NGU-rapport 87.139

Dextral strike-slip duplexes of Mesozoic age along the Hitra-Snåsa and Verran Faults, Møre-Trøndelag Fault Zone, Central Norway

25

Norges geologiske undersøkelse
Leiv Eirikssons vei 39, Postboks 3006, 7001 Trondheim - Tlf. (07) 92 16 11
Oslokontor, Drammensveien 230, Oslo 2 - Tlf. (02) 50 25 00

Rapport nr. 87.139	ISSN 0800-3416	Åpen~~/Fortrolig til~~

Tittel:

Dextral strike-slip duplexes of Mesozoic age along the Hitra-Snåsa and Verran Faults, Møre-Trøndelag Fault Zone, Central Norway

Forfatter: Arne Grønlie and David Roberts	Oppdragsgiver: NGU/Nord-Trøndelagsprogrammet
Fylke: Nord- og Sør-Trøndelag	Kommune:
Kartbladnavn (M. 1:250 000)	Kartbladnr. og -navn (M. 1:50 000)
Forekomstens navn og koordinater:	Sidetall: 24 Pris: Kr. 70,- Kartbilag: 1

Feltarbeid utført: 1987	Rapportdato: 26.11.87	Prosjektnr.: 1889.67.22	Prosjektleder: A. Grønlie

Sammendrag:

The prominent, ENE-WSW, Verran and Hitra-Snåsa Faults of the long-lived Møre-Trøndelag Fault Zone(MTFZ) have been investigated employing methods ranging from Landsat TM lineament analysis down to the scale of field mapping and detailed study of the fault rock products.
The fault array recognised 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, straight and topographically less well developed 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, sinistral, Riedel-like faults comprise mylonites, hydrothermally altered rocks and small-scale recrystallised breccias. Along the main Verran Fault evidence of late, polyphasal deformation is seen in several discrete episodes of brecciation on all scales, hydrothermal alteration, and locally pervasive prehnite and stilbite veining.
The fault structures along the Hitra-Snåsa and Verran Faults, as reflected in the geological map picture, are thought to have originated as a sinistral transpressive system of Late Devonian age, especially for the Hitra-Snåsa lineament. Subsequent to Devonian time, fault-displacive 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. The Beitstadfjord basin is considered to be floored by Middle Jurassic sediments(found locally as shoreline, plant-fossiliferous boulders), and is here interpreted as an in-line grabenal basin formed as a consequence of the Mesozoic, dextral, strike-slip movement along the Verran Fault system.

Emneord	Strike-slip faulting	Verran Fault
Hitra-Snåsa Fault	Zeolites	Breccia
Cataclasites	Fault rocks	Landsat TM

DEXTRAL STRIKE-SLIP DUPLEXES OF MESOZOIC AGE ALONG THE HITRA-SNÅSA AND VERRAN FAULTS, MØRE-TRØNDELAG FAULT ZONE, CENTRAL NORWAY.

Arne Grønlie and David Roberts

Abstract

The prominent, ENE-WSW, Verran and Hitra-Snåsa Faults of the long-lived Møre-Trøndelag Fault Zone(MTFZ) have been investigated employing methods ranging from Landsat TM lineament analysis down to the scale of field mapping and detailed study of the fault rock products. An initial investigation involving Landsat satellite imagery, aerial photograph interpretation, and assessment of the available published and manuscript geological maps 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 braiding wrench-faulting, e.g., the San Andreas Fault System(SAFS) of California.

The fault array recognised 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, straight and topographically less well developed 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, sinistral, Riedel-like faults comprise mylonites, hydrothermally altered rocks and small-scale recrystallised breccias. Along the main Verran Fault evidence of late, polyphasal deformation is seen in several discrete episodes of brecciation on all scales, hydrothermal alteration, and locally pervasive prehnite and stilbite veining.

The fault structures along the Hitra-Snåsa and Verran Faults, as reflected in the geological map picture, are thought to have originated as a sinistral transpressive system of Late Devonian age, especially for the Hitra-Snåsa lineament. Subsequent to Devonian time, fault-displacive 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. The Beitstadfjord basin is considered to be floored by Middle Jurassic sediments(found locally as shoreline, plant-fossiliferous boulders), and is here interpreted as an in-line grabenal basin formed as a consequence of the Mesozoic, dextral, strike-slip movement along the Verran Fault system.

Introduction

The westernmost parts of the counties of Møre and Nord-and Sør-Trøndelag in Central Norway are characterized by a prominent ENE-WSW topographic grain. Although, to a large extent, this reflects the dominant strike trend of a variety of lithological units(Sigmond et al. 1984), 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 many 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(Pl.1). 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, e.g. 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 in the southwest to Snåsa in the northeast(Fig.1 and Pl.1), a distance of over 200km. In the Verran district, the complex fault zone has a width of over 20km. 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 are themselves strongly Caledonised; in the context of Caledonide tectonostratigraphy they are at least parautochthonous and may constitute 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 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 fault segment, 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 postdates the deposition of these Mesozoic sediments in this part of Norway.

