

Tectonic lineaments of Norway

Roy H. Gabrielsen, Alvar Braathen, John Dehls & David Roberts

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Tectonic lineaments of the Norwegian mainland have been outlined and characterised in a new lineament map of Norway. The underlay is a national coverage of Landsat TM 7 scenes with 15 m pixel resolution, which have been interpreted at a scale of 1:750,000. The database contains nearly 8000 lineaments that, with the aid of statistical tools (orientation, density) and general characteristics, have been separated into distinct spatial zones, populations and sets.

The most prominent lineament zones of Norway are the N-S-striking Oslo-Trondheim and Bergen zones. The former is considered to represent a Neoproterozoic fracture system, since it clearly affects the geographical extent of younger lineament populations. Both zones were active in the Permian, whereas the Bergen Zone also underwent Mesozoic rejuvenation. Today, both zones experience relatively frequent, though minor earthquakes. Another important N-S feature, albeit more dispersed, is the Finnmark Zone.

The regional, ENE-WSW-striking Møre-Trøndelag Fault Complex is clearly displayed in the scenes. It consists of mainly ENE-WSW (NE-SW) major and minor faults with a documented history ranging from Devonian to Recent, mirroring activity on the shelf. The Agder Zone has a similar orientation, consisting of two sets (NE-SW and ENE-WSW), and can be traced from Stavanger to the western margin of the Oslo Graben. Faults with km-scale displacement and various types of fault rocks reflect the post-Caledonian activity of this lineament population.

Other lineament populations are more dispersed. This is especially the case for the NW-SE to WNW-ESE-oriented lineaments, which occur throughout the entire country. Approximately E-W-oriented structures are found in southern, western and central Norway. In the Sunnfjord area, they constitute major faults with documented Permian, Jurassic-Cretaceous and possible Cenozoic activity.

Information relating to the lineaments is compiled in a database, which is regularly updated subsequent to field checking and detailed mapping of lineaments. The present consensus is that almost all of the lineaments identified or interpreted by remote sensing methods are faults, many of which have been affected by multiple faulting events. More surprisingly, many faults also contain soft (non-cohesive) fault rocks, distinctive for upper crustal deformation, suggesting Mesozoic-Cenozoic activity, and some may even carry components of post-glacial displacement.

Roy H. Gabrielsen, Geological Institute, University of Bergen, Allégaten 41, N-5007 Bergen, Norway. E-mail: roy.gabrielsen@geol.uib.no
Alvar Braathen, John Dehls & David Roberts, Geological Survey of Norway, N-7491 Trondheim, Norway.

Introduction

Acknowledgement of the importance of regional fracture systems in topographical analysis has a long tradition in Norway (Kjærulf 1876, 1879; Hobbs 1904, 1911, Høltedahl 1967; Nilsen 1973). Perhaps because of this, the potential for application of lineament studies in correlation of onshore and offshore structural features motivated several regional studies in the 1970s and 1980s using modern remote sensing techniques (Ramberg et al. 1977; Gabrielsen & Ramberg 1979; Gabrielsen et al. 1980; Rathore & Hospers 1986). Such studies identified several lineament zones of seemingly regional significance (Fig. 1). More dedicated investigations aiming at more specific targets either regionally (Rindstad & Grønlie 1987; Rueslåtten et al. 1996) or with emphasis on particular structures or fault complexes (Grønlie & Roberts 1989; Grønlie et al. 1991; Karpuz et al. 1993a, 1995; Roberts et al. 1997) followed.

Appreciation of the influence of the basement structural grain on the structuring of the Norwegian continental margin (Gabrielsen & Ramberg 1979; Frost et al. 1981; Rathore & Hospers 1986; Doré & Gage 1987;

Gabrielsen & Færseth 1989; Doré 1991; Færseth et al. 1995; Gabrielsen et al. 1999) and the observation that some master fault systems have a great potential for reactivation (Gabrielsen 1984; Gabrielsen et al. 1999; Smethurst 2000; Pascal & Gabrielsen 2001) have further motivated such studies. Simultaneously, the need for a better understanding of the fracture systems on the mainland in connection with assessment of water resources and the pollution and risk arising from planned engineering constructions (e.g., tunnels, earthquakes) has received increasing attention (Fossen et al. 1997; Nordgulen & Rønning 2000; Gudmestad & Lindholm 2001). In the light of this, it is clear that the existing regional lineament databases for Norway, which are based on the maps published by Ramberg et al. (1977) and Gabrielsen & Ramberg (1979), are outdated, and hence the Geological Survey of Norway together with the University of Bergen have taken an initiative for the generation of a new lineament database. This database will be a part of the public domain of the Geological Survey of Norway (www.ngu.no), and will, when complete, contain geological information on individual lineaments and faults in addition to lineament maps.

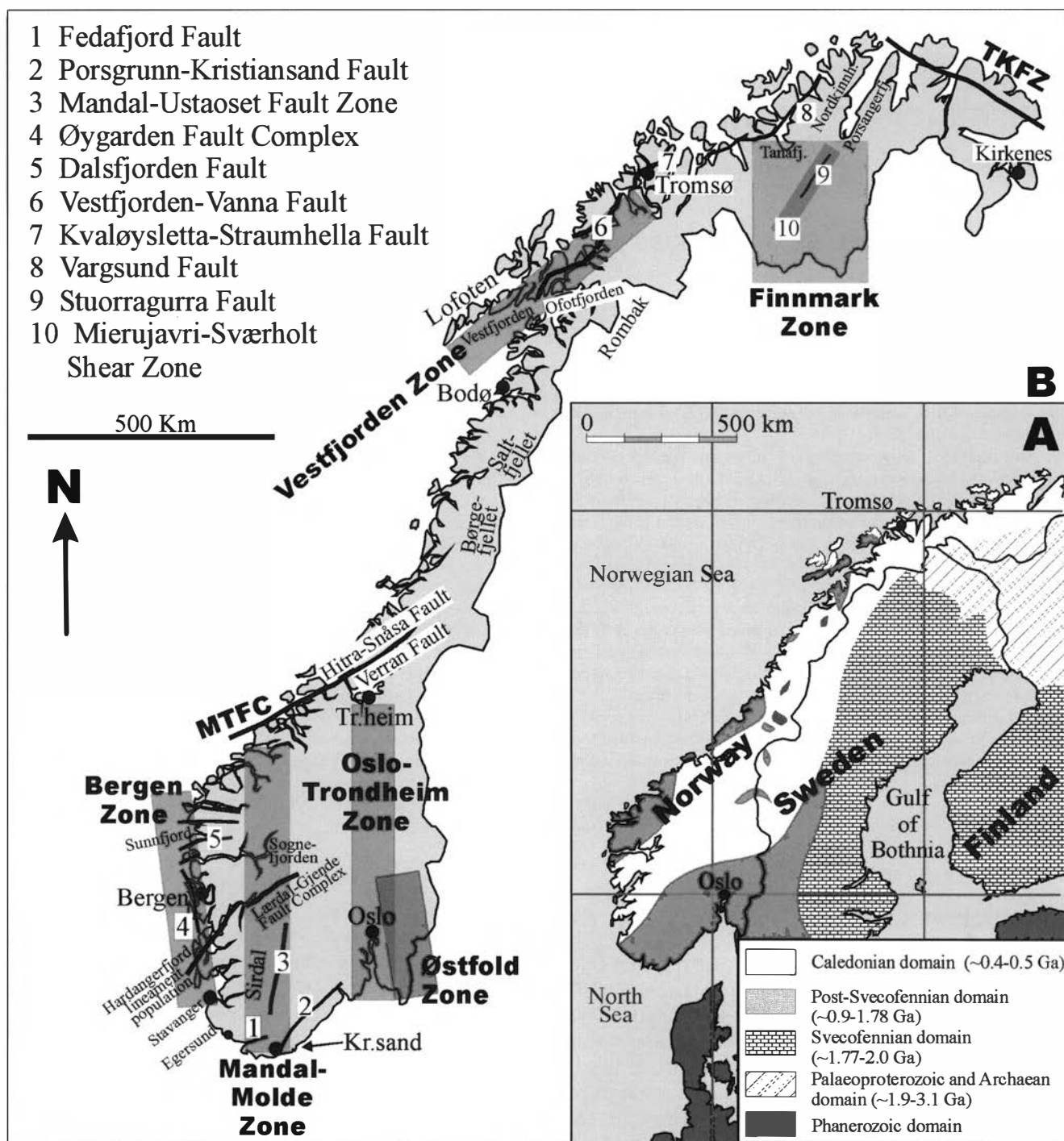


Fig. 1. Key map showing lineament zones, major faults and geographical locations referred to in the text. The Oslo-Trondheim, Bergen and Finnmark zones are similar to those proposed by Gabrielsen & Ramberg (1979). MTFC – Møre-Trøndelag Fault Complex; TKFZ – Trollfjorden-Komagelva Fault Zone.

The Landsat database

The present lineament mapping was performed in two steps. The first stage included the analysis of a mosaic of Landsat MSS data. Due to financial restrictions, this mosaic was of variable quality, and it was not possible to obtain a homogeneous lineament map of sufficiently high quality covering the entire Norwegian mainland. However, the quality was good enough to improve the

existing datasets and, most important, to generate a classification scheme for lineaments which was more complete than that proposed by Gabrielsen & Ramberg (1979). This scheme included orientation, style, cross-cutting relationships and geological information (age, types of fault rocks, etc.). The second stage included the generation of a complete mosaic from Landsat TM 7 data covering the Norwegian mainland, and a re-mapping of the entire study area. The results were compa-

red to that of the MSS dataset, and the interpretation was reassessed in areas where the two interpretations were dissimilar.

In this work, particular emphasis was placed on not including foliation in the final lineament database. This was done with the appreciation that foliations represent profoundly different structural information, and therefore should be mapped and analysed separately. Hence, the lineaments included in the present maps are selected according to the definition of O'Leary et al. (1976): "A *lineament* is a linear or sub-linear feature on the Earth's surface, which presumably represents a zone of weakness in the sub-surface". This means that low-angle and thereby topographically curved structures, such as thrust faults and some extensional faults, and strongly curved features like (possible) impacts and volcanogenic features (e.g., calderas), as well as mega-lineations generated by ice movements, have been excluded from the present dataset.

Some definitions

Following Gabrielsen et al. (1984) and Nystuen (1989), fractures or lineaments may constitute *sets*, *systems*, *complexes* and *zones*. Lineaments commonly appear in groups characterised, e.g., by common orientation or style. In the following, we term such groups '*lineament populations*'. Furthermore, we use the term '*lineament set*' for a population that consists of subparallel elements of similar style, and which is assumed to belong to one and the same deformational event. A '*lineament system*' consists of two or more sets, both or all of which are affiliated with one and the same event, and possess the same deformational style. In contrast, a '*lineament complex*' consists of two or more sets of different styles which are either related to different deformational episodes, or comprise cases where these relationships are unknown. Finally, a '*lineament zone*' is characterised by its higher lineament density as compared to that of its neighbouring areas.

In the literature, it is not uncommon for authors to use the terms lineament, fracture zone and fault as synonyms. However, in the present study we advise and encourage use of the following definitions: The term *lineament* should be strictly reserved for linear or curvilinear features identified by remote sensing methods (*sensu* O'Leary et al. 1976), and *fracture lineament* for those lineaments that are *assumed* to reflect a zone of stress-induced mechanical weakness in the bedrock (e.g., Braathen & Gabrielsen 1998, 2000). During field investigations, lineaments are commonly identified as zones of enhanced fracture frequency (ff) as compared to the surrounding areas. If identified as such by field study, the term *fracture swarm* should be applied. We

suggest that the term 'fracture zone' should not be applied in this context, to avoid confusion with the applied nomenclature of plate tectonics, where this term is reserved for structures defining the extension of a transform fault (e.g., Heezen et al. 1964). Quite commonly, detailed investigation is necessary to determine whether or not movements have taken place parallel to the fracture swarm. When such displacements are either proven or disproven, the term fracture lineament should then be abandoned, and the nature of the structure should be indicated by using precise structural terms such as extensional, contractional, strike-slip or oblique-slip *fault/fault zone or joint zone*. Joint zones differ from fault zones in that they do not show any signs of fault-parallel displacement; hence, they consist dominantly of tensile fractures. It is thereby clear that most (but not all) faults are fracture swarms, but also that not all fracture swarms are faults.

Based on the identification of such features by the use of remote sensing methods, fracture swarms may be subdivided into steep (near vertical) and inclined. In steeply dipping structures, the pattern of zonation is commonly symmetrical (Braathen & Gabrielsen 1998). Basement faults studied by us reveal the typical architecture of larger faults, with a high-strain fault core and a low-strain damage zone (e.g., Caine et al. 1996). This deformation is generally superimposed on a *background fracture system* (Gabrielsen et al. 1997; Knipe et al. 1998). Inclined faults commonly appear to have an asymmetric fracture distribution when footwall and hangingwall are compared. In most inclined fracture zones studied by us, the bulk of the strain seems to have been taken up in a wider zone in the hangingwall and in a narrower zone in the footwall. This is in accordance with observations from many larger faults in sedimentary rocks (e.g., Gabrielsen et al. 1997), although the opposite relationship is sometimes found (Steen & Andresen 1999).

The lineament maps

The new lineament map of Norway contains approximately 7800 lineaments, which have been identified from Landsat TM 7 data (15 m pixel size) at 1:750,000 scale (Fig. 2). A mosaic of all Landsat scenes was created and displayed within a GIS environment. During interpretation, each lineament was checked against the Landsat background data. Lineament density maps were made by counting the total length of lineaments within a moving 10 km search window. Separate density maps were made for each lineament population, several groups of populations, and each 10° azimuth sector (Fig. 3).

