Journal of Structural Geology, Vol. 8, No. 7, pp. 753 to 765, 1986
Printed in Great Britain

0191-8141/86 $03.00+0.00

The Caledonian thrust front and palinspastic restorations in the southern Norwegian Caledonides

C. K. Morley

Amoco Production Company, P.O. Box 3092, Houston, Texas 77079, U.S.A.

(*Received* 1 *February* 1985; *accepted in revised form* 12 *December* 1985)

Abstract—The Osen–Røa thrust sheet of the southern Norwegian Caledonides comprises the coarse clastic late Precambrian Sparagmite region, and the folded and imbricated Cambro-Silurian rocks of the Oslo region. Ramp-flat geometries occur in the hangingwall of the Osen–Røa thrust in the Mjøsa district. Two major ramps are recognized. One coincides with the strike of the Ringsaker inversion, while the other coincides with the traditional thrust front in the Gjøvik area. The Osen–Røa thrust cuts up section in the transport direction (south), eventually cutting out all late Precambrian rocks, to lie as a 150 km long flat in the Cambrian Alum shales of the Oslo region. The now eroded detachment termination probably died out horizontally in the Alum shales to end as a buried thrust front in the southern Oslo region. Restoration of hanging- and footwall cutoffs allows the amount of overthrusting to be calculated; the Sparagmite region/Oslo region boundary restores to a minimum of 130 km to the NNW. This displacement estimate agrees with estimates of 135 km NNW transport calculated from balanced cross-section restorations through the Oslo region.

INTRODUCTION

The Mjøsa district and Sparagmite region (see Fig. 1) comprise deformed and thrusted late Precambrian to Silurian sediments which rest on thin, weakly deformed, but essentially autochthonous sediments of late Precambrian to Cambrian age. These weakly deformed sediments were folded and imbricated during footwall collapse and moved a few kilometers from their original depositional area. They rest on autochthonous Precambrian gneissic basement. In the Oslo region, the late Precambrian series (Sparagmite) has completely thinned out, by onlap, and the lowermost few meters of the Cambrian Alum shales are completely autochthonous.

Traditionally the Caledonian nappe front has been positioned in the southern Mjøsa area along a line that separates imbricated late Precambrian Quartz–Sandstone nappe units (later called the Osen–Røa nappe by Nystuen 1981) to the north from the folded Cambro-Silurian sequence of the Oslo region to the south (Skjeseth 1963) (Fig. 1). The Cambro-Silurian sequence of the Oslo region has been regarded as a para-autochthonous tectonic unit (Bockelie & Nystuen 1984).

The structural models proposed for the Sparagmite region of southern central Norway have been summarized by Nystuen (1981, pp. 73–75). There are two; a para-autochthonous model (Schiotz 1902, Skjeseth 1963) and an allochthonous model (Oftedahl 1943). Schiotz (1902) proposed that there were local, basement controlled, fault-bounded basins within the late Precambrian sequence (called the Hedmark Group by Bjørlykke *et al.* 1967). This model requires the detachment of the Ekre shales from the underlying rocks and the transport of the overlying Osen nappe (previously the "Quartz Sandstone nappe" and later the Osen–Røa nappe complex, Nystuen 1981) by about 50 km to the

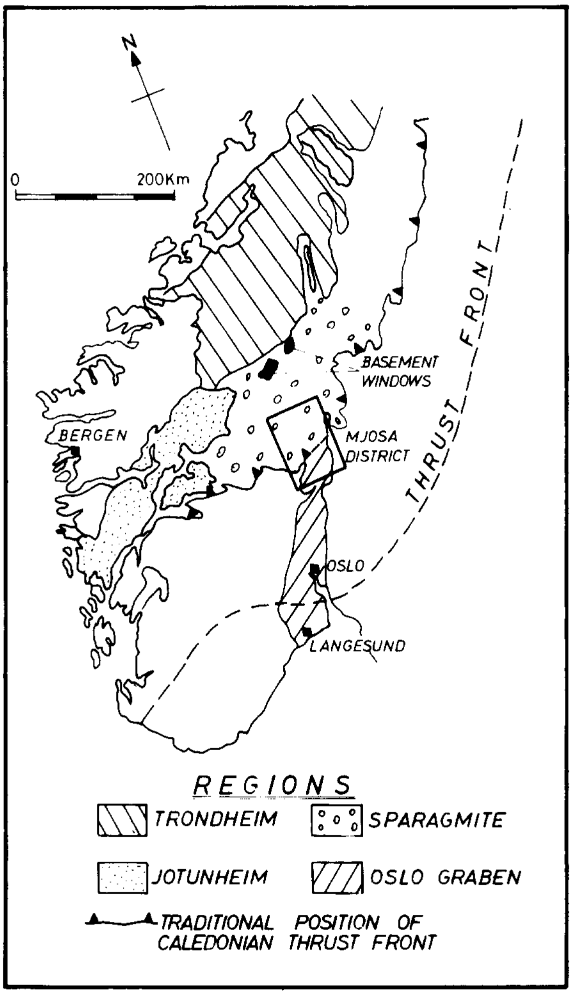

Fig. 1. Location map of the tectonic regions of the southern Norwegian Caledonides (partly after Holtedahl & Dons 1960).

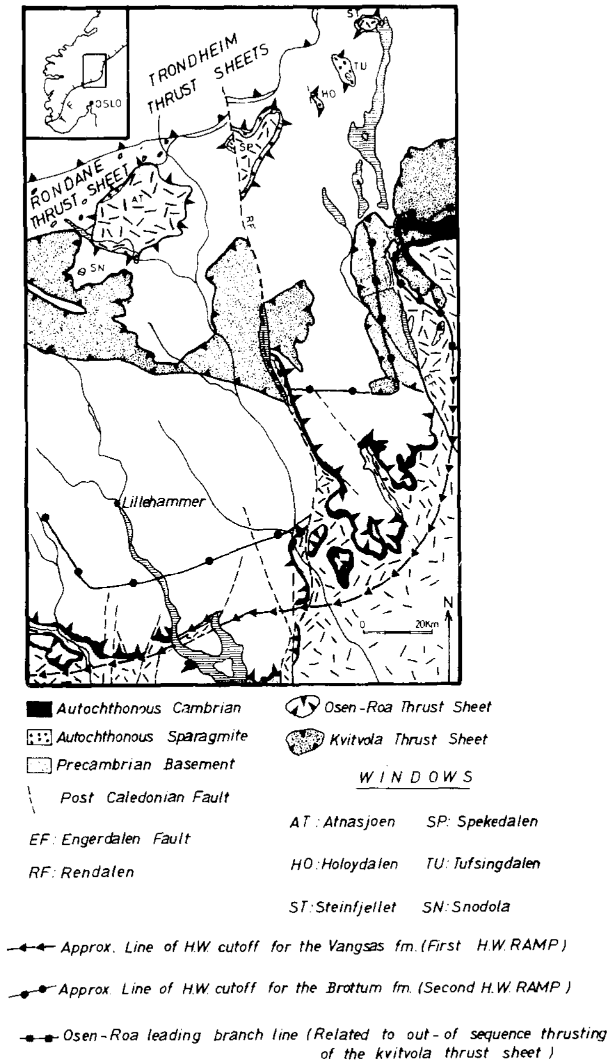

Fig. 2. Diagram of the sparagmite region (after Nystuen 1983), showing the present day positions of hangingwall ramps in the Osen–Røa thrust sheet.

south. The remainder of the sequence is thought to have been deformed internally and transported south by 20–30 km.

Oftedahl (1943) (and later Høy & Bjørlykke 1980) recognized that the Cambro-Silurian sediments of both the Oslo region and the Sparagmite region were underlain by the same thrust. Oftedahl (1943) assumed constant 50% shortening in the Oslo region. He restored Cambro-Silurian rocks from the undeformed foreland at Langesund (see Fig. 1) and concluded that the Palaeozoic rocks at Mjøsa had been displaced by 150 km. He assumed 50% internal shortening for the whole Osen–Røa thrust sheet, which gave transport distances of up to 300 km from the NW to SE; that is transport from an original position northwest of the basement windows (see Figs. 1 and 2). Later models (Oftedahl 1954a,b, Holmsen & Oftedahl 1956) also placed the main depositional basin north of the basement windows, whilst an intermediate model, with basins on the northern and southern sides of the windows, was proposed by Prost (1977). Recently Kumpulainen & Nystuen (1984) have estimated that transport distances may be up to 230 km from the NW to the SE, for the southern margin of the Sparagmite basin.

The allochthonous model has been gaining greater acceptance amongst workers in the Sparagmite region. For example, Nystuen (1981) estimated between 200 and 400 km displacement for the Osen–Røa nappe. Yet workers have not attempted to prove whether the overall 50% shortening estimate for internal deformation of the Osen–Røa thrust sheet in the Oslo region (Oftedahl 1943) is accurate. The estimate of internal strain is one of the most important keys to determining the amount of displacement along the Osen–Røa thrust. Estimated hanging- and footwall cut-off positions can be made using the location of ramp-related structures in the hangingwall, and outcrops of rocks in the footwall revealed in tectonic windows. These estimates coupled with estimates of internal strain for the thrust sheet using balanced cross-sections (Hossack 1979) are applied in this paper to determine the amount of displacement undergone by the Osen–Røa thrust sheet.

