Pergamon

Journal of Structural Geology, Vol. 16, No. 5, pp. 619 to 631, 1994
Copyright © 1994 Elsevier Science Ltd
Printed in Great Britain. All rights reserved
0191-8141/94 $07.00+0.00

Fold-generated imbricates: examples from the Caledonides of Southern Norway

C. K. MORLEY

Elf Aquitaine (Production), Avenue Larribau, 64018 Pau, France

(*Received* 10 *February* 1992; *accepted in revised form* 20 *June* 1993)

Abstract—The Cambro-Silurian sequence of the Oslo Region contains fold trains and closely spaced imbricate thrust faults. The imbricates could be interpreted as having ramped off the sole detachment and generated fault-propagation folds. Several imbricate thrusts, however, appear to die out both downwards and upwards into folds. This suggests that the thrusts were generated within the Cambro-Silurian sequence and propagated down to the sole thrust rather than propagating upwards from the sole thrust. The mechanical stratigraphy is apparently responsible for this style where, during folding, relatively brittle limestone members faulted in the highly strained fold forelimbs prior to through-going faulting developing in the shales. Understanding the origin of such imbricates is important when choosing a method of section restoration.

INTRODUCTION

THE external zones of thrust belts can be viewed as displaying two end-member geometries. The first is dominated by semi-brittle deformation, where most of the shortening occurs along thrust faults and folding mechanisms are dominantly fault-bend and fault-propagation folding (Rich 1932, Elliott 1976, Suppe & Namson 1979, Suppe 1983, 1985). Both folding mechanisms are driven by faulting, the first by draping and the second by strain accommodation at a propagating fault-tip. The second end member geometry is that seen in thrust belts dominated by a series of fold trains that suggest buckling, note thrusting was the dominant deformation style within the thrusts sheets (e.g. Zagros, Jura Mountains). Whether part of a thrust belt deformed dominantly by buckling or faulting is largely a question of how the mechanical stratigraphy behaved under different combinations of stresses, temperatures, lithostatic pressures and pore-fluid pressures. In this paper, imbricates at the base of the Osen–Røa thrust sheet in Norway are examined to determine whether imbrication occurred first and the accompanying folding occurred in response to thrusts ramping off the master detachment or whether folding preceded imbrication.

GEOLOGICAL SETTING

The Caledonian deformation style in the Cambro-Silurian sequence of the Oslo Graben is dominated by imbrication, back thrusting and folding above a detachment horizon formed in the Cambrian Alum Shales (Brøgger 1882, 1890, Kiaer 1908, Holtedahl & Schetelig 1923, Strand 1960, Skjeseth 1963, Owen 1977, 1978, Harper & Owen 1983, Bockelie & Nystuen 1984, Morley 1986a,b, 1987). The underlying Precambrian basement is undeformed by Caledonian events. The Asker area Cambro-Silurian stratigraphy is dominated by a sequence of alternating shales and limestones; major limestone units are thicker and occupy a greater percentage of the stratigraphic column upwards (Skjeseth 1963, Owen 1978, Bockelie & Nystuen 1984, Morley 1986a, 1987). The sequence is capped by the thick (in places over 1000 m thick) Ringerike sandstone. The effect on deformation style of the variations in stratigraphy is to produce closely spaced imbricate thrusts in the lower part of the sequence (Cambro-Lower Ordovician) which become more widely spaced higher in the sequence (Fig. 1) (Morley 1986a). Generally first-order folds become more open and have greater wavelengths passing up section (Morley 1986a).

This paper focuses on the deformation style within the Cambro-Mid Ordovician section (Fig. 1). The Cambro-Lower Ordovician sequence is composed predominantly of black–dark grey shales and thin limestones. It is about 150 m thick, with one 7–10 m thick limestone (Huk Formation; previously called the Orthoceras Limestone) occurring about 90 m high in the section. Capping the sequence investigated here is the 40 m thick Vollen Formation (formerly Ampyx limestone), which marks the beginning of a sequence of evenly-spaced alternating limestone and shale units between 30 and 50 m thick that compose the Middle Ordovician.

OBSERVATIONS ON DEFORMATION STYLE OF CAMBRO-MID ORDOVICIAN SEQUENCE

In the Oslo area, good sections through the Cambro-Mid Ordovician sequence are present on the Island of Bygdoy and at Slemmestad (Figs. 2 and 3). Slemmestad gives the best (partial) down-plunge view due to rising topography to the west and a 10–15° westward plunge to the area.

The lowest part of the section comprises the black Cambrian Alum Shales and dark grey–black Ordovician Shales (Tøyen Formation). The main sole thrust (Osen–Røa detachment) lies within the Alum Shales as a zone

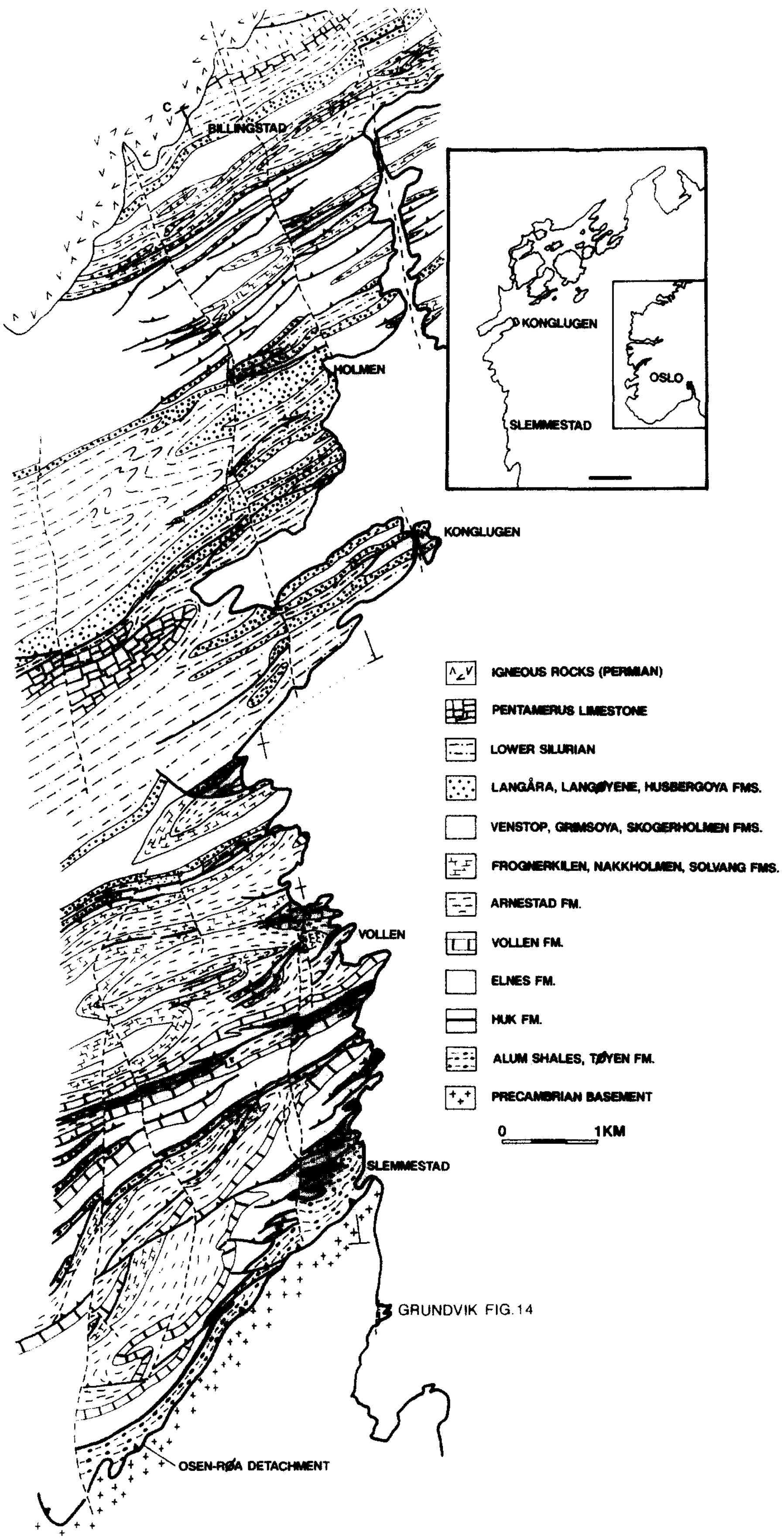


Fig. 1. Map of the Asker–Baerum Region, Oslo, simplified from unpublished maps by Morley.

