Neotectonic deformation in Norway and its implications: a review

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Reports of neotectonic deformation in Norway, including Svalbard and offshore areas, have been graded into five classes depending on the quality of documentation and their most likely origin. A large number of the mainland locations have been visited and careful field investigations carried out, while offshore localities have been analysed by 2D and 3D seismic and multibeam data. After a critical evaluation of the 79 neotectonic claims in Norway as a whole, we have classified three of these as 'A - Almost certainly neotectonics' and another seven as 'B - Probably neotectonics.' The majority of the reports are attributed to effects other than tectonic. The present grade A claims include two postglacial faults in northern Norway and one postglacial fault in southern Norway. The NE-SW oriented, reverse Stuoragurra Fault in western Finnmark constitutes the Norwegian part of the postglacial Lapland Fault Province. The NW-SE striking Nordmannvikdalen fault in northern Troms is a normal fault trending perpendicular to the extensive system of NE-SW trending reverse faults in northern Fennoscandia. The grade B claims include supposed secondary effects of large-magnitude earthquakes such as abundant liquefaction structures, rock-slope failures and other collapse structures in northern and western Norway.

There are indications that three separate, large-magnitude earthquakes affected the Finnmark-Troms region during the period 11,000-9,000 BP. Palaeoseismic events have also been postulated in western Norway. There is, for example, evidence of three regional slide events in western Norway, including one episode shortly after the deglaciation and two events at c. 8,000 and c. 2,000 calendar years BP. The 8,000 y. BP event has been interpreted as the effect of a tsunami generated by the Storegga slide while another 8,000 y. BP liquefaction event, in Nord-Trøndelag, may also be related to an earthquake.

The offshore investigations have not confirmed any firm evidence of neotectonic deformation events, although several distortions in Quaternary reflectors have been mapped in the northern North Sea area, where subtle features may represent faults associated with gas leakage.

A major seismic pulse most likely accompanied each of the deglaciations following the multiple glaciation cycles in mainland Fennoscandia and Scotland during the last 600,000 years. The interaction of the contraction and dilation of fissures associated with these glaciation cycles may have facilitated fluid and gas leakage through the reservoir seals and gas chimneys, ultimately forming pockmarks on the sea floor. This mechanism could also have contributed to the concentration and pumping of hydrocarbons from their source rocks to reservoir formations. A possible example of this mechanism is shown by a recent earthquake along the postglacial Stuoragurra Fault, which has significantly influenced the groundwater circulation. Our understanding of past and future tectonic activity is especially important for the evaluation of hazard risk related to rock-slope stability.

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Introduction

Observations of features related to neotectonic activity and recent crustal movements have been reported in Norway as neotectonic 'claims' since the 1880s, and have been increasing steadily in number. With the introduction of the concept of plate tectonics in the 1960s, neotectonic research became focused on the interplate processes, and for a time intraplate tectonics attracted less interest. Following reports of neotectonic features in Sweden (Lundqvist & Lagerbäck 1976), intraplate tectonics again attracted the attention of geoscientists in Scandinavia. Kujansuu (1964) had described similar structures in Finland more than a decade earlier, but this account was published in Finnish and not widely known before publication of the Swedish studies.

The number of reports of neotectonic activity during each decade after the first account in 1888 had varied from 0 to 3 (with the exception of 8 during the 1920s) until the number surged in the 1980s with 25 reports followed by 23 in the 1990s (not including the NEONOR and Seabed Reports). The number of neotectonic reports in Norway has now reached a total of 79 (Fig. 1, Appendices A & B). Almost 80% of the registered reports were published after 1980. Our understanding of the claims, however, has not kept pace with the

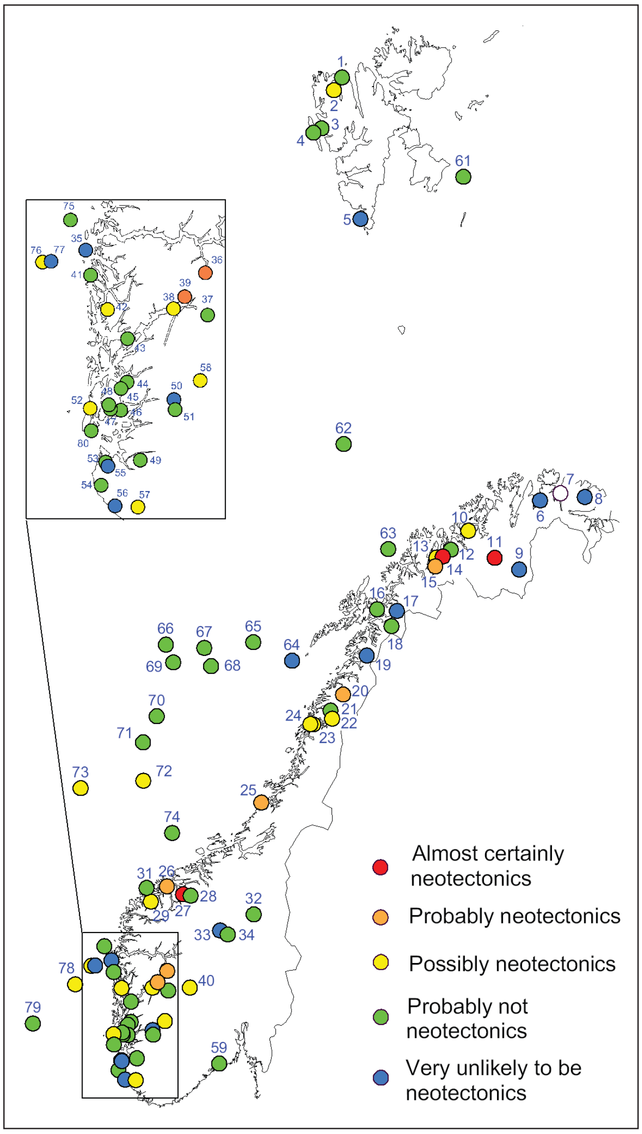

Fig. 1. Locations of the 59 onshore and 20 offshore neotectonic claims that have been compiled and classified. Five offshore reports in the Norwegian Sea have been evaluated within the Seabed Project. The colours refer to the quality grading, and the numbers on the map refer to the location numbers in Appendices A & B.

increasing number. The documentation of the large-scale postglacial faulting (faults up to 150 km in length and with 30 m offset; Figs. 2, 3 & 4) in northern Fennoscandia (Lagerbäck 1979; Olesen et al. 1992a; Kuivamäki et al. 1998) and conclusions drawn from evaluation of numerous claims obviously justify a re-evaluation of the extent and importance of Quaternary and recent deformation in Norway.

The Geological Survey of Norway, NORSAR, the Norwegian Petroleum Directorate and the Norwegian Mapping Authority initiated a 3-year research project 'Neotectonics in Norway, NEONOR' in 1997. The aim of this project was to investigate neotectonic phenomena through a multidisciplinary approach both onshore and offshore (Olesen et al. 2000a, Dehls et al. 2000a). Significant effort was put into the quality analysis of all the neotectonic reports to establish a scientific foundation for neotectonic research in Norway. Such understanding is desirable from a scientific point of view, but also has practical implications, including various aspects of geological risk assessment and the distribution and flow of fluids in rocks. In this paper we present a summary of this analysis.

Methods

We have applied structural bedrock mapping, study of aerial photographs, trenching, drilling, ^{14}C dating, geodetic levelling and ground penetrating radar profiling to study potential postglacial faulting onshore Norway. Seismic surveying (including available 3D data) and multibeam echo-sounding techniques were used to examine possible offshore postglacial faulting. The shallow parts of 8 seismic 3D cubes (located in seismically active areas) have been studied to try to locate potential Quaternary deformation. Results from rock-avalanche hazard projects in Troms and western Norway (Geological Survey of Norway [NGU]) and the Seabed Project (NORSAR/NGI/UiO/SINTEF) have been included. The present report gives a synthesis of current, combined knowledge of neotectonics in Norway. Our aim in neotectonic studies follows that of the International Association for Quaternary Research (INQUA), in accordance with the definition "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)." In the present account, we have concentrated on studying **postglacial faulting**, i.e., tectonically induced movements along distinct fracture surfaces or shear planes that have occurred since the end of the last glaciation. Criteria for the identification of postglacial faulting have been presented earlier by Fenton (1991, 1994) and Muir Wood (1993):

1) Offset of an originally continuous surface or sedimentary sequence 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-induced 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 and differential compaction or deposition over a pre-existing

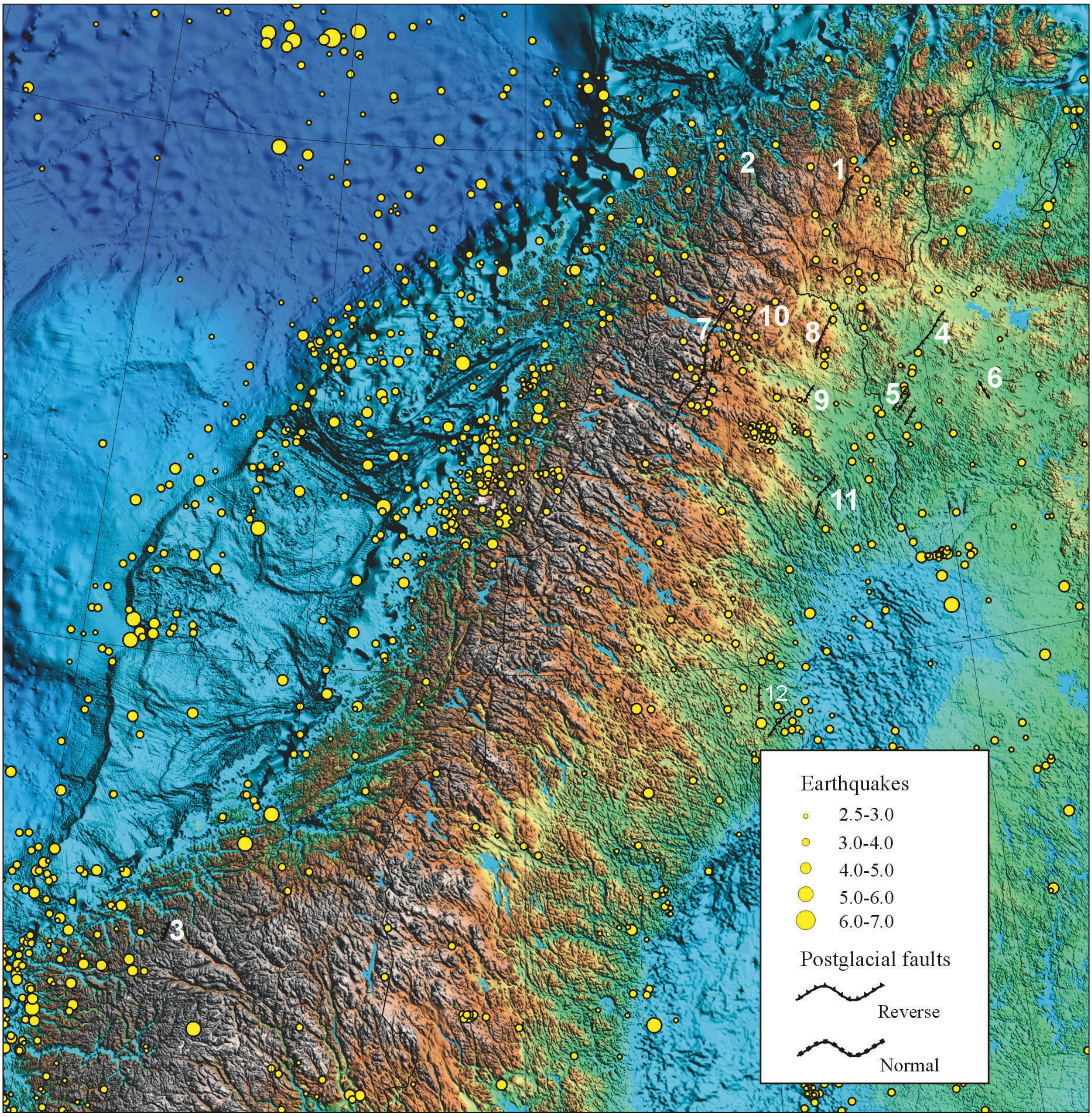

Fig. 2. Earthquakes during the period 1965-1998 and postglacial faults in northern and central Fennoscandia (modified from Dehls et al. 2000b). The size of the earthquake symbols increases with rising magnitude. The faults occur in areas with increased seismicity. The numbers adjacent to the faults refer to the numbers in Table 1.

erosional scarp being the cause of an apparent offset in overburden.

