Geometry and kinematics of extensional deformation along the northern edge of the Rombak Window, Nordland, North Norway

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Deformation along the northern edge of the Rombak Window documents an unusual extensional event during the evolution of a collisional orogen. The extension occurred along a series of ductile deformation zones that strike slightly east of north and dip moderately west; both mesoscopic and microscopic kinematic indicators demonstrate normal motion on these zones. Two adjacent zones are major features, extending at least 6 km along strike (representing a structural depth of 1.1 - 1.6 km) without changing orientation. The remainder are fairly superficial features, dying out at depths of 100 to 200 m; they are thought to represent local adjustments to offset on the major zones. Fault zones with normal offset along strike at the southern edge of the Rombak Window are thought to be part of the same feature, although they formed at shallower depths. A prominent N-S-trending structural lineament and isolated patches of Dividal Group sedimentary rocks in the central part of the window may represent the trace of this extensional feature. The extension was preceded by emplacement of the Bjørnfjell Thrust Complex, containing granitic basement and autochthonous sedimentary rocks of Baltoscandian affinity. Both of these events occurred under greenschist facies (biotite grade) conditions. The extension was followed by emplacement of higher nappe sheets containing a variety of rock types, and generally considered to be exotic with respect to the Baltic craton.

Three types of models which could create the required extension of the subducting craton, preceded and followed by large-scale compressional deformation, are being considered: (1) Extension of the upper surface of the Baltic craton during flexing prior to subduction. (2) Extension due to the flexing of a crystalline thrust sheet as it moved over a ramp in an underlying detachment. (3) Extension due to an unrecognized deformational event during the 80 Ma age bracket allowed by the broadest interpretation of the age constraints on Caledonien deformation in this area.

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Introduction

Deformation along the northern edge of the Rombak Window, in the Caledonian orogen of North Norway (Fig. 1), documents an unusual extensional event during the evolution of a convergent plate margin. The Scandinavian Caledonides developed in Early to Middle Paleozoic time from the collision of the Greenland and Baltic cratons (Laurentia and Baltica), following the closing of the Iapetus Ocean (Roberts & Gee 1985). Although the polarity of subduction has been debated, the presence of Late Ordovician to Early Devonian intrusive rocks in the East Greenland Caledonides (Henriksen & Higgins 1976) and their near absence in Scandinavia suggests to most workers that, at least in its late stages, subduction was west-directed. In the final stages of the collision, a series of thrust sheets containing rocks of both oceanic and continental affinities was emplaced eastward onto the Baltoscandian platform. Subsequent deep erosion has exposed Baltic granitic basement and autochthonous sedimentary cover in the Rombak Window, while preserving much of the overlying nappe sequence.

Although continent-continent collision zones are characterized primarily by compressional deformation, several recent studies have documented extensional deformation in collisional orogens. In most of these examples, the extension occurred in the overriding plate late in the evolution of the mountain belts, and is thought to have resulted from gravitational collapse of a topographic high (Elliott 1976,

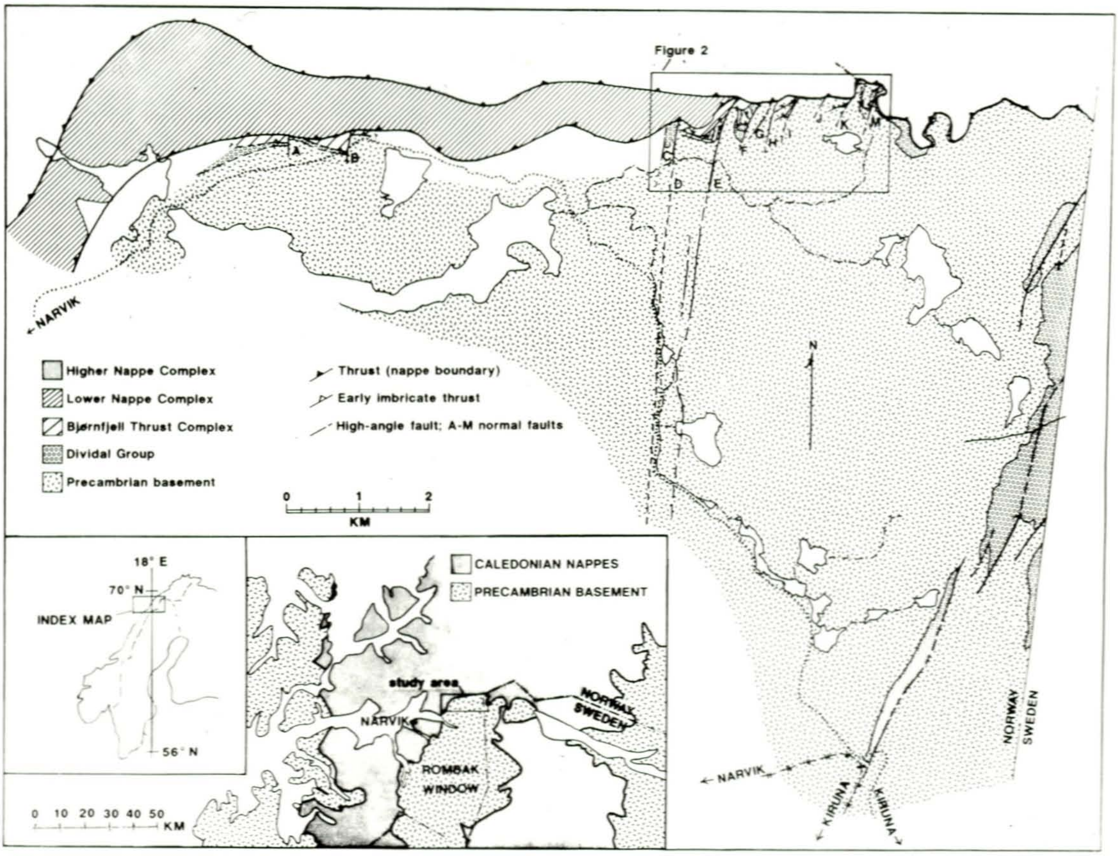

Fig. 1. Regional geologic map, showing the location of the Rombak Window and of the study area, along its northern edge. Dotted line = highway between Narvik, Norway, and Kiruna, Sweden. Hatchured line = Ofotbanen (railroad between Narvik and Kiruna).

