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Vertical strain variations in the Osen–Røa thrust sheet, North-western Oslo Fjord, Norway

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Abstract—Vertical variations in deformation style and shortening within the Osen–Røa thrust sheet are examined on the north-western side of the Oslo Fjord. Using thrust distribution diagrams and graphs of throw against height in the stratigraphy, particular formations are identified in which thrusts are either created or destroyed. Many thrusts are killed by a combination of (1) dissipation of slip by splaying of thrusts in shales, and (2) the presence of a thick competent unit that requires a thrust to attain a specific displacement value in order to propagate through the unit in one jerk. The Upper Didymograptus Shales and Ampyx Limestone make an effective combination that kills thrusts with less than 50 m of throw. Within the thrust sheet, deformation styles change vertically from imbricate slices, pop-up and triangle zones with tip-line folds in the Cambro-Ordovician shales and limestones, to buckle folds in the Silurian limestones, sandstones and shales. This change is accompanied by a decrease in shortening from 34% in the former to 17% in the latter. Hence one or several higher, bedding-parallel detachment horizons need to be invoked to separate areas of varying deformation character.

INTRODUCTION

THE INFLUENCE of stratigraphic variations on deformation style has been investigated for a long time (e.g. Willis 1893, Rich 1934) although usually on a regional scale. Knowledge of the geometric variations of structures vertically within a rock sequence and the interrelationships between mesoscopic structures (cleavage, folds and faults) is necessary to determine the deformation history and estimate total strains. This paper documents the vertical and horizontal changes in structural elements, deformation style and shortening along a 15 km cross-strike section in the most external thrust sheet of the Norwegian Caledonides. The aim is to demonstrate how lithological contrasts in local stratigraphy create a multilayer package in which the competent and incompetent layers display different structural styles and non-uniform shortening vertically within a thrust sheet (see also Bockelie & Nystuen 1984).

GEOLOGICAL SETTING

The unpinned (allochthonous) Cambro-Silurian stratigraphy of the Oslo region underwent contractional deformation at the end of the Caledonian orogeny. These sediments lie tectonically and stratigraphically above pinned (autochthonous) Precambrian and lowermost middle Cambrian rocks. The thrust which separates the pinned and unpinned sections is called the Osen–Røa detachment (Nystuen 1981, Morley 1983). The detachment forms a flat in the Alum Shales (Cambrian) throughout the Oslo region and terminates (blind) in a buried thrust front north of Langesund–Skien (see Fig. 1). In the Oslo area the deformation is relatively uncomplicated, with no tectonic overprinting by deformation from other thrust sheets. Only minor structures are involved in shortening the stratigraphy of the thrust sheet (see Fig. 1). Shallow depths of burial of about 2 km have been inferred from conodont coloration indices (Bergstrom 1980, Hossack 1985). In this area there is a marked alternation of competent and incompetent lithologies (Fig. 2). Hence the Oslo area is an ideal place to study the effects of deformation on a stratigraphic package of variable lithologies.

LITHO-TECTONIC UNITS

The Cambro-Silurian rocks have been divided numerically into stages (Brøgger 1887, Kiaer 1908, Vogt 1924). These units are essentially chronostratigraphic, the Cambrian representing numbers 1–2d, Ordovician 2e–5b and Silurian 6–10. The subdivision of numerical stages commonly coincides with lithostratigraphic units; e.g. 3ac corresponds with the Ceratopyge limestone. This terminology is currently under review by Owen, Bruton and Bockelie (Owen pers. comm.).

The deformation style of the Osen–Røa thrust sheet in the districts of Asker and Baerum changes vertically in the stratigraphic succession. An increase in the proportion of competent units up the succession (Fig. 2) resulted in the lower units deforming by faulting and folding more readily than the higher units. On the basis of coincidental change in tectonic style and lithology it is possible to divide the stratigraphy into four litho-tectonic units as follows (see Fig. 2): Alum shales, 1ca–2e (50 m thick); Lower to Middle Ordovician limestone and shale, 3a–4d (about 310 m thick); Upper Ordovician limestone, shale and sandstone, 5a–b (about 150 m thick); Silurian limestone, shale and the Ringerike sandstone, 6–10 (about 1140 m thick). Their different deformational characteristics are described below.

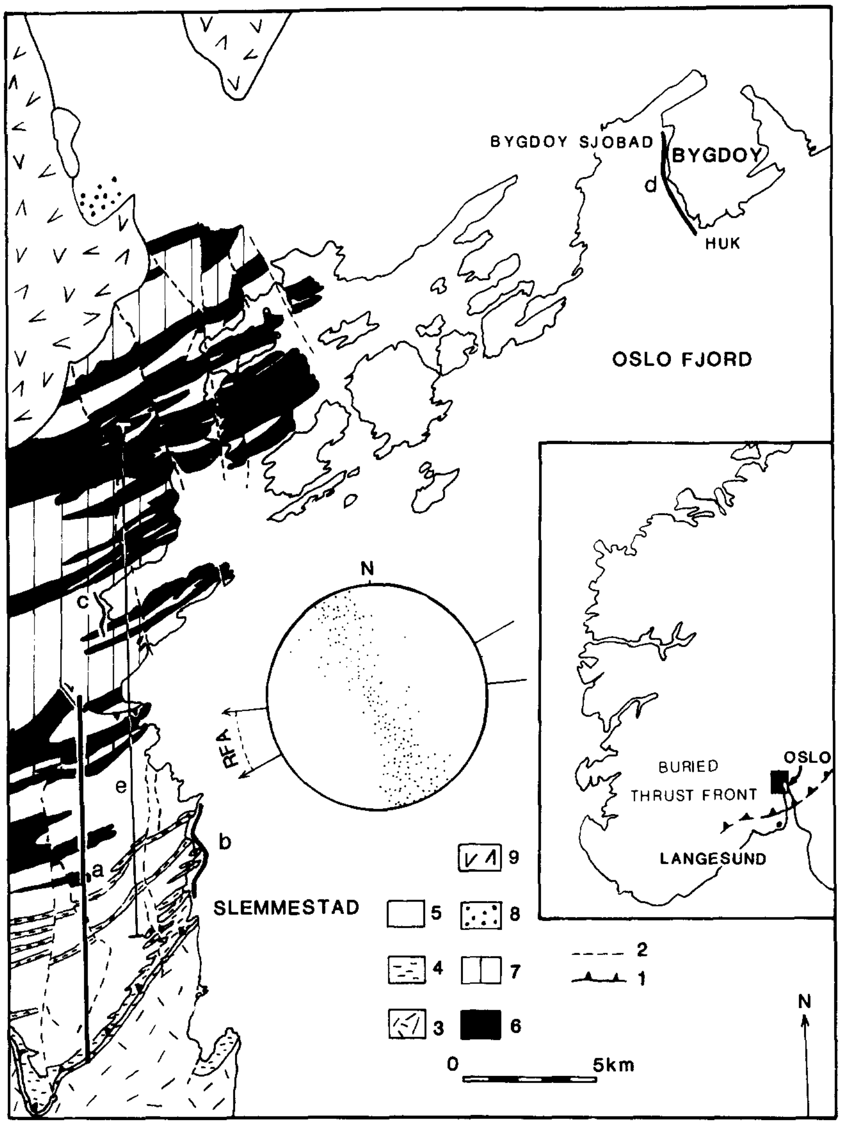

Fig. 1. Geological and location map for the Asker–Baerum area, north-western Oslo fjord. 1, thrust; 2, normal fault; 3, Precambrian gneiss; 4, Cambrian–Lower Ordovician (2a–3c); 5, Middle Ordovician; 6, Mid–Upper Ordovician (4c–5); 7, Silurian (6–9); 8, Ringerike sandstone (10); 9, Asker group (Carboniferous–Permian). a, location of Fig. 9; b, Fig. 8; c, Fig. 6; d, Fig. 7. Stereonet for poles to bedding (196); RFA, regional fold axis trend.

