II

THE STRUCTURAL GEOLOGY OF THE SOUTHERN NORWEGIAN CALEDONIDES IN THE OSLO GRABEN AND SPARAGMITE REGION

Volume one

by

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The structural geology of the Southern Norwegian Caledonides in the Oslo Graben and Sparagmite region, by C.K. Morley

ABSTRACT

In order to construct the most continuous balanced cross-section from undeformed foreland to higher thrust sheets in the southern Caledonides of Norway, selected areas of Cambro-Silurian rocks were mapped in the Oslo Graben. Undeformed rocks are only present in the southern part of the Oslo Graben and palinspastic reconstructions of the Oslo Graben restore the traditional thrust front in southern Mjosa 135km NNW of its current position. Therefore it is proposed that the thrust front now be recognised in the southern Oslo Graben.

The traditional thrust front is interpreted here as the most southerly of a series of ramps in the Osen-Roa Thrust as it cuts up section towards the SSE. After ramping through the Hedmark Group (Eocambrian) the Osen-Roa Thrust forms the bed-parallel detachment in the Alum Shales (Middle Cambrian) of the Oslo Graben. Therefore it is proposed that the Osen-Roa Thrust Sheet continues into the Oslo Graben.

The Osen-Roa Thrust Sheet developed by gradually accreting foreland rocks onto its leading edge. Inital deformation around the master detachment tip produced pressure-solution and thrust wedging in competent units and layer parallel thickening in shales. Later deformation, perhaps at sticking points, resulted in the formation of second order faults, tip line and buckle folds and fracture cleavage. The deforming wedge of rock shortened unevenly, shortening less in the upper more competent part of the thrust sheet. This caused a bed-parallel upper detachment horizon to develop which transported the hangingwall rocks towards the hinterland relative to the underthrusting footwall rocks.

Balanced cross-sections from undeformed foreland through the Jotunheim and Trondheim regions restore to about 900km and 1300km respectively. In order to balance the crudely reconstructed Caledonian thrust belt a crustal pop-up model is proposed. Syn-orogenic sedimentation indicates movement of the Jotun Thrust Sheets from the Arenig to early Silurian. The Trondheim thrust sheets also began moving in the Arenig, but continued into the early Devonian when the Osen-Roa Thrust Sheet moved in the Oslo Graben. Thrust sheet transport directions swing from W-E to NNW-SSE with time.

ACKNOWLEDGEMENTS

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I thank Alan Owen who introduced me to the Hadeland and Ringerike areas and who gave me useful data on the stratigraphy of the Oslo Graben.

Many thanks are due to the staff of the City of London Polytechnic for their help and encouragement especially Dr. R. Skelhorne, Mr K. Roberts (chief technician) and Mr W. J. Ralph (who produced mountains of photographs for me).

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CONTENTS

LIST OF FIGURES

APPENDIX 1

LIST OF TABLES AND PLATES

CHAPTER 1

INTRODUCTION TO THE SOUTHERN NORWEGIAN CALEDONIDES.

1.1 The plate tectonic setting of the Caledonian orogeny.

The Caledonian was defined by Suess (1906, p.82) as 'Those pre-Devonian mountains which proceed from Norway and form the whole of Scotland.....', however, because some Devonian deformation is an obvious continuation of earlier, late Caledonian activity the pre-Devonian limit is too restrictive. Therefore Nicholson (1979) defined the limit of the Caledonides in space as the line enclosing all cleaved autochthonous Cambro-Silurian (and sometimes Devonian) rocks, so that the spatial limit is the deformation front.

The Caledonian Orogeny lasted from the Cambrian to Devonian times in Norway and was caused by the collision of the Eurasian and North American Plates (see Fig.1.1). This process probably involved the subduction of a hypothetical Proto-North Atlantic Oceanic Plate, which is now lost except for some volcanic suites in Britain, Norway and Newfoundland. For example the Storen and Koli Thrust sheets in the Trondheim region of Norway may be obducted slices of oceanic cover rocks (Gale and Roberts 1974) and a few true ophiolites e.g. the Karmoy Ophiolite (Sturt et al 1979), have been recognised. A cratonised belt of mainly continental crust and cover was accreted as a result of this collision onto the Russian and American platforms, (i.e. the Eurasian and North American continental masses).

CHAPTER 1

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1.1 The plate tectonic setting of the Caledonian orogeny.

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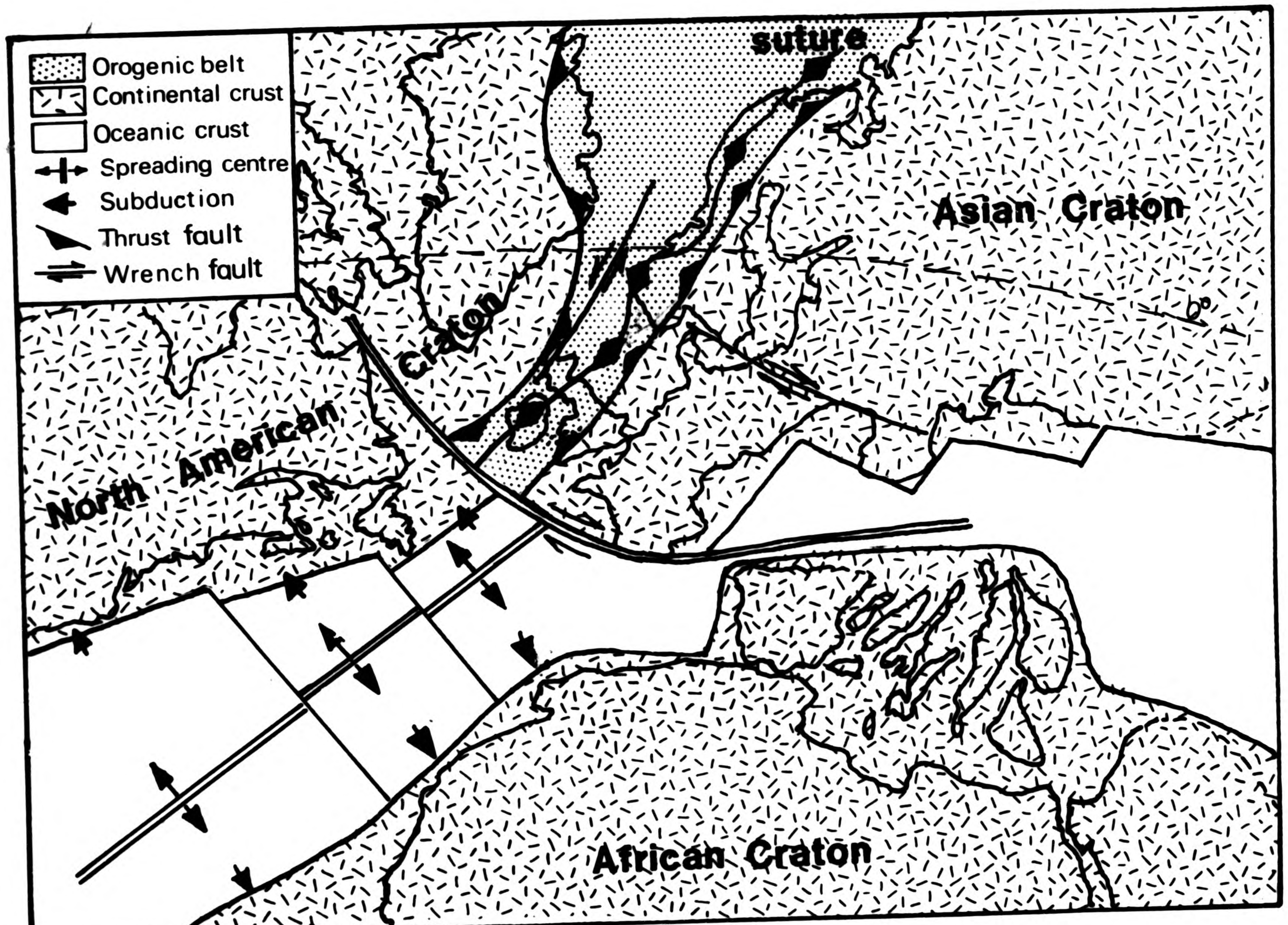
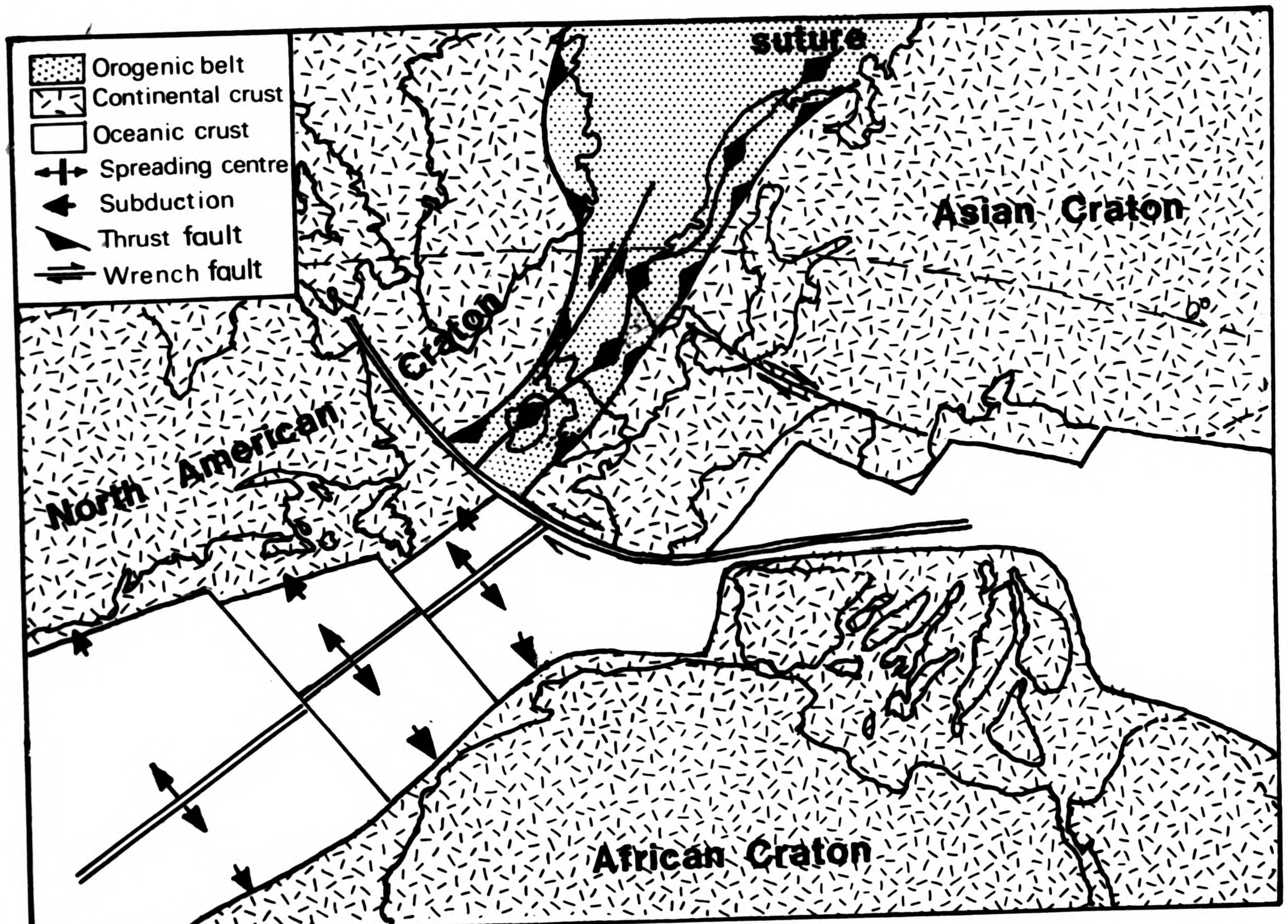
Fig.1.1 The plate-tectonic setting of the Caledonian orogeny (after Zeigler 1975).


Orogenic belt
Continental crust
Oceanic crust
Spreading centre
Subduction
Thrust fault
Wrench fault
suture
Asian Craton
Craton
North American
African Craton



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The North American plate has undeformed foreland to the west or north-west of the main thrust belts, which run from east Greenland, through north-west Scotland and Newfoundland and into the northern part of the Appalachians. In contrast the Norwegian and British Caledonides (outside N Scotland) have foreland rocks to the SSW or SW of the thrust belt. The two continents either side of the Proto-Atlantic ocean (or Iapetus) are supposed to be characterised in the Cambrian to mid Ordovician by separate faunas (Mc Kerrow and Cocks 1976); but though the North American thrust belts have a totally North American fauna present, the Scandanavian thrust belt includes tectonic units like the Storen Thrust sheet which have a North American fauna, in a region where Baltic faunas should be found (Neumann and Bruton 1974, Jaanusson 1973). These are called exotic thrust sheets by Hossack and Cooper (in press), they form the higher units in the thrust belt and could represent remnants of island arcs, transported on the subducting oceanic crust which collided with the Eursian plate in the lower and middle Ordovician.

The actual collision of the North American and Eurasian continental plates probably began to take effect in some areas in the late Cambrian to early Ordovician times along a very wide continental shelf, and deformation continued into the Devonian. The eventual uplift of the thrust belt to form land occurred at different times in different places, but approximates to the late Silurian or early Devonian and resulted in the widespread, continental, Old Red Sandstone deposits, derived by erosion of the rising Caledonide mountain chain.

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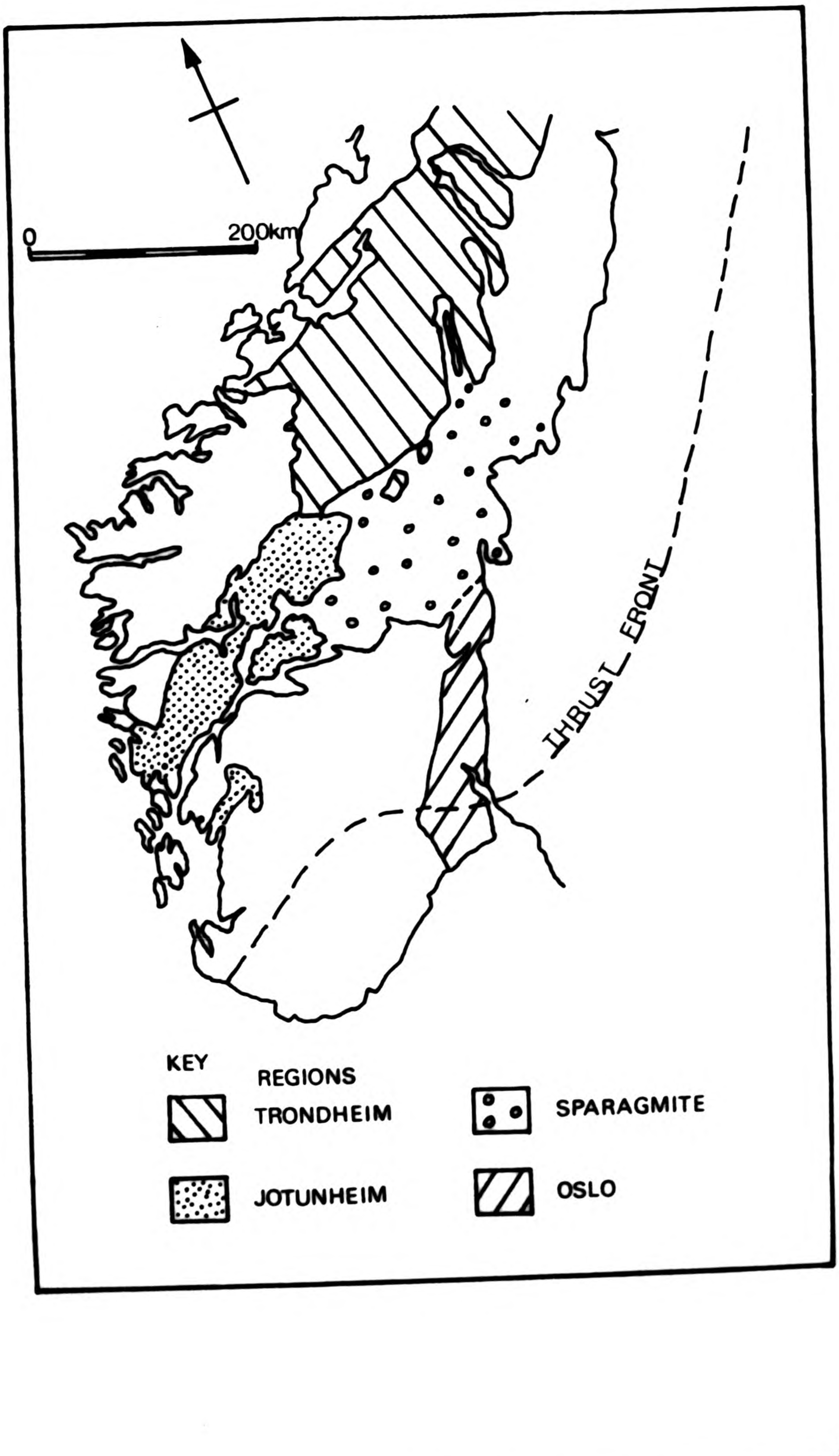
Fig.1.2 <u>The regions of the southern Norwegian Caledonides.</u>


0
200km
THRUST FRONT
KEY
REGIONS
TRONDHEIM
SPARAGMITE
JOTUNHEIM
OSLO

1.2 Introduction to the Geology of the Oslo Graben

The Southern Norwegian Caledonides form a deeply eroded mountain belt which trends roughly north east to south west along its axis. Erosion has removed most of the thrust belt, leaving the central spine of the thrust belt bounded to the NNW and SSE by Precambrian, Baltic shield gneisses. To the east and NE of the Jotunheimen the Caledonian belt broaden out into two regions (see Fig.1.2). The southern region is a broad area of late Precambrian clastic rocks called Sparagmites and the northern, Trondheim region is made up of stacked thrust sheets of mainly Cambrian to Silurian age. To the south of these areas is the Oslo Graben which is a north to south trending strip of Cambro-Silurian rocks, Precambrian basement and Upper Palaeozoic sediments and igneous rocks, which run from Larvik on the southern Norwegian coast up to the Sparagmite region, around Lake Mjosa, in the north.

The Lower Palaeozoic rocks of the Oslo Graben, unlike the other outliers on the Precambrian Baltic shield, have been deformed by Caledonian events along most of their length. Comparisons in deformation style have been made with the Jura Mountains of the Alps (Holtedahl 1934, Strand 1972) and both of these areas are characterised by a detachment horizon which has transported allochthonous rocks in the hangingwall over an autochthonous footwall.

The Lower Palaeozoic succession of the Oslo Graben comprises a thin shaly Cambrian succession with a missing lower Cambrian portion representing an unconformity before the transgressive Cambrian seas reached the area. The Ordovician is much thicker, with a cyclic sequence of alternating shales and limestones representing a shallowing sequence, with tidal bars at the top (Brenchley and Newall 1975). This is followed

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The rocks are best exposed along the motorways leading out of Oslo, on islands in the fjords and along beach, road and railway sections. The best and most frequent exposures occur in the Oslo area and steadily deteriorate inland, where glacial deposits frequently mask the bedrock.

Resting unconformably on the Lower Palaeozoic rocks are the late Palaeozoic rocks which are unique in the Fenno-Scandian shield to the Oslo Graben. These mainly comprise late Carboniferous to Permian intrusive and extrusive rocks, but also include thin non-marine clastics. The intrusives form a large part of the graben, coinciding with a phase of major (mainly) N-S trending Permian normal faulting. The intrusives which range from gabbroic to granitic composition, include pink granites and the famous syenitic Larvikites. The intrusions have caused many fine examples of cauldron subsidence with associated ring dikes and cone-sheets which form circular outlines in plan. Occasionally the roof rocks comprising Cambro-Silurian sediments are downfaulted and preserved as isolated blocks in the intrusions. Permian extrusives are also extensive and include the famous rhomb porphyries.

The Oslo Graben structure is caused by a north-south trending series of Permian normal faults affecting the basement and cover rocks, which display small grabens and horsts within the major structure. For example the Precambrian gneiss of the Nesodden peninsula in the Oslo Fjord are upfaulted between Cambro-Silurian rocks to the west and east which form islands in the fjord. The Oslo Graben is a failed arm of a late Palaeozoic rift system affecting Europe. This particular system of faults was abandoned early on in its development, whilst other European rift systems e.g. the Rhine and Rhone Graben continued to deform into Triassic times (Ager 1980).

1.3 Introduction to the geology of the Sparagmite region

At the northern end of the Oslo Graben is a thick sequence of late Precambrian (or Eocambrian) clastic sediments which form the Sparagmite region of central southern Norway. In the past the upper part of the Eocambrian sequence was thought to have become detached along the Ekre Shale horizon (see Chapter 2) and been transported up to 35km to the SE to overthrust autochthonous Cambrian shales which rest directly on Precambrian basement (e.g. Schioz 1902, O.Holtedahl 1915, Strand 1954). This led to the assumption, by the same authors, that the sparagmite deposits were laid down in fault bounded or depressed basins on Archaen basement. It was thought that these rocks were in a tectonically protected position and did not move very far.

However, the model above ignored the presence of thin autochthonous sparagmite deposits underlying the oldest deformed rocks of the Sparagmite region in the basement window areas at the northern end of the Sparagmite region. Oftedahl (1943) first recognised this relationship and suggested an allochthonous model for the Sparagmite region, estimating thrust distances of 300km. This model has later been supported by Nystuen (1981), who called the lowest thrust sheet in southern Norway, (which comprises most of the Sparagmite region), the Osen-Roa Nappe.

Lying in large and small klippen on top of the Osen-Roa Thrust Sheet in the northern part of the Sparagmite region are metamorphic, light coloured rocks, which often form fine grained and schistose flagstones, called "light sparagmites". These were grouped into one tectonic unit by Oftedahl (1954) and called the Kvitvola Nappe. This "light sparagmite" with characteristic dolomite and conglomerate horizons is thrust over the fossiliferous Osen-Roa Thrust Sheet Ordovician sediments at Hogberget (Oftedahl 1954). In other places it has complex relationships with the Osen-Roa Thrust Sheet: sometimes the Kvitvola Thrust sheet lies over truncated Osen-Roa Thrust Sheet folds, whilst in other places the Osen-Roa Thrust Sheet and minor imbricates cut the Kvitvola Thrust Sheet (Nystuen in press). Around the western edge of the Atnasjoen windows the Kvitvola Thrust Sheet actually lies on top of the autochthonous tillites (Holmsen 1950), suggesting that the trailing edge of the lowest thrust sheet (the Osen-Roa Thrust Sheet) is located close to the northern edge of the Sparagmite region.

The most common deformation style within the Osen-Roa and Kvitvola Thrust Sheets is imbrication, which gives widespread northerly dips in the region. These have resulted in the juxtaposition of Eocambrian to Ordovician sediments and augen gneisses, which were delimited before deformation by sub-horizontal surfaces (e.g.Holmsen and Oftedahl 1956 and Strand 1951a).

