Neotectonics, seismicity and contemporary stress field in Norway – mechanisms and implications

Odleiv Olesen[1], Hilmar Bungum[2], John Dehls[1], Conrad Lindholm[2], Christophe Pascal[1*] and David Roberts[1]

[1]Geological Survey of Norway (NGU), P.O. Box 6315 Sluppen, 7491 Trondheim, Norway.
[2]NORSAR, P.O. Box 53, 2027 Kjeller, Norway.
[*]Present address: Ruhr University, Bochum, Germany.
E-mail: Odleiv.Olesen@ngu.no

Neotectonics in Norway are characterised by: 1) geological features: two documented postglacial faults in northern Norway; Neogene doming of sedimentary depocentres in the Vøring area. 2) seismicity: enhanced earthquake activity along the coastal areas of northern, western and southeastern Norway; palaeoseismic events in western and northern Norway; present-day seismicity along the Stuoragurra postglacial fault indicates that the fault is active at depth. 3) rock stress: local deviations from a general NW–SE-oriented compressional in situ rock stress; areas with observed extension from fault-plane solutions in western and northern Norway. 4) uplift: increasing present-day uplift from west to east with the highest values in Trøndelag and eastern Norway (4 mm yr^{-1}); Neogene long-term uplift of western and northern Norway as indicated by raised pre-Weichselian sediments and coastal caves; an active area of extension and subsidence in the outer Ranafjorden area. These neotectonic features are likely to be mostly related to gravitational effects of excess mass along the Mohns Ridge, within the Iceland Plateau and the southern Scandinavian mountains, to Pliocene/Pleistocene sedimentary loading/unloading, and to postglacial rebound. A major seismic pulse most likely accompanied each of the deglaciations following the multiple glaciation cycles in mainland Fennoscandia during the last 600,000 years. Seismic pumping associated with these glaciation cycles may have facilitated fluid and gas leakage from organic-rich sediments and reservoirs through 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. Pressure decrease associated with removal of sedimentary overburden on the Norwegian shelf has caused expansion of gas and resulted in expulsion of oil from the traps. Where uplift and tilting resulted in local extension, seal breaching and spillage have also occurred. Future rock avalanches and landslides, triggered by earthquakes, could generate tsunamis in fjords and lakes and constitute the greatest seismic hazard to society in Norway. Our understanding of neotectonic activity is consequently important for the evaluation of hazard and risk related to rock-slope instability.

Olesen, O., Bungum, H., Dehls, J., Lindholm, C., Pascal, C. and Roberts, D. (2013) Neotectonics, seismicity and contemporary stress field in Norway – mechanisms and implications. *In* Olsen, L., Fredin, O. and Olesen, O. (eds.) *Quaternary Geology of Norway*, Geological Survey of Norway Special Publication, **13**, pp. 145–174.

Introduction

Over the last thirty years, through studies of neotectonic phenomena, it has become evident that the present-day Baltic Shield is not the uniformly quiet, stable, continental-crustal area that was earlier commonly assumed. In Norway, and northern Fennoscandia as a whole, detailed seismotectonic investigations, recordings of Late Quaternary faults, stress measurements and observations of stress-release features have all indicated that neotectonic movements have been, and still are, quite significant (Kujansuu 1964, Lagerbäck 1979, 1990, Olesen 1988, Bungum 1989, Slunga 1989, Talbot and Slunga 1989, Roberts 1991, 2000, Olesen et al. 1992a, 1995, 2004, Myrvang 1993, Bungum and Lindholm 1997, Muir Wood 1989a, 2000, Stewart et al. 2000, Roberts and Myrvang 2004, Pascal et al. 2005a,b, 2006). Monitoring of seismicity in the adjacent continental shelf, together with data from borehole breakouts, has also greatly increased our knowledge of the contemporary, regional stress regime (Bungum et al. 1991, Gölke and Brudy 1996, Hicks et al. 2000a, Byrkjeland et al. 2000), a factor of no mean importance for the offshore petroleum industry. Neotectonics, and the potential hazards associated with such crustal motions, thus constitute an important component of the Quaternary geology of Norway.

Our approach to neotectonic studies follows the definition of neotectonics as given by the International Association for Quaternary Research (INQUA); "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 Norway, the first known report of neotectonic activity is that of Morsing (1757), and over the last 250 years the number of such reports has increased steadily and has now reached more than 80 (Olesen et al. 2004). Additional reports deal with three shallow earthquake swarms along the coast of Nordland (Bungum and Husebye 1979, Bungum et al. 1979, Atakan et al. 1994, Hicks et al. 2000b) and four separate swarms on Svalbard (Bungum et al. 1982, Mitchell et al. 1990, Pirli et al. 2010) that could, dependent on definition, be added to the list (Figure 1). Almost 80% of the reports were published after 1980. Twenty of the claims are situated in the offshore area and more than 60 are located on mainland Norway.

A first coordinated attempt to assess the status and many facets of neotectonic activity in Norway came with the 'Neotectonics in Norway' (NEONOR) project during the years 1997–2000. This aimed at investigating neotectonic phenomena through an integrated approach including structural bedrock mapping, monitoring of microseismicity, recording of stress-release features, study of aerial photographs, trenching, drilling, ^{14}C dating, geodetic levelling and ground-penetrating radar profiling (Dehls et al. 2000a, Fjeldskaar et al. 2000, Hicks et al. 2000a, b, Roberts 2000, Olesen et al. 2004, Rise et al. 2004). Seismic surveying (including available 3D data) and multibeam echo-sounding techniques were used to examine possible offshore postglacial faulting. The shallow parts of eight seismic 3D cubes (located in seismically active areas) were studied to try to locate potential Quaternary deformation features. Results from rock-avalanche hazard projects in Troms and western Norway (Geological Survey of Norway [NGU]) and the 'Seabed Project' (NORSAR/NGI/UiO/SINTEF) were also included in this major assessment of neotectonic activity on the Norwegian mainland and continental shelf.

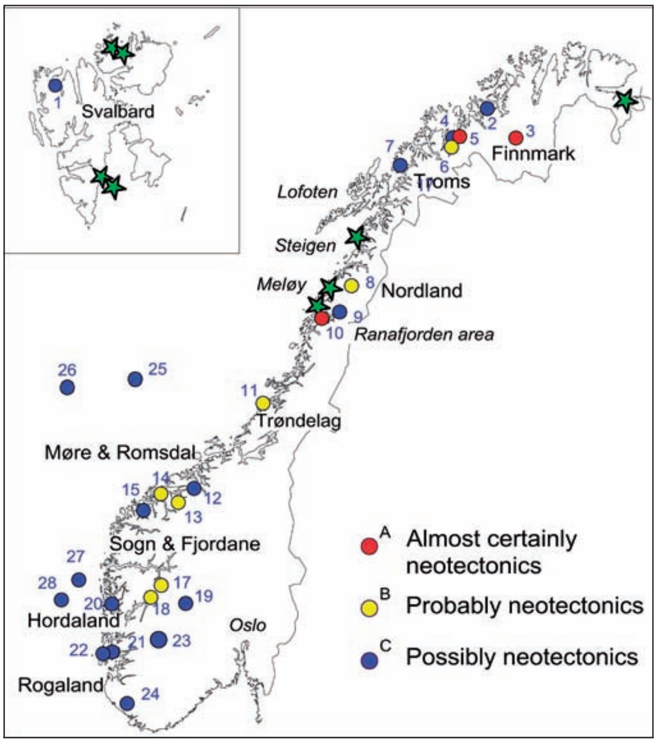

Figure 1. Locations of 28 neotectonic claims that have been classified as A, B and C. Location No. 16 covers the coastal area between Sogn & Fjordane and Lofoten and is not shown on the map. Reports with grades D and E are not included, but are shown on a similar map by Olesen et al. (2004). Green stars denote shallow earthquake swarms (Bungum and Husebye 1979, Bungum et al. 1979, 1982, Mitchell et al. 1990, Atakan et al. 1994, Hicks et al. 2000b, Pirli et al. 2010). The numbers refer to information on the neotectonic claims listed in the Appendix.

In this paper we summarise our current knowledge and understanding of neotectonics in Norway by grouping the reports and data into four categories, namely: postglacial faulting, postglacial and contemporary uplift, seismicity, and the contemporary stress field.

Postglacial faulting

Onshore

Two postglacial faults have been documented on mainland Norway (Olesen 1988, Tolgensbakk and Sollid 1988). The NE–SW-oriented, reverse Stuoragurra Fault (Olesen 1988, Muir Wood 1989a, Olesen et al. 1992a,b, Dehls et al. 2000a) in western Finnmark constitutes the Norwegian part of the postglacial Lapland Fault Province (Figures 2–5, Table 1). The fault consists of numerous segments within a 80 km-long and 2 km-wide zone and has a maximum scarp height of 7 m (Figures 3a and 6). The dip of the fault is approximately 55° to the southeast near the surface (Figure 6a), A total of three percussion drillholes and one core drilling down to a depth of 135 m are located along a profile perpendicular to the Stuoragurra postglacial fault (Olesen et al. 1992a,b, Roberts et al. 1997, Dehls et al. 1999, Kukkonen et al. 2010). The drillholes revealed that the postglacial fault at a depth of *c.* 50 m has a dip of *c.* 40° to the southeast and consists of several thin (a few cm thick) zones of clay minerals within a 1.5 m-thick interval of fractured quartzite (Olesen et al. 1992a,b, Roberts et al. 1997). The clay zones consist of kaolinite, vermiculite, smectite, goethite and chlorite, and most likely represent a weathered fault gouge (Åm 1994). Several 2–3 m-thick zones of lithified breccia within a 25 m-wide interval reveal that the postglacial fault occurs within an old zone of weakness partly coinciding with the margins of deformed Palaeoproterozoic albite diabases. Magnetic modelling of the albite diabase in the vicinity of the drillholes shows a dip of *c.* 40° to the southeast (Olesen et al. 1992a,b) consistent with the results from the drilling. Resistivity and refraction seismic profiling show both low resistivity (900 ohmm) and low seismic velocity (3800 m s^{-1}) and indicate a high degree of fracturing.

Focal mechanism solutions for five earthquakes recorded along or close to the Stuoragurra Fault and observation of stress-release features in Finnmark (Roberts 2000, Pascal et al. 2005a) have indicated that the maximum principal compressive stress, S_{Hmax}, is oriented approximately NW–SE. The individual focal mechanisms (Bungum and Lindholm 1997) were poorly constrained and were located southeast of the Stuoragurra surface expression at shallow depths. The reverse/oblique nodal planes were oriented so that one plane could be associated with the fault strike for all events; however, σ_H varied from N–S to E–W (averaging to NW–SE).

Olesen (1988) and Muir Wood (1989a) noted that both the Pärvie and Stuoragurra faults occur along a physiographic border. The mountainous area to the northwest has an average higher elevation than the area to the southeast. The ice was consequently thickest in the southeastern area. This would have involved more depression during the period of maximum glaciation and consequently a greater contribution to the subsequent postglacial stress regime. The differential loading of ice across a prestressed zone of weakness might consequently be sufficient to have caused reactivation of the old zone, and so produce a fault scarp.

This model, however, will not explain the other postglacial faults in Fennoscandia. Muir Wood (1993, 2000) suggested that interference between polarised tectonic (ridge push) and radial deglaciation strain fields produce alternating quadrants of enhanced seismicity and aseismic regions around rebound domes and former peripheral forebulges. He argued that the observed postglacial faults occur within such a seismic quadrant

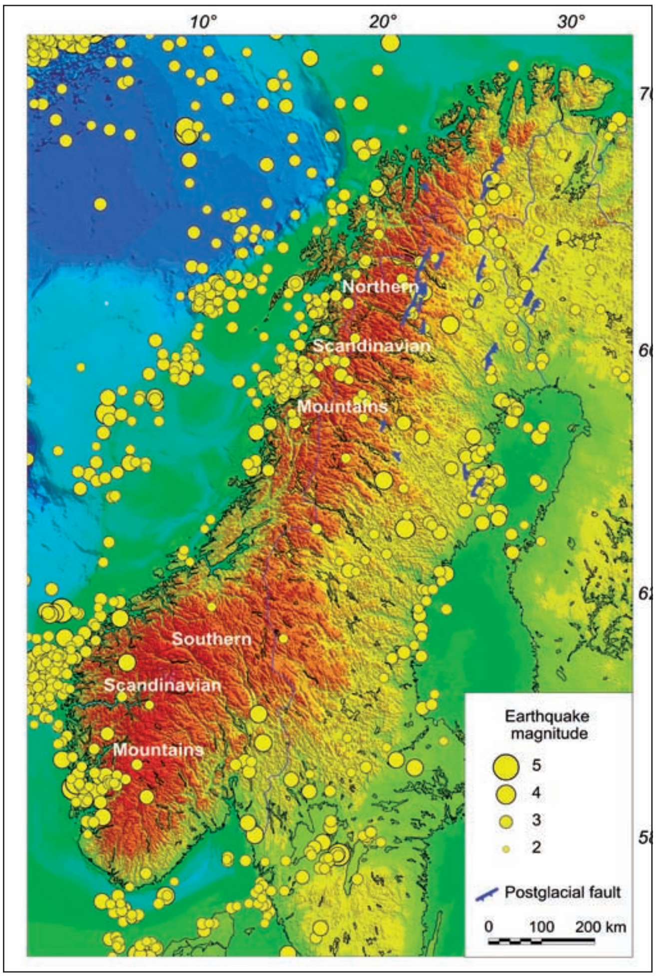

Figure 2. Earthquakes during the period 1980–2011 and postglacial faults in Fennoscandia (modified from Dehls et al. 2000b, Olesen et al. 2004, Lagerbäck and Sundh 2008 and Bungum et al. 2000, 2010). The Norwegian National Seismological Network at the University of Bergen is the source of the earthquake data in Norway, Svalbard and NE Atlantic. Data on the other earthquakes in Denmark, Finland and Sweden are downloaded from the web pages of the Institute of Seismology at the University of Helsinki; http://www.seismo.helsinki.fi/english/bulletins/index.html. We have established a lower threshold at magnitude 2.5 to reduce the probability of contamination by explosives. The size of the earthquake symbols increases with rising magnitude. The postglacial faults occur in areas with increased seismicity.

in northern Fennoscandia where ridge-push stress and rebound stress are superimposed.

The 2 km-long and NW–SE-striking Nordmannvikdalen fault (Figure 3b, Tolgensbakk and Sollid 1988, Dehls et al. 2000a) near Kåfjord in northern Troms is a normal fault trending perpendicular to the NE–SW-trending, postglacial reverse faults in northern Fennoscandia. The kinematics of the fault still fit the regional stress pattern and may relate to local relief effects allowing release along the NW–SE trend. The Nordmannvikdalen fault may also be considerably longer but its full extent is difficult to estimate because of missing overburden along the possible extensions to the southeast and northwest.

The NNE–SSW-trending and reverse Berill Fault (site 13 in Figure 1 and Appendix, Figure 3c and 3d) occurs in Møre & Romsdal county in southern Norway (Anda et al. 2002)

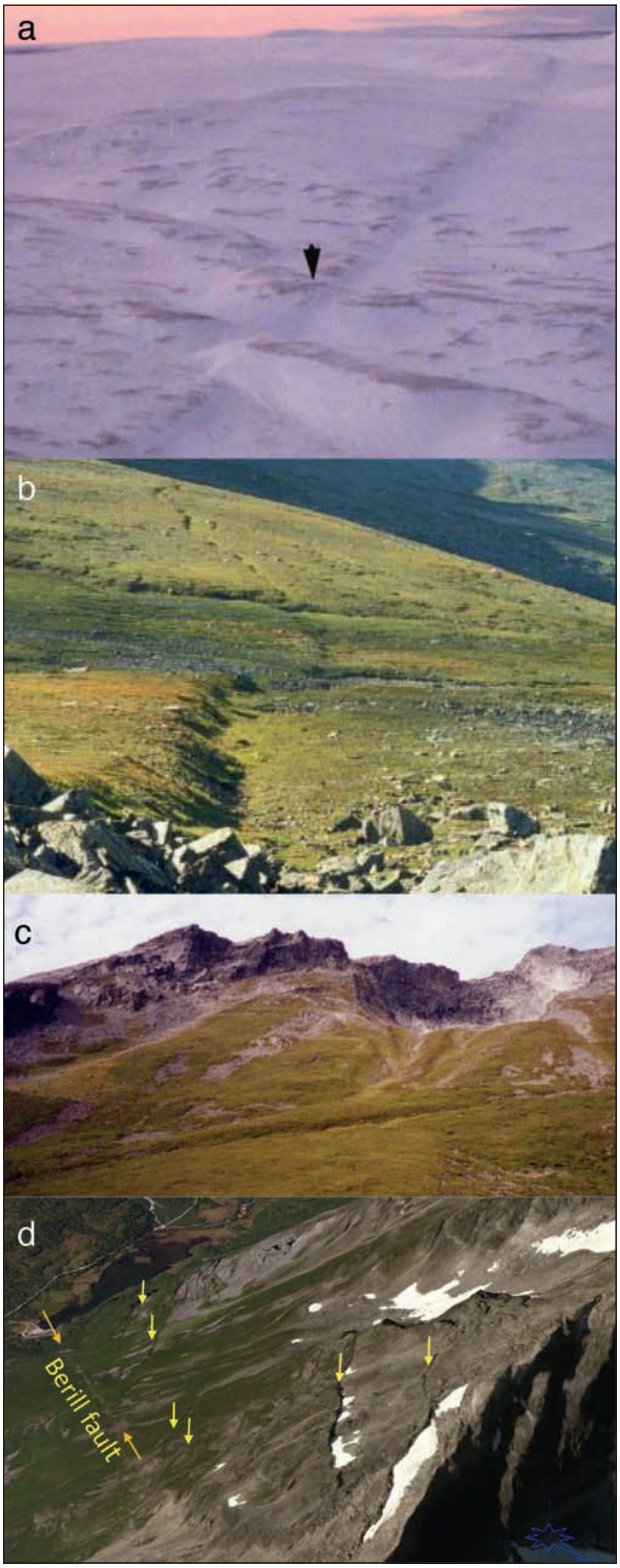

Figure 3. Two postglacial faults in Norway and a sackung structure previously classified as a tectonic fault. (a) Oblique aerial photograph of the Stuoragurra Fault (Location 3 in Figure 1 and fault 1 in Figure 5 and Table 1) as it crosses Finnmarksvidda at Stuoragurra, 15 km NNE of Masi (Olesen et al. 2004). The fault cuts through an esker (UTM 611400E, 7717300N). 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. (b) The Nordmannviken Fault (fault 2 in Figure 5 and Table 1) viewed from the southeast (Dehls et al. 2000a). The fault scarp runs parallel to the valley floor. The surface slope is at most 15–20° and it is therefore not likely that the fault scarp is due to gravitational sliding. (c) The NNE–SSW-trending and reverse Berill Fault (Anda et al. 2002) has previously been classified as a tectonic fault (Olesen et al. 2004). The length of the fault is minimum 2.5 km and the scarp height is 3 m and it dates most probably to the latter half of the Holocene. This reverse fault is located at the foot of the Middagstinden mountain and appears to be part of a sackung structure (see text). (d) Open clefts with upward-facing scarps (yellow arrows) along the Middagstinden mountain ridge occur in the hanging-wall block of the Berill Fault (located between the orange arrows) and are typical features of gravity-induced sackung structures. The image is produced using www.Norgei3D.no.

and has previously been classified as a tectonic fault (Olesen et al. 2004). The length of the fault is minimum 2.5 km and the scarp height is 3 m and it dates probably to the latter half of the Holocene. This reverse fault is located at the foot of the Middagstinden mountain and appears to be part of a sackung structure (Savage and Varnes 1987). The open clefts with upward-facing scarps along the mountain ridge in the hanging-wall block of the reverse fault (Figure 3d) are typical features of gravity-induced sackung structures. The low offset/length ratio (1:500) of the fault also points to a nontectonic origin. We have decided to remove the Berill Fault from the list of 'A – almost certainly neotectonics'. The structures may, however, have been triggered by adjacent large-magnitude earthquakes and the fault is therefore classified as 'B probably neotectonics' in Figure 1. For details on the remaining, probable and possible, neotectonic observations in Figure 1 (yellow and blue), readers are referred to Dehls et al. (2000a) and Olesen et al. (2004).