Alum shales

The Osen–Røa detachment forms a zone of numerous minor sub-horizontal slip planes characterized by smooth porcellaneous surfaces or shiny graphitic surfaces, within the Alum Shales. Below this zone pinned Alum Shales rest unconformably on Precambrian basement gneisses (or local Permian intrusive rocks). There is a strong cleavage sub-parallel to bedding, which has subsequently been folded. Mesoscopic folds are asymmetrical and disharmonic with wavelengths up to 4 m and amplitudes up to 3 m. These folds are probably parasitic on larger anticlinal folds. The mesoscopic folds probably developed during flow of the Alum Shales from synclines into areas of low mean stress such as anticlinal cores (Wiltschko & Chapple 1977). Most cleavage and slip planes are sub-horizontal, which indicates that second and third order thrusts also flatten out approaching the Osen–Røa detachment.

Lower to Middle Ordovician limestone and shale

This sequence of alternating limestone and shale beds displays the effects of deformation by second and third order contraction faults that fan off the Osen–Røa detachment (second order contraction faults splay directly from the Osen–Røa detachment and third order faults splay off second order faults). In outcrop it can frequently be demonstrated that the largest folds fold an earlier spaced cleavage, or have a syn-folding spaced cleavage imposed on them. Commonly one fold limb (usually the forelimb) is displaced by a slightly later second order thrust. Along the Oslo fjord north and south of Slemmestad twelve imbricate repetitions of Orthoceras Limestone are present. Of the twelve repetitions nine display hangingwall anticlines in the Orthoceras Limestone (Fig. 3) whilst five out of eight footwall exposures of limestone display a footwall syncline geometry. This consistency of field relationships

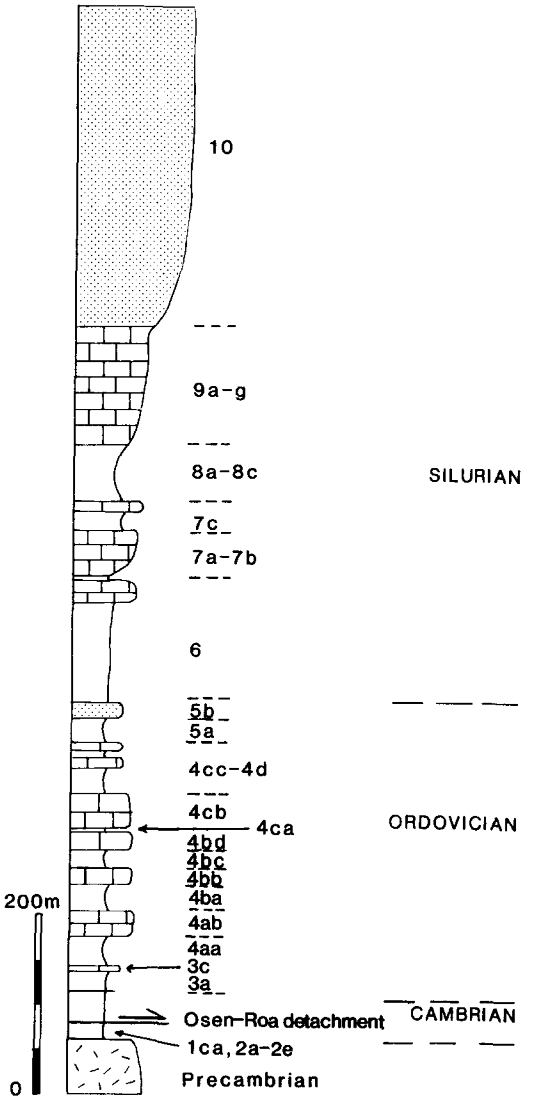

Fig. 2. Stratigraphy of the Asker Baerum area. 1ca, basal Cambrian; 2a–2e, Alum Shales (middle Cambrian–lowermost Ordovician); 3a, Ceratopyge Limestone and Shale; 3b, Lower Didymograptus Shale; 3c, Orthoceras Limestone; 4aa, Upper Didymograptus Shale; 4ab, Ampyx Limestone; 4bb, Lower Chasmops Limestone; 4bc, Upper Chasmops Shale; 4bd, Upper Chasmops Limestone; 4ca, Tretraspis Shale; 4cb, Tretraspis Limestone; 4cc–4d, Upper Tretraspis Limestone-Isotelus Series; 5a–5b, Upper Ordovician shale; sandstone and limestone; 6, Lower Silurian shale; 7a–b, Pentamerus Limestone; 7c, Crinoid Shale and Upper Coral Limestone; 8a–c, Lower Spiriferid Series; 9a–g, Upper Spiriferid Series; 10, Ringerike Sandstone. This stratigraphy is currently being revised by Bruton, Bockeli, Owen and others into lithostratigraphic terms.

indicates an intimate relationship between folds and thrusts in this stratigraphic unit.

The relationship between folds, spaced cleavage and thrusts can be explained by development of folds and cleavage in the ductile bead (Elliott 1976, House & Gray 1982, Williams & Chapman 1983) which advanced ahead of the propagating second order thrusts. Folding and cleavage formation were probably approximately synchronous, with cleavage formation usually preceding folding (see Fig. 4). The folds generated at the thrust tips were then displaced by the thrusts and gave rise to the hangingwall anticline, footwall syncline geometry commonly seen in the Oslo region.

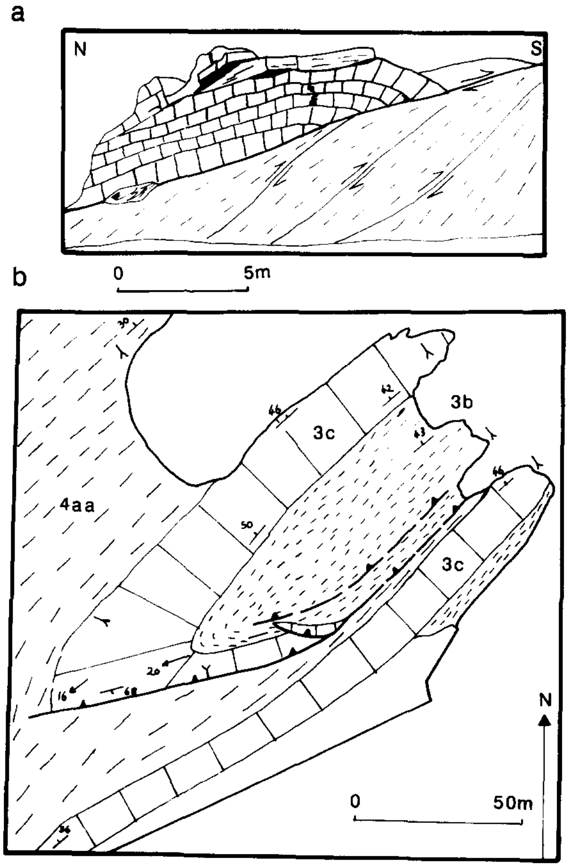

Fig. 3. Hangingwall anticlines in Orthoceras Limestone, Slemmestad industrial estate, (a) Eternite factory (grid reference 841 292) and (b) Djuptrekkodden (grid reference 842 298).

Upper Ordovician limestone, shale and sandstone

The Upper Ordovician rocks form the tectonic transition zone between the thrust-dominated rocks below and fold-dominated rocks above. Many thrusts generated from the main detachment die out within the Cambrian to mid-Ordovician rocks, and the great majority die out at the top of the Ordovician (Fig. 5). There are also some low-angle thrusts present that are not related to the folds they truncate because they displace both fold limbs.

Silurian shale, limestone and the Ringerike Sandstone

The dominant mode of shortening in the Silurian sequence is by folding. Shortening decreases upwards because the stiff, competent layers become thicker at higher levels and therefore more resistant to deformation. This tendency culminates in the 500 m (minimum) thick Ringerike Sandstone. Folds become broader with more gently dipping limbs and progressively less thrusting is displayed in rocks of younger age.

In the lower Silurian, thrusts formed in response to accommodation problems caused by folding. They fan off locally formed detachments and commonly cut up and down section through folded rocks (Fig. 6). These thrusts rarely exhibit displacements greater than a few metres. There are also a few thrusts that pass up through the Cambro-Ordovician sequence to penetrate and die out in the Silurian rocks.