THE RAMP-FLAT MODEL

Major thrust sheets usually display a stepped trajectory composed of long bed-parallel flats and short sections where the thrust cuts across stratigraphic boundaries called ramps (Rich 1934). The position on a fault plane, where a ramping section of the thrust intersects a particular stratigraphic boundary, is called the cut-off line. When displacement of the thrust commences, the corresponding hanging- and footwall cutoffs are moved further and further apart. Usually displacement of the hangingwall of major thrusts is of the order of a few kilometers to tens of kilometers. In such cases, the hanging- and footwall ramps are still close enough to generate passively folded anticlines and synclines in the upper plate. The cutting out of beds by frontal hangingwall ramps generate foreland dips above the ramp, while frontal footwall ramps generate hinterland dips. The creation of hinterland dips over the footwall ramp may be minimized by a progressive increase in the thickness of the upper plate towards the hinterland (Fig. 3c), and leave a simple foreland-dipping monocline above the hangingwall ramp. Alternatively, if the upper plate is transported for a considerable distance (tens of kilometers) away from the footwall ramps, only the effects of hangingwall ramps will be seen in the upper plate (Fig. 3b). This will cause a foreland-dipping monocline to be developed over each hangingwall ramp.

The Osen–Røa thrust sheet rests on a footwall flat of slightly displaced Cambrian Alum shales, that can be seen in the windows at the north of the Sparagmite region to rest on a thin Sparagmite succession (Figs. 1 and 2). The undeformed length of this footwall flat must correspond to a hangingwall flat of similar length in the Alum Shales somewhere further to the SSE in the transport direction. The Oslo region succession is the only area that has a hangingwall flat in the Alum shales

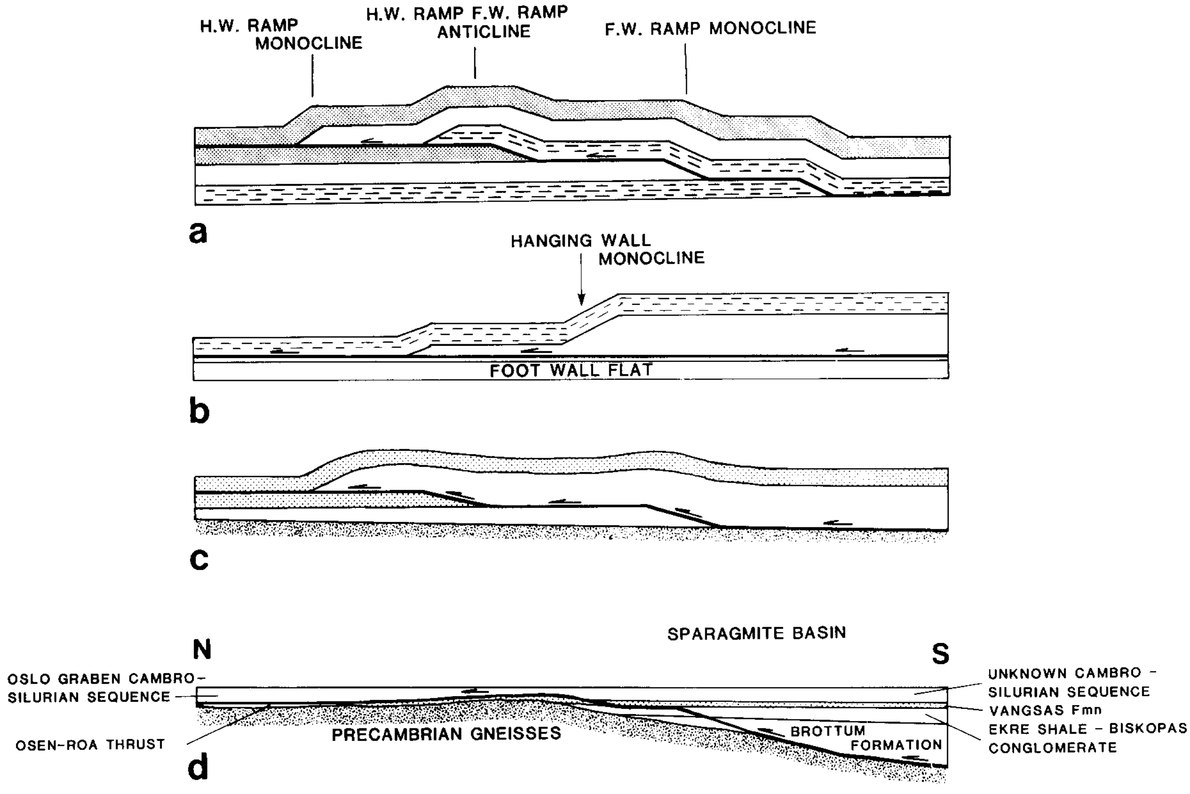

Fig. 3. The consequences of a ramp-flat thrust geometry. (a) Typical passive anticlinal features caused by a combination of hangingwall and footwall ramps cutting a layer cake stratigraphy (after Rich 1934, Gretener 1972). (b) With a long footwall flat, only hangingwall monoclines, in the vicinity of hangingwall ramps will be produced. (c) If stratigraphic thicknesses vary (in this example the unornamented bed thins in the transport direction), the effects of footwall ramps may be smoothed out. (d) The Osen–Røa thrust sheet is a combination of the factors illustrated in (b) and (c). The schematic diagram shows the Osen–Røa thrust propagating through a basin with changing thickness of sediments. This hinterland-thickening sequence was then emplaced onto a long footwall flat after cutting up through the Vangsås Formation.

that could match the extent of the Alum shales in the footwall flat. Hence the undeformed length of the footwall sequence must correspond to the undeformed length of the Cambro-Silurian sequence in the Oslo region.

In the Oslo region, the Osen–Røa thrust probably did not undergo frontal ramping to the synorogenic surface, but instead died out as a buried thrust front in the Alum Shales just north of Langesund (Oftedahl 1943, Morley 1983). The buried thrust front allows balanced cross-sections to be constructed from a pin line in the undeformed foreland, from which palinspastic restorations of the Oslo region and Sparagmite region can be made. Progressive loss of the oldest units from the Osen–Røa thrust sheet toward the south, west and east is explained by frontal, lateral and oblique ramps (Butler 1982) in the Osen– Røa thrust. The approximate positions of cutoff lines that mark the positions of the ramps are given in Fig. 2.

In the following section, the deformation style above the areas of ramps and flats is described in order progressing from south to north, toward the hinterland of the thrust belt. 1:50,000 geological maps of the Gjøvik (Bjørlykke 1979), Hamar (Høy & Bjørlykke 1980) and Bruflat (Bjørlykke & Skålvoll 1979) areas and observations from traverses through the Sparagmite area were used to define the positions of ramps and flats.

The Cambro-Silurian area of southern Mjøsa: first flat

This area is the northernmost extent of the 150 km long flat of the Oslo region. The Cambro-Silurian stratigraphy of the area comprises predominantly shaly rocks with some limestone units in the Cambrian–mid-Ordovician sequence below a more predominantly limestone and sandstone sequence, with subordinate shales in the mid-Ordovician–Silurian succession (see Fig. 4). There is a strong stratigraphic control on deformation style in this area, as in the whole of the Oslo region, with imbrication of the lower, Cambrian to mid-Ordovician units, and buckle folding of the higher mid-Ordovician–Silurian units (see Figs. 4 and 5).

The amount of shortening achieved by imbrication in the Cambrian–mid-Ordovician has not been calculated due to the poor exposure. However, estimates for shortening of 60% further south in Hadeland for imbrication of the Cambrian–mid-Ordovician sequence (Fig. 6) (Morley 1983) indicate the amount of shortening that might be inferred for the Mjøsa section. Skjeseth (1963, p. 96) does refer to one section where folding and thrusting have repeated the Stein limestone twenty times in 400 m. Estimates of shortening from a study of well-exposed sections suggest an average repetition of imbricate thrusts every 150 m. However, published maps and sections do not display this density of thrusting.

