odda in Hardanger and Aurland in Sogn (Fig. 1.4.9). Large-scale sliding and debris flow deposits have been mapped on the continental slope, with the Storegga Slide as the best known. It has been speculated that these slides were triggered by large earthquakes (e.g. Bugge *et al.* 1988, Evans *et al.* 1996). New data from Voldafjorden indicate that there are some regional events that have led to collapse of the entire fjord margins with the development of debris flows and turbidites covering the entire fjord basin (Anda *et al.* 2000).

Altogether there are numerous gravitational-slope failures both onshore and offshore Norway which could have been formed and triggered during intense palaeoseismic activity. There are indications that point to large-scale earthquakes both shortly after the deglaciation and during later phases of the Holocene. However, a better understanding of the spatial distribution and their age are needed in order of understand their possible triggering mechanisms.

Future work

A systematic work on mapping large-scale gravitational-slope features onshore Norway, including fjords, is still limited to areas in Troms and Møre & Romsdal. In order to get a realistic spatial distribution pattern of such features a more systematic mapping needs to be initiated. This includes mapping and detail studies in Nordland, Sogn & Fjordane, Hordaland and Rogaland, where we know that large-scale collapse features occur. A dating program on such features in order of see if there are any age grouping will also be of fundamental importance. Detailed studies in different fjords will be one major task, and it is important to test the potential link of onshore features to the large-scale slides on the continental slope.

It is our opinion that a better understanding of the evolution and history of large-scale gravitational-slope events since the last ice age is fundamental in order of evaluating possible palaeoseismic activity. Such data will be essential for the estimation of possible future seismic activity, including the possibility of getting high-magnitude earthquakes. Large-scale slope failures both onshore and offshore Norway have very large consequences, and risk evaluations needs thus to incorporate the possibility of large earthquakes. NORSAR & NGI (1998) have shown that the largest, future earthquakes in Norway will probably occur in a region covering northwestern Norway. Historical data from the 20th century in northwestern Norway show that 85% of all people killed by different types of avalanches were due to large rock avalanches and related tsunamis (Blikra *et al.* 1999).

We propose that studies onshore Norway, including fjord studies should be coupled with projects offshore in order of getting an understanding of the palaeoseismic activity and thus a better possibility of evaluating potential large earthquakes in the future.

2.   OFFSHORE NEOTECTONICS

By Fridtjof Riis (NPD), Jan Inge Faleide (University of Oslo) & Odleiv Olesen (NGU)

2.1 Summary of Neogene tectonics

The present and post-glacial deformation of the crust is caused by (a) glacial loading and unloading, (b) large-scale tectonic compression from the mid-Atlantic Ridge, (c) possibly by a tectonic regional uplift of northwestern Scandinavia, and (d) possibly by local subsidence. It is important to distinguish between the effects of tectonic stresses in the crust and stresses induced by loading, even if they act together. Such a distinction could possibly be achieved by, 1) referring to the tectonism preceding the glaciations, and, 2) by quantifying the glacial and sediment loads. Presently, there are not enough data available to carry out a detailed study along these lines, however, a brief summary is included as a background to the interpretation of the offshore neotectonics.

2.1.1   Pre-glacial tectonic activity

Pre-glacial, Miocene and Pliocene sediments are widely distributed in the offshore areas. Careful biostratigraphic studies and seismic interpretation (Eidvin *et al.* in press, Gradstein & Bäckström 1996) have revealed a complex stratigraphy.

Mid-Miocene tectonism

A mid-Miocene tectonic phase can be interpreted seismically as an onlap surface, and locally it is truncating domes and faults. Stratigraphically, it is commonly expressed as a hiatus, and it is often separating sediments of different composition or depositional environments. The most complete section is found in the Central Trough and southern Viking Graben. Here, the stratigraphic break is assigned a late Middle Miocene age (between 11 and 14 Ma). In this area, it defines the top of a faulted and overpressured shale sequence. In the central North Sea, it is located at the base of the Utsira Formation, which was sourced from the Shetland Platform. In the northernmost North Sea, it forms the base of sediments analogous to the Utsira Formation, which were derived from North-West Norway. In the Norwegian Sea, the mid-Miocene represents an important phase of growth of the large dome structures located north of the Jan Mayen Fracture Zone (see index map on enclosed Neotectonic map Norway and adjacent areas, scale 1:3 mill., Dehls *et al.* this report), and it correlates with a hiatus on the Trøndelag Platform. This tectonic phase may be correlated with the onset of rapid subsidence of the deep-water areas in the Norwegian Sea (Brekke 2000). In the Barents Sea there are not enough data to justify a correlation of a mid-Miocene tectonic phase. A Miocene section has only been penetrated west of Bjørnøya, where there is a hiatus between the Lower

Miocene and the Upper Pliocene. In Northern Spitsbergen, a poorly dated, Neogene, volcanic sequence was strongly uplifted and eroded after its deposition.

The observed mid-Miocene tectonism apparently fits into a plate tectonic setting coinciding with Alpine orogeny, as well as uplift of the Faeroe-Iceland Ridge and along the Tornquist-Teisseyre lineament. In the Atlantic, regular magnetic spreading anomalies along the Kolbeinsey Ridge date back to the mid-Miocene. It is suggested that the mid-Miocene tectonism coincides with the termination of the Oligocene-Miocene plate reorganisation which was expressed by the change of spreading axis between Iceland and Jan Mayen (Brekke 2000).

Since the mid-Miocene, there have been minor changes in the geometry of the main plate boundaries, and it is possible that the character of the mid-Miocene deformation is related to the present state of tectonic stress. As shown in the enclosed neotectonic map (Dehls *et al.* this report), large dome structures were reactivated in the deep-sea areas. In the North Sea, reactivation of compressive structures in the Central Graben as well as of normal faults in the Troll area have been observed. It is likely that renewed uplift of the Scandinavian and Spitsbergen domes was also taking place, although the exact timing cannot yet be established. This pattern seems to be broadly consistent with the present state of stress as shown in the enclosed neotectonic map (Dehls *et al.* this report).

Late Miocene and Pliocene deposition

The Late Miocene and Pliocene apparently represent a tectonically quiet period. The sedimentary record indicates a relative rise in sea level, which resulted in condensed sections in the Early Pliocene, and created space for the thick Upper Pliocene deposits which cover most of the offshore area (enclosed neotectonic map (Dehls *et al.* this report). The Upper Pliocene wedges contain a significant amount of glacially eroded material, and it is well documented that the large increase in sedimentation rates in the Late Pliocene coincide with the onset of major glaciations at approximately 2,5 Ma (Eidvin *et al.* in press).

It is not clear whether an additional tectonic component existed, which could explain the relative subsidence of the shelf and the continuing uplift of Scandinavia in the Pliocene.

2.1.2   Plio-Pleistocene glacial loading and unloading (ice distribution, Quaternary sediments)

The load of glacial ice on the crust during the last glaciation resulted in a glacio-isostatic depression and rebound of Scandinavia (enclosed map) and a corresponding forebulge uplift succeeded by subsidence of the shelf areas when the ice retreated. The shelf subsidence is indicated by subsided shorelines as discussed below, but there are no precise measurements of present offshore subsidence rates.

In the modelling of glacio-isostatic (and flexural) effects it is assumed that given sufficiently long time after the glacial load has been applied and removed, the crust will return to the same position where it was before the load was applied.

- There are, however, additional effects that are irreversible.

- Locally, faults may be reactivated when the ice load disappears.

- The unloading of Scandinavia by erosion and sediment loading of the depositional basins on the shelf has an isostatic effect (Riis & Fjeldskaar 1992)

- Irreversible effects on the crust and mantle of cyclic glacial loading and unloading during long time periods cannot be ruled out.

There may be a contribution of tectonic forces in addition to the rebound, which cause the present rates of crustal vertical movements (Fjeldskaar & Lindholm, Chapter 3.2 this report).

Knowledge about previous glaciations is necessary to interpret neotectonic features that were active in the Quaternary, and as discussed above, such knowledge may even be of importance to understand the modern activity.

Deep-sea drilling data indicate that in the period from 2,5 to approximately 1 Ma, there were several glaciations, with a cyclicity of approximately 40,000 years, that did not extend out onto the shelves. The larger glaciations during the last 1Ma have a cyclicity of approximately 100,000 years (e.g. Jansen & Sjøholm 1991). This is consistent with data from the Troll geotechnical drilling 31/6-U- 21. In this well, a basal till of approximately 1 Ma is overlain by glaciomarine sediments and tills from the Elsterian(?), Saalian and Weichselian epochs (Sejrup *et al.* 1995). In the Norwegian Sea, seismic stratigraphic studies (e.g. King *et al.* 1991) indicate that the large ice sheets advanced to the shelf edge during the last glaciation and during the large previous glaciations. In the northern Barents Sea, glaciers may have advanced to the shelf edge earlier than 1 Ma (Eidvin *et al.* in press).

The offshore shelf areas can be divided in three regions with respect to the glacially derived sediments (Fig. 2.1):

1) The eastern region, where erosional processes predominate. This region comprises mainly the Barents Sea. The Quaternary cover is thin, and consists of Late Pleistocene and Holocene sediments. In the Barents Sea, an average of several hundred meters of Tertiary sedimentary cover has been removed. This eroded region continues into onshore Scandinavia. These glacially eroded regions have been isostatically uplifted.

2) The intermediate region is located between the eroded and uplifted areas to the east, and the subsiding region to the west. In the intermediate region, the Pleistocene rests on pre-glacial sediments. The base Pleistocene is commonly developed as an angular

unconformity (URU), implying tilting from the east to the west, prior to the formation of the unconformity.

3) The western region, where thick Late Pliocene and Pleistocene sections have been deposited in the outer shelf and deep water areas.
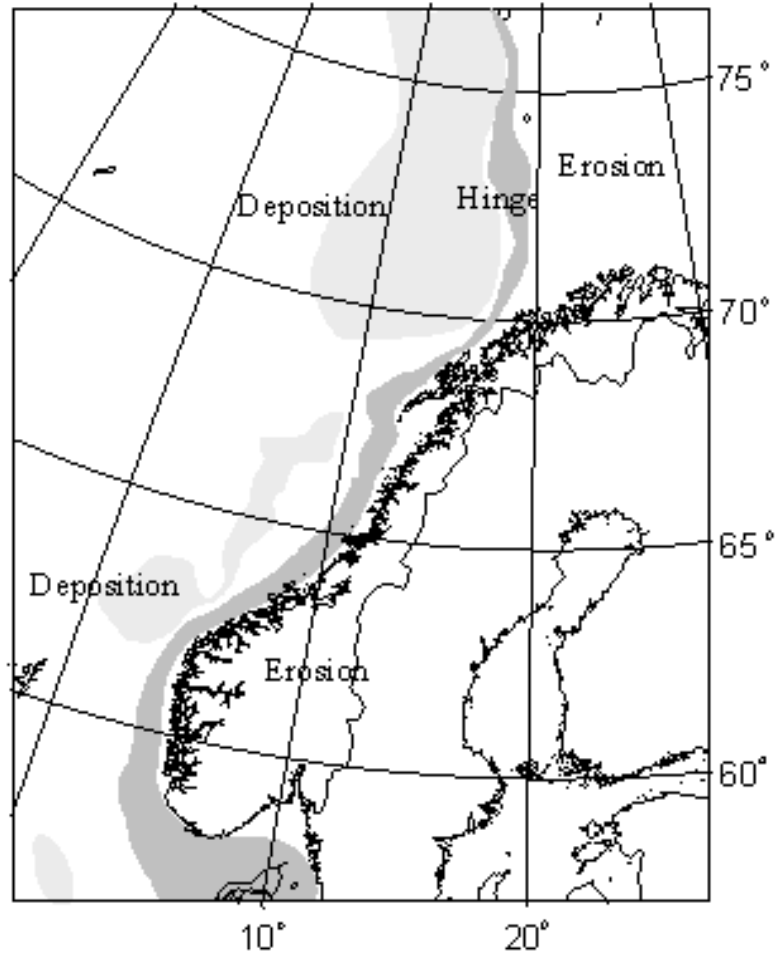
Fig. 2.1   Areas of glacial erosion and deposition. Late Pliocene depositional centra are shaded. In the hinge zone, pre-Pleistocene sediments are generally tilted to the west.

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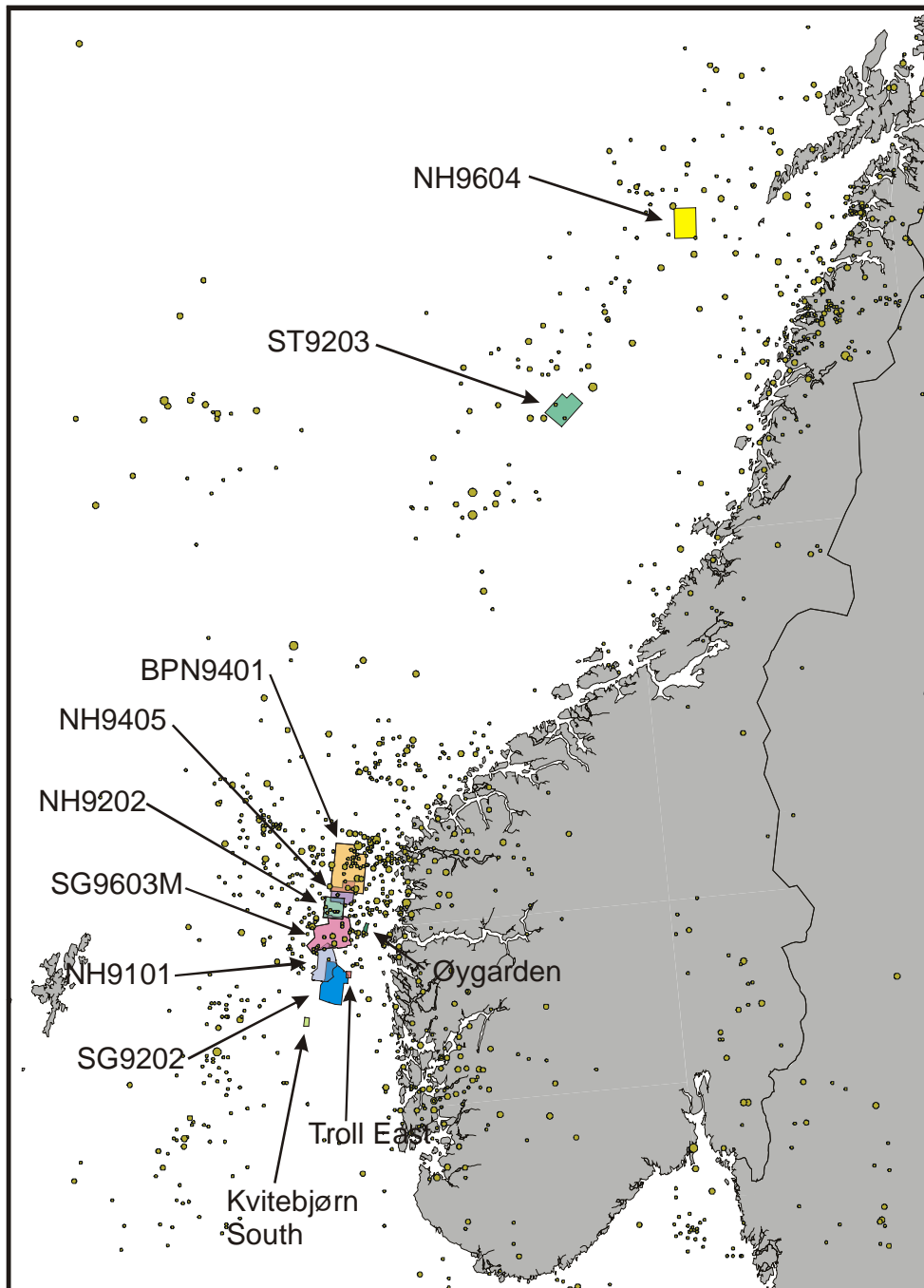
Fig. 2.2   Location of the interpreted 3D surveys in the northern North Sea and Norwegian Sea. The outline of the three multi-beam echo-sounding surveys in the North Sea is also included on the map. Locations of earthquakes (small circles) are provided by NORSAR.

It could be expected that the intermediate region act as a tectonically active hinge zone between the uplifted eastern and the subsiding western areas. In particular, it has been suggested that the Norwegian Channel was formed by downfaulting (or downwarping) of the North Sea relative to the uplifted Scandinavia (Holtedahl 1960, Riis 1992). However, recent faulting has not been proved in the Norwegian Channel, even if the present study indicates small-scale tectonic movements. Recent studies in south-western Norway indicate that the

Norwegian Channel is an erosional feature and that its development must be understood in the context of the large ice streams which have occupied the channel during the glacial maxima (Sejrup *et al.* 1995, 1998).

According to the inset map (map enclosure), the seismicity in the hinge zone and the main depositional wedges appears to be slightly higher than in the eastern, eroded and uplifted areas.

2.2 Present tectonic setting

2.2.1   Seismic activity

The offshore seismicity is concentrated in certain areas and zones, which apparently correlate with basement faults and sea floor topography. Except for the deep ocean rift axes, the following areas of offshore seismicity can be recognised (see enclosed neotectonic map, Dehls *et al.* 2000):

- Viking Graben-Møre area, northernmost North Sea and Møre margin, south of Storegga slide. The locations of earthquakes correlate with the Øygarden and Viking Graben fault systems.

- The shelf break between Lofoten and the Storegga slide. The earthquake locations correlate with the major basement involved faults along the shelf break (Klakk Fault Complex, Ytreholmen Fault Zone, and Utgard High, Blystad *et al.* 1995).

- A broad area, mainly in deep water (oceanic crust), west of the Senja Fracture Zone, extending towards Lofoten.

- The coastal zone of west Norway south of 61 degrees. The zone corresponds to the intermediate region described above, and extends to Jutland. Within the zone, N-S trending Mesozoic faults are located in the coastal area.

- The coastal zone of Helgeland, south of Lofoten.

- The graben system of the North Sea.

- The shelf break of the northern Barents Sea.

In general, offshore seismicity seems to be concentrated in areas with significant, basement involved, Mesozoic and Cenozoic faults. Increased seismicity can also be correlated with the shelf break and the coastal zone. To a large extent, the topographic boundaries coincide with underlying fault systems.

Fault plane solutions are consistent with deep (20 km) reverse faulting with a regional compressive stress directed WNW-ESE. The data are further discussed by Bungum *et al.* (Chapter 3.1, this report).

2.2.2   Post-glacial subsidence.

Subsided shorelines have been interpreted at the shallow banks at several offshore localities, typically between 100 and 200 m depth. Their subsidence is a result of eustatic rise, possibly combined with the rebound of the forebulge, which was uplifted during the glacial maximum in areas peripheral to the ice load. Some of the shorelines have been interpreted based on geophysical evidence, while others are sampled. It has been difficult to incorporate these shoreline data into the isostatic modelling, mainly because of a lack of precise data on the timing of transgression.

The subsided shorelines of the North Sea Plateau were described by Rokoengen *et al.* (1982). The present depth to these shorelines increases gradually to the north, from 130 to 160 m, and it has been suggested by Holtedahl (1993) that there was a tectonic contribution to the subsidence and slope of these shorelines.

2.3 Observed features indicating Pleistocene tectonic activity

2.3.1   Areas studied

The objective of the study was to make a screening of large shelf areas in order to identify possible neotectonic structures. Existing reports on possible neotectonics were evaluated, and additional selected areas (Fig. 2.2) were interpreted in detail. The areas were selected by the following criteria:

- Further study of areas where neotectonic activity has been suggested.

- Studied areas have a sufficiently thick and sufficiently layered Pleistocene cover, favouring areas with reflective, glaciomarine sediments and excluding large areas in the Barents Sea with thin Pleistocene cover, where recent faulting cannot be distinguished from drape of older structures.

- 3D seismic coverage or detailed bathymetry was regarded as necessary to define subtle faults or lineaments.

- Most selected areas are located within zones of high seismicity.

The study has been directed towards faults and lineaments that can be readily observed. As discussed above, it has been suggested that there could be a tectonic component in the formation of some of the major offshore features, such as the Base Pleistocene angular

unconformity, the Norwegian Channel and the tilt of the North Sea Plateau. The existence of these structures is now known to be linked to the offshore extension of the large Scandinavian ice sheets. However, a contribution of crustal tectonics to their formation should not be ruled out without careful studies and modelling.