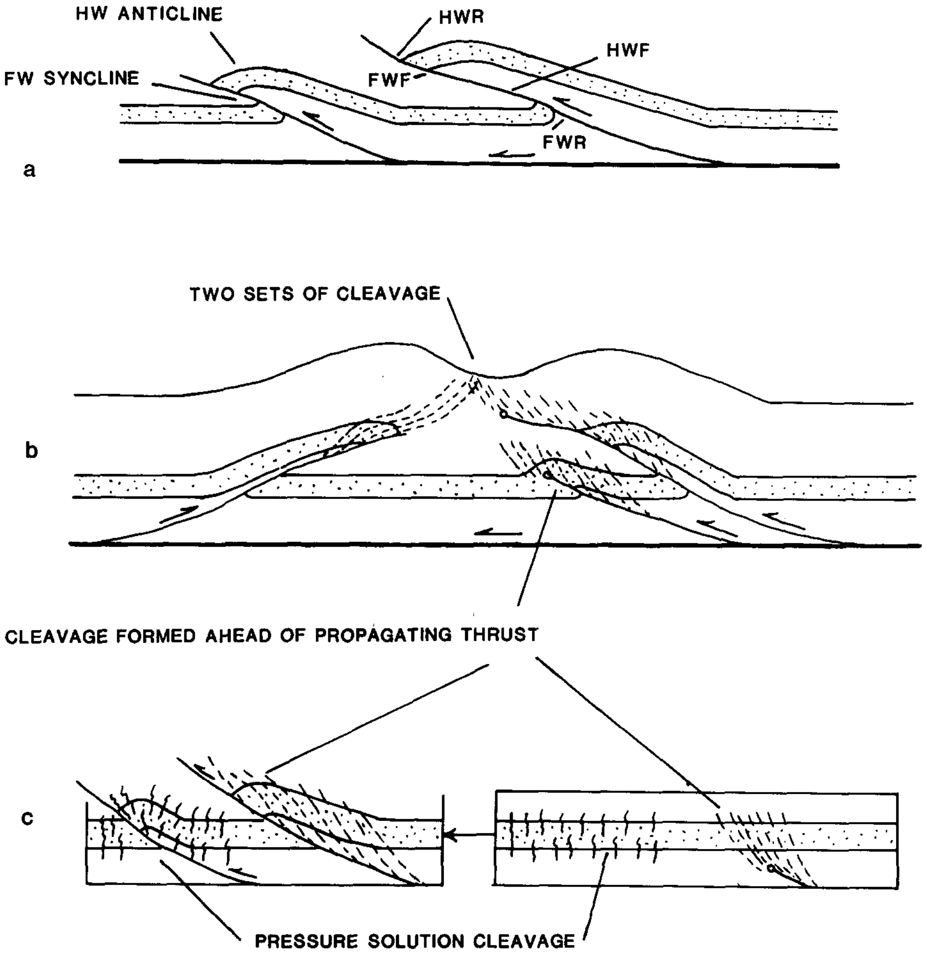

Fig. 4. Relationships between thrusts, folds and cleavage in the Cambrian to mid-Ordovician Units. (a) Thrust geometry, HW, hangingwall; FW, footwall; R, ramp; F, flat. (b) Spaced cleavage forming ahead of thrust tip lines. (c) Relationships between thrusts and early cleavage. These are idealized diagrams based on real examples.

STRUCTURAL ELEMENTS

Second and third order thrusts

Areas where the second order thrusts consistently dip towards the hinterland are present in several different vertical and horizontal zones. These zones of imbrication are separated by areas of mixed back- and forethrusts. The most important imbricate zones are those formed in the units between the Alum Shales and Upper Didymograptus Shales, which are well displayed at Slemmestad and Bygdoy (Figs. 7 and 8). At Slemmestad the average spacing between imbricates thrusts is 240 m.

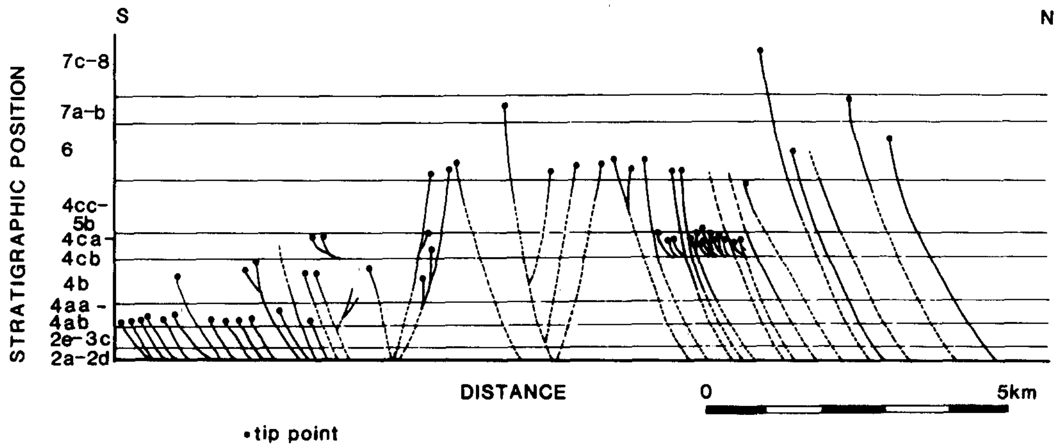

Fig. 5. Second order thrust distribution diagram for the area of Cambro-Silurian rocks in Fig. 1. The diagram displays backthrusts, forethrusts, splays, and the stratigraphic horizons the thrusts are observed in. The thrust distribution in the Cambrian–Lower Middle Ordovician is unknown after the most southerly 3.5 km. Predicted extents of thrusts are shown by dashed lines.

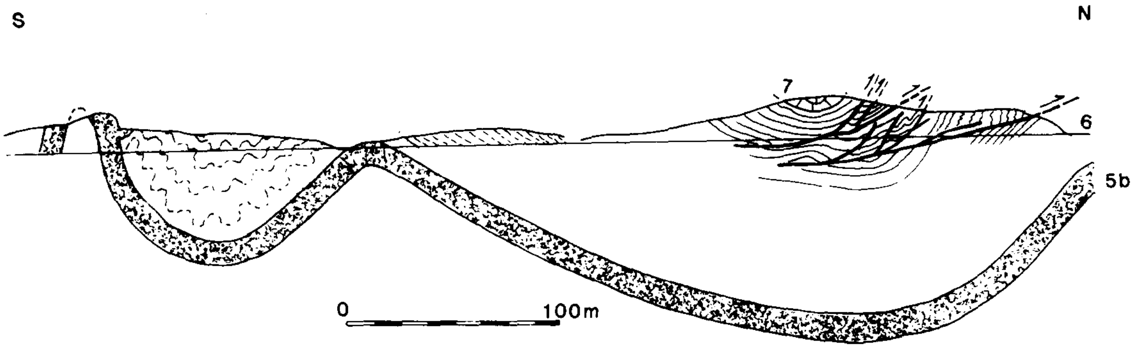

Fig. 6. Section along road no. 165 at Tangen displaying out-of-syncline thrusting in response to buckling in lower Silurian rocks. Line of section shown in Fig. 1.

Imbricate thrusts display an average throw of 50 m (the average shortening estimated from a balanced section is 27% shortening). At Bygdoy the average spacing is 160 m with an average throw of 30 m (30% shortening, estimated from a balanced section). In both cases the imbricate thrusts tend to die out either in the Upper Didymograptus Shales or the Ampyx Limestone.

The other commonly imbricated unit is the Tretraspis Shale and Limestone (4ca–4cb). About 60 m of stratigraphy is imbricated by faults spaced every 1–50 m with the more important thrusts displaying displacements of 10–20 m. The imbricate zones of the Tretraspis Limestone form either as a sequence of splaying out-of-syncline thrusts (Dahlstrom 1970) or as a relatively long detachment horizon unrelated to folding. In the latter case lower-level thrusts occasionally breach the higher detachment zone.

