Nappe and Thrust Structures in the Sparagmite Region, Southern Norway

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The Osen–Røa Nappe Complex is thrust upon a crystalline basement and a thin autochthonous sediment cover. The nappe complex is characterized by a sole thrust cutting up-section toward the SSE, by flats, ramps and contraction faults separating subordinate thrust sheets. Duplex geometry is present in the western part of the leading edge and within some minor thrust sheets. An arcuate fold system developed during the emplacement of the nappe. The Kvitvola Nappe, resting on the Osen–Røa Nappe Complex with a regional disconformity, may have been emplaced on an erosional surface and carried further by piggy-back transport. Another possibility is that the disconformity is the result of out-of-sequence thrusting when the Kvitvola thrust became reactivated. Post-thrust deformation gave rise to the Snødøla–Steinfjellet basement antiform and other undulations in the basement and broad synforms and antiforms in the nappe cover. The driving force of the thrusting is briefly discussed.

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Introduction

The Caledonian front in Scandinavia includes a series of nappes with varying mutual contacts, lithologies, thrust and fold structures and histories of structural evolution. The *Osen–Røa Nappe Complex* and the *Kvitvola Nappe* are two such major tectonostratigraphical units in the Sparagmite Region in southern Norway (Fig. 1). They belong to the Lower and Middle Allochthon, respectively, of the nappe pile in the Scandinavian Caledonides (Roberts & Gee 1981), and both consist of uppermost Proterozoic to Lower Palaeozoic sedimentary strata and sheets of mid-Proterozoic crystalline basement rocks (Fig 2). The Osen–Røa Nappe Complex has been derived from a fault-bounded cratonic basin and the Kvitvola Nappe from a shelf basin on the western part of the Baltoscandian craton. A displacement towards the SE of 200–400 km has been estimated for the Osen–Røa Nappe Complex and more than 400 km for the Kvitvola Nappe (Nystuen 1981, 1982). The sedimentary evolution of the sequences has been described and discussed by K. Bjørlykke et al. (1976) and Nystuen (1980, 1981, 1982). An outline of the Caledonian tectonostratigraphy and the general geology of the area is given by Bockelie & Nystuen (in press). The present paper deals with the thrust and fold geometry of the nappes, their contact relationships and their structural evolution. Terminology on nappes and thrusts are according to Dahlstrom (1970), Elliot & Johnson (1980), McClay (1981), Boyer & Elliott (1982) and Butler (1982).

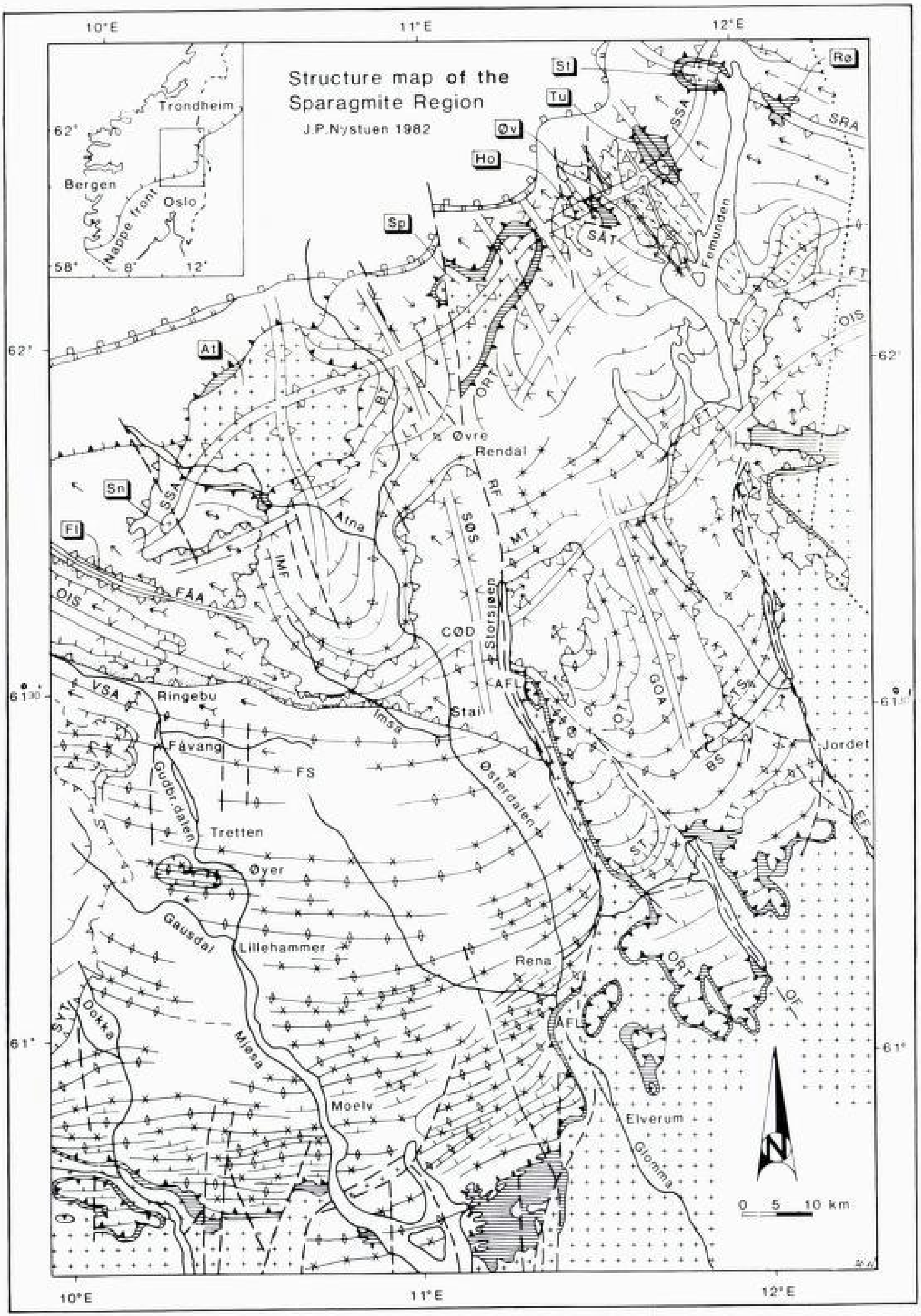


Fig. 1a. Structure map of the Sparagmite Region. Sources are cited in Sæther & Nystuen (1981, Fig. 1).