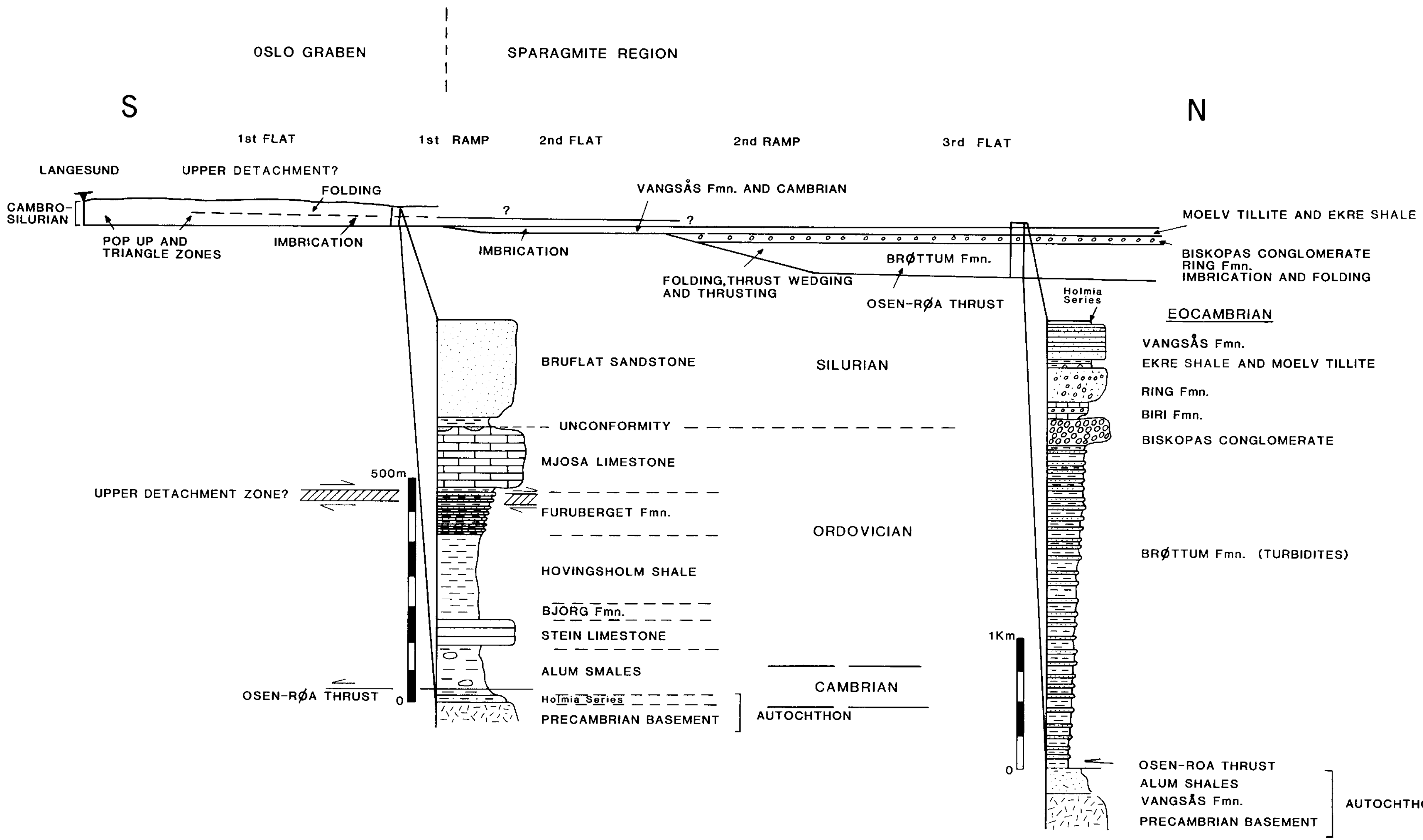

Fig. 4. Schematic diagram of the Osen–Røa thrust sheet, showing the position of ramps and flats, type of internal deformation, and the Eocambrian–Lower Palaeozoic stratigraphy.

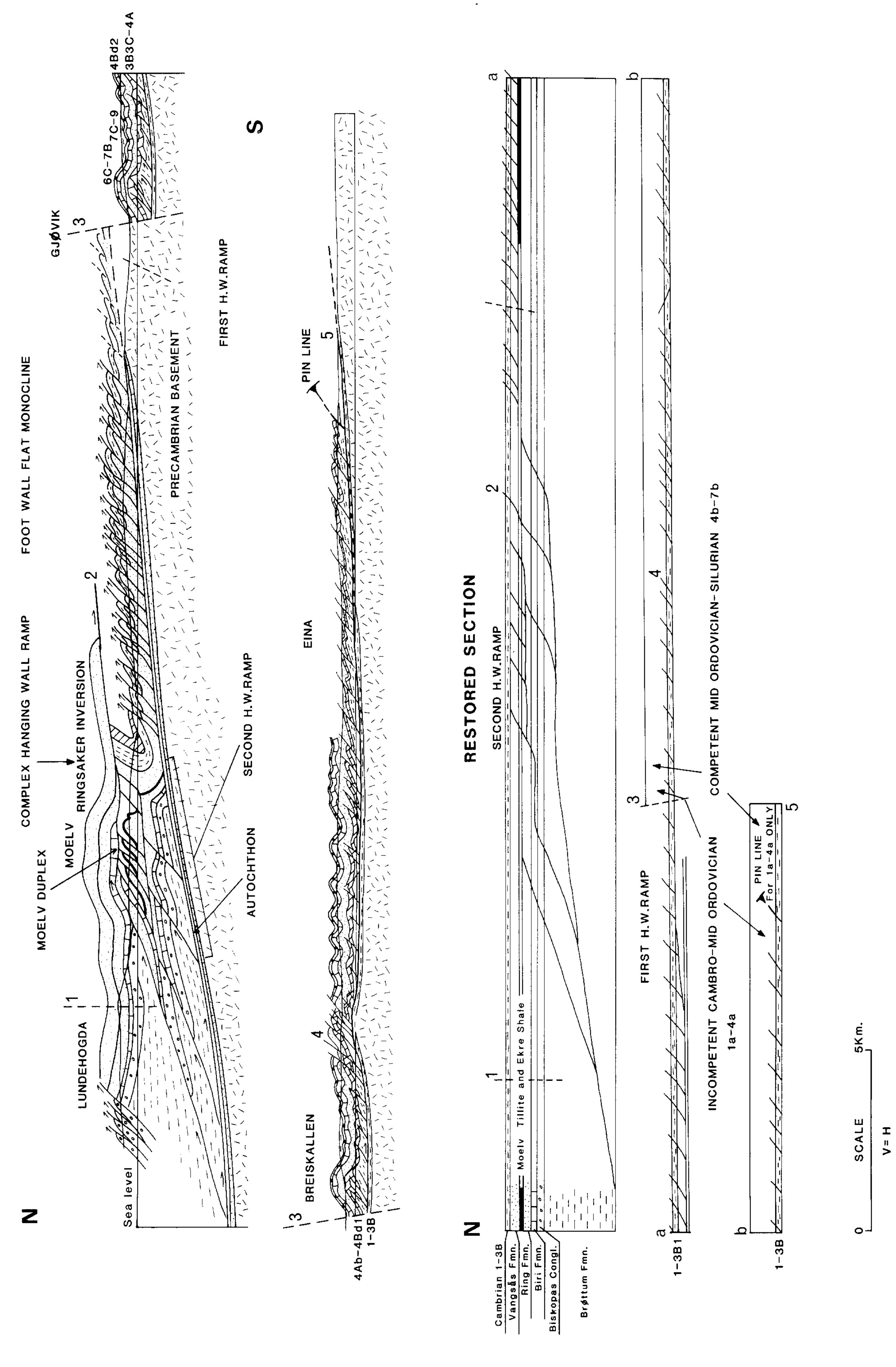

Fig. 5. Balanced cross-section from Lundehogda to Eina (see Fig. 7 for line of section).

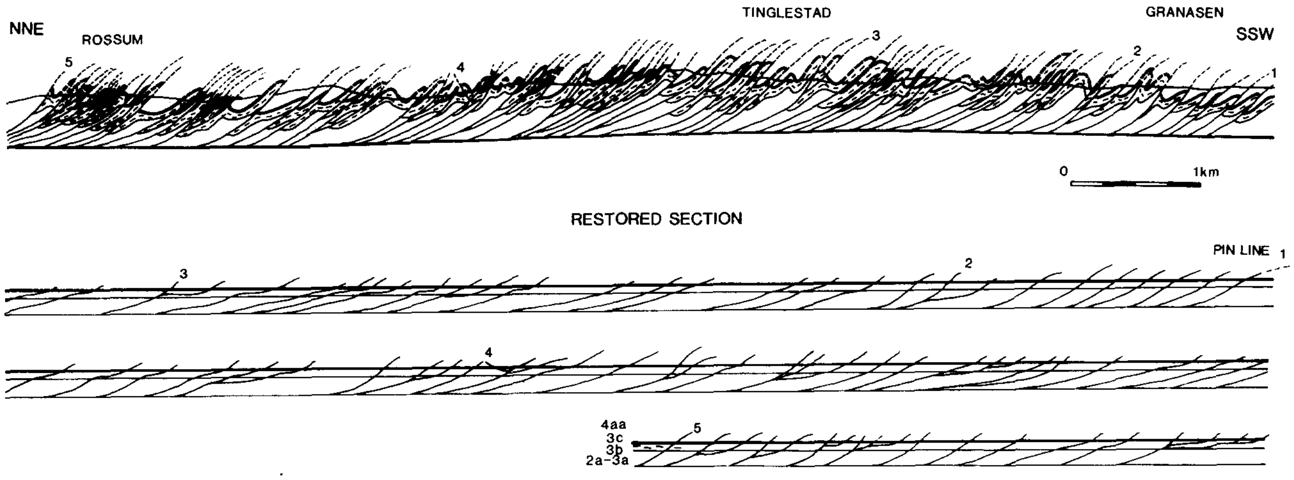

Fig. 6. Cross-section through the imbricated Cambro-Ordovician sequence of North Hadeland. 2a–3a, Alum Shales (Cambrian–Lowermost Ordovician); 3b, Ceratopyge Series; 3c, Orthoceras Limestone; 4aa, Kirkerud Group; (mid-Ordovician).