Horizontally between the regions of imbrication, pop-up and triangle zones are developed (Fig. 9). On a regional scale the alternating triangle pop-up zones and imbricate zones of the Oslo region are transitional between dominantly imbricate zones to the north and pop-up and triangle zones to the south (Morley 1983). The presence of overturned backthrusts on Bygdoy (Fig. 7) in the Alum Shales demonstrates that backthrusts are not necessarily only a feature of deformation at levels above the Alum–Upper Didymograptus Shale imbricate zone.

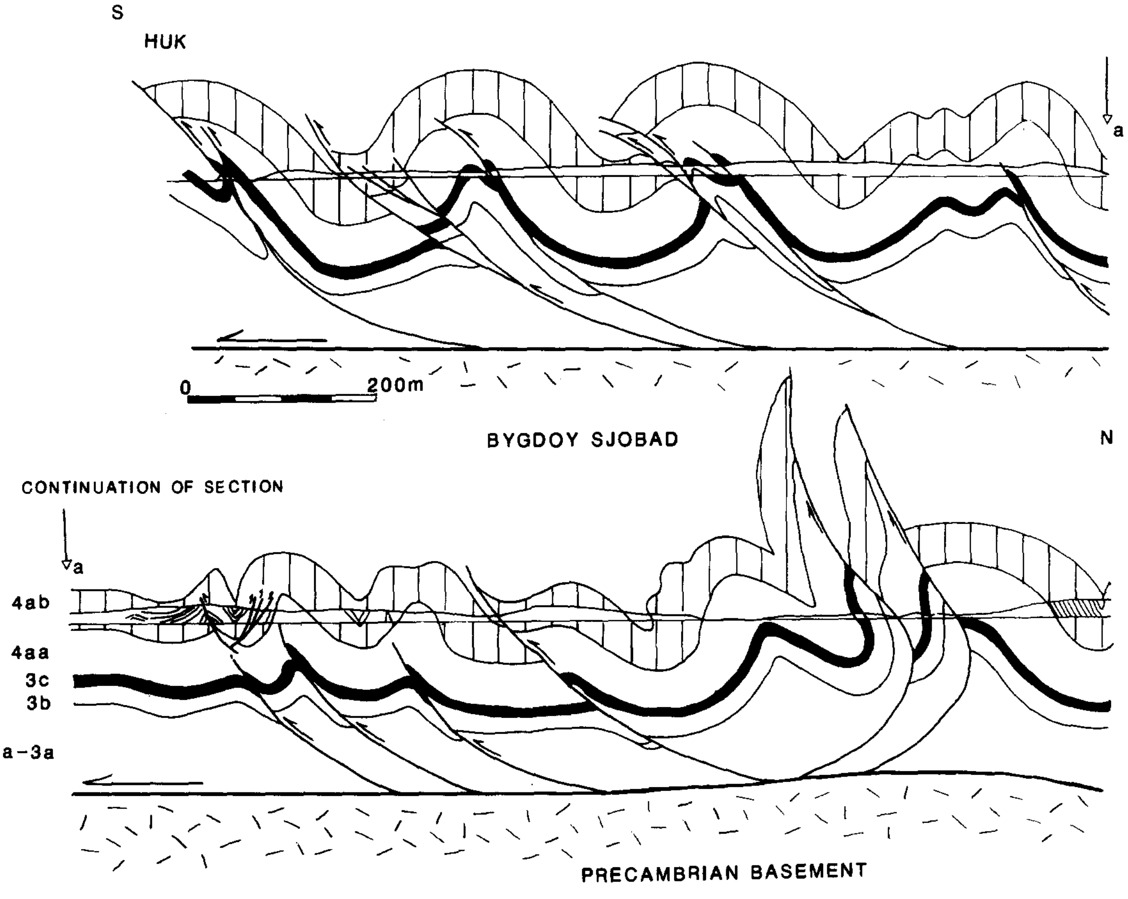

Fig. 7. Cross-section along west coast of Bygdoy from Huk to Bygdoy Sjobad. Line of section shown in Fig. 1.

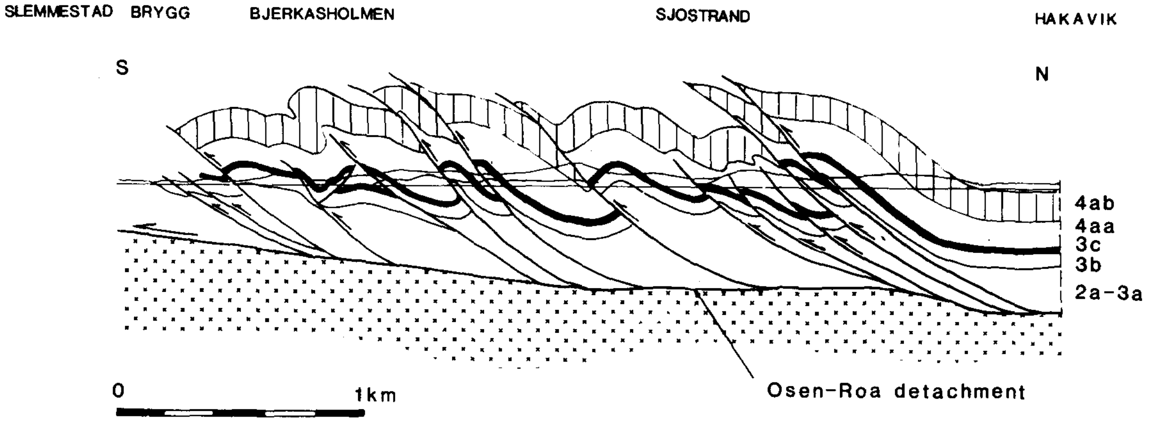

Fig. 8. Cross-section through imbricated Cambrian–Lower Ordovician rocks from Hakavik to the cement factory, Slemmestad. Line of section shown in Fig. 1.

Vertical variations in thrust density

Elliott (1977) outlined the potential for particular formations to spawn or kill off thrusts, and his terms are used below. An idealised rectangular portion of the Oslo region stratigraphy is envisaged, called the control volume (CV). The number of thrusts that enter the CV from below or from the sides change into a different number N of thrusts that exit from the CV. The number of thrusts changes as they pass through the various formations. The number (Nf) of thrusts which splay is a process of fission. Some thrusts will die (Nd) in the CV, some will be born (Nm), whilst others will pass through the CV without any change. The total number of thrusts which leave (No) plus the number which die within the CV is equal to the number that enter (Ni) the CV, plus those created by splaying (Nf) and materialising (Nm)

$$\mathrm{No} + \mathrm{Nd} = \mathrm{Ni} + \mathrm{Nm} + \mathrm{Nf}. \qquad (1)$$

The change (ΔN) in the number of thrusts across the CV is

$$\mathrm{No} - \mathrm{Ni} = \mathrm{Nm} + \mathrm{Nf} - \mathrm{Nd}. \qquad (2)$$

The total number residing in the CV and available for survival or death within the CV is Ni + Nm + Nf, so that the probability of births (Pb) and deaths (Pd) is respectively

$$\mathrm{Pb} = \frac{\mathrm{Nm} + \mathrm{Nf}}{\mathrm{Ni} + \mathrm{Nm} + \mathrm{Nf}} \quad \text{and} \quad \mathrm{Pd} = \frac{\mathrm{Nd}}{\mathrm{Ni} + \mathrm{Nm} + \mathrm{Nf}}. \qquad (3)$$

Pb is 0 when there are no births and 1 when all the thrusts are born within the CV, from which the percentage of births and deaths is easily calculated. Using this method of Elliott (1977) the way individual formations may spawn thrusts (Pb > Pd) or kill thrusts off (Pb < Pd) is calculated for the Oslo region (see Table 1 and Fig. 11).