1.4 The aims and scope of the study in this thesis

The causes of the present geological boundaries (apart from erosion) of the Sparagmite region have not been sufficiently explained in the literature (especially the southern margin). In this thesis using modern ideas on thrust geometries, the factors delimiting the edges of the Sparagmite region have been re-interpreted. This has resulted in the development of a thrust ramping model where the edges of the Sparagmite region are thought to be limited by the sole thrust to the region cutting up section (ramping). The sites for the abandoned footwall sections resulting from ramping are proposed.

By using a frontal ramp model to explain the southern limit of the Sparagmite region, the Osen-Roa Thrust which forms the sole thrust to the sparagmite region can be demonstrated to pass into the Cambro-Silurian rocks of the Oslo Graben as a detachment zone in the Alum Shales (Cambrian). Therefore if undeformed foreland rocks can be found to provide a pin line (see Chapter 1, balanced cross sections), a balanced cross-section can be constructed from the Oslo Graben into the Sparagmite region. This means that palinspastic reconstructions of the Sparagmite region and higher thrust sheets can be made.

This study has involved the mapping of Cambro-Silurian rocks at various scales ranging from 1:1000 to 1:50 000 in several areas of the Oslo Graben including Eiker-Sandsvaer, Asker-Baerum, northern Ringerike and North Hadeland. This was necessary in order to allow the most continuous balanced cross-section possible to be drawn from undeformed foreland in Langesund-Skien through the Oslo Graben and into the Sparagmite region.

By unstraining the balanced section to produce an undeformed stratigraphic template, with the position of the future faults marked on it, an accurate estimate of the amount of shortening in the Oslo Graben can be made. Because the Sparagmite region and the Oslo Graben are both parts of the Osen-Roa Thrust Sheet it is possible to palinspastically restore the Sparagmite region back to its original depositional area. Whilst attempts have been made in the past to estimate the unstrained length of the rocks in the Oslo Graben (e.g.Brogger 1882) these were not based on maps for the whole length of the Oslo Graben and though based on well drawn sections they were structurally inaccurate.

Once the lowest thrust sheet is restored to its original depositional area, the higher thrust sheets in the Trondheim and Jotunheimen areas, by using published and unpublished maps, can also have balanced cross-sections drawn through them. This enables an estimate of the width of the Caledonian Baltic shelf to be made. In attempting to draw balanced cross-sections through these areas is becomes apparent that simple piggy back thrust relationships are not always present and that the thrust sheets of the Jotunheimen and Trondheim regions were probably emplaced at different times.

Having established the approximate amount of shortening within the southern Norwegian Caledonides it is possible to compare the region with other areas on the opposite side of the Caledonian orogenic belt and suggest some overall model for the original thrust belt.

1.5 AN INTRODUCTION TO BALANCED CROSS-SECTIONS.

Oil geologists in Alberta originally developed the technique of restoring geological cross-sections back to their undeformed state (Dahlstrom, 1969a). Subsequently, Elliott (in prep) defined the amount of confidence which can be placed in a geological cross-section and suggested that there were four levels of confidence, these are detailed below.

1. An unbalanced section. This represents the inital investigation of the area, displaying conjectural structures.

2. An unrestorable section. If a line of section crosses structures eg. oblique or lateral ramps or non-cylindrical folds, the section generally cannot be balanced because the amount of material entering the section during deformation does not equal the amount leaving it. The section could still be valid but does not benefit from balancing.

3. A restorable and admissible cross-section. An admissible cross-section is one that uses structural style as a guideline for the construction of a section. Most cross-sections are based on an exposed area comprising only a small part of the vertical height of the whole section. Therefore it is necessary to have a reliable set of geometric rules which can be used to project structures above and below the exposed section. For example the three basic concepts of structural style developed by Canadian geologists are as follows: regional dip, no basement involvement and structural families (Dahlstrom, 1970).

Regional dip.

The regional dip idea assumes that in the undeformed foreland just outside a thrust-fold belt (providing there has been no later deformation) the "layer cake" sequence dips gently towards the hinterland allowing the regional dip to be calculated. This can be extrapolated into the deformed mountain belt, as it is assumed that the main thrust fault displacements occur along planes parallel to bedding. At the margin of the thrust belt the leading edge of the thrust sheets and imbricates push the beds above "regional", but the trailing edge of the thrust sheet remains at regional height. Further into the thrust belt, deformation below a specific horizon will result in it being raised above its regional height.

No basement involvement.

In the external parts of a mountain belt it is assumed that the structures are "thin skinned" so that the crystalline basement is not actively involved in the deformation. Thus the cover sedimentary rocks have slipped over the basement and the deformed allochthonous cover is separated by a detachment horizon from the autochthonous basement.

Structural families.

For a particular structural environment there is a characteristic assemblage (or family) involving a restricted number of structural forms. In many structural definitions eg. concentric or similar folding there is the idea of structural families associated with them. Bucher (1933) and De Sitter (1956) thought that a structural province can only contain a limited suite of structures e.g. the structural assemblage known as the "Foothills family" consists of a.low angled thrust faults (commonly folded);b. tear faults;c. concentric folds and their attendant detachment horizons and d. late normal faults (commonly low angle).

The concept of structural assemblages limits the number of acceptable solutions in any field problem. If the concept is rejected then in complicated problems the number of acceptable solutions becomes very large involving numerous structural styles. By studying well exposed sections in the area of study the structural styles available for use in the construction of an admissible section should become apparent.

4. A viable cross-section. This is a section which can be restored to the unstrained state. Usually plane strain is assumed to exist in the plane of section and the section must be chosen to lie parallel to the regional slip direction. There are two methods of balancing a section to produce a restored section, these are described below.

1.5.1 Line length balancing.

A template of the undeformed stratigraphy is constructed and the distance around the folds and between faults is measured with a curvimeter or string and plotted on the template. The distance is measured away from the starting point, known as the pin-line across which there has been no interbed slip. Such lines can be located as any normal to the regional dip in undeformed foreland. It is also thought that pin-lines can be drawn along fold axial surfaces, as ideally in flexural slip folds interbed slip dies out at the axial surface. Pin-lines in present and restored sections must themselves restore as straight lines, except where polyphase deformation may result in zig zag pin-lines being acceptable. Faults can also act as pin-lines, as they should be surfaces where no interbed slip has occurred on either side.

If a section does not balance it must be re-drawn until it does. Bed length can be altered by slightly changing the dip of the beds or the angle between faults and bedding. It is a trial and error process which reduces the number of possible sections whereas an unbalanced section is merely speculative and could encompass many inaccurate ideas.

1.5.2 Equal area balancing.

Usually a section is first balanced by measuring the sinuous bed length and then checked by compairing the areas of at least two marker horizons in the deformed and undeformed sections to ensure they are the same.

The equal area method is not necessary for concentric folding, but where the rocks have deformed by any type of flow the equal area balance must be used. In an area of competent and incompetent horizons, it is the incompetent horizons which are most likely to have undergone flow, so it is they that should be area balanced.

When plane strain conditions cease to exist, which may be indicated by the presence of pressure solution cleavage, slaty cleavage and bulk flow by by minor folds and faults, an estimate of the area lost from the section has to be made. This is then distributed equally throughout the section to compensate for the loss of material, (unless sufficient detail is available to compensate in specific areas of the section).

A balanced cross-section is by definition both viable and admissible. Though a valid balanced cross-section is not a unique solution, if various sources of data are used quantitatively and supported by evidence from boreholes and geophysical data a section might by sufficiently restricted to allow little flexibility of alternative interpretation.

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1.6 Thrust and fold geometries and their sub-surface prediction

1.6.1 Folds and fold associated structures.

The simplest fold style is concentric folding where the bedding has remained parallel during deformation. An idealised shape for these folds is given in Fig.1.3a, where it can be seen that the folds die out above and below the centre of maximum curvature into an upper detachment horizon (which may be the land surface) and into a lower detachment horizon (Dahlstrom, 1969b). The latter may have generated the folds by movement prior to buckling or may have formed in response to buckling.

Problems of conserving bed length throughout a stratigraphy deformed by a series of concentric folds have been outlined by Dahlstrom (1969) (see Fig.1.3a and Carey (1962) Fig 1.3b). Above and below the centre of curvature the bed lengths around the fold arc decrease with increasing distance away from the centre. This results in concentric folding being modified because it cannot accommodate the full length and volume of the beds beyond the centre of curvature.

The problem of accommodating bed lengths has been solved in several ways. Goguel (1962) maintained bed length by the progressive crumpling of an anticlinal core see Fig.1.3c. Although this satisfies the problem in the diagram it does not solve the problem close to the decollement horizon nor does it solve the problem for a series of folds. De Sitter (1956) proposed that the lack of space in fold cores results in higher pressure there and causes break thrusts in the core. Another method he proposed involved the diapiric rise of incompetent rocks into the fold core to produce box folds.

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Fig.1.3 <u>Concentric folds</u>

a. The idealised geometry of concentric folds (after Dahlstrom 1969b)

b The problem of decreasing shortening in concentric folds, demonstrated by folded and unfolded sections (after Carey 1962). The extra amount of bed length in the upper part of the section is indicated by 1.

c. Methods of solving the discrepancies in bed length caused by concentric folding by i, crumpling the core of a fold (after Goguel 1962), ii, thrusting in the core of a fold (De Sitter 1956).

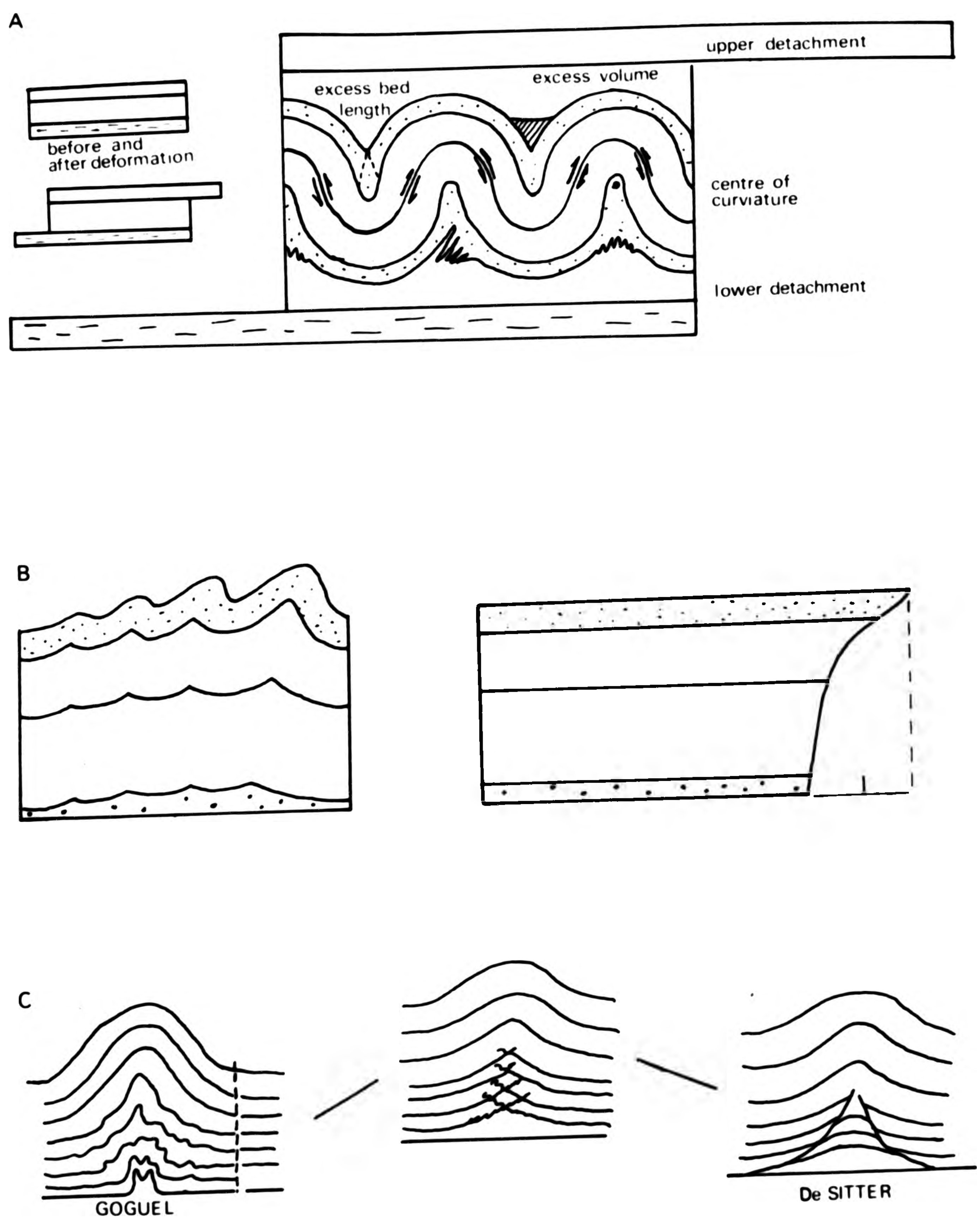
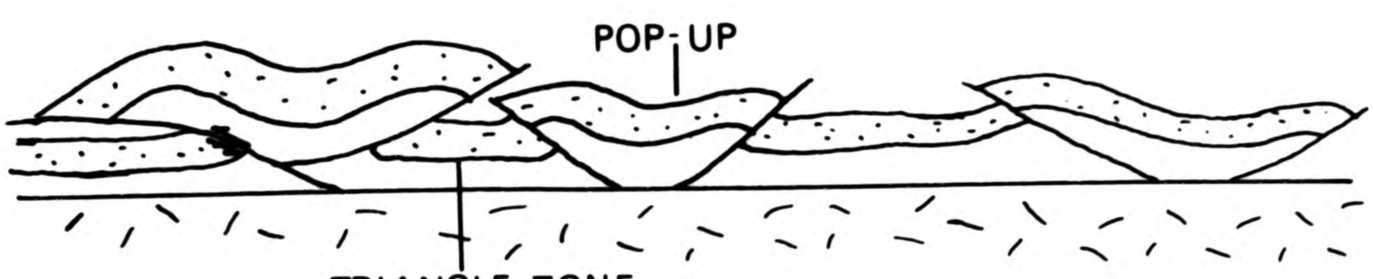

A
upper detachment
excess bed length
excess volume
before and after deformation
centre of curviature
lower detachment
B
C
GOGUEL
De SITTER

Fig.1.4 <u>Pop-up and triangle zones.</u>

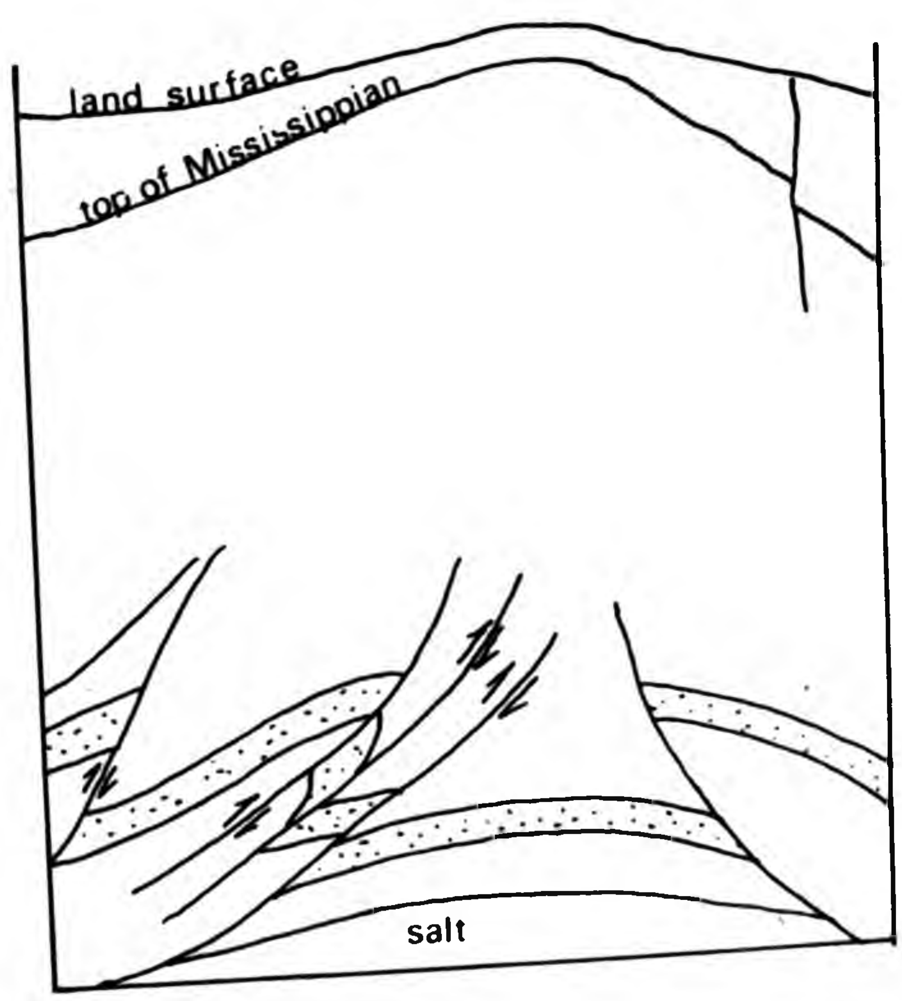
A. Idealised series of pop-up and triangle zones.

B. Blind thrusting in a triangle zone in Devonian rocks, Griffin Dome, Chestnut Ridge Anticline, Pennsylvania, using bore hole data (after Gwinn 1964).

A


POP-UP
TRIANGLE ZONE

B


land surface
top of Mississippian
salt

The thrusts of opposing dip observed in anticlinal cores produce patterns of faulting that have been termed triangle and pop up zones (Elliott and Johnson 1980) (see Fig.1.4). Structures like these frequently have to be drawn in balanced cross-sections, although not seen at the surface, in order to increase bed length in the lower horizons.

The concentric fold style is not the only flexural slip fold style found in large scale folds. Where fold geometry consists of nearly planar limbs and curved hinges, kink bands or chevron folds may offer a more realistic explanation, whilst certain stratigraphic levels may thicken in the hinges to produce a similar fold form.

Danton (1940)and Gwinn (1964) postulated upward shearing to produce large scale kink band folds. Later, Faill (1969) suggested that large scale kink bands could be recognised in the Appalachians which formed by buckling and he was able to explain complex fold geometries eg. doubly plunging anticlines, in terms of kink band geometry (see Fig.1.5c).

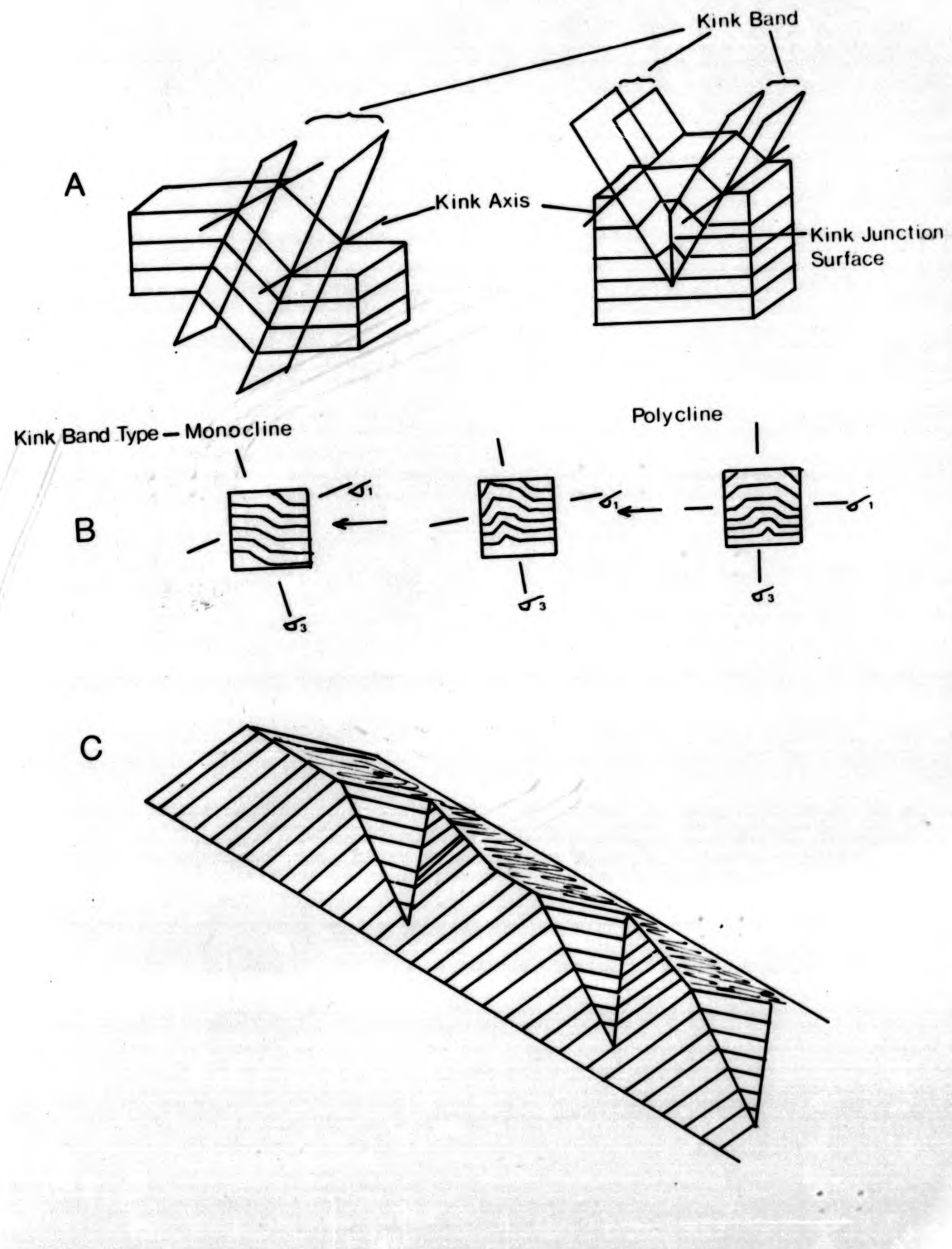
Kink bands often form without upward shearing, therefore there is no accommodation problem for an individual fold and no need for accommodation faults (see Fig 1.3). Kink band geometry is such that no decollement horizon is required to separate the kink band folds from non-folded layers below (Faill, 1969) (see Fig.1.6). However this does not mean that that decollement horizons do not exist below a series of kink band folds because kink bands when restored without crumpled cores or faults produce non-uniformly shortened sections. Accommodation structures in kink bands are similar to those found in chevron folds, (see Fig.1.7).

