Journal of Structural Geology, Vol. 11, No. 3, pp. 295 to 305, 1989
Printed in Great Britain

0191-8141/89 $03.00 + 0.00
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Resurgent strike-slip duplex development along the Hitra-Snåsa and Verran Faults, Møre-Trøndelag Fault Zone, Central Norway

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(*Received* 5 *April* 1988; *accepted in revised form* 14 *September* 1988)

Abstract—Lineament analysis of the ENE–WSW Verran and Hitra-Snåsa Faults of the long-lived Møre-Trøndelag Fault Zone (MTFZ), has revealed the presence of a complex array of anastomosing faults and fractures. This has the geometric configuration of a major, dextral, strike-slip fault zone and compares well with characteristic patterns of braided wrench-faulting, e.g. the San Andreas Fault System of California. The fault array recognized in conjunction with the Verran Fault is clearly post-Caledonian and is considered to define a dextral, strike-slip duplex system. Associated with the parallel Hitra-Snåsa Fault are Riedel-like structures which tend to point to an earlier component of sinistral movement. Rock products present along the Hitra-Snåsa Fault and its secondary faults comprise mylonites, hydrothermally altered rocks and small-scale recrystallized breccias. Along the main Verran Fault, evidence of late polyphasal deformation is seen in several discrete episodes of brecciation, hydrothermal alteration, and locally pervasive prehnite and stilbite veining.

The fault structures occurring along the Hitra-Snåsa and Verran faults are thought to have originated as a sinistral fault system of late Devonian age, especially for the Hitra-Snåsa lineament. Subsequently, strike-slip movement reversed in sense and shifted locus towards the Verran Fault system during the late Jurassic or early Cretaceous. During this strike-slip reversal, some earlier fractures related to the sinistral system were rejuvenated within the stress field of the evolving dextral duplex system. Strike-slip displacements of a similar age are known from fault complexes on the Norwegian continental shelf and in the northern North Sea. The regional picture indicates that the MTFZ was almost certainly linked to the fault systems of northern Scotland, prior to the opening of the Viking Graben.

INTRODUCTION

IN Central Norway the westernmost parts of the counties Møre and Nord- and Sør-Trøndelag are characterized by a prominent ENE–WSW topographic grain. To a large extent this reflects the dominant Caledonide strike trend of a variety of lithological units (Sigmond *et al.* 1984), but there is also substantial evidence favouring the existence of major regional faults of this same general trend (Oftedahl 1975, Aanstad *et.al.* 1981), a pattern which has been confirmed by satellite remote-sensing lineament studies (Ramberg *et al.* 1977, Offield *et al.* 1982, Rindstad & Grønlie 1986).

While the satellite imagery analyses have been of immense value in detecting regional-scale lineament sets and systems (cf. Offield *et al.* 1982), the interpretation of these structures is severely limited without follow-up from field investigations. In particular, geological mapping in most cases provides the key to a secure interpretation of lineaments; not all can be assumed to represent major faults, and some have proved to be topographic expressions of Quaternary morphotectonic elements.

In the present study we have combined lineament patterns derived from satellite imagery with an interpretation of aerial photographs and close examination of available published and unpublished 1:50,000 geological maps, in an analysis of the northeastern part of the Møre-Trøndelag Fault Zone (MTFZ) (Gabrielsen & Ramberg 1979, Gabrielsen *et al.* 1984), to the northwest and north of Trondheimsfjord (Fig. 2). This study has revealed the presence of a complex array of anastomosing faults and fractures which display the geometric configuration of a major, dextral strike-slip fault zone. The pattern is one which compares readily with those described from well-known right-lateral fault complexes, such as the San Andreas Fault System (SAFS), California (Crowell 1974, Dibblee 1977), and has not hitherto been reported from Scandinavia.

GEOLOGICAL SETTING

The part of the MTFZ considered here extends from Stjørnfjord, outer Trondheimsfjord, in the southwest, to Snåsa in the northeast (Figs. 1 and 2), a distance of more than 200 km. In the Verran district, the complex fault zone has a width of over 20 km. The bedrock involved in the faulting comprises a basal Precambrian crystalline complex of heterogeneous gneisses with some metagranitoids and metagabbros. This is tectonostratigraphically overlain by amphibolite facies psammites, schists and amphibolites and, higher up, by low-grade metasediments and greenstones (Wolff 1976, Sigmond *et al.* 1984). These cover rock sequences represent fragmented slices of the Lower to Upper Allochthons of the Caledonide orogen (Gee *et al.* 1985). The Precambrian gneissic basement rocks, forming part of the Western Gneiss Region, are themselves strongly Caledonized; in the context of Caledonide tectonostratigraphy they are considered to form part of the Lower Allochthon (Roberts & Wolff 1981, Wolff 1984, Gee *et al.* 1985, Roberts 1986).

Another important element of MTFZ geology, though one occurring to the southwest of the segment described here, is that of the late-orogenic Old Red