The use of throw in the analysis of thrust distribution

The description of the thrust and fold distribution in the Oslo region has so far been qualitative. In the next

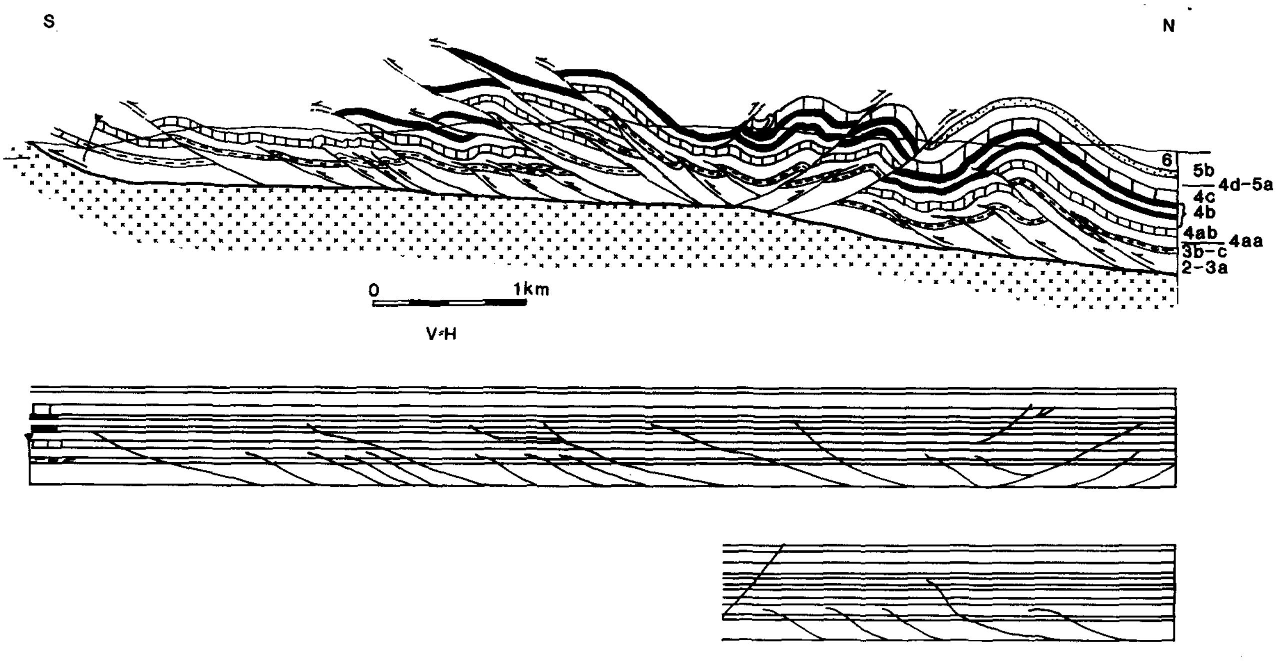

Fig. 9. Cross-section through Cambro–Ordovician rocks from Foss to Blakstad. Line of section shown in Fig. 1.

section the field and map data is analysed and placed in a quantitative content by the use of actual and idealized thrust-distribution diagrams and graphs that plot a variety of thrust parameters. One problem with this analysis is the difficulty of obtaining accurate data on the maximum true displacement on the second order thrust faults. This is a problem in the Oslo region where the maximum displacement on most faults cannot be accurately determined. Throw between the hangingwall and footwall can be measured from a map, but it is not necessarily a useful replacement for the true displacement along a fault. If the majority of second order faults exhibit a smooth, listric trajectory that steepens in dip upwards then the throw is likely to be closely related to true displacement. However a ramp and flat geometry in second order thrusts is likely to include a considerable horizontal component in the true displacement. Hence there is more potential variation between the vertical and horizontal components that make up the true displacement of ramp-flat second order thrusts than of listric second order thrusts. Consequently thrusts with a staircase trajectory will exhibit a poorer correlation between throw and displacement than thrusts with a listric trajectory. Most thrusts in the Oslo region appear to exhibit a smooth trajectory and the fifteen thrusts for which the true displacement can be accurately determined from good field exposures exhibit a linear relationship when plotted against throw (Fig. 10). The replacement of true displacement by throw is not ideal when analysing second order thrusts in the Oslo region because throw consistently underestimates the value for true displacement. This difference is relatively unimportant, however, because the relationship between throw and true displacement is linear (Fig. 10). Figures 11 and 12 can therefore be plotted using throw as an adequate replacement for true displacement. This would not be permissible if Fig. 10 exhibited a non-linear relationship.

Table 1

For a 5 km CV length	Number of thrusts in a stratigraphic unit	Rate of change in number of thrusts in adjacent units
Number of thrusts in Alum Shales (Ni)	25	
Number of thrusts entering Orthoceras Limestone	29	13.7% (Pb > Pd) birth rate for Lower Didymograptus Shales
Number of thrusts leaving Upper Didymograptus Shales	15	48% (Pb < Pd) death rate for Upper Didymograptus Shales
Number of thrusts leaving Ampyx Limestone	11	26% (Pb < Pd) death rate for Ampyx Limestone
Number of thrusts leaving Chasmops Series	8	27% (Pb < Pd) death rate for Chasmops Series
Number of thrusts in Tretraspis Limestone	50	525% (Pb > Pd) birth rate for Tretraspis Limestone
Number of thrusts entering Silurian Shales	10	80% (Pb < Pd) death rate for Upper Ordovician
Number of thrusts leaving Silurian Shales (No)	3	70% (Pb < Pd) death rate for Silurian Shales

Change (ΔN) in number of thrusts across CV is:

$$-22 = No(3) - Ni\ (25) = Nm\ (32) + Nf\ (12) - Nd\ (66).$$

Analysis of thrust distribution

The process of fission that increases the birth rate of thrusts by splaying in one unit often causes the death of thrusts in succeeding units because slip initially along one fault is then divided up along the splays. There appears to be a threshold value of slip for thrusts in the Cambro-Silurian rocks which a thrust must exceed in order to pass through certain units (Fig. 12). Splaying

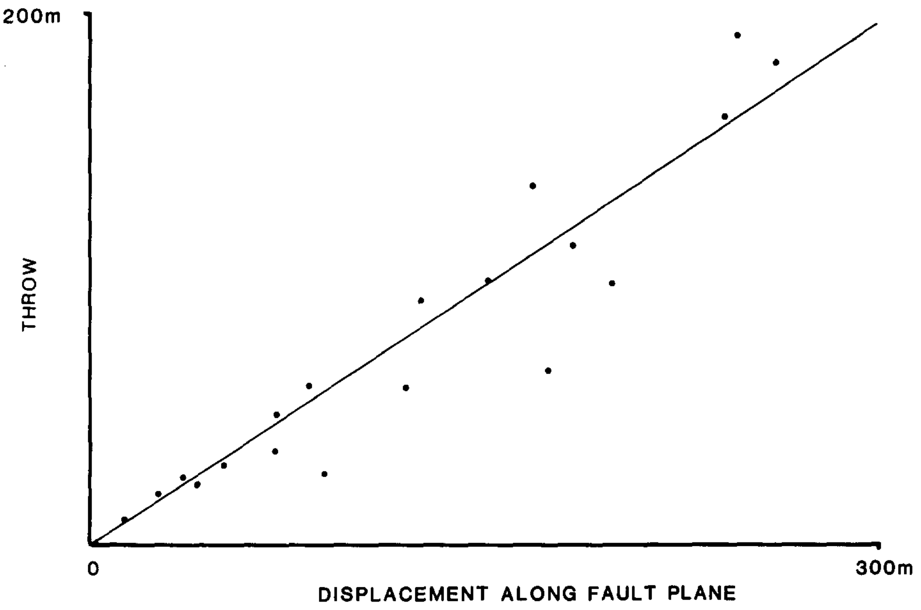

Fig. 10. Plot of throw against displacement along fault plane for 19 faults in Asker Baerum.