Osen–Røa Nappe structures

OSEN–RØA THRUST

Adopting the practice of Elliot & Johnson (1980, p. 70), a thrust fault or the surface on which a nappe or thrust sheet rests, is named after the thrust unit. The *sole thrust* of the Osen–Røa Nappe Complex, the *Osen–Røa thrust* (ORT), is exposed along the fringed erosional nappe front in the south and along the rims of several windows in the north (Fig. 1). It is a blind thrust (McClay 1981, p. 9) in most parts of the area; its presence is indicated by folds and subsidiary thrusts in the décollement-moved strata above. The Osen–Røa thrust is conformable with the smooth basement surface, and with the footwall (Butler 1982, p. 239) dominated by Cambrian shales and phyllites. The thrust nappe also rests directly on the basement or on the Vendian tillite or quartzites. The oldest rocks in the hangingwall (Butler 1982, p. 239) are basement sheets in the north at Femunden. The thick Brøttum and Rendalen Formations (Fig. 2) can be traced from overthrust positions at the windows in the north towards the southern part of the Sparagmite Region; thus, the Rendalen Formation is exposed in the hangingwall east of lake Storsjøen (Fig. 1) (see map, Fig. 2 in Nystuen 1982). In the southern 20–50 km of the thrust complex the Osen–Røa thrust cuts up stratigraphically through the Hedmark Group (fig. 2), and

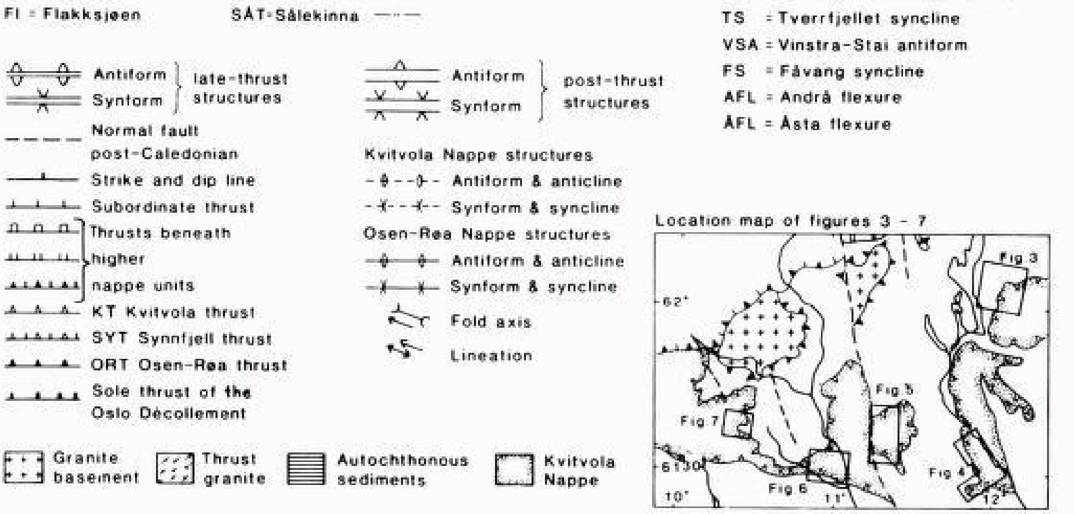


Fig. 1b. Legend to structure map of the Sparagmite Region (Fig. 1a) and location map of Figures 3–7.

in the Mjøsa area the ORT continues into the sole thrust of the décollement-folded Cambro-Silurian sequence of the Oslo Region (A. Bjørlykke et al. 1980). The stratigraphic separation decreases further southwards in the Oslo Region through a series of splay thrusts (Bockelie & Nystuen, in press).

Along mean strike of the Osen–Røa thrust (c. 70°) it cuts up and down stratigraphic section (Dahlstrom 1970) through the Hedmark Group. This is demonstrated in a WSW–ENE traverse from Lillehammer to Jordet (Fig. 1) (see map, Fig. 2 in Nystuen 1982). The hangingwall consists of the Brøttum Formation (or older unknown units) west of the Rendalen fault (RF) and of the Biri Formation and younger formations east of the RF. The post-Caledonian (Permian) Rendalen normal fault is here thought to intersect by acute angle a steep lateral ramp (Butler 1982, p. 240) which trends c. 130°, and which is exposed as the *Imsdalen fault* (IMF) (fig. 1). The IMF dips steeply to the SW and separates turbidites of the Brøttum Formation in the SW from the fluvial Rendalen Formation and younger units in the NE (Sæther & Nystuen 1981, Nystuen 1982).

The hangingwall rocks are deformed by cataclasis along shear planes in the south and by penetrative slaty cleavage, phyllonitization and locally thin mylonitic banding in the north. Locally increased friction by rough gliding has given rise to slicing of the footwall and adherence of small imbricate sheets of basement and sedimentary rocks in the frontal area (Elvsborg & Nystuen, 1978, Sæther 1979).

