JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. B3, PAGES 6221-6236, MARCH 10, 2000

Seismotectonics of the Norwegian continental margin

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Abstract. The Norwegian continental margin and surrounding areas are seismically less active than some other passive margins worldwide, indicating a potential earthquake deficit. The adjacent oceanic crust is mostly aseismic except for parts of the Lofoten and Norway Basins which have experienced rapid deposition of glacial sediments. The excess load has enhanced the local stress field and, in turn, the seismic activity. The marginal highs along the continent-ocean transition and the part of the Møre and Vøring Basins which experienced crustal extension prior to the early Tertiary breakup are practically aseismic. This region is also underlain by high-velocity lower crust emplaced during breakup, suggesting crustal strengthening, which also may increase the return periods for the largest events. Farther landward, a spatial correlation of seismic activity and the glacial sediment wedge suggests a causal relationship, expressed through preferential rejuvenation of Late Jurassic-Early Cretaceous faults. The locally high seismic activity in the coastal region occurs in areas where the continental crust is relatively thick (25-30 km) but still thinner than in the shield area farther east (45-50 km). Although stress relations are complex, we suggest that increased stress due to appreciable postglacial rebound gradients in the coastal region may be a contributing factor. While the stress field along the margin complies in general with the ridge push force, we infer that regional and local stress enhancement factors are not only present in this region but also necessary for explaining the earthquake activity. The relative importance of local stress sources is supported by several cases of 90° stress rotations relative to the ridge push direction. The superposition of regional and local stress, together with the existence of weakness zones and faults, yields potentials for earthquakes, primarily through structural reactivation.

1. Introduction

The concept of stable continental regions has been developed to compensate ergodically for the long return periods of larger intraplate earthquakes by trading time for space within geologically similar regions [e.g., *Johnston and Kanter*, 1990]. Stable continental regions, i.e., stable continental crust including passive margins and failed rifts, cover about two thirds of all continental crust [*Johnston et al.*, 1994; see also *Sengör*, 1999]. The global pattern of stable continental region earthquakes shows that most of the seismic moment release is confined to old rifts and to passive margins. Earthquakes above magnitude 7 have been experienced in many of these regions. Studies of stress suggest complex interactions between different sources of stress and between the stress field and zones of weakness, which under favorable conditions may result in reactivation of older fault zones [e.g., *Mandal et al.*, 1997].

The Norwegian continental margin (Plate 1) comprises a stable continental region with modest, but spatially variable, seismic activity (Plate 2 and Table 1). The largest known historical earthquake is not larger than magnitude 6, and global comparisons with other passive margins indicate a possible moment release deficit [*Bungum et al.*, 1991; *Johnston et al.*, 1994]. Although the seismicity of Fennoscandia has been discussed extensively [e.g., *Husebye et al.*, 1975; *Bungum and Fyen*, 1979; *Bungum et al.*, 1991; *Arvidsson and Kulhanek*, 1994; *Lindholm et al.*, 1999; *Fejerskov and Lindholm*, 1999], few studies have focused on the passive margin. Because the tectonomagmatic and depositional margin framework is now well established, it is possible to study seismotectonic relations in more detail than before. Here, we investigate the spatial correlations between geological features, geophysical anomalies, and seismological data by establishing local seismotectonic provinces in an attempt to reveal information about causal connections and contemporary deformation processes.

2. Geologic Setting

Structurally, the Norwegian margin (62-74°N) is predominantly of a rifted type south of 70°N and of a sheared type farther north. It comprises four physiographic provinces, the Møre, Vøring, Lofoten-Vesterålen, and Barents Sea margins (Plates 1-2). The Vøring margin has a wide shelf and the slope is interrupted by the large Vøring Plateau at 1200-1500 m depth, whereas the adjacent

Paper number 1999JB900275.
0148-0227/00/1999JB900275$09.00

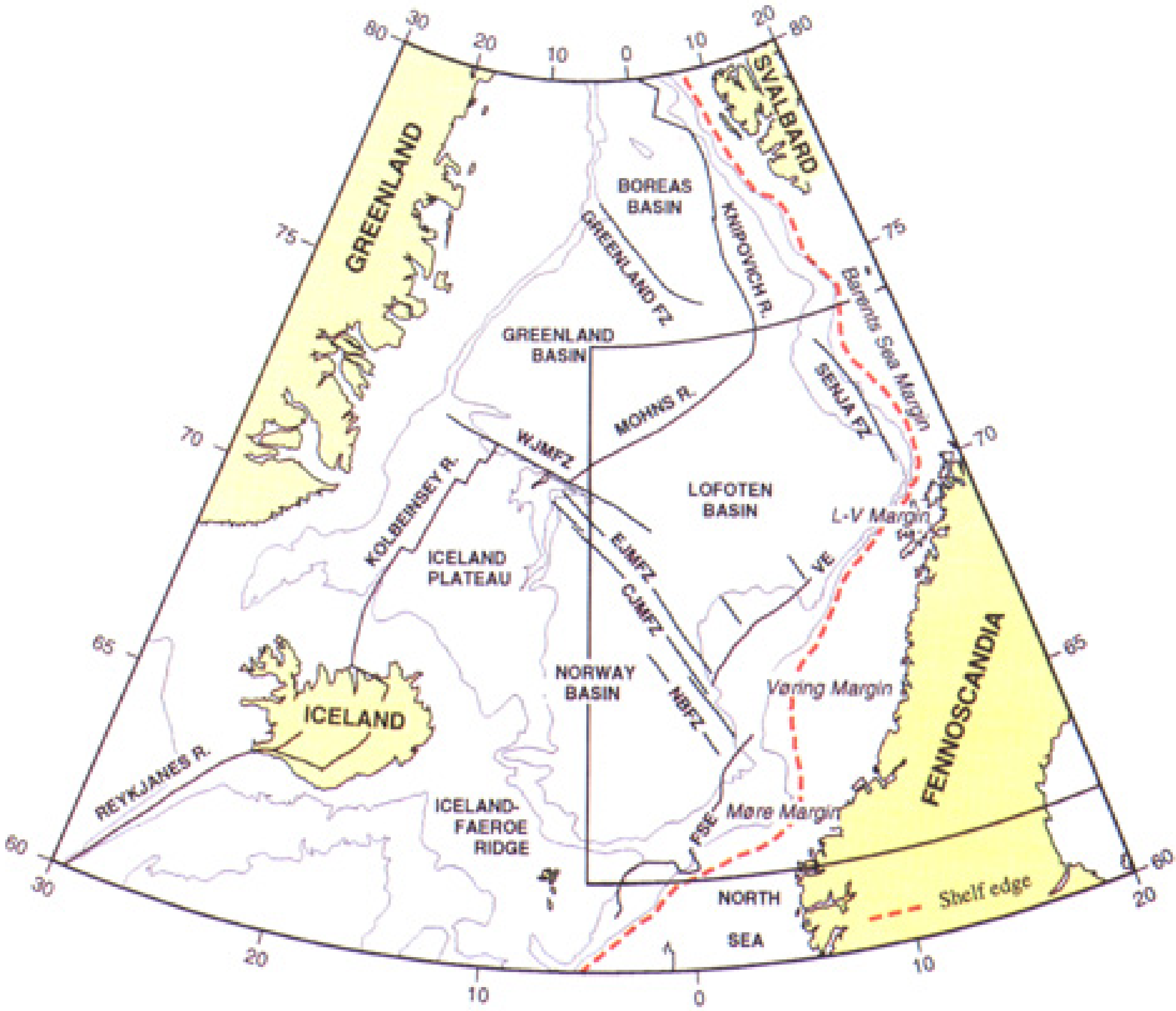

Plate 1. Regional setting of the study area (within box). Depth contours are at 1000 and 2000 m [*Perry et al.*, 1980]. CJMFZ, Central Jan Mayen Fracture Zone (FZ); EJMFZ, East Jan Mayen FZ; FSE, Faeroe-Shetland Escarpment; L-V, Lofoten-Vesterålen; NBFZ, Norway Basin FZ; VE, Vøring Escarpment; WJMFZ, West Jan Mayen FZ.

margin segments have narrower shelves and steeper slopes. A wide, gentle slope reappears off the Barents Sea.

The margin segmentation primarily reflects the interaction of structures associated with the Late Cretaceous-Paleocene (75-55 Ma) rifting and subsequent breakup of Eurasia and Greenland, and preexisting Late Jurassic-Early Cretaceous extensional structures. Large-scale igneous activity accompanied the breakup and initial seafloor spreading, constructing marginal highs capped by thick flood basalts west of the Faeroe-Shetland and Vøring Escarpments (Plate 2). Moreover, the extrusive complexes along the continent-ocean transition on the rifted margin segments are underlain by lower high-velocity crust emplaced during breakup [*Eldholm et al.*, 1989].

The Cenozoic depositional history comprises three stages [*Hjelstuen et al.*, 1997]. The Paleocene-middle Eocene was characterized by restricted basins receiving sediments from uplifted rift blocks and marginal highs in the west. This was followed by margin subsidence and modest sedimentation until late Pliocene time when the combined effects of tectonic uplift of Fennoscandia and the onset of the Northern Hemisphere glaciation led to greatly

Table 1. Seismic Activity Rates for the Seismotectonic Provinces in Plate 3

Location	Seismic Zone	a Value	M>4 100 years
Coast and on shore	North Nordland Coast	3.0	4.0
	Møre Coast	2.8	2.5
	South Nordland Coast	2.6	1.6
	Lofoten-Vesterålen Coast	2.5	1.3
Shelf and slope	Lofoten-Vesterålen Shelf	3.0	4.0
	Møre Shelf	2.9	3.2
	East Vøring Basin	2.9	3.2
	Møre Basin	2.8	2.5
	Barents Slope	2.8	2.5
Oceanic basins	East Lofoten Basin	3.4	10.0
	East Norway Basin	2.9	3.2

The a values are normalized to 1 year and 10^4 km^2, from the recurrence formula $\log N = a - bM$, based on b=1.1 as derived from the regional earthquake catalog [*Byrkjeland*, 1996]. The corresponding number of M>4.0 events in 100 years are given per 10^4 km^2. In addition, there are seven seismically less active or aseismic zones (Plate 3).

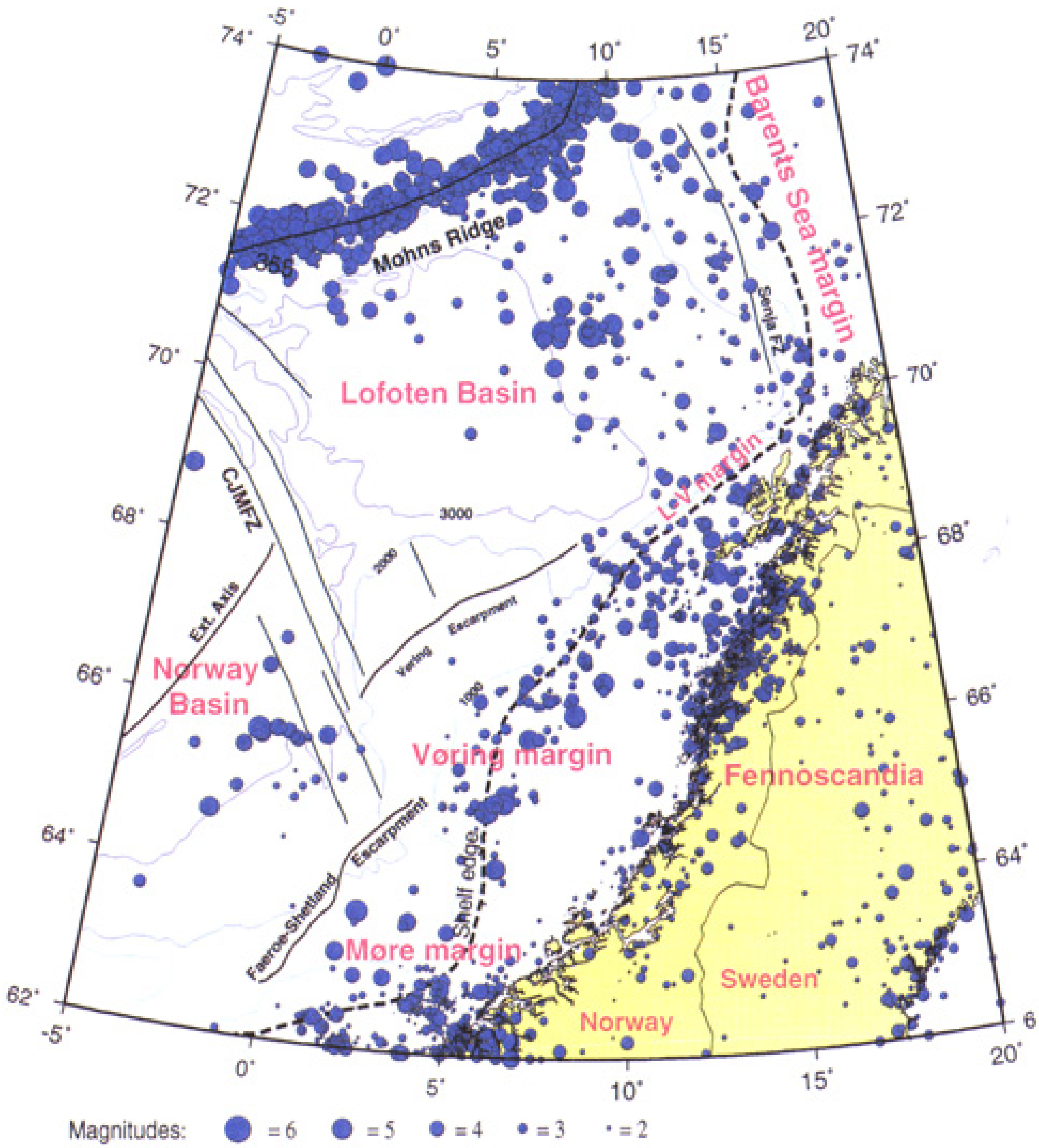

Plate 2. Seismicity of the Norwegian margin and adjacent ocean basins including all events in the earthquake catalog since 1880 above magnitude 2.0. Bathymetry is in meters [*Perry et al.*, 1980]. Structural elements are from *Talwani and Eldholm* [1977] and *Skogseid and Eldholm* [1987]. Acronyms are as in Plate 1.

