The geology between Salangsdalen and Gratangenfjord, Troms, Norway

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Barker, A.J. 1986: The geology between Salangsdalen and Gratangenfjord, Troms, Norway. *Nor. geol. unders. Bull. 405*, 41—56.

The geology of an area in southernmost Troms, Norway, is presented. Seven Caledonian nappes are recognised, and these rest with thrust contact above Precambrian crystalline basement. The same D_2—D_4 deformation history is recognised in all nappes, but pre-D_2 structures are not well understood since they have been largely obliterated by the intense S_2 regional schistosity. S_1 inclusion fabrics are observed in many garnet porphyroblasts, and remnants of small pre-S_2 fold closures are locally observed within the S_2 fabric. Whilst D_2—D_4 probably document Scandian deformation it is possible that some pre—D_2 structures may represent Finnmarkian and/or Precambrian deformation.

The regional schistosity (S_2) is axial planar to major F_2 recumbent isoclinal folds. F_3 folds are also overturned to recumbent, tight to isoclinal structures, and locally have an associated S_3 clevage. These structures are thought to have formed largely by simple shear, whilst upright generally open F_4 folds and crenulations are considered to have developed solely by lateral compression. The nappes vary in metamorphic grade from greenschist to mid-amphibolite facies. Peak metamorphism (MP1) occurred between S_1 and S_2, but with at least some garnet growth synchronous with S_2. A second event (MP2) gave rise to localised new garnet and mica growth. The main thrusting is largely a late-D_2 or D_3 event since the major thrusts truncate both metamorphic isograds and F_2 folds, but are folded by F_4 structures (e.g. the Ofoten Synform). Associated with the main thrusting extensive retrogression of porphyroblasts occurred in the vicinity of thrust planes. On structural and metamorphic grounds the Høgtind Nappe is shown to be the inverted limb of a major F_2 fold, whilst all other nappes either are right way up, or cannot be proved otherwise.

Correlation with rock units occurring in the Skånland—Håfjell area to the southwest shows that there may be strong grounds for placing a thrust between the Evenes and Bogen Groups. Further south, the Raudvatnet Complex and Sjurvatnet Schist of the Efjord region are shown to be correlatives of the Grønfjellet and Kvernmo Nappes, respectively, of the Gratangsbotn region.

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Introduction

The area of study lies in southernmost Troms, Norway, and is situated about 30 km north-northeast of Narvik (Fig. 1). Following important contributions by Th. Vogt (1942, 1950) and Gustavson (1966, 1969, 1972, 1974a,b) the general nature of the regional geology was established. This contribution presents in more detail the geology of the area between Upper Salangsdalen in the east and Gratangenfjord in the west (Fig. 1). It is largely a summary of thesis work (Barker 1984), and for more detailed description of lithologies and field relationships, the reader is referred to this work. The area is of particular interest since it exposes many of the main tectonostratigraphic units of this part of the Scandinavian Caledonides; from basement 'windows' in the east, up to the middle of the Salangen Group (Gustavson 1966) in the west which forms part of the Upper Allochthon of Gee & Zachrisson (1979). Fossil evidence from Sulitjelma (e.g. Vogt 1927) and the north Troms (Olaussen 1977, Binns & Gayer 1980, Binns & Matthews 1981) suggests that at least some of the rocks under consideration are likely to be of Ordovician—Silurian age, but no fossils have yet been recovered from rocks in the nappes in southern Troms.

Two main orogenic events, both of which involved thrusting, are recognised in the Caledonian history of Scandinavia. The earliest of these occurred from mid Cambrian to earliest Ordovician times and is termed the Finnmarkian phase (Sturt et al. 1978). It is most clearly recorded in the rocks of northernmost Norway (Finnmark). A later more extensive period of orogenesis occurred from mid Silurian to early Devonian times, and is generally referred to as the Scandian phase (Gee 1975). It is so pervasive that it obscures the evidence of earlier Caledonide orogenesis in many areas (Roberts & Gee

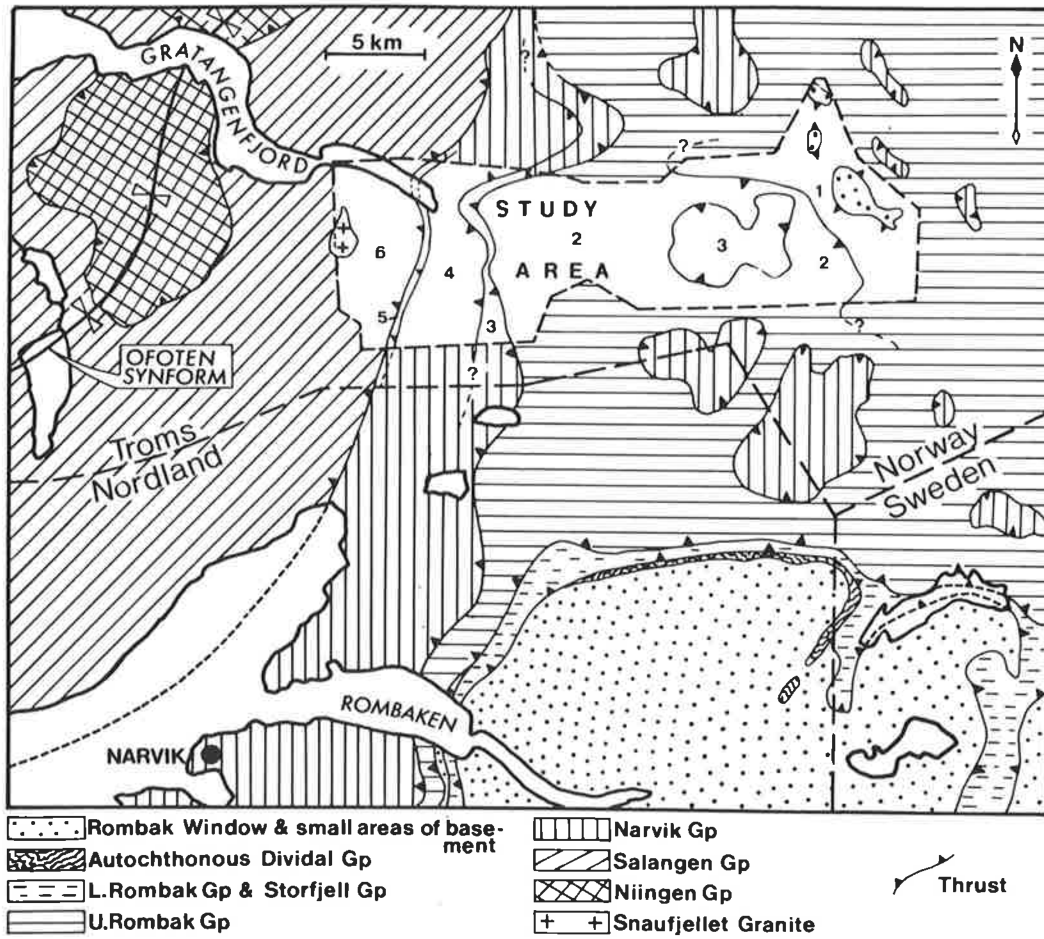

Fig. 1. Location of study area, and generalised geology of the region. (Information from Gustavson 1966, 1974a,b; Kulling 1964; Vogt 1950.) Numbers refer to nappes of the study area: see Fig. 2.

1985). The present lack of fossils and radiometric dates in southern Troms allow only speculation about the exact timing of deformation and metamorphic events. However, regional correlations suggest that the major structures are Scandian.

Fig. 2 shows a simplified geological map of the Salangsdalen—Gratangenfjord area. The lithological outcrop pattern shows broad similarities with previous mapwork by Vogt (1950), Lund (1965) and Gustavson (1966, 1974b). Notable differences include the lack of a basement slice (or 'window') 3 km south-southeast of Melkefjell, as shown on the maps of Vogt (1950) and Gustavson (1966, 1974b), and fewer marble bands in the Fossbakken Nappe. Additionally, an extensive area of amphibolites (part of the Grønfjellet Nappe) is recognised 3 km east-southeast of Øse. Important new structural observations include the recognition of several additional major thrust surfaces, and the recognition of major sub-horizontal early isoclinal folds in the Høgtind Nappe (Barker 1984), the rocks of which are equivalent to the uppermost part of the Rombak Group of Gustavson (1966). On various grounds this nappe can be shown to have an inverted stratigraphy, and the evidence for this will be discussed.