The continental shelf/margin off Mid-Norway (Norwegian Sea) was not included in the NEONOR study, but the findings and main conclusions on neotectonics from the Seabed Project (NORSAR 1999) are integrated. The Seabed study focused on localities where Mesozoic and early Tertiary structures appear to be associated with fault offsets in the Quaternary sediments at or close to the sea floor. Most of these observations are made in areas where little or no historical seismicity has been documented (Faeroe-Shetland Escarpment, Vøring Escarpment, Nyk High, Gjallar Ridge, Helland-Hansen Arch; Fig. 2.3). On the other hand, the offshore areas associated with historical seismicity, notably the Nordland Ridge and southward along the Halten Terrace, show no evidence of late Quaternary surface faulting.
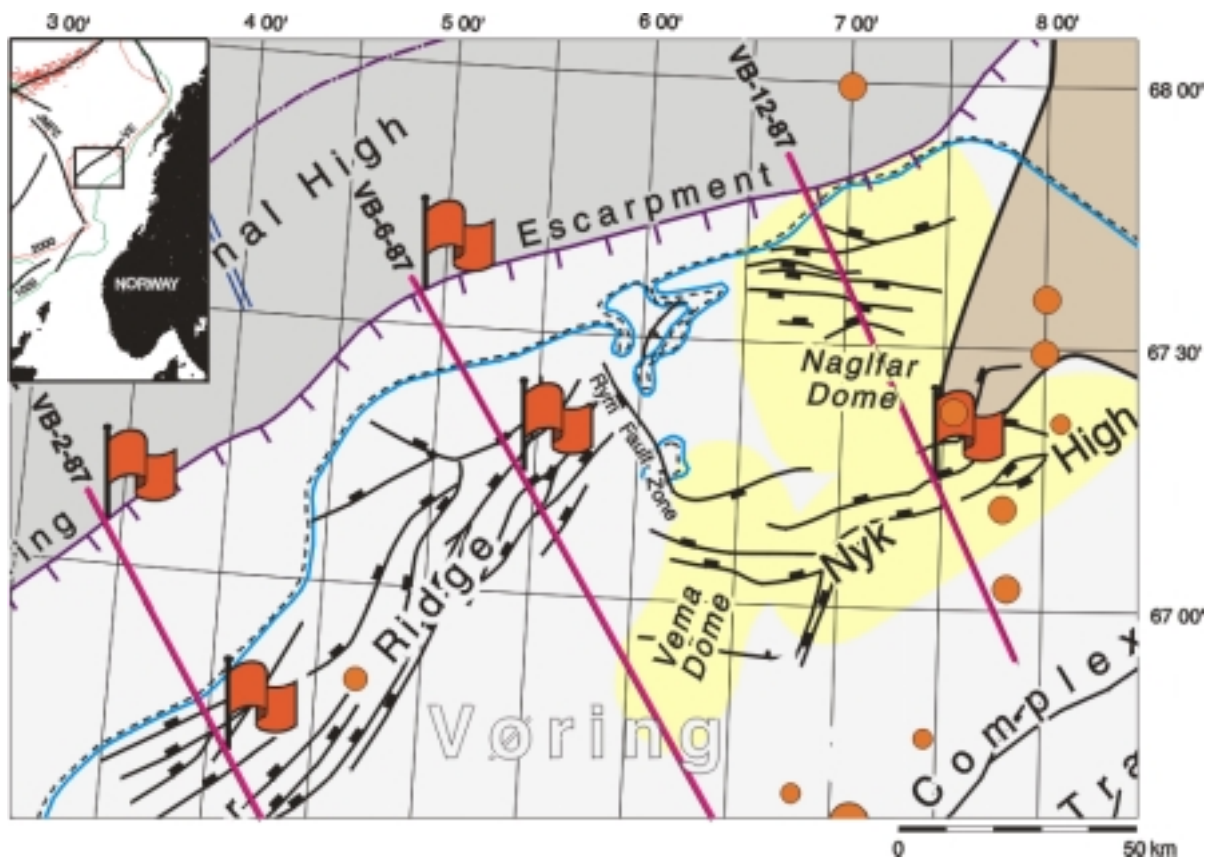

Fig. 2.3   Inferred active faults (red flags) and location of regional seismic profiles across the Vøring margin (modified from NORSAR 1999).

2.3.2   Methods and resolution

Recent fault throws are likely to be in the order of a few meters or less. Such throws are not identifiable in conventional 2D seismic data with a 4 ms sampling interval. In deep water,

such data typically have a dominant frequency around 40 Hz close to the sea floor. Assuming a seismic velocity of 2 km/s this corresponds to a dominant wavelength of about 50 m. The maximum vertical resolution possible is between one quarter and one eighth of the dominant wavelength. The vertical resolution close to the sea floor may therefore be no better than about 10 m. The vertical resolution is slightly better in the 3D seismic data. Single channel shallow seismic data with a sampling interval of 0,25 ms give much better resolution, but they fail to resolve the orientation of lineaments and faults. Multi-beam echo-sounding bathymetry gives excellent resolution, and is well suited to study lineaments that occur at the sea floor.

In the Norwegian Channel, several 3D surveys with a sampling interval of 4 ms were interpreted (Fig. 2.2). The surveys were loaded on a Charisma workstation. Even if subtle lineaments were not visible in 3D inlines and crosslines, they showed up in time slices and in horizon maps. Glacial grooves at the base of tills are excellently mapped in the 3D surveys. Based on these observations, it is thought to be likely that lineaments with a few meters of relief can be observed in these data.

Consequently, a collection of 3D seismic data was selected for the new interpretation in the NEONOR project. Some 2D lines were added in the coastal areas. Multi-beam echo-sounding bathymetry was acquired and interpreted on six of the reported neotectonic phenomena. Three of the areas are located in the northeastern North Sea (Fig. 2.2). The three other are located in the Norwegian Sea; Malangsdjupet and offshore Røst (Fanavoll & Dehls 1998) and in Tjeldsundet (Longva *et al.* 1998).

The Seabed Project had access to a comprehensive seismic database, comprising

- Conventional 2D seismic data in a regional grid

- 3D or 2D exploration seismic data from five deep water licence areas

- 2D high-resolution multichannel seismic data

- Mini airgun and deep tow boomer data

The high-resolution 2D multichannel seismic data typically have a dominant frequency around 80 Hz close to the sea floor, which corresponds to a vertical resolution of about 5m. The mini airgun data and in particular the deep tow boomer data have even better resolution (Fig. 2.4). The boomer data have frequencies in the order of 500 Hz giving rise to a vertical resolution of less than 1 m. However, the penetration is limited in the high-resolution seismic data.
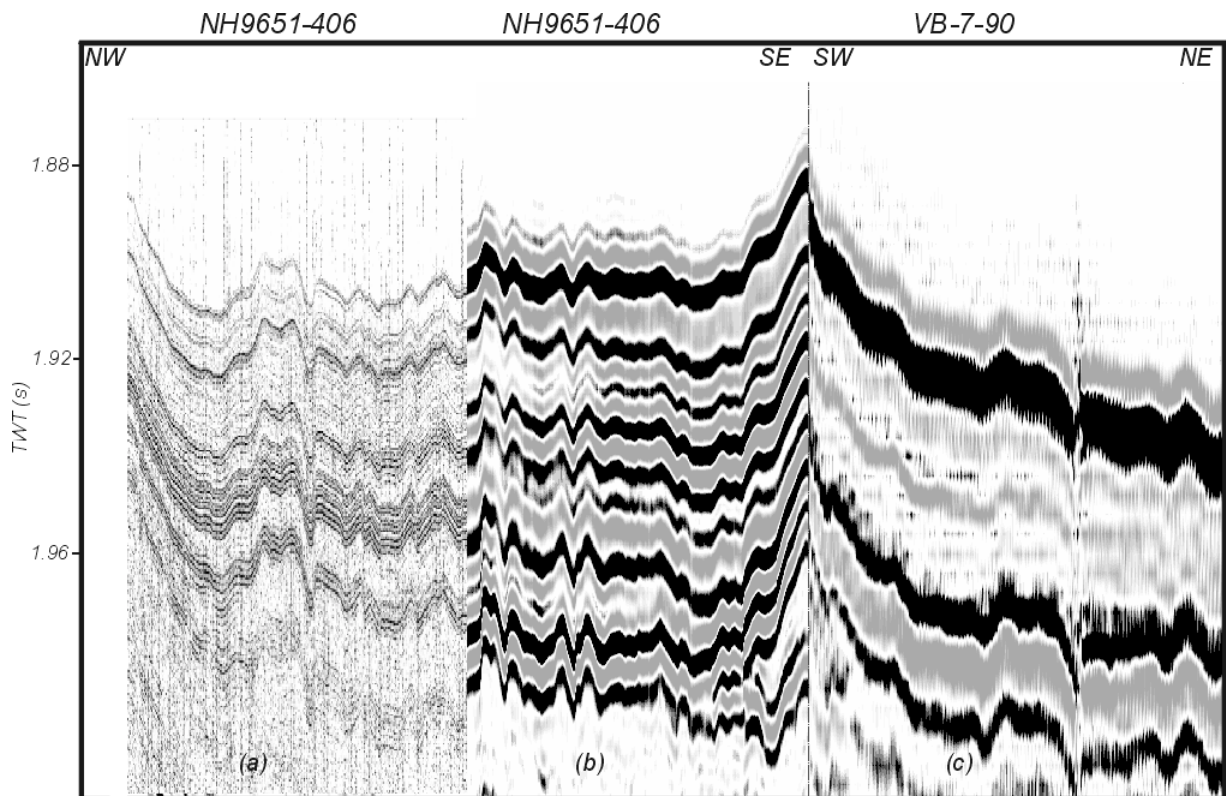
Fig. 2.4   Comparison of seismic resolution in (a) deep tow boomer data, (b) high-resolution multichannel seismic data and (c) conventional seismic data (from Seabed Report).

The various data sets are complementary to each other with respect to vertical resolution and penetration (Fig. 2.4) and should be combined when using the main criteria to infer active tectonic faulting. However, high-resolution data such as deep tow boomer data have not been acquired along the key multichannel reflection lines with inferred active faulting. This is a major shortcoming of the database, making it difficult to constrain the timing and nature of the shallow faulting.

2.3.3   Criteria to distinguish neo-tectonic features from other types of deformation

In a glacial environment, many depositional features like slumping and glacio-tectonics may easily be interpreted as tectonic movements caused by stresses in the crust. The best way of identifying "true" tectonic movements is to interpret glacio-marine layers in areas where glacio-tectonics is not likely to happen. It should be noted that the glacio-marine beds often show a considerable draping of irregularities in the underlying surfaces. Such draping may be caused by a large input of ice-dropped material, and it may penetrate sections with a thickness of several tens of meters, thus simulating faults with vertical throws.

As noted above, errors in the data such as small scale static shifts, may be erroneously interpreted as real offsets in the bedding. In the 3D surveys, the static shifts between the lines

are sufficiently large that small scale offsets parallel or close to parallel with the shooting direction will have a low chance to be detected. The main criteria used in the main project are (Figs. 2.5 & 2.6):

- Faults should be recognisable in the time slices and in the mapped surfaces.

- One fault should be recognised in a number of time slices.

- Fault orientations should be oblique to the line direction (because of static shifts).

- Glacially induced structures, such as grooves, plough-marks and glacial deformation must not be interpreted as tectonic faults.
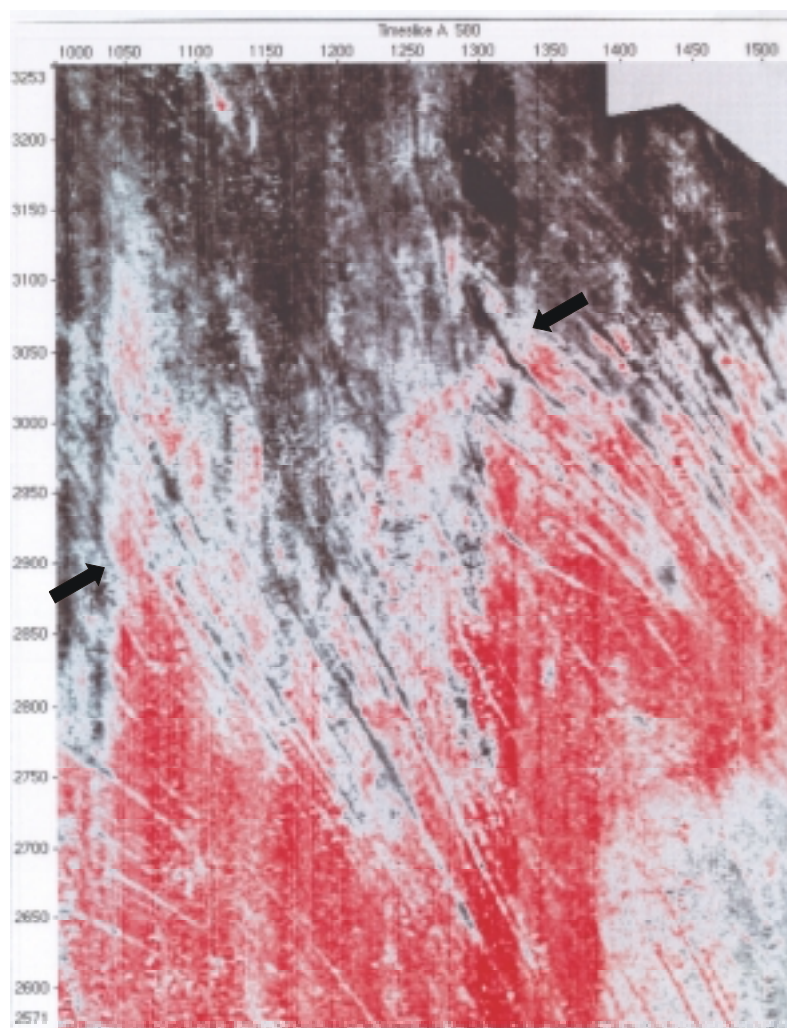
Fig. 2.5   Time slice at 580ms from the SG9202 survey in the Troll East area indicating a NE-SW trending tectonic lineament (shown by the arrows) crosscutting glacial forms.
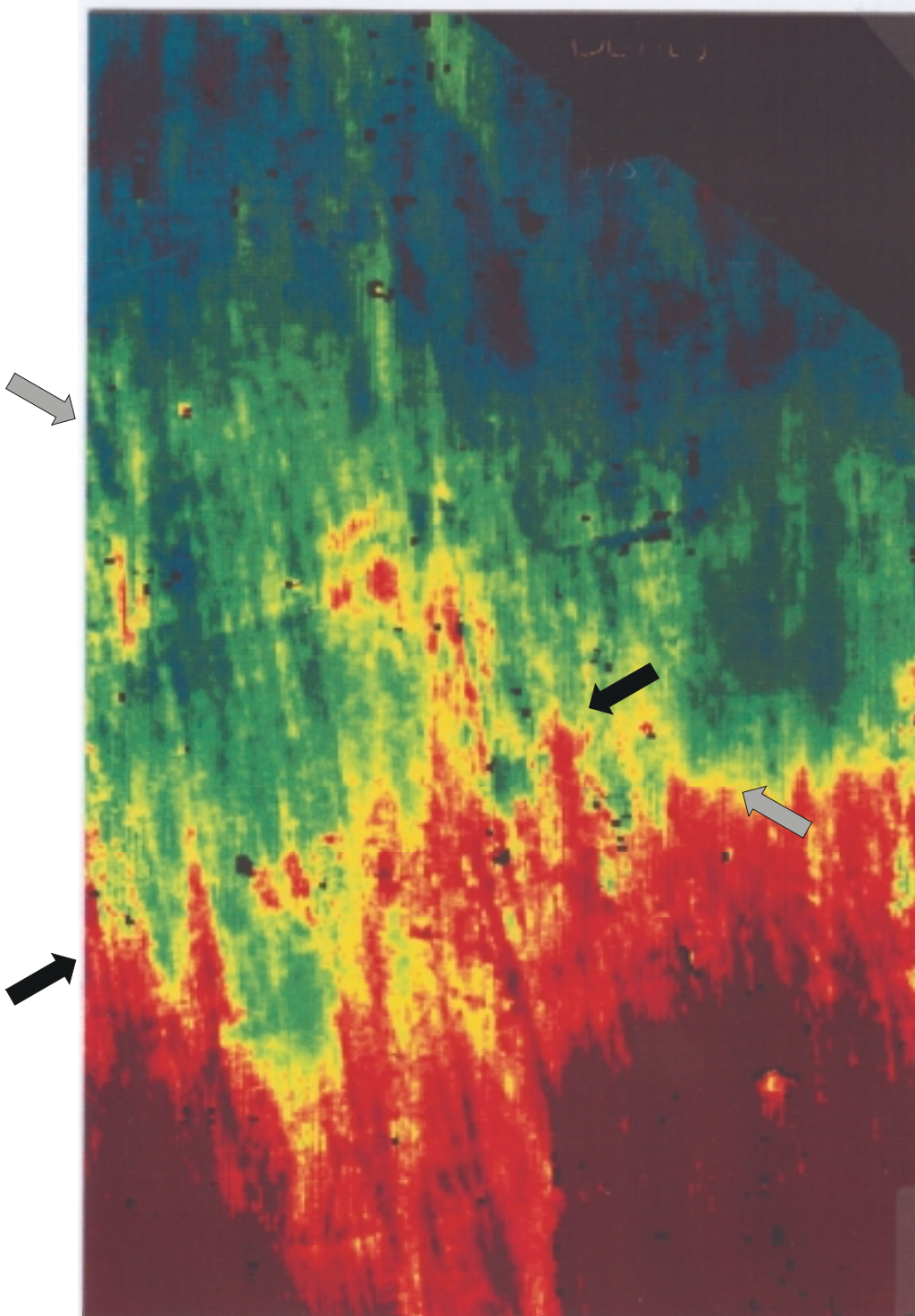
Fig. 2.6   Automatic time interpretation of Lower Pleistocene reflector, SG9202 survey from the Troll East area. Glacial grooves are trending NNW-SSE. A black arrow indicates a potential tectonic lineament trending ENE-WSW. A NW-SE trending lineament indicated by grey arrows is more diffuse.

The main criteria used in the Seabed Project to infer active tectonic faulting include:

- displacements of the seafloor or shallow sedimentary layers by faults that clearly displace deeper geological strata at the same localities

- evidence of fault control on late Quaternary sedimentation

- displacement of the seabed or near-surface sediments that are co-located with evidence of large-scale land-sliding or slumping

- displacement of the seafloor and deeper strata in the opposite sense to the local bathymetric gradient

2.3.4 Evaluation of observed features

General

No faults with throws larger than a few meters have been observed in the shelf areas. With a possible exception for the deep-water areas with poor seismic coverage, there are no offshore neotectonic faults of comparable size to the onshore features in northern Fennoscandia.

There exist different types of possible neotectonic features:

- Fissures and lineaments correlated with areas of gas leakage, not obviously related to basement faults

- Subtle lineaments with possible fault throws

- Probable reactivation of Miocene dome structures in the deep sea

The subtle lineaments are shown in Fig. 2.7. In addition, submarine slides and/or gas leakage may be secondary effects of tectonic activity in some areas.

Most of the offshore neotectonic reports (Appendix B, Figs. 1.1.3 & 2.3) have been classified as grade D (probable not neotectonics). The faults to the south of Kvitebjørn (Hovland 1983), north of the Storegga slide (Evans *et al.* 1996) and in the Troll area (Riis 1998) are graded as 'C' (Possibly neotectonics).
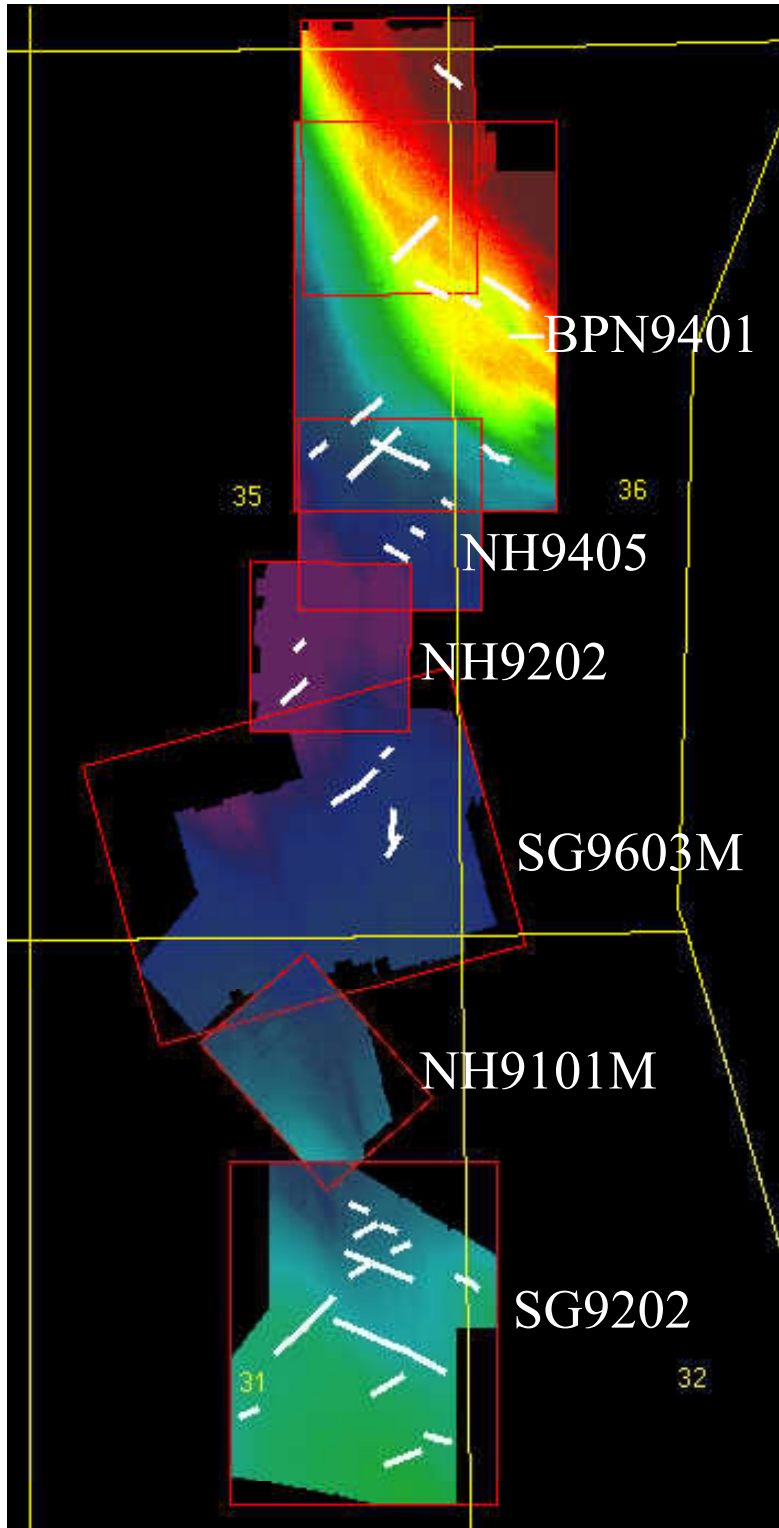
Fig. 2.7   Interpretation of two way travel time to seabed on the 3D surveys in the northern North Sea, including the observed subtle lineaments in the lower Pleistocene (from Riis 1998 and Olesen et al. 1999b). The two southernmost surveys cover the Troll area.

