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Lateral and vertical changes of deformation style in the Osen–Røa thrust sheet, Oslo Region

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Abstract—Changes in deformation style and amounts of shortening in the Osen–Røa thrust sheet of the Oslo Region occur vertically and laterally approaching the thrust front in the south. Deformation in the Cambro–Middle Ordovician sequence passes laterally from closely spaced imbricates in the north (50–60% shortening), through triangle, pop-up and imbricate zones toward the south (20–37% shortening) to widely spaced zones of deformation (up to 20% shortening) approaching the thrust front. Changes in deformation style are attributed to changing boundary conditions across the Klekken thrust, declining end-of-orogenic forces and an increase in thickness of competent units in the Ordovician rocks to the south. Vertical changes in deformation style are attributed to the increasing percentage of competent units upward in the Cambro–Silurian sedimentary rocks. In the north, the accompanying decrease in shortening upwards requires a structurally necessary upper detachment horizon to separate folded late Middle Ordovician–Silurian sediments from imbricated early Cambro–Middle Ordovician sediments below; while southward in the Oslo area the upper detachment needs to be placed between Silurian and Cambro–Ordovician units. Finally, in Eiker, with less than 20% shortening, the whole Cambro–Silurian sequence appears to have deformed as a single unit. In the northern Oslo Region, the upper detachment probably has a backthrust sense of motion above an imbricate stack (passive roof duplex). Further south the upper detachment is probably directed toward the foreland.

INTRODUCTION

THIS PAPER describes the lateral and vertical changes in shortening and deformation style displayed by the Osen–Røa thrust sheet. These changes are described along the regional dip direction of the thrust sheet, approaching the thrust front of the Southern Norwegian Caledonides in the Oslo Region. The area studied in the Oslo Region is unique in the Scandinavian Caledonides because only here can rocks deformed during the Caledonian orogeny be traced laterally into undeformed foreland (Oftedahl 1943, Hossack *et al.* 1985, Hossack & Cooper 1986).

The deformed Cambro–Silurian sedimentary sequence of the Osen–Røa thrust sheet has been split into isolated areas and preserved between Permian intrusive igneous rocks emplaced during the formation of the Oslo graben (Strand & Kulling 1972, fig. 1). Maps of the Asker–Baerum–Oslo area have been made by Brøgger (1882, 1890), Bockelie in Bryhni *et al.* (1981) and by many unpublished Scandinavian University projects. The Langesund–Eiker area has been mapped by Kiaer (1908), the Ringerike area by Kiaer (1908), Owen (1977) and Harper & Owen (1983), the Hadeland area by Holtedahl & Schetelig (1923) and Owen (1977, 1978) and the Lake Mjøsa area by Skjeseth (1963) and Høy & Bjørlykke (1980). Mapping by Morley (1983) at 1:5000 and 1:12,000 of several of these Cambro–Silurian areas (Eiker, Asker–Baerum, north Ringerike and north Hadeland) took place during 1981 and 1982. In addition, regional traverses were conducted through areas previously mapped by other workers. These included Langesund–Skien and south Ringerike, South Hadeland and South Mjøsa. This allowed a regional cross-section to be constructed through the Oslo Region. The most continuous string of Cambro–Silurian rocks were joined up in a NNW–SSE direction (Figs. 1 and 2), parallel to the transport direction of the Osen–Røa thrust sheet, which is assumed to be perpendicular to the strike of fold hinges and imbricate thrust faults (Fig. 3). Poles to bedding (Fig. 4) are assumed to be aligned parallel to the transport direction (NNW–SSE). The most common sense of thrusting in imbricate thrust zones is toward the SSE, but some less common NNW directed backthrusts are also present.

The regional cross-section (Fig. 2) begins in undeformed foreland to the south in Langesund–Skien, passes through weakly deformed rocks around Holmestrand and finally ends 150 km farther north in imbricated rocks of the Mjøsa district. This paper is largely concerned with the evolution of structures displayed in this cross-section.

GEOLOGICAL SETTING

The Lower Palaeozoic rocks of the Oslo Region, unlike most other outliers on the Precambrian Baltic Shield of Scandinavia, have been deformed along most of their length. Comparisons have been made between the Caledonide deformation in the Oslo Region and the Jura (Holtedahl *et al.* 1934, Strand & Kulling 1972), because both areas are deformed above a horizontal detachment that separates younger deformed rocks from older undeformed rocks. In the Oslo Region, the Lower Palaeozoic sequence has been folded and thrusted above a detachment zone in Cambrian shales and Precambrian basement that remained unaffected by Caledonian events. Oftedahl (1943), Høy & Bjørlykke (1980),

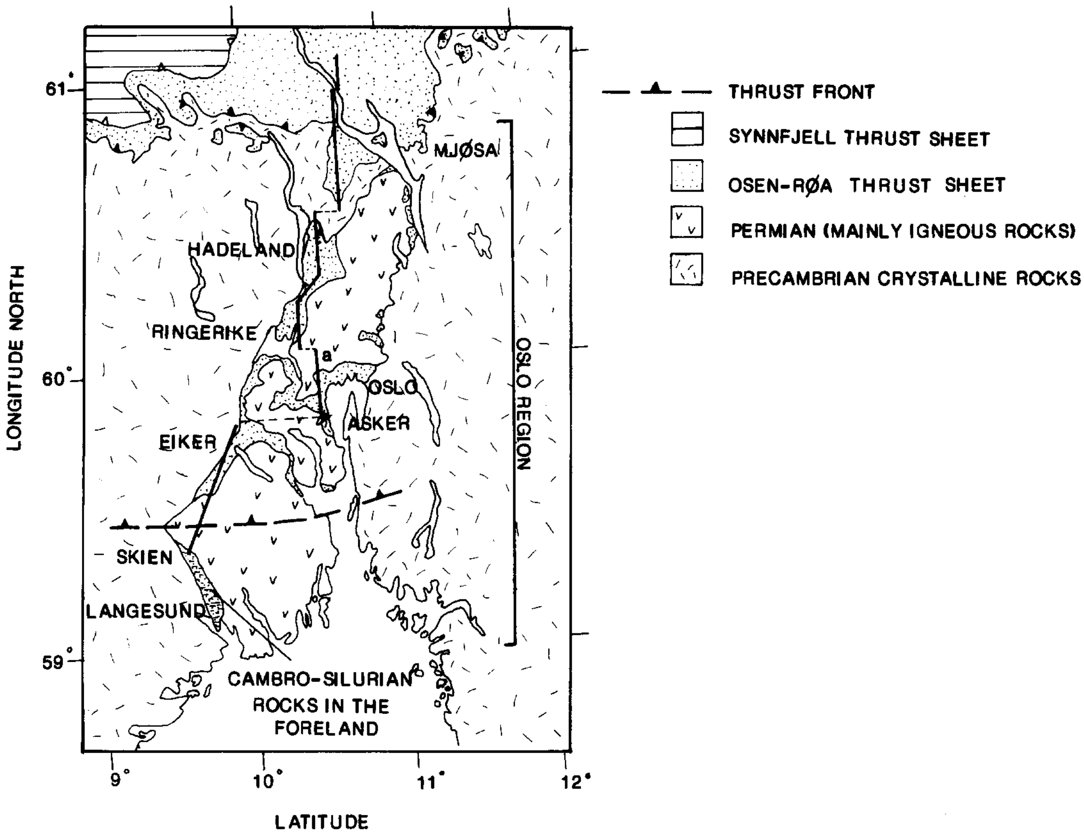

Fig. 1. Location map of the Osen–Røa sheet in the Oslo Region (after Bockelie & Nystuen 1984); a is line of section of Fig. 2. Areas of Cambro–Silurian rock correspond to areas of the Osen–Røa thrust sheet, except beyond the thrust front in the Langesund area.

Nystuen (1981), Hossack & Cooper (1986) and Morley (1986c) regard the detachment as the continuation of the Osen–Røa thrust of the Sparagmite region. Deformation probably occurred during the Upper Silurian (Hossack & Cooper 1986) or early Devonian, after deposition of the Ringerike Sandstone (Ludlow–Downtonian, Bockelie & Nystuen 1984).

