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ANALYSIS OF FRACTURE PATTERNS IN SOUTHERN NORWAY

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ABSTRACT

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Linear features (believed to represent fractures of some kind) seen on Landsat satellite images, topographic maps and geological maps have been mapped for the area of southern Norway (roughly the region south of the 65° parallel). Special attention is given to the area of the Oslo Graben. The results of the analysis are related to the main geological and geophysical features of the region, of which a brief description is given.

A system of NW-SE and NE-SW sets of lineaments is present over most of the region and predominates in the Precambrian area; it is thought to be the oldest structural element. In the Caledonian belt the NE-SW set is predominant, in accordance with the general strike. A roughly N-S trending set is obviously associated with the Oslo Graben but extends well to the north of the latter; a similar pattern is also present near the west coast. An E-W set is locally associated with Devonian movements. The coastlines of southern Norway conform closely to the directions of the dominant fracture pattern in the vicinity.

INTRODUCTION

During the early 1970's the first Landsat (formerly called ERTS) satellite imagery of southern Norway was recorded. Although techniques for analysing these data have been available for some time, a general structural synthesis using Landsat imagery from this area has not been published as yet. The present study is a first attempt at making such an analysis. Refinement and continued interpretation of the fracture pattern will by necessity continue after publication of this article. Primarily, the object has been to prepare a basis for further analyses of this type in southern Norway. Secondly, the results are intended for use in a correlative study of lineaments in the landmasses around the North Sea basin.

The methods of structural geological analysis based on remote sensing are still in the development stage. One of the main problems has been to link the observed imagery features to field data. Combined field and photo analysis has been carried out in a number of areas. Comprehensive studies from New York State (Gold *et al.*, 1973; Isachsen, 1976), the Afar region (Mohr, 1973, 1974, 1976; Kronberg *et al.*, 1975) and other areas (see e.g. Hodgson *et al.*, 1976) may set the guidelines for future photogeological analyses.

The most conveniently used imagery is the positive black-and-white type. The method may, however, be improved in various ways by the application of more sophisticated techniques; for instance by using single negatives, combined negative/positive transparencies or "raised plastic relief maps" (Wise, 1969a,b), or various computer-aided techniques including anologue processing of images, optical Fourier filtering, etc. (e.g. Corrêa & Lyon, 1976; O'Leary & Offield, 1977). Similar methods with direct printouts of lineaments, based on digital computer data, are currently being employed (by a research group at the Norwegian Geological Survey) for lineament trend analysis in various parts of Norway (H. Barkey, pers. comm., 1977).

In this article, we have applied the term *lineament*, according to current usage (e.g. El-Etr, 1976; Gary *et al.*, 1972), as a descriptive and non-genetic term for any lineation within or on a rock, ten to one hundred kilometres

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long; *megalineament* when more than one hundred kilometres; and *linear* when less than ten kilometres long. The term *fracture* (joints or faults) concerns naturally occurring lineaments of tectonic origin.

METHODS OF ANALYSIS – IDENTIFICATION OF LINEAMENTS

In this study the lineaments recorded are based on a combined analysis of Landsat satellite photos, topographic maps and geological field data in the form of published maps. In addition to the Landsat images, about 400 topographic maps (largely photo-based maps, scale 1:50 000) and over 100 geological maps have been carefully surveyed for lineaments, known faults and joints.

Landsat imagery

The mapping of lineaments from Landsat imagery has been done by direct tracing from 18 cm square black-and-white prints (spectral bands 5 and 7). The lineations recorded are only those which are 10 km long or more (Encl. 1), although it is clear that closer attention to fine details might have revealed further information in some areas. For the Oslo Graben and vicinity, smaller features (linears) have been included (Encl. 2). Direct lineament mapping is believed to have the advantage of more effective discrimination between tectonic and non-tectonic features than strictly automatic methods. Exclusion of the linears tends to have the same effect.

The lineaments are usually linear or very slightly curvilinear; there is a tendency for them to occur in groups. The lineaments recognised on the prints are generally quite clear and frequent, and no painstaking effort has been made to pick out subtly expressed lineaments possibly reflecting lithological contacts, foliation etc. On the contrary, most lineaments recorded are clearly expressed and commonly coincide with ground-identified faults and joints where such data exists. Thus, the bulk of the lineaments must have a tectonic origin, largely representing faults, fault breccias, closely spaced joints, shear zones etc. Since there is only a negligible amount of soft sedimentary cover to the basement in Norway, the variations in frequency and directional trends of the lineaments are believed to represent true differences in the structural character of the crystalline (basement) rocks within the various subregions.

Topographic maps

The analysis of the topographic maps was intended as a supplementary method to Landsat mapping, and indeed proved in some areas to provide information not supplied by Landsat imagery. The same limits were set for the length of the strike (minimum 10 km). The numerous, marked linear valleys, lakes and drainage systems form a systematic pattern generally in accordance with the Landsat lineaments and previously ground-checked tectonic features. In the enclosed maps, no distinction is therefore made between the "topographic" and the Landsat lineaments, which are both represented by dashed lines.

Geological maps

With regard to the published geological maps, surprisingly few faults are indicated. Type and age of the faults are seldom known, owing to the general lack of stratigraphic markers in a terrain largely composed of Precambrian and early Palaeozoic ("Caledonian") rocks. Only the Permo-Carboniferous faulting associated with the Oslo Graben, the boundary faults of the Eocambrian "Sparagmite" basin and features in a few other provinces represent fault structures of presumed known age, although a maximum age can be assumed in some other places. Observed, field-checked faults are indicated as full lines on the accompanying maps (Encls. 1 and 2). Thicker (or thinner) traces mark more (or less) prominent faults. The downthrown side of the faults is ticked (where known) and arrows indicate the sense of motion on transcurrent faults.

General remarks

In a study like this, numerous biases and errors may influence the final interpretation. Such factors include: influence of the azimuth of solar illumination; varying degree of vegetation, cover and exposed rocks; age of structural elements; confusion between strike lines, joints and other fractures; man-made lineaments; etc. (e.g. Mohr, 1973; Isachsen, 1976; Kowalic & Gold, 1976). Of these factors, Isachsen (1976) found that confusion between strike lines (foliation) and fracture lines occurs most frequently. Hence, care has been taken to avoid such errors. We feel our best tool in this respect to be cross-checking between Landsat images, topographic maps and existing geological maps. Where such control is possible, there seems to be a satisfactory conformity between the various sets of data. Human weaknesses and dispositions can, of course, never be ruled out, as emphasized for instance by Wise (1976).

PREVIOUS STUDIES

As early as 1879, the Norwegian geologist Theodor Kjerulf constructed a "lineament map" of southern Norway (Kjerulf, 1879). This study was based on the drainage pattern as seen on the existing topographic maps. Thus, Kjerulf's work represents one of the earliest attempts ever made of a uniform synthesis of "lineaments". Kjerulf's results have later been re-interpreted by Hobbs (1911) and were quite recently included in a review paper by Hodgson (1976); see Fig. 1.

Brøgger (1884) made a study of similar features, but on a much more local scale (the Skien-Langesund area of the Oslo Region). Other studies include those of Størmer