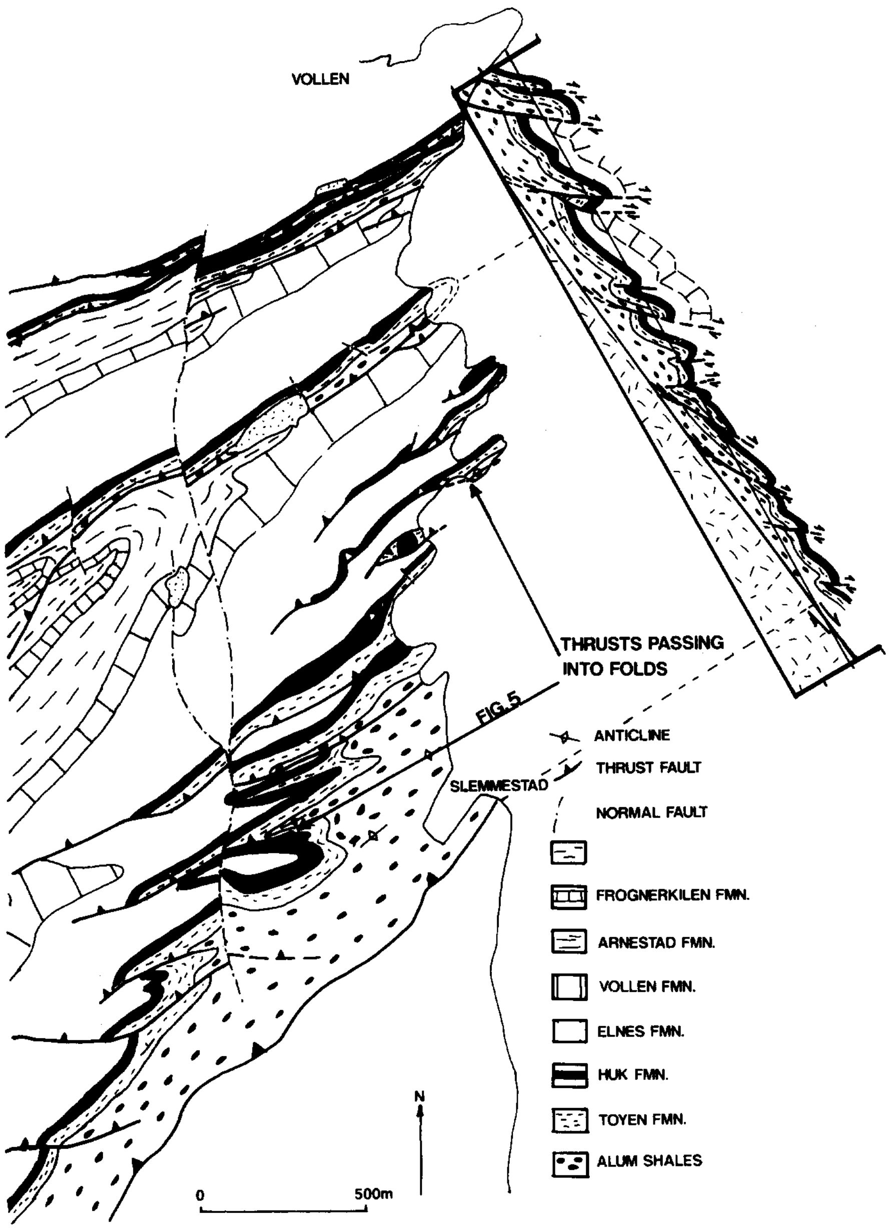
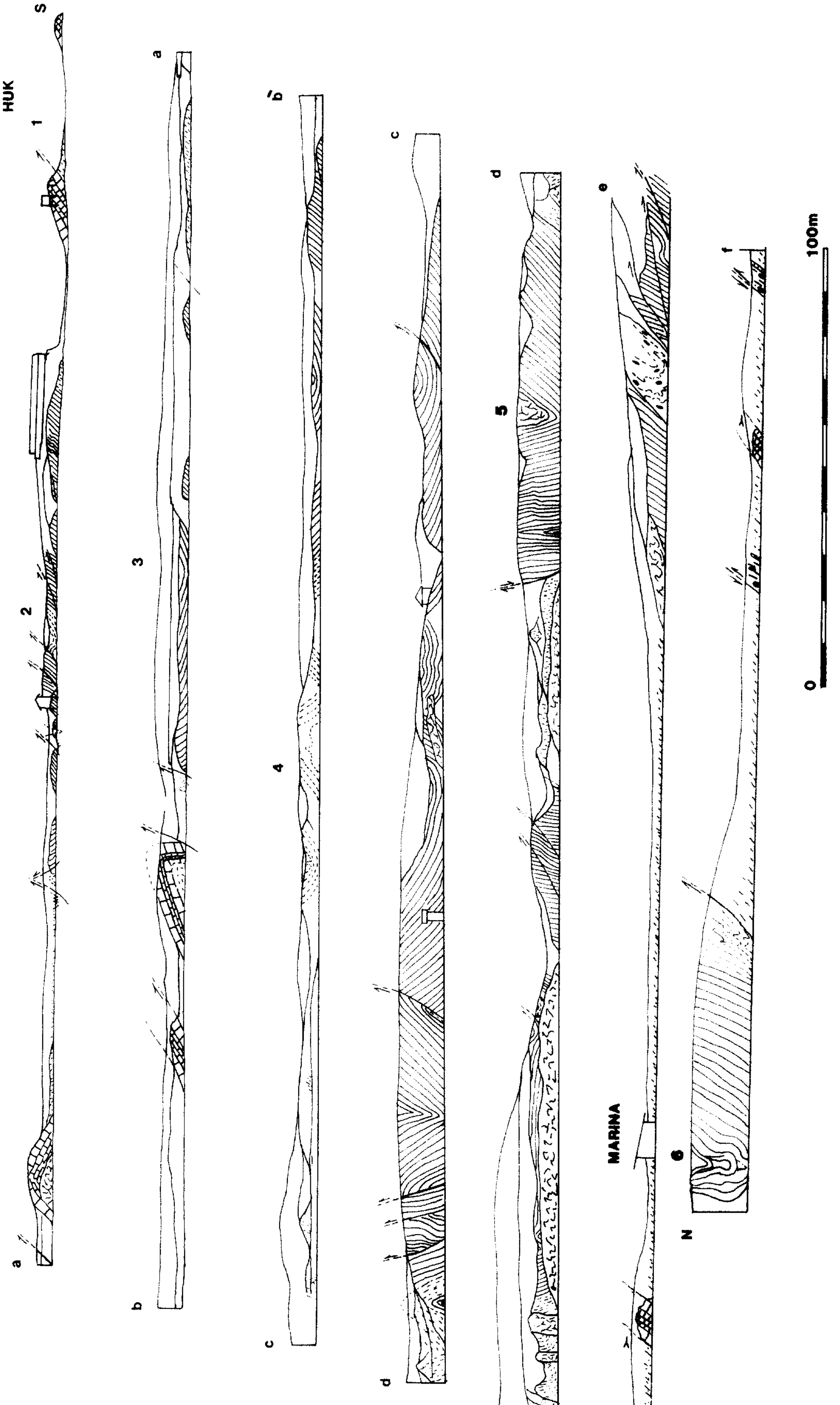