The 2 km thick Lower Palaeozoic succession of the Oslo Region (Bockelie & Nystuen 1984) comprises thin shaly Middle and Upper Cambrian strata. The Ordovician is much thicker with a cyclic sequence of alternating shales and limestones. In the Upper Ordovician, sandstones, limestones and shales represent a shallowing sequence with tidal bars at the top (Brenchley & Newall 1975). This was followed by a Silurian transgression as the region went into deeper water. Though the Silurian has the shortest timespan of the Lower Palaeozoic systems it is the thickest and passes up from marine to continental beds in the Wenlock. Figure 5 displays the variations in Cambro–Silurian lithologies along the Oslo Region; it can be seen that the early Cambro–Middle Ordovician sequence is dominated by incompetent

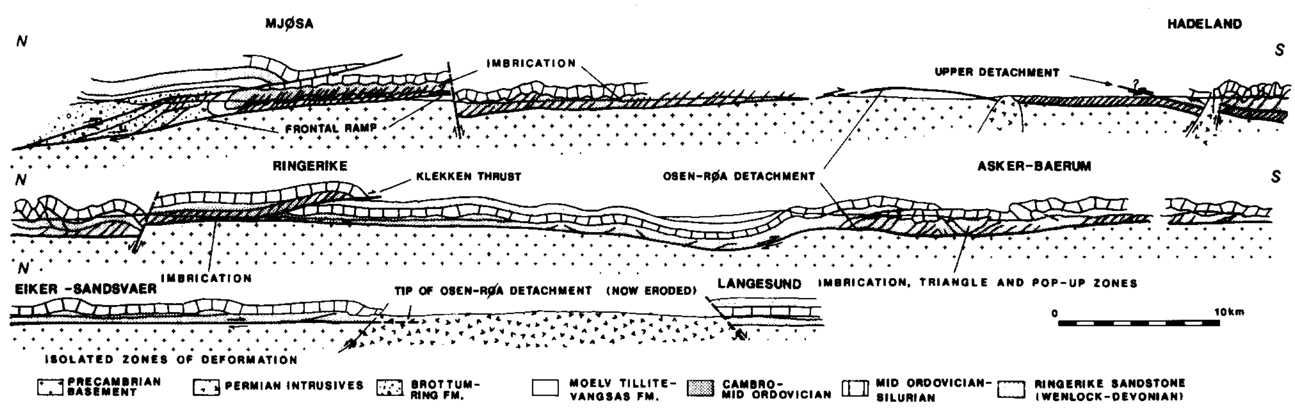

Fig. 2. Cross-section through the Oslo Region (see Fig. 1 for line of section), vertical = horizontal scale (after Morley 1986). Brottum–Ring Formation and Moelv Tillite–Vangsas Formation are late Precambrian clastic sequences of the Sparagmite region. 1 is the Klekken (or Stubdal) thrust, 2 and 3 are unnamed large second-order thrusts in Asker and Eiker. The scale is too large to represent the number of thrusts actually present in the Oslo Region. For detailed cross-sections, see Figs. 6, 7 and 8.

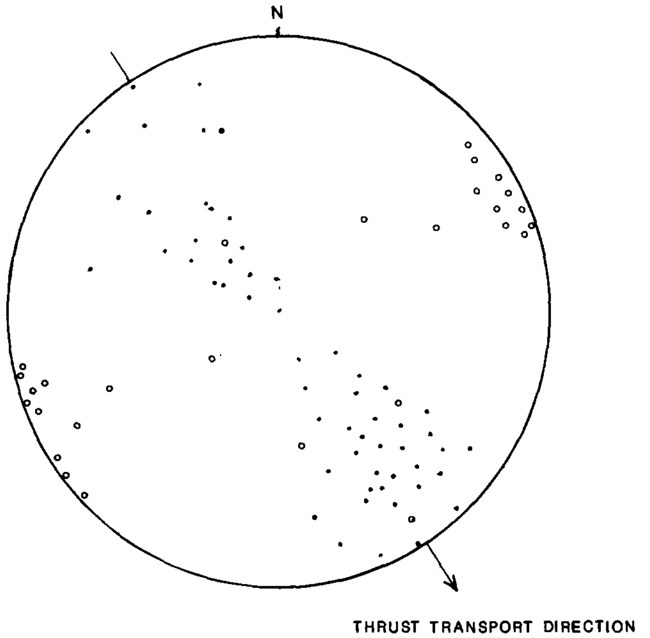

Fig. 3. Poles to minor thrusts (dots) and minor fold hinge lineations (circles) for north Hadeland and Asker.

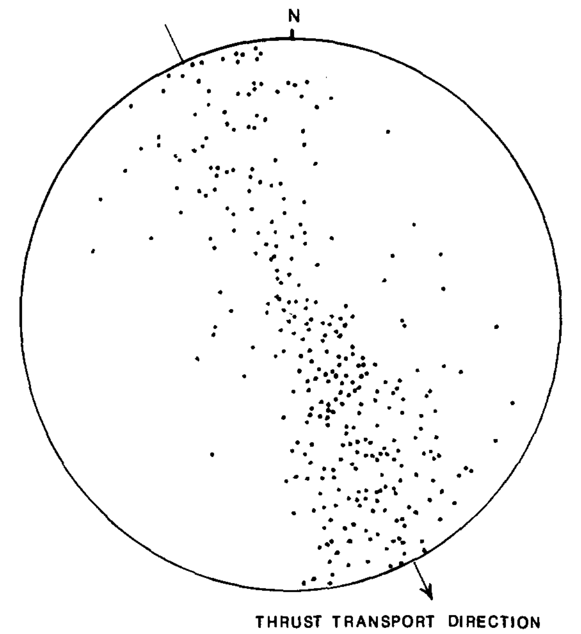

Fig. 4. Poles to bedding (326 poles) for north Hadeland and Asker.

units, whilst the late Middle Ordovician–Silurian sequence is thicker and dominated by competent units which increase in number upwards. The most important of these is the Ringerike Sandstone which caps the sequence and can be 500–1000 m thick (Bockelie & Nystuen 1984). The importance of stratigraphical control on deformation and increased shortening with depth in the Osen–Røa thrust sheet has been recognized (e.g. Strand 1960, Bockelie & Nystuen 1984), and considered specifically for the Asker–Baerum area by Morley (1986b).

The deformation of the Cambro–Middle Ordovician sequence in the northern areas of the Oslo Region is broadly characterized by the presence of numerous minor thrusts and associated folds, whilst broad buckle folds deform the Middle Ordovician–Silurian rocks above. These structures vary in dimensions within the region (see Table 1) but they generally reflect the decreasing amount of shortening both laterally to the south approaching the thrust front and vertically within the thrust sheet. For example, the dimensions and (vertical) displacements of second-order contraction faults decrease toward the south, whilst spacing between the faults increases (Table 1).

Folds can be divided into those formed in fold trains by active buckling, and isolated folds formed at the tips of propagating second-order faults, which give rise to footwall syncline–hangingwall anticline geometries. Buckle folds are more common higher in the stratigraphy, while tip-line or thrust-tip folds (e.g. Chapman & Williams 1984, 1985) are most common in the Cambrian to Middle Ordovician rocks. Typical dimensions for tip-line folds in early Ordovician rocks which appear on 1:12,000 scale maps are: wavelengths 30–352 m, amplitudes 20–250 m and interlimb angles between 40 and 140°. These dimensions contrast strongly with those for typical buckle folds in Silurian rocks which have wavelengths of 300–2000 m, amplitudes of 120–1000 m and interlimb angles between 70 and 150°.