Directional analysis was done using the intercept method (Launeau & Robin 1996). The technique is based

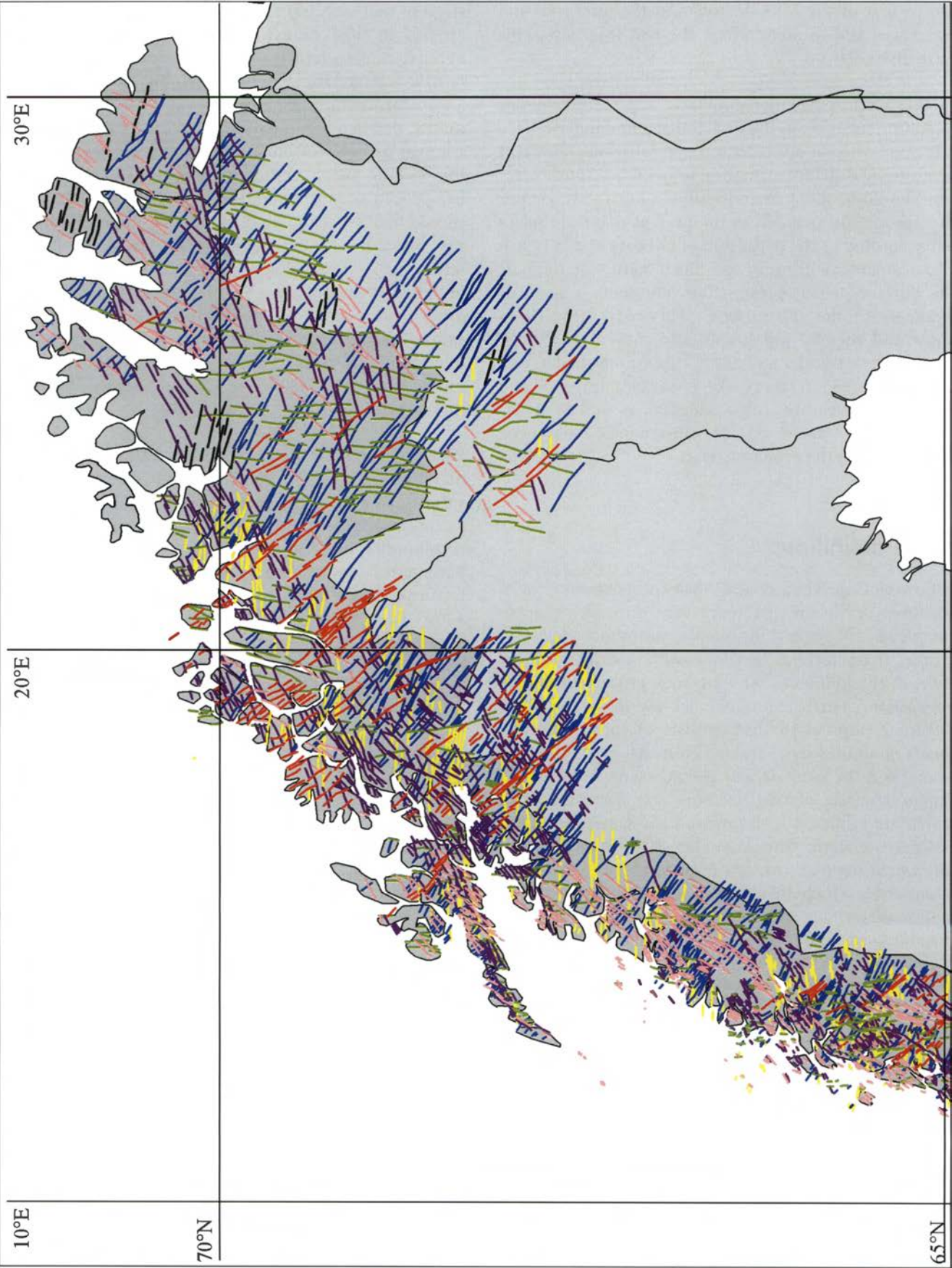
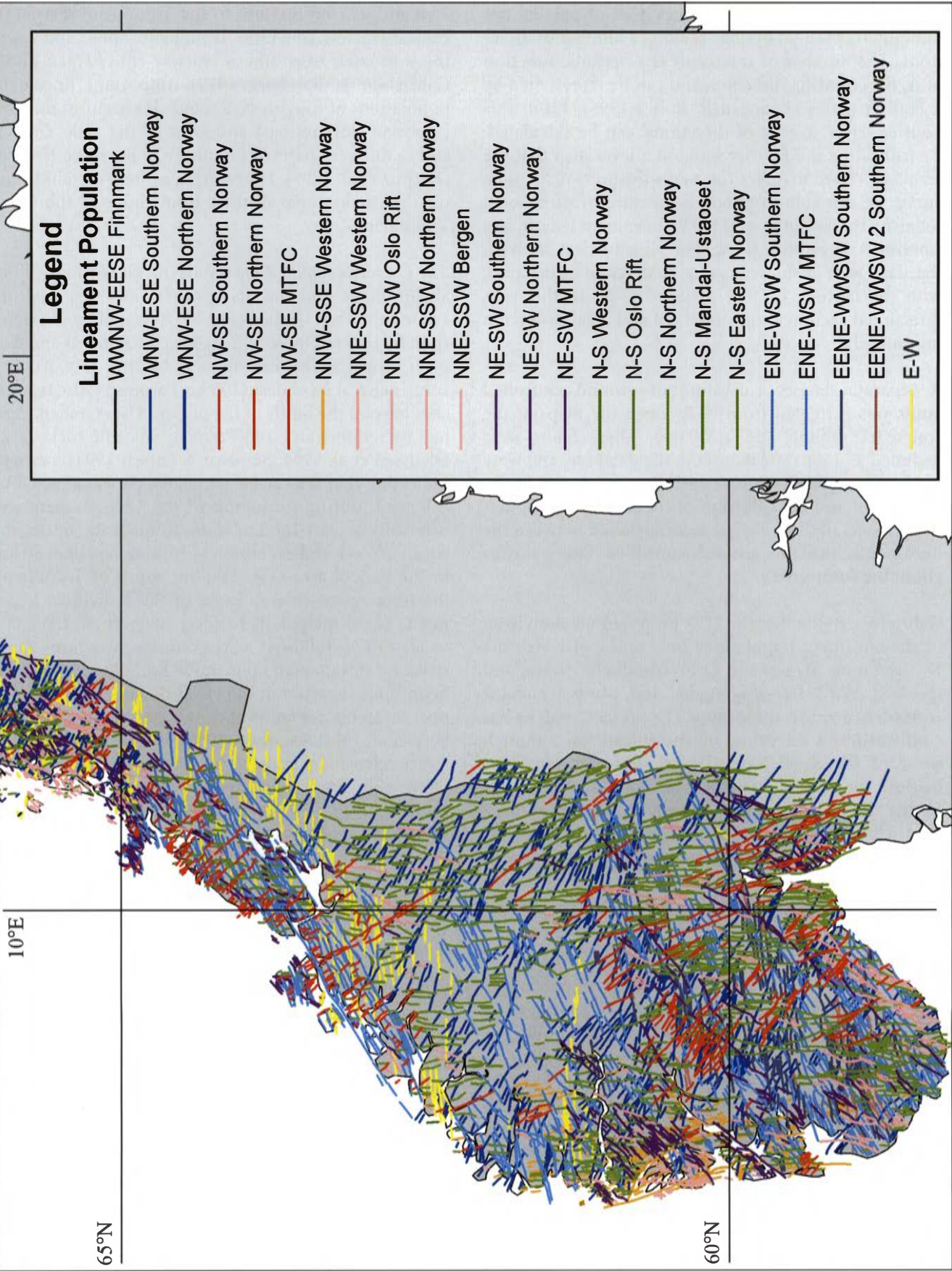


Fig. 2. Lineament map of Norway based on interpretation of a Landsat TM mosaic at a scale of 1:750,000, created and displayed within a GIS environment, with colour key for identification of populations. The database contains approximately 7800 lineaments. See text for description of lineament populations.



on counting the number of times a set of parallel test lines intercepts a set of objects along a number of directions. The number of intercepts is a periodic function of α , the counting direction, and can be represented by a Fourier series (Launeau & Robin 1996). From this Fourier series, a 'rose of directions' can be calculated. By truncating the Fourier series at a level such that the resulting curve matches the main features of the data curve, we are able to obtain a measure of directional intensity that is both weighted by lineament length, and smoothed to remove noise. For all statistical analysis, the data were displayed using a Mercator projection, with the latitude of true scale at 65°N. In this way, directional accuracy was preserved and areal distortion minimized.

A separate dataset consisting of ground-controlled faults was extracted from NGU open-file maps at the scales 1:1 million and 1:250,000. These faults were included as a separate dataset in the database, and were used in the qualification of each lineament, and in the assessment and classification of the lineament populations. Generally, there is a good correlation between the lineaments and the ground-controlled faults throughout the study area.

Gabrielsen & Ramberg (1979) proposed a subdivision of the lineament populations into zones, of which the N-S-trending Bergen and Oslo-Trondheim zones, and the ENE-WSW-trending Agder and Møre-Trøndelag zones are the most important. The present analysis has confirmed the relevance of these features, although some of the zonal borders were adjusted. However, because the present analysis applied additional criteria for the classification, and due to the availability of more advanced data-processing techniques, a more sophisticated assessment of lineament populations has been possible.

N-S lineament populations

N-S-trending lineaments define one of the most important lineament populations on the Norwegian mainland as well as on the continental shelf (Fig. 1; e.g., Gabrielsen & Ramberg 1979; Rathore & Hospers 1986; Ziegler 1990; Doré 1991; Gabrielsen et al. 1999). By closer inspection, several zones and sets can be identified, some of which have slightly contrasting trends, and others that are associated with certain styles of deformation or with particular geological units. In several cases, clear cross-cutting relations can be seen between these lineament sets.

Well-defined populations of approximately N-S-trending (i.e. N340°W to N020°E; Figs. 3 and 4a) lineaments are of particular significance in the Oslo Graben

area and its continuation to the Trondheim district of central Norway (the Oslo-Trondheim Zone) and along the west coast of southern Norway (the Bergen Zone; Gabrielsen & Ramberg 1979). Important lineament populations of roughly N-S trend also occur in the Precambrian terranes east and west of the Oslo Graben and in different parts of Finnmark in northern Norway (Karpuz et al. 1995). However, these bear certain features that make them distinct from those of the Oslo-Trondheim Zone.

The Oslo-Trondheim Zone stands out clearly in the lineament maps and has its greatest lineament density around the Oslo Graben (Fig. 5a). It is mainly characterised by N-S to NNW-SSE-striking lineaments and displays a clear strike maximum at N178°E (Fig. 6). The zone is also at its widest (100 km) around Oslo. It stretches beyond the limits of the present Oslo Graben, defined by sedimentary and Permian volcanic rocks (e.g., Olaussen et al. 1994; Sundvor & Larsen 1994), perhaps indicating that the crustal panel, which was affected by extension during formation of the Oslo Graben, was originally at least 180 km wide. Towards the north, the zone narrows, and eventually shrinks to less than 80 km in the Folldal area (Fig. 5a), but south of Trondheim the zone again widens. Some of the individual lineaments (as displayed in Landsat imagery at 1:500,000 scale) can be followed as continuous structures along strike for distances of up to 30–40 km. The Oslo-Trondheim Zone incorporates the well-documented, extensional, steep master faults of the Oslo Graben (e.g., Ramberg et al. 1977; Swensson 1990) as well as some of the larger extensional faults to the north, like the Rendalen, Osen and Engerdalen faults ('Østerdal Aulacogen'; Roberts & Gale 1977). It has been suggested that the master faults of this population are autochthonous and that they were active as extensional faults during deposition of the Neoproterozoic 'sparagmite series' (Schjøtz 1902; Bjørlykke et al. 1976; Bjørlykke 1978). However, Nystuen (1981), following Oftedahl (1949), argued that the 'sparagmites' are allochthonous. He also emphasised that the NNW-SSE-trending faults cut the 'sub-Cambrian peneplain' as well as all Caledonian structures. Skjeseth (1963) suggested that the Rendal fault was active as a sinistral transfer fault with a horizontal displacement of 15–20 km during the Caledonian nappe emplacement. The total post-Caledonian vertical throw on these structures is estimated to between 1000 and 2000 m (Holmsen & Holmsen 1950).

It is beyond doubt that faults incorporated in the Oslo-Trondheim Zone were either activated in the Permian, or were reactivated at that time (e.g., Brøgger 1886; Sundvor & Larsen 1994). It has also been suggested that narrow N-S-trending, fault-bounded troughs had some control on the deposition in the Oslo area in Cambro-Silurian times (Henningsmoen 1952; Størmer 1967). These structures are paralleled by regional tectono-

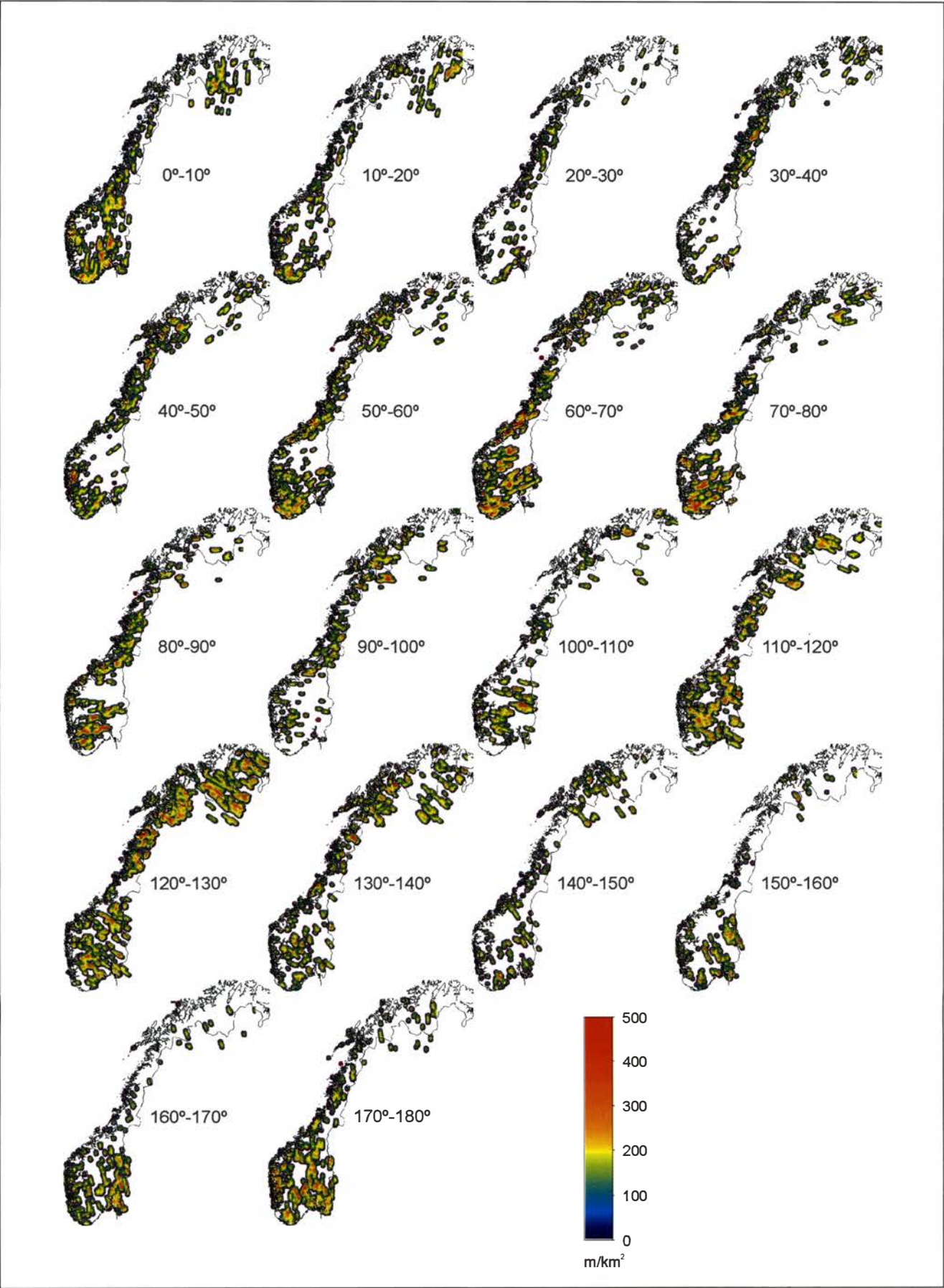


Fig. 3. Lineament density maps made by counting the total lengths of lineaments within a moving 10 km search window; green represents low values, yellow intermediate values, whereas red indicates high bulk length values. Separate density maps are displayed for each 10°-azimuth sector.

magmatic systems of intrusions at the western margin of the Oslo region (Ramberg 1976), demonstrating the deep-seated origin of this graben-marginal fault.