The Møre-Trøndelag Fault Zone

Lineament interpretations based on imagery delivered by the Landsat-borne Multispectral Scanner(MSS) led Gabrielsen & Ramberg into defining the Møre-Trøndelag Fault Zone(MTFZ). 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 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 1,500m 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 et al.(1984), discussing offshore fault patterns, argued for right-lateral movements in Cretaceous time. Dextral movement is also favoured by V.Larsen(in prep.), 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 echelon fractures within the part of the MTFZ between Stjørnfjord and Beitstadfjord (Pl.1, Fig.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.

Fault mechanics of 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(Pl.1). 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.2 and 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 echelon fractures.

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 mega-fractures along the Hitra-Snåsa Fault and the en echelon, 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 simple shear, described the general en echelon arrangement of 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 extension and Riedel shears at a higher angle (Fig.4). 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.2 and 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 with isolated shear lenses, or horses. This braiding 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 (Pl.1) 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 echelon N-S and ENE-WSW trending fractures along the Verran Fault at Verrabotn appears to have the characteristics of contractional strike-slip duplex structures(Fig.5)(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, successive imbricate slices, 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 SAFS 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 (Sylvester & Smith 1976), 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 (Fig.6). This sequence differs from that observed by Tchalenko(1970), in which the P-shears form subsequent to R-shears. In addition, X-shears(Fig.6) 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 echelon P-shears formed during a period of dextral transpression (e.g. the Elvdal Fault, Pl.1 and Fig.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 echelon fractures along the north side of the Verran Fault PDZ(Pl.1) 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) is 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.7). These cataclasites are possibly related to sinistral transpression on the Verran Fault(see chapter on Fault Rocks).

If all the en echelon faults north of Verrabotn originated in a dextral strike-slip regime they should fit into the corresponding strain ellipse(Fig.6), 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) states 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 randomness, 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.

Fault rocks of the Verran and Hitra-Snåsa Faults

A study of the fault rocks occurring along the Hitra-Snåsa and Verran Faults and their respective secondary structures has been initiated and will be treated more fully in a later report.

Along the Hitra-Snåsa Fault between Stjørnfjord and Hjellebotn and its secondary, Riedel-like structures, fault rocks comprise mylonites and small-scale recrystallized breccias, as well as some quartz and epidote veining. Mylonitic rocks are clearly dominant over the brittle fault rocks, giving the impression of a fairly deep crustal section with mainly ductile deformation(Sibson 1977) 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, hydro-thermal alteration and pervasive prehnite and stilbite veining. 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.7) 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 the ductile deformation there, persisted long enough to leave a brittle deformation impact on the Verran Fault. The prehnite-matrixed cataclasites are then cut by stilbite veins 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 200m north of the shoreline of Verrasundet.

Secondary structures, such as the Rautingdal Fault, commonly expose a 10m-wide zone of hydrothermally altered protocataclasite and a 1m-wide recrystallized fault gouge and ultracataclasite zone with a matrix of prehnite and quartz. Laumontite occurs in a 0.1m-wide zone adjacent to the slickensided fault plane. The fault breccia is cut by stilbite veins. Flinn(1977) in studying the Walls Boundary and Nesting Faults on Shetland, concluded that gouge-like laumontite in subsidiary shears was probably formed by mechano-chemical reactions along the fault plane.

In Elvdalen (Fig.3), which carries one of the intra-duplex fractures subparallel to the Verran Fault PDZ, the entire valley is floored by intensely crushed and stilbite-veined granodioritic gneiss. This is in turn cut by hematite stained dark-red anorthite and quartz matrixed cataclasites containing stilbite fragments. This observation is consistent with this being part of the latest formed duplex structure in the district.

Stilbite is usually associated with near-surface pressure and temperature conditions, and laumontite and prehnite with conditions transitional between zeolite and greenshist 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.

Discussion on the age of formation of the Verran and Hitra-Snåsa Faults.

There is at the present time no general consensus as to the timing of the main strike-slip movements on the MTFZ. Due to reactivation it is to be expected that the MTFZ represents a long-lived tectonic zone (Gabrielsen & Ramberg 1979, Aanstad et al. 1981), with components of movement possibly from Precambrian until Late Mesozoic times. Although the implications for the MTFZ are unclear, Hutton(1987) has argued for sinistral strike-slip movement on the Highland Boundary Fault in Ordovician times, and that many of the major faults in the British and Irish Caledonides were active as sinistral strike-slip zones in the end-Silurian to pre-mid Devonian period. Later, Holocene, minor displacements also cannot be discounted.

On a large 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

Following the Late Silurian Scandian orogenesis which resulted in the suturing of the continents Baltica and Laurentia, a complex wrench fault system is believed to have developed sub-parallel to the axial grain of the Caledonide fold belt during the Devonian(Harland 1973, Ziegler 1981). A large-scale sinistral displacement of the order of 2000km along the Great Glen Fault(GGF) was postulated by Van der Voo & Scotese(1981), based on palaeomagnetic data. 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).

Later, Smith & Watson(1983) rejected the major sinistral displacement hypothesis on the GGF, stating that the original figure of 100km 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 minor magnitude during or prior to Devonian time.