Tectonostratigraphy

The local tectonostratigraphy is summarized in Fig. 3 and consists essentially of seven major

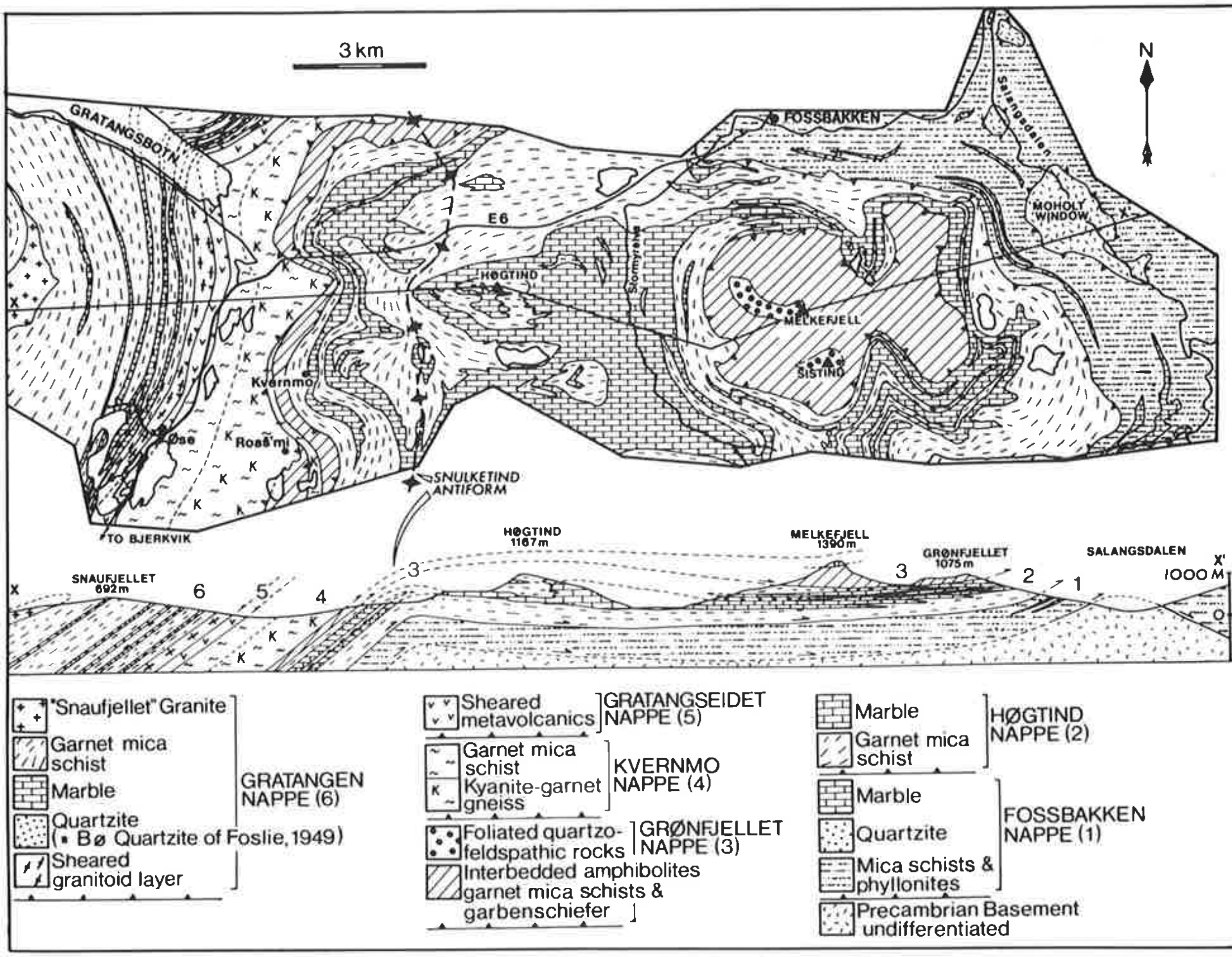

Fig. 2. Simplified geological map and cross section of the study area (after Barker 1984).

Caledonian nappes overlying Precambrian basement. The thrusts at the base of the Rombak Nappe Complex, Narvik Nappe Complex and Gratangen Nappe are all major thrusts possibly with considerable displacement. However, the relative importance of some of the other thrusts is uncertain, and indeed the presence of a thrust separating the Fossbakken Nappe from the Høgtind Nappe is based solely on a distinctive metamorphic change, and a major zone of retrogression at the proposed boundary.

Precambrian Basement

In the valley floor of Upper Salangsdalen, crystalline basement rocks are exposed in several areas. These are presently considered to be Precambrian basement windows, but it is also possible that they may represent basement slices within the Rombak Nappe Complex. Alternatively, the culmination across Salangsdalen, which is responsible for the outcrop of the window, may be due to the presence of an underlying thrust horse in the basement. The Upper Salangsdalen 'windows' are dominated by gabbroic diorites, which are demonstrably the oldest rocks exposed. Younger augen gneisses are found largely in the southeastern part of the Moholt window (Fig. 2). Both the augen gneiss and the gabbroic diorites are intruded by microgranite and granite pegmatite dykes, which are the youngest basement lithologies seen. Extensive mylonite/protomylonite zones are generally observed at the contact between the Moholt window and the overlying Fossbakken Nappe. These are particularly well exposed in a fresh

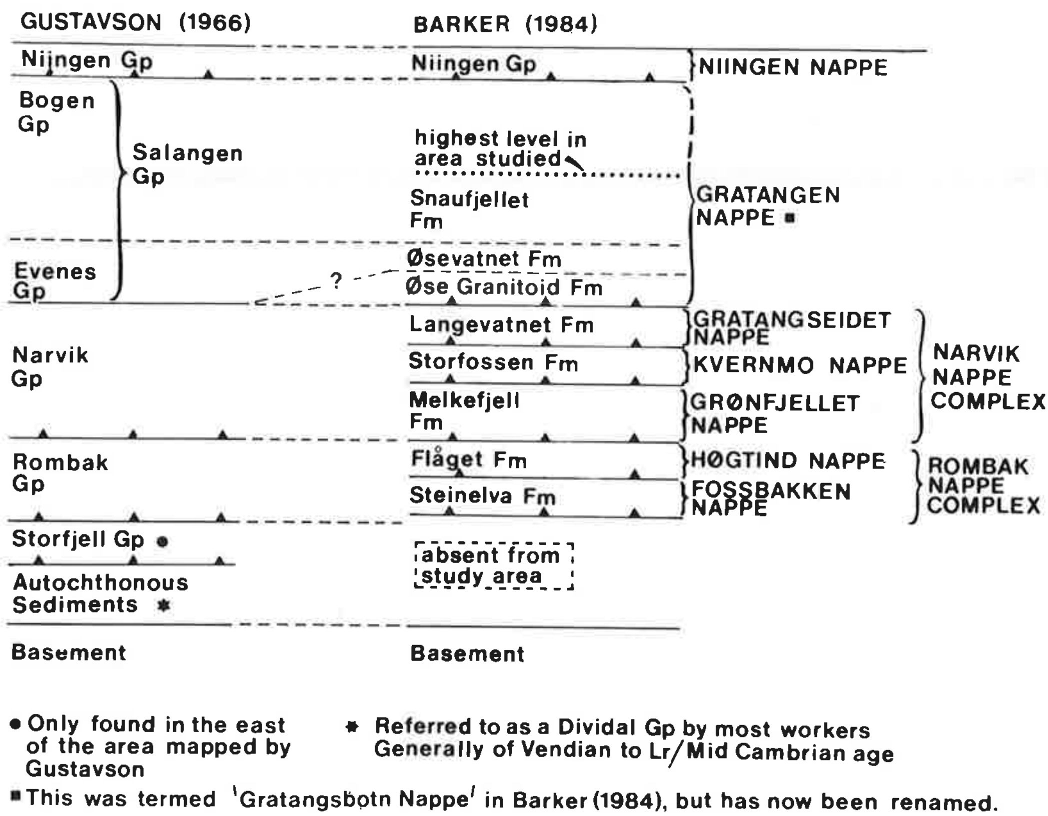

Fig. 3. The tectonostratigraphy of South Troms, Norway.

road-cut at the southeastern margin of the window.

Fossbakken Nappe
Overlying the basement 'windows' with thrust contact is the Fossbakken Nappe. The rocks of this nappe are probably equivalent to the middle part of the Upper Rombak Group of Gustavson (1974a). The sequence is dominated by biotite-grade mica schists, which for the most part have a phyllonitic character. Rare discontinuous thin horizons of marble and quartzite occur within this nappe, but constitute less than 5% of all lithologies.