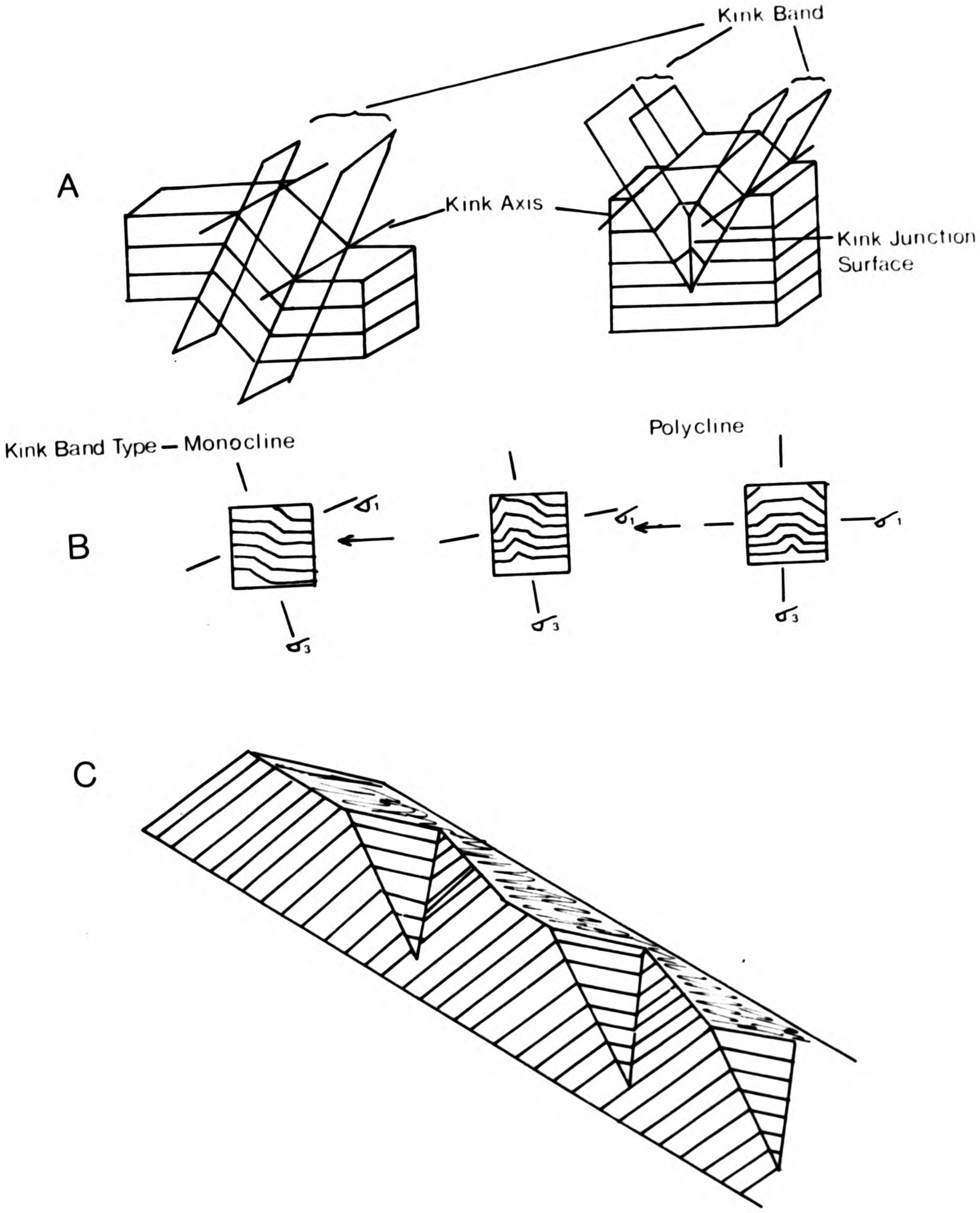
Fig.1.5 Kink band geometry

a. Some terms used to describe kink band geometry

b. Progressive rotation of the maximum and minimum principle stress directions with respect to bedding, will result in a change from polyclinal to monoclinal kink bands (after Johnson 1977)

c. A major fold with superimposed en-echelon minor folds. This results in short, doubly plunging folds in the major fold hinge (after Faill 1973).


Kink Band
A
Kink Axis
Kink Junction
Surface
Kink Band Type — Monocline
Polycline
B
σ_1
σ_3
C

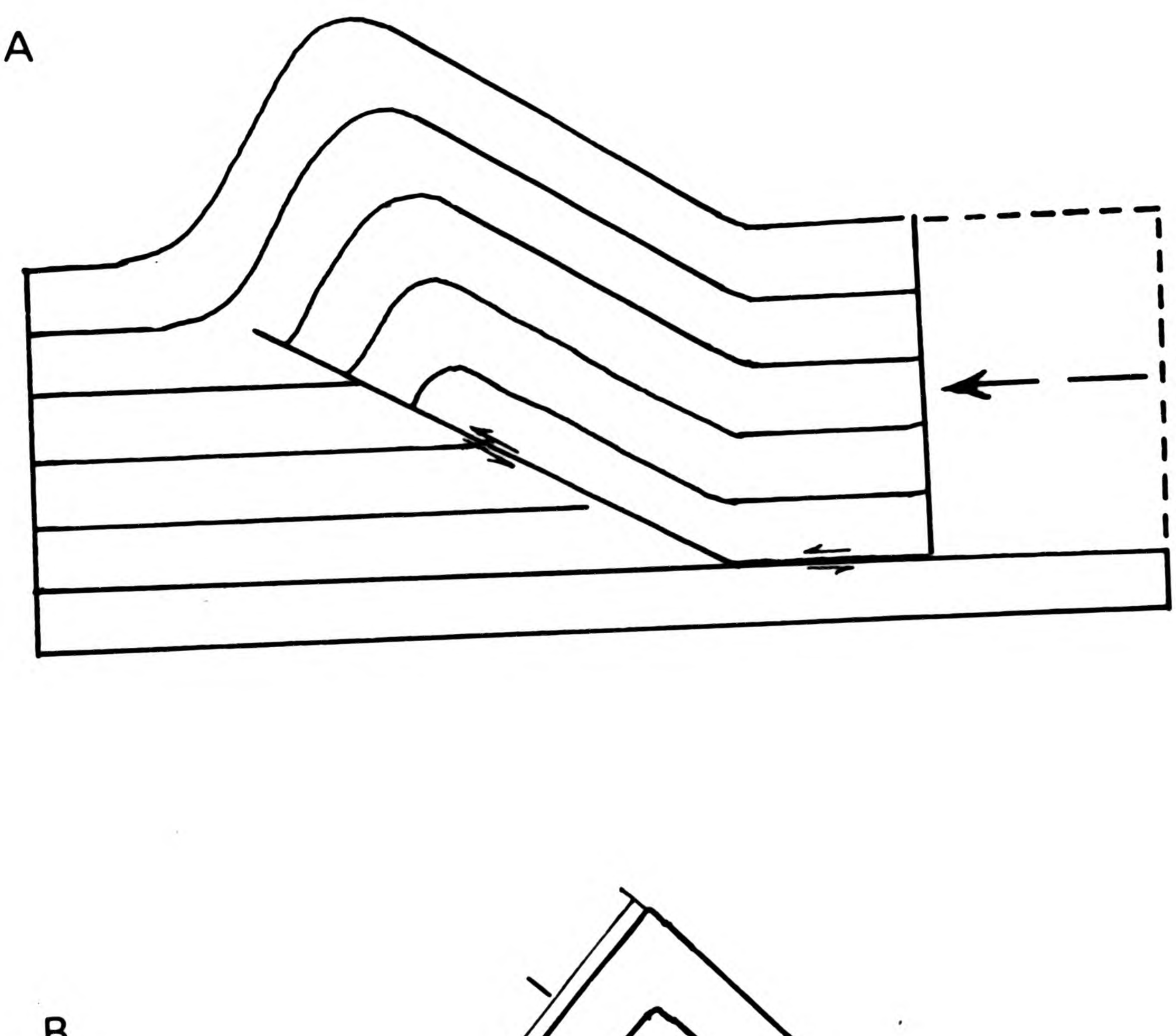


Kink Band
A
Kink Axis
Kink Junction
Surface
Kink Band Type — Monocline
Polycline
B
C

Fig.1.6a Fold with thrust fault in core to relieve conjestion of beds. The inital assumption is implicit that all the folded layers must have been equally shortened and thus there must be a bed-parallel detachment fault between the folded and non-folded layers.

Fig.1.6b Kink band fold. For a given dip of bedding (d) the amount of shortening (s) of a layer is a function of the length of the layer (l) in the fold. Because the layer length decreases towards the fold core, the amount of shortening similarly decreases and thus there is no bed-parallel detachment fault between the folded and non-folded layers (Faill 1973).

A



B

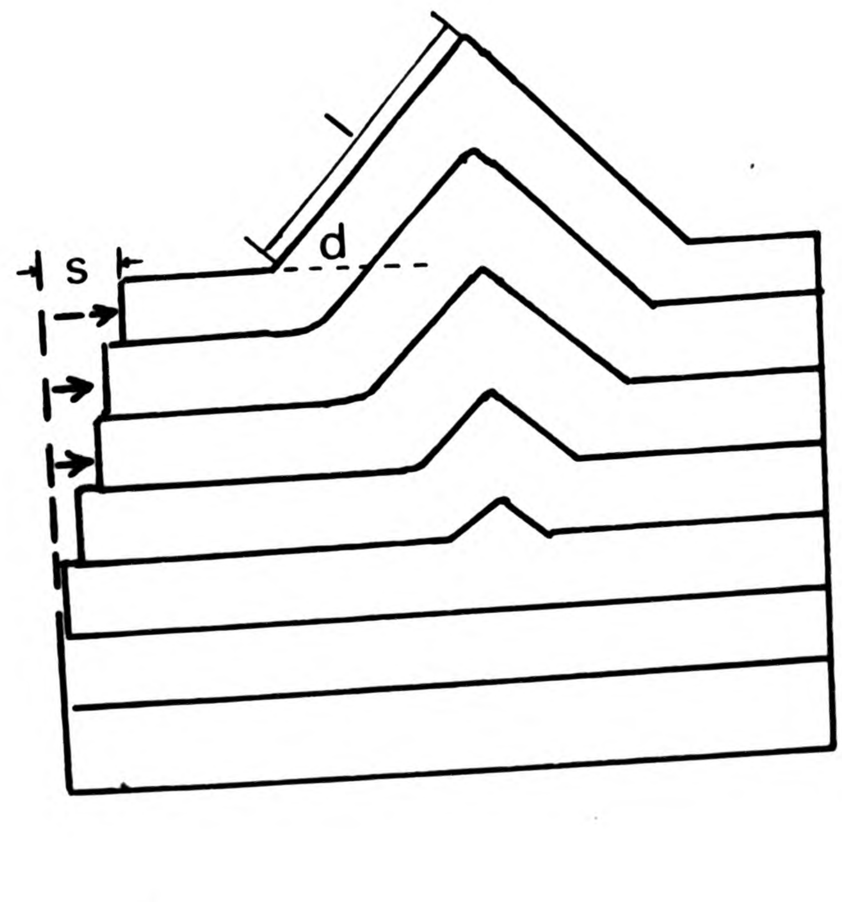
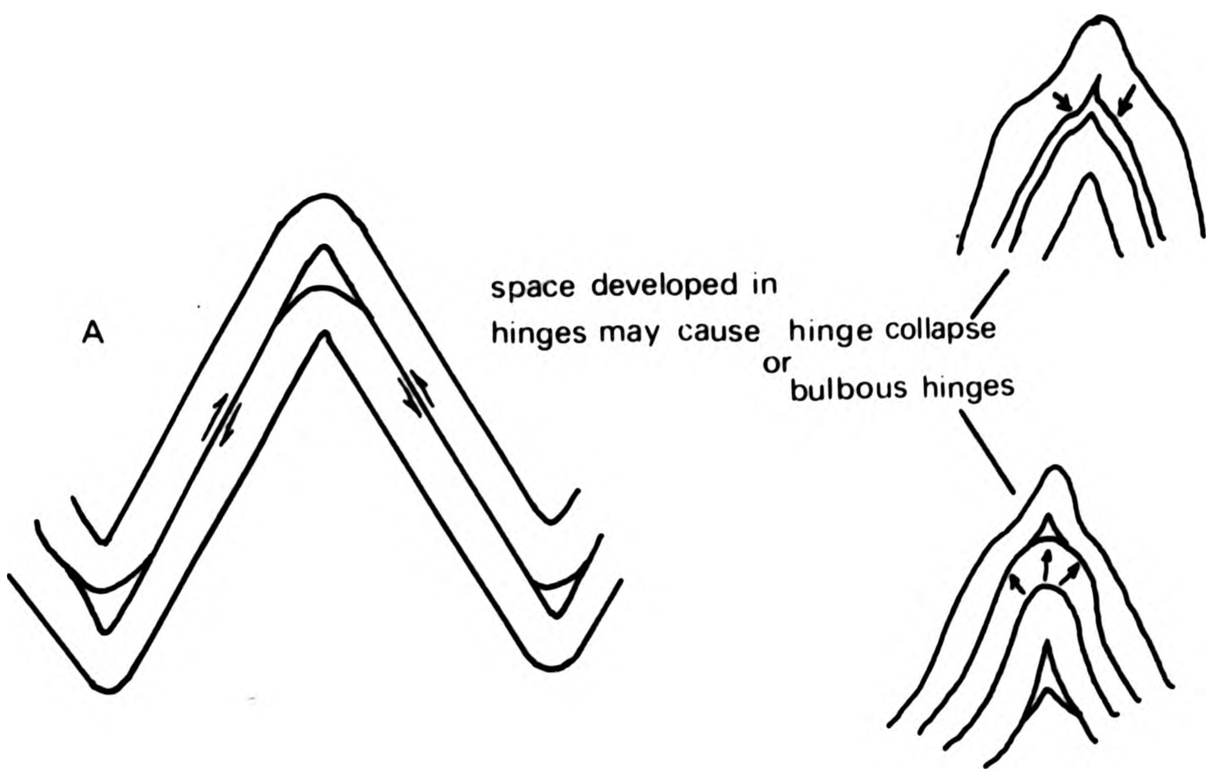


Fig.1.7 Accommodation structures caused by flexural slip within chevron folds (after Ramsay 1974).

a. Flexural slip model of chevron fold, an anamolously thick folded layer may produce a bulbous hinge.

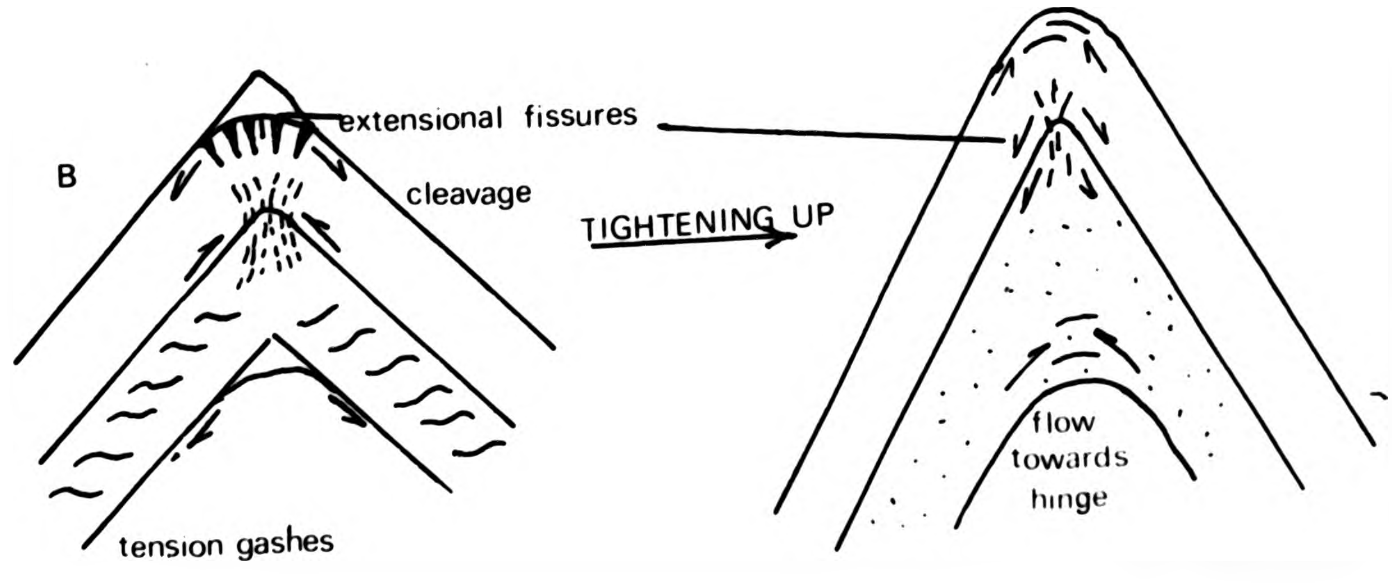
b. Potential development of small scale structures in chevron folds.

A



space developed in
hinges may cause hinge collapse
or
bulbous hinges

B



extensional fissures
cleavage
TIGHTENING UP
tension gashes
flow
towards
hinge

There are two methods for projecting fold geometries above and below the surface, they are as follows.

1. The Busk Construction. This assumes there is always a centre of curvature from which the folds die out upwards and downwards. Constant bed thickness is maintained so that all bedding planes are drawn parallel to each other. Disharmonic folds cannot be reconstructed by this method.
2. Isogon technique. This method was described by Prof.J.Ramsay in a lecture to the T.S.G. at the Geology Society, London, 1982. A standard section is established from a good field section which is considered representative of the regional fold style. From this section, thickness variations and the dip isogon patterns are established. The geometric pattern is built up and using the isogon template derived from the field section, standard isogon curves are constructed and drawn in on areas of similar geometry in the section being constructed. From this isogon pattern the fold shape is constructed. This method works for harmonic folds, but not for disharmonic folds.

Fig.1.8 Ramp and flat geometries

a. Potential path of a thrust with staircase trajectory ramps form at steep angles to bedding and fault plane cut off may be up to 40° in competent rocks. Flats are bedding parallel glide zones usually found in incompetent rocks. Ratio of length of thrust in flats and ramps about 20:1 (after Rich 1934).

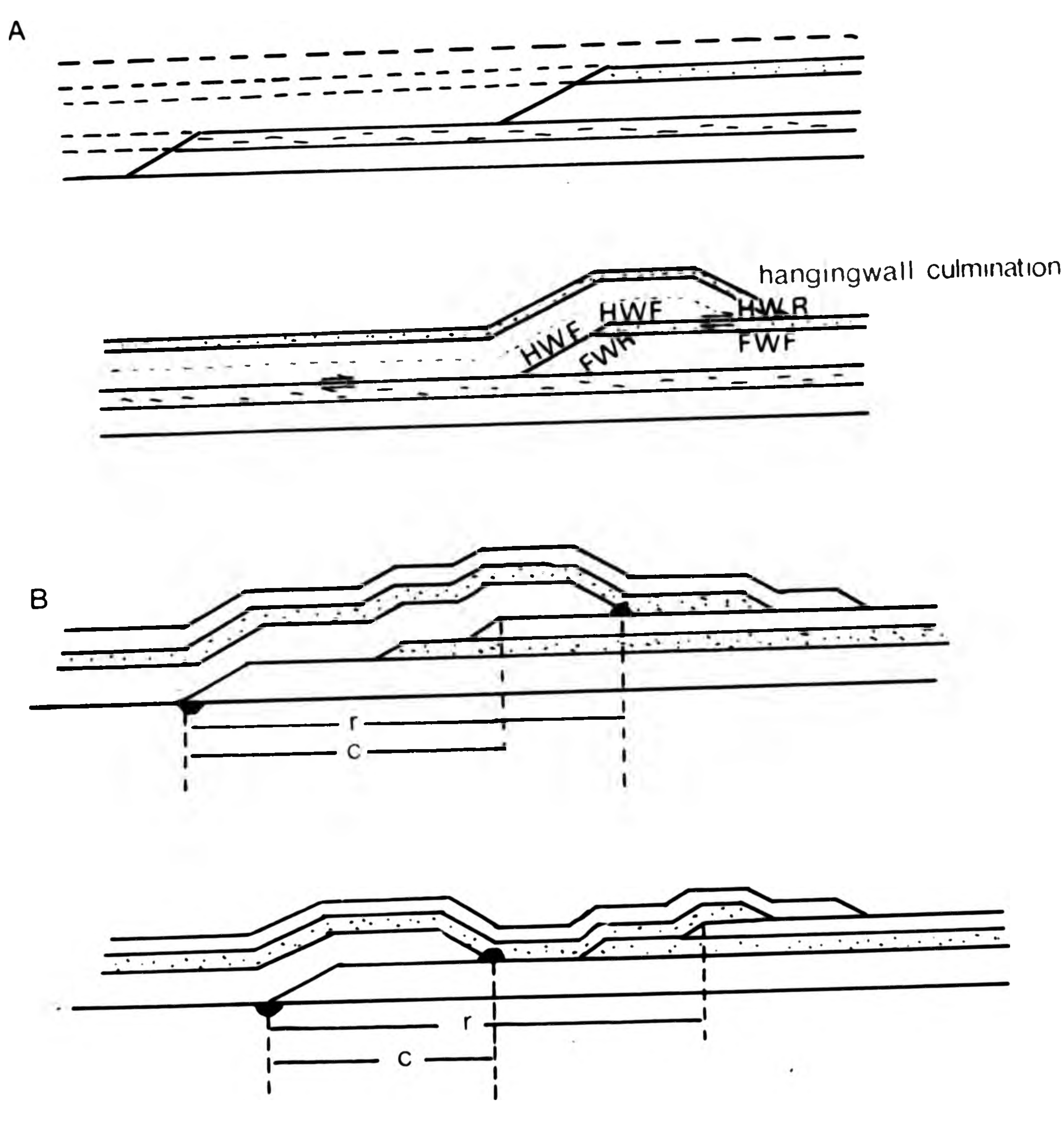
b. The effect of spacing of ramps and fault displacements on culmination geometry (after Gretener 1972).