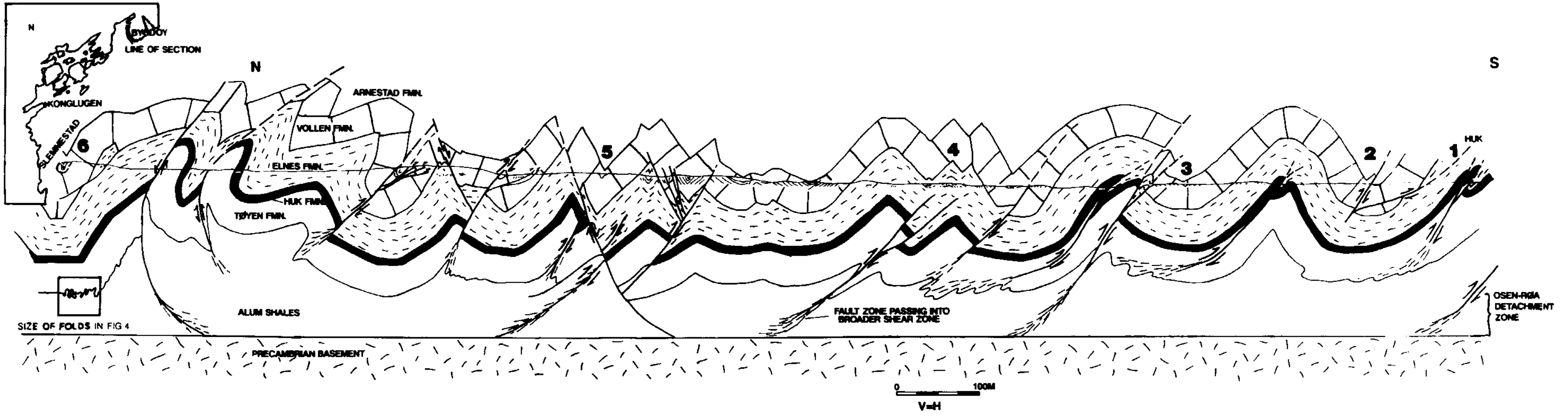
Fig. 2. Detailed map of the Cambro–Ordovician sequence in the Slemmestad area (detail of Fig. 1).

characterized by numerous slip planes which tend to follow bed-parallel fissility. The shale mass is also folded; fold wavelengths range from a few millimetres to tens or hundreds of metres. The folds are disharmonic. One example of intense deformation within the shales is given in Fig. 4. Tight to isoclinal disharmonic folds are present where the wavelength is smaller than the amplitude. In one case (the southernmost fold, Fig. 4), all the shale was squeezed out from the centre of a syncline in the limestone. Apparently, folding could not accommodate all the shortening and at some late stage, high-angle faults developed and accommodated the upward displacement of the shales begun by the strong amplification of the folds. To give an idea of the scale of these folds the small box within Fig. 3 shows the folding at the scale of Fig. 4. Intense minor folds are also displayed in map view at Slemmestad (Ramberg & Bockelie 1981). The intense short wavelength deformation is not seen in the overlying Huk Formation, where most shortening occurs on widely-spaced imbricate thrusts and folds with wavelengths of 100 m or more.

In coastal exposures extending approximately 1.5 km across strike near Slemmestad, the Huk Formation is repeated by 13 imbricate thrusts with horizontal offsets up to 150 m. Four of the thrusts pass down dip and laterally into anticlines within the Alum Shales (Fig. 5). The largest thrusts place Alum Shales over the Vollen Formation. These imbricates do not die in diffuse structures within the shales but form narrow fault zones. The lateral equivalence of folds and small displacement faults suggests that at least four of the thrusts did not propagate upward from the basal detachment but nucleated within the thrust sheet and propagated upwards and downwards. This observation suggests a 'break thrust' or 'strut thrust' origin for some of the imbricates (e.g. Brøgger 1890, Willis 1893, Willis & Willis 1934, Fischer & Woodward 1991, Fischer *et al.* 1992). Such faults would have grown by propagating down through



(a)



(b)

Fig. 3. Cross-section along coastal exposure of western side of Bygdoy. (a) Section along the west coast showing the basic geology from which the cross-section in (b) was constructed. (b) Interpretation of geology illustrated in (a).

the folds to meet the Osen-Røa detachment zone (Figs. 6 and 7). The largest thrust faults do not display easily recognizable break thrust characteristics, although that may have been their origin.

CROSS-SECTION CONSTRUCTION

The maximum vertical relief of exposures is limited to a few tens of metres, but coastal sections are very continuous. Thus in order to construct cross-sections, it is necessary to use regional surface maps to predict the structural style above and below the exposed section and local surface maps to project structural information into the line of section (e.g. Morley 1986a,b, 1987). Figure 3(a) illustrates the actual data that were used (from a long coastal exposure) to generate Fig. 3(b). A variety of structural models exist which predict how folds and thrusts such as those in Fig. 3(a) can be projected into the subsurface. The Vollen Formation displays some tight folds with angular hinges that suggest a kink band fold geometry is appropriate. Thus application of fault-bend or fault-propagation fold modelling techniques to the section (e.g. Suppe 1985, Jamison 1987) would appear to be appropriate. However, for these models to be appropriate, the folds should be generated in response to thrusting. The actual data show trains of folds, suggestive of buckle folding, rather than thrust-generated folds. Folding of some thrusts also indicates a buckling component to the deformation and the two back limb thrusts are uncharacteristic of fault-progagation folds. Thus a significant part of the deformation cannot apparently be modeled by simple fault-propagation fold geometries.

The cross-section in Fig. 3(b) was constructed assuming that the folds style is approximately parallel, however minor flowage of the shale units and minor accommodation faulting in both the shales and limestones can locally modify this simple assumption. The limestone units were line-length balanced. However, the presence of locally occurring pressure solution cleavage, particularly in fold axes suggests that simple line-length balancing is not entirely appropriate. Probably the error caused by the presence of cleavage is small (about 5%). Where the Lower Ordovician occupies a large, well exposed area (e.g. Slemmestad area Figs. 1 and 2), the Huk Formation is imbricated on average every 140 m. Spacing of imbricates in the overlying Vollen Formation is greater, indicating that some imbricates die out within the intervening Elnes Formation (Figs. 1 and 2). In the Bygdoy cross-section (Fig. 3) the Vollen Formation crops out for large portions of the cliff section (Fig. 3a), consequently, the presence of blind imbricates in the underlying Huk Formation needs to be predicted. Some very small displacement faults in the Vollen Formation are assumed to increase in displacement downwards, whilst other imbricates within the Huk Formation are assumed to terminate as blind thrusts in the Elnes Formation. These predicted thrusts were inferred to preferentially form on the fore limbs of folds, following the observed deformation style in the Slemmestad area (Fig. 2). The presence of blind thrusts is also required to help increase the line length of the Huk Formation to equal that of the Vollen Formation. Typically, when constructing cross-sections the interpreter assumes that the imbricate thrusts connect with the sole detachment. In the Bygdoy section, the smaller imbricate faults (with less than 50 m displacement) are illustrated as dying out downwards into folds (such as those illustrated in Fig. 4) and having formed as break thrusts. The reasons for this interpretation are based on mapping in the Slemmestad area and are discussed in detail in this paper.

CHARACTERISTICS FOR IDENTIFYING BREAK THRUSTS

The one diagnostic characteristic that separates break thrusts from upwards propagating thrusts is the pattern of displacement on the fault plane. Ideally, a thrust which developed by splaying off another thrust should display a displacement maximum at the branch line between the two thrusts and convex upwards and lat-

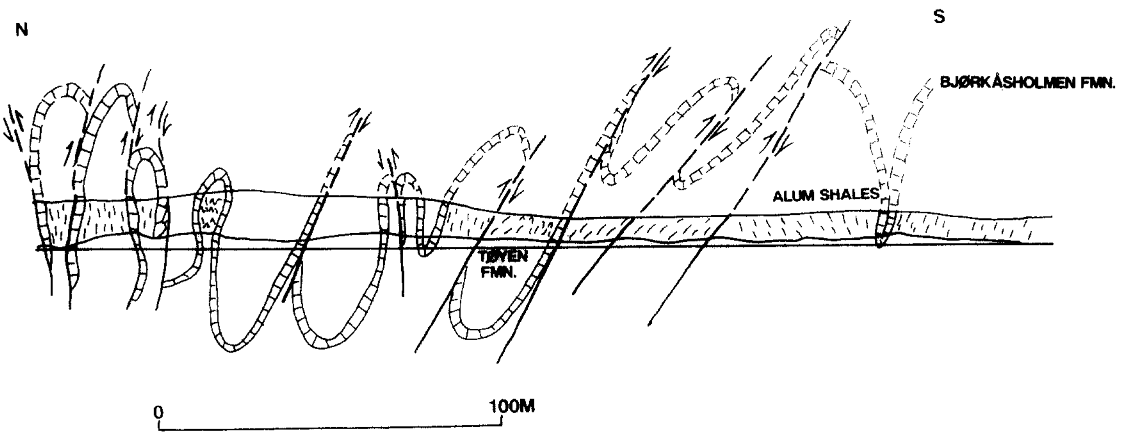


Fig. 4. Sketch of outcrop illustrating the deformation of the Alum Shales–Tøyen Formation in the Ringerike area. Section constructed from roadside outcrop. A map illustrating this type of deformation in the Slemmestad area is illustrated in fig. 3 of Ramberg & Bockelie (1981).