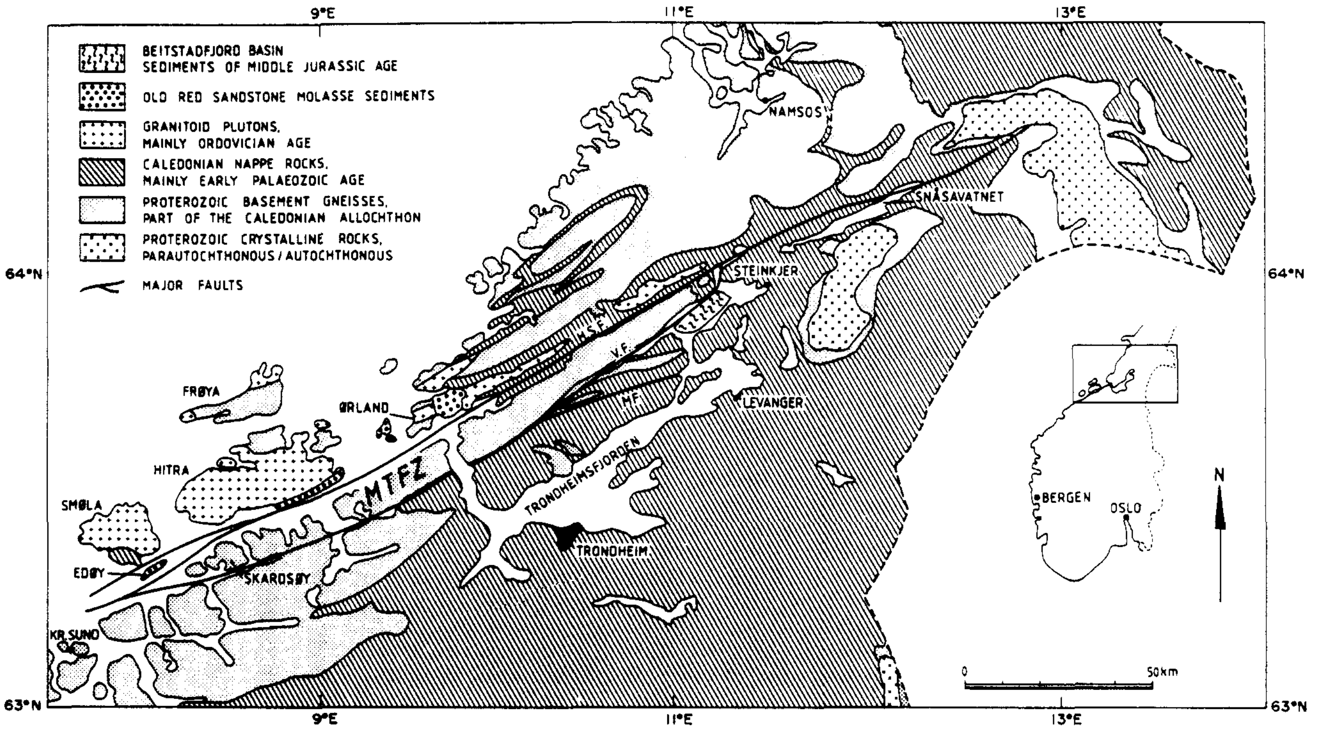

Fig. 1. Simplified outline geological map of the northern Trondheim Region showing the main tectonostratigraphic complexes and other rock units, and the principal strike-parallel faults. H.S.F.—Hitra-Snåsa Fault. V.F.—Verran Fault. M.F.—Mosvik Fault. M.T.F.Z. —Møre-Trøndelag Fault Zone.

Sandstone sediments on Ørlandet, Hitra and islands south of Smøla (Steel *et al.* 1985). These sandstones and conglomerates are of late Silurian to Middle Devonian age. Within the Stjørnfjord-Snåsavatn segment of the MTFZ, the geology of Beitstadfjord affords interesting clues bearing on the age of the fault movements. Pebbles of coal and boulders of sideritic ironstone with a plant fauna found on northern and western shores of this fjord are considered to have been derived from the fjord bottom (Oftedahl 1972, 1975) during Quaternary ice erosion, and are of Middle Jurassic age (Vigran 1970). This denotes that an important component of fault activity postdated the deposition of these Mesozoic sediments in this part of Norway, a notion supported by the results of a recent, shallow seismic reflection profiling programme (R. Bøe personal communication 1988).

THE MØRE-TRØNDELAG FAULT ZONE

Lineament interpretations based on imagery delivered by the Landsat-borne Multispectral Scanner (MSS) led Gabrielsen & Ramberg (1979) into defining the Møre-Trøndelag Fault Zone. This is a complex of ENE–WSW-trending parallel to subparallel and branching faults which can be followed from inland areas of Nord-Trøndelag west-southwestwards along the coastline of Sør-Trøndelag and Møre, between the islands of Hitra and Smøla and the mainland, and then just offshore, bounding the extensive Møre Basin (Gabrielsen *et al.* 1984). Individual faults within the 20–30 km wide fault zone include the Hitra and Verran Faults of Oftedahl (1972, 1975).

Until recently, the character of the MTFZ has been the subject of much speculation. Dip-slip normal motions have been assumed (Oftedahl 1972, Gabrielsen *et al.* 1984), and in the case of the Verran Fault, a 1500 m throw postulated (Oftedahl 1975). Based on field evidence Aanstad *et al.* (1981) concluded that small-scale dextral strike-slip movements had occurred along some of the faults. Subordinate, dextral strike-slip to oblique-slip movements along the MTFZ in Devonian times were proposed by Roberts (1983) while Price & Rattey (1984) and Gabrielsen & Robinson (1984), discussing offshore fault patterns, argued for right-lateral movements in Cretaceous time. Dextral movement is also favoured by Larsen (1987), related to a late Jurassic and Neocomian transpressional tectonic phase.

Moving back on land, recent lineament studies of this part of Trøndelag using high-resolution Landsat-TM data (Rindstad & Grønlie 1986) have revealed a distinct pattern of roughly N–S and ENE–WSW en échelon fractures within the part of the MTFZ between Stjørnfjord and Beitstadfjord (Figs. 2 and 3), delimited by the Hitra-Snåsa and Verran Faults. This feature also appeared to favour dextral movement and led to the more detailed structural analysis, the results of which are reported here. Fieldwork has so far been concentrated on the actual nature of the fault rocks in the better exposed portions of the fault zones. Systematic measurement of slickensides and other minor structures will form a major part of the next phase of this study. Slickenside striae so far recorded show a great variation in plunge within any one fault zone; these may relate either to separate displacements or to gradually changing slip vectors within one movement phase after early fault surfaces became sealed.