Coward 1982, 1983, Burg et al. 1984, Burchfiel & Royden 1985). In the remaining examples, the normal faulting is a fairly local phenomenon which results from progressive simple shear along a major thrust surface (Ramsay et al. 1983, Platt & Leggett 1986). The extensional faulting reported in this study, however, is a possibly unique example of geological evidence for extensional faulting at mid-crustal depths (biotite-grade conditions) and early in the evolution of the collisional belt, faulting which was preceded and followed by large-scale compressional deformation.

Preliminary structural mapping of the basement/cover contact along the northern edge of the Rombak Window – intended to document basement involvement in Caledonian deformation – revealed a complex deformation history with several superimposed faulting events, as shown by crosscutting ductile deformation zones (Andresen & Cashman, 1984a, b; Andresen & Cashman, in review). The initial mapping suggested that one of these events was characterized by normal offset. This conclusion is so unusual that a more detailed structural study was warranted: Geological evidence for normal faulting at relatively deep structural levels and fairly early in the development of an orogenic belt has not been described. Such faulting has been suggested from seismic reflection profiles and earthquake seismology (e.g. Lillie 1984, 1985, Lillie & Yousef 1986); however, in these examples thrusting followed, but did not precede, the

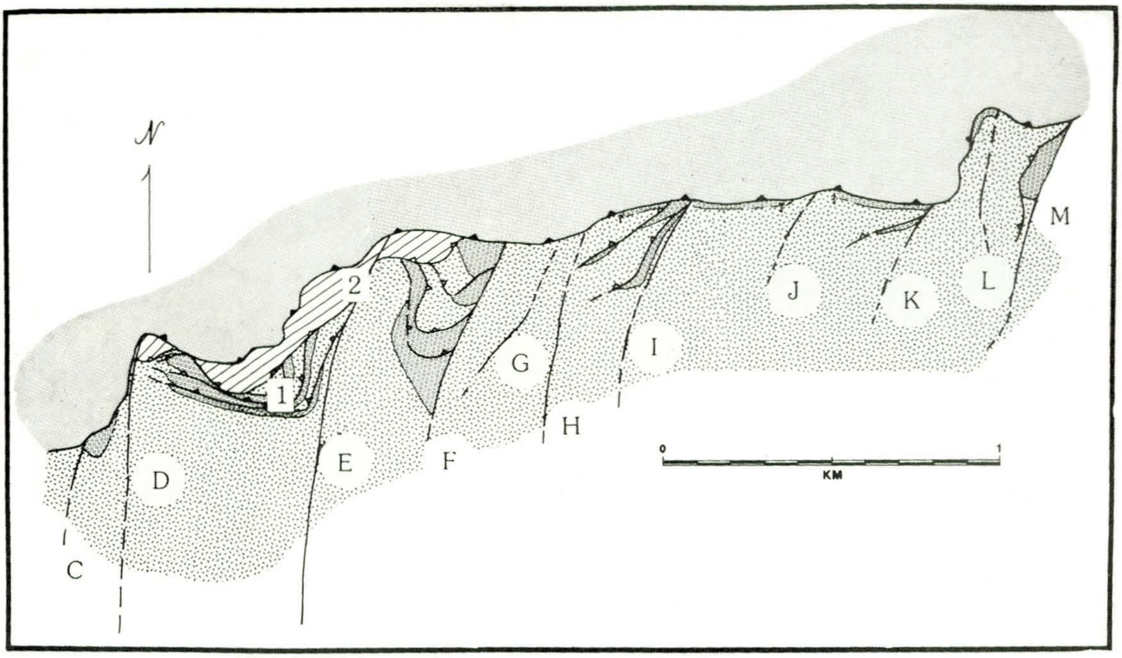

Fig. 2. Detailed geologic map showing the four major lithologic groups and the cross-cutting structural relationships within the study area. Lithologic and geologic symbols are the same as those used in Fig. 1. Numbers show station locations for structural data in Fig. 6.

extensional faulting. Detailed examination of this field example may shed new light on the progressive deformation associated with nappe emplacement. The objective of the present study was to examine these features in more detail — to determine their structural geometry, kinematics and timing, and to constrain the mechanisms by which they could have formed. Field mapping concentrated on deformation fabrics and mesoscopic structures. Oriented samples were collected for petrographic analysis of deformational mechanisms, and for detailed kinematic and strain studies. This paper represents an interim report on a study still in progress, and will be concerned primarily with the geometry and kinematics of the normal ductile deformation zones. Strain analyses are currently underway, and will be included in a future report. Further mapping is also necessary, to establish the full extent and regional significance of the normal ductile deformation zones.

Several revisions to the regional-scale map have also emerged from this detailed structural mapping: The basal quartzite/conglomerate section of the Dividal Group is not continuously exposed around the northern edge of the Rombak Window (Figs. 1 & 2), in contrast to the way it is shown on the Narvik 1:250,000 map-sheet (Gustavson 1974). The discontinuous exposure is in part attributable to primary relief on the basement/cover contact. Several lines of evidence point to this relief — including variation in the compositional and textural maturity of the basal sediments — in addition to mappable relief on the contact itself. In addition to primary relief, tectonism is also responsible for some of the gaps in the basal quartzite/conglomerate section. Locally, the allochthonous nappe sheets are emplaced directly over autochthonous crystalline basement. Basement highs seem to have been areas of thinner initial deposits, and, being higher, they may also have been more apt to be tectonically stripped during later low-angle thrusting. The major implication of the discontinuous nature of the autochthonous cover is that crystalline basement of the Rombak Window is clearly involved in Caledonian deformation, rather than being physically isolated from it by a detachment which is confined to the autochthonous sedimentary section, as is suggested by previous mapping.

Geology of the northern edge of the Rombak Window

The rocks along the northern edge of the Rombak Window can be divided into four groups of fundamentally different structural and tectonic significance (Fig. 2): The first, Precambrian crystalline basement, is dominated by the 1700 Ma Rombak Granite (Heier & Compston 1969, Gunner 1981) and also contains xenoliths of mafic gneiss and felsic intrusive rocks which intrude the granite. The Rombak Granite is coarse-grained, and composed of 1-3 cm K-feldspar porphyroclasts in a matrix of recrystallized quartz, plagioclase, microcline and biotite. The biotite occcurs in elongated clots, possibly indicating that biotite is an alteration product of some other primary mafic phase. The granite exhibits a variably-developed but generally very weak foliation — defined by the preferred orientation of feldspar porphyroclasts and the sub-parallel orientation of biotite grains — which dips steeply and strikes generally N-S.