In contrast to the imbricate style, the deformation style in the overlying mid-Ordovician–Silurian unit can be seen on published geological maps and in several sections to form broad, gentle folds as at Bruflat, Helgoya and along the Brumunderlv River (Skjeseth 1963, pp. 81, 97 and 83, respectively).

These folds have vertical and sub-vertical axial planes and the wavelengths of the main folds in the Mjøsa Limestone range from 275 to 1000 m (averaging 500 m). However, in the northern part of the area, above imbricated rocks where the Vangsås Formation is present at the base, the wavelength increases to an average of 100 m. Amplitudes for the whole area range from 150 to 500 m, with interlimb angles between 90 and 130°. The amount of shortening achieved by folding is about 28%. Hence, the discrepancy in the amount of shortening between the incompetent and competent sequences requires a detachment zone to be inferred between the folded and imbricated parts of the succession (see Fig. 4; Morley 1983).

The first ramp

The first ramp is marked by the first appearance of the Vangsås Formation and Ekre shale in the Osen–Røa thrust sheet (see Figs. 2 and 7). The area just north of Gjøvik and Berg on the western and eastern sides of Lake Mjøsa, respectively, marks the southernmost extent of late Precambrian rocks in Norway (see Fig. 1). There is a ragged eroded E–W boundary to the western part of this area which is separated from the Cambro-Silurian rocks of the Oslo region by a thin strip of Precambrian basement (see Fig. 7).

The present eroded southern boundary of the Sparagmite region is traditionally known as the Caledonian nappe front (Fig. 1). Evidence that the Osen–Røa thrust does not end at the nappe front but passes into the Oslo region can, however, be found on the eastern side of Lake Mjøsa where erosion has not yet separated the late Precambrian from the Cambro-Silurian rocks (see Fig. 7). The Lower Palaeozoic rocks lie at first on top of, and are deformed together with the late Precambrian, while further south they lie on Precambrian basement. Therefore, the nappe front is actually the line where the Vangsås Formation is removed from the hangingwall of the Osen–Røa thrust, that is, the Vangsås Formation hangingwall cutoff line.

The base of the Osen–Røa thrust sheet is exposed in several hillside and Lake Mjøsa shoreline outcrops. At Furuset, 1 km north of Gjøvik (Fig. 7), the Ekre shale at the base of the thrust sheet can be seen to be overthrusting a footwall of younger, folded, weakly deformed sandstone and Cambrian shales. The sandstone is not proven to be Vangsås Formation; however it most probably represents a transgressive littoral facies of the Holmia stage and is the younger on-lap equivalent of the Ringsaker quartzite in the Vangsås Formation (anonymous reviewer pers. comm.). The Furuset section is important as it displays what must be the most southerly extent of the Sparagmite facies. Everywhere to the south of Furuset the Cambrian Alum shales are the only autochthonous sediments found along the traditional nappe front and they rest directly on Precambrian basement gneisses. The presence of the Vangsås Formation or its onlap equivalent in the footwall of the Osen–Røa thrust in the Gjøvik area indicates that the absence of the Vangsås Formation in the Osen–Røa thrust sheet to the south is due to ramping of the Osen–Røa thrust.

Further west of Furuset at Fluberg (G.R. 688 392) the Osen–Røa thrust sheet can be seen thrust over Precambrian basement in the surrounding hillsides (Holtendahl 1915). This is illustrated in Fig. 7. At this point, a road cut exposes the Vangsås Formation of the Osen–Røa thrust sheet, which is thrust over the Alum Shales. The thrust plane has therefore cut up section laterally between Furuset and Furuberget, eliminating the Ekre Shale from the hangingwall.

The second flat

The Osen–Røa thrust lies at the base of the Ekre Shale, or Moelv Tillite. The late Precambrian rocks

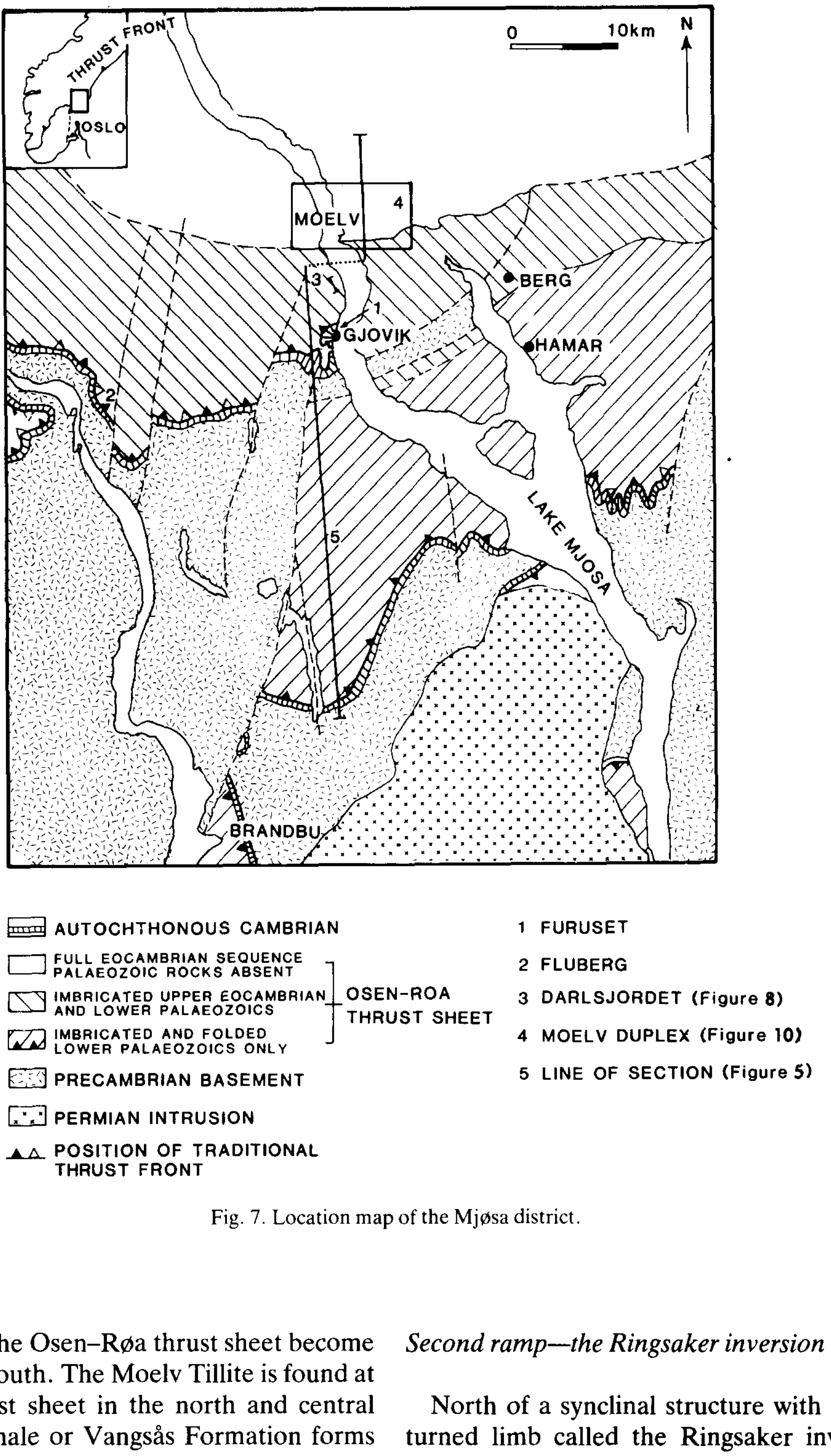

Fig. 7. Location map of the Mjøsa district.

found at the base of the Osen–Røa thrust sheet become younger toward the south. The Moelv Tillite is found at the base of the thrust sheet in the north and central areas, whilst Ekre Shale or Vangsås Formation forms the base in the south. The thrust sheet is internally deformed by hinterland-dipping imbricate faults, associated folds and occasionally by back-thrusting and thrust-wedging. The deformation style within the thrust sheet is well displayed at Darlsjordet where a section along the main Gjøvik–Lillehammer road contains thirteen imbricate repetitions of Vangsås Formation and Cambrian shales in 2 km (see Fig. 8). The spacing of the imbricates thrusts along the section averages one every 165 m, with displacements along thrust planes up to 200 m. The northern part of the section shows that some thrust planes within the thrust sheet have been oversteepened by subsequent foreland-progressing imbrication.