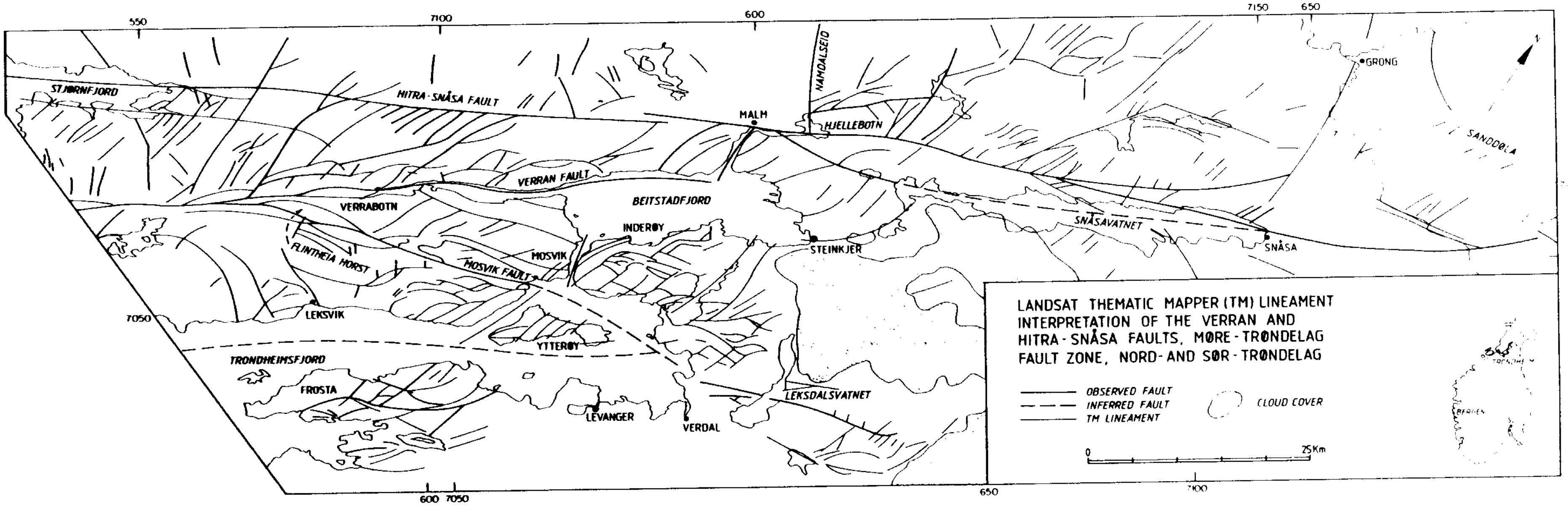

Fig. 2. Landsat Thematic Mapper (TM) lineament interpretation of the Verran and Hitra-Snåsa Faults, Møre-Trøndelag Fault Zone (MTFZ), Central Norway.

THE VERRAN AND HITRA-SNÅSA FAULTS

The main elements of the MTFZ in the area between Stjørnfjord and Snåsavatn are the Hitra-Snåsa Fault and the Verran Fault with their respective, associated, secondary structures (Fig. 2). The Hitra-Snåsa Fault defines a nearly straight, ENE–WSW-trending lineament from Stjørnfjord to Hjellebotn. Secondary, Riedel-like structures are, however, evident in the area north of Verrabotn (Fig. 3). The Verran Fault, aligned subparallel to the Hitra-Snåsa Fault, comprises a complex, anastomosing zone of braided segments and an array of N–S- and ENE–WSW-trending en échelon fractures.

Fault rock products

Along the Hitra-Snåsa Fault between Stjørnfjord and Hjellebotn and its secondary N–S strands, fault rocks comprise mylonites and small-scale recrystallized breccias, as well as some quartz and epidote veining. Cohesive mylonitic rocks are clearly dominant over the more brittle fault-rock products, giving the impression of a fairly deep crustal section with mainly crystal–plastic ductile deformation (Sibson 1977, White 1982) but with a later, small-scale, brittle overprint. The topographic expression of the Hitra-Snåsa Fault in this area is moderate.

Along the main Verran Fault, evidence of late polyphasal deformation is seen in several discrete episodes of brecciation on all scales, hydrothermal alteration and pervasive prehnite, stilbite and laumontite veining (Fig. 4a). Quartz–epidote matrixed breccias which probably relate to a period of normal faulting are cut by prehnite-matrixed protocataclasites with a NNE–SSW trend (Fig. 4b) parallel to the Rautingdal Fault (Fig. 3). These cataclasites are believed to have formed in tensional joints related to a period when the greatest horizontal principal stress was aligned parallel to the trend of the Rautingdal Fault. They must therefore be genetically related to a sinistral transpressional phase. This indicates that the reversal to dextral movement along the Verran Fault was a relatively late event as the sinistral transpressive regime which affected structures along the Hitra Fault, as shown by its ductile deformation, persisted long enough to leave a brittle deformation impact on the Verran Fault. The prehnite-matrixed cataclasites are then cut by stilbite and calcite veins (Fig. 4b) which in turn are affected by small-scale faulting. A large part of the Verran crush-breccia zone consists of intensely crushed rocks lacking cohesion. The crush-breccia is very well exposed in road-cuts and is also transected by a hydropower tunnel which shows that the intensely crushed gneiss zone extends for approximately 200 m north of the shoreline of Verrasundet.

Secondary structures, such as the Rautingdal Fault, commonly expose a 10 m-wide zone of hydrothermally altered protocataclasite and a 1 m-wide recrystallized fault gouge and ultracataclasite zone with a matrix of prehnite and quartz. Laumontite occurs in a 0.1 m-wide zone adjacent to the slickensided fault plane. The fault breccia is cut by stilbite veins.

In Elvdal (Fig. 3), the entire valley is floored by intensely crushed and stilbite-veined granodioritic gneiss. This in turn cut by haematite-stained, dark-red, anorthite- and quartz-matrixed cataclasites containing stilbite fragments (Fig. 4c). Stilbite is usually associated with near-surface pressure and temperature conditions, and laumontite and prehnite with conditions transitional between zeolite and greenschist facies. As these minerals now occur close to the present surface it is likely that they formed at different depths and therefore at different times. This is consistent with field observations showing that stilbite is the youngest mineral. It probably formed near the surface in connection with a faulting episode in late Mesozoic times.

Geometric framework and fault kinematics

In order to explain the secondary structures observed along the two main fault zones, a changing stress field has to be postulated. The first-order stress field, which refers to the conditions under which faulting was initiated on the Hitra-Snåsa Fault, is inferred to have 'inverted' at the time of the main faulting episode on the Verran Fault, by means of an interchange of the maximum and minimum principal stresses. It is the second-order structures which formed in response to the re-adjusted stress field as faulting proceeded along the main faults that are the most useful kinematic indicators on a regional scale, although complexities arose as already existing structures were either reactivated or locked and abandoned. Structures which are thought to be important in this respect are the Riedel-like megafractures along the Hitra-Snåsa Fault and the en échelon, duplex-like structures north of the main Verran Fault.