Troll East

Seismic interpretation - survey SG9202
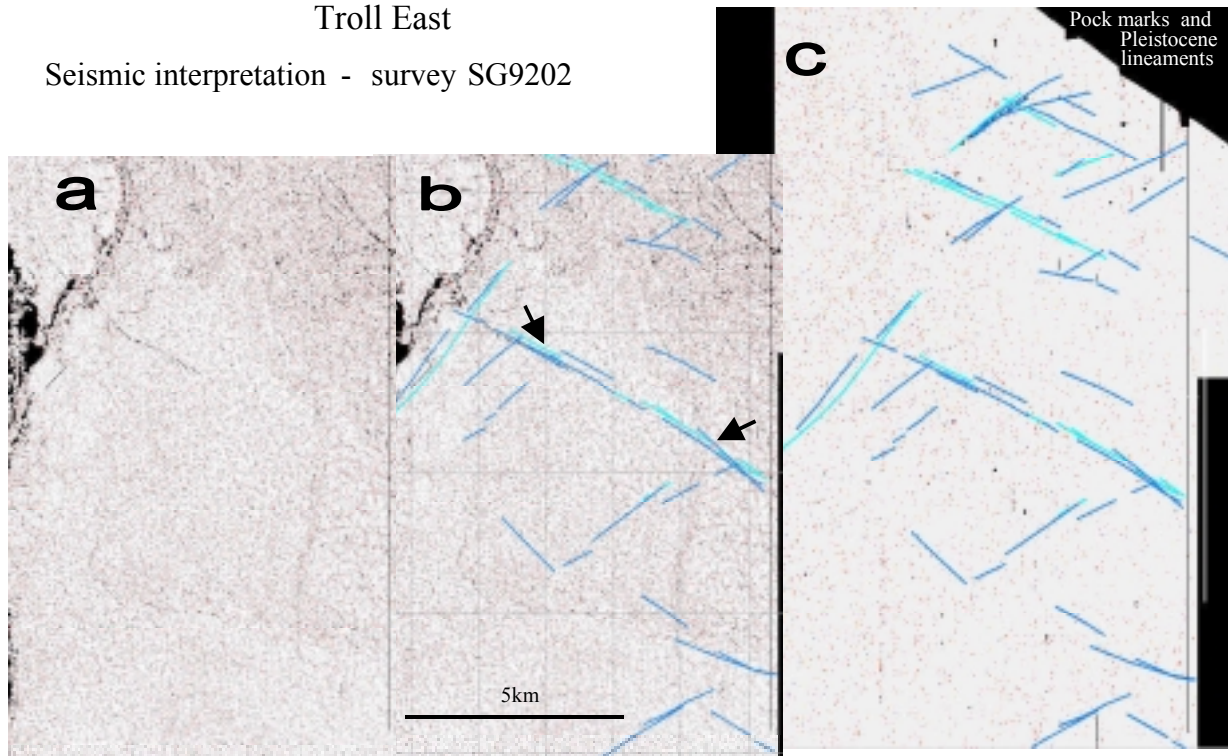
Fig. 2.8   Cenozoic fault pattern mapped at Cretaceous horizon (Fig. a), overlain by Pleistocene lineaments (blue lines, Fig. b). The arrows show correlating Pleistocene lineaments and deeper faults (green). Fig. c shows pockmarks at sea floor. Note increased pock mark concentration along major fault in the north-west, and hexagonal Cenozoic fault pattern with a few minor WNW trending faults.

Norwegian Channel, Troll area.

The Troll area is located in the Norwegian Channel, and is covered with approximately 200 m (200-250 ms) of Pleistocene sediments (Fig. 2.9). The sediments consist of alternating diamicton and glacio-marine deposits, and rest with an angular unconformity on westerly dipping Eocene, Oligocene and Miocene sediments.

Interpreted horizons and time slices exhibit well developed glacial grooves and iceberg plough-marks (Fig. 2.5). The sea floor has a high concentration of pockmarks with variable density.

Northern Troll area, NH 9101

Shallow gas and shallow faults in the northernTroll area.
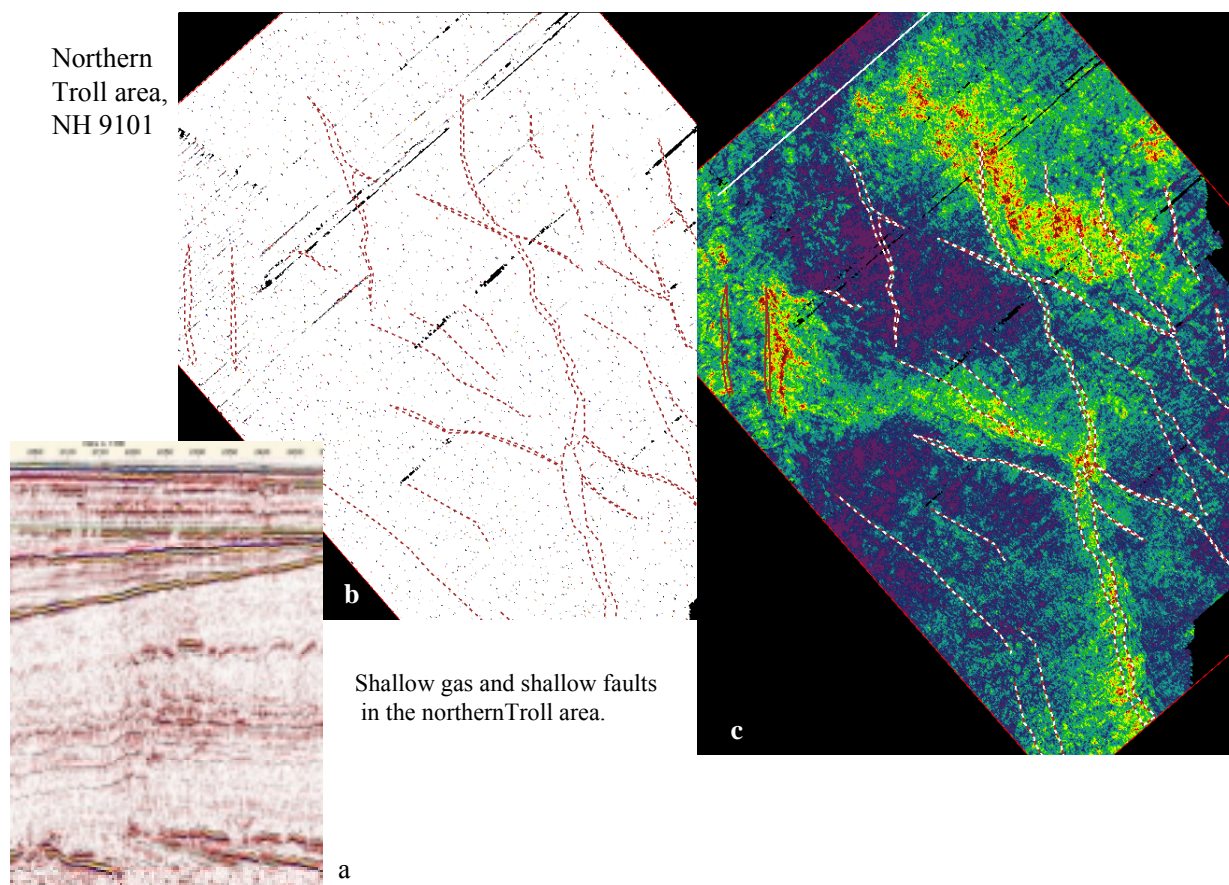
Fig. 2.9   Gas effects in the northern Troll area. The seismic profile (a) shows brightening of reflectors along the main fault trace, where all pre-Miocene rocks have been displaced. The map (c) shows a good correlation between high reflection strength and faults at the Jurassic Top Sognefjord level. The distribution of pockmarks (b) at the sea floor does not seem to correlate with the deeper gas distribution.

The deeper structure is characterised by basement involved, rotated fault blocks. The main faults were reactivated in the Tertiary. Fig. 2.8 shows a map of the fault pattern on a Cretaceous level, obtained by subtracting the time map from a spatially filtered version of the time map. In Fig. 2.8, a hexagonal fault pattern indicating compaction is combined with linear faults, which represent reactivation of deeper, Mesozoic structures. The seismic profiles indicate that such reactivation took place until the Miocene (Fig. 2.9a).

Fig. 2.9 was compiled to show the relation between the Mesozoic faults and gas escape. Shallow gas is encountered above the Troll Field, and it causes seismic bright spots (Fig. 2.9a). A map of reflection strength in the Eocene section above the northern part of the field (Fig. 2.9b) shows that the brightening is correlated with the Mesozoic fault traces mapped at

the reservoir level. In the Pleistocene, pock marks and seismic brightening is more distributed, and there is no obvious relation to the deeper faults (Fig. 2.9c).

Because of the Pliocene-Pleistocene tilting of the Troll area, it is likely that the major gas cap in the northern and eastern parts was established in the last few million years. Much of the gas leakage probably occurred after the development of the gas cap, and is therefore relatively recent. There are different alternatives, and combinations of alternatives, for the mechanisms of gas leakage:

• Continuous seepage of gas, which selects the most permeable conduits along fault zones.

• Increased leakage during earthquake events, which affect the fault zones up to a certain level.

• Increased leakage during events that lowered the total pressure on the gas in the field, such as the erosion event when the Norwegian Channel was formed, and rapid deglaciation events (ice pump). Such pressure reduction will force the gas to expand.

Fig. 2.8 shows the relation between the deeper faults and the subtle lineaments in the Pleistocene. The WNW and ENE trending lineaments were interpreted in the glacio-marine Early Pleistocene sequence, and are shown with blue lines in Fig. 2.8 (b and c). The most interesting correlation occurs between one of the WNW lineaments and a deeper fault (arrows in Fig. 2.8b, central part of the figure). At the sea floor, no lineaments can be mapped, but there seems to be an increased concentration of pock marks related to this fault, as well as to the major Cenozoic fault in the NW corner of the map. It should be noted that the WNW orientation coincides with the main direction of horizontal compressive stress.

In summary, the study of the northern part of the Norwegian Channel has revealed no faults that extend to the surface, in spite of the presently high seismic activity. Although recent motion on deep-seated faults has not penetrated to the surface, it is not unlikely that earthquakes have triggered gas seepage.

Norwegian Channel, Kvitebjørn area.

In the basal western slope of the Norwegian Channel, Hovland (1983) described faulting of a soft, silty clay at the sea floor on boomer profiles. The faults terminate at shallow depths, and are not connected to deeper structures. Hovland (1983) related these structures to areas of high gas saturation in the shallow sediments, and associated the structures with release of gas.

A multi-beam echo-sounding survey carried out in 1999 confirms the finds of Hovland. The sea floor topography in this area is characterised by NS trending faults and fissures, and large, elongate pockmarks (Fig. 2.10). Fault throws are up to 1-2 m. An azimuth map of the sea floor in the Kvitebjørn area, slightly to the north of the bathymetry survey, indicates a similar set of structures (Fig. 2.11). In this area too, there are spots of high gas saturation at shallow depth.

The shape and orientation of the faults suggest that they were neither formed by gravity sliding, or by glacial deformation. This supports Hovland's explanation that they are connected to gas release.
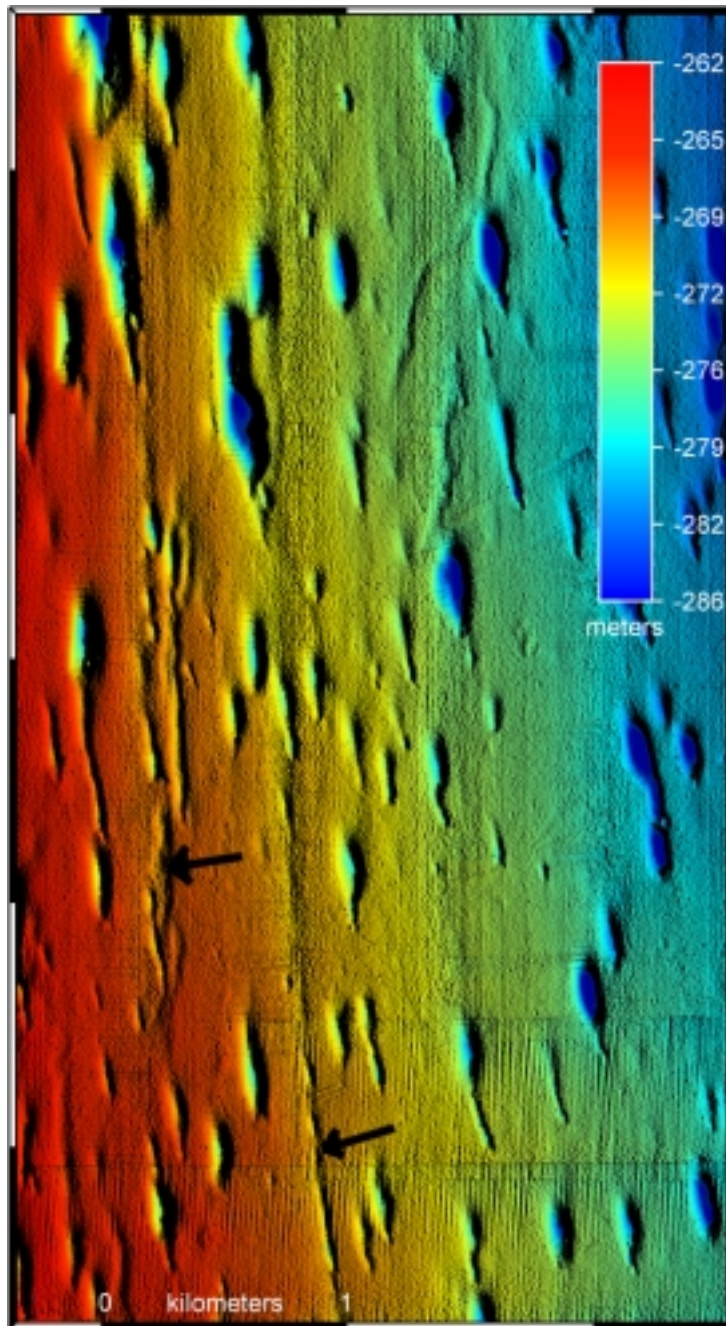
Fig. 2.10   Bathymetry, western margin of Norwegian Channel south of Kvitebjørn. An abundance of pockmarks (up to 500 m long and 10 m deep) occur in the area. The arrows show postglacial faults, which seem to be related to the formation of elongated pockmarks. The fault offset is approximately 1 m. The multi-beam echo-sounding data have been acquired by the Norwegian Mapping Authority. The faults were originally reported by Hovland (1983).
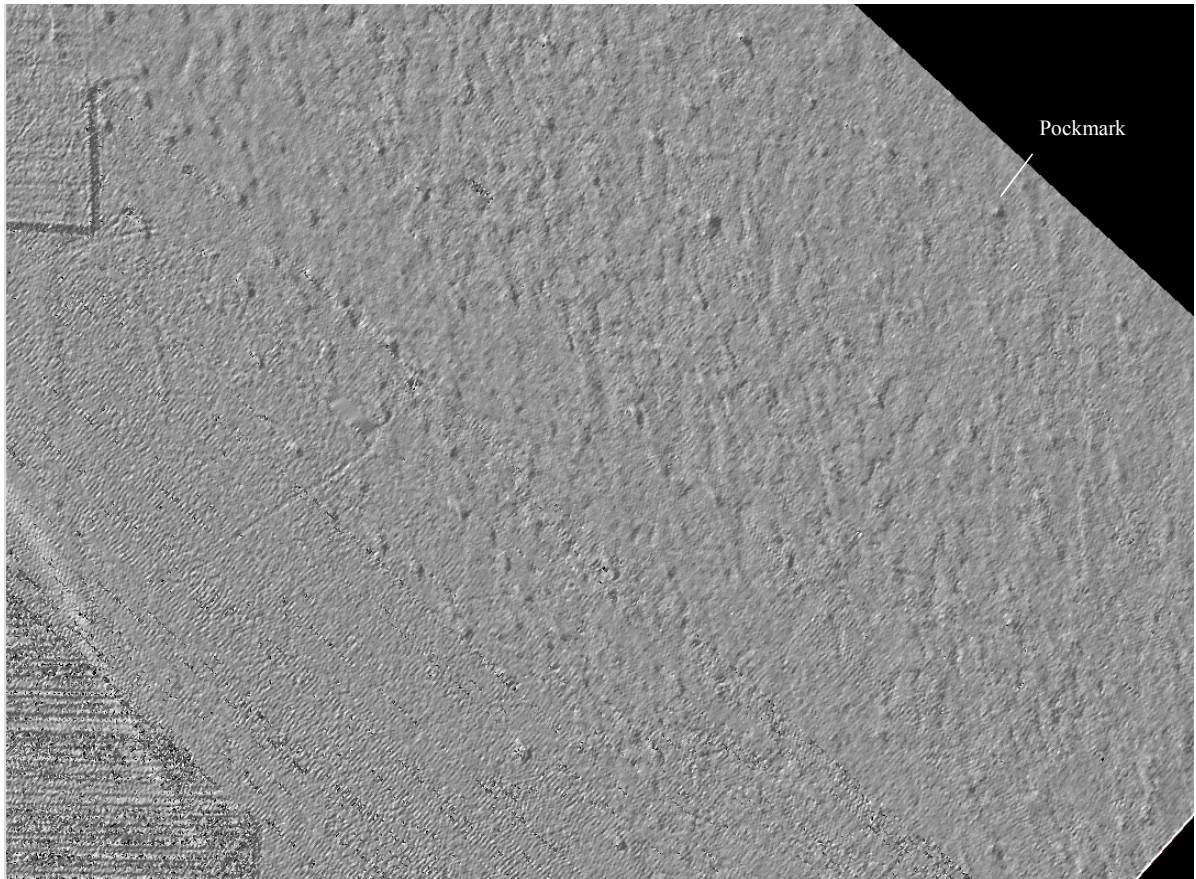
Fig. 2.11   Azimuth map of sea-floor reflector, Kvitebjørn area. The angle of illumination is parallel to the shot direction of the main survey (135º). Merged 3D surveys show up as areas with a strong lineation parallel to the shooting direction, because of minor static shifts between the lines. Note the pipe-lines in the western part. The eastern part of the survey covers the western slope of the Norwegian Channel, and contains large elongated pockmarks and lineaments/shallow faults similar to the features described by Hovland (1983).

Norwegian Sea (Seabed Project)

In general, it is clear that the main criteria used to infer active tectonic faulting cannot be fully applied without integration of various seismic data sets of different resolution and penetration. We have to address several critical questions such as:

- Are the shallow fault scarps observed in the conventional seismic data presently active, or could there be a thin layer of post-glacial sediments draping some of them?

- Is the observed relief caused by faulting, sliding or differential subsidence?

- Is it possible to obtain stratigraphic calibration of the youngest seismic sequences affected by faulting?

In the Seabed project the following conclusions were drawn:

- Based on an integration and careful analysis of all available data no clear evidence of active tectonic faulting was found. Recent faulting has been interpreted in the Vøring Margin (Fig. 2.3 and Appendix B), and the faults were formed by different mechanisms.

- In the Vøring Margin (e.g. Vøring Escarpment, Nyk High and Gjallar Ridge; Fig. 2.3; Blystad *et al.* 1995) there is need for high resolution seismic data along the key conventional lines where active faults are inferred to better constrain the timing and nature of the most recent faulting.

- The shallow faulting and sea floor morphology observed along the Vøring Escarpment (Fig. 2.12 and Appendix B) and Nyk High (Fig. 2.13 and Appendix B) is most likely related to differential compaction/subsidence and sliding rather than active tectonic faulting.