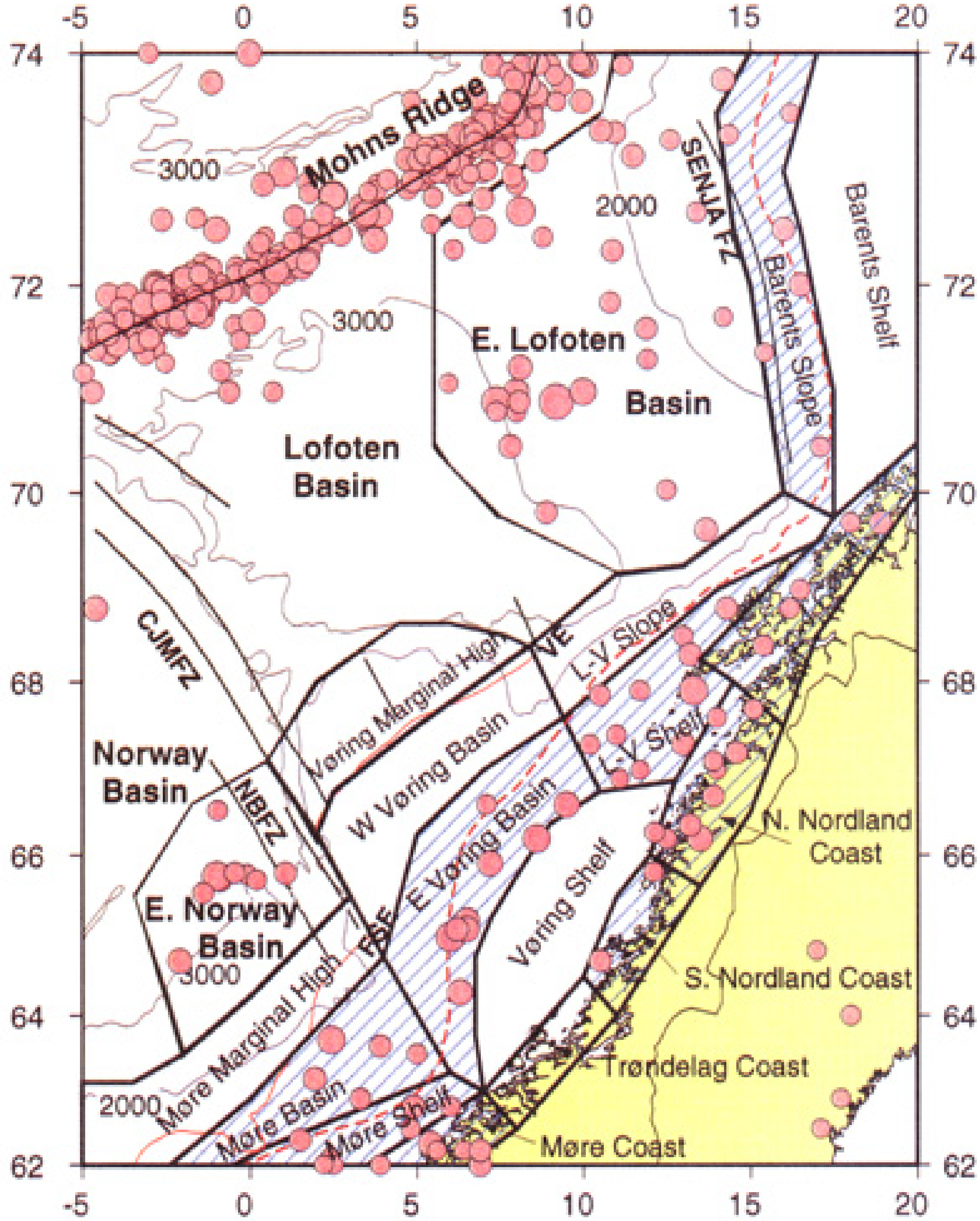

Plate 3. Seismotectonic provinces and distribution of earthquakes with magnitude 3.0 or larger since 1880. The seismically active provinces are shown hatched, while the seismically active zones in oceanic crust are double-hatched. Oceanic crust is beige.

increased erosion and sedimentation. In fact, >50% of the Cenozoic sediment volume has been deposited during the last 2.6 Myr. The corresponding increase in sedimentation rate may be particularly important for the present stress situation because of the rapid lateral transfer of a voluminous sediment mass.

3. Data

The geophysical and geological data compiled to evaluate spatial relations between seismicity and structure include [*Byrkjeland*, 1996]: bathymetry, free-air gravity anomalies, crustal thickness, crustal stress orientations from earthquakes and in situ measurements, regional structural elements, depth to crystalline basement, thickness and sedimentation rates for Cenozoic and late Pliocene-Pleistocene sediments, neotectonic observations, and postglacial rebound rates.

The seismological data are based on the NORSAR catalogs, incorporating historical data [*Ambraseys*, 1985; *Muir Wood and Woo*, 1987] as well as instrumentally recorded data from a variety of seismic stations and reporting agencies [*Bungum et al.*, 1986, 1991; *Havskov et al.*, 1992]. The precision of earthquake epicenters varies with time of occurrence as most were determined from felt reports prior to the mid-1950s. *Muir Wood et al.* [1988] have re-evaluated all historically felt larger earthquakes in Norway,

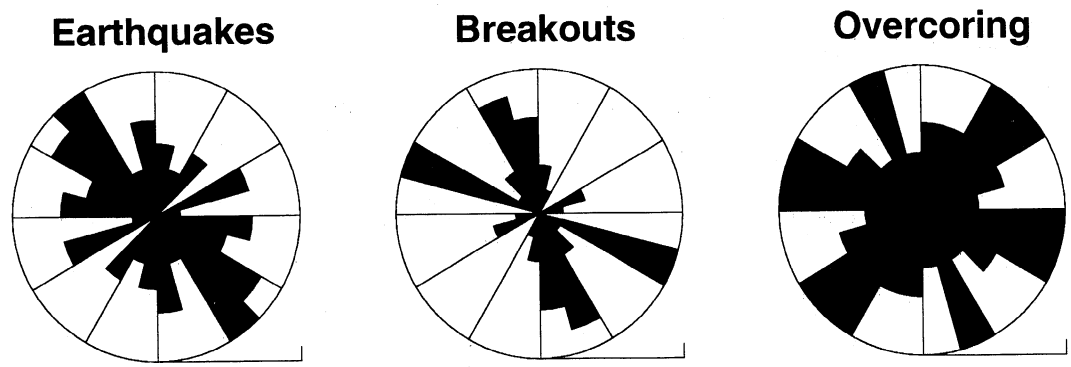

Figure 1. Rose diagrams, with sectors of 15°, of all the S_{Hmax} directions as obtained from (left) focal mechanisms, (center) borehole breakout, and (right) overcoring measurements along the Norwegian margin (courtesy of E. Hicks), with six, six, and five observations behind each one, respectively.

establishing consistent and comparable locations and magnitudes. However, the location uncertainties of these earlier events is normally 20-60 km, compared to 20-25 km for instrumentally localized earthquakes during 1955-1979. Since 1980, the uncertainty when using microearthquake networks is generally <15 km [*Bungum et al.*, 1991]. The seismicity catalog (Plate 2) includes a quality assessment, and presumed explosions have been removed.

The catalog used until recently has for the largest events been based on surface wave magnitude M_S, where the link to older data was based on correlation between felt area and instrumentally measured M_S [*Muir Wood and Woo*, 1987]. Lately, however, the catalog has been converted to moment magnitude M_W [*NORSAR and Norwegian Geotechnical Institute (NGI)*, 1998], based on a combination of approaches which include direct estimation from seismic moment for both older and newer earthquakes, combined with correlations between seismic moment and different types of magnitude. The result is relations which allow conversion to M_W (albeit, at different quality levels) for the entire catalog, where for the larger events, M_W is quite similar to M_S. In the following, only M is used for magnitude, implying the newly established M_W. The catalog (Plate 2) is reasonably complete since 1880 for magnitudes $M >\sim 4.5$ [*Muir Wood and Woo*, 1987; *Byrkjeland*, 1996], while the post-1960 completeness threshold is $M \sim 4.0$-4.3. The improvements in station coverage during the 1980s have further lowered the detection threshold.

The focal depths are generally distributed within the entire crystalline crust, including relatively frequent lower crustal earthquakes [*Bungum et al.*, 1991; *Lindholm et al.*, 1999]. Notable exceptions are some 3-8 km deep earthquake swarms and sequences in northern Norway, i.e., Meløy [*Bungum et al.*, 1979, 1982], Steigen [*Atakan et al.*, 1994] and Ranafjord [*Hicks et al.*, 1999].

4. Seismicity and Earthquake Generating Mechanisms

The seismicity and our seismotectonic regionalization are shown in Plates 2-3. The cumulative energy release during the last 100 years in a 200-km-wide area off the coast (62-71°N) corresponds to about 10^6 J yr^{-1} km^{-2} or to a moment release rate of about 2×10^{10} N m yr^{-1} km^{-2}. This is of the same order as in the northern North Sea but significantly less than along the Barents Sea margin [*Byrkjeland*, 1996]. However, a single M 6.1 earthquake in the East Lofoten Basin in 1929 represents ~40% of the energy released since 1880 (Plate 3), demonstrating the sensitivity of the seismic moment budget to the largest events. To illustrate the seismic activity levels differently, we first projected all the seismic activity onto a vertical plane along the margin, then estimated the moment release rate $\dot{M}_0$ and converted it to slip (displacement) rate S based on the *Brune* [1968] relation $S = \dot{M}_0/(\mu A)$, where μ is the shear modulus and A is the total area of the crustal size "fault plane", assuming complete seismic coupling. The resulting slip rate was very low, of the order of 20 m Myr^{-1} [*Byrkjeland*, 1996]. Compared to stable continental regions worldwide, a moment release rate off Norway of 10^{10}-10^{11} N m yr^{-1} km^{-2} is higher than for Asia east of Ural and Antarctica, of the same order as for Australia, Africa, and South America but lower than for India, China, and eastern North America [*Johnston et al.*, 1994; see also *Johnston* 1995a, b; 1996].

A simple assessment of the magnitude-frequency characteristics delineates the seismic activity rates for 11 seismically active provinces (Table 1, Plates 2-3). There are also seven less active or "aseismic" zones, of which three are located east of the shelf edge. Even the more active zones have only 1-10 earthquakes with $M \geq 4$ every hundred years per 10^4 km^2 area (Table 1). The historical record indicates that the recurrence times for the largest earthquakes probably is quite long; in fact, we know of no earthquakes of the size reported in many other stable continental regions [e.g., *Johnston and Kanter*, 1990], possibly indicating an earthquake deficit.