A thin, discontinuous sedimentary sequence, generally referred to as the Dividal Group, makes up the second lithologic group. It is in depositional contact over the crystalline basement. Rykkelid & Andresen (1988) have traced the characteristic basal sequence of this unit westward to Ofoten and eastward to Torneträsk. The latter is the type area of the Torneträsk Formation, which is the basal formation in the Dividal Group in northern Norbotten (Thelander 1982). This confirms earlier correlations of these sedimentary sequences (Kautsky & Tegengren 1952, Kautsky 1953, and Kulling 1964, as cited in Björklund 1985). Stephens et al. (1985) also support a tectonostratigraphic correlation of the autochthonous sedimentary rocks from the Ofoten area to the Caledonian thrust front, based on the similarities of rock type, rock sequence, and the state of preservation of the basement/cover contact. Although no fossils have been found in the study area, fossils from the Dividal Group date it as Vendian - Cambrian in age (e.g. Kulling 1972). Björklund (1985) concludes that the autochthonous sedimentary rocks in the Akkajaure and Tysfjord areas, to the south, include rocks only as young as Middle Cambrian, with higher units having been tectonically removed. This is based on stratigraphic control and on low radioactivity values, which rule out the presence of the highly radioactive Cambrian Alum Shale of Kulling (1964) from the upper part of the Dividal Group. Similar age constraints probably also apply to the autochthonous sedimentary rocks in the study area, which are thin and discontinuous, and probably only include the lowermost part of the section.

Along the northern edge of the Rombak Window, this sedimentary unit is metamorphosed to biotite grade and is composed of phyllite, quartzite, feldspathic meta-arenite and quartzose metaconglomerate. Its composition seems to vary systematically with position: in the more eastern exposures it is generally less conglomeratic, and contains a greater percentage of fine sandstone and mudstone (now phyllite and quartzite). Primary structures are locally well preserved; these include trough cross-bedding, nested channel cut-and-fill structures and lag deposits in the sand-dominated beds, and suggestions of ripple cross-laminae in the fine sand and mudstone beds. Where observed, primary sedimentary structures consistently show the section to be upright. Cross-bed orientations suggest that current directions were toward the south and southwest; a similar conclusion was reached by Tull et al. (1985). Conglomerate appears to be confined to the lowest part of the section, where it makes up laterally persistent beds up to 3 m thick. The conglomerate beds (approximately 30% of the section in the westernmost exposures) are poorly organized, crudely stratified to unstratified, clast-supported and texturally mature. All Dividal Group rocks in the study area are interpreted to be of fluvial to near-shore origin. Petrography of the clasts suggests granitic and recycled cratonic sources. (J.H. Trexler, Jr., pers. comm. 1986).

The third lithologic group (here informally called the 'Lower Nappe Complex' of Figs. 1 & 2) is composed of a series of thrust or nappe sheets of Baltoscandian affinity; these nappes are composed of metasedimentary rocks in probable depositional contact with highly deformed Precambrian granitoid rocks. Two tectonic units are recognized within the map area; they are distinguished on the basis of the types of metasedimentary rocks associated with the metagranites, and the degree of mylonitization of the metagranites. The lower of these two units, informally termed the Bjørnfjell Thrust Complex, contains deformed metasedimentary rocks (primarily quartzite and metaconglomerate, locally overlain by schist) in depositional (?) contact on deformed granitoid rocks. These rocks are clearly derived from the underlying autochthonous granite and Dividal Group sedimentary rocks. They occur in a series of fault-bounded slices; internal deformation generally increases with structural height of the slices. The higher unit, here informally termed the Treldal Thrust Complex, is composed of metagranite, gabbro, blastomylonitic quartzite, schist and minor dolomite marble. These rocks are generally more deformed than those in the Bjørnfjell Thrust Complex, and are slightly higher (garnet) metamorphic grade. Tull et al. (1985) describe some of the internal structure of the Treldal Complex (part of their 'Nappe 1'), and conclude that the rocks, like those of the Bjørnfjell Complex, represent folded and imbricated autochthonous basement and sedimentary cover. The greater deformation and higher metamorphic grade, however, suggest a more distant root zone than that of the Bjørnfjell Complex.

These informal names for the units in the third lithologic group are the local names suggested by A. Andresen (pers. comm. 1983, 1986), and are preferred for two reasons. (1) Detailed mapping that would follow these units from the study area to the type sections for more widely used terminologies remains to be done. (2) Some of the existing terminology seems to be inappropriate. A tentative correlation of the informal units used in this study with other terminologies is suggested here. The nappes of Baltoscandian affinity on the Swedish side of the border are known as the Rautas and Abisko Nappes (Kulling 1964), and correspond to the Lower and Middle Allochthons of Gee & Zachrisson (1979). These may be equivalent to the Bjørnfjell and Treldal Complexes, respectively. Units comparable to the Bjørnfjell Complex along the southern edge of the Rombak Window are termed the Storrit Complex by Hodges (1982) and Tilke (1986); similar shear-zone rocks along the west edge of the Rombak Window are termed the Storfjell Group by Gustavson (1974, 1978); and locally-derived slices of crystalline rock and its metasedimentary cover in the eastern part of the Rombak Window are termed Hoiganjvri Complex by Bax (this volume). Gustavson (1974, 1978) includes allochthonous basement rocks in both the Storfjell Complex and the base of the Rombak Group. Mapping by Tull et al. (1981, 1985) has shown that the thrust separating the Storfjell and Rombak Groups does not have regional significance; nor does it correspond to the thrust between the Middle and Lower Allochthons in Sweden. More detailed mapping is necessary to resolve some of these regional problems, and to reduce the number of parallel and/or overlapping terminologies.