There seems to be an anomalously high number of rock avalanches in the vicinity of the Nordmannvikdalen fault suggesting a link between rock-slope failures and palaeoseismic events (Braathen et al. 2004, Osmundsen et al. 2009). The Nordmannvikdalen fault was most likely formed shortly after the deglaciation.

Dehls et al. (2000a) and Olesen et al. (2004) graded existing neotectonic reports into the following classes according to their reliability (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. 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) differential compaction, (6) shallow, superficial stress-release features, (7) inconsistent shoreline correlation, (8) unstable benchmarks and levelling errors.

Critical evaluation of more than 60 neotectonic claims in mainland Norway and Svalbard has resulted in three claims of grade A and eight claims of grade B. The grade A claims include

*Table 1. Summary of properties of the documented postglacial faults in Finland, Norway and Sweden (modified from Olesen et al. 2004 and Lagerbäck and Sundh 2008). The major faults are NE–SW-trending reverse faults and occur within a 400 x 400 km area in northern Fennoscandia. The normal Nordmannvikdalen fault is a minor fault trending perpendicular to the reverse faults. The NW–SE-trending Storuman fault in northwestern Sweden may be an analogue to the Nordmannvikdalen fault but the sense of movement along the fault has not been studied yet (Lagerbäck and Sundh 2008). The NW–SE-trending Vaalajärvi fault in northern Finland has been removed from the table since it is most likely not postglacial (M. Paananen, pers. comm. 2007). The scarp height/length ratio is generally less than 0.001. The Merasjärvi Fault has a scarp height/length ratio of 0.002. *Moment magnitudes calculated from fault offset and length utilising formulas by Wells and Coppersmith (1994).*

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 1998
2.	Nordmannvik-dalen	Norway	2	1	0.0005	NW–SE	Normal	6.0		Tolgensbakk and Sollid 1988
3.	Suasselkä	Finland	48	5	0.0001	NE–SW	Reverse	7.0		Kujansuu 1964
4.	Pasmajärvi–Venejärvi	Finland	15	12	0.0008	NE–SW	Reverse	6.5	Two separate sections	Kujansuu 1964
5.	Pärvie	Sweden	155	13	0.0001	NE–SW	Reverse	7.6		Lundqvist and Lagerbäck 1976
6.	Lainio–Suijavaara	Sweden	55	*c.* 30	0.0005	NE–SW	Reverse	7.1		Lagerbäck 1979
7.	Merasjärvi	Sweden	9	18	0.002	NE–SW	Reverse	6.3	Possible extension of the Lainio–Suijavaara Fault	Lagerbäck 1979
8.	Pirttimys	Sweden	18	2	0.0001	NE–SW	Reverse	6.5		Lagerbäck 1979
9.	Lansjärv	Sweden	50	22	0.0004	NE–SW	Reverse	7.1		Lagerbäck 1979
10.	Burträsk–Röjnoret	Sweden	60	*c.* 10	0.0002	NE–SW N–S	Reverse	7.1	Two separate faults	Lagerbäck 1979
11.	Sorsele	Sweden	2	1.5–2	0.0009	NE–SW	Reverse	6.1		Ransed and Wahlroos 2007
12.	Storuman	Sweden	10	10	0.001	NW–SE	?	6.3	Several separate faults	Johansson and Ransed 2003

the two postglacial faults described in the sections above and an active area of extension and subsidence in the outer Ranafjorden area (Olesen et al. 2012b). The grade B claims include areas with secondary effects, probably triggered by large-magnitude earthquakes, such as liquefaction and semiliquefaction structures in the Flatanger (Nord-Trøndelag) and Rana (Nordland) areas, and gravitational spreading and faulting features (sackung) on Kvasshaugen in Beiarn (Nordland), Berill in Rauma 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) 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 triggering these events (Anda et al. 2002, Braathen et al. 2004, Blikra et al. 2006). 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. The Tjellefonna and Silset rock avalanches in 1756 in the Møre & Romsdal county were possibly caused by an earthquake (Morsing 1757) and are therefore classified as a C claim (possibly neotectonics) in the present study.

A majority of the neotectonic claims can consequently be attributed to causes other than tectonic (Olesen et al. 2004). Gravity-induced sliding and glacial erosion along pre-existing faults and fractures were 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 and Eisbacher (1995) showed that moving glaciers in the Canadian Cordillera tend to pluck bedrock along extensional fractures parallel to the

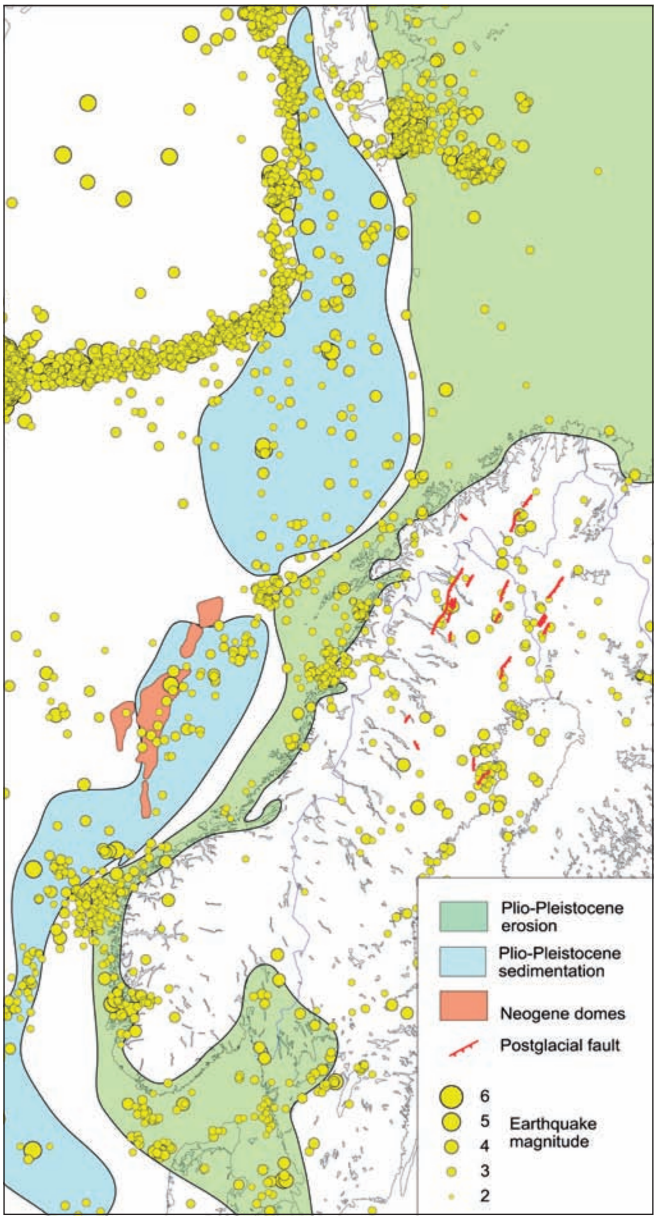

Figure 4. Earthquakes (1980–2011), postglacial faults, Neogene domes and areas of interpreted Pliocene/Pleistocene deposition and erosion along the Norwegian continental margin (modified from Blystad et al. 1995, Riis 1996, Lidmar-Bergström et al. 1999, Bungum et al. 2000, 2010, Dehls et al. 2000b, Lagerbäck and Sundh 2008, Kukkonen et al. 2010). The areas of Pliocene/Pleistocene sedimentation and erosion coincide with present-day seismicity, indicating that recent loading/unloading is causing flexuring and faulting in the lithosphere. The erosion of the central and southwestern Barents Sea may be older than the erosion of the Svalbard region and the coastal areas of northern, western and southeastern Norway since the seismicity of the former area is low. Focal-plane solutions (Dehls et al. 2000b, Hicks et al. 2000a) indicate the dominating compressional events in the areas with loading, whereas the regions with recent unloading have predominantly extensional or strike-slip events.

direction of maximum horizontal stress. An inland glacier could, in a similar way, cause a higher degree of bedrock plucking by basal glacier shear along favourably oriented fractures in areas with highly anisotropic rock stress.

The highest numbers of neotectonic claims have been reported from Rogaland, Hordaland and Nordland (Figure 1), but no postglacial faults have, up until now, been documented in these areas. Helle et al. (2007) made a new review of neotectonic reports from the former two counties. They emphasised the observed deviations from the general pattern in the Younger Dryas maximum highstand shoreline as indications of movements younger than *c.* 10,500 ^{14}C years BP. These deviations are in the order of 2–6 m and are mostly based on single observation points. Helle et al. (2007) were not able to relate these anomalous locations to any nearby postglacial faults. There are, however, indications of postglacial faulting on high-resolution, multibeam, echo-sounding data to the west of Bokn (Figs. 5.2 and 5.3 in Rønning et al. 2006). This 3 km-long and NNE–SSW-trending fault occurs along a line that may constitute an extension of Skjoldafjord to the southwest. There is unfortunately no high-quality bathymetry in the Skjoldafjord area that could be utilised to link the Bokn fault to the observed offset in the Yrkje area on the eastern shore of Skjoldafjord. The scarp faces west, consistent with the eastern part of the Yrkje area being uplifted. The height of the scarp along the Bokn fault varies between 0 and 60 m and this variation is too high to be related to faulting along this short fault segment (see criteria in Fenton 1994, Muir Wood 1993, Olesen et al. 2004). The postglacial faulting could, however, be superimposed on a pre-existing erosional scarp. The postglacial scarp can locally be covered by marine clay due to variability of the currents in the area.

Helle et al. (2007) also referred to observed apparent offsets of sediments on seismic profiles in Hardangerfjorden (Hoel 1992) as indications of postglacial faults. An interpretation of modern seismics and multibeam, echo-sounding surveys for the planning of a subsea power line in the Hardangerfjorden has revealed that the seafloor offsets are related to submarine landslides (Eriksson et al. 2011, Oddvar Longva, pers. comm. 2012).We therefore do not regard these reports as compelling evidence of postglacial faulting and have consequently graded them as D (probably not neotectonics). Modern, multibeam, echo-sounding surveying is an efficient method for scrutinising deep fjords and lakes in the potential neotectonic areas for postglacial faulting.

The Ranafjorden–Meløy area in Nordland is another area with numerous reports of neotectonic deformation (Figures 1 and 5). Olesen et al. (1995) suggested that the 50 km-long Båsmoen fault could be a candidate for a postglacial fault. They based their evidence on the observed escarpments facing NNW and an anomalous present-day uplift pattern along the fault. No conclusive evidence, however, has been found for postglacial movements along the fault (Olesen et al. 2004), although trenching has indicated a 40 cm offset along the fault in the Båsmoen area (Olsen 2000, Olesen et al. 2004). The observed seismicity (Hicks et al. 2000b) seems to occur along N–S-trending fractures and faults with pronounced escarpments in the Handnesøya–Sjona area (Figures 7 and 8 and Olesen et al. 1995). These scarps have been partly attributed to plucking effects by the moving inland ice. It is also intriguing that there

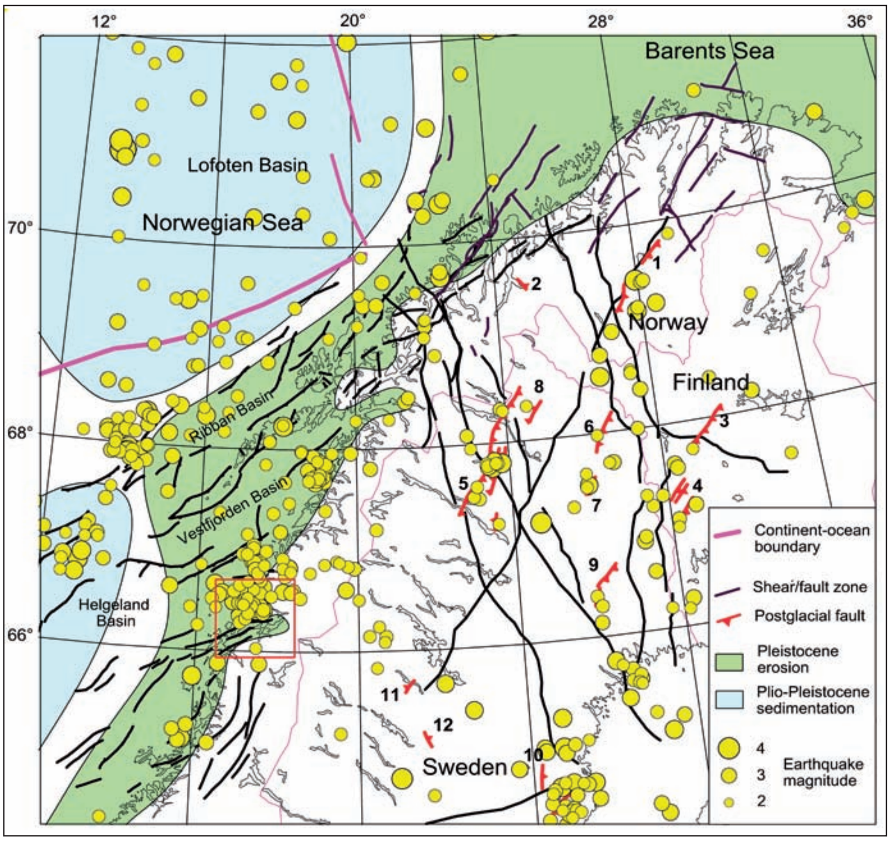

Figure 5. Earthquakes (M >2.5) during the period 1980–2011, postglacial faults and main basement structures in northern and central Fennoscandia. Details of the postglacial faults are shown in Table 1. The postglacial faults occur in areas with increased seismicity indicating that they are active at depth. The numbers adjacent to the faults refer to the numbers in Table 1. The interpreted basement structures (shear zones and detachments) from northern Fennoscandia are compiled from Henkel (1991), Olesen et al. (1990, 2002) and Osmundsen et al. (2002).

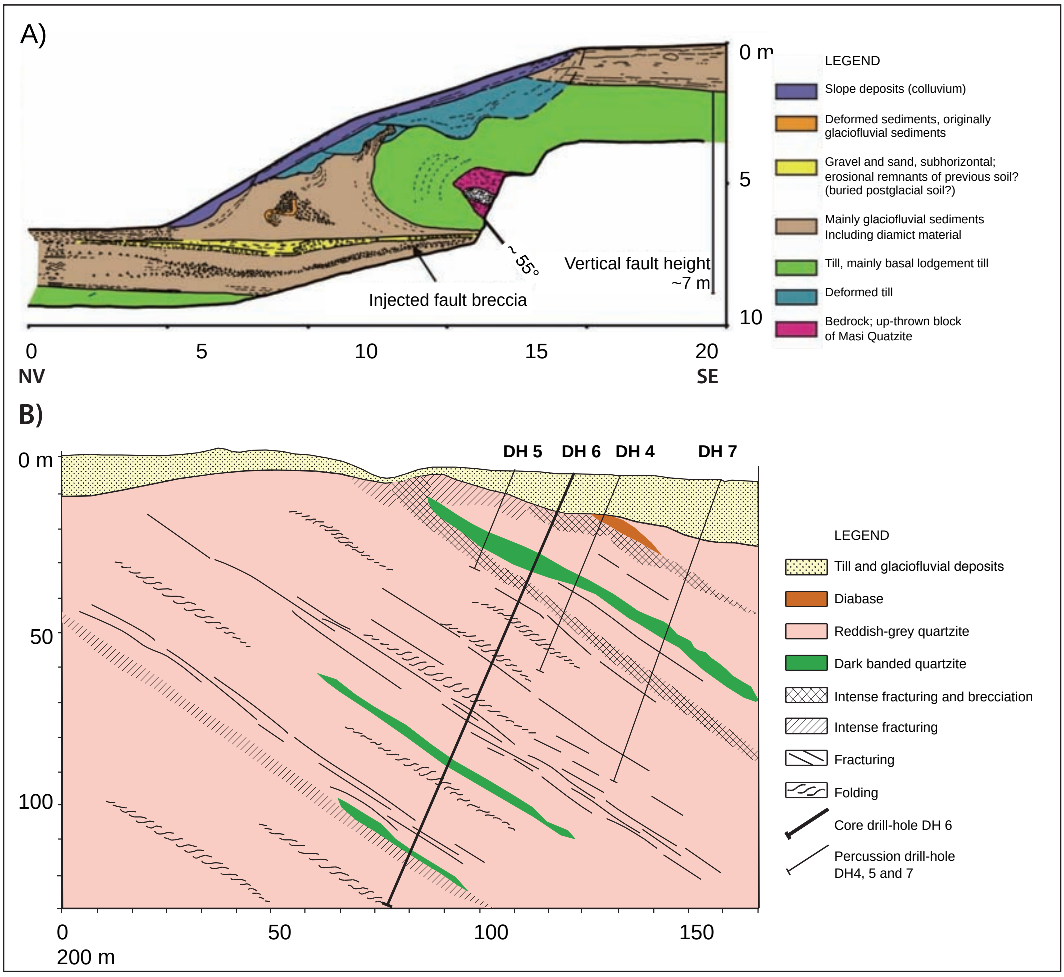

Figure 6. Stuoragurra Fault. (a) Folded Quaternary sequence consisting of basal till and glaciofluvial sediments above and in front of the up-thrown hanging-wall block of the Stuoragurra Fault. Note the fault breccia that has been injected into the glaciofluvial sediments most likely as a mixture of rock fragments and high-pressure groundwater (Modified from Dehls et al. 2000a). (b) Interpretation profile across the Stuoragurra Fault based on core (DH6) and percussion (DH4, 5 and 7) drilling and geophysical measurements (Olesen et al. 1992a,b, Roberts et al. 1997, Olesen et al. 2000, Kukkonen et al. 2010). The trench in (a) is located c. *100 m to the northeast of the profile in (b). See Figure 16 in Olesen et al. (1992b) for more details on the two locations.*

Figure 7. Several vertical fracture zones on Handnesøya (Olesen et al. 1994, 1995). The western blocks seem to be downfaulted. Part of the scarps could be the effect of subglacial plucking from the moving inland ice (Olesen et al. 2004). The two westernmost scarps appear to coincide with the linear seismicity clusters in Figure 8. Looking north from the quay in Nesna.

are no observed offsets of marine sediments on reflection-seismic profiles in the fjord to the north or the south of Handnesøya (Longva et al. 1998).