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.1) could point to a major, earlier, possibly Scandian strike-slip phase, a view which is also supported by the presence of a rotated granitic gneiss block east of Vanvikan (Pl. 1). The Caledonian rocks south of the Verran Fault could, however, have been better preserved from erosion if the southern block had simply been downfaulted in relation to the northern area.

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 the Viking and Central Graben(Ziegler 1981).

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 affecting the GGF. On the GGF there is evidence of 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, V.Larsen in prep.).

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 NW-SE 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 accomodate 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. 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 V.Larsen's(in prep.) tectonic phase III, a Late Jurassic and Neocomian transpressional event with accompanying uplift. "The gradual closure of the Tethys Sea and the onset of sea-floor spreading between the Azores and Charlie Gibbs FZ 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 wrenching 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 Bear Isle Basin. This is suggested to be due to the relative movements between Greenland and NW Europe.

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. Observations of this downfaulted sequence (Oftedahl 1975) are strongly suggestive of an origin as a strike-slip related pull-apart basin or in-line graben(Crowell 1974,Dibblee 1977). 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).

Conclusions

The MTFZ has existed as a zone of crustal weakness since Siluro-Devonian time, and 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 transpression. Later, the strike-slip movement shifted locus towards the Verran Fault and reversed in sense.

Along and adjacent to the Verran Fault, strike-slip duplex structures, or at least dextrally rotated preexisting fractures, indicate late dextral displacement on the MTFZ of post Middle Jurassic age; this is supported by the presence of the Beitstadfjord wrench-related in-line 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 (V.Larsen in prep.).

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 an anticlockwise rotation of Smøla and the Devonian island of Edøy(Sturt et al. 1987). This rotational movement occurred during Late Devonian or Early Carboniferous time.

References

Aanstad, K.M. 1982: Bruddtektonikk på fastlandet og kontinentalsokkelen mellom 62oN og 68oN. Norge. Cand.Real.thesis, University of Oslo. 195 pp.

Aanstad, K.M., Gabrielsen, R.H., Hagevang, T., Ramberg, I.B. & Torvanger, O. 1981: Correlation of offshore and onshore structural features between 62oN and 68oN, Norway. NSE 11/1-24.

Arthaud, F. & Matte, P. 1977: Late Paleozoic strike-slip faulting in southern Europe and northern Africa: Result of a right lateral shear zone between the Appalachians and the Urals. Geological Society of America Bulletin 88, 1305-1320.

Bartlett, W.L., Friedman, M. & Logan, J.M. 1981: Experimental folding and faulting of rocks under confining pressure. Tectonophysics, 79, 255-277.

Brekke, H. & Riis, F. 1987: Tectonics and basin evolution of the Norwegian Shelf between 62oN and 72oN. 17 pp. Lecture given at TSGS-Conference, Stavanger 25-27.11.1986.

Bucovics, C., Cartier, E.G., Shaw, N.D. & Ziegler, P.A. 1984: Structure and development of the mid-Norway Continental Margin. Petroleum Geology of the North European Margin, 407-423.

Crowell, J.C. 1974: Origin of Late Cenozoic basins in southern California. In: Dickinson,W.R.(ed.) Tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists Special Paper 22, 190-204.

Dibblee, T.W. 1977: Strike-slip tectonics of the San Andreas Fault and its role in Cenozoic basin evolvement. In: Nilsen, T.H.(ed.): Late Mesozoic and Cenozoic sedimentation and tectonics in California. San Joaquin Geological Society, 26-38.

Flinn, D. 1975: Evidence for post Hercynian transcurrent movement on the Great Glen Fault in the Moray Firth. Scott.J.Geol. 11, 266-267.

Flinn, D. 1977: Transcurrent faults and associated cataclasis in Shetland. Jl.geol.Soc.Lond. 133, 231-248.

Gabrielsen, R.H. & Ramberg, I.B. 1979: Fracture patterns in Norway from Landsat imagery: results and potential use. NSS/23,1-28.

Gabrielsen, R.H. & Robinson, C. 1984: Tectonic inhomogeneities of the Kristiansund-Bodø Fault Complex, offshore mid-Norway. Petroleum Geology of the North European Margin, 397-406.

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. Petroleum Geology of the North European Margin, 41-60.

Gamond, J.F. 1987: Bridge structures as sense of displacement criteria in brittle fault zones. J.Structural Geol.9, 609-620.

Gee, D.G., Guezou, J.C., Roberts, D. & Wolff, F.C. 1985: The central-southern part of the Scandinavian Caledonides. In: Gee, D.G. & Sturt, B.A.(eds.). The Caledonide orogen-Scandinavia and related areas. John Wiley & Sons, Chichester, 109-133.

Gibbs, A.D. 1984: Structural evolution of extensional basin margins. J.Geol.Soc.London, 141, 609-620.

Granier, T. 1985: Origin, damping, and pattern of development of faults in granite. Tectonics 4, 721-737.

Harland, W.B. 1971: Tectonic transpression in Caledonian Spitsbergen. Geol.Mag.108, 27-42.