Høgtind Nappe
The Høgtind Nappe is thought to overlie the Fossbakken Nappe with an essentially layer-parallel thrust contact. No distinct thrust contact has been observed in the field, and initially the change from biotite-grade to garnet-grade pelites was simply considered to represent a metamorphic inversion. However, detailed mapping and thin-section studies have clearly demonstrated a major zone of retrogression at the supposed 'garnet-isograd', and it is now concluded that a thrust (Høgtind Thrust) exists at this level in the tectonostratigraphy. The Høgtind Nappe is characterised by schists in its lower part; these pass upwards into a marble-dominated unit. Virtually all schists of the Høgtind Nappe are very garnetiferous, and in the upper part of the nappe a rock with 5% staurolite and trace amounts of kyanite has been recorded. The rocks of the Høgtind and Fossbakken Nappes equate with the Upper Rombak Group of Gustavson (1974a), but since in this area at least two nappes appear to be developed, the present author proposes the use of the term Rombak Nappe Complex to describe the unit.

Grønfjellet Nappe
The Rombak Nappe Complex is overlain with thrust contact by the Narvik Nappe Complex

(= Narvik Group of Gustavson, 1966) which is composed of three nappes. The thrust at the base of this nappe complex is termed the Grønfjellet Thrust, and the lowest of the three nappes the Grønfjellet Nappe. The junction between the Grønfjellet Nappe and the underlying Rombak Nappe Complex is essentially layer parallel, but mapping has demonstrated slight regional angular discordance and the presence of both hangingwall and footwall cut-offs. The rocks of the Grønfjellet Nappe are equivalent to the lower part of Gustavson's Narvik Group. They consist largely of schistose amphibolite, garbenschiefer and garnet-mica schists, with rare marble, quartzite and extremely rare retrogressed ultramafic (orthopyroxenite) pods. The nappe shows considerable thinning westwards from 700 m thickness in the Melkefjell area, to less than 400 m in the Kvernmo—Roaš'mi area. This nappe locally contains staurolite in its lower levels, but garnet appears to be the highest index mineral in the higher levels of the nappe. It is possible that compositional controls may restrict the development of staurolite and kyanite within the nappe. However, preliminary geochemical investigations (Barker 1984), with data plotted on diagrams used by Hoschek (1967, 1969), suggests that for some lithologies at least this is not the case.

Kvernmo Nappe

Above the Grønfjellet Nappe is the Kvernmo Nappe. The evidence for the Kvernmo Thrust separating these two units is based on the presence of recrystallized ribbon quartz mylonitic fabrics in basal rocks of the Kvernmo Nappe. Additionally, a very sudden change in metamorphic grade is observed. The upper part of the Grønfjellet Nappe is garnet grade (assuming no compositional controls), whilst the Kvernmo Nappe is clearly kyanite grade (Fig. 5). This nappe consists of kyanite gneisses in the lower two thirds, and garnet-mica schists devoid of kyanite in the upper third (Figs. 2 and 5). Additional evidence of the high-grade nature of the Kvernmo Nappe is the presence of 'granitoid' pods (commonly highly sheared) which occur in abundance at several levels within the nappe. Although the nappe is dominated by high-grade pelitic gneisses, rare discontinuous horizons of marble and amphibolite also occur. A final point to note is that in the Roaš'mi area, (Fig. 2), there is an interleaving of kyanite gneisses of the Kvernmo Nappe with garnet-mica shists and amphibolites of the Grønfjellet Nappe. This interleaving is considered to be tectonic, and may involve structures from more than one orogenic event. It could represent: 1) Scandian dismembering of a single unit of Precambrian gneisses; 2) Imbrication of Finnmarkian kyanite gneisses during the Scandian thrusting event; or 3) local late-stage Scandian thrusting giving rise to complication of the Scandian tectonostratigraphy. The data relating to this nappe is at present insufficient to resolve the matter.

Gratangseidet Nappe

Above the Kvernmo Nappe and forming the uppermost part of the Narvik Nappe Complex, is the Gratangseidet Nappe. This represents a 100—150 m wide biotite-grade shear zone, consisting of a suite of sheared and retrogressed metavolcanites with amphibolite pods. Distinctive green chlorite—actinolite/anthophyllite schists are common, and may represent sheared ultrabasic rocks. Pelitic schists are relatively uncommon in this unit.

Gratangen Nappe

The Gratangseidet Nappe is overlain by the Gratangen Nappe, the upper levels of which have not been studied. The base of this nappe corresponds approximately with the base of the Salangen Group of Gustavson (1966, 1974a,b), although there is no equivalent to the Elvenes Conglomerate. The Gratangen Nappe commences with a laterally continuous, highly sheared, 200—700 m thick granitoid layer (Øse granitoid unit), not shown on the maps of Gustavson (1966, 1974a). Though the boundary is not exposed, the highly sheared character of this granitoid unit and the nature of the underlying Gratangseidet Nappe clearly indicates that a major tectonic boundary probably exists. Above the Øse granitoid unit is the Øsevatnet Formation. In Barker (1984), the upper boundary of this formation was taken as the continous marble horizon above (west of) the Bø Quartzite (Fig. 2). However, it is now realised that a more correct place for the boundary is at the marble below (east of) the Bø Quartzite (Fig. 2). Placing the boundary between the Øsevatnet Formation and Snaufjellet Formation above this marble means that these two units directly equate with the Evenes and Bogen Groups of Gustavson (1966). In the Gratangsbotn area this contact also marks an important metamorphic break (Fig. 5) and will be discussed later. The Øsevatnet Formation consists of 600 m of interbanded marble and mica schist. The overlying Snaufjellet Formation is a sequence consisting largely of garnet-mica schists in excess of 2.5 km thickness. The Bø quartzite (12—100 m thick) occurs near the base of the unit (Fig. 2), and sporadic, usually discontinuous marble horizons are also present. A major lensoid granite body (Snaufjellet Granite) crops out over 2.5 km^2 (Fig. 2) and a few small discontinuous schistosity-parallel granitoid lenses are also developed. Rare occurrences of amphibolite pods (commonly biotitised) have also been observed.

Structure

Several phases of deformation, here abbreviated as D_1 to D_4, are recognised in each nappe. Phases D_2 to D_4 are considered to have affected all rocks of the area (Barker 1984), and probably represent Scandian deformation. However, from the present studies little is known about pre-D_2 structures since they appear to have been largely obliterated by the intensely pervasive S_2 regional schistosity. Evidence of an earlier fabric is preserved as an inclusion trail in certain porphyroblasts (garnet in particular). It may be that in some units more than one pre-D_2 deformation occurred, and that rocks in some nappes experienced 'Finnmarkian' and/or 'Precambrian' deformation. More detailed field and thin-section studies will be required to elucidate this very difficult subject, which is fundamental to the understanding of the overall geology of the region. Until this is carried out, only rather speculative interpretations of the early deformation history can be made.

D_1

The first recognisable fabric (S_1) is locally preserved in garnets, as an inclusion fabric generally at a high angle to the external foliation (S_2), which is the regional schistosity. S_1 is usually defined by fine quartz, epidote and opaque inclusions. Associated F_1 folds have not been definitely recognised by the present author, although remnants of small isoclinal fold closures are locally observed within the S_2 fabric and probably represent dismembered pre-S_2 structures.

D_2

S_2 is axial planar to major F_2 folds although penetrative hinge relationships are seldom observed. It probably formed by the transposition of the earlier S_1 fabric. The S_2 regional schistosity was developed synchronously with peak metamorphism and continued to develop for a short while after this peak, which in some units attained kyanite grade (Fig. 5). Thin-section studies of inclusion trails in garnet have shown that in the majority of cases S_1 is discordant to S_2. However, in some spiralled inclusion trails, S_1 is seen to pass directly into S_2, thus demonstrating the transposition of the earlier fabric into the later fabric as part of a continuous deformation sequence. It also suggests that the exact timing of main garnet growth relative to S_2 was not the same across the entire region. However, no consistent pattern of internal fabric variations could be demonstrated, and thus lithological control on the timing of garnet nucleation is considered to be an important factor. In the west of the study area (west of the Snulketind antiform axial trace), the S_2 regional schistosity dips consistently 25°—35° west (Fig. 4 A). Elsewhere the dip direction is variable, and usually at a shallower angle (Fig. 4 B & C). A pronounced L_2 stetching lineation has a consistent NW—SE trend throughout the region (Fig. 4 E). As would be expected L_2 is perpendicular to boudin necks, which are sometimes observed in amphibolite and granitoid layers and to a lesser extent in psammite and marble horizons.