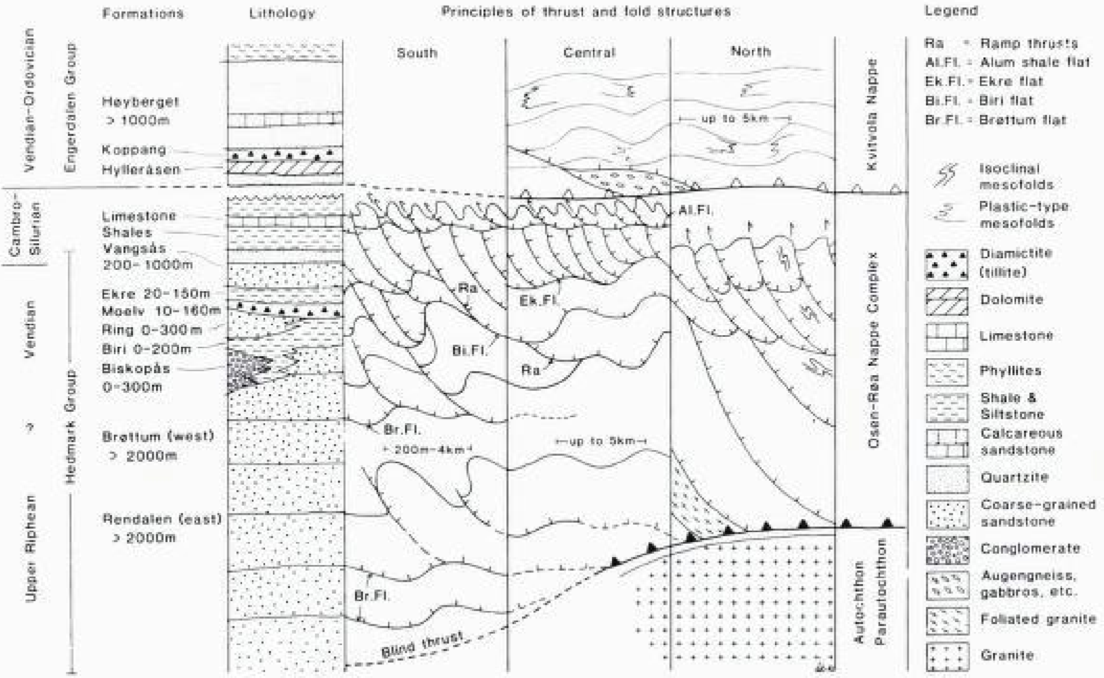


Fig. 2. Simplified stratigraphical sections through the Osen–Røa Nappe Complex (K. Bjørlykke et al. 1976, Nystuen 1982) and the Kvitvola Nappe (Nystuen 1980) and with main types of thrusts and folds in the nappe units.

The basement surface and the Osen–Røa thrust dip 1–2° towards the north at the nappe front but steepen to c. 10° at the Andrå flexure (AFL); a similar flexure probably exists at Åsta (ÅFL) (Fig. 1). These surfaces again rise in the dome-shaped window structure further north (see later discussion on basement geometry). Slip along the ORT in the direction of movement (SSE), measured from the eroded front at Elverum, is 70 km to the Andrå flexure and 125 km to the northern margin of the Spekedalen window.

INTERNAL THRUSTS AND IMBRICATE STRUCTURES

The overall structure of the Osen–Røa Nappe Complex consists roughly of an imbricate frontal zone, a central part dominated by subhorizontal flats (Butler 1982, p. 239) and open, large-scale folds, and a trailing edge, in the north, which displays low- and high-angle contraction faults (McClay 1981, p. 8). Incompetent shale beds have acted as flats at several stratigraphical levels (Fig. 2). In the deeper sections, relative displacements have taken place by gliding along shales in the Brøttum (Englund 1972) and Rendalen (Oftedahl 1943) Formations. There is probably a system of flats and NW-dipping ramps, joining the sole thrust (ORT), thus forming a branching staircase trajectory which is typical of many thrust belts (Dahlstrom 1970, Elliot & Johnson 1980, Butler 1982).

A flat within Biri shales forms the floor thrust (Dahlstrom 1970, p. 357, Butler 1982) of an imbricate stack (Butler 1982, p. 241) in stratigraphically overlying units in the Tretten–Øyer area. The imbrication has been produced by reverse listric faults cutting folds overturned to the south (Englund 1972).

The *Langtjørna thrust* (LT) in the Øvre Rendal area cuts up through the Rendalen Formation and enters the Biri dolomites as a flat, separating a middle and upper thrust sheet. The middle thrust sheet is separated from a lower thrust sheet by the *Brennåsen thrust* (BT) which occurs as a flat in the Moelv Tillite and the Ekre Shale (Nystuen & Ilebekk 1981). The collective slip along these thrusts is at least 25 km. Flats occur in the Ekre Shale beneath imbricate Vangsås Formation in the Tretten–Øyer area (Englund 1972) and in the Fåvang area (Englund 1973).

The *Slemdalen thrust* (ST) and the *Osdalen thrust* (OT) (Fig. 1) are low-angle thrusts following the Ekre Shale as flats for kilometres. The Slemdalen thrust cuts up stratigraphically from the Osen–Røa thrust and appears as a contraction fault with a minimum slip of 14 km. The origin of the Osdalen thrust is uncertain as the hangingwall rocks here are younger than those in the footwall. However, both thrusts form the floor thrusts of imbricate stacks in the Vangsås Formation (Nystuen 1975a, 1975b).

The *Tennåsen thrust* (TT) is a major listric contraction fault along which the Biri Formation is emplaced above the Vangsås Formation (Nystuen 1975c). The TT joins the Osen–Røa thrust in dip-direction, and the minimum slip is about 3 km.

Other mapped major flats follow Cambro–Ordovician phyllites west of Fåvang and separate here three thin sheets with flat-lying Vangsås Formation; the stacking includes a shortening of at least 45 km (Englund 1973, pers. comm. 1982). At a still higher level a flat within Ordovician phyllites probably forms the floor thrust of the Synnfjell Nappe (Duplex) west of Gudbrandsdalen (Hossack et al. in press).

The *Synnfjell thrust* (SYT) acts as the roof thrust (Butler 1982, p. 241) of the frontal imbricate structure and the Osen–Røa thrust as the floor thrust. The imbricate stack, named the *Aurdal duplex* in the Dokka–Valdres area by Hossack et al. (in press), comprises in the Mjøsa area the Vangsås Formation and overlying Palaeozoic strata in the south, whereas progressively older units are included in the imbricate structure towards the north (A. Bjørlykke 1979). North of Moelv the imbrications are replaced by less compressed folds which have their southern limbs overturned to the south (Englund 1978). The Mjøsa imbricate structure, in which imbricate slices are bounded by reverse listric faults dipping north, continues northeastwards to the Rena area (Høy & A. Bjørlykke 1980, K. Bjørlykke 1976).

Imbrications, floored by a blind thrust,occur within the Elstad Formation at Fåvang. This formation,lying structurally beneath the Brøttum Formation, was correlated with the Vangsås Formation by Englund (1973). Adopting this lithostratigraphical correlation, Hossack et al. (in press) interpreted the Elstad structure as a window beneath a thrust with the Brøttum Formation as hangingwall. However, according to J.-O. Englund (pers. comm. 1983), the stratigraphical and structural position of the Elstad Formation relative to the Brøttum Formation is still uncertain, and further studies are needed in order to explain the structural geometry here.

An imbricate stack, with individual slices bounded by NW-dipping reverse listric faults, also occurs within the Rendalen Formation in the Atna area (Sæther & Nystuen 1981). The tectonic shortening provides evidence for the presence of a blind thrust at depth.

