Crustal stress in and around Norway: an evaluation of stress-generating mechanisms

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Abstract: Recent stress observations from in situ measurements and earthquake focal mechanisms in the Norwegian onshore and offshore areas are evaluated with the aim of characterizing the most important mechanisms for the present stress field in and around Norway. The evaluation is based on a set of stress indicators that include both shallow measurements (overcoring and borehole breakouts) and deep data (earthquake focal mechanisms). Computer simulations of simple stress-generation models were used to constrain the relative importance of different stress-generating mechanisms. The ridge push force associated with sea-floor spreading in the North Atlantic is considered to be the primary source of the compressional stress field observed in Norway. Regional influences from the continental margin density contrast, topography and flexure induced by sediment loading are of limited lateral extent, but are important in reorienting the stress field in certain areas. The observed tectonics and stresses are generally also in accord with tectonics expected from Fennoscandian uplift.

The orientation of the stresses in the crust is among the principal indicators of current dynamic processes. Earthquake focal mechanisms together with in situ measurements (overcoring, hydraulic fracturing and borehole breakout analysis) are important sources of information on stress orientation and magnitude.

The first in situ stress determination methods were developed in the 1950s (see Hast 1958), and were primarily related to mining activity. Before that time, rock stresses had only been regarded as gravity induced, but in the 1950s the new measurements indicated that horizontal stresses exceeded what could have been expected from only gravitational forces, and since the 1960s stress data were interpreted in a wider geophysical context. Since the first measurements were obtained in Norwegian areas, the stress database has increased dramatically, primarily as a result of three scientific programmes: the Fennoscandian Rock Stress Data Base (Stephansson et al. 1987), the World Stress Map (Zoback et al. 1989; Zoback 1992), and the Dynamics of the Norwegian Margin (Fejerskov et al. 1995; Lindholm et al. 1995b). In the mapping of crustal stresses in northwestern Europe and Norway, the following contributions can be considered as milestones: Hast (1969), Ranalli & Chandler (1975), Bungum & Fyen (1979), Klein & Barr (1986), Clauss et al. (1989), Bungum et al. (1991), Müller et al., (1992) and Müller (1993).

Parallel to the compilation of new data on observed stresses, analytical and numerical models and computer simulations were applied to investigate the characteristics of different stress-generating mechanisms. Models ranging from global analysis of different plate driving forces (Forsyth & Uyeda 1975; Bott & Kuszmir 1984; Richardsson 1992) to regional and local features such as density inhomogeneities, and flexural stresses from sediment loading, glacial rebound and topography (Stephansson 1988; Stein et al. 1989; Spann et al. 1991) were developed. The present paper reviews available data and modelling results with the goal of characterizing the most important stress-generating processes behind the horizontal stress field in Norway and adjacent offshore areas.

Data
Ranalli & Chandler (1975) were the first to compile stress data from Scandinavia. On the
basis of Hast’s measurements (largely overcor- 
ing) they concluded that the direction of the 
principal horizontal stresses was E–W in sou- 
tern Scandinavia and N–S in northern Scandina-
via. Although this picture has become more 
differentiated with the acquisition of additional 
data, the main conclusion of this early investiga-
tion is still valid. The database now at hand 
has been compiled and quality checked, and has 
been presented by Fejerskov et al. (1995) and 
Lindholm et al. (1995b). A synthesis of all the 
data is shown in Figs 1 and 2, together with 
the regionalization used in this paper. Within the 
area defined in Fig. 1 altogether 351 data points 
give the azimuth of the largest principal hor- 
izontal stress component, and the observed 
stress directions are summarized as follows:

- The maximum horizontal stress direction 
  ($\sigma_{1h}$) rotates from N–S in northern Norway 
  and the Barents Sea to WNW–ESE in 
  western Norway and the northern North Sea.
- The stress directions at shallow depths deter-
  mined by in situ techniques, and deeper 
  observations from the middle to lower crust 
  based on earthquake focal mechanisms, are 
  similar and indicate that the tectonic stresses 
  are homogeneous in direction over a large 
  depth range.
- In offshore areas reverse and strike-slip 
  faulting dominates, indicating compressive 
  stress regimes.
- Shallow earthquakes, particularly found 
  in an area around Stord, but also in the 
  Oslo region and in the Meløy and Steigen 
  sequences (Bungum et al. 1979; Atakan et al. 
  1994) indicate tensional stress regimes with 
  normal faulting.
- No change in horizontal stress direction is 
  observed between sedimentary and crystal-
  line rocks.
- Overcoring measurements show a more scat-
  tered stress direction compared with borehole 
  breakout and earthquake focal mechanisms.

Fig. 1. Five regions with rose diagrams indicating the maximum horizontal stress direction ($\sigma_{1h}$) determined from 
focal mechanisms (F), borehole breakouts (B) and overcoring (C). A detailed description of the data used has 
been given by Fejerskov et al. (1995) and Lindholm et al. (1995a,b). The shelf edge is shown with the dashed line. 
S, Stord area; M, Meløy; St, Steigen; V.B., Voring Basin; Sv, Svaritsen; J, Jostedalsbreen; F, Folgefonna; 
M.B., More Basin; Esc., Escarpment; Gr., Graben; F.Z., Fracture Zone.
They also reveal high stress magnitudes (10–20 MPa tectonic stress), particularly in massive gneiss areas of mid-Norway.