Large recumbent isoclinal folds up to several kilometres amplitude typify F_2. Although demonstrably present in most nappes, these structures are best observed in the distinctly interbanded units such as the Flåget Formation of the Høgtind Nappe. In this unit, superb exposure allows the outcrop pattern of the marble horizons to be accurately mapped, and closure zones recognised. Small-scale F_2 fold axes have rather variable orientation, but typically plunge north to northwest at angles less than 20° (Fig. 4 D).

D_3

F_3 structures fold the S_2 regional schistosity. They are typically tight to isoclinal overturned to recumbent folds, and are generally smaller than F_2 folds. Their style varies according to the type of lithology in which they are developed, and in pelitic schists they are generally seen to have an axial planar spaced cleavage. The orientation of F_3 minor fold axes is variable, but with a weak maximum towards the northwest

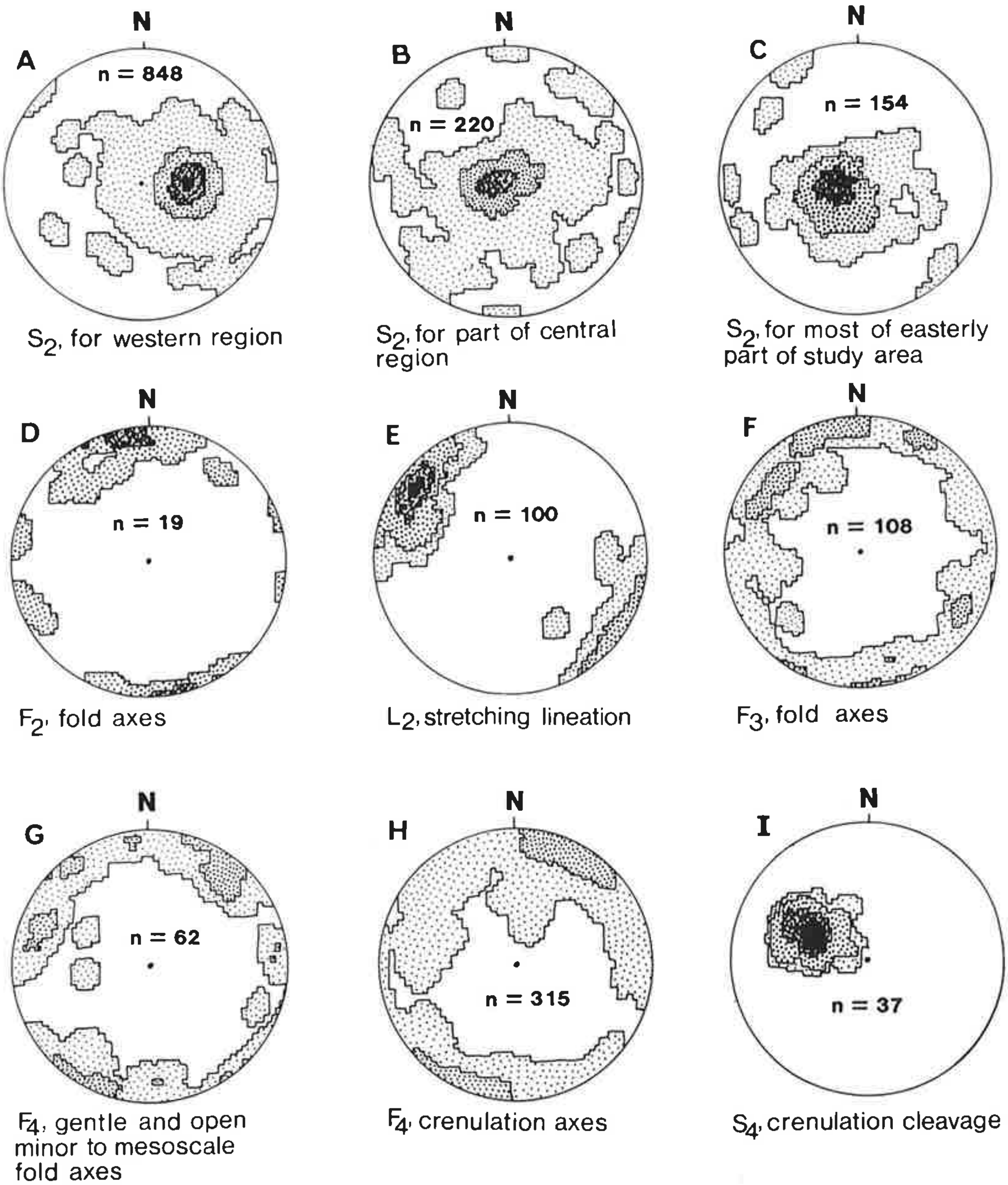

Fig. 4. Contoured equal area stereonets showing structural data from the Upper Salangsdalen—Gratangenfjord region. (N.B. All planar fabrics are plotted as poles to planes; contour intervals are 0.1, 5, 15 and 25%).

sector (Fig. 4 F). Because of the variation in orientation of these fold axes it can be appreciated that the attitude of fold axial surfaces and direction of overturning is also highly variable. Geometrical analysis of a limited number of F_3 fold profiles (Barker 1984) by the dip isogon technique, after Elliott (1965), and plotted on t' α plots (see Ramsay 1967) demonstrated that most folds had an overall profile close to Class 2 (similar) type, though with a tendency towards Class 1C. In interbanded sequences competency contrasts give Class 3 folds in pelitic bands and

Class 1B/1C folds in semi-pelitic/psammitic layers.

The locally developed non-penetrative S_3 spaced cleavage is seen in polished specimen and thin-section to form by the transposition of S_2 by a series of microfolds with axial surfaces parallel to those of major F_3 structures. This process involves the segregation of mica and quartz into separate domains (microlithons), by re-orientation of old grains, in addition to pressure solution and the growth of new grains.

Because of the overturned to recumbent nature of F_3 and earlier folds, and the significant rotation of some garnet porphyroblasts it is reasonable to suggest that a strong component of simple shear was responsible for the formation of most, if not all, of the early structures.

D_4

F_4 folds are typically open structures, and range in size from crenulations to folds of many kilometres amplitude (e.g. Snulketind Antiform (Fig. 2) and Ofoten synform of Gustavson (1972)). The generally upright and symmetrical nature of these structures suggests a lack of, or minimal amount of shearing. Thus, the majority of F_4 structures are considered to have formed simply as a result of late orogenic compression. It is possible that structures such as the Snulketind Antiform may represent culminations above basement 'horses', but present data and level of erosion cannot demonstrate this unequivically. Metamorphic evidence shows that D_4 structures formed at higher crustal levels compared to early structures (see below). F_4 minor fold axes have variable orientations, but plunge at shallow angles (Figs. 4G & H). The variable orientation probably results from several minor late phases of deformation, and local variations in orientation of principal stress axes. In some areas, two sets of crenulations approximately perpendicular to each other are seem, and produce Type 1 (Ramsay 1967) interference patterns. Associated with the NNE—SSW trending crenulation set (Fig. 4H), an S_4 crenulation cleavage is well developed in the north of the area studied. The crenulations with which it is associated are overturned to the north-northwest, and S_4 dips 40°—60° towards east-southeast Fig. 4I).

Timing and nature of thrusting

Since the Gratangenfjord area lies in the internal part of the Scandinavian Caledonides, and has experienced intense ductile shearing under epidote—amphibolite facies conditions, it does not exhibit the 'ramp—flat' tectonics and imbrication associated with frontal regions of thrust belts. Instead, most nappe boundaries are concordant, or very close to being concordant, and can therefore prove difficult to recognise if only a cursory field examination is given. The present studies have revealed six major thrusts in the Upper Salangsdalen—Gratangenfjord area (Figs. 2 & 3). Mylonites are well developed above the basement 'windows', but at other nappe boundaries they seem to be absent or else highly recrystallised. This is probably due to the fact that most, if not all, of the higher nappes were emplaced under upper greenchist (biotite grade) to epidote amphibolite facies (garnet grade) conditions, whereas the basal thrust of the area (above the basement 'windows') probably operated during more brittle low-greenschist or sub-greenschist facies conditions. At the base of the Grønfjellet Nappe (the base of the Narvik Group of Gustavson (1966)), F_2 fold truncation is observed (Fig. 2). Both hangingwall and footwall cut-offs can be demonstrated by the outcrop patterns of different lithologies. Metamorphic grade changes, and zones of extensive retrogression (especially of garnets) are also used as evidence of important thrusts (see 'metamorphism' section, and Figs. 5 & 6). Movement along the major thrusts initiated shortly after peak metamorphism, and in addition to F_2 fold truncation, metamorphic isograds are truncated. Some late minor thrusts are observed to truncate F_3 structures, but D_4 structures seem unaffected. As mentioned earlier, it could be that some major D_4 structures, such as the Snulketind antiform, represent folds above major basement horses, and are thus associated with thrusting. However, this is only speculation, and F_4 folds are presently considered simply as late structures, folding all thrusts (Fig. 2) and associated with the final compressional movements of orogeny.