High- to low-angle contraction faults underlie basement sheets in the Femunden area (Nystuen 1978, 1979). Some of these sheets have a prismatic shape, being laterally bounded by steep ramps trending 130°. The amount of slip along the *Sålekinna thrust* (SÅT) is a minimum of 30 km. The thrust sheets at the eastern side of Femunden are here referred to the *Femunden thrust zone;* the frontal thrust, *Femunden thrust* (FT), is indicated in Fig. 1. This zone includes several NW-dipping thrust sheets, some of which reveal a duplex geometry (Dahlstrom 1970, p. 352, Boyer & Elliot 1982, p. 1199), arranged in a piggy-back fashion (Nystuen 1979). The whole structure can be interpreted as a giant complex horse (Elliot & Johnson 1980, p. 73), bounded by the ORT as floor thrust and the *Kvitvola thrust* as roof thrust. However, the Femunden thrust zone deforms the Kvitvola thrust (Fig. 3). Hence, in this area the ORT is, at least partly, younger than the overlying Kvitvola thrust, and a piggy-back sequence of thrusting (Elliot 1976, p. 958) can be proved in this section (Fig. 3) (Nystuen 1979).

The *Mistra thrust* (MT) is a contraction fault carrying the overthrust *Mistra basement sheet* (Holmsen & Oftedahl 1956, Sæther 1979). This thrust structure also deforms the overlying Kvitvola thrust (Fig. 5).

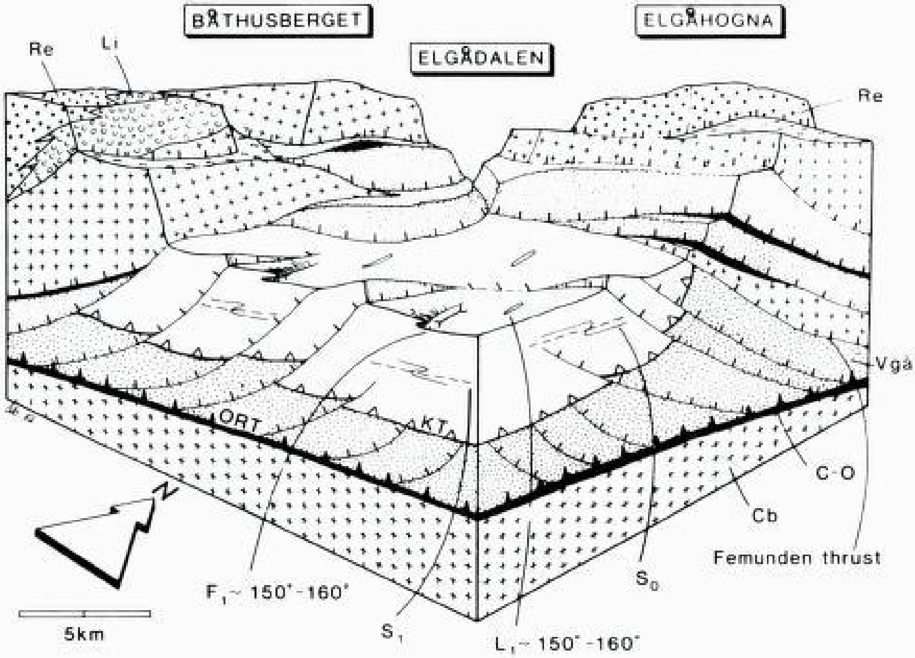


Fig. 3. Femunden thrust zone. Conceptual diagram from the front of the thrust zone. Source: Nystuen (1979). ORT = Osen–Røa thrust, KT = Kvitvola thrust, Cb = Crystalline basement, C–O = Cambro-Ordovician, Vgå = Vangsås Formation, Li = Litlesjøberget Conglomerate, Re = Rendalen Formation. Location shown in Fig. 1b.

FOLD GEOMETRY

Large-scale folds are strongly compressed, overturned to the south and cut by listric faults in the front areas. Open and broad synforms and antiforms dominate in the central areas between Gudbrandsdalen and Østerdalen and between Femunden and Øvre Rendal (Fig. 1). Recumbent folds facing SSW occur in the western part of the *Vinstra–Stai antiform* (VSA) (Englund 1973). Fold hinges are curved in plan view, resulting in arcuate axial surface traces with dimensions ranging from 70–80 km (Dokka–Rena) to about 500 m across. Listric faults are conformably arced. Fold axes plunge slightly away from the central, symmetry lines (c. 165°) of the arcuate structures, and overturned folds verge towards the convex sides. The bending of the hinge lines is continuous without any evidence of superposed folding.

A similar arcuate pattern in the Valdres Nappe was discussed by Nickelsen (1974). He favoured an origin by the rotation of originally NE–SW trending early F_1-folds towards the longest axis of the deformation ellipsoid (NW–SE, nearly parallel to the elongation lineation L_2 of that area) during a D_2-deformation. In the Valdres area, this is favoured by the fact that F_1-folds are transected by later penetrative S_2-cleavages which occur as axial surfaces of F_2-folds (Nickelsen 1974). Structural elements similar to these in the Valdres area occur in the northwestern part of the Osen–Røa Nappe Complex (Englund 1973), but have not been recognized farther east. The deformation phase which has produced the early F_1-folds has probably affected only those sequences which originally were located rather far west on the Baltoscandian craton. The arcuate folds in the Osen–Røa Nappe Complex are here interpreted to be the result of one single phase of deformation. Rotation of folds, which were initiated with a NE–SW trend, may have been brought about by regional variations in rate of tectonic mass transport towards the SSE. The protruding noses of the arcuate fold structures have probably moved with higher velocities than the flanking segments. Such variations in rate of movement may be due to local differences in nappe thickness, surface slope and friction.

MINOR FOLDS, CLEAVAGE AND LINEATIONS

Small-scale folds comprise mainly 'drag folds' with an orientation congruent with that of the host folds. The axial trend of irregular disharmonic folds in incompetent units may deviate considerably from the orientation of regional folds. Folding has taken place by flexural slip along bedding surfaces, but particularly in the northern and northwestern part of the nappe complex this type of folding has been modified by differential flow or shear along cleavage.

Spaced cleavage is developed as an axial surface cleavage. It becomes more pronounced and penetrative towards the northwest and north and passes into a slaty cleavage. Quartz grains and conglomerate pebbles are flattened in the cleavage surface and elongated (110°–160°) (Fig. 1). Local boudins are nearly normal to this direction (Fig. 7). Quartz segregations and quartz veins are common in the northern part of the nappe complex. The cleavage and elongation lineation are interpreted as cogenetic with the regional folds and main phase of thrusting, but cleavage of later origin also occurs, as described below.