Second ramp—the Ringsaker inversion

North of a synclinal structure with a northern overturned limb called the Ringsaker inversion an extra 2–2.5 km vertical thickness of older late Precambrian clastics abruptly appear in the Osen–Røa thrust sheet. These features can be related to the presence of a major hangingwall ramp, that cuts down section northwards to lie at the base of the Brøttum Formation as the third flat. This hangingwall ramp is a very persistent feature in the Sparagmite region (see Fig. 2).

Hangingwall anticlines are geometrically necessary features above footwall ramps (Rich 1934, Gretener 1972), whereas hangingwall monoclines are produced where a hangingwall ramp rests on a footwall flat (see Fig. 3). By applying this model to the Mjøsa area, the Ringsaker inversion is a hangingwall ramp/footwall-flat monocline that has later been overturned during trans-

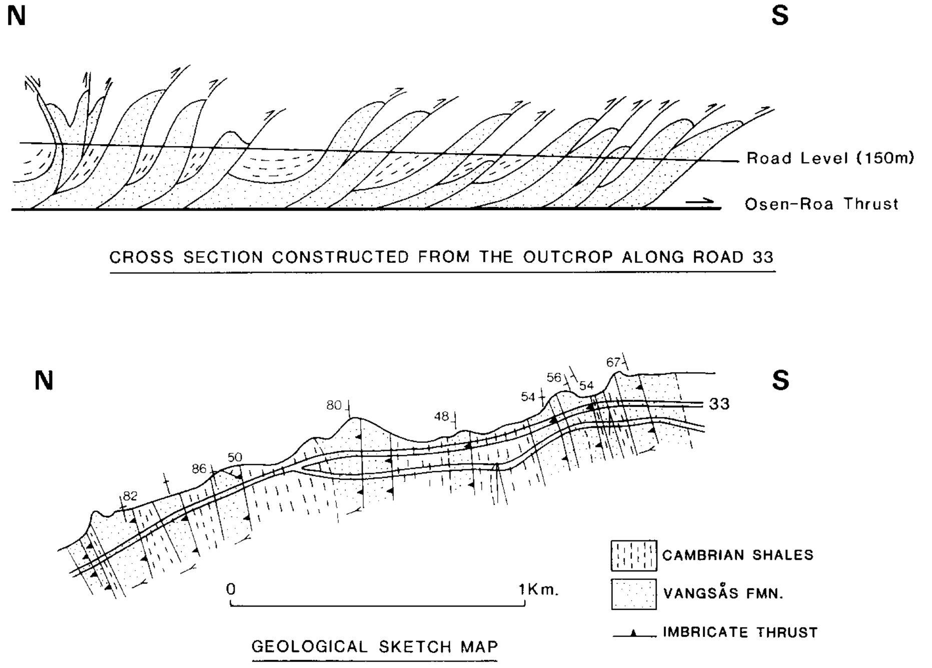

Fig. 8. Details of the section along road 33, Darlsjordet, displaying imbrication of Vangsås Formation and Cambrian shales in the area of the second hangingwall flat (see Fig. 7 for location).

port. The Cambrian shales are known to extend as a footwall flat at least as far as their exposure in the basement windows in the north of the Sparagmite region (1 : 1,000,000 map, Holtedahl & Dons 1960). Hence the hangingwall ramp has a corresponding footwall ramp north of the basement windows and has travelled at least 130 km over a footwall flat. By moving from a footwall ramp onto a footwall flat, the hangingwall ramp has been rotated to a sub-horizontal orientation. The vertical section has decreased by approximately 2–2.5 km because of the ramp, and this has caused a major frontal-ramp monocline to develop.

Third flat

In the Ringsaker–Lillehammer area, the full sequence of late Precambrian rocks is present (see Fig. 4). At the base of the Osen–Røa thrust sheet, the 2000 m thick turbidite sequence, the Brøttum Formation, is succeeded by the Biri Limestone, Biskopas Conglomerate, Ring Formation, Moelv Tillite, Ekre Shale and Vangsås Formation. The only completely shaly unit is the Ekre Shale (40 m thick), although other formations may contain some shale units that act as minor detachment horizons (Nystuen 1983).

Deformation in the Brøttum Formation differs from that found in the imbricated rocks south of the Ringsaker inversion, as it is deformed by tight folds, thrusts and thrust wedges (see Fig. 9). Thrusts are of secondary importance to buckle folds. These folds range from broad open folds of Class 1b (Ramsay 1967) with interlimb angles up to 120°, to tight angular folds with interlimb angles down to 45° that display the thickened hinges and thinned limbs of Class 2 folds (Ramsay 1967). Thrust wedging is a very important shortening mechanism in these beds, and may locally produce up to 50% contraction along a single bed. Pencil cleavage is sometimes strongly developed within the Brøttum Formation. Long thin pencils that indicate intense cleavage (Reks & Gray 1982) are formed by the intersection of a bedding parallel cleavage and a hinterland- or foreland-dipping spaced cleavage.

A CROSS-SECTION THROUGH THE LILLEHAMMER–GJØVIK AREA

The following structural features of the Lillehammer–Gjøvik area have to be considered when constructing a cross-section through the area (see Fig. 5). (1) The rocks at the base of the Osen–Røa thrust sheet become progressively younger southward. (2) The disappearance of the Brøttum and Biri Formations to the south is too rapid to be sedimentary, and coincides with the line of the Ringsaker inversion. (3) The disappearance of the Vangsås Formation in the hangingwall north of Gjøvik is also achieved over a short distance, and this cannot be due to sedimentary thinning because the Vangsås Formation is present in the footwall of this area (Bjørlykke 1979). (4) The extent of the autochthonous Cambrian shales in the footwall must correspond to a hangingwall flat of Cambrian shales in the Osen–Røa thrust sheet. The only known hangingwall flat of Cambrian shales is in the Oslo region, which must therefore form the leading edge of the Osen–Røa thrust sheet (formerly called the Oslo thrust sheet by Oftedahl 1943). (5) The Moelv area has been the subject of much discussion concerning the recognition and importance of tectonic units. Vogt (1953) described the geology on both sides of Mjøsa at Moelv–Biri (see Fig. 10) and introduced the terms Biri

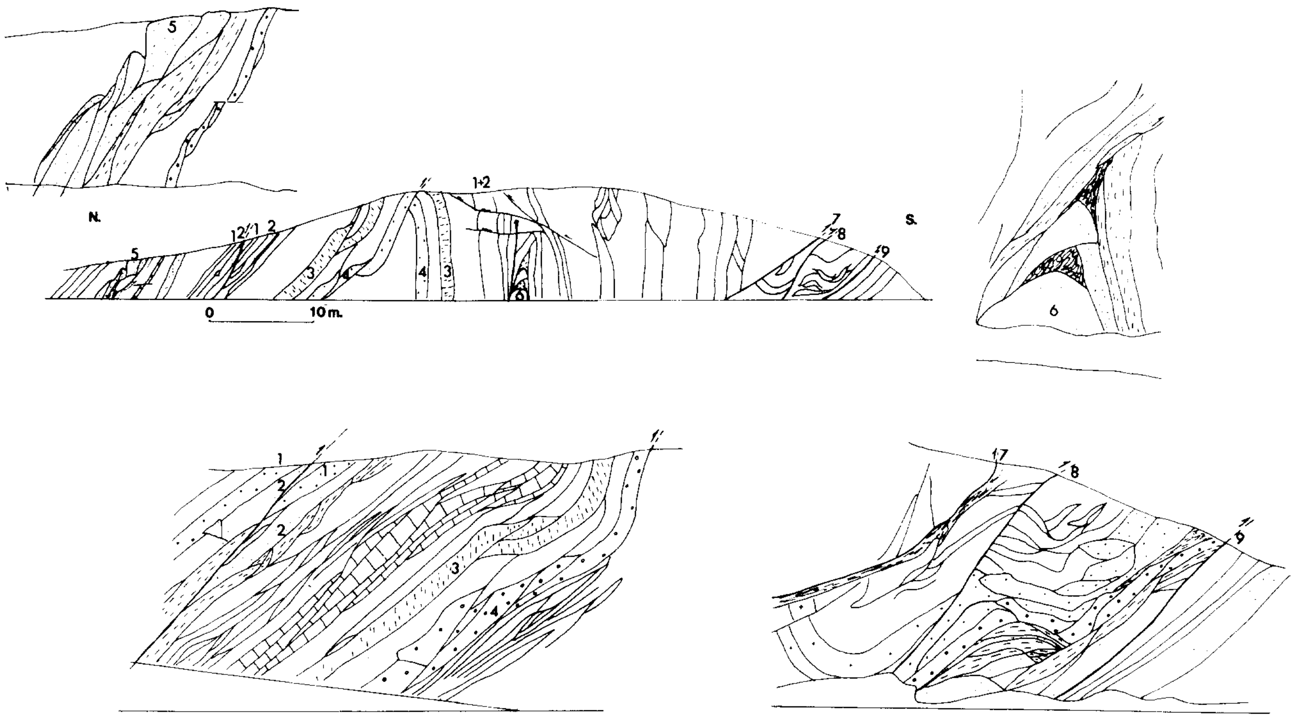

Fig. 9. Typical folding and thrust wedging in the Brottum Formation, road E6, Delhi (G.R. 842 658).

nappe and Moelv window for what he recognized as an allochthonous and autochthonous series, respectively. The section drawn by Vogt (1953) through the Moelv window displays the geometry of a duplex. Imbricate thrusts repeat the Ring–Vangsås Formations in the window, with a floor thrust that probably lies at the base of the Ring Formation. The Biri Formation and higher units have been thrust over the top of the imbricate slices, forming the roof thrust.