A conspicuous swarm of intermediate to basic dykes, among which the longest is the 150 km-long Mjøndalen-Etnedalen Dyke (Sundvor & Larsen 1994) is also included in this structure set. The traces of the NNW-SSE fault system can be followed offshore in the outer part of the Oslofjord as bathymetric lineaments (Solheim & Grønlie 1983), and farther into the Skagerrak Graben (Ramberg & Smithson 1975) where movements of Jurassic age have been documented (Ro et al. 1990). The fault system is still active, and a major seismic event ($M = 5.6$) occurred within the zone as recently as in 1904 (e.g., Bungum & Fyen 1980).

The Bergen Zone, which is dominated by a population of NNW-SSE-trending lineaments, parallels the coast of southwestern Norway (Figs. 5b and 6). It incorporates a system of faults with approximate N-S trends (Braathen 1999), as well as parallel dyke swarms with Permo-Triassic ages of intrusion (Fossen & Dunlap 1998), possibly including a Jurassic event (Færseth et al. 1976; Færseth 1978; Løvlie & Mitchell 1982; Torsvik et al. 1997). Master faults that occur offshore immediately west of the coast (the Øygarden Fault Complex; Hamar et al. 1980; Smethurst 2000) reflect the presence of a deep, basement-involved zone of weakness (Badley et al. 1984; Gabrielsen 1986, 1989; Færseth et al. 1995). Some branches of the upper part of the Øygarden Fault Complex offset Tertiary sequences (Muir-Wood et al. 1988), and the zone seems to have been the locus of some Recent seismic activity (Gabrielsen 1989; Karpuz et al. 1991).

The Østfold Zone defines the eastern border of the Oslo-Trondheim Zone (Figs. 1b and 5d). Two populations (N-S and NNW-SSE) are defined (Fig. 6), of which the NNW-SSE lineaments in particular follow the pronounced structural grain of southwestern Sweden, incorporating Sveconorwegian ductile shear zones (e.g., Stephens et al. 1996; Andersson et al. 2002). Brittle deformation fabrics locally overprint these features.

Some of the large-scale N-S to NNW-SSE-trending ductile fault zones that affect rocks in South Sweden, can be traced into Norway (Skjernaa 1972). The most conspicuous of those are 'the Mylonite Zone' and Dalsland Boundary Fault and their related structures. These are interpreted as shear zones defining Sveconorwegian terrane boundaries (e.g., Andersson et al. 2002). Lineament analysis in the Stora Le – Vänern area on the Swedish side of the border displays a complex of regional NNW-SSE and N-S lineaments ($N150 - 165^\circ E$; Lindh 1980; Tirén & Beckholmen 1992). Some of the most prominent of those coincide with the large shear zones,

which are loosely dated to Sveconorwegian (Page et al. 1996; Stephens et al. 1996).

The Mandal-Molde Zone affects the larger part of western South Norway (Fig. 1). The lineaments, which have a dominant NNE-SSW strike, are generally evenly distributed throughout the area, but the zone becomes diffuse towards the north, where it reaches a minimum width around Jotunheimen (Figs. 5c and 6). The zone again becomes more clearly expressed in the coastal area around Molde. The Mandal-Molde Zone encompasses major topographic lineaments defining valleys and drainage systems carved in intensely fractured bedrock (e.g., Sirdalen), as well as large-scale composite structures like the Mandal-Ustaoset Fault Zone (Sigmond 1985). The latter is a complex feature characterised by wide, steep to moderately dipping, ductile shear zones and steep to moderately inclined, east-dipping faults exposing brittle deformation structures. Near Molde, a N-S-striking neotectonic fault with 2-4 m reverse displacement, the Berill Fault (Anda et al. 2002), is a unique example of Quaternary movements along this lineament zone. On a broad scale, a particularly significant feature is that the lineaments of the Mandal-Molde Zone seem to be truncated by the Oslo-Trondheim Zone.

The Finnmark Zone (N-S-striking) is particularly well developed in central Finnmark, and can be followed southwards where it merges with the NNE-SSW-trending, 30 km-wide, Baltic-Bothnia megashear zone (Berthelsen & Marker 1986) of northern Sweden (Fig. 5e; see also Gabrielsen & Ramberg 1979, Henkel & Eriksson 1987; Henkel 1991). Bertelsen & Marker (1986) and Nironen (1997) also proposed the existence of other Proterozoic megashears along this N-S trend in northern Scandinavia. On closer inspection, it is clear that this zone is composed of two lineament sets striking slightly east of north ($N00^\circ - 20^\circ E$) and west of north ($N165^\circ - 180^\circ E$), respectively (Fig. 2). Karpuz et al. (1995) and Roberts et al. (1997) reported that multiple episodes of movement have occurred along the NNE-SSW-trending fault populations (e.g., the Battevarri and Karlebotn lineament zones), including both ductile and brittle features. Karpuz et al. (1993b, 1995) recorded similar deformational styles along minor structures striking NNW-SSE, notably the Hauksjøen and Kirkenes-Nikel lineament zones, where mylonites and ultramylonites are superceded by cataclasites and breccias.

The N-S trend also parallels some major offshore faults or fault complexes (e.g., Ringvassøy-Loppa Fault Complex; Gabrielsen 1984; Gabrielsen et al. 1990). The lineament zone seems to have a fairly constant width as far as it has been followed inland from the coast, to the south. However, the N-S trend is less prominent when the zone is followed offshore towards the north. We

take this as an indication that the zone is basically associated with a Precambrian basement structural grain that to a lesser extent has been reactivated in post-Palaeozoic times. Still, it is noted that movements along individual faults of the Ringvassøy-Loppa Fault Complex can be traced well into the Cretaceous (Gabrielsen 1984, Gabrielsen et al. 1990), and that even later reactivation may have occurred (Gabrielsen & Kløvjan 1997).

Apart from the Oslo-Trondheim, Bergen and Finnmark zones, N-S-trending lineaments in the study area are sparse, with the exception of some areas in Nordland and Troms. Little detailed field information exists as far as the deformational style and age of these lineaments are concerned. However, Braathen et al. (2002) and Osmundsen et al. (2003) described brittle reactivation of approximately N-S-striking Devonian(?) extensional shear zones along the western margin of the Børgfjellet and Saltfjellet basement windows. A similar pattern is indicated for the Rombak window (Fossen & Rykkelid 1992; Rykkelid & Andresen 1994), where an Early Carboniferous age of these movements has been proposed (Coates et al. 1999).

NNW-SSE and N-S trends are also associated with some of the major basins and fault complexes on the Norwegian continental shelf, such as the Viking Graben of the northern North Sea and the Klakk Fault Complex off Mid Norway. Several such structures were probably active during the Permian structuring, and were reactivated to become the most important structures during the Jurassic extension (see Gabrielsen et al. 1999, and references therein).

Based upon the descriptions given above, it can be concluded that the major N-S-trending lineament complexes of the Norwegian mainland have roots back into the Proterozoic. Later periods of activity following the thrust emplacement of Scandian nappes include steep and low-angle, Devonian faulting in West Norway (e.g., Andersen & Jamtveit 1988; Fossen 1992; Braathen 1999; Eide et al. 1999), and in Central Norway (Rindstad & Grønlie 1987; Séranne 1992; Ihlen 1995; Braathen et al. 2000, 2002; Osmundsen et al. 2003). Permian extension affected the Oslo-Trondheim Zone, the fault complexes of western Norway and the offshore area (Gabrielsen et al. 1990; Olaussen et al. 1994; Færseth et al. 1995, 1997). Recent studies have also revealed Jurassic-Cretaceous activity in the extensional fault systems of West Norway. Fault rocks with similar characteristics to those encountered in the extensional systems of western Norway (green cataclasite, red breccia and fault gouge; Torsvik et al. 1992; Eide et al. 1997) crosscut the Proterozoic rocks and Caledonian nappes of the Norwegian mainland (Grønlie & Roberts 1989; Grønlie et al. 1990, 1991; Braathen & Gabrielsen, unpublished data). Firm age relationships between these fault rocks, however, have in many cases yet to be established.

NE-SW and ENE-WSW lineament populations

Southern Norway is transected by a very complex pattern of lineament populations with trends varying from E-W to NE-SW (Ramberg et al. 1977; Gabrielsen & Ramberg 1979; Rathore & Hospers 1986) (Fig. 3). In contrast to the N-S-trending populations described above, these lineaments are more evenly distributed, and define sets and zones to a lesser degree. On a regional scale, it seems that E-W- to ENE-WSW-trending lineaments are less well developed in Finnmark and most common at the southernmost tip of southern Norway (Fig. 4d). Lineaments belonging to these populations are generally also common between Bergen and Sognefjord. Detailed inspection of the lineament maps indicates that five sets and several major fault zones can be distinguished among the E-W- to NE-SW-trending lineaments in southern Norway.

Lineament sets with a strict NE-SW orientation (azimuth sector N040°E to N060°E) do not seem to be very common at the northwestern margin of the Baltic Shield (Figs. 3 and 4d). Nevertheless, lineaments of this trend are associated with large-scale faults such as the Kristiansand-Porsgrunn fault (the 'Great Breccia' of Bugge 1928, 1965), which is closely associated with the exposed Permo-Carboniferous rocks occurring along the western margin of the Oslo Graben, and hence may have a continuation along this boundary. The fault zone is characterised by ductile to cohesive brittle fault rocks and several generations of non-cohesive breccia and gouge. This trend is sub-parallel to an older grain, which was reactivated in the 'early Sveconorwegian' event. These structures originated as shear zones in connection with top-to-northwest shortening (Starmer 1993, 1996).

The onshore part of the NE-SW-striking *Hardangerfjord Shear Zone* has been defined through deep seismic reflection soundings (Hurich & Kristoffersen 1988, Færseth et al. 1995, Hurich 1996) and recent field investigations (Fossen 1992), and have demonstrated that this structure roots deeply in the crust, and that it truncates both the Scandian (Caledonian) basal detachment and structures associated with extensional top-to-the-west ductile reactivation. The principal structure of the Hardangerfjord lineament population is the Lærdal-Gjende Fault Complex, which can be traced from the innermost region of the Hardangerfjord and far inland as a major, NW-dipping fault that juxtaposes footwall Proterozoic gneisses with hangingwall nappe rocks (e.g., Milnes et al. 1997). The fault zone exposes mylonites that are cut by cataclasites, both of which are incorporated as clasts in breccia and gouge zones. The palaeomagnetic signature of some of the brittle fault rocks indicates both Permian and Late Jurassic-Early

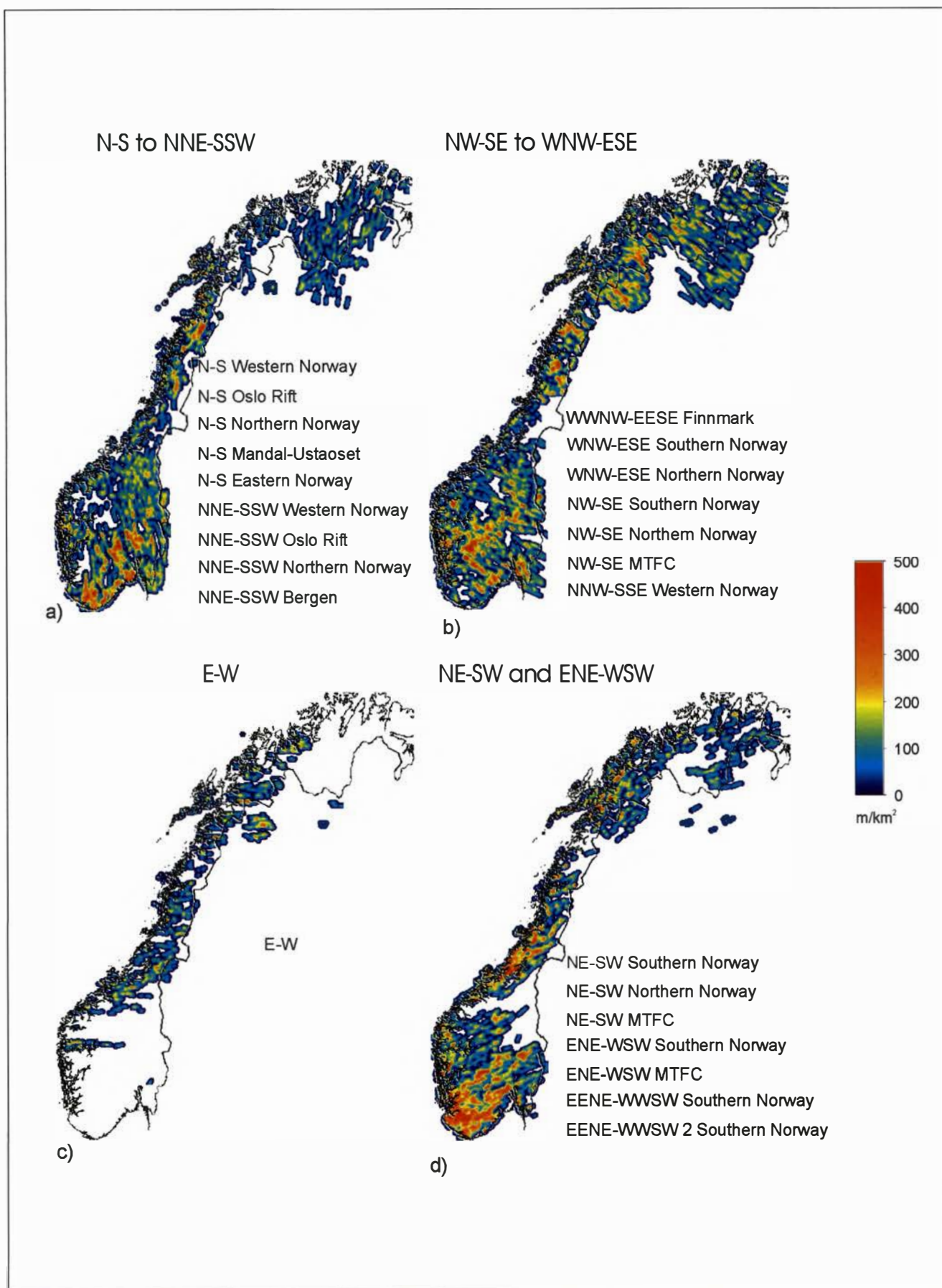


Fig. 4. Lineament density maps for a) N-S, b) NW-SE to WNW-ESE, c) E-W and d) NE-SW and ENE-WSW populations. See text for description of each population.