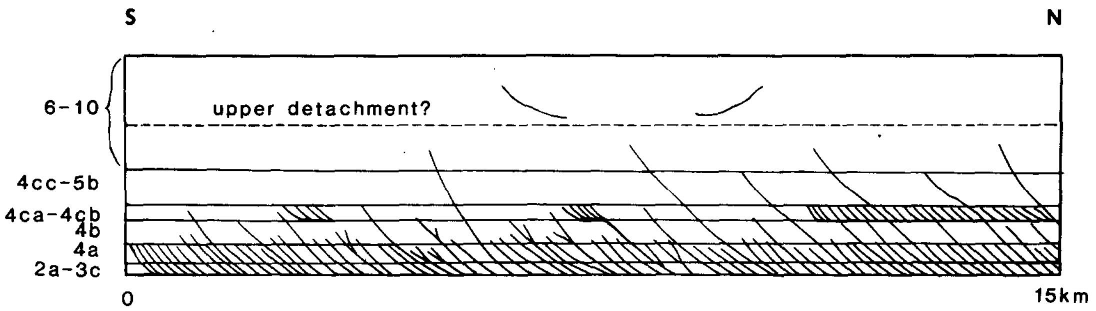

Fig. 11. Density of thrusts in a 15 km long control volume. This idealized diagram of a section along line e (see Fig. 1) shows how the number of faults changes within different units. Dip directions of thrusts are not fully represented, only density.

may reduce the slip on a thrust surface so that it does not meet the slip threshold necessary to pass through a particular unit. Figure 12 plots the vertical distance of a thrust tip from the Osen–Røa detachment against its throw. This graph was designed to demonstrate how a particular minimum displacement value is necessary at specific stratigraphic units for a thrust to continue propagating into higher units. This value is called the displacement threshold. Thrusts that have failed to attain this displacement threshold plot as a line of points parallel to the throw axis. Ideally no points should plot above this line of points, but instead the plots should shift to the right of the lower plots for higher positions in the stratigraphy (see Figs. 12e & f). This pattern can be detected in Fig. 12(a) although it is a modified version of the idealized trend. The main cause of the modification is that ideally only the maximum throw of thrusts that originate solely from the Osen–Røa detachment should be plotted (Fig. 12b). Some of the points represent thrusts that display less than maximum throw in outcrop. These inadmissible throw measurements are made approaching tip lines and at thrusts formed by local detachments or splays. They are difficult to filter out and therefore complicate the graph.

Figure 12(b) displays two noticeable lines of points that show thrusts which terminate at a particular strati-

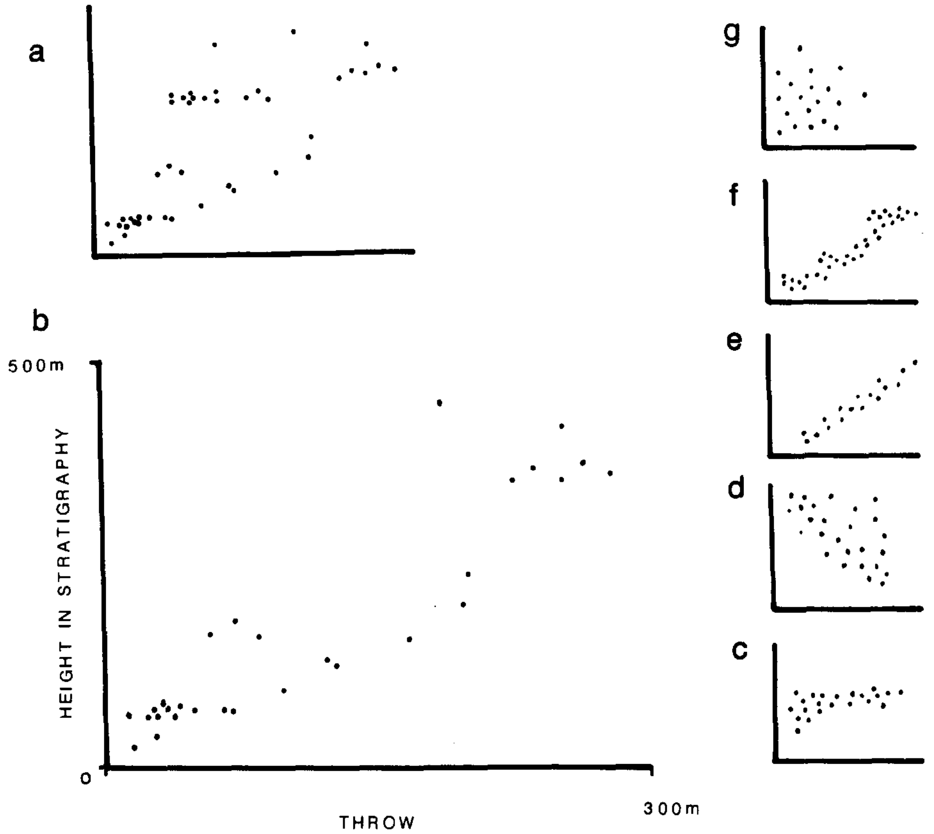

Fig. 12. Slip threshold diagram. (a) Height of a thrust tip above the Osen–Røa detachment plotted against maximum observed throw of thrusts. (b) Same diagram as (a) after filtering out thrusts probably formed by the detachment at the base of the Tretraspis series (4c). (c)–(g) Examples of patterns produced by the slip threshold diagram. (c) One stratigraphic unit has a strong influence on fault termination. (d) Steady decrease in the amount of throw on faults upwards in the stratigraphy. (e) Steady increase in the amount of throw on faults is required for faults to exist in the upper part of the stratigraphy. (f) Same as (e) except clustering indicates particular levels at which thrusts below a certain value of throw terminate. (b) Also displays this pattern. (g) Random scatter, no correlation between amount of throw on faults and height in stratigraphy.

graphic level. This distribution is related to thrusts which have insufficient displacement to jump to the next level. The cluster at the 100–160 m level reflects deaths in the Upper Didymograptus Shale/Ampyx Limestone units. Thrusts appear to need stratigraphic separation in excess of 60–70 m before they can overcome the ability of these horizons to kill thrusts. The cluster of points around the base of the lower Silurian shales shows that these shales kill thrusts with throws of up to 115 m. Higher up in the same shales thrusts with throws up to 200 m are killed. One exception is a thrust with 180 m throw that penetrates the Silurian Shales, but it is quickly killed off by the overlying Pentamerus Limestone.

The plot of average throw against a specific stratigraphic interval (Fig. 13) supports the validity of the plot in Fig. 12. The two horizons identified as killing off thrusts in Fig. 12 correspond to the curves of increasing average throw in Fig. 13. Below these curves are two stratigraphic units that display a noticeable decrease in average throw. The plot of average throw in the lowest stratigraphic units, from the Osen–RØa detachment to the base of the Upper Didymograptus Shale reflects the dominance of numerous imbricate thrusts with throws of about 50 m or less. They are killed in the Ampyx Limestone and Upper Didymograptus Shales. Hence the average throw increases in the Chasmops Series to about 80 m, higher than in the first 110 m of the sequence. Another major reduction in the average throw occurs in the Tretraspis Shale and Limestone. This reflects the second unit that was deformed by numerous thrust imbrications of small displacement. Above the Tretraspis Shale the lithology kills thrusts and progressively higher displacements are required for thrusts to survive.

Lithological influence on thrust propagation

Splaying and birth of thrusts usually occur in shales (see Table 1). Thrusts approaching limestones usually die out below the base of the limestones, or pass through the limestone without splaying. This variation of birth, death and splaying events between different lithologies is probably related to how brittle deformation passes into ductile deformation at propagating thrust tips. With thrusts of large enough displacement thick limestone units may form large tip-line anticlines that buckle the whole unit. The limestones do not display development of small, intra-formational folds. Small folds need thin layers in order to develop, because at shallow depths of burial they tend to form by flexural slip. Thin layers of alternating competent and incompetent beds are usually absent in the Ordovician limestones. This absence of thin layers probably made it difficult for thrusts of small displacement to propagate part way into a limestone unit and die out into small tip-line folds. Thrusts of small displacement were therefore halted at limestone units, because they were unable to propagate through them in a series of small displacements.