The eastern closure of the window (Vogt 1953) is conjectural (Fig. 10), and possibly incorrect. Recent mapping by Høy & Bjørlykke (1980) indicates that the Biri thrust passes eastwards into an imbricate fan and perhaps more complex thrust geometries. It is possible that the erosion level has cut down to the east and south to expose the middle of the duplex, or the duplex roof in this area may be difficult to detect because it has been imbricated by the underlying thrusts (leaky roof duplex). The small stratigraphic separation between the hanging- and footwalls of the Biri thrust (maximum of 750 m) indicates that the Biri thrust is perhaps only of local significance.

The structural features discussed above have been incorporated into a cross-section through the Mjøsa area (see Fig. 5). Although this section has been balanced, it is not a viable section because it contains two potential sources of error (Elliott 1983). Firstly, the line of section in the north passes through Moelv on the eastern side of

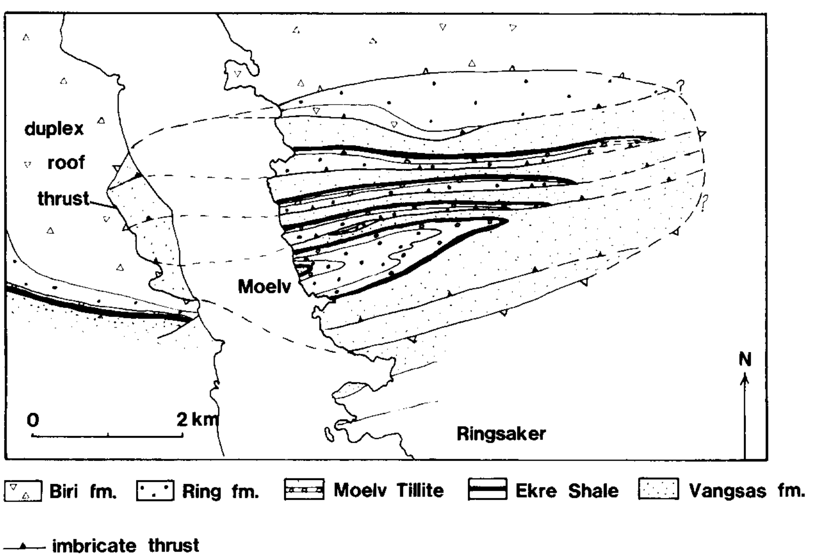

Fig. 10. Geological map of the Moelv duplex window (based on Vogt 1953) (see Fig. 7 for location).

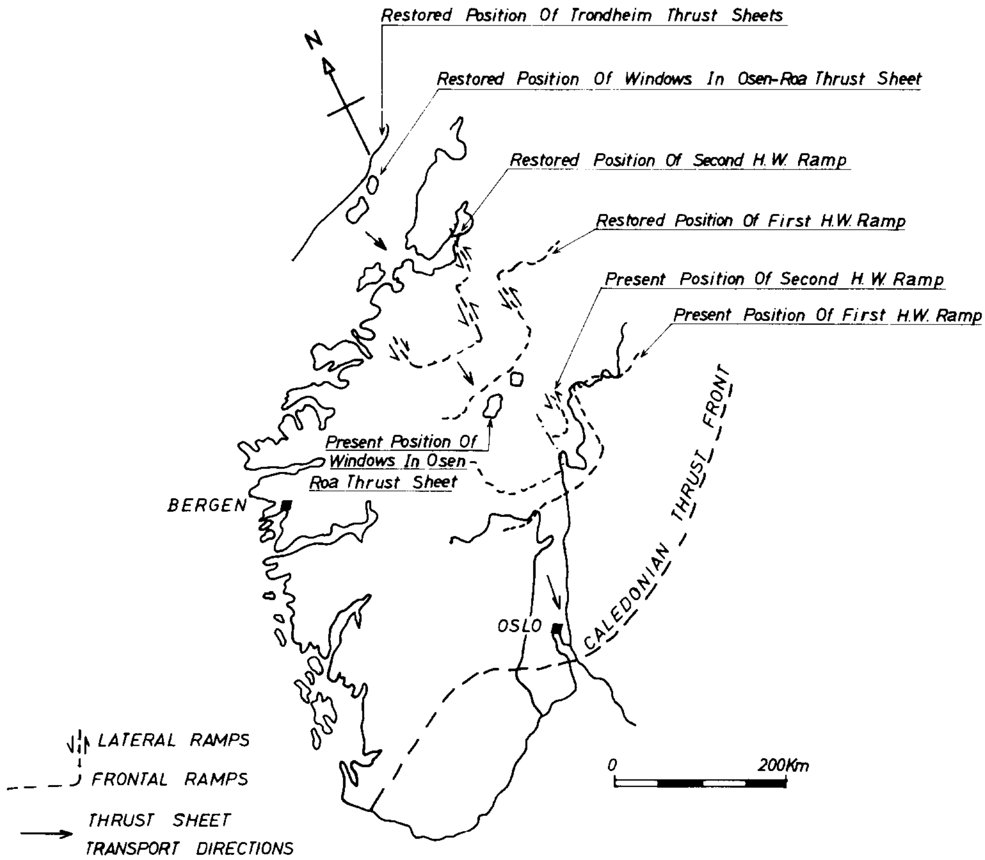

Fig. 11. Palinspastic restoration of the hangingwall ramps in the Osen–Røa thrust sheet.

the lake (see Fig. 1). It then has to be projected along strike on an offset onto the west side of Mjøsa so that the section does not continue in water. However, this does not affect the amount of shortening displayed in the section, nor the interpretation, because the structures on both sides of the lake are similar and the distance down dip from the Ringsaker inversion can be kept constant in the projection along strike. Secondly, the southern part of the section is drawn through the Cambro-Silurian rocks between Gjøvik and Eina, mapped by Skjeseth (1963). Although this work quite accurately shows the folding in the Silurian rocks, the scale is too small to reflect the deformation within the Cambrian–mid-Ordovician rocks. Imbrication marked by the Stein limestone is intense, and considering the deformation seen in the northern Oslo region in North Hadeland (Fig. 6), it is likely that the Cambro-Silurian rocks have shortened by at least 50%. This will not be reflected in a section drawn through Skjeseth's map (1963), but no other map is available.

The section from Lundehogda to Eina explains the structural features of the Mjøsa area listed above by showing the trajectory of the Osen–Røa thrust plane as a series of ramps and flats. The Brøttum–Ring Formations are cut out by a hangingwall ramp just north of the Ringsaker inversion. This large monoclinal fold has undergone deformation, probably during transport, so that it has been modified by structures of local significance which include the Moelv duplex and the Biri nappe. South of the Ringsaker inversion, the Osen–Røa thrust forms a flat, at first lying below the Moelv Tillite, which is then cut out by a minor ramp so that the thrust lies at the base of the Ekre Shale. This now much thinned late Precambrian to Lower Palaeozoic sequence is imbricated, a style which is continued into the Oslo region. Just north of Gjøvik the Osen–Røa thrust ramps through the Ekre Shale and Vangsås Formation. It then forms a flat so that the thrust lies within the Alum Shales and continues to do so through the Oslo region. The autochthonous Alum Shales in the footwall must, therefore, extend under the Osen–Røa thrust sheet, towards the hinterland, by a distance equal to the amount of shortening in hangingwall Cambro-Silurian rocks; that is from undeformed foreland in Langesund–Skein to the hangingwall ramp which cuts out the Vangsås Formation at Gjøvik (see Fig. 5). The palinspastic reconstruction using the relationships described above can be seen in Fig. 11. The pinned sequence must eventually include late Precambrian rocks which form the footwall cutoffs to the hangingwall ramps in the Vangsås and Brøttum–Ring Formations of Figs. 2 and 5. These ramps will be separated by the undeformed distances of the Ekre Shale and Moelv Tillite flats. The footwall ramps are not seen because they are either buried under the trailing edge of the Osen–Røa thrust sheet or under the Trondheim thrust sheets.