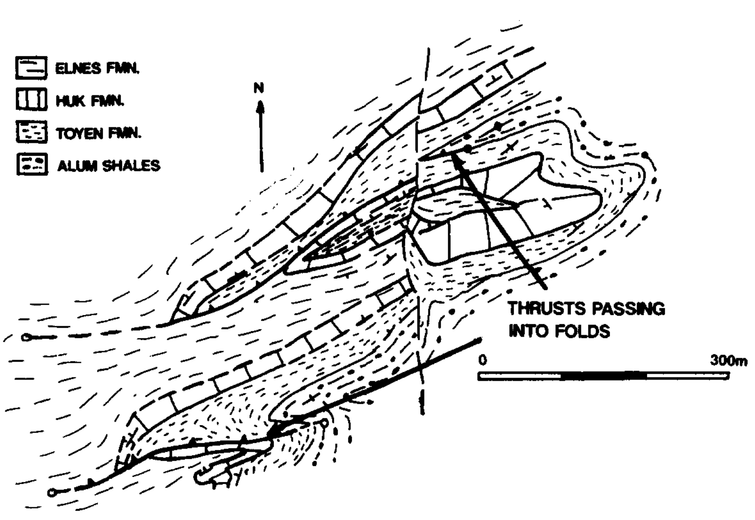


Fig. 5. Detailed maps from the Slemmestad area illustrating thrusts passing down-section into folds (see Fig. 2 for location).

erally away from the region of maximum displacement (Fig. 6b). Conversely a break thrust should be an elliptical fault plane with a displacement maximum at the centre, and the displacement contours should decrease in value concentrically away from the centre (the idealized somigliana dislocation geometry, Eshelby 1973, Elliott 1976, Williams & Chapman 1983) (Fig. 6a). Such a dislocation would propagate in all directions, although physical modeling suggests that the initial lateral propagation of faults (until they begin to coalesce) might be an order of magnitude faster than the vertical propagation (Mulugeta & Koyi 1987).

As a break thrust propagates downwards it might reach a detachment horizon, at which point the break thrust (if it does not propagate through the detachment zone) might be captured by the detachment zone. Thus two different displacement gradients will be superimposed on one fault (Fig. 6c).

While it is possible to describe such fault systems theoretically, it is difficult to impossible to find good

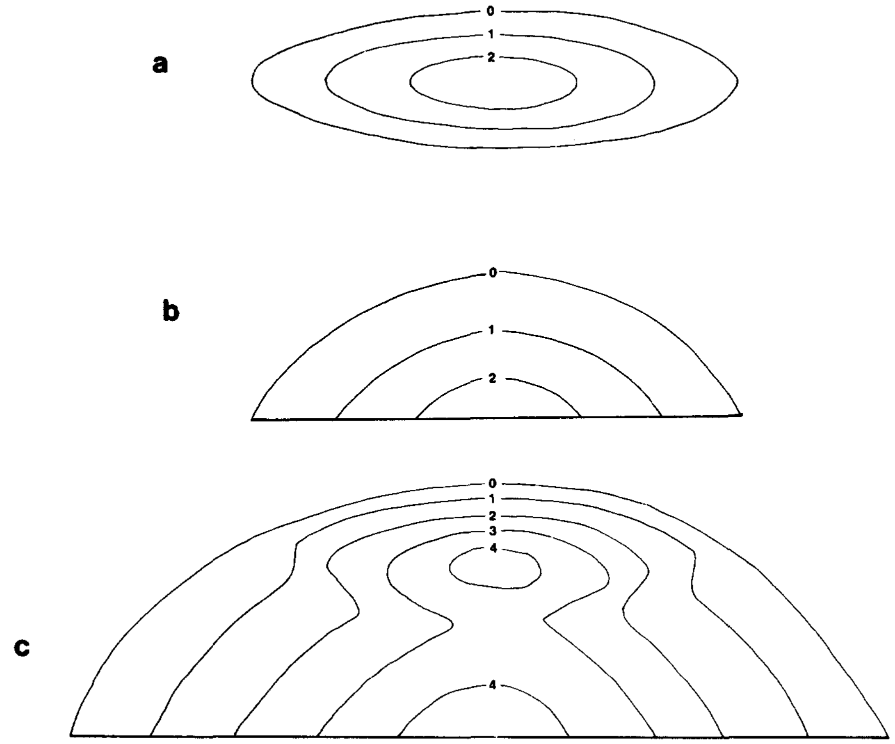


Fig. 6. Schematic diagrams of displacement contours on a fault plane illustrating: (a) displacement decreasing concentrically away from a central nucleation point (i.e. break thrust situation); (b) displacement decreasing upwards and laterally; downwards displacement is not possible (i.e. thrust splaying off a larger fault); and (c) superimposed displacement contours on hybrid thrust where, for example, a later splaying thrust (b) has incorporated an earlier break thrust (a) into its displacement field.

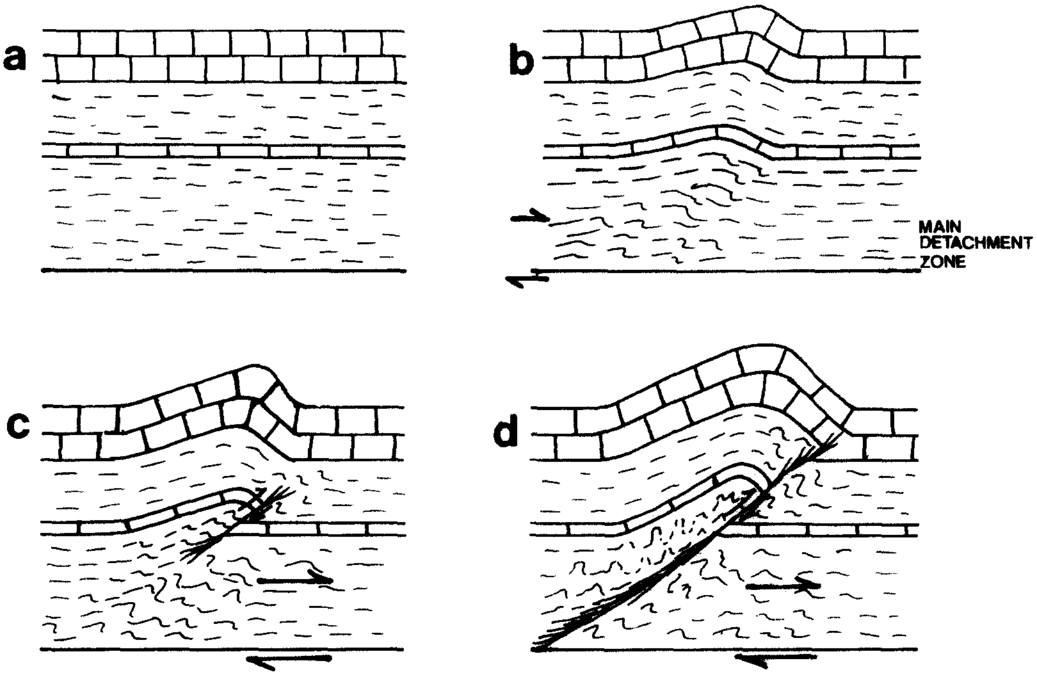


Fig. 7. Idealized evolution of a break thrust that develops in a relatively competent unit during folding.

enough exposures to demonstrate conclusively such displacement patterns in the field particularly on larger faults. It is, therefore, necessary to examine other aspects of fold and thrust geometry for additional diagnostic characteristics. These characteristics are discussed below with specific reference to the Oslo Region.

Evidence for relative timing of structures

Break thrusts develop during folding, consequently, if faulting occurred prior to folding a break thrust origin is not possible. However, the synchronous or post-folding timing of thrust development is a characteristic of both fault-propagation folding and break thrusting. So, although the correct timing of structures must be demonstrated, this characteristic alone is insufficient to definitely prove a break thrust origin.

