Tectonic analysis of the Meløy earthquake area based on Landsat lineament mapping

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The on-going Meløy earthquake swarm is an intraplate phenomenon which is briefly viewed, using fracture mapping based on satellite imagery (Landsat), other geological data, and stress measurements from neighboring Nordland areas. The bulk of the data is consistent with a model in which the earthquake activity is associated with the development of shallow NNE-SSW trending oblique-slip faults.

The Meløy earthquake sequence which peaked in November–December 1978 with several hundred earthquakes a day (Bungum & Husebye 1979), also triggered a number of questions ranging from seismic hazard evaluations to the ultimate origin and significance of this unusual seismotectonic event. Of particular interest is the relationship of the seismicity with geotectonic and structural information. Lineament (or fracture) analysis based on Landsat images is considered relevant information, and preliminary results are briefly reported and discussed here.

Tectonic setting

The Meløy area is part of the Caledonian fold belt of north Norway and is situated close to the Precambrian ‘tectonic windows’ of the Glomfjord district, an area generally characterized by a predominant E–W trending structural grain. The region is underlain by a rather thick (ca. 35 km) continental crust and is far removed from present plate boundaries. Thus the seismic event appears to represent a typical intraplate phenomenon.

Except from the relative steep regional gravity gradients (ca. 1.2 mgal/km), indicating rapid westward thinning of the crust, no major geophysical anomalies (gravity, magnetics, heat flow) have been recorded. However, the earthquake area is situated near the ‘Norwegian Shelf seismicity zone’ (Husebye et al. 1978), in an area with a relative concentration of instrumentally recorded large earthquakes (magnitudes >4.0-4.5) as seen in Fig. 1.

Meløy earthquake swarm

The first seismic activity in the area was felt around 20 October 1978, and systematic instrumental seismic recordings have been carried out in the local area since 18 November 1978 with three to five seismographs (Bungum & Husebye 1979). Up to 820 events per day have been recorded (2 December 1978), and the epicenters are located in an area of 8 km (E–W) by 10 km (N–S) with a concentration around 66.8°N, 13.6°E (Fig. 2). Computed depths vary between 3 and 9 km, and the most severe event had a local magnitude (ML) of 3.2 and a maximum MM intensity of 6. The data indicate that the activity tends to migrate periodically in a N–S direction, and a focal mechanism solution indicates normal faulting with a fault plane striking N25°E and dipping 60°E (Bungum & Husebye 1979).

Lineament analysis

Earthquakes with shallow foci probably occur as the result of faulting. In principle, the Landsat satellite system (see e.g. Sabins 1978) provides information that can be used in the study of fractures and fracture systems, and active fault systems may be mappabl(e.g. Campbell 1976). A preliminary lineament study has been com-
completed in southern Norway (Ramberg et al. 1977) and a similar study of northern Norway is close to completion.

In the Meløy area, lineaments (as defined by O'Leary et al. 1976) have been mapped from the enlarged Landsat imagery (50 × 50 cm), frame 2168–10012, band 7. Care has been taken to avoid confusion between lineaments and foliation, which may be a major source of bias. Thus, foliation mapped from Landsat imagery has been checked against existing geological data (Rutland & Nicholson 1965, Gustavson 1978) and is assigned a special symbol in Fig. 2.

The map (Fig. 2) reveals several lineament systems, some of which are of regional significance. The most prominent system has an ENE–WSW trending direction parallel to the main fjords (N80°–85°E) and is cross-cutting the area between Svartisen and Meløy. The zone, here termed the 'Glomfjord intensity zone' clearly contrasts the areas to the north and south. The area of seismic activity is further intersected by less well pronounced, shorter lineaments with a NNE–SSW (N20°E to N35°E) direction, although other directions also may be recognized (Fig. 2). Both the ENE–WSW and the NNE–SSW trending lineaments are rectilinear and are seen to cut foliation on a regional scale. Furthermore, they show no detectable azimuthal deviation when passing from altitude down to sea level, thus indicating a near-vertical or steep attitude of the possible fracture planes.