The highest lithologic group (the 'Higher Nappe Complex' of Figs. 1 & 2; and 'Nappe 2' of Tull et al. 1985) contains a wide variety of metasedimentary and meta-igneous rocks. This group corresponds to the Upper and Uppermost Allochthons of Gee & Zachrisson (1979), and includes metasedimentary and metavolcanic rocks, and minor bodies of granite, trondhjemite, diorite, norite and gabbro (Gustavson 1969, 1972). The rocks of this group occur along the northern edge of the map area and probably correspond to the Köli sequence of the Seve-Köli nappe of Kulling (1960) in the Tornetrask region of Sweden. Gustavson (1977) subdivided these rocks into several tectonic units (Rombak Group, Narvik Group, Salangen Group and Niingen Group) on the basis of lithology and metamorphic grade. More recently, possible ophiolite fragments have been recognized within these upper nappes (Boyd 1983). Viewed as a whole, the rocks of the highest group have a eugeoclinal character, and they are considered to be exotic with respect to the other groups.

Detailed mapping along the northern edge of the Rombak Window reveals a complex faulting history (Andresen & Cashman 1984a, b, in review): At least three sets of ductile deformation zones offset the basement/cover contact. These three fault sets are therefore not the result of Precambrian deformational events, but can be attributed to Caledonian deformation. Syn- to post-tectonic growth of biotite in all three sets of ductile deformation zones indicates that faulting took place prior to or during conditions indicative of middle greenschist facies or higher.

The oldest ductile deformation zones are low-angle, imbricate thrust zones with a well-developed LS fabric (Fig. 2). The zones and the foliation dip west-northwest, and the lineation trends 300°. These early reverse faults are locally structurally overlain by a duplex composed of blastomylonitic granite and quartzite of the Bjørnfjell Thrust Complex. The early reverse faults and the Bjørnfjell Thrust Complex are offset by N-S-striking, west-dipping ductile deformation zones with normal offset (Fig. 2) (Andresen & Cashman 1984b); these are discussed in detail below. A third set of ductile deformation zones occurs near the eastern edge of the study area (Fig. 1), and exhibits reverse motion. These zones strike NNE-SSW and dip steeply east; they have been mapped in detail by Naruk (1987).

Normal ductile deformation zones

A set of at least thirteen ductile deformation zones striking at 190° - 200° and dipping 50° - 60° west cuts crystalline basement along the northern edge of the Rombak Window. The dips of the zones shallow upward in the proximity of the contact with the overriding nappe sheets; this change in orientation is also observed in lithologic contacts and other structural features, and seems to be due to later flattening and/or simple shear strain associated with emplacement of the nappes.

The ductile deformation zones range from 5 m to grater than 20 m in thickness. Most of the zones are fairly regularly spaced, and occur within a 5 km distance (Fig. 2). West of this area, the ductile deformation zones are farther apart, and exhibit less offset (Fig. 1). Reconnaissance mapping east of this area did not reveal any more ductile deformation zones in this set. Six of the zones are easily recognizable on the geologic map because the basal sedimentary sequence (Dividal Group) is preserved in the hanging wall but not the footwall (Fig. 2). Field identification is based on rotation of contacts and pre-existing fabrics toward parallelism with the zones, and the development of a new mylonitic to ultramylonitic LS fabric in the interiors of the zones. Two adjacent zones (D and E on Figs. 1 and 2) continue as major structures in the basement for an along-strike distance of over 6 km. Most of the remaining zones seem to be fairly superficial features localized along the basement/cover contact: they become less well-defined with structural depth, and most cannot be traced more than 0.5 - 0.7 km from the contact with the overlying nappe sheets (which corresponds to a structural depth of 100 - 200 m below the nappe sheets).

Fig. 3. Foliated Rombak Granite in a ductile deformation zone; view is toward the north. Note the asymmetric augen indicating normal motion along this zone.

The most ubiquitous mesoscopic structure in the ductile deformation zones in crystalline basement is the foliation. Fault rocks of the ductile deformation zones cover the full range of the mylonite series as defined by Sibson (1977): granites at the boundaries of the zones are protomylonites, with feldspar augen (sometimes asymmetric) in anastomosing zones of matrix biotite and quartz (Fig. 3). Although fabric development is inhomogeneous, the percentage of matrix generally increases toward the center of the ductile deformation zone, resulting in a band of true mylonite between the boundaries and the center of the zone. Narrow areas of higher strain commonly occur within this mylonitic granite; these ultramylonite zones commonly range from 10 cm to 20 cm in thickness, and resemble a finely laminated gneiss. The central part of each ductile deformation zone, which generally is between 2 m and 5 m in thickness, is also composed of ultramylonite.

In some of the foliated granites, two planar anisotropies can be recognized in the outcrop and/or in thin section. These correspond to the C-surfaces and S-surfaces of Berthé et al. (1979). The C-surfaces, or slip surfaces, appear as thin layers of fine-grained, recrystallized quartz, biotite and feldspar; they are parallel to the main shear-zone boundary. The S-surfaces, or mineral foliation, are defined by compositional layering and preferred mineral shape orientation; this is most easily recognizable mesoscopically as the preferred orientation of the large feldspar porphyroclasts. The orientation of foliation (S-surfaces) changes across the ductile deformation zones. Foliation, at an acute angle to the C-surfaces near the zone boundaries, approaches parallelism with the C-surfaces in the ultramylonites at the central part of the ductile deformation zones. Fine-grained mafic xenoliths and/or dikes in the basement are commonly — but not always — associated with the high strain zones in the center of the ductile deformation zones. It is unclear whether these rocks deformed preferentially once the ductile deformation zone was established, and thus became the areas of highest strain, or whether the ductile deformation zones may have formed along these inhomogeneities in the basement.

A mineral lineation is also developed in the mylonites and ultramylonites; it lies in the plane of the foliation. Petrographically, the lineation is defined by preferred shape orientation of large feldspar porphyroclasts, linear concentrations of recrystallized biotite grains, and local preferred shape orientation of subgrains and recrystallized grains in pressure shadows. These lineations range from 260° to 315° in trend (approximately down-dip in the ductile deformation zones) throughout the field area. In zones D and E, where the greatest range in depth can be observed, the trend of the lineation can be seen to change with structural depth, from 300° near the contact with the overlying nappes to 270° at deeper levels (Fig. 4). This suggests that the initial trend of all the lineations was 270°, and later deformation during nappe emplacement modified the orientations near the nappe contact.