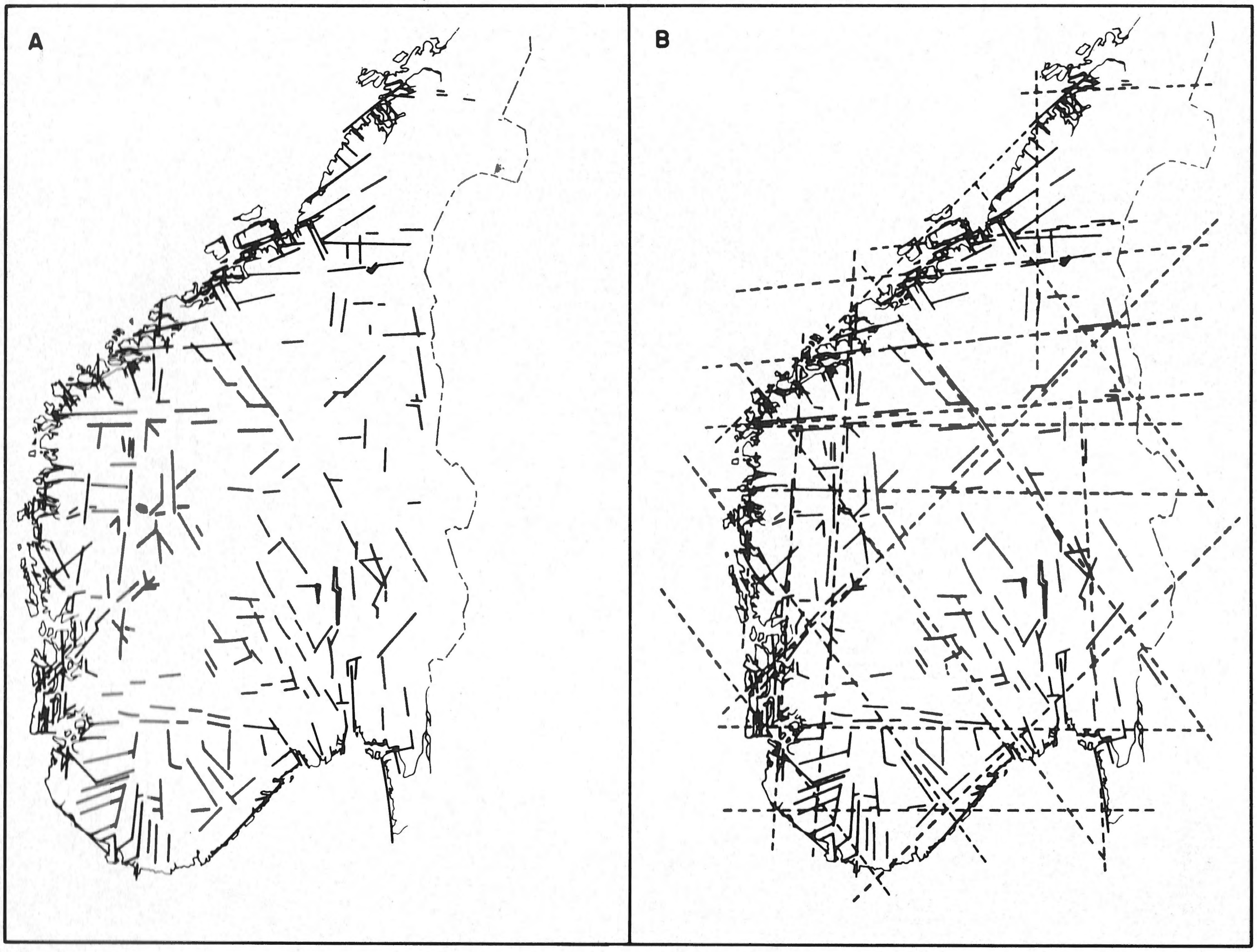

Fig. 1
A: Linear elements in southern Norway (after Kjerulf, 1879).
B: Hobbs' interpretation of Kjerulf's map (after Hobbs, 1911).

(1935) and K v a l e (1948), and a number of papers concerning more restricted areas which will not be reviewed here.

Preliminary versions of the various fracture maps (enclosed) were presented by L a r s e n (1975) and R a m b e r g (1975). Geological and geophysical evidence of possible deep fracture zones have been presented by e.g. R a m b e r g (1973) and H u s e b y e *et al.* (1977).

MAIN GEOLOGICAL FEATURES OF SOUTHERN NORWAY

The observed fracture pattern has been superimposed on a simplified geological map of southern Norway (encl. 3) to demonstrate a possible correlation with lithology, age of rocks, etc. Below, the main geological features are reviewed in brief. For general references, see H o l t e d a h l (1960), B a r t h & R e i t a n (1963) and S t r a n d (1972).

Norway constitutes the western margin of the Fennoscandian (or Baltic) Shield (Fig. 2). In sharp contrast to Central European regions, Norway is characteristically composed of predominantly old rocks. In fact, Precambrian and Cambro-Silurian rocks account for close to 97% of the area. Roughly, the rocks of southern Norway may be divided into four main structural elements: (1) Precambrian provinces, (2) Late Precambrian (Eocambrian) basins, (3) the Caledonian mountain belt, and (4) younger units, mainly Permian rocks of the Oslo Graben and a few Devonian basins.

The Precambrian basement

The Precambrian is divided into three main regions, separated by the Caledonian mountain belt and the Oslo Graben (see Fig. 2 and Encl. 3): i.e. the northwestern (or Møre) gneiss complex and the Precambrian provinces of central and southeastern Norway. All regions consist of heterogeneous gneisses partially covered by folded supracrustals of various ages. Radiometric datings range from about 1700 m.y. (northwestern gneiss complex: P i d g e o n & R å h e i m, 1972; southeastern province: P e d e r s e n,

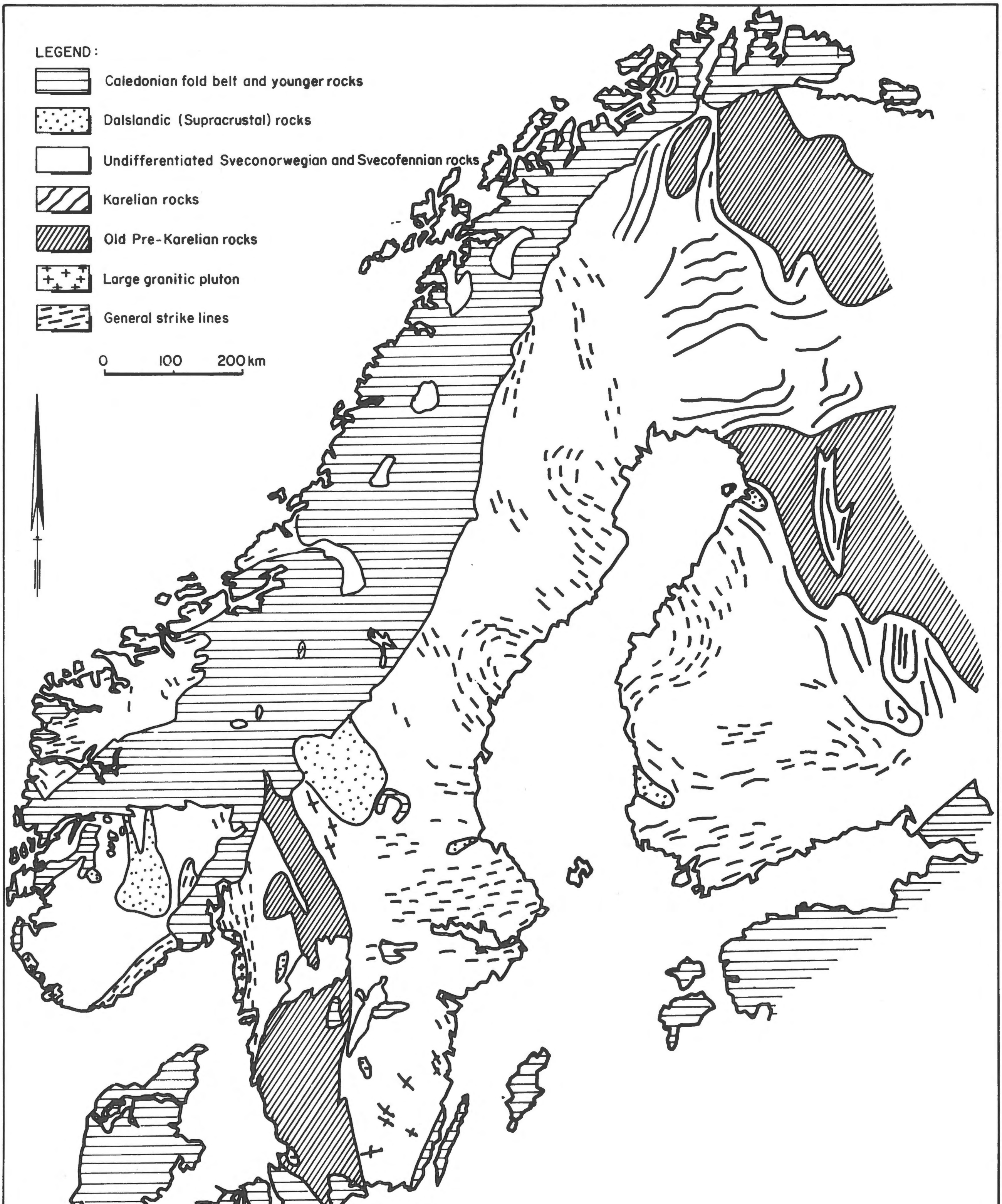

Fig. 2
Simplified geological sketch map of Scandinavia (after Strand, 1973).

1976) to about 1000 m.y. (O'Nions & Baadsgaard, 1971; O'Nions & Heier, 1972; Brueckner, 1972; Jacobsen, 1975; Berg, 1977). These ages include the Svecokarelian, Gothian and Dalslandic episodes (eras) of Lundgårdh (1971). Younger Precambrian plutonic rocks have been found to intrude most of these units (Broch, 1964; Priem *et al.*, 1976).

Within the Precambrian, highly complex folding reveals repeated orogenic events. Despite this, a few dominant structural trends can be recognised. For instance, in the southeastern province an overall NNW trend (Fig. 3) is emphasized by the occurrence of cataclastic zones (e.g. Skjernaa, 1972) and alternating lithological units of contrasting composition. In all the regions, fault breccias and major dislocation zones are found, particularly in the NW-SE and the NE-SW directions. Repeated fragmentation has been demonstrated in a number of places, implying recurrent deformations along the same tectonic zones.

Precambrian rocks are also recognised within the extensive nappes of the Caledonian fold belt.

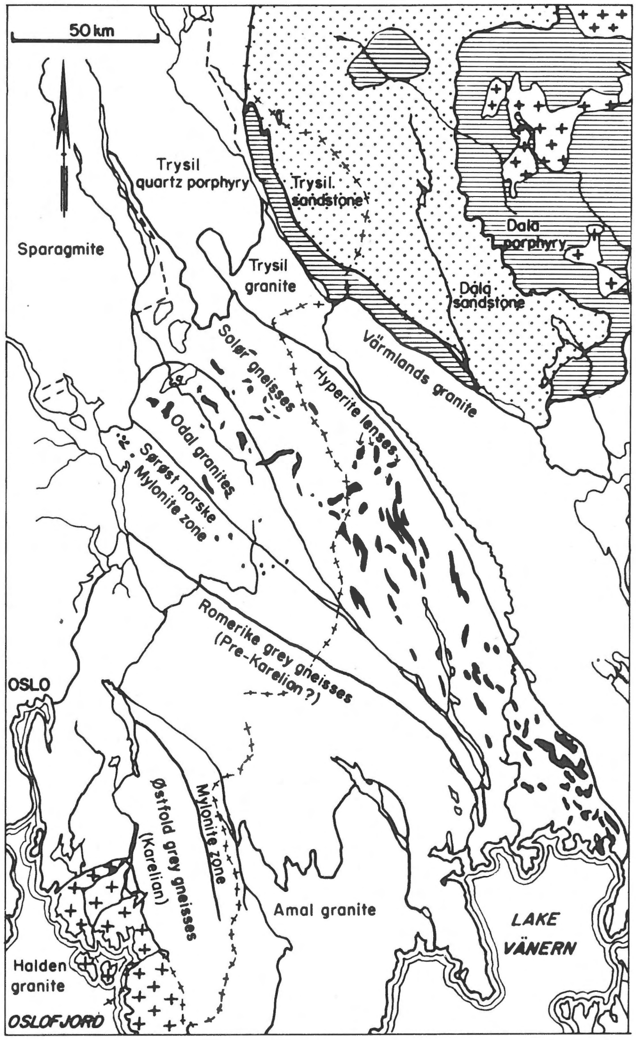

Fig. 3
Geological sketch map of southeastern Norway (after Oftedahl, 1974).