The minimum displacement undergone by the Vangsås hangingwall cutoff from its footwall cutoff can be estimated by using the basement windows at the northern end of the Sparagmite region. Autochthonous

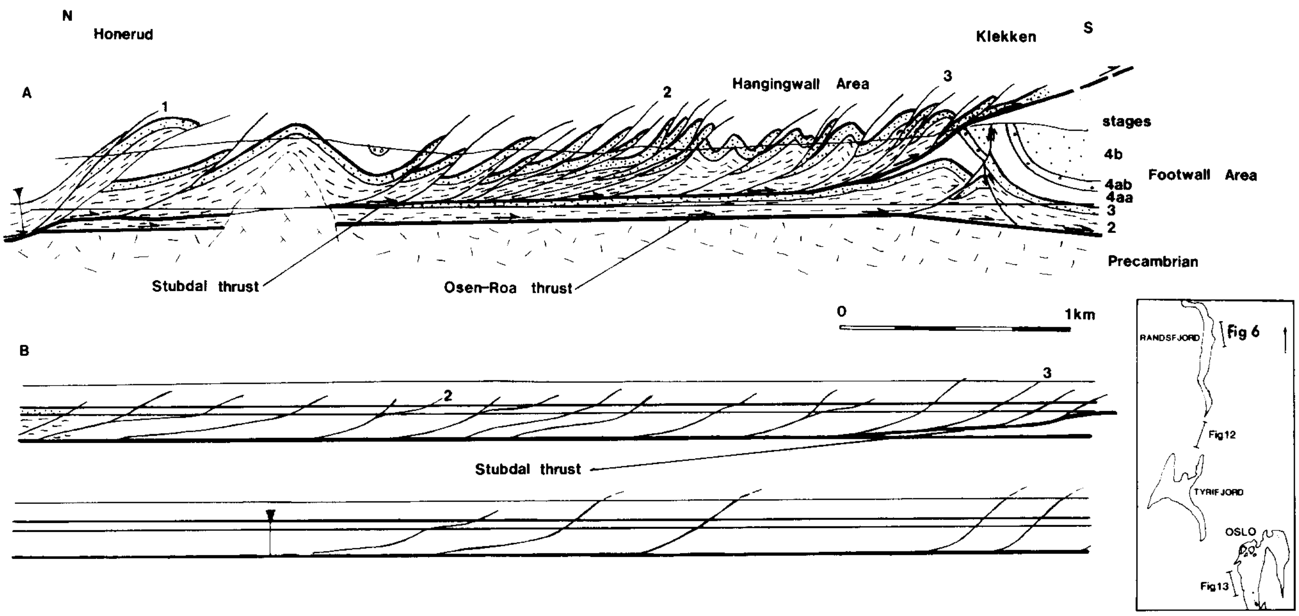

Fig. 12. Cross-section through north Ringerike. 2, Cambrian; 3, Lower Ordovician; 4aa–4b, Mid Ordovician. Note change in deformation style south of Stubdal fault. Inset displays locations of sections in Figs. 6, 12 and 13.

Vangsås Formation and Moelv Tillite can be seen in places around the Atnasjoen window (see Fig. 2), 130 km north of the hangingwall cutoff of Vangsås Formation at Gjøvik. This gives a minimum displacement of 130 km.

BALANCED CROSS-SECTION METHOD OF LOCATING THE VANGSÅS FORMATION FOOTWALL CUTOFF

Oftedahl (1943), referring to the deformed Oslo region sequence, realized that: "If we want to know how far the northern part of this fold nappe has moved, we can grasp the northern part of the sequence at Mjøsa and keep it fixed at Langesund". He made two assumptions: (1) that the sequence was shortened by 50% (Strand 1960 also assumed this figure) and (2) that there was no significant overthrusting at the leading edge of the thrust sheet in Langesund. This led him to estimate 150 km transport for the Mjøsa area. The same approach is used here, except that the variations in internal shortening of the Oslo region are more accurately determined by the use of balanced cross-sections constructed from the 1:5,000 maps of Morley (1983). Recently Ramberg & Bockelie (1981) and Bockelie & Nystuen (1984) have suggested that the Osen–Røa thrust continues into the Langesund area and can be seen to ramp in that area. If this is true, then an unknown amount of displacement has occurred at the thrust front, so that balanced cross-sections cannot be accurately pinned and undeformed from the Langesund area. The ramp interpretation is probably not valid, for two main reasons. (1) The sections drawn by Ramberg & Bockelie (1981) and Bockelie & Nystuen (1984) show older Cambrian rocks in the footwall overthrust by younger Ordovician rocks. Thrusting usually causes stratigraphic repetition, not omission, and emplaces older rocks on top of younger rocks. Hence the ramping thrust explanation for the absent Upper Cambrian and Upper Orthoceras Limestone beds in the Langesund area is probably incorrect. The traditional idea of non-deposition (the Langesund hiatus) is more likely, unless an actual fault plane can be proven. If there is a fault, it is most likely to be a normal fault. (2) The amount of internal strain within the Osen–Røa thrust sheet decreases toward the south of the Oslo region (Figs. 6, 12, 13, 14 and Table 1). The deformation therefore appears to be dying out above a detachment that is losing displacement, and is not about to ramp to the surface.

A prediction of this hypothesis is that the Osen–Røa detachment dies out to zero displacement within the Alum Shales. It is therefore possible to unstrain the Cambro-Silurian rocks of the Oslo region from a pin line in the Langesund area, and get an accurate figure for the amount of displacement undergone by the Mjøsa area. Figures 11–13 show several balanced cross-sections through the Oslo region. Table 1 shows the amount of shortening estimated by this method for districts within this area. Integration of the strain data in a NWW–SSE direction through the region gives an estimate of 135 km internal shortening. The north end of the Mjøsa area has therefore also undergone 135 km transport. It should be

Table 1. Variations in internal shortening for the Osen–Røa thrust sheet in the Oslo region

Area	*South* Eiker	Asker-Oslo	*North* N. Ringerike	Hadeland
Average % shortening				
Lower Ordovician	15%	35%	50%	60%
Lower Silurian	15%	27%	?	29%

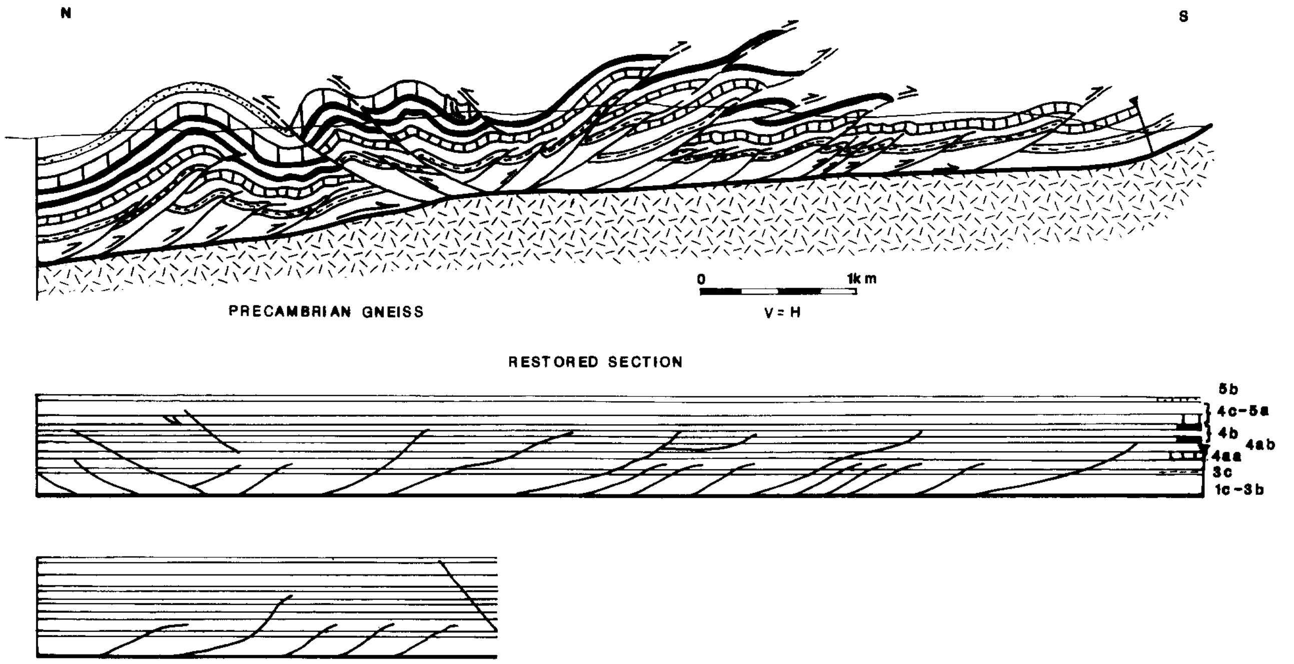

Fig. 13. Cross-section through southern Asker, of the deformed Cambro-Ordovician sequence. 2a–3b, Cambrian–Lowermost Ordovician, Alum Shales; 3b–3c, lower Ordovician shales and Orthoceras Limestone; 4aa, Upper Didymograptus shales; 4ab, Ampyx Limestone; 4ba–4bd, Chasmops series; 4c, Tretraspis series; 4d, Isotelus series; 5a–b, Upper Ordovician shales, sandstones and limestones.

noted that the decrease in internal shortening upwards within the Cambro-Silurian sequence must be compensated by an increase in overthrusting along one or a series of upper detachments (Morley 1983).