Regions

Five main regions with different regional horizontal stress trends have been identified in Norway. The region boundaries do not represent abrupt changes in the stress field, but a continuous lateral variation.

Northern Norway and the Barents Sea

As seen from Fig. 1 the area comprises large offshore areas and the northernmost part of Norway (Finnmark). In situ measurements in the Barents Sea reveal a clear N–S stress direction (Dart et al. 1995; Fejerskov et al. 1995). Overcoring measurements from onshore Finnmark are consistent with the offshore observations and reveal very high tectonic stresses (15–25 MPa) both in N–S and E–W directions at shallower depths (0–200 m) (Myrvang et al. 1993). In contrast to the low seismic activity in the Barents Sea, neotectonic movements associated with large prehistoric earthquakes have been mapped in Finnmark and northern Sweden. Displacements on NE–SW and NNW–SSE trending structures indicate a compressional stress regime with a NNW–SSE stress direction (Olesen et al. 1992; Bungum & Lindholm in prep.).

Mid-Norway and the Norwegian Sea

This areas comprises a large continental platform and mid-Norway. In situ stress observations on the continental platform and in mid-Norway indicate a NW–SE stress direction, which is consistent with earthquake focal mechanisms. The seismic activity in the region is generally high, with two recent interesting earthquake swarms recorded in the coastal region at Meløy and Steigen (Bungum et al. 1979; Atakan et al. 1994). Earthquake focal mechanisms reveal a compressional stress regime offshore, whereas seismic onshore activities close to highly elevated and glaciated regions, such as the Meløy–Steigen area, indicate a shallow tensional stress regime. Overcoring measurements in mid-Norway reveal high tectonic stresses (up to 30 MPa), especially in massive gneiss regions (Hanssen & Myrvang 1986).
Western Norway and the northern North Sea

In situ stress observations in the northern North Sea yield a WNW–ESE regional stress direction, but a NNE–SSW direction is also weakly indicated both by in situ measurements and by earthquake focal mechanisms (Lindholm et al. 1995a). The seismic activity offshore is high, especially centred around 61.5°N and 3.0°E, and a compressional stress regime is indicated. Onshore, seismic activity is concentrated on the seaward side of a highly elevated and glaciated region just east of the island of Stord. Focal mechanisms indicate a small area with shallow tensional stress regime in this area. Stress direction and magnitudes from overcoring measurements in western Norway are often strongly influenced by topography, however, indicating high tectonic stresses (10–15 MPa).

Southwestern Norway and the central North Sea

Borehole breakouts in the central North Sea yield a complex stress pattern. The NW-SE European regional trend is observed in the dataset, but also other stress directions frequently appear. The observations are of very low quality and probably also largely reflect local features such as faults and salt diapirs (Cowgill et al. 1994; Ask 1996). As relatively few focal mechanisms and overcoring measurements have been obtained for this area, it has been difficult to accomplish a regional interpretation. The seismic activity in this region is low.

Southeastern Norway

This region is centred around the Permian Oslo Graben, and because of the proximity to seismic monitoring stations focal mechanisms could be calculated for many minor events. The data indicate both relatively deep and shallow seismic activity with a dominance of normal faulting in the upper crust. The focal mechanisms indicate a NW–SE compressional (NE–SW tensional) stress direction. This is only partly confirmed by overcoring measurements, which generally yield a NE–SW trend more parallel to the graben structure, and with stresses up to 20 MPa at shallower depths.

Stress-generating mechanisms

Stresses in the Earth’s crust may be distinguished with respect to their origin and lateral extent (Engelder 1974; Sykes & Sbar 1994), and can be divided into continental, regional and local stress fields (Table 1). The observed stress is then composed of a plate-wide continental stress field overprinted by regional and local effects (Zoback 1992). To identify the stress sources in the Norwegian areas, it is important to examine and identify the most important stress-generating mechanisms and to quantify the stress magnitude, lateral extension and depth variation. This has been achieved primarily by analytical or numerical stress modelling, where the plate has been regarded as pure elastic. This is a coarse simplification of the crust’s brittle-ductile behaviour. In the simplified models the computed stress directions and stress regimes will be close to reality, whereas absolute stress magnitudes are probably exaggerated. Hence the models may be used only qualitatively, and to derive appropriate stress magnitudes the effects of rheology have to be evaluated (Cloetingh & Burov 1996). In cases where we have not performed the modelling a review of other modelling results and a qualitative evaluation has been made.