Lithospheric stress is dependent on the contemporary forces generated along diverging plate boundaries, and the ridge push force is probably the dominant cause of stress in continental regions, resulting in a stress field that is uniform over large areas [*Zoback*, 1992]. Intraplate earthquakes generally occur along preexisting zones of weakness and result from a buildup of stress and a reduction of the effective strength or favorable fault orientation [e.g., *Sibson*, 1985]. Earthquake focal mechanisms and in situ stress data in Norway show that the maximum compressive stress complies well with the NW-SE direction expected from the ridge push force (Figure 1, Plates 4-5), but also that regional and local sources of stress dominate in particular regions [*Hicks*, 1996; *Hicks et al.*, 1999].

In oceanic lithosphere the strength of the ridge-push force and thereby also the compressional deviatoric stresses, increase slowly (as $t^{1/2}$) with lithospheric age [*Dahlen*, 1981]. The average value of stress (~20-30 MPa) induced by the plate-driving forces probably also depends on the thickness of the lithosphere, since the tectonic force is proportional to the product of stress and thickness [e.g., *Bott and Kusznir*, 1984; *Bott*, 1991]. *Fejerskov and Lindholm* [1999] infer that the average crustal stress is proportional to the thickness of the crystalline crust, thus amplifying the regional ridge push force in thin (oceanic) crust. In continental crust, *Bott* [1991] finds lower stress values (~10 MPa), but he recognizes also that across passive margins subcrustal density differences [*Fleitout and Froidevaux*, 1983] may increase this value by as much as 30 MPa. In shield areas, however, the mean stress is probably lower, so that local effects are more likely to be of importance there.

While the ridge-push force is the first-order source of stress, second-order stress components may originate from several sources. Among these are lateral density contrasts, topography and its compensation at depth (of quite variable significance), changes in crustal thickness, and flexural loading and unloading. Loading on an elastic lithosphere will cause deflection and induce flexural stress which can be quite large (>100 MPa), perturbing the regional stress field at wavelengths that depend on the lateral extent of the load [e.g., *Walcott*, 1970; *McNutt and Menard*, 1982]. However, topographic loads that are compensated at depth should not be expected to generate compressive stress, since the load will be counterbalanced [*Fejerskov and Lindholm*, 1999]. Density contrasts across a continent-ocean boundary will induce margin-normal extension within the continental lithosphere and compression in the oceanic lithosphere [*Bott and Dean*, 1972; *Fejerskov and Lindholm*, 1999]. Stresses related to variation in crustal thickness and topography tend to be most significant in areas of accentuated relief [*Zoback*, 1992]. Similarly, crystalline basement blocks at marginal highs will induce tensional stresses within the high and compressive stresses on either side. On the basis of data and models from the Beaufort-Mackenzie Basin, *Stephenson and Smolyaninova* [1999] find a more local tectonic mechanism related to the lithosphere-asthenosphere transition to be favored, predicting a localized zone of uplift, with maximum shear stresses (~30 MPa), in an area of well-defined seismicity.

Flexural stresses include glacial loading and unloading, with potential dramatic effects during and following deglaciation [*Bungum and Lindholm*, 1997], whereas their residual effects at present (~10 MPa?) are debated [cf. *Stephansson*, 1988; *Stein et al.*, 1989; *Johnston et al.*, 1994]. Sediment loading may create large stresses (~100 MPa) on passive margins [*Frohlich*, 1982; *Stein et al.*, 1989; *Forsyth et al.*, 1990], and the geometry of the load will determine how the flexural stresses are superimposed on the regional stress field [e.g., *Muir Wood*, 1993]. Thick sediment loads do not necessarily enhance the local stress field, however, since stresses relax with time. If the sediments are deposited rapidly and/or recently, they may enhance the local stress field significantly and thereby influence the level of seismic activity [*Stein et al.*, 1989].

The main mechanism for creating flexural stresses in the study area is the loading and unloading of the continent during glacial and interglacial periods and the rapid deposition of glacial sediments on the margin. The loading effect on seismic activity may differ between extremes; i.e., while water and sediment loads may trigger earthquakes, ice loads may under certain conditions suppress seismicity [*Johnston*, 1987; *Muir Wood*, 1989a; *Wu and Hasegawa*, 1996a, b; *Johnston et al.*, 1998]. Thus the concept of loading/unloading is complex, involving both the rate of stress and strain accumulation.

While it is recognized that stresses caused by glacial unloading contribute to passive margin and continental seismicity, their importance is disputed. It appears that key boundary conditions are determined by the glacial loading history and the plate relaxation time [*Fejerskov and Lindholm*, 1999]. Long and short relaxation times are consistent with the models of *Stephansson* [1988] and *Stein et al.* [1989], respectively. In fact, earthquake focal mechanisms on the Norwegian and Canadian margins indicate a change from predominantly normal and strike slip faulting toward land to more thrust faulting seaward [*Adams and Basham*, 1991; *Bungum et al.*, 1991; *Lindholm et al.*, 1999], supporting the deglaciation model of *Stein et al.* [1989]. *Wu and Hasegawa* [1996a, b] suggest that the response to glacial loading/unloading, including fault stability, is quite sensitive to the overburden conditions, while *Johnston et al.* [1998] show that the lateral extent of the Fennoscandian ice sheet is important, predicting maximum fault instability at ~9000 years ago, consistent with field observations.

Today the limited intraplate seismicity in Fennoscandia indicates a complex mixture of dominantly thrust but also strike slip and normal deformation with no clear or consistent relationship to the rebounding area [e.g., *Gregersen*, 1992; *Zoback*, 1992]. Off Norway, however, earthquake focal mechanisms show reverse reactivations of old normal faults [*Gabrielsen*, 1989; *Bungum et al.*, 1991]. Moreover, in situ data in the northern North Sea, Møre and Vøring Basins, and the western Barents Sea show stress directions consistent with focal mechanisms [*Fejerskov and Lindholm*, 1999].

Finally, we point out that most of the main topographic and structural trends off Norway are either subparallel or perpendicular to the ridge push force, as is the regional trend of the glacial depocenters. Hence one of the stress components will align with the ridge push stress vector, [*Bungum et al.*, 1991; *Hicks*, 1996].

5. Oceanic Basins and Marginal Highs

The observed decrease in seismic moment release with increasing age of the oceanic lithosphere suggests that its strength and ability to store stress is a function of cooling and thickening [*Wiens and Stein*, 1983; *Wiens et al.*, 1985; *Bergman*, 1986]. Seismic activity that occurs in relatively old lithosphere may relate to local weakness zones or to particularly high stress levels. Most of the older (30-55 Ma) oceanic crust in the Norway and Lofoten Basins is practically aseismic, except for the East Norway and the East Lofoten Basins (Plates 2-4).

The Møre and the Vøring Marginal Highs are anomalous, both in terms of seismicity and crustal structure. The crust is 15-22 km thick [*Planke et al.*, 1991; *Olafsson* et al., 1992]. No earthquakes have been located on the Vøring Marginal High, and only one small event has been reported on the Møre Marginal High, making them among the most quiescent regions on the entire margin (Plates 2, 3 and 5). The aseismic nature is surprising because the highs have undergone considerable tectonomagmatic activity during rifting and breakup (60-53 Ma) [*Eldholm et al.*, 1989], and some postbreakup structural rejuvenation may have taken place [*Talwani and Eldholm*, 1972; *Skogseid and Eldholm*, 1989].

Local stress from density contrasts across the continent-ocean boundary will be superimposed on the ridge push stress field, resulting in tensional stress on the landward side and compressive stress on the seaward side. Moreover, the basement relief will induce tensional stress within the high, and the expanded crust will further reduce the compressive stress. The superposition of local stress components will thus reduce the compressive ridge push stress within the high. In addition, cooling, contraction and the thickening of the crust may strengthen the lithosphere [e.g., *Coward*, 1994]. Thus we suggest that the apparent aseismic nature is related to a combination of locally induced stress decreasing the ridge push and a strengthened lithosphere. The historic record is short, however, and with a greater crustal strength the potentials for larger, infrequent earthquakes cannot be disregarded.

The East Norway Basin (Plate 3) is characterized by intermediate seismic activity. Several earthquakes cluster near the Norway Basin Fracture Zone (NBFZ), in 50-48 Ma crust, while there is less activity near the Central Jan Mayen Fracture Zone (CJMFZ) which marks the sheared continent-ocean boundary. The existence of the two fracture zones may introduce potential zones of weakness and a complex local stress field due to topographic relief, density differences and sediment load. However, fracture zones support stresses significantly higher than ridge push stresses and are therefore expected to be seismically less active [*Dahlen*, 1981; *Sandwell and Schubert*, 1982]. The province is associated with very low heat flow [*Langseth and Zielinski,* 1974; *Sundvor et al.*, 1999], suggesting anomalously cold lithosphere. The only focal mechanism shows a steep reverse fault (Plate 5), implying a local stress component that adds constructively to the ridge push stress, whereas lateral density and topography contrasts across the CJMFZ should induce stress almost perpendicular to the ridge push direction.

Most earthquakes in the Norway Basin are located west of a huge slide scar on the continental slope. The oldest slide is dated to 30-50 ka, and the last occurred only at 6-8 ka [*Bugge et al.*, 1987; *Jansen et al.*, 1987]. In fact, several events lie on the western flank of a modest, 1.4-0.4 km thick sediment pile in front of the slide [*Johansen and Eldholm,* 1989] between NBFZ and CJMFZ (Plate 5). Despite its moderate size, the recent and rapid deposition may generate significant stress in the oceanic lithosphere [e.g., *Stein et al., 1989*], which superimposed on the regional ridge push stress will enhance the probability for earthquakes in the cold, brittle lithosphere.

The relatively high seismicity of the East Lofoten Basin (Plate 2) is characterized by several larger earthquakes within the 50-34 Ma crust in western province. These include the 1929 M 6.1 earthquake and a 1959 M 5.8 earthquake with an extensional focal mechanism [*Lazareva and Misharina*, 1965], both within a cluster of events in 42-33 Ma crust (Plate 4). Some larger events also appear within 50-47 Ma crust farther south, at ~70°N, 9°E. In fact, the seismic activity level at 2-3000 m water depth is the highest in the entire study area, with local seismic moment release rates about one order of magnitude greater than the worldwide average in stable oceanic lithosphere [*Johnston et al.*, 1994]. In contrast, the remainder of the Lofoten Basin has almost no seismic activity regardless of crustal age, except near the plate boundary [*Bergman*, 1986; *Bungum et al.*, 1991].

An M 4.2 earthquake in 1975 west of the Senja Fracture Zone yielded a strike-slip focal mechanism [*Savostin and Karasik*, 1981], while an M 4.4 earthquake on the flank of Bjørnøya Fan in 1981 had a reverse-oblique fault plane with maximum NW-SE horizontal stress subparallel to the ridge push direction (Plate 4) [*Bungum et al.*, 1991]. There are also several other events near the fracture zone, most on the seaward side where the oceanic crust is relatively thin and has higher average velocity than farther west [*Jackson et al.*, 1990]. Some events near its southern end may suggest a relationship to the structurally complex rift-shear interaction in this area [*Faleide et al.*, 1993].

There is an intriguingly good spatial correlation between seismic activity and the glacial late Pliocene-Pleistocene Bjørnøya Fan (Plate 6), which leads us to explore loading-induced mechanisms. A correlation of seismicity and total Cenozoic sediment thickness in the Lofoten Basin was suggested by *Husebye et al.* [1975]. However, we now focus on the glacial deposits which constitute as much as 70% of the total postopening sediment volume [*Faleide et al.*, 1996], noting that the East Lofoten Basin is partly covered by the Bjørnøya Fan (Plate 6), representing greatly increased sedimentation rates and loading [*Fiedler and Faleide*, 1996]. The fan is certainly large enough (~400 km wide, up to ~3.5 km thick) to induce significant flexure in the lithosphere. We note that a forebulge is observed in seismic reflection profiles [*Fiedler and Faleide*, 1996] and that faulting is seen in high-resolution profiles on the distal fan (P. R. Vogt, personal communication, 1998). The seismic activity beneath the fan varies, probably resulting from complex interactions between the ridge push force and loading induced stress, combined with variations in crustal strength. The present enhanced state of stress beneath the Bjørnøya Fan may be explained either by sediment loading stress relaxing over time or by a depth-dependent rheology causing a reduction in flexural stress [*Stein et al.*, 1989]. In either case, the rate of sediment loading is more important for seismic activity than the total sediment thickness.