A wide variety of structures may develop within a wrench system. Wilcox *et al.* (1973), using a simple shear model, described the general en échelon arrangement of fault structures. Modifications to this system involve the introduction of either compression or extension across the wrench zone, termed transpression or transtension, respectively (Harland 1971, Sanderson & Marchini 1984). Compression causes a reorientation of the maximum compressive principal stress. This produces local extension and Riedel shears develop at a higher angle. In this context, looking at the complex of secondary fractures originating from the straight segment of the Hitra-Snåsa Fault, these structures can be explained as Riedel shears in a sinistral transpressive system, while the NNE–SSW-trending Rautingdal Fault (Fig. 3) would represent an extensional fracture oriented parallel to the trend of the maximum compressive stress. Minor faults splaying from the north side of the Hitra-Snåsa Fault northeast of Beitstadfjord form an extensional strike-slip fan to this sinistral system. These are similar to the 'horsetail' structures of Granier (1985).

The main Verran Fault, as interpreted from the TM-lineament map, consists of an anastomosing fault zone

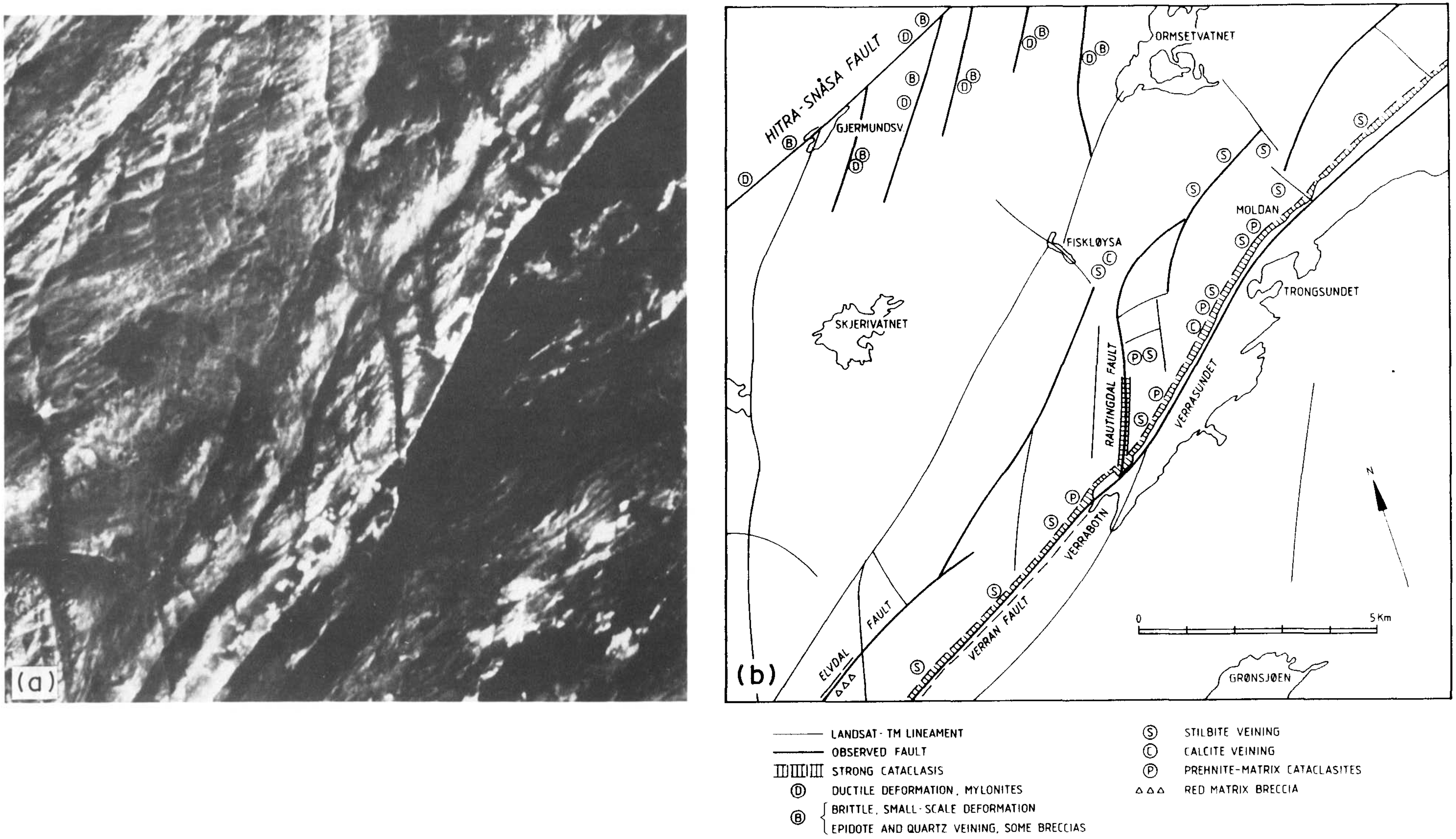

Fig. 3.(a) Landsat TM 4/5/7 FCC image of the Verrabotn area, Verran and Hitra-Snåsa Faults, MTFZ. The area covered is 15 × 15 km (512 × 512 pixels). (b) Lineament map of the Verrabotn area shown in (a) with field observations and laboratory determinations of fault rock products.