Several independent datasets in the outer Ranafjorden region indicate that the area is currently experiencing a regime of WNW–ESE extension (Figure 8). A six-station seismic network in this region during an 18 month period from July 1997 to January 1999 detected *c.* 300 earthquakes, many of them occurring as swarms. Fault-plane solutions indicate E–W extensional faulting. The outer Ranafjorden district is also the location of the largest earthquake recorded in Fennoscandia in historical times, i.e., the *c.* 5.8 magnitude in 1819 (Muir Wood 1989b, Bungum and Olesen 2005). Liquefaction structures in the postglacial overburden point to the likely occurrence of large, prehistoric earthquakes in this area. Three measurements of uplift of acorn barnacle and bladder wrack marks on the islands of Hugla and Tomma in the outer Ranafjorden area (Figure 8) show anomalously low land uplift from 1894 to 1990 (0.0–0.07m) compared to the uplift recorded to the north and south (0.23–0.30 m). Dehls et al. (2002) observed an irregular relative subsidence pattern from InSAR permanent scatterer data during the period 1992–2000 (Figure 8) in the areas with high seismicity and the observed fault scarps. The relatively low seismicity occurring at a depth of 2–12 km could therefore have created the observed irregular subsidence pattern at the surface. We have established a network of benchmarks to measure the active strain in the Ranafjorden area by use of the Global Positioning System (GPS). Three 15–20 km-long profiles were established across outer, central and inner Ranafjorden. GPS campaign measurements in 1999 and 2008 indicate that the bench marks along the western profile have moved *c.* 1 mm yr^{-1} to the NW and W relative to the stations along the two eastern profiles (Olesen et al. 2012b) (Figure 8). Fault-plane solutions indicate E–W extensional faulting (Hicks et al. 2000b).

Some of the earthquake clusters in the Handnesøya and Sjona areas are located along NNW–SSE-trending fracture zones with escarpments facing to the west. They were most likely formed by glacial plucking of the bedrock along the fractures by the moving inland ice. Ice-plucking features may, however, be indirectly related to neotectonics.

Studies of rock avalanches indicate two separate, large-magnitude earthquakes in the North Troms–Finnmark region during the period 11,000–9,000 BP (Dehls et al. 2000a, Blikra et al. 2006). There is also a possible event in the Astafjorden–Grytøya area in southern Troms where a relatively high con-

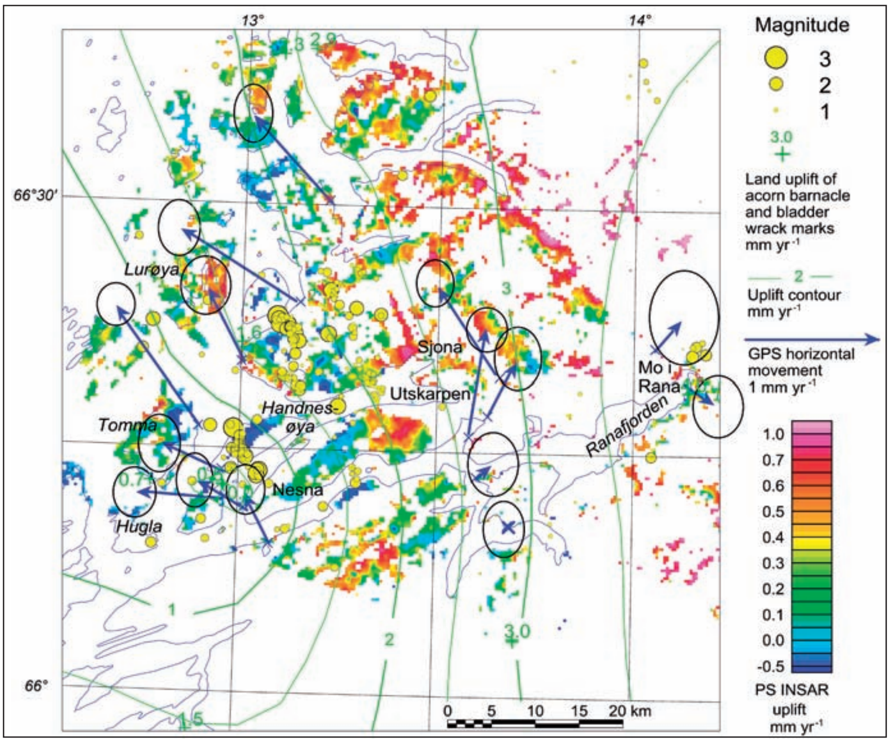

Figure 8. Annual uplift during the period 1992–2000 from the InSAR permanent scatterer method (Dehls et al. 2002). The observed seismicity from July 1997 to January 1999 (Hicks et al. 2000b) seems to occur along N–S-trending clusters that coincide with areas of relative subsidence and mapped fractures and faults with pronounced escarpments (Olesen et al. 1995). These scarps have been partly attributed to plucking effects by the moving inland ice. GPS stations to the west of the earthquake clusters have moved c. *1 mm yr^{-1} to the west relative to the stations on the eastern side during the period from 1999 to 2008 (Olesen et al. 2012b). Fault plane solutions indicate E–W extensional faulting (Hicks et al. 2000b).*

centration of rock avalanches has been recorded (Blikra et al. 2006). The latter observation has been graded as C (possibly neotectonics). Palaeoseismic events have also been postulated in western Norway (Bøe et al. 2004, Blikra et al. 2006, Longva et al. 2009). 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 2,000–2,200 calendar years BP. The 8,000 yr BP event has been attributed to the tsunami generated by the Storegga slide. An 8,000 yr BP liquefaction event registered in Nord-Trøndelag may have been triggered by an earthquake.

Offshore

Detailed analysis of offshore 2D and 3D seismic data has not yet revealed any definite neotectonic deformation structures. Several distortions in the Quaternary reflectors, however, have 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 deeper parts of the Norwegian Sea.

The NEONOR project evaluated 14 reports of 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 outermost areas overlying the oceanic crust.

Hovland (1983) described faulting of a soft, silty clay on the sea floor at the basal western slope of the Norwegian Channel. The faults terminate at shallow depths and are 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 a release of this gas. A multibeam, echo-sounding survey (Olesen et al. 2004) carried out in 1999, within the frame of the NEONOR project, confirmed the findings of Hovland (1983). The seafloor topography in this area is characterised by N–S-trending faults and fissures with up to 1–2 m throws, and also by large, elongate pockmarks (Figure 9). Olesen et al. (2004) also reported a similar set of structures in the Kvitebjørn area located immediately to north of the bathymetric survey. In this area, there are also indications of high gas saturation at shallow depth.

Chand et al. (2012) reported a comparable set of faults in the SW Barents Sea. Unloading due to deglaciation and erosion resulted in opening of pre-existing faults and creation of new ones, facilitating fluid migration and eventual escape into the water from the subsurface. Expressions of hydrocarbon gas accumulation and fluid flow such as gas hydrates and pockmarks are widely distributed in the Barents Sea. Several gas flares, some of them 200 m high in echograms, occur along a segment of the Ringvassøy–Loppa Fault Complex, indicating open fractures and active fluid flow (Chand et al. 2012). These open fractures resemble the vertical fractures observed on mainland Nordland, which are most likely also related to Pleistocene unloading (Olesen et al. 2004, 2012b).

Faults and pockmarks similar to the ones reported from the North Sea and the Barents Sea also exist in the Storegga area on the Mid-Norwegian shelf (Fulop 1998). In these cases, it has also not been possible to relate the faults and fissures to any deeper structures. Judd and Hovland (2007) discussed the occurrence and distribution of the numerous pockmarks in relation to the present-day seismicity in the North Sea, and concluded that the seismicity was too low to have triggered a flow of fluids

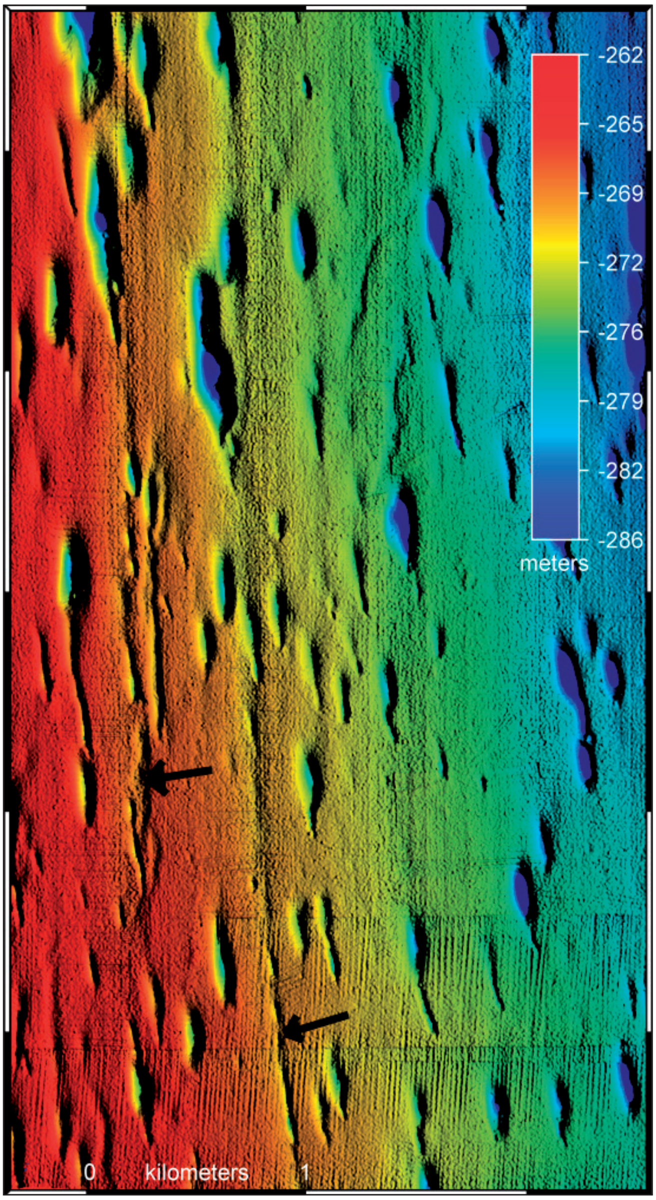

Figure 9. Bathymetry along the western margin of the Norwegian Channel south of Kvitebjørn. Abundant pockmarks (up to 500 m long and 10 m deep) occur in the area (location 28 in Figure 1 and in the Appendix). The arrows show postglacial faults, which seem to be related to the formation of the elongated pockmarks. Offset along the faults is approximately 1 m. The elongate form of the 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).

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. Bungum et al. (2005) have also suggested that large-scale postglacial earthquakes could have occurred along hidden thrusts beneath the seabed offshore Mid-Norway.

Another possible neotectonic feature that has been identified on the Mid-Norwegian continental shelf is the probable reactivation of Neogene dome structures in the deeper parts of the Norwegian Sea (Blystad et al. 1995, Vågnes et al. 1998, Lundin and Doré 2002). Contractional structures (large anticlines and synclines, reverse faults and inverted depocentres) were initiated during the Palaeogene in the Vøring and Møre Basins. There are indications that some of these structures have been growing from the Eocene to the present (Vågnes et al. 1998), with an episode of more prominent deformation in the Miocene (Lundin and Doré 2002). Doré et al. (2008) related the domal structures to the gravitational effects from the mass excess within the Iceland Plateau.

The shelf edge of the Norwegian and Barents Seas is presently a region of relatively high seismicity. Large-scale slumping also occurred 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, whilst others, like the main Storegga slide, are definitely postglacial. Bugge et al. (1988) and Solheim et al. (2005) speculated that earthquakes triggered the large slides. Submarine slides may, consequently, be secondary effects of neotectonic activity in some areas.

A several km-long and NNW–SSE-trending escarpment has been mapped *c.* 40 km to the SSE of Sørkapp on Svalbard (Angelo Camerlenghi, pers. comm.. 2010 on unpublished SVAIS Project multibeam data). The scarp is facing to the WSW and its height appears to be consistent. It is a candidate for a postglacial fault, but high-resolution seismic profiling is needed to validate the claim.

Seismicity

On a global scale, the seismicity of Norway is low to intermediate, even though it is the highest in northern Europe. The available historical data indicate a cumulative recurrence relation $\log(N) = 4.32–1.05M_W$ (Bungum et al. 2000), which means one earthquake of M 5 or larger every 8–9 years and one of M 6 or larger every 90–100 years. The largest earthquakes in historical times in Norway and surrounding offshore areas occurred in Storfjorden, Svalbard, in 2008, M 6.0 (Pirli et al. 2010), in the Rana region in 1819, M 5.8 (Muir Wood 1989b, Bungum and Olesen 2005), in the Vøring Basin in 1866, M 5.7, in the outer Oslofjord in 1904, M 5.4 (Bungum et al. 2009) and in the Viking Graben in 1927, M 5.3 (Bungum et al. 2003). The most recent M>5 earthquakes include an M 5.3 event in the Vøring Basin in 1988, in an area with almost no earlier seismicity (Byrkjeland et al. 2000), and an M 5.2 event in the northeastern North Sea in 1989 (Hansen et al. 1989). This indicates that we might anticipate another larger earthquake in Norway relatively soon in one of the seismically active areas, either in the Oslofjorden region or in the coastal areas of western and northern Norway, given that it is now more than 20 years since we had the last 1-in-10-year earthquake. Even so, the occurrence of earthquakes is still essentially Poisson distributed (memory free), and the location of future, large, intraplate earthquakes is also highly uncertain in a region where the causative fault is not likely to be known.

The seismicity of Norway is strictly intraplate, also along the passive continental margin, but even so it covers a region with strain rates with several orders of magnitude variation (Bungum et al. 2005, Kierulf et al. 2012) and with large variations also in tectonic conditions. The main control on the seismicity in this region may be the passive continental margin itself, with the large lateral variations in structural composition within it. Moreover, some of the large sedimentary basins (depocentres) also seem to be correlated with seismicity (especially in the Lofoten Basin), as discussed in detail by Byrkjeland et al. (2000). In the Nordland region there is also a parallel, shallow-seismic lineation along the coast, representing mostly extensional stress failure. Other seismic areas are in the failed graben structures in the North Sea and in the Oslo Rift zone (Bungum et al. 2000, Bungum et al. 2009). This pattern of seismicity is fairly consistent with the conclusions from a global study of so-called stable continental regions (SCR) (Johnston and Kanter 1990, Johnston et al. 1994, Schulte and Mooney, 2005), maintaining that rifted passive margins and failed rifts are the two main types of host structures responsible for the largest earthquakes in such areas. There are on the order of 20 such earthquakes above M 7 known to us on a global scale (Bungum et al. 2005), and recent studies from Australia (Leonard and Clark 2011, Clark et al. 2012) indicate that this number is likely to be steadily increasing. It should be kept in mind, however, that the recurrence times at any given SCR location could easily be thousands of years, in contrast to decades or centuries at plate margins. This is the situation that has given rise to recent claims that some large earthquakes in low-seismicity regions have not been 'predicted' by published hazard maps (Hanks et al. 2012). In any case, given that the largest historical earthquake on mainland Norway is on the order of M 6, it has been suggested that there may be a significant earthquake deficit in this region (Bungum et al. 2005).

Another potentially important factor for the seismicity of Norway is the fact that Fennoscandia has been fairly recently deglaciated, where we know that the initial and rapid uplift connected to this deglaciation resulted in a burst of larger earthquakes (Johnston 1987, 1989, Muir Wood, 1989a, Dehls et al. 2000a, Olesen et al. 2004), possibly even triggering the giant Storegga submarine slide (Solheim et al. 2005). We do not yet have a good understanding of the way in which the transition from the high seismicity of 10,000–6,000 years ago to the low seismicity of today has taken place, except that there are strong indications that the present-day seismicity is largely related to contemporary tectonic processes rather than being an effect of remaining glacioisostatic adjustments (Bungum et al. 2005).

Contemporary stress field

The contemporary stress field has been discussed extensively in terms of possible driving mechanisms by Fejerskov and Lindholm (2000). The discussions of potential stress-driving sources include ridge push, glacial rebound, flexural stresses through sedimentation and topography. In Norway, as well as globally, the earthquake focal mechanisms represent a unique source for understanding the underlying stresses since the earthquakes sample the deeper parts of the crust. It is, however, also important to understand the limitations, since even in regions where the global stress model is clear (e.g., in the Himalayas), each single earthquake focal mechanism may deviate significantly from the regional picture. Moreover, small earthquakes are more influenced by smaller-scale, stress-modifying factors than larger events, which carry a higher regional significance.

There is now strong evidence that the stress regime responsible for the observed seismicity appears to be the result of diverse stress-generating mechanisms at scales ranging from crustal plate to local, and that the stress field at any given place is therefore multifactorial (e.g., Bungum et al. 1991, 2005, Byrkjeland et al. 2000, Fejerskov and Lindholm 2000, Fejerskov et al. 2000, Lindholm et al. 2000, Olesen et al. 2004). Earthquakes generally occur along pre-existing zones of weakness and result from a buildup of stress and reduced effective shear strength along favourably oriented faults (Bungum et al. 2005). A key factor in reaching a better understanding of the seismicity will therefore be to improve our understanding of the interaction between the resultant stress field and the various zones of weakness in the crust.

In situ stress measurements argue for relatively high deviatoric stress magnitudes at shallow depths below the ground (Stephansson et al. 1986). The recent discovery of impressive stress-relief structures in different regions of Norway (Roberts 1991, 2000, Roberts and Myrvang 2004, Pascal et al. 2005a,b, 2006, 2010) adds support to this conclusion. Such features include reverse-fault offsets of drillholes in road-cuts and quarries, and consistently oriented, tensional axial fractures in vertical drillholes (Figure 10). Although stress deviations are observed locally in Norway, maximum principal stress axes determined both by in situ stress measurements (Figure 11) and by stress-relief features (Figure 12) are, in general, horizontal and strike NW–SE to WNW–ESE (Dehls et al. 2000b, Reinecker et al. 2005, Pascal et al. 2006), suggesting ridge-push as an important contributing mechanism (e.g., Bungum et al. 1991, Byrkjeland et al. 2000, Pascal and Gabrielsen 2001). Postglacial rebound has quite commonly been advanced as a secondary source. The viscoelastic readjustment of the lithosphere is theoretically prone to generate deviatoric stresses of a much greater magnitude than in the case of ridge-push (i.e., ~100 MPa, Stein et al. 1989). However, no clear radial pattern can be observed in the present-day stress compilations (Reinecker et al. 2005) indicating that, in contrast to the situation that prevailed just after deglaciation (Wu 1998, Steffen and Wu 2011), rebound stresses are currently relatively low. While shallow seismicity with extensional (flexural) mechanisms in the coastal regions of Nordland has earlier been associated with glacioisostatic adjustments (Hicks et al. 2000b, Bungum et al. 2005), flexure due to erosion and unloading may be a more important factor here. Flexural loading of offshore basins by high rates of sedimentation during Pliocene to Pleistocene time represents another stress source, explaining reasonably well a part of the offshore seismicity, such as in the Lofoten Basin (Byrkjeland et al. 2000), the outer part of the Mid-Norwegian shelf and the central axis of the North Sea (Figure 4). The volume of sediments deposited along the continental margin in the Pleistocene Naust Formation has been well mapped during the last decade (Figure 13, Rise et al. 2005, Dowdeswell et al. 2010) and can be used to constrain the amount and timing of onshore erosion. Average sedimentation rates during the last ice age are estimated to have been ~0.24 m kyr^{-1} with 2–3 times higher rates for the most recent 600 kyr (Eidvin et al. 2000, Dowdeswell et al. 2010). The substantial sediment erosion must have led to significant onshore exhumation and isostatic rebound. The main present-day topography, however, is considered to be much older; outcrops of deeply weathered basement rocks in the Vestfjorden and Ranafjorden areas, for example, indicate a primary inheritance from the Mesozoic (Olesen et al. 2012a).