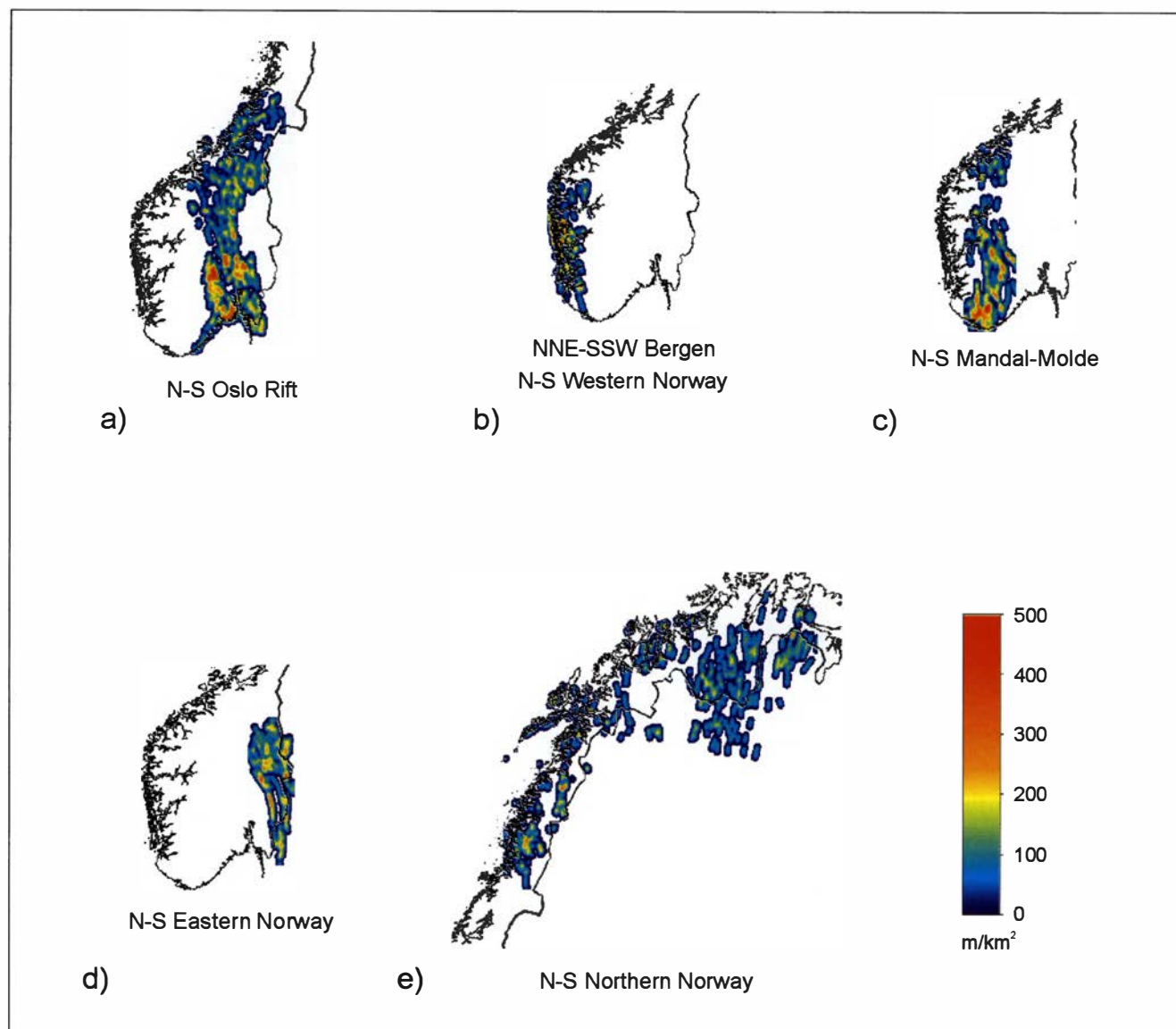


Fig. 5. Lineament density maps for major lineament zones with approximate N-S-trends; a) Oslo-Trondheim Zone and related structures, b) Bergen Zone, c) Østfold Zone d) Mandal-Molde Zone, and e) N-S-trending lineament zones in northern Norway, including the Finnmark Zone. See text for descriptions of each zone.

Cretaceous activity (Andersen et al. 1999), in accordance with faulting along the coast farther west (e.g., Eide et al. 1997).

Several of the NE-SW-trending faults in northern Scandinavia have been found to offset post-glacial topographic elements (e.g., Dehls et al. 2000) and, hence, stand out clearly as lineaments. In general, NE-SW-trending lineament sets of North Norway are particularly prominent within the Caledonian nappe terranes. Notable lineaments of the NE-SW population are the Vestfjorden-Vanna Fault of coastal Troms, which is characterised by several kilometres of cumulative, sinistral-oblique displacement, and the normal Kvaløysletta-Straumhella Fault, which is possibly Permian in age (Olesen et al. 1997), with indications of Tertiary-Recent reactivation. Also the Vargsund Fault in

Finnmark, and its southwestern prolongation into Troms county (Worthing 1984, Lippard & Roberts 1987), belongs to this population. This fault appears to be traceable offshore into the inner margin of the Troms-Finnmark Platform.

The age relationships of the faults belonging to the NE-SW population of Norway are complex. For example, the 20 km-wide Mierujavri-Sværholt Fault Zone is most clearly developed in the Palaeoproterozoic rock complexes of inner Finnmark (Olesen et al. 1992a,b) where it is developed as a complex system of strike-slip contractional duplexes. It can be followed northeastwards into and beneath the thin Caledonian nappes, and may possibly link farther northeast with younger, offshore faults in the southern Barents Sea (Lippard & Roberts 1987). To the southwest, the Mierujavre-Svær-

holt Fault Zone terminates against the NNW-SSE-trending Baltic-Bothnia Zone, an interference feature which is reminiscent of lineament truncation along the Oslo-Trondheim Zone in southern Norway.

The anastomosing Mierujavre-Sværholt Fault Zone displays evidence of post-glacial activity. The most conspicuous of these is the southeast-dipping Storrågrurra Fault (Olesen 1988; Olesen et al. 1992a,b; Roberts et al. 1997; Dehls et al. 2000). This structure is still seismically active. A comparable structure in Sweden is the Pärve Fault (Lundquist & Lagerbäck 1976; Lagerbäck 1979, 1990, 1992; Talbot & Slunga 1989). These faults are believed to represent basement structures that have been reactivated by the Early Tertiary-Recent far-field (ridge-push) stresses (e.g., Fejerskov et al. 2000; Lindholm et al. 2000).

Except for these large-scale features, lineaments with a NE-SW orientation are found only locally, e.g., along the southern margin of the Bergen Arcs (Fossen et al. 1997). Commonly, they appear as subordinate structures associated with other major fault zones such as the Møre-Trøndelag Fault Complex.

The ENE-WSW lineament system is covered by the azimuth sector N060°E to N080°E. On closer inspection, it becomes clear that this lineament system can be divided into two separate, cross-cutting populations (sets 1 and 2, see description below and Figs. 6 and 7), although the age relationship between the two is uncertain. The lineaments of the two populations are relatively evenly distributed in a region from the Hardangerfjord to the Oslo area.

In southern Norway, two elongate zones, one following the coast to the northeast from Kristiansand, and another that is parallel to Hardangerfjord, can be distinguished. Lineaments belonging to these populations are also common between Bergen and Sognefjorden. The system is particularly well developed south of a line from Oslo to Bergen, where it defines two intense zones with high lineament concentrations around Sirdal-Kvinesdal and east of Boknafjorden (Figs. 4 and 7). When following the lineaments towards the ENE, it is commonly observed that they abut against the western margin of the N-S Oslo-Trondheim Zone. In fact, all the ENE-WSW lineament sets of southern Norway show a clear tendency to become less intense when crossing the western border of the N-S-trending Oslo-Trondheim Zone, and then to completely disappear at its eastern margin (Fig. 7). On the regional scale, this lineament system encompasses large-scale structures like the Møre-Trøndelag Fault Complex, the Hardangerfjord Shear Zone and the Vestfjorden Zone.

Set 1 of the ENE-WSW lineament system (azimuth sector N060°E to N070°E) shows a heavy concentration in

the southwestern part of South Norway, where it defines several zones of high lineament intensity (Figs. 4d and 7; see also Rathore & Hospers 1986). One such zone parallels the coast northeast from Kristiansand, and another is found inland from that area between Egersund and Stavanger. The latter zone encompasses major topographic lineaments such as Ørdsalen and Gyadalen. The Hunnedalen dyke swarm in Rogaland, which intrudes the Vest Agder Gneiss Complex, belongs to this population. The dyke swarm embraces more than 30 individual vertical dykes, some of which can be followed for more than 20 kilometres. The dykes post-date the Sveconorwegian ductile deformation in the area, and have yielded ages in the range of 855-835 Ma (Maijer & Verschure 1998; Walderhaug et al. 1999). Their very consistent orientation suggests that they were generated in a NNW-SSE stress field. When following this lineament zone towards the east-northeast, its intensity diminishes when abutting against the western margin of the N-S Oslo-Trondheim Zone. However, some of the major features can still be traced across the Oslo-Trondheim Zone in the area between Oslo and Gjøvik (Fig. 7).

The Fedafjorden fault (Falkum 1982; Aamodt 1997) is a large-scale structure belonging to the ENE-WSW population. It has a fault core that is up to 30 m wide, and shows evidence for multiple faulting events. Typically, lenses of both red and green cataclasite are found within 10-30 cm-wide zones of gouge and/or as fragments in m-thick zones of breccia. The map pattern suggests a dextral separation in the order of 2 km along this fault zone.

Set 2 of the ENE-WSW lineament system (azimuth sector N070°E to N080°E) has a distribution in southern Norway that is rather similar to that of Set 1 (see above). However, the two sets are distinguished because of their cross-cutting relations and also as the lineaments of Set 2 appear to define fracture swarms that differ from those seen for Set 1 (Figs. 4d and 7). One zone in particular is characteristic for set 2; it is situated east of the inner part of Hardangerfjord and stretching eastwards from Hardanger through the northern bend of Hallingdal. Also, the relationship between set 2 and the Oslo-Trondheim Zone is clear, since set 2 structures terminate abruptly at the junction with the Oslo-Trondheim Zone.

Some set 2 lineaments associated with the E-W to ENE-WSW lineaments are very pronounced around the Devonian basins of West Norway (see description below). There are also some lineament zones belonging to this population in northernmost Trøndelag and Nordland. Apart from these zones, ENE-WSW lineaments of set 2 are uncommon in northern Norway, except for a region in Finnmark from northwestern Varanger Peninsula to Porsangerfjord and Sørøya in the

Caledonian nappes (Lippard & Roberts 1987). Breccias and younger gouges have here been recorded along some of these structures (Roberts 1971).

The most pronounced ENE-WSW lineament zone of Norway is associated with the *Møre-Trøndelag Fault Complex* (Figs. 1, 2, 4d and 6), which is well exposed on land on the Fosen Peninsula in Mid Norway. To the west-southwest this fault complex parallels the coastline and then continues offshore along the southern margin of the Møre Basin (Brekke & Riis 1987) and into the West Shetland Basin (Price & Rattey 1984, Doré 1991; Doré et al. 1997). Gravimetric data show that the fault complex is marked by two zones of coast-parallel highs separated by an elongated low (Fichler et al. 1998). The magnetic data show a clear, but more complex signature (Bråstein 1997; Doré et al. 1997), suggesting that faulting was accompanied by hydrothermal alteration. Both datasets imply that the fault complex has deep roots in the subsurface, a feature that has also been indicated by seismic reflection data (Hurich 1996; Hurich & Roberts 1997). This is also in accordance with field observations and geochemical evidence (Sturt et al. 1997). It seems reasonable to ascribe the contrasting development in the northern North Sea basins, as compared to that of the Møre Basin to the influence of this fault complex, which separates the two regions (see Gabrielsen et al. 1999, and references therein).

Grønlie & Roberts (1989) and Séranne (1992) speculated that the Møre-Trøndelag Fault Complex may have had a Precambrian or Early Palaeozoic precursor in the Palaeoproterozoic basement. The fault has also been inferred to represent part of a possible Caledonian suture (Torsvik et al. 1989). However, its importance for the late-Caledonian, Devonian development of the region is clear (Braathen et al. 2000, 2002; Titus et al. 2002). Hurich & Roberts (1997) noted that the two main, steeply dipping faults of the Møre-Trøndelag Fault Complex (the Hitra-Snåsa and Verran faults) appear to be listric into the late-Caledonian extensional Stadland shear zone. It seems clear that reactivation of the onshore part of the Møre-Trøndelag Fault Complex took place in the Carboniferous and Permian, as indicated by palaeomagnetic and isotope datings of dykes, breccias and pseudotachylite (Torsvik et al. 1989; Watts et al. 2000; Watts 2001). The complex was also active in the Mesozoic and Cenozoic (Grønlie & Roberts 1989; Grønlie et al. 1990; Bering 1992; Roberts 1998), and there is evidence that it is still seismically active today, though on a minor scale (e.g., Pascal & Gabrielsen 2001).

The Vestfjorden Zone defines the border between the islands of Lofoten and Vestfjorden. It is seen as a well-defined zone of lineaments composed of two separate sets trending ENE-WSW and NE-SW, respectively. On

closer inspection, the lineaments are recognised as faults characterised by multiple stages of brittle deformation (Pilskog Øvrelid 1995). The regional significance of the Vestfjorden lineament zone has not yet been investigated in any detail.

E-W lineament populations

Lineament sets with an E-W orientation (azimuth sector N080°E to N100°E) occur dominantly as zones (Fig. 3). These structures are relatively common in southern Norway where, to a large extent, they follow the distribution pattern of the ENE-WSW lineament populations. They commonly terminate at the western contact of the Oslo-Trondheim Zone, although some minor E-W sets can be traced through this zone to the point where they abut against its eastern border. When following the northern and southern border faults of the Devonian basins of West Norway, a distinct lineament population can be seen (Braathen 1999; Fig. 4c,d). This zone, which trends approximately E-W, was first recognised by Kjærulf (1876, 1879) and confirmed by Gabrielsen & Ramberg (1979). In more detail, it can be shown that this zone also contains elements of set 2 of the ENE-WSW lineament population.

Major E-W-trending faults of this population are well known in western Norway, especially from the Sunnfjord region. They include the Solund, Dalsfjord, Standal, Eikefjord and Grøndal faults, which are steeply north or south dipping and up to 100 m-wide fault zones that bound the northern and southern margins of the Devonian basins (e.g., Torsvik et al. 1992; Eide et al. 1997; Braathen 1999). These faults appear to truncate the N-S lineaments (Braathen 1999). Faults of this set commonly reveal evidence of multiple faulting events, seen as several generations of fault rocks ranging from cataclasite and breccia to fault gouge and, in some places, mylonite/phylionite and foliated cataclasite. Some of the events affecting the Dalsfjord fault have been dated, including a Permian, green siliceous cataclasite, and a red, carbonate-cemented breccia of Late Jurassic-Early Cretaceous age (Torsvik et al. 1987, 1992; Eide et al. 1997, 1999).