The Osen–Røa thrust sheet in the Oslo Region displays a progression of deformation styles that occurred within a single major thrusting episode. Some of the earliest structural features are pressure solution cleavage and thrust wedges that were rotated during later folding and thrusting (Morley 1986a,b, 1987). The relationship between folding and thrusting is, in places, complex. Some folding prior to thrusting can be demonstrated where faults cut across both fold limbs or when overturned beds display footwall cutoffs with an unfolded fault. For example, Fig. 8 illustrates a thrust which cuts laterally across the overturned forelimb of an anticline, across a synclinal axis to lie on the backlimb of

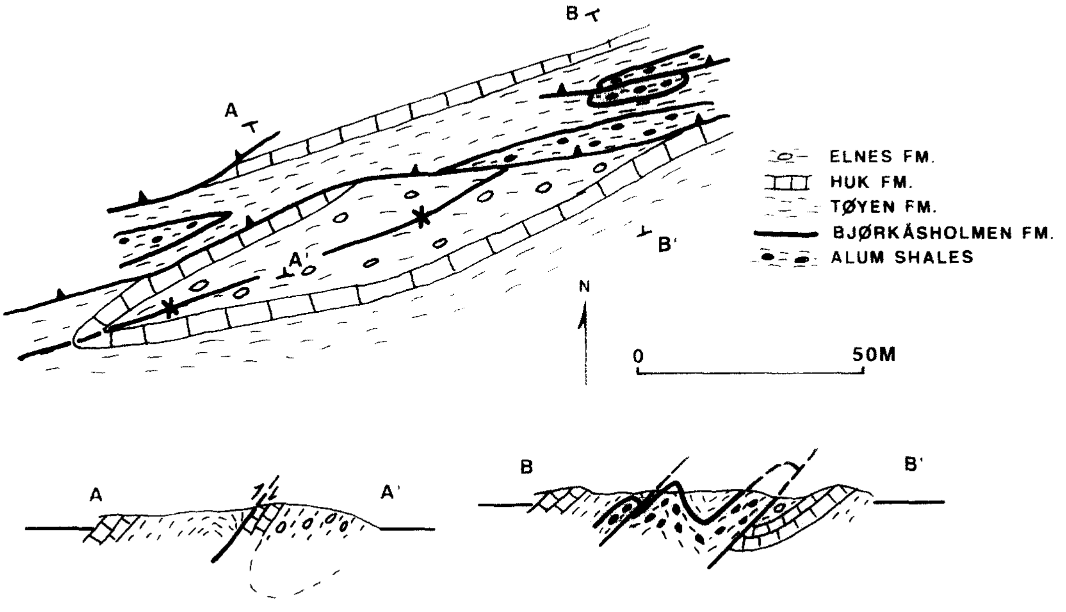


Fig. 8. Geological sketch map illustrating a relatively early fold axis cut by a relatively late thrust. Ringerike (grid ref. 734 718). Sections projected from outcrops exposed in road cuts.

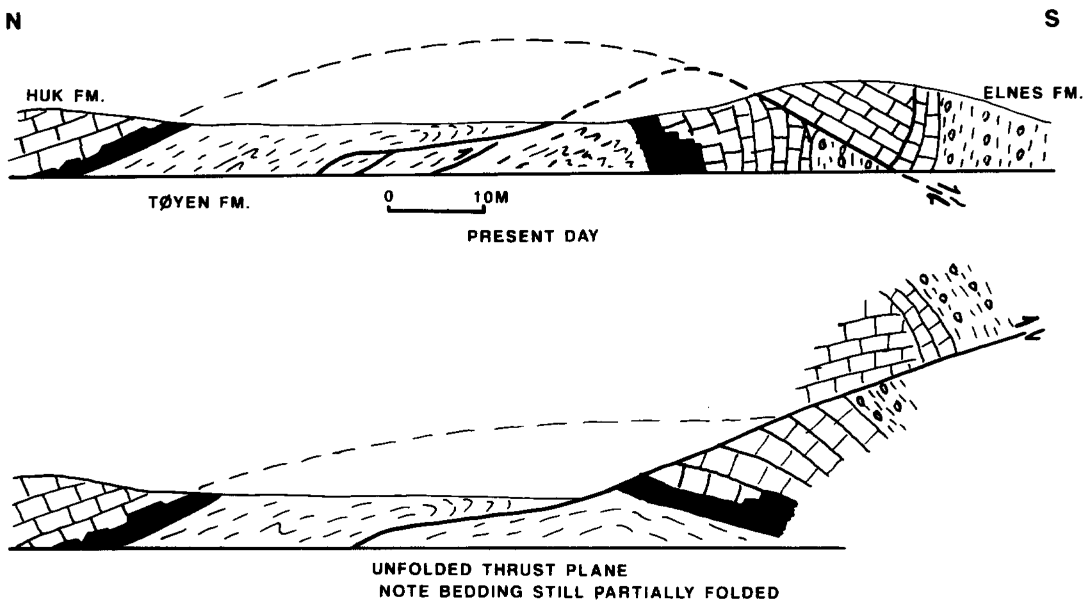


Fig. 9. Profile through folded and thrusted lower Ordovician rocks Hamar (North Oslo Region, grid ref. 081 484), partially unfolding the section shows that thrusting occurred during folding.

the next anticline to the south. Other outcrops show that some folds have later continued to tighten and have folded earlier thrusts (Figs. 9 and 10). Consequently, the development of folding and thrusting appears to have a complex and synchronous history.

Section balancing, forward modelling

One of the characteristics of both fault propagation folds and break thrusting is the presence of a long hangingwall flat–footwall ramp below the hangingwall ramp which truncates the anticline forelimb (Fig. 11). In the case of fault propagation fold, the hangingwall flat lies within the master detachment horizon (Fig. 11b). This is not necessarily the case for a break thrust (Fig. 11c). Hence if the apparent detachment zone lies in a mechanically unreasonable lithology, there would be good grounds for suspecting a break thrust origin.

The hangingwall flat geometry can, however, be generated without fault-propagation folds or break thrusts by two different ways in computer-generated forward models as follows. (1) Out-of-sequence imbri-

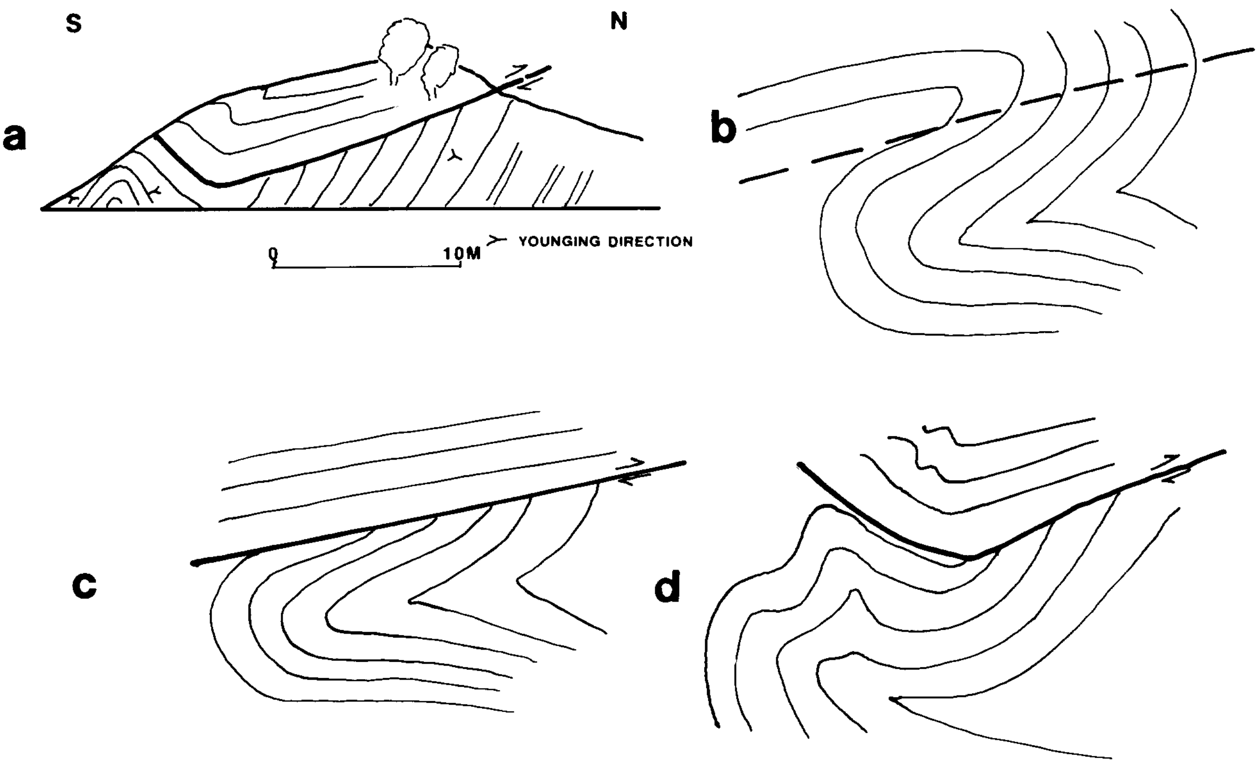


Fig. 10. Sketch of Huk Formation outcrop, Hamar area (grid ref. 160 412).