Estimates of shortening in the Oslo Region

Balanced cross-sections through the Oslo Region have been constructed through several Cambro–Silurian

Table 1. Variations in selected structural parameters within the Oslo Region

	Area					
Area	Eiker	Oslo	N. Ringerike	Hadeland	S. Mjøsa	N. Mjøsa
2nd-order thrusts						
Average strike length	?	3 km	In excess of 2 km	In excess of 2 km	?	5 km
Average displacement	100 m	150 m	158 m	180 m	?	185 m
Average spacing strained	1000 m	280 m	180 m	160 m	150 m ?	165 m
unstrained	1150 m	400 m	360 m	330 m	305 m ?	375 m
Average % shortening (e)						
Lower Ordovician	15%	37%	50%	60%	55%	60%
Lower Silurian	15%	27%	?	29%	28%	(Eocambrian)

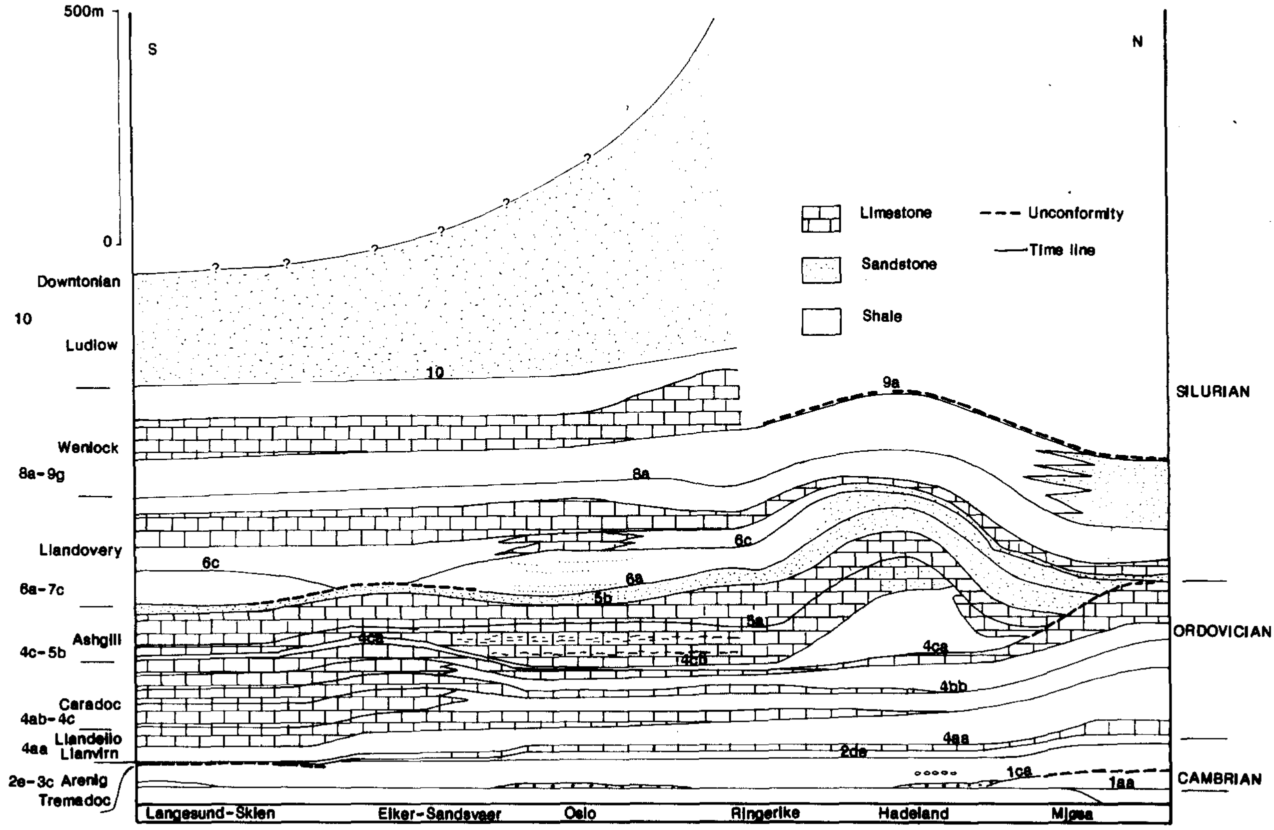

Fig. 5. Diagram illustrating N–S lithology changes in Cambro–Silurian rocks of the Oslo Region, compiled from Kiaer (1908), Størmer (1953, 1967), Owen (1977, 1978), Holtedahl & Schetelig (1923), Skjeseth (1963) and Henningsmoen (1960). 1a Lower Cambrian, 1c–2d Mid-Upper Cambrian, 2e–5b Ordovician, 6–10 Silurian. Sandstone lithology above line 10 is the Ringerike Sandstone.

areas using maps by Morley (1983) for Eiker, Asker, North Ringerike and North Hadeland, and maps by other authors for South Ringerike (Kiaer 1908, Owen 1977), South and Central Hadeland (Holtedah & Schetelig 1923, Owen 1977, 1978) and Mjøsa (Skjeseth 1963, Bjørlykke 1979, Bjørlykke & Skalvoll 1979, Høy & Bjørlykke 1980). Figures 6, 7 and 8 show examples of balanced cross-sections through Asker, Ringerike & Hadeland, with estimates of shortening presented in Table 1. The discrepancy between internal shortening of the Cambrian–Middle Ordovician and Middle Ordovician–Silurian units (Table 1) emphasises the importance of trying to avoid pinning sections in deformed areas. The practice of pinning on surface folds or along faults, without first being absolutely sure about the deformation style of the whole stratigraphic package, would clearly be inadvisable in areas similar to the Oslo region. It is, however, possible to pin the Osen–Røa section in the undeformed foreland of Langesund–Skien because the Osen–Røa thrust ends in a buried thrust front (Oftedahl 1943, Morley 1986c). From this pin line the whole Osen–Røa thrust sheet can be restored. This is the only place where it is possible to unstrain the whole Cambro–Silurian sequence together. Farther north in the Oslo Region it is possible to independently unstrain the upper or lower parts of the Cambrian–Silurian sequence from pin lines across which no flexural-slip has occurred. In this way, shortening has been calculated for the upper and lower sequences in the Osen–Røa thrust sheet for each area (Table 1).

Shortening in the Cambrian–Middle Ordovician sequence of Hadeland and North Ringerike calculated from balanced cross-sections is a fairly constant 50–60% and corresponds closely to the estimate of 50% shortening throughout the Oslo Region by Oftedahl (1943). The amount of shortening then declines for the next 80 km to the north of the undeformed Langesund–Skien area. Figure 9 is a graph of the average amount of shortening in the Lower Ordovician sequence for each district plotted against distance. The trend shows a steady decline in the amount of shortening toward the south after a fairly constant amount of shortening in the northern areas. In more detail, shortening declines markedly in the footwall of the Klekken thrust in Ringerike which has at least 5 km minimum horizontal displacement (first described in Stubdal by Størmer (1934), Harper & Owen (1983) and Morley (1983)) and south of a large imbricate thrust in Eikeren (see Fig. 2). In Ringerike, the Cambro–Middle Ordovician rocks in the hangingwall of the Klekken thrust are imbricated while in the footwall they are weakly deformed by folds and minor back- and fore-thrusts. Areas of deformed rock occur between essentially undeformed panels. Shortening decreases from about 50% in the hangingwall to less than 20% in the footwall. Passing further south into the Oslo area, the intensity of deformation increases again. An approxi-