There are two ductile deformation zones that appear to be significant structures in the basement, labelled D and E on the geologic map (Fig. 2). Zone E is the best exposed, and will be described as an example of this style: Zone E extends as a prominent topographic lineament at least 6 km southward from the edge of the Rombak Window, representing a structural depth of 1.1 - 1.6 km below the overlying nappes. Several traverses across this zone demonstrate that the lineament is defined by granitic mylonite and ultramylonite 15 m - 20 m thick. L and S orientations are rotated near the edge of the window — as described above — but otherwise remain constant as far south as the lineament was traced (Fig. 4).

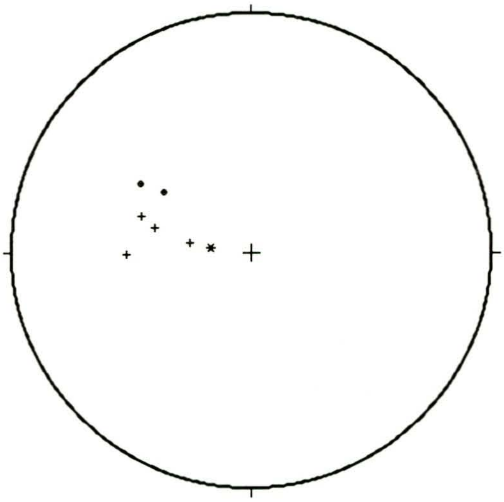

Fig. 4. Stereogram showing the modification of lineation orientations from ductile deformation zone E in the vicinity of the overlying nappe sheets. Dots are lineation orientations within 500 m of the edge of the Rombak Window, crosses are lineation orientations within 2-3 km of the edge of the window, and the star is the lineation orientation approximately 5 km from the edge of the window.

Kinematic indicators at depth (most commonly sigma-type asymmetric augen (Passchier & Simpson 1986) in protomylonite and mylonite) are similar to those at the northern end of the zone, and document normal motion. No thinsections are yet available from the deeper parts of these zones, so a comparison of deformational styles with structural depth is not possible at present. Zone D is not well exposed away from the edge of the window, and was inferred initially from strong topographic lineaments. Several exposures of mylonite and ultramylonite several km south of the edge of the window and west of zone E, and analogy with zone E, are the basis for considering this zone also to be continuous with depth. It is probably significant that these two extensive zones are adjacent to each other, and are west (down-dip) of most of the other, more superficial, normal ductile deformation zones.

The remaining of the ductile deformation zones differ from zones D and E in that they become less well-defined with increasing structural depth. There is no evidence of a subhorizontal sole fault into which some or all of them could merge, and, with two possible

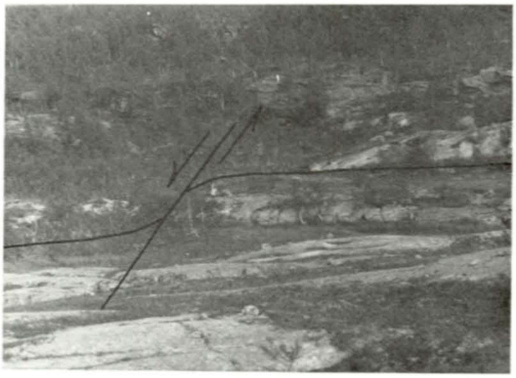

Fig. 5. Offset of basement/cover contact and rotation of bedding at ductile deformation zone A; view is toward the north, so offset is down-to-the-west. Zone A, the westernmost zone mapped, is atypical in that the offset is small (on order of 10 m, whereas some of the other zones have minimum offsets of 60 m) and the basement/cover contact is preserved on both sides of the zone. Note geologist immediately to the right of the fault zone for scale.

exceptions (see below), there is no evidence that any of the zones are listric. In a typical case, the protomylonite to ultramylonite in the center of one of these zones can be traced with confidence for distances of 0.5 - 0.7 km away from (or 100 - 200 m structurally below) the contact with the nappe sheets at the edge of the Rombak Window. Orientations of foliation and lineation remain constant, where observed, over this distance, with the exception of flattening in the immediate proximity of the overlying nappes. Where exposures permit, it can be seen that the ultramylonite zones become narrower and fewer with depth, but the foliation in the adjacent granite is developed over a wider area (suggesting that the strain becomes more widely distributed with depth). Xenoliths and/or dikes in the granite are invariably associated with the deeper exposures of these ductile deformation zones, and the deformation commonly cannot be traced beyond the occurrence of these exotic rock types. In two cases, zones F and G, field relations suggest that the zones could flatten with depth, and merge with zone E, to the west; however, exposures are insufficient to resolve this unequivocally. (Note that the 'flattening' involves only enough change in orientation to merge with the neighbouring major fault zone to the west; the term does not imply that these zones approach sub-horizontal.) All of the other zones maintain a constant orientation until they die out with depth. Petrographically, these superficial zones are identical to zones D and E, exhibiting plastic deformation of quartz, cataclastic deformation of feldspar, and numerous kinematic indicators demonstrating normal motion.

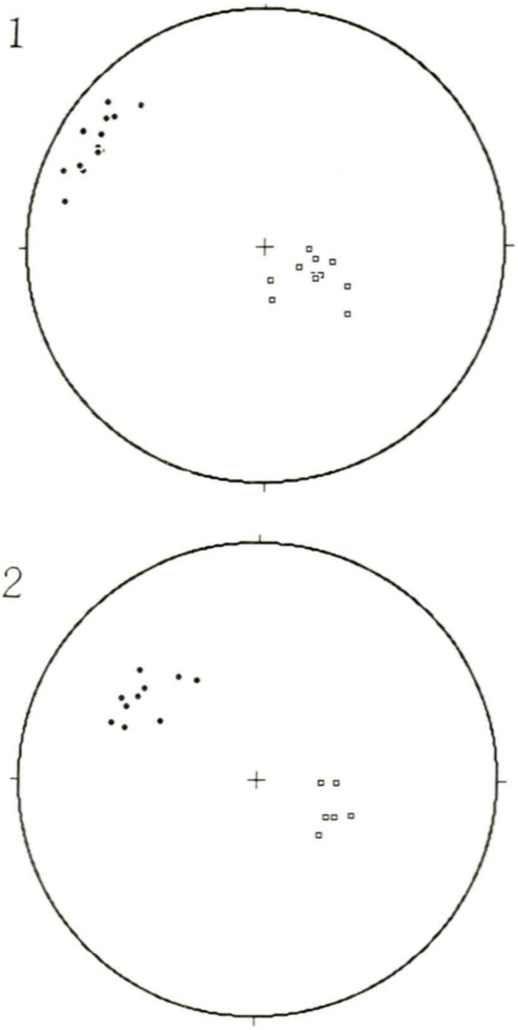

Fig. 6. Representative lower-hemisphere stereograms showing rotation of LS fabrics of the Bjørnfjell Thrust Complex in the vicinity of the normal ductile deformation zones. Dots represent lineation orientations; open squares represent poles to foliation. Stereogram 1 shows typical LS fabric orientations from the Bjørnfjell Complex; stereogram 2 shows LS fabric orientations adjacent to a normal ductile deformation zone. Numbers correspond to station locations shown in Fig. 2.