The Eocambrian basin

The Late Precambrian (Eocambrian) rocks, the so-called "Sparagmite" or Hedmark Group (Encl. 3), are a succession of mainly coarse feldspathic sandstones and arkoses, which were deposited in a marginal faulted basin in an early stage of the Caledonian orogeny (Bjørlykke *et al.*, 1976). In space, but not in time, the basin represents a roughly northward continuation of the Oslo Graben (Encl. 3), although post-Caledonian movements have clearly occurred along some of the major faults.

The Caledonian mountain belt

This belt forms the backbone of Norway, defining a gentle arc from the southwestern tip all the way to northern Norway. It is thought to continue southwestwards into the Scottish Caledonides. Hence, Caledonian rocks probably form a substanstial part of the North Sea basement rocks (Ziegler, 1977). In southern Norway, the mountain belt is characterised by piles of nappes which for a considerable part include Precambrian rocks (Strand, 1972; Naterstad *et al.*, 1973; Sturt *et al.*, 1975). Cambro-Silurian rocks are found as a thin veneer of autochthonous to parautochthonous rocks beneath the nappe pile or involved within the nappe system (e.g. Strand, 1972; Naterstad *et al.*, 1973; Gee, 1975).

The structural style is characterised by nappes which were generally thrust from northwest to their present position in elongate tectonic troughs trending almost perpendicular to the direction of transportation. Major features of this kind are the Bergen Arc system (Kvale, 1960; Sturt *et al.*, 1975) and the Central Trough (or "Faltungsgraben" of Goldschmidt, 1916) with its northeastward extension into the axial depression of the Trondheim region (Roberts *et al.*, 1970; Gee, 1975). The troughs are flanked by geanticlinal axes as defined by basement domes and culminations (Ramberg, 1966).

The major tectonic phase of the Norwegian Caledonides took place in Upper Silurian (Roberts, 1971; Kvale, 1975) whereas large-scale structures such as the geanticlinal axes and Central Trough seem to have formed in the Devonian. The Central Trough itself is offset by N-S to NNW-SSE trending faults along the west coast of Norway. Associated alkaline dikes reveal Permian to Mesozoic radiometric ages (Færseth *et al.*, 1976).

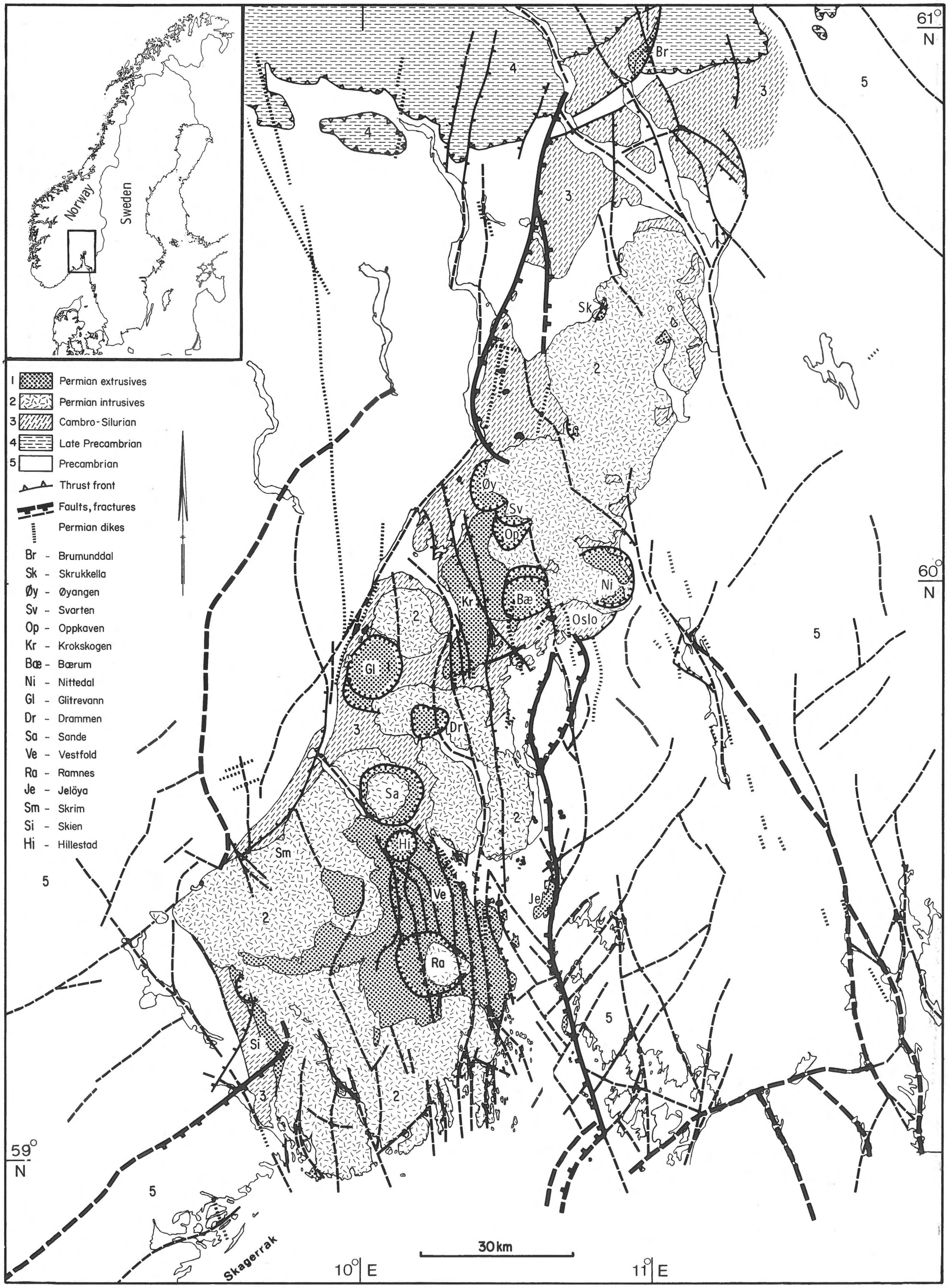

Fig. 4
Oslo Graben, simplified geological map.

The Oslo Graben

The Oslo Graben (O f t e d a h l, 1960; R a m b e r g, 1976), which is approximately 220 km long and 40 – 60 km wide (Encl. 3 and Fig. 4), subsided into the surrounding gneisses in Late Carboniferous to Early Permian time. It is part of an extended continental rift (the Oslo Rift) which has been associated towards the north, with a series of N-S to NNW-SSE trending faults following the "Sparagmite Basin". Towards the south, there is an overall southwestward extension below the Skagerrak (R a m b e r g & S m i t h s o n, 1975), where it ties in with the regional fracture system below the North Sea Basin (B u r k e & D e w e y, 1973; W h i t e m a n *et al.*, 1975; Z i e g l e r, 1975, 1977).

The rather complex graben is bound by normal faults, antithetic step faults and monoclinal flexures. The fracture pattern is sometimes well recorded in the morphological and bathymetric features (Encl. 4). Superimposed on the linear elements, a pronounced system of ring complexes and cauldrons is recognised (Fig. 4).

Many of the Permian faults clearly follow older fractures and mylonite belts, and repeated activity may have persisted well into the Mesozoic (R a m b e r g, 1976). Extensional faulting and associated alkaline igneous activity within the Scandinavian landmass and North Sea rift system exhibit a remarkable contemporaneity (Fig. 5).

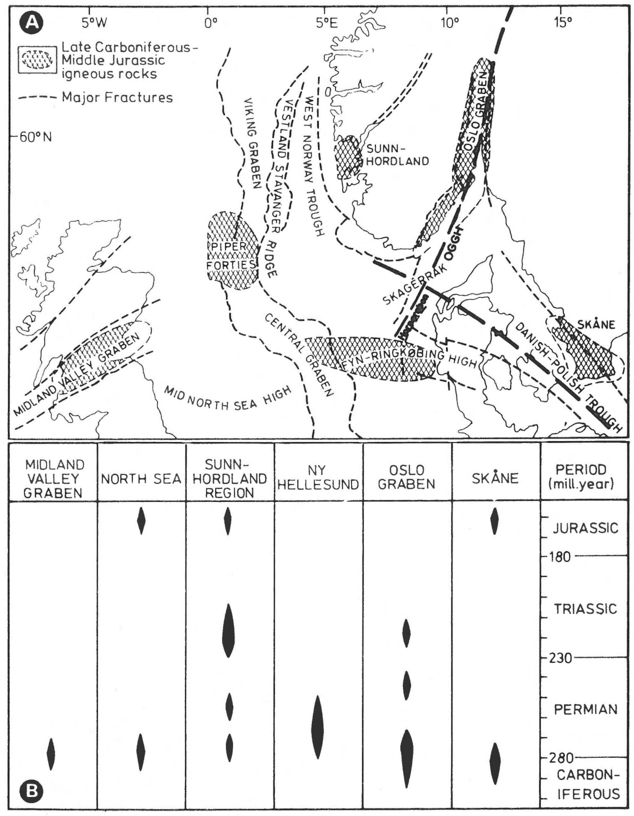

Fig. 5

A: Oslo Graben and North Sea Rift System. OGGH = Oslo Graben gravity high.