Harland, W.B. 1973: Tectonic evolution of the Barents Shelf and related plates. Am.Assoc.Pet.Geol.Mem.9, 599-608.

Hay, J.T.C. 1978: Structural development in the northern North Sea. Journal of Petroleum Geology,1,65-78.

Hutton, D.H.W. 1987: Strike-slip terranes and a model for the evolution of the British and Irish Caledonides. Geol.Mag.124, 405-425.

Kennedy, W.Q. 1946: The Great Glen fault. Geological Society of London Quarterly Journal 102, 41-72.

Larsen, V. (in prep.): Tectonic related stratigraphy in the North Atlantic region from Bathonian to Cenomanian time. Unpublished manuscript, 35pp.

Laughton, A.S. 1975: Tectonic evolution of the Northeast Atlantic Ocean; a review. Norges geol. unders. 316, 169-193.

McQuillin, R., Donato, J.A. & Tulstrup, J. 1982: Development of basins in the Inner Moray Firth and the North Sea by crustal extension and dextral displacement on the Great Glen Fault. Earth and Planetary Science Letters 60, 127-139.

Moore, J.McM. 1979: Tectonics of the Najd Transcurrent Fault System, Saudi Arabia. J.Geol.Soc.London 136, 441-454.

Naylor, M.A., Mandl, G. & Sijpesteijn, C.H.K. 1986: Fault geometries in basement-induced wrench faulting under different initial stress states. Journal of Structural Geology 8, 737-752.

Offield, T.W., Miller, G.B. & Petterson, B.A. 1982: Regional setting and uranium occurrence, Olden-Hotagen District of Sweden and adjacent Norway: Preliminary Landsat interpretation. U.S.Geol.Surv. (unpubl. manus.), 25pp.

Oftedahl, C. 1972: A sideritic ironstone of Jurassic age in Beitstadfjorden, Trøndelag. Nor.geol.tidsskr. 52, 193-214.

Oftedahl, C. 1975: Middle Jurassic graben tectonics in mid-Norway. JNNSS/21, 1-13.

Pegrum, R.M. 1984: The extension of the Tornquist Zone in the Norwegian North Sea. Norsk Geologisk Tidsskrift 64, 39-68.

Price,I. & Rattey,R.P. 1984: Cretaceous tectonics off mid-Norway: implications for the Rockall and Faeroe-Shetland troughs. J.geol.Soc. London 141, 985-992.

Ramberg, I.B., Gabrielsen, R.H., Larsen, B.T. & Solli, A. 1977: Analysis of fracture pattern in southern Norway. Geol. en Mijnbouw 56, 295-310.

Rindstad,B. & Grønlie,A. 1986: Landsat TM-data used in the mapping of large-scale geological structures in coastal areas of Trøndelag, Central Norway. NGU Bull.407,1-12.

Roberts, D. 1986: Structural-photogeological and general features of the Fosen-Namsos Western Gneiss Region of Central Norway. NGU Bull.407, 13-25.

Roberts,D. & Sturt, B.A. 1980: Caledonian deformation in Norway. Jour.Geol. Soc.London 137, 241-250.

Roberts, D. 1983: Devonian tectonic deformation in the Norwegian Caledonides and its regional perspectives. Norges geol.unders. 380,85-96.

Roberts, D. & Wolff, F.C. 1981: Tectonostratigraphic development of the Trondheim region Caledonides, central Norway. J.Structural Geol.3, 487-494.

Sanderson,D.J. & Marchini, W.R.D. 1984: Transpression. Journal of Structural Geology 6,449-458.

Sibson, R.H. 1977: Fault rocks and fault mechanisms. Jl.Geol.Soc.Lond. 133, 191-213.

Sigmond, E.M.O, Gustavson, M. & Roberts, D. 1984: Berggrunnskart over Norge. M.1:1 million. Norges geologiske undersøkelse.

Smith, D.I. & Watson, J. 1983: Scale and timing of movements on the Great Glen fault, Scotland. Geology 11, 523-526.

Speight, J.M. & Mitchell, J.G. 1979: The Permo-Carboniferous dyke-swarm of northern Argyll and its bearing on dextral displacement on the Great Glen fault. Jl.Geol.Soc.Lond. 136, 3-11.

Speksnijder, A. 1987: The structural configuration of Cormorant Block IV in context of the Viking Graben structural framework. Geologie en Mijnbouw 65, 357-379.

Steel, R.J., Siedlecka, A. & Roberts, D. 1985: The Old Red Sandstone basins of Norway and their deformation: a review. In: Gee, D.G. & Sturt, B.A.(eds.). The Caledonide orogen-Scandinavia and related areas. John Wiley & Sons, Chichester, 293-315.

Sturt, B.A., Torsvik, T.H. & Grønlie, A. 1987: Dating of hydrothermal alteration-zones and breccias in the Trondheimsfjord region: The Møre-Trøndelag Fault Zone. Inpubl. NGU-rapport 87.138, 11pp.

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

Tchalenko, J.S. & Ambraseys, N.N. 1970: Structural analysis of the Dasht-e Bayaz(Iran) earthquake fractures. Geological Society of America Bulletin 81, 41-60.