Sense of offset along the ductile deformation zones is shown by offset of the basement/cover contact, sense of rotation of earlier fabrics, and kinematic indicators such as S/C fabrics and asymmetric augen within the zones. The basement/cover contact is offset in ten of the mapped zones; Dividal Group rocks are preserved in the down-dropped hanging wall, but not the footwall, of six of these (Fig. 2). Drag folding of the basement/cover contact — indicating normal motion — can be mapped in the vicinity of these zones (Fig. 5). Rotation of pre-existing fabrics is best shown, however, by the imbricate thrust faults and related foliation in the Bjørnfjell Complex near zones E and F (Fig. 6). The imbricate thrusts steepen dramatically as they approach the ductile deformation zones, and they too show offset compatible with normal motion. Asymmetric feldspar augen (sigma-type (Passchier & Simpson 1986)) are the most widespread kinematic indicators, and are best developed in protomylonites and mylonites. The 'tails' of the augen show down-to-the-west (normal) motion (Fig. 3).

Petrographic kinematic indicators include almost all of the shear sense criteria evaluated by Simpson & Schmid (1983); all confirm normal motion along the ductile shear zones. The most obvious feature in many of the granites is displaced broken feldspar grains. Displacement along the microfractures in these grains may be in the same sense or in the opposite sense as the overall sense of shear, depending on the orientation of the microfractures relative to the shear planes. C-surfaces and S-surfaces are developed in some rocks; plastically deformed quartz, particularly useful in defining the s-surfaces, commonly curves into the c-surfaces, indicating the sense of shear. Asymmetric augen — in which recrystallized material from the porphyroclast is drawn out along the shear surfaces — and asymmetric pressure shadows are developed in some rocks. Subgrains and recrystallized grains with a preferred shape orientation are locally observed, but their orientations seem to be more strongly influenced by local conditions (e.g. pull-aparts in large feldspar porphyroclasts) than by the bulk deformation of the rock.

A minimum amount of offset across the normal ductile deformation zones can be estimated from those in which the Dividal Group rocks are preserved in the hanging-wall. Offsets range from about 10 m (on the westernmost zone) to a minimum of 60 m (on zones E and F), and total over 250 m in an across-strike distance of 3 km between zones C and M. Dividal Group rocks are only preserved along the northern edge of the Rombak Window, and there are no other markers for estimating offset; thus, it cannot be determined whether offsets change with structural depth in the zones which continue some distance into the basement.

The relative age of formation of the normal ductile deformation zones is clearly shown by cross-cutting relationships in the field area. Both the imbricate thrust zones and the Bjørnfjell Thrust Complex are rotated and offset by the normal ductile deformation zones (Figs. 2 & 6). Later thrusting — in the form of emplacement of the higher nappe sheets ('Higher Nappe Complex' of Figs. 1 & 2) — cross-cuts the normal ductile deformation zones with no offset, and so clearly post-dates normal faulting (Fig. 2). It is therefore inescapable that an extensional deformational event — manifested as normal motion along west-dipping ductile deformation zones — occurred in the study area between major compressional events.

No conclusive data exist regarding the absolute timing of emplacement of nappes with Baltic affinity (e.g. Bjørnfjell Complex) in the Tornetrask — Rombak area. Data from Finnmark (well to the north) suggest that the lower allochthons in that area were emplaced during the early to middle Ordovician Finnmarkian phase of Caledonian deformation (Pringle 1973, Sturt et al. 1975, 1978). Data from south of the study area indicate that nappe emplacement there was of Late Silurian to Devonian age, known as the Scandian event (Gee & Wilson 1974). The higher nappe sheets in the study area were emplaced during or slightly after the Scandian event, as shown by the fact that Upper Ordovician to Silurian fossils have been reported (Olaussen 1976, Binns & Matthews 1981, Bjørlykke & Olaussen 1981) in units which are correlative with the Rombak and Salangen Groups (Tull et al. 1985, Steltenpohl et al. 1985). Using these broad regional constraints for the widest reasonable age bracket, it is therefore possible that the normal ductile deformation zones in the study area could have formed any time between Early or Middle Ordovician (Finnmarkian) and Late Silurian or Devonian (Scandian). However, careful geochronology along the southern edge of the Rombak Window by Tilke (1986) suggests a much tighter age bracket (430 - 410 Ma) for metamorphism and thrusting of Baltic basement and cover (equivalent to formation of Bjørnfjell Complex?) through imbrication and emplacement of the 'Upper Nappe Complex' onto the Baltoscandian Platform (equivalent to emplacement of 'Higher Nappe Complex' of this study?).

Discussion

Any interpretation of the origin of the normal ductile deformation zones must satisfy the following geometric and kinematic constraints:

(1) Discounting later modification of the structurally highest part of the zones, they strike slightly east of north (010°) and dip moderately west (50° - 60°).

(2) Field relations and kinematic indicators demonstrate that the offset is normal.

(3) Deformation occurred under greenschist facies (biotite grade) or higher conditions.

(4) Metamorphic lineations developed within the zones trend approximately down-dip (270° - 280°), indicating that motion was parallel to this trend. (Lineations developed in response to both earlier and later compressional faulting, in contrast, trend 300° - 305°).

(5) Two adjacent zones are major features, continuing more than 6 km to the south with no change in orientation or degree of deformation.