Kvitvola Nappe structures

KVITVOLA THRUST

The Engerdalen Group in the Kvitvola Nappe is derived from an open shelf basin, and there is no obvious lateral stratigraphic continuity between the Osen–Røa Nappe Complex and the Kvitvola Nappe, though a general lithostratigraphical correlation exists (Nystuen 1980).

The sole *Kvitvola thrust* (KT) cuts those folds and thrusts which are described in the Osen–Røa Nappe Complex, and the Kvitvola Nappe rests on the lower as well as the higher formations of the Hedmark Group. The nappe also overlies autochthonous basement and Cambrian shales east of the Engerdalen fault (EF). A total absence of structural conformity between the nappes can be directly observed in many outcrops and can be demonstrated regionally (Figs. 1, 4–7). However, in the Ringebu–Vinstra area there is a coincidence between trends of fold axes and lineations in the two nappes (Englund 1973), and local concordance also exists in other places (Fig. 7). On

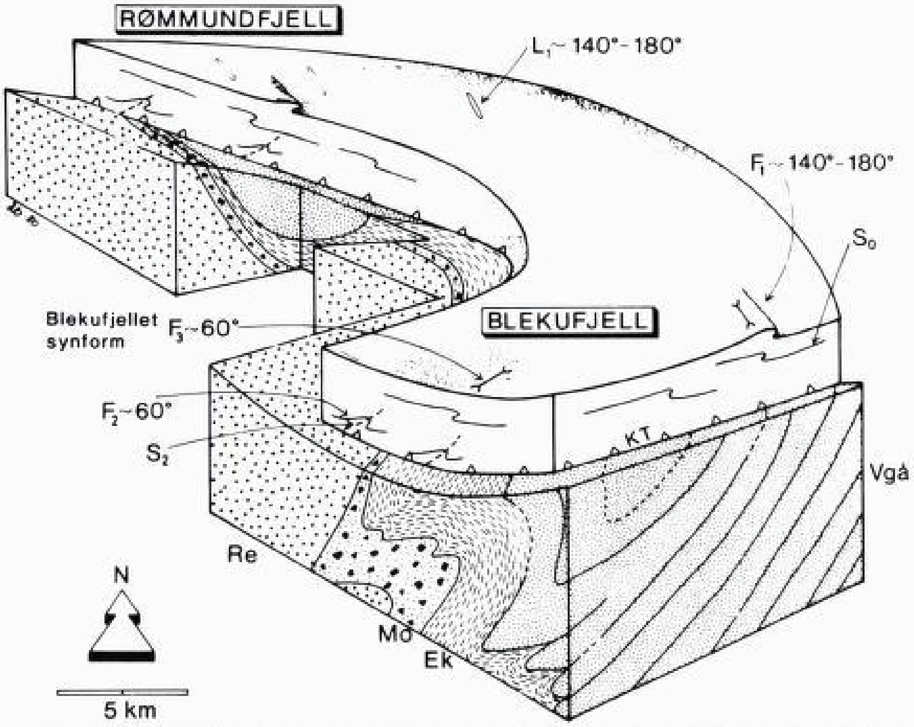


Fig. 4. Blekufjellet synform and structural relations between the Kvitvola Nappe and the Osen–Røa Nappe Complex. Conceptual diagram. Sources: Nystuen (1975a, 1975b, 1975c). KT = Kvitvola thrust, Re = Rendalen Formation, Mo = Moelv Tillite, Ek = Ekre Shale, Vgå = Vangsås Formation. Location shown in Fig. 1b.

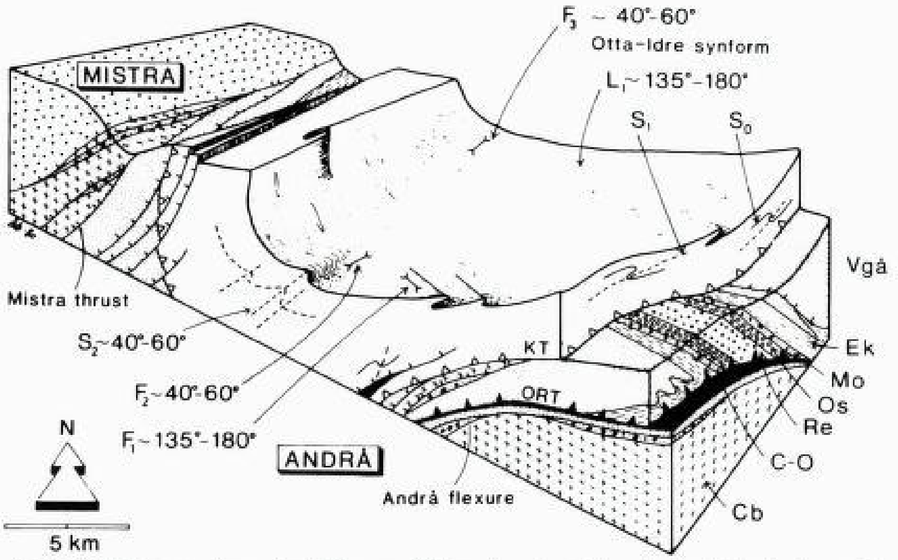


Fig. 5. Otta–Idre synform, Andrå flexure, Mistra thrust and structural relation between the Osen–Røa Nappe Complex and the Kvitvola Nappe. Conceptual diagram. Source: Sæther (1979). ORT = osen–Røa thrust, KT = Kvitvola thrust, Cb = Crystalline basement, C–O = Cambro–Ordovician, Re = Rendalen Formation, Os = Osdalen Conglomerate, Mo = Moelv Tillite, Ek = Ekre Shale, Vgå = Vangsås Formation. Location shown in Fig. 1b.

a regional scale it appears that the thrusting of the Kvitvola Nappe is *younger* than the thrusting of the Osen–Røa Nappe Complex. Nevertheless, the structural features of the Femunden thrust zone (Fig. 3) and the Mistra thrust (Fig. 5) show that in these places the thrusting of the Kvitvola Nappe is *older* than movements along the Osen–Røa thrust.