The generally accepted explanation for the observed first-order intraplate stresses are plate tectonic forces acting at convergent and divergent plate boundaries (Zoback 1992). Several workers, who have modelled the significance and relative magnitude of different plate tectonic

<table>
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<tr>
<th>Table 1. Stress-generating mechanisms</th>
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<tr>
<td>Stress field</td>
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<tr>
<td>Lateral extent</td>
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<tr>
<td>Stress-generating mechanisms</td>
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forces, have concluded that ridge push, slab pull and collisional resistance forces are the principal contributors both to plate kinematics and for the global stress field (Forsyth & Uyeda 1975; Chapple & Tullis, 1977; Richardsson 1992). Müller (1993) analysed the European stress field and concluded that the dominant source of regional tectonic stress in western Europe is a combination of collision-related forces at the southern plate boundary and ridge push along the western and northern boundary. This is based on a match between ridge push and collisional torque directions and stress directions (Richardsson 1992), and a similarity between stress orientations and relative plate motion directions between the African–Eurasian and North American–Eurasian plates. Because of the Norwegian region's proximal position relative to the Mid-Atlantic and Arctic spreading ridge, the major first-order tectonic stresses in this region are attributed to the ridge push force.

Second-order stress fields arise from regional density inhomogeneities, topographical loads and plate flexure related to deglaciation or sediment loading. Some local effects, as indicated in Table 1 are below the resolution of our stress observations and are therefore not discussed in detail in this paper.

In addition to stress-generating features the paper also focuses on the effect of crustal thickness as a stress-modifying feature that has importance in Norwegian regions. As tectonic stresses are concentrated in the brittle part of the crust, a local or regional crustal thinning will significantly enhance the stress magnitude and vice versa (Hasegawa et al. 1985).

The ridge push force

Mid-ocean ridges are areas of shallow bathymetry in approximately isostatic equilibrium because the elevated crust is compensated at depth by hot, low-density material. As the

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**Fig. 3.** Schematic cross-section of the spreading ridge model (a). Variation in temperature (b), density (c) and deviatoric stresses (d) as a function of age and depth. Assumed temperature and density of the mantle are 1350°C and 3300 kg m⁻³, respectively; a thermal diffusivity of 0.008 cm² s⁻¹ and coefficient of thermal expansion of 3.2 × 10⁻⁵°C⁻¹ are anticipated.
Table 2. Stress magnitudes associated with ridge push reported by various researchers

<table>
<thead>
<tr>
<th>Reference</th>
<th>Stresses related to ridge push</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bott &amp; Kusznir (1984)</td>
<td>Average tectonic stress of the order of 20–30 MPa</td>
</tr>
<tr>
<td>Stein et al. (1989)</td>
<td>Average tectonic stress of a few tens of MPa</td>
</tr>
<tr>
<td>Bott (1991)</td>
<td>Maximum deviatoric stress of about 40 MPa in the upper lithosphere 200 km from the crest</td>
</tr>
<tr>
<td>Dahlen (1981)</td>
<td>Maximum deviatoric stress of 31 MPa at the surface of 60 Ma oceanic lithosphere</td>
</tr>
<tr>
<td>Fleitout &amp; Froidevaux (1983)</td>
<td>Average tectonic stress of 25 MPa for an 80 km thick 60 Ma oceanic crust</td>
</tr>
</tbody>
</table>

Oceanic lithospheric ages and moves away from the mid-ocean ridge it cools and subsides. The ridge elevation creates an outward compressional, gravity-generated force perpendicular to the crest. As a result of the rather simple ridge geometry and the well-constrained boundary conditions the ridge push force is quantitatively well understood and has been analysed both analytically and numerically (Lister 1975; Parsons & Richter 1980; Dahlen 1981).

By applying a cooling half-space model, Dahlen (1981) was able to estimate the stresses as a function of both depth and age of the oceanic lithosphere, and on the basis of his work. Fig. 3 shows the distribution of temperature, density and deviatoric stresses in the oceanic lithosphere. (Deviantic stress (S) is the difference between total stress (σ) and mean Earth pressure (P),

\[
\begin{bmatrix}
\sigma_v \\
\sigma_H \\
\sigma_p
\end{bmatrix} = \begin{bmatrix}
P & 0 & 0 \\
0 & P & 0 \\
0 & 0 & P
\end{bmatrix} + \begin{bmatrix}
S_v \\
S_H \\
S_p
\end{bmatrix}
\]

where \( P = (\sigma_v + \sigma_H + \sigma_p)/3 \), and \( S_H = -S_v \) and \( S_H = 0 \) is assumed.

The ridge push force \( (F_R) \) will be zero at the ridge crest and increase linearly with age. The deviatoric stresses increase with age, but will decrease with depth. For a 60 Ma oceanic crust, a maximum deviatoric stress of 31 MPa is obtained. This corresponds well to values reported by various workers listed in Table 2.

Density contrast at the continental margin

The transition from denser and thinner oceanic crust to lighter and thicker continental crust will create a tensional stress state in the continental crust where it tends to ‘spread out’ over the oceanic lithosphere (Artyushkov 1973), whereby tensional deviatoric stresses will be generated in the continental crust and compressional deviatoric stresses in the oceanic crust. Stein et al. (1989) computed maximum deviatoric stresses of 40–50 MPa (tension in the continental crust and compression in the oceanic crust) close to the margin slope, decreasing with both depth and distance from the margin. The effect is not expected to penetrate more than about 100 km into the continental plate.

As long as the continental effect is evaluated alone, stresses will always act perpendicular to the margin, but Gölke et al. (1995) showed that stress direction and stress anisotropy near the continental margin are dependent on the angle between the applied ridge push force and the continental margin. Figure 4 illustrates the effect of a change in orientation of the continental margin. Where margins orientated normal to the tectonic far-field stress direction were found to exhibit lower stress anisotropy (close to zero) in the continental crust compared with margins orientated parallel to the far field.