(6) The remainder are fairly superficial features, dying out with depth; there is no evidence that these faults are listric, and no sub-horizontal fault into which they could sole out. Most of these occur in the footwall of the two major faults described above, and most are associated with concentrations of xenoliths and/or dikes in the basement.

(7) The faults are not evenly distributed along the northern edge of the Rombak Window, but are concentrated in one fairly small area.

Fault zones with normal offset have also been described along the southern edge of the Rombak Window, northwest of Kaisejaure and north-northwest of Tutturjaure, by Tilke (1986). These zones are along strike from the zones described here, and are very similar in orientation (striking 030° - 040°, with maximum dips of 40° - 50°W). The offsets of these faults (a minimum of several tens of meters) are comparable to those along the northern edge of the Rombak Window, as is the timing of deformation (after some imbricate thrusting, but prior to final emplacement of the overlying nappe sheets). Mesoscopically, they differ from the zones along the northern edge of the Rombak Window in ways that indicate formation at shallower structural levels.

The fault zones described by Tilke are 1 cm - 3 cm in width, with no deformation evident on either side. Epidote recrystallization and slickensides (trending 300° - 340°) are common along the fault zones. Six individual faults were mapped, but they were only noted where there were extensive exposures of Dividal Group rocks in the hanging-wall. Tilke describes the faults as being sigmoidal in cross-section, shallowing upward due to later rotational shear strain, and shallowing downward as a result of original listric geometries. (The direction of nappe emplacement in this area is from NW toward SE (120°), just like it is at the northern edge of the window.) He did not attempt to trace the faults structurally downward, where basement is juxtaposed against basement, so it is not clear whether there may be one or more major faults that continue to depth without changing orientation, in addition to the more numerous faults that flatten (or die out?) with depth. The evidence is strong that the normal faults at the northern and southern edges of the Rombak Window are parts of the same feature. A prominent structural lineament in the central part of the window along strike with several N-S elongate patches of Dividal Group rocks are suggestive of the continuity of this structure across the window. Mapping between the two is necessary to establish this uniquivocally, and is the next objective of the on-going study reported here.

Close examination of published examples of extensional faulting in collisional belts reveals few geometric similarities with the normal fault zones of the Rombak Window: In some instances (e.g. Coward 1982, 1983 and Elliott 1976), the faults are listric, and sole into a basal detachment. The faults reported by Platt & Leggett (1986) are the only other normal faults reported in the lower plate, but they differ from the faults reported here in that they dip in the direction of thrust transport. Other normal faults (e.g. Burchfiel & Royden 1985, Burg & others 1984) are low-angle and sub-parallel to the thrusts, and are thought to be reactivated thrust surfaces. The normal faults described by Ramsay et al. (1983) formed in appropriately oriented limbs of rotating buckle folds. None of these characteristics apply to the normal faults of the Rombak Window. In addition to the geometrical differences, the timing of the faulting (i.e. fairly early in the evolution of the orogen, but after some compressional deformation) and the location of the faulting (i.e. in the lower plate) are unusual or unique to these faults, and it is clear that a new mechanism for their formation must be invoked.

Although the origin of the normal ductile deformation zones cannot be determined unequivocally without further napping and structural analysis, three types of models which would create the required extension of the basement/cover contact preceded and followed by compressional deformation should be considered:

(1) Extension of the upper part of the Baltic crust would be expected as the crust was flexed into a foreland basin in front of the advancing higher nappe sheets (Andresen & Cashman 1984a, b). Normal faults in other collisional orogens which have been attributed to thrust loading share many attributes with the normal ductile deformation zones along the northern edge of the Rombak Window. Lillie (1984, 1985) distinguishes two types of normal faults in the footwalls of major thrusts in the Appalachian - Ouachita orogenic belt from seismic reflection profiles. Of these, normal faults related to earlier continental rifting have large offsets (up to 7 km) and variable dip directions, and do not offset the overlying shelf strata; normal faults related to thrust loading have relatively small displacements (0 - 2 km), dip consistently in the direction opposite to the transport direction of the overriding thrust sheets, and offset basement and whatever overlies it up to the thrust contact. Well data from the foreland of the Ouachita Mountains supplements the seismic interpretation for the latter type of normal fault: synorogenic deposits thicken across the normal faults, but the older shelf sediments do not, implying that the normal faults only slightly pre-date the thrust emplacement (Buchanan & Johnson 1968, Briggs & Roeder 1975, Fay et al. 1979, as cited in Lillie & Yousef 1986, Lillie et al. in press).

A modern analog has been described from the Himalayan foreland in Pakistan (Lillie & Yousef 1986). Here, seismic, sections show normal offset of basement and the overlying evaporite section in the footwall of the Salt Range thrust. This locality is near the 1966 Ganga Basin earthquake, which has been attributed (Molnar et al. 1976) to normal faulting associated with flexural loading of the Indian plate; Lillie & Yousef (1986) think that the fault in the seismic section is 'apparently of similar origin' to the one that caused the earthquake. Calculations of lithospheric flexure (based on extensive seismic reflection and gravity data sets) support the correlation, concluding that normal faulting of the upper crust beneath the Salt Range is consistent with extension of the upper part of the elastic plate in that region (Duroy 1986).

Several observations argue against a direct analogy between the thrust loading normal faults described above and the ductile deformation zones along the northern edge of the Rombak Window, however. First, the zones in the Rombak Window are not oriented precisely perpendicular to the emplacement direction of the overriding nappe sheets (as might be expected by a crustal flexing model), and the slip direction along them is not exactly parallel to the emplacement direction. The formation of the zones may have been controlled by pre-existing planes of weakness, in the form of the variably-developed, N-S striking, Precambrian fabric in the crystalline basement. The normal faults farther south reported by Tilke (1986) probably represent a shallower level of the normal fault zone. The orientation of these faults and the slip directions on them are very close to what would be expected for this model, and may demonstrate that pre-existing fabrics did not exert a dominating influence on fault formation at shallower structural levels.

Second, the zones in the Rombak Window were formed at biotite grade or higher conditions, which indicates that they were buried to a moderate depth at the time that they formed. The depth itself is not a problem — in a modern analog, normal fault earthquakes in the Himalayan collision zone occur at depths of about 20 km. (Focal mechanism studies (Ni & Barazangi 1984) identify two earthquakes which show normal faulting with extension axes normal to the Himalayan trend. Both events occurred beneath the Ganges foredeep, in front of the Main Boundary thrust, a position comparable to that suggested by this model for the zones in the Rombak Window. Ni & Barazangi (1984) attribute the earthquakes to flexing of the Indian plate as it bends and underthrusts beneath the Himalaya.) The question, however, is what was burying the Rombak Window zones to this depth at the time that they formed.