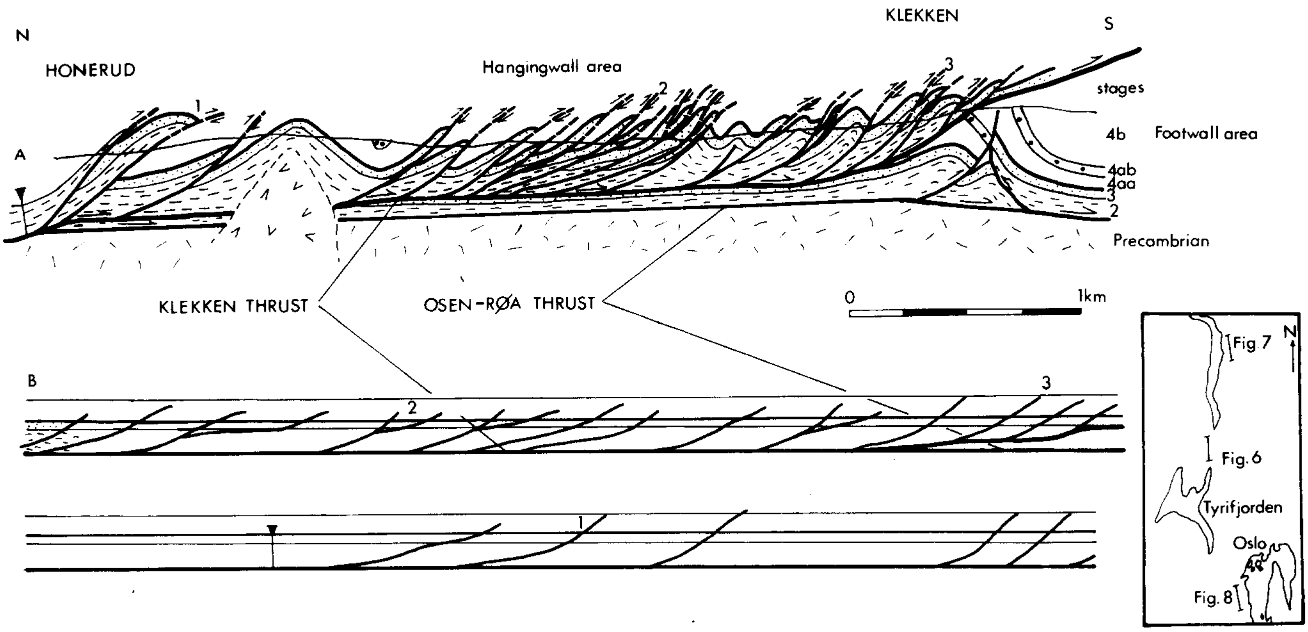

Fig. 6. Cross-section through north Ringerike. 2: Cambrian; 3: Lower Ordovician; 4aa–4b: Middle Ordovician. Note change in deformation style south of Klekken fault. Inset displays locations of sections in Figs. 6, 7 and 8.

mate representation of the variations in shortening by folds, imbricate- and back-thrusts is given in Fig. 9(b); the large decline in the Ringerike area represents the footwall area of the Klekken thrust. The graph in Fig. 9(a) is smoothed by adding 5 km of shortening, achieved by displacement along the Klekken thrust, to the estimate of shortening achieved by folding and minor thrusting. In southern Eikeren, pop-up, triangle and imbricate zones pass into widely spaced localized zones of deformation (e.g. the Holmestrand area) (see Fig. 2). Shortening is markedly less in the Langesund–Skien area compared with the Oslo and Eiker areas (Fig. 9b).

By comparing Figs. 2 and 9 it can be seen that the deformation style within the Cambro–Ordovician of the Osen–Røa thrust sheet changes once the amount of shortening begins to decrease. The strong vertical variations in deformation style require that lateral changes must be considered separately for the Cambrian–Middle Ordovician and Middle Ordovician–Silurian sequences. Figures 10 and 11 demonstrate this vertical difference in deformation style in Hadeland (Holtedahl & Schetelig 1923), where imbricated Cambrian–Middle Ordovician rocks are found in the northern area, underlying broadly folded Middle Ordovician–Silurian rocks to the south (Owen 1977, 1978).

The lateral changes in deformation style in the Cambrian–Middle Ordovician units are much more marked than in the Middle Ordovician–Silurian sequence. The latter is always dominantly deformed by folds and the change in deformation style to the south is much less marked than in the lower unit. The amount of internal shortening in the Silurian rocks is almost entirely accomplished by buckle folding, with only minor shortening by cleavage, layer-parallel thickening or faulting. Also the decline in shortening of the Silurian sequence is not noticeable until south of the Oslo area (see Table 1).

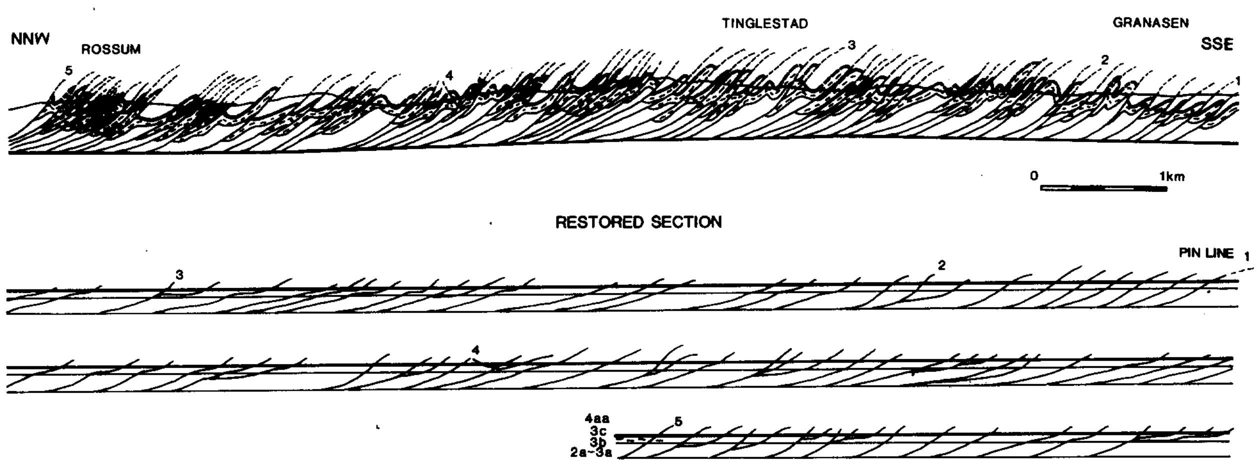

Fig. 7. Cross-section through the imbricated Cambro–Ordovician sequence of North Hadeland. 2a–3a: Alum shales (Cambrian–lowermost Ordovician); 3b: Caratopyge Series; 3c: Orthoceras Limestone; 4aa: Kirkerud Group (Mid Ordovician).

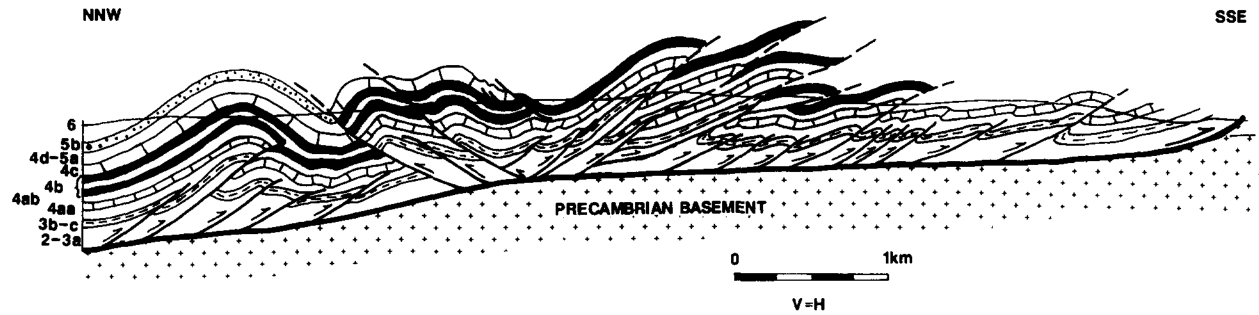

Fig. 8. Cross-section through southern Asker, of the deformed Cambro–Ordovician sequence. 2a–3b: Cambrian–lowermost Ordovician Alum shales; 3b–3c: Lower Ordovician shales and Orthoceras Limestone; 4aa: Upper Didymograptus shales; 4ab: Ampyx Limestone; 4ba–4bd: Chasmops series; 4c: Tretraspis series; 4d: Isotetus series; 5a–b: Upper Ordovician shales, sandstones and limestones.

South of Eiker the whole thrust sheet is probably internally shortened by a similar amount. Thus only for 30 km north of the thrust front is it possible for the Cambro–Silurian sequences to have deformed as a single unit.

The internal deformation of the upper part of the Osen–Røa thrust sheet can be restored from 150 km present length (Langesund to Mjøsa) to about 215 km original length, whilst the lower part restores from 150 to 285 km. Hence in order to balance the section, an extra 70 km of shortening in the Silurian needs to be accounted for. It could be argued that this extra shortening was achieved by more intense deformation in the now eroded areas of Silurian rock. Whilst this cannot be disproved, such an explanation would require a remarkable coincidence since the amount of shortening in the exposed Silurian sequence is consistently less than the shortening in nearby Cambrian–Middle Ordovician sequences.