B: Ages if igneous rocks from areas indicated in Fig. 5A. (Mainly after Færseth et al., 1976).

GEOPHYSICAL FEATURES

A preliminary contour map of the Mohorovičić discontinuity was presented by S e l l e v o l l (1973). This map, with minor changes due to more recent studies in the Oslo Region and the NORSAR (Norwegian Seismic Array) area (R a m b e r g, 1976; B e r t e u s s e n, 1977; H u s e b y e & R a m b e r g, 1977; E n g l a n d *et al.*, 1977), is shown superimposed on the fracture map (Encl. 5).

Fig. 6, a recently compiled Bouguer anomaly map of southern Norway (R a m b e r g, 1976), together with Encl. 5, shows some important large-scale features.

(1) Outside the Oslo Graben, the Bouguer values correlate inversely with topography; the isogal lines run closely parallel to the smoothed coastline, except in the graben area. This relationship reflects the gross structure of the crust; the calculated "gravity normal crust" (R a m b e r g, 1976 – fig. 18) correlates closely with the Moho contouring shown (Encl. 5).

(2) The Oslo region is marked by a distinct gravity high due to crustal thinning and the presence of mafic rocks intruded into the base of the crust during the initial stages of the taphrogenesis (Fig. 7). The extension of the gravity high far outside the graben area, especially to the SW below the Skagerrak, indicates the continuation of the Oslo Rift in these regions.

(3) A broad gravity low follows the main trend of the Caledonian belt. However, the lowest values occur over the foreland. Here, the axis of minimum gravity anomalies coincides precisely with the miogeanticlinal axis as well as with the largest curstal thicknesses (Encl. 5).

(4) A marked gravity high, associated with the Central Trough, divides the "Caledonian low" into two parts. This high defines a major tectonic line which, according to some authors, represents a palaeo-subduction zone. More likely, however, it marks a zone of Late Caledonian subsidence.

Aeromagnetic maps (H a n n a f o r d & H a i n e s, 1969; S e l l e v o l l & A a l s t a d, 1971; Norwegian Geol. Surv., Trondheim, maps of scale 1 : 50 000) support the suggested existence of Oslo-type igneous rocks below the Skagerrak; the whole rift zone is, in fact, marked by pronounced positive magnetic anomalies centred above the major felsic batholiths. Furthermore, the magnetic anomalies strengthen the impression of several fracture zones parallel to the NNE trend of the Oslo Graben (e.g. the parallel-trending Vättern Graben in southern Sweden).

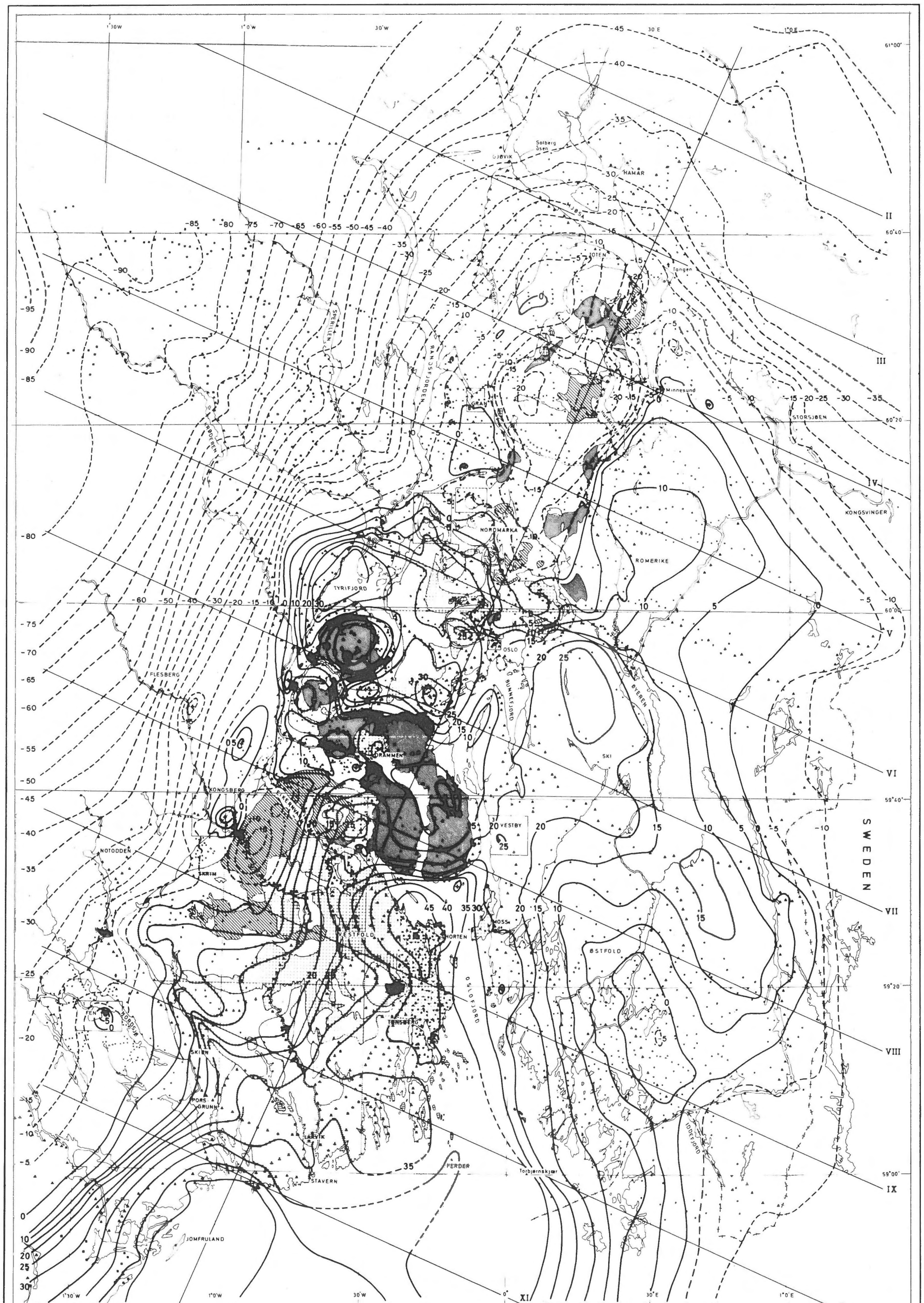

Fig. 6
Bouguer gravity map of the Oslo region (after Ramberg, 1976).