The Kvitvola thrust cuts the stratigraphic section (Fig. 2) with flats following the base of the incompetent Hylleråsen Formation over large areas. The Høyberget Formation dominates in the hangingwall in the northern part, whereas the lower units are recognized in the southern part; this may indicate that the basal thrust on a regional scale cuts up-section at the trailing edge. However, stratigraphical and structural data are still too limited to allow any definite conclusion to be drawn on the nature of the sole thrust.

Thrusts are developed as footwall imbricates (Butler 1982, p. 242) in several areas. Imbricate sheets derived from the footwall are squeezed into the basal zone of the nappe along contraction faults east of the Engerdalen fault (Nystuen 1974), east of Storsjøen (Sæther 1979) and in Åstdalen (Fig. 7). Fracture cleavage (S_2) and shear folds (F_2) are limited to the basal zone and also penetrate into the footwall within the *Stai fracture zone* (Fig. 6).

EARLY CLEAVAGE, FOLDS, LINEATIONS AND THRUSTS

The rocks of the Kvitvola Nappe reveal a slaty cleavage (S_1) which is penetrative except in the southeasternmost areas (Figs. 1, 3–7). It behaves as an axial plane foliation to recumbent and isoclinal plastic-type folds (F_1). The fold

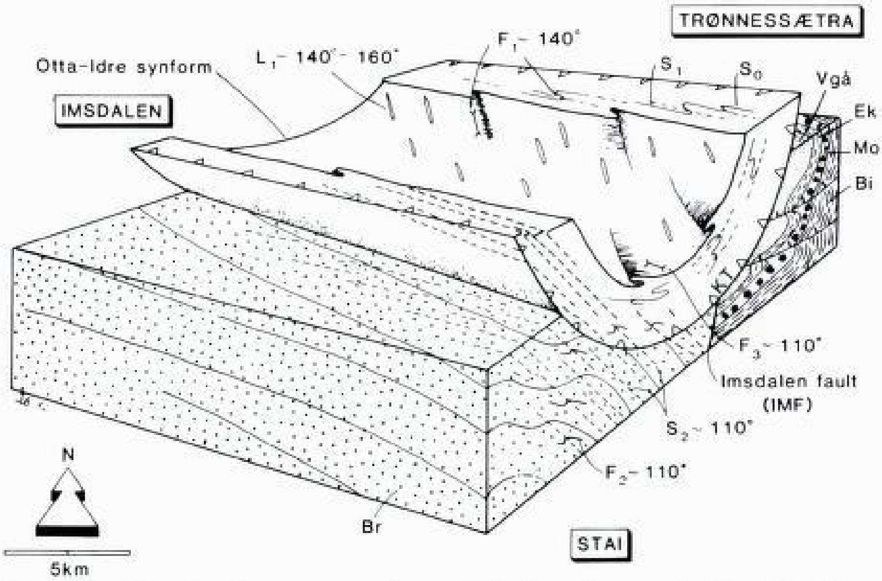


Fig. 6. Otta-Idre, Stai fracture zone and structural relation between the Osen–Røa Nappe Complex and the Kvitvola Nappe. Conceptual diagram. Sources: Elvsborg & Nystuen (1978) and Sæther & K. Bjørlykke (1981). KT = Kvitvola thrust, Br = Brøttum Formation, Bi = Biri Shale, Mo = Moelv Tillite, Ek = Ekre Shale, Vgå = Vangsås Formation. Location shown in Fig. 1b.

trends are parallel (110°–180°) to a mineral elongation (L_1); and the stretched and flattened quartz and feldspar grains lie within the S_1-cleavage. Early formed quartz-microcline-hematite segregations are frequently deformed into S_1 and produce a lineation parallel with L_1.

The incorporation of basement rocks, such as augen-gneiss, granite mylonite, meta-anorthosite and metagabbro, must belong to an early stage in the structural evolution of the nappe. These rocks are now present as sheets at the base of the nappe or within the sedimentary sequence, bounded by folded thrust surfaces. An upper and folded thrust sheet in the Ringebu area, revealing repeated lithostratigraphy, is also of early tectonic origin (J.-O. Englund, pers. comm. 1982).

LARGE-SCALE FOLDS AND ASSOCIATED THRUSTS

The sedimentary strata of the Engerdalen Group are mostly flat-lying. Large folds are open and broad with fold axis orientations varying from about 110° in the west to 040° in the east. In the Engerdalen area, one of these folds, the *Tverrfjellet syncline* (TS), is asymmetric with the northern limb slightly overturned to the southeast.

Towards the Mistra and Femunden thrusts (Fig. 1) listric contraction faults increase in frequency within the Kvitvola Nappe and are well marked topographically at the SE edge of the Femunden thrust zone (Figs. 3 & 5).

Furusjøen–Åstdalen antiform

The *Furusjøen–Åstdalen antiform* (FÅA) deforms the Kvitvola thrust as well as the underlying Brøttum Formation (Figs. 1 & 7). The Brøttum Formation crops out within the *Flakksjøen window* along the antiform axis, and another window is probably present at Furusjøen further to the NW, outside the map area of Fig. 1 (J.-O. Englund, pers. comm. 1982).

At Åstdalen, early structures in the Kvitvola Nappe and slaty cleavage and lineation in the Osen–Røa Nappe Complex are overprinted by a brittle-type deformation along the FÅA (Fig. 7). The deformation appears to be concentrated to a zone of about ± 50 m below and above the Kvitvola thrust, and comprises small-scale tight folds (F_{3a}) overturned to the NNE, crenulation cleavage (S_{3a}) which dips to the SSW and small contraction faults with dip in the same direction. The structural features here can be explained as a local zone of late folding verging NE. It could also be the result of collapse of a lateral ramp (Butler 1982), and hence the axes could lie in the movement direction. Further structural studies are needed along the Furusjøen–Åstdalen antiform.