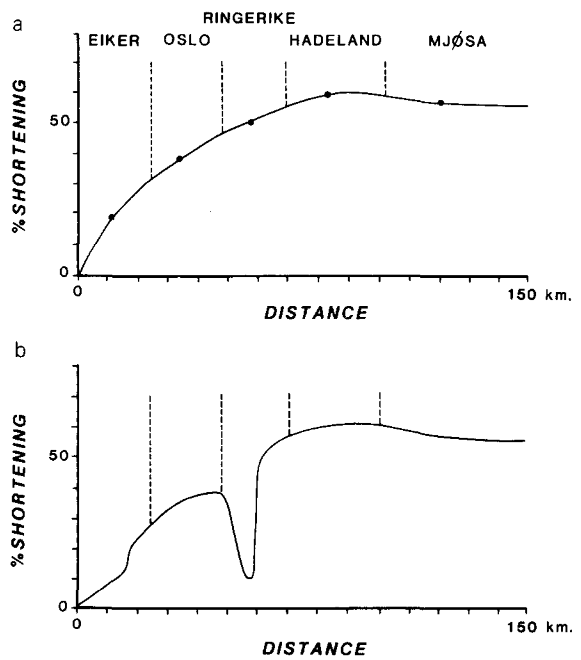

Fig. 9. Graphs of distance from foreland, north to south in the Oslo Region, against average amount of shortening in the Lower Ordovician for each district. a: average amount of shortening for each district; b: estimated variations in amount of shortening by folds and minor thrusts in each district to illustrate drop in amount of shortening south of the Klekken thrust in Ringerike.

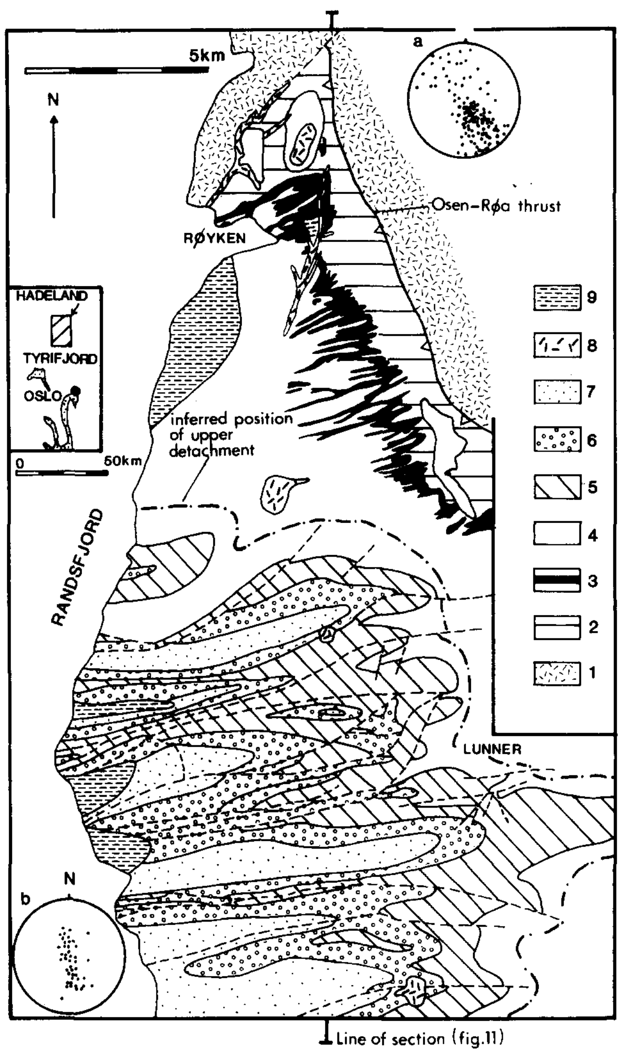

Fig. 10. Geological map of Gran, Hadeland. Northern Cambro–Middle Ordovician area after Morley (1983), Central and Southern Middle Ordovician–Silurian area after Owen (unpubl. 1977, 1978) and Holtedahl & Schetelig (1923). Note change in style of structure from N to S, with repetition of Lower Ordovician units by approximately 90 hinterland dipping imbricates in North Hadeland, and shortening in Middle Ordovician–Silurian by broad folds. Dashed lines indicate steeply dipping reverse and normal faults. 1: Precambrian basement gneisses; 2: Alum shales, Cambro–lowesmost Ordovician; 3: Lower Ordovician shales and limestones, Ceratopyge Limestone, Didymograptus Shales and Orthoceras Limestone; 4: Middle Ordovician shales, Kirkerud Group; 5: Middle–Upper Ordovician limestones and shales, Solvang, Lunner, Gagnum and Kalvasjo Formations; 6: Lower Silurian Sandstone, Skoyen Formation; 7: Middle Silurian, Rytteraker Fm, Ek Shale and Bruflat Fm (sandstone); 8: Permian intrusives; 9: glacial drift.

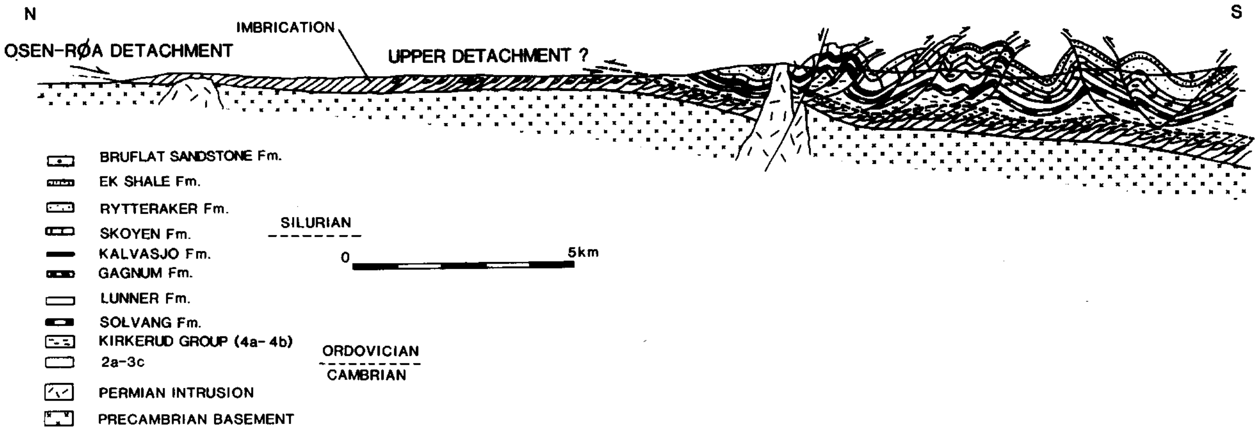

Fig. 11. N–S section through the Gran map, Hadeland (see Fig. 10 for location of section).

UPPER DETACHMENT IN THE OSEN–RØA THRUST SHEET

Any cross-section drawn through the Cambro–Silurian of the Oslo Region must account for the discrepancy in shortening and change in structural style between the upper and lower stratigraphic units of the Osen–Røa thrust sheet. This change occurs within Middle Ordovician shales in the northern Oslo Region. Farther south competent units increase in number in the Ordovician (Fig. 5) and strengthen the lower sequence. In the Oslo area, the effect of this stratigraphic change is to reposition the boundaries of shortening and deformation style domains to a higher stratigraphic level, in the Lower Silurian shales. In order to allow this change to occur, a bedding parallel detachment horizon is postulated. The amount of overthrusting at the leading edge of the upper detachment needs to have been 70 km in order to balance the 'missing' 70 km of Silurian section. This upper detachment could either have transported the hangingwall toward the foreland or the hinterland (Figs. 12 and 13).

The foreland directed upper detachment model (Fig. 12) is limited by the absence of thrusts in the folded sequence in the hangingwall of the upper detachment. Since this precludes the upper detachment having transferred slip to the surface via closely spaced faults, widely spaced faults must be invoked. The only thrust that can be proven to have penetrated the whole Silurian sequence is the Klekken fault in Ringerike (Størmer 1934, Harper & Owen 1983), with other possible large displacement thrusts in Eiker and north Asker (Fig. 2). If a foreland directed upper detachment is favoured, then transfer of slip up to the probable land surface can only have occurred along these widely spaced thrusts. This situation requires the upper detachment to have propagated into the foreland a considerable distance ahead of the sole thrust tip, by perhaps as much as 20 km. Figure 12 shows how shortening below the upper detachment could have proceeded by the transfer of slip to the upper detachment (with an intra-thrust sheet duplex geometry) until deformation reached the ramp in the upper detachment. Once the imbricates reached the position of the upper detachment ramp, the upper detachment is then required to propagate a considerable distance into the foreland and repeat the cycle.