6. Barents Sea Margin

The continental lithosphere comprises two seismotectonic provinces separated by the shelf edge (Plates 3-4). The seismic activity on the Barents Slope, an area of rapid crustal thinning towards the continent-ocean boundary, is intermediate (Table 1). The Barents Shelf is characterized by Cretaceous rift basins, with only a thin cover of younger sediments. The province has an accentuated Moho relief, and the deepest basins are underlain by only ~4 km of crystalline crust [*Jackson et al.*, 1990; *Faleide et al.*, 1993]. Despite the intense crustal extension and Tertiary regional uplift and erosion, both the basin region and the Finnmark Platform closer to the coast are seismically quiescent with only few, small-magnitude earthquakes recorded during the last decade of improved instrumentation (Plate 4). The relatively aseismic Barents Shelf is interpreted to reflect weak ridge push forces acting on a thinned but strong crust where destructive interference with tensional stresses related to the Plio-Pleistocene erosional unloading of the Barents Sea [*Fiedler and Faleide*, 1996] should be expected.

The sediment distribution implies that glacial loading is a stress- inducing mechanism also on the Barents Slope. The load-induced stress has a component which superimposes constructively on the compressive ridge push force acting obliquely on the margin (Plate 4). However, the compressive stress component orthogonal to the margin is relatively low compared to the rifted margins farther south. In this narrow shear margin setting, significant local stress may be induced by topography, rapid crustal thinning between the shelf edge and the Senja Fracture Zone, and lateral density difference between the two types of lithosphere. The superposition of these, largely orthogonal, margin stress components and the small orthogonal ridge push component makes the composite stress pattern complex. However, the apparent continuity of the seismic activity from the East Lofoten Basin to the Barents Slope and the spatial correspondence with the glacial depocenter suggest late Pliocene-Pleistocene loading as the most important stress inducing factor. Possibly, the stress enhancement may lead to structural adjustments along deeper north-trending fault blocks.

7. Lofoten-Vesterålen Margin

South of 70°N the shelf edge divides the margin in two seismotectonic provinces bounded to the south by the prolongation of the Lofoten Fracture Zone which marks the transition from the structurally elevated shelf to the deep Vøring Basin (Plates 3-4). Cenozoic sediments are thin or absent on the shelf off the Lofoten Islands but reappear on the slope and south of the islands, while a thick wedge covers the shelf north of 69°N. The along-margin changes in structural and depositional style may reflect old crustal lineaments predetermining the location of Mesozoic transfer faults and Early Tertiary transforms [e.g., *Myhre et al.*, 1992].

The seismic activity is relatively high, even though seismic stations able to detect smaller events have only been operating since 1987. Stronger earthquakes have, however, been recorded macroseismically since 1880 [*Bungum et al.*, 1991; *Havskov et al.*, 1992]. The seismic activity, and thus the seismic moment release rate, on the Lofoten-Vesterålen Shelf is among the highest in the study area, with a concentration in the area south of 69°N, where there is a cluster in the vicinity of the Røst High (Plate 4), a fault block along the shelf edge with a core of shallow basement. The seismicity continues south into the East Vøring Basin (Plates 2-3). Despite evidence of major Early Tertiary faulting and recent mass wasting [*Eldholm et al.*, 1979], there is little seismic activity on the narrow and steep Lofoten-Vesterålen Slope, which forms the northern extension of the practically aseismic West Vøring Basin.

In view of the modest thicknesses of the Cenozoic sediment cover in the area of main seismic activity, we focus on the effects of local stress generating or modifying mechanisms. Focal mechanisms for three 10-20 km deep events, two beneath the slope and one beneath the shelf (Plate 4) [*Hicks*, 1996; *Bungum et al.*; 1991] reveal normal fault motion indicating local horizontal extension. Focal depths are generally poorly determined; however, full waveform modeling of an event at 67.9°N, 10.0°E resulted in a depth of ~10 km [*Hicks*, 1996]. Because rupture and reactivation occur most easily in a tensile stress regime, there may be a relationship between the high seismic activity on the shelf and local tensional stress. The Lofoten-Vesterålen Shelf was structured into a margin-parallel horst-graben system during the Late Jurassic-Early Cretaceous rift episode, with possible rejuvenation and uplift during the Tertiary [*Brekke and Riis*, 1987; *Løseth and Tveten*, 1996]. Basement faults have exposed Precambrian rocks in the Lofoten Islands and on the Utrøst Ridge (Plate 4). Though the thickness of pre-Cenozoic sediment cover varies, it is thin except in local basins [*Mokhtari*, 1991]. Consequently, the shallow basement involved fault zones are more easy to reactivate than more deeply buried faults, since low confining pressure decreases the frictional fault strength [*Scholz*, 1990].

Neither topographic stress, amplified by shallow high-density basement rocks, or stress caused by lateral density differences between oceanic and continental lithosphere explains the seismicity contrast north and south of 69°. On the other hand, the basement ridges on the shelf may be associated with deviatoric tension changing to weak compressive crustal stress in the neighboring deep basins. Moreover, the crystalline crust is thinnest beneath the slope and between the basement ridges, thereby enhancing the ridge push stress component. The basement ridges are believed to be underlain by high-density lower crust [*Talwani and Eldholm*, 1972]. However, crust of the same thickness, or thinner, exhibits little seismic activity on the outer Vøring and Møre margins. An amplified ridge push force is therefore inferred to be only marginally important.

To summarize, it appears that local factors influence the stress field significantly, even though it is not possible to resolve their relative contributions. Basement topography is believed to be of importance since it may account for the deviatoric tension consistent with focal mechanisms near basement highs. This leads to a relatively lower reactivation threshold compared to purer compressive stress regime; i.e., local deviatoric tension may lead to reactivation of basement faults yielding a higher seismic moment release rate.

8. Vøring Margin

The seismicity varies significantly across the margin (Plate 3). The main structural element on the Vøring Shelf is the wide Trøndelag Platform, an area of relatively thick crust which has been a stable structural unit for the past 200 Myr. Although the main platform area is quiet, its boundaries along the coast, and along major fault systems in northwest and west, are all seismically active (Plate 5). The only larger earthquake, an M 5.3 event in 1903, occurred near the western boundary. The West Vøring Basin, corresponding to the crust that was faulted and extended prior to the early Tertiary breakup, is seismically quiet. The high-velocity lower crust continues from the Vøring Marginal High as an underplated body below the extended continental crust [*Skogseid and Eldholm*, 1989; *Skogseid*, 1994]. Hence this crust corresponds to two adjacent, nearly aseismic, seismotectonic provinces.

The East Vøring Basin on the outer shelf and upper slope (Plates 3, 5) covers the main Late Jurassic-Early Cretaceous rift zone characterized by normal faults and thinned crust [*Skogseid et al.*, 1992]. The majority of earthquakes have occurred landward of the shelf edge, i.e., on the eastern rift flank (Plate 5). The seismic activity is intermediate, with earthquakes of different sizes, including two M>5.0 events before 1880 (Plate 5). About 50% of the larger events occurred before 1950, including the cluster on the Halten Terrace where 50% occurred more than 100 years ago [*Bungum et al.*, 1991]. The epicenters largely follow N and NE trending fault zones (Plate 5), but some events are located near the Neogene Helland Hansen Arch. There is also a clear spatial correspondence with the voluminous glacial sediment wedges which have prograded westward since 2.6 Ma [*Stuevold and Eldholm*, 1996]. The Halten Terrace cluster lies below the main depocenter, while other epicenters occur on the landward flank farther north and south (Plate 6).

Six events have focal mechanisms, including three reverse, two normal and one strike-slip [*Bungum et al.*, 1991; *Lindholm et al.*, 1995; *Hicks*, 1996], indicating a prevailing NW-SE compressive stress regime, with local variations (Plate 5). There are many in situ stress measurements, mostly from the Halten Terrace, which indicate more scattered horizontal principal stress directions as expected from measurements in basin sediments [*Bjørlykke*, 1995].

The geological data make us focus on the relationship of seismic activity and far-field stress, rejuvenation of crustal weakness zones, Tertiary intraplate doming and epeirogenic uplift [*Stuevold et al.*, 1992], and glacial sediment loading [*Hjelstuen et al.*, 1997]. The most likely candidates for rejuvenation in a compressional regime are the abundant Mesozoic and Cenozoic extensional faults, which strike approximately perpendicular to the ridge push force; i.e., they will reactivate by ridge push more easily than faults with other trends, provided sufficient fluid pressure. Thus one would expect that the ridge push force would trigger earthquakes over the entire margin including the breakup related

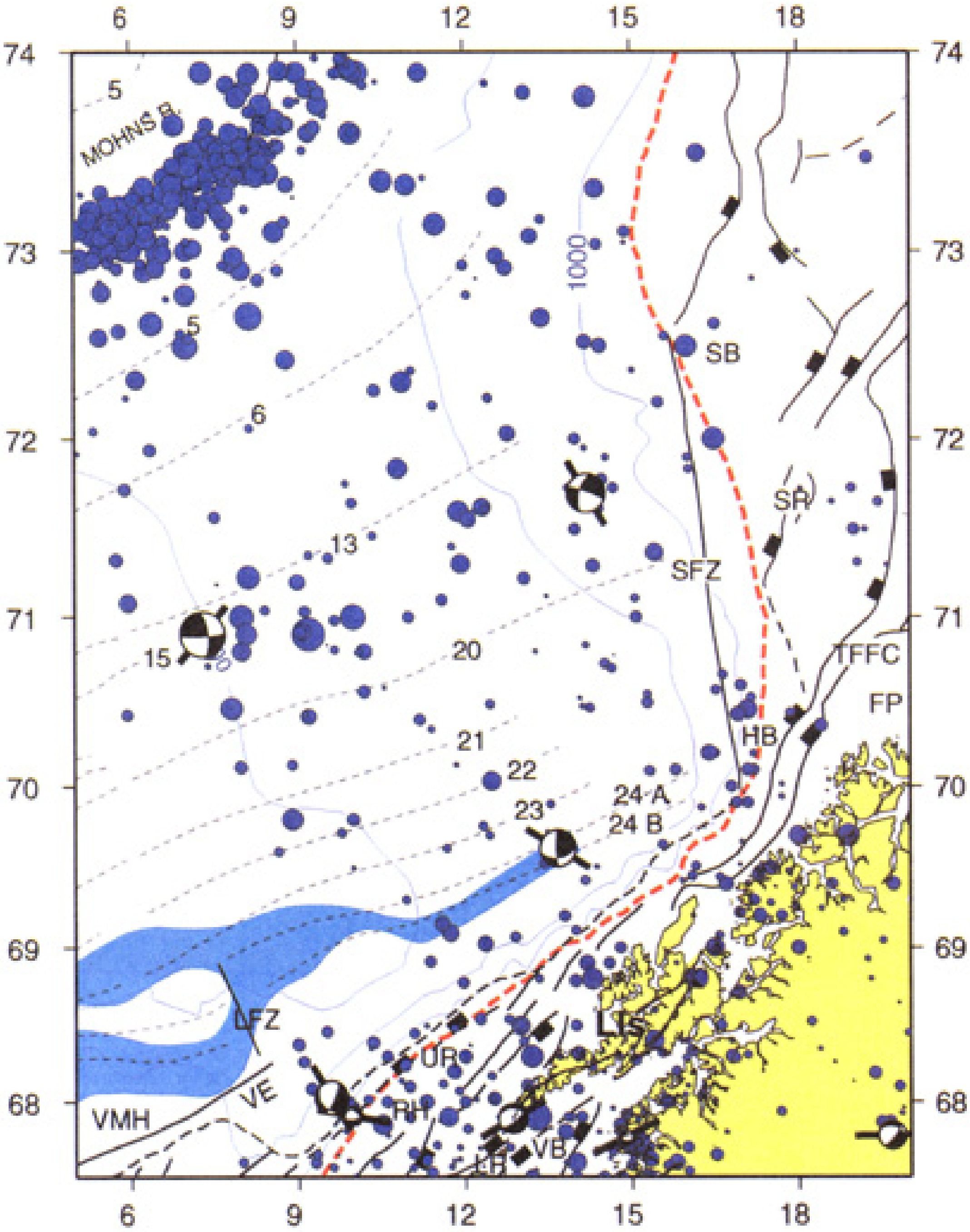

Plate 4. Seismic activity on the Barents Sea and Lofoten-Vesterålen margins, including all earthquakes in the catalog above magnitude 1.0. Main structural elements are from *Blystad et al.* [1995]. Seafloor spreading magnetic anomalies are from *Talwani and Eldholm* [1977]. FP, Finnmark Platform; HB, Harstad Basin; LFZ, Lofoten Fracture Zone; LIs, Lofoten Islands; LR, Lofoten Ridge; RH, Røst High; SB, Sørvestnaget Basin; SFZ, Senja Fracture Zone; SR, Senja Ridge; TFFC, Troms-Finnmark Fault Complex; UR, Utrøst Ridge; VB, Vestfjorden Basin; VE, Vøring Escarpment; VMH, Vøring Marginal High.

detachment systems in the West Vøring Basin, since gently dipping listric faults reactivate more easily in the reverse mode [*Sibson*, 1985].