Torsvik,T.H.,Løvlie,R. & Sturt,B.A. 1985: Palaeomagnetic arguments for a stationery Spitsbergen relative to the British Isles (Western Europe) since late Devonian and its bearing on North Atlantic reconstruction. Earth Planet.Sci.Lett.75,

Van der Voo, R. & Scotese, C. 1981: Palaeomagnetic evidence for a large (ca.2000km) sinistral offset along the Great Glen Ffault during Carboniferous time. Geology 9, 583- .

Vigran, J.O. 1970: Fragments of a Middle Jurassic Flora from the Northern Trøndelag, Norway. Norsk Geol.Tidsskr.50, 193-214.

Wilcox,R.E., Harding, T.P. & Seely, D.R. 1973: Basic wrench tectonics: AAPG Bull.57,74-96.

Woodcock,N.H. & Fischer,M. 1986: Strike-slip duplexes. Journal of Structural Geology 8,725-735.

Wolff,F.C. 1976: Geologisk kart over Norge, berggrunnskart Trondheim 1:250.000. Nor.Geol.Unders.

Wolff, F.C. 1984: Regional geophysics of the Central Norwegian Caledonides. NGU Bull. 397, 1-27.

Ziegler, P.A. 1981: Evolution of sedimentary basins in North-West Europe. Petroleum Geology of the Continental Shelf of North-West Europe, 3-39. Institute of Petroleum, London.

FIGURE CAPTIONS

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.

Fig. 2. Landsat TM 4/5/7 FCC image of the Verrabotn area, Verran and Hitra-Snåsa Faults, MTFZ. The area covered is 15 x 15 km (512 x 512 pixels).

Fig. 3. Lineament map of the Verrabotn area with field observations and laboratory determinations of fault rock products. Compare this figure with Fig. 2.

Fig. 4. Arrangement of various structures in transpression zones (Sanderson & Marchini 1984). (a) Compression across zone; (b) simple shear; (c) extension across zone. C - compression, E - extension, V - vein, N - normal fault, F - fold, T - thrust, R & R' - Riedel shears.

Fig. 5. Definition of strike-slip duplex geometries; after Woodcock & Fisher (1986).

Fig. 6. Orientations and slip directions of Riedel (R and R'), P, X and Y shears relative to the overall right-lateral sense of shear. T is the extension fracture conjugate to R and R'. Ø is the angle of internal friction. From Bartlett et al. (1981).

Fig. 7. Rose diagram of strike trends for prehnite-matrix cataclasites occurring in the crush breccia of the Verran Fault (Fig. 3).

PLATE CAPTION

Plate 1. Landsat Thematic Mapper (TM) lineament interpretation of the Verran and Hitra-Snåsa Faults, Møre-Trøndelag Fault Zone (MTFZ).