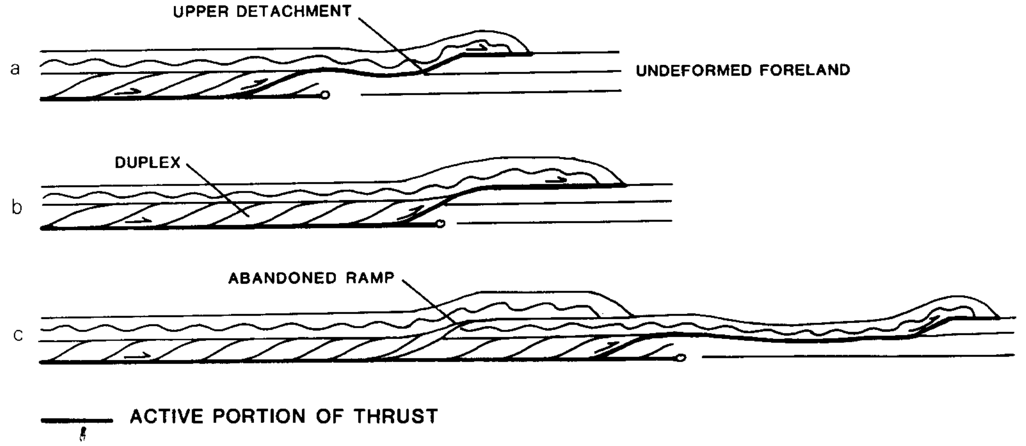

Fig. 12. Progressive development of a foreland directed upper detachment.

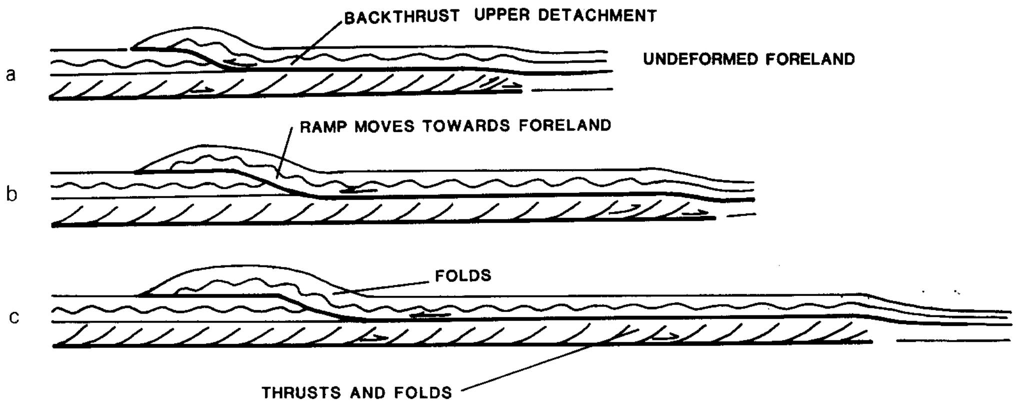

Fig. 13. Progressive development of a hinterland directed upper detachment.

The hinterland directed model for the upper detachment hangingwall sequence allows incremental progression toward the foreland of the upper detachment and the sole thrust together (Fig. 13). As the rocks at the sole thrust-tip deform, the resulting discrepancy in the internal shortening between the foot- and hangingwall sequences of the upper detachment is taken up by backthrusting. Figure 13 shows that the hangingwall ramp of the upper detachment remains stationary whilst the footwall ramp moves progressively toward the foreland by underthrusting. The backthrusting model allows deformation in the whole Cambro–Silurian sequence to progress toward the foreland simultaneously, whilst the foreland thrusting model requires deformation above the upper detachment to progress ahead of the footwall sequence.

Models similar to those above have been proposed for a number of thrust belts. The back-thrust duplex roof is called a triangle zone by Jones (1982), and a passive-roof-duplex by Banks & Warburton (1986). Such a geometry is thought to exist in various parts of the Canadian Rocky Mountains (Price 1981, 1986, Jones 1982, McMechan 1985); the Kirthar and Sulaiman mountain belts, Pakistan (Banks & Warburton 1986); the MacKenzie mountains, Canada and the Peruvian Andes (Vann *et al.* 1986). In some areas, e.g. Alberta syncline, the along-dip extent of the back-thrust may be fairly limited, perhaps 10–15 km. In other parts of the Canadian Rocky Mountains the area underlain by backthrusts may be at least 75 km wide (McMechan 1985).

The foreland-directed detachment forms a particular type of duplex where the roof thrust forms a flat; younger rocks are displaced over older without any stratigraphic omission or repetition. Displacement on the roof thrust is entirely the result of slip transferred via imbricate thrusts from the floor thrust (Washington in press). Perry (1978) has described such a duplex from the central Appalachian Valley and Ridge. The term passive roof duplex is being used in the Appalachians to describe this type of duplex (Herman & Geiser 1985, Washington 1986). Unfortunately, this clashes with the use of the same term by Banks & Warburton (1986), discussed above.

There is little evidence for the nature of the structurally necessary upper detachment in the Oslo Region. This is due to poor inland exposure especially in the Middle Ordovician shales and the bedding-parallel nature of the predicted detachment. In the northern 60 km of the Oslo Region, from Hadeland to Mjøsa there is no evidence of a large ramp through the Silurian sequence required for the foreland directed upper detachment. Although this could be explained by erosion in the area of the ramp, the upper detachment with a backthrust sense is the preferred, but unconfirmed, interpretation adopted here. The presence of large thrusts that pass through the Cambro–Silurian sequence in the 55 km of the Ringerike (Klekken thrust), Oslo and Eiker areas allow a foreland directed upper detachment to be inferred to the more southern areas. But, it is also possible to postulate that an upper detachment with a backthrust sense was formed first and was later displaced by thrusts in Ringerike, Oslo and Eiker. In the most southerly 30 km of the deformed Cambro–Silurian sequence, the small amounts of shortening (0–20%) throughout the stratigraphy permits the interpretation that the whole Cambro–Silurian sequence deformed together, without the need for an upper detachment horizon.

DISCUSSION

The following questions arise from the changes in deformation style observed in the Oslo Region. What is the mechanical significance of vertical changes in rock competency, and what factors govern lateral changes in deformation style toward the thrust front?

The main ways in which the stratigraphy may influence deformation style are by lateral and vertical variations of thickness of units and by vertical and lateral changes in lithology. Interaction between these factors can produce complex changes in deformation style. Some examples of the more basic variations in deformation style that can be imposed by the stratigraphy are now examined to determine whether such changes are applicable to the lateral and vertical changes in deformation style observed in the Osen–Røa thrust sheet.

(1) Thickness variations can influence the spacing of thrusts and the wavelength of folds. For example, in the Canadian Rockies the major thrust sheets in the Front