The absence of earthquakes in the West Vøring Basin indicates important structural and geodynamic differences from the central to the outer part of the margin, raising questions as to whether the crust might be stronger in this province, or if local stresses adding constructively to the ridge push stress are higher in the East Vøring Basin. Local stress induced by the continent-ocean boundary is restricted to the West Vøring Basin, where it will be tensional, counteracting the compressive ridge push stress, and lowering the deviatoric stress in the crystalline basement. However, the spatial correspondence of the high-velocity lower crust and the two aseismic provinces may imply that the crust has been strengthened by the melts emplaced during breakup.

The rapid glacial sediment loading may still be a significant

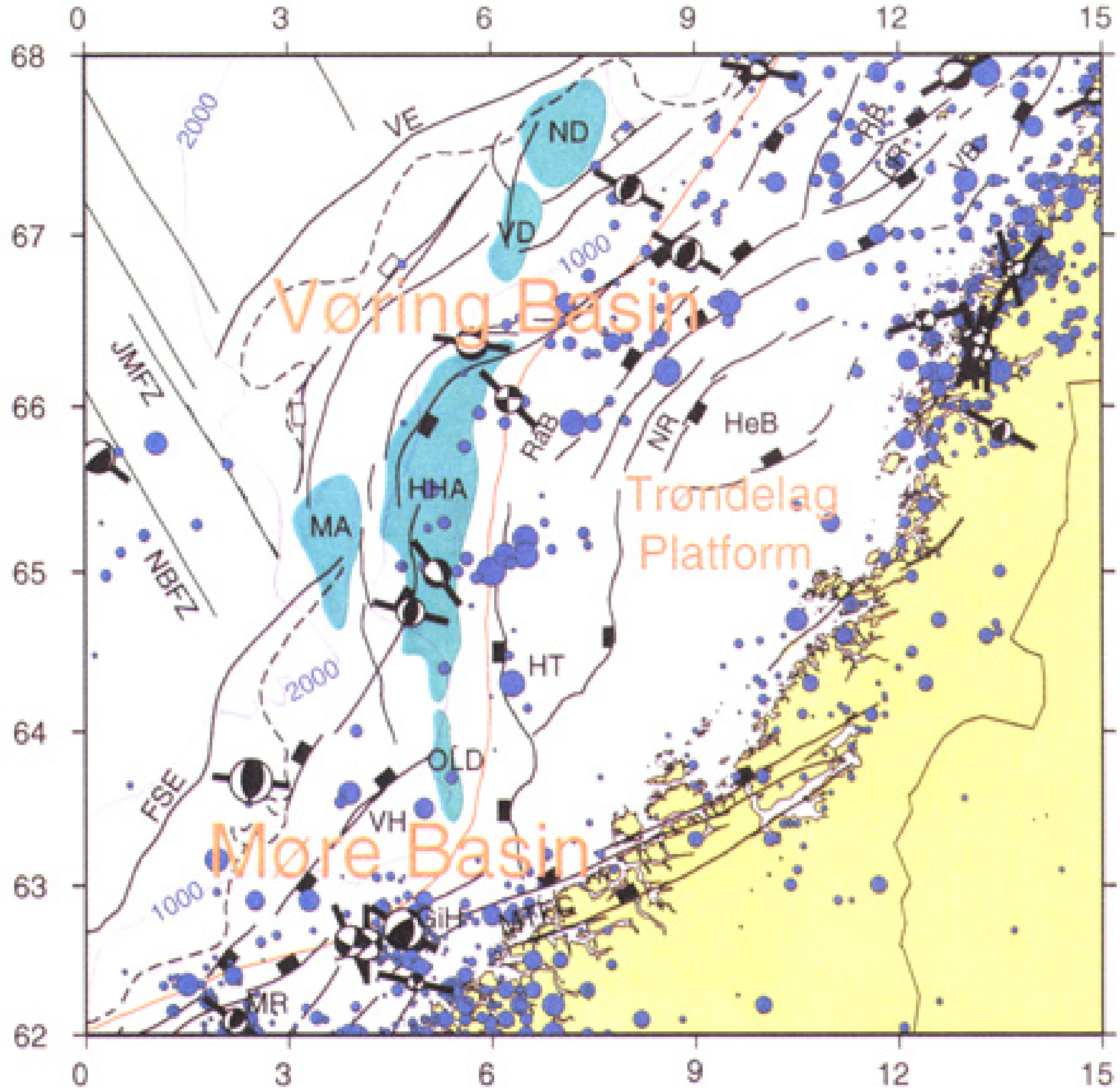

Plate 5. Seismic activity on the (top) Vøring and (bottom) Møre margins, including all earthquakes in the catalog above magnitude 1.0. Main structural elements are from *Blystad et al.* [1995]. FSE, Faeroe-Shetland Escarpment; GH, Giske High; HeB, Helgeland Basin; HHA, Helland Hansen Arch; HT, Halten Terrace; JMFZ, Jan Mayen Fracturs Zone; LR, Lofoten Ridge; MA, Modgunn Arch; MR, Manet Ridge; MTFC, Møre-Trøndelag Fault Complex; ND, Naglfar Dome; NR, Nordland Ridge; OLD, Ormen Lange Dome; RB, Ribban Basin; RåS, Rås Basin; VB, Vestfjorden Basin; VE, Vøring Escarpment; VD, Vema Dome; VH, Vigra High.

local stress source in the East Vøring Basin. The seismic activity is concentrated below the eastern part of the glacial depocenter which covers the eastern Late Jurassic-Early Cretaceous rift flank (Plate 6). Five of the six focal mechanisms on the Vøring margin (Plate 5) are located in crystalline basement, while one normal mechanism at 10 km depth is close to basement [*Hicks*, 1996]. The most plausible reason for the earthquake distribution is that the glacial deposits load the basement involved boundary faults between the Trøndelag Platform and the Vøring Basin (Plate 5), whereas less pronounced rift structures farther west have a smaller glacial load. Similarly, the glacial cover in the West Vøring Basin and on the Trøndelag Platform is considerably thinner than in the East Vøring Basin (Plate 6); thus loading stresses are significantly less and may even become tensional in forebulge areas.

Local stress components are important in the Helland Hansen Arch area where both normal as well as reverse and strike-slip focal mechanisms have been reported (Plate 5). A possible crustal forebulge in front of the glacial load [*Skogseid and Eldholm*, 1989] spatially coincides with this arch where two normal focal mechanisms show local tensional deviatoric stress (Plate 5). The East Vøring Basin is underlain by thin crust below the Late Jurassic-Early Cretaceous rift graben, thus enhancing the ridge push stress. The same effect is expected from the lateral change in crustal density between the Trøndelag Platform and the East Vøring Basin, which also induces tensile stress in the platform proper.

We infer significant differences in the stress field across the Vøring Margin. Locally induced stresses beneath the quiescent West Vøring Basin and the apparently aseismic Trøndelag Platform counteract the ridge push stress, while generating compressive stresses that add constructively to the regional stress in the crystalline crust beneath the East Vøring Basin. Furthermore, the

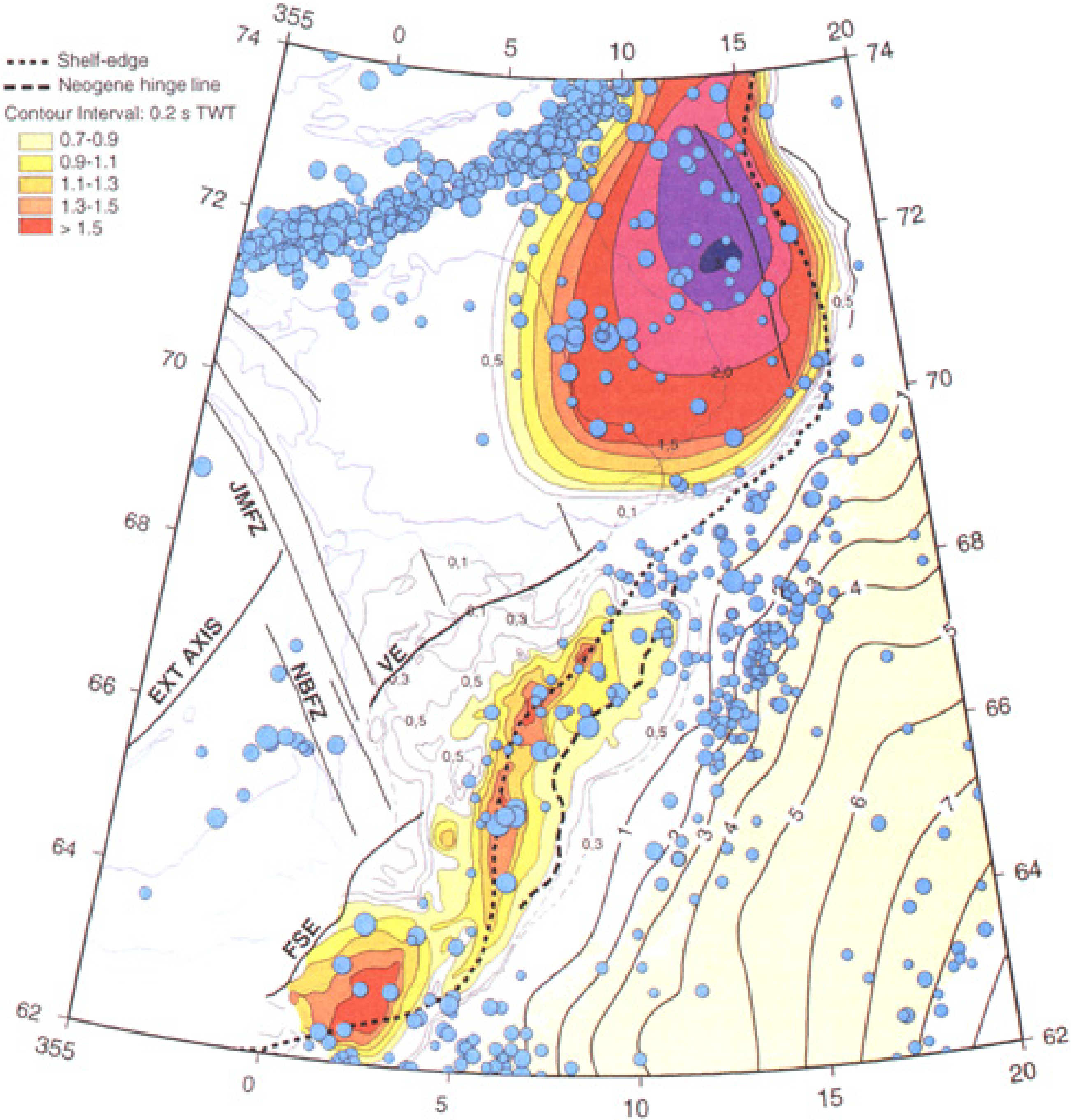

Plate 6. Seismic activity on the Norwegian and Barents Sea margins (events above magnitude 3.0 since 1880) and the glacial depocenters. Shading indicates glacial sediment distribution (s two-way time (TWT)) compiled from *Fiedler and Faleide* [1996], *Hjelstuen* [1997], *Hjelstuen et al.* [1996], *Stuevold* [1989], *Rossavik* [1993], and *Skogseid and Eldholm* [1989]. Contour lines for postglacial uplift (mm yr^{-1}) are from *Dehls and Olesen* [1999] and Neogene Fennoscandian epeirogenic uplift hinge line from *Stuevold and Eldholm* [1996]. The large depocenter north of 69°N is the Bjørnøya Fan. The 1 s TWT corresponds to a depth of ~1 km.

glacial sediment loading is superimposed on the modified ridge push stress field. Because both the loading and the crustal thinning will have amplified the regional stress field in the East Vøring Basin, it is difficult to determine the dominant mechanism. The fact that the thinned, fractured continental crust may be weaker than oceanic crust suggests that loading of glacial sediments may have led to preferential rejuvenation of crustal fault zones.