The clear contrast in pattern between lineaments and foliation supports the interpretation of the lineaments as zones of weakness. Comparison with known lithologies, nappes, main structural elements (folds) and foliation of the area (e.g. Rutland & Nicholson 1965, Holmes 1966, Wells & Bradshaw 1970, Gustavson 1978) stresses their cross-cutting nature.
Discussion

According to the lineament analysis, active fault planes should be sought along one of the two directions WNW–ESE (N80–85°E) and NNE–SSW (N20–35°E). This suggestion is based on the assumption that the fault planes have been active for a time span sufficient for visible lineaments to be developed on the surface, or that the neotectonic activity follows pre-existing planes of weakness. Alternatively, the present activity may be connected to a developing fault system which does not transect the surface, or cannot yet be traced by lineament analysis.

Under the assumption that the fault planes can be traced, the WNW–ESE system seems the most plausible judged from its intensity in the actual area. However, the epicenter distribution, the suggested composite focal mechanism (Bungum & Husebye 1979) and the fracture systems represent supplementary pieces of evidence which favor relative movements along the NNE–SSW fracture directions. Thus, the earthquake sequence might be explained by repetitive energy release along a major fault plane, or fault zone, striking N20°–35°E and dipping 60°E. This zone may indeed consist of several individual, en echelon arranged, steeply dipping fault planes.

Additional information may be gained from field observations and in situ stress measurements. No detailed 'post-earthquake' ground observation has yet been carried out in the Meløy area. However, there is some evidence of neotectonic activity in the neighboring districts. The best documented example is perhaps some of the NNE-trending faults in the Lofoten area, continuing the axial trend of the deep, block-faulted Vestfjord Basin (Rønnevik & Navrestad 1977). Gustavson (1972) suggests a post-Caledonian, right-lateral strike-slip movement of the order of 10 km along the Tjeldsund fault. Grønnlie (1922) has shown that dip-slip motion occurred along the Tjeldsund fault also in postglacial times. From Sweden, the impressive 150 km long, westward facing Pärve fault represents another postglacial tectonic feature (Lundquist & Lagerbäck 1976). Thus, observed late-tectonic (postglacial) faults of the larger area are generally coast-parallel and also parallel to the suggested NNE-trending Meløy fault zone.

In situ stress measurements from Nordland are few and located in the mining areas (amongst other, Sulitjelma, Rana and Bleikvassli) and no single measurement is closer to Meløy than about 50 km (Myrvang 1976 and pers. comm. 1979). The tri-axial measurements invariably show large horizontal stresses, with the largest compressive stress axis (σ3) commonly oriented NNW–SSE, or less commonly NE–SW.

The directions of principal stress in the Meløy area may also be estimated from the fault plane solution by assuming that these directions bisect

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**Fig. 2.** Lineament map of the Meløy area. Full lines: lineaments mapped from Landsat imageries. Stippled lines: foliation from geological maps and Landsat imageries. Ellipse marks approximate area of seismic activity. Lower right: Rose diagram based on lineament map from regional studies of the area. Right half shows vector units (v) in percent, left half percent of total number of lineaments (N). Circle indicates 20% cumulative length of frequency of lineaments.
the angle between the nodal planes and are located in a plane perpendicular to the two nodal planes (Fig. 3). The inferred axis of 'maximum tension' (or minimum compressive stress) is shown on Fig. 3, trending NW–SE. Thus, if the Meløy area has a NE–SW trending axis of maximum horizontal stress (σt), as is the case in some areas in Nordland, then the stress configuration will fit the rest of the data. In that case, the NNE-striking fault zone is characterized by a large component of normal fault motion and a minor component of right-lateral strike-slip motion (as read from Fig. 3).

The ultimate source of the lithospheric stress released in the Meløy earthquake swarm is highly uncertain, but may principally be due to one of several stress-generating mechanisms:

- Glacial uplift of Fennoscandia (or loading or unloading in general),
- Global tectonics, via present plate motions, or
- Accumulated remnant stresses due to tectonic events throughout geological times.

The dominant cause for Fennoscandian earthquake sequences has traditionally been ascribed to glacial rebound (Båth 1954) or to a continuation of the Tertiary uplift (Kvåle 1960). An active tectonic component has been advocated by Mörner (1975), and Båth (1978) points out that a marked break in the energy-time release curves for Fennoscandian earthquakes, and their similarity with world-wide curves, suggesting a relation-