Unlike the other limestone horizons that do not exhibit tight folds, the Tretraspis Limestone often exhibits small very ductile tight folds. This ability to form small folds probably enabled thrusts of low displacement to grow by small incremental displacements in this limestone, unlike most of the other more rigid limestone units. Why the Tretraspis Limestone exhibits such different behaviour is unclear. The most likely explanation is the presence of nodules for 10–20 m above the base of the limestone that are much smaller than

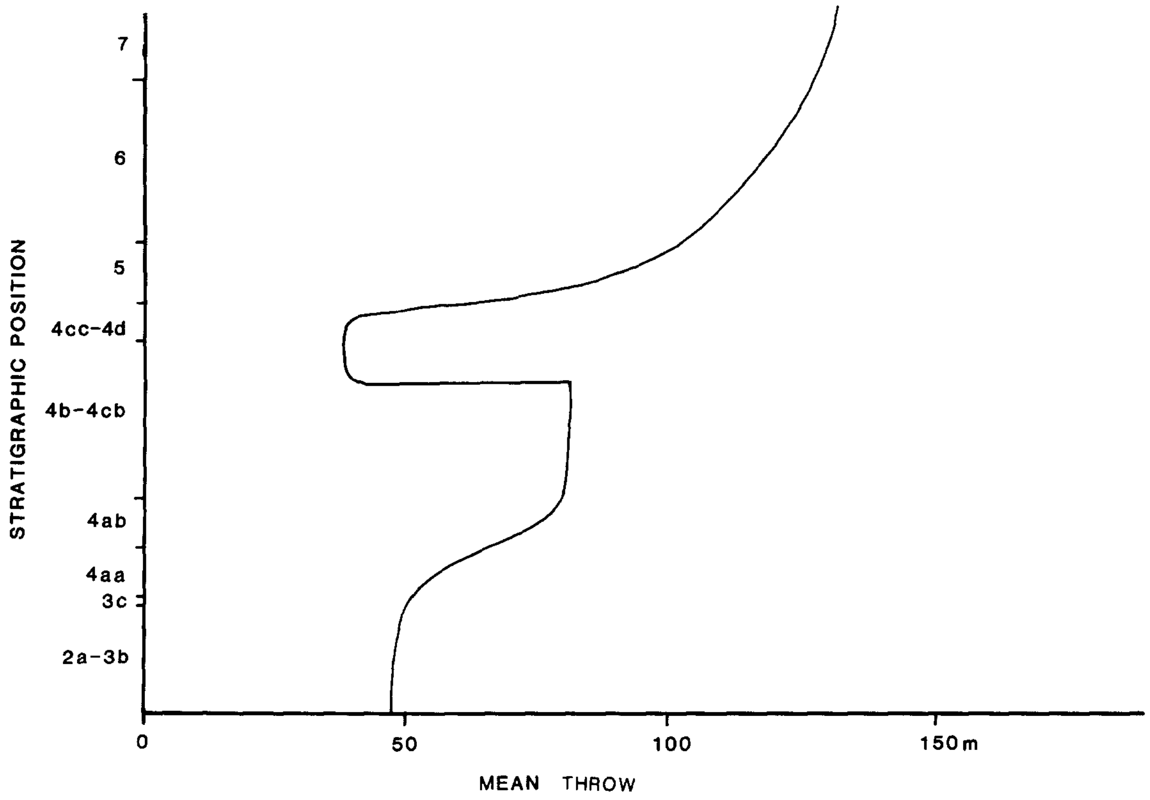

Fig. 13. Graph of position in the stratigraphy against average throw for all thrusts in a particular stratigraphic interval.

those of the other limestone units. This characteristic probably enabled the shales surrounding the nodules to exert a greater influence on the rock behaviour and allow flexural slip between nodule beds, so that smaller and tighter folds were allowed to develop.

Strains are commonly dissipated in shale, but concentrated in the competent units. This is illustrated by the presence of widely spaced pressure-solution cleavage in limestone, but closely spaced pencil cleavage in shale, and of thrust wedging in limestone, but layer-parallel thickening in shales. The same is often true for thrusts. The transfer of brittle to ductile strains at fault tips is not easily accomplished in competent units. They therefore need to be broken through in one deformation pulse by a thrust. In contrast the shale units can absorb thrust displacement by splaying, passing into bed-parallel detachments and layer-parallel thickening, and ending in tip-line folds. The resulting combination of splaying in the thick Upper Didymograptus Shales, and resistance to propagation of thrusts by small increments in the thick Ampyx Limestone, kills thrusts of low displacement.

Folds

Two orders of folds can be recognized in Asker–Baerum. Firstly large-scale passive folds are present which are due to draping of the sediments over basement topography. In the Oslo area two major synclines are present that preserve Silurian rocks. One of these synclines is present in the Konglugen area where Silurian rocks are preserved in a broad depression about 4 km wide between Ordovician rocks. Secondly mesoscopic folds are present which are responsible for most of the shortening observed in much of the sequence. Mesoscopic folds can be divided into two groups based on structural association and geometry.

Group 1: folds related to thrusts

Group 1 folds occur mainly in the Cambro-Ordovician rocks where their attitude and tightness are related to the presence of contractional faults and minor detachment surfaces. Folds generated ahead of thrust tips in the Orthoceras and Ampyx Limestones form tight, symmetrical and asymmetrical folds with wavelengths of 120–280 m (e.g. Figs. 7–9) and moderate amplitudes of 70–135 m. They display gently plunging hinges and interlimb angles of 65–90°. The axial planes of tip-line folds, when inclined, dip in the direction of the fault plane responsible for their formation. Inclination of the axial planes is usually between 60 and 90° to the NNW or SSE. Their fold geometry is either Class 1B or 1C (Ramsay 1967).

Group 2: buckle folds

This group of folds has formed by active buckling, not at the tip lines of thrusts, although thrusts may disrupt them. Buckle folds can be distinguished from tip line folds because they form fold trains, with folds of similar wavelength and orientation. The tightness of the folds decreases and wavelength increases passing up the sequence (Fig. 14), which reflects the decreasing amounts of shortening passing up the sequence.

In the Ordovician rocks the major folds form moderately broad, open folds with wavelengths of 270–1400 m and amplitudes of 120–300 m (Fig. 14); fold geometry is class 1B (Ramsay 1967). Axial planes are steep to upright with dips of 80–90°, and interlimb angles fall between 85 and 110°. Buckle folding in the Silurian is a more important shortening mechanism than thrusting, and forms broad open folds of class 1B with wavelengths of 800–2000 m and amplitudes of 120–280 m. The folds

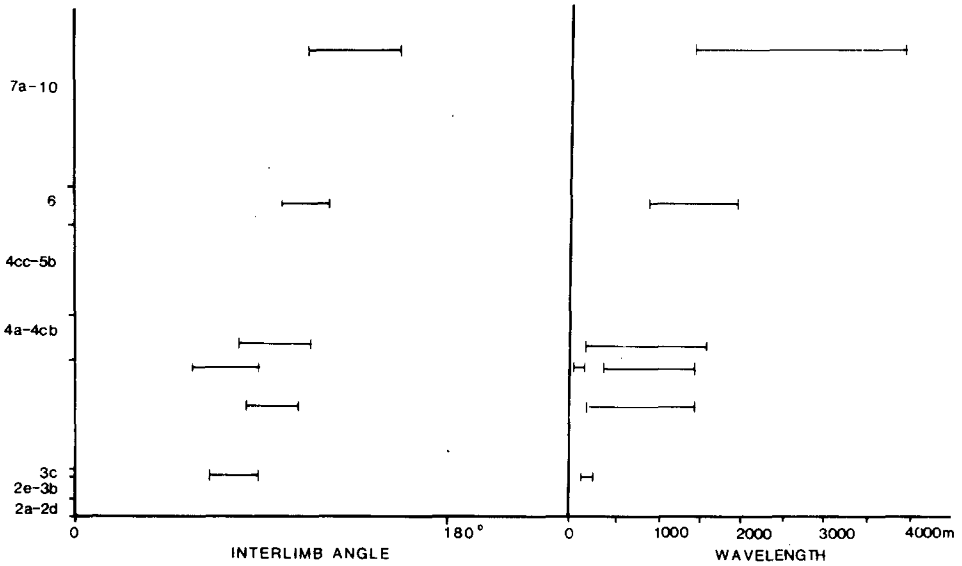

Fig. 14. Graphs of fold interlimb angle and wavelength plotted against position in the stratigraphy.

are upright or slightly inclined, with axial planes that dip to the NNW between 70 and 90° and exhibit interlimb angles of 100–120°. Capping the sequence, the thick Ringerike sandstone forms even broader folds with wavelengths up to 4000 m and amplitudes up to 870 m.