- In the Gjallar Ridge and adjacent regions (Figs. 2.14-2.16 and Appendix B), faults within acoustically well layered pelagic Neogene sediments appear to be associated with intra-formational fracturing rather than being a response to regional tectonism.
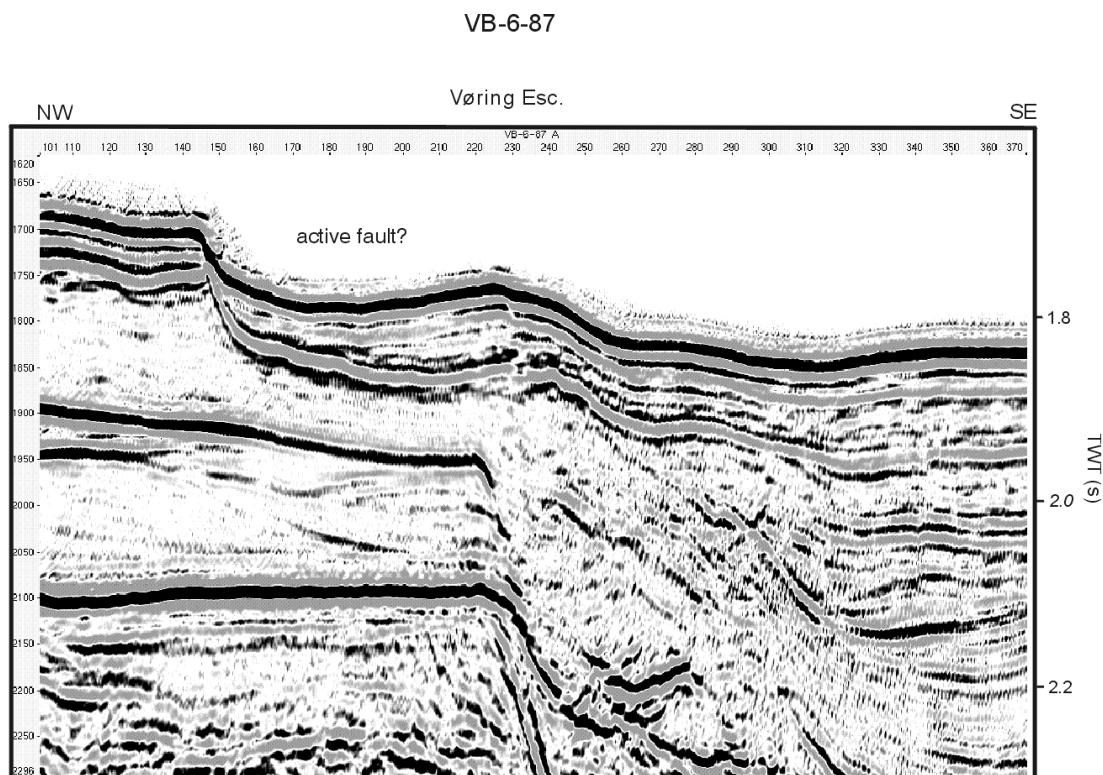
Fig. 2.12   Close-up of seismic line VB-6-87 across the inferred active fault associated with the Vøring Escarpment. See Fig. 2.3 for location. From Seabed Report (NORSAR 1999).
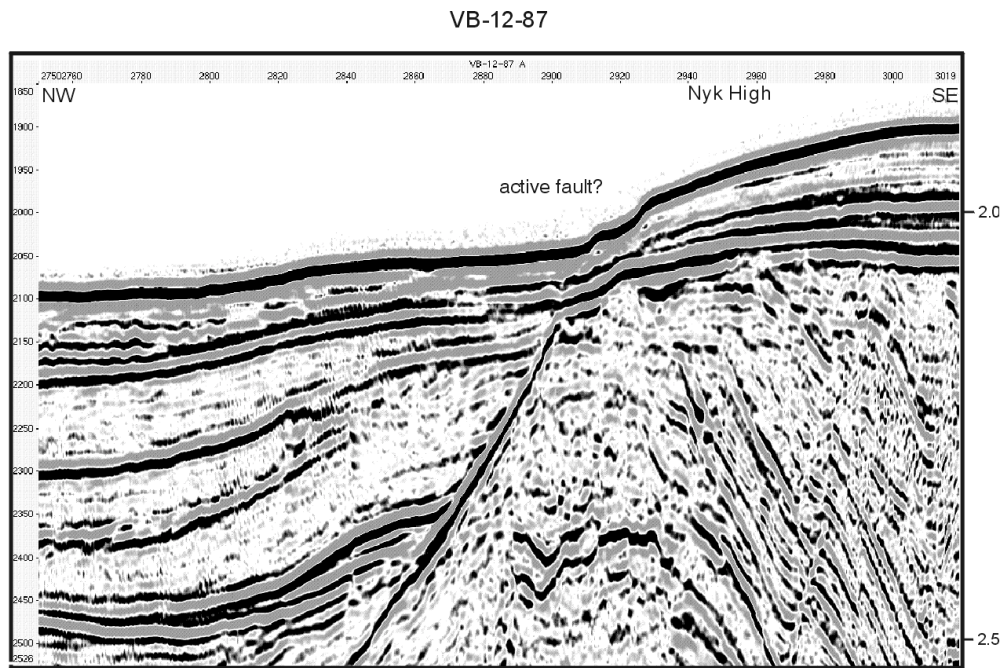
VB-12-87

Fig. 2.13   Close-up of seismic line VB-12-87 across the inferred active fault associated with the western boundary of the Nyk High. See Fig. 2.3 for location. From Seabed Report.
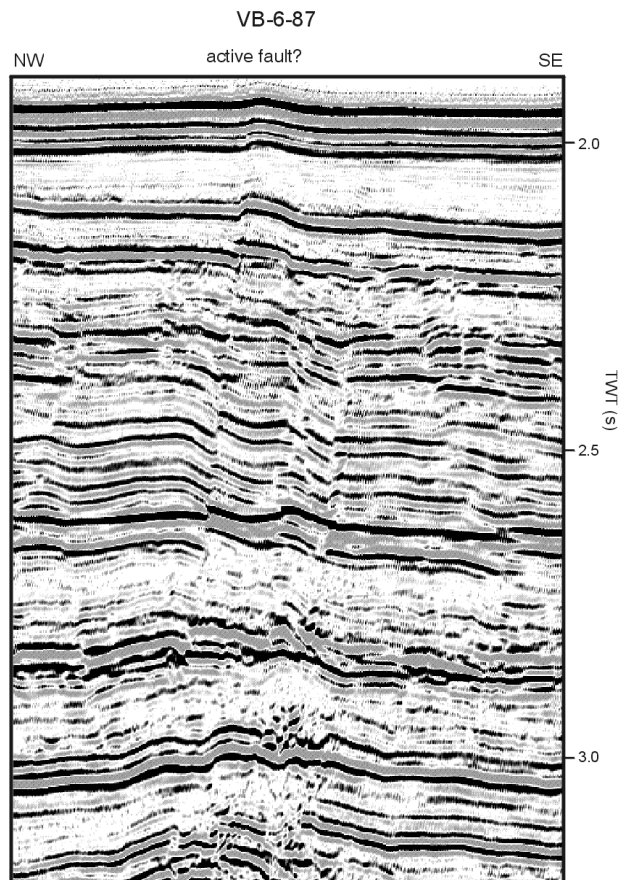
VB-6-87

Fig. 2.14   Close-up of seismic line VB-6-87 across the inferred active fault above the Gjallar Ridge. See Fig. 2.3 for location. From Seabed Report (NORSAR 1999).
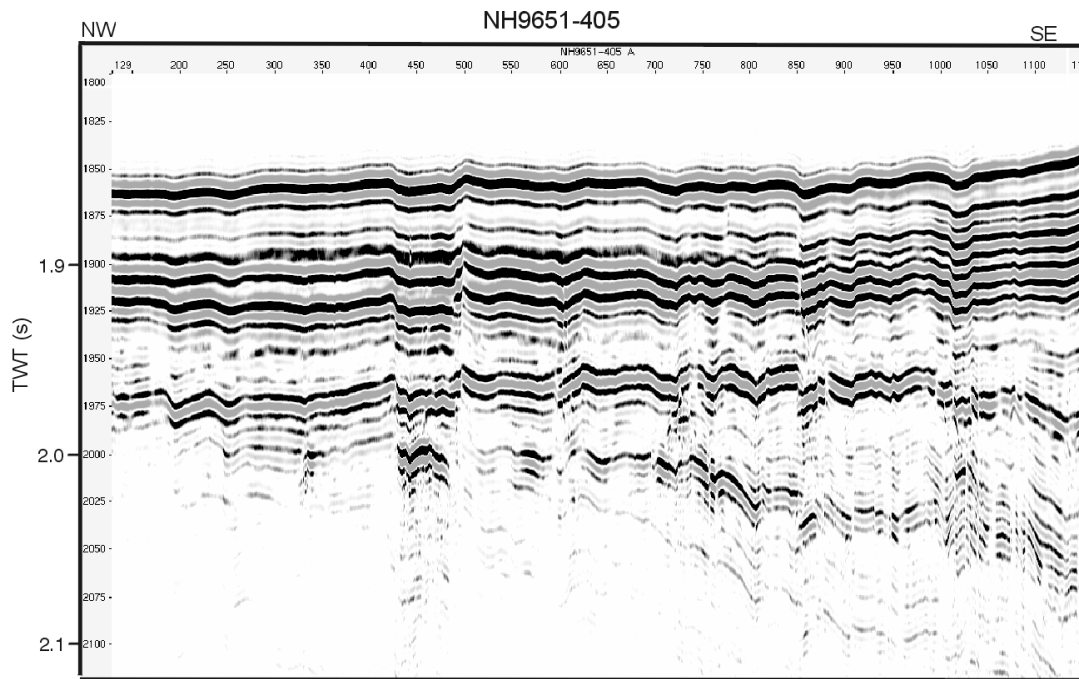
Fig. 2.15 High-resolution multichannel seismic line NH9651-405 in the Gjallar Ridge area showing shallow faulting. From Seabed Report.
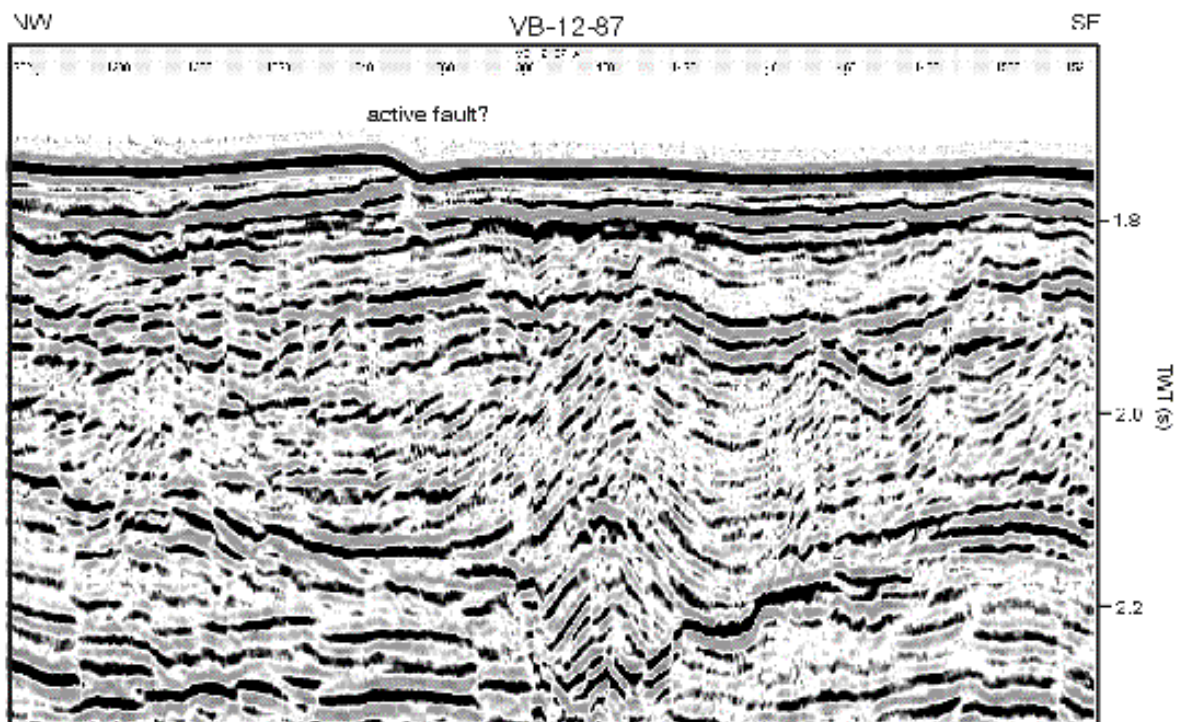
Fig. 2.16 Close-up of seismic line VB-12-87 showing shallow faulting in the Naglfar Dome area. See Fig. 2.3 for location. From Seabed Report (NORSAR 1999).

2.4 Events possibly triggered by earthquakes

The shelf edge of the Norwegian and Barents Sea, is presently a region of relatively high seismicity. Large scale slumping has also taken place along the shelf edge in the Holocene. Buried Pleistocene and older slides are also common. Some slides were formed when the shelf edge was loaded by glaciers, while others, like the main Storegga slide, are definitely post-glacial. It has been speculated (e.g. Bugge *et al.* 1988) that the large slides have been triggered by earthquakes. Weakening of the shallow sediments by gas leakage or by dissolution of gas hydrates are alternative explanations.

Hovland & Judd (1988) have suggested that gas leakage is commonly related to tectonic activity. Such a relation is possible in the Troll Field, as described above. Olesen & Riis (1999) discuss the relation between earthquakes and fluid motion (see also section 'iii Implications' in the Summary Chapter of present report).

3. REGIONAL DEFORMATION MODELS

3.1 Seismotectonics of Norway and adjacent areas

Hilmar Bungum, Conrad Lindholm, Erik Hicks (NORSAR) & Arne Myrvang (NTNU)

3.1.1 Introduction

Earthquakes represent direct manifestations of crustal movements and as such they provide important, albeit not unequivocal, insights into the tectonic processes which are behind also neotectonic movements. Information from earthquakes comes in two different ways, either from individual earthquakes (source parameters, stress drop, faulting, etc.) or from ensemble assessments (spatio-temporal characteristics, moment rates, growth of faults, etc.), and both of these are important in a seismotectonic analysis. In this context it is less important to note that postglacial movements not really are 'tectonic', since this is a distinction which is not seen in terms of stress generation and, in turn, in earthquake occurrence. In fact, there is no real consensus on the definition of tectonic stress, which Engelder (1992) defines as "that quantity of stress added to or subtracted from a horizontal component of stress to cause the state of stress to deviate from a reference state", where the reference state may be defined in different ways.

Rates of deformation (strain) in the crust, are generally in the range between 10^{-6} yr^{-1} for the most active plate margin areas and 10^{-13} yr^{-1} for stable continental regions. Across the Norwegian continental margin the tectonic strain rate is probably at most of the order of 10^{-9} to 10^{-10} yr^{-1}, while rates within the Baltic Shield are expected to be lower by at least two orders of magnitude (Muir Wood 1993). Strain energy can, however, accumulate over very long time, and even regions with low strain rates can exhibit large earthquakes (Johnston and Kanter 1990) and often with more energy release per unit fault area because of generally higher stress drops. Even though the larger earthquakes carry a similarly large regional significance the smaller events, such as those seen at present in Fennoscandia, still provide us with important information on current crustal deformation, both as single events and ensemble wise.

3.1.2 Present seismicity and crustal stress

The seismicity of Norway and adjacent areas (see Fig. 3.1.1, left) is intermediate in level, and even though it is the highest of northwestern Europe it is still lower than in many other stable continental (intraplate) regions (Byrkjeland *et al.* in press). In a major seismic zonation study for Norway (NORSAR & NGI 1998), the following regression relation for all of Scandinavia, including offshore regions, was established:

$$LogN=4.32-1.05 \; M_W$$

where M_W is moment magnitude. This corresponds to an M4 earthquake every 9 months, M5 every 9 years, M6 earthquake every 96 years, and M7 every 1072 years, on the average. In comparison, and consistent with this, there were two M5+ earthquakes offshore western Norway in 1988 and 1989, one M5.4-5.6 earthquake in the Oslofjord region in 1904 (in addition to some offshore in the same size range during the last 100 years), while the largest known in historical times in the whole region is an M5.8-6.2 earthquake in the Rana region in 1819. The hazard model used by NORSAR and NGI (1998) has a maximum magnitude of 6.0, 6.5 and 7.0, with weights of 0.4, 0.4 and 0.2, reflecting the opinion that the catalogue itself may not fully account for the potentials in this region. A central point in this discussion is that the return times for the largest earthquakes in intraplate region such as Fennoscandia could be several thousand years.
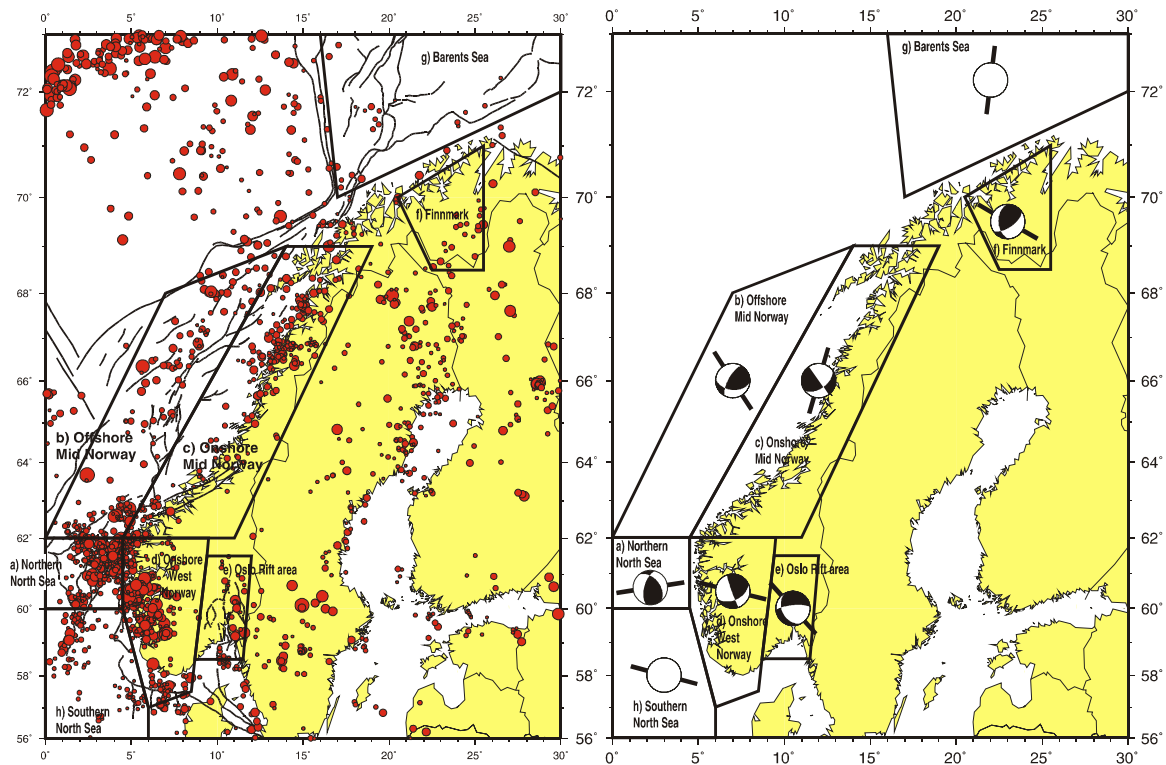
Fig. 3.1.1   Left: Earthquakes in Norway and surrounding areas for the time period 1980-1999, for magnitudes greater than or equal to 2.0. Right: Composite focal mechanism solutions derived from an inversion (Gephart and Forsyth 1984) of all available solutions within given areas, where the northernmost and the southernmost ones have only in-situ data. Both are from Hicks et al. (submitted).

A recent study (Hicks *et al.* submitted) of stress indicators from 112 earthquakes and various in-situ data is summarised in Fig. 3.1.1 (right), where the data within each of the areas are

inverted for the best fitting stress tensor using the method of Gephart & Forsyth (1984). The result support the earlier finding (Bungum *et al.* 1991; Lindholm *et al.* in press; Fejerskov & Lindholm in press) that the maximum horizontal compressive stress comply with the expected NW-SE directions of the ridge push force. There are important deviations, however, and notably so in the Rana region where data from the NEONOR project and earlier studies reveal an apparent 90º rotation of the direction of maximum horizontal stress as interred from shallow earthquakes in the region, related to local stress perturbations and possibly also to dilation effects (Hicks *et al.* in press). These events are mostly normal faulting earthquakes, however, which with coast-perpendicular tensional axes are consistent with what should be expected if the stress was related to postglacial uplift. Similar rotation phenomenon is seen also, albeit less pronounced, in the Sogn Graben/Tampen Spur region (Lindholm *et al.* in press).

In general, *in situ* stress directions comply with those inferred from earthquakes (Fejerskov *et al.* 1995), but with important deviations in the western Barents Sea (Fig. 3.1.1, right) where the ridge push force there should be expected to be different both in direction and strength, reflecting the change both in direction, morphology and rheology as one moves from the Mohns Ridge and into the Knipovich Ridge. In the northern North Sea, however, from where there are no earthquake focal mechanisms (Fig. 3.1.1, right), the NW-SE direction is maintained, in contrast to the Central Graben where the in-situ stress directions are more or less random (Ask 1997), expected to be related to a difference in the ability of the sedimentary rocks in the two regions to support regional stress propagation (Bjørlykke 1995).

The present context is one in which stress information is used as a tool for understanding and explaining the occurrence of earthquakes and thereby also contemporary crustal movements. In this sense we note that it is the deviatoric stress tensor which is instrumental in brittle fracture, which in contrast to tectonic stress is precisely defined, and in such a way that each component of the deviatoric stress tensor is the difference between a normal stress component of the stress tensor and the mean stress, which in turn is defined simply as $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$. The deviatoric and thereby also the differential ($\sigma_3 - \sigma_1$) stress will therefore always be influenced by a large number of sources of stress in combination, while the Mohr failure criterion for frictional slip in addition will be dependent on the strength of the fault as expressed through confining pressure, coefficient of friction, fault orientation, etc.

3.1.3   Contemporary seismotectonics

Based on this understanding of stress it is clear that the seismotectonic situation is similarly complex. In a recent study, Byrkjeland *et al.* (in press) has aimed at assessing the seismotectonics of the Norwegian continental margin by reviewing the many different sources of stress which could be active in this region and their relative importance based on modelling

studies, combining this in turn with the actual occurrence of earthquakes. Some of the conclusion drawn in this study are (see Fig. 3.1.2):

- Even though the stress field originating from the ridge push force clearly is reflected in the present earthquake activity, the ridge push effects in themselves are not sufficient for releasing earthquakes in this region. Other regional and local stress factors, together with favourably oriented and sufficiently weak faults, are therefore responsible for the nature, occurrence, and distribution of earthquakes.

- The oceanic crust away from the plate boundary is mostly aseismic apart from areas that have experienced rapid glacial loading since 2.6 Ma, i.e. the East Lofoten and East Norway Basins. Here, thick sediment loads and high deposition rates are considered to be responsible for high local stress fields and corresponding earthquake activity.

- The marginal highs and the adjacent basins that experienced rifting and crustal thinning prior to the early Tertiary breakup are almost entirely aseismic, suggesting that the crustal thickening and underplating resulting from the igneous breakup event have strengthened the crust.