An additional stress source that has commonly been mentioned in the literature, and tentatively quantified by Fejerskov and

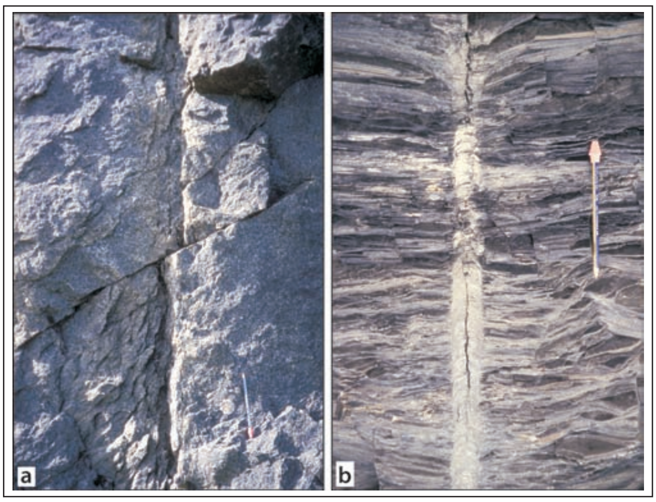

Figure 10. (a) Drillhole offset in a reverse sense along a joint surface in granulite gneisses, south of Beskelandsfjorden, Roan, Fosen Peninsula, Sør-Trøndelag; looking south. Locality – 1:50,000 map-sheet 'Roan' 1623 III, 3–NOR edition, grid-ref. NS6075 1815. (b) Well developed axial fracture in a drillhole in slates of the Friarfjord Formation, Laksefjord Nappe Complex, from the roofing slate quarries at Friarfjord, close to the old quay. 1:50,000 map-sheet 'Adamsfjord' 2135 I, 3–NOR edition, grid-ref. MU9695 1810. This particular quarry face trends N–S, and the photo is taken looking due west.

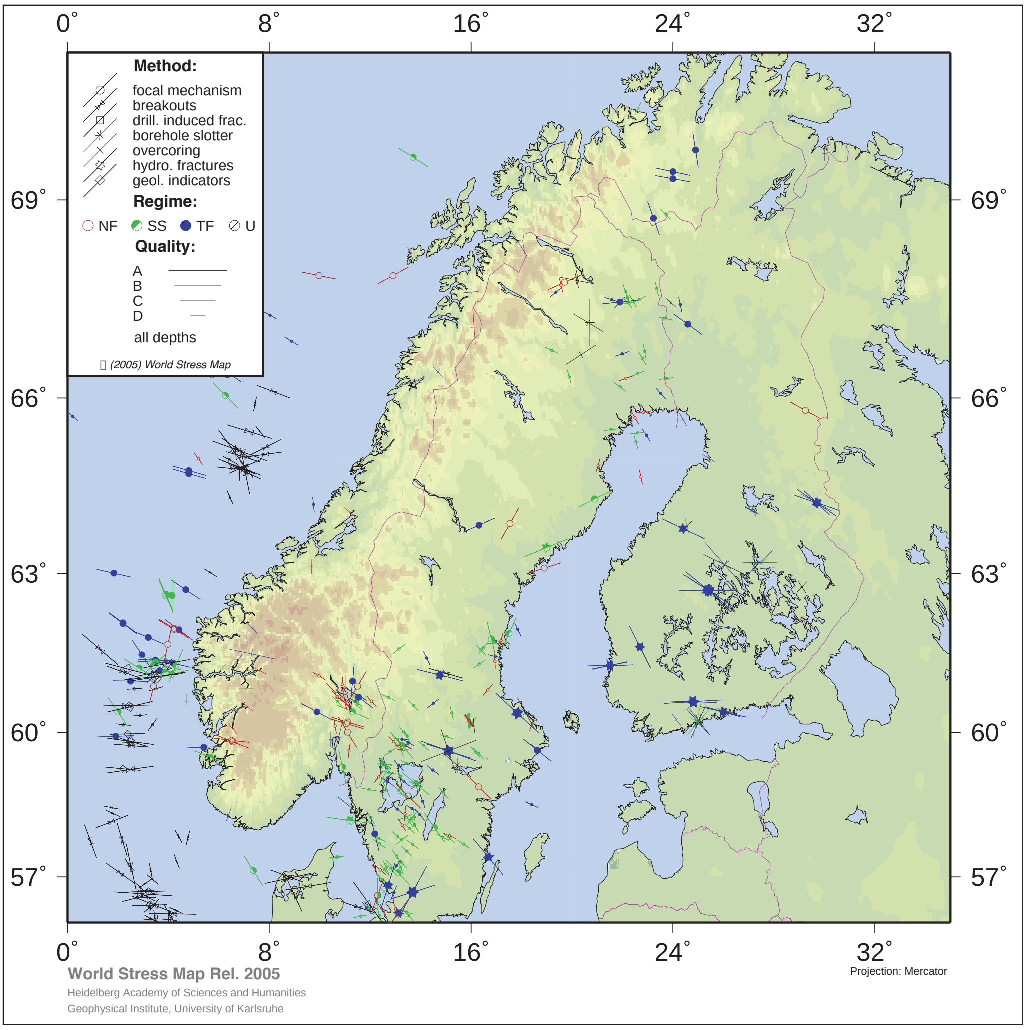

Figure 11. Contemporary stress orientations in Fennoscandia taken from the World Stress Map (Reinecker et al. 2005). Note that S_{Hmax} is predominantly NW–SE oriented.

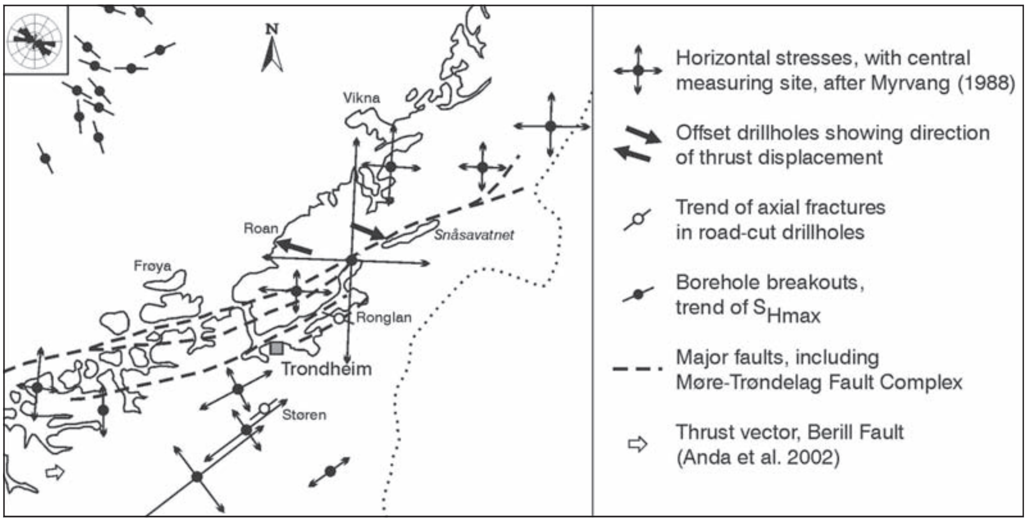

Figure 12. Outline map showing the diverse rock-stress orientation data from central Norway and the Trøndelag Platform. The small rose diagram (inset, top left) is from Hicks et al. (2000a, p. 243) and depicts the trends of maximum horizontal compressive stress as derived from earthquake focal mechanism solutions in the area of offshore Mid Norway (period 1980–1999). The figure is from Roberts and Myrvang (2004).

Lindholm (2000), is associated with the anomalous elevation differences of southern and, to a lesser extent, northern Norway. It has been shown recently, for example, that the southern Scandinavian mountains are likely to generate significant gravitational stresses in adjacent offshore sedimentary basins (Pascal and Cloetingh 2009). This model offers an alternative explanation to the anticlockwise stress rotation observed from the Norwegian margin to the northern North Sea, which Fejerskov and Lindholm (2000) found to be consistent with gradually changing ridge-push directions. The NE–SW stress orientations detected southeast of the Møre–Trøndelag Fault Complex (Figure 12) (Roberts and Myrvang 2004) have also been interpreted (Pascal and Cloetingh 2009) in terms of changes in gravitational stresses. In the Oslo Region and Nordland (Ranafjord area, see Hicks et al. 2000b), the stress patterns appear to be more complex, probably simply because there are more observations from these regions. In the Oslo Region, the orientation of the maximum horizontal stress axis is, in general, WNW–ESE, but with local deviations and stress permutations (Hicks et al. 2000a, Dehls et al. 2000b, Pascal et al. 2006, 2010). There is, for example, a (weak) tendency for focal mechanisms of shallow (<13 km) earthquakes to relate mostly to normal faulting, whereas deeper events indicate strike-slip and reverse faulting (Hicks 1996). It is tempting to interpret this complex stress pattern in terms of flexuring due to Neogene erosion and unloading and, perhaps, in terms of structural complexity (including lateral changes in rheology) inherited from the Permian magmatic and rifting event.

In Nordland, as mentioned earlier, inversion of focal mechanisms of earthquakes indicates a coast-perpendicular extensional stress regime with shallow earthquakes (Figure 14), which is directly opposite to what is found along the margin farther offshore (Hicks et al. 2000b, Bungum et al. 2010). There are, however, also some strike-slip earthquakes here, with coast-parallel compressions. This anomalous stress field (contrasting with the regional one) appears to be associated with a locally enhanced uplift pattern and a related flexuring mechanism. This may in turn be related to remaining glacioisostatic adjustments, but since very recent erosion has taken place in Nordland, the crust there may be strongly flexed, which also would result in coast-perpendicular extension.

In Trøndelag, central Norway, rock-stress measurements and stress-release features have shown that the Møre–Trøndelag Fault Complex marks an important structural divide separating crustal blocks with disparate, present-day stress fields (Roberts and Myrvang 2004), as previously suggested by numerical-modelling studies (Pascal and Gabrielsen 2001). A NW–SE to WNW–ESE horizontal compression prevails in coastal areas northwest of the fault complex, and accords with borehole breakout and earthquake focal mechanism solution data acquired offshore (Figure 11). This linked stress pattern, from onshore to offshore, provides further support for the notion that the dominant S_{Hmax} trend is likely to relate to a distributed ridge-push force arising from divergent spreading along the axial ridge between the Norwegian and Greenland Seas.

Some important points, however, should be kept in mind here. Firstly, small earthquakes have a similarly small regional

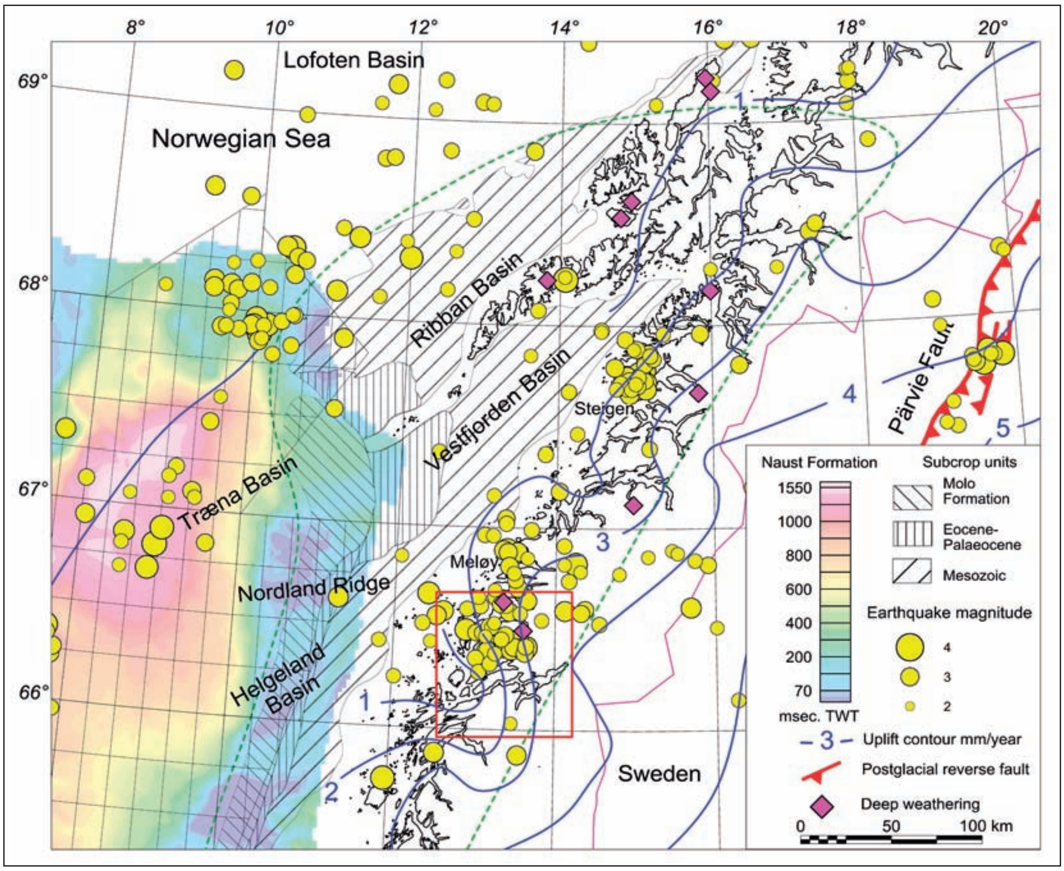

Figure 13. Map of the Nordland margin, including source catchment area of glacial erosion (green dashed line) and area of offshore deposition (isopach map of thickness of the Naust Formation in milliseconds of two-way travel time, where 1 ms is ~1 m). Blue line marks present shelf edge. Adapted from Dowdeswell et al. (2010). Zones of deep weathering up to 100 m thick and more than 10 km wide occur within the eroded area indicating that the present landscape is to a large degree of Mesozoic age. Subcrop units (modified from Sigmond 2002) underlying the Naust Formation are mainly Tertiary, Cretaceous, and Jurassic sedimentary rocks (hatched pattern). Earthquakes from the period 1989–2011 are shown in yellow and the size of the circles reflects the magnitude on the Richter scale. The red frame depicts the location of Figure 8.

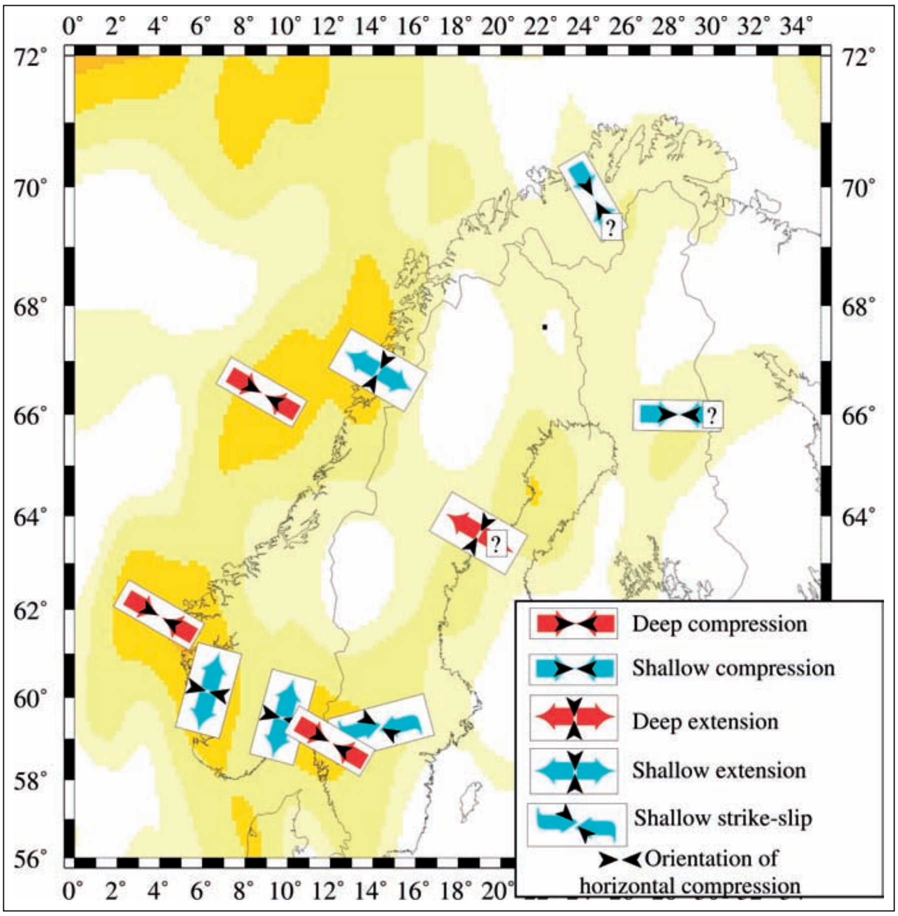

Figure 14. Stress orientations, type of faulting and focal depths synthesised from earthquake focal mechanisms and in situ stress measurements (from Fjeldskaar et al. 2000). Areas with sparse data are indicated with question marks. Intensity of yellow indicates intensity of seismicity. Note that offshore depocentres generally coincide with areas of dominating compressional events whereas the coastal areas have a predominantly extensional regime.

significance and their inferred stress orientations may deviate from the regional stress pattern for a variety of reasons, also because of the assumption that the stress axes bisect the angles between the nodal planes and because earthquakes in general occur along pre-existing faults (e.g., Sibson 1990). Secondly, the crustal stress tensor everywhere is built up with contributions from a number of sources and therefore cannot be explained by a single contributing source. It is, therefore, surprising that the stress orientations are as stable and consistent as they have been shown to be.

Postglacial and contemporary uplift

A dataset of the absolute vertical uplift of Fennoscandia compiled from tide gauges, precise levelling and continuous GPS stations (Vestøl 2006) has been combined with seismicity recorded during the period 1980–2011 and is shown in Figure 15a. The figure shows no clear correlation between onshore uplift and seismicity in Fennoscandia. However, in a model that combines offshore subsidence with onshore uplift, it is readily understood that the coastal regions will be relatively most susceptible to crustal flexuring and deformation, as also confirmed by present-day seismicity. The BIFROST GPS network (Milne et al. 2001, Lidberg et al. 2007) 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 yr^{-1} occurs in the Umeå area (Milne et al. 2001, Scherneck et al. 2001, 2003, Lidberg et al. 2007). The horizontal movements are directed outward from this location on all sides with the highest values located to the northwest and east (reaching 2 mm yr^{-1}). The northwestern area coincides with the Lapland province of postglacial faulting in northern Fennoscandia. Kakkuri (1997) also measured a maximum, present-day, horizontal strain in the region of postglacial faults in northern Finland. Pan et al. (2001), however, reported differential horizontal displacements along the border zone between the Fennoscandian Shield and the European lowland.