We have, in addition to the evaluation of postglacial faulting, also evaluated reported secondary effects of pre-historic, large-magnitude earthquakes such as liquefaction and semi-liquefaction structures in Holocene deposits, large-scale, gravity-induced faulting and rock avalanches.

Existing neotectonic reports were graded according to their reliability into the following classes (Muir Wood 1993; Fenton 1994): (A) almost certainly neotectonics, (B) probably neotectonics, (C) possibly neotectonics, (D) probably not neotectonics and (E) very unlikely to be neotectonics. In this context, slight glacial modification of scarps suggesting a late glacial or interglacial age would fall outside our definition of neotectonic activity. The most likely nature of the proposed neotectonic deformation was identified whenever possible and placed in the following categories; (1) tectonic faults, (2) gravity-induced faults, (3) erosional phenomena, (4) overburden draping of bedrock features, (5) diffe-

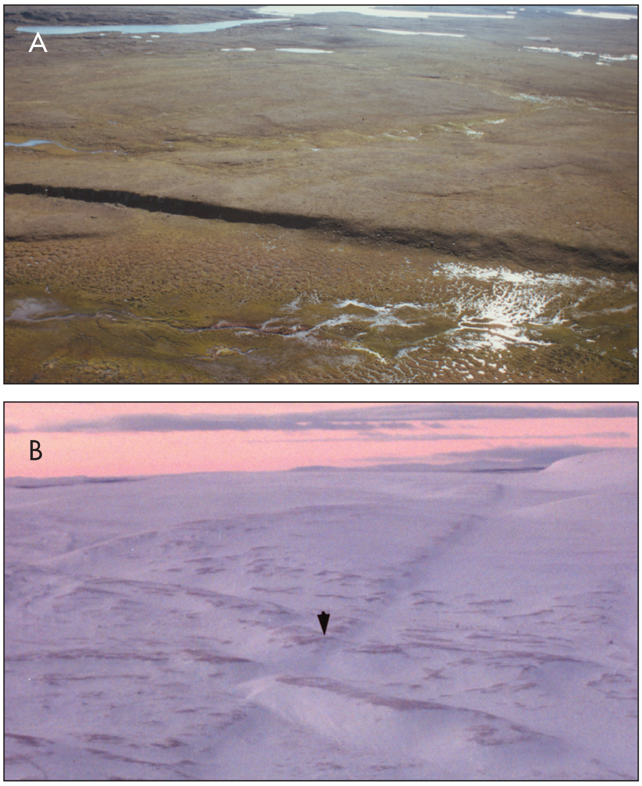

Fig. 3. Oblique aerial photographs of the Stuoragurra Fault (Location 11 in Fig. 1 and fault 1 in Fig. 2) as it crosses Finnmarksvidda at Stuoragurra, 12 km NNE of Masi. a) Photograph from August 1989; looking southeast (Olesen et al. 1992a). Large amounts of groundwater poured out of the escarpment to the right sometime between the earthquake on 21 January, 1996 and August 1996. b) Photograph from January 1996, looking south. The fault is cutting through an esker (UTM 611400-7717300). The intersection between the fault scarp and the esker is shown by the arrow. The fault was consequently formed after the deglaciation at approximately 9300 BP.

rential compaction, (6) shallow, superficial stress-release features, (7) inconsistent shoreline correlation, (8) unstable benchmarks and levelling errors, (9) Insufficient data resolution.

Results

Indications of neotectonics in Norway were first summarised by Muir Wood (1993, 1995) who initiated the quality assessment of reported neotectonics in Norway and documented 13 claims (6 on mainland Norway and 7 offshore). We have added 53 onshore and 13 offshore reported claims to form the lists presented in Appendices A & B. Twenty of the claims are situated in the offshore area and 59 are located on mainland Norway (Fig. 1).

Onshore

A total of 22 locations have been visited in the field for closer geological and geophysical examination (Dehls & Braathen 1998, Olesen & Dehls 1998 and Olesen et al. 2000b). Longva et al. (1998) and Rise et al. (1999) also carried out an evaluation of neotectonic claims in Tjeldsundet and Hjeltefjord-Gannsfjord. In addition, four localities on Svalbard have been studied using aerial photographs.

Critical evaluation of 59 neotectonic claims in mainland Norway and Svalbard resulted in three claims of grade A and seven claims of grade B. The grade A claims include the postglacial faults in Masi (Figs. 3 & 4) and Kåfjord (Olesen 1988; Tolgensbakk & Sollid 1988, Dehls et al. 2000a) in northern Norway, and the

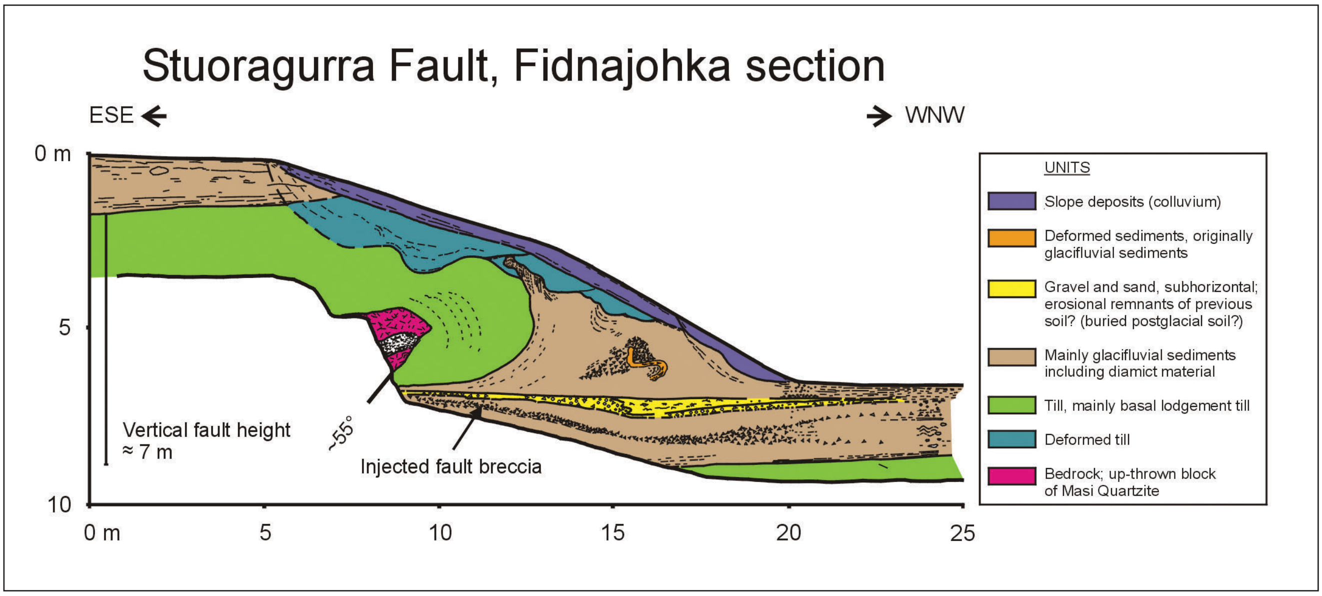

Fig. 4. Folded Quaternary sequence consisting of basal till and glaciofluvial sediments above and in front of the up-thrown hangingwall block of the Stuoragurra Fault. Note the fault breccia that has been injected into the glaciofluvial sediments most likely as a mixture of rock fragments and high-pressure groundwater (Modified from Dehls et al. 2000a). The excavation did not reach bedrock of the footwall.

Fig. 5. Corrugations in fine-grained sand from Fagervika, 6 km southwest of Hugla (Location 24 in Fig. 1 and in Appendix A) and 20 km to the northeast of Sandnessjøen (Olesen et al. 1994). The sand was deposited after the deglaciation and may be a liquefaction phenomenon associated with a large-magnitude earthquake. Similar structures occur close to the Lansjärv postglacial fault in northern Sweden (Lagerbäck 1990).

Berill fault (Anda et al. 2002) in southern Norway. The grade B claims include areas with secondary effects, probably triggered by large-magnitude earthquakes, such as liquefaction and semi-liquefaction structures in the Flatanger (Nord-Trøndelag) and Rana (Nordland) areas (Fig. 5), gravitational spreading and faulting features (sackungen) on Kvasshaugen (Fig. 6) in Beiarn (Nordland) and Øtrefjellet in Haram (Møre & Romsdal). A series of gravitational fault systems and large rock-slope failures in zones from Odda to Aurland (Hordaland and Sogn & Fjordane)(Fig. 7) and in northern Troms have also been classified as grade B. The gravitational spreading, gravitational faults and large-scale rock avalanches are obviously caused by gravity collapse, but their spatial occurrence and the relatively gentle slopes associated with some of the features, indicate that another mechanism assisted in the triggering mechanisms (Blikra et al. 2000b, 2000, in press; Anda et al. 2002; Bøe et al. this volume; Braathen et al. this volume). The most likely cause is strong ground shaking from large-magnitude earthquakes. Two examples of collapse structures (in Haram and Ulvik) occur in gently sloping terrain and were probably not induced by gravity alone.

A majority of the neotectonic claims can be attributed to causes other than tectonic. Gravity-induced sliding (Fig. 8) and glacial erosion along pre-existing faults and fractures (Fig. 9) are the dominant agents responsible for forming the geomorphological features that were earlier claimed to be of neotectonic origin. Ice-plucking features may, however, be indirectly related to neotectonics. Bell & Eisbacher (1995) have shown that moving glaciers in the Canadian Cordillera tend to pluck bedrock along extensional fractures parallel to the direction of maximum horizontal stress. An inland glacier would, in a similar way, cause a higher degree of