CONCLUSIONS

The Osen–Røa thrust sheet cuts up section by a series of ramps and flats to lie within the Cambro-Silurian sequence of the Oslo region, so that the Osen–Røa thrust sheet continues into the Oslo region. The Caledonian nappe front (at Mjøsa) is therefore a meaningless term and it should actually be called the Vangsås Formation hangingwall cutoff. The term thrust front should be applied to the limit of deformation in the Oslo region south of deformed rocks at Holmstrand, and north of undeformed rocks at Langesund as recognized by

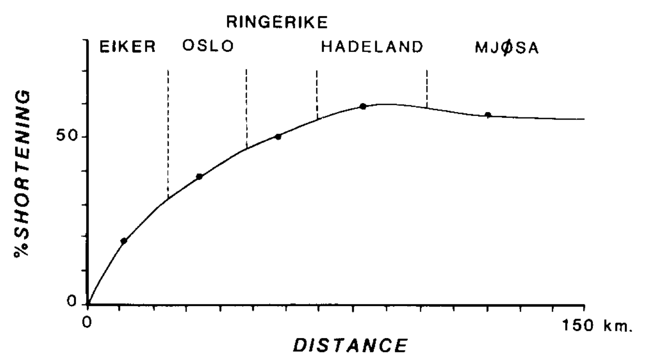

Fig. 14. Graph of variations in average strain for the Ordovician rocks of the Osen–Røa thrust sheet, Oslo region. The graph corresponds to a N–S trending line through Eiker in the south to Mjøsa in the north.

Oftedahl (1943) (see Fig. 1). Although the existence of Caledonian deformation in the Oslo region has been recognized since the 19th century (e.g. Brøgger 1882), the limit of Caledonian deformation has, on almost all published maps, been incorrectly located at the "Caledonian nappe front" instead of at the thrust front north of Langesund.

Balanced cross-sections pinned in the Langesund area suggest that the northernmost extent of the Oslo region has been shortened by 135 km. Hence Palinspastic restorations restore the southern Mjøsa area 135 km to the NNW. A totally independent check on these figures and the position of the deformation front comes from restoring the cutoff points of the hanging- and footwall ramps in the Vangsås Formation. This requires at least 130 km of displacement to the NNW to restore the hangingwall ramp past the most internal footwall exposure of Vangsås Formation. The 230 km estimate of transport by Kumpulainen & Nystuen (1984) is, therefore, an overestimate.

Although the Osen–Røa thrust probably ended as a blind detachment at the leading edge, the internal deformation of this very long, thin thrust sheet has caused considerable overthrusting of the more internal portions to occur. The thrust sheet is currently 280 km long and has an undeformed stratigraphic thickness of about 2–4 km. The trailing edge of the thrust sheet (which has accumulated a large amount of slip because of the internal deformation) has probably overthrust autochthonous late Precambrian rocks by 275 km. Even the northern end of the Oslo region, formerly called para-autochthonous and positioned south of the thrust front, has travelled a minimum distance of 130 km. Hence the conclusions drawn here support Oftedahl's (1943) allochthonous model for the Sparagmite region, and the extension of the Osen–Røa thrust sheet and Caledonian thrust front into the Oslo region (as also proposed by Høy & Bjørlykke 1980).

The use of the term para-autochthonous in the Sparagmite region is misleading because the Osen–Røa thrust sheet displays about 275 km displacement at its trailing edge and zero displacement at its leading edge. According to the common use of the terms above, at some arbitrary point in the Osen–Røa thrust sheet it should cease being called allochthonous and become para-autochthonous. This point has usually been taken at the Caledonian nappe front, hence the Oslo region has been described as para-autochthonous while the Sparagmite region is autochthonous. This gives the impression that the two regions are tectonically separate units which they are not. It also gives the impression that the Mjøsa area has not been displaced very far when it has actually moved at least 130 km. Hence the use of para-autochthonous to describe the Cambro-Silurian of the Oslo region (e.g. Bockelie & Nystuen 1984) should be discontinued.

Acknowledgements—I would like to thank Jake Hossack and Bob Standley for their help and guidance and City of London Polytechnic for funding the fieldwork. I am grateful to an anonymous reviewer for a detailed and very helpful review, and also to John Grocott and Ron Nelson for reviewing the manuscript.

REFERENCES

Bjørlykke, A. 1979. Gjøvik og Dokka (Description to the geological maps 1819 I and 1816 IV, Scale 1:50,000). *Norges geol. Unders.* **344**, 48 (two maps).

Bjørlykke, A. & Skålvoll, H. 1979. Bruflat, berggrunnsgeologisk kart 1719 I, M. 1:50,000. *Norges geol. Unders.*

Bjørlykke, K., Englund, T. O. & Kirkhusmo, L. A. 1967. Latest Precambrian and Eocambrian stratigraphy of Norway. *Norges geol. Unders.* **251**, 5–17.

Bockelie, J. F. & Nystuen, J. P. 1984. The southern part of the Scandinavian Caledonides. In: *The Caledonide Orogen* (edited by Gee, D. G. & Sturt, B. A.). Wiley, New York.

Brøgger, W. C. 1882. Die silurischen Etagen 2 und 3 im Kristianiagebiet. Universitats programm fur 2. Sen. 1882. Christiania, Oslo, 376.

Butler, R. W. H. 1982. The terminology of structures in thrust belts. *J. Struct. Geol.* **4**, 239–245.

Elliott, D. 1983. The construction of balanced cross-sections. *J. Struct. Geol.* **5**, 101.

Gretener, P. E. 1972. Thoughts on overthrust faulting in layered sequences. *Bull. Can. Petrol. Geol.* **20**, 583–607.

Holmsen, P. & Oftedahl, C. 1956. Ytre Rendal og Storelv. *Norges geol. Unders.* **194**, 173.

Holtedahl, O. 1915. Iagttagelser over fjeldbygningen omkring Randsfjordens nordende. *Norges geol. Unders.* **75**(1), 32.

Holtedahl, O. & Dons, J. A. 1960. Geologisk Kart over Norge. 1:1,000,000 Oslo. *Norges geol. Unders.*

Hossack, J. R. 1979. The use of balanced cross-sections in the calculation of orogenic contraction: a review. *J. geol. Soc. Lond.* **136**, 705–711.

Høy, T. & Bjørlykke, A. 1980. Hamar, berggrunnsgeologisk kart 1916 IV, M. 1:50,000. *Norges geol. Unders.*

Kumpulainen, R. & Nystuen, J. P. 1984. Late Proterozoic basin evolution and sedimentation in the westernmost part of Baltoscandia. In: *The Caledonide Orogen* (edited by Gee, D. G. & Sturt, B. A.). Wiley, New York.

Morley, C. K. 1983. The structural geology of the southern Norwegian Caledonides in the Oslo graben and Sparagmite region. Unpublished Ph.D. thesis, City of London Polytechnic.

Nystuen, J. P. 1981. The late Precambrian "Sparagmites" of southern Norway: a major Caledonian allochthon—the Osen–Røa Nappe Complex. *Am. J. Sci.* **281**, 69–94.

Nystuen, J. P. 1983. Nappe and thrust structures in the Sparagmite region, southern Norway. *Norges geol. Unders.* **380**, 67–83.

Oftedahl, C. 1943. Oerskyvininger i den norsk fjellkjede. *Naturen*, Oslo **5**, 243–250.

Oftedahl, C. 1954a. Dekketektonikken i den nordlige del av det Ostlandske Sparagmittomrade. *Norges geol. Unders.* **188**, 5–20.

Oftedahl, C. 1954b. Skyvedekken i det sydnorsk sparagmittomrade. *Geol. Fören. Stock. Förh.* **76**, 156–162.

Prost, A. E. 1977. Repartition et évolution géodynamique des externides Caledoniennes Scandanavies. *Revue Géogr. phys. Géol. dyn.* **19**, 431–432.

Ramsay, J. G. 1967. *Folding and Fracturing of Rocks.* McGraw-Hill, New York.

Ramberg, I. B. & Bockelie, J. F. 1981. Geology and tectonics around Oslo. Guide to excursion B-4. 4th International Conference on Basement Tectonics, Oslo, August, 1981. *Nytt fr Oslofeltgrupper* **7**, 81–100.

Reks, I. J. & Gray, D. R. 1982. Pencil cleavage and strain in weakly deformed mudstone and stilstone. *J. Struct. Geol.* **4**, 161–176.

Rich, J. L. 1934. Mechanics of low-angled overthrust faulting as illustrated by Cumberland thrust block Virginia, Kentucky and Tennessee. *Bull. Am. Ass. Petrol. Geol.* **18**, 1584–1596.

Schiotz, O. E. 1902. Den Sydostlige del av Sparagmit–Kvartsfjeldet i Norge. *Norges geol. Unders.* **35**, 131.

Skjeseth, S. 1963. Contributions to the geology of the Mjøsa District and the classical sparagmite area in southern Norway. *Norges geol. Unders.* **220**, 1–126.

Strand, T. 1960. The pre-Devonian rocks and structures in the region of Caledonian deformation. In: *Geology of Norway* (edited by Holtedahl, O.). *Norges geol. Unders.* **208**, 170–284.

Vogt, T. 1953. Biri-dekket og Moelv-vinduet ved Mjøsa. *Kgl. Norske Vidensk. Selsk. Forh.* **25**, 131–138.