Glacial rebound and flexural stresses related to deglaciation

Glaciers can form a significant load on the lithosphere, and deglaciation, or removal of the ice load, introduces stress changes in the upper crust. Two models, both considering the crust as elastic, have been proposed to estimate horizontal stresses caused by glacial rebound.
Glacier Reference state

Glacier

Uplift Reference state

Uplift

Deviatoric tension

Deviatoric compression

**Fig. 5.** Two models for the estimation of stresses associated with post-glacial rebound. The model of Stephansson (1988) (a) predicts compressional horizontal stresses of the order of 2–3 MPa beneath an ice sheet of 2 km thickness with 140 m of uplift remaining. The model of Stein et al. (1989) (b) predicts tensional stresses of a few tens of MPa for an ice load of 2 km thickness.

Stephansson (1988) assumed the lithosphere to be in equilibrium before ice loading and computed compressional stresses beneath the ice, so that when the ice is removed horizontal stresses slowly diminish until the uplift ceases and equilibrium is reached. Stein et al. (1989) assumed the plate to be in equilibrium with the ice load applied and thus derived tensional stresses associated with the uplift.

The choice of model depends on glacial history and the preferred plate relaxation time. If the plate relaxation time is long compared with the glacial history, the plate will not have time to adjust its equilibrium and stresses from deglaciation are best calculated by using an undeformed plate (Stephansson’s model). For short relaxation times some viscous deformation would appear in the lithosphere, changing the state of equilibrium, which makes the model of Stein et al. more appropriate.

Close to the former ice margin the model of Stein et al. (1989) computed deviatoric stresses in the order of 30 MPa for a 2 km thick ice sheet (Fig. 6). The model of Stephansson predicts much smaller stress magnitudes (3–4 MPa) and an opposite stress pattern. In reality, the result is assumed to lie somewhere between the two models, probably favouring slight tension (P. Johnston, pers. comm.).

**Flexural stresses from sediment loading**

Subsiding sediment basins are driven by a combination of tectonic crustal stretching and thinning and the increasing sediment load. As in the case of ice loading, the sediment load will introduce flexural stresses with compressional stresses in the upper crust underneath the sediment basin and tensional stresses outside the basin (Fig. 7). Stein et al. (1989) computed stresses of several hundred MPa for a 10 km thick sedimentary basin. This is an obvious artefact of the elastic model, and by introducing viscoelastic and brittle-ductile plate behaviour stresses decrease to some tens of MPa. By varying lithosphere thickness and sedimentation rates, Stein et al. further concluded that the highest stresses are related to basins with high sedimentation rates underlain by a thin lithosphere. Very few places in the world show sufficiently high sedimentation rates to generate strong seismic activity, which leads to the conclusion that sediment loading generally has only a minor influence on the regional stress field. Recent observations from the Norwegian area, where areas of extraordinary high sedimentation rates occur, however, show a correlation between seismicity and sedimentary basins (Byrkjeland 1996).

**Topography**

Topography represents a load on the lithosphere, which has to be supported by stresses in the crust. Three main types of topographical surface loading situations may be identified (Bott 1971), and are qualitatively illustrated in
Fig. 6. Deformation and horizontal stress magnitudes resulting from the removal of 2000 m of ice from an elastic crust floating on a fluid. Modelling parameters used are: flexural rigidity ($D = 10^{25}$), flexural parameter ($\alpha = 205$ km), restoring density ($\rho_r = 2300$ kg m$^{-3}$), plate thickness ($T = 110$ km).

For small surface loads less than 50 km wide, the lithosphere will not bend significantly, and stresses are adequately modelled by applying the load on an elastic half-space (Jaeger & Cook 1969; Bott & Kusznir 1984). Beneath the applied load deviatoric tension develops, whereas beyond the edge of the load, slight compression appears. More general models of symmetrical ridges in both two dimensions (Savage et al. 1985; Pan & Amadei 1993) and three dimensions (Liu & Zoback 1992) arrive at similar conclusions, but indicate slightly lower stresses compared with a constant load. In all cases the stresses are believed to be too small to cause tectonic activity, but may be of local importance and trigger earthquakes in areas with enhanced regional stress or pre-existing zones of weakness.

For surface loads significantly wider than 50 km, which are not compensated at depth, the same type of bending as caused by sediment loading will appear. The flexure associated with bending creates compression on the concave side of the plate and tension on the convex side, and the stress magnitudes can be very high (several hundreds of MPa) if elastic models are applied (Bott 1971). Brittle-ductile behaviour, however, reduces the stress magnitudes significantly and entails stress dissipation by transient creep over a relative short geological time scale.

If the surface load is compensated at depth, the load will be counterbalanced by an upthrust and no bending will occur. The vertical stresses...
Sources of observed stresses in the Norwegian provinces

On the basis of the described sources of crustal stress and the observational data it is now time to link the stress-generating mechanisms to the defined stress provinces. The effect of each stress-generating mechanism in each stress province is discussed in view of the stress observations, and the source models are evaluated in order of lateral extent (plate-wide to local) and ranked in order of importance. Figure 9 provides an overview of the regional variations and Table 4 contains a summary of the results.