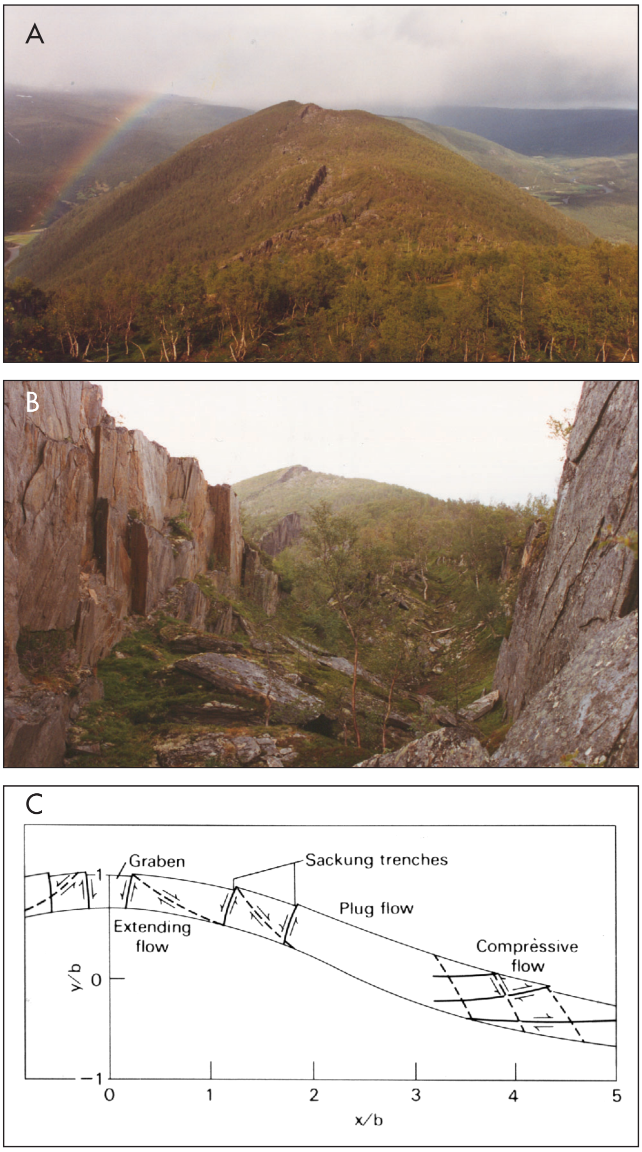

Fig. 6. Gravity-induced faults at the crest of Kvasshaugen in Beiarn (Location 20 in Fig. 1 and in Appendix A) have been interpreted as neotectonic faults (Grønlie 1939; Muir Wood 1993). Graben structures are up to 10 metres deep, and 20 metres wide. A) Overview photograph from Monsfjellet looking north with Beiardalen to the east and Gråtådalen to the west. The farthermost part of the ridge is called the Gråtahaugen while the continuation to the south on the picture is termed Kvasshaugen. B) picture (looking north) of open clefts on Kvasshaugen with Gråtahaugen in the background. Note the scarp edges of the escarpments. C) Sketch illustrating formation of sackung features (Savage & Varnes 1987). The potential flow regions and rupture surfaces on a symmetric gravitational ridge are indicated. Inactive rupture surfaces are dashed.

bedrock plucking by basal glacier shear, along favourably oriented fractures in areas with highly anisotropic rock stress.

Features that have proved conducive for determining the local and regional, contemporary stress fields are reverse-slip offsets and axial fractures in boreholes, in road-cuts and quarry walls in different parts of Finn-

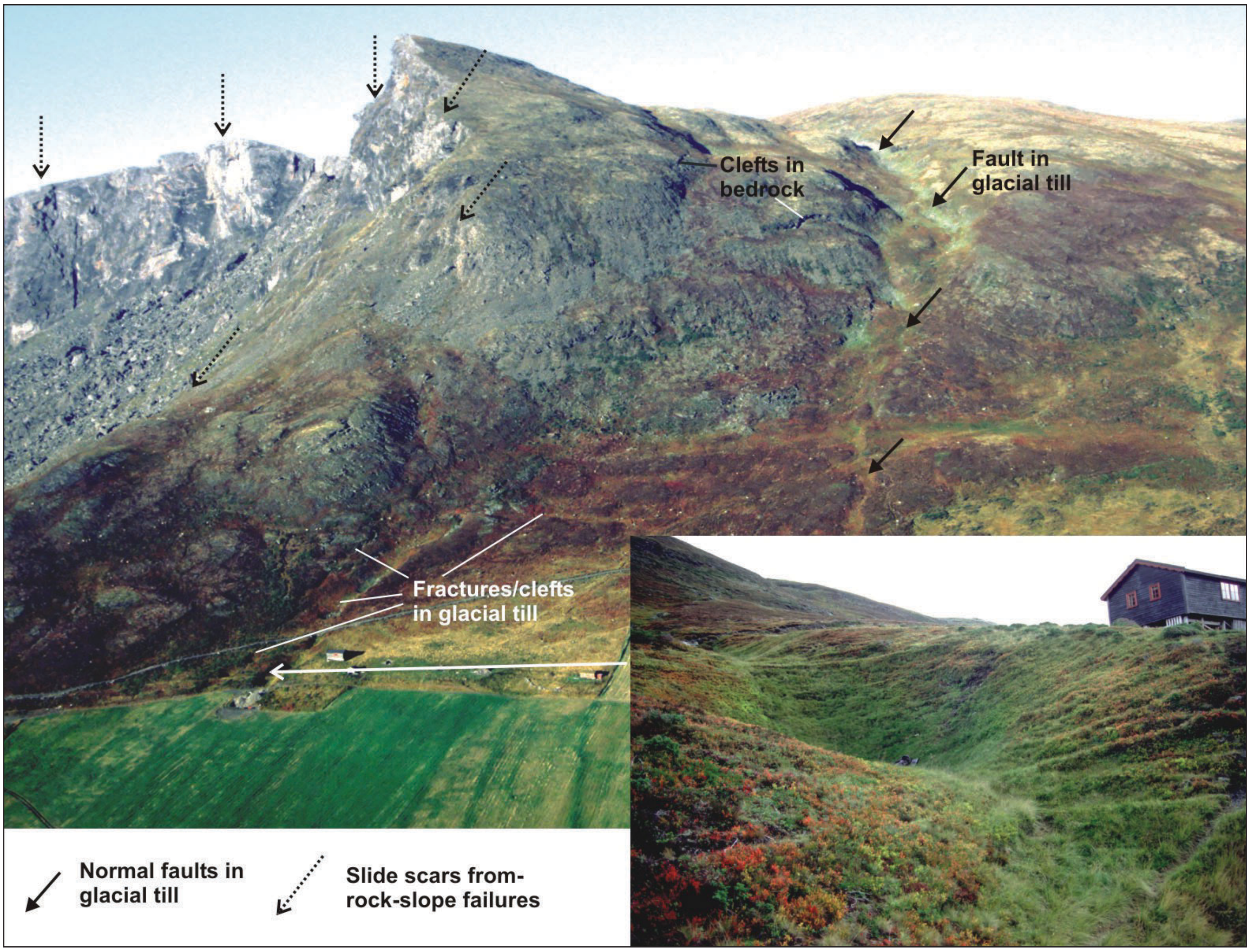

Fig. 7. Gravitational faults and other fractures in Gudmedalen (Location 36 in Fig. 1 and in Appendix A), looking towards the mountain Ramnanosi in Aurland, east of Flåmsdalen. The prominent normal fault to the east (right-hand side) can be traced for 4 km and displays an offset of 1-2 m. The fractures to the left show an internal graben feature. The faults and fractures are interpreted to be gravity-controlled, but it cannot be excluded that the main fault may be related to deeper tectonic structures. The detail photograph shows a sink hole development along a fracture zone. Note the prominent slide scars to the west which provide evidence of major rock-slope failures.

mark (Roberts 1991, 2000). Displacement vectors, in these particular cases, are towards ESE to SE. These minor thrusts, with offsets of a few centimetres, are complemented by extensional axial fractures in drillholes in nearby, differently oriented road-cuts, which support a c. ESE-WNW orientation of S_{Hmax} at or close to the bedrock surface in central Finnmark. Although falling under the category of stress-release phenomena, initiated at the time of rock blasting, these structural features are, nevertheless, of potential value as stress orientation indicators. In Finnmark at least, the broad consistency of orientation of reverse-slip offset vectors and axial fractures is believed to reflect the regional stress pattern and is not simply a manifestation of the local geology or topography.

There have been earlier reports (from geodetic measurements) of contemporary movements along faults in Yrkje and Ølen in southwestern Norway (Anundsen 1989) and along the Stuoragurra Fault in Finnmark (Olesen et al. 1992a). Repeated levelling within the NEONOR project failed, however, to provide any support for aseismic movements along any of these faults (Sylvester 1999; Bockmann & Grimstveit 2000). It is therefore suggested that most of the local anomalies in the uplift pattern are related to inaccuracies in the levelling data. The intermediate component of the regional uplift pattern (anomaly areas with 100-500 km wavelength and 0.5-1 mm/year) may, however, be related to tectonic processes other than glacioisostasy (see Fig. 14B & D and discussion below).

Offshore

The NEONOR Project evaluated 14 reports on possible offshore neotectonic events. In addition, the Seabed Project assessed five neotectonic claims in the Møre and Vøring Basins (NORSAR 1999). The offshore study areas included the shelf and slope regions, but not the areas overlying the oceanic crust. No postglacial faults

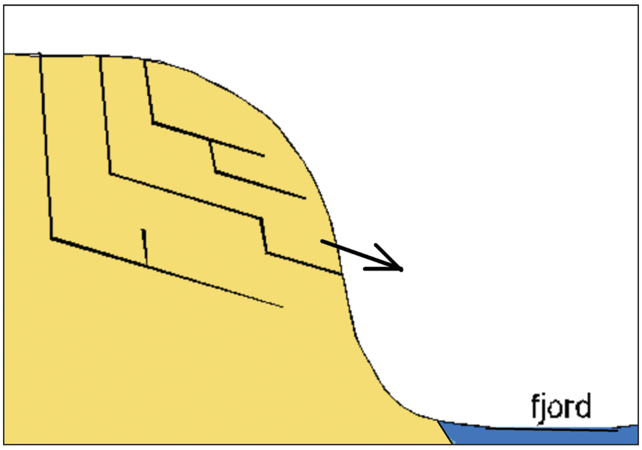

Fig. 8. Schematic diagram showing examples of gravity-induced faults along fjords in western and northern Norway. Large blocks slide along schistosity surfaces towards the fjord.

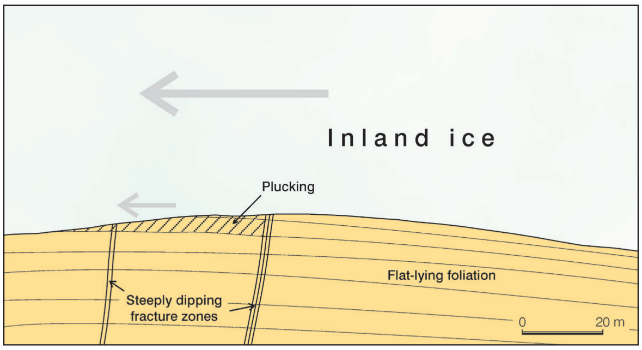

Fig. 9. Schematic diagram illustrating how scarps are formed by plucking from the moving inland ice. Blocks are removed along steeply dipping fracture zones and sub-horizontal foliation.

with throws larger than a few metres have been observed on the Norwegian continental shelf. The evaluation of 19 offshore reports resulted in a total of 3, 13 and 2 of grade C, D and E, respectively. One location was not graded due to lack of data.