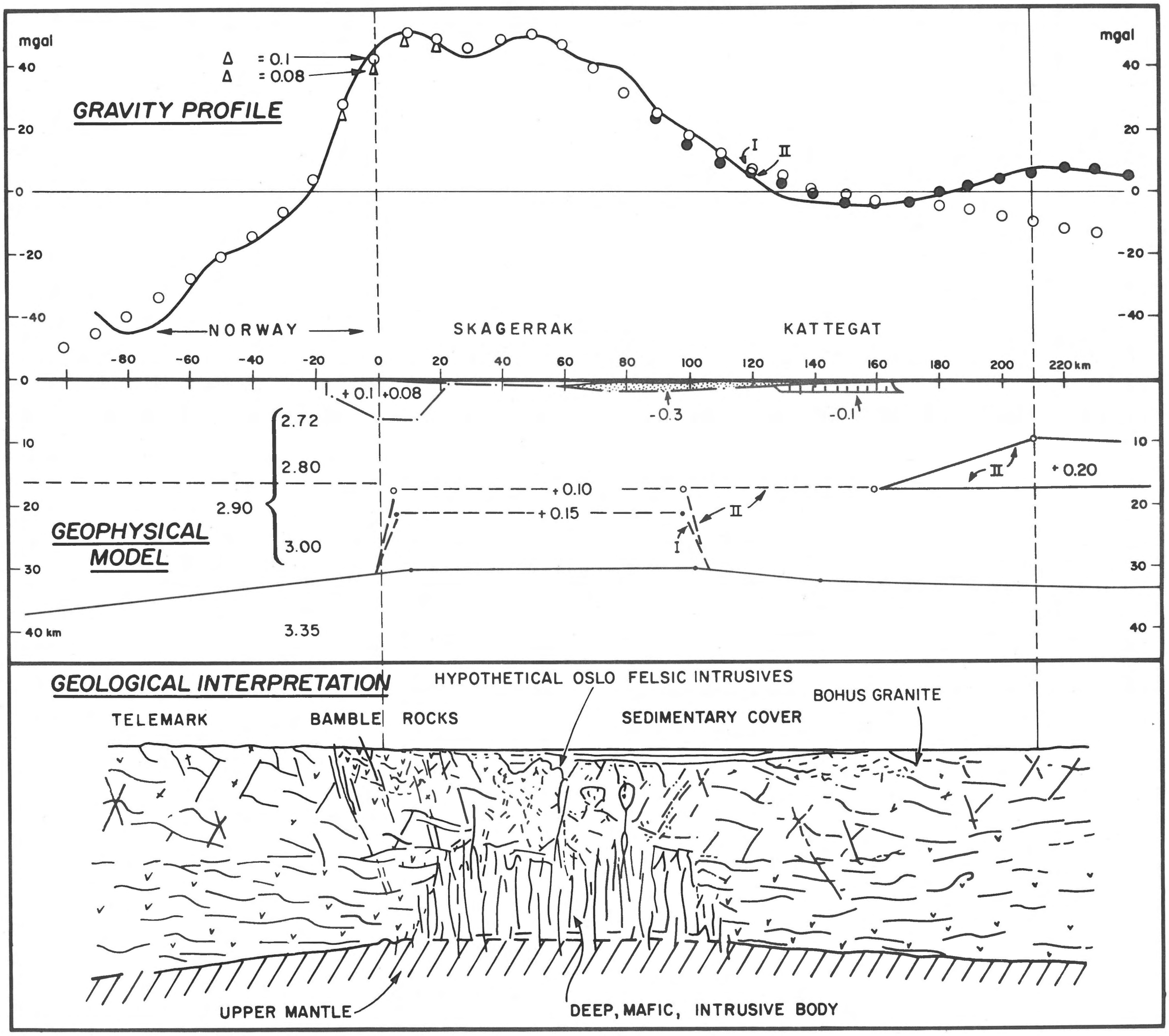

Fig. 7
Gravity profile, geophysical model and geological interpretation of a NW-SE section across the Skagerrak south of the exposed Oslo Graben. Model indicates crustal thinning and position of palaeorift "cushion" below graben (after Ramberg & Smithson, 1975).

FRACTURE ANALYSIS

The prime value of Landsat imagery to structural geology is the regional scale on which the features can be sought and mapped. Perhaps the most striking discoveries to emerge from the study are the marked regularity of the pattern and the pronounced differences in fracture frequency from one area to another, the main features of which were demonstrated by the very early studies of Kjerulf (1879). However, the difference that appears may be of importance to the final interpretation of the pattern.

A glance at the map (Encl. 1) reveals that the *intensity* and *frequency* of the lineaments vary widely. Areas of distinctly higher frequency and intensity occur in the south-eastern parts, in a narrow strip along the west coast and in the Møre gneiss region to the northwest. These differences are definitely real, and if anything, the areas of high intensity are probably somewhat underrepresented with respect to the central zones, where the lineaments are significantly less common and more weakly expressed.

In addition to the frequency and intensity of expression, the *orientation* (or direction of strike) varies distinctly from

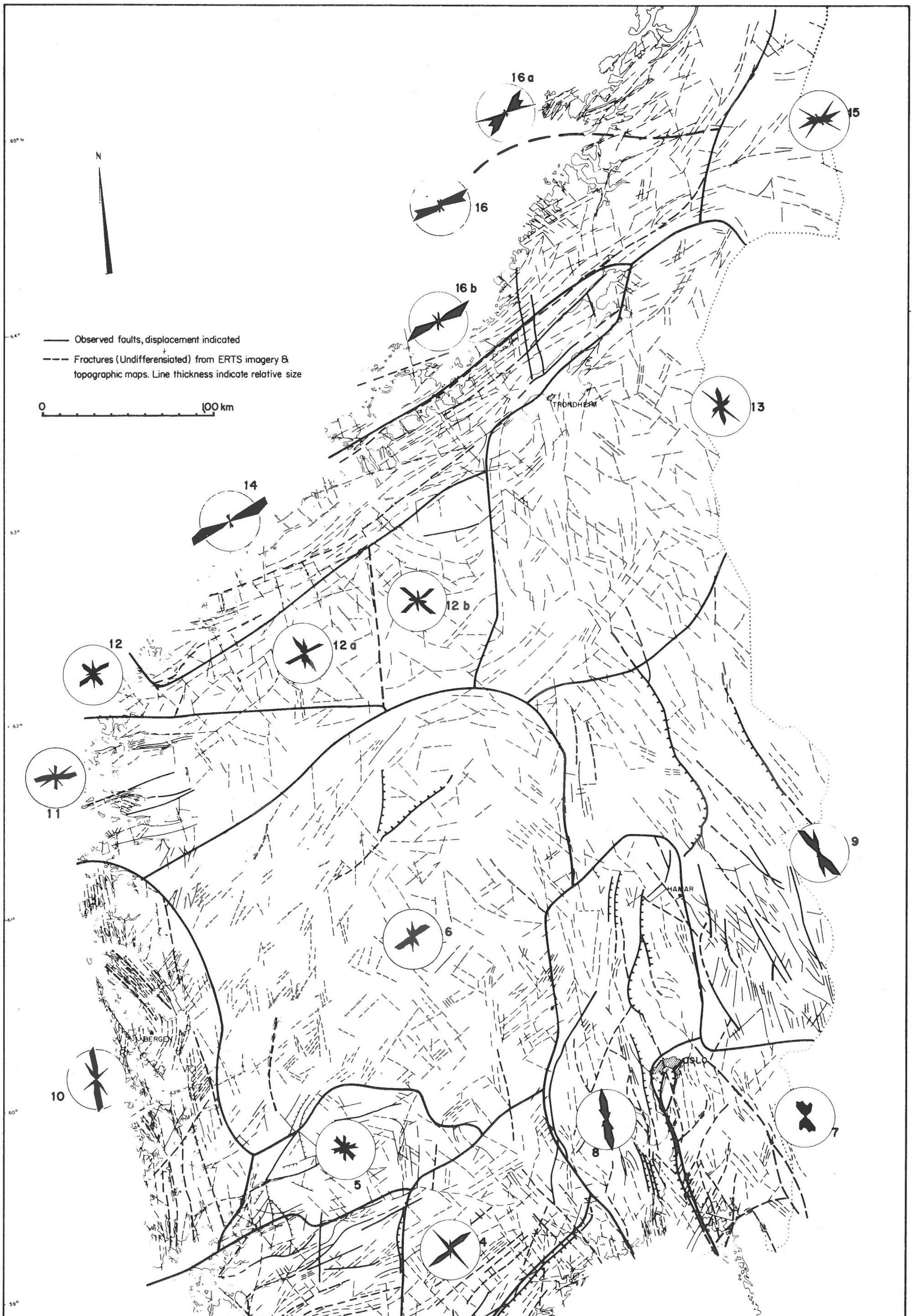

Fig. 8
Fracture pattern,southern Norway, with subarea boundaries and rose diagrams superimposed.

one region to another. In order to study these directional changes, southern Norway has been divided into 16 subareas.

The subareas (S 1 – S 16) were chosen preferentially from structural criteria and *after* plotting of the lineaments. Ideally, each subarea contains a limited number of fracture sets of constant direction. However, the boundaries between areas with homogeneous fracture patterns, in most cases, also separate fields of regional geological significance (Encl. 3 and Fig. 8). In a few cases (S 12 and S 16) the subareas are further subdivided to illustrate special features. Further subdivision might also have been useful for other areas but this would involve problems of a statistical nature.

Rose diagrams were constructed for all subareas (Fig. 9). Fig. 8 displays the diagrams in their appropriate subareas. The recorded fractures vary in number from 34 (S 15) to 378 (S 6). In the diagrams, however, vector units of 10 km length have been used, instead of the actual number of fractures. Thus, more weight has been given to a long fracture line than to a short one. Apart from the strike length, no distinction has been made between major and minor fractures in the diagrams.

Subareas 1 – 4

All these subareas show characteristic maxima in the NE-SW direction, although a distinctly more northerly trend is found for S 3 (the Bamble sector). This difference is tentatively interpreted as being caused by rotation of the Bamble block relative to the adjacent landmass. In addition, gradual curving of the NE-SW trend is observed, going from S 2 to S 4 where it terminates rather abruptly against the Oslo Graben. The NE-SW direction is less marked in S 1. This subarea also reveals a more complex pattern, probably caused by interference of several fracture sets.

NW-SE and N-S trends are recognised in all four subareas, the former being particularly well developed in S 3 and S 4. The same tendency of rotation of the S 3 block is again recognised.

Subarea 5

This subarea seems to represent an area of transition between S 1 – S 4 and the subareas to the north. The N-S direction is becoming more clearly expressed. An E-W trend, elsewhere only associated with the Devonian basins, is rather pronounced.

Subarea 6

This represents the largest area and therefore also contains the largest numbers of fractures recorded; it is distinguished from the other subareas by a lower frequency and weaker development of recognisable lineaments. However, the same general directions as in S 1 – S 4 can be found, with the NE-SW trend (Caledonian direction) being the most dominant.

Subareas 7 & 9

These show predominant N-S and NNW-SSE directions. A NE-SW trend, which is found in S 7 (and in particular close to Oslo Graben), is much less prominent in S 9. The NNW-SSE direction in S 9 is parallel to the boundary faults of the "Sparagmite basin". These faults may have been re-activated during the formation of the Oslo Graben in late Palaeozoic time.

Subarea 8

Subarea 8 (Oslo Graben and vicinity) is characterised by a predominance in the N-S trend, which is the direction of many of the observed faults and dikes of the graben area (see also Encl. 2). The formation of the Oslo Graben peaked in Permo-Carboniferous time (Oftedahl, 1960; Ramberg, 1976). Hence, a late Palaeozoic to Mesozoic age is likely for the (last?) movement along the N-S trend.

Although much less frequent, the NW-SE and NE-SW or "diagonal" trends are also found within S 8.