- Another main observation is the spatial correlation between seismic activity and the late Pliocene-Pleistocene glacial wedge which suggests that rapid sediment loading has led to preferential rejuvenation of Late Jurassic-Early Cretaceous faults. The glacial load may have modified the local stress field in the underlying crust, thereby reactivating favourably oriented fault zones.

- East of the main glacial wedge most of the seismic activity is found along the coast where the postglacial rebound is small. The seismicity decreases farther east where the crust is thicker and rebound rates are higher. However, the relative subsidence west of the hinge line makes the coastal region an area of high postglacial rebound gradients which may relate to the increased seismicity.
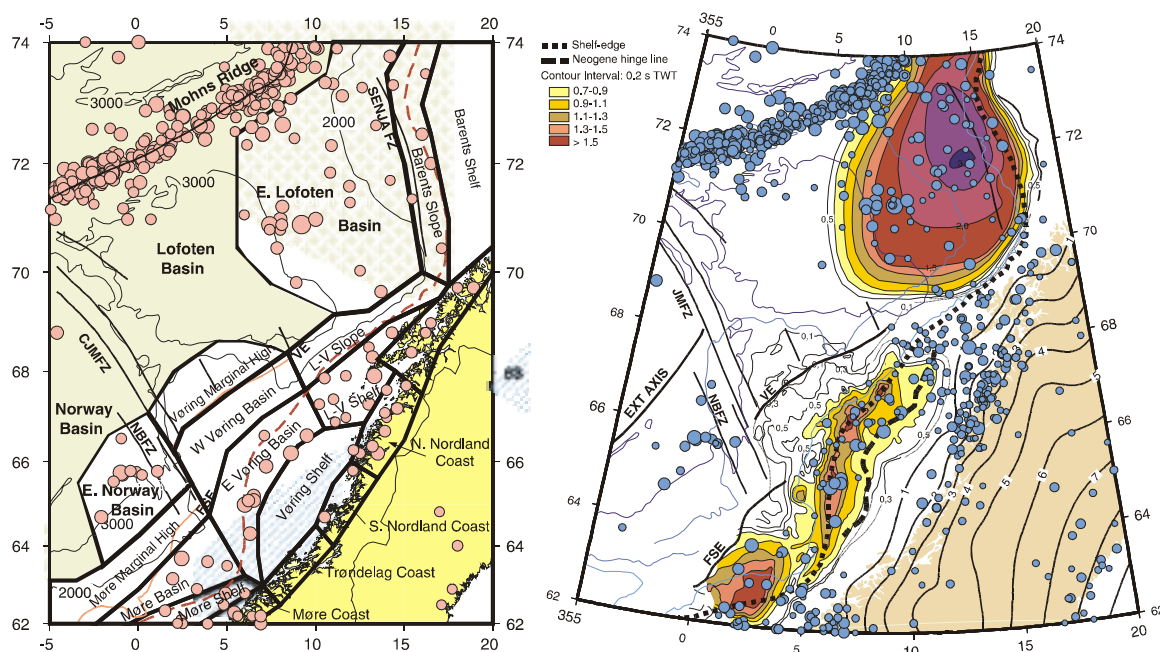
Fig. 3.1.2   Left: Seismotectonic provinces and distribution of earthquakes since 1880. Seismically active provinces are hatched, seismically active zones in oceanic crust are double-hatched. Oceanic crust is beige. Right: Seismic activity on the Norwegian and Barents Sea margins and the glacial (late Plio-Pleistocene) depocenters, where the one north of 69ºN is the Bjørnøya Fan. The landward contours are postglacial uplift rates from Dehls and Olesen (1999). Both are from Byrkjeland et al. (in press).

Based to a large extent on modelling studies, the following review of the main sources of stress in and around Norway can be done:

- Ridge push. In oceanic lithosphere the level may be 20-30 MPa, increasing with age. Enhanced in thinner crust. Reduced in continental crust, but subcrustal density differences across the margin may reverse this.

- Flexural stresses (loading/unloading). May be quite large (>100 MPa). Depends on lateral extent of the load. Less important if compensated at depth. Sedimentation rates important (stress relax with time). Residual effects at present of glacial loading/unloading are disputed.

- Density differences (including topography). Depends strongly on scale length and on spatial variation. Density contrasts across continental/oceanic boundaries may create both extension (in continental lithosphere) and compression (in oceanic lithosphere).

The above conclusions are fully compatible with those inferred from the NEONOR studies in the Rana region (Hicks et al, in press), where moreover even higher order sources of stress, with shorter lateral extents, are considered to be important. The fact that no simple connection is found between seismicity and the potentially neotectonic Båsmoen fault is also consistent with the fact that a weak relation between seismicity and mapped faults is the rule, even though there is a good correlation between earthquake activity and the density of mapped faults (such as along the continental margin and in the North Sea). The main reasons for this weak correlation is believed to be related to earthquake location uncertainties, to the limited geologic structures needed to accommodate even an M5 earthquake (~5 km), and to the greater depths of the earthquakes (~5-30 km).

3.1.4   Neotectonics and deformation models

One of the important contributions from the NEONOR project, besides the thorough assessment of the potentially neotectonic phenomena themselves, leaving very few of the older claims as significant, is the reassessment of the glacial uplift patterns. The results here are uplift contours which are more complex and spatially varying than usually reported (with the exception of Muir Wood 1993). This is reasonable firstly because the last glaciation was quite non-uniform both in terms of ice cover and in terms of the spatio-temporal retreat patterns, but also because it is reasonable to expect an interaction between glacio-isostatic uplift and local topography, structure and tectonics, even if the greater wavelengths in the underlying lithospheric and upper mantle processes naturally will be dominating. These local variations should in turn be expected to affect the seismicity, and one important question which relates to this is the fact that the major postglacial faults seem to be concentrated in northern Fennoscandia.

This unresolved interaction between uplift and tectonics is important in the understanding and modelling of slip rates on mapped faults, where Quaternary averages may be over-conservative since most of the slip may have accumulated during especially active periods such as during the early Holocene, a time period (say, 9,000-6,000 yr. BP) of very high docu-mented seismicity in Fennoscandia (Olesen 1988).

A simple sketch of a model for this interaction is shown in Fig. 3.1.3, where it is assumed that 80% of the slip accumulated during the last 10,000 years developed during the first half of that time period, and that the slip rate during the last half has been conservatively assumed to be constant (and not exponentially decreasing as indicated by accepted rebound models). This gives a slip rate which is 40% of the Holocene average (and not 20% as one could intuitively assume). Most likely, the number should be lower.

Even with the presently relatively low uplift rates as compared to early Holocene, the associated deformation is still very large as compared to the seismicity, indicating a very low

ratio between seismic and 'uplift' moment rates. An interesting numerical comparison here was done by Byrkjeland *et al.* (in press), who projected all the seismic activity onto a vertical plane along the margin, then estimated the moment release rate and converted it to slip rate assuming that the slip occurred over the total area of the crustal size 'fault plane', with complete seismic coupling. The resulting slip rate was very low, of the order of 0.002 mm/yr, indicating that the postglacial uplift is coupled to seismicity by a number several orders of magnitude below unity.

As a part of this analysis Byrkjeland *et al.* (in press) found a moment release rate off Norway of 10^{10}-10^{11} N m yr^{-1} km^{-2}, which compared to other stable continental regions is higher than for Asia east of the Urals and Antarctica, of the same order as for Australia, Africa, and South America but lower than for India, China, and eastern North America (Johnston *et al.* 1994). This may indicate a present potential for larger earthquakes in Norway than known from our short documented history.
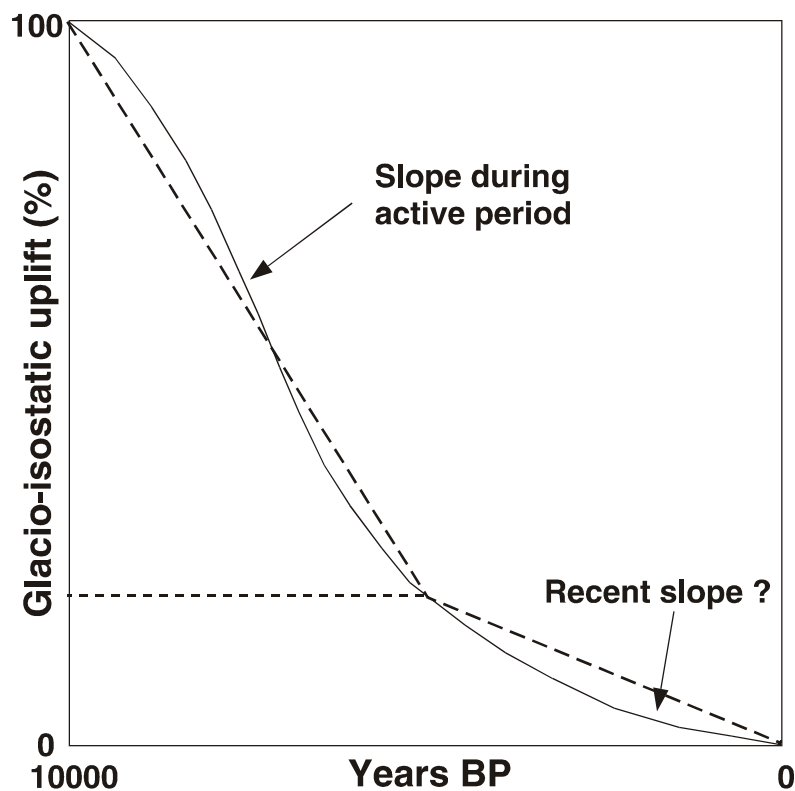
Fig. 3.1.3   A simple sketch of glacio-isostatic uplift over Holocene (based on models from Påsse 1997).

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3.2 Geodynamic modelling, regional and local

Willy Fjeldskaar (Rogaland Research,) Conrad Lindholm (NORSAR), John F. Dehls (NGU) & Ingrid Fjeldskaar (University of Bergen)

3.2.1 Introduction

In historic time the rate of uplift along the coasts of Fennoscandia has been so high that its effects are easily observed within one generation. From the 18th century the rate of displacement has been intensively discussed. At first the phenomenon was variously explained in terms of global changes in sea level, changes in the earth's rotation or elevation of the crust. It was not until the middle of the 19th century that the theory of an Ice Age was presented.

The domelike present rate of uplift in Fennoscandia is now generally explained in terms of glacial isostasy. In previous papers Fjeldskaar (1994, 1997) analysed the deglaciation of Fennoscandia together with data on the tilting of palaeo-shorelines and the present rate of uplift, and concluded that the mantle viscosity in the area is close to 10^{21} Pas. It is also suggested that there is a low viscosity asthenosphere with a thickness less than 150 km and viscosity less than 7.0 x 10^{19} Pas. The most likely glacier thickness model gives a flexural rigidity of 10^{23} Nm ($t_e \approx 20$ km) at the Norwegian coast, increasing to above 10^{24} Nm ($t_e \approx 50$ km) in central parts of Fennoscandia.

The seismicity in Fennoscandia is remarkably high, with high seismicity concentrated in regional areas. The mechanism for the seismic activity has been debated for many years. It has been presumed that the seismicity, to a large extent, was due to the postglacial uplift. While this may be a plausible explanation, the compiled stress directions are also in line with a ridge push effect. The aim of this chapter is to find a possible tectonic component in the post-glacial uplift, to locate it and quantify it by means of movement direction. The results will be also be published by Fjeldskaar *et al.* (in press).

3.2.2 Earthquake activity

It was first in the 1980's that Norway installed the first electromagnetic seismographs focussed on the detection of micro-earthquakes (earthquakes not felt by people). Sweden, Finland and Denmark made installations around the same years. With the low seismic activity of Scandinavia this means that our mapping of the micro-seismicity (and thereby our understanding of the Fennoscandian earthquake activity) is largely based on 20 years of micro-seismic data. The Fennoscandian earthquake activity is clearly concentrated in certain regions:

1) Western Fennoscandia, off shore Norway.

2) The highest activity off shore Norway is found in a belt west of mid Norway, and in the northern end of the North Sea Viking Graben. These areas also regularly exhibits larger earthquakes (M=4 to 5).

3) The largest historical earthquakes (Rana 1819 and Oslo 1904) occurred in areas that have been relatively quiet the past 20 years.

4) Onshore seismicity is characterised by lower activity and lower magnitudes. These areas comprises Norwegian coastal areas, Oslofjord area, Vänern area, Norrland and Västerbotten in Sweden and along the Sweden-Finland border.

Earthquake focal mechanisms and stress directions

In spite of the low seismic activity of Scandinavia more than 120 earthquake focal mechanisms have been computed. With few stations and small earthquakes the reliability of each single mechanism is not high, and in addition we should never expect nature to be simple and homogeneous. In spite of these quality and homogeneity considerations the emerging picture provides some trends:

The earthquake focal mechanism resolves the main stress directions and the mode of faulting (normal, reverse or strike slip). Fig. 3.2.1 synthesises the main trends in terms of seismic activity, type of faulting and direction of horizontal stress. Where the amount of data is large, as offshore Norway, onshore western and northern Norway and in the Oslofjord area the synthesised type of faulting and stress directions in Fig. 3.2.1 are representative. In the areas of less data, however, the reduced confidence is indicated with question marks. From Fig. 3.2.1 the following is remarkable:

- The deep earthquakes occur mainly offshore. They are dominated by reverse faulting and reflect stress directions that can be attributed to the Mid-Atlantic ridge push.

- The shallow earthquakes occur predominantly onshore. Normal faulting (extensional deformation) is dominating and the direction of horizontal tension is largely coast perpendicular.

(The observant reader should bear in mind that the above trends are simplifications of a heterogeneous data set, before drawing firm conclusions).
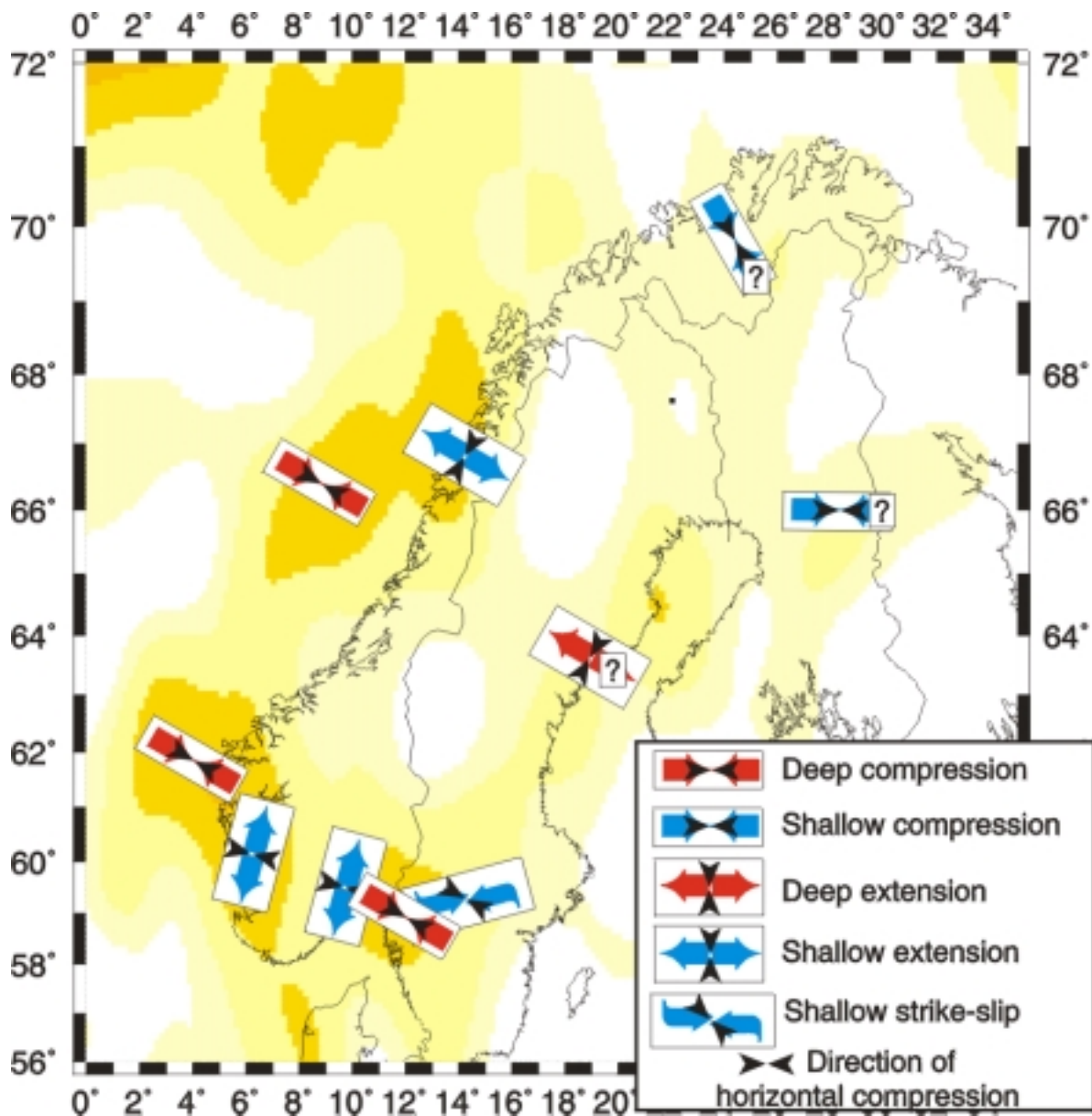
Fig. 3.2.1   Stress directions, type of faulting and focal depths synthesised from earthquake focal mechanisms and in situ stress measurements. Areas of less data are indicated with questionmarks. Intensity of yellow indicates intensity of seismicity (from Hicks et al. in press).

3.2.3   Post-glacial uplift

Data on the uplift can be grouped in two: i) present rate of uplift and ii) shoreline tilts versus time. These observations are mainly results of the movements of the solid Earth, they are scarcely affected by movements of the sea level. The movements of the solid Earth are here assumed to have glacial isostatic origin connected to the melting of the last ice sheets. It is, however, not unreasonable to assume that there is a neotectonic component in the uplift rate and the palaeoshoreline gradients. The general pattern of the uplift is here believed to be a result of glacial isostasy, but there may be local disturbances to this general pattern caused by

tectonic processes. The observed present rate of uplift is now collected on a high-resolution grid, which shows areas of local disturbances (Fig 3.2.2).

3.2.4 Basic assumptions

The crustal properties used in the model were presented in the introductory section. The basic additional assumptions are that:

- The model with the regionally optimal fit depicts the glacial isostatic uplift correct.

- The areas of local misfit reflect additional uplift caused by non-isostatic processes. This uplift is interpreted as tectonically generated uplift.

3.2.5 Neotectonics

We have done new modelling based on the same concepts as described in Fjeldskaar and Cathles, 1991), but now with higher spatial resolution, approximately 20 by 20 km. A modified ice model for 20,000 BP is developed (Fig. 3.2.3). The present day topography in Scandinavia was also taken into account in the modelling. The net glacier thickness in glacial time, will be the ice models of Fig. 3.2.3 subtracted the palaeo topography. The palaeo topography is calculated as the present topography modified by the glacial isostasy at the various time steps, calculated by the Earth rheology parameters mentioned above.