E-W-trending lineaments are relatively common in Mid Norway and northwards throughout north-central and northern Norway (Fig. 4d). These are fairly evenly distributed, and no obvious lineament concentrations are recognized, perhaps with the exception of the lineament set that borders the islands of Lofoten and the fjord Ofotfjorden (Gabrielsen & Ramberg 1979). In the northernmost coastal areas of Finnmark between Tanafjord and Porsangerfjord, lineaments trending between E-W and WNW-ESE are prominent in the Caledonian nappes (Fig. 4b). On the Nordkinn Peninsula, NNE-SSW linea-

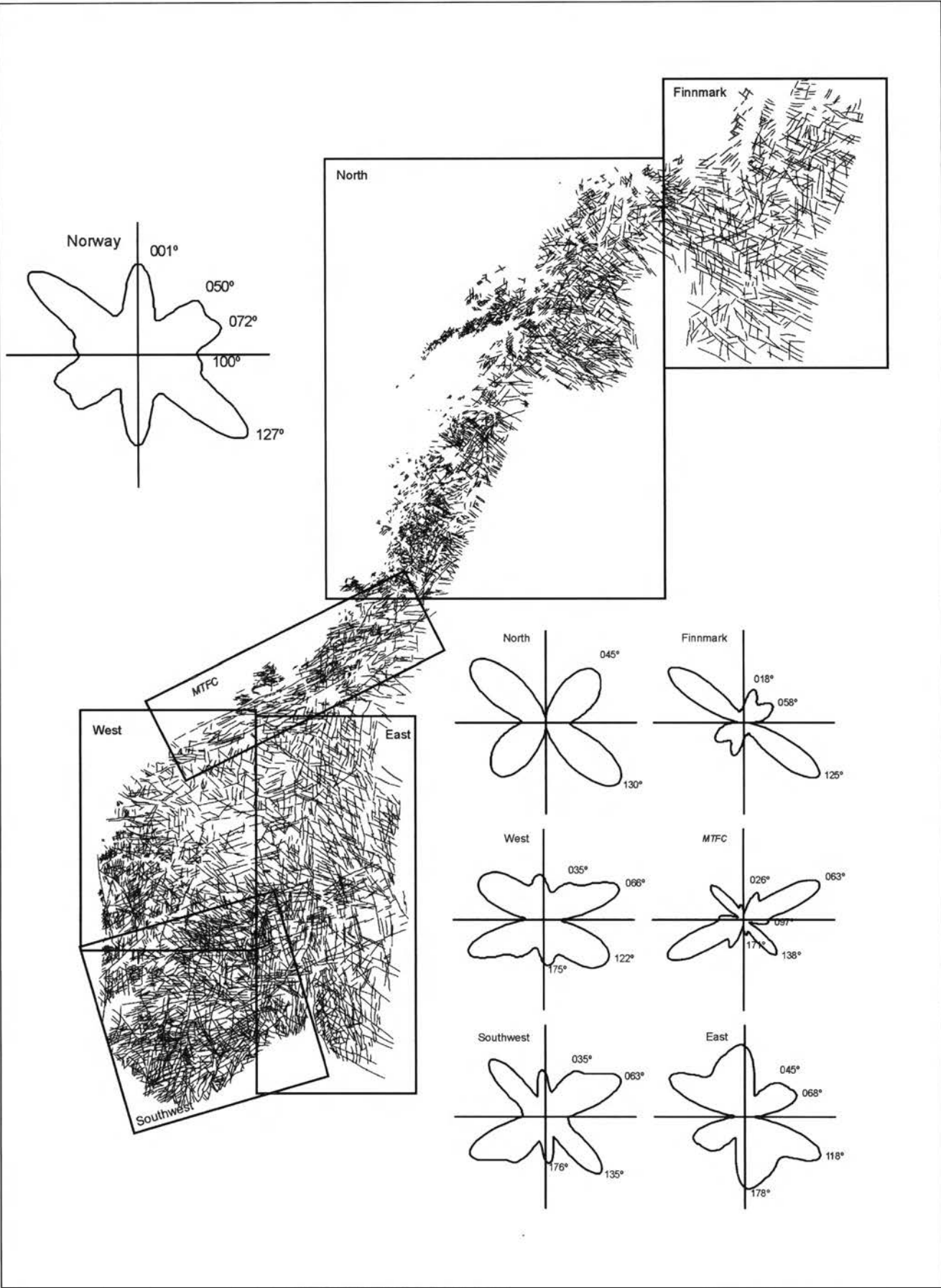


Fig. 6. Rose diagrams for lineament trends in Norway and within several major geographical regions. Note the dominance of NW-SE, N-S and NE-SW trends in the total lineament population. MTFC is the Møre-Trøndelag Fault Complex.

ments are offset along some of the major, E-W faults. Although subordinate to the major N-S-trending fault systems, the E-W structural trend is also recognized in the northern North Sea. However, there it mostly constitutes a pattern of steep faults with minor offsets that interlink with the master faults on both sides of the Viking Graben (e.g., the Snorre Field; Hollander 1987). To the knowledge of the present authors, these faults are not seen to affect the base Cretaceous unconformity.

NW-SE to WNW-ESE lineament populations

A NW-SE to WNW-ESE-trending structural grain is well documented in the Precambrian basement of Sweden and Finland, where master shear zones of this trend separate Svecofennian and Sveconorwegian terranes (e.g., Högdahl & Sjöström 2001; Högdahl et al. 2001). On the Kola Peninsula in NW Russia, similarly trending major lineaments mark important terrane boundaries between Archaean crustal blocks (Gaal & Gorbachev 1987; Karpuz et al. 1995; Roberts et al. 1997). This trend is also clearly expressed in the lineament map of Norway and, in contrast to several of the other lineament populations, the lineaments of this trend are more or less evenly distributed throughout the study area (Fig. 4b). On closer inspection, however, it is clear that this population can also be subdivided into several sets.

The WNW-ESE lineament population of southern and central Norway (Figs. 2 and 6) consists of long and continuous elements, some of which can be traced for up to several tens of kilometres. Although they are generally evenly distributed, one 'quiet area' is identified at the southernmost tip of Norway (Fig. 4b). The frequency of WNW-ESE lineaments is also suppressed when crossing the Oslo-Trondheim Zone. In central Norway, in the twin counties of Trøndelag, there are two areas of lower lineament density, and in this region the WNW-ESE lineaments seem to abut against the southeastern border of the Møre-Trøndelag Fault Complex. The WNW-ESE lineament system of central Norway partly parallels Devonian, low-angle, extensional shear zones (Braathen et al. 2000, 2002) and associated supradetachment faults. However, these lineaments also occur widely in the nappes and in the autochthonous Fennoscandian basement farther east, indicating a likely Precambrian origin for some of these structures.

A number of prominent magnetic/gravimetric, NW-SE-trending lineaments, which transect the Precambrian basement of Sweden, can be followed into Norway (Henkel & Eriksson 1987, Henkel 1991). The most conspicuous of those is the Sveconorwegian Protogine

Zone (e.g., Page et al. 1996). Although the physical-topographical expression of several of these lineaments disappears below the Caledonian nappe front, some geophysical lineaments can still be distinguished within the Caledonide domain. This suggests that these are deep-seated zones of weakness affecting the basement all the way to the west coast of Norway (Henkel & Eriksson 1987), which is supported by field analysis of NW-SE-trending lineaments in the Torneträsk area in Sweden (Romer & Bax 1992). These authors concluded that these structural features represent faults of Proterozoic origin that were reactivated during one or more phase of Caledonian deformation.

The WNW-ESE to NW-SE lineament population of northern Norway (Fig. 4b) is well developed in Nordland, where short lineaments of this trend appear to be common. In contrast, the WNW-ESE lineaments of Troms and Finnmark display a similar, even distribution and architecture to those present in southern Norway (Fig. 2).

In a zone stretching from northern Finnmark and eastwards through northwestern Russia, several regional WNW-ESE-trending faults and shear zones have been reported (Gaal & Gorbachev 1987; Melezhik & Sturt 1994). These include the multiphase Ravduraggi lineament zone west of Kirkenes (Karpuz et al. 1995), which can be followed using potential field data over some 30 kilometres to the northwest beneath the Caledonian nappes. Fault rocks within this lineament zone vary from mylonites to breccias and phyllonites. The 20 km-wide Murmansk Shear Zone of the Kola Peninsula, which is considered to be a terrane boundary, also extends into the northeasternmost parts of Finnmark (Karpuz et al. 1995; Roberts et al. 1997). This composite lineament zone has a strike extent of c. 150 km, and its multiphase history includes reverse and strike-slip ductile deformation of Late Archaean age.

The Trollfjorden-Komagelva Fault Zone (TKFZ of Fig. 1; Siedlecka & Siedlecki 1967, 1972; Roberts 1972; Karpuz et al. 1993a), which strikes approximately N125°E, belongs to this population. This is a crustal-scale, multiphase zone of weakness of Neoproterozoic origin, which is considered to have initiated as an extensional structure during Riphean-Vendian basinal sedimentation (Siedlecka & Siedlecki 1972), and was later inverted during the Timanian (Baikalian) orogeny (Roberts 1993, 1995; Herrevold 1994; Roberts & Karpuz 1995). This was followed by strike-slip and dip-slip reactivations in Palaeozoic and Mesozoic times. It is also believed to have acted as a transfer zone during Caledonian nappe emplacement (Kjøde et al. 1978; Rice et al. 1989, 1995). Along strike to the southeast, this major fault zone is recognised in Northwest Russia (Roberts 1995), while its offshore continuation to the northwest shows evidence of reactivation in Triassic-Jurassic time

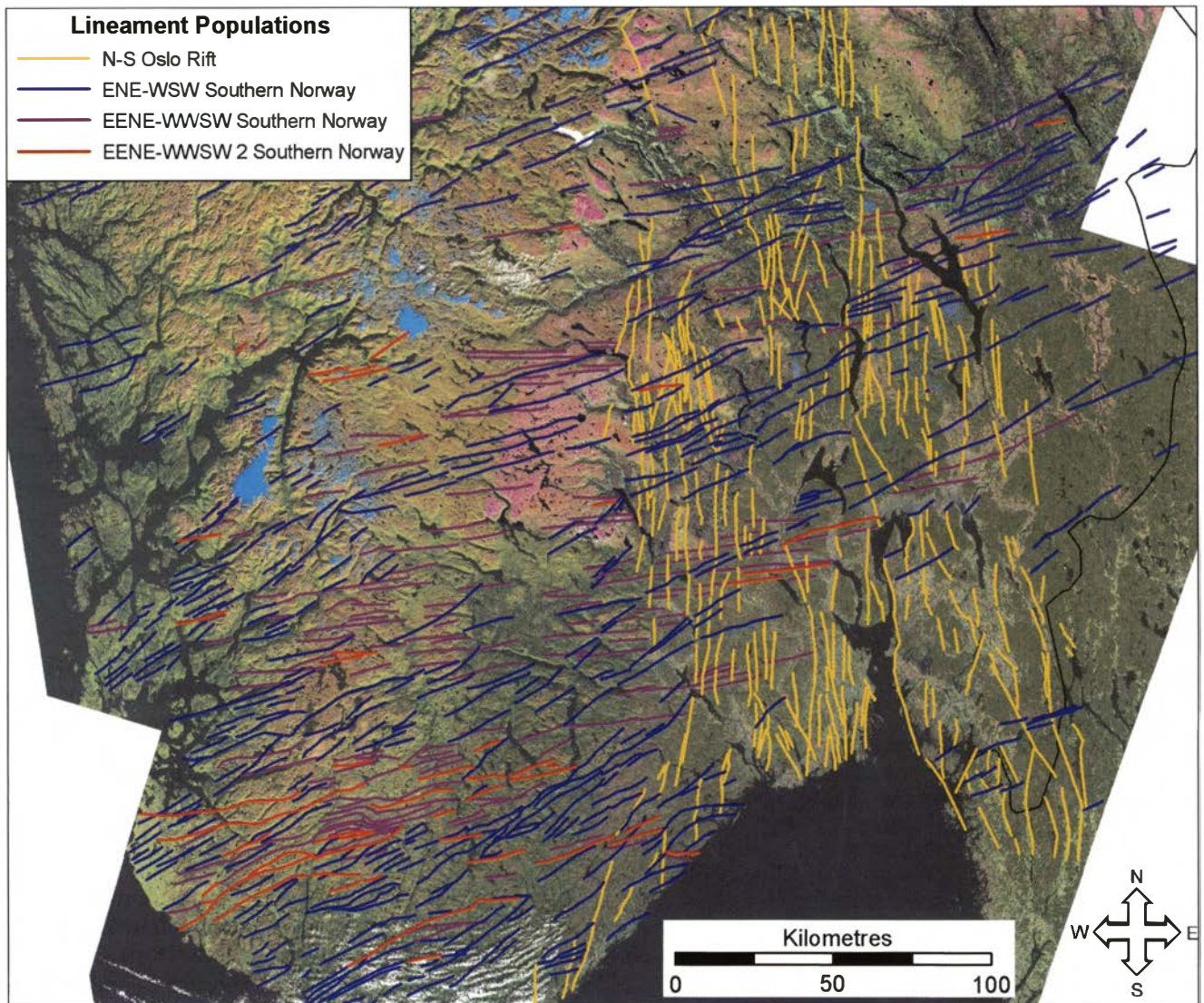


Fig. 7. Filtered lineament map of southern Norway, displaying the southern part of the Oslo-Trondheim Zone and the NE-SW to E-W lineaments of south-central Norway. Note that the NE-SW to E-W lineaments include at least three populations with cross-cutting relations. Also, note that most of these lineaments terminate abruptly on intersecting the N-S-trending population of the Oslo-Trondheim Zone. The Oslo zone is wider than the present Oslo Graben, and the zone narrows towards the north.

(Gabrielsen & Færseth 1989).

The Caledonian nappes of Finnmark are transected by NW-SE to WNW-ESE-trending lineaments, many of which are prominent faults with breccia and gouge zones. It has been shown that some of these structures can be followed offshore into the Troms-Finnmark Platform (Lippard & Roberts 1987; Gabrielsen & Færseth 1988, 1989). Reactivation along these structures is inferred to have occurred in Late Palaeozoic and mid Mesozoic time during the formation of offshore sedimentary basins.

The NW-SE lineaments of the Møre-Trøndelag Fault Complex are significantly different from the WNW-ESE lineament populations in that they are shorter, and constrained either within the very fault complex itself, or especially on its northwestern side (Olsen et al. 2001; Titus et al. 2002). They also form an angle of approxi-

mately 20° with the Møre-Trøndelag Fault Complex. Field investigations suggest that this population includes faults that are partly secondary, rotational fractures within the Møre-Trøndelag Fault Complex (Olsen et al. 2001), and partly segments of a larger fault system (Eliassen et al. 2001). It has been postulated by Grønlie et al. (1991) that these NW-SE fractures are related to a stress field of Tertiary age related to ridge-push forces, the inversional effects of which are known from offshore Mid Norway (e.g., Våagnes et al. 1997; Pascal & Gabrielsen 2001).