Otta–Idre synform and Snødøla–Steinfjellet antiform

The erosional remnants of the Kvitvola Nappe are preserved within depressions along the *Otta–Idre synform* (OIS) and the parallel *Blekufjellet synform* (BS) which are folds (F_3 & F_{3b}) defined by contours on the Kvitvola thrust

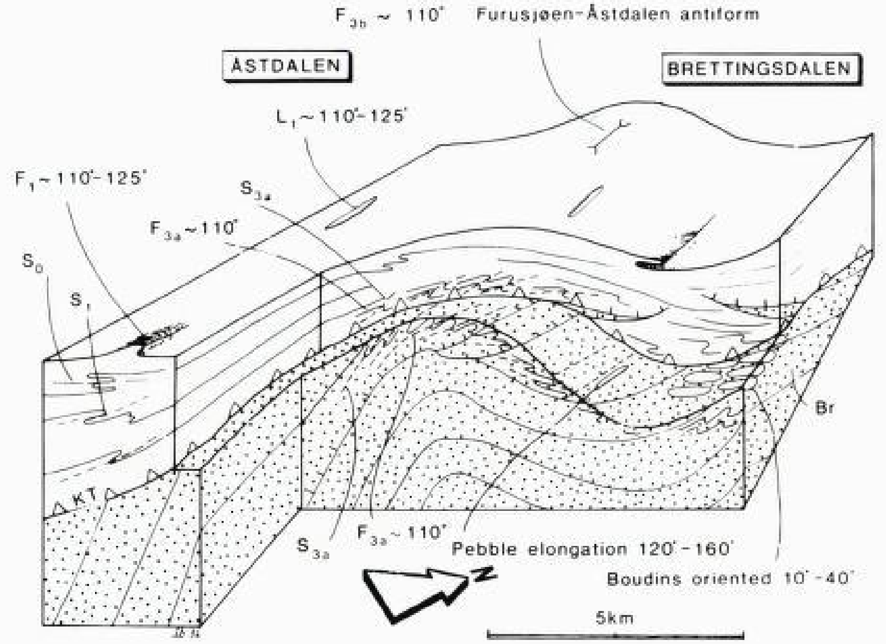


Fig. 7. Part of the Furusjøen–Åstdalen antiform and structural relationship between the Osen–Røa Nappe Complex and the Kvitvola Nappe. Conceptual diagram. KT = Kvitvola thrust, Br = Brøttum Formation. Location shown in Fig. 1b.

(Figs. 1, 4–6). Strand (1960) related the Gudbrandsdalen part of the OIS to a Caledonian cross-folding, but the regional pattern of the axial plane trace displays an arcuate structure, though much more open-arced than those in the Osen–Røa Nappe Complex. The OIS interferes with transverse synforms and antiforms; the *Central Østerdalen Depression* (CØD) is formed at the intersection between OIS and the *Storsjøen–Øvre Rendalen* synform (SØS) (Sæther & Nystuen 1981).

The windows exposing the basement in the north are eroded domes along the *Snødøla–Steinfjellet antiform* (SSA). The domes ans saddles between them can be interpreted as originating by an interference between the NE-trending SSA and several other SSE-trending synforms and antiforms (Fig. 1). The outcrop pattern of the Kvitvola Nappe is controlled by the erosion along such a transverse antiform south of the Atnsjøen window and along the *Grøndalen–Osdalen antiform* (GOA) between Storsjøen and Trysilelva. Strike and dip of bedding and coincident cleavage in sandstones indicate that the SSA is bounded by a broad, parallel synform on its southeastern side. A fracture cleavage which dips steeply to the NW and trends parallel to the SSA, cuts basement and slaty cleavage in the nappe cover and is interpreted to have been formed together with the basement antiform (SSA) (Nystuen & Ilebekk 1981). The basement antiform continues NNE-wards as the 'Riksgrense antiform' which also deforms the Caledonian nappe cover (e.g. Gee 1980). Additional basement antiforms exist still further north in the Scandinavian Caledonides.

Origin of the Snødøla–Steinfjellet antiform

Geophysical studies in the fold belts of the Canadian Rocky Mountains and the Appalachians have demonstrated basement surfaces which dip slightly and evenly for 150–200 km beneath a nappe cover towards the central zone of the orogen (e.g. Price 1981, Brewer et al. 1981, Hatcher 1981). A major implication of this discovery is that basement domes exposed within the nappe regions have been interpreted as allochthonous, underlain by a master thrust fault. Thus, in this way, Hossack et al. (in press) interpreted the basement of the Beito window in the Valdres area to be allochthonous. A major question arises: are all basement antiforms within the nappe region in the Scandinavian Caledonides allochthonous, underlain by a regional sole thrust? The answer is fundamental to all attempts to construct balanced cross sections (Dahlstrom 1969) through the mountain belt.

Limited data are available on the structural behaviour of the autochthonous basement beneath the nappe cover in the Scandinavian Caledonides. From the Sparagmite Region a map showing depths to the magnetic basement has been published by K. Åm (Fig. 6, in Nystuen 1981). In the Caledonian nappe front in Jämtland, Elming (1980) found high magnetic susceptibilities only in the granitic basement, and this is probably valid also for present area. In northern Jämtland, calculated depth to magnetic basement coincided well with depth to crystalline basement found by drilling (Hesselblom 1979). Thus, the magnetic basement of Åm (in Nystuen 1981) is here interpreted to approximate to the crystalline basement surface beneath the nappe cover. The morphology of this surface is characterized by 'lows' and 'highs' which coinside well with the late synforms, antiforms, domes and saddles expressed by the surface geology (Fig. 1). This indicates that the Snødøla–Steinfjellet basement antiform (SSA) was formed in late Caledonian time (Lower to Middle Devonian?) together with similar basement undulations farther south as well as with the Otta–Idre synform and related synforms and antiforms. Basement flexure at Andrå (AFL) and Åsta (ÅFL) may mark a southern limit of this deformation.

Structural evolution: discussion and conclusion

In the Scandinavian Caledonides nappes advanced from the west to the east. In the central and southern parts of the orogen emplacement of thrust sheets on to the Baltoscandian craton commenced by the partial closure of the Iapetus Ocean during the early Ordovician. The main phase of nappe translations occurred during the Middle to Upper Silurian (Roberts & Gee 1981).