c = spacing between ramps

r = fault slip

top diagram slip > c

bottom diagram slip < c



KEY

FWF = FOOTWALL FLAT
FWR = FOOTWALL RAMP
HWF = HANGINGWALL FLAT
HWR = HANGINGWALL RAMP

Fig.1.5 Kink band geometry

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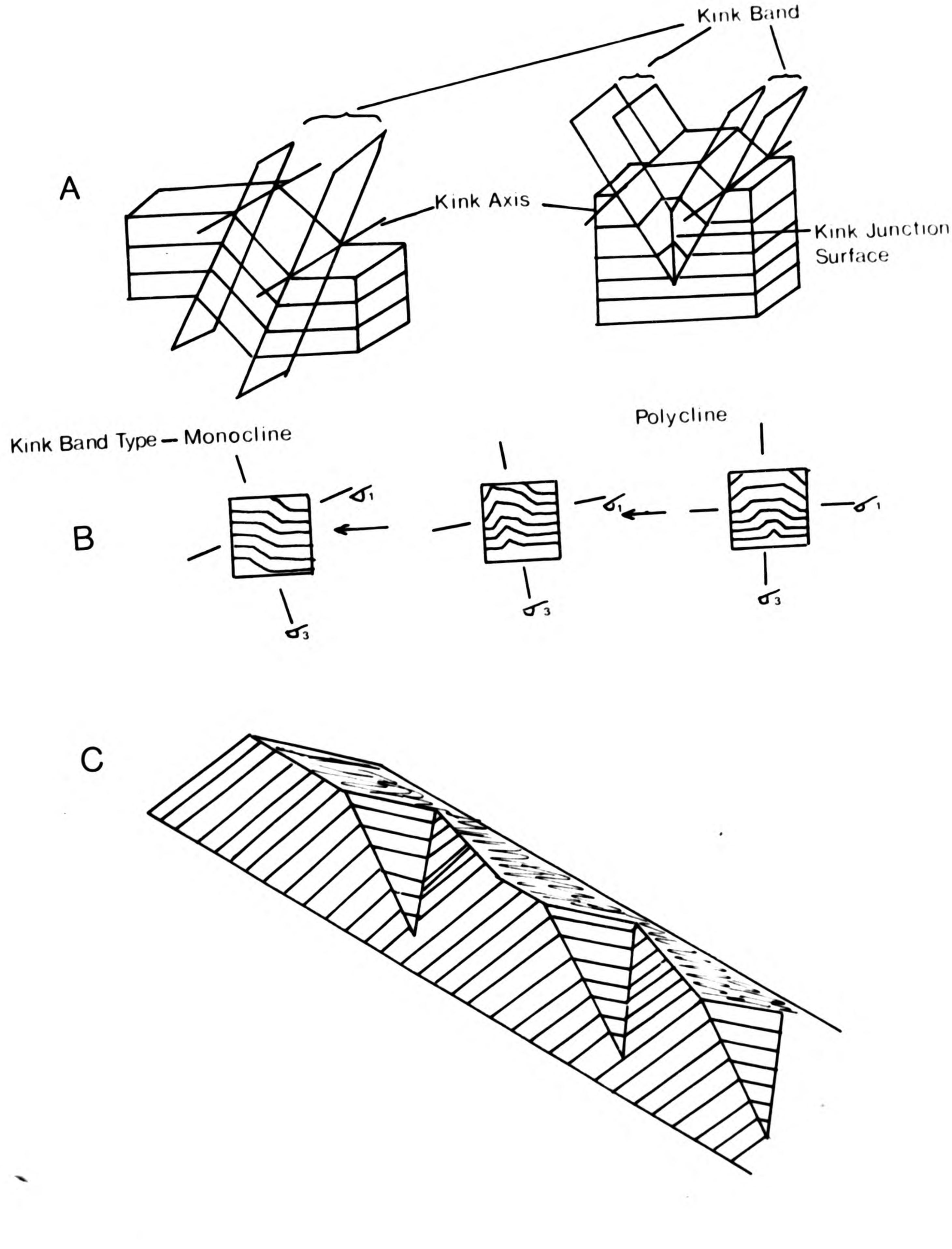
Kink Band
A
Kink Axis
Kink Junction
Surface
Kink Band Type — Monocline
Polycline
B
σ_1
σ_3
C

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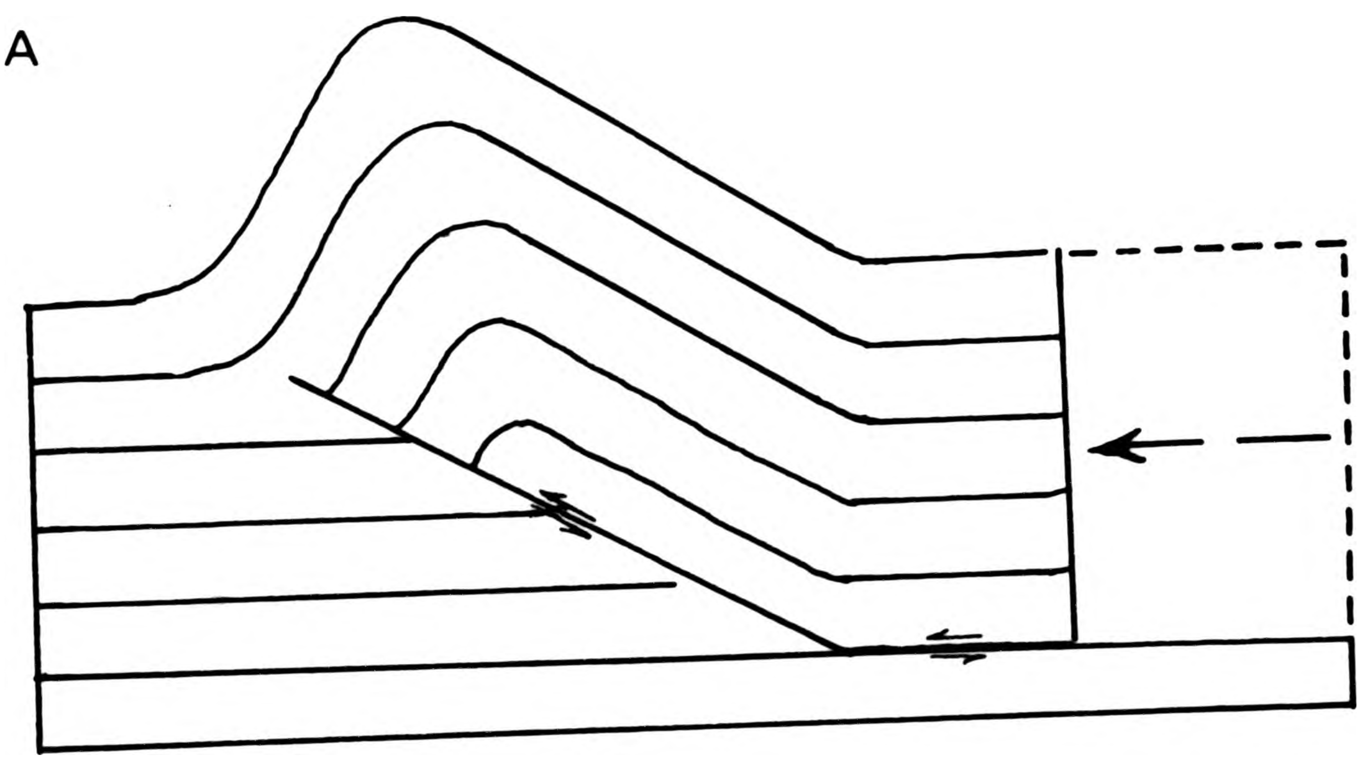
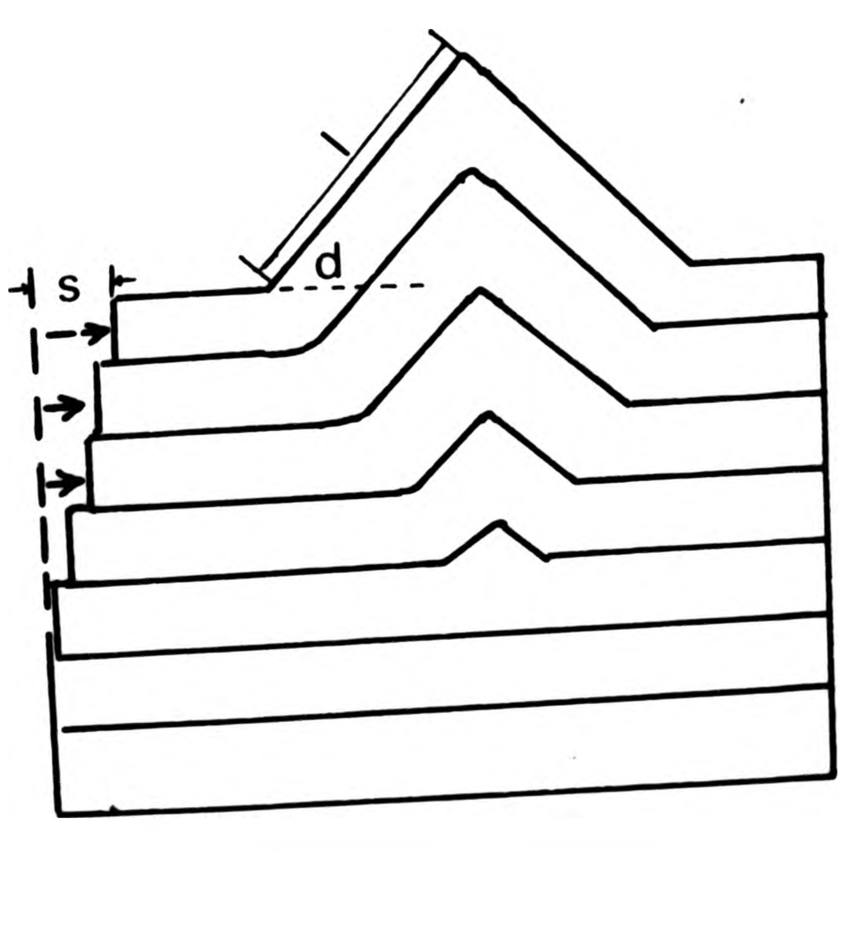
A



B



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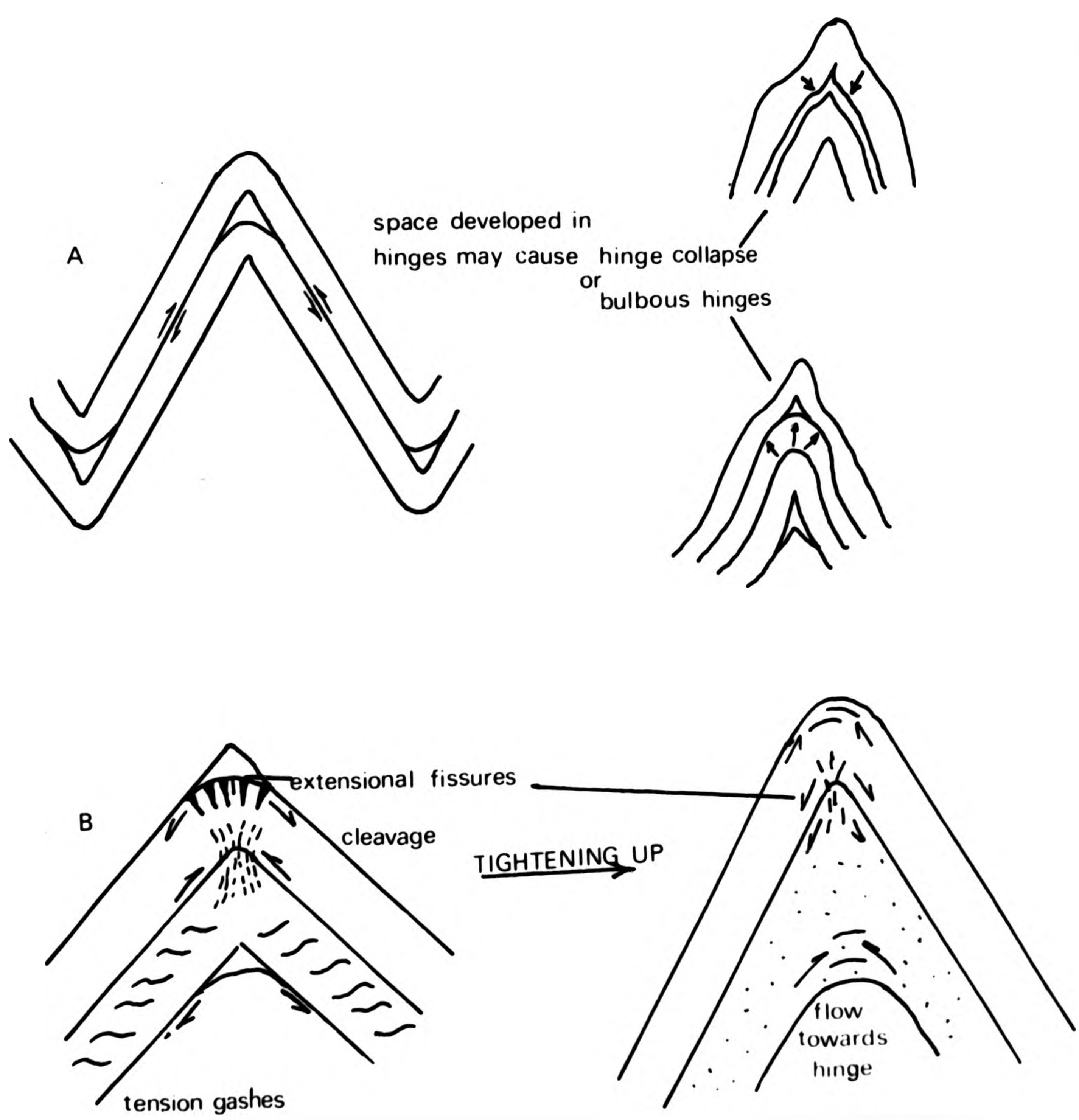
A
space developed in
hinges may cause hinge collapse
or
bulbous hinges
B
extensional fissures
cleavage
TIGHTENING UP
tension gashes
flow
towards
hinge

There are two methods for projecting fold geometries above and below the surface, they are as follows.

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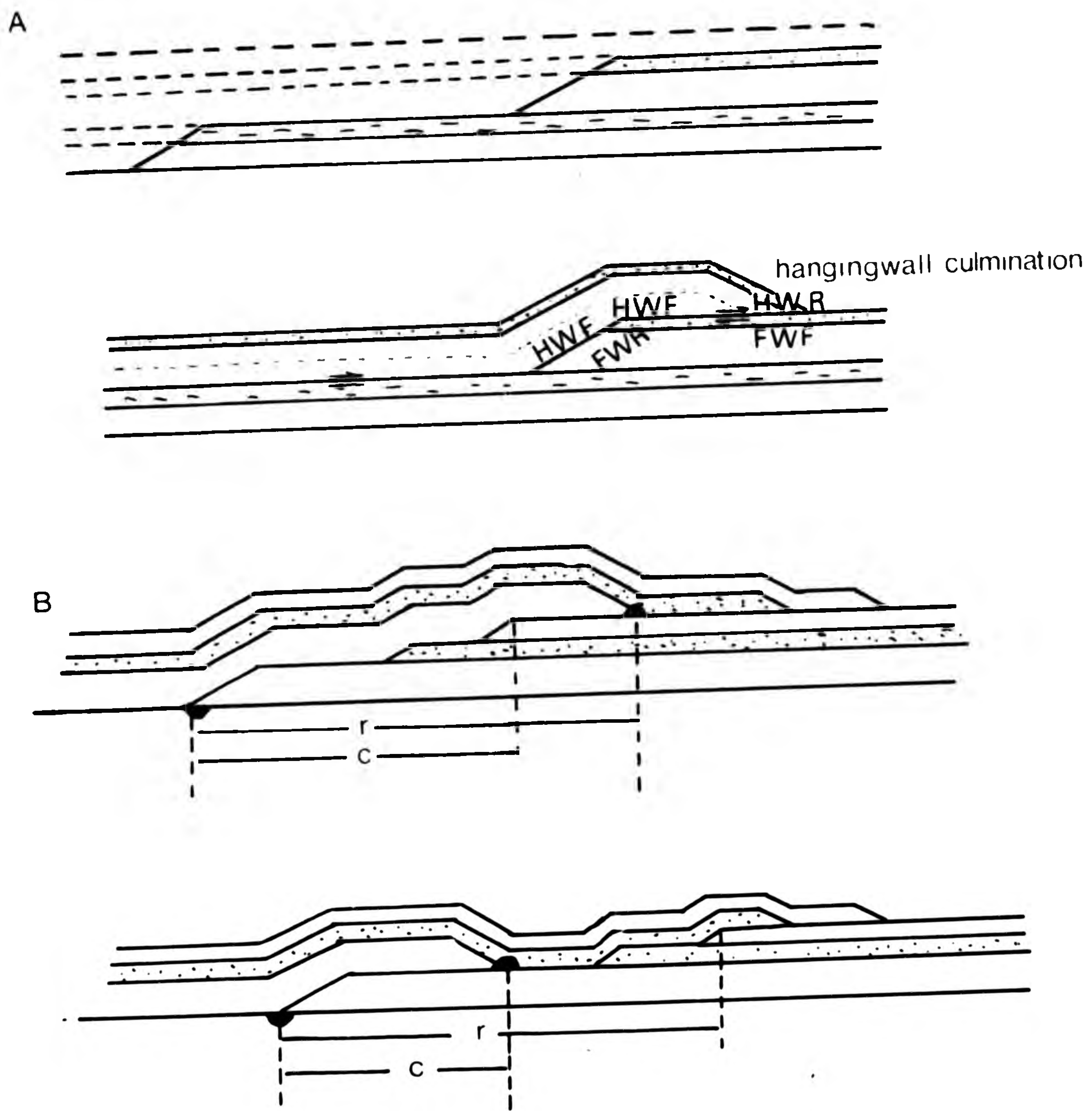


KEY

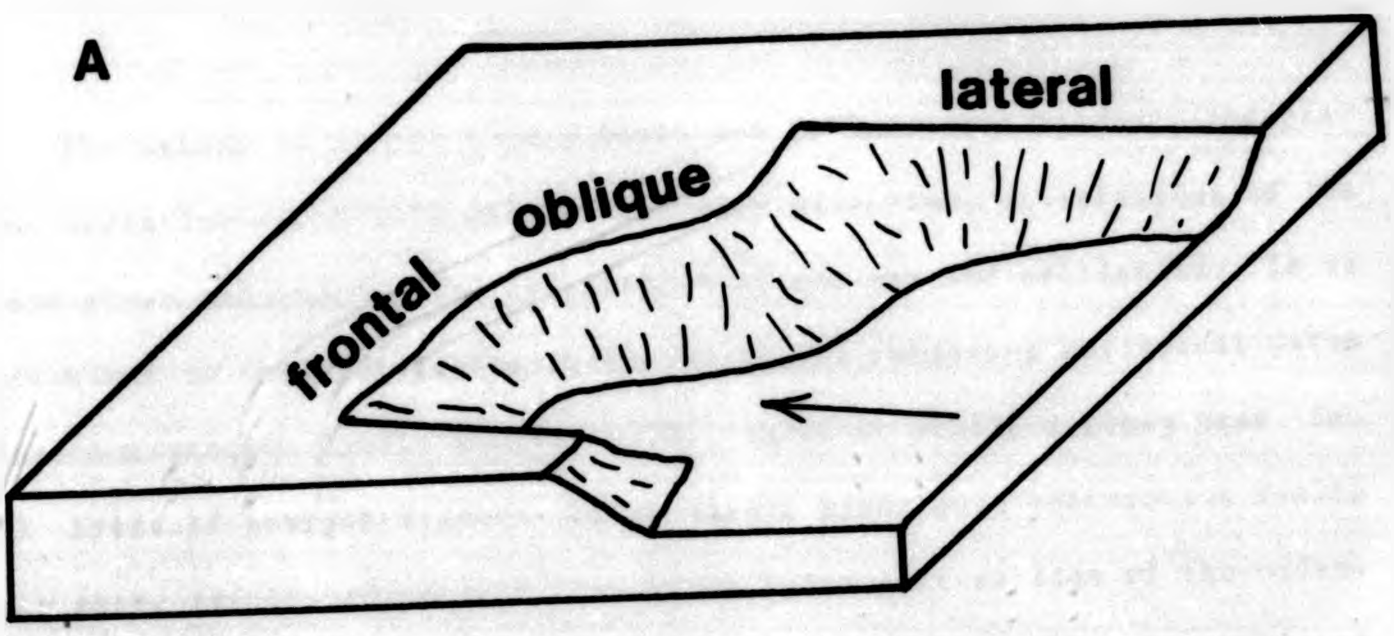
FWF = FOOTWALL FLAT
FWR = FOOTWALL RAMP
HWF = HANGINGWALL FLAT
HWR = HANGINGWALL RAMP

Fig.1.9 <u>Ramp geometry (partly after Dahlstrom 1970)</u>

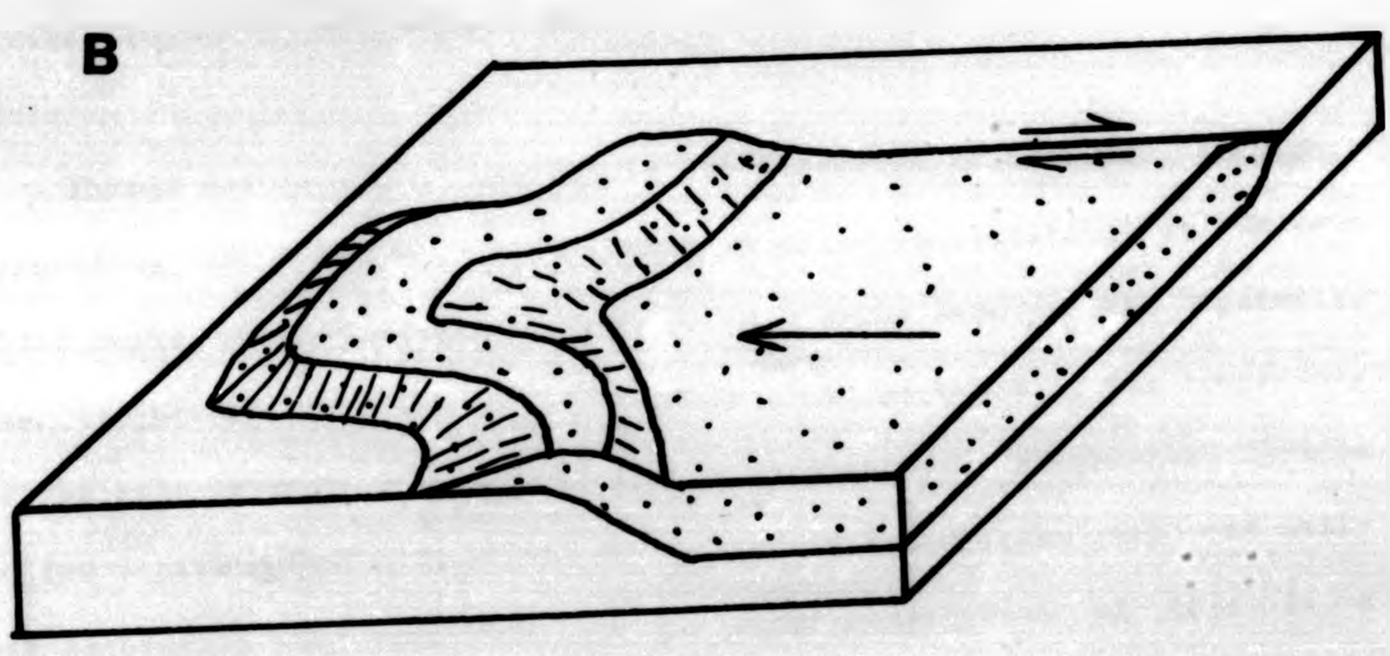
a. 3d view of types of footwall ramps

b. 3d view of hangingwall culminations and wrench faults as a result of movement across the surface in Fig.1.8a