Discussion

The present lineament analysis is different, in several respects, from those previously performed in Norway

(Ramberg et al. 1977; Gabrielsen & Ramberg 1979; Rathore & Hospers 1984). In this case, two completely new Landsat datasets were acquired, and processing was carried out by use of modern standard methods. This implies that the resolution is generally higher, and that all images are of a similar high quality. Hence, the database as such is considered to be much more homogeneous. Furthermore, based on recently acquired field knowledge about the fracture systems on the Norwegian mainland as a whole, as well as applying modern computer methods for the flexible handling of data, it was possible to identify separate lineament populations from the start, and to test and adjust this classification during the course of the work. Recent, more refined techniques for the dating of fault rocks, as well as improved possibilities for offshore-onshore correlation, have facilitated absolute and relative age determinations. Finally, statistical and contouring methods have been used in the analysis. Although such methods have also been used previously (Rueslåtten et al. 1996), those early analyses were conducted using the old lineament dataset (Gabrielsen & Ramberg 1979). In general, however, the re-investigation of the lineament systems does seem to confirm the broad conclusions drawn by Gabrielsen & Ramberg (1979).

Taking the Norwegian mainland as a whole, several zones of high lineament frequency are defined along diverse trends. The most prominent N-S-trending lineament sets are the Oslo-Trondheim, Bergen and Finnmark zones. It has been possible to map these populations in greater detail and to identify more clearly their internal architecture and crosscutting relationships to other lineament zones. Considering the close spatial relationship between the Oslo-Trondheim Zone and the Oslo Graben, it is obvious that many of the fractures (some of which are filled with dykes) associated with this zone are of Permian age. In contrast, both magmatic and tectonic activity continued throughout the Triassic (Fossen & Dunlap 1998) and into the latest Jurassic in the Bergen Zone (Færseth et al. 1976; Færseth 1978; Eide et al. 1997; Fossen et al. 1997). More detailed investigation has revealed that, although striking nearly N-S on a regional scale, both the Oslo-Trondheim and the Bergen zones are composed of individual lineaments varying in strike from NNE-SSW to NNW-SSE (Fig. 5). A similar pattern of anastomosing lineaments is seen in the case of the Baltic-Bothnian Zone in northern Norway and Sweden.

The two major, N-S-trending lineament zones of southern Norway (Oslo-Trondheim and Bergen zones) are flanked by regional sets of NNE-SSW to NNW-SSE-trending lineaments. These are affiliated both with older basement faults and with shear zones, many of which are characterised by ductile deformation (Mandal-Ustaset Fault Zone - Sigmond 1985; the Kongsberg-Bamble fault system - Starmer 1993, 1996; the

Protogine Zone - Berthelsen & Marker 1986; Gorbachev & Bogdanova 1993). It is therefore concluded that these lineament trends together represent a megafracture pattern of profound weakness, which has had a strong influence on later structuring of the Norwegian mainland and the adjacent continental shelf (Gabrielsen et al. 1999).

The ENE-WSW lineament complexes repeat themselves with some regularity (Gabrielsen & Ramberg 1979). Three main zones belong to this population, namely the South Norway Zone, the Møre-Trøndelag Fault Complex and the Vestfjorden Zone. On closer inspection, however, these zones are quite different in terms of architecture, age and history. Thus, the E-W to ENE-WSW lineament population encompasses at least three separate lineament sets varying in strike between E-W and ENE-WSW. Among these are fault zones with a long and complex history and with displacements in the order of kilometres (e.g., the Fedafjorden Fault - Falkum 1982; Aamodt 1995) and dyke swarms of Neoproterozoic age (Bingen et al. 1998; Bingen & Damaiffe 1999). Recent field studies have demonstrated that many faults of these populations have been reactivated under low P-T conditions (Aamodt 1995; Braathen & Gabrielsen 1998, 2000, unpubl. data). However, it is clear that the bulk strain is more or less evenly distributed over the entire zone.

In contrast, strain has been concentrated along a few master fault strands along the Møre-Trøndelag Fault Complex, which show evidence of multiple reactivations (Grønlie et al. 1990; Watts 2001). Thus, this fault complex, which is strongly hydrothermally altered and mineralised, has accommodated diverse components of contractional, extensional and strike-slip movements through time. Stress-strain inversion modelling (Pascal & Gabrielsen 2001), and structural and microscopic investigations, have indicated that some of the faults in the fault complex are extremely weak, arising from a pervasive fluid influx that led to a profound long-term weakening at depth (Watts et al. 2000; Watts 2001). This confirms the great potential for reactivation of the fault complex. As noted earlier, The Møre-Trøndelag Fault Complex has regional dimensions, and can be traced offshore where it defines the southern margin of the Møre Basin, and across the northern North Sea towards Shetland. In contrast to the ENE-WSW lineaments of southernmost Norway, the Møre-Trøndelag Fault Complex cuts through the Oslo-Trondheim Zone, confirming its status as a structure along which significant deformation has taken place at a later (Mesozoic) stage.

The offshore part of the Vestfjorden zone is expressed as an extensional fault with a throw in the order of kilometres, delineating the Vestfjorden Basin to the north. The involvement of Late Jurassic rocks sets a clear time

constraint on this activity. Although easily identified as a lineament zone in remote sensing data, it is a less pronounced structure than the Møre-Trøndelag Fault Complex.

Accordingly, it is concluded that the E-W to ENE-WSW lineament populations incorporate a variety of structures covering a time span from Neoproterozoic to Tertiary. It is likely that they reflect an old system of crustal weakness zones, which has been reactivated to a varying degree. However, based on the data currently at our disposal, it is not possible to verify this assumption.

The NW-SE to WNW-ESE lineament populations are clearly different from those mentioned above in that the lineaments are almost evenly distributed throughout the study area. Also, there is a clear tendency for these lineaments not to penetrate significantly into the Oslo Graben area and the Møre-Trøndelag Fault Complex. This seems to confirm that the NW-SE to WNW-ESE lineament trends represent an inherited structural grain, arising from a megafault pattern imposed on the western Fennoscandian Shield during Proterozoic time (Strömberg 1976). Evidence from northern Scandinavia and Russia shows, in fact, that several of these NW-SE to ENE-WSW lineaments originated during the Archaean.

Conclusions and future work

The present work provides a new lineament database for Norway, which is more flexible for statistical analysis and correlation than those that have been available so far. It is important to realise that the interpretation has been performed at the scale of 1:750,000. Data are compiled in a digital format that can be overlain upon all types of satellite data and aerial photographs, topographic data, and geological and geophysical maps, which can then be magnified according to the needs of the analyst. In such operations, however, the resolution of the lineament interpretation will be inadequate, and may result in cases where the lineament traces may appear to cut or displace geological and topographical elements. Combining lineament data of different scales should therefore be avoided. In spite of these restrictions, it can be mentioned that a program for enhanced interpretation of key areas at a scale of 1:250,000 or less is in progress, and these interpretations will be added to the present database as they appear. These additional interpretations will also be supplemented by field investigations covering the most important lineaments. Such field and other data will be available through the central database of NGU (www.ngu.no).

Field checking of lineaments is progressively adding data to the lineament database. Characteristically,

almost all lineaments visited in the field turn out to be faults. The clarity of their topographic expression generally reveals their structural importance, but there are cases where an impressive topographic signature is controlled by minor fracturing or other features. In most cases, multiple faulting events can be distinguished and many of the fault cores are characterised by a late stage of soft fault rocks, suggesting very late movements. Hence, the lineament/fault zones have recorded most, if not all, post-Caledonian tectonic events that have affected the Norwegian mainland.

Acknowledgements. – The comprehensive reference list contains articles and a few recent theses directly relevant to the subject; however, due to limitations of journal space, it has not been possible to include the vast number of contributions describing fractures and fault zones on the Norwegian/Nordic mainland. The authors are grateful to H. Fossen, H. Sjöström and Ø. Steen for their helpful and constructive reviews of the manuscript.

References

- Aamodt, L.R. 1997: *Paleozoiske til kenozoiske bruddsystemer i det sydlige Norge og det tiliggende kontinentalsokkelområdet*. Unpublished cand. scient thesis, University of Bergen, 157 pp + appendices.
- Anda, E., Blikra, L.H., & Braathen, A. 2002. The Berill fault - first evidence of neotectonic faulting in southern Norway. *Norwegian Journal of Geology* 82, 175-182.
- Andersen, T.B. & Jamtveit, B. 1990: Uplift of deep crust during orogenic extensional collapse: A model based on field studies in the Sogn-Sunnfjord Region of Western Norway. *Tectonics* 9, 1097-1111.
- Andersen, T.B., Torsvik, T.H., Eide, E.A., Osmundsen, P.T. & Faleide, J.I. 1999: Permian and Mesozoic extensional faulting within the Caledonides of central South Norway. *Journal of the Geological Society, London* 156, 1073-1080.
- Andersson, J., Möller, C. & Johansson, L. 2002. Zircon geochronology of migmatite gneisses along the Mylonite Zone (S Sweden): a major Sveconorwegian terrane boundary in the Baltic Shield. *Precambrian Research* 114, 121-147.
- Badley, M.E., Egeberg, T. & Nipen, O. 1984: Development of rift basins illustrated by the structural evolution of the Oseberg structure, Block 30/6, offshore Norway. *Journal of the Geological Society, London* 141, 639-649.
- Bering, D. 1992: The orientation of minor fault plane striae and the associated deviatoric stress tensor as a key to the fault geometry in part of the Møre-Trøndelag Fault Zone, on-shore central Norway. *Norsk Petroleumsforening Special Publication* 1, 83-90.
- Berthelsen, A. & Marker, M. 1986: 1.9-1.8 Ga old strike-slip megashears in the Baltic Shield, and their plate tectonic implications. *Tectonophysics* 126, 163-181.
- Bingen, D. & Demaiffe, D. 1999: Geochemical signature of the Egersund basaltic dyke swarm, SW Norway, in the context of late-Neoproterozoic opening of the Iapetus Ocean. *Norsk Geologisk Tidsskrift* 79, 69-86.
- Bingen, B., Demaiffe, D. & Breemen, O. 1998: The 616 Ma old Egersund basaltic dike swarm, SW Norway, and late Neoproterozoic opening of the Iapetus Ocean. *Journal of Geology* 106, 565-574.
- Bjørlykke, K. 1978: The eastern marginal zone of the Caledonide orogen in Norway. In: IGCP Project 27, Caledonide-Appalachian Orogen.

- gen in the North-Atlantic Region. *Canada Geological Survey Paper* 78-13, 49-55.
- Bjørlykke, K., Elvsborg, A. & Høy, T. 1976: Late Precambrian sedimentation in the central sparagmite basin of South Norway. *Norsk Geologisk Tidsskrift* 56, 233-290.
- Braathen, A. 1999: Kinematics of post-Caledonian polyphase brittle faulting in the Sunnfjord region, western Norway. *Tectonophysics* 302, 99-121.
- Braathen, A. & Gabrielsen, R.H. 1998: Lineament architecture and fracture distribution in metamorphic and sedimentary rocks, with application to Norway. *Norges geologiske undersøkelse Report* 98.043, 78 pp.
- Braathen, A. & Gabrielsen, R. 2000: Bruddsoner i fjell – oppbygning og definisjoner. *Norges geologiske undersøkelse, Gråsteinen* 7, 1-20.
- Braathen, A., Nordgulen, Ø., Osmundsen, P.T., Andersen, T.B., Solli, A. & Roberts, D. 2000: Devonian, orogen-parallel, opposed extension of the Central Norway Caledonides. *Geology* 28, 615-618.
- Braathen, A., Osmundsen, P.T., Nordgulen, Ø., Roberts, D. & Meyer, G. B. 2002: Orogen-parallel extension of the Caledonides in northern Central Norway: an overview. *Norwegian Journal of Geology* 82, in press.
- Brekke, H. & Riis, F. 1987: Tectonics and basin evolution of the Norwegian shelf between 62° and 72°N. *Norsk Geologisk Tidsskrift* 67, 295-322.
- Bråstein, E. 1997: *Møre-Trøndelagforkastningssone - den nordøstlige forlengelsen og dens avslutning nord for Grong-Olden kulminasjonen i Nord-Trøndelag*. Unpublished cand.scient. thesis, University of Bergen, 134 pp.
- Brøgger, W. 1886: Über die Bildungsgeschichtedes Kriatianiafjords. *Nyt Magazin for Naturvidenskapene* 30, 99-231.
- Bugge, A. 1928: En forkastning i det syd-norske grunnfjell. *Norges geologiske undersøkelse* 130, 124 pp.
- Bugge, A. 1965: Iakttakelser fra rektangelbladet Kragerø og Den Store Grunnfjellsbrekke. *Norges geologiske undersøkelse* 229, 115 pp.
- Bungum, H. & Fyen, J. 1980: Hypocentral distribution, focal mechanisms, and tectonic implications of Fennoscandian earthquakes 1954-1978. *Geologiska Föreningens i Stockholm Förhandlingar* 101, 261-271.
- Bungum, H. & Lindholm, C. 1996: Seismo- and neotectonics in Finnmark, Kola and the southern Barents Sea, part 2: Seismological analysis and seismotectonics. *Tectonophysics* 270, 15-28.
- Caine, J.S., Evans, J.P. & Forster, C.B. 1996: Fault zone architecture and permeability structure. *Geology* 24, 1025-1028.
- Coates, B.H., Zeltner, D.L., Carter, B.T., Steltenpohl, M.G., Andresen, A. & Kunk, M.J. 1999: $^{40}\text{Ar}/^{39}\text{Ar}$ and structural investigations of extensional development of the North-Central Norwegian margin. *Geological Society of America Abstracts with Programs* 31, 118.
- Dehls, J.F., Olesen, O., Olsen, L. & Blikra, L.H. 2000. Neotectonic faulting in northern Norway; the Stuoragurra and Nordmannvikdalen postglacial faults. *Quaternary Science Reviews* 19, 1447-1460.
- Doré, A.G. 1991: The structural foundation and evolution of Mesozoic seaways between Europe and the Arctic. *Palaeogeography, Palaeoclimatology, Palaeoecology* 87, 441-492.
- Doré, A.G. & Gage, M.S. 1987: Crustal alignments and sedimentary domains in the evolution of the North Sea, north-east Atlantic margin and Barents shelf. In Brooks, J. & Glennie, K. (eds.): *Petroleum Geology of North West Europe*, 1131-1148. Graham & Trotman.
- Doré, A.G., Lundin, E.R., Fichler, C. & Olesen, O. 1997: Patterns of basement structure reactivation along the NE Atlantic margin. *Journal of the Geological Society, London* 154, 85-92.
- Eide, E.A., Torsvik, T.H. & Andersen, T.B. 1997: Absolute dating of brittle fault movements: Late Permian and Late Jurassic extensional fault breccias in western Norway. *Terra Nova* 9, 135-139.
- Eide, E.A., Torsvik, T.H., Andersen, T.B. & Arnaud, N.O. 1999. Early Carboniferous Unroofing in Western Norway: a tale of alkali feldspar thermochronology. *Journal of Geology* 107, 353-374.
- Eliassen, H., Gabrielsen, R.H. & Kyrkjebø, R. 2001: Møre-Trøndelag forkastningskompleks og betydningen av tverrstrukturer på forkastningssonens utvikling på Møre-kysten. Relasjon til Jan Mayen-lineamentet. Abstract. Norsk Geologisk Forenings XVII. Landsmøte, Program og sammendrag, *Geonytt* 44.
- Falkum, T. 1982: Geologisk kart over Norge, berggrunnskart MAN-DAL – 1:250 000. Norges geologiske undersøkelse.
- Fejerskov, M., Lindholm, C., Myrvang, A. & Bungum, H. 2000: Crustal stress in and around Norway: A compilation of in-situ stress observations. *Geological Society of London Special Publication* 167, 441-450.
- Fichler, C., Rundhovde, E., Olesen, O., Sæther, B.M., Rueslåtten, H., Lundin, E. & Doré, A.G. 1998: Image enhancement and structural discussion of regional gravity and magnetic data covering the Norwegian Sea and adjacent mainland. *Tectonophysics* 306, 183-197.
- Fossen, H. 1992. The role of extensional tectonics in the Caledonides of southern Norway. *Journal of Structural Geology* 14, 1033-1046.
- Fossen, H. 2000: Extensional tectonics in the Caledonides: Synorogenic or postorogenic? *Tectonics* 19, 213-224.
- Fossen, H. & Dunlap, W.J. 1998: On the age and tectonic significance of Permo-Triassic dikes in the Bergen-Sunnhordaland region, southwestern Norway. *Norsk Geologisk Tidsskrift* 79, 169-178.
- Fossen, H., Mangerud, G., Hesthammer, J., Bugge, T. & Gabrielsen, R.H. 1997: The Bjorøy Formation: a newly discovered occurrence of Jurassic sediments in the Bergen Arc System. *Norsk Geologisk Tidsskrift* 77, 269-287.
- Fossen, H. & Rykkeli, E. 1992. Post-collisional extension of the Caledonian orogen in Scandinavia: structural expressions and tectonic significance. *Geology* 20, 737-740.
- Frost, R.T.C., Fitch, F.J. & Miller, J.A. 1981: The age and nature of the crystalline basement of the North Sea. In: Illing, L.W. & Hobson, G.D. (eds.): *Petroleum Geology of the Continental Shelf of North-West Europe*. Institute of Petroleum, London, 43-57.
- Færseth, R.B. 1978: Mantle-derived lherzolite xenoliths and megacrysts from Permo-Triassic dykes, Sunnhordland, western Norway. *Lithos* 11, 23-35.
- Færseth, R.B. & Gabrielsen, R.H. & Hurich, C.A. 1995: Influence of basement in structuring of the North Sea Basin offshore southwest Norway. *Norsk geologisk Tidsskrift* 75, 105-119.
- Færseth, R.B., Knudsen, B.E., Liljedahl, T., Midbøe, P.S. & Söderström, B. 1997: Oblique rifting and sequential faulting in the Jurassic development of the northern North Sea. *Journal of Structural Geology* 19, 1285-1302.
- Færseth, R.B., MacIntyre, R.M. & Naterstad, J. 1976: Mesozoic alkaline dykes in the Sunnhordland region, western Norway: ages, geochemistry and regional significance. *Lithos* 9, 331-345.
- Færseth, R.B., Sjøblom, T.S., Steel, R.J., Liljedahl, T., Sauar, B.E. & Tjelland, T. 1995: Tectonic controls on Bathonian-Volgian syn-rift successions on the Visund fault block, northern North Sea. *Norwegian Petroleum Society Special Publication* 5, 325-346.
- Gaál, G. & Gorbachev, R. 1987: An outline of Precambrian evolution of the Precambrian Shield. *Precambrian Research* 35, 15-52.
- Gabrielsen, R.H. 1984: Long-lived fault zones and their influence on the tectonic development of the south-western Barents Sea. *Journal of the Geological Society, London* 141, 651-662.
- Gabrielsen, R.H. 1986: Structural elements in graben systems and their influence on hydrocarbon trap types. In Spencer et al. (eds.): *Habitat of Hydrocarbons on the Norwegian Continental Shelf*. Norwegian Petroleum Society, 55-60.
- Gabrielsen, R.H. 1989: Reactivation of faults on the Norwegian continental shelf and its implications for earthquake occurrence. In Geregeresen, S. & Basham, P.W. (eds.): *Earthquakes at the North-Atlantic Passive Margins: Neotectonics and Postglacial rebound*, 67-90. Kluwer Academic Publishers.
- Gabrielsen, R.H., Aarland, R.K. & Alsaker, E. 1997: Distribution of tec-