In the basal western slope of the Norwegian Channel, Hovland (1983) described faulting of a soft, silty clay on the sea floor. This was detected on boomer profiles, the faults terminating at shallow depths, and not connected to deeper structures. Hovland (1983) related these faults to areas of high gas saturation in the shallow sediments, and associated the structures with release of this gas. A multibeam echo-sounding survey carried out in 1999 confirmed the findings of Hovland. The sea-floor topography in this area is characterised by N-S-trending faults and fissures, and large, elongate pockmarks (Fig. 10). Fault throws are up to 1-2 m. An azimuth attribute map of the sea floor in the Kvitebjørn area, slightly to the north of the bathymetric survey, indicates a similar set of structures (Fig. 11). In this area, there are also indications of high gas saturation at shallow depth. The shape and orientation of the faults

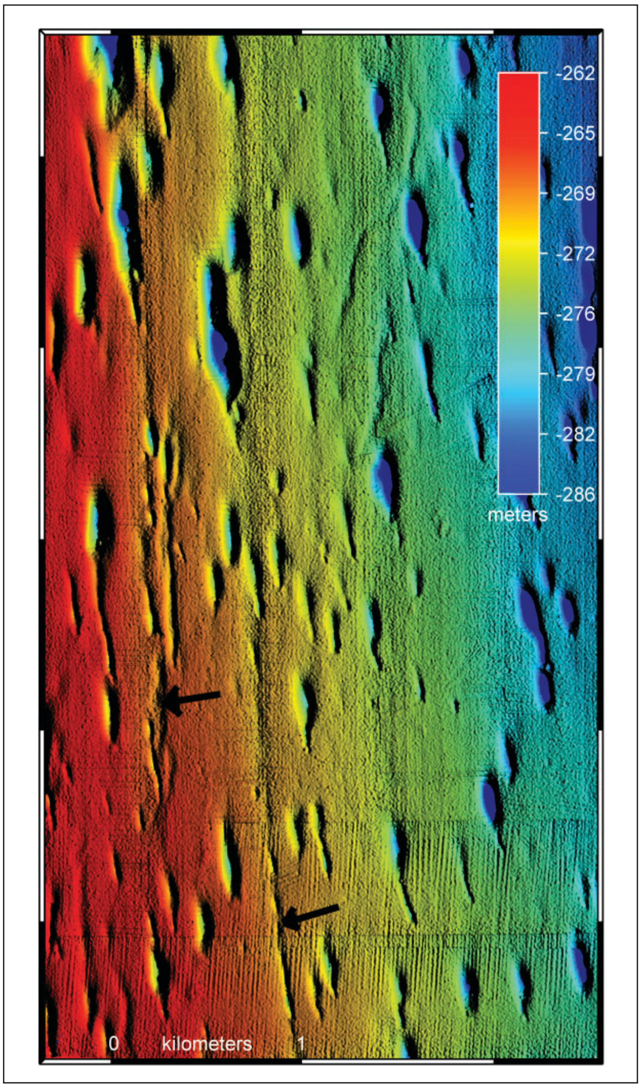

Fig. 10. Bathymetry, western margin of the Norwegian Channel south of Kvitebjørn. Abundant pockmarks (up to 500 m long and 10 m deep) occur in the area (Location 78 in Fig. 1 and in Appendix B). The arrows show postglacial faults, which seem to be related to the formation of the elongated pockmarks. The fault offset is approximately 1 m. The elongate form of the many pockmarks is most likely a result of the influence of strong currents in the shallow sea immediately after the deglaciation of the area. The multibeam echo-sounding data have been acquired by the Norwegian Mapping Authority. The faults were originally reported by Hovland (1983).

would suggest that they cannot have been formed by gravity sliding or by glacial deformation. This supports Hovland's suggestion that the faults can be attributed to gas release. Similar faults and pockmarks also exist in the Storegga area on the Mid-Norwegian shelf (Fulop 1998). It is common to find pockmarks in associations with active tectonic faults (Hovland & Judd 1988). This suggests that gas release is related to reactivation of old fault zones. However, in the present case it has not been possible to relate these faults and fissures to any deeper structures. Hovland & Judd (1988) discussed the occurrence and distribution of the numerous pockmarks in relation to the present-day seismicity in the North Sea,

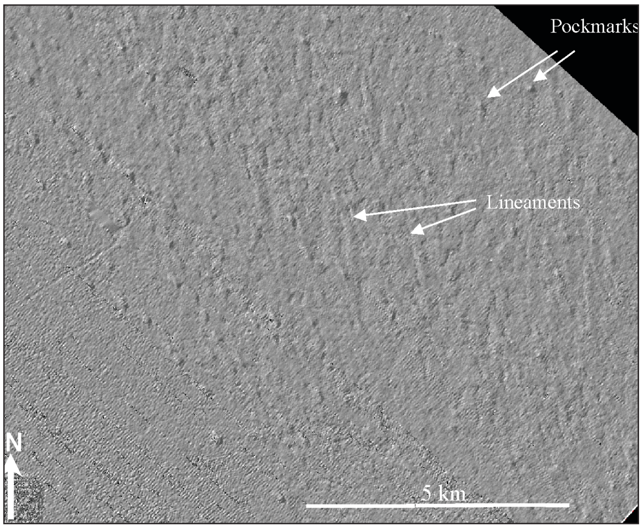

Fig. 11. Azimuth map of sea-floor reflector, Kvitebjørn area (Location 78 in Fig. 1 and in Appendix B). The direction of illumination is parallel to the shot direction of the main survey (135°). Merged 3D surveys show up as areas with a strong lineation parallel to the shooting direction, because of minor static shifts between the lines. Note the pipelines in the western part of the area. 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) (see Fig. 10).

and concluded that the seismicity was too low to trigger a flow of fluids and gas from the sediments. Nevertheless, one could argue that deglaciation-induced seismic pulses could have provided the necessary energy to release large quantities of gas from the North Sea sedimentary basins immediately after the last retreat of the inland ice.

Another possible neotectonic feature that has been identified on the Mid-Norwegian continental shelf is the probable reactivation of Miocene dome structures in the deeper parts of the Norwegian Sea. Contractional structures (large anticlines and synclines, reverse faults and inverted depocentres) 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 may be secondary effects of neotectonic activity in some areas. The shelf edge of the Norwegian and Barents Seas is presently a region of relatively high seismicity. Large-scale slumping has also taken place along the shelf edge in the Holocene; and buried Pleistocene and older slides are common. Some slides were formed when the shelf edge was loaded by glaciers and glacial deposits, while others, like the main Storegga slide, are definitely postglacial. 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, or simply by the build-up of sediment wedges to critical angles, are alternative explanations (e.g., Bryn et al. 2002).

Hydrogeological response to earthquakes

Several semi-permanent, small groundwater springs occur along the postglacial Stuoragurra Fault, similar to the springs along the postglacial faults in northern Sweden (Lagerbäck 1979). Large amounts of water poured out of the Stuoragurra fault escarpment some time between the 21 January 1996 earthquake (magnitude 3.8) and August of that year. The vegetation along and below the escarpment was locally washed away by the outpouring water. At this location, all soil was removed and only gravel remained (Fig. 12). During a field visit to this location two days after the earthquake water had not yet begun to gush out along the fault.

The water level in the Iesjåkka river, which drains the area where the earthquake occurred, was reduced by 15-20% during the first weeks after the earthquake, and it remained low during the following 3-4 months (Fig. 13). The climate of Finnmarksvidda is typical for an inland region with low precipitation (200-300 mm/year), cold winters and warm summers. The reduced water level in late January is therefore not related to precipitation since the surface temperature was far below zero and groundwater seepage charges the river during the winter months. This observed fluctuation in water level is of regional character, and cannot be directly related to water flowing out of the fault scarp some time after the earthquake. Variable ice conditions can locally change the water flow within the Iesjåkka river during wintertime but it is unreasonable to expect that abnormal conditions should persist for several months. Reduced water flow after large, reverse-fault earthquakes has also been reported from Alaska and Japan by Muir Wood & King (1993), who also pointed out that normal-fault earthquakes commonly cause increased groundwater outflow.

The fault plane mechanism from the 21 January 1996 earthquake shows it to be a reverse-fault earthquake (Bungum & Lindholm 1997). This pumping mechanism must occur regionally in the bedrock surrounding the fault zone. Drilling through the Stuoragurra Fault revealed a groundwater yield among the highest ever recorded in Norway. The yield was estimated to greatly exceed 17 m^3/hour, which is the capacity of the most powerful pump available for the 5.5" diameter well (Klemetsrud & Hilmo 1999). The average yield for a borehole in crystalline bedrock in Norway is about 0.4 m^3/hour. Groundwater was encountered at a depth of 35 m in the drillhole, in the damage zone, i.e., 2 m above the fault core. [The fault zone nomenclature is adapted from Caine et al. (1996) and Braathen & Gabrielsen (2000).] After penetrating the fault gouge

Fig. 12. Large amounts of water poured out of the Stuoragurra fault escarpment (Location 11 in Fig. 1 and in Appendix A) after the January 1996 earthquake (magnitude 3.8). Photograph from August 1997 showing washed-out soil (only gravel is left). The photograph is from the central part of an oblique aerial photograph from 1989 shown in Fig. 3A where there are no signs of gravel in the escarpment. A field visit to this location two days after the January 1996 earthquake did not reveal any outpouring of groundwater (see Fig. 3B). This spring must therefore have been active some time later, but before August 1996.

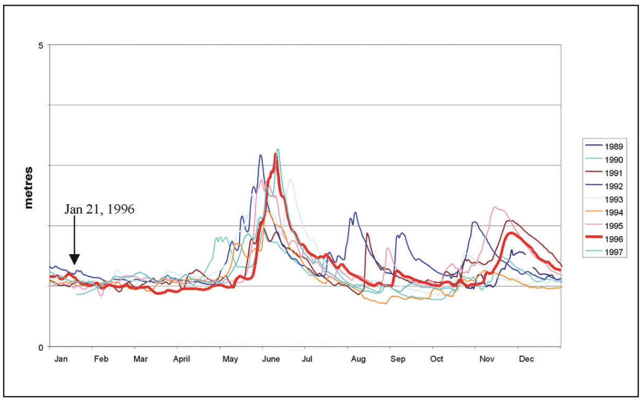

Fig. 13. Measured water level at a gauge in Jergul, 20 km to the west of Karasjok. The data represent raw data and are provided by the Norwegian Water Resources and Energy Administration, NVE (R. Sværd, pers. comm. 1998). The water level was reduced by 15-20 % during the first weeks after the earthquake and stayed low during the months of February, March and April.

and breccia at a depth of 37 m the groundwater was drained off but reappeared in the damage zone at a depth of 40 m. Consequently, the fault gouge membrane generated a perched groundwater table above the main fault zone. We conclude that the fault gouges in the Stuoragurra Fault have sealing properties, even though the > 10 m-wide damage zone is totally fractured and water-bearing at greater depths. A spring occurs 20 metres to the west of the Stuoragurra fault escarpment. Nothing but the flower *Viscaria alpina* grows in a 25 m long and 3-5 m wide zone downstream from the spring, revealing that the groundwater here has a quite high content of heavy metals.

The hydrological effects of the magnitude 5.8 earthquake in 1819 in the outer Ranafjord area have been described as follows: "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 streambanks" (Sommerfeldt 1827). Several pockmarks occur on the sea floor in Lyngen(fjord) in Troms (Hovland & Judd 1988). Most of the locations are situated along the northwestward extension of the Nordmannvikdalen postglacial fault and the nearest pockmark is located only 5-6 km from the exposed fault. It is quite possible that an earthquake associated with the formation of this postglacial fault triggered the release of groundwater or gas. Hovland & Judd (1988) and Plassen & Vorren (2003) described similar pockmarks with linear alignments in the neighbouring Ullsfjord where Blikra & Longva (2000) and Blikra et al. (in press) identified a regional palaeoseismic event. Karpuz et al. (1991) have also reported disturbed groundwater flow and the formation of ponds after the M4.2 earthquake at Etne, Hordaland, in 1989.

There are numerous reports of changed groundwater flow and active pockmarks after earthquakes in the western USA and the Mediterranean region (Clifton et al. 1971, Nardin & Henyey 1978, Field & Jennings 1987, Hovland & Judd 1988, Hasiotis et al. 1996). It is suggested that some of the pockmarks in the North Sea are formed during shallow, postglacial faulting.

Discussion

By indirect means, a number of structural features can be associated with earthquakes. For example, sackungen structures, seen as bi-directional extension of the ridge crest, occur along the mountain Kvasshaugen in Beiarn, Nordland. Up to 20 m-wide and 10 m-deep clefts bounded by normal faults can be followed along an approximately 5 km-long, NNE-SSW-trending zone (Grønlie 1939). The large-scale faults are most likely of postglacial age since there is no sign of glacial sculpturing along the escarpments. Muir Wood (1993) classified the faults as some of the most reliable evidence for neotectonic surface fault rupture in Scandinavia, but he pointed out that they might 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, the Rocky Mountains and in New Zealand (Zischinsky 1969; Savage & Varnes 1987; Varnes et al. 1989; Beck 1968).