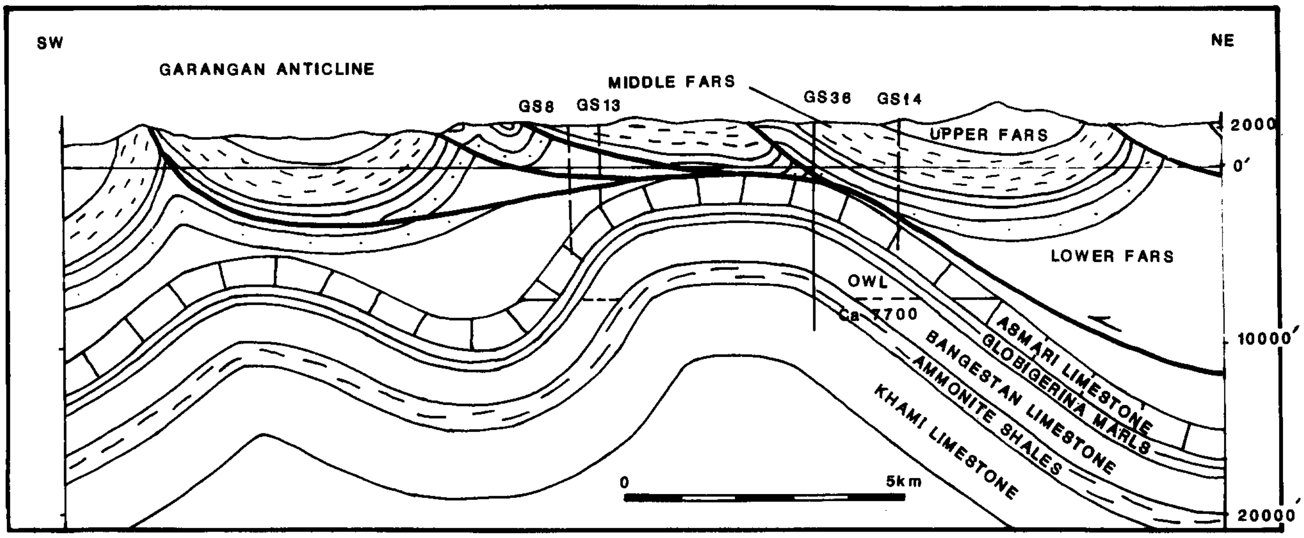

Fig. 14. Cross-section through the Zagros Fold Belt at Gachsaran (after Mineral resources and development series 1963).

Ranges are spaced about every 5 km, while more externally in the foothills belt they are spaced every 1–2 km. This change in spacing is accompanied by a reduction in stratigraphic thickness from 4 to 10 km in the Front Ranges to 1–1.5 km in the Foothills Belt (Suppe 1985, p. 484).

It has been observed that folds in a thick stratigraphic sequence are larger than those which form in a thin sequence (e.g. Goguel 1962). Theoretical and experimental data help towards an understanding of which lithological and stratigraphic factors influence such changes in fold style and size. Experimental data indicate that a contrast in viscosity between layers is necessary for buckle folds to develop (e.g. Biot 1961). Fold wavelength is largely governed by the viscosity ratios between the layers and matrix and the thickness of the layers (e.g. Biot *et al.* 1961, Currie *et al.* 1962, Ramberg 1964, Fletcher 1974). Log–log plots of fold wavelength against member thickness for field examples led Currie *et al.* (1962) to suggest that fold wavelength is approximately equal to 27 times the thickness of the dominant member in a stratigraphic package. Spacing between the layers can also affect the fold shape, and buckle folds of different wavelengths may be superimposed if the layers are close enough to interfere (e.g. Currie *et al.* 1962, Ramberg 1964).

(2) Lateral changes in lithology may cause lateral variations in deformation style. The foothills and Front Ranges belt of the Southern Canadian Rocky Mountains change deformation style along strike (Tippet *et al.* 1985), particularly when thick Palaeozoic carbonate sequences in the south (Price 1981) pass northward into thick shale packages (Thompson 1981). The thick carbonate sequence tends to deform by imbricate thrusts that reach the present land surface, with only limited folding of the sequence. In the shale-dominated sequence, most major faults are blind and die out into complex disharmonic hangingwall folds (Thompson 1981, Tippet *et al.* 1985). Spacing of imbricate faults in the competent sequence tends to be much wider than that in the incompetent sequence.

(3) Vertical changes in lithology may cause sufficient contrast in material behavior to result in different deformation styles developing within a single thrust sheet. In such cases a bed-parallel detachment horizon or zone is likely to form along the interface between the contrasting deformation styles. The Zagros fold belt exhibits such features (Fig. 14), where the predominantly incompetent Fars Unit is disharmonically folded and imbricated above a lower competent sequence of rock whose uppermost unit is the Asmari Limestone (Colman-Sadd 1978). The competent sequence is deformed into a series of broad gentle folds which exhibit greater wavelengths than folds found in the incompetent sequence.

Vertical changes of deformation style in the Osen–Røa thrust sheet are probably caused by sedimentary units becoming thicker and more competent upwards. Hence the influence of 1 and 3 above are combined in the Oslo Region. The presence of the Ringerike Sandstone at the top of the sequence appears to be very influential on deformation style. In such a thick competent unit shortening by stratigraphic repetition along large overthrusts was probably mechanically easier than by internal deformation of the slab by second-order thrusting and folding. The position of the Ringerike sandstone within the thrust sheet may also be important in influencing the overall deformation behaviour. For example, Fig. 15(a) illustrates how the vertical changes in deformation style in the Oslo Region might develop in a simple compression model, with the competent unit deforming independently on top of an incompetent unit. The competent unit deforms by overthrusting on a single fault plane, whilst the incompetent unit below deforms by folding and layer-parallel thickening. When the situation is reversed, with the competent unit (on a thin easy-slip layer) below the incompetent unit (Fig. 15b) then the competent unit at the base is able to exert a much stronger control on the deformation style in the incompetent unit (e.g. Zagros fold belt). An upper detachment may still develop, but the large folds in the competent unit are still likely to affect the incompetent unit and buckle their fold envelope. Also the periodicity

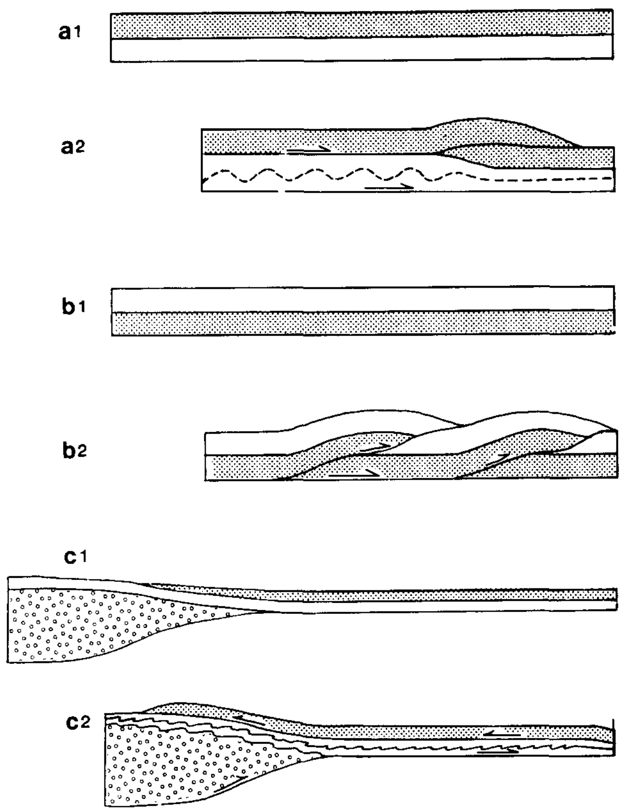

Fig. 15. The effects of vertical changes in competency on deformation style in a thrust sheet. Stippled: competent unit; unshaded: incompetent unit. (a[1]) Competent unit is the upper unit, (a[2]) deformation produces independent structural styles in lower and higher units. (b[1]) Competent units is the lower unit, (b[2]) deformation style is controlled by the lower competent unit. (c[1]) Schematic cross-section through Oslo Region with the sequence thickening northward. 1: Late Precambrian clastics; 2: Cambro–Middle Ordovician sequence; 3: Middle Ordovician–Silurian sequence. (c[2]) Driving in of the deformed Precambrian clastics as a wedge, deformation concentrated in Cambro–Middle Ordovician sequence whilst Middle Ordovician–Silurian sequence undergoes 'passive backthrusting'.

at which the competent unit forms thrust sheets, and thereby foregoes shortening by internal deformation in favor of overthrusting, may limit internal deformation of the incompetent unit.

The lateral changes in deformation style of the Osen–Røa thrust sheet may, in part, be analogous to the southern Subalpine chains in the Maritime Alps. The more external part of the Subalpine chain is strongly folded, while the more internal area is only slightly folded (Lemoine 1973). Goguel (1949) suggested that the increasing thickness of the sedimentary package toward the north, from 2 km to over 4 km, was responsible for the change in deformation style. Greater energy would be required to fold the northern area than to allow the rock to slip along the basal incompetent evaporite-bearing Trias. The horizontal displacement of the northern area was taken up by folding in the thinner and therefore weaker southern area.