Metamorphism

Fig. 5 shows the highest grade index mineral observed in pelitic schists from about two thousand localities in the Gratangsbotn—Salangsdalen region. The map shows that garnet is widespread in all nappes except the Fossbakken and Gratangseidet Nappes, and that the Kvernmo Nappe contains abundant kyanite. A few occurrences of staurolite are found in the upper

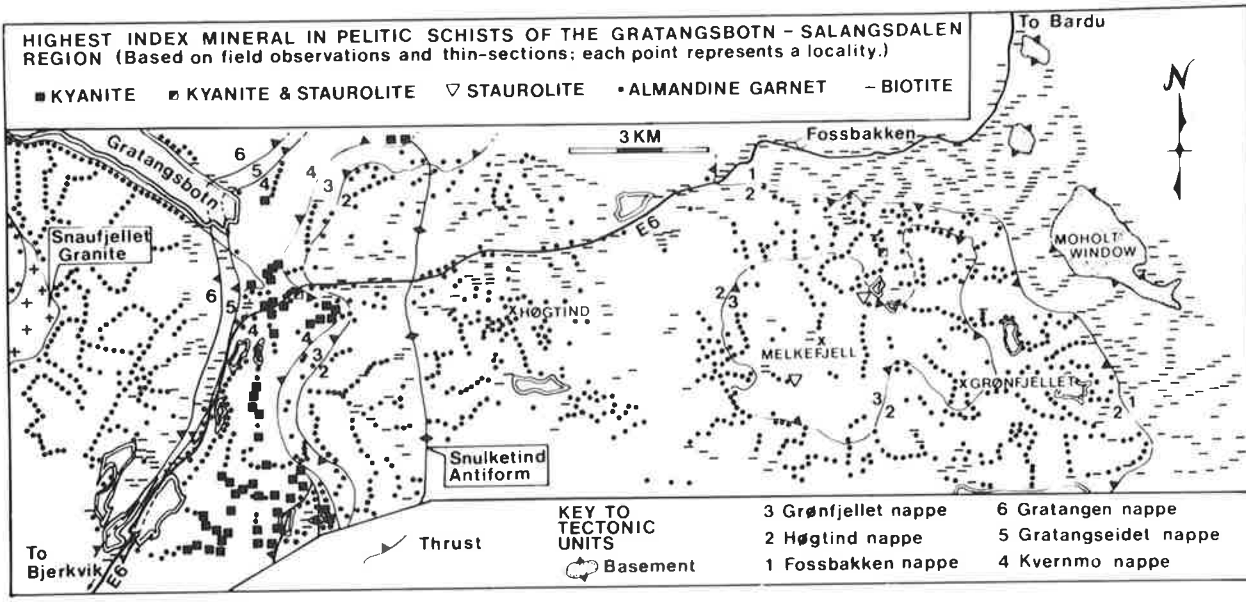

Fig. 5. Map showing the highest grade index mineral in pelitic schists of the Gratangsbotn—Salangsdalen region.

part of the Høgtind Nappe, and lower levels of the Grønfjellet Nappe.

In schists of the Gratangsbotn—Salangsdalen region, muscovite, biotite, chlorite and epidote formed during D_1, thus defining S_1. In the period between D_1 and D_2 pressure (P) and temperature (T) conditions rose considerably, leading to the porphyroblastic growth of chloritoid, garnet, staurolite, kyanite and hornblende. The kyanite grade peak of metamorphism (MP1) was attained just prior to the development of S_2. In some rocks, where garnet growth continued during S_2, spiralled inclusion fabrics were produced. A second metamorphic peak (MP2) has been observed, but is not distinct throughout the region. It attained a maximum of garnet grade, although in many areas late biotite development appears to be the only indication of MP2. MP2 gave rise to the late rim growth seen in some garnets from a variety of localities across the region, and the entirely post-S_2 garnet growth seen in many specimens from the base of the Snaufjellet Formation. After MP2 there was a decline in PT conditions. This gave rise to extensive retrogression within and adjacent to major thrust planes , where fluid movements were probably concentrated. The retrogression is shown by extensive late chlorite development, and the breakdown of earlier porphyroblasts, partic- ularly garnet (Fig. 6).

The lack of garnet, hornblende and Al_2SiO_5 polymorphs in schists from the Fossbakken Nappe indicates that it is of low grade. Low biotite Mg/Fe ratios (i.e. 0.5—1.0) and the presence of phengitic muscovites (Velde 1965, Miyashiro 1973) suggest low grades of metamorphism. Additionally, plagioclase crystals from pelites were shown by probe analysis to have albitic compositions (An_{1-2}). Putting all these lines of evidence together it is concluded that the Fossbakken Nappe is biotite grade, greenschist facies throughout.

The overlying Høgtind Nappe is of significant higher grade than the Fossbakken Nappe. The majority of schists contain garnet, and garbenschiefer rocks contain garnet and hornblende. A single occurrence of garnet-mica schists containing 5% staurolite and trace amounts of kyanite has been recorded from the upper levels of the Høgtind Nappe 3 km south-southeast of Fossbakken (Fig. 5). Biotite Mg/Fe ratios are consistently 0.85—1.00, with the exception of some specimens in the upper part of the nappe where values of 1.45—1.60 have been recorded. This variation, coupled with the isolated occurrence of a staurolite—kyanite schist from the upper part of the nappe, tends to suggest that the nappe could be inverted. However, it is well known that the development of minerals such as staurolite are influenced by bulk rock chemistry (Hoschek 1967, 1969). Therefore, until it can be proved by detailed geochemical studies that suitable rocks for staurolite development are present throughout the Høgtind Nappe it is necessary to look for other evidence to confirm whether the sequence is inverted. Structural evidence, such as fold vergence, can be used to demonstrate on which limb of a major structure an area is situated, but in an area of recumbent isoclinal folding such as the one being studied, it is first necessary to demonstrate the direction of thrusting and fold overturning. Based on stretching lineation data (Fig. 4E) it is clear that the main thrusting trend was NW—SE. However, present evidence from the Gratangsbotn—Salangsdalen area alone is not sufficient at present to define the polarity of thrusting. Lack of knowledge of the pre-thrusting stratigraphy is the greatest problem. However, work by Lindström (1955, 1957) in the nearby area of west Torneträsk, and recent work by Hodges et al. (1982) and Hodges (1985) in the relatively nearby Efjord—Sitasjaure area (Fig. 7) has demonstrated that main Scandian (mid to late Silurian) thrusting and fold overturning in this region was directed towards the southeast. Accepting this, the fact that medium-scale structures of the Høgtind Nappe consistently have westerly vergence (e.g. see area east-southeast of Høgtind, Fig. 2) suggests that this nappe is positioned in the inverted limb of a major F_2 antiform.

Garnet—biotite pair estimates (Ferry & Spear 1978) for the temperature of metamorphism of the Høgtind Nappe proved to be unrealistic (even after corrections suggested by Ganguly (1979)). This was because the almandine garnet studied were too calcareous (typically 15—22% grossular component), and fall well outside the limits imposed by Ferry & Spear (1978). At the base of the Høgtind Nappe, garnet and locally hornblende crystals show intense retrogression and pseudomorphing by chlorite (Fig. 6). It is on this basis, and the distinct junction between biotite-grade and garnet-grade rocks (Fig. 5) that the thrust is located. Placing a thrust on these grounds is considered justifiable since the clearly demonstrable Grønfjellet Thrust at the base of the Grønfjellet Nappe, where hangingwall and footwall cut-offs are seen, is also closely related to a zone of intense retrogression (Fig. 6) whereas in the rest of the nappe thin-section studies have shown that garnets are entirely fresh. It will be noticed from Fig. 6 that within the main part of the Høgtind Nappe not all garnets are fresh, indeed some are totally pseudomorphed by chlorite. Originally the possibility of a thrust at the base of the thick marble unit of the Høgtind Nappe was envisaged. However, since this boundary is clearly affected by F_2 folding, yet no other thrusts were, it was considered unlikely. A seemingly more reasonable conclusion favoured here is that this boundary, between two very contrasting lithologies, like a thrust, would act as a major pathway for fluids and thus give rise to considerable retrogression.