Ridge push

Since late Paleocene time (60 Ma) spreading has occurred from both the mid-Atlantic ridge and its northward continuation, the Arctic mid-ocean ridge (Jackson & Gunnarsson 1990). In the polar region the ridge geometry is well defined and the Barents Sea is expected to be subjected to a SSE-directed ridge push from the Arctic mid-ocean ridge (Fig. 9a). In the northern Atlantic Ocean, the ridge (Knipovitch and Molloy Ridges) turns N–S and is cut by several transform zones, and these zones complicate the ridge geometry and reduce the ridge push effect. It should therefore be anticipated that the Barents Sea is influenced by NNW–SSE tectonic stresses, which, for a 60 Ma crust, generate maximum deviatoric stresses of the order of 20–30 MPa. The observed stress direction (N–S) in the Barents Sea is rotated c. 20° clockwise from the expected ridge push direction and hence ridge push alone cannot explain the observations in this region.

Further south, the Mohns Ridge, a relatively straight ENE–WSW striking ridge bounded by the Jan Mayen and Senja fracture zones, generates a clear NNW–SSE tectonic stress. This is consistent with the observed stress direction in the Norwegian Sea and northern Norway, and

### Table 3. Predicted patterns and magnitudes of stress associated with topographical loading

<table>
<thead>
<tr>
<th>Type of loading</th>
<th>Maximum stress magnitude (MPa)</th>
<th>Lateral variation</th>
<th>Variation with depth</th>
<th>Zone of influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow load</td>
<td>25</td>
<td>Compression outside load</td>
<td>Monotonic</td>
<td>Local</td>
</tr>
<tr>
<td>Wide load, uncompensated</td>
<td>~240</td>
<td>Tension underneath</td>
<td>Reverses</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Wide load, compensated</td>
<td>40</td>
<td>Tension outside load</td>
<td>Monotonic</td>
<td>Regional</td>
</tr>
</tbody>
</table>

All values are computed for a 1500 m elevation.
Fig. 9. Four important stress-generating mechanisms and their regional effect on Norway and adjacent regions.
(a) The mid-Atlantic spreading ridge induces a NW–SE deviatoric stress field of the order of 20–30 MPa in the oldest oceanic crust. The magnitude is lowered somewhat in the thick continental crust, but might show local maxima in areas with thinned crust. (b) The continental margins are characterized by a deviatoric tensional stress field in the continental crust, and deviatoric compression in the oceanic crust, normal to the margin. (c) Post-glacial uplift contours indicate substantial vertical movement of Fennoscandia since deglaciation of the region. Deviatoric stresses, tension beneath the former ice, and compression beyond the ice edge, are associated with deglaciation in accordance with the model of Stein et al. (1989). Maximum stresses occur close to the former ice margin, and will reverse both with depth and laterally. (d) Sediment loading causes bending stresses to develop in the lithosphere, with compression beneath the load and tension on the flanks with stress reversal at depth. Bending stresses are dependent on a high sedimentation rate.

modelling also here indicates maximum deviatoric stresses of the order of 20–30 MPa close to the continental margin.

South of Jan Mayen, the Iceland–Jan Mayen Ridge defines the mid-Atlantic spreading ridge. Although the ocean-floor geometry in this region is complicated by the Jan Mayen microcontinent, the Ægir Ridge and the oceanic swell beneath Iceland, a net ridge push force is generated with a NW–SE direction. The stress
direction may show a radial orientation around Iceland, as pointed out by Bott (1991), but the first-order stress pattern is expected to be oriented normal to the ridge (NW–SE). The stress magnitude is difficult to assess from a simple cooling model, but it is expected to be similar to or slightly less than that computed for the original 60 Ma oceanic crust (20–30 MPa).

The tectonic stresses set up by the ridge push are known to penetrate the entire north European plate (Müller et al. 1992; Müller 1993) and will therefore be active both in the northern and southern North Sea, as well as in southwestern Norway. In the northern North Sea and western Norway the predicted NW–SE direction fits the observations fairly well. In the central North Sea and southwestern Norway a complex stress pattern appears, but also here a NW–SE direction is clearly present in the data.

The compressional stress magnitude from the ridge push is affected by crustal thickness and plate rheology. Because the crustal thickness of the Baltic Shield is significant, a force like the ridge push will have to be distributed over a wider depth range. This will eventually reduce the tectonic stress regionally in central parts of Norway and Fennoscandia, and enhances the possibilities for second-order stress generators to dominate the observed stress field. On the other hand, the thinned crust underneath offshore rifted basins (mid-Norwegian margin, Viking and Central Grabens) enhances tectonic stresses and explains the compressional focal mechanisms and high seismic activity observed in this regions.

In summary, the ridge push explains most of the stress observations in the Norwegian area and no area seems to be outside the influence of this stress. However, the observed stress direction in the Barents Sea, as well as local onshore tectonic regions and possible lateral variations in horizontal stress anisotropy, imply that second-order effects are also present. Other stress-generating mechanisms, such as the continental margin effect and flexural stresses associated with sediment loading or deglaciation, therefore need to be taken into consideration.