- tonic and non-tectonic fractures in siliciclastic porous rocks. *Geological Society of London Special Publication* 127, 49-64.
- Gabrielsen, R.H., Engeness Mørk, M.B., Tveiten, B. & Ramberg, I.B. 1980: Regional geological, tectonic and geophysical features of Nordland, Norway. *Earth Evolution Sciences* 1, 14 - 26.
- Gabrielsen, R.H. & Færseth, R.B. 1988: Cretaceous and Tertiary reactivation of master fault zones of the Barents Sea (extended abstract). *Norsk Polarinstitute Report Series* 46, 93-97.
- Gabrielsen, R.H. & Færseth, R.B. 1989: The off-shore extension of the Trollfjord-Komagelv fault zone - a comment. *Norsk Geologisk Tidsskrift* 69, 57-62.
- Gabrielsen, R.H., Grunnaleite, I. & Rasmussen, E. 1997: Cretaceous and Tertiary inversion in the Bjørnøyrenna Fault Complex, south-western Barents Sea. *Marine and Petroleum Geology* 142, 165-178.
- Gabrielsen, R.H., Færseth, R., Hamar, G. & Rønnevik, H. 1984: Nomenclature of the main structural features on the Norwegian continental shelf north of the 62nd parallel. In: Spencer et al. (eds.): *Petroleum Geology of the North European Margin*. Norwegian Petroleum Society (Graham & Trotman, London), 41-60.
- Gabrielsen, R.H., Færseth, R.B., Jensen, L.N., Kalheim, J.E. & Riis, F. 1990: Structural elements of the Norwegian continental shelf. Part I: The Barents Sea. *Norwegian Petroleum Directorate Bulletin* 6, 33 pp.
- Gabrielsen, R.H., Færseth, R.B., Steel, R.J., Idil, S. & Kløvjan, O.S. 1990: Architectural styles of basin fill in the northern Viking Graben. In Blundell, D.J. & Gibbs, A.D. (eds.): *Tectonic Evolution of the North Sea Rifts*, 158-179. Clarendon Press, Oxford.
- Gabrielsen, R.H. & Kløvjan, O.S. 1997: Late Jurassic- early Cretaceous caprocks of the southwestern Barents Sea: Fracture systems and rock mechanical properties. *Norwegian Petroleum Society Special Publication* 7, 1-18.
- Gabrielsen, R.H., Odinsen, T. & Grunnaleite, I. 1999: Structuring of the Northern Viking Graben and the Møre Basin; the influence of basement structural grain, and the particular role of the Møre-Trøndelag Fault Complex. *Marine and Petroleum Geology* 16, 443-465.
- Gabrielsen, R.H. & Ramberg, I.B. 1979: Fracture patterns in Norway from Landsat imagery: Results and potential use. Proceedings, Norwegian Sea Symposium, Tromsø 1979, *Norwegian Petroleum Society NSP* 1-28.
- Gorbatshev, R. & Bogdanova, S. 1993: Frontiers in the Baltic Shield. *Precambrian Research* 64, 3-21.
- Grønlie, A., Nilsen, B. & Roberts, D. 1991: Brittle deformation history of fault rocks on the Fosen Peninsula, Trøndelag, Central Norway. *Norges geologiske undersøkelse Bulletin* 421, 39-57.
- Grønlie, A., Harder, V. & Roberts, D. 1990: Preliminary fission-track ages on fluorite mineralisation along fracture zones, inner Trondheimsfjord, Central Norway. *Norsk Geologisk Tidsskrift* 70, 173-178.
- Grønlie, A. & Roberts, D. 1989: Resurgent strike-slip duplex development along the Hitra-Snåsa and Verran faults, Møre-Trøndelag Fault Zone, Central Norway. *Journal of Structural Geology* 11, 295-305.
- Gudmestad, O.T. & Lindholm, C. 2001. Jordskjelv i Norge - liten sannsynlighet for katastrofe. *Geo* 5-2001, 48-50.
- Hamar, G.P., Jacobsson, K.H., Ormaasen, D.E. & Skarpnes, O. 1980: Tectonic development of the North Sea north of the central Highs. In *The Sedimentation of the North Sea Reservoir Rocks*, 23 pp. Norwegian Petroleum Society.
- Henkel, H. 1991: Magnetic crustal structures in northern Fennoscandia. *Tectonophysics* 192, 57-66.
- Henkel, H. & Eriksson, L. 1987: Regional aeromagnetic and gravity studies in Scandinavia. *Precambrian Research* 35, 169-180.
- Henningsmoen, G. 1952: Early middle Cambrian fauna from Rogaland, SW Norway. *Norsk Geologisk Tidsskrift* 30, 13-31.
- Herrevold, T. 1994: *Strukturgeologisk analyse av den austlegaste delen av Trollfjorden-Komagelvforkastninga, Varanger*. Unpublished Cand.scient thesis, University of Bergen, 176 pp.
- Hobbs, W.H. 1904: Lineaments of the Atlantic border region. *Geological Society of America Bulletin* 15, 483-506.
- Hobbs, W.H. 1911: Repeating patterns in the relief and in the structure of the land. *Geological Society of America Bulletin* 22, 123-176.
- Hollander, N.B. 1987: Snorre Field. In Spencer et al. (eds.): *Geology of the Norwegian Oil and Gas Fields*, 307-318. Graham & Trotman.
- Holmsen, P. & Holmsen, G. 1950: Tynset. Beskrivelse til det geologiske rektangelkart. *Norges geologiske undersøkelse* 175, 64 pp.
- Holtedahl, H. 1967: Notes on the formation of fjords and fjord-valleys. *Geografiska Annaler* 49, Serie A-1967, 188-203.
- Hurich, C.A. 1996: Kinematic evolution of the lower plate during intracontinental subduction: An example from the Scandinavian Caledonides. *Tectonics* 15, 1248-1263.
- Hurich, C.A. & Kristoffersen, Y. 1988: Deep structure of the Caledonide Orogen in southern Norway: new evidence from marine seismic profiling. *Norges geologiske undersøkelse Special Publication* 3, 96-101.
- Hurich, C.A. & Roberts, D. 1997: A seismic reflection profile from Stjørdalen to outer Fosen, Central Norway: a note on the principal results. *Norges geologiske undersøkelse Bulletin* 433, 18-19.
- Högdahl, K. & Sjöström, H. 2001: Evidence for 1.82 Ga transpressive shearing in a 1.85 Ga granitoid in central Sweden: implications for the regional evolution. *Precambrian Research* 105, 37-56.
- Högdahl, K., Sjöström, H. & Gromet, L.P. 2001: Character and timing of Svecokarelian, late-orogenic, ductile deformation zones in Jämtland, west central Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 123, 225-236.
- Ihlen, P.M. 1995: Gold mineralisation in relation to batholith magmatism in the Helgeland Nappe Complex and its immediate substrata, the Caledonides of north-central Norway. *Geological Survey of Greenland Open File Series*, 95/10, 42-46.
- Karpuz, M.R., Gabrielsen, R.H., Engell-Sørensen, L. & Anundsen, K. 1991: Seismotectonic significance of the January 29, 1989 Etne earthquake, southwest Norway. *Terra Nova* 3, 540-549.
- Karpuz, M.R., Roberts, D., Moralev, V.M. & Terekhov, E. 1995: Regional lineaments of eastern Finnmark, Norway, and the western Kola Peninsula, Russia. *Norges geologiske undersøkelse Special Publication* 7, 121-135.
- Karpuz, M.R., Roberts, D., Olesen, O., Gabrielsen, R.H., & Herrevold, T. 1993a: Application of multiple data sets to structural studies on Varanger Peninsula, northern Norway. *International Journal of Remote Sensing* 14, 979-1003.
- Karpuz, M.R., Roberts, D., Olesen, O., Gabrielsen, R.H., & Herrevold, T. 1993b: Regional lineament framework of eastern Finnmark, western Kola Peninsula, Russia and the southern Barents Sea. Proceedings 9th Thematic Conference on Geological Remote Sensing, Pasadena, USA, 733-750.
- Kjærulff, T. 1876: Et stykke geografi i Norge. *Cristiania Videnskabs-Selskabs Forhandlinger* 3, 1-18.
- Kjærulff, T. 1879: *Udsigt over det sydlige Norges geologi*. W.C. Fabritius, Cristiania, 262pp (including atlas).
- Kjode, J., Storetvedt, K.M., Roberts, D. & Gidskehaug, A. 1978: Palaeomagnetic evidence for large-scale dextral movement along the Trollfjord-Komagelv Fault, Finnmark, north Norway. *Physics of the Earth and Planetary Interiors* 16, 132-144.
- Knipe, R.J., Fisher, Q.J., Jones, G., Clennell, M.R., Farmer, A.B., Harrison, A., Kidd, B., McAllister, E., Porter, J.R. & White, E.A. 1998: Fault seal analysis: successful methodologies, application and future directions. *Norwegian Petroleum Society Special Publication* 7, 15-40.
- Lagerbäck, R. 1979: Neotectonic structures in northern Sweden. *Geologiska Föreningen i Stockholm Förhandlingar* 100, 271-278.
- Lagerbäck, R. 1990: Late Quaternary faulting and paleoseismicity in northern Fennoscandia with particular reference to the Lansjärv area, northern Sweden. *Geologiska Föreningens i Stockholm För-*