9. Møre Margin

The level of seismic activity (Plate 5) is intermediate, with seismic moment release rate of the same order of magnitude as in stable continental regions [*Johnston et al.*, 1994]. The seismic activity varies spatially, and the frequency of small events changes from high on the shelf to low on the slope east of the Møre Marginal High. Event locations are reasonably reliable, and focal mechanisms [*Hansen et al.*, 1989; *Bungum et al.*, 1991; *Lindholm et al.*, 1995; *Hicks*, 1996], indicate a compressive stress regime generally complying with the ridge push stress field, with local perturbations.

The Møre Shelf (Plate 3) has intermediate to high seismic activity (Table 1) with earthquakes concentrated in two clusters along the Møre-Trøndelag Fault Complex, one near the Manet Ridge and another near the Giske High (Plate 5). The fault complex is an old and deep zone of structural weakness within the crystalline basement and reactivated during Late Jurassic-Early Cretaceous rifting [*Blystad et al.*, 1995]. Focal mechanisms include two strike-slip and one thrust fault near the Giske High with depth estimates of 10, 17, and 20 km, respectively, and a lower crustal reverse fault near the Manet Ridge (Plate 5) [*Hansen et al.*, 1989; *Bungum et al.*, 1991; *Lindholm et al.*, 1995; *Hicks*, 1996]. The shallow event may have occurred within Paleozoic sediments, but the others are located in the crystalline crust or uppermost mantle. Thus brittle deformation may still occur at the deep Møre-Trøndelag Fault Complex, while the Late Jurassic-Early Cretaceous faults may be sealed in the Møre Basin, as suggested for the Halten Terrace.

Two larger earthquakes occurred in the central Møre Basin (Plate 5). The 1988 M 5.3 earthquake at a depth of ~25 km (most likely sub-Moho) show reverse faulting with WNW-ESE compressive stress [*Hansen et al.*, 1989]. The event is intriguing because of the paucity of seismicity in this area [*Bungum et al.*, 1991]. Except for its southeastern flank, the Møre Basin has a poorly mapped Late Jurassic-Early Cretaceous fault pattern [*Blystad et al.*, 1995]; however, a correlation with seismic events can be made near the Vigra High. The Giske High earthquake cluster (Plate 5) spatially correlates with a body of high-velocity mantle, 8.5 km s^{-1} [*Olafsson et al.*, 1992], and a positive gravity anomaly [*Talwani and Eldholm*, 1972]. A dense, local subcrustal body may be an important source of local stress in this region of thin glacial sediments and relatively thick crust (Plate 6).

The crustal thinning across the Møre Basin [*Olafsson et al.*, 1992; *Skogseid*, 1994] indicates weakness zones within the crystalline crust, and the earthquakes near the Vigra High probably suggest basement involved faulting as do the other larger events in the Møre Basin (Plate 5). In the northern province some larger earthquakes spatially coincide with the southern flank of a -40 mGal gravity low along the landward prolongation of CJMFZ (Plate 2).

The overall similarity in seismicity with the Vøring margin suggests similar stress generating mechanisms. In particular, the strike of the Møre-Trøndelag Fault Complex approximately perpendicular to the ridge push force suggests a relatively high probability of reactivation, and a relatively low frictional resistance against slip is suggested by the high rate of earthquakes. The differential subsidence between the shelf and the basin increases the probability of slip along the basement involved faults. However, the many small events may in part be ascribed to a low detection threshold at nearby onshore stations. The absence of events at the intersection of the fault complex and the Sogn Graben in the northern North Sea may reflect locked faults and increased strength against reactivation. The crystalline crust thins seaward, while a high-velocity lower crust expands the crust in the western Møre Basin. This setting will amplify the ridge push stress in the central basin.

A few larger events occur within the 100-150 km wide area of Late Cretaceous-Paleocene rifting [*Skogseid et al.*, 1992] east of the Møre Marginal High, i.e., the region underlain by underplated crust. Thus the crust in the western basin appears stronger than farther east. The few seismic events may be caused by rupture rather than reactivation since deeply buried faults under high confining pressure are strong and require large differential stress to be reactivated [*Byerlee*, 1978; *Scholz*, 1990].

As on the Vøring Margin, there is an obvious spatial correlation between seismic activity and the semicircular glacial depocenter (Plate 6). Again we note that the earthquake distribution is primarily confined to the landward flank which is underlain by major normal Late Jurassic-Early Cretaceous faults (Plate 5). Yet, some large events occur beneath the northwestern flank. It is also difficult here to resolve the relative contribution of the stress-generating mechanisms. The glacial depocenter, however, is located farther west with respect to the shelf edge than on the Vøring margin, and the West Vøring Basin has only a thin glacial cover. The fact that larger earthquakes occur in the western Møre Basin and no events in the West Vøring Basin strengthens the causal connection between the glacial sediment loading and seismicity. The loading stress perturbation superimposed on enhanced ridge push stress within the thin crystalline crust beneath the deep Møre Basin increases the probability for earthquakes by rejuvenation of Late Jurassic-Early Cretaceous faults, whereas the absence of smaller events in the Møre Basin is ascribed to crustal strengthening by underplating.

10. Coastal and Onshore Areas

Late Paleozoic to Cenozoic sediments thin on the inner shelf, and Caledonian and Precambrian basement rocks are exposed near the coast and onshore. We therefore discuss this region separately, dividing it in four seismotectonic coastal provinces (Plate 3) with an onshore relief up to 1500 m and 30-35 km thick crust [*Kinck et al.*, 1993]. Although the seismic activity is highly variable, it contrasts strongly with the low activity in NW Fennoscandia where only few events are known to have occurred in the last 100 years. The majority of focal mechanisms indicate tensile stresses within the Fennoscandian shield, where hypocenter depths vary from 10 to 40 km [*Slunga*, 1989; *Slunga et al.*, 1984; *Arvidsson and Kulhanek*, 1994]. Old weakness zones along the coast have been active during several tectonic episodes, while there is little evidence of Mesozoic or Cenozoic faulting within the Fennoscandian shield [*Muir Wood*, 1993].

The Møre Coast province (Plate 3) reveals intermediate seismic activity (Plate 5), and two in situ stress measurements show NW maximum horizontal components [*Zoback*, 1992]. The quiet Trøndelag Coast, forming an apparent coastal seismic gap, has only smaller earthquakes. One in situ stress measurement shows N-S maximum horizontal stress (Plate 5) [*Stephansson et al.*, 1987]. The main part of the Møre-Trøndelag Fault Complex cuts the coastline and continues onshore affecting Precambrian and lower Paleozoic rocks [*Blystad et al.*, 1995] without appreciable seismic activity.

The seismic activity along the Nordland Coast (Plate 3) is intermediate in the south and relatively high in the north (Plates 4-5). The frequency of larger earthquakes increases by a factor of 2 to the north, where also swarm-like occurrences are more frequent. Similar swarms are observed on the Greenland margin [*Gregersen*, 1989; *Chung and Gao*, 1997]. The earthquakes occur both onshore and offshore in the south but mostly onshore in the north, and although several fault systems exist along the coast [*Blystad et al.*, 1995], there is no obvious correlation with seismic activity (Plate 5).

An M 5.8-6.0 earthquake in the Ranafjord area (66.3°N, 13.0°E) in 1819, resulting in both liquefaction effects and landslides (Plate 5) is the largest event ever reported in NW Europe [*Muir Wood*, 1989b, 1993]. Focal mechanisms shallower than 10 km suggest quite different modes of faulting [*Vaage*, 1980; *Slunga et al.*, 1984; *Bungum et al.*, 1979; *Atakan et al.*, 1994], implying a dominantly vertical local stress regime. The horizontal principal stress directions in the Ranafjord area trend NE-SW [*Dehls and Olesen*, 1998, 1999; *Hicks et al.*, 1999], or orthogonal to the ridge push average. Such stress rotation is found also in the northern North Sea [*Bungum et al.*, 1991; *Lindholm et al.*, 1995, 1999], and may be explained by an interchange of σ_H and σ_h (the largest and smallest horizontal stress components), which more easily can been achieved when the σ_H/σ_h ratio is not far from unity. This demonstrates significant local stress variations as well as the importance of local stress sources.

The seismic activity on the Lofoten-Vesterålen Coast (Plate 3) is intermediate and characterized by smaller and scattered earthquakes; however, some larger events are located near the Lofoten-Vesterålen Islands and one near the southern Troms-Finnmark Fault Complex. Several faults cut the exposed Precambrian basement and two larger events correlate spatially with these faults (Plate 4).

The setting of the coastal provinces leads us to explore other stress generating mechanisms than those discussed previously. The regional ridge push stress is clearly also present within Fennoscandia [e.g., *Gregersen*, 1992; *Zoback*, 1992] but will become weaker than on the margin because of the increase in crustal thickness to >45 km beneath the central shield. Consequently, the stress contribution from local sources may be even more important than on the margin, consistent with the increased scatter in the maximum horizontal stress directions.

A series of large reverse faults have ruptured the bedrock near the center of the former Fennoscandian ice cap in response to the last glacial unloading [*Lundquist and Lagerbäck*, 1976; *Olesen*, 1988; *Muir Wood*, 1989a]. If single earthquakes have been responsible for the dislocations as proposed by *Bäckbom and Stanfors* [1989] and *Dehls and Olesen* [1998, 1999], these earthquakes should have been in the range M 7.4-8.2 [*Arvidsson*, 1996; *Bungum and Lindholm*, 1997]. In fact, these faults may still be active. If the seismicity was largely suppressed when the ice cap was in place [*Johnston*, 1987], then the buildup of elastic strain from the entire last ice age would have been released over a relatively short time period since the onset of deglaciation [*Muir Wood*, 1989a; *Johnston et al.*, 1998].

The postglacial rebound measured today [*Ekman*, 1996; *Ekman and Mäkinen*, 1996; *Dehls and Olesen*, 1999] is commonly related to isostatic compensation after the last deglaciation [*Muir Wood*, 1993], even though additional tectonic causes have been suggested [*Mörner*, 1991]. By evaluating the poor indication of a hinge line in Plate 6 and rates of present postglacial rebound, we find that the majority of events on the Møre and Lofoten-Vesterålen coasts are located in crust with negligible uplift and in an area of <3 mm yr^{-1} rebound rate along the Nordland Coast. Thus the present rate of glacial rebound is indeed small in all coastal provinces (Plate 6), and it cannot explain the relatively high seismic activity. This is consistent with the observation of low seismicity in the high rebound rate areas of NW Fennoscandia. In fact, the seismicity appears to decrease with tectonic age and crustal thickness, regardless of rebound rate [*Kinck et al.*, 1993]. Fennoscandia has also experienced epeirogenic uplift probably initiated in the early Miocene and continuing to late Pliocene time. This created a high-relief landmass prone to erosion, particularly during the Northern Hemisphere glaciation which in turn amplified the uplift [*Stuevold and Eldholm*, 1996; *Hjelstuen et al.*, 1997]. Uplift and erosional unloading will cause the lithosphere to bend convexly upward inducing extensive stresses in the upper crust. This effect, combined with sediment deposition and loading on the margin, causes differential vertical movements along a hinge zone (Plate 6) from which remaining stresses may relate to the seismic activity along the coast.

The topography along the Møre, Nordland, and Lofoten coasts is steep compared to the more low-lying Trøndelag Coast. Hence the former areas have significantly higher topographic stress, being tensional in the elevated crust and compressive on the low coast and inner shelf. *Stuevold and Eldholm* [1996] have proposed that the change in relief is related to the magnitude of tectonic Fennoscandian epeirogenic uplift. It now seems that the seismic activity along the also coast correlates with topography and that the most elevated provinces have a relatively high seismic activity (Plate 3). It is intriguing that the coastal province with lowest seismic activity includes the pronounced Møre-Trøndelag Fault Complex (Plate 5). A possible explanation is that stresses are released nearly aseismically or that the faults are weak, resulting in only small amounts of elastic strain buildup before slip or creep occurs.

11. Concluding Remarks

The Norwegian continental margin has experienced several rift episodes followed by basin formation since the end of the Caledonian orogeny. The last rift episode culminated with intense magmatic activity during continental breakup at the Paleocene-Eocene transition. These events have divided the margin into a number of structural provinces differing in tectonomagmatic style and crustal structure. During the Northern Hemisphere glaciation, voluminous glacial sediments prograded across the margin creating a thick, up to ~4 km, late Pliocene-Pleistocene wedge reflecting very high deposition rates. Hence the glacial load may have modified the local stress field in the underlying crust, thereby reactivating favorably oriented fault zones.