**Continental margin**

To the west, the Barents Sea is bounded by a N–S trending continental margin, which generates extensional horizontal deviatoric stresses perpendicular to the margin in the continental crust (Fig. 9b). When superimposing this margin effect on the stresses from the ridge push a stress rotation can appear. Depending on the ratio between the stresses set up by the margin effect and the stresses generated from ridge push, the continental margin may rotate the stresses so that the stress direction will be more or less parallel to the margin. Close to the margin, where the deviatoric stresses from the continental margin are at their maximum, the continental margin effect will be most significant and hence may explain the clockwise rotation from the NNW–SSE ridge push direction to the observed N–S direction.

In the Norwegian Sea the continental margin is defined by the Møre and Voring escarpments and the shelf edge off the Lofoten islands. The margin here is approximately parallel to the spreading ridge, which means that the continental margin effect introduces deviatoric tensional stresses in the continental crust parallel to the compressional stresses caused by the ridge push. The overall effect will be a more isotropic stress state in the continental crust near the margin.

Further south the continental margin bends around the United Kingdom and is relatively distant from the region under focus. Its effect in the North Sea and southern Norway will thus be insignificant.

**Sediment loading**

During Tertiary and Quaternary time the Barents Sea region was uplifted and extensively eroded, and the eroded sediments were redeposited as a wedge of up to 3 km thickness covering the continental margin (Reemst et al. 1994). The sedimentation rate in Pliocene time (1.6 mm a⁻¹) was sufficiently high to set up significant deviatoric stresses in the underlying rock. Computations indicate that for a sediment wedge of 2–3 km thickness covering the continental margin, tensional deviatoric stresses of the order of 10–20 MPa can be set up in the continental crust close to the margin. The stresses align with the continental margin effect and may be significant both in reorienting the stress field and in increasing the stress anisotropy close to the margin in the Barents area.

In the mid-Norway and Norwegian Sea province a strong differential tilt and uplift of the mainland initiated a strong erosion and deposition of a thick prograding sequence (about 1500 m) over the mid-Norwegian Shelf in late Neogene time. The high sedimentation rate in Pliocene time (up to 0.8 mm a⁻¹) may have been large enough to cause flexural stresses on the Mid-Norwegian Shelf. Byrkjeland (1996) also found a clear correlation between seismic activity and Pleistocene and post-Miocene sediment
<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Theoretical effects and magnitudes</th>
<th>Effects in Fennoscandia</th>
<th>Comments</th>
</tr>
</thead>
</table>
| Ridge push (continental)| 20 30 MPa for 60 Ma old oceanic crust  
Normal to ridge  
Compression in oceanic and continental crust  
Monotonic with depth | The basic stress generator throughout Fennoscandia                                      | Yields a WNW ESE to NNW SSE stress field, affecting the whole region                                                                          |
| Crustal thickness (regional) | 10 50 MPa  
Normal to margin  
Tension in continental crust and compression in oceanic crust  
Monotonic with depth | Probably important in the western Barents Sea and on the Norwegian continental margin  
High compressional stresses in the thinned crust under the offshore basins of mid- and central Norway may be reflected by the high seismic activity  
The thick Fennoscandian crust dampens the tectonic stresses in central parts of Norway and Sweden | In the western Barents Sea, the continental margin effect supplements the tectonic stress from ridge push; at the Norwegian continental margin this mechanism counteracts the ridge push; this accounts for the observed reduction in stress anisotropy from north to south |
| Continental margin (regional) | 160 MPa for 2 3 km of sediments (decreases with time)  
Compression beneath basins and tension at margins  
Compression is strongest in the centre and decreases outwards  
Stress direction reverses with depth  
High sedimentation rates required | Western Barents Sea and tentatively the Norwegian margin, Viking and Central Grabens  
The Western Barents Sea was the locus of moderate sedimentation rates in Paleocene time; bending stresses in the Barents Sea may reinforce the tectonic stresses from ridge push; on the Norwegian margin and in the Viking and Central Grabens the sedimentation rates are lower and the effect is less clear |                                                                                                                                                                                                  |
| Deglaciation (regional) | 20 30 MPa for 2 3 km ice load (decreases with time)  
Tension beneath uplifted areas and compression beyond  
Most prominent close to the former ice margin  
Stress reverses with depth | Tentatively affects whole region                                                              | In Norway the effect will be small compared with other mechanisms; observed fault types in northern Norway may be explained by this mechanism, as also the normal faulting mechanisms observed in coastal areas in mid- and west Norway |
<table>
<thead>
<tr>
<th>Topographical wide load (regional)</th>
<th>40 MPa for 1500 m elevated region</th>
<th>Tension beneath the ice load and compression beyond</th>
<th>Monotonic with depth</th>
<th>Topography is moderate (c. 1000 m elevation); underneath the elevated regions in northern and southwestern Norway tectonic stresses from ridge push will be reduced, whereas in the surrounding (both coastal and landward) areas the tectonic stresses are expected to increase slightly; in offshore regions to the northwest the direction of compression will be similar to that of ridge push</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topographical narrow load (local)</td>
<td>25 MPa for 1500 m elevated region</td>
<td>Tension beneath the elevated regions and compression beyond</td>
<td>Uncertain</td>
<td>Centres of seismicity with normal faulting mechanisms are located close to the glaciers Svartisen and Folgefonna (remnants from the glaciation?); this may be explained by local areas of high topography and possibly strengthened by local uplift connected to the glaciers</td>
</tr>
<tr>
<td>Surface relief (local)</td>
<td>10–30 MPa</td>
<td>Compressional stress acts parallel to the surface gradient</td>
<td>Throughout region, but particularly in high-relief areas of northern and southwestern Norway</td>
<td>The large variation in stress direction from shallow onshore measurements along fjords and valleys in the coastal regions of northern and western Norway may be explained by local, shallow topographical effects; depending on the orientation of fjords and valleys, topographical stress may or may not interact with the regional stress</td>
</tr>
<tr>
<td>Faults (local)</td>
<td>Modifies the present stress field</td>
<td>Stress rotates normal or parallel to the faults</td>
<td>Throughout the region, but most clearly observed in the North Sea basins</td>
<td>Large variation in stress direction (sometimes rotation?) in the North Sea basins may be explained by low horizontal stress differences favouring local influence from faults</td>
</tr>
<tr>
<td>Inclusions (local)</td>
<td>Modifies the present stress field (up to 50% change in stress magnitude)</td>
<td>Stress bends around soft inclusions such as salt diapirs and is directed into areas of high stiffness such as massive rock masses</td>
<td>Salt diapirs beneath the southern North Sea Gneiss windows in mid-Norway</td>
<td>The complex stress pattern in the Central Graben may possibly be explained by low horizontal stress differences favouring local influence from salt and other doming structures</td>
</tr>
</tbody>
</table>