The calculated present rate of uplift in Fennoscandia is shown in Fig. 3.2.4 (note the development of the forebulge offshore mid Norway). This is the model that best fits with the observations. We assume here that this is a good measure of the glacial isostatic process. In accordance with this assumption there will be local areas that have significant differences between the observations and the calculated uplift.
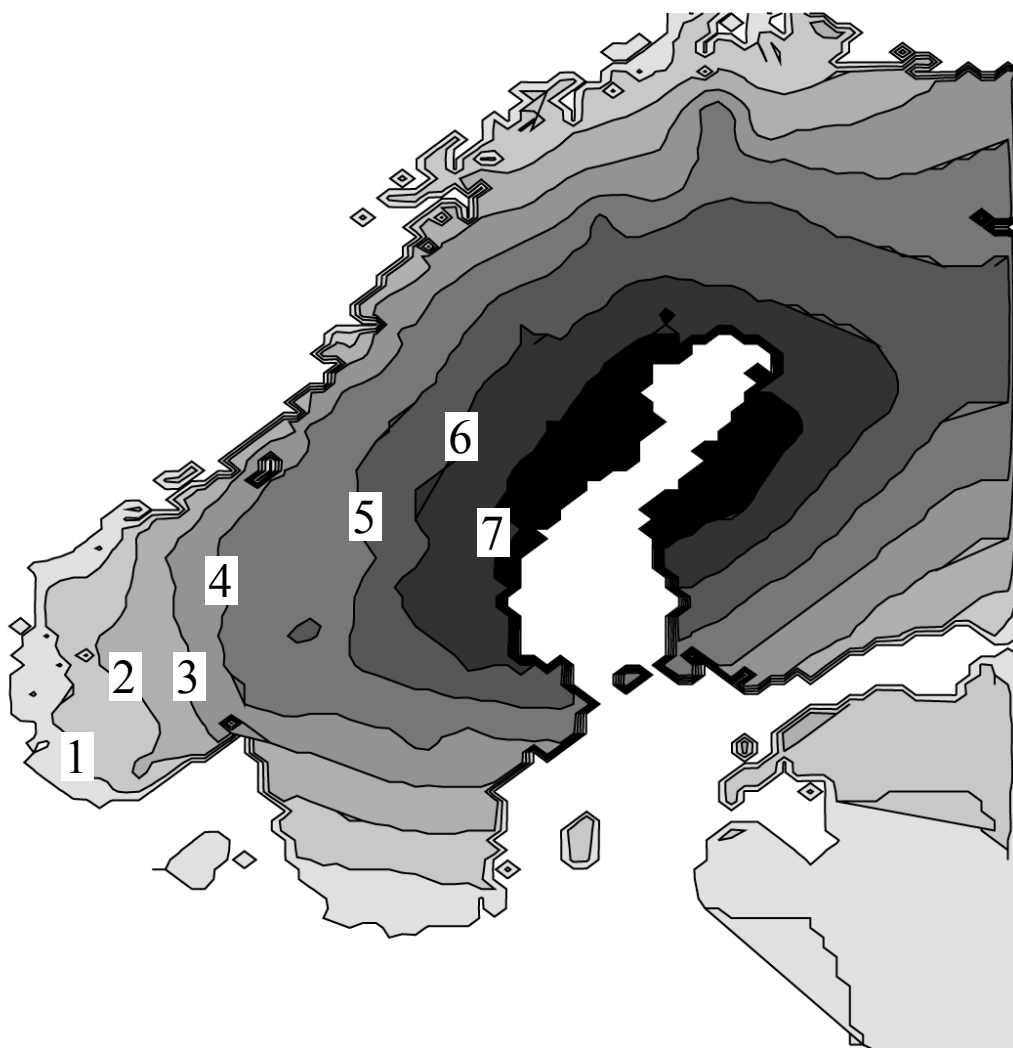
Fig. 3.2.2   Observed present rate of uplift. Contour interval is 1 mm/yr. The uplift of the central area is above 8 mm/yr.
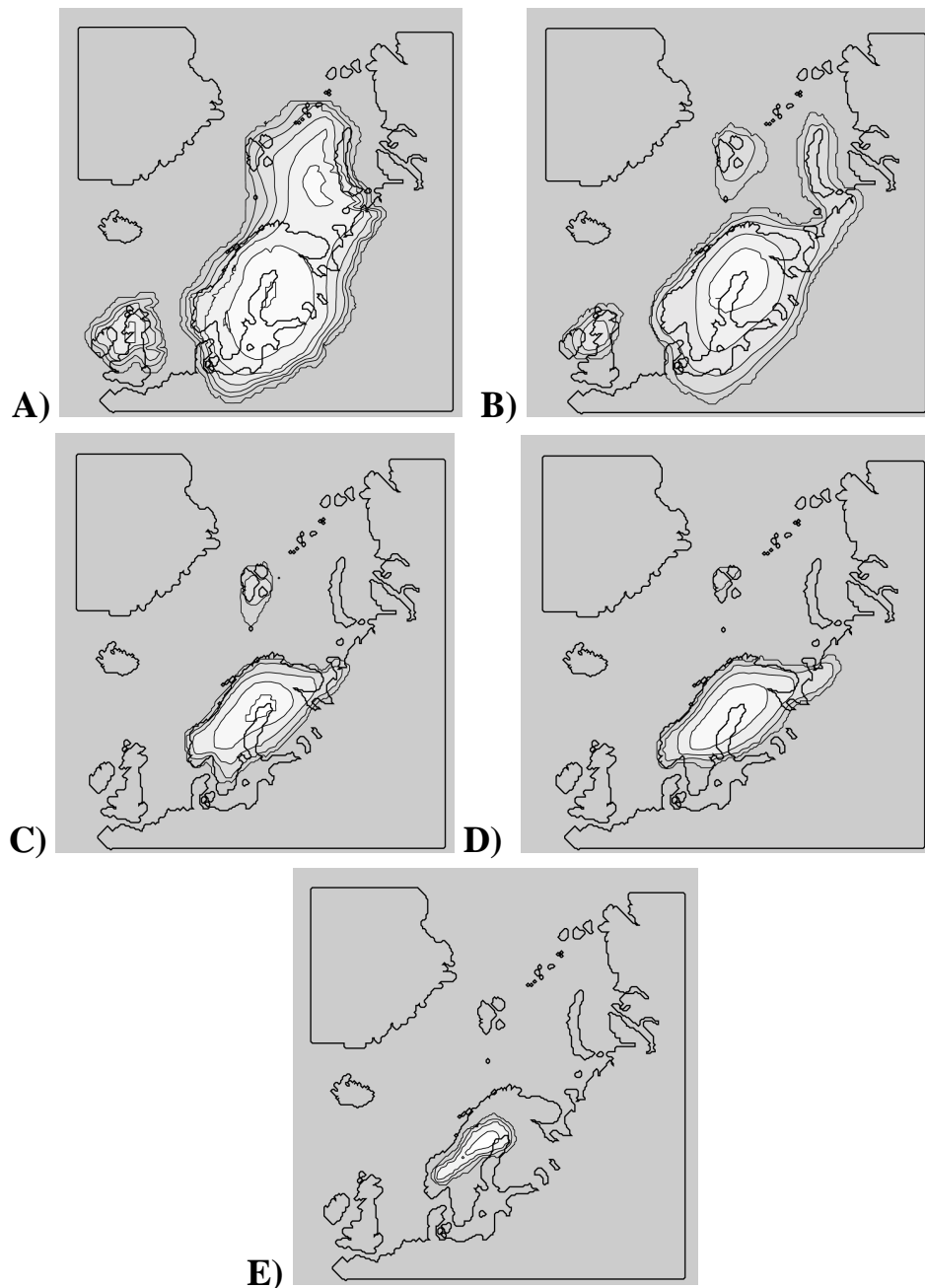
Fig. 3.2.3   The extent and thickness of the ice sheet during the deglaciation in Northern Europe partly based on Denton & Hughes (1981): (a) 20,000 years BP, (b) 15,000 years BP, (c) 11,500 years BP, (d) 10,500 years BP, and (e) 9,300 years BP Contour interval is 500 m, except for (e), where the contour interval is 200 m.
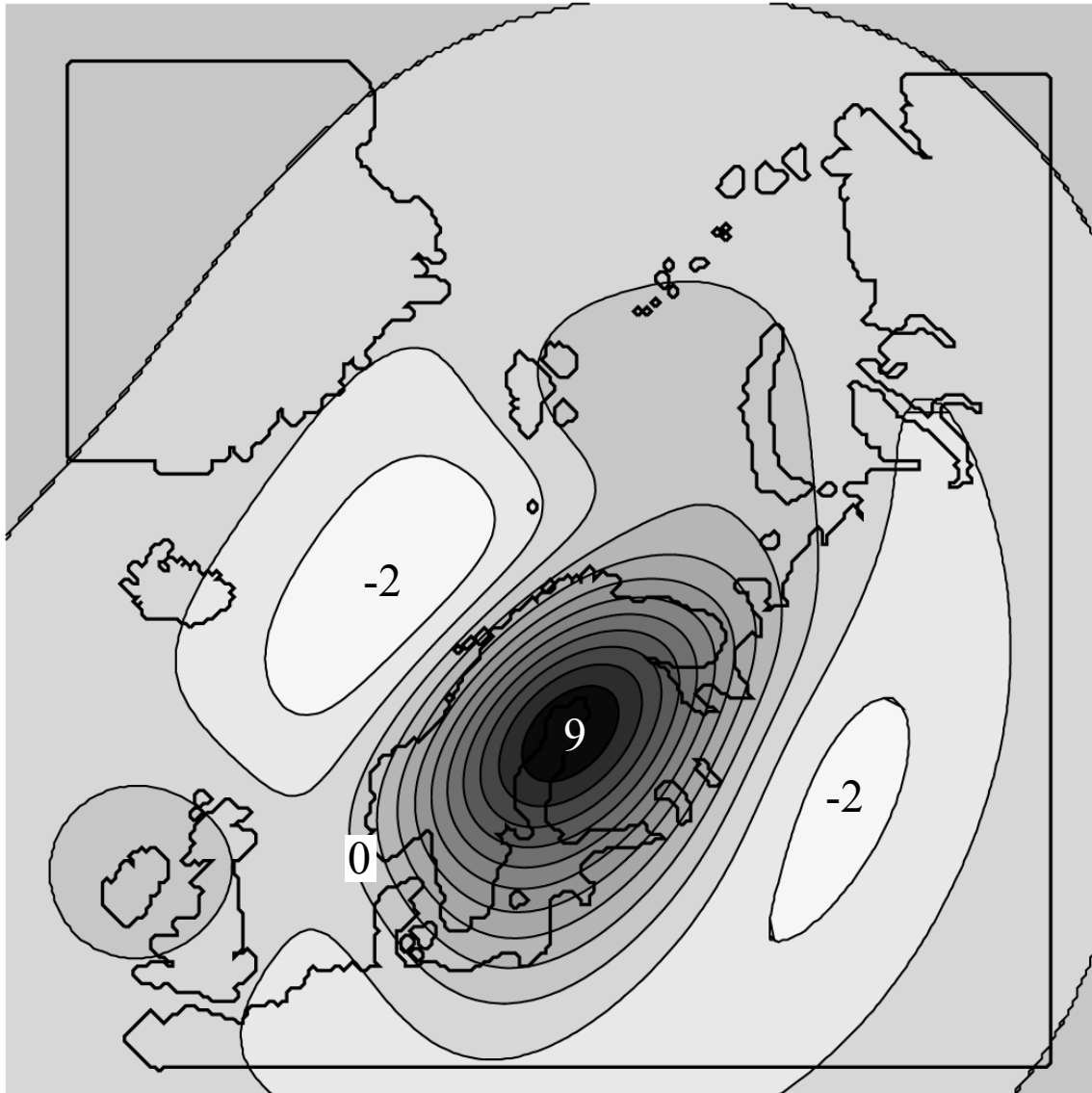
Fig. 3.2.4   Theoretical present rate of uplift in Fennoscandia.

3.2.6   Discussion and conclusion

The calculated deviations are done only for land areas, and for Norway and Sweden, only. The areas with significant positive deviations (>1.0mm/yr) between the observations and the calculated uplift are shown in Fig. 3.2.5. There are significant anomalies onshore northern and southern Norway. Fig. 3.2.6 shows that there is an area of significant negative (>1.0 mm/yr) anomaly in the Bay of Bothnia.
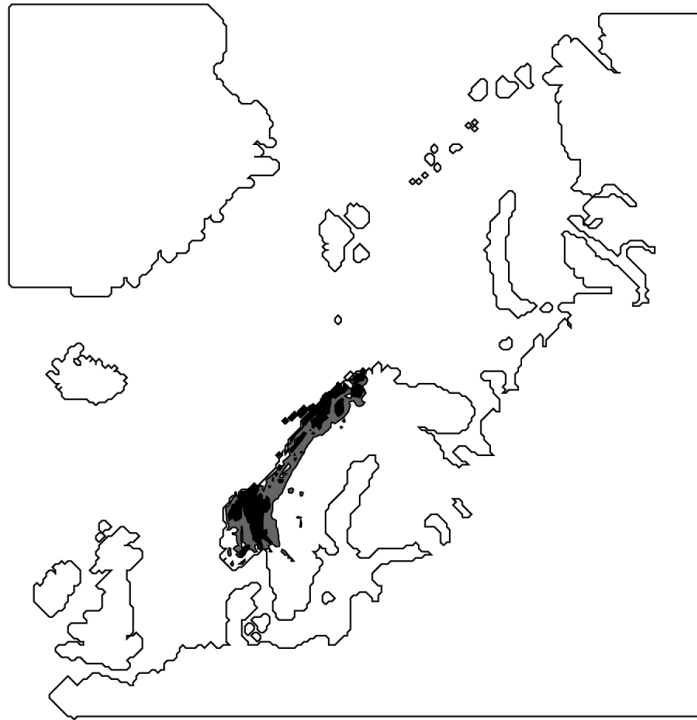
Fig. 3.2.5   Areas with significant positive deviations (grey areas>1.0mm/yr; black areas>1.5mm/yr) between the observations and the calculated glacial isostatic uplift.

Fig. 3.2.6   Areas with significant negative deviations (grey areas>0.5mm/yr; black areas>1.5mm/yr) between the observations and the calculated glacial isostatic uplift.

There are three areas of significant anomalies in Scandinavia, relative to predicted glacial isostasy, mid Norway, southern Norway, and the area onshore in the Bay of Bothnia. This is assumed to be areas that experience tectonic movements today. The anomalies may be a consequence of the Plio-Pleistocene erosional pattern, which is of glacial origin. The erosion has supposedly a maximum (marginal highs) in the mountainous areas of Norway (southern and northern Norway), and there will be a pronounced central depression in the Gulf of Bothnia. This is supported by the present investigation, both in terms of seismicity and calculated uplift residuals.

The glacio-isostatic model predicts a forebulge offshore Norway. The transitional area between this forebulge and the coast (that was depressed) is the area of the highest uplift gradient and also the area where the largest earthquakes occur. The NW-SE compression of the lower crust is in accord with the uplift model, but the same stress direction would also be caused by ridge push from the mid Atlantic ridge. The fact that this stress direction is found also far from the coast, but in less active regions, indicate that this region experience stress from two distinct forces (uplift and ridge push) that act constructive.

The concordance between the observed seismicity and the areas of isostatic model misfit is best in the coastal areas, but earthquake activity also occurs in areas where the model does not predict tectonic activity. The conclusion is therefore that even when the model seems to map the main areas of a possible tectonic uplift, there may be local areas where other forces (e.g. local terrain differences) may influence the deformation. In addition it is important to acknowledge the influence of the regional uplift model (Fig. 3.2.2): It is to be expected that many local features are not included due to very sparse uplift data.

4. NEOTECTONIC MAP, 1:3 MILLION

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[2] Norwegian Mapping Authority
[3] Norwegian Petroleum Directorate
[4] NORSAR

4.1 Introduction

The Neotectonic Map of Norway and Adjacent Areas is an attempt at integrating the many different types of information gathered during the project. The data include elevation and bathymetry, seismic activity, *in situ* stress measurements, postglacial faults and isostatic uplift rate contours. The objective of the map is to assist in identifying areas of correlation between the different types of data. To assist in this, related compilations of onshore and offshore tectonic features, sediment transport and *in situ* stress are presented on inset maps.

4.2 Methods

The map was constructed using a number of software packages. The map background consists of a colour-shaded relief map of the land surface and ocean floor. Production of this image required the merging of eight separate data sets, each with a different cell size. This was done using ER-Mapper. Fairly complex histogram transformations had to be applied in order to highlight the important areas of topographic relief. This was due to the fact that the difference between the deepest and highest points was more than 7,000 metres, whereas most of the area of interest was within a much smaller elevation difference. The result is that the morphology of the continental shelf is artificially enhanced.

Some raster data sets were constructed from line or point data. The TIN module in Arc/Info was used to do this. Bathymetry data for Svalbard and the Barents Sea area were obtained from the Norwegian Mapping Authority and the US navy. These data were supplied as bathymetric contours. The contours were imported to create a triangular irregular network (TIN) and a raster image created using quintic interpolation.

The uplift rate data detailed below were all point data. These were gridded using Geosoft Oasis Montaj, using a minimum curvature algorithm. The resulting image was then loaded into ER-Mapper, where a set of vector contours was produced.

Other than the raster data, all data is stored within Arc/Info in two projections. The first projection is a geographic projection, with coordinates stored as decimal degrees. This projection allows GIS software such as ArcView to reproject the data on-the-fly into any other projection. The second projection is the projection used on the map itself. This projection is a

transverse mercator projection similar to UTM zone 33. It is slightly modified to reduce the distortion produced when using a UTM projection outside of its zone.

The final map was produced using a combination of ER-Mapper, Arc/Info and Corel Draw. The background image produced in ER-Mapper was exported as a georeferenced TIFF file, with an even cell size of 250 metres. Elements of the inset map, as well as text, tables, titles, scale bar and logos were produced in Corel Draw and exported as an encapsulated postscript file. The map was then produced using Arc/Info.

4.3 Data sets

4.3.1   Topography and bathymetry

The bathymetry data for a large part of the map come from Smith and Sandwell (1997). Higher resolution data for the northern part of the map and the coast of Norway were supplied by the Norwegian Mapping Authority and the US Naval Oceanographic Office. Very coarse data to fill in the gaps in coverage were taken from a global data set supplied with the ER-Mapper software.

High-resolution topography data for Norway were supplied by the Norwegian Mapping Authority. Topography for the rest of the map was taken from the GTOPO30 data set (http://edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.html).

4.3.2   Uplift

The present rate of uplift in Fennoscandia was calculated using data from tide-gauges, precise levelling, GPS and gravity measurements.

Tide-gauges

The Norwegian Hydrographic Service (NHS) maintains a network of 23 gauges on mainland Norway and two in the Arctic. The NHS computes monthly and annual means. The Geodetic Division has the responsibility for land uplift calculations and for the levelling from the tide gauge to the tide gauge bench mark. These data are included in the NEONOR database. Additional tide gauge records from around the Baltic Sea (Ekman 1998) are also included to help constrain the regional uplift pattern.

Precision levelling

The first order levelling network in Norway consists of about 13,000 bench marks and observation lines back to 1916. The net is connected to the tide-gauge records. A common adjustment in 1954 defines the national height reference. Since 1954, a number of additional lines and benchmarks have been surveyed. The accuracy in the network is about 1mm per km.

Uplift rates calculated from repeated precise levelling along roads throughout Norway, Sweden and Finland make up the bulk of the NEONOR uplift data. Levelling results from the

northern part of Finland have been used, together with the 1st, the 2nd, and a few lines from the 3rd precision levelling of Sweden. Data from all available Norwegian precision levelling lines were used, including the lines measured by surveyors from the Norwegian Railways (Danielsen, pers. comm.).

Acorn barnacle/ bladder wrack marks

Along the coast of Norway Acorn barnacle/bladder wrack marks were placed during the period 1889-1897. The marks are mostly grooves cut into rock at or close above the rim of acorn barnacle or bladder wrack. The land uplift rate is determined from remeasurement of the height of the groove relative to these rims. The method relies on the correctness of the assumption that these rims define a marine biological level that has a constant height relationship to mean sea level over time at a particular site. The accuracy is also dependant on the time scale for the reaction in the growth of acorn barnacle and bladder wrack to variations in the height of mean sea-level. Marine biologists are of the opinion that acorn barnacle adjust to the variation in sea level over a one to two year period and bladder wrack over a three to four years period. We can therefore probably assume that the rims of acorn barnacle and bladder wrack corresponds to the height of mean sea-level over a one to two year period and a three to four year period respectively. This method has been used as a significant and valuable contribution to the determination and extrapolation of the isobases for the rate of land uplift along the coast. During the period from 1975 to 1992 altogether 14 points in southern Norway and 56 points in northern Norway were found and remeasured.

These data are included in the NEONOR database, but were not used in the calculation of the uplift contours on the map due to their lower precision. In general, the values fit well with the other data sets, and do not alter the contours significantly.

Gravity

Between 1966 and 1984, repeated precise gravity measurements were performed on three lines across Norway, Sweden and Finland to determine the rate of uplift (Mäkinen *et al.* 1986).

GPS

Permanent GPS stations located in Sweden and Finland have also provided measurements of uplift rate (Ekman 1998).

4.3.3   Seismicity

The earthquake catalogue was produced by NORSAR, and contains modern and historical events from 1497 to 1998. For the period 1497 to 1982, only earthquakes with magnitudes greater than or equal to 5.0 are reported. For the period from 1983 to the end of 1998, only earthquakes with magnitudes greater than or equal to 2.0 are reported.

4.3.4 Crustal stress

The stress data derived from earthquake focal mechanism solutions are based on Hicks *et al.* (in press), which includes the new solutions determined under the NEONOR project. The in-situ stress measurements, consisting of borehole breakouts offshore and overcoring measurements onshore, are taken from the IBS-DNM project (Fejerskov *et al.* 1996).

4.3.5 Neogene volcanics

Volcanic rocks of both Quaternary and Miocene/Pliocene age on northern Spitsbergen (Prestvik 1977, Skjelkvåle *et al.* 1989) and Late Pliocene volcanic rocks on the western Barents Sea Shelf margin (Mørk & Duncan 1993) have been added to the neotectonic map.

4.3.6 Postglacial faults

The Lapland postglacial fault province (Table 1.1) occurs in northern Finland (Kujansuu 1964, Kuivamäki *et al.* 1998), northern Norway (Olesen 1988, Tolgensbakk & Sollid 1988) and northern Sweden (Lundqvist & Lagerbäck 1976, Lagerbäck 1979) within a 400 x 400 km large area. The Pärve Fault is up to 150 km in length. The Lainio-Suijavaara Fault has an escarpment of 30 m in height. The major faults are NE-SW trending reverse faults while the two minor faults, the Nordmannvikdalen and Vaalajärvi faults, have a NNW-SSE direction that is perpendicular to the trend of the reverse faults. The Nordmannvikdalen fault in northern Troms is a normal fault. The dip of the parallel Vaalajärvi Fault in northern Finland is not known, but recent trenching indicates a normal fault (Kuivamäki *et al.* in press).

4.3.7 Basement faults and flexural hinges

Many of the large faults and fault complexes that form the boundaries of major structural elements involve the crystalline basement and show evidence of several periods of reactivation since their origination in Palaeozoic to Triassic times (Brekke et al. 1989, Gabrielsen et al. 1990, Vejbæk & Britze 1994, Blystad et al. 1995). In some areas the boundary zones between platforms and the major Cretaceous basins appear to be major monoclinal flexures rather than cross cutting faults. On the map they are marked as flexural hinge lines. These flexures involve both basement and cover and are characteristic of the flanks of the Møre and Vøring Basins (Brekke 2000).

4.3.8 Offshore avalanches

The extent of avalanches in the Norwegian Sea is based on published maps by Vorren *et al.* (1999). The map shows the Storegga, Trændjupet, Andøya and Bjørnøyrenna slides.

4.3.9 Centres of Neogene uplift and sediment deposition

The data on Neogene domes and Plio-Pleistocene prograding sedimentary wedges are based on compilations by Riis (1996).