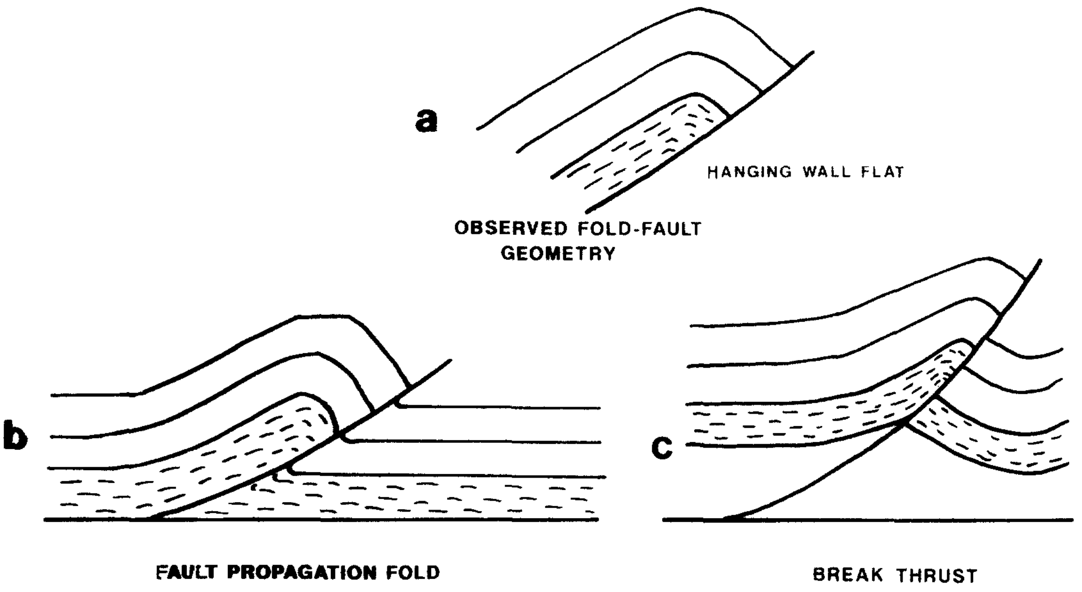


Fig. 11. Two basic subsurface interpretations that can be made from the same surface geometry (a): (b) fault propagation fold: and (c) break thrust.

cation superimposed on in-sequence imbricates. This deformation sequence requires the later imbricates to propagate near the backlimb of the first generation fold bend folds (Fig. 12). It produces a pattern of alternating relatively high and low intersection angle between bedding and the imbricate thrusts, corresponding to the in-sequence and out-of-sequence thrusts, respectively. (2) The imbricates initially had staircase trajectories (Fig. 13).

The main detachment zone for the Oslo Region lies within the Alum Shales, up to 100 m below the Huk Formation. If the imbricates were modelled as simple fault-propagation folds, they would commonly flatten into a primary detachment zone above the Alum Shales or at the top of the Alum Shales (Fig. 11b). Such geometry would require another ramp to reach the master detachment (Fig. 11c). This geometry is atypical for simple imbricate systems (where a listric or planar thrust propagates upwards from basal detachment). It could, however, be argued that the imbricates originally had a staircase trajectory (Fig. 13) and that the fold geometry is a result of a combined fault-propagation fold and ramp flat imbricate geometry.

Fault-bedding geometry is not a very helpful discrimination technique. A number of the possible solutions are not appealing or require considerable fortuitous coincidences (e.g. the out-of-sequence imbricate solution), but that does not enable them to be ruled out completely.

Fold geometry

In natural and graphic models of fault-propagation folds, the footwall syncline area tends to be horizontal to

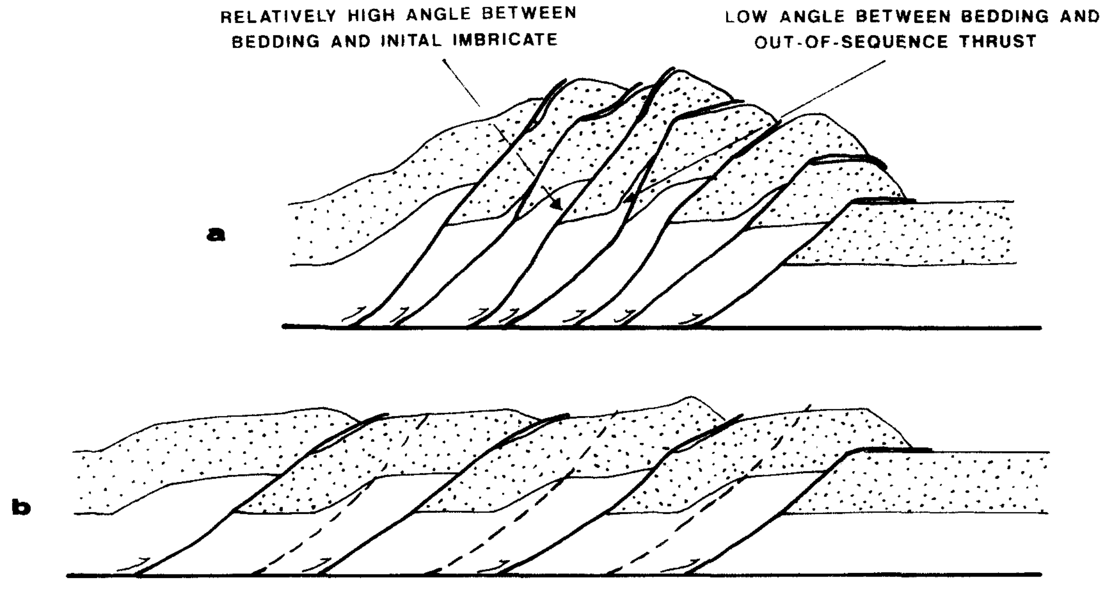


Fig. 12. Forward model of imbricates with a later set of faults superimposed on a set of earlier imbricates (software used: Midland Valley, flexural-slip algorithm).