Above the Høgtind Nappe rests the Grønfjellet Nappe. Garnet and hornblende occur throughout the nappe, and staurolite is locally present in the lower levels of the nappe in the Melkefjell area. The metamorphic grade of this nappe is therefore much the same as that of the Høgtind Nappe (i.e. epidote—amphibolite to low amphibolite facies). No firm evidence for the way-up of this nappe has been obtained, but a limited amount of data on plagioclase composition from pelitic and semi-pelitic schists of the Melkefjell area show that they have a composition of An_{17-20} at the base of the nappe, An_{16-17} through the main part of the nappe and An_{10} at the top. This, coupled with the occurrence of staurolite at the base, but not at the top of the nappe, may suggest the presence of a normal metamorphic gradient within the nappe, and thus that the nappe is possibly right way-up. However, due to compositional controls on staurolite development, and the vary small data set, this suggestion remains equivocal. As mentioned above, intense late retrogression of garnets (and staurolite) occurs in the vicinity of the Grønfjellet Thrust. On Fig. 6 this is shown for the area around Melkefjell, but the same feature is also well exhibited in E6 road-cuts 2.5 km southeast of Gratangsbotn. At this locality the intensely retrogressed garnets in schists from the upper part of the Høgtind Nappe can be clearly observed in hand specimen.

Overlying the Grønfjellet Nappe is the high-grade Kvernmo Nappe, consisting of kyanite gneisses in the lower two thirds, but with garnetiferous schists (apparently without kyanite) in the upper third (Figs. 2 & 5). This may suggest that metamorphic grade decreases upwards, but a full study of possible geochemical constraints has yet be carried out. Probe analysis of minerals in a kyanite gneiss from the base of the nappe has been made, but detailed microprobe studies of minerals from the remainder of the nappe are lacking. Like the vast majority of

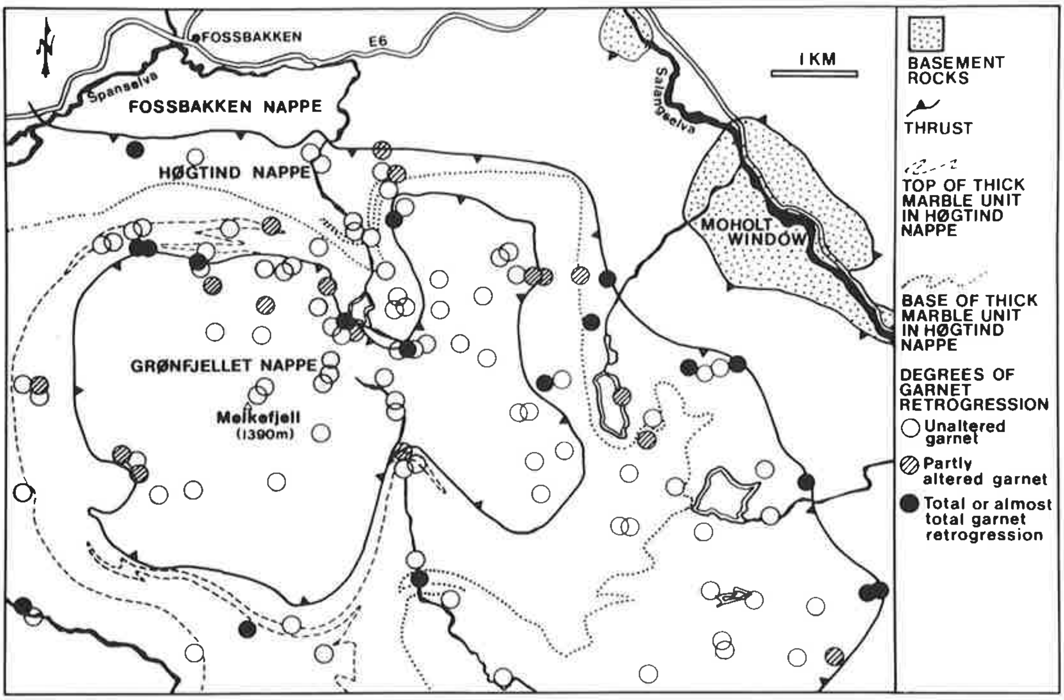

Fig. 6. Map showing the degree of garnet retrogression in pelites from the Melkefjell region (based on thin-section studies).

garnets from the region, garnets from the kyanite gneiss (specimen 135/82) show Mn-bell profiles and have not homogenised. This indicates that temperatures have not exceeded 640° ± 25°C (Yardley 1977). Since almandine garnets from specimen 135/82 contain only very small amounts of Ca and Mn in their structure (i.e. <4% total) it was possible to obtain an estimate for temperature of metamorphism using the garnet—biotite pair technique (Ferry & Spear 1978). The value obtained (Barker 1984) was 594° (±50°C), which is reasonable for a kyanite-grade rock.

The metamorphic grade of the highly sheared Gratangseidet Nappe is biotite grade (greenschist facies) Biotite has been observed in the pelitic schists from this nappe, and in the sheared metavolcanic rocks the assemblage actinolite (± anthophyllite) + albite + epidote/zoisite + sphene + quartz ± biotite ± calcite is most typical. In many of the coarser grained ampibolites the plagioclase crystals are partially pseudomorphed by an aggregate of fine-grained zoisite crystals. This is a common feature of plagioclase decalcification when equilibrating to lower PT conditions. It may represent either primary breakdown from the original calcic plagioclase present in the igneous rocks, or else retrogression of an amphibolite facies assemblage. Both possibilities are equally plausible, but because of intense alteration observed at other thrust or shear zones in the area, the retrogression model is presently favoured.

The highest nappe studied is the Gratangen Nappe. This unit is dominantly pelitic but with several thin marble layers and a single quartzite (= Bø Quartzite of Foslie (1949)). Staurolite and kyanite have not been recorded from this nappe, but almandine garnet is ubiquitous in the Snaufjellet Formation. However, with just two exceptions (where garnet has been noted) the Øsevatnet Formation appears to be of biotite grade (see Figs. 2 & 5). The highly calcareous nature of much of this sequence may be part of the reason why almandine is restricted, but a full geochemical study will be required to resolve this. Probe analyses of plagioclases from pelites in the Øsevatnet Formation have yet to be undertaken, but within the Snaufjellet Formation plagioclase crystals so far analysed have a composition An_{13-15}. The only exception is from a sample immediately above the Bø Quartzite where albitic plagioclaces (An_{1-3}) are recorded. Plagioclase with a composition of An_{13-15} is common in pelites that have experienced epidote—amphibolite facies to low amphibolite facies metamorphism, whilst An_{1-3} suggests greenschist facies conditions. Garnets from the Snaufjellet Formation show classic Mn-bell profiles (Hollister 1966), which according to Yardley (1977) suggest temperatures below 640° ± 25°C. Because of this it is clear that sillimanite grade was probably not reached, but we cannot rule out the possibility that low to mid amphibolite facies conditions (staurolite to kyanite grades) were attained. The lack of the key aluminosilicate index minerals may be due to compositional restrictions; the rocks being too calcareous. The calcareous nature of the sediments is shown by the high Ca-content of the almandines, and thus renders them useless for garnet—biotite pair (Ferry & Spear 1978) temperature estimates. Steltenpohl & Bartley (1984), in the neighbouring area of Skånland 25 km to the west (Fig. 7), have noted 3 occurrences of staurolite and 2 of kyanite within the Bogen Group. This tends to suggest that compositional retstrictions may be the reason for the lack of staurolite and kyanite at this level in the Gratangsbotn area. Alternatively it may indicate lateral variations in metamorphic grade within this unit.

Thin-section studies on various pelites from the Gratangen Nappe have demonstrated a distinct zone of retrogression at, or immediately below the level of the Bø Quartzite; that is to say at the very base of the Snaufjellet Formation. In most specimens from this level the garnets show intense retrogression and pseudomorphing, whereas throughout the rest of the nappe garnets are entirely fresh. The association of retrogression with major thrusts elsewhere in the region gives strong evidence for a thrust at this level, and this is currently being investigated in more detail. Placing a thrust here supports the conclusion of Steltenpohl & Bartley (1984) that the Evenes and Bogen Groups constitute separate nappes that were juxtaposed by thrusting. However, it should be noted that Steltenpohl & Bartley (1984) did not find retrogression to be concentrated at any particular structural level.