Third, the zones in the Rombak Window are clearly preceded, as well as followed, by large-scale compressional deformation. In all of the analogs described above from seismic records, well data and focal mechanism studies, the normal faulting seems to have occurred prior to the arrival of any overriding thrust sheets.

(2) Extension would also be expected to occur locally in a thrust sheet as it moved over ramps in the basal decollement. Bax (1986, this volume), Tilke (1986), and Naruk (1987, pers. comm. 1988) have suggested that the granite of the Rombak Window is allochthonous. Bax's arguments are based primarily on regional lithostratigraphic correlations. His cross-sections show numerous high-angle faults in the crystalline basement of the window; these faults flatten and merge with depth into a sub-horizontal detachment. No field structural evidence for this interpretation is cited. Naruk, working only with the reverse faults at Bjørnfjell which offset the overlying Treldal Complex, was able to document that these faults do flatten with depth (from 70° - 80° at the structurally highest exposures to 30° - 40° at the structurally lowest exposures), possibly lending support to this aspect of Bax's model. Tilke suggests that the window is underlain by a detached slice of crystalline basement approximately 1 km thick. His interpretation is based on structural relationships, most notably the involvement of Rombak crystalline basement in an asymmetric fold which verges toward 120°, the direction of thrust transport. He interprets this fold to be related to motion on a deeper thrust. The Matert thrust, which crops out in the Singis Window, to the east, may be the surface expression of this deeper thrust. The major difference between these models of an allochthonous Rombak Window is the continuity of the basement slice beneath the window: Bax (1986) shows a highly fragmented crystalline basement, while Tilke (1986) suggests a single, relatively undeformed basement slice which deformed according to the ramp-flat geometry of a 'typical' thrust belt in a layered sedimentary rocks.

If these interpretations are correct, some deformation of the basement could be expected as the thrust sheet moved over steps in the underlying detachment. However, Tilke (1986) specifically argues against the presence of any ramps under the Rombak Window (because of the absence of monoclines in the basement and overlying nappes), and there is no independent evidence for a ramp which would explain the present position of the normal faults. Another possible problem with this explanation is the theoretical question of whether a series of step-like ramps and flats could form in crystalline rocks: This style of thrust deformation is characteristic of layered sedimentary rocks, where ramps cut up across the more competent layers and flats form in the less competent ones (e.g Rich 1934, Harris 1979, Suppe 1983). Studies of geometry and mechanics of basement deformation in thrust belts have shown that the geometry of major decollements vary markedly (e.g. Brewer et al. 1980, Ramsay 1980, Laubscher 1983, Rathbone et al. 1983, Suarez et al. 1983, Cashman et al. 1986, Yonkee & Bruhn 1986, 1987); both thin and thick slices of crystalline basement have been described in thrust belts, but a step-like basal decollement in crystalline rocks has not been observed.

(3) An unrecognized extensional event is possible in the ›80 Ma bracket allowed by the broadest possible interpretation of the regional age constraints (480 - 400 Ma) (see above). This is considered to be unlikely, however, because the structural similarities between compressional events before and after the normal faulting indicate that they formed as part of the same tectonic regime: The Bjørnfjell Thrust Complex (which predates normal faulting) and the deformation at the base of the higher nappe sheets (which post-dates normal faulting) are both characterized by LS fabrics with foliation dipping gently to the north and northwest, and lineation trending toward 300°. On the basis of structural arguments, therefore, extensional faulting seems to have occurred during a fairly short time period in the evolution of this convergent orogen.

Furthermore, careful geochronology by Tilke (1986) tightly brackets the ages of metamorphic and deformational events along the southern edge of the Rombak Window. If these dates can be applied to the northern edge of the window — as seems likely — then the deformational events of interest here occurred between 430 and 410 Ma. Tilke (1986) dates the early metamorphism of the Storrit Complex (the probable equivalent of the Treldal and/or Bjørnfjell Complex) at 430 - 420 Ma; in his interpretation, this represents early thrusting onto the Baltoscandian Platform. Tilke's dates on syntectonic metamorphic minerals from the sole thrust of the Storrit complex and the underlying 'basement' of the Rombak Window are 415 - 410 Ma. Tilke interprets these to be recrystallization ages, rather than cooling ages, and to represent the involvement of crystalline basement in the continued thrusting onto the Baltoscandian Platform. Similar recrystallization ages along thrusts higher in the nappe pile indicate that continued imbrication and emplacement of the higher nappe complex continued during and after this time. A distinct extensional event therefore seems to be an unlikely explanation for the origin of the normal ductile deformation zones along the northern edge of the Rombak Window. A modification of this model — i.e. that normal faulting was a result of relaxation and/or isostatic adjustment during a period of decreased convergence rates — remains a possibility.

In summary, none of the proposed models provides a completely satisfactory explanation for the origin of the normal faults. It is hoped that further work, particularly field work, will make it possible to identify the mechanism that satisfies all of the geometric, kinematic, and geochronological constraints. Mechanisms related to model (1) — flexing due to crustal loading from the advancing nappe sheets — would be strengthened by an explanation for the timing of flexing (after the emplacement of the Baltica-derived thrust sheets), the burial depth at the time of flexing, and the reason flexing didn't occur perpendicular to the transport direction. Model (2) — flexing of a fairly rigid crystalline thrust sheet as it moved over steps in an underlying detachment — would be enhanced by further evidence for a detachent underlying the entire Rombak Window, by an explanation for the formation of ramps and flats in crystalline rock, and by independent field evidence for a ramp in this part of the Window. Model (3) — an extensional episode during a compressional regime at convergent plate boundary — is tightly enough constrained by the geochronology of Tilke (1986) that a separate extensional orogenic event is unlikely, but a modification of the compressional regime is still a possibility. This model would be bolstered by independent evidence for a change in convergence rate or direction that might allow for a period of relaxation and/or isostatic readjustment of the downgoing slab at the time of the observed normal faulting.

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