Semiregional deviations from the regional uplift pattern in the order of 1–2 mm yr^{-1} have been reported by Olesen et al. (1995) and Dehls et al. (2002) for the Ranafjorden area in northern Norway. This conclusion is deduced from two independent datasets, namely repeated levelling and permanent scatterer techniques. Fault-plane solutions reported by Hicks et al. (2000b) show extensional faulting in the same area. Vestøl (2006) has carried out a least-squares collocation adjustment of the combined precise levelling, tide gauge recordings and time series from continuous GPS stations. He concluded that some semiregional uplift anomalies in Fennoscandia are related to inaccuracies in the original levelling data.

The Fennoscandian Shield was affected by a Neogene phase of passive doming (approximately 1,000 m amplitude) in southern Norway and in the Lofoten–Troms area (Riis 1996). Hence, the present elevation of Scandinavia is partly the result of Neogene uplift and exhumation of a fault-controlled topography (Osmundsen et al. 2010). 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 actually deposited during the last 2.6 m.y (last 5% of the time period).

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^{-1} during the Quaternary, in addition to postglacial uplift, as also suggested by Mörner (1980). Recent studies of uplifted, Middle and Upper Weichselian, marine sediments (Olsen and Grøsfjeld 1999) show, however, that the inland ice sheet fluctuated quite frequently during the 50,000–18,000 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 presence of elevated Weichselian marine clay on Høg–Jæren and coastal caves above the maximum Holocene marine limit on the innermost strandflat in western and northern Norway. These elevated caves have also been interpreted in terms of a Neogene tectonic uplift (Holtedahl 1984, Sjöberg 1988).

Fjeldskaar et al. (2000) argued that the long-term Neogene uplift of western Scandinavia is still active and can explain approximately 1 mm yr^{-1} 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 specific 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

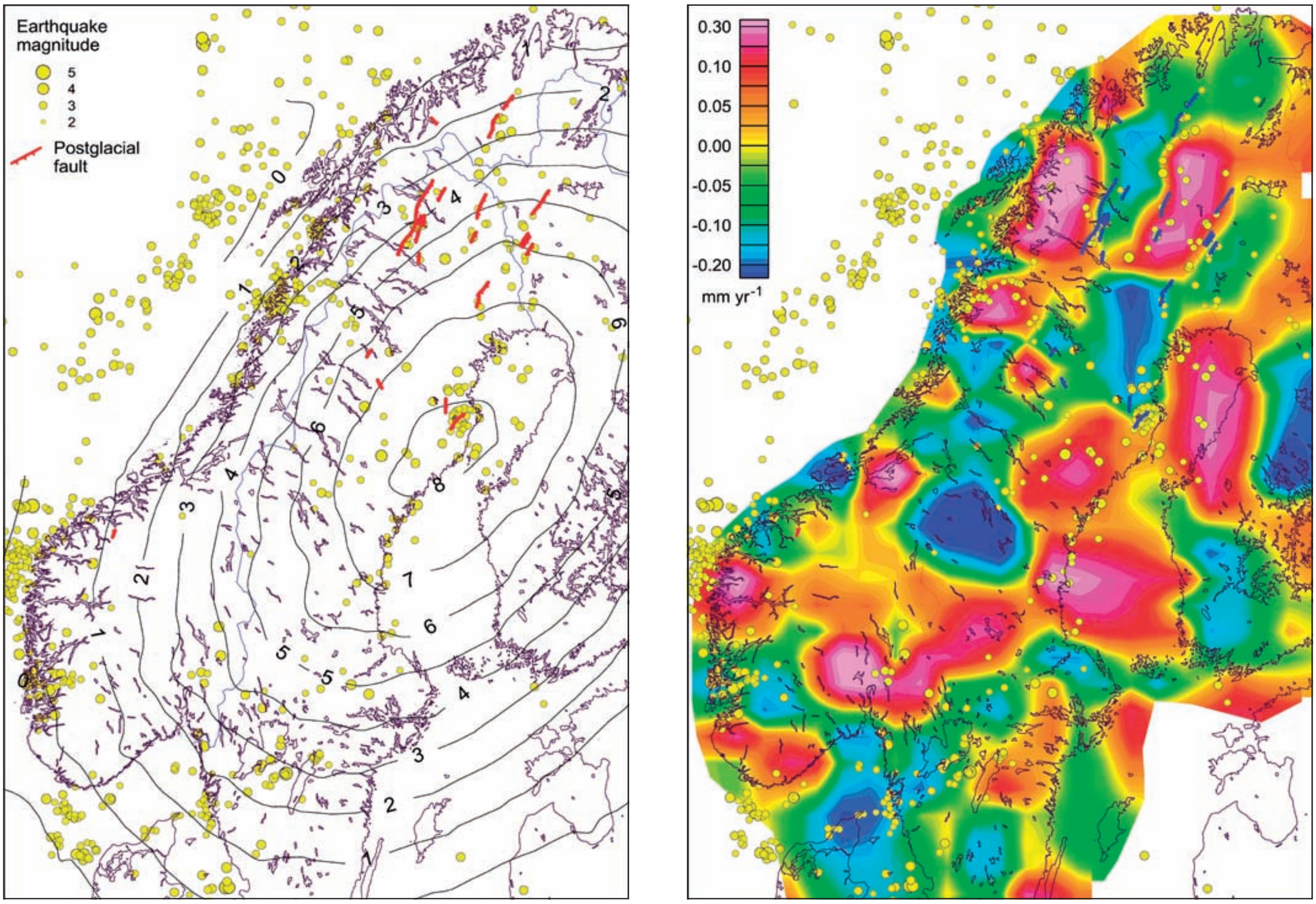

Figure 15. Present-day annual velocity of the Fennoscandian bedrock. (a) Amount of uplift in mm per year (Vestøl 2006) and 1980–2011 earthquake epicentres in Fennoscandia. There is no direct correlation between uplift pattern and seismicity in Fennoscandia (Bungum et al. 2010). (b) Deviation from a fifth-order polynomial trend surface of the present-day annual uplift in A) (Vestøl 2006). The anomalies in the order of ±0.3 mm yr^{-1} could represent systematic or random noise, tectonic components or deviations in the uplift pattern as a result of thickness variations of the inland ice (Bungum et al. 2010).

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.

Vestøl (2006) compiled uplift data from precise levelling, tide gauge recordings and time series from continuous GPS stations applying the Kriging adjustment method, and concluded that it is, in general, hard to claim uplift anomalies with wavelengths shorter than 50–100 km and amplitudes greater than ±0.4 mm in Norway (Figure 15b). Vestøl (2006) also subtracted the modelled glacial isostatic uplift determined by Lambeck et al. (1998) from his own postglacial uplift data and arrived at a similar conclusion as Fjeldskaar et al. (2000). The three anomalous uplift areas are, however, larger and reveal a larger wavelength component than the anomalous areas of Fjeldskaar et al. (2000). The anomalous uplift of about 0.4 mm yr^{-1} over a *c.* 50 km-wide area in the Oslo region also seems to be significant (Vestøl 2006). There is, however, a need to check the reliability of the semiregional uplift anomalies produced with the InSAR permanent scatterer technique (Bungum et al. 2010). Uplift anomalies of several millimetres in the Lyngen area, Troms (Osmundsen et al. 2009), are, for instance, inconsistant with the anomalous uplift dataset produced from repeated levelling). The recorded seismic events in outer Lyngenfjorden are most likely related to blasting during the molo construction at Årviksand harbour in the winter of 1999. The recorded negative arrivals from these events support this alterative interpretation. The small-magnitude events in the Norwegian earthquake catalogue are contaminated by explosions.

There have been earlier reports (from geodetic measurements) of contemporary movements along a fault in 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 either of these faults (Sylvester 1999, Bockmann and Grimstveit 2000). It is, therefore, suggested that most of the local anomalies in the uplift pattern are related to inaccuracies in the levelling data (Olesen et al. 2004). The intermediate component of the regional uplift pattern (anomaly areas with *c.* 100 km wavelength and 0.5–1 mm yr^{-1}) may, however, be related to tectonic processes other than glacioisostasy.

Discussion

A number of Late Quaternary to Holocene deformation features in Norway can be associated with earthquakes. Sackung structures, for example, occur as a result of bidirectional extension of the Kvasshaugen ridge in Beiarn, Nordland. Clefts up to 20 m wide and 10 m deep can be followed along an approximately 5 km-long, NNE–SSW-trending zone (Grønlie 1939, Olesen et al. 2004). The reverse Berill Fault at the foot of the Middagstinden mountain is associated with open clefts with upward-facing scarps along the mountain ridge in the hanging-wall block, which are also features typical of gravity-induced sackung structures.

Similar sackung structures, consisting of double-crested ridges, linear troughs and both upslope-facing and downslope-facing scarps, occur in the Alps, the Rocky Mountains and in New Zealand (Beck 1968, Zischinsky 1969, Savage and Varnes 1987, Varnes et al. 1989). These characteristic geomorphological forms are considered to be produced by gravitational spreading of steep-sided ridges (Varnes et al. 1989). Ambrosi and Crosta (2006) conclude that sacking structures are complex mass movements controlled by many different factors: recent geological history (e.g. glaciation and deglaciation, periglacial conditions, erosion and valley deepening, tectonic stress, uplift, seismicity, and landsliding); structural features (joints, faults, foliations); slope materials (lithology, weathering, and metamorphism); topographic factors (slope length and gradient); and groundwater conditions. Whether initiation of the movements is by strong ground-shaking (earthquakes), faulting, long-term creep, or a combination of these factors, has long been a matter of debate (Jibson 1996, Ambrosi and Crosta 2006). Varnes et al. (1989) and McCalpin and 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, Russia and Italy have concluded that earthquake shaking was a likely fault-triggering mechanism (Jahn 1964, Beck 1968, Jibson 1996, Ambrosi and Crosta 2006), partly because the sackung features occur in seismically active areas in these particular cases. Kvasshaugen is also situated in a seismically active area; hence, earthquake shaking could have been the triggering mechanism (Olesen et al. 2004). Similar structures on Øtrefjellet in Haram, Møre & Romsdal, are located on the margins of a seismically active area (Anda et al. 2002, Braathen et al. 2004, Blikra et al. 2006). Oppikofer et al. (2008) have suggested that sections of the Åknes rockslide in western Norway represent sackung structures. Ambrosi and Crosta (2006) argue that such slow, deep-seated gravitational movements can damage or destroy infrastructure, and sections of individual sackung may accelerate during rainstorms or with climate change.

In southern Norway, there is no conclusive evidence for any postglacial faulting, even though the majority of the original neotectonic claims were reported from this region. There are, however, other indirect palaeoseismic indications along a NNE–SSW-trending zone from Odda in Hardanger to Aurland in Sogn and on the coast of Møre & Romsdal, seen as a series of rock-slope failures, many in relatively gently dipping terrain (Braathen et al. 2004, Blikra et al. 2006). The former zone is situated within the Mandal–Molde lineament zone of Gabrielsen et al. (2002). Liquefaction and semiliquefaction structures in sand located close to the intersection of two topographical lineaments in Flatanger, Nord-Trøndelag (site 11 in Figure 1 and Appendix), have also been taken as evidence of a large postglacial earthquake (Olsen and Sveian 1994). There is a general lack of Quaternary overburden in western Norway and, consequently, there are few means of identifying and dating 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.

It is considered likely that the postglacial faults, and the varying stress fields and vertical uplifts, were caused mainly by an interaction of the ridge-push force from the Knipovich and Mohn ridges and other processes such as postglacial rebound, gravitational effects from mass excess within the Seiland Igneous Province, the Lofoten–Vesterålen metamorphic complex and mountainous areas in Scandinavia (Muir Wood 1989a, 2000, Olesen 1991, Olesen et al. 1992a, Bungum and Lindholm 1997) and sedimentary loading (Byrkjeland et al. 2000, Hicks et al. 2000b) and unloading in the coastal and offshore areas. Considering that the Pliocene/Pleistocene loading of the relatively stiff oceanic crust causes seismicity in the Norwegian Sea, it is also likely that a comparable unloading of the coastal areas in western and northern Norway may induce earthquake activity. It has also been argued by Lidmar-Bergström (1995) and Lidmar-Bergström et al. (1999) that the coastal areas of southeastern Norway, together with the Skagerrak and Kattegat, were exhumed in the Neogene. Unloading of the crust in these areas can therefore also partly explain the observed seismicity in that region.

In this context it is also important, however, to appreciate the potential significance of aseismic movements which, in fact, are found over a wide range of strain-rate conditions. Recent research in subduction zones has demonstrated the importance of so-called silent earthquakes, filling the gap between brittle and ductile deformation. One effect of this is to generate significant variations in coupling ratios, relating seismic moment rates to geological moment rates. For example, following the 2004 M 9.2–9.3 Sumatra earthquake, more than 20 cm of afterslip has been documented in that region. Even though rates and scales are greatly different in Fennoscandia, there are reasons to believe that some of the same principles may apply with respect to the range of deformational processes involved.

A related question here is whether earthquakes and earthquake swarms, which in Norway are usually quite shallow, should be considered as neotectonic triggering phenomena in cases where they are not specifically related to mapped faults. This is really a question of definition, since such activities clearly also reflect movements on faults, albeit at different scales in time and displacement than are otherwise considered as neotectonics.

Isostatic modelling by Olesen et al. (2002) and Ebbing and Olesen (2005) indicates that the mountains in southern Norway are supported by low-density rocks at typical Moho and sub-Moho depths. The gravity field in the northern Scandinavian mountains, on the other hand, seems to be compensated by low-density masses at a relatively shallow depth in the upper crust. The results are in agreement with the conclusions of Riis (1996) and Lidmar-Bergström et al. (1999) that the southern Norwegian plateau was partly uplifted in the Neogene, whereas the northern mountains originated mainly as a rift-shoulder in Late Cretaceous to Early Tertiary times. In this regard, Hendriks and Andriessen (2002) reported that apatite fission-track analytical data along a profile from Lofoten into northern Sweden fit best with those expected from a retreating scarp model.

The distinct concentration of gravitational faults and slope failures in the Odda–Aurland area (site 17 in Figure 1 and Appendix) in Sogn & Fjordane and Hordaland, and in parts of Møre & Romsdal and Troms, may indicate the occurrence of large-magnitude prehistoric earthquakes in these areas (see discussions in Braathen et al. 2004 and Blikra et al. 2006). 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. One conclusion that can be drawn from these observations and inferences is that palaeoseismology will be an important field of further research in Norway. It will be critical to date the individual rock avalanches, landslides and liquefaction events to determine whether or not they can be related to large-magnitude earthquakes.

Morsing (1757) concluded that the Tjellefonna and Silset rock avalanches on 23 February 1756 in Møre & Romsdal county were caused by an earthquake (Bungum and Lindholm 2007, Redfield and Osmundsen 2009). The Tjellefonna rock avalanche created a 40 m-high tsunami that caused catastrophic damage to the settlements along Langfjorden and Eresfjorden. A total of 32 people perished in the disaster (Schøning 1778). A landslide and several smaller rock avalanches were triggered by the 1819 M 5.8 earthquake in the Rana–Sjona area (Heltzen 1834, Muir Wood 1989b, Bungum and Olesen 2005). Although no lives were lost in this disaster, the landslide and one of the rock avalanches destroyed substantial areas of farmland (Heltzen 1834, Muir Wood 1989b, Bungum and Olesen 2005). We therefore conclude that rock avalanches and landslides, potentially triggered by future earthquakes, would almost certainly generate tsunamis in fjords and lakes and consequently constitute the greatest seismic hazard to society in Norway. The giant 1958 landslide at the head of Lituya Bay in Alaska was triggered by an earthquake and generated a wave with an initial amplitude of 524 m (Miller 1960). The mega-tsunami surged over the headland opposite, stripping trees and soil down to bedrock, and surged along the fjord which forms Lituya Bay, destroying a fishing boat anchored there and killing two people.

Trenching across the Stuoragurra Fault has shown that fault breccia was injected over a horizontal distance of more than 12–14 m from the fault zone into the lower part of the glacial overburden (Figure 6 and Dehls et al. 2000a). In order for such an injection to occur, the fault breccia must have been fluidised with high-pressure groundwater or gas. This observation shows that a sudden flow of fluids or gas can locally be associated with seismic pulses. Muir Wood (1989a) emphasised the role of pore-water pressure for reducing the effective stress in the upper part of the crust during deglaciation. Lagerbäck and

Sundh (2008) pointed out the possible significance of an assumed overpressuring of pore water beneath a thick layer of permafrost in the formation of the young faults. These same authors have also argued that the modest glacial erosion during the Weichselian would have allowed fault scarps of a similar magnitude to the Fennoscandian postglacial faults to be preserved, had they occurred. Following the mechanism that large continental ice sheets suppress the release of earthquakes during glaciations (Johnston 1987), it is still likely that previous deglaciations were accompanied by large earthquakes though not necessarily the size of those in post-Weichselian time.

Erosion and uplift of offshore areas along the coast of Norway and in the Barents Sea would most likely release gas from hydrates within the sediments (Chand et al. 2012). The climatic implications of the deglaciation-related seismicity is therefore of special interest. Seismic pumping (Sibson et al. 1975) and the release of hydrocarbons during deglaciation-induced seismic pulses may partly explain the improved climate immediately after the Weichselian deglaciation as a result of an increased greenhouse effect (Olesen et al. 2004). The greenhouse effect of CH_4 is 23 times greater than that of CO_2 (Forster et al. 2007). Paull et al. (1991) presented a scenario of a *c.* 100 m sea-level fall 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 have eventually triggered 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, moreover, explain why glaciations generally terminate rather abruptly.

We would also like to stress that although the level of seismicity in Norway is stable, the physical and societal vulnerability to earthquakes has increased enormously over historical time, like in most other parts of the world. When comparing the population and infrastructure of the Rana region of the early 1800s, where the 1819 M 5.8 earthquake (Muir Wood 1989b, Bungum and Olesen 2005) occurred, with the population and infrastructure of the same area today, we realise how many more people and elements of modern infrastructure are at risk. The population has increased from 3,000 to 30,000. Very few roads, no industry and mostly one-storey wooden houses existed in the Rana area in 1819 whereas today we find a major road system, railways, hydropower plants, bridges, tunnels, smelters and tall buildings. The 1992 M 5.8–5.9 earthquake at Roermond, in the Netherlands, for example, cost Dutch society about 100 million Euros (Berz 1994, van Eck and Davenport 1994). Even though the geology and population density in this industrialised flood plain area is not directly comparable to Norway, the Roermond earthquake still illustrates the importance of carrying out state-of-the-art seismic-hazard analyses also in Norway.