5.   CONCLUSIONS

The present elevation of Scandinavia is mostly a result of Neogene uplift. The combined effect of tectonic uplift of Fennoscandia and the onset of the northern hemisphere glaciation led to greatly increased erosion and sedimentation. More than 50% of the volume of Cenozoic sediments has been deposited during the last 2.6 m.y. The modelled uplift of Fennoscandia shows that the observed uplift of parts of western and northern Norway can not be attributed to the glacial rebound. The western margin of these two areas shows increased seismicity and are assumed to be areas that experience tectonic movements today. The two areas with residual uplift (>1.0mm/yr) do also party coincide with the Neogene domes in Fennoscandia (see index map on enclosed neotectonic map at the scale 1:3 million). The uplift relative to predicted glacial isostasy may be a consequence of the Plio-Pleistocene erosional pattern, which is of glacial origin. The erosion has supposedly a maximum in the mountainous areas of Norway (southern and northern Norway), but a plate-tectonic cause of the intraplate deformation cannot be ruled out. There is also some evidence (e.g. Mangerud *et al.* 1981, Sejrup 1987) that the Norwegian coast may have been subject to tectonic uplift in the order 0.1-0.3 mm/yr during the Quaternary, in addition to postglacial uplift. Examination of recent seismicity in Scandinavia (Figs. 1.2.11 & 3.1.1) shows a pattern clearly not correlated with current uplift rates (Fig. 1.2.11), but rather consistent with continued tilting of Norway and Sweden. A flexural hinge zone along the eastern border of the tilted Scandinavian block is represented with an area of increased seismicity. This zone continues through southern Sweden and along the western coast of the Bothnian Sea northwards to Finnmark in northern Norway. The postglacial Lapland Fault Province is situated along the northern part of this hinge zone. The western hinge zone along the Norwegian coast is also coinciding with a seismic active area.

Across the Norwegian continental margin the tectonic strain rate is probably at most in the order of 10^{-9} to 10^{-10} yr^{-1}, which is 3-4 magnitudes lower than that of an active plate margin but at least two orders of magnitude higher than within the Baltic Shield. Strain energy can accumulate over a very long period of time, and even regions with low strain rates can exhibit large earthquakes and often with more energy release per unit fault area because of generally higher stress drops. The seismicity of Norway and adjacent areas is intermediate in level, and even though it is the highest in northwestern Europe it is still lower than in many other stable continental (intraplate) regions.

Existing neotectonic claims have been graded into five classes based upon careful field investigations wherever possible. After a critical evaluation of 64 neotectonic claims in Norway we have classified five claims as 'A - Almost certainly neotectonics' and another five as 'B - Probably neotectonics.' The majority of the claims can be attributed to effects other than tectonic. The present grade A claims include postglacial faults on Finnmarksvidda (Stuoragurra Fault) and in Kåfjord (Nordmannvikdalen Fault) and earthquake swarms in

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northern Norway (Steigen, Meløy and Sjona). The grade B claims include a potential postglacial fault in the Rana area and areas with large numbers of rock avalanches, gravitational spreading and gravitational faults in northern and western Norway. These structures are caused by gravity collapse, but their spatial occurrence and the relative gentle slopes related to some of the features strongly indicate that another mechanism is necessary to trigger the features. This extra loading is most likely to have been caused by strong shaking from large-magnitude earthquakes.

There was a major seismic 'pulse' (with several magnitude 7-8 earthquakes) immediately after the deglaciation of northern Fennoscandia. There is good evidence for the Nordmannvikdalen postglacial fault being part of a conjugate set of normal faults perpendicular to the extensive system of NE-SW trending reverse faults in northern Fennoscandia. Small earthquakes along the postglacial faults indicate that the faults are active at depth. Focal mechanisms are consistent with a reverse faulting with a dip to the southeast. This continuous fault failure could have been suppressed for as long as the last inland ice existed. The accumulation of tectonic strain energy beneath a large ice-sheet for 10,000 years or more could provide the energy source and explanation for the large-scale, late-glacial faulting in northern Fennoscandia.

No postglacial faults with throws larger than a few metres have been observed on the Norwegian continental shelf. With a possible exception of the deep-water areas with poor seismic coverage, there are no offshore neotectonic faults of comparable size to the postglacial faults of the Lapland Fault Province. Three different types of possible neotectonic features have, however, been identified in the offshore area: 1) Fissures and lineaments correlated with areas of gas leakage (not obviously related to basement faults). 2) Subtle lineaments with possible fault throws identified on 3D seismic data in the northeastern North Sea. 3) Probable reactivation of Miocene dome structures in the deep part of the Norwegian Sea. Contractional structures (large anticlines and synclines, reverse faults and inverted centres of deposition) were initiated during the Paleogene in the Vøring and Møre Basins. There are indications that some of these structures have been growing from the Eocene to the present, interrupted by an episode of more prominent deformation in the Miocene. In addition, submarine slides and/or gas leakage may be secondary effects of neotectonic activity in some areas.

Results from the NEONOR seismic mini-arrays in the Rana area have shown that the return period of magnitude 6 and 5 earthquakes in the Rana area is 1500 and 130 years, respectively. An earthquake with magnitude 5.8-6.2 occurred in this area in 1819 and triggered several rock avalanches and landslides. The enormous large Storegga slide at the continental margin occurred 7,200 years ago and was possibly triggered by a large earthquake. Recent mapping of rock avalanches and submarine debris flows within the Quaternary sediments may indicate that large earthquakes have occurred in the Møre & Romsdal area. Similar studies in Troms county indicate large earthquakes before or during the Younger Dryas period (11,000-10,000

BP), possibly associated with the formation of the Nordmannvikdalen postglacial fault. Another slightly younger event seems to have been of an even larger magnitude. Several hundred large rock avalanches and landslides were triggered during these events. The collapse of mountainsides into the deep fjords of Troms would set up many metres high waves, which would be disastrous to the population along the shores. Such phenomena represent the most hazardous effects of earthquakes in Norway with its mountainous terrain, deep fjords and relatively large areas with unstable quick-clay. The slope failures in Troms county seem to be old (during and shortly after the deglaciation), and are likely related to the high seismic activity during and immediately after the deglaciation. The large-scale rock avalanches in the Møre & Romsdal region are much younger, and the frequency seems to have increased during the second half of the Holocene period (5,000 years). The studies of the effects of the historical earthquakes around the world evidence a high number of slope failures related to earthquake magnitude 6 and larger. Recurrence intervals of M7 earthquakes every 1,000 years as postulated by NORSAR and NGI (1998) means that large-scale slope failures onshore and offshore Norway need to be taken into account when evaluating hazard. A problem worth noting is that although the level of seismicity in Norway is stable, the level of vulnerability of society to earthquakes has increased enormously during the last tens of years.

The groundwater yield (minimum 17m³/hour) from a well through the postglacial Stuoragurra Fault is among the highest ever measured in hard rock aquifers in Norway. The CO_2 content of the groundwater in the Stuoragurra Fault is 10-100 times higher than usual. A literature review on gas geochemistry and seismotectonics (Toutain & Baubron 1999) concluded that CO_2-degassing from deep crust and mantle through active faults is a common phenomenon. The rupturing along the Stuoragurra Faul approximately 9,000 years ago penetrated through most of the crust. There are numerous reports of changed groundwater flow and active pockmarks after earthquakes in the international literature. Neotectonic activity in the Etne, Rana, Masi and Kåfjord areas seems also to have influenced the groundwater flow. Some of the pockmarks in the North Sea seem to be formed during postglacial faulting. If large earthquakes occurred after each of the numerous glaciations during the last 600,000 years the dilatation and closing of fissures in the surrounding bedrock could increase the migration of hydrocarbons from the relatively impermeable source rocks up into reservoir or to pockmarks at the sea floor. These seismic pulses associated with the glaciation-deglaciation cycles could also explain why the groundwater content in bedrock fractures is positively correlated with the present land uplift in Norway. Repeated pulses of high-pressure groundwater through faults and fractures could prevent the continuous void spaces from being clogged by clay minerals. Subglacial meltwater will cause additional flushing of relatively shallow aquifers during the glacial periods and assist in keeping fractures open. This information is of importance for planning of both groundwater supply and tunnels. Release of hydrocarbons on the continental shelf and/or CO_2 in crystalline basement during deglaciation-induced seismic pulses could explain the improved climate immediately after the deglaciation as a result of increased greenhouse effect.

During the percussion drilling of the Stuoragurra Fault groundwater was encountered at a depth of 35 m (2 m above the main fault zone). After penetration of the fault gouges at a depth of 37 m the ground water was drained but appeared again at a depth of 40 m. The fault gouges consequently caused a 'hanging' ground water surface above the main fault zone. We conclude that the fault gouges in the Stuoragurra Fault have sealing properties, even if the more than 10 m wide fault-zone is totally fractured and water-bearing at larger depths. This phenomenon indicates that even young faults on the continental shelf may have sealing properties with regard to migration of petroleum.

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APPENDIX A: REPORTED EVIDENCES OF NEOTECTONICS ON THE MAINLAND OF NORWAY AND ASSESSMENTS OF THE CLAIMS

The locations are ordered from north to south. The criteria for classification of postglacial faulting by Fenton (1991; 1994) and Muir Wood (1993) have been utilised for grading the claims into the classes: (A) Almost certainly neotectonics, (B) Probably neotectonics, (C) Possibly neotectonics, (D) Probably not neotectonics and (E) Very unlikely to be neotectonics. The most likely cause of the proposed neotectonic deformation have been included as 'TYPE' in the fifth column: (1) Tectonic fault; (2) Gravity-induced faults, (3) Erosional phenomena (4) Overburden draping of bedrock features, (5) Stress release features.

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
1	Lebesby, Laksefjord, Finnmark Roberts (1991).	A road-cut drillhole penetrating cleaved phyllites has been observed to be offset in a reverse fault sense by 5.8 cm along a 40° dipping fault surface. This displacement occurred at some time during the period 1986 to 1989.	Stress release phenomena of surficial character. The direction of offset indicates the direction of maximum horizontal stress (Roberts in press).	E5
2	Tanafjord, Finnmark (no exact location) by J.E. Rosberg according to Tanner (1907).	Postglacial fault (no published description).		
3	Skipskjølen, Varanger peninsula, Finnmark Olesen *et al.* (1992b)	WNW-ESE trending 4 km long escarpment within the Trollfjord-Komagelv Fault Zone has been observed from aerial photographs. The northern block seems to be downfaulted.	The scarp has been sculptured and rounded by the moving inland ice. The height of the scarp is varying considerable along the scarp (Olesen & Dehls 1998).	E3
4	Gæssagielas, Karasjok, Finnmark Olsen (1989)	E-W trending 1.5 km long assumed Late Quaternary fault. The northern block is depressed.	The scarp is interpreted to represent a till draped escarpment in the underlying bedrock (Olesen & Dehls 1998).	E4

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
5	Masi-Iešjav'ri area, Finnmark Olesen (1988), Muir Wood (1989b), Olesen *et al.* (1992a, 1992b, 1992c), Bungum & Lindholm (1997) Roberts *et al.* (1997)	The NE-SW trending postglacial Stuoragurra Fault extends for 80 km in the Masi-Iešjav'ri area in the Precambrian of Finnmarksvidda. The fault is manifested in the surface as a fault scarp up to 7 metres high and is situated within the regional Proterozoic Mierujavri-Sværholt Fault Zone. The Stuoragurra Fault is a southeasterly dipping reverse fault. A c. 1 m thick zone containing several thinner (a few cm wide) zones of fault gouge represents the actual fault surface. The 21 January earthquake (M 4.0) in the Masi area was most likely located along the Stuoragurra Fault at a depth of c. 10 km.	The age of the SF is constrained in that it crosscuts glaciofluvial deposits northeast of Iešjav'ri and an esker northeast of Masi. Thus it formed after the deglaciation (c. 9,300 yr. BP).	A1
6	Storslett, Nordreisa, Troms Wontka (1974)	An up to 150 m high scarp to the southeast of Storslett is interpreted in terms of a postglacial reactivation of the Caledonian Jyppyrä fault which has an apparent accumulated displacement of approximately 700 m.	The height of the scarp varies considerably and also appears to be rounded by glacial erosion. The scarp is most likely formed by plucking of the moving inland ice along a Caledonian fault (Olesen & Dehls 1998).	D3
7	Lyngen, Troms and Øksfjord-Alta, Finnmark Holmsen (1916)	Postglacial uplift has been estimated from levelling of shorelines in northern Troms and western Finnmark. The uplift shows negative anomalies from the regional trend in the order of 5 metres in the Lyngen and Øksfjord areas. This effect has been attributed to gabbro massifs.	The interpretation is hampered by poor age control on the formation of the shorelines.	C
8	Nordmannvik-dalen, Kåfjord, Troms Tolgensbakk & Sollid (1988), Sollid & Tolgensbakk (1988), Olesen & Dehls (1998), Dehls (1999), Blikra & Longva (2000)	NW-SE trending postglacial faults in the Kåfjord area, North Troms. Normal faults dipping 30-50º to the northeast (Olesen & Dehls 1998). The height and length of the main escarpment is approximately 1 m and 2 km, respectively.	The fault is sub-parallel to the Nordmannvikdalen valley. The slope of the terrain is 10-12º and the elevation difference between the fault scarp and valley bottom is 150-200 m. According to Varnes *et al.* (1989) gravity induced sliding is less likely to occur when the elevation difference is less than 300 m. We do therefore favour a tectonic origin of the fault.	A1

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
9	Balsfjord-Lyngen area Blikra & Longva (2000)	A distinct concentration of gravitational faults and slope failures may indicate a large-magnitude (M7) prehistoric earthquake. Several hundred large rock avalanches and land-slides were triggered during this event.	The slope failures in Troms county seem to be old (during and shortly after the deglaciation), and is likely related to the high seismic activity caused by the deglaciation	B1,2
10	Tjeldsundet, Troms Grønlie (1922), Vogt (1923)	Displacement of Holocene shorelines (an offset of c. 2.2 m down to the west). Lower shorelines appeared to be unbroken indicating that the inferred faulting occurred immediately after the deglaciation. Vogt (1923) pointed at the striking coincidence of the young faulting occurring in an old regional fault-zone along Tjeldsundet. Several large-scale rock avalanches occur along Astafjorden (Blikra & Longva 2000). The fjord is lying along the NE extension of the Vestfjorden-Vanna Fault Zone through Tjeldsundet.	Multibeam echo-sounding data and marine seismic profiling (Longva *et al.* 1998) do not reveal any fault scarps in the sediments or bedrock at the sea floor of Tjeldsundet. The different altitudes of the shorelines may therefore be due to variations of the currents through the sound during deposition of the shorelines.	D
11	Vassdalfjellet, 4 km east of the E6 in Kvanndalen north of Bjerkvik, Nordland Bargel *et al.* (1995)	A series of parallel east-west-oriented open fractures can be observed on the western part of the top of the ridge. Some of these are over 1 m wide and many are so deep that their depth is difficult to assess. There have been vertical movements along some of the fractures.	The most continuous fault is 600 m long. They are situated close to a steep 600 m high wall along the southernmost slope of Vassdalfjellet. The faults are interpreted to be effects of gravity-induced sliding (Olesen & Dehls, 1998). The faults may resemble a small scale sackung feature (Varnes *et al.* 1989) due to gravity spreading of Vassdalfjellet.	E2
12	Reinneset, Skjomen, Nordland Bargel *et al.* (1995)	A 1.5 to 10 m high escarpment on the headland between Skjomen and Sørskjomen is interpreted in terms of a reverse postglacial fault dipping to the north. The fault continues to the west on the other side of Skjomenfjorden. Foliated granite can be observed in a few dm wide zone at the foot of the escarpment. The high, sharp-edged fault wall facing the direction of the moving inland ice points to a young age.	An inspection of the locality has shown that the top of the escarpment is rounded and that the height of the escarpment varies considerable over short distances along the fault. These observations point towards a formation due to erosion along an older zone of weakness (Olesen & Dehls 1998).	D3

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
13	Tysfjord-Kobbelv area, Nordland Myrvang (1993)	Large-scale rock bursting and even buckling at the surface due to high horizontal stress in the order 30-40 MPa.	Stress release phenomena of superficial character.	E5
14	Steigen, Nordland Atakan *et al.* (1994)	The earthquake swarm occurred in 1992 and contained 200 shocks but no main shock was recorded. The magnitude of the shocks was up to 3.6.	Earthquake swarms usually occur in volcanically or tectonically active areas such as plate boundaries but have also been reported from passive continental margins surrounding the northern part of the Atlantic Ocean and the Arctic Sea.	A1
15	Meløy, Nordland Bungum *et al.* (1979), Bungum & Husebye (1979) and Gabrielsen & Ramberg (1979)	The spectacular earthquake swarm on Meløy was located within the seismicity zone of the Nordland coast. The swarm occurred in 1977/1978 and contained 10,000 shocks, but no main shock was recorded. The magnitude of the shocks was up to 3.2.	These swarms are generally interpreted to be related to the formation of new zones of weakness in relatively competent bedrock (R. Muir Wood pers. comm.).	A1
16	Kvasshaugen mountain between the valleys of Beiardalen and Gråtådalen, Nordland Grønlie (1939), Johnsen (1981), Muir Wood (1993)	NNE-SSW trending clefts occur along an approximately 5 km long NNE-SSW trending zone. These clefts are up to 20 m wide and 10 m deep and the eastern sides are locally down-faulted.	The faults may be classified as sackung features (Varnes *et al.* 1989) due to gravity spreading of the 500 m high ridge along Gråtåhaugen, Kvasshaugen and Monsfjellet (Olesen & Dehls 1998). The initiation of movements may, however, be triggered by large earth-quakes	B1,2
17	Austerdalsisen, Rana, Nordland Olesen *et al.* (1994, 1995)	Interpretation of aerial photographs unveiled an area of north-south trending, vertical dipping fractures and faults in the Austerdalsisen area to the NW of Mo i Rana. There seems to be a vertical offset of the bedrock surface across these structures. The foliation of the mica schist is sub-parallel to the bedrock surface.	Field inspected revealed that the features are probably of erosional origin. The moving inland ice has most likely been plucking blocks from the bedrock along steeply dipping N-S trending fractures (Olesen & Dehls 1998).	D3

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NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
18	Sjona-Ranafjord area, Nordland Hicks *et al.* (1998, 1999, 2000, this volume), Helzen (1834), Muir Wood (1989a)	A total of 250 earthquakes have occurred within the Sjona-Ranafjord area during the last two years. Four main clusters of earthquakes have been observed in time and space. The earthquakes range in magnitude from 0.1-2.8 and hypocenter depths are shallow, mainly around 5-12 km.	The clusters resemble the previously observed earthquake swarms in Meløy and Steigen, though on a smaller scale. The Sjona region coincides with the area of strongest effects from the 1819 earthquake (M 5.8-6.2) and accompanying eathquake swarms (Heltzen 1834, Muir Wood 1989a).	A1
19	Ranafjord area, Nordland Helzen (1834), Grønlie (1923), Muir Wood (1989a), Bakkelid (1990), Olesen *et al.* (1994, 1995) Hicks *et al.* (1998, 1999, 2000, this volume).	The Båsmoen Fault consists of SSE-dipping (40-70°) fault segments within a 2-km wide and 50 km long zone. There is evidence for anomalous land uplift along the Båsmoen Fault at the locations Utskarpen, Straumbotn, Båsmoen on the northern shore of Ranafjorden and Hemnesberget and on the Hugla and Tomma islands. The fault bears resemblance to the postglacial faults reported from the Lapland area of northern Fennoscandia.	No conclusive evidence has yet been found for postglacial movements along specific fault scarps. Trenching of the fault scarp does indicate a 40 cm offset along the Båsmoen fault. A new seismic mini-array has registered numerous earthquakes in the outer Ranafjord area. They do not, however, seem to be attributed to the Båsmoen fault (Hicks *et al.* 1998, 1999, 2000, this volume).	B1,3
20	Handnesøya, Nesna, Nordland Olesen *et al.* (1994, 1995)	North-south trending, vertical dipping fractures and faults occur on Handnesøya, north of Nesna. There seems to be a vertical offset of the bedrock surface across these structures. The foliation of the mica schist is sub-parallel to the bedrock surface.	Field inspection revealed that the features are probably of erosional origin since the scarps seem to be sculptured by the moving inland ice. The ice has most likely been plucking blocks from the bedrock along steeply dipping N-S trending fractures (Olesen & Dehls, 1998). Monitoring of the seismicity in the area has, however, shown that more than 20 earthquakes occurred along one of these fault zones in 1998 indicating that the fault is active at depth (Hicks *et al.* 1999)	C1,3

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
21	Otrefjellet, Haram, Møre og Romsdal (Anda *et al.* 2000)	A two km long, N-S oriented mountain ridge, 100-300 m above the surrounding terrain, is heavily fractured. Crushed or collapsed bedrock occur locally within a 500 m wide zone. The slopes of the ridge are too gentle to cause any gravity sliding (Anda *et al.* 2000). An earthquake could provide the necessary energy to trigger the failure.	An alternative mechanism is frost shattering during Weichselian nunatak phases. The ridge is, however, situated 200-300 m below the distinct 'weathering zone' of the region (Anda *et al.* 2000).	B1,2
22	Børa, Rauma, Møre og Romsdal Anda (1995), Anda & Blikra (1988), Anda *et al.* (2000)	Concentration of rock-avalanches correlates with a 500-700 m high regional escarpment of the land surface. This large-scale geomorphic feature is attributed to a fault zone associated with the Cenozoic uplift of Norway.	It is likely that the regional escarpments reflect fault segments along the Mesozoic Møre-Trøndelag Fault Zone. Mesozoic sediments may have filled local basins along the fault zone (similar to the basins in Beistandfjorden and Trond-heimsleia). Glacial erosion will more easily remove these soft sediments (than the more competent basement rocks) subsequent to the Cenozoic exhumation of Norway.	D3
23	The Norwegian coast between Stadt and Vesterålen Holtedahl (1984, 1998), Møller (1985), Sjöberg (1988).	Several authors have observed that sea-formed caves are located at a higher altitude than the postglacial marine shore level along the coast between Stadt and Vesterålen They concluded that a long-term neotectonic uplift continued through the late Quaternary period. The sills of several caves are situated c. 30 m above the upper marine shore line and the height of the opening is in addition 30-50 m.	Olsen & Grøsfjeld (1999) have reported uplifted (40-90 m) Middle and Late Weichselian marine sediments at several locations in Norway. These positions indicate a frequently fluctuating ice sheet during the interval 18-50 ka BP. Repeated rapid ice retreat following heavy ice loading can explain the location of sea-formed caves above the postglacial marine limit.	D3
24	Breisunddjupet, Møre og Romsdal Holtedahl (1959)	The elevation of the strand flat to the north of the NW-SE trending Breisunddjupet seems to be lower than the strand flat to the south.	Later, more detailed studies by H. Holtedahl (pers. comm. 1995) and Holtedahl (1998) have questioned this observation. Inspection of the topographic maps (1:50,000) in the area has not revealed any altitude change of the strandflat across Breisunddjupet.	D