Subarea 10

Three directions prevail: the "diagonal" sets are superimposed by a predominant N-S (or NNW-SSE) trend. The latter is associated with the relatively young fault and dike system dated as Permian to Triassic (Færseth *et al.*, 1976; Nilsen, 1973, 1976). This configuration is strikingly similar to that of S 8, the Oslo Graben and vicinity.

The NE-SW trend is parallel to the Central through (Goldschmidt, 1916). The Bergen Arc system which may be one of the areas where the lineaments partly represent foliation strike lines, seems responsible for most of the NW-SE lineaments (see Encl. 3).

Subarea 11

This subarea has a significant E-W maximum and is influenced by both the linear systems which dominate S 6 and the northerly areas S 12 – S 16. The E-W trend is associated with the boundary faults of the Devonian sedimentary basins (Bryhni, 1964a,b; Bryhni & Skjerlie, 1976).

Subareas 12 – 16

These are highly influenced by the NE-SW direction which also parallels the coast line. The coastline features define megalineaments that can be traced far into the Norwegian Sea by means of geophysical data (e.g. Talwani & Eldholm, 1972). A roughly N-S trend is also recognised but is subordinate to the former. It seems to represent the northern extension of the N-S fracture belt through the Oslo Graben. Post-Caledonian dikes have been reported from these areas (Carstens, 1961; Råheim, 1974).

The gradual change of the NE-SW trend from S 12 to S 16

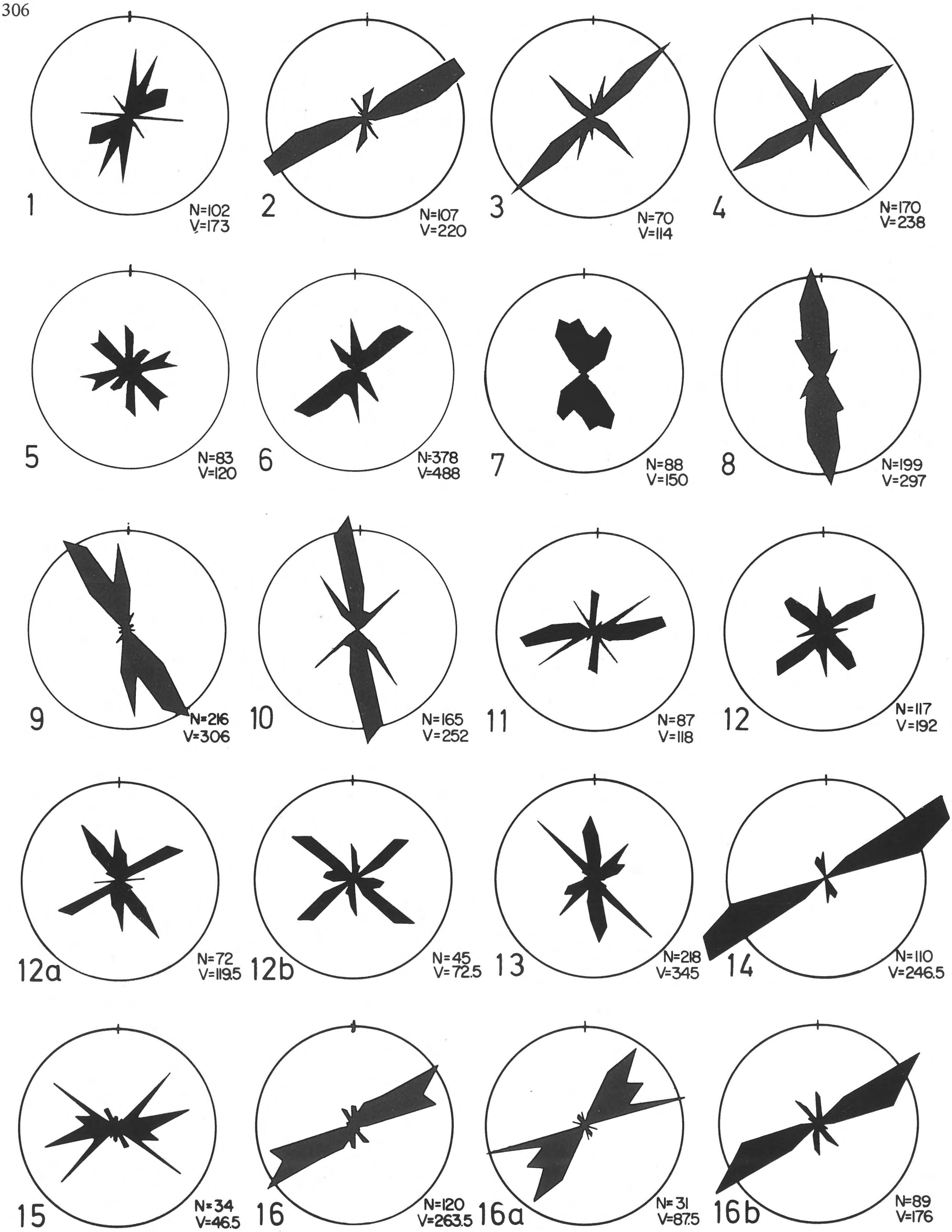

Fig. 9
Rose diagrams of subareas, nos. 1 - 16. Number of vector units of lineament length (10 km) are plotted in 10° wide azimuth sectors. Circle indicates 20% cumulative length of the fractures, N = number of lineaments and V = vector units of length.

is tentatively interpreted as representing truly curved lineaments. However, in S 16 (especially S 16a), another lineament system with a more northerly direction appears superimposed in the NE-SW trend. This "new" NNE-SSW trend is followed by a similar change in the overall coastal direction.

Subarea 13 (Caledonides of the Trondheim region) reveals the same trends as S 12 and S 16, but with the NW-SE and N-S trends more strongly developed. The apparent rotation of the lineaments in the southwestern part of the areas reflects the arching of the Trondheim region itself, and is worth noting.

DETAILS OF THE OSLO GRABEN AND VICINITY (SUBAREA 8)

Within the Oslo Graben, intrusive rocks constitute a large part of the area, whereas extrusives occur mainly within two lava plateaus (Vestfold and Krokskogen) and within the cauldrons (see Fig. 4 for details).

In detail, the fracture pattern of the Oslo Graben and vicinity appears much more complicated than on the regional scale (Encl. 2). From the simplified geological map (Fig. 4), one will see that the complex graben is subdivided into two graben segments: one to the NNE, the other to the SSW. The graben segments occur on both sides of the major, central boundary fault of the main graben, and are symmetrical about the cluster of cauldrons just north of the city of Oslo. This type of *en echelon* offsetting is supposed to characterise the overall SW-ward continuation of the Oslo Rift below the Skagarrak.

Subareas 4 & 6 (to the west of the graben), subarea 8 (graben area) and subareas 7 & 9 (east of the graben) reveal that the striking N-S fracture set within the graben is hardly developed in the thick crustal block to the west, but is quite common to the east. This may reflect the asymmetry of the palaeorift "cushion" which is terminated much more abruptly to the west than to the east. It is also of interest to note that the present seismicity of the area seems to be concentrated along the Oslo Graben *and* the area immediately to the east.

The great Oslofjord boundary fault has the appearance of a complex fault system with branching NW- and NE-trending splay faults (Encl.2 and Fig.4, southern halves). The main fault itself has an aggregate dip-slip displacement of about 3 km in the south and about 1 km in the north. Observed strike-slip displacement of about 200 m in the north reveals a right-lateral sence of movement, whereas several of the NE-trending "splay" faults display left-lateral movement. Although the relative movements in the Oslo Graben fault system have not as yet been worked out in detail, many of the structural features are compatible with a general NE (to NNE) trending left-lateral shear zone, parallel to the Great Glen fault which was subjected to major left-lateral displacement at this time.

CONCLUDING REMARKS

Mapping of the Landsat imagery and topographic map lineaments has revealed a strikingly regular pattern in southern Norway. In general, the significance of the lineaments observed in Landsat images is still a matter of debate. For instance, the importance of the individual lineaments cannot be simply derived from their intensity of expression, and the distinction between lithological and fracture lineaments can be difficult. However, in a terrain of fairly strong relief and of generally well-exposed, folded, crystalline rocks, as in Norway, one would expect that fracture lineaments would usually appear with an unmistakable clarity and linearity compared with lithological boundaries. This, combined with the accordance with geological observations, suggests that the majority of the lineaments included in the fracture maps (Encls. 1 & 2) indeed represent fractures (faults, closely spaced joints, breccias, mylonite belts etc.).

With due reserve, some of the results of this preliminary study are summarised below.

(1) The overall coastal direction of the various parts of southern Norway reflects the trends of the most prominent, local fracture set (mostly either N-S or NE-SW, but also NNE-SSW in the northernmost part).

(2) A "diagonal" set of roughly NW-SE and NE-SW trending fractures is almost omnipresent. The NE-SW trend is most intensely expressed in two wide belts along the Precambrian regions of the south coast (Sørlandet) and the northwest coast (Møre). The NW-SE direction predominates in the eastern part of the region.

(3) N-S fractures occur specifically in belts through the Oslo region and along the west coast, forming two broad megalineaments separated by a 250 km wide zone, which is much less influenced by the N-S fractures.

(4) E-W fractures are moderately developed in some coastal regions, associated in part with the migrating Devonian sedimentary basins.

(5) The mountainous central part of southern Norway forms a trapezoidally shaped cratonic fragment bordered by the two N-S and the two NE-SW trending belts.

(6) Superimposed on the regular fracture pattern, nonsystematic local fractures occur throughout the study area. They are associated partly with known geological features (such as plutonic rocks and explosion vents) and partly with hitherto unexplained local features.