The mountain ranges in western Norway may support this mechanism.
depopulating the idea of sedimentation-induced stresses. Analysis of focal mechanisms under-neath the loaded area yields a compressional regime whereas onshore mechanisms indicate a tensional regime. It is, however, difficult to assess the quantitative importance of the sediment loading effect, as it acts constructively and in the same direction as ridge push.

In Pleistocene time, the Viking and Central Grabens subsided and the sedimentation rate was relative low. Hence, bending stresses are relatively small and the sediment loading effect is expected to be negligible here.

Deglaciation

The deglaciation models indicate maximum deviatoric stress concentrations close to the former ice edge, with a shift in polarity across the edge (largely along the coast) (Fig. 9c). This is also to some extent observed in the region, with compressional offshore focal mechanisms and some shallow onshore mechanisms (Stord, Oslo and Meloy–Steigen) indicating a tensional stress regime. The observations thus support the deglaciation model of Stein et al. (1989) well. However, the onshore faulting may also be explained by sediment loading and topography effects.

Finnmark and the southern Barents Sea have also been covered by thick ice sheets (Kjemperud & Fjeldskaar 1992), possibly inducing tectonic stresses in connection with deglaciation. The observed shallow reverse faulting in Finnmark, with a NNW–SSE compression reported by Olesen et al. (1992) and Bungum & Lindholm (in prep.), may favour Stephansson’s uplift model, but no lateral shift in stress regime is identified from the available data. The deglaciation effect in the northern part of Norway is therefore believed to be either negligible or masked by other regional effects. The observed compressive stress regime is more probably connected to effects such as the compression from ridge push.

If the deglaciation effect is an important source for the observed stress field in Norway the observations surely favour the model of Stein et al. (1989).

Topography

The bathymetry of the Barents Sea is relatively shallow and the onshore relief is low with gentle slopes. The topographical effects, both on a regional and on a local scale, are therefore not expected to play an important role in northern Norway. Mid-Norway is characterized by locally high-altitude mountains, especially in the northern part of the region, and topography clearly influences the near-surface stresses. The mountains can be regarded as narrow loads and modelling has shown that tensile deviatoric stresses extend downward to a depth comparable with the width of the load. In the Meloy–Steigen areas there are examples of locations relatively near high mountain complexes. Here earthquake swarms, indicating inhomogeneous stress conditions, are observed; however, the shallow normal faulting focal mechanisms are contrary to what should have been expected from topographical loading (Fig. 8).

Western Norway is also characterized by high mountains cut by deep fjords and valleys, and hence, near in situ measurements are very much influenced by local topographical features. The mountain range also contribute on a more regional scale, as the large topographical features act as a wide compensated load, introducing tensile deviatoric stresses underneath elevated onshore areas. The shallow tensional focal mechanisms observed in southwestern Norway can be attributed to topographical effects.

The relief in southern and eastern Norway is lower and more gentle than in western Norway. Hence, topographical effects will not be of the same importance as in the high-relief and high-altitude areas and may therefore be neglected.

Discussion

The N-S stress direction observed along the western margin of the Barents Sea is well explained by the ridge push, when modified in azimuth by the continental margin effect and flexure associated with rapid sedimentation. The ridge push is also believed to cause the shallow reverse faulting and high horizontal stress magnitudes measured in northern Norway. The consistent stress direction in this region indicates a relatively high stress anisotropy. In contrast, the low seismic activity should indicate low stress anisotropy. This behaviour is difficult to explain, and as yet is not fully understood.