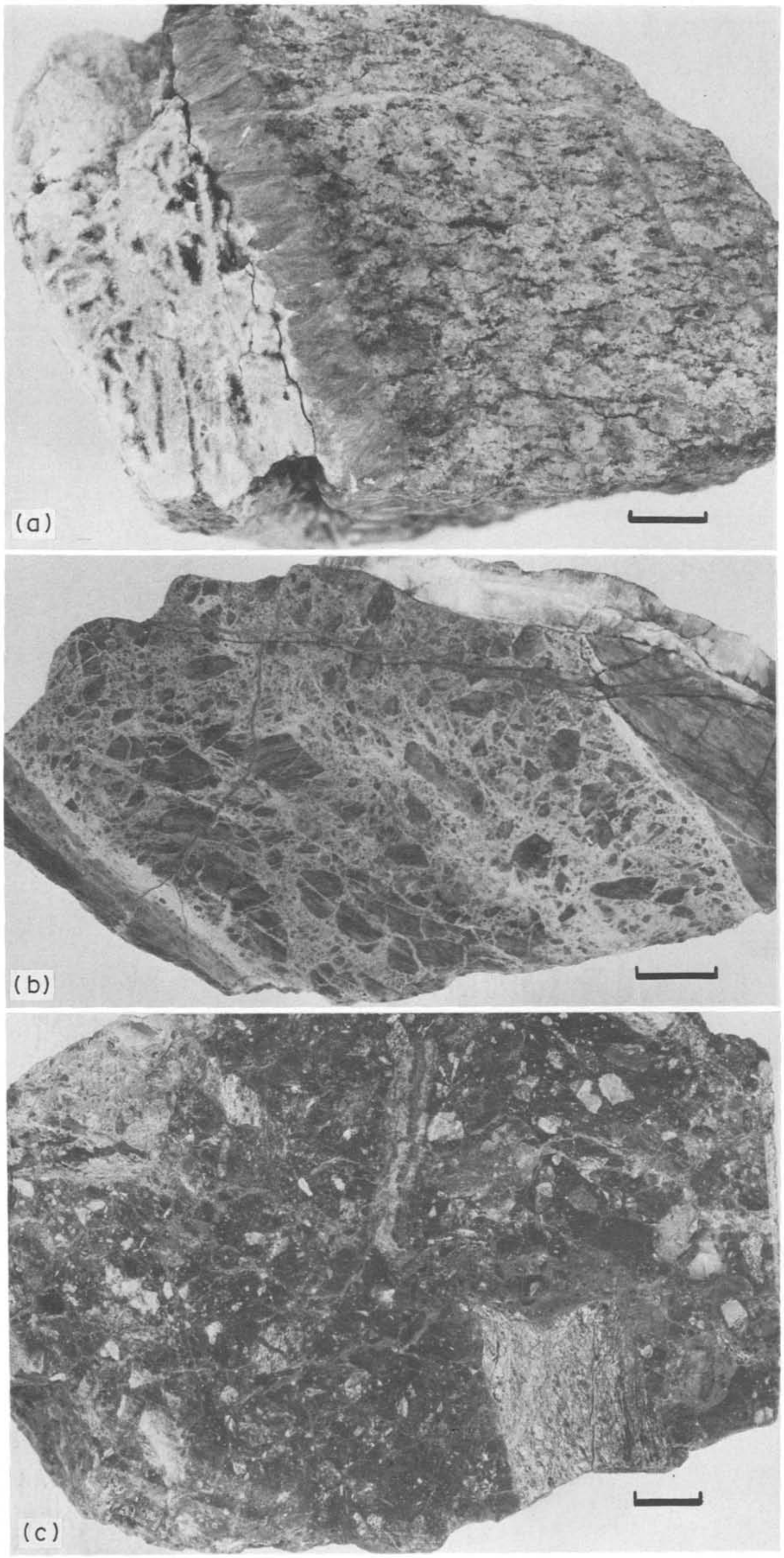

Fig. 4.(a) Part of a strongly altered granodioritic gneiss fragment in a breccia from the Verran Fault, Moldan (Fig. 3b), showing a stilbite vein (grey, left of centre) and a younger drusy vein of laumontite (white, left). The gneiss is also transected by thin veinlets of stilbite. Bar scale = 1 cm. (b) Fragments of granodioritic gneiss in a matrix of prehnite and quartz. The breccia is cut by stilbite veinlets and a later vein of calcite (white, top). From the Verran Fault, Trongsundet (Fig. 3b). Bar scale = 1 cm. (c) Breccia from Elvdal with fragments of granodioritic gneiss, quartz and vein-stilbite. The dark matrix (brick red in actual colour) consists of fine-grained anorthite with inclusions of ilmenite and haemo-ilmenite. Bar scale = 1 cm.

with isolated shear lenses, or horses. This braided pattern along the principal displacement zone (PDZ) of the Verran Fault is a common feature of many wrench faults, e.g. the SAFS (Crowell 1974, Dibblee 1977). The lineament pattern (Fig. 2) suggests the formation of small in-line horsts and grabens along the PDZ, similar to those described by Crowell (1974) and Dibblee (1977). In our view, this has implications for the interpretation of the Beitstadfjord Basin (Oftedahl 1975).

The pattern of en échelon N–S- and ENE–WSW-trending fractures along the Verran Fault at Verrabotn appears to have the characteristics of contractional strike-slip duplex structures (Woodcock & Fischer 1986). The initiation and formation of duplexes at bends in a strike-slip system is analogous to that of duplex formation at ramps in dip-slip systems. Horses are cut off from the wall of the major fault by propagation of new imbricate faults outward from the parent fault. This mechanism has earlier been described from the San Andreas Fault System by Crowell (1974) and Dibblee (1977).

In the present case, a more northerly trend on the main Verran Fault along Beitstadsundet has led to the formation of contractional duplexes north of the PDZ. Lengths of individual horses bounded by the imbricate fractures in the area between the Hitra-Snåsa and Verran Faults vary between a half and two times their spacing. Viewed in vertical section this contractional duplex system is likely to define a flower structure (Harding & Lowell 1979), in which the faults may converge at depth into a single shear zone. Such shear-zone structures have also been confirmed by sandbox experiments (Naylor *et al.* 1986).

By studying experimentally induced strike-slip fault zones in limestone Bartlett *et al.* (1981) found that upon loading to peak shear strength, Riedel-shears and a *P*-shear formed simultaneously. This sequence differs from that observed by Tchalenko (1970), in which the *P*-shears form subsequent to *R*-shears. In addition, *X*-shears (Bartlett *et al.* 1981) are formed in the post-peak region. Tchalenko & Ambraseys (1970) found that for large deformations that tend toward direct (pure) shear conditions, a new shear fracture (*P*-shear) formed in a position approximately bisecting the obtuse angle between the Riedel-shears and close to the principal axis of the strain ellipse. In our field example, the structures directly north of the Verran Fault PDZ can most readily be interpreted as a system of slightly rotated, en échelon *P*-shears formed during a period of dextral transpression (e.g. the Elvdal Fault, Figs. 2 and 3). It is, however, quite likely that the more northerly trending Rautingdal Fault (Fig. 3) may represent a reactivated feature inherited from the Hitra Fault sinistral transpressional phase.