The compression in the Oslo Region sector of the Osen–Røa thrust sheet (up to 2 km stratigraphic thickness) was transferred via the thick wedge of deformed Precambrian clastics (perhaps up to 4 km thick) present in the Sparagmite region (of the Osen–Røa thrust sheet to the north) (Fig. 15c). After initial compression, the wedge of Precambrian clastic material perhaps underwent horizontal displacement and deformation was concentrated away from the thick, more resistant Precambrian clastics and into the weaker Cambro–Ordovician sequence of the Oslo Region. The rocks above the upper detachment, including the Ringerike Sandstone, acted as a 'lid' to this strong deformation in the Cambro–Ordovician sequence and could have in effect been underthrust by the Precambrian clastic sequence and Cambro–Ordovician sequence as shown in Fig. 15(c).

Lateral variations in deformation style within the Oslo Region are probably due to a number of factors including those listed below, whose relative importance is uncertain.

(1) A sequential, foreland progressing deformation sequence results in an ever-increasing distance between the thrust front and the hinterland. Hence forces have to be transmitted for increasingly greater distances to the thrust front. Ultimately the system may develop to a point where it becomes more favourable to re-deform the internal zones (by out-of-sequence thrusting, retrocharriage and re-folding, etc.) than to deform rocks any further into the foreland. For example, the slope of the sole thrust and syn-orogenic surface may change with time and affect whether internal deformation or stable sliding of the thrust belt is the preferred shortening mechanism (Davis *et al.* 1983).

(2) The amount of overburden on a thrust sheet may vary and affect the slope of the syn-orogenic surface thereby affecting the thrust sheet boundary conditions (e.g. Hafner 1951, Mandl & Shippam 1981). The vertical normal stress exerted by the overburden on the lower, developing thrust sheet may also influence deformation style by elevating pore fluid pressures and by opposing vertical movements.

(3) Resistance to deformation by a lateral change toward more competent units may halt deformation and cause it to rebound and re-deform rocks toward the hinterland.

(4) A poorly known, but potentially very important, factor is the way compressive forces decline in magnitude as orogenic activity dies out. Amongst the variables that can accompany declining forces and which may affect deformation style are the way principal stress directions become re-oriented passing toward the foreland, changing strain rates and variations in differential stress.

(5) Changes in the effective strength of the detachment zone can be accomplished either by a change in lithology or pore-fluid pressure. Changes in lithology of the Triassic detachment zone in the Jura Mountains are thought to be responsible for changes in deformation style (Trumpy 1980). Davis & Engelder (1985) have noted that the appearance of box folds, pop-up and triangle zones in several thrust belts are related to the presence of a super-weak basal detachment horizon formed by evaporites. They suggest that the taper of a thrust belt wedge which overlies a zone in evaporites is much less than that of a thrust belt which overlies a basal detachment with moderately overpressured pore fluids

(λ = 0.7) and no evaporites. The orientation of stress trajectories within the more strongly tapering wedge favors hinterland dipping minor thrusts, while the weakly tapering wedge favors a mixture of hinterland and foreland dipping thrusts.

The Cambro–Ordovician sequence undergoes a noticeable decline in the amount of shortening and change in deformation style across the Klekken thrust in Ringerike (Størmer 1934, Harper & Owen 1983) (see Figs. 2 and 9). This coincidence suggests that the Klekken thrust influenced the deformation style. One possible explanation is that a regime of high pore-fluid pressures existed in the hangingwall of the Klekken thrust. This condition led to numerous attempts by the sole thrust to ramp (through the relatively weak rocks) and the formation of an extensive closely spaced imbricate stack. If the Klekken thrust separated different pore-fluid pressure regimes in the hanging- and footwall blocks, the resulting differences in shear-strength may have been sufficient to cause the observed variations in deformation style (e.g. Mandl & Shippam 1981). Whilst the role of pore-fluid pressures is conjectural, it is certain that displacement along the Klekken thrust created a tectonic overburden on the footwall rocks that was not present in the hangingwall. Probably an extra 1.5 km thickness of rocks locally covered the footwall block. Deformation in the footwall rocks may have been inhibited since the vertical component of movement involved in contractional deformation would have been opposed by the increased vertical normal stress (compared with the hangingwall sequence) imposed by the tectonic overburden. It seems reasonable to suggest that the strengthening effect of the overburden (e.g. Mandl & Shippam 1981) caused deformation to be concentrated in areas further south, where the effect of the tectonic overburden had decreased.

There is no obvious factor (such as the Klekken thrust) that can be invoked to account for the changes in deformation style and amounts of shortening between the Oslo area and Langesund (Fig. 1). A number of explanations for these changes can be offered including lateral variations in lithology, changing pore-fluid pressures and variations in strain rate. Probably no one factor is entirely responsible. An increase in the number of competent Ordovician units occurs southward between Oslo and Langesund (Fig. 5), hence an increased resistance to deformation is likely. There are no obvious lithological changes in the Cambrian shales which form the main detachment zone, hence any changes in the effective strength of the detachment zone would require a lateral change in pore-fluid pressures. A factor which suggests that the role of pore-fluid pressures was not very important is the nature of the detachment zone. The Osen–Røa thrust forms a broad zone of deformation which involves pressure-solution processes and sliding on numerous minor fault planes (Morley 1986b). According to Wojtal & Mitra (1986), such a thrust zone is more characteristic of ductile processes than frictional sliding. Hence it is unlikely that elevated pore-fluid pressures which affect the frictional resistance to sliding could have exerted a major influence on the behavior of the detachment zone. However, the possible influence of the detachment zone on the deformation style, although minimized here, is a largely unknown factor which could bear detailed research.

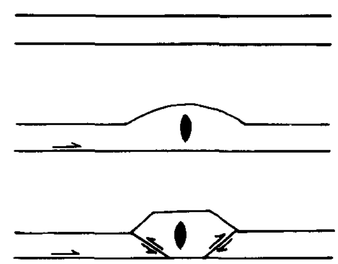

Fig. 16. Development of a pop-up. (a) Layer parallel shortening at a propagating thrust tip (b) continuing strain produces a pop-up, after Butler (1982).

The appearance of opposed dip-fault complexes is a common occurrence close to thrust fronts (e.g. Rocky Mountains, Thompson 1981; Appalachians, Gwinn 1964, Wiltschko & Chapple 1977). These structures usually exhibit low amounts of shortening (up to about 35%) compared with the average of 50% shortening commonly observed in more internal thrust sheets (e.g. Boyer & Elliott 1982). Pop-up and triangle zones are probably areas that locally concentrated high strains over a stuck sole thrust or perturbation in basement (e.g. Laubscher 1977). An initial layer-parallel shortening event followed by fore- and back-thrusting is the explanation given by Butler (1982; see Fig. 16) for such features. The structural style of the southern Oslo Region may have evolved under variable but declining stresses which underwent periods when stresses were too low to induce deformation. Then, as stresses built up at a particular point, the area became locally strained. The sole thrust may have unstuck, propagated some distance, then lapsed into inactivity until stresses built up again (Gretener 1981).

CONCLUSIONS

The vertical changes in deformation style and shortening within the Osen–Røa thrust sheet suggest that a bed-parallel upper detachment horizon exists between the Cambro–Middle Ordovician and Middle Ordovician–Silurian units in the northern Oslo Region and between the Cambro–Ordovician and Silurian units in the Oslo area. The upper detachment in the Mjøsa and Hadeland areas may have a backthrust sense although a foreland directed model can also be postulated. The presence of imbricates below the upper detachment gives rise to a passive roof duplex geometry (Banks & Warburton 1986). In the Ringerike and Oslo areas, the upper detachment probably changed to a foreland directed thrust sense, accompanied by large thrusts that penetrate the Silurian sequence.

Lateral changes in deformation style in the Cambro–Ordovician of the Oslo Region occur in a NNW–SSE direction and pass from imbricates in the north to triangle and pop-up zones in the south. The amount of shortening also decreases from 60% in the north to zero at the blind sole thrust tip. At this stage, only tentative causes for the change in deformation style can be postulated. Such causes include tectonic loading in the vicinity of the Klekken thrust, declining end-of-orogenic forces, and southward increasing competency. Variable pore-fluid pressures may also have affected the deformation style.

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