Table 1. Summary of properties of the documented postglacial faults in Norway. Similar faults in Finland and Sweden have been added to the table for purposes of comparison. The major faults are NE-SW trending reverse faults and occur within a 400 x 400 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 & Coppersmith (1994).

No.	Fault	Country	Length (km)	Max. scarp height (m)	Height length ratio	Trend	Type	Moment magnitude*	Comment	Reference
1	Stuoragurra	Norway	80	7	0.0001	NE-SW	Reverse	7.3	Three separate sections	Olesen 1988
2	Nordmannvikdalen	Norway	2	1	0.0005	NW-SE	Normal	6.0		Tolgensbakk & Sollid 1988
3	Berill	Norway	2,5 (15?)	3	0.0012 (0.0002)	NNE-SSW	Reverse	6.1 (6.5?)	Field evidence indicates that the fault may be longer (15 km).	Anda et al. 2002
4	Suasselkä	Finland	48	5	0.0001	NE-SW	Reverse	7.0		Kujansuu 1964
5	Pasmajärvi-Venejärvi	Finland	15	12	0.0008	NE-SW	Reverse	6.5	Two separate sections	Kujansuu 1964
6	Vaalajärvi	Finland	6	2	0.0003	NW-SE	??	6.1		Kujansuu 1964
7	Pärve	Sweden	150	13	0.0001	NE-SW	Reverse	7.6		Lundqvist & Lagerbäck 1976
8	Lainio-Suijavaara	Sweden	55	c. 30	0.0005	NE-SW	Reverse	7.1		Lagerbäck 1979
9	Merasjärvi	Sweden	9	18	0.002	NE-SW	Reverse	6.3	Possible extension of the Lainio-Suijavaara Fault	Lagerbäck 1979
10	Pirttimys	Sweden	18	2	0.0001	NE-SW	Reverse	6.5		Lagerbäck 1979
11	Lansjärv	Sweden	50	22	0.0004	NE-SW	Reverse	7.1		Lagerbäck 1979
12	Burträsk-Bastuträsk	Sweden	60	c. 10	0.0002	NE-SW N-S	Reverse	7.1	Two separate faults	Lagerbäck 1979

These characteristic geomorphic forms are produced by gravitational spreading of steep-sided ridges (Varnes et al. 1989). Several different interpretations of the causes responsible for the structures have been proposed. Whether initiation of movements is by strong groundshaking (earthquakes), faulting, long-term creep, or a combination of these factors, has long been a matter of debate (Jibson 1996). Varnes et al. (1989) and McCalpin & Irvine (1995) argued that the movement originates from long-term, gravity-driven creep, but the former authors exclude earthquake shaking as a possible contribution. Other investigations in New Zealand, Slovakia and Russia conclude that earthquake shaking was the most likely mechanism triggering movements (Jahn 1964; Beck 1968; Jibson 1996), partly because the sackungen features occur in seismically active areas. Kvasshaugen is also situated in a seismically active area; hence, earthquake shaking could be a triggering mechanism. Similar structures on Øtrefjellet in Haram, Møre & Romsdal are located marginally to a seismically active area (Anda et al. 2000).

There is conclusive evidence for only one case of postglacial faulting in southern Norway even though the majority of the original neotectonic claims were reported from this area (35 of a total of 57). There are, however, other indirect palaeoseismic indications along a NNE-SSW-trending zone from Odda in Hardanger to

Aurland in Sogn and at the coast of Møre & Romsdal, seen as a series of rock-slope failures, many in relatively gently dipping terrain (Anda et al. 2000; Blikra et al. 2000a,b, 2002, in press; Bøe et al. this volume; Braathen et al. this volume). The former zone is situated within the Mandal-Molde lineament zone of Gabrielsen et al. (2002). Liquefaction and semi-liquefaction structures in sand located close to the intersection of two topographical lineaments in Flatanger, Nord-Trøndelag, are also taken as evidence of a large postglacial earthquake (Olsen & Sveian 1994). There is a general lack of Quaternary overburden in western Norway and, consequently, there are few means to identify and date movements along the abundant bedrock scarps in the area. We cannot, therefore, totally rule out the possibility of more extensive postglacial faulting in this region.

There is no conclusive evidence of postglacial faulting (> 1 m) in southern Finland and southern Sweden (Muir Wood 1993; Kuivamäki et al. 1998). Mörner (1996, 2003) and Tröften & Mörner (1997) have, however, reported seismotectonically disturbed varves and liquefaction structures that were formed immediately after the deglaciation of southern Sweden. Bungum et al. (in press) suggest that large-scale postglacial earthquakes could have occurred on hidden thrusts in the offshore mid-Norway region. Firth & Stewart (2000) describe six postglacial faults in the highlands of northwestern Scotland. The offsets and lengths of these postglacial faults are 1 - 4 m and 1 - 14 km, respectively, which are significantly less than for the northern Fennoscandian faults.

It is considered likely that the postglacial faults, and the varying stress fields and vertical uplifts are caused mainly by an interaction between the postglacial rebound and the ridge-push force from the Knipovich and Mohn ridges in the Norwegian/Greenland Seas (Olesen 1988; Muir Wood 1989b, 2000; Bungum & Lindholm 1997), in addition to sedimentary erosion-loading in the coastal and offshore areas (Byrkjeland et al. 2000; Hicks et al. 2000).

The vertical uplift of Fennoscandia compiled from tide-gauges, precise levelling, and GPS and gravity measurements (Dehls et al. 2000b) is displayed in Fig. 14A. The BIFROST GPS-network (Milne et al. 2001) offers a regional 3D image of the bedrock deformation within the Fennoscandian Shield and provides, for the first time, information on the horizontal movement of the bedrock. Both datasets show that the first-order deformation is dominated by the glacial isostatic adjustment. The maximum vertical uplift of 11.2 ± 0.2 mm/year occurs in the Umeå area (Milne et al. 2001). The horizontal movements (Fig. 14C) are directed outward from this location on all sides with the highest values located to the northwest and east (reaching 2 mm/year). The northwestern area coincides with the Lapland province of postglacial faulting in northern Fennoscandia. Unfortunately, there is only one BIFROST station in Norway (Tromsø) and consequently the horizontal movement of bedrock in southern Norway has not therefore been mapped. Kakkuri (1997) has also reported a maximum present-day horizontal strain in the region of postglacial faults in northern Finland.

Semi-regional deviations in the order of 1-2 mm/year from the regional uplift pattern are reported by Olesen et al. (1995) and Dehls et al. (2002) for the Ranafjord area in northern Norway. This conclusion is deduced from two independent datasets, levelling and permanent scatterer techniques, respectively. Fault-plane solutions by Hicks et al. (2000) show extensional faulting in the same area. Figs. 14B & D show the intermediate and short wavelength components (< 500 km) of the uplift dataset for Fennoscandia. Both the varying direction of the in situ stress (Myrvang 1993) and the intermediate wavelength anomalies of the uplift dataset indicate that the Norwegian bedrock consists of individual blocks that, to some degree, move independently of each other as a response to postglacial rebound, farfield stress and Plio-Pleistocene erosion and deposition.

The Fennoscandian Shield was also affected by a Neogene phase of passive doming (approximately 1,000 metres amplitude) in southern Norway and in the Lofoten-Troms area (Riis 1996). Hence, the present elevation of Scandinavia is largely the 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 was deposited during the last 2.6 m.y.

Fjeldskaar et al. (2000) argued that the long-term Neogene uplift of western Scandinavia is still active and can explain approximately 1 mm/year of the present uplift of the southern and northern Scandinavian mountains. Geodynamic modelling of the present and postglacial uplift data shows that the bulk of the present-day uplift can be explained as a response to glacial unloading (Fjeldskaar et al. 2000). The model for uplift within 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 positive deviations. 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 responsible for the present-day uplift.

Isostatic modelling by Olesen et al. (2002) indicates

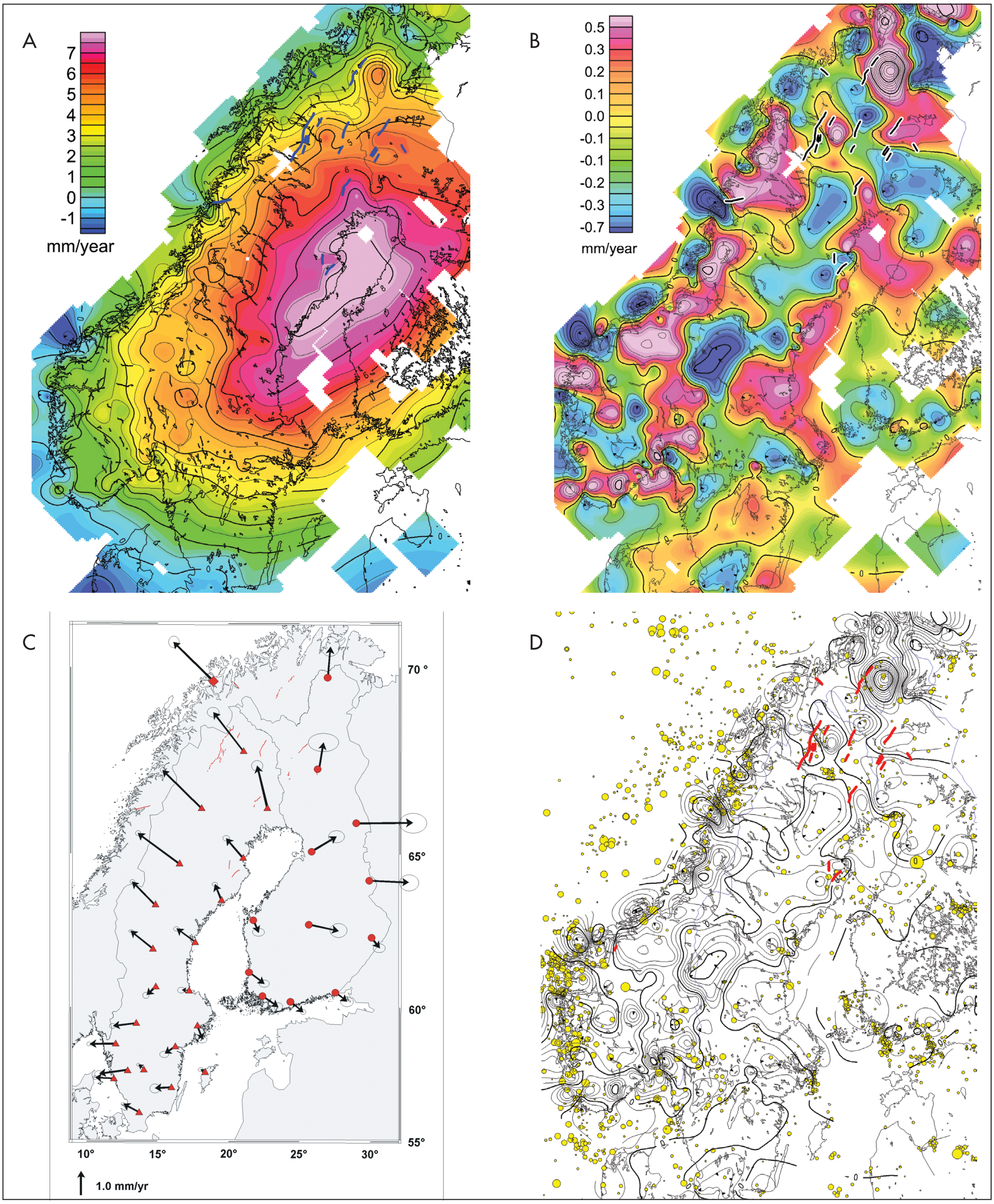

Fig. 14. Present annual velocity of the Fennoscandian bedrock. A) Amount of uplift per year in Fennoscandia (Dehls et al. 2000b). B) High-pass filtered uplift data with a cut-off wavelength of 500 km. Note that some of these anomalies may be related to inaccuracies in the original levelling data. C) Horizontal velocity vectors estimated at each BIFROST GPS site. The scale represented by each of these vectors, as well as with the associated 1σ error ellipses, is given at the base of the plot (Milne et al. 2001). The red lines show the locations of known postglacial faults (Vuorela & Kuivamäki 2002). D) Contours of the high-pass filtered uplift data in Fig. B and earthquake epicentres from Dehls et al. (2000b). Both seismically active zones and the postglacial faults occur to a large extent in areas with deviations from the long-wavelength glacial isostatic rebound.

that the mountains in southern Norway are, to a large extent, supported by low-density rocks within the mantle. The gravity field in the northern Scandinavia mountains, on the other hand, seems to be compensated by low-density masses at a relatively shallow depth in the upper crust. The southern Scandinavian dome may therefore be caused by an asthenospheric upwelling related to the Iceland hotspot. The results are in agreement with the conclusions of Riis (1996) and Lidmar-Bergström (1999) that the southern Norwegian plateau was partly uplifted in the Neogene, while the northern Scandinavian mountains originated mainly as a rift-shoulder in Late Cretaceous to Early Tertiary times. Hendriks & Andriessen (2002) reported that analyses of observed apatite fission-track data along a profile from Lofoten into Sweden fit best with those expected from a retreating scarp model.