A possible alternative to the duplex explanation of the en échelon fractures along the north side of the Verran Fault PDZ (Fig. 2) is that they could represent sinistral Riedel-shears inherited from the Hitra-Snåsa Fault sinistral event, but later reactivated and rotated by dextral movement on the Verran Fault. This would imply that the late Elvdal Fault (Fig. 3) may be the only true dextral duplex fault. This view is supported by the occurrence of NNE–SSW-trending prehnite-matrixed cataclasites cutting the Verran crush-breccia (Fig. 5). These cataclasites are possibly related to sinistral transpression on the Verran Fault.

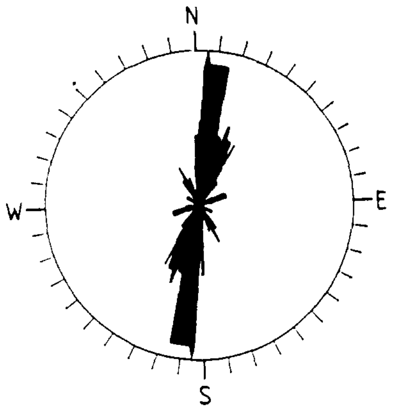

Fig. 5. Rose diagram of strike trends for prehnite-matrix cataclasites occurring in the crush breccia of the Verran Fault (Fig. 3b).

If all the en échelon faults north of Verrabotn originated in a dextral strike-slip regime they should fit into the corresponding strain ellipse, from which they are most readily interpreted as *P*-shears. As laboratory shear experiments on rock samples (Bartlett *et al.* 1981) have indicated that Riedel-shears and *P*-shears form simultaneously, the reason why dextral Riedel-shears apparently do not occur just north of the Verran Fault requires an explanation. This could be found in the anisotropy of the basement gneisses or in pre-existing zones of weakness. Gamond (1987) stated that "although no interpretation in terms of stress can be proposed concerning the genesis of right-stepping right-lateral fractures, which usually form as second-generation shear fractures, they also produce first-generation fault arrays shown in many field examples".

It is not to be expected that laboratory experiments should be able to simulate exactly natural field conditions with all its inhomogeneities, and there will always be room for more than one possible interpretation. In the case of the Verran Fault System the homogeneous granodioritic gneiss lithology and parallel and conjunctive strike trend of faulting and bedrock foliation makes it very difficult to establish the precise sense of movement along the secondary faults without a very thorough mapping programme and microstructural study. Displacement along the secondary structures is expected to be small (Flinn 1977). Also, maximum offset along the major strike-slip faults generally occurs in the central part of a fault trace and decreases laterally to zero at the terminations (Moore 1979). Offsets are therefore not likely to be very large in this part of the MTFZ.

AGE OF FORMATION OF THE VERRAN AND HITRA-SNÅSA FAULTS

Until recently there has been no general consensus as to the timing of the main displacive movements along the on-land portion of the MTFZ. Detailed field studies of the fault rocks were lacking, and no isotopic or palaeomagnetic dating had been attempted. It has generally been considered, however, that the MTFZ represents a long-lived tectonic zone (Gabrielsen & Ramberg 1979, Aanstad *et al.* 1981), with components of reactivation possibly from Precambrian to late Mesozoic or even Tertiary time. Later minor displacements during the Holocene also cannot be discounted. The MTFZ thus provides a good example of Hills' (1956) concept of resurgent fault tectonics — repeated movement following periods of quiescence (see also White *et al.* 1986).

On a larger scale the evolution of the MTFZ is considered to be intimately linked to the general tectonic evolution of NW Europe. Important events with a probable bearing on the evolution of the MTFZ are: (1) the accretion of terranes during the terminal stages of the Caledonian orogeny; (2) the Hercynian suturing of Pangea; (3) the Permo-Triassic instability of the Pangean megacontinent and events connected with the initial rifting and opening of the central and northern Atlantic; and (4) the Cenozoic opening of the Norwegian–Greenland Sea.

Palaeozoic

Evidence of movement along the major faults of the MTFZ in early Palaeozoic time, prior to the late Silurian Scandian orogenesis, is lacking. Indeed, it is doubtful if the MTFZ existed as such before the period of Scandian nappe-stacking, especially as the Precambrian crystalline rocks of the Western Gneiss Region are themselves largely allochthonous. However, major faults almost certainly existed in this western basement block, and these were rejuvenated and caused disruption of the overlying Caledonian nappes during the Scandian suturing of the continents Baltica and Laurentia.

To the southwest, in the British area, Hutton (1987) has argued for sinistral strike-slip movement on the Highland Boundary Fault in Ordovician time, and more significantly that many of the major NE–SW faults in the British and Irish Caledonides were active as sinistral strike-slip zones in the end-Silurian to pre-Middle Devonian period. Although the implications of this scenario for the MTFZ are unclear, it is more than conceivable that the Scandian orogenesis involved an element of transpression and sinistral strike-slip shear as a result of oblique collision of Baltica and Laurentia and intervening microcontinental fragments. Following the Scandian orogeny, it has long been believed that a complex wrench fault-system developed sub-parallel to the axial grain of the Caledonide fold belt during the Devonian (Harland 1973, Ziegler 1981). A sinistral displacement of the order of 2000 km along the Great Glen Fault (GGF) was postulated by Van der Voo & Scotese (1981), based on palaeomagnetic data. Later, Smith & Watson (1983) rejected the major sinistral displacement hypothesis on the GGF, stating that the original figure of 100 km left-lateral movement proposed by Kennedy (1946) would be more compatible with geological observations. Also, palaeomagnetic work by Torsvik *et al.* (1985) from Svalbard shows that the Caledonide axial region was not subjected to post-Devonian strike-slip motions in the order of thousands of kilometres. However, this does not preclude strike-slip faulting of lesser magnitude during or prior to Devonian time; and a major sinistral mega-shear zone located along the axis of the future Norwegian–Greenland Sea (Ziegler 1981) could have led to the development of secondary, dextral strike-slip faults in western Norway, including the MTFZ (Roberts 1983).