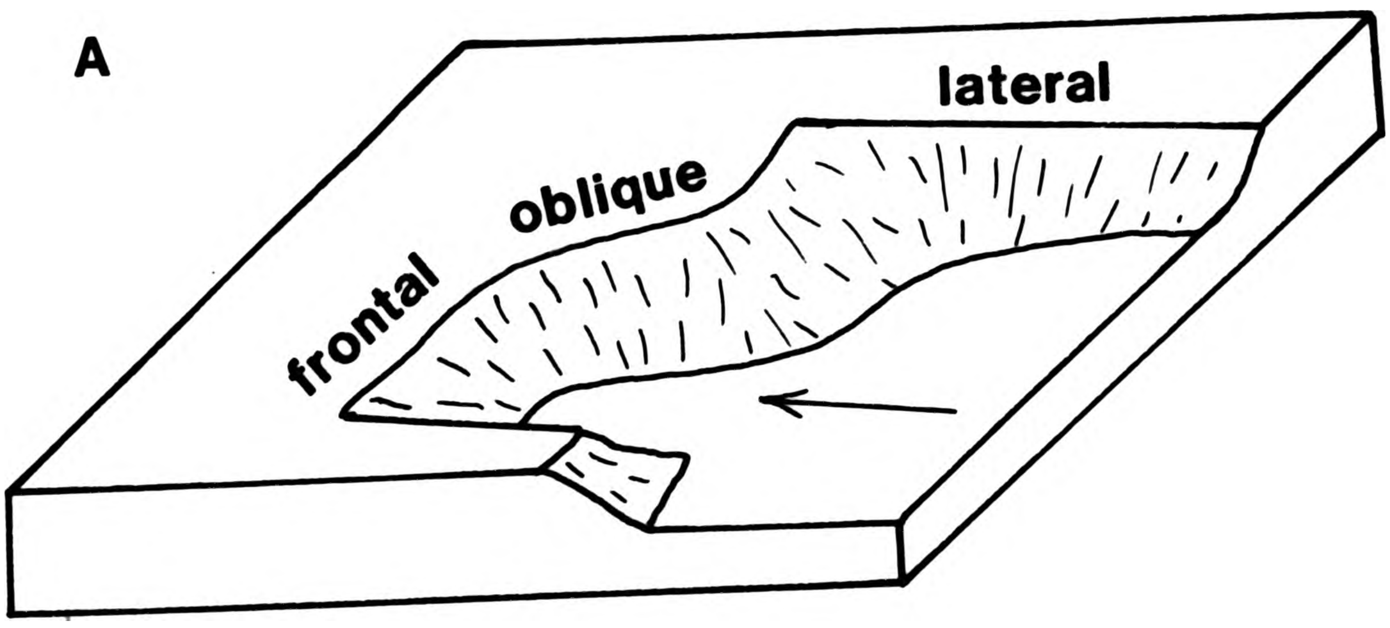
A



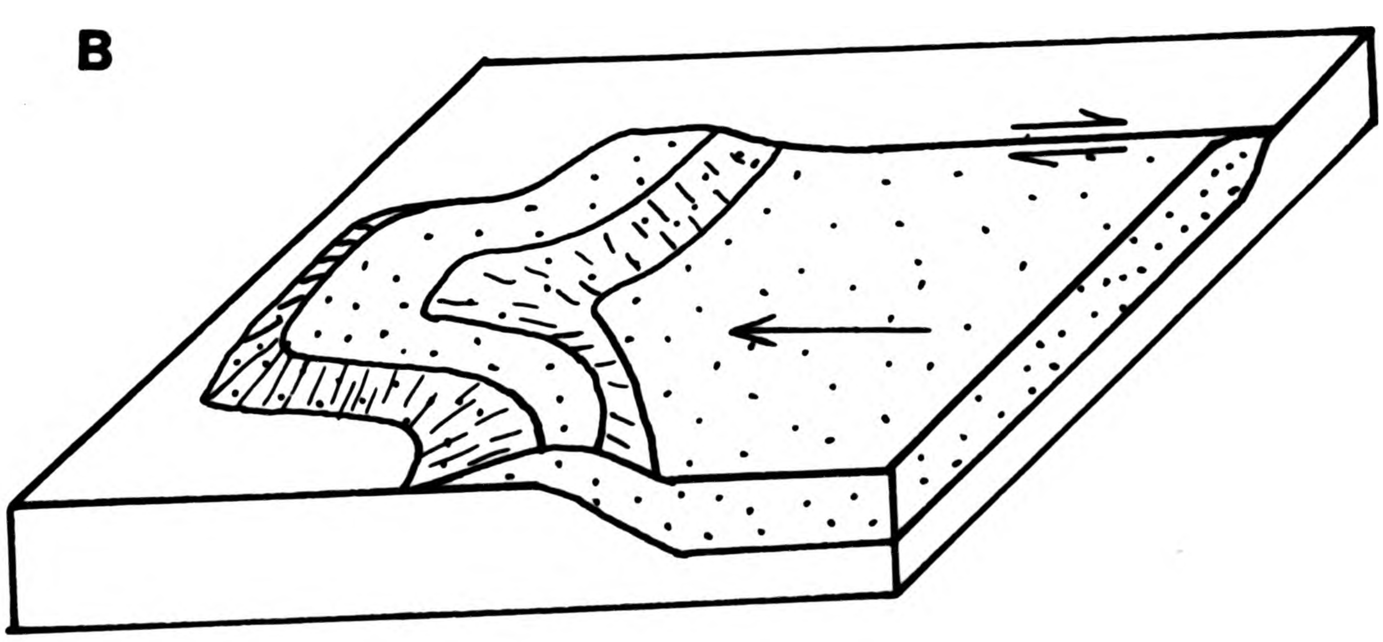
B



A



B



1.6.2 Thrust geometries.

In American terminology thrust fault is equated with "low angle reverse fault". Regionally the faults are low angled but locally because of folding or rotation caused by imbrication, they may be very steeply dipping.

The nature of an individual fault can be described by five independant variables comprising slip sense, slip direction, orientations of the fault plane and bedding and orientation of the map and section(s). It is convenient to call all faults which shorten an arbitrary horizontal datum plane contraction faults (Norris 1958), which is really a group name for all types of reverse faults. Price (1967) broke down contraction faults into three orders, the definitions given below give an idea of the orders of magnitude involved, not hard and fast dimensions. The main regional thrusts, called first order thrusts have displacements measured in tens of kilometers. Second order thrusts branch off first order thrusts and have displacements measured in tens of meters and strike lengths of up to 2-3km. Third order thrusts have displacements of less than 10 meters and strike lengths of less than 0.5km.

Thrust faults cut up section in the direction of tectonic transport (providing there has been no deformation prior to thrusting) and emplace older rocks of the hangingwall over younger rocks forming the footwall. The trajectory of a thrust fault tends to be governed by the competency of the unit through which the fault has propogated. Frequently thrusts follow a path which is parallel to bedding in incompetent rocks and oblique to bedding in competent rocks. The consequence of this is a staircase trajectory (Rich 1934) of flats where the thrust plane is sub-parallel to bedding for long distances and ramps where the thrust plane may be inclined up to 40° from horizontal and cut obliquely for short distances across bedding from one flat to another, (see Fig.1.8a).

Ramps may be reduced in steepness with time when a new thrust cuts through the footwall of the ramp (footwall shortcut) and incorporates the footwall horse into the main thrust sheet (Serra 1977). If many such footwall shortcuts have occurred during the emplacement of a thrust sheet it becomes very difficult to reconstruct in balanced cross-sections the original positions their footwall cut offs. A ramp may also collapse due to intense simple shearing, which flattens the footwall, and lowers the angle of the ramp. This may result in locally complex folding and faulting of the hangingwall.

The consequence of staircase thrust trajectories is to produce folds in the hanging wall block (see Fig.1.8a) where broad anticlines are formed over footwall ramps (F.W.R.) and large flat bottomed synclines form over footwall flats (F.W.F.). The horizontal spacing between ramps affects the size of the folds found in the hanging wall (see Fig.1.8b, after Gretener 1972). Folds produced over ramps can either be concentric or kink band like in style.

It is possible for ramps to form at an angle to the direction of thrust sheet transport these are called oblique ramps, except where they run parallel to the thrust transport direction, when they are known as lateral ramps (Butler 1982,). These ramps may be manifest in the surface geology as wrench faults, complex fault zones or culminations (Dahlstrom 1970, see Fig.1.9). The lowest external thrust plane, which separates autochthonous basement from allochthonous cover are frequently restricted to one stratigraphic horizon and do not display ramp and flat geometry as described above. A decollement horizon may however be draped over an existing basement topography so that movement of the thrust sheet over basement rises and hollows will cause folds to be developed as though over ramps and flats, without the thrust plane itself cutting up section.

The front of a propogating fault plane is known as the tip line and ahead of the propogating thrust is a zone of deformation called the ductile bead (Elliott 1976b), which dies out via a combination of minor structures (which might include complex or simple folds, numerous fractures of small displacement or shear zones) into undeformed rock. A simple thrust exposed on the surface has in plan two tip points. Any thrust not exposed at the surface but which is known to exist or is structurally necessary to exist below the surface is called a blind thrust.

<u>Second and third order thrust fault terminology.</u>

Second and third order thrusts are the subsiduary thrusts within a thrust sheet. Characteristically these thrusts may dip rather steeply in their upper parts (up to 60°, Elliott and Johnston 1980) but flatten in dip as they approach and join the underlying detachment horizon or sole thrust. This concave upwards or listric form is characteristic of thrust faults.

When asymmetric folds are present Dahlstrom (1970) called thrusts cutting through the long, gently dipping "back" limb of a fold, back limb thrusts and those cutting the short steep fold limb as fore limb thrusts. Since frequently the thrust faults dip more gently than the axial planes of the folds they must change in structural position from back limb to fore limb as they cut up section through a series of folds. Certain stratigraphic horizons might favour a particular back or fore limb position for a thrust, defining in a restored section ramps and flats for the high angled thrust, in much the same way as for the sole thrust, (see Fig.1.10).

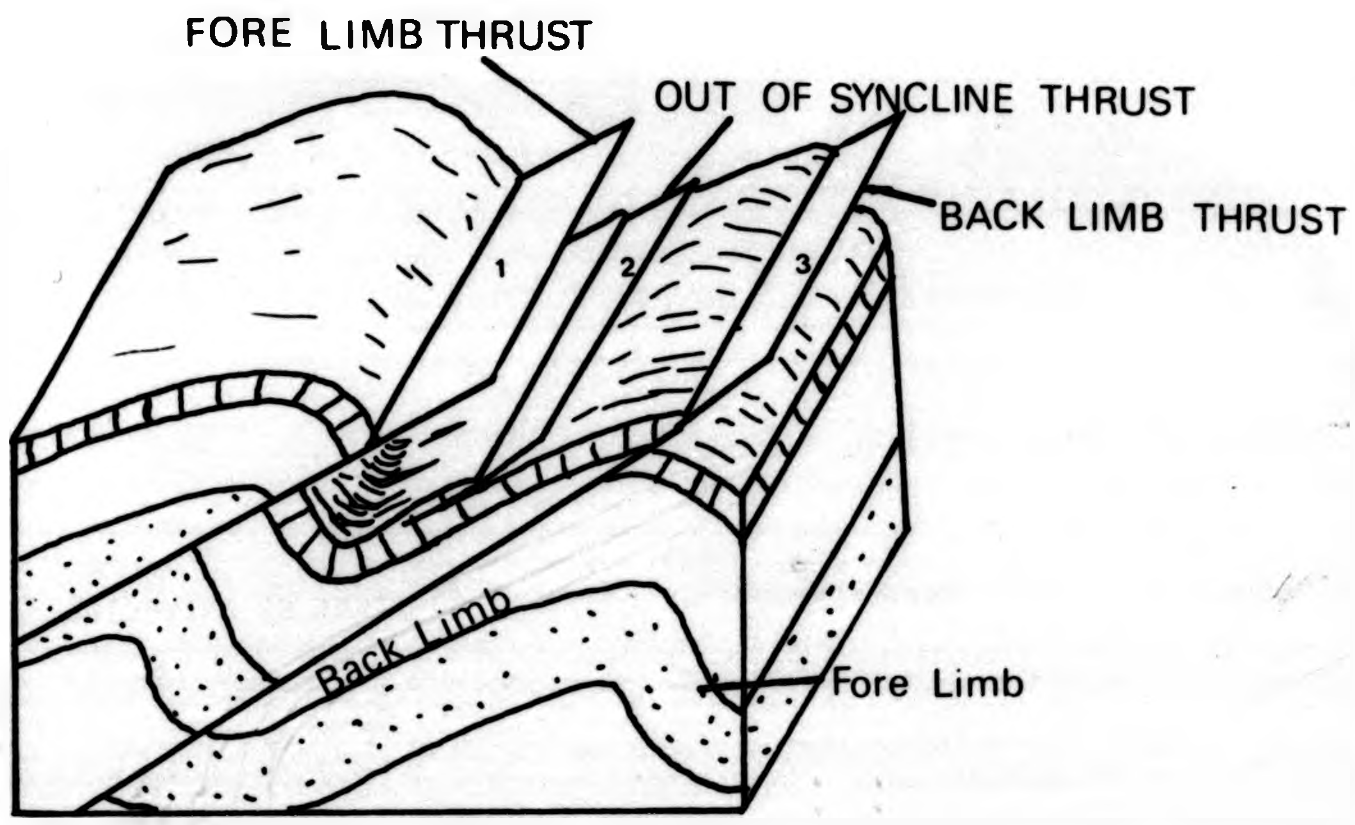
Interbed slip in asymmetric folds frequently gives rise to numerous small, low angled "out of syncline thrusts", (see Fig.1.10 , Hake, Addison and Willis, 1942) or numerous drag folds, under different stratigraphic conditions.

Thrust splays

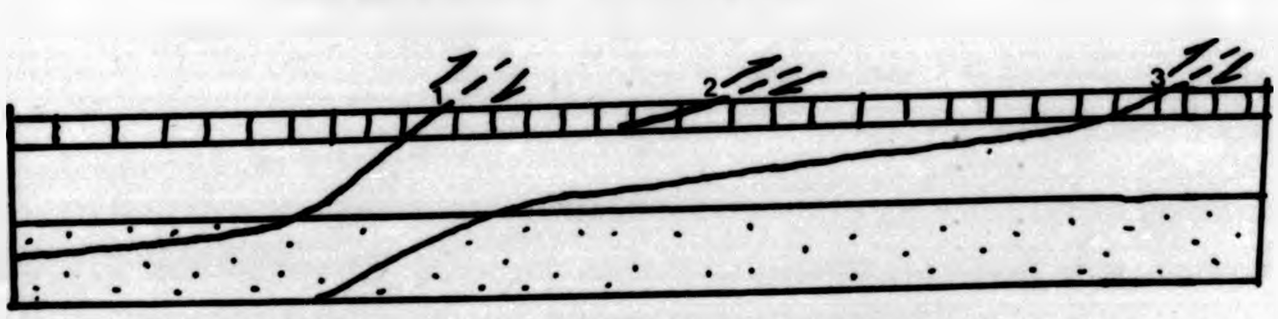
If a thrust joins another thrust at depth the line where the two fault planes join has a corner point at either end (Elliott 1977, Boyer and Elliott 1982) see Fig.1.11. Where two faults join on the outcrop surface to merge into one fault is known as a branch line (Boyer and Elliott 1982; Hossack in press; see Fig.1.11). Various types of splay fault relationships can be defined by using corner points and branch lines.

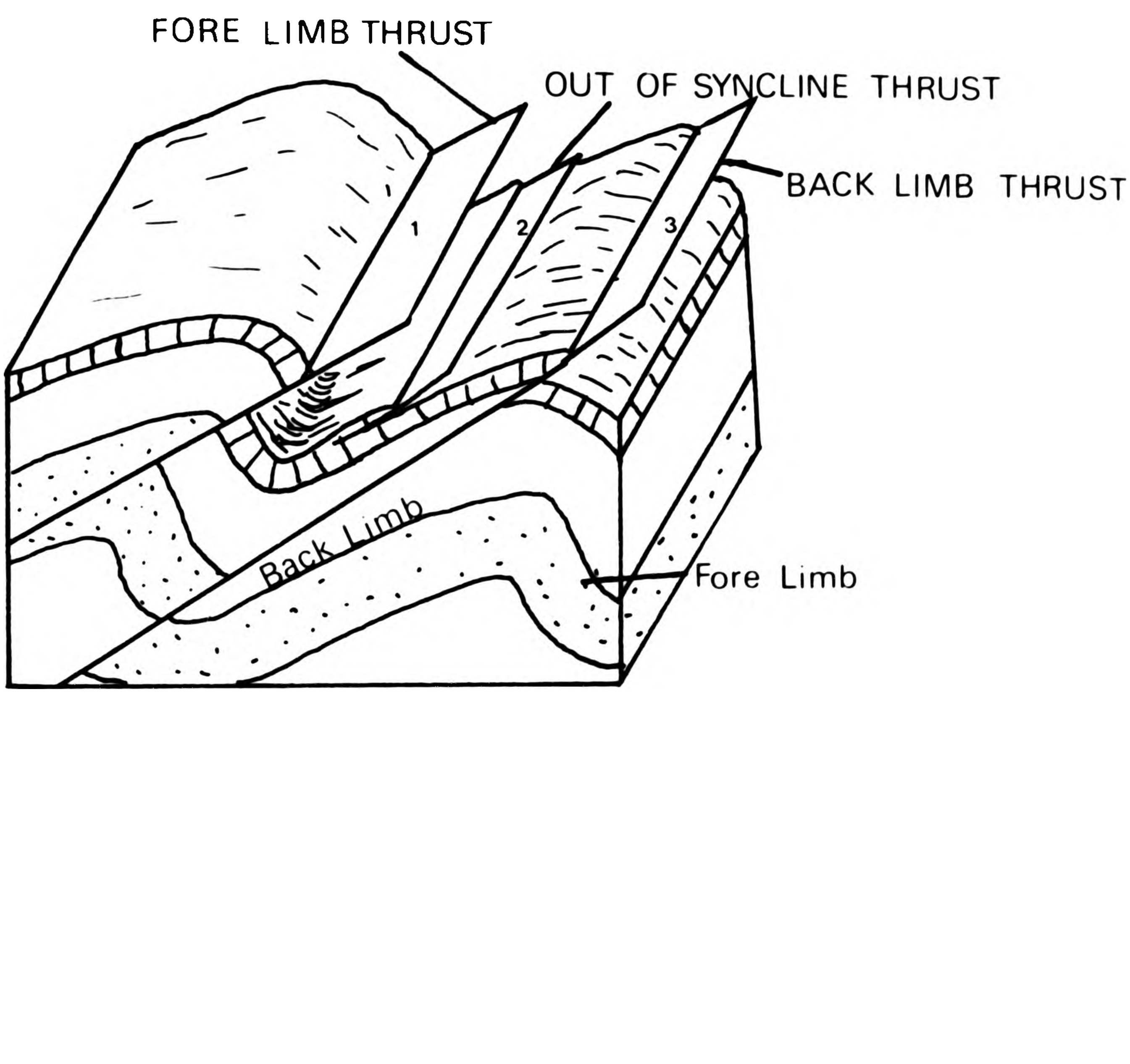
1. An isolated splay fault has two corner points only.
2. A diverging splay occurs when erosion cuts the branch line and the tip line only once.
3. A rejoining splay is where two branch lines are present for the same two faults.
4. A connecting splay has two branch lines joined to two separate faults at the surface.
5. A horse is a structure completely surrounded by branch lines ie. a rock slice bound on all sides by faults.

Fig.1.10 Second order thrust fault geometry in areas of asymmetrical folding (after Dahlstrom 1970).



RESTORED SECTION





RESTORED SECTION

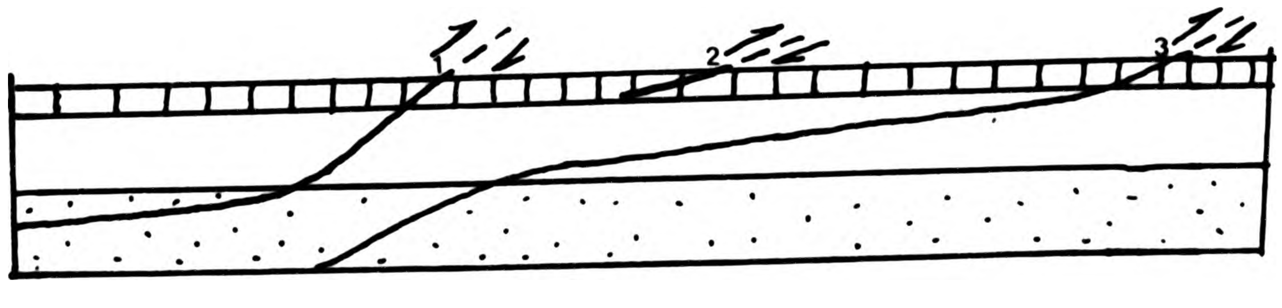


Fig.1.11 <u>Thrust splay geometry (after Boyer and Elliott 1982)</u>

KEY

C = Corner point

D = Branch line

M = Major thrust sheet

Figures

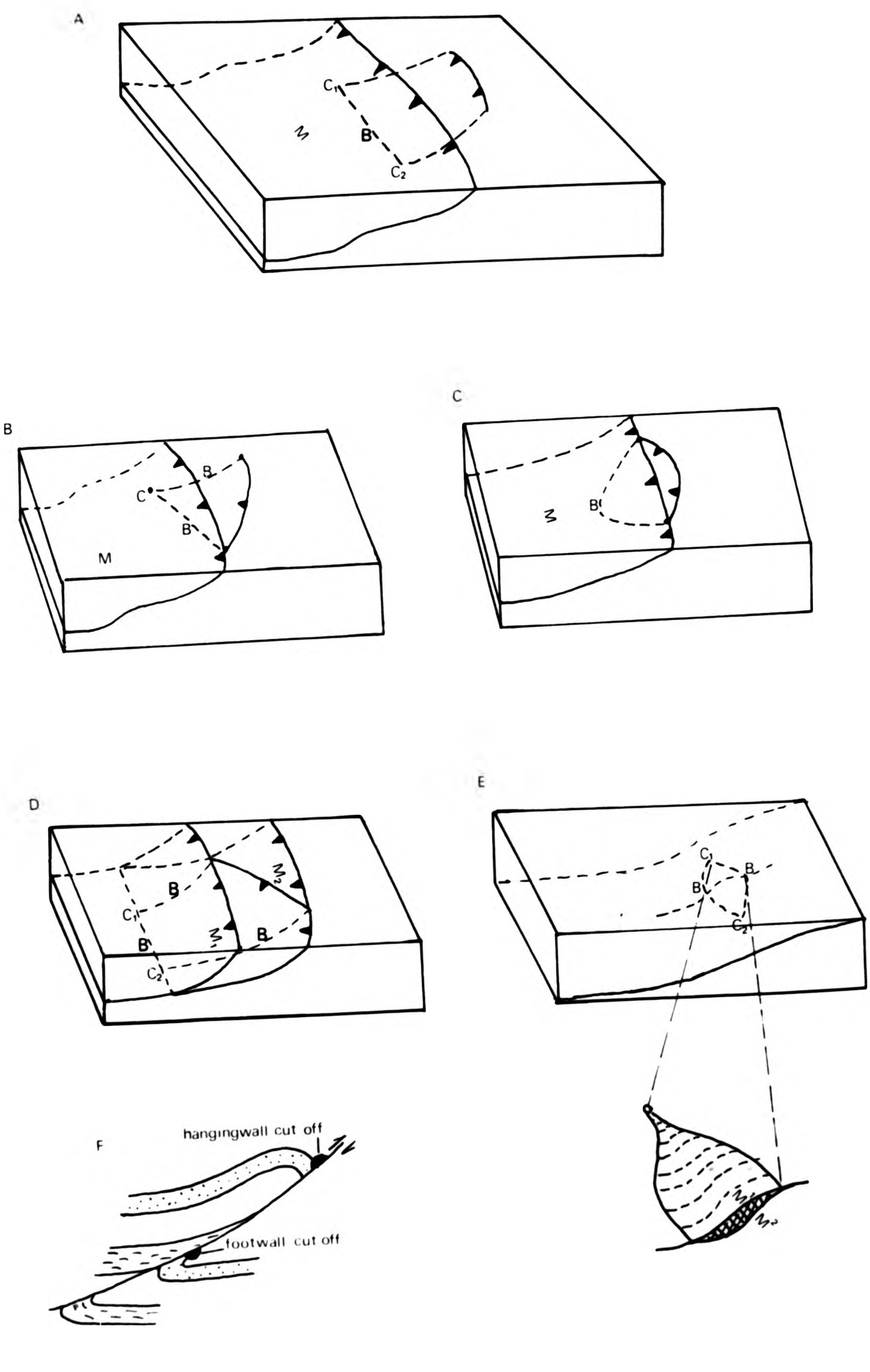
A. Isolated splay

B. Diverging splay

C. Rejoining splay

D. Connecting splay

E. Horse


A
C1
M
B
C2
B
C
B
B
M
C
M
B
D
B
C1
M2
M2
B
B
C2
E
C1
B
B
C2
F
hangingwall cut off
footwall cut off
M2

The intersection of a stratigraphic horizon with a thrust plane is called a cutoff line (Douglas 1958). A cutoff line intersects branch lines and tip lines and marks the crossing of two surfaces, see Fig.1.11f.