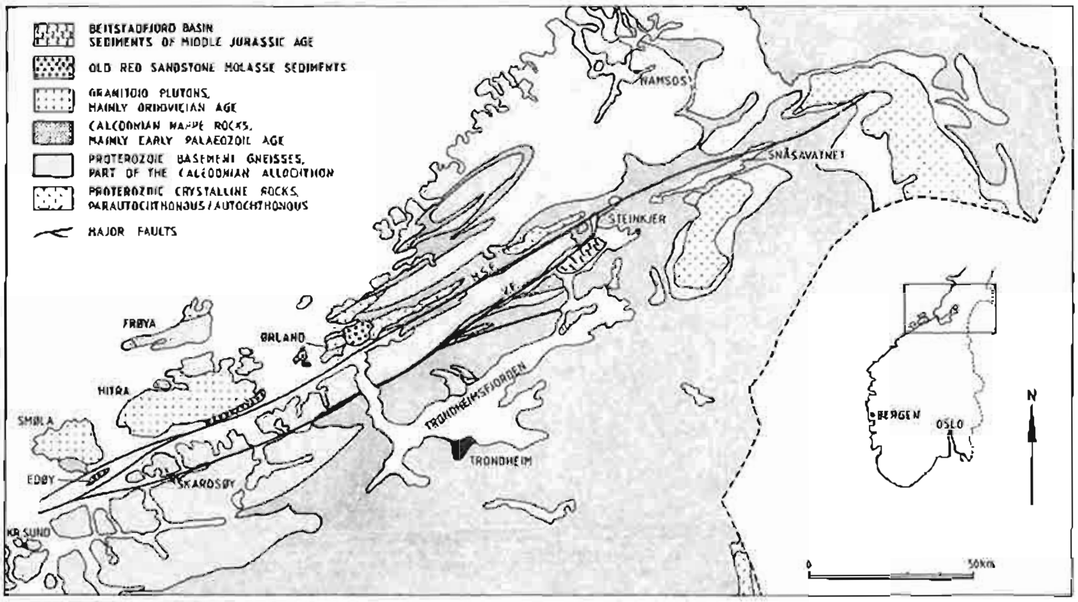
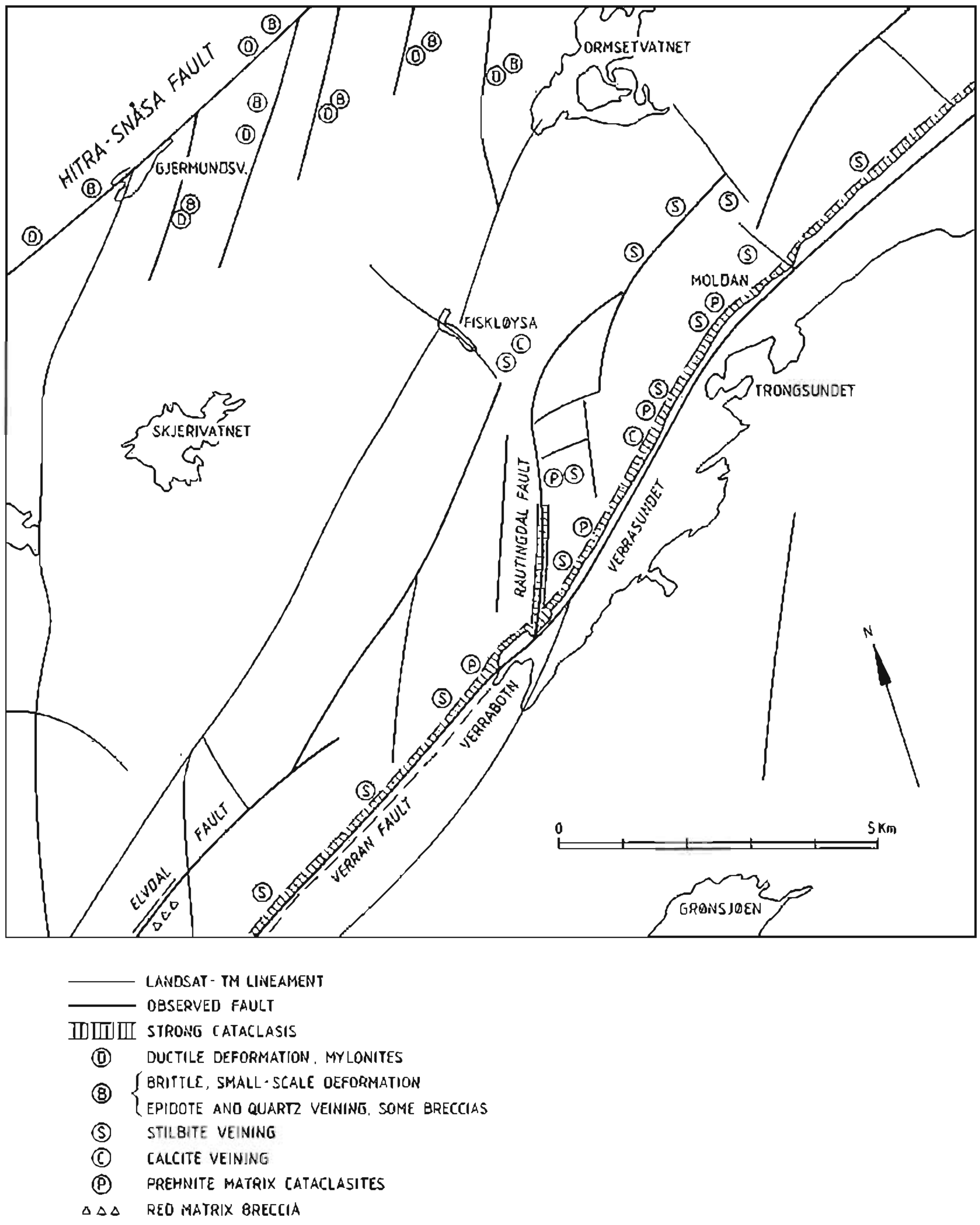

BEITSTADFJORD BASIN
SEDIMENTS OF MIDDLE JURASSIC AGE
OLD RED SANDSTONE MOLASSE SEDIMENTS
GRANITOID PLUTONS,
MAINLY ORDOVICIAN AGE
CALEDONIAN NAPPE ROCKS,
MAINLY EARLY PALAEOZOIC AGE
PROTEROZOIC BASEMENT GNEISSES,
PART OF THE CALEDONIAN ALLOCHTHON
PROTEROZOIC CRYSTALLINE ROCKS,
PARAUTOCHTHONOUS/AUTOCHTHONOUS
MAJOR FAULTS
NAMSOS
SNÅSAVATNET
STEINKJER
M.S.F.
V.F.
FRØYA
ØRLAND
HITRA
SMØLA
EDØY
SKARDSØY
KR.SUND
TRONDHEIMSFJORDEN
TRONDHEIM
BERGEN
OSLO
N
0
50km