In the case of the MTFZ, late Devonian fold structures (Roberts & Sturt 1980) in the Stjørnfjord-Hjellebotn area are cut by the early Hitra-Snåsa Fault and the later Verran Fault and their secondary structures, thus indicating a late- or post-Devonian development of this part of the MTFZ. The general geological map picture showing the Verran Fault as a dividing line between Proterozoic gneisses to the north and Caledonian nappes to the south (Wolff 1976) (Fig. 2) could point to a major, earlier, possibly Scandian strike-slip phase. Also, bedrock mapping in the Malm area (Fig. 2) by T. Thorsnes (personal communication 1988) indicates the possibility that a precursor fault to the Hitra-Snåsa Fault could have been active in Ordovician time and partly controlled the deposition of sandstones and conglomerates.

At the time of transition from the Devonian to the Carboniferous, convergence between Gondwana and Laurentia–Baltica led to the onset of the Variscan orogeny (Ziegler 1981). During the late Carboniferous and early Permian a right-lateral wrench-fault system developed linking the southern Uralides and northern Appalachians and resulted in a complex pattern of conjugate shear faults and related pull-apart structures (Arthaud & Matte 1977). This conjugate system supposedly affected the Tornquist and Elbe lines as well as the GGF (sinistrally). During the late early Permian this major transcurrent system became inactive. Based on palaeomagnetic studies on Smøla, Sturt *et al.* (1987) have suggested that the MTFZ functioned as a sinistral strike-slip zone in late Devonian or early Carboniferous time, as considerable terrane rotations then took place as a late stage of brittle faulting relating to the Svalbardian or Solundian orogeny.

Mesozoic

The Triassic was a time of intensified rifting activity in the North Atlantic region. Structural elements resulting from this tensional system include the Rockall-Færøy Trough, the Bay of Biscay Rift, and in the North Sea (Fig. 6) the Viking and Central Grabens (Ziegler 1981) and the Moray Firth half-graben (McQuillin *et al.* 1982).

Crustal extension led to crustal separation in the Arctic–North Atlantic in its various segments during Mesozoic and early Tertiary times. As the opening of the North Atlantic proceeded from south to north (Laughton 1975), events influencing the MTFZ are likely to have occurred at a later stage than events

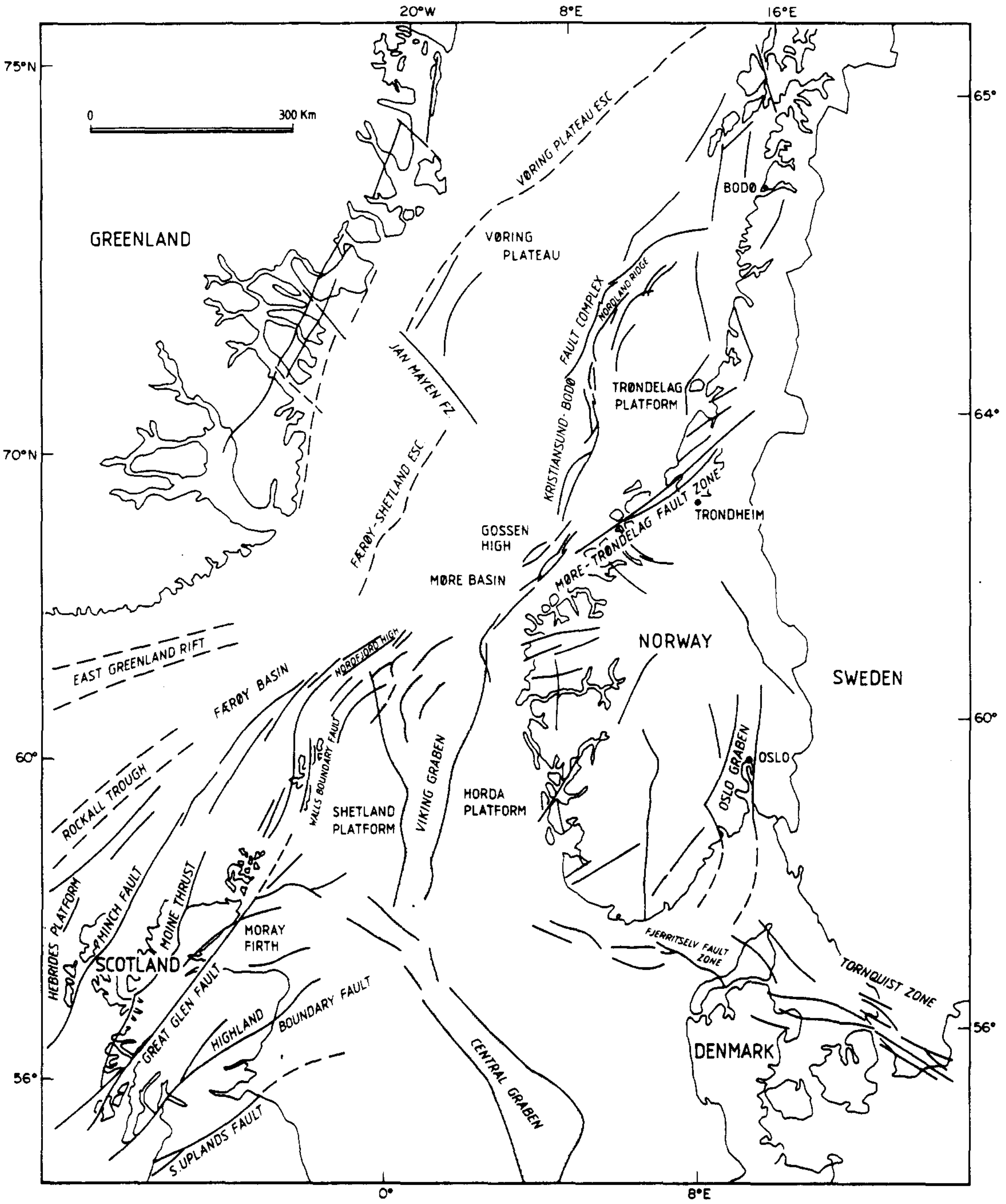

Fig. 6. Map showing some of the major tectonic–structural features of the northern North Sea and Norwegian Sea, and principal on-land faults in Scotland and Norway. Modified from Færseth (1984).

affecting the GGF. On the GGF there is evidence of dip-slip movement during the Trias, and also of later Mesozoic dextral displacement in the order of a few tens of kilometres (Flinn 1975, Speight & Mitchell 1979, McQuillin *et al.* 1982). This movement has not been accurately dated but it is to be expected that Mesozoic strike-slip movements on the GGF, and possibly MTFZ, must be related to pulses of rifting preceding the various stages of sea-floor spreading in this area. The Arctic–North Atlantic Rift, north of the Charlie Gibbs Fracture Zone, remained active throughout Jurassic and Cretaceous times (Ziegler 1981, Larsen 1987).