Kukkonen et al. (2010) have suggested that we should explore the postglacial faults in northern Fennoscandia through scientific drilling and study their characteristics, including structure and rock properties, present and past seismic activity and state of stress, as well as hydrogeology and the associated deep biosphere. This cumulative research is anticipated to advance our knowledge of neotectonics, hydrogeology and the deep biosphere, and provide important information for nuclear waste disposal, petroleum exploration on the Norwegian continental shelf and safety of hydropower dams and other infrastructure.

Conclusions

While firm evidence for postglacial deformation has been found in northern Norway, we have not yet been able to find similar evidence in southern Norway. Indications of neotectonic deformation include, however, secondary effects of possible large prehistoric earthquakes such as liquefaction and semiliquefaction structures in the Flatanger (Nord-Trøndelag) and Rana (Nordland) areas, and gravitational spreading and faulting features (sackung) on Kvasshaugen in Beiarn (Nordland) and at Berill in Rauma 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 (probably neotectonics). Gravitational processes primarily control the large-scale rock avalanches, mountain-ridge spreading and normal faulting, but their spatial occurrence and locations 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.

The observed neotectonic deformation in Norway supports previous conclusions regarding a major seismic 'pulse' (with several magnitude 7–8 earthquakes) which followed immediately after the Weichselian deglaciation of northern Fennoscandia (Lagerbäck 1990, 1992, Kuivamäki et al. 1998, Lagerbäck and Sundh 2008). The 80 km-long Stuoragurra Fault constitutes the Norwegian part of the Lapland Fault Province, which consists of ten NE–SW-striking reverse faults (Table 1). 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 (Dehls et al. 2000a).

Large continental ice sheets suppress the release of earthquakes (Johnston 1987). There were, therefore, most likely major seismic pulses in mainland Fennoscandia accompanying each of the deglaciations that followed the multiple glaciation cycles during the last 600,000 years. It is possible that seismic pumping (Sibson et al. 1975) 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 (Muir Wood and King 1993, Olesen et al. 2004).

There is some evidence from uplifted pre-Weichselian sediments and caves along the coast of western Norway that the

Norwegian coast may have been subject to tectonic uplift of the order of 0.1–0.3 mm yr^{-1} during the Quaternary, in addition to postglacial uplift. Unloading of the coastal area of Norway and loading of the outer shelf and deep water areas in the Norwegian Sea are a likely contributor to this tectonic uplift. A significant part of the seismicity along the Norwegian continental margin occurs within these two, distinctly different, tectonic regimes.

The severe Pliocene/Pleistocene uplift and erosion of coastal areas of Norway and the Barents Sea have effects on the petroleum exploration. Where uplift and tilting resulted in local extension, seal breaching and spillage may also have occurred, as in the Barents Sea (Nyland et al. 1992). The cooling of the source rocks owing to vertical movement may also cause hydrocarbon generation to decrease.

We conclude that the distribution of earthquakes, in situ rock stress, Neogene and present uplift and postglacial faulting in Norway and along the Norwegian margin seem to be primarily related to gravitational effects of excess mass along the Mohns Ridge, within the Iceland Plateau and in the southern Scandinavian mountains, to Pliocene/Pleistocene sedimentary loading/unloading, and also to postglacial rebound.

We also conclude that magnitude 6+ earthquakes are possible today in the most seismically active areas in Norway, such as the coastal parts of western Norway, Nordland and the Oslo rift zone. Rock avalanches and landslides, potentially triggered by earthquakes, could generate tsunamis and thus constitute a significant seismic hazard to society in Norway.

Acknowledgements

The present review of neotectonic deformation, seismicity and the contemporary stress field in Norway was originally compiled in 2007 for a new edition of NGUs ‘Geology of Norway’. The plans were, however, modified after the comprehensive ‘Making of a land’ was published by the Geological Society of Norway (NGF) in 2008. The original manuscript text has been updated with the recent literature for the present NGU Special Publication. Olav Vestøl at the Norwegian Mapping and Cadastre Authority provided the digital absolute-uplift data from Fennoscandia. Berit Marie Storheim and Kuvvet Atakan at the Department of Earth Science, University of Bergen, provided the seismicity catalogue of Norway, Svalbard and the northeast Atlantic. We are grateful for detailed and constructive reviews from John Adams, Ian S. Stewart and Christopher Talbot which helped to improve the paper.

References

Ambrosi, C. & Crosta, G.B. (2006) Large sackung along major tectonic features in the Central Italian Alps. *Engineering Geology*, **83**, 183-200.

Anda, L.H., Blikra, L.H. & Longva, O. (2000) Large-scale slope failures in Møre & Romsdal – palaeoseismic evidence? *In* Dehls, J. & Olesen, O. (eds.) *Neotectonics in Norway, Annual Technical Report 1999*. Norges geologiske undersøkelse Report 2000.001, 20-25.

Anda, E., Blikra, L.H. and Braathen, A. (2002) The Berill fault – first evidence of neotectonic faulting in southern Norway. *Norsk Geologisk Tidsskrift*, **82**, 175–182.

Anundsen, K. (1985) Changes in shore-level and ice-front position in Late Weichsel and Holocene, southern Norway. *Norsk Geologisk Tidskrift*, **38**, 205–225.

Anundsen, K. (1989) Late Weichselian relative sea levels in southwest Norway: observed strandline tilts and neotectonic activity. *Geologiska Föreningens i Stockholm Förhandlingar*, **111**, 288–292.

Anundsen, K. and Fjeldskaar, W. (1983) Observed and theoretical late Weichselian shore-level changes related to glacier oscillations at Yrkje, south-west Norway. *In* Schroeder-Lanz., H. (ed.) *Late- and postglacial oscillations of glaciers: glacial and periglacial forms*, A. A. Balkema, Rotterdam, The Netherlands, pp. 133–170.

Atakan K., Lindholm, C.D. and Havskov, J. (1994) Earthquake swarm in Steigen northern Norway: an unusual example of intraplate seismicity. *Terra Nova*, **6**, 180–194.

Bakkelid, S. (1990) Innmåling av rur- og tangrandmerker i Nordland. *Statens Kartverk Report 3/1990*, 90 pp.

Bakkelid, S. (2001) Overvåking av rur- og tangrender for bestemmelse av landhevning langs Norges kyst. Erfaringer og resultater fra overvåkningsprogram 1990–1999. *Statens Kartverk Report March 2001*, 73 pp.

Beck, A.C. (1968) Gravity faulting as a mechanism of topographic adjustment. *New Zealand Journal of Geophysics*, **11**, 191–199.

Bell, J.S. and Eisbacher, G.H. (1995) Stress orientation indicators (neotectonic plucking fractures) in bedrock of glacier forefields, southeastern Cordillera, western Canada. *Geological Survey of Canada Current Research 1995–B*, 151–159.

Berz, G. (1994) Assessment of the losses caused by the 1992 Roermond earthquake, the Netherlands (extended abstract). *Geologie en Mijnbouw*, **73**, 281.

Blikra, L.H., Longva, O., Braathen, A. and Anda, E., Dehls, J. and Stalsberg, K. (2006) Rock-slope failures in Norwegian fjord areas: examples, spatial distribution and temporal pattern. *In* Evans, S.G., Scarawcia Mugnozza, G., Strom, A.L. and Hermanns, R.L. (eds.) *Massive rock slope failure: New models for hazard assessment*. Nato Science Series: IV: Earth and Environmental Sciences, 49, Kluwer Academic Publishers, Dordrecht, The Netherlands, 475–496.

Blystad, P., Brekke, H., Færseth, R.B., Larsen, B.T., Skogseid, J. and Tørudbakken, B. (1995) Structural elements of the Norwegian continental shelf, Part II. The Norwegian Sea Region. *Norwegian Petroleum Directorate Bulletin*, **8**, 45 pp.

Bockmann, L. and Grimstveit, L. (2000) Norwegian Mapping Authority: Report for 1999. *In* J. F. Dehls and O. Olesen (eds.) *Neotectonics in Norway, Annual Technical Report 1999*. Norges geologiske undersøkelse Report 2000.001, 54–67.

Braathen, A., Blikra, L.H., Berg, S.S. and Karlsen, F. (2004) Rock-slope failures of Norway; type, geometry, deformation mechanisms and stability. *Norwegian Journal of Geology*, **84**, 67–88.

Bryn, P., Østmo, S.R., Lien, R., Berg, K. and Tjelta, T.I. (1998) Slope stability in the deep water areas off Mid-Norway. OTC 8640 paper presented at the 1998 Offshore Technology Conference, Houston, Texas, 4–7 May.

Bugge, T., Belderson, R.H. and Kenyon, N.H. (1988) The Storegga Slide. *Philosophical Transactions of the Royal Society, London*, **325**, 357–388.

Bungum, H. (1989) Earthquake occurrence and seismotectonics in Norway and surrounding areas. *In* Gregersen, S. and Basham, P.W. (eds.) *Earthquakes at North-Atlantic passive margins: Neotectonics and postglacial rebound*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 501–519,

Bungum, H. and Husebye, E. S. (1979) The Meløy, northern Norway, earthquake sequence – a unique intraplate phenomenon. *Norsk Geologisk Tidsskrift*, **59**, 189–193.

Bungum, H. and Lindholm, C. (1997) Seismo- and neotectonics in Finnmark, Kola Peninsula and the southern Barents Sea. Part 2: Seismological analysis and seismotectonics. *Tectonophysics*, **270**, 15–28.

Bungum, H. and Lindholm, C. (2007) Tsunamigenic seismic sources in the North Sea, the Norwegian Continental Margin and the Norwegian–Greenland Sea. ICG/NORSAR Transfer Report WP2, 18 pp.

Bungum, H. and Olesen, O. (2005) The 31st of August 1819 Lurøy earthquake revisited. *Norwegian Journal of Geology*, **85**, 245–252.

Bungum, H., Hokland, B.K., Husebye, E.S. and Ringdal, F. (1979) An exceptional intraplate earthquake sequence in Meløy, Northern Norway. *Nature*, **280**, 32–35.

Bungum, H., Mitchell, B.J. and Kristoffersen, Y. (1982) Concentrated earthquake zones in Svalbard. *Tectonophysics*, **82**, 175–188.

Bungum, H., Alsaker, A., Kvamme, L.B. and Hansen, R.A. (1991) Seismicity and seismotectonics of Norway and surrounding continental shelf areas. *Journal of Geophysical Research*, **96**, 2249–2265.

Bungum, H., Lindholm, C.D., Dahle, A., Woo, G., Nadim, F., Holme, J.K., Gudmestad, O.T., Hagberg, T. and Karthigeyan, K. (2000) New seismic zoning maps for Norway, the North Sea and the UK. *Seismological Research Letters*, **71**, 687–697.

Bungum, H., Lindholm, C. and Dahle, A. (2003) Long period ground motions for large European earthquakes, 1905–1992, and comparisons with stochastic predictions. *Journal of Seismology*, **7**, 377–396.

Bungum, H., Lindholm, C. and Faleide, J.I. (2005) Postglacial seismicity offshore mid-Norway with emphasis on spatio-temporal-magnitudal variations. *Marine and Petroleum Geology*, **22**, 137–148.

Bungum, H., Pettenati, F., Schweitzer, J., Sirovich, L. and Faleide, J.-I. (2009) The MS 5.4 October 23, 1904, Oslofjord earthquake: Reanalysis based on macroseismic and instrumental data. *Bulletin of the Seismological Society of America*, **99**, 2836–2854, doi: 10.1785/0120080357.

Bungum, H. Olesen, O., Pascal, C., Gibbons, S., Lindholm, C. and. Vestøl, O. (2010) To what extent is the present seismicity of Norway driven by postglacial rebound? *Journal of the Geological Society, London*, **167**, 373–384.

Byrkjeland, U., Bungum, H. and Eldholm, O. (2000) Seismotectonics of the Norwegian continental margin. *Journal of Geophysical Research*, **105**, 6221–6236.

Bøe, R., Longva, O., Lepland, A., Blikra, L.H. Sønstegaard, E., Haflidason, H., Bryn, P. and Lien, R. (2004) Postglacial mass movements and their causes in fjords and lakes in western Norway. *Norwegian Journal of Geology*, **84**, 35–55.

Chand, S., Thorsnes, T., Rise, L., Brunstad, H., Stoddart, D., Bøe, R., Lågstad, P. and Svolsbru, T. (2012) Multiple episodes of fluid flow in the SW Barents Sea (Loppa High) evidenced by gas flares, pockmarks and gas hydrate accumulation. *Earth and Planetary Science Letters*, **331–332**, 305–314.

Clark, D., McPherson, A. and Van Dissen, R. (2012) Long-term behaviour of Australian stable continental region (SCR) faults. *Tectonophysics*, **566–567**, 1–30.

Dehls, J.F. and Olesen, O. (1998) NEONOR: Neotectonics in Norway: Annual Technical Report 1997. *Norges geologiske undersøkelse Report 98.016*, 149 pp.

Dehls, J.F., and Olesen, O. (1999) NEONOR: Neotectonics in Norway: Annual Technical Report 1998, *Norges geologiske undersøkelse Report 99.007*, 206 pp.

Dehls, J.F., and Olesen, O. (2000) NEONOR: Neotectonics in Norway: Annual Technical Report 1999. *Norges geologiske undersøkelse Report 2000.001*, 207 pp.

Dehls, J.F., Olesen, O., Blikra, L. H. and Olsen, L. (1999) Neotectonic excursion guide to Troms and Finnmark. *Norges geologiske undersøkelse Report 99.082*, 34 pp.

Dehls, J.F., Olesen, O., Olsen, L. and Blikra, L.H. (2000a) Neotectonic faulting in northern Norway; the Stuoragurra and Nordmannvikdalen postglacial faults. *Quaternary Science Reviews*, **19**, 1447–1460.

Dehls, J.F., Olesen, O., Bungum, H., Hicks, E., Lindholm, C.D. and Riis, F. (2000b) Neotectonic map, Norway and adjacent areas 1:3 mill. *Geological Survey of Norway, Trondheim*.

Dehls, J.F., Basilico, M. and Colesanti, C. (2002) Ground deformation monitoring in the Ranafjord area of Norway by means of the Permanent Scatterers technique, Geoscience and Remote Sensing Symposium, 2002. IGARSS '02. 2002 IEEE International, Volume 1: Toronto, 203–207.

Doré, A.G., Lundin, E.R., Kusznir, N. and Pascal, C. (2008) Potential mechanisms for the genesis of Cenozoic domal structures on the NE Atlantic margin: pros, cons and some new ideas, *In* H., Johnson, et al. (eds.) The Nature and Origin of Compression in Passive Margins. *Geological Society of London Special Publications*, **306**, 1–26.

Dowdeswell, J.A., Ottesen, D. and Rise, L. (2010) Rates of sediment delivery from the Fennoscandian Ice Sheet through an ice age. *Geology*, **38**, 3–6.

Ebbing, J. and Olesen, O. (2005) The Northern and Southern Scandes – Structural differences revealed by an analysis of gravity anomalies, the geoid and regional isostasy. *Tectonophysics*, **411**, 73–87.

Ehlers, J. (1990) Reconstructing the dynamics of the North-West European Pleistocene ice sheets. *Quaternary Science Reviews*, **9**, 71–83.

Eidvin, T., Jansen, E., Rundberg, Y., Brekke, H. and Grogan, P. (2000) The upper Cainzoic of the Norwegian continental shelf correlated with the deep sea record of the Norwegian Sea and the North Atlantic. *Marine and Petroleum Geology*, **17**, 579–600.

Eriksson, R., Bruteig, I.E., Sletten, K., Bunæs, V. and Krokeide, C. (2011) Teknologi, økonomi og andre forhold knyttet til en sjøkabelløsning, Rapport fra sjøkabelutredningen for Olje og energidepartementet, 124 pp.

Evans, D., King, E.L., Kenyon, N.H., Brett, C. and Wallis, D. (1996) Evidence for long-term instability in the Storegga Slide region of western Norway. *Marine Geology*, **130**, 281–292.

Fejerskov, M. and Lindholm, C.D. (2000) Crustal stress in and around Norway; an evaluation of stress-generating mechanisms. *In* Nøttvedt. A. (ed.) *Dynamics of the Norwegian margin*, Geological Society, London, Special Publications, **167**, 451–467.

Fejerskov, M., Lindholm, C., Myrvang, A. and Bungum, H. (2000) Crustal stress in and around Norway: a compilation of in situ stress observations. *In* Nøttvedt, A. (ed.) *Dynamics of the Norwegian margin*, Geological Society, London, Special Publications, **167**, 441–449.

Fenton, C.H. (1994) Postglacial faulting in eastern Canada. *Geological Survey of Canada Open file Report 2774*, 98 pp.

Fjeldskaar, W., Lindholm, C., Dehls, J.F. and Fjeldskaar, I. (2000) Post-glacial uplift, neotectonics and seismicity in Fennoscandia. *Quaternary Science Reviews*, **19**, 1413–1422.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M. and Van Dorland, R. (2007) Changes in atmospheric constituents and in radiative forcing. *In* Solomon, S., et al. (ed.) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Fulop, A. (1998) *A seismostratigraphic study of the Late Quaternary sediments, north-east of the Storegga slide area, off Mid-Norway*. Unpubl. M.S. Thesis, University of Wales, Bangor, 60 pp.

Gabrielsen, R.H., Braathen, A., Dehls, J.F. and Roberts, D. (2002) Tectonic lineaments of Norway. *Norwegian Journal of Geology*, **82**, 153–174.

Gölke, M. and Brudy, M. (1996) Orientation of crustal stresses in the North Sea and Barents Sea inferred from borehole breakouts. *Tectonophysics*, **266**, 25–32.

Grønlie, O. T. (1923) Har Høgtuva steget i vor tid? *Naturen*, **7**, 139–141.

Grønlie, O. T. (1939) Some remarks on the land area in Nordland between the glacier Svartisen, and the frontier. *Norsk Geografisk Tidsskrift*, **7**, 399–406.

Hanks, T.C., Beroza, G.C. and Toda, S. (2012) Have Recent Earthquakes Exposed Flaws in or Misunderstandings of Probabilistic Seismic Hazard Analysis? *Seismological Research Letters*, **83(5)**, 759–764.

Hansen, R.A., Bungum, H. and Alsaker, A. (1989) Three recent larger earthquakes offshore Norway. *Terra Nova*, **1**, 284–295.

Helle, S.K., Rye, N., Stabell, B., Prösch-Danielsen, L. and Hoel, C. (2007) Neotectonic faulting and the Late Weichselian shoreline gradients in SW Norway. *Journal of Geodynamics*, **44**, 96–128.

Heltzen, I. A. (1834) Ranens Beskrivelse, *Rana Museums og Historielag*, Mo i Rana, 290 pp.

Hendriks, B. W. H. and Andriessen, P. A. M. (2002) Pattern and timing of the post-Caledonian denudation of northern Scandinavia constrained by apatite fission track thermochronology. *In* Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. and White, N.J. (eds.) *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration*, Geological Society of London Special Publication, **196**, 117–137.

Henkel, H. (1991) Magnetic crustal structures in Northern Fennoscandia. *In* Wasilewski, P. and Hood, P. (eds.) *Magnetic anomalies – land and sea*. Tectonophysics, **192**, 57–79.