The observed regional stress direction on the Norwegian margin is consistent with the direction of ridge push, and the high tectonic stresses observed are also attributable to this source. Because of the local thinning of the continental crust, the tectonic stresses may be amplified, and this may explain the reverse faulting and high seismic activity observed offshore, which in a broad sense is concentrated in areas of thinned crust. Sediment loading effects also induce
offshore compressional deviatoric stresses underneath the basins. The observed stress anisotropy seems to be lower on the Norwegian margin than in the Barents Sea, presumably because of the continental margin effect counteracting the ridge push effect. As three effects (sediment loading, topography and deglaciation) produce more or less the same stress pattern in this area it is difficult to evaluate their relative importance.

The regional stress direction in western Norway and the northern North Sea correlates well with the direction of ridge push. Local thinning of the crust is also assumed to be an important factor in amplifying tectonic stresses in the continental crust underneath the graben. This explains the large amount of earthquakes (many with reverse focal mechanisms) observed in this region. Sediment loading fits partly with the observed stresses, and may also possibly be an important factor in the areas of extreme sedimentation rates in recent time. The observed local stress reorientation in the northern North Sea may indicate that stress anisotropy is lower in this region compared with other areas, or that local features are prominent and deflect the regional stress field. Onshore, the shallow normal faulting activity is attributed to regional and local topography, but regional deglaciation effects may also be important. Possible important local stress modifiers are faults, as well as local topographical features such as fjords and valleys.

The major stress direction in southwestern Norway and the central North Sea coincides with the ‘European trend’ (Müller et al. 1992), indicating that ridge push is an important source here as well. None of the other stress-generating mechanisms examined in this paper seem to be of great importance in this region. The complex stress pattern observed from borehole breakouts in the Central Graben area is primarily believed to be a result of low-quality data, but may also tentatively be caused by low horizontal stress anisotropy and significant local influence by geological structures such as faults and salt diapirism.

The NW–SE stress direction observed in southeastern Norway may be attributed to the ridge push effect, but as crustal thickness increases eastward the region will probably be subjected to somewhat lower tectonic stresses. Of the other effects analysed in this paper only the deglaciation effect was found to be able to influence the stress field in this region. Very tentative indicators (reversal of stress regime with depth indicated by focal mechanisms and N–S to NE–SW stress directions from overcoring) favour the deglaciation model Stein et al. It should be noted that also in this region the zones of enhanced seismic activity coincide with areas of thinned crust (the Oslo Graben) and that near-surface overcoring measurements often yield directions parallel to the major faults in this region.

Conclusions

All stress-generating mechanisms examined in this paper are summarized in Table 4 together with a brief description of their importance for the Norwegian area. The internal ranking has been based on lateral extension or regional influence, as most mechanisms are capable of generating high deviatoric stresses. Some of the mechanisms, known as non-renewable, relieve with time, and the magnitudes reported may exaggerate their importance, as they are maximum values computed for a perfectly elastic crust. Other, more local mechanisms, which are not formally stress generators, but more precisely described as modifiers, are also included in Table 4.

The only continental stress-generating mechanism that can be responsible for the high compressional stresses observed throughout the Norwegian region is the ridge push effect. Modelling indicates that horizontal deviatoric stresses from ridge push in the oceanic crust are of the order of 20–30 MPa. In the continental crust the changes in tectonic stresses depend on crustal thickness and ability of the crust to accommodate differential stresses. Regions with thinned crust, such as the Norwegian margin, the North Sea Graben system and the Oslo Graben, will have higher tectonic stresses. This is also clearly demonstrated by the enhanced seismic activity in these regions.

The other stress-generating mechanisms analysed here are found to be of variable regional importance. They modify the tectonic stresses generated by the ridge push and are responsible for locally observed stress reorientation, horizontal stress anisotropy and variations in seismicity.

Close to the western margin of the Barents Sea both the continental margin and recent high sedimentation rates act constructively with the ridge push and play an important role in rotating and strengthening the tectonic stress field. In the Norwegian Sea the continental margin acts against the ridge push, causing a lower stress anisotropy in this region.

Along the coast of southern Norway local and regional topography plays an important role in modifying stress magnitudes and explaining the shallow normal focal mechanisms observed.
The deglaciation of Fennoscandia has been regarded as an important stress-generating mechanism. The modelling did not indicate this as a source of high stress anisotropy, but all along the coastal areas and in southeastern Norway the observed stress directions and tectonics are in reasonable accord with predictions from deglaciation.

Stress modelling based on an elastic plate behaviour is a coarse simplification of the crust’s brittle ductile behaviour. Nevertheless, the models can be applied qualitatively. For more accurate determination of stress magnitudes viscoelastic modelling is required, where the yield strength is accounted for (Cloetingh & Burov 1996). Further research should therefore be based on more realistic models. A quantitative evaluation of the contribution from different stress-generating mechanisms can then be conducted under otherwise identical mechanical and boundary conditions. This will shed more light on the mutual contribution from topography, sediment loading and deglaciation, taking both loading history (duration and time since maximum loading) and lateral influence into consideration.

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