The regional stress field within lithospheric plates is dominated by forces originating at diverging plate boundaries, and most plate interiors experience compressive forces. This is, in the study area, consistent with a first-order regional compressive stress field caused by ridge push forces from the mid-Atlantic plate boundary. Although this stress field clearly is reflected in the present earthquake activity, we find that the ridge push stress effects in themselves are not sufficient for releasing earthquakes in this region.

Our main inferences about earthquake activity and earthquake-generating mechanisms on the margin are therefore that other regional and local stress factors, together with favorably oriented and sufficiently weak faults, are responsible for the nature, occurrence, and distribution of earthquakes. Nonetheless, it is important to keep in mind that the relative short duration for which observational data exist in such a low-seismicity region will affect both our understanding of maximum magnitude and the appreciation of the limits between active and inactive seismotectonic provinces.

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

The marginal highs and the adjacent basins that experienced rifting and crustal thinning prior to the early Tertiary breakup are almost entirely aseismic, suggesting that the crustal thickening and underplating resulting from the igneous breakup event have strengthened the crust. It is, however, important to make allowance for the fact that the return times for the larger earthquakes in these settings probably are very long.

Another main observation is the spatial correlation between seismic activity and the late Pliocene-Pleistocene glacial wedge which suggests that rapid sediment loading has led to preferential rejuvenation of Late Jurassic-Early Cretaceous faults.

East of the main glacial wedge most of the seismic activity is found along the coast where the postglacial rebound is small. The seismicity decreases farther east where the crust is thicker and rebound rates are higher. However, the relative subsidence west of the hinge line makes the coastal region an area of high postglacial rebound gradients which may relate to the increased seismicity.

Acknowledgments. We thank Erik Hicks for providing invaluable help with local and regional seismicity, stress, and crustal uplift data and Hugh Cowan for critically reviewing an earlier version of this paper. Comments from two anonymous reviewers and from the Associate Editor Cynthia Ebinger have been much appreciated. All figures were generated with the GMT software of *Wessel and Smith* [1991].

References

Adams, J., and P. Basham, The seismicity and seismotectonics of eastern Canada, in *Neotectonics of North America*, edited by D.B. Slemmons et al., Geology of North America, Decade Map Vol. 1, pp. 261-276, Geol. Soc. of Am., Boulder, Colo., 1991.

Ambraseys, N.N., The seismicity of western Scandinavia, *Earthquake Eng. Struct. Dyn.*, *13*, 361-399, 1985.

Arvidsson, R., Fennoscandian earthquakes: Whole crustal rupturing related to postglacial rebound, *Science*, *274*, 744-746, 1996.

Arvidsson, R., and O. Kulhanek, Seismodynamics of Sweden deduced from earthquake focal mechanisms, *Geophys. J. Int.*, *116*, 377-392, 1994.

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

Bäckbom, G., and R. Stanfors, Interdisciplinary study of postglacial faulting in the Lensjärv area, northern Sweden 1986-1988, *SKB Tech. Rep. 89-31*, Swed. Nucl. Fuel and Waste Mange. Co., Stockholm, 1989.

Bergman, E.A., Intraplate earthquakes and the state of stress in the oceanic lithosphere, *Tectonophysics*, *132*, 1-35, 1986.

Bjørlykke, K., Fracturing and brittle/ductile properties of sedimentary rocks in relation to diagenesis and *in situ* stress, in *Proceedings of the Workshop: Rock Stresses in the North Sea, 13-14 February*, edited by M. Fejerskov and A.M. Myrvang, pp. 64-75, Univ. of Trondheim, Norway, 1995.

Blystad, P., H. Brekke, R.B. Færseth, B.T. Larsen, J. Skogseid, and B. Tørudbakken, Structural elements of the Norwegian continental shelf, part II, The Norwegian Sea region, NPD Bull. 8, 45 pp., Norwegian Petroleum Directorate, Stavanger, 1995.

Bott, M.H.P., Ridge push and associated plate interior stress in normal and hot spot regions, *Tectonophysics*, *200*, 17-23, 1991.

Bott, M.H.P., and D.S. Dean, Stress systems at young continental margins, *Nature Phys. Sci.*, *235*, 23-25, 1972.

Bott, M.H.P., and N.J. Kusznir, The origin of tectonic stress in the lithosphere, *Tectonophysics*, *105*, 1-13, 1984.

Brekke, H., and F. Riis, Tectonics and basin evolution of the Norwegian shelf between 62'N and 72'N, *Nor. Geol. Tidsskr.*, *67*, 295-322, 1987.

Brune, J.N., Seismic moment, seismicity, and rate of slip along major fault zones. *J. Geophys. Res.*, *73*, 777-784, 1968.

Bugge, T., S. Befring, R.H. Belderson, T. Eidvin, E. Jansen, N.H. Kenton, H. Holtedahl, and H.P. Sejrup, A giant three-stage submarine slide off Norway, *GeoMar. Lett.*, *7*, 191-198, 1987.

Bungum, H., and J. Fyen, Hypocenter distribution, focal mechanisms, and tectonic implications of Fennoscandian earthquakes, 1954-1978, *Geol. Fören. Stockholm Förh.*, *101*, 261-273, 1979.

Bungum, H., and C. Lindholm, Seismo- and neotectonics in Finnmark, Kola, and the southern Barents Sea, part 2, Seismological analysis and seismotectonics, *Tectonophysics*, *270*, 15-28, 1997.

Bungum, H., S. Vaage, and E.S. Husebye, The Meløy earthquake sequence, northern Norway: Source parameters and their scaling relations, *Bull. Seismo. Soc. Am.*, *72*, 197-206, 1982.

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

Bungum, H., J. Havskov, B.K. Hokland, and R. Newmark, Contemporary seismicity of northwest Europe, *Ann. Geophys.*, *Ser. B*, *4*, 567-576, 1986.

Bungum, H., A. Alsaker, L.B. Kvamme, and R.A. Hansen, Seismicity and seismotectonics of Norway and surrounding continental shelf areas, *J. Geophys. Res.*, *96*, 2249-2265, 1991.

Byerlee, J., Friction of rocks, *Pure. Appl. Geophys*, *116*, 615-626, 1978.

Byrkjeland, U., Seismotectonics of the Norwegian continental margin, 62°-71°N., Cand. scient. thesis, 144 pp, Dept. of Geol., Univ. of Oslo, 1996.

Chung, W.-Y., and H. Gao, The Greenland earthquake of 11 July 1987 and postglacial fault reactivation along a passive margin, *Bull. Seismo. Soc. Am.*, *87*, 1058-1068, 1997.

Coward, M., Inversion tectonics, in *Continental Deformation*, edited by P.L. Hancock, pp. 289-304, Pergamon, Tarrytown, N. Y., 1994.

Dahlen, F.A., Isostacy and the ambient state of stress in the oceanic lithosphere, *J. Geophys. Res.*, *86*, 7801-7807, 1981.

Dehls, J., and O. Olesen, NEONOR: Neotectonics in Norway: Annual technical report 1997, *Rep. 98.016*, 149 pp., Norges Geol. Undersøkelse, Trondheim, 1998.

Dehls, J., and O. Olesen, NEONOR: Neotectonics in Norway: Annual technical report 1998, Rep. 98.007, 206 pp., Norges Geol. Undersøkelse, Trondheim, 1999.

Ekman, M., A consistent map of the postglacial uplift of Fennoscandia, *Terra Nova*, *8*, 158-165, 1996.

Ekman, M., and J. Mäkinen, Recent postglacial rebound, gravity change and mantle flow in Fennoscandia, *Geophys. J. Int.*, *126*, 229-234, 1996.

Eldholm, O., E. Sundvor, and A.M. Myhre, Continental margin off Lofoten-Vesterålen, northern Norway, *Mar. Geophys. Res.*, *4*, 3-35, 1979.

Eldholm, O., J. Thiede, and E. Taylor, Evolution of the Vøring volcanic margin, *Proc. Ocean Drill. Program, Sci. Results*, *104*, 1033-1066, 1989.

Faleide, J.I., E. Vågnes, and S.T. Gudlaugsson, Late Mesozoic-Cenozoic evolution of the south-western Barents Sea in a regional rift-shear tectonic setting, *Mar. Pet. Geol.*, *10*, 186-214, 1993.

Faleide, J.I., A. Solheim, A. Fiedler, B.O. Hjelstuen, E.S. Andersen, and K. Vanneste, Late Cenozoic evolution of the western Barents Sea-Svalbard margin, *Global Planet. Change*, *318*, 53-74, 1996.

Fejerskov, M., and C. Lindholm, Crustal stress in and around Norway: An evaluation of stress generating mechanisms, *Geol. Soc. Spec. Publ.*, in press, 1999.

Fejerskov, M., A.M. Myrvang, C. Lindholm, and H. Bungum, In-situ rock stress pattern on the Norwegian continental shelf and mainland, in *Proceedings of the Workshop: Rock Stresses in the North Sea, 13-14 February*, edited by M. Fejerskov and A.M. Myrvang, pp. 191-201, Univ. of Trondheim, Norway, 1995.

Fiedler, A., and J.I. Faleide, Cenozoic sedimentation along the southwestern Barents Sea margin in relation to uplift and erosion of the shelf, *Global Planet. Change*, *318*, 75-93, 1996.

Fleitout, L., and C. Froidevaux, Tectonic stresses in the lithosphere, *Tectonics*, *2*, 315-324, 1983.

Forsyth, D.A., J. Broome, A.F. Embry, and J.F. Halfpenny, Features of the Canadian Polar Margin, *Mar. Geol.*, *93*, 146-177, 1990.

Frohlich, C., Seismicity of the central gulf of Mexico, *Geology*, *10*, 103-106, 1982.

Gabrielsen, R., Reactivation of faults on the Norwegian continental shelf and its implications for earthquake occurrence, in *Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound*, edited by S. Gregersen and P.W. Basham, *NATO ASI Ser.*, *266*, 231-259, 1989.

Gregersen, S., The seismicity of Greenland, in *Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound*, edited by S. Gregersen and P.W. Basham, *NATO ASI Ser.*, *266*, 345-353, 1989.

Gregersen, S., Crustal stress regime in Fennoscandia from focal mechanisms, *J. Geophys. Res.*, *97*, 11,821-11,827, 1992.

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

Havskov, J., L.B. Kvamme, R.A. Hansen, H. Bungum, and C. Lindholm, The northern Norway seismic network: Design, operation and results, *Bull. Seismo. Soc. Am.*, *82*, 481-496, 1992.

Hicks, E., Earthquake focal mechanisms and derived focal stresses, Cand. scient. thesis, Dept. of Geol., Univ. of Oslo, 1996.

Hicks, E., H. Bungum, and C. Lindholm, Seismic activity in the Rana and Bremanger area, in *Neotectonics in Norway: Annual Technical Report 1998*, edited by J. Dehls and O. Olesen, pp. 177-185, Norges Geol. Undersøkelse, Trondheim, 1999.

Hjelstuen B.O., The Cenozoic Vøring and Barents Sea continental margins, Dr. scient. thesis, Dept. of Geol., Univ. of Oslo, 1997.

Hjelstuen, B.O., A. Elverhøi, and J.I. Faleide, Cenozoic erosion and sediment yield in the drainage area of the Storfjorden Fan, *Global Planet. Change*, *12*, 95-117, 1996.

Hjelstuen, B.O., O. Eldholm, and J. Skogseid, Vøring Plateau diapirs and their structural an depositional settings, *Mar. Geol.*, *144*, 33-57, 1997.

Husebye, E. S., H. Gjøystdal, H. Bungum, and O. Eldholm, The seismicity of the Norwegian-Greenland Sea, *Tectonophysics, 26*, 55-70, 1975.

Jackson, H.R., J.I. Faleide, and O. Eldholm, Crustal structure of the sheared southwestern Barents Sea continental margin, *Mar. Geol., 93*, 119-146, 1990.

Jansen, E., S. Befring, T. Bugge, T. Eidvin, H. Holtedahl, and H.P. Sejrup, Large submarine slides on the Norwegian continental margin: Sediments, transport and timing, *Mar. Geol.*, *78*, 77-107, 1987.