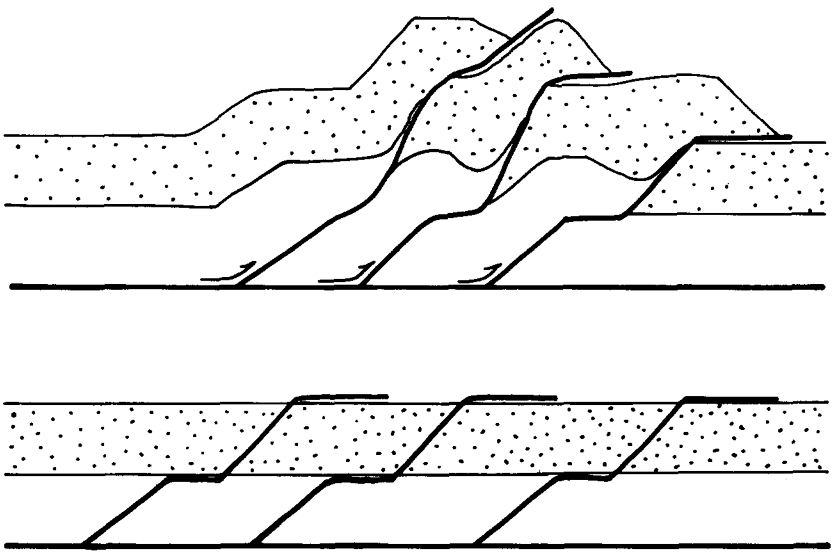


Fig. 13. Forward model of staircase imbricates trajectories (software used: Midland Valley, flexural-slip algorithm).

sub-horizontal and displays much less shortening by folding than the hangingwall (e.g. Chester & Chester 1990, Mitra 1990) (Fig. 10b). The Ordovician rocks of the Oslo Region display trains of folds rather than isolated folds localized near the thrust plane. The synclines and anticlines are commonly of equal amplitude and wavelength (more akin to Fig. 10c) and in places a series of anticlines and synclines largely unbroken by significant thrusts can be found. Fischer *et al.* (1992) noted that fault propagation and detachment fold theory predicts a large range of fold wavelengths that depend upon how far the fold has evolved. Buckle folding predicts a relationship between fold wavelength and the thickness of competent layering. This relationship between fold wavelength and thickness of the competent layer is well displayed in the southern Asker area (Fig. 1), where the thin competent Huk Formation is folded on wavelengths of 20–200 m, while the relatively competent Middle Ordovician sequence (Vollen, Arnestad, Frognerkilen, Nakkholmen and Slovang Formations) displays wavelengths of 200–500 m. The relationships discussed above suggest that buckle folding is an important deformation style in the Oslo Region.

One other piece of evidence in favour of fold-generated faults comes from a small transfer zone at Grundvik (Fig. 14). The northern part of the peninsula contains an anticline in the Huk Formation. The western side of the anticline verges to the south and the southern limb is cut by a (fore) thrust. Passing eastwards, the northern limb becomes strongly vergent towards the north and is displaced by a backthrust. The thrusts die out laterally where the fold limb becomes more gently dipping. If this were a fault propagation fold it would be difficult to understand the lateral change in vergence and how two faults which converged at depth could operate simultaneously without one fault cutting and deactivating the other. It is easier to understand the geometry in terms of buckle folding, where the two faults nucleated within the Huk Formation in response to buckling.

The buckle fold style becomes more apparent passing up section. Figure 1 shows that many of the thrusts in the Lower Ordovician-Cambrian sequence did not penetrate the Vollen Formation (west of Slemmestad). Within the middle and upper Ordovician sequence thrusts are much less frequent than in the lower Ordovician (Fig. 3). The section along Bygdoy illustrates the mixture of concentric fold and kink band–chevron style of folding in the middle and upper Ordovician units. In places dips change abruptly along tight angular hinges and hinge collapse structures occur. The section was constructed with the assumption that many of the smaller thrusts pass downwards into folds within the Alum Shales, the larger thrusts are shown to have reached the Osen–Røa detachment. These relationships cannot be demonstrated on Bygdoy, but are consistent with the observations made in the Slemmestad area (Fig. 2).

Both fault-propagation folds and fold-generated faults tend to cut through the forelimbs of anticlines and are superficially geometrically rather similar. In Asker, exposure is generally not good enough to accurately determine whether changes in displacement occur upwards from the base of the master thrust, as would be predicted for a fault-propagation fold, or upwards and downwards from a point part way along an imbricate thrust, as predicted for a fold-generated fault (Fig. 6). Consequently, it is not possible to demonstrate conclusively that all the imbricate thrusts in Figs. 2 and 5 have the same origins. Indeed a mixture of imbricate types is likely.

There is some experimentally evidence which suggests that break thrusts should occur in nature. Previous work on nucleation of thrusts suggests that they may be initiated within the most competent layers (e.g. Chamberlain & Miller 1918, Balicki & Spang 1975; see previous work section in Eisenstadt & De Paor 1987). More recent studies on the evolution of thrust structures in multi-layered physical models suggests that thrusts nucleate from stiff layers initially deformed into buckle folds (Dixon & Tirrul 1991, Liu & Dixon 1990, 1991).

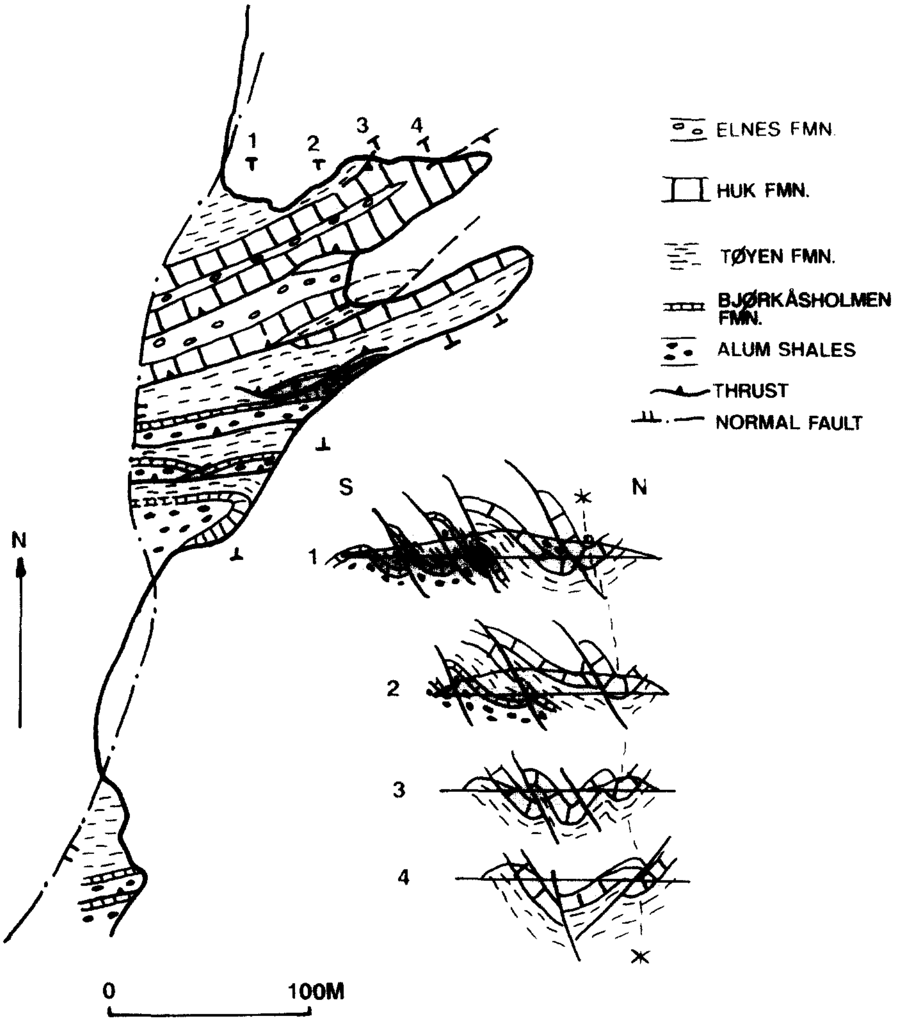


Fig. 14. Geological map and cross-sections of the Peninsula of Grundvik, see Fig. 1 for location.

Consequently, the nucleation of thrusts within the Huk Formation seems mechanically reasonable because it is a relatively brittle limestone encased in relatively ductile shales. The folds in the Oslo Region commonly verge strongly (to the southeast), hence the strains are highest in the forelimbs of anticlines. It is, therefore, likely that during fold development as the forelimbs became more highly strained, the Huk Formation tended to fault while the shales continued to deform by folding (as illustrated schematically in Fig. 7).

CONCLUSIONS

In earlier papers, Morley (1986a, 1987) assumed that imbrication in the Cambro-Lower Ordovician sequence of the Oslo Region was a product of thrusts ramping and splaying off the main sole thrust (Osen-Røa detachment). This is a common assumption made in many thrust belts. In some examples, however, the imbricate thrusts located within the Lower Ordovician sequence die out rapidly laterally and possibly downwards into folded strata within the Alum Shales. These imbricate thrusts generally cut the forelimbs of folds in limestones of the Huk Formation. It can, therefore, be proposed that certain imbricates were initiated during folding within the more competent Huk Formation, while folding continued in the surrounding shales (Brøgger 1890). As the shortening increased, the thrusts propagated both upwards and downwards (towards the master detachment). It is likely that faulting could have initiated in other relatively brittle members of the Cambro-Lower Ordovician sequence and that the larger imbricates are the products of the linkage of several faults as proposed by Eisenstadt & De Paor (1987). After the faults propagated down to the detachment a new displacement pattern could have been superimposed on the original one.