In the northern Viking Graben, strike-slip movements have been suggested on a NE–SW-trending fault set in the continuation of the MTFZ. A sinistral strike-slip of Middle to late Jurassic age has been proposed by Hay (1978) and later by Speksnijder (1987) who claims that these NE–SW-trending faults are basement-involved. A stress regime leading to sinistral movement on NE–SW basement-involved faults in the Northern Viking Graben could also possibly have affected onshore faults of the MTFZ. However, these faults have been called transfer faults by Gibbs (1984) implying that they are necessary features to accommodate extension in the Viking Graben and therefore of a more local character.

Price & Rattey (1984) proposed that a part of the Kristiansund-Bodø Fault Complex (KBFC) (Gabrielsen *et al.* 1984) had been subject to dextral shear in Mid-Cretaceous times, finding support for this hypothesis from observations on the MTFZ (Aanstad *et al.* 1981, Aanstad

1982). Their main argument for dextral shear on the MTFZ during the Cretaceous is the supposedly Cretaceous age for rifting and sea-floor spreading in the Rockall Trough (Price & Rattey 1984).

Gabrielsen & Robinson (1984) developed a dextral shear model for the Nordland Ridge segment of the KBFC (Fig. 6). In this model NE–SW- and ENE–WSW-trending dextral fractures, NNW–SSE-trending sinistral shears and folds with NE–SW-trending axes would fit the corresponding strain ellipsoid. These authors maintain that dextral strike-slip movements on the Nordland Ridge started in late Jurassic, with reactivation in late Cretaceous and Tertiary times. This is in keeping with Larsen's (1987) tectonic phase III, a late Jurassic and Neocomian transpressional event with accompanying uplift. This involved the gradual closure of the Tethys Sea and the onset of sea-floor spreading between the Azores and Charlie Gibbs FZ, which brought about changes in the North Atlantic rift system. In the Mid-Norway area, late Jurassic N–S rift faults are superseded by NE–SW dextral wrench faults of Neocomian age. According to Larsen the northward increase in the rate of early Cretaceous dextral transpression in the North Sea and the dominant NE-SW tectonic lineaments in Haltenbanken, Møre and the West Shetlands, indicate a regional NE–SW tectonic regime centred along a line from the Rockall Trough to the Bjørnøya Basin. This is suggested to be due to the relative movements between Greenland and NW Europe. H. Fossen (personal communication 1988) interprets some of the faults and structures within the Gullfaks oil field as the result of late Jurassic/Neocomian dextral transpression along NE–SW faults of the Tampen Spur, a southwestern continuation of the MTFZ fault trend (Fig. 6).

Along the MTFZ the presence of the downfaulted Middle Jurassic sequence in Beitstadfjord gives a strong indication of post Middle Jurassic strike-slip movements on the Verran Fault. Earlier observations of this downfaulted sequence by Oftedahl (1975) suggested to us an origin as a strike–slip related pull-apart basin or in-line graben (Crowell 1974, Dibblee 1977). Recent seismic reflection profiling in Beitstadfjord favours a half-graben solution (R. Bøe personal communication 1988), with SE downthrow along the Verran Fault, although this was superseded by dextral strike-slip movements.

Viewing this post Middle Jurassic strike-slip event in the context of the evolution of the Arctic–North Atlantic Ocean, the major early Cretaceous rifting pulse (late Cimmerian Phase) affected the Arctic–North Atlantic and North–West European rift system. It preceded the Neocomian onset of sea-floor spreading between the Azores and the Charlie Gibbs Fracture Zone (Ziegler 1981). Slip motions have varied widely, from strike-slip to dip-slip, at different times.

CONCLUSIONS

The MTFZ has existed as a zone of crustal weakness since Siluro-Devonian time, and the proto-faults to this structure possibly as far back as the Precambrian (Gabrielsen & Ramberg 1979, Aanstad *et al.* 1981).

A study of the fault rocks occurring along the Verran and Hitra-Snåsa Faults shows that the latter is dominated by products of ductile deformation with a small-scale brittle overprint. The Verran Fault shows evidence of polyphasal deformation in several discrete episodes of brecciation, hydrothermal alteration and pervasive prehnite and stilbite veining. This indicates that the segment of the Hitra-Snåsa Fault between Stjørnfjord and Hjellebotn was active earlier than the Verran Fault.

An analysis of the fault mechanics of the system indicates that the earliest strike-slip phase was one of sinistral movement, dating probably to late Devonian time. Some sinistral or oblique motion at the end of the late Silurian, Scandian orogenesis also cannot be ruled out. Later, the strike-slip shear movement shifted locus towards the Verran Fault and reversed in sense to one of dextral displacement. Along and adjacent to the Verran Fault, dextrally rotated fractures, which define strike-slip duplex structures, indicate late dextral displacement on the MTFZ of post-Middle Jurassic age; this is supported by the presence of the fault structures affecting the Beitstadfjord half-graben. This phase of evolution of the MTFZ was probably related to a late Jurassic to Neocomian transpressional phase relating to sea-floor spreading between the Azores and Charlie Gibbs FZ and a clockwise rotation of the Greenland plate relative to the European plate (Larsen 1987).

Fieldwork along the Hitra-Snåsa Fault has provided evidence which indicates that a small-scale sinistral movement predates the component of dextral displacement. Indications of a sinistral movement on the Hitra-Snåsa Fault have been given by palaeomagnetic studies pointing to a clockwise rotation of Smøla and adjacent islands exposing Devonian rocks (Sturt *et al.* 1987). This rotational movement occurred during late Devonian or early Carboniferous time.

Acknowledgements—The authors are grateful to Arne Dalland, Roy Gabrielson and Asbjørn Thon for their helpful comments on an earlier draft of the manuscript.

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