There is some evidence (e.g., Mangerud et al. 1981; Sejrup 1987) that the Norwegian coast may have been subject to tectonic uplift of the order of 0.1-0.3 mm/yr during the Quaternary, in addition to postglacial uplift. Recent studies of uplifted Middle and Late Weichselian marine sediments (Olsen & Grøsfjeld 1999) show, however, that the inland ice sheet fluctuated quite frequently during the 18,000-50,000 yr. BP interval. Repeated and 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 (Holtedahl 1984; Sjöberg 1988).

Implications

Hazard

According to generalized estimates by Bungum et al. (1998), a M6 earthquake is likely to occur on average every 100 years, and a M7 every 1000 years in Norway. In comparison, and consistent with this prediction, there was one M5.4-5.6 earthquake in the Oslofjord region in 1904, while the largest known in historical times from the entire region is the M5.8 earthquake that occurred in the Rana region in 1819. This indicates a current potential for larger earthquakes in Norway than has so far been experienced within our relatively short-term historical records. The return times for the largest earthquakes in intraplate regions such as Fennoscandia could, however, be several thousand years. One conclusion that can be drawn from this is that paleoseismology will be an important field of further research in Norway. The distinct concentration of gravitational faults and slope failures in the Lyngen-Balsfjord area in Troms and in parts of Møre & Romsdal may indicate large-magnitude prehistoric earthquakes in these areas (see discussion by Blikra et al. 2000b, in press; Braathen et al. this volume). The Nordmannvikdalen postglacial fault, of possible Younger Dryas age, is situated in the Troms area while the Berill postglacial fault is located in Møre & Romsdal. An abundance of liquefaction structures in the postglacial overburden in the Ranafjord area and the clusters of rock-slope failures in western Norway also point to the likely occurrence of large, prehistoric earthquakes in these areas. The results from onshore Norway should be compared with the large-scale offshore sliding features reported from the Norwegian continental margin (e.g., the Storegga, Trænadjupet and Andøya slides; Bryn et al. 1998; 2002). Ongoing and future research concerning the age relations of slope failures will contribute to a better understanding of the possible role of large-magnitude earthquakes in destabilizing slopes both onshore and offshore.

Hydrogeology

The concept of 'seismic pumping' has been suggested as a signal of earthquake activity on the basis of outpourings of warm groundwater along fault traces following some magnitude 5-7 earthquakes (Sibson et al. 1975). Earthquakes are known to have triggered gas seepage at several locations in California, New Brunswick and Greece (Clifton et al. 1971; Nardin & Henyey 1978; Field & Jennings 1987; Pecore & Fader 1990; Hasiotis et al. 1996). Many observations suggest that large-scale earthquakes followed shortly 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 rocks could increase the migration of hydrocarbons from the relatively impermeable source rocks up into reservoirs, and further through gas chimneys to pockmarks on the sea floor (Hovland & Judd 1988, Muir Wood & King 1993).

Rohr-Torp (1994) and Morland (1997) found a positive correlation between the groundwater yield in bedrock wells and the present land uplift in Norway. Henriksen (in press) extended this correlation study to Sweden and concluded that the uplift was of lesser importance compared with more local factors such as proximity to fracture-related lineaments and topography. The occurrence of postglacial faults in Fennoscandia indicates that multiple deglaciations reactivate regional fault zones both in areas with present-day low uplift as well as in areas with high uplift (western Norway and Bay of Bothnia, respectively). This process may consequently have assisted in improving the ground-water yield along regional fault zones in large parts of Fennoscandia.

Gudmundsson (1999) has suggested a mechanism to explain the observed correlation between land uplift and groundwater yield. Bedrock fractures are kept open or reopened due to doming-generated tensile stresses associated with the postglacial rebound. According to this model, the tensile stress at the surface would 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, no clear correlation between observed *in situ* stress values (Myrvang 1993) and distance from the centre of uplift in the Bay of Bothnia.

Trenching of the Stuoragurra Fault has shown that fault breccia was injected from the fault zone and more than 12-14 m horizontally into the lower part of the glacial overburden (Fig. 4). In order for such injection to occur, the fault breccia must have been fluidised with high-pressure groundwater or gas. This observation shows that flow of fluids or gas can locally be associated with seismic pulses. Shaking of the ground would most likely release gas from hydrates within offshore sediments. Mörner (2000, 2003) has suggested that the deglaciation phase was associated with methane venting and rock fracturing of the Precambrian bedrock of central Sweden.

Release of hydrocarbons during deglaciation-induced seismic pulses may partly explain the improved climate immediately after the deglaciation as a result of an increased greenhouse effect. The greenhouse effect of CH_4 is 10 times higher than that of CO_2 (Haq 1998). Paull et al. (1991) offered a scenario of sea-level fall (c. 100 m) associated with the Pleistocene glaciations, leading to gas hydrate instability and major slumping on the continental margins. The release of large quantities of methane into the atmosphere could eventually trigger a negative feedback to advancing glaciation once the methane emissions increased over a threshold level, leading to termination of the glacial cycle. This process could thus explain abrupt termination of glaciations. Thawing of permafrost containing hydrates (Haq 1998) and increased leakage of methane from sediments during seismic pulses at high latitudes could provide a positive feedback to the postglacial warming. De Batist et al. (2002) have shown that the Lake Baikal hydrates are destabilized above fault zones with a tectonically driven, upward flow of fluids.

Conclusions

After a critical evaluation of all neotectonic claims in Norway we have graded them according to an established five-fold classification where group A is assessed as the most reliable and 'almost certainly neotectonics', and group E is categorised as 'very unlikely to be neotectonics'. Of the 59 reports of neotectonic activity on the Norwegian mainland and on Svalbard, we have graded just three to group A and seven to group B. Fully 60% of these mainland and Svalbard claims are assessed as probably not, or very unlikely to be neotectonics. Of the 20 offshore reports, none is judged to be particularly reliable, the highest (only 4 claims) falling in group C.

The three grade A claims include the postglacial faults in Masi and Kåfjord in northern Norway and the Berill fault in southern Norway. The grade B claims include secondary effects of possible large, pre-historic earthquakes such as liquefaction and semi-liquefaction structures in the Flatanger (Nord-Trøndelag) and Rana (Nordland) areas and gravitational spreading and faulting features (sackungen) on Kvasshaugen in Beiarn (Nordland) and Øtrefjellet in Haram (Møre & Romsdal). A series of gravitational fault systems and large rock avalanches in zones from Odda to Aurland (Hordaland and Sogn & Fjordane) and in northern Troms are also included in the grade B group. Gravitational processes primarily control the large-scale rock avalanches, mountain spreading and normal faulting, but their spatial occurrence and location on relatively gentle slopes indicate that other mechanisms were also involved. Extra loading due to strong ground-shaking from large-magnitude earthquakes might have been an important factor.

Our work supports previous conclusions regarding a major seismic 'pulse' (with several magnitude 7-8 earthquakes) which followed immediately after the deglaciation of northern Fennoscandia (Lagerbäck 1990, 1992). 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 (M 7.4-7.7) 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 postglacial Nordmannvikdalen fault being part of a conjugate set of normal faults perpendicular to the extensive system of NE-SW-trending reverse faults in northern Fennoscandia.

We entertain the idea that reactivation of regional fault zones can explain some of the observed high groundwater yields along regional fault zones in Norway. There was most likely a major seismic pulse in mainland Fennoscandia and Scotland accompanying each of the deglaciations that followed the multiple glaciation cycles during the last 600,000 years. It is possible that the regional contraction and dilation of fissures associated with these glacial cycles may have assisted in extracting hydrocarbons from their source rocks and pumping them to reservoir formations and further, through gas chimneys, to produce pockmarks on the sea floor. For onshore and near-shore examples, such as the Etne, Rana, Masi and Kåfjord areas, neotectonic activity clearly seems to have influenced the groundwater flow.

Detailed analysis of offshore 2D and 3D seismic data has not yet revealed any definite neotectonic deformation structures. Several distortions in the Quaternary reflectors have, however, been mapped in the northern North Sea area. Two types of possible neotectonic features have been identified on the Norwegian continental shelf: 1) Fissures and lineaments correlated with areas of gas leakage (not obviously related to basement faults). 2) Probable reactivation of Miocene dome structures in the deep part of the Norwegian Sea.

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Appentix A: Reported evidence of neotectonics on the mainland of Norway and on Svalbard and assessments of the claims

The locations are ordered from north to south. The criteria for classification of postglacial faulting proposed 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 nature of the proposed neotectonic deformation has been included as 'TYPE' in the fifth column: (1) Tectonic fault, (2) Gravity-induced fault, (3) Erosional phenomena, (4) Overburden draping of bedrock features, (5) Differential compaction, (6) Stress release features, (7) Inconsistent shoreline correlation, (8) Unstable benchmarks or levelling errors, (9) Insufficient data resolution.