Discussion

In this section the lithological, structural and metamorphic features of nappe rocks in the Gratangsbotn—Salangsdalen region are compared with rocks described from other nearby areas. In particular, comparison is made with the Skånland area (Fig. 7) (Steltenpohl & Bartley 1984) and the Efjord—Sitasjaure area (Hodges 1985).

The Skånland area (Fig. 7) has recently been described by Steltenpohl & Bartley (1984) who examined the metamorphic grade of Evenes and Bogen Groups which constitute the Salangen Group of Gustavson (1966). Strictly the Evenes and Bogen units should be termed 'Formations' since together they constitute a 'Group' (Salangen Group). However, it may prove better to retain the terms Evenes Group and Bogen Group, and abandon the term Salangen Group, since the findings of Steltenpohl & Bartley (1984), and preliminary results of the present studies, strongly suggest that there is an important thrust separating the two units. The Evenes Group is a marble-dominated unit, which south of Ofotfjorden rests unconformably above the Narvik Group (Gustavson 1966). The conglomerate separating the two units is the Elvenes Conglomerate and marks the base of the Evenes Group.

The relationships north of Ofotfjorden are somewhat different. In Skånland, the entire Narvik Group and the Elvenes Conglomerate are cut out by thrusting (Steltenpohl & Bartley 1984). The presently studied area from Øse to Gratangsbotn also exhibits significant thrusting at this level with no conglomerate horizon. However, it should be noted that an isolated conglomerate occurrence has been reported immediately north of Gratangsbotn (unpublished observation by Mitsem (1964), referred to by Gustavson (1966)). In the Øse—Gratangsbotn area (Fig. 2), the highly sheared Gratangseidet Nappe marks the top of the Narvik Nappe Complex. It is overlain by a sheared granitoid layer, and above this is an interbanded marble-schist sequence (Øsevatnet Formation) which equates with the Evenes Group.

There appear to be significant differences in metamorphic grade between the Evenes Group at Skånland, and that on the opposite (eastern) side of the Ofoten Synform at Gratangsbotn. Garnet and sporadic kyanite and staurolite are seen in Evenes Group pelites at Skånland (Steltenpohl & Bartley 1984). However, in the Gratangsbotn area the Evenes pelites appear to be of biotite grade, with just two isolated occurrences of garnet and no aluminosilicates. Schists above the Bø Quartzite are garnetiferous in both Skånland and Gratangsbotn. In Skånland,

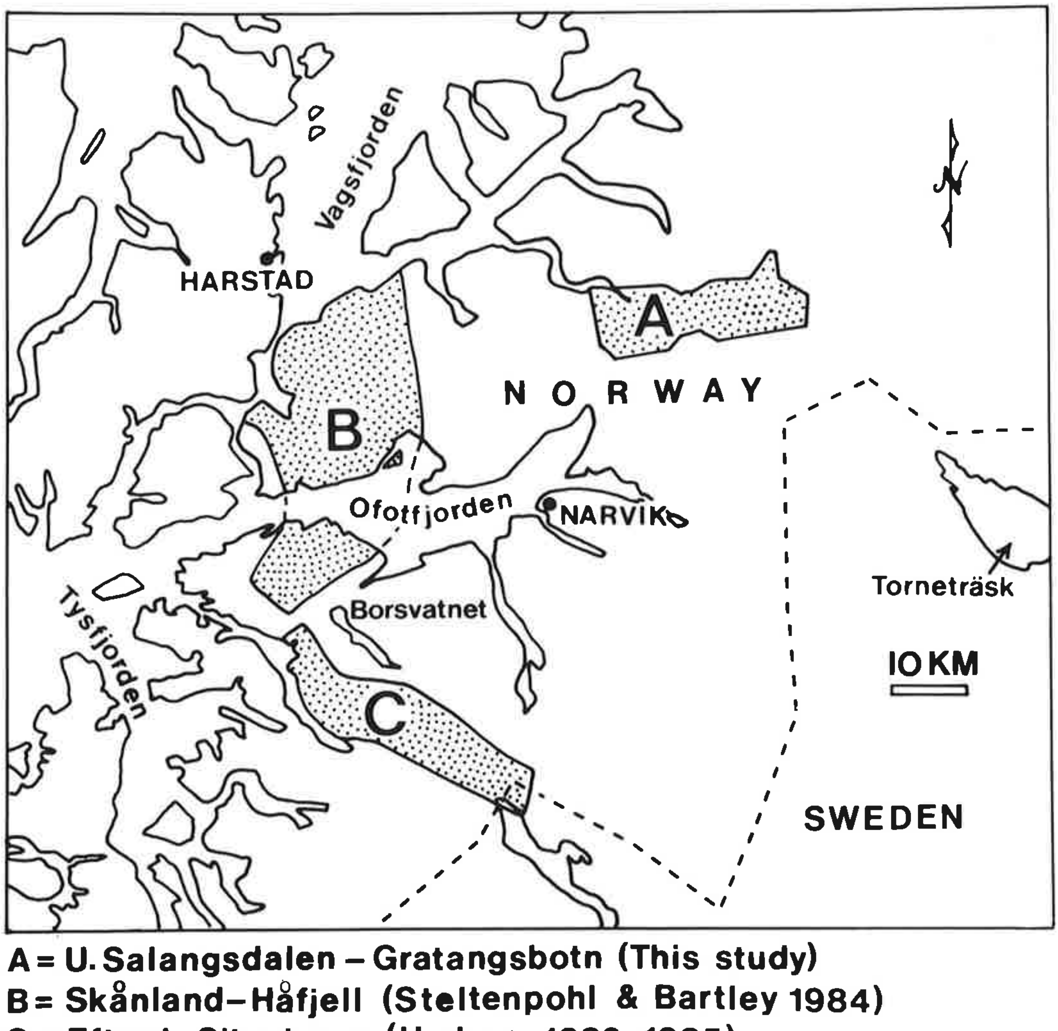

Fig. 7. Map showing the geographical location of areas studied by Steltenpohl and Bartley (1984) and Hodges (1982, 1985) in relation to the Upper Salangsdalen—Gratangsbotn area.

these Bogen Group schists locally contain staurolite and more rarely kyanite (Steltenpohl & Bartley 1984), whereas at Gratangsbotn these minerals have yet to be recorded. Highly calcareous schists inhibit the development of these aluminosilicates, and it is quite probable that the Bogen Group sequence at Gratangsbotn attained low to mid amphibolite facies but lacks staurolite and kyanite because of compositional controls.

The present study, in common with of Steltenpohl & Bartley (1984), finds no truncation of the principle metamorphis fabric (regional schistosity). Steltenpohl & Bartley (1984) argue that thrusting pre-dates peak metamorphism since the regional schistosity is not truncated. However, in the Gratangsbotn area this fabric (S_2) envelops garnet, kyanite and staurolite porphyroblasts and is axial planar to recumbent isoclinal S_2 folds, and since these folds have been truncated by the major thrusts, peak metamorphism is interpreted as having occurred just