Hicks, E. (1996) *Crustal stresses in Norway and surrounding areas as derived from earthquake focal mechanism solutions and in situ stress measurements*. Cand. Scient. Thesis, University of Oslo, 164 pp.

Hicks, E.C., Bungum, H. and Lindholm, C.D. (2000a) Stress inversion of earthquake focal mechanism solutions from onshore and offshore Norway. *Norsk Geologisk Tidsskrift*, **80**, 235–250.

Hicks, E., C., Bungum, H. and Lindholm, C.D. (2000b) Seismic activity, inferred crustal stresses and seismotectonics in the Rana region, northern Norway. *Quaternary Science Reviews*, **19**, 1423–1436.

Hoel, C. (1992) *Seismisk stratigrafi av sedimentene i Hardangerfjorden og sidefjorder*. Unpubl. M.Sc. Thesis, University in Bergen, 121 pp.

Holmsen, G. (1916) Om strandlinjers fald omkring gabbro-omraader (Summary in English). *Norsk Geologisk Tidsskrift*, **4**, 7–20.

Holtedahl, H. (1984) High Pre-Late Weichselian sea-formed caves and other marine features on the Møre-Romsdal coast, West Norway. *Norsk Geologisk Tidsskrift*, **64**, 75–85.

Holtedahl, H. (1998) The Norwegian strandflat – a geomorphological puzzle. *Norsk Geologisk Tidsskrift*, **78**, 47–66.

Hovland, M. (1983) Elongated depressions associated with pockmarks in the western slope of the Norwegian Trench. *Marine Geology*, **50**, M11–M20.

INQUA (1982) International Association for Quaternary Research (INQUA) Commission Reports 1978–1982. *Striolae*, **1982:1** *(INQUA Newsletter 4)*, 36–38.

Jahn, A. (1964) Slopes morphological features resulting from gravitation. *Zeitschrift für Geomorphologie Supplementbände*, **5**, 59–72.

Jibson, R.W. (1996) Using landslides for paleoseismic analysis. *In* McCalpin, J.P (ed.) *Paleoseismology*. International geophysics series, **62**. Academic Press, San Diego, 397–438.

Johansson, K. and Ransed, G. (2003) Map of the Quaternary deposits 23H Stensele, scale 1:100 000. *Sveriges geologiska undersökning*, **Ak 43**.

Johnston, A.C. (1987) Suppression of earthquakes by large continental ice sheets. *Nature*, **330**, 467–469.

Johnston, A.C. (1989) The effects of large ice-sheets on earthquake genesis. *In* Gregersen, S. and Basham, P.W. (eds.) *Earthquakes at North-Atlantic passive margins: neotectonics and postglacial* *rebound*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 581–599.

Johnston, A.C. and Kanter, L.R. (1990) Earthquakes in stable continental crust. *Scientific American*, **262**, 67–75.

Johnston, A.C., Coppersmith, K.J., Kanter, L.R. and Cornell, C.A. (1994) The earthquakes of stable continental regions. *Technical Report, EPRI TR–102261s–V1–V5. Electric Power Research Institute (EPRI), Palo Alto, CA*.

Judd, A.G. and Hovland, M. (2007) *Seabed fluid flow, the impact on geology, biology, and the marine environment*. Cambridge University Press, Cambridge, 475 pp.

Kakkuri, J. (1997) Postglacial deformation of the Fennoscandian crust. *Geophysica*, **33**, 99–109.

Kierulf, H.P., Ouassou, M., Simpson, M.J.R. and Vestøl, O. (2012) A continuous velocity field for Norway. *Journal of Geodesy. DOI 10.1007/s00190–012–0603–2*

Kuivamäki, A, Vuorela, P. and Paananen, M. (1998) Indications of postglacial and recent bedrock movements in Finland and Russian Karelia. *Geological Survey of Finland Report YST–99*, 97 pp.

Kujansuu, R. (1964) Nuorista sirroksista Lapissa. Summary: Recent faults in Lapland. *Geologi*, **16**, 30–36.

Kukkonen, I.T., Olesen, O., Ask, M.V.S. and the PFDP Working Group (2010) Postglacial Faults in Fennoscandia: Targets for scientific drilling. *Geologiska Föreningens i Stockholm Förhandlingar (GFF)*, **132**, 71–81.

Lagerbäck, R. (1979) Neotectonic structures in northern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar*, **100** (1978), 271–278.

Lagerbäck, R. (1990) Late Quaternary faulting and paleoseismicity in northern Fennoscandia, with particular reference to the Lansjärv area, northern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar*, **112**, 333–354.

Lagerbäck, R. (1992) Dating of Late Quaternary faulting in northern Sweden. *Journal of the Geological Society, London*, **149**, 285–291.

Lagerbäck, R. and Sundh, M. (2008) Early Holocene faulting and paleoseismicity in northern Sweden. *Sveriges geologiska undersökning*, **C836**, 80 pp.

Lambeck, K., Smither, C. and Ekman, M. (1998) Tests of the glacial rebound models for Fennoscandia based on instrumented sea- and lake-level records. *Geophysical Journal International*, **135**, 375–387.

Leonard, M. and Clark, D. (2011) A record of stable continental region earthquakes from Western Australia spanning the late Pleistocene: Insights for contemporary seismicity. *Earth and Planetary Science Letters*, **309**, 207–212.

Lidberg, M., Johansson J.M., Scherneck, H-G. and Davis J.L. (2007) An improved and extended GPS-derived 3D velocity field of the glacial isostatic (GIA) in Fennoscandia. *Journal of Geodesy*, **81**, 213–230

Lidmar-Bergström, K. (1995) Relief and saprolites through time on the Baltic Shield. *Geomorphology*, **12**, 45–61.

Lidmar-Bergström, K., Olsson, C.D. and Roaldset, E. (1999) Relief features and palaeoweathering remnants in formerly glaciated Scandinavian basement areas. *In* Thiry, M. and Simon-Coinçon, R. (eds.) *Palaeoweathering, palaeosurfaces and Related Continental Deposits*. International Association of Sedimentologists, Special Publications, **27**, 275–301.

Lindholm, C., Bungum, H., Hicks, E. and Villagran, M. (2000) Crustal stress and tectonics in Norwegian regions determined from earthquake focal mechanisms. *In* Nøttvedt, A. (ed.) *Dynamics of the Norwegian margin, Geological Society*, London, Special Publications, **167**, 429–439.

Longva, O., Rise, L. and Dehls, J.F. (1998) Marine geological investigations of neotectonic features in the Rana and Tjeldsundet aeras. *In* Dehls, J.F. and Olesen, O. (eds.) *Neotectonics in Norway. Annual Technical Report 1997*. Norges geologiske undersøkelse Report 98.016, 93–103.

Longva, O., Blikra, L.H. and Dehls, J.F. (2009) Rock avalanches – distribution and frequencies in the inner part of Storfjorden, Møre og Romsdal County, Norway. *Norges geologiske undersøkelse Report 2009.002*, 23 pp.

Lundin, E.R. and Doré, A.G. (2002) Mid-Cenozoic post-breakup deformation in the 'passive' margins bordering the Norwegian-Greenland Sea. *Marine and Petroleum Geology*, **19**, 79–93.

Lundqvist, J. and Lagerbäck, R. (1976) The Pärve fault: A lateglacial fault in the Precambrian of Swedish Lapland. *Geologiska Föreningens i Stockholm Förhandlingar*, **98**, 45–51.

Mangerud, J., Sønstegaard, E., Sejrup, H.-P. and Haldorsen, S. (1981) A continuous Eemian-Early Weichselian sequence containing pollen and marine fossils at Fjøsanger, western Norway. *Boreas*, **10**, 137–208.

McCalpin, J.P. and Irvine, J.R. (1995) Sackungen at the Aspen Highlands Ski Area, Pitkin County, Colorado. *Environmental and Engineering Geoscience*, **1**, 277–290.

Miller, D. J. (1960) Giant waves in Lituya Bay, Alaska. *United States Geological Survey, Professional Paper no. 345–C*, Reston, Virginia.

Milne, G. A., Davis, J.L., Mitrovica, J.X., Scherneck, H.-G., Johansson, J.M., Vermeer, M. and Koivula, H. (2001) Space-geodetic constraints on glacial isostatic adjustement in Fennoscandia. *Science*, **291**, 2381–2385.

Mitchell, B.J., Bungum, H., Chan, W.W. and Mitchell, P.B. (1990) Seismicity and present-day tectonics of the Svalbard region. *Geophysical Journal International*, **102**, 139–149.

Morsing, C. (1757) En kortelig Beskrivelse over Jordskiælvet, og Fjeldets Nedfald Som skede udj Nesset-Præstegiæld, I Romsdalen Provstie, og Trondhiems Stift udj Norge, nestafvigte Aar, Natten til dend 23 Februarij 1756. Manuscript at the Royal Library, Copenhagen, 4 pp.

Muir Wood, R. (1989a) Extraordinary deglaciation reverse faulting in northern Fennoscandia. *In* Gregersen, S. and Basham, P.W. (eds.) *Earthquakes at North-Atlantic passive margins: neotectonics and postglacial rebound*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 141–173.

Muir Wood, R. (1989b) The Scandinavian earthquakes of 22 December 1759 and 31 August 1819. *Disasters*, **12**, 223–236.

Muir Wood, R. (1993) A review of the seismotectonics of Sweden. Swedish Nuclear Fuel and Waste Management Co. (SKB)

Technical Report **93–13**, 225 pp.

Muir Wood, R. (2000) Deglaciation Seismotectonics: a principal influence on intraplate seismogenesis at high latitudes. *Quaternary Science Reviews*, **19**, 1399–1411.

Muir Wood, R. and King, G.C.P. (1993) Hydrological signatures of earthquake strain. *Journal of Geophysical Research*, **98**, 22,035–22,068.

Myrvang, A. (1993) Rock stress and rock stress problems in Norway. *In* Hudson, J.A. (ed.) *Comprehensive rock engineering. Vol. 3, Rock testing and site characterization*. Pergamon Press, 461–471.

Møller, J. (1985) Coastal caves and their relation to early postglacial shore levels in Lofoten and Vesterålen, North Norway. *Norges geologiske undersøkelse Bulletin*, **400**, 51–65.

Mörner, N.-A. (1980) The Fennoscandian uplift: Geological data and their geodynamical implications. *In* Mörner, N.-A. (ed.) *Earth Rheology, Isostasy and Eustasy*. John Wiley & Sons, New York, 251–284.

NORSAR (1999) Evidence for active or recently active tectonic faulting on the continental margin offshore Mid-Norway. Report No. SP–31–NS–01R–00000–99 for Norsk Hydro Production a.s. on behalf of the Seabed Group, September 1999, 99pp.

Nyland, B., Jensen, L.N., Skagen, J., Skarpnes, O. and Vorren, T.O. (1992) Tertiary uplift and erosion in the Barents Sea: magnitude, timing and consequences. *In* Larsen, R. M., Brekke, H., Larsen, B. T. & Talleraas, E. (eds.) *Structural and tectonic modeling and its applications to Petroleum Geology*, 153–162. Elsevier, Amsterdam.

Olesen, O. (1988) The Stuoragurra Fault, evidence of neotectonics in the Precambrian of Finnmark, northern Norway. *Norsk Geologisk Tidsskrift*, **68**, 107–118.

Olesen, O. (1991) *A geophysical investigation of the relationship between old fault structures and postglacial faults in Finnmark, northern Norway*. Unpubl. Dr. ing. thesis. 1991:54, University of Trondheim, Norwegian Institute of Technology. 126 pp.

Olesen, O., Roberts, D., Henkel, H., Lile, O.B. and Torsvik, T.H. (1990) Aeromagnetic and gravimetric interpretation of regional structural features in the Caledonides of West Finnmark and North Troms, northern Norway. *Norges geologiske undersøkelse Bulletin*, **419**, 1–24.

Olesen, O., Henkel, H., Lile, O.B., Mauring, E., Rønning, J.S. and Torsvik, T.H. (1992a) Neotectonics in the Precambrian of Finnmark, northern Norway. *Norsk Geologisk Tidsskrift*, **72**, 301–306.

Olesen, O., Henkel, H., Lile, O.B., Mauring, E. and Rønning, J.S. (1992b) Geophysical investigations of the Stuoragurra postglacial fault, Finnmark, northern Norway. *Journal of Applied Geophysics*, **29**, 95–118.

Olesen, O., Gjelle, S., Henkel, H., Karlsen, T.A., Olsen, L. and Skogseth, T. (1994) Neotectonic studies in the Ranafjorden area, northern Norway. Norges geologiske undersøkelse Report 94.073, 43 pp.

Olesen, O., Gjelle, S., Henkel, H., Karlsen, T.A., Olsen, L. and Skogseth, T. (1995) Neotectonics in the Ranafjorden area, northern Norway (Extended abstract). *Norges geologiske undersøkelse Bulletin*, **427**, 5–8.

Olesen, O., Riis, F. and Fanavoll, S. (1999) Interpretations of 3D seismic surveys in the northern North Sea and Nordland II and VI areas. In Dehls, J.F. and Olesen, O. (eds.) Neotectonics in Norway, Annual Technical Report 1998. *Norges geologiske undersøkelse Report 99.007*, 48–86.

Olesen, O., Blikra, L.H., Bockmann, L., Bungum, H., Dehls, J.F., Faleide, J.I, Fjeldskaar, W., Hicks, E., Lindholm, C., Longva, O., Olsen, L., Riis, F., Rise, L. and Roberts, D. (2000) Neotectonics in Norway, Final Report. *Norges geologiske undersøkelse Report 2000.002*, 135 pp.

Olesen, O., Lundin, E., Nordgulen, Ø., Osmundsen, P.T., Skilbrei, J.R., Smethurst, M.A., Solli, A., Bugge, T. and Fichler, C. (2002) Bridging the gap between the Nordland onshore and offshore geology. *Norwegian Journal of Geology*, **82**, 243–262.

Olesen, O., Blikra, L.H., Braathen, A., Dehls, J.F., Olsen, L., Rise, L., Roberts, D., Riis, F., Faleide, J.I. and Anda, E. (2004) Neotectonic deformation in Norway and its implications: a review. *Norwegian Journal of Geology*, **84**, 3–34.

Olesen, O., Bering, D., Brönner, M., Dalsegg, E., Fabian, F., Fredin, O., Gellein, J., Husteli, B., Magnus, C., Rønning, J.S., Solbakk, T., Tønnesen, J.F. and Øverland, J.A. (2012a) Tropical Weathering In Norway, TWIN Final Report. *NGU Report 2012. 005*, 188 pp.

Olesen, O., Brönner, M., Dehls, J.F., Kierulf, H.P., Lindholm, C. and Rise, L (2012b) Onshore-offshore neotectonics in Nordland, northern Norway. *In* Hendriks, B. and Haukdal, G.K. (eds.) *Onshore-offshore relationships on the North Atlantic Margin*. Abstracts and Proceedings of the Geological Society of Norway, **2**, 54–56.

Olsen, L. (1998) Quaternary studies in the Sjona – Ranafjorden area with some additional information from other areas in northern Norway. *In* Dehls, J. and Olesen, O. (eds.) *Neotectonics in Norway. Annual Technical Report 1997*. Norges geologiske undersøkelse Report 98.016, 104–114.

Olsen, L. (2000) Quaternary geology and trenching of the Båsmoen fault. *In* Dehls, J. and Olesen, O. (eds.) *Neotectonics in Norway. Annual Technical Report 1999*. Norges geologiske undersøkelse Report 2000.001, 43–46.

Olsen, L. and Sveian, H. (1994) Hovedtrekk av kvartærgeologien i området Namsfjorden – Salsnes. *In* Bargel, T.H., et al. (eds.) Guide til Midtnordenekskursjonen 1994. *Kvartærgeologi og miljøgeologi i Midt Norge*. Norges geologiske undersøkelse Report 94.071, 21–34.

Olsen, L. and Grøsfjeld, K. (1999) Middle and Late Weichselian high relative sea levels in Norway: implications for glacial isostasy and ice-retreat rates. *Norges geologiske undersøkelse Bulletin*, **435**, 43–51.

Olsen, L., Dehls, J.F., Olesen, O. and Rønning, J.S. (1999) Late Quaternary faulting and paleoseismicity in Finnmark, northern Norway. *In* Dehls, J.F. and Olesen, O. (eds.) *Neotectonics in Norway. Annual Technical Report 1998*. Norges geologiske undersøkelse Report 99.007, 93–102.

Oppikofer, T., Jaboyedoff, M., Blikra, L.H. and Derron, M.-D. (2008) Characterization and monitoring of the Åknes rockslide using terrestrial laser scanning. *In* Locat, J., Perret, D., Turmel, D., Demers, D. and Leroueil, S. (eds.). *Comptes rendus de la 4e Conférence canadienne sur les géorisques: des causes à la gestion*. Proceedings of the 4th Canadian Conference on Geohazards. From Causes to Management. Presse de l'Université Laval, Québec, 594 pp.

Osmundsen, P.T., Sommaruga, A., Skilbrei, J.R. and Olesen, O. (2002) Deep structure of the Mid Norway rifted margin. *Norwegian Journal of Geology*, **82**, 205–224.

Osmundsen, P.T., Henderson, I., Lauknes, T.R., Larsen, Y., Redfield, T.F. and Dehls, J. (2009) Active normal fault control on landscape and rock-slope failure in northern Norway. *Geology*, **37**, 135–138.

Osmundsen, P.T., Redfield, T.F. Hendriks, B.H.W., Bergh, S., Hansen, J.-A. Henderson, I.H.C., Dehls, J., Lauknes, T.R., Larsen, Y., Anda, E. and Davidsen, B. (2010) Fault-controlled alpine topography in Norway. *Journal of the Geological Society, London*, **167**, 83–98.

Pan, M., Sjöberg, L.E. and Talbot, C.J. (2001) Crustal movements in Skåne between 1992 and 1998 as observed by GPS. J*ournal of Geodynamics*, **31**, 311–322.

Pascal, C. and Gabrielsen, R.H. (2001) Numerical modelling of Cenozoic stress patterns in the Mid Norwegian Margin and the northern North Sea. *Tectonics*, **20**, 585–599.

Pascal, C. and Cloetingh, S.A.P.L. (2009) A quantitative analysis on the impact of gravitational potential stresses on passive margins with emphasis to the Mid-Norwegian Margin. *Earth and Planetary Science Letters*, **277**, 464–473.

Pascal, C., Roberts, D. and Gabrielsen, R.H. (2005a) Quantification of neotectonic stress orientations and magnitudes from field observations in Finnmark, northern Norway. *Journal of Structural Geology*, **27**, 859–870.

Pascal, C., Roberts, D. and Gabrielsen, R.H. (2005b) Tectonic significance of present-day stress-relief phenomena in formerly glaciated regions. *Journal of the Geological Society, London*, **167**, 363–371.

Pascal C., Roberts, D. and Gabrielsen, R.H. (2006) Present-day stress orientations in Norway as deduced from stress-release features. *In* Lu, M., Li, C.C., Kjørholt, H. and Dahle, H. (eds.) *In-situ Rock Stress, Measurement, Interpretation and Application*. Taylor & Francis, London, 209–214.