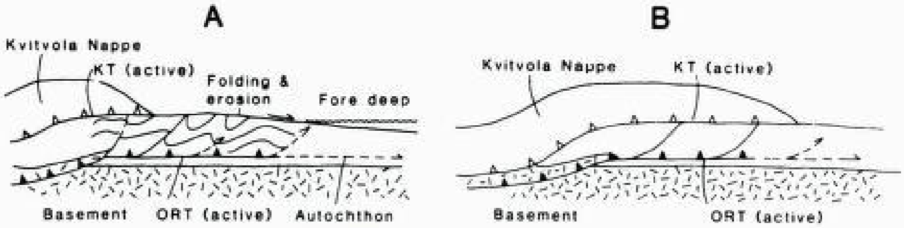
The detachment of Kvitvola Nappe from a shelf basin was brought about when higher tectonostratigraphical units approached the shelf from still more western, continental margin areas and eugeosynclinal zones. The initial fracture, starting in the crystalline basement, propagated into the ductile Hylleråsen Formation (carbonate-shale) and mainly followed this stratigraphical level as the sole thrust (KT). Penetrative slaty cleavage (S_1), mineral elongation (L_1), plastic-type folds (F_1) and phyllonite and mylonite zones give evidence of flattening and extension, perhaps related to gravitational collapse (Ramberg 1981) under the overburden of a thick nappe pile. Metamorphism under greenschist facies conditions took place. The laterally extended horizontal stratification indicates that the major thrust movements occurred along a low-frictional sole thrust. However, locally the nappe body collapsed along low- and high-angle contraction faults.

Initial detachment and movement of the Osen–Røa Nappe Complex started when the advancing nappe pile reached the cratonic 'sparagmite basin' some 200–400 km NW of the present Sparagmite Region. In this phase, slaty cleavage, lineations and phyllonite zones were formed due to increase in temperature, confining pressure and simple shear (mesoscale folds (F_1) in the northwest may be still older). The initial fracture originated also in this case in the crystalline basement; it cut up-section and entered the ductile Cambrian shale beds which rested on the eastern foreland basement. A major amount (minimum 125 km) of slip has taken place along this sole thrust (ORT). Imbrication, folding and evolution of the arcuate fold structures took place concurrently with the southeastwards propagation of the active thrust system.

The regional structural disconformity between the Osen–Røa Nappe Complex and the Kvitvola Nappe can be explained in two fundamental different ways (Fig. 8). The imbrications and folds in the Osen–Røa Nappe Complex may have suffered erosion contemporaneously with their formation. The Kvitvola Nappe was emplaced on the erosional surface and became later imbricated and folded during piggy-back transport by the still active Osen–Røa thrust (ORT) (Fig. 8A). The Bruflat Sandstone of upper Llandovery to lower Wenlock age in the Mjøsa area is a possible fore-deep sediment originated from erosion of the advancing Osen–Røa Nappe Complex.

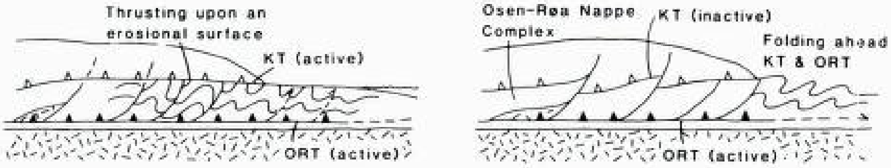
J. R. Hossack (written communication 1982) proposed that the contact relations between the two nappe units were the result of *out-of-sequence thrusting* (Fig. 8B). The ORT and secondary thrusts were formed when the Kvitvola Nappe was emplaced on the 3–4,000 m thick sequence in the 'sparagmite basin'. Further movements along ORT gave rise to piggy-back transport of the Kvitvola Nappe and imbrications in both nappe units (Femunden thrust zone). Folding occurred ahead the nappes, and during reactivation of the Kvitvola thrust (KT) the out-of-sequence thrusting occurred in this area while the ORT still propagated towards the SE. Similar out-of-sequence thrusting has been described from the Moine Thrust Zone in Scotland by McClay & Coward (1981). The mechanism implies that the reactivated KT has truncated the high-angle faults and folds in the Osen–Røa Nappe Complex and thus acts as the roof thrust of a giant duplex in the footwall (see Boyer & Elliott 1982, p. 1209). Both hypotheses (Fig. 8A & B) need further structural analyses.

Late-thrust structures are the open NE-trending folds (e.g. Tverrfjellet syncline), the Stai fracture zone (Fig. 6), the Furusjøen–Åstdalen antiform (Fig. 7), the Mistra thrust (Fig. 5) and the Femunden thrust zone (Fig. 3). Post-



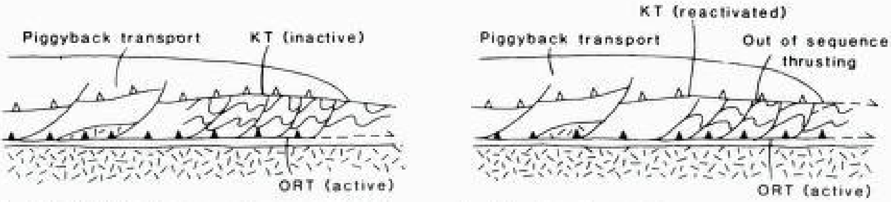
1 The Kvitvola Nappe overthrusts Osen-Røa Nappe rocks. Folding and erosion ahead KT.

1 The Kvitvola Nappe overthrusts Osen-Røa Nappe rocks.



2 Thrusting of the Kvitvola Nappe upon folded and eroded Osen-Røa Nappe rocks.

2 Piggyback transport and imbrication of the Kvitvola Nappe.



3 The Kvitvola Nappe rests on a regional disconformity. ORT propagates further to the SE.

3 Reactivation of KT gives rise to out of sequence thrusting. KT and ORT propagate into the folded zone.

Fig. 8. Interpretations of the structural evolution of the Osen–Røa Nappe Complex and the Kvitvola Nappe. In *A* the structural conformity between the nappe units is explained as an erosional surface and in *B* (after J. R. Hossack, written comm. 1982) as the result of tectonic truncation by KT during out of sequence thrusting.

thrust deformation affected the basement and gave rise to the Snødøla–Steinfjellet antiform, the Otta–Idre synform and related arc and saddle structures (Fig. 1).

The nappe structures of the present area display similarities with thrust structures believed to have formed by gravitational spreading (Elliott 1976, Cooper 1981). However, serious objections have been raised against this hypothesis of thrusting (Chapple 1978, Murrell 1981). Burchfiel & Davis (1972), Price (1981) and Hatcher (1981) maintained that compressional thrusting including formation of low-angle contraction faults into the crystalline basement were brought about by a laterally directed pressure acting from the hot mobile central zone. No definite conclusion can be drawn regarding the driving force for the compressional nappe structures in the Sparagmite Region. However, the great volume of the thrust bodies and the incorporation of basement sheets indicate that the operating stress probably has been higher than that which could have been formed gravitationally only from a surface slope of the nappes (cf. Chapple 1978).

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