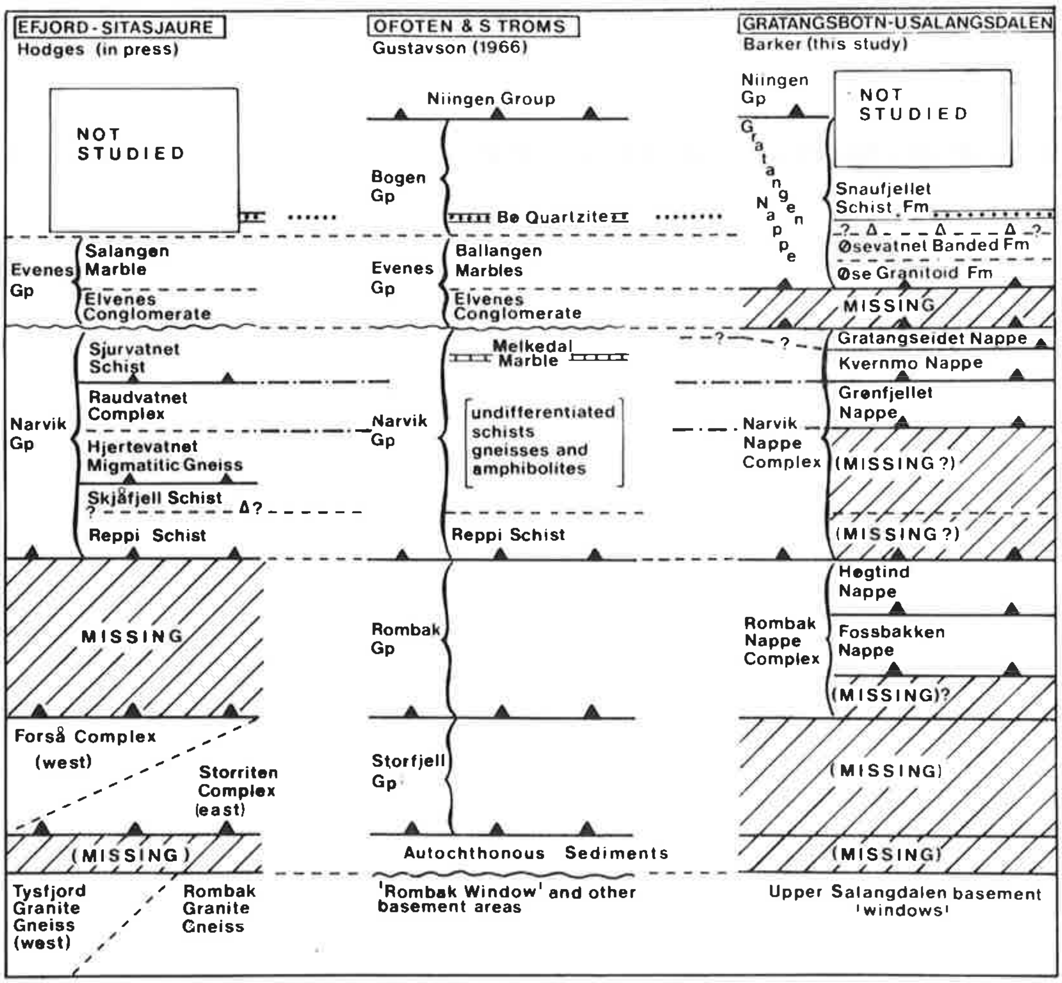

Fig. 8. Tectonostratigraphic correlations in the Ofotfjorden—Tysfjorden region (not to scale).

prior to main thrusting. The regional schistosity is apparently not truncated since thrusting occurred largely parallel to it.

In the Efjord—Sitasjaure area Hodges (1982, 1985) has examined the tectonostratigraphic sequence from the Tysfjord granite gneiss basement up to the Evenes Group. Up to the level of about the middle of the Narvik Group there seems to be nothing in common with the Gratangsbotn—Upper Salangsdalen region (Fig. 8).

Above the basement rocks at Efjord is the Forså complex 'Schuppen Zone', which involves basement and cover rocks. At the same tectonostratigraphic level near the Swedish border, the Storriten Complex occurs. This unit is also a 'Schuppen Zone' (= duplex), and together with the Forså Complex is correlated (Hodges 1985) with the Storfjell Group (Gustavson 1966). There is no equivalent of this unit in the Gratangsbotn—Upper Salangsdalen area.

Below the Reppi Schist (Foslie 1941), which Gustavson (1966) places as basal Narvik Group, there is the Rombak Group; termed Rombak Nappe Complex in this study. This unit is absent from the Efjord—Sitasjaure area, but represented in the Gratangsbotn—Upper Salangsdalen region by the Fossbakken and Høgtind Nappes. The distinctive Reppi schist (Foslie 1941) with its large clinozoisite porphyroblasts is absent from the Gratangsbotn—Upper

Salangsdalen sequence, and it is also doubtful whether the Skjåfjell schist and Hjertevatnet migmatitic gneiss described by Hodges (1985) are present. However, the overlying Raudvatnet Complex of the Efjorden area, with its mixture of amphibolites, impure marbles, trondhjemites, ultramafic pods, and garnet-mica schists, is quite likely to be a correlative of the Grønfjellet Nappe. Based on the descriptions of Hodges (1985) the main differences between these two units are that the Grønfjellet Nappe contains very few marble horizons or pods, and lacks trondhjemite dykes. However, within the tectonostratigraphy of the Ofoten region, there are few amphibolite-dominated units, and all occur at much the same level in the sequence. On these grounds it is therefore suggested that the two units are related. The argument is strengthened by the fact that the overlying units found in both areas can undoubtedly be correlated. In the Efjord area the Sjurvatnet schist is a sequence of kyanite—garnet gneisses, with small veins and pods of quartz (± feldspar, muscovite and kyanite) permeating the sequence. Hodges (1985) states that in some exposures the Sjurvatnet schist has 'a striking augen schist texture', with augen of plagioclase. This distinctive unit has the same features as the Kvernmo Nappe gneisses from the Gratangsbotn area (see earlier description). Further proof of the correlation is that the Melkedal Marble (Foslie 1941) occurs within the Sjurvatnet schist sequence. This distinctive thin marble horizon is shown on the maps of Gustavson (1966, 1974b) to extend from the Efjorden region along strikes as far north as Rombaken where it peters out just north of the fjord. In the Skjomen—Rombaken region Vogt (1950) shows the Melkedal Marble to lie within a unit shown on the map key as 'Schist and injection gneiss with trondhjemite intrusions'. This unit is demonstrably an extension of the Kvernmo Nappe, and can be traced continuously from the north shore of Rombaken to Gratangsbotn. In conclusion, the evidence clearly shows that this unit of kyanite gneisses is a distinctive marker horizon within the tectonostratigraphy and can be traced from Efjord northwards to Gratangsbotn. Based on the descriptions of Foslie (1941), the Gicce Gneiss of the Tysfjord region, which occur near the border with Sweden, may also be a correlative of the Kvernmo Nappe kyanite gneisses.

In the Gratangsbotn area the Kvernmo Nappe is overlain by the Gratangseidet Nappe which forms the uppermost part of the Narvik Nappe Complex. This is a low-grade unit consisting largely of sheared metavolcanites. At Narvik the Lillevik Dyke Complex described recently by Boyd (1983) is probably a lateral extension of the same unit. It is less certain whether the unit can be traced continuously to Efjord. However, Foslie (1941, 1949) describes a locally extensive unit of amphibolite and hornblende—gabbro at a comparable level in the area immediately northwest of Borsvatnet (Fig. 7).

Above the Narvik Nappe Complex is the Evenes Group. In the Efjord—Håfjell region, this commences with the Elvenes Conglomerate. Hodges (1985) recognised two distinct conglomeratic facies, but neither of these is present in the Gratangsbotn region, and as discussed previously the Elvenes Conglomerate has probably been cut out by thrusting. The overlying marbles of the Evenes Group can be traced around both sides of the Ofoten Synform (see Gustavson 1974b), and are represented in Gratangsbotn by the Øsevatnet Formation.

From the above discussion it is clear that several major tectonostratigraphic units can be traced from Efjord to Gratangsbotn. However, other units are missing from the Gratangsbotn region but occur in the Efjord area, and vice versa (Fig. 8). In conclusion therefore, broad nappe complexes can be traced over the 80 km tract between the two areas, yet many of the nappes within these complexes wedge out laterally. This suggests that there is a complex interleaving of units comprising the nappe pile in this portion of the Scandinavian Caledonides, and that along strike regional correlation is not possible for all nappes.

The deformation sequence observed by Hodges at Efjord has many broad similarities to that described from Gratangsbotn, in this paper. F_2 and S_2 structures at Efjord record the same event as F_2 and S_2 at Gratangsbotn, and Hodges (1985) notes that S_2 was synchronous with peak metamorphism, which is the same conclusion reached in this study. An important difference in the structural history is that Hodges (1985) recognises several major thrusts which are premetamorphic peak. This relationship has not been recognised at Gratangsbotn, and all thrusts are considered to have occurred after the peak of metamorphism, being either late-D_2 or else D_3. The 'D_5-Basement-involved thrusting' of Hodges (1985) also appears to be absent from the Gratangsbotn—Upper Salangsdalen region.

Acknowledgements

I would like to thank R. Binns, R. Gayer and R. Mason for helpful discussion and comments on early drafts of this paper. I would also like to thank two anonymous referees for their helpful comments and criticism, and additional comments by K.B. Zwaan. Thanks are also given to Anthea Dunkley for drafting the diagrams, Nottingham University for carrying out X.R.F. analyses, and Cambridge University for the use of their electron microprobe. The original fieldwork and research was carried out at University College. Cardiff, under the tenure of a N.E.R.C. studentship (GT4/80/GS/141); this is gratefully acknowledged.

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