- handlingar 112, 333-354.
- Lagerbäck, R. 1992: Dating of late Quaternary faulting in northern Sweden. *Journal of the Geological Society, London* 149, 285-291.
- Launeau, P. & Robin, P. Y. F. 1996: Fabric analysis using the intercept method. *Tectonophysics* 267, 91-119.
- Lindh, A. 1980: Correlation of Landsat lineaments in the southwestern margin of the Baltic Shield. *Geologiska Föreningens i Stockholm Förhandlingar* 102, 1-12.
- Lindholm, C.D., Bungum, H., Hicks, E. & Villagran, A. 2000: Crustal stress and tectonics in Norwegian regions determined from earthquake focal mechanisms. *Geological Society of London Special Publication* 167, 429-440.
- Lippard, S.J. & Roberts, D. 1987: Fault systems in Caledonian Finnmark and the southern Barents Sea. *Norges geologiske undersøkelse Bulletin* 410, 55-64.
- Lundquist, J. & Lagerbäck, R. 1976: The Pärve Fault: a late-glacial fault in the Precambrian of Swedish Lapland. *Geologiska Föreningens i Stockholm Förhandlingar* 98, 45-51.
- Løvlie, R. & Mitchell, J.G. 1982: Complete remagnetization of some Permian dykes from western Norway induced during burial/uplift. *Physics of the Earth and Planetary Interior* 30, 415-421.
- Majner, C. & Verschure, R.H. 1998: Petrology and isotope geology of the Hunnedalen monzonitic dike swarm, SW Norway: The Hunnedalen dike swarm as a possible late expression of Egersund anorthosite magmatism. *Norges geologiske undersøkelse Bulletin* 434, 83-107.
- Melezhik, V.A. & Sturt, B.A. 1994: General geology and evolutionary history of the early Proterozoic Polmak-Pasvik-Pechenga-Imandra/Varzuga-Ust'Ponoy Greenstone Belt in the northeastern Baltic Shield. *Earth-Science Reviews* 36, 205-241.
- Milnes, A.G., Wennberg, O.P., Skår, Ø. & Koestler, A.G. 1997: Contraction, extension and timing in the south Norwegian Caledonides - The Sognefjord Transect. *Journal of the Geological Society, London, Special Publication* 121, 123-148.
- Muir Wood, R., Woo, G. & Bungum, H. 1988: The history of earthquakes in the northern North Sea. In: *Historical seismograms and earthquakes of the World*, 297-306. Academic Press.
- Nironen, M. 1997: The Svecofennian Orogen: A tectonic model. *Precambrian Research* 86, 21-44.
- Nordgulen, Ø. & Rønning, J.S. 2000: Tunnelproblemer løses ikke på stoff. *Geo* 5-2000, 17-20.
- Nystuen, J.P. 1981: The Late Precambrian "Sparagmites" of southern Norway: A major Caledonian Allochthon - the Osen-Røa Nappe Complex. *American Journal of Science* 281, 69-94.
- Nystuen, J.P. (ed.) 1989: Rules and recommendations for naming of geological units in Norway. *Norsk Geologisk Tidsskrift* 69 (Supplement 2), 110 pp.
- Oftedahl, C. 1949: Skyvedekker i det centrale Norges Sparagmitt-formasjon. *Norsk Geologisk Tidsskrift* 27, 164-170.
- Olaussen, S., Larsen, B.T. & Steel, R. 1994: The Upper Carboniferous-Permian Oslo Rift: Basin fill in relation to tectonic development. *Canadian Society of Petroleum Geologists Memoir* 17, 175-197.
- O'Leary, D.W., Friedman, J.D. & Pohn, H.A. 1976: Lineaments, linear, lineation: some proposed new names and standards. *Geological Society of America Bulletin* 87, 1463-1469.
- Olesen, O. 1988: The Stuuragurra Fault, evidence of neotectonics in the Precambrian of Finnmark, northern Norway. *Norsk Geologisk Tidsskrift* 68, 107-118.
- Olesen, O., Henkel, H., Lile, O.B., Mauring, E. & Rønning, J.S. 1992a: Geophysical investigations of the Stuuragurra postglacial Fault, Finnmark, northern Norway. *Journal of Pure and Applied Geophysics* 29, 95-118.
- Olesen, O., Henkel, H., Lile, O.B., Mauring, E., Rønning, J.S. & Torsvik, T.H. 1992b: Neotectonics in the Precambrian of Finnmark, northern Norway. *Norsk Geologisk Tidsskrift* 72, 301-306.
- Olesen, O., Torsvik, T.H., Tveten, E., Zwaan, K.B., Løseth, H. & Henningsen, T. 1997: Basement structure of the continental margin in the Lofoten-LoppHAVet area, Northern Norway: Constraints from potential field data, on-land structural mapping and palaeomagnetic data. *Norsk Geologisk Tidsskrift* 77, 15-30.
- Olsen, Å.E., Gabrielsen, R.H. & Redfield, T. 2001: NV-SØ-strykende dekstrale forkastninger på Osen, Trøndelag. *Norsk Geologisk Forenings XVII. Landsmøte, Program og sammendrag, Geonytt*, 88-89.
- Osmundsen, P.T., Braathen, A., Nordgulen, Ø., Roberts, D. Meyer, G.B. & Eide, E. 2003: Late/post-Caledonian extension in North-Central Norway: The Nesna shear zone and its regional implications. *Journal of the Geological Society, London* 160, 1-14, in press.
- Page, L.M., Möller, C., & Johansson, L. 1996: $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology across the Mylonite Zone and the South-west Swedish Granulite Province of the Sveconorwegian orogen of S. Sweden. *Precambrian Research* 79, 239-259.
- Pascal, C. & Gabrielsen, R.H. 2001: Numerical modelling of Cenozoic stress patterns in the mid Norwegian Margin and the northern North Sea. *Tectonics* 20, 585-599.
- Pilskog Øvrelid, S. 1995: *Brottektikk på land i Vesterålen og tilstøtende område på sokkelen vest for Lofoten*. Unpublished Cand.scient. thesis, University of Bergen.
- Priem, H.N.A., Verschure, R.H., Boelrijk, N.A.I.M. & Hebeda, E.H. 1968: Rb-Sr and K-Ar age measurements of phlogopitic biotite from the ultrabasic lamprophyre dyke on the island of Ytterøy, Trondheimsfjord, Norway. *Norsk Geologisk Tidsskrift* 48, 319-321.
- Ramberg, I.B. 1976: Gravity interpretation of the Oslo Graben and associated igneous rocks. *Norges geologiske undersøkelse* 325, 193pp.
- Ramberg, I.B., Gabrielsen, R.H., Larsen, B.T. & Solli, A. 1977: Analysis of fracture patterns in southern Norway. *Geologie en Mijnbouw* 56, 295-310.
- Ramberg, I.B. & Smithson, S.B. 1975: Geophysical interpretation of crustal structure along the southeastern coasts of Norway and the Skagerrak. *Geological Society of America Bulletin* 86, 769-774.
- Rathore, J.S. & Hospers, J. 1986: A lineament study of southern Norway and adjacent off-shore areas. *Tectonophysics* 131, 257-285.
- Rice, A.H.N., Gayer, R.A., Robinson, D. & Bevins, R.E. 1989: Strike-slip restoration of the Barents Sea Caledonides terrane, Finnmark, North Norway. *Tectonics* 8, 247-264.
- Rice, A.H.N. & Reiz, A. 1995: The structural relations and regional tectonic implications of metadolerite dykes in the Kongsfjord Formation, North Varanger Region, Finnmark, N. Norway. *Norsk Geologisk Tidsskrift* 74, 152-165.
- Rindstad, B. & Grønlie, A. 1987: Landsat TM data used in the mapping of large-scale geological structures in the coastal areas of Trøndelag, central Norway. Proceedings, *Earthnet Pilot Project on Landsat Thematic Mapper Applications*, Frascati, Italia, 169-181.
- Ro, H.E., Stuevold, L.M., Faleide, J.I. & Myhre, A.M. 1990: Skagerrak Graben - the offshore continuation of the Oslo Graben. *Tectonophysics* 178, 1-10.
- Roberts, D. 1971: Patterns of folding and fracturing in northeast Sørøy. *Norges geologiske undersøkelse* 269, 89-95.
- Roberts, D. 1972: Tectonic deformation in the Barents Sea region of Varanger peninsula, Finnmark. *Norges geologiske undersøkelse* 282, 1-39.
- Roberts, D. 1993: Aspects of the structural geology of Rybachi and Sredni Peninsulas, and some comparisons with Varanger Peninsula. 1st. International Barents Symposium, October 1993. Abstract Volume, *Norges geologiske undersøkelse*.
- Roberts, D. 1995: Principal features of Rybachi and Sredni Peninsulas, Northwest Russia, and some comparisons with the Varanger Peninsula. *Norges geologiske undersøkelse Special Publication* 7, 247-258.
- Roberts, D. 1998: High-strain zones from meso- to macro-scale at different structural levels, Central Norwegian Caledonides. *Journal of Structural Geology* 20, 111-119.

- Roberts, D. & Gale, G.H. 1977: The Caledonian-Appalachian Iapetus Ocean. In Tarling, D.H. (ed.): *Evolution of the Earth's Crust*, 255-342. Academic Press, London.
- Roberts, D., Olesen, O. & Karpuz, M.R. 1997: Seismo- and neotectonics in Finnmark, Kola Peninsula and the southern Barents Sea. Part 1: Geological and neotectonic framework. *Tectonophysics* 270, 1-13.
- Roberts, D. & Karpuz, M.R. 1995: Structural features of the Rybachi and Sredni Peninsulas, Northwest Russia, as interpreted from Landsat-TM imagery. *Norges geologiske undersøkelse Special Publication* 7, 145-150.
- Romer, R.S. & Bax, G. 1992: The rhombohedral framework of the Scandinavian Caledonides and their foreland. *Geologische Rundschau* 81, 391-401.
- Rueslåtten, H., Strøm, A., Sæther, B. & Gabrielsen, R.H. 1996: Visualisation and classification of linear features on images and maps using the HOUGH Transform. Proceedings, *Eleventh Thematic Conference and Workshops on Applied Geologic Remote Sensing*, Las Vegas, Nevada, Volume II, 675-681.
- Rykkelid, E. & Andresen, A. 1994: Late Caledonian extension in the Ofoten area, northern Norway. *Tectonophysics* 231, 157-169.
- Skjernaa, L. 1972: The discovery of a regional crush belt in the Ørje area, south-east Norway. *Norsk Geologisk Tidsskrift* 52, 459-461.
- Séranne, M. 1992: Late-Paleozoic kinematics of the Møre-Trøndelag fault zone and adjacent areas, central Norway. *Norsk Geologisk Tidsskrift* 72, 141-158.
- Siedlecka, A. & Siedlecki, S. 1967: Some new aspects of the geology of Varanger peninsula (northern Norway). *Norges geologiske undersøkelse* 247, 288-306.
- Siedlecka, A. & Siedlecki, S. 1972: Lithostratigraphic correlation and sedimentology of the late Precambrian of Varanger Peninsula and neighbouring areas of East Finnmark, northern Norway. 24th International geological Congress, Section 6, 349-358.
- Sigmond, E.M.O. 1985: The Mandal-Ustaoset line, a newly discovered major fault zone in south Norway. In Tobi, A.C. & Touret, J.L.R. (eds.): *The Deep Proterozoic Crust in the North Atlantic Provinces*, 323-331. Reidel Publishing Company.
- Skjeseth, S. 1963: Contributions to the geology of the Mjøsa districts and the classical sparagmite area in southern Norway. *Norges geologiske undersøkelse* 220, 1-126.
- Smethurst, M.A. 2000: Land-offshore tectonic link in western Norway and the northern North Sea. *Journal of the Geological Society, London* 157, 769-781.
- Solheim, A. & Grønlie, G. 1983: Quaternary sediments and bedrock geology in the outer Oslofjord and northernmost Skagerrak. *Norsk Geologisk Tidsskrift* 63, 55-72.
- Starmer, I.C. 1993: The Sveconorwegian Orogeny in southern Norway, relative to deep crustal structures and events in the North Atlantic Proterozoic Supercontinent. *Norsk Geologisk Tidsskrift* 73, 109-132.
- Starmer, I. 1996: Oblique terrane assembly in the Late Proterozoic during the Labradorian-Gothian Orogeny in Southern Scandinavia. *Journal of Geology* 104, 341-350.
- Steen, Ø. & Andresen, A. 1999: Effects of lithology on geometry and scaling of small faults in Triassic sandstones, East Greenland. *Journal of Structural Geology* 21, 1351-1368.
- Stephens, M., Wahlgren, C.-H., Weijermars, R. & Cruden, A.R. 1996: Left-lateral transpressive deformation and its tectonic implications, Sveconorwegian Orogen, Baltic Shield, southwestern Sweden. *Precambrian Research* 79, 261-279.
- Strömberg, A.B.G. 1976: A pattern of tectonic zones in the western part of the East European Platform. *Geologiske Föreningens i Stockholm Förhandlingar* 98, 227-243.
- Sturt, B.A., Askvik, H. & Sundvoll, B. 1997: A probable Permian hydrothermal alteration age for a quartz syenite dyke from Stabben, Nordmøre. *Norges geologiske undersøkelse Bulletin* 432, 71-75.
- Størmer, L. 1967: Some aspects of the Caledonian geosyncline and foreland west of the Baltic Shield. *Geological Society of London Quarterly Journal* 123, 183-214.
- Sundvor, E. & Larsen, B.T. 1994: Architecture and early evolution of the Oslo Rift. *Tectonophysics* 240, 173-189.
- Swensson, E. 1990: Cataclastic rocks along the Nesodden Fault, Oslo Region, Norway: a reactivated Precambrian shear zone. *Tectonophysics* 178, 51-65.
- Talbot, C.J. & Slunga, R. 1989: Patterns of active shear in Scandinavia. In Gregersen, S. & Basham, P.W. (eds.): *Earthquakes at the North-Atlantic passive margins: Neotectonics and postglacial rebound*, 441-466. Kluwer Press.
- Titus, S.J., Fossen, H., Pedersen, R.B., Vigneresse, J.L. & Tikoff, B. 2002: Pull-apart formation and strike-slip partitioning in an obliquely divergent setting, Leka Ophiolite, Norway. *Tectonophysics* 345, 101-119.
- Torsvik, T.H., Sturt, B.A., Swensson, E., Andersen, T.B. & Dewey, J.F. 1992: Palaeomagnetic dating of fault rocks: evidence for Permian and Mesozoic brittle deformation along the extensional Dalsfjord Fault, western Norway. *Geophysical Journal International* 109, 565-580.
- Torsvik, T.H., Andersen, T.B., Eide, E. & Walderhaug, H.J. 1997: The age and tectonic significance of dolerite dykes in western Norway. *Journal of the Geological Society, London* 154, 961-973.
- Torsvik, T.H., Sturt, B.A., Ramsay, D.M., Grønlie, A., Roberts, D., Smethurst, M., Atakan, K., Bøe, R. & Walderhaug, H.J. 1989: Palaeomagnetic constraints on the early history of the Møre Trøndelag Fault Zone, central Norway. In Kissel, C. & Laj, C. (eds.): *Palaeomagnetic Rotations and Continental Deformation*, 431-457. Kluwer Academic Publishers.
- Torsvik, T.H., Sturt, B.A., Ramsay, D.M. & Vetti, V. 1987: The tectono-magnetic signature of the Old Red Sandstone and pre-Devonian strata in the Håsteinen area, western Norway, and implications for the later stages of the Caledonian Orogeny. *Tectonics* 6, 305-322.
- Vågnes, E., Gabrielsen, R.H. & Haremo, P. 1998: Late Cretaceous-Cenozoic intraplate contractional deformation at the Norwegian continental shelf: timing, magnitude and regional implications. *Tectonophysics* 300, 29-46.
- Walderhaug, H.J., Torsvik, T.H., Eide, E.A., Sundvoll, B. & Bingen, B. 1999: Geochronology and palaeomagnetism of the Hunndalen dykes, SW Norway; implications for the Sveconorwegian apparent polar wander loop. *Earth and Planetary Science Letters* 169, 71-83.
- Watts, L.M. 2001: *The Walls Boundary Fault Zone and the Møre-Trøndelag Fault Complex: a case study of two reactivated fault zones*. Ph.D. thesis, University of Durham, UK, 550 pp.
- Watts, L.M., Holdsworth, R.E. & Roberts, D. 2000: Fault rock heterogeneity, fluid influx and reactivation: an example from the Møre-Trøndelag Fault Complex, Central Norway. Abstract volume, Tectonic Studies Group Annual Meeting, University of Manchester, UK.
- Worthing, M.A. 1984: Fracture patterns on eastern Seiland, north Norway and their possible relationships to regional faulting. *Norges geologiske undersøkelse* 396, 35-41.
- Ziegler, P.A. 1990: *Geological Atlas of Western and Central Europe*. Shell International Petroleum Maatschappij B.V., 239 pp.