Paull, C., Ussler, W. III and Dillon, W. (1991) Is the extent of glaciation limited to marine gas hydrates. *Geophysical Research Letters*, **18**, 432–434.

Piepjohn, K. (1994) *Tektonische Evolution der Devongräben (Old Red) in NW-Svalbard*. Unpubl. Ph.D. thesis, Westfälischen Wilhelms-Universität, Münster. 170 pp.

Pirli, M., Schweitzer, J., Ottemöller, L., Raeesi, M., Mjelde, R., Atakan, K., Guterch, A., Gibbons, S.J., Paulsen, B., Dębski, W., Wiejacs, P. and Kværna, T. (2010) Preliminary analysis of the 21 February 2008 Svalbard (Norway) seismic sequence. *Seismological Research Letters*, **81**, 63–75.

Ransed, G. and Wahlroos J.-E. (2007) Map of the Quaternary deposits 24H Sorsele, scale 1:100 000. *Sveriges geologiska undersökning*, **K 42**.

Redfield, T.F. and Osmundsen, P.T. (2009) The Tjellefonna fault system of Western Norway: Linking late-Caledonian extension, post-Caledonian normal faulting, and Tertiary rock column uplift with the landslide-generated tsunami event of 1756. *Tectonophysics* **474**, 106–123.

Reinecker, J., Heidbach, O., Tingay, M., Sperner, B. and Müller, B. (2005) The 2005 release of the World Stress Map (available online at http://www.world-stress-map.org).

Riis, F. (1996) Quantification of Cenozoic vertical movements of Scandinavia by correlation of morphological surfaces with offshore data. *Global and Planetary Change*, **12**, 331–357.

Riis, F. (1998) Seismic investigations in the North Sea. *In* Dehls, J.F. and Olesen, O. (eds.): *Neotectonics in Norway, Annual Technical Report 1997*. Norges geologiske undersøkelse Report 98.016, 59–70.

Rise, L., Olesen, O., Rokoengen, K., Ottesen, D, Riis, F. (2004) Mid Pleistocene ice drainage pattern in the Norwegian Channel imaged by 3D seismic. *Quaternary Science Reviews*, **23**, 2323–2335.

Rise, L., Ottesen, D., Berg, K. and Lundin, E. (2005) Large-scale development of the mid-Norwegian margin during the last 3 million years. *Marine and Petroleum Geology*, **22**, 33–44

Roberts, D. (1991) A contemporary small-scale thrust-fault near Lebesby, Finnmark. *Norsk Geologisk Tidsskrift*, **71**, 117–120.

Roberts, D. (2000) Reverse-slip offsets and axial fractures in road-cut boreholes from the Caledonides in Finnmark, northern Norway: neotectonic stress orientation indicators. *Quaternary Science Reviews*, **19**, 1437–1445.

Roberts, D. and Myrvang, A. (2004) Contemporary stress orientation features and horizontal stress in bedrock, Trøndelag, central Norway. *Norges geologiske undersøkelse Bulletin*, **442**, 53–63.

Roberts, D., Olesen, O. and Karpuz, M. R. (1997) Seismo- and neotectonics in Finnmark, Kola Peninsula and the southern Barents Sea; Part 1, Geological and neotectonic framework. *Tectonophysics*, **270**, 1–13.

Rønning, J.S., Dalsegg, E., Dehls, J.F., Haase, C., Nordgulen, Ø., Olesen, A., Saintot, A. and Solli, A. (2006) Geological and geophysical investigations for the ROGFAST Project. *Norges geologiske undersøkelse Report 2006.076. 91* pp.

Savage, W.Z. and Varnes, D.J. (1987) Mechanics of gravitational spreading of steep-sided ridges ('sackung'). International *Association of Engineering Geologists Bulletin*, **35**, 31–36.

Scherneck, H.-G., Johansson, J.M., Vermeer, M., Davis, J.L Milne, G.A. and Mitrovica, J.X. (2001) BIFROST project: 3–D crustal deformation rates derived from GPS confirm postglacial rebound in Fennoscandia. *Earth Planets and Space*, **53**, 703–708.

Scherneck, H.-G., Johansson, J.M. Koivula, H., van Dam, T. and Davis, J.L. (2003) Vertical crustal motion observed in the BIFROST project. *Journal of Geodynamics*, **35**, 425–441.

Schulte, S.M. and Mooney, W.D. (2005) An updated global earthquake catalogue for stable continental regions: reassessing the correlation with ancient rifts. *Geophysical Journal International*, **161**, 707–721.

Schøning, G. (1778) *Reise som giennem en Deel af Norge i de Aar 1773, 1774, 1775 paa Hans Majestets Kongens Bekostning er giort og beskreven av Gerhard Schøning*. Gyldendal, København.

Sejrup, H.-P. (1987) Molluscan and foraminiferal biostratigraphy of an Eemian-Early Weichselian section on Karmøy, southwestern Norway. *Boreas*, **16**, 27–42.

Sibson, R.H. (1990) Rupture nucleation on unfavorably oriented faults. *Bulletin of the Seismological Society of America*, **80**, 1580–1604.

Sibson, R.H., Moore, J. McM. and Rankin, A.H. (1975) Seismic pumping – a hydrothermal fluid transport mechanism. *Journal of the Geological Society, London*, **131**, 653–659.

Sigmond, E.M.O. (2002) Geological map, land and sea areas of northern Europe, Scale 1:4 million. Geological Survey of Norway.

Simonsen, A. (1963) *Kvartærgeologiske undersøkelser i Indre Hardanger, Ulvik hd. Hordaland*. Unpubl. M.Sc. Thesis, University of Bergen, 67 pp.

Sjöberg, R. (1988) Coastal caves indicating preglacial morphology in Norway. *Cave Science*, **15**, 99–103.

Sletten, K. (2000) Slides in low-gradient areas of Finnmarksvidda. *In* Dehls, J.F. and Olesen, O. (eds.) *Neotectonics in Norway, Annual Technical Report 1999*. Norges geologiske undersøkelse Report 2000.001, 41–42.

Slunga, R. (1989) Focal mechanisms and crustal stresses in the Baltic Shield. *In* Gregersen, S. and Basham, P.W. (eds.) *Earthquakes at North-Atlantic passive margins: neotectonics and postglacial rebound*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 261–276.

Solheim, A., Berg, K., Forsberg, C.F. and Bryn, P. (2005) The Storegga Slide complex: repetitive large scale sliding with similar cause and development. *Marine and Petroleum Geology*, **22**, 97–107.

Solli, A. (1988) Masi 1933 IV - Bedrock Map. *Norges geologiske undersøkelse, Trondheim*.

Sollid, J. L. and Tolgensbakk, J. (1988) *Kvartærgeologisk og geomorfologisk kartlegging på Svalbard og fastlands-Norge*. Abstract, Nordic Geological Winter-Meeting, Copenhagen, 380–381.

Steffen, H. and Wu, P. (2011) Glacial isostatic adjustment in Fennoscandia – A review of data and modeling. *Journal of Geodynamics*, **52**, 169–204.

Stein, S., Cloetingh, S., Sleep, N.H. and Wortel, R. (1989) Passive margin earthquakes, stresses and rheology. *In* Gregersen, S. and Basham, P.W. (eds.) *Earthquakes at North-Atlantic passive margins; neotectonics and postglacial rebound*. NATO ASI Series, Series C: Mathematical and Physical Sciences **266**. D. Reidel Publishing Company. Dordrecht-Boston, 231–259.

Stephansson, O., Särkkä, P. and Myrvang, A. (1986) State of stress in Fennoscandia. *In* Stephansson, O. (ed.) *Proceedings of the International Symposium on Rock Stress and rock stress measurements*, Stockholm, 1–3 September 1986, Lulea, Sweden, 21–32.

Stewart, I.S., Sauber, J. and Rose, J. (2000) Glacio-seismotectonics: ice sheets, crustal deformation and seismicity. *Quaternary Science Reviews*, **19**, 1367–1389.

Sveian, H. and Olsen, L. (1984) A shoreline displacement curve from Verdalsøra, Nord-Trøndelag, Central Norway. Norsk Geologisk Tidsskrift, 64, 27–38.

Sylvester, A.G. (1999) Evaluation of repeated levelings across the Stuoragurra Fault, Finnmark, Norway, 1987 to 1996. *In* Dehls, J.F. and Olesen, O. (eds.) *Neotectonics in Norway, Annual Technical Report 1998*. Norges geologiske undersøkelse Report 1999.007, 154–164.

Talbot, C.J. and Slunga, R. (1989) Patterns of active shear in Fennoscandia. *In* Gregersen, S. and Basham, P.W. (eds.) *Earthquakes at North-Atlantic passive margins: neotectonics and postglacial rebound*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 441–466.

Tolgensbakk, J. and Sollid, J. L. (1988) Kåfjord, kvartærgeologi og geomorfologi 1:50 000, 1634 II. *Geografisk institutt, University of Oslo*.

van Eck, T. and Davenport, C.A. (1994) Seismotectonics and seismic hazard in the Roer Valley Graben: an overview. *Geologie en Mijnbouw*, **73**, 95–98.

Varnes, D. J., Radbruch-Hall, D. H. and Savage, W. Z. (1989) Topographic and structural conditions in areas of gravitational spreading of ridges in the Western United States. *US Geological Survey Professional Paper* **1496**, 28 pp.

Vestøl, O. (2006) Determination of postglacial land uplift in Fennoscandia from leveling, tide-gauges and continuous GPS stations using least squares collocation. *Journal of Geodesy*, **80**, 248–258.

Vågnes, E., Gabrielsen, R.H. and Haremo, P. (1998) Late Cretaceous-Cenozoic intraplate contractional deformation at the Norwegian continental shelf: timing, magnitude and regional implications. *Tectonophysics*, **300**, 29–46.

Wells, D. L. and Coppersmith, K. J. (1994) Empirical relationships among magnitude, rupture length, rupture area, and surface displacement. *Bulletin of the Seismological Society of America*, **84**, 974–1002.

Wu, P. (1998) Intraplate earthquakes and Postglacial Rebound in Eastern Canada and Northern Europe. *In* Wu, P. (ed.) *Dynamics of the Ice Age Earth: A Modern Perspective*. Trans Tech Publications, Switzerland, 603–628.

Zischinsky, U. (1969) Über Sackungen. Rock Mechanics, 1, 30–52.

Åm, M., (1994) *Mineralogisk og petrologisk karakterisering av vitrings/sleppemateriale fra Stuoragurraforkastningen, Finnmark*. Norwegian University of Science and Technology Project Report, 102 pp.b

Appendix

Reported evidence of neotectonics in Norway and Svalbard and assessments of the claims. The locations are ordered from north to south and are shown in Figure 1. The criteria for classification of postglacial faulting proposed by Fenton (1994) and Muir Wood (1993) have been adapted for grading the claims into the classes: (A) Almost certainly neotectonics, (B) Probably neotectonics and (C) Possibly neotectonics. Grade D, Probably not neotectonics and E, Very unlikely to be neotectonics, are omitted in the present table but are listed in Olesen et al. (2004). 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	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
2	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 m 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
3	Masi–Iešjav'ri area, Finnmark (Olesen 1988, Solli 1988, Muir Wood 1989a, Olesen et al. 1992a,b, Bungum and Lindholm 1997, Roberts et al. 1997, Olsen et al. 1999, Dehls et al. 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 m high and is situated within the regional, Proterozoic, Mierujavri–Sværholt Fault Zone. The SF is a southeasterly dipping reverse fault. A c. 1m-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
4	Lyngen, Troms (Holmsen 1916)	Holocene uplift was assessed from levelling of shorelines in northern Troms. Negative uplift anomalies in the order of 5 m were ascribed to gabbro massifs within the Lyngen Ophiolite.	The interpretation is hampered by poor age control on the formation of the shorelines.	C7
5	Nordmannvik-dalen, Kåfjord, Troms (Tolgensbakk and Sollid 1988, Sollid and Tolgensbakk 1988, Blikra et al. 2006, Dehls et al. 2000a, Osmundsen et al. 2009)	NW–SE-trending postglacial faults in the Kåfjord area, North Troms. Normal faults dipping 30–50º to the northeast (Dehls et al. 2000a). The height and length of the main escarpment is approximately 1 m and 2 km, respectively.	The fault is subparallel to the Nordmannvikdalen valley. The slope of the terrain is 10–12º and the elevation difference between the fault scarp and valley bottom is 150–200 m. According to Varnes et al. (1989) gravity-induced sliding is less likely to occur when the elevation difference is less than 300 m. We therefore favour a tectonic origin for the fault.	A1
6	Balsfjord–Lyngen area, Troms (Blikra et al. 2006)	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
7	Astafjorden–Grytøya area, Troms (Blikra et al. 2006)	A relatively high concentration of rock avalanches.	The number of rock avalanches is not as high as in the Balsfjord–Lyngen area farther north, but is much higher than in the Senja area where the topography is considerably rougher.	C1, 2
8	Kvasshaugen, between the valleys of Beiardalen and Gråtådalen, Nordland (Grønlie 1939, 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 et al. 2004). The initiation of movements, however, may have been triggered by large earthquakes.	B1, 2
9	Ranafjord area, Nordland (Helzen 1834, Grønlie 1923, Muir Wood 1989b, Bakkelid 1990,2001, Olesen et al. 1994, 1995, Hicks et al. 2000b, Olsen 1998, 2000)	The Båsmoen fault consists of SSE-dipping (40–70º) 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 miniarray 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. 2000b).	B1, 3

Loc.No.	Location and reference	Observation	Comment	Grade/ type
10	Nesna islands, (Handnesøya, Hugla and Tomma), Nesna, Nordland (Bakkelid 1990, 2001, Olesen et al. 1994, 1995, 2012b)	N–S-trending, steeply dipping fractures and faults occur on Handnesøya. There seems to be a vertical offset of the bedrock surface across these structures. The foliation of the mica schist is subparallel 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. Monitoring of the seismicity in the area, however, has 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. 2000b). The observed uplift of acorn barnacle and bladder wrack marks at two different locations on the neighbouring island Hugla deviates 1–2 mm yr^{-1} from the regional trend. The benchmarks were established in 1894 and remeasured in 1990. GPS campaign measurements in 1999 and 2008 by the Norwegian Mapping Authority (Kartverket) indicate that the bench marks to the west of the earthquakes have moved c. 1 mm yr^{-1} to the NW and W relative to the stations to the east of the earthquake swarms (Olesen et al. 2012b). Dehls et al. (2002) reported irregular subsidence in the order of 0.5 mm yr^{-1} from InSAR permanent scatterer data during the period 1992–2000.	The ice has most likely plucked blocks from the bedrock along steeply dipping N–S-trending fractures (Olesen et al. 2004). The observed uplift at the two locations on Hugla is 0.0 and 0.5 mm yr^{-1}. The benchmark with the zero 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 (Hicks et al. 2000b). The consistent pattern of present-day extension and subsidence from four different methods is a strong indication of active deformation in the outer Ranafjorden area, although no direct active fault scarp has been detected at the surface.	A1
11	Klubbsteinen, Nord-Flatanger, Nord-Trøndelag (Olsen and Sveian, 1994, Olsen 1998)	A thick deposit of fine to medium sand with clast-supported conglo-meratic 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 character of the sand resembles the compositions of similar sands recorded at c. 10 other sites in Mid and North Norway. Earthquakes seem to be a likely cause of the production of these characteristics, 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 conglomeratic feature 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 features 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 and Olsen 1984).	B1
12	Tjellefonna, Langfjorden, Nesset, Møre & Romsdal (Morsing 1757, Bungum and Lindholm 2007, Redfield and Osmundsen 2009)	Morsing (1757) concluded that the Tjellefonna and Silset rock avalanches on 23 February 1756 in Møre & Romsdal county were caused by an earthquake (Bungum and Lindholm 2007, Redfield and Osmundsen 2009). The Tjellefonna rock avalanche created a 40 m-high tsunami that caused catastrophic damage to the settlements along Langfjorden and Eresfjorden and killed a total of 32 people. Redfield and Osmundsen (2009) suggest that an earthquake on a nearby fault caused the already weakened Tjelle hillside to fail.	It is possible that the Tjellefonna rock slide was triggered by an earthquake since the historical records suggest a contemporaneous rockslide at Silset located 15 km farther north. Morsing (1757) described a long rumbling noise just before the Tjellefonna rock avalanche plunged into the Langfjorden. He interpreted this in terms of an earthquake.	C1, 2
13	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.	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. This reverse fault appears to be part of a sackung structure (Savage and Varnes 1987). The open clefts with upward-facing scarps along the mountain ridge in the hanging-wall block of the reverse fault are typical features of gravity-induced sackung structures. The low offset/length ratio (1/500) of the fault also points to a nontectonic origin. A nearby large-magnitude earthquake may have triggered the collapse structure.	B2
14	Oterøya–Øtrefjellet, Haram, Møre og Romsdal (Braathen et al. 2004, Blikra et al. 2006)	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 occurs locally within a 500 m-wide zone. The slopes of the ridge are too gentle to cause any gravity sliding (Braathen et al. 2004, Blikra et al. 2006). 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

Loc.No.	Location and reference	Observation	Comment	Grade/ type
15	Ørsta–Vanylven, Møre og Romsdal (Bøe et al. 2004, Blikra et al. 2006)	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 BP event is interpreted to be related to the tsunami generated by the Storegga slide.	C3
16	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 and Grøsfjeld (1999) have reported uplifted (40–90 m) Middle and Upper 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 could, to some extent, explain the location of sea-formed caves above the postglacial marine limit. It is, however, an open question if this model would imply sufficiently long time periods for the caves to have been formed by sea erosion. Deeply weathered fracture zones could have facilitated the formation of such caves.	C3
17	Aurland–Flåm, Sogn & Fjordane (Blikra et al. 2006)	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
18	Geitura, Ulvik, Hordaland (Simonsen 1963, Blikra et al. 2006)	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. 2006). Neotectonic activity in the Hardangerfjord area is supported by recent work on shoreline displacement by Helle et al. (2000).	B1
19	Finse–Geilo area, Hordaland–Buskerud (Anundsen et al. submitted)	Anomalous uplift from repeated levelling.	A careful analysis of the levelling methods is pending.	C8
20	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 1990). This difference in the rate of deglaciation may explain the occurrence of marine Eemian sediments at elevated positions on Fjøsanger.	C
21	Yrkje area (Anundsen and 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).	C7
22	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
23	Egersund–Flekkefjord area, Rogaland (Anundsen 1989, Anundsen et al. submitted)	A subsidence of 2–2.5 mm yr^{-1} has been recorded in the Egersund Anorthosite–Gabbro Province. The zone of maximum subsidence coincides with a maximum gravity anomaly in the area.	A follow-up geodetic study is needed to carry out a better evaluation of this claim.	C8
24	Haukeligrend, Vinje, Telemark (Anundsen et al. submitted)	Anomalous subsidence from repeated levelling.	A careful analysis of the levelling methods is pending.	C8
25	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 pockmarks in the area. The faulting may be related to gas escape, as suggested by Fulop (1998). The faults bear a 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
26	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 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
27	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
28	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 commonly 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 cannot therefore be ruled out.	C1