Tip lines are the generation areas of thrusts (Elliott 1976b) and the degree of connection between tip lines depends upon the deformation history of that portion of the thrust belt being studied (Boyer and Elliott 1982). Ideally horses are more common towards the older part of the thrust belt, whilst blind thrusts and isolated and divergent splays favour the younger, external shallower parts.

<u>Imbricate thrusts.</u>

Arrays of branching thrusts may become numerous enough to form an imbricate system of overlapping, concave upwards, listric shaped thrust faults fanning off a master fault of lower dip. These were first termed Schuppen structures by Suess (1904). The high angled imbricate faults ideally dip up to 60° but may be steepened up by subsequent imbrication towards the foreland. The imbricates are often regularly spaced and parallel or sub-parallel to one another. Bedding within individual imbricate structures is folded into an elongate s pattern (see Fig.1.12).

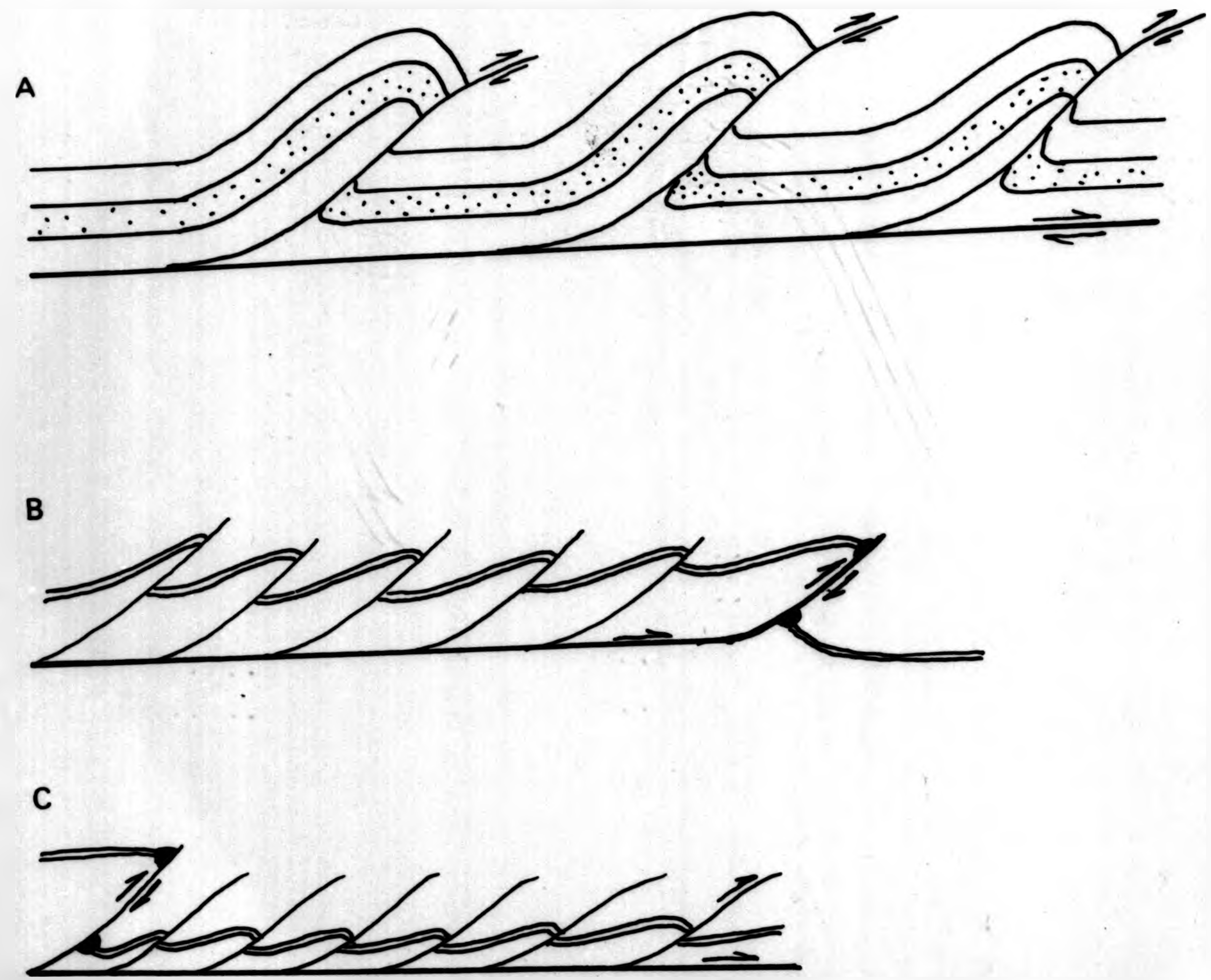
When an imbricate fan has the thrust with maximum slip at the front Boyer and Elliott (1982) called these leading imbricate fans and when maximum slip is along the thrust at the back it is termed a trailing imbricate fan, see Fig.1.12.

Fig.1.12 Imbricate thrust geometry (after Boyer and Elliott 1982)

a. Imbricate thrust displaying footwall syncline and hangingwall anticline geometry.

b. Leading imbricate (greatest displacement on leading edge thrust).

c. Trailing imbricate (greatest displacement on trailing edge thrust).


A
B
C

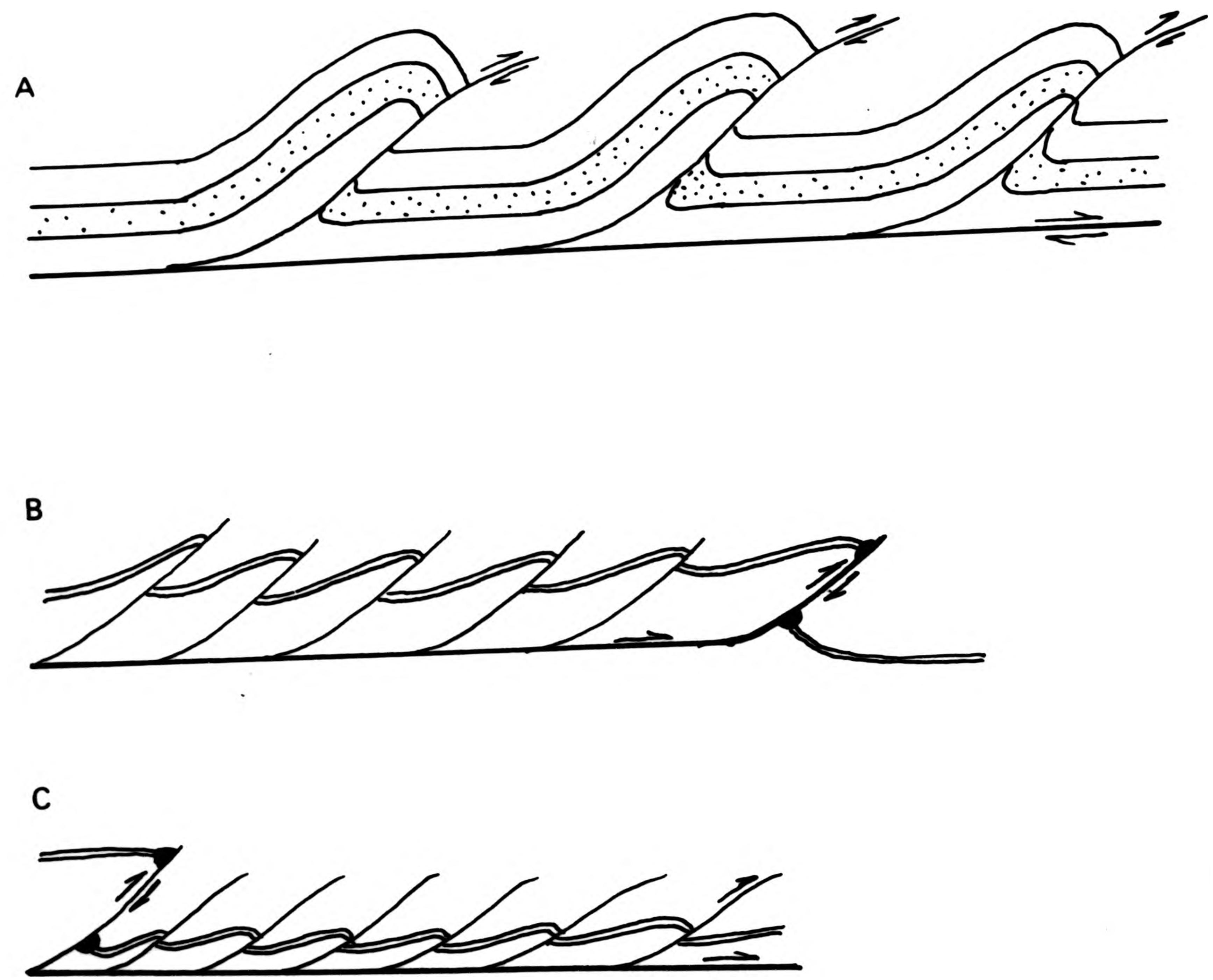

A
B
C

Fig.1.13 <u>Mechanisms for producing backthrusts</u>

A. Chisel fault (after Jacobeen and Kanes 1974).

A1, Position of future thrust

A2, Compression is induced and an anticline is formed

A3, Stick on the fault plane occurs going up the ramp

A4, Sticking results in a backthrust forming as material towards the hinterland is pushed into the anticlinal core.

B. Layer parallel shortening followed by fracturing (after Elliott and Johnson 1980).

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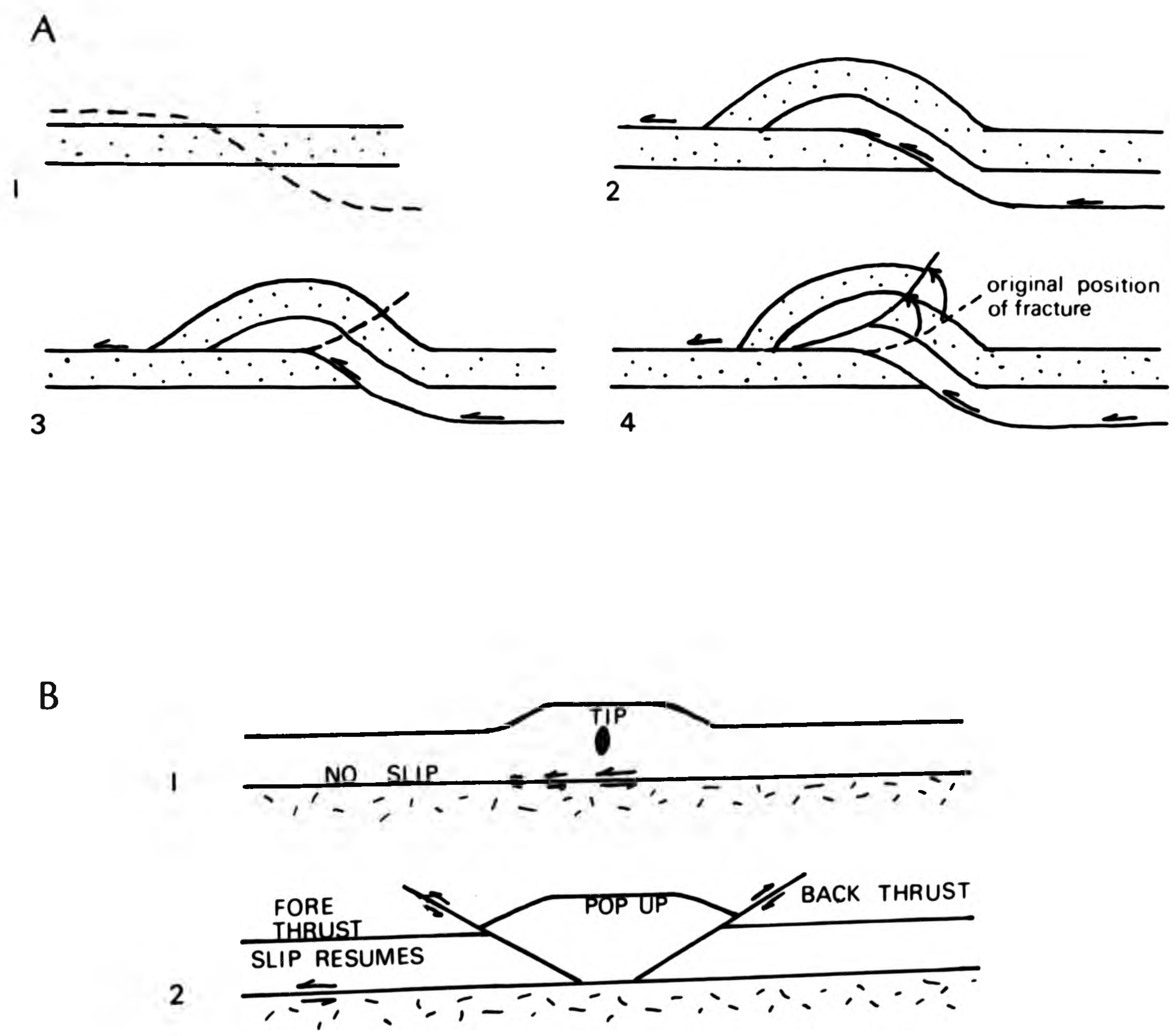

A
1
2
original position of fracture
3
4
B
TIP
NO SLIP
1
FORE THRUST
POP UP
BACK THRUST
SLIP RESUMES
2

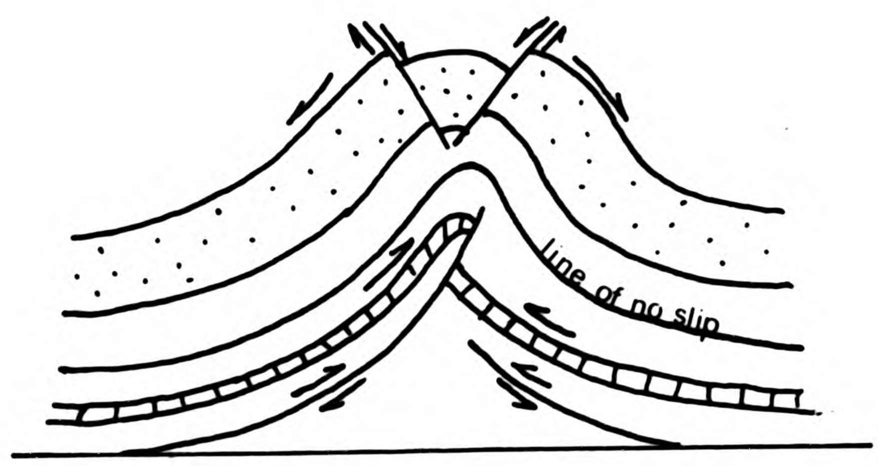
Fig.1.14 <u>Mechanisms for producing extensional faults in compressional regimes</u>

a. Extension in areas above the line of no flexural slip (after De Sitter 1956).

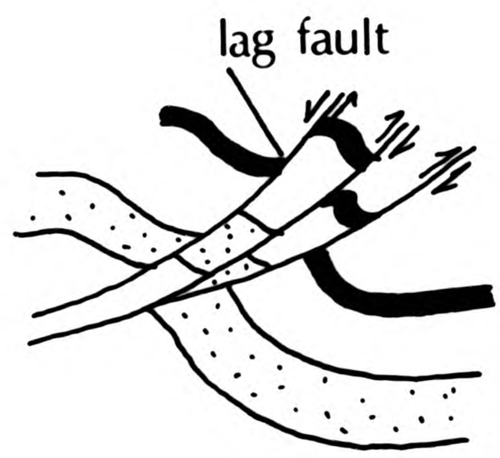
b. Lag fault (after Marr 1906).

c. Progressive shear within a thrust sheet (Ramsay 1980).

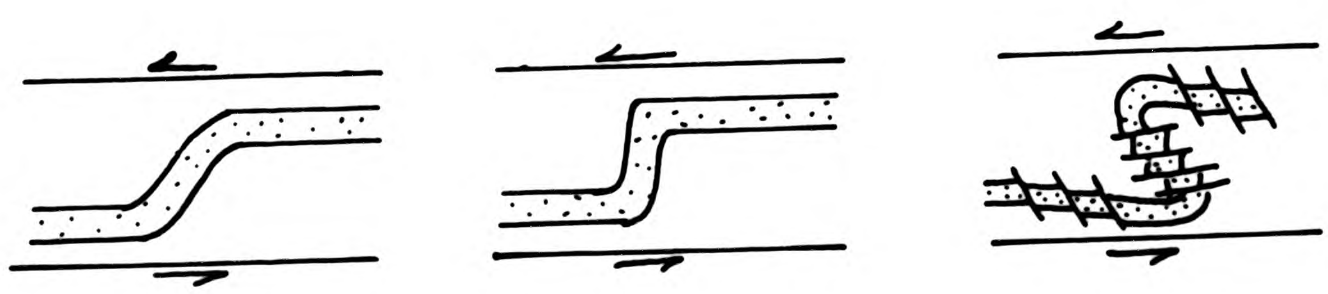
A



B



C



Imbricate zones display considerable amounts of shortening (frequently about 50%) despite the small amounts of throw displayed by individual faults. Most imbricate thrusts dip towards the hinterland, however in many areas which display imbricate fans or in areas with more isolated thrusts, normal faults and back thrusts (dipping towards foreland) are developed in association. There are several explanations listed below for the origins of normal faults and second and third order back thrusts developed in thrust belts.

<u>The causes of back thrusts.</u>

1."Chisel faults". Jacobeen and Kanes (1974) proposed these developed by underthrusting a fold limb as the ramp thrust sticks under the developing fold. Back thrusts on ramps have also been described in the field by Serra (1977) and experimentally by Morse (1977), (see Fig.13a).

2.Accommodation structures in the cores of concentric folds, De Sitter (1956), Gwinn (1964), (see Fig.1.4).

3.Stick on the propogating fault tip causes the rocks to begin to fold and suffer bulk layer parallel shortening, defining a series of pop up and triangle zones, Elliott and Johnston (1980), see Fig.1.13b. Knipe (in prep) proposes that minor perturbations in bedding encountered by a propogating thrust are likely to be areas where bulk layer parallel shortening can develop.

<u>The causes of normal faults during compressional tectonics.</u>

1.Local extensional environments can be set up by flexuring within folds causing small normal faults to develop, (see Fig.1.14a) De Sitter (1956).

2.Lag faults. Low angled faults with normal displacement may have resulted from the upwards movement of the footwall in a region of thrusting, where the hanging wall has lagged behind regional movements, (Marr 1906), see Fig.1.14b.

3.Progressive shear within a thrust sheet may rotate fold limbs during buckling, resulting in competent layers changing from a contractional environment to an extensional environment and the formation of normal fault systems,(Ramsay 1980), (see Fig.1.14c).

4.Rotation of thrust faults to appear like normal faults in outcrop.

5.Early extension before thrusting began.

6.Syn-orogenic normal faulting in the foreland related to the passage of a foreland bulge through the region, (Buchanan and Johnson 1968).

7.Extension as a thrust sheet moves over a ramp, (Laubscher 1973).

<u>Duplex structures.</u>

Duplex structures are characterised by relatively flat-lying roof and floor thrusts, joined by high angle reverse faults which are regularly spaced and sub-parallel to one another. These define horses within the duplex (see Fig.1.15). Bedding within the horse may be shortened by folding in a characteristic elongate "s" pattern, by layer parallel shortening and by cleavage/pressure solution.

There are few published cross-sections displaying duplex zones but recently more of these structures are being recognised and described. The most important recent works on duplex structures come from Boyer (unpublished thesis 1978) and Boyer and Elliott (1982) where many examples of duplexes are cited or proposed and where the geometry and mechanics of duplex structures is discussed.

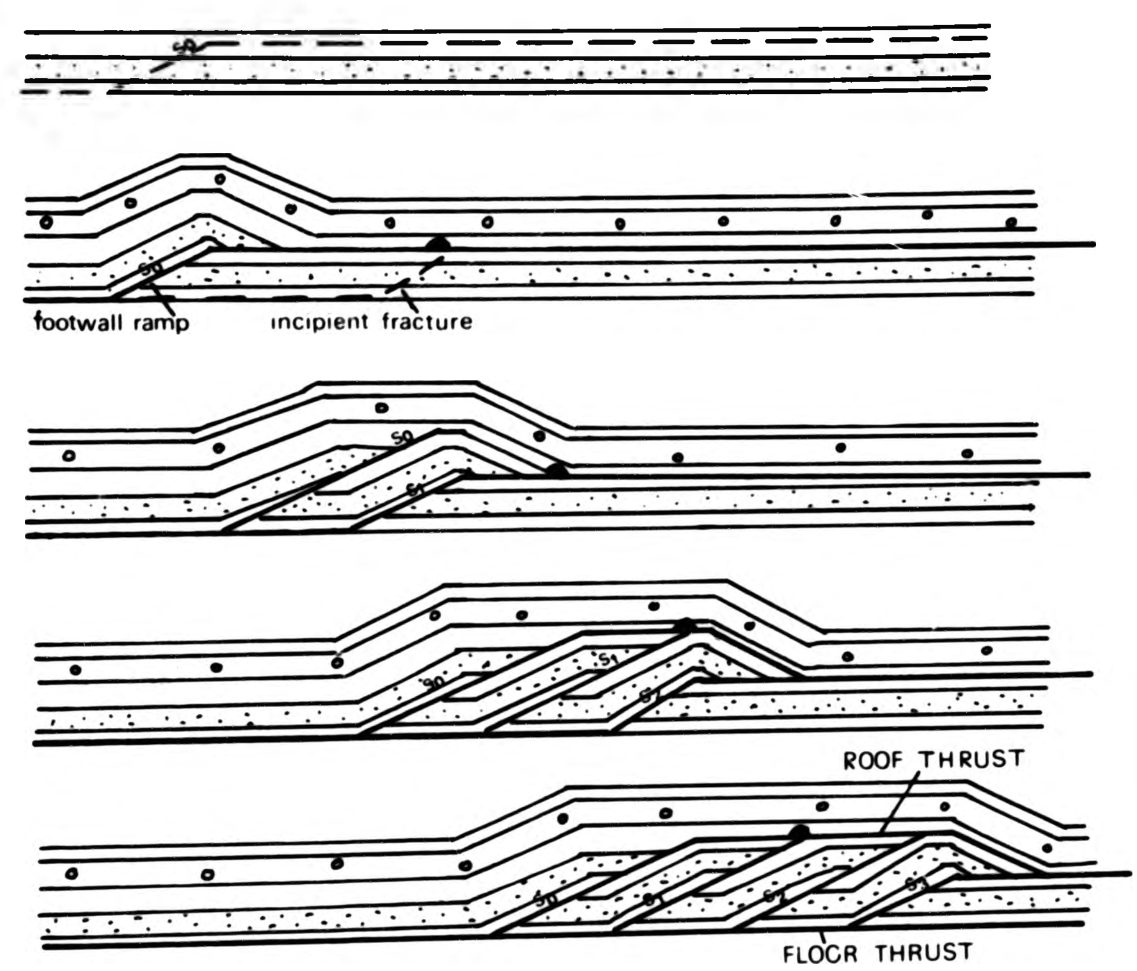
Often the idealised duplex structure (Cooper et al in press) is not found. Instead the roof thrust is frequently breached by the imbricates from the sole thrust, (leaky duplex). This implies in such circumstances, that either the roof thrust was earlier than the floor thrust, or that the imbricates were reactivated at a later stage, after the duplex developed. In a sequence of piggy back thrusting where the older thrust sheet lies on top of a newly deforming thrust sheet the imbricates of the newly forming thrust sheet may penetrate the thrust sheet above. This may be the most common cause of 'leaky' duplex structures. However, because a true duplex structure is thought to transfer slip to a higher slip horizon, a leaky duplex geometry caused by this means cannot be regarded as a true duplex.