Johansen, B., Marine geophysical studies in the northern Atlantic with the emphasis on sedimentation, crustal structure and subsidence, Dr. scient. thesis, Dept. of Geol., Univ. of Oslo, 1989.

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

Johnston, A.C., Seismic moment assessment of earthquakes in stable continental regions, I, Instrumental seismicity, *Geophys. J. Int., 124*, 381-414, 1995a.

Johnston, A.C., Seismic moment assessment of earthquakes in stable continental regions, II, Historical seismicity, *Geophys. J. Int., 125*, 639-678, 1995b.

Johnston, A.C., Seismic moment assessment of earthquakes in stable continental regions, III, New Madrid 1811-12, Charleston 1886 and Lisbon 1755, *Geophys. J. Int., 126*, 314-344, 1996.

Johnston, A.C., and L.R. Kanter, Earthquakes in stable continental crust, *Sci. Am.*, *262*(3), 42-49, 1990.

Johnston, A.C., K.J. Coppersmith, L.R. Kanter, L.R., and C.A. Cornell, The earthquakes of stable continental regions, *Tech. Rep., EPRI TR-102261s-V1-V5*, Electr. Power Res. Inst., Palo Alto, Calif., 1994.

Johnston, P., P. Wu, and K. Lambeck, Dependence of horizontal stress magnitude on load dimension in glacial rebound models, *Geophys. J. Int.*, 132, 41-60, 1998.

Kinck, J. J., E.S. Husebye, and F.R. Larsson, The Moho distribution in Fennoscandia and the regional tectonic evolution from Archaean to Permian times, *Precambrian Res.*, *64*, 23-51, 1993.

Langseth, M.G., and G.W. Zielinski, Marine heat flow measurements in the Norwegian-Greenland Sea and in the vicinity of Iceland, in *Geodynamics of Iceland and the North Atlantic Area*, edited by L. Kristjanson, pp. 277-295, D. Reidel, Norwell, Mass., 1974.

Lazareva, A. P., and L.A. Misharina, Stresses in earthquake foci in the Arctic seismic belt, *Izv. Earth Phys. Ser., 2*, 5-10, 1965.

Lindholm, C., H. Bungum, R.K. Bratlie, B.S. Aadnøy, N. Dahl, B. Tørudbakken, and K. Atakan, Crustal stress in the northern North Sea as inferred from in situ measurements and earthquake focal mechanisms, *Terra Nova*, *7*, 51-59, 1995.

Lindholm, C.D., H. Bungum, E. Hicks, and M. Villagran, Crustal stress and tectonics in Norwegian regions determined from earthquake focal mechanisms, *Geol. Soc. Spec. Publ.*, in press, 1999.

Løseth, H., and E. Tveten, Post-Caledonian structural evolution of the Lofoten and Vesterålen offshore and onshore areas, *Nor. Geol. Tidsskr.*, *76*, 215-229, 1996.

Lundquist, J., and R. Lagerbäck, The Pärve fault, A late-glacial fault in the Precambrian of Swedish Lapland, *Geol. Fören. Stockholm Förh.*, *98*, 45-51, 1976.

Mandal, P., A. Mangik, and R.N. Singh, Intraplate stress distribution induced by topography and crustal density heterogeneities beneath the Killari, India, region, *J. Geophys. Res.*, *102*, 11,719-11,729, 1997.

McNutt, M.K., and H.W. Menard, Constraints on yield strength in oceanic lithosphere derived from observations of flexure, *Geophys. J. R. Astron. Soc.*, *71*, 363-394, 1982.

Mokhtari, M., Geological model for the Lofoten continental margin, Dr. scient. thesis, Inst. of Solid Earth Phys., Univ. of Bergen, Bergen, Norway, 1991.

Mörner, N.-A., Course and origin of the Fennoscandian uplift: The case for two separate mechanisms, *Terra Nova, 3*, 408-413, 1991.

Muir Wood, R., Extraordinary deglaciation reverse faulting in northern Fennoscandia, in *Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound*, edited by S. Gregersen and P.W. Basham, *NATO ASI Ser., 266*, 141-174, 1989a.

Muir Wood, R., The Scandinavian earthquakes of 22 December 1759 and 31 August 1819, *Disasters*, *12*(3), 223-236, 1989b.

Muir Wood, R., A review of the seismotectonics of Sweden, Rep. 43-01-R-001, Rev. 2, EQE Int., Warrington, U.K., 1993.

Muir Wood, R., and G. Woo, The historical seismicity of the Norwegian Continental Shelf, ELOCS (*Earthquake Loading on the Norw. Continental Shelf) Rep. 2-1*, Norw. Geotech. Inst., Oslo, 1987.

Muir Wood, R., G. Woo, and H. Bungum, The history of earthquakes in the northern North Sea, in *Historical Seismograms and Earthquakes of the World*, edited by W.H.K. Lee, H. Meyers, and K. Shimazaki, pp. 297-306, Academic, San Diego, Calif., 1988.

Myhre, A.M., O. Eldholm, J.I. Faleide, J. Skogseid, S.T. Gudlaugsson, S. Planke, L.M. Stuevold, L.M., and E. Vågnes, Norway-Svalbard margin: Structural and stratigraphical styles, in *Geological Evolution of Atlantic Continental Rises*, edited by C.W. Poag and P.C. Graciansky, pp. 157-185, Van Nostrand Reinhold, New York, 1992.

NORSAR and Norw. Geotech. Inst., Seismic zonation for Norway, Rep., 188 pp., Norwegian Council for Building Standardization (NBR), Oslo, 1998.

Olafsson, I., E. Sundvor, O. Eldholm, and K. Grue, Møre Margin: Crustal structures from analysis of expanded spread profiles, *Mar. Geophys. Res.*, *14*, 137-162, 1992.

Olesen, O., The Stuoragurra fault, evidence of neotectonics in the Precambrian of Finnmark, northern Norway, *Nor Geol. Tidskr.*, *68*, 107-118, 1988.

Perry, R.K., H.S. Fleming, N.Z. Cherkis, R.H. Feden and P.R. Vogt, Bathymetry of the Norwegian, Greenland and Western Barents Seas. *Geol. Soc. Am. Map and Chart Series, MC 21*, 1980.

Planke, S., J. Skogseid, and O. Eldholm, Crustal structure off Norway 62° to 72° North, *Tectonophysics*, *189*, 91-107, 1991.

Rossavik, K., Møresokkelen: Kenozoisk strategrafi og geologisk utvikling, Cand. scient. thesis, Dept. of Geology, Univ. of Oslo, 1993.

Sandwell, D., and G. Schubert, Lithospheric flexure at fracture zones, *J. Geophys. Res.*, *87*, 4657-4667, 1982.

Savostin, L. A., and A.M. Karasik, Recent plate tectonics of the Arctic Basin and of northwestern Asia, *Tectonophysics*, *74*, 111-145, 1981.

Scholz, C.H., *The Mechanics of Earthquake Faulting*, 439 pp., Cambridge Univ. Press, New York, 1990.

Sengör, A.M.C., Continental interiors and cratons: Any relation? *Tectonophysics*, *305*, 1-42, 1999.

Sibson, R.H., A note on fault reactivation, *J. Struct. Geol.*, *7*(6), 751-754, 1985.

Skogseid, J., Dimensions of the Late Cretaceous-Paleocene northeast Atlantic rift derived from Cenozoic subsidence, *Tectonophysics*, *240*, 225-247, 1994.

Skogseid, J., and O. Eldholm, Early Cenozoic crust at the Norwegian continental margin and the conjugate Jan Mayen Ridge, *J. Geophys. Res. 92*, 11,471-11,491, 1987.

Skogseid, J., and O. Eldholm, Vøring Plateau continental margin: Seismic interpretation, stratigraphy, and vertical movements, *Proc. Ocan Drill. Program, Sci. Results*, *104*, 993-1032, 1989.

Skogseid, J., T. Pedersen, O. Eldholm, and B.T. Larsen, Tectonism and magmatism during NE Atlantic continental break-up: the Vøring Margin, in *Magmatism and the Causes of Continental Break-up*, edited by B.C. Storey, T. Alabaster, and R.J. Pankhurst, *Geol. Soc. Spec. Publ.*, *68*, 305-320, 1992.

Slunga, R., Earthquake mechanisms in northern Sweden Oct. 1987 - Apr. 1988, *SKB Tech. Rep. 89-28*, Swed. Nucl. Fuel and Waste Manage. Co., Stockholm, 1989.

Slunga, R., P. Norrman, and A.-C. Glans, Baltic Shield seismicity, *Geophys. Res. Lett.*, *11*, 1247-1250, 1984.

Stein, S., N.H. Sleep, R.J. Geller, S.-C. Wang, and G.C. Kroeger, Earthquakes along the passive margin of eastern Canada. *Geophys. Res. Lett.*, *6*, 537-540, 1979.

Stein, S., S. Cloetingh, N.H. Sleep, and R. Wortel, R., Passive margin earthquakes, stresses and rheology, in *Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound*, edited by S. Gregersen and P.W. Basham, *NATO ASI Ser., 266*, 231-259, 1989.

Stephansson, O., Ridge push and glacial rebound as rock stress generators in Fennoscandia, *Bull. 14*, pp. 39-48, Geol. Inst., Univ. of Uppsala, Uppsala, 1988.

Stephansson, O., L.-O. Dahlström, K. Bergström, Särkkä, Väätäinen, A.

Myrvang, O. Fjeld, and T.H. Hanssen, Fennoscandian rock stress data base - FRSDB, *Res. Rep. 1987:06*, Luleå Univer., Luleå, Sweden, 1987.

Stephenson, R.A., and E.I. Smolyaninova, Neotectonics and seismicity in the south-eastern Beaufort Sea, polar continental margin of the northwestern Canada. *J. Geodyn.*, *27*, 175-190, 1999.

Stuevold, L.M., Den tertiære Fennoskandiske landhevning i lys av vertikalbevegelser på midtnorsk kontinentalmargin: En undersøkelse basert på analyse av maringeofysiske data. Cand. scient. thesis, Dept. of Geology, Univ. of Oslo, 1989.

Stuevold, L.M., and O. Eldholm, Fennoscandian continental uplift inferred from a study of the mid-Norwegian margin, *Global Planet. Change*, *12*, 359-386, 1996.

Stuevold, L.M., J. Skogseid, and O.Eldholm, Post-Cretaceous uplift events on the Vøring continental margin, *Geology*, *20*, 919-922, 1992.

Sundvor E., O. Eldholm, T.P. Gladczenko, and S. Planke, Norwegian-Greenland Sea thermal field, *Geol. Soc. Spec. Publ.*, in press, 1999.

Talwani, M., and O. Eldholm, The continental margin off Norway: A geophysical study, *Geol. Soc. Am. Bull.*, *83*, 3575-3608, 1972.

Talwani, M., and O. Eldholm, Evolution of the Norwegian-Greenland Sea, *Geol. Soc. Am. Bull.*, *88*, 969-999, 1977.

Vaage, S., Seismic evidence of complex tectonics in the Meløy earthquake area, *Nor. Geol. Tidsskr.*, *60*, 213-217, 1980.

Walcott, R.I., Flexural rigidity, thickness, and viscosity of the lithosphere, *J. Geophys. Res.*, *75*, 3941-3954, 1970.

Wessel, P., and H.F. Smith, Free software helps map and display data. *Eos Trans. AGU*, *72*, 441, 445-446, 1991.

Wiens, D.A., and S. Stein, Age dependence of oceanic intraplate seismicity and implications for lithospheric evolution, *J. Geophys. Res.*, *88*, 6455-6468, 1983.

Wiens, D.A., C. DeMets, R.G. Gordon, S. Stein, D. Argus, J.F. Engeln, P. Lundgren, D. Quible, S. Stein, S. Weinstein, and D.F. Woods, A diffuse plate boundary model for Indian Ocean tectonics, *Geophys. Res. Lett.*, *12*, 429-432, 1985.

Wu, P., and H. Hasegawa, Induced stresses and fault potential in eastern Canada due to a disc load: A preliminary analysis, *Geophys. J. Int.*, *125*, 415-430, 1996a.

Wu, P., and H. Hasegawa, Induced stresses and fault potential in eastern Canada due to a realistic load: a preliminary analysis, *Geophys. J. Int.*, *127*, 215-229, 1996b.

Zoback, M. L., First- and second-order patterns of stress in the lithosphere: The World Stress Map Project, *J. Geophys. Res.*, *97*, 11,703-11,728, 1992.

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(Received November 10, 1998; revised July 12, 1999;
accepted August 9, 1999.)