(7) Inclusion of linears (lineations shorter than 10 km) would partly have tended to emphasise the irregular part of the pattern (see Encl. 2) and partly have strengthened the intensity of expression within the fracture belts mentioned.

From the above description, one can tentatively suggest that the two "diagonal" sets, which are most apparent in the Precambrian terrains, represent an old, possibly regmatic shear pattern of repeatedly rejuvenated fractures. The pattern is characteristic of the greater part of the southwest margin of the Fennoscandian Shield, which also extends further SW-ward as basement below most of the North Sea Basin. The "diagonal" pattern is an extremely common fracture or lineament pattern (e.g. H. Cloos, 1928; Riedel, 1929; E. Cloos, 1932, 1955; Tchalenko, 1970; Wilcox *et al.*, 1973; Holmgren, 1976; Fielder *et al.*, 1976) which may (initially) have formed in response to planetary forces.

The main Caledonoid trend in southern Norway follows one of the diagonal directions (NE-SW), and some of the major faults and flexures in the south central area (S 6 and S 10) reflect the same orientation. Some of the lineaments are clearly Late Caledonian, indicating possible dependence of the Caledonian structures upon older trends. In itself the Caledonian fold belt seems to represent a zone of less intense fracturing (on the scale discussed here). In general, the NE-SW set is regarded as a complex system with several distinguishable azimuthal directions caused partly by block-faulting and rotation (in the south) and partly by interfering fracture systems (in the north).

The E-W trend, which appears in some coastal areas, is again complex, being associated with Precambrian dikes in the south (S 1 and S 2) as well as with boundary faults of Devonian sedimentary basins further to the north (S 11). These basins may have a wide distribution within the North Sea area and are also known from Scotland.

The N-S trend appears to cross-cut other trends and is clearly associated with the youngest tectonic elements in Norway. The Oslo Graben and the west coast area (adjacent to the West Norwegian Trough) are both characterised by tensional tectonics and alkaline igneous rocks of Permian to Mesozoic age. These ages accord well with similar events within the North Sea Basin and adjacent landmasses. The west coast of Norway and the Oslo Graben (and its axial projection) also represent the regions of the largest seismic acitivity in southern Norway (Huseby *et al.*, 1977). However, the activity is relatively moderate.

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REFERENCES

Barth, T.F.W. & P. Reitan, (1963) – Precambrian of Norway. *In*: Rankama, K. (ed.): The Precambrian, Vol. I. Interscience Publ., New York, P. 27-80.

Berg, Ø. (1977) – En geokronologisk analyse av prekambriske basement i distriktet Røldal-Haukelisaeter-Valldalen ved Rb-Sr-whole-rock metoden, dets plass i den sørvestnorske provinsen, og en vurdering av denne provinsen i lys av det generelle geokronologiske mønster i det nord-atlantiske prekambriske området. Unpubl. cand. real. thesis, Univ. of Oslo, 125 pp.

Berteussen, K.-A. (1977) – Moho depth determinations based on spectral ratio analysis of long period P-waves. Phys. Earth Planet. Int. (in press).

Bjørlykke, K., A. Elvsborg & T. Høy, (1976) – Late Precambrian sedimentation in the central sparagmite basin of South Norway. Norsk geol. Tidsskr., 56, p. 233-290.

Broch, O.A. (1964) – Age determinations of Norwegian minerals up to March 1964. Nor. geol. Unders., 228, p. 84-113.

Brøgger, W.C. (1884) – Spaltenverwerfungen in Gegend Langesund-Skien. Nyt Mag. Naturvidensk., 28, p. 253-419.

Brueckner, H.K. (1972) – Interpretation of Rb-Sr ages from the Precambrian and Paleozoic rocks of southern Norway. Am. J. Sci., 272, p. 334-358.

Bryhni, I. (1964a) – Migrating basins on the Old Red continent. Nature, 202, p. 384-385.

——, (1964b) – Sediment structures in the Hornelen series. Nor. geol. Tidsskr., 44, p. 486-488.

Bryhni, I. & F.J. Skjerlie (1975) – Syndepositional tectonism in the Kvamshesten district (Old Red Sandstone), western Norway. Geol. Mag., 112, p. 593-600.

Burke, K. & J.F. Dewey (1973) – Plume-generated triple junctions; key indicators in applying plate tectonics to old rocks. J. Geol., 81, p. 406-433.

Carstens, H. (1961) – A post-Caledonian ultrabasic biotite lamprophyre dyke of the island Ytterøy in the Trondheimsfjord, Norway. Nor. geol. Unders., 215, p. 10-21.

Cloos, E. (1932) – "Feather joints" as indicators of the direction of movements on faults, thrusts, joints, and magmatic contacts. Proc. Nat. Acad, Sci., 18, p. 387-395.

——, (1955) – Experimental analysis of fracture patterns. Geol. Soc. Am., Bull., 66, p. 241-256.

Cloos, H. (1928) – Experimente zur innern Tektonik. Centralblatt Miner., Abt. B., p. 609-621.

Corrêa, A.C. & R.J.P. Lyon (1976) – An application of optical Fourier analysis to the study of geological linear features in ERTS-1 imagery of California. *In*: R.A. Hodgson *et al.* (eds.): Proc. First Internat. Conf. on the New Basement Tectonics, Utah 1974. Utah Geol. Ass. Publ., 5, p. 462-479.

El-Etr, H.A. (1976) – Proposed terminology for natural linear features. *In*: R.A. Hodgson *et al.* (eds.): Proc. First. Internat. Conf. on the New Basement Tectonics, Utah 1974. Utah Geol. Ass. Publ., 5, p. 480-489.

England, P.C., E.S. Husebye & I.B. Ramberg (1977) – The ideal body concept in interpretation of the Oslo Rift and their correlation with seismic observations. NATO Advanced Study Institute on Paleorift Systems, July/Aug. 1977, Oslo (Abstract).

Færseth, R.B., R.M. MacIntyre & J. Naterstad (1976) – Mesozoic alkaline dykes in the Sunnhordland region, western Norway; Ages, geochemistry and regional significance. Lithos, 9, p. 331-345.

Fielder, G., R.J. Fryer, P.J.S. Gash, J.L. Whitford-Stark & L. Wilson (1976) – Lineament patterns on the Moon, Mars and Mercury. *In*: R.A. Hodgson *et al.* (eds.): Proc. First Internat. Conf. on the New Basement Tectonics, Utah 1974. Utah Geol. Ass. Publ., 5, p. 379-387.

Gary, M., R. McAfee Jr. & C.L. Wolf (eds.) (1972) – Glossary of geology. Am. Geol. Inst. Wash., 805 pp.

Gee, D.G. (1975) – A tectonic model for the central part of the Scandinavian Caledonides. Am. Jour. Sci., 275-A, p. 468-515. geology. Am. Geol. Inst. Wash., 805 pp.

Gold, D.P., R.R. Parizek & S.S. Alexander (1973) – Analysis and application of ERTS-1 data for regional geological mapping. Technical presentations of symposium on significant results obtained from the Earth Resources Technology Satellite-1. NASA SP-327, 1, p. 231-246.

Goldschmidt, V.M. (1916) – Übersicht der Eruptive-gesteine im Kaledonischen Gebirge zwischen Stavanger und Trondhjem. Skr. Vidensk. Selsk., Christiania, 2, 140 pp.

Hannaford, W. & G.V. Haines (1969) – A three-component aeromagmetic survey of the Nordic countries and the Greenland Sea. Publ. Can. Dom. Obs., 37, p. 113-149.

Hobbs, W.H. (1911) – Repeating patterns in the relief and in the structure of the land. Geol. Soc. Am., Bull., 22, p. 123-176.

Hodgson, R.A. (1976) – Review of the significant early studies in lineament tectonics. *In*: R.A. Hodgson *et al.* (eds.): Proc. First Internat. Conf. on the New Basement Tectonics, Utah 1974. Utah Geol. Ass. Publ., 5, p. 1-10.

Hodgson, R.A., S. Parker Gay Jr. & J.Y. Benjamins (eds.) (1976) – Proceedings of the First International Conference on the New Basement Tectonics, Utah 1974. Utah Geol. Ass. Publ., 5, 636 pp.

Holmgren, D.A. (1976) – Major fracture patterns in the British Isles. *In:* R.A. Hodgson *et al.* (eds.): Proc. First Internat. Conf. on the New Basement Tectonics, Utah 1974. Utah Geol. Ass. Publ., 5, p. 263-278.

Holtedahl, O. (ed.) (1960) – Geology of Norway. Nor. geol. Unders., 208, 540 pp.

Husebye, E.S., H. Bungum, J. Fyen & H. Gjøystdal (1977) – Earthquake activity in Fennoscandia between 1449 and 1975 and intraplate tectonics. Norsk geol. Tidsskr. (in press).

Husebye, E.S. & I.B. Ramberg (1977) – Geophysical investigations. *In:* J.A. Dons & B.T. Larsen (eds.): The Oslo Paleorift. Guidebook to excursions, Nor. geol. Unders., (in press).

Isachsen, Y.W. (1976) – Fracture analysis of New York State using multistage remote sensor data and ground study; possible application to plate tectonic modeling. *In:* R.A. Hodgson *et al.* (eds.): Proc. First Internat. Conf. on the New Basement Tectonics, Utah 1974. Utah Geol. Ass. Publ., 5, p. 200-217.