Fig.1.15 <u>Duplex geometry (after Boyer and Elliott 1982)</u>

a. Development of a duplex fault zone

b. Types of duplex geometry

A



PROGRESSIVE ROTATION OF A DUPLEX OVER A RAMP

B

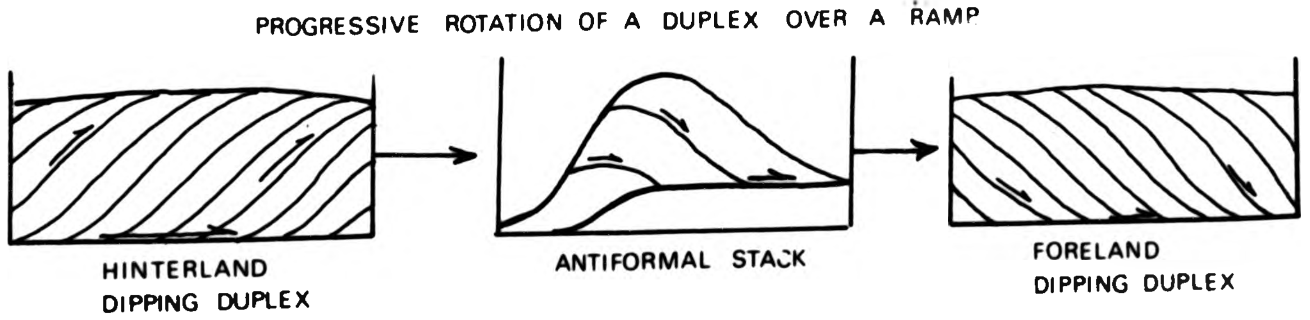
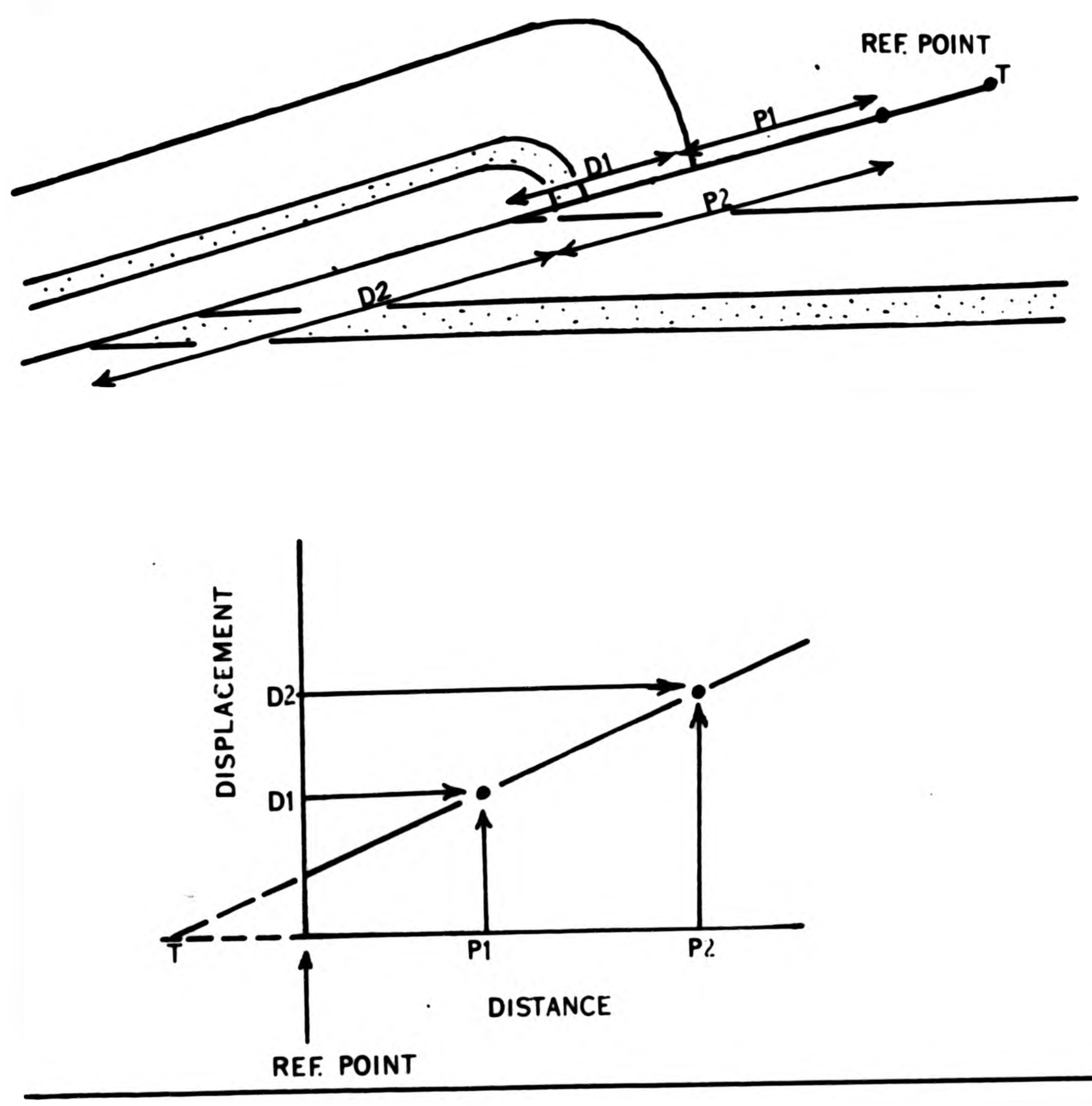


Fig.1.16a <u>Predicting the distance to a thrust tip (Williams and Chapman in press)</u>

Fig.1.16b <u>Bow and arrow rule (Elliott 1977).</u>

A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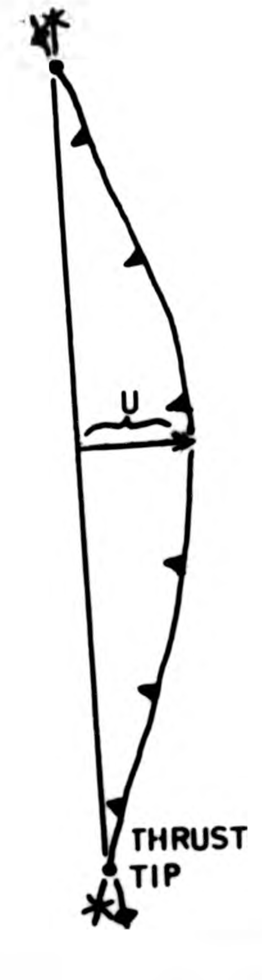
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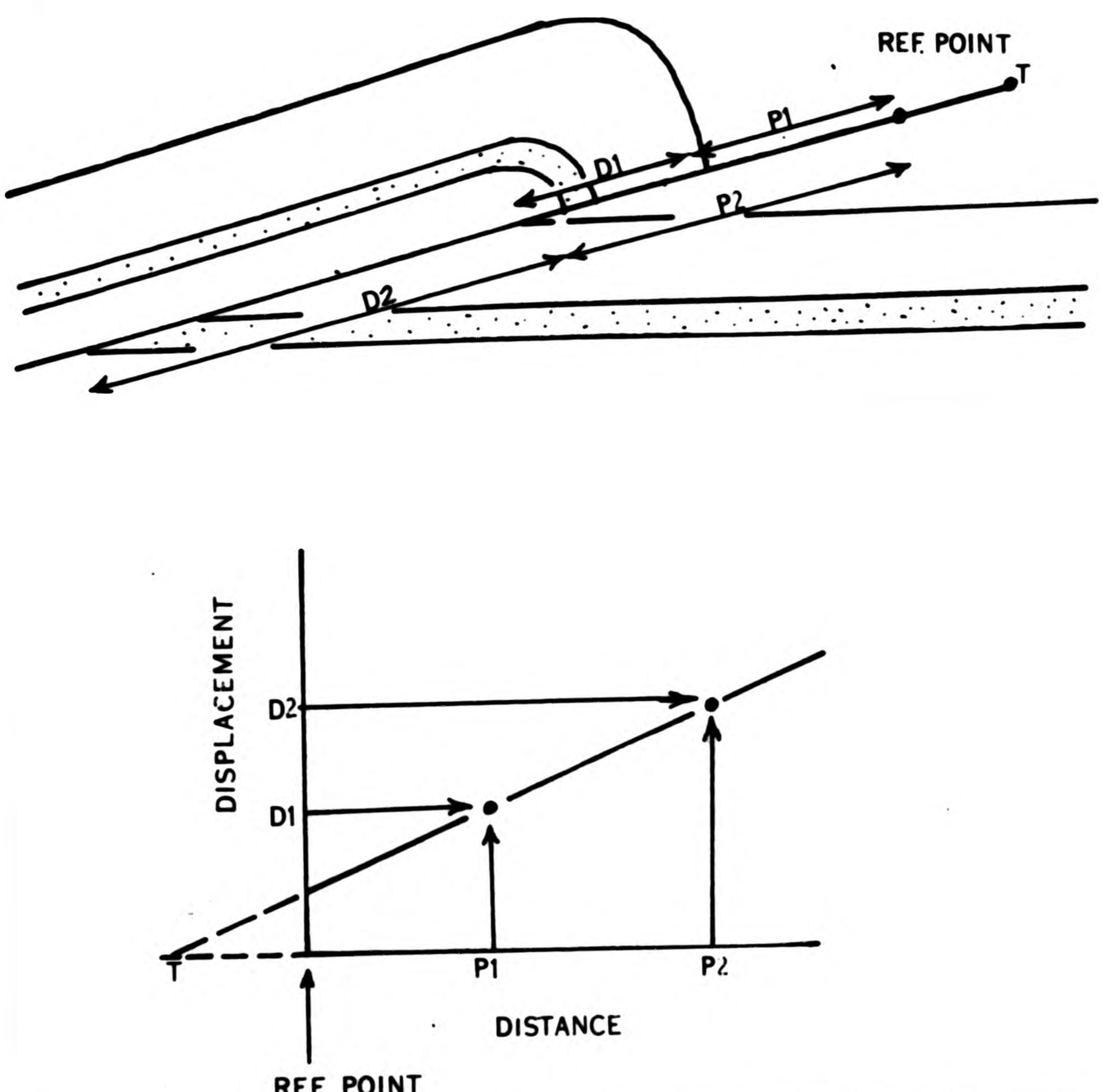
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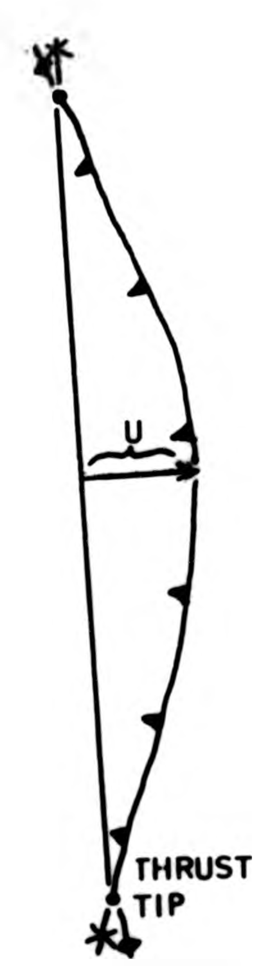
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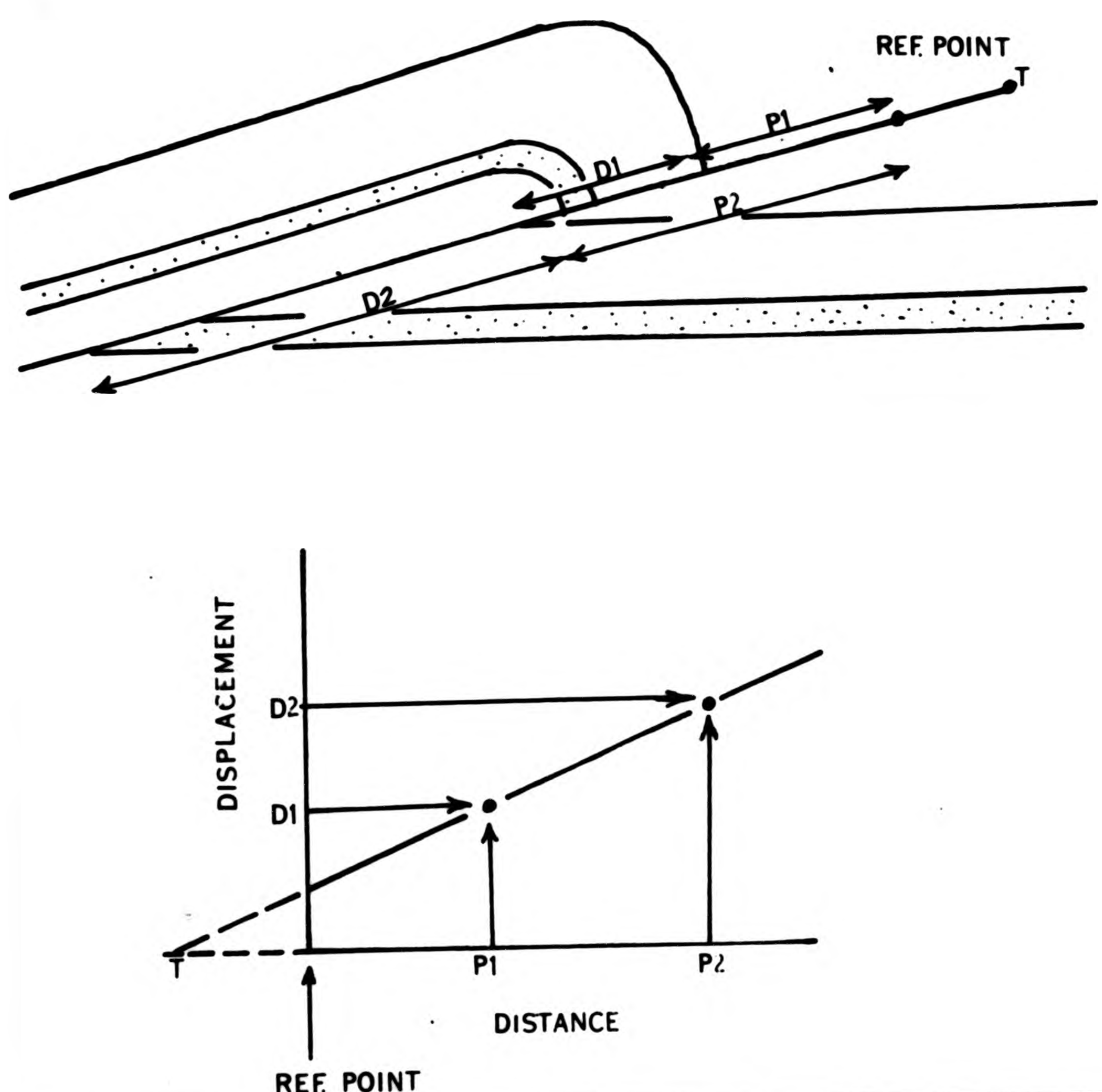

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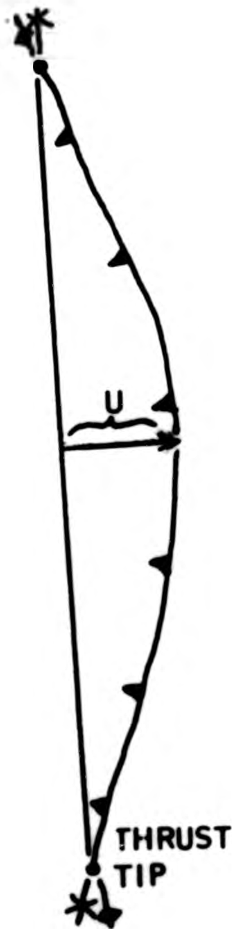

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1.6.3 Techniques for predicting thrust fault geometries.

Stratigraphic separation diagrams.(Elliott 1977).

These diagrams are used to find out what statigraphic units are the most likely to contain thrusts and also to find out where ramps and flats are likely to occur. (They can also allow extensional and contractional faults to be distinguished). To achieve this a graph is constructed which plots the stratigraphic position of the fault in the hanging- and footwalls respectively, against distance along the fault. The longer the fault remains in a particular horizon the more likely it is to form flats.

Trial and error method of finding the fault displacement when the fault geometry is unknown.(Elliott 1977).

The fault displacement is found by following the method outlined below.

1.Draw strike lines on the fault of interest.

2.Draw isopach map of the thickness of the rock in the undeformed state between marker horizons on the hanging wall side of the thrust surface.

3.Calculate the slip along the thrust by moving the isopach map.

4.Draw strike lines on the marker horizon in the deformed state.

Bow and arrow rule of thumb.(Elliott 1977).

Climbing thrusts usually have a curved outline in plan, the concave side marking the leading edge of the thrust sheet. If the two tip lines of the thrust are present, the maximum displacement along the thrust can be calculated as follows. A chord is constructed between the two tip lines, the normal bisectrix of the chord is constructed where the thrust outcrop is furthest from the chord, enabling the maximum displacement to be estimated by measuring the distance in plan, between the chord and thrust, see Fig.1.16b.

Predicting the distance a thrust extends above the surface (Williams and Chapman in press).

Using an arbitrary reference point on the thrust plane, bed displacements are measured at various distances from the reference point, see Fig.1.16a . Then by plotting a graph of the separation of a bed in the hangingwall and footwall against displacement measured from the arbitary reference point, the line constructed through the points on the graph can be projected onto the horizontal axis. This gives the distance to the propogating tip. The method only works for exposures of thrusts near the tip lines where displacement is decreasing up the fault, if a thrust in outcrop displays constant displacements, a horizontal line will be produced on the graph which will never cut the horizontal axis.

By using the procedures and rules outlined above and iterative modelling the most valid structural model for an area should be obtained.

CHAPTER 2

THE CAMBRO-SILURIAN STRATIGRAPHY OF THE OSLO GRABEN

2.1 Introduction

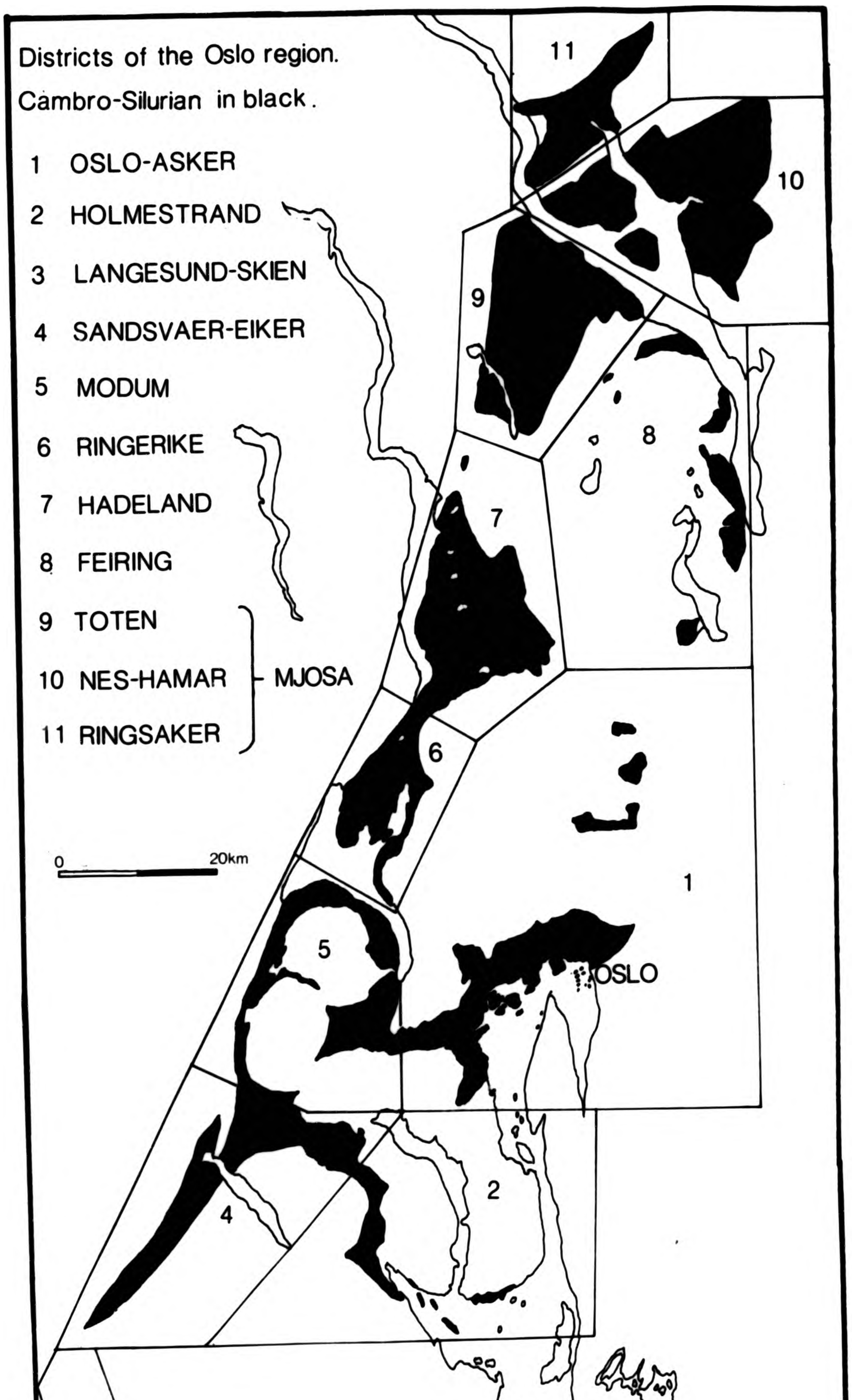
An attempt to describe the stratigraphy of the Oslo region in detail is outside the range of this thesis, however detailed descriptions are given for the areas personally mapped (see Appendix 2),whilst more generalized descriptions are given for the areas mapped by other workers.