If fold-generated faulting initiated imbrication then the assumption of geometric fault-propagation–folding construction that thrust displacements only decrease upwards and laterally (Suppe 1985, Suppe & Medwedeff 1990) is invalid. However, in many areas it is very difficult to demonstrate how the displacements on faults change, and, thus, be able to distinguish between the two mechanisms. The main geometric features that suggest break thrusts are present are as follows: (1) appropriate deformation style is present (i.e. buckle folds, fold trains; Fischer *et al.* 1992); (2) faulting was synchronous with thrusting; (3) fault displacements decrease downwards (as well as laterally and upwards); (4) restored cross-sections show minor faults with a ramp–flat geometry above the master detachment; (5) some transfer zone geometries may be incompatible with upward propagating imbricates. Enlarging on point (1) above, probably the most common feature in the field that strongly suggests a buckle fold origin is the nature of the footwall deformation. In particular, the footwall syncline geometry is very important (Fig. 11). A relatively short wavelength, low amplitude syncline, with a sub-horizontal footwall (assuming no later back-rotation) suggests a fault propagation fold origin, a footwall syncline with a similar amplitude and wavelength to the hangingwall wall fold and with a strongly inclined forelimb suggests a buckle fold origin and hence a possible break origin for the thrust.

Acknowledgements—I would like to thank Dave Ferrill and Nick Woodward for very helpful criticism of the original manuscript.

REFERENCES

Balicki, M. A. & Spang, J. M. 1975. Multi-layer clay models of thrust faults and associated structures. *Geol. Soc. Am. Abs. w. Prog.* **7**, 586–587.

Bockelie, J. F. & Nystuen, J. P. 1984. *The Southern Part of the Scandinavian and Caledonides Orogen* (edited by Gee, D. G. & Sturt, B. A.). Wiley, New York.

Brøgger, W. C. 1882. Die Silurischen Etagen 2 and 3 in Kristiama-Gebret. *Universitatsprogramm Für Z, Sem.* 1882. Christiania, Oslo, 376.

Brøgger, W. C. 1890. Geologisk Kart Over Oerne Ved Kristiania. *Nye Magazin Naturvidenskaberne* **31**, 162–195.

Chamberlain, R. T. & Miller, W. Z. 1918. Low angle faulting. *J. Geol.* **26**, 1–44.

Chapple, W. M. 1978. Mechanics of thin-skinned fold-and-thrust belts. *Bull. geol. Soc. Am.* **89**, 1189–1198.

Chester, J. S. & Chester, F. M. 1990. Fault-propagation folds above thrusts with constant dip. *J. Struct. Geol.* **12**, 903–910.

Davis, D., Suppe, J. & Dahlen, F. A. 1983. Mechanics of fold-and-thrust belts and accretionary wedges. *J. geophys. Res.* **88**, 1153–1172.

Dixon, J. M. & Tirrul, R. 1990. Centrifuge modelling of fold–thrust structures in a tripartite stratigraphic succession. *J. Struct. Geol.* **13**, 3–20.

Eisenstadt, G. & De Paor, D. G. 1987. Alternative model of thrust fault propagation. *Geology* **15**, 630–633.

Elliott, D. 1976. The energy balance and deformation mechanisms of thrust sheets. *Phil. Trans. R. Soc. Lond.* **A283**, 289–312.

Eshelby, J. D. 1973. Dislocation theory for geophysical applications. *Phil. Trans. R. Soc. Lond.* **A283**, 289–312.

Fischer, M. P. & Woodward, N. B. 1991. The geometric evolution of foreland thrust systems. In: *Thrust Tectonics* (edited by McClay, K. R.). Unwin-Hyman, London, 181–190.

Fischer, M. P., Woodward, N. B. & Mitchell, M. M. 1992. The kinematics of break-thrust folds. *J. Struct. Geol.* **14**, 451–460.

Harper, D. A. T. & Owen, A. W. 1983. The structure of the Ordovician rocks of the Ringerike District: evidence of a thrust system within the Oslo region. *Norsk Geol. Tidsskr.* **63**, 111–116.

Holtedahl, O. & Schetelig, J. 1923. Kartbladet Gran. *Norsk Geol. Unders.* **97**, 46.

Jamison, W. R. 1987. Geometric analysis of fold development in overthrust terranes. *J. Struct. Geol.* **9**, 207–219.

Kiaer, J. 1908. Das Obersilur Im Kristiania. *Skr. Norske Vidensk Selsk. Mat. Naturv.* **2**, 595.

Link, T. A. 1928. Relationship between over-and-under-thrusting as revealed by experiments. *Bull. Am. Ass. Petrol. Geol.* **12**, 825–854.

Liu, S. & Dixon, J. M. 1990. Centrifuge modelling of thrust faulting: strain partitioning and sequence of thrusting in duplex structures. In: *Deformation Mechanisms, Rheology and Tectonics* (edited by Knipe, R. J. & Rutter, E. H.). *Spec. Publs geol. Soc. Lond.* **54**, 431–444.

Liu, S. & Dixon, J. M. 1991. Centrifuge modelling of thrust faulting: strain partitioning and sequence of thrusts in duplex structures. In: *Deformation Mechanics, Rheology and Tectonics* (edited by Knipe, R. J.). *Spec. Publs geol. Soc. Lond.* **54**, 431–434.

Mitra, S. 1990. Fault-propagation folds: geometry, kinematic evolution and hydrocarbon traps. *Bull. Am. Ass. Petrol. Geol.* **74**, 921–945.

Morley, C. K. 1986a. Vertical strain variations in the Osen–Røa thrust sheet, North-western Oslo Fjord, Norway. *J. Struct. Geol.* **8**, 621–632.

Morley, C. K. 1986b. The Caledonian thrust front and palinspastic restorations in the Southern Norwegian Caledonies. *J. Struct. Geol.* **8**, 753–765.

Morley, C. K. 1987. Lateral and vertical changes of deformation style in the Osen–Røa thrust sheet, Oslo Region. *J. Struct. Geol.* **9**, 331–343.

Mulugeta, G. & Koyi, M. 1987. Three-dimensional geometry and kinematics of experimental piggyback thrusting. *Geology* **15**, 1052–1056.

Owen, A. W. 1977. Upper Ordovician stratigraphy and trilobite faunas of the Oslo region with special reference to Ringerike and Hadeland. Unpublished Ph.D. thesis, University of Glasgow.

Owen, A. W. 1978. The Ordovician and Silurian Stratigraphy of Central Hadeland, South Norway. *Norges geol. Unders.* **338**, 1–23.

Ramberg, I. B. & Bockellie, J. F. 1981. Geology and tectonics around Oslo. In: *Guide to Excursion* B-4. 4th *Int. Conf. Basement Tectonics, Oslo* (edited by Larsen, B. T.). 81–99.

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.

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.

Suppe, J. 1983. Geometry and kinematics of fault-bend folding *Am. J. Sci.* **283**, 684–721.

Suppe, J. 1985. *Principles of Structural Geology.* Prentice-Hall, Englewood Cliffs, New Jersey.

Suppe, J. & Medwedeff, D. A. 1984. Fault-propagation folding. *Geol. Soc. Am. Abs. w. Prog.* **16**, 670.

Suppe, J. & Medwedeff, D. A. 1990. Geometry and kinematics of fault propagation folding. *Ecolog. geol. Helv.* **83**, 409–454.

Suppe, J. & Namson, J. 1979. Fault-bend origin of frontal folds of the western Taiwan fold-and-thrust belt. *Petrol. Geol. Taiwan* **16**, 1–18.

Williams, G. & Chapman, T. 1983. Strains developed in the hanging walls of thrusts due to their slip-propagation rate: a dislocation model. *J. Struct. Geol.* **5**, 563–571.

Willis, B. 1893. Mechanics of Appalachian structure. *U.S. geol. Surv. Annu. Rep.* **13**, (1891–1892), Part 2, 217–281.

Willis, B. & Willis, R. 1934. *Geological Structures.* McGraw-Hill, New York.