Cleavage

Spaced solution cleavage and pencil cleavage occur within the Cambro-Silurian rocks but is not always present. Spacing varies from 0.2 to 5 cm. Cleavage is more common and intense in the lower part of the succession, although it can also be intense in the lower Silurian Stricklandia shales (Stage 6). It is not usually present in rocks younger than the Pentamerus Limestone.

Pressure-solution cleavage is developed in limestone and sandstone beds and can sometimes be demonstrated to pass vertically into pencil cleavage developed in shales. The strike direction of the pressure-solution cleavage and the long axis of the pencil cleavage are orientated roughly parallel to minor and regional fold hinges. Pressure solution seams are orientated perpendicular or at a high angle to bedding. The seams vary in intensity from weakly stylolitic to strongly anastomosing seams. Shortening by pressure-solution, calculated by reconstructing partially removed fossils in Asker, reaches a maximum of 15%; but because pressure solution is localized and varies in intensity the amount of shortening averaged over the region is about 5% for the limestone horizons.

The pressure-solution seams have been reorientated from their original sub-vertical orientation by folding and thrusting. Although pressure-solution is related to the Caledonian event, it must therefore have occurred earlier than or synchronous with the main folding and faulting events.

STRAIN DISTRIBUTION AND TOTAL AMOUNT OF SHORTENING

Several deformation mechanisms contribute to the total strain within Asker–Baerum. The absence of consistent strain markers for measuring layer-parallel shortening in the shales makes direct measurement of strain in the shales very difficult. The amount of layer-parallel shortening can be indirectly measured instead by calculating the shortening by pressure solution and thrust wedging in the competent beds, and assuming that this figure equals the amount of shortening in the shales. In a few localities strained fossils in shales are present and in the lower Ordovician strained graptolites in zones of pencil cleavage have been shortened by up to 26% (N–S) with the long axis of the strain ellipse orientated E–W. Very commonly however the fossils are unstrained, and strain variations between areas of deformed and undeformed fossils are difficult to determine because of the scarcity of strain markers.

Pressure-solution

Pressure-solution produced a maximum shortening of 15%. Associated with the pressure-solution are extensional veins filled with the products of pressure-solution. Chocolate-tablet structures are locally developed in the lower limestone units, which indicate extension parallel to regional strike. The assumption of plane strain, therefore, no longer applies. In order to compensate for non-plane strain the effects of pressure-solution must be added onto any balanced cross-section constructed through the area.

Folding and thrusting

The amount of shortening achieved by folding and thrusting was calculated by constructing balanced cross-sections through the area (Figs. 7–9). By comparing original length (l_0) with the deformed length (l_1) the shortening ($l_1 - l_0/l_0$) can be calculated from a line-length balance (Hossack 1979).

The principal natural shortening

$$\mathrm{ET} = \mathrm{Elps} + \mathrm{Eb} + \mathrm{Ef} + \mathrm{Eps}, \tag{4}$$

where Elps is layer parallel shortening; Eb, buckling strain; Ef, contractional faulting and Eps, pressure-solution (Simon & Gray 1982). The factors contributing to ET (total natural strain) may vary according to rock-type and position in the thrust sheet. Examples are given below, with determined values substituted for the terms in eqn (4).

Orthoceras Limestone: ET = −0.036 − 0.250 − 0.130 − 0.000 = −0.416 or 34% shortening

Upper Didymograptus Shale: ET = −0.011 − 0.250 − 0.13 − 0.025 = −0.416 or 34% shortening

Lower Silurian: ET = −0.020 − 0.185 − 0.040 − 0.056 = −0.306 or 26% shortening

Upper Silurian ET = 0.000(?) − 0.160 − 0.000(?) − 0.030 = −0.190 or 17.5% shortening.

CONCLUSIONS

From the analysis of the distribution of strain it is clear that the Cambro-Silurian stratigraphy of the Oslo region has not been uniformly deformed.

Deformation style changes upwards in the stratigraphic sequence from imbricate thrusts, triangle and pop-up zones to buckle folds. Unlike the higher buckle-folded parts of the stratigraphy many folds in the Cambro-Ordovician part of the thrust sheet have been produced by the transfer of brittle to ductile strains at fault tip lines. Spaced and pressure-solution cleavage development also preceded the propagating thrusts. Subsequent deformation folded the cleavages and displaced fold limbs giving rise to a hangingwall anticline–footwall syncline geometry along second order thrusts.

The change in deformation style is accompanied by a decrease in the amount of shortening upwards. Shortening ranges from about 34% in the Cambrian to mid-Ordovician sequence to 17.5% in the Ringerike Sandstone. Hence balanced cross-sections for the whole Cambro-Silurian sequence cannot be constructed from pin-lines on folds or faults in the Oslo region. Sections can, however, be made through the whole Oslo region when pinned in undeformed foreland. Sections pinned within the deformed sequence can be balanced if they are only made for a particular stratigraphic interval that exhibits uniform shortening, such as the Cambrian to mid-Ordovician sequence.

The decrease in the amount of shortening upwards in the Osen–Røa thrust sheet is repeated throughout the Oslo region (Strand 1960, Morley 1983). In order to balance the amount of shortening achieved by internal deformation of the lower units, the higher units must have achieved the same amount of shortening by overthrusting, i.e. 34% shortening by Cambro-Ordovician sequence, comprising 17% shortening by buckling of the Ringerike Sandstone and 17% by overthrusting. Therefore one or perhaps a series of bedding-parallel detachments need to be invoked to separate units of varying shortening and deformation style. Probably the most important higher detachment level is the boundary that separates the fold dominated rocks from thrust dominated rocks. This would place the upper detachment in the Lower Silurian Stricklandia shales (Stage 6) (Fig. 11). The regional implications for the upper detachment horizon(s) are discussed by Morley (1983 and in prep.).

The deformation style is not even uniform in the Cambro-Ordovician stratigraphy. A high density of thrusts is found in the Cambrian–Lower Ordovician sequence which is made up predominantly of shales with two (1 m and 7 m thick) limestone horizons that act as marker horizons for the imbrication. The presence of the first thick limestone unit (40–50 m thick Ampyx Limestone) causes a 56% drop in the number of second order thrusts present and a rise of 36 m in the average throw of thrusts in the Chasmops Series compared to the Cambrian to Lower Ordovician sequence. The tendency for greater displacement on fewer thrusts upwards is reversed at the level of the Tretraspis Shale and Limestone. There the intense imbrication from local detachment horizons in the Tretraspis Shales produces a 525% increase in the number of thrusts and a decrease in the average stratigraphic separation by 44 m. The thrusts of small displacement present in the Tretraspis Limestone are rapidly killed off upwards. The 150 m thick lower Silurian Shale sequence enables thrusts of even large throw to dissipate their slip in a variety of ways. Almost all thrusts generated from the Osen–Røa detachment are killed at the top of the Silurian shales.

Vertical lithological variations within the Cambro-Silurian sequence have critically influenced the deformation style exhibited by the Osen–Røa thrust sheet. The influence of the lithology on deformation style includes several factors: (1) gross lithological type, (2) thickness of lithological units, (3) subtle lithological variations in the size of limestone nodules and ratio of limestone nodules to shale (e.g. the difference between the Tretraspis limestone and other limestones), (4) vertical position of a lithological unit within a thrust sheet and (5) general lithological trends, such as an overall increase in competent units upwards.

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