Jacobsen, S.B. (1975) – Geochronological, geochemical and petrological investigations of Precambrian rocks in the Kongsberg area. Unpubl. cand. real. thesis, Univ. of Oslo, 134 pp.

Kjerulf, T. (1879) – Udsigt over det sydlige Norges geologi. W.C. Fabritius, Christiania, 262 pp. (including atlas).

Kowalic, W.S. & D.P. Gold (1976) – The use of Landsat-l imagery in mapping lineaments in Pennsylvania. *In:* R.A. Hodgson *et al.* (eds.): Proc. First Internat. Conf. on the New Basement Tectonics, Utah 1974. Utah Geol. Ass. Publ., 5, p. 236-249.

Kronberg, P., M. Schönfeld, R. Günther & P. Tombos (1975) – ERTS-1 data on the geology and tectonics of the Afar/Ethiopia and adjacent regions. *In:* A. Pilger & A. Rösler (eds.): Afar Depression of Ethiopia. Proc. Internat. Symp. on the Afar Region and related rift problems, held in Bad Bergzabern (F.R. Germany, 1974), 1, p. 19-27. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

Kvale, A. (1948) – Petrologic and structural studies in the Bergsdalen quadrangle, Western Norway. Part II. Structural geology. Bergen Mus. Årbok 1946-1947. Naturvit rekke, 1, 225 pp.

_____, (1960) – The nappe area of the Caledonides in Western Norway. Nor. geol. Unders., 212, 43 pp.

_____, (1975) – Caledonides in Scandinavia compared with East Greenland. Bull. geol. Soc. Denmark, 24, p. 129-160.

Larsen, B.T. (1975) – Geology and tectonics of the Oslo Rift Zone. Tech. Rep., Norges Vassdrags- & El.-verk. Job no. 6777-01, Feb. 1975, p. 27-62. (Including Oslo Region Tectonic Map, 1:250,000).

Lundegårdh, P.H. (1971) – Neue Gesichtspunkte zum Schwedischen Präkambrium. Geol. Rundsch., 60, p. 1392-1405.

Mohr, P.A. (1973) – Structural geology of the African rift system: Summary of the new data from ERTS-l imagery. Presented at 3rd ERTS Symposium, Washington, D.C., December; Center Astrophys. Prepr. Ser., 41, 25 pp.

_____, (1974) – Mapping of the major structures of the African rift system from ERTS-l imagery. Smithsonian Astro. Obs. Spec. Rept; 361, 70 pp.

_____, (1976) – ENE-trending lineaments of the African rift system. *In:* R.A. Hodgson *et al.* (eds.): Proc. First Internat. Conf. on the New Basement Tectonics. Utah 1974. Utah Geol. Ass. Publ., 5, p. 327-336.

Naterstad, J., A. Anderson & K. Jorde (1973) – Tectonic succession of the Caledonian nappe front in the Haukelisæter-Røldal area, Southwest Norway. Nor. geol. Unders; 292, 20 pp.

Nilsen, T. (1973) – The relation of joint patterns to the formation of fjords in western Norway. Norsk geol. Tidsskr; 53, p. 183-194.

_____, (1976) – Mesozoic rifting of the North Sea region and the formation of joints on the west coast of Norway. Norsk geol. Tidsskr; 56, p. 455-456.

Oftedahl, Chr. (1960) – Permian rocks and structures of the Oslo Region. *In:* O. Holtedahl (ed.): Geology of Norway. Nor. geol. Unders., 208, p. 298-343.

_____,(1974) – Norges Geologi. Tapir, Trondheim, 169 pp.

O'Leary, D.W. & T.W. Offield (1977) – New Basement tectonics. Geotimes, 22, p. 21-22.

O'Nions, R.K. & H. Baadsgaard (1971) – A radiometric study of polymetamorphism in the Bamble region, Norway. Contr. Mineral. Petrol., 34, p. 1-21.

O'Nions, R.K. & K.S. Heier (1972) – A reconnaissance Rb-Sr-geochronological study of the Kongsberg area, south Norway. Norsk geol. Tidsskr., 52, p. 143-150.

Pedersen, S. (1976) Rb/Sr-dateringer af plutoniske bjergarter fra Østfold. Abstracts, XII Geologivintermøtet, Gøteborg, jan. 1976. Geol. Inst. Chalmars tekn. högskola, 43.

Pidgeon, R.T. & A. Råheim (1972) – Geochronological investigation of the gneisses and minor intrusive rocks from Kristiansund, west Norway. Norsk geol. Tidsskr., 52, p. 241-256.

Priem, H.N.A., N.A.I.M. Boelrijk, E.H. Hebeda, E.A.Th. Verdurmen & R.H. Verschure, (1976) – Isotope geochronology of the Eidfjord granite, Hardangervidda, West Norway. Nor. geol. Unders., 327, p. 35-39.

Ramberg, H. (1966) – The Scandinavian Caledonides as studied by centrifuged dynamic models. Uppsala Univ. Geol. Inst., Bull., 43, 72 pp.

Ramberg, I.B. (1973) – Gravity studies in the Fen Complex, Norway, and their petrological significance. Contr. Mineral. Petrol., 38, p. 115-134.

_____, (1975) – Southern Norway and Vicinity – a tectonic synopsis. Tech.Rep., Norges Vassdrags- & El.-verk. Job no. 6777-01, Feb. 1975, p. 1-24 (2 maps, including 1:1,000,000 Tectonic Map.).

_____, (1976) – Gravity interpretation of the Oslo Graben and associated igneous rocks. Nor. geol. Unders., 325, 194 pp.

Ramberg, I.B. & S.B. Smithson (1975) – Geophysical interpretation of crustal structure along the southeastern coast of Norway and the Skagerrak. Geol. Soc. Am., Bull., 86, p. 769-774.

Riedel, W. (1929) – Zur Mechanik geologischer Brucherscheinungen: Ein Beitrag zum Problem der Fiederspalten. Zentralbl. Min. Geol, Pal., Abt. B., p. 354-368.

Roberts, D. (1971) – Timing of Caledonian evorogenic activity in the Scandinavian Caledonides. Nature Phys. Sci., 232, p. 22-23.

Roberts, D., J. Springer, & Fr.Chr. Wolff, (1970) – Evolution of the Caledonides in the northern Trondheim region, Central Norway: a review. Geol. Mag., 107, p. 133-145.

Råheim, A. (1974) – A post-Caledonian syenite porphyry dyke in the western gneiss region, Tusna, central Norway. Norsk geol. Tidsskr., 54, p. 139-148.

Sellevoll, M.A. (1973) – Mohorovičić discontinuity beneath Fennoscandia and adjacent parts of the Norwegian Sea and the North Sea. Tectonophysics, 20, p. 359-366.

Sellevoll, M.A. & I. Aalstad (1971) – Magnetic and seismic profiling in the Skagerrak. Marine Geophys. Res., 1, p. 284-302.

Skjernaa, L. (1972) – The discovery of a regional crush belt in the Ørje area, Southeast Norway. Norsk geol. Tidsskr., 52, p. 459-461.

Strand, T. (1972) – The Norwegian Caledonides. *In:* T. Strand & O. Kulling (eds.): Scandinavian Caledonides. Wiley-Interscience. London-New York, p. 5-145.

———, (1973) – Geologi er også vårt lands historie. *In:* I.Th. Rosenqvist (ed.): Geologien og mennesket. Gyldendal Norsk Forlag, Oslo, 293 pp.

Sturt, B.A., A.T. Ohanian, I.R. Pringle & O. Skarpnes (1975) – A reconnaissance Rb/Sr isochron study in the Bergen Arc System, and regional implications. Nature, 253, p. 595-599.

Størmer, L. (1935) – Contribution to the geology of the southern part of the Oslofjord. The rhomb porphyry conglomerate with remarks on younger tectonics. Norsk geol. Tidsskr., 15, p. 43-133.

Talwani, M. & O. Eldholm (1972) – Continental margin off Norway: A geophysical study. Geol. Soc. Am. Bull., 83, p. 3575-3606.

Tchalenko, J.S. (1970) – Similarities between shear zones of different magnitudes. Geol. Soc. Am., Bull., 81, p. 1625-1640.

Whiteman, A., D. Naylor, R. Pegrum & G. Rees (1975) – North Sea troughs and plate tectonics. Tectonophysics, 26, p. 39-54.

Wilcox, R.E., T.P. Harding & D.R. Seely (1973) – Basic wrench tectonics. Bull. Am. Assoc. Petr. Geol., 57, p. 74-96.

Wise, D.U. (1969a) – Pseudo-radar topographic shadowing for detection of subcontinental sized fracture systems. Proc. of 6th. Internat. Symp. on Remote Sensing of the Environment, Univ. of Mich., p. 603-615.

———, (1969b) – Regional and subcontinental sized fracture systems detectable by topographic shadow techniques. *In:* A.J. Baer & D.K. Norris (eds.): Research in Tectonics, Geol. Soc. Can. Paper, 68-52, p. 175-199.

———, (1976) – Linesmanship: Guidelines for a thriving geological artform. *In:* R.A. Hodgson *et al.* (eds.): Proc. First Internat. Conf. on the New Basement Tectonics, Utah 1974. Utah Geol. Ass. Publ., 5, p. 635-636.

Ziegler, P.A. (1975) – North Sea basin history in the tectonic framework of North-Western Europe. *In*: A.W. Woodland (ed.): Petroleum and the continental shelf of North-West Europe. 1, Geology. Applied Science Publ., London, p. 131-148.

———, (1977) – Geology and hydrocarbon provinces of the North Sea. Geo-Journal, 1, p. 7-31.