LOC. NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
1	Woodfjord, Svalbard (Piepjohn 1994)	The pattern of Holocene shorelines differs on either side of Woodfjord. The shorelines on Reinsdyrflya (on the western shore of Woodfjord) dip to the west and show an irregular development with three uplift cessations. The shorelines on Andrée Land (to the east of Woodfjord) dip to the south and seem to have developed regularly during continuous Holocene land uplift.	Otto Salvigsen (pers. comm. 2002) has mapped the Quaternary geology in the area and has not observed any irregular shoreline pattern. He also claims that the shorelines in Woodfjord are rising to the south, which is contradicting the observation by Piepjohn (1994).	D7
2	Bockfjord, Lihøgda Svalbard (Piepjohn 1994)	A N-S trending, c. 2 km-long escarpment in the Devonian sediments on the western shore of Bockfjord, (an arm of Woodfjord). The apparent downthrow is to the east.	The fault scarp is linear and has a rather consistent height. The overburden, however, is thin and consists mostly of weathered bedrock. Dating of the scarp is therefore difficult.	C1, 3
3	Kaffiøyra, Forlandssundet, Svalbard (Wójcik 1981)	Tectonic deformations of Quaternary age are recognised on longitudinal profiles of raised marine beaches. The strandflat seems to be uplifted more in the central areas of NE Kaffiøyra and SE Saraøyra (70-120 m a.s.l.) than on both extremities represented near Dahlbreen and Engelskbukta, respectively (10-20 m a.s.l.).	No fault scarp can be observed on aerial photographs.	D7
4	Geddesfjellet, Prins Karls Forland, Svalbard (Gabrielsen et al. 1992)	Fresh fault scarps are observed to the northeast of Geddesfjellet. The fresh appearance indicates that the faults have not suffered any strong glacial erosion.	No faults with consistent scarp height can be observed on aerial photographs. The varying scarp height indicates that the scarp has been generated by plucking below the inland ice.	D3
5	Breinesflya, Sørkapp Land, Svalbard (Lindner et al. 1986)	A photogeological analysis and field mapping indicate a 7 km-long system of postglacial horsts and grabens. The faults within this system cut raised marine beaches. The maximum vertical displacement is reported to be 100 m.	The observed vertical displacement is too large compared with the fault length. The ratio height/length is more than 0.01 which is ten times higher than the required 0.001 ratio (Fenton 1991). We cannot identify any pronounced fault scarps on aerial photographs from the area. Moreover, Salvigsen & Elgersma (1993) did not find any evidence of Late Quaternary tectonics in the area.	E7

LOC. NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
6	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 (in this case towards ESE) indicates the direction of maximum horizontal stress (Roberts 2000).	E6
7	Tanafjord, Finnmark J.E. Rosberg (pers. comm.) according to (Tanner 1907).	Postglacial fault (neither an exact location nor a published description is available).		
8	Skipskjølen, Varanger peninsula, Finnmark (Olesen et al. 1992a)	WNW-ESE trending, 4 km-long escarpment within the Trollfjorden-Komagelva Fault Zone has been observed from aerial photographs. The northern block seems to have been downfaulted.	The scarp has been sculptured and rounded by the moving inland ice. The height of the scarp varies considerably along its length (Olesen & Dehls 1998).	E3
9	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
10	Øksfjord-Alta, Finnmark (Holmsen 1916)	Postglacial uplift has been estimated from levelling of shorelines in western Finnmark. The uplift shows negative anomalies diverging from the regional trend in the order of 5 metres in the Øksfjord area. This effect was attributed to the gabbro massifs within the Seiland Igneous Province.	The interpretation is hampered by poor age control on the formation of the shorelines.	C7
11	Masi-Iešjav'ri area, Finnmark (Olesen 1988; Solli 1988; Muir Wood 1989b; Olesen et al. 1992a, 1992b, 1992c; Bungum & Lindholm 1997; Roberts et al. 1997; Olsen et al. 1999; Dehls et al. 1999, 2000a; Sletten 2000)	The NE-SW trending postglacial Stuoragurra Fault (SF) extends for 80 km in the Masi-Iešjav'ri area in the Precambrian of Finnmarksvidda. The fault is manifested on the surface as a fault scarp up to 7 metres high and is situated within the regional Proterozoic Mierujavri-Sværholt Fault Zone. The SF 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 1996 earthquake (M 4.0) in the Masi area was most likely located along the SF at a depth of c. 10 km.	The age of the SF is constrained in that it cross-cuts glaciofluvial deposits northeast of Iešjav'ri and an esker northeast of Masi. Thus, it formed after the deglaciation (c. 9,300 yr. BP).	A1
12	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 have been rounded by glacial erosion. The scarp was most likely formed by plucking of the moving inland ice along a Caledonian fault (Olesen & Dehls 1998).	D3

LOC. NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
13	Lyngen, Troms (Holmsen 1916)	Holocene uplift was assessed from levelling of shorelines in northern Troms. Negative uplift anomalies in the order of 5 metres were ascribed to gabbro massifs within the Lyngen Ophiolite.	The interpretation is hampered by poor age control on the formation of the shorelines.	C7
14	Nordmannvikdalen, Kåfjord, Troms (Tolgensbakk & Sollid 1988; Sollid & Tolgensbakk 1988; Olesen & Dehls 1998; Blikra & Longva 2000; Dehls et al. 1999, 2000a)	NW-SE trending postglacial faults in the Kåfjord area, North Troms. Normal faults dipping 30-50° 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 10-12° 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 therefore favour a tectonic origin of the fault.	A1
15	Balsfjord-Lyngen area (Blikra & Longva 2000; Braathen et al. this volume)	A distinct concentration of gravitational faults and slope failures may indicate a large-magnitude, prehistoric earthquake. Several hundred, large rock-slope failures and landslides were triggered during this event.	The slope failures in Troms county seem to be old (during and shortly after the last deglaciation), and are most likely related to the enhanced seismic activity shortly after the deglaciation.	B1,2
16	Tjeldsundet, Troms (Grønlie 1922; Vogt 1923)	Displacement of Holocene shorelines (an offset of c. 2.2 m down to the west). Lower shorelines appear to be unbroken indicating that the inferred faulting occurred immediately after the deglaciation. Vogt (1923) pointed to the striking coincidence of the young faulting occurring in an old regional fault-zone along Tjeldsundet. Several large-scale rock avalanches occur along Astafjord (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 on 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 shoreline sediments.	D7
17	Vassdalfjellet, 4 km east of the E6 in Kvanndalen north of Bjerkvik, Nordland (Bargel et al. 1995)	A series of parallel E-W-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 actual depths are difficult to assess. There have been vertical movements along some of the fractures.	The most continuous fracture is 600 m long. The fractures are situated close to a steep 600-m high wall along the southernmost slope of Vassdalfjellet. The inferred fractures are interpreted to be effects of gravity-induced sliding (Olesen & Dehls 1998). The fractures may resemble a small-scale sackung feature (Varnes et al. 1989) due to gravity spreading of Vassdalfjellet.	E2
18	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 Skjomenfjord. 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 its height varies considerably 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

LOC. NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
19	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.	E6
20	Kvasshaugen 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, have been triggered by large earthquakes.	B1,2
21	Austerdalsisen, Rana, Nordland (Olesen et al. 1994, 1995)	Interpretation of aerial photographs unveiled an area of N-S trending, vertical 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 inspection revealed that the features are probably of erosional origin. The moving inland ice has most likely plucked blocks from the bedrock along steeply dipping N-S trending fractures (Olesen & Dehls 1998).	D3
22	Ranafjord area, Nordland (Helzen 1834; Grønlie 1923; Muir Wood 1989a; Bakkelid 1990,2001; Olesen et al. 1994, 1995; Hicks et al. 2000; Olsen 1998, 2000)	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 and Båsmoen on the northern shore of Ranafjord and Hemnesberget. Numerous liquefaction structures have been observed in the area. 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 indicates a 40 cm offset along the Båsmoen fault (Olsen 2000). A new seismic mini-array has registered numerous minor earthquakes in the outer Ranafjord area. They do not, however, seem to be attributed to the Båsmoen fault (Hicks et al. 2000).	B1,3
23	Handnesøya, Nesna, Nordland (Olesen et al. 1994, 1995)	N-S trending, steeply 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 have been sculptured by the moving inland ice. The ice has most likely plucked 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. 2000).	C1,3
24	Hugla, Nesna, Nordland (Bakkelid 1990, 2001)	The observed uplift of acorn barnacle and bladder wrack marks at two different locations deviates 1-2 mm/year from the regional trend. The benchmarks were established in 1894 and remeasured in 1990.	The observed uplift at the two locations is 0.0 and 0.5 mm/year. The benchmark with the lowest observed uplift may, however, have been moved from its original position (S. Bakkelid, pers. comm. 2000). Fault plane solutions from some of the frequent earthquakes in the area reveal extensional faulting consistent with the observed subsidence.	C1,8

LOC. NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
25	Klubbsteinen, Nord-Flatanger, Nord-Trøndelag (Olsen & Sveian 1994; Olsen 1998)	A thick deposit of fine to medium sand with clast-supported conglomeratic character is recorded in the c. 4 m-high sections of a sand pit near the intersection of two old fault/fissure lineaments. The sand is truncated on the top and overlain by a subhorizontal, bedded, gravelly sand of c. 1.0 m thickness. The two sand units comprise the material of a strand terrace which corresponds to the Tapes maximum sea level.	The observed clast-supported conglomeratic structure of the sand resembles the structures of similar sands recorded at c. 10 other sites in Mid and North Norway. Earthquakes seem to be a likely cause of these structures, and are, in fact, in some cases, e.g. at Klubbsteinen (named Sitter in Olsen 1998), the only reasonable triggering mechanism for this phenomenon. The structure has clearly been developed quite suddenly, some time after the original subhorizontal and alternating layering of fine and medium sand. The age of these earthquake-related structures must be older than the regression from the maximum Tapes sea level, but younger than the culmination of the Tapes transgression, i.e. c. 7000 - 7500 ^{14}C-yr BP (Sveian & Olsen 1984).	B1
26	Oterøya-Øtrefjellet, Haram, Møre og Romsdal (Anda et al. 2000; Blikra et al. in press; Braathen et al. in press)	Concentrations of rock-slope failures and collapsed bedrock. This includes a 2 km-long, N-S oriented mountain ridge on Øtrefjellet. It is situated 100-300 m above the surrounding terrain and 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 have provided the necessary energy for triggering the failure.	An alternative mechanism is that of processes related to permafrost conditions during colder phases after the Weichselian maximum. The ridge is situated 200-300 m below the distinct 'weathering zone' of the region, thought to represent the ice-limit during the Weichselian maximum (Anda et al. 2000).	B1,2
27	Berill, Rauma, Møre og Romsdal (Anda et al. 2002)	The NNE-SSW trending Berill Fault is 2.5 km long and has an offset of 2-4 m. The reverse fault dips to the west. It truncates well-defined colluvial fans and was formed after the Younger Dryas period. The fault is little modified by avalanche processes, suggesting that it originated during the second half of the Holocene. There are fault scarps up to 15 km in length but dating of these sections is lacking.	This fault could be significantly younger than similar faults within the postglacial Lapland Fault Province. The fault represents a reactivation of an older fault zone (cohesive cataclasite) and it occurs in a zone with a large number of rock-slope failures.	A1
28	Romsdalen, Møre og Romsdal (Anda 1995; Anda & Blikra 1998; Anda et al. 2000; Blikra et al. in press)	Concentration of rock-avalanches correlates with a 400-500 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 escarpment reflects fault segments generated during Mesozoic movements along the Møre-Trøndelag Fault Complex. Mesozoic sediments may have filled local basins situated along the fault zone (similar to the basins in Beistandfjord and Trondheimsleia). Glacial erosion will have more easily removed these soft sediments (than the more competent crystalline basement rocks) subsequent to the Cenozoic exhumation of Norway.	D3

LOC. NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
29	Ørsta-Vanylven, Møre og Romsdal (Bøe et al. this volume; Blikra et al. 2002, in press)	Several large rock-slope failures and regional slide events in several fjords indicate that earthquakes may have played a role as a triggering mechanism.	There are indications of three regional slide events, one shortly after the deglaciation, one at 8000 and one at 2000 calendar years BP. The 8000 PB event is interpreted to be related to the tsunami generated by the Storegga slide.	C3
30	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 shoreline and the height of the cave opening varies between 30 and 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
31	Breisunddjupet, Møre og Romsdal (Holtedahl 1959)	The elevation of the strandflat to the north of the NW-SE trending Breisunddjupet seems to be lower than the strandflat 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.	D7
32	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 were relevelled in 1999. The shorelines showing anomalous altitudes were most likely formed at a different time than the regional shorelines and cannot be used to estimate crustal deformation (Thoresen 2000).	D7
33	Rudihø, Heidal, Oppland (Werenskiold 1931)	Two 100-200 m-long and 1 m-wide NW-SE trending fractures. One side seems to be downfaulted and the fractures are 1-2 m wide and up to 6 m 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 represent gravity-induced phenomena.	E2
34	Gnedden, Holsætrin, Sel, Oppland (Werenskiold 1931)	An escarpment up to 7 m high and 1 km long trending WSW- ENE (N065°) across a small mountain crest. There is a large variation in scarp height along the western part of the scarp, but it is more consistent to the east (3-5 m). The escarpment seems to have been sculptured by the inland ice.	The escarpment was most likely formed by erosion by the inland ice along a pre-existing fracture in the bedrock.	D3
35	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 displacements of 0.5-2 m. One of the faults cuts a glacial splay channel.	The scarps have been sculptured by the moving inland ice and vary considerably in height. We conclude that the scarps are due to glacial and meltwater erosion and are not caused by any tectonic process.	E3