A knowledge of the stratigraphy is necessary to determine the structure of a region. Also, in order to construct an accurate balanced section reliable estimates of stratigraphic thickness are essential, especially when area balancing. Finally, unconformities and variations in the timing and types of sediment deposited in clastic wedges which may form in front of advancing thrust sheets can be used to determine the timing and rates of tectonic events.

Unit terminology in the Oslo Graben

It was found convenient to divide the Oslo region up into the districts used by Stormer(1953) see Fig.2.1. All references made to districts in this thesis apply to this figure.

Fig.2.1 <u>The districts of the Oslo Graben (after Stormer 1953).</u>


Districts of the Oslo region.
Cambro-Silurian in black.
1 OSLO-ASKER
2 HOLMESTRAND
3 LANGESUND-SKIEN
4 SANDSVAER-EIKER
5 MODUM
6 RINGERIKE
7 HADELAND
8 FEIRING
9 TOTEN
10 NES-HAMAR
11 RINGSAKER
MJOSA
0
20km
OSLO

The stratigraphic division of the Cambro-Silurian rocks had been somewhat consistent. Originally Kjerulf(1855) divided up the region numerically into "Etangen" or stages 1-9. Subsequent writers elaborated on this, splitting up the original units into smaller ones; thus stage 3 has been sub-divided into 3aa,3ab, 3ac,3b,3ca,3cb, and 3cc. The numerical symbols now used are largely those introduced by Vogt(1924) for the Lower Cambrian, by Brogger(1878,1882, 1887) for the Middle Cambrian, the Upper Cambrian and Lower Ordovician and for the Middle and Upper Ordovician respectively and by Kiaer(1908) for the Silurian. These units are essentially chronostratigraphic, the Cambrian representing numbers 1-2d, the Ordovician 2e-5b and the Silurian 6-10.

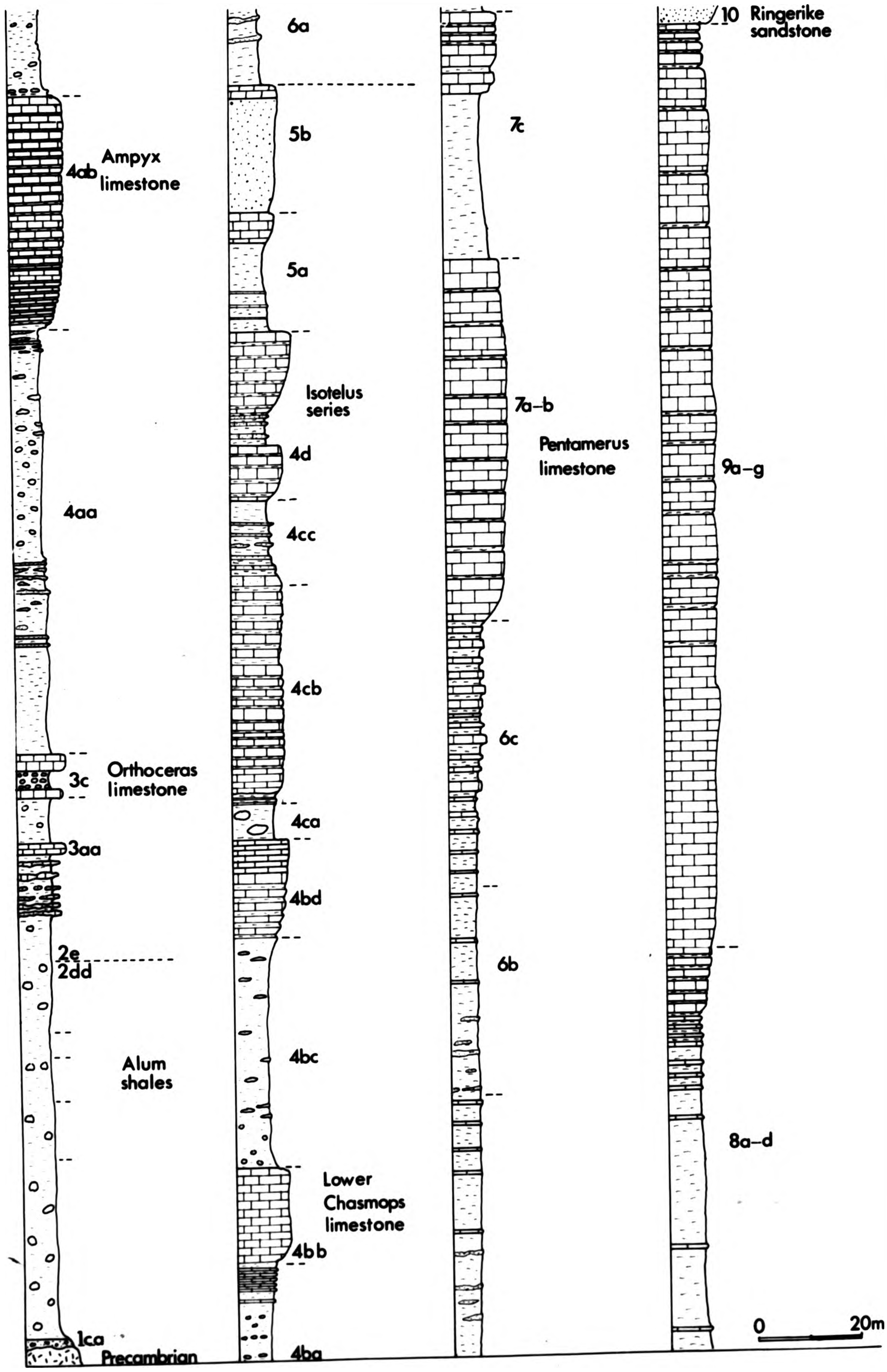
The subdivisions of the numerical symbols frequently coincide with lithostratigraphic units (especially in the Oslo district) eg.3ac corresponds with the Ceratopyge Limestone. These lithostratigraphic units are confusing because they have for the most part not been formally defined. The undesirable use of fossil names associated with these lithostratigraphic units has led to erroneous bio-stratigraphic inferences e.g. the Orthoceras Limestone though packed with orthoconic nautiloids does not contain Orthoceras sp..

During the inital exploration of the region, some workers failed to appreciate lateral facies changes, which resulted in some mis-interpretation of local sequences. Confusion also arose over imposing information from sequences outside the Oslo-Asker succession and vice-versa. Owen (1977) remarked that in the districts outside Oslo-Asker it has been common for workers to attempt to apply the stratigraphic divisions of the Oslo type area before describing the local succession, whilst more recently workers have indiscriminantly used chrono-stratigraphic terms for litho and bio-stratigraphic units within and outside the Oslo-Asker district.

The recognition of local series is therefore important in rectifying the problems outlined above. As a result of detailed palaeontological and stratigraphic study of measured Middle Ordovician sections in the Oslo district by Dr. D.Bruton and Mr.F.Bockelie of the Oslo Palaeontology Museum and Dr.A.Owen of Dundee University, a new terminology deriving unit names from their type localities will soon be published. This terminology has already been applied to the Ordovician of Ringerike and South Hadeland by Owen(1977).

In this thesis a mixture of the terminologies mentioned above will be applied because unfortunately the work using local series names is still incomplete. Litho-stratigraphic units are the most important to use when determining the structural geology of an area, because the deformational characteristics of a sedimentary succession are usually governed by competent and incompetent units which coincide with a litho-stratigraphic division. These units will be used when local names are not available.

Fig.2.2 <u>The Cambro-Silurian stratigraphy of the Asker-Baerum district (see text for unit names of stage numbers).</u>


6a
5b
Ampyx limestone
4ab
5a
Isotelus series
4d
4aa
4cc
4cb
Orthoceras limestone
3c
4ca
3aa
4bd
2e
2dd
Alum shales
4bc
Lower Chasmops limestone
4bb
1ca
Precambrian
4ba
7c
7a–b
Pentamerus limestone
6c
6b
10 Ringerike sandstone
9a–g
8a–d
0
20m

2.2 Stratigraphy of the study areas (see maps, Appendix 2).

2.2.1 Asker-Baerum district.

This area is part of the Oslo district which displays the fullest Cambro- Silurian stratigraphy in the region (see Fig.2.2). The rocks are well exposed along the coast, near Oslo, so naturally this district has been used as the regional type area. The stratigraphy here is well described, particularly through the work of Brogger(1882, 1887) and Kier(1908).

Cambrian.

The lowest beds of the Cambrian are missing and the Cambrian, Precambrian unconformity indicates that a land area existed prior to the transgression of the Cambrian sea.

1c. Basal Transgressive Beds, thickness 5-10m

An autochthonous arkosic basal conglomerate, of irregular thickness, containing weathered Precambrian Gneiss clasts is in contact with the Precambrian basement. Following on is a thin, hard, fragmental, limestone above which is a highly fossiliferous, dark grey, bedded limestone.

2a-2de. Alum Shales, thickness 45-50m

These black, often vitreous, shales form a monotonous lithology stained by sulphurous yellow streaks and white powdery crusts deposited from percalating ground waters. The shales contain concretions and occasional layers of dark bituminous limestone (stinkstones) which smell of H_2S when broken. The concretions are ellipsoidal to spherical in shape and may be more than 1m in diameter. Many are highly fossiliferous, containing mainly small trilobites and horny brachiopods and some parts of the concretions are composed of impure dark calcite which often display a cone-in-cone structure.

The Alum Shales were worked for alum, hence their name, in Oslo from 1737-1818 They also contain up to 15% carbon, grains of pyrite and calcite that are visible to the naked eye and small amounts of uranium (Skjeseth 1958).

The fossils present are mainly Olenid series trilobites almost entirely from the Olenidae family, together with a few agnostid trilobites, horny brachiopods and sponge spicules. Often horizons are very fossiliferous but contain only a few species.

Ordovician

2e-3a. Ceratopyge Series, thickness 20m

The Ceratopyge Series comprises a shale unit passing up into a thin limestone. The basal unit (2e) is a continuation of the Alum Shales from the Cambrian and is marked by the presence of Dictyonema flabelliforme. This unit grades into the 3aa-3ab units where the rocks become a dark grey colour and contain smaller concretions and nodules, (representing a change from stagnant to well aerated conditions). Accompanying this is an invasion of a new fauna containing trilobites, brachiopods, gastropods and cephalopods.

The Ceratopyge Limestone is light grey, in parts glauconitic and frequently contains large crossed crystals of pseudomorphs after barytes. Near the coast the limestone weathers with distinctive reddish/brown patches. Locally it is very fossiliferous containing many trilobites. It is about 1.5m thick.

3bc-3be. Lower Didymograptus Shales, thickness 20m

The Lower Didymograptus Shale is dark grey and rich in graptolites. Towards the base there are thin limestone beds, poor in fossils. These lower beds frequently weather to a rusty brown colour near the present sea shore

3c. Orthoceras Limestone, thickness 7-9m

This limestone found throughout most of the Oslo region, is really a thin extension of the much thicker Orthoceras Limestone of Sweden and the Baltic, where it has a longer stratigraphic interval. It can be subdivided into three units, a middle unit of shales and limestone nodules sandwiched between two compact, bedded limestone layers. This triplet is made up of the Megitaspis Limestone (3ca), Asaphus Limestone and shale (3cb) and the Endoceras Limestone (3cc). In the limestone glauconitic and phosphatic material is present at some levels. The limestone contains a very rich fauna of Asaphidae and Illaenide trilobites and orthoconic Nautilloids. The latter provide way up markers as in the majority of examples the siphuncles lie downwards towards the base of the bed. The abundance of fossils, especially cephalopods and way up markers make this a very useful, easily distinguishable marker unit for determining the the structure of the area.

4aa. Upper Didymograptus Shale, (total thickness 50-60m)

The lowest ten metres of this unit are made up of dark grey to black shales without nodules, which become richer in mica towards the top. Graptolite-rich zones are found in the shales. After these shales follows 6m of dark grey shales with arenaceous beds or large nodules, which pass into about 25m of black shales. These contain rounded limestone lenses which weather to a yellowish brown colour.

Ogygiacaris Shales.

The Ogygiacaris Shales are distinguished from the Upper Didymograptus Shales by the replacement of the rounded lenses by flat lenses which weather to a light grey colour. Towards the top of this unit dark and light shale bands alternate with calcareous silty bands and lenses. The silty bands frequently display current bedding and become more numerous as the unit grades into the Ampyx Limestone.

Rhythmic sedimentation in the Ordovician

The middle and upper Ordovician sequences which follow are notable in the Oslo district for their rhythmic appearance. A typical rhythmn starts with shales and passes upwards into shales with an increasing percentage of nodular limestone, containing a scarce shelly benthonic fauna (Henningsmoen 1974). These cycles are not recognised outside the immediate Oslo district and have been attributed to local tectonic control by Brenchley and Newall (1980) and to glacio-eustatic control by Bjorlykke (1974).

4ab. Ampyx Limestone, thickness 40m

Micrite limestone nodules and bands form rhythmic repetitions within this unit, each cycle is about 0.5-1m thick and involves increasing amounts of shale between the limestone bands and nodules. The limestone is light or dark bluish grey in colour, weathers to a light grey colour and contains few fossils. The top of the unit grades into the Lower Chasmops Shales

4ba. Lower Chasmops Limestone, thickness 30-45m

This black to greyish coloured shale weathers to a lighter grey.

The lowest part of the unit contains layers of limestone nodules 2-8cm thick separated vertically by about 20-40cm of shale. Towards the top, these limestone nodules become 10-15cm thick, separated by 10-30cm of shale. Frequently there are thin layers of greenish bentonites present. At Vollen one such horizon is about 0.5m thick, but generally they are rarely over 1-2cm thick. Fossils vary in abundance but some weathered nodules can be packed, especially in brachiopods and bryozoans.

4bb. Lower Chasmops Limestone, 17-20m

This limestone is characterised by parallel layers of densely packed, irregular limestone nodules separated by shale bands. The nodule layers are about 3-5cm thick with 1-3cm of shale between. Towards the top more pronounced limestone beds about 10cm thick can be seen. Fossils are sparse.

4bc. Upper Chasmops Shale, thickness 35-40m

The shales are generally dark grey in colour but occasionally are a lighter grey. They frequently contain small aggregates of pyrites and chalcopyrites cubes. In the lower part of the shales large limestone lenses up to 100cm x 30cm may be found, whilst towards the top in intervals of usually 2-3m there are horizons of ellipsoidal, parallel bedded and equi-dimensional micritic limestone nodules about 10cm across. The nodules are dark to mid-grey when fresh but weather with a white dusty appearance. Fossils are sparse.

4bd. Upper Chasmops Limestone, thickness 23m

In Asker this unit can be divided into three zones. A lower 15m of nodular limestone, a middle 5-6m of parallel bedded, compact limestone with continuous beds 10-15cm wide separated by shale bands 8-10m wide, followed by an upper 2-2.5m of more irregular reefy limestone. The bedded limestone when fresh is a characteristic stark white, but it weathers to a creamy colour and then shows characteristic bioturbations with well developed chondrites.

<u>4ca. Lower Tretraspis Shale, thickness 6-10m</u>

This thin, dark grey, calcareous shale is bioturbated and contains large, scattered, ellipsoidal nodules about 1x0.5m in diameter. There is a relatively large shelly fauna present in the shale

<u>4cb. Tretraspis Limestone, thickness 50m</u>

A transition zone about 1.5m thick of shales alternating with parallel bedded limestones forms the base of the Tretraspis Limestone unit. Above this zone is 10-15m of very characteristic densely packed, parallel bedded, small limestone nodules 3-5cm wide, separated by thin shale layers. The unit passes upwards into an indistinctive nodular limestone and shale unit which displays irregular, discontinuous, parallel-bedded nodules which gradually become more lensoidal, isolated and argillaceous upwards. As the shale bands thicken, sandstones in the upper part of the sequence sometimes occur as isolated bands (often with flat bases and bioturbated tops) about 10cm thick, with well developed cross bedding

The sequence of rocks from 4ca to the base of 5a were mapped as one unit, because structurally they behaved as one unit. They represent three shale units separated by two argillaceous limestone units, with transitional contacts.

<u>4cc. Upper Tretraspis Shale, thickness 22-48m</u>

These light grey shales, which weather to a rusty brown colour, display well developed sandstone lenses, with bottom structures, planar or rippled internal structure and trace fossils. The shale horizons can be up to 50cm thick between silty limestone and sandstone lenses, but are generally less than 20cm thick

4da. Lower Isotelus Limestone, thickness 10m

As the contact is transitional the limestone is said to be reached when there is less than 50% shale present. It is a rubbly dark grey limestone, which weathers to a light grey. The impersistent bedding of the limestone often passes laterally into shales. Dark grey calcareous sandstone horizons are also present, which weather to a creamy white. Between these beds are dark grey shales. All horizons are poorly fossiliferous.

4db Isotelus Shale, thickness 3-5m

This is a very distinctive unit composed almost entirely of dark grey shales, with rare thin limestones and bioturbated siltstones. It is poor in fossils.

4dc. Upper Isotelus Limestone, thickness 12-15m

This is made up of rubbly, frequently lensoidal limestone bands that alternate regularly with shales and siltstones. The limestone weathers to a creamy white.

The upper Ordovician.

The 5a and 5b successions have been described in great detail by Brenchley and Newall (1975 and 1980) who note how the 5b unit is especially complex in its facies changes. The thickness of stage 5 varies greatly also so that in Sandvika it is nearly 80m whilst on Bronnoya it is only 35m thick (Brenchley and Newall 1980).

5a. Husbergoya Shales, thickness 20-40m

The unit begins with dark shales containing thin discontinuous limestone and sandstone bands, whilst upwards the sandstones become rippled and more continuous. This cycle ends unlike others in a more massive limestone called the Langara Limestone-Shale Formation, which has been attributed to the increase of precipitation rates and the reduction of the influx of terrigenous material (which forms only very thin shale bands).

A 3-5m brown, bioturbated sandstone is often present about 5m from the top of the massive limestone. Thick and lacking in sedimentary structures it represents a different style of deposition and it therefore was used by Brenchley and Newall (1975) to mark the base of 5b.

In some areas the Husbergoya Shales form the whole of 5a and the Langoyene sandstone (Brenchley and Newall 1975) coincides with 5b, which represents a coarse clastic shoaling sequence. Elsewhere the Langara Limestone-Shale Formation straddles the 5a/5b boundary and represents a more open shelf type sediment.

<u>5b, thickness up to 50m</u>

The rocks of 5b are very chararacteristic, though variable. They can be a mixture of limestones, shales and sandstones; thick limestone; or just sandstone units. The sandstones are usually laminated, with beds up to 1m thick, cross bedded and frequently channeled. Sometimes the sandstones are channeled by or pass laterally into, conglomerates which fine upwards. Oolitic limestones may be present in the middle or at the top of the thick sandstone formation.

The limestones form thick, well-bedded sequences which usually contain nodules. Two fossils characterise the limestones : around Sandvika a brachiopod called Holorhynchus is present in great numbers, whilst elsewhere the limestone usually contains a tubular coral called Palaeoporella.

Generally the sequence can be said to get thicker and more calcareous to the north west.

<u>Silurian.</u>

The Silurian rests with a very sharp lithological boundary on stage 5 and represents a rapid subsidence to deeper water sedimentation (Seilacher and Meischner 1964).

<u>6a. Stricklandia Shales, thickness up to 60m</u>

The shales resting on 5b rocks are dark, silty and friable, with lensoidal, rippled storm sands more frequently developed higher in the unit. The deposits are of variable thickness depending on the topography cut into 5b upon which they are draped. The storm sands are replaced by nodular limestone lenses and bioclastic bands about 4cm thick towards the top of the unit.

<u>6b. thickness 50-55m</u>

The base of 6b is marked by a return of ripple drift sands replacing the limestone nodules. The sands occur in groups of between 2-5 bands separated by about 1m of shale. After about 20m the sandstones are suddenly replaced by bioclastic limestone bands 1-1.5m thick. The limestones increase in thickness and frequency towards the top of this unit and the stromatoporoids and corals they contain become larger and more abundant.

<u>6c. thickness 55-60m</u>

The base of 6c is placed at the position where the limestone/shale ratio is 1:1. The limestone is rich in brachiopods and corals, though the coral and stromatoporoid frequency is reduced upwards as the brachiopod Stricklandia lens becomes abundant. Upwards the faunal density remains high but the diversity is reduced and the favosites and stromatoporids present (though fewer in number) are characteristically large in size.

Sharply overlying the coral nodular limestone are shales and ripple drift sands. The sands are thicker at the base and are separated by about 1m of shale, which contains bioclastic limestone lenses.

Thickness 55-60m.

<u>7a-b Pentamerus Limestone, thickness 70-90m</u>

The shales of 6cb become rapidly richer in limestone nodules and grade into the Pentamerus Limestone above. The limestone contains small densely packed nodules at the base , similar in appearance to the nodules at the base of the Tretraspis Limestone. Upwards the limestone becomes massive, is a light grey colour, and frequently displays an almost reticulate pattern. Fossils are fairly abundant, but not of the quantity (especially brachiopods) found in Ringerike and Hadeland.

<u>7c. Crinoid Shale and Upper Coral Limestone, thickness 50m</u>

This calcareous shale can be either green or red in colour in the Oslo region. In Baerum it is hard, red, quite compact and contains numerous crinoid stems, some up to 3m. long, but no crowns are present. It grades upwards into a fossiliferous nodular limestone which is light grey in colour, called the Upper Coral Limestone.

<u>8a-d. Lower Spiriferid Series, thickness 80m</u>

The lowest unit is the Malmoya Shale, it has a shale rich base which increases in limestone content upwards. The dark grey, graptolitic shale is zoned by Monograptus species and Cyrtograptus species, whilst the layers of nodular limestone contain a shelly fauna.

The Malmoya Shale grades upwards into the light grey, fossiliferous Malmoya Limestone, which is 10-15m thick.

9. Upper Spiriferid Series, thickness 190m

This series is limestone rich, some limestones are massive and thick whilst others are nodular. The light grey limestones are fairly rich in fossils which include brachiopods, corals, bryozoans and graptolites

10. Ringerike Sandstone, thickness up to 600m

There is a rapid transition from grey shallow marine limestones to the red sandstones and marls forming deltaic and continental deposits forming this unit. In the first few metres of red beds marine fossils are still present, but after that only very occasional terrestrial plants and animals have been found.

2.2.2 The stratigraphy of the Ringerike area.

The Silurian stratigraphy is best known through the work of Kiaer (1908), whilst the middle-upper Ordovician stratigraphy was summarised (mainly from unpublished work), by Stormer (1953), a more recent revision was made by Owen (1977). A brief summary of the Ringerike succession is given in Fig.2.3.

The Cambro-middle Ordovician sequences described below are badly exposed in most of the area south of Klekken, where the rocks strike roughly NNE- SSW on the east bank of the river Storelva. Around Klekken and to the north there is a better opportunity to study the sequence, where it strikes WSW- ESE, and is repeated by imbricate thrusting.

Cambrian

1cb-2dd. Alum Shales, thickness 60m