FIG.1

FIG.2

FIG.3


HITRA-SNÅSA FAULT
GJERMUNDSV.
ORMSETVATNET
FISKLØYSA
SKJERIVATNET
MOLDAN
TRONGSUNDET
RAUTINGDAL FAULT
VERRASUNDET
VERRABOTN
VERRAN FAULT
ELVDAL FAULT
GRØNSJØEN
N
0
5 Km
LANDSAT - TM LINEAMENT
OBSERVED FAULT
STRONG CATACLASIS
Ⓓ DUCTILE DEFORMATION, MYLONITES
Ⓑ BRITTLE, SMALL-SCALE DEFORMATION
EPIDOTE AND QUARTZ VEINING, SOME BRECCIAS
Ⓢ STILBITE VEINING
Ⓒ CALCITE VEINING
Ⓟ PREHNITE MATRIX CATACLASITES
△△△ RED MATRIX BRECCIA

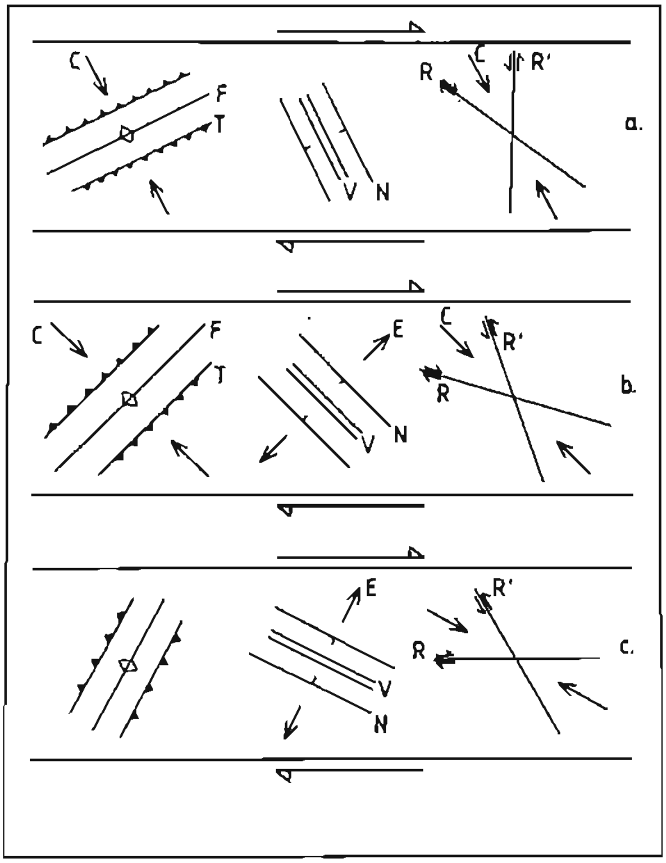

C
F
T
V
N
R
C
R'
a.
C
F
T
E
V
N
C
R'
R
b.
E
V
N
R'
R
c.

Fig. 4

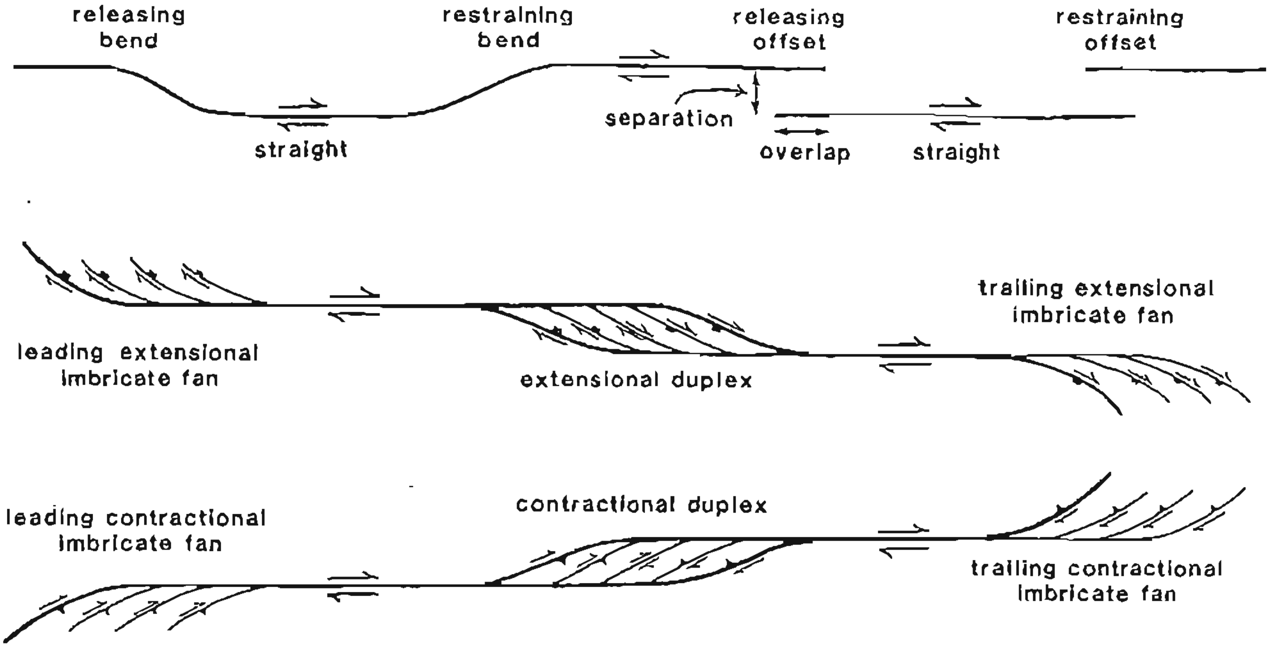

releasing bend
restraining bend
releasing offset
restraining offset
straight
separation
overlap
straight
leading extensional imbricate fan
extensional duplex
trailing extensional imbricate fan
leading contractional imbricate fan
contractional duplex
trailing contractional imbricate fan