LOC. NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
36	Aurland-Flåm, Sogn og Fjordane (Blikra et al. 2002, in press)	A series of rock-slope failures, including an up to 4 km-long normal fault of probable gravitational origin. Dating of cores from the fjord suggests that large-scale rock-slope failures occurred shortly after the deglaciation.	It is still uncertain whether the normal fault is simply a gravitational feature, or if it may be linked to a tectonic structure at depth.	B1,2
37	Grytehorgi and Vøringfossen, Eidfjord, Hordaland (Reusch 1901)	NNE-SSW trending fault on Grytehorgi. The downfaulted block is to the west. Ice striations seem to be offset by 1 m (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 considerably along the scarp (within approximately 30-40 metres length). The foliation of the bedrock phyllite is flat-lying. The lowermost part of the scarp faces west. We conclude that the scarp was 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
38	Utnefjord, 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 many slumps, slides and pockmarks have been observed within the fjord. Hoel (1992) interpreted these phenomena to be effects of large earthquakes.	C
39	Geitura, Ulvik, Hordaland (Simonsen 1963; Blikra et al. 2000a)	A large rock-avalanche on 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. However, postglacial fault scarps have not been found. Other large rock-avalanches have also been identified in the area (Blikra et al. 2000a, in press). Neotectonic activity in the Hardangerfjord area is supported by recent work on shoreline displacement by Helle et al. (2000).	B1
40	Finse - Geilo area, Hordaland - Buskerud (Anundsen et al. submitted)	Anomalous uplift from repeated levelling.	A careful analysis of the levelling methods is pending.	C8
41	Hjeltefjord, 30 km northwest of Bergen (Unpublished NTNF-NORSAR and NGI 1985)	At the northern end of Hjeltefjord a boomer seismic survey was undertaken in the mid-80s 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). This is much greater than the required 1/1,000 ratio (Fenton 1991).	D
42	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 at 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

LOC. NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
43	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 has not been 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
44	Etne, Hordaland (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 was most likely caused by ground shaking and is not considered to be a deep-seated tectonic fault.	D
45	Ølen, Hordaland, (Anundsen 1989)	A subsidence is observed from precision levelling (20 mm of movement over 19 years).	The benchmark with anomalously large uplift is most likely placed on an unstable slab of rock (Bockmann 1999).	D8
46	Ringja, Vindafjord, Tysvær, 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 can be observed.	The sub-parallel crevasses, along with an orthogonal set, can be explained by gravitational sliding along a very strong bedrock foliation dipping towards the fjord. The step-like nature of the fjord walls appears to be an erosional feature (Dehls & Braathen 1998).	D2
47	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 have taken place along the Yrkjefjord fault zone. Annual measurements over a period of 10 years indicate that the movement sense has changed, i.e. the sense of displacement, horizontal and vertical, has oscillated.	The displacements are very small and are not consistent in time (alternating normal and reverse faulting).	D8
48	Yrkje area (Anundsen 1982; Anundsen & Fjeldskaar 1983; Anundsen 1985)	A 7-10 m 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 shows 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).	D7
49	Ulvegrovene, north of Røssdalen, Rogaland (Anundsen 1988a)	Active subsidence along a narrow zone. The turf along the escarpments seems to have been torn apart. The structure is parallel to the valley of Røssdalen.	Most likely a gravity-induced structure (Dehls & Braathen 1998).	D2
50	Mosvatnet, Suldal, Rogaland (Anundsen 1988b)	The sides of open fractures in the bedrock are located at different levels indicating vertical movements along the fractures.	Believed to be due to erosion of a fine-grained amphibolite dyke (Dehls & Braathen 1998).	E3

LOC. NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
51	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
52	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. 42 at Fjøsanger.	C
53	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°, 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' was partly formed by the northward moving Skagerrak glacier (Larsen et al. 1998). Seismic profiling in the Gannsfjord has not revealed any postglacial faulting (Larsen et al. 1998). The steep contact most likely represents an erosional boundary.	D3
54	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 have been 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 Gannsfjord lineament. Olsen & Grøsfjeld (1999) have reported a frequently fluctuating ice sheet during the interval 18-50 ka BP.	D3
55	Ragnhildnuten, Sandnes, Rogaland (Feyling-Hanssen 1966)	Postglacial fault (with dip-slip and sinistral offsets, each of 30 m) 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
56	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 over a period of 34 years.	S. Bakkelid (pers. comm. 1998) has concluded that a 40 mm error in the benchmark B39N9-Eide, measured by the surveying company Ing. Dahls Oppmåling in 1951/52, affected several levelling lines in the area.	E8
57	Egersund-Flekkefjord area, Rogaland (Anundsen 1989; Anundsen et al. submitted)	A subsidence of 2-2.5 mm/yr has been recorded in the Egersund Anorthosite-Gabbro Province. 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.	C8
58	Haukeligrend, Vinje, Telemark (Anundsen et al. submitted)	Anomalous subsidence from repeated levelling.	A careful analysis of the levelling methods is pending.	C8

LOC. NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
59	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.	The pothole is probably blasted away, as it has not been possible to find it today (Løset 1981, Selnes 1983). It most likely represents a stress release phenomenon since it was located in the vicinity of an open pit.	D6

Appentix B: Summary of the offshore neotectonic claims

Locations 61-64 have been evaluated within the NEONOR Project and locations 66-69, 71 and 73 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 has been included as 'TYPE' in the fifth column: (1) Tectonic fault, (2) Gravity-induced fault, (3) Erosional phenomena, (4) Overburden draping of bedrock features, (5) Differential compaction, (6) Stress release features, (7) Inconsistent shoreline correlation, (8) Unstable benchmarks or levelling errors, (9) Insufficient data resolution.

LOC. NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
61	Barents Sea, 50 km east of Edgeøya (Fanavoll & Dahle 1990)	A fault seems to offset the sea floor 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. There is no indication of postglacial faulting on the neighbouring seismic lines NPD 7730-80B and NPD-2600-80B.	D3
62	Bjørnøyrenna, Barents Sea margin (Fiedler 1992; Muir Wood 1995)	Offsets of shallow reflectors along the southern Barents Sea margin have 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 a scarp at the sea floor. We therefore favour a gravity-induced mechanism for this feature.	D2
63	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.	Multibeam 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). There is, however, a possibility that the short fault scarp is a secondary structure related to strike-slip movements along the NW-SE trending Bothnian-Senja Fault Complex	D3
64	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 have been 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.	Multibeam echo-sounding data acquired in the NEONOR Project indicate that the scarps are effects of erosion rather than tectonic processes (Fanavoll & Dehls 1998).	E3

LOC. NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
65	Continental slope, Røst Basin, Nordland (Mokhtari 1991; Mokhtari & Pegrum 1992)	Evidence of recent downslope gliding along the continental slope.	The faulting is most likely not caused by a deep-seated tectonic process but rather by gravity gliding.	D2
66	Vøring Escarpment (Seabed Project; NORSAR 1999)	Minor scarps on the sea floor above the Vøring Escarpment (VE). A larger offset on the sea floor than along underlying reflectors implies sliding on glide planes.	The shallow faulting/sliding is most likely related to differential compaction/ subsidence across the VE.	D5
67	Naglfar Dome (Seabed Project; NORSAR 1999)	On the northern flank of Naglfar Dome, an offset of ~19 m on the sea bed may be related to underlying deep-seated faulting.	Difficult to constrain timing because of limited seismic resolution. Shale diapirism is associated with the fault.	D9
68	Nyk High (Seabed Project; NORSAR 1999)	Shallow faults, clearly affecting Pleistocene sediments, are present on the NW flank of the high. Slide escarpments on the sea bed (max. 40 m) cannot be linked to underlying faults. Larger relief at sea floor level than on 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.	D5,9
69	Gjallar Ridge (Seabed Project; NORSAR 1999)	Well-layered Neogene sediments are cut by numerous faults along the Gjallar Ridge and adjacent regions. Some faults can be traced up to (or close to) the sea floor.	Most of this faulting appears to be associated with intra-formational fracturing rather than a response to regional tectonism.	D
70	Fles Fault Complex, 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 western boundary of the Helland-Hansen Arch.	The Pliocene reflectors beneath the offset Quaternary reflector do not seem to be offset, thus contradicting the hypothesis of young faulting.	D9
71	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.	D9
72	Storegga (Evans et al. 1996; Bryn et al. 1998)	Postglacial N-S trending faults and a graben, up to 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 of the composite structure 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, which have also been attributed to gas leakage. The features have possibly been triggered by earthquakes	C,D
73	Faeroe-Shetland Escarpment, (Seabed Project; NORSAR 1999)	A 25-30 m-high offset in the Storegga slide deposits above the Faeroe-Shetland Escarpment.	The fault cannot be observed on any of the adjacent lines and must consequently be shorter than 20 km. The height/length ratio of the fault is consequently 0.0012-0.0015, which is greater than for most other postglacial faults in Fennoscandia.	C,D

LOC. NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
74	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 appear to have a near-vertical 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. In recent years the area has also been covered with 3D seismic surveys.	D9
75	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 to the bedrock surface beneath the thick Quaternary sedimentary cover. The major scarp that has developed along the fault has the appearance of a fault-scarp (with vertical offset up to 150 m), and although offsets have not been observed in the overlying sedimentary section itself, sediments onlap the scarp, with some suggestion of dips steepening 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 multibeam echo-sounding data and 2D seismic lines shows that the Quaternary sediments are draped along the fault scarp (Rise et al. 1999).	D3
76	Troll-Fram area, North Sea (Riis 1998; Olesen et al. 1999)	WNW-ESE lineaments in the Early Pleistocene, interpreted in 3D surveys, coincide with Mesozoic faults reactivated in the Tertiary.	The lineaments are close to, or below, the seismic level of resolution. There is abundant faulting in the pre-Miocene rocks, related to escape of fluids and/or gas.	C
77	East of Troll, North Sea (Riis 1998)	Possible fault cutting the Quaternary section, continuing into a basement fault that was active in the Tertiary.	A bathymetric survey revealed that the apparent fault was caused by pull-up below a pockmark.	E
78	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 were detected with a deep-towed boomer during the Statpipe route survey in 1981. The fault cuts soft, silty, cohesive clay.	The fault occurs 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 supports the conclusion reached by Hovland (1983). Release of gas does not, however, explain the 1-2 m offset of the sea floor. A tectonic cause can therefore not be ruled out.	C1
79	Holene, west of northern Karmøy, close to the British sector (Hovland 1984)	Several faults cut the sea floor within a more than 2 km long and 10 m-deep N-S trending depression (Holene). The faults trend NE-SW, NNW-SSE and N-S and have approximate lengths of 100 m.	The faults are most likely of superficial character, because of their limited scarp length. Hovland (1984) has related the faulting to gas seepage.	D

LOC. NO.	LOCATION AND REFERENCE	OBSERVATION	COMMENT	GRADE /TYPE
80	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 landslide to the southwest of Vestre Bokn was most likely triggered by an earthquake since the slope gradient is very low and there is no indication of particularly strong bottom currents in this area (Rise & Bøe 1999).	D