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
25	Tronden (Tron), Tynset and Alvdal, Hedmark Holmsen (1916)	Local postglacial uplift has been estimated from levelling of shorelines left by ice-dammed lakes. Gabbro massifs (Tron and Klettene) have been subject to separate postglacial upheaval on the order of 3 metres.	The shorelines was relevelled in 1999. The shorelines showing anomalous altitude is most likely formed at a different time than the regional shorelines and can not be used to estimate crustal deformation (Thoresen 2000).	D3
26	Rudihø, Heidal, Oppland Werenskiold (1931)	Two 100-200 metres long and one metre wide SE-NW trending fractures. One side seems to be down-faulted and the fractures are 1-2 metres wide and up to 6 metres deep. The clefts are arc-shaped with the concave side facing a 500 m high, almost vertical mountain side. The distance from the fractures to the steep mountain side is 10-40 metres.	The fractures are interpreted to be gravity-induced.	E2
27	Gnedden, Holsætrin, Sel, Oppland Werenskiold (1931)	Up to 7 metres high and 1 km long escarpment trending in the ENE-WSW direction (N65°) across a small mountain crest. Large variation in scarp height along the western part of the scarp, more constant to the east (3-5 m). The escarpments seem to be sculptured by the inland ice.	The escarpment is most likely formed by erosion by the inland ice along a pre-existing fracture in the bedrock.	D3
28	Ytre Byrknes Archipelago, Gulen, Sogn og Fjordane Michelsen *et al.* (1986)	NNE-SSW trending open fractures 0.5- 3 m wide and 50-100 m apart. Some are normal faults with vertical displacement of 0.5-2 m. One of the faults cuts a glacial splay channels.	The scarps have been sculptured by the moving inland ice and varies considerable in height. We conclude that the scarps are due to glacial and melt-water erosion and are not caused by any tectonic process.	E3

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
29	Grytehorgi and Vøringfossen, Eidfjord, Hordaland Reusch (1901)	NNE-SSW trending fault on Grytehorgi. The down-faulted block is to the west. Ice-striation seems to be offset by 1 metre (normal fault). Other N-S sharp escarpments in the Vøringsfossen area are also suggested to be effects of postglacial faulting.	The height of the scarp is generally between 0 and 3 metres and varies frequently along the scarp (within approximately 30-40 metres length). The foliation of the phyllite is flat-lying. The lowermost part of the scarp is towards the west. We conclude that the scarp is caused by plucking by the westward moving inland ice. Løset (1981) also questioned the postglacial age of the Grytehorgi fault since it is filled with till and erratic blocks.	D3
30	Utnefjorden, Ullensvang, Hordaland Hoel (1992)	5-10 m offset of the seabed along two airgun profiles (2 km apart) crossing a NNW-SSE trending zone. The SW side seems to be downfaulted.	Turbidites occur in the deepest part of the fjord and an abundance of slumps, slides and pockmarks have been observed within the fjord. Hoel (1992) interpret these phenomena to be effects of large earthquakes.	C
31	Geitura, Ulvik, Hordaland Simonsen (1963) Blikra *et al.* (2000a)	A large rock avalanche in a fairly gentle slope. An earthquake has most likely triggered the avalanche.	This observation indicates the occurrence of at least one large magnitude earthquake in the inner Hardanger area. Postglacial fault scarps have, however, not been found. Other large rock avalanches have also been identified in the area (Blikra *et al.* 2000a). Neotectonic activity in the Hardangerfjord area is supported by recent work on shoreline displacement by Helle *et al.* (2000).	B1
32	Finse - Geilo area, Hordaland - Buskerud Anundsen *et al.* submitted	Anomalous uplift from repeated levelling.	A careful analysis of the levelling methods is pending.	C

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
33	Hjeltefjorden, 30 km northwest of Bergen Unpublished NTNF-NORSAR and NGI (1985)	At the northern end of Hjeltefjorden a boomer seismic survey was undertaken in the mid-80's for a possible tunnel crossing. Several E-W lines between Seløy and Uttoska, appeared to show a consistent offset of the superficial sediments in the floor of the fjord, along a NNW-SSE trending dislocation, involving down to the west displacement of 5-10m (Muir Wood 1993).	The offset-length ratio of the fault scarp is 1/80 (height 5-9 m/length 400 m) which is much higher than the required 1/1,000 ratio (Fenton 1991).	D
34	Fjøsanger, Hordaland Mangerud *et al.* (1981)	A considerable long-term neotectonic uplift, 10-40 m, of the Bergen area during the last 125,000 years is based on investigations of marine sediments from the Eemian interglacial.	The ice melted more rapidly at the end of the Saalian than the end of the Weichselian (Ehlers *et al.* 1984, Ehlers 1990). This difference in deglaciation may explain the occurrence of marine Eemian sediments at elevated positions on Fjøsanger.	C
35	Lygre, northern side of the mouth of Hardangerfjord Reusch (1888)	Potential postglacial fault occurring as a N-S trending escarpment. The western block seems to be down-faulted. The length of the escarpment is not reported, but an accompanying drawing indicates a length of approximately 1 km.	There is no evidence for displacement. The scarp is an erosional feature along a fracture zone, which may be part of a regional lineament (Dehls & Braathen 1998).	D3
36	Etne, Rogaland Karpuz *et al.* (1991)	The 4.25 (±0.25) magnitude Etne earthquake (29 Jan. 1989) occurred as a result of predominately normal faulting on a NW-SE trending fault. Secondary effects of the earthquake were observed as surface fissures in Quaternary sediments. The basement and walls of a farmhouse were damaged as a result of this slope instability.	The structure is most likely caused by ground shaking and is not a deep-seated tectonic fault.	D

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
37	Ringja Vindafjorden, Tysvær - Ølen area, Rogaland, Anundsen (1989)	A 7 km wide and c. 30 km long N-S trending active half-graben has been reported. Along the eastern slope of Vindafjord, and on the mountain plateau to the east of the fjord, a series of long sub-parallel crevasses is observed. A present subsidence is supported by precision levelling (20 mm movement over 19 years)	The sub-parallel crevasses, along with an orthogonal set, can be explained by gravitational sliding along a very strong foliation dipping towards the fjord. The step-like nature of the fjord walls appears to be an erosional feature (Dehls & Braathen 1998). The benchmark with anomalous high uplift is most likely emplaced in an unstable slab of rock (Bockmann 1999).	D2,3
38	Yrkjefjord Anundsen *et al.* submitted	Levelling in combination with repeated triangulations between concrete pillars, showed that both horizontal and vertical displacements in the order of 0.1-0.9 mm/year take place along the Yrkjefjord fault zone. Annual measurements during a period of 10 years indicate that movements change, i.e. are reversed in some periods.	The displacements are very small and are not consistent in time (alternating normal and reverse faulting).	D
39	Yrkje area Anundsen (1982), Anundsen & Fjeldskaar (1983), Anundsen (1985)	A 7-10 metre offset (since 10,400 BP) of the Younger Dryas transgression level across a NE-SW trending fault. The observation is based on a study of the marine isolation of six basins and one of these basins show anomalous uplift.	The offset is only observed at one location. No further work has been undertaken to study other lake basins in this area. From a limited set of dates and cores the fault explanation for the apparent variation in isolation levels, is not unique (Muir Wood 1993).	D
40	Ulvegrovene, north of Røssdalen, Rogaland Anundsen (1988a)	Active subsidence of a narrow zone. The turf along the escarpments seems to be torn apart. The structure is parallel to the valley of Røssdalen.	Most likely a gravity induced structure (Dehls & Braathen 1998).	D2
41	Mosvatnet, Suldal, Rogaland Anundsen (1988b)	The sides of open fractures in the bedrock are located at different levels indicating vertical movements along the fractures.	Erosion of a fine-grained amphibolitic dyke (Dehls & Braathen 1998).	E3

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
42	Spronget, Krossvatnet, Suldal, Rogaland Anundsen (1988b)	The sides of open fractures in the bedrock are located at different levels indicating vertical movements along the fractures.	Inspection of aerial photographs shows that the scarp has a limited length compared with the height. We think that it is the result of erosion along an old fault or an amphibolitic dyke.	D3
43	Bø, Karmøy, Rogaland Sejrup (1987)	The location of Eemian sediments at an estimated altitude of 15-45 m above the Eemian sea level is applied to deduce a long-term uplift of the Karmøy area during the last 125,000 years.	See comments on location No. 34 Fjøsanger.	C
44	Gann, Sandnes, Rogaland Abandoned clay pit at about 10-30 m above sea level on the western side of the Sandnes Harbour. Feyling-Hanssen (1966)	Drilling has revealed a NE-SW trending boundary, steeper than about 60 degrees, between mostly marine clay to the west and sand to the east. The clay is overlain by Weichselian till.	Recent work indicates that the N-S trending escarpment separating 'Høg-Jæren' from 'Låg-Jæren' is partly formed by the northwards moving Skagerrak glacier (Larsen *et al.* 1998). Seismic profiling in the Gannsfjord does not indicate any postglacial faulting (Larsen *et al.* 1998). The steep contact represents most likely an erosional boundary.	D3
45	Gannsfjord lineament, Jæren, Rogaland Opstad and Høgemork at about 200 above sea level to the east of the Gannsfjord lineament. Fuggeli & Riis (1992)	Glaciomarine clays of Weichselian age to the east of the Gannsfjord fault appear to uplifted by recent tectonic movements.	Repeated rapid ice retreat following heavy ice loading can explain the deposition of interstadial marine clays at high altitudes to the east of the Gannsfjorden lineament. Olsen & Grøsfjeld (1999) has reported a frequently fluctuating ice sheet during the interval 18-50 ka BP.	D3
46	Ragnhildnuten, Sandnes, Rogaland Feyling-Hanssen (1966)	Postglacial fault (with dip-slip and sinistral offsets of 30 m each) splitting a 'mountain' in two.	The hill has a 50 m high escarpment along the western side, due to erosion along a fracture zone. The escarpment is part of a NNW-SSE lineament through 2 other ridges, about 3-4 km away (Dehls & Braathen 1998).	E3

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
47	Egersund, Rogaland Bakkelid & Skjøthaug (1985), Bakkelid (1986), Bakkelid (1989)	Part of the town of Egersund was uplifted approximately 4 cm relative to the other part of the town during 34 years.	S. Bakkelid (pers. comm. 1998) has concluded that a 40 mm error in the bench mark B39N9-Eide measured by the surveying company Ing. Dahls Oppmåling in 1951/52 spread out along several levelling lines in the area.	E
48	Egersund-Flekkefjord area, Rogaland Anundsen (1989), Anundsen *et al.* (submitted)	The Egersund Anorthosite-Gabbro Province shows a subsidence of 2-2.5 mm/yr. The zone of maximum subsidence coincides with a zone of maximum gravity anomaly.	A follow-up geodetic study is needed to carry out a better evaluation of this claim.	C
49	Haukeligrend, Vinje, Telemark Anundsen *et al.* (submitted)	Anomalous subsidence from repeated levelling	A careful analysis of the levelling methods is pending.	C
50	Ødegården, Bamle, Telemark Brøgger (1884)	Approximately 0.2 metre sinistral offset of a 0.5 by 0.6 m pothole along a WNW-ESE trending fault. The pothole is estimated to be of Quaternary age.	Probably blasted away, not possible to find today (Løset 1981, Selnes 1983). Represents most likely a stress release phenomenon since it was located in the vicinity of an open pit.	D5

APPENDIX B: SUMMARY OF THE OFFSHORE NEOTECTONIC CLAIMS

Location 101-114 are evaluated within the NEONOR Project and locations 115-119 within the Seabed Project (NORSAR 1999). We have applied the same grading as in Appendix A. (A) Almost certainly neotectonics, (B) Probably neotectonics, (C) Possibly neotectonics, (D) Probably not neotectonics and (E) Very unlikely to be neotectonics. The most likely cause of the proposed neotectonic deformation have been included as 'TYPE' in the fifth column: (1) Tectonic fault; (2) Gravity-induced faults, (3) Erosional phenomena (4) Overburden draping of bedrock features, (5) Stress release features.

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE/ TYPE
101	Barents Sea, 50 km east of Edgeøya Fanavoll & Dahle (1990)	A fault seems to offset the seafloor on the seismic line BFB-76-35.	The Quaternary is very thin in the northern Barents Sea area and the hard sea floor is causing strong multiples. The poor quality of the seismic data reduces the reliability of the claim. Neither have any indications of postglacial faulting been observed on the neighbouring seismic lines NPD 7730-80B and NPD-2600-80B.	D3
102	Bjørnøyrenna, Barents Sea margin Fiedler (1992), Muir Wood (1995)	Offset of shallow reflectors along the southern Barents Sea margin has been interpreted as effects from sea floor instability and postglacial strike-slip faulting by Fiedler (1992) and Muir Wood (1995), respectively.	There is no offset of the reflectors below the scarp at the sea floor. We do therefore favour a gravity-induced mechanism.	D2
103	Malangsdjupet, offshore Malangen, Troms Fanavoll & Dahle (1990), Fanavoll & Dehls (1998)	An offset of Quaternary reflectors can be observed on IKU shallow sparker line IKU-C84-306. A step at the sea floor marks the shallow termination of the fault.	Multi-beam echo-sounding data acquired in the NEONOR Project reveal a limited extent of the fault (0.5 km) which reduces the grade of this claim (Fanavoll & Dehls 1998). It is, however, a possibility that the short fault scarp is a secondary structure to strike-slip movements along the NW-SE trending Bothnian-Senja Fault Complex	D3

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE/ TYPE
104	NW of the island of Røst, Nordland Rokoengen & Sættem (1983), Fanavoll & Dehls (1998)	The sea floor relief shows several abrupt changes in level and slope that were interpreted in terms of potential postglacial faults. The main escarpment is located 1.2 km beyond the steep boundary between the crystalline basement and deformed sedimentary sequences.	Multi-beam echo-sounding data acquired in the NEONOR Project indicate that the scarps are effects of erosion rather than tectonic processes (Fanavoll & Dehls, 1998).	E3
105	Continental slope, Røst Basin, Nordland Mokhtari (1991), Mokhtari & Pegrum (1992)	Evidence of recent downslope gliding along the continental slope.	This fault is most likely not caused by a deep-seated tectonic process but rather by gravity gliding.	D2
106	Fulla Ridge, Vøring Basin Muir Wood (1995)	Muir Wood (1995) interpreted seismic data by Granberg (1992) in terms of a mid-late Quaternary reverse fault, activating Miocene faults along the Fulla Ridge.	The Pliocene reflectors beneath the potential offset Quaternary reflector do not seem to be offset, contradicting the hypothesis of a young faulting	D
107	Southern end of the Klakk Fault Complex, about 100 km to the west of Hitra island Muir Wood & Forsberg (1988), Muir Wood (1993)	On a NW-SE regional seismic reflection profile (B-4-72) a faulted offset of Tertiary reflectors appears to pass up through the youngest base Quaternary (?) reflector (c.63.7ºN.-6.6ºE). The fault involves downward displacement to the west and the reflector offset is several tens of metres. The underlying fault appeared to be near vertical in dip and probably trends approximately N-S.	Muir Wood (pers. comm., 1999) has studied more modern 2D seismic data from the area and has not been able to identify the fault on other seismic profiles. The area has also been covered with 3D seismic surveys lately.	D

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE/ TYPE
108	Storegga Evans *et al.* (1996), Bryn *et al.* (1998)	Postglacial N-S trending faults and graben, typically 150 m wide reaching the sea bed or coming to within a few metres of it. Throws of up to 4 m have been recorded. The length is more than 5 km.	There are no regional deep-seated faults below the fault scarps. There is an abundance of pock marks in the area. The faulting may be related to gas escape as suggested by Fulop (1998). The faults bear resemblance to the structures observed by Hovland (1983) at the western margin of the Norwegian Channel. They have also been attributed to gas leakage. The features are possibly triggered by earthquakes	C,D
109	Øygarden Fault Rokoengen & Rønningsland (1983), Muir Wood & Forsberg (1988)	The northern half of the N-S trending Øygarden Fault (between 61° and 61°45'N) runs parallel with the coast of western Norway and marks a significant change in the depth of the bedrock surface beneath the thick Quaternary sedimentary cover. The major scarp that has developed along the fault has some of the appearance of a fault-scarp (with vertical offset up to 150m), and although offsets have not been observed in the overlying sedimentary section itself, sediments onlap the scarp, with some suggestion of dips steeping towards the fault (Muir Wood 1993).	The fault bounds crystalline basement in the east from relatively soft Cretaceous sediments in the west. A combined interpretation of multi-beam echo-sounding data and 2D seismic lines shows that the Quaternary sediments are draped along the fault scarp (Rise *et al.* 1999).	D3

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE/ TYPE
110	Western slope of the Norwegian Trench, south of Kvitebjørn, offshore Øygarden Hovland (1983)	A N-S trending normal fault-zone with 1-2 m offset. The fault-zone has a length of minimum 2 km and consists of 2-4 parallel faults often forming a subsided internal zone. The eastern zone is generally down-faulted. The faults are detected with a deep-towed boomer during the Statpipe route survey in 1981. The fault cuts soft, silty, cohesive clay.	The fault is occurring in an area with abundant pockmarks and Hovland (1983) has suggested a genetic link between the two phenomena. A multibeam echo-sounding survey carried out by the Norwegian Mapping Authority in 1999 support the conclusion by Hovland (1983). Release of gas does not, however, explain the 1-2 m offset of the seafloor. A tectonic cause can therefore not be ruled out.	C
111	Holene, west of northern Karmøy, close to the British sector Hovland (1984)	Several faults are cutting the seafloor within a more than 2 km long and 10 m deep N-S trending depression (Holene). The faults are trending NE-SW, NNW-SSE and N-S and have approximately a length of 100 m.	The faults are most likely of superficial character, because of the limited scarp length. Hovland (1984) has related the faulting to gas seepage.	D
112	Karmsundet, 20 km northwest of Stavanger, Rogaland Bøe *et al.* (1992)	The Karmsundet Basin is a small half-graben bounded to the east by the major Kvitsøy Fault and filled with sediments of assumed Jurassic age. Overlying Quaternary sediments show plentiful evidence of instability including slump scars, rotated sedimentary units and superficial fault structures.	The majority of these superficial features do not correspond with underlying faults in till and bedrock and hence cannot be considered as direct evidence of outcropping fault-rupture (Muir Wood 1993). A land slide to the southwest of Vestre Bokn is most likely triggered by an earthquake since the slope gradient is very low and there is no indication of extraordinary strong bottom currents in this area (Rise & Bøe 1998).	D
113	East of Troll	Possible fault cutting the Quaternary section, continuing into a basement fault active in the Tertiary (Neonor 1998)	A bathymetry survey revealed that the apparent fault was caused by pull-up below a pockmark	E

NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE/ TYPE
114	Troll area	WNW-ESE Lineaments in the Early Pleistocene, interpreted in 3D survey SG9202, BPN 9401, coinciding with Mesozoic faults reactivated in the Tertiary (Riis 1998)	The lineaments are close to, or below, the seismic level of resolution. Abundant faulting below, related to fluid/gas escape.	C
115	Vøring Escarpment (Seabed Project; NORSAR 1999)	Minor scarps at the seafloor above the Vøring Escarpment (VE). Larger offset at sea floor than underlying reflector's implies sliding on glide planes.	The shallow faulting/sliding is most likely related to differential compaction/ subsidence across VE	D2
116	Nyk High (Seabed Project; NORSAR 1999)	Shallow faults, clearly affecting Pleistocene sediments, are present at NW flank of the high. Slide escarpments at seabed (max 40 m) can not be linked to underlying faults. Larger relief at sea floor than underlying intra-Pleistocene reflector.	Faulting/sliding along the NW flank of Nyk High probably related to differential compaction/ subsidence. Difficult to constrain timing because of limited seismic resolution.	D2
117	Gjallar Ridge (Seabed Project; NORSAR 1999)	Well-layered Neogene sediments are cut by numerous faults in the Gjallar Ridge and adjacent regions. Some faults can be traced up to (or close to) the sea floor.	Most of this faulting appear to be associated with intra-formational fracturing rather than a response to regional tectonism.	D
118	Naglfar Dome (Seabed Project; NORSAR 1999)	At N flank of Naglfar Dome, an offset of ~19 m on the seabed may be related to underlying deep-seated faulting.	Difficult to constrain timing because of limited seismic resolution. Shale diaprism associated with the fault.	D
119	Helland-Hansen Arch (Seabed Project; NORSAR 1999)	Shallow faulting on line MB-1-91 is attributed to deep-seated tectonic movements.	Difficult to constrain timing because of limited seismic resolution.	