Fig.5

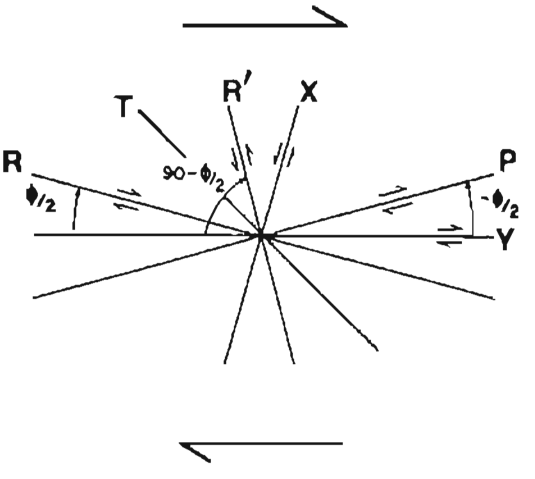
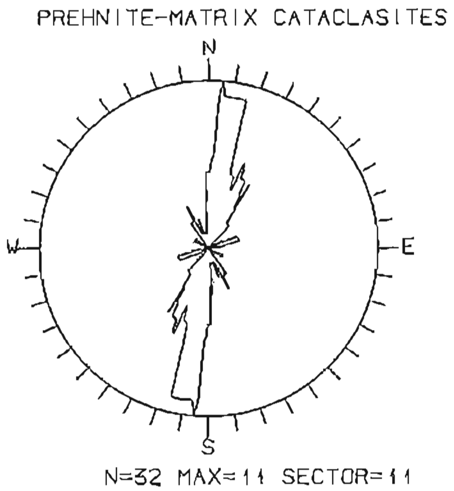


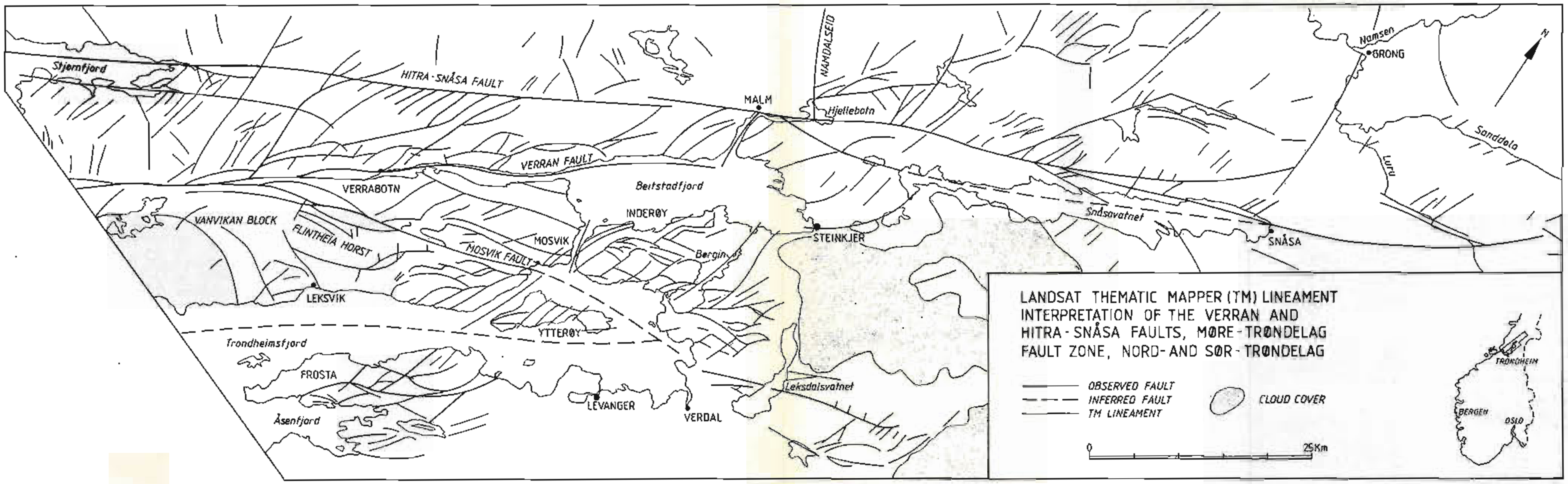
Fig.6


PREHNITE-MATRIX CATACLASITES

N=32 MAX=11 SECTOR=11

Fig.7

Pl. 1



LANDSAT THEMATIC MAPPER (TM) LINEAMENT
INTERPRETATION OF THE VERRAN AND
HITRA-SNÅSA FAULTS, MØRE-TRØNDELAG
FAULT ZONE, NORD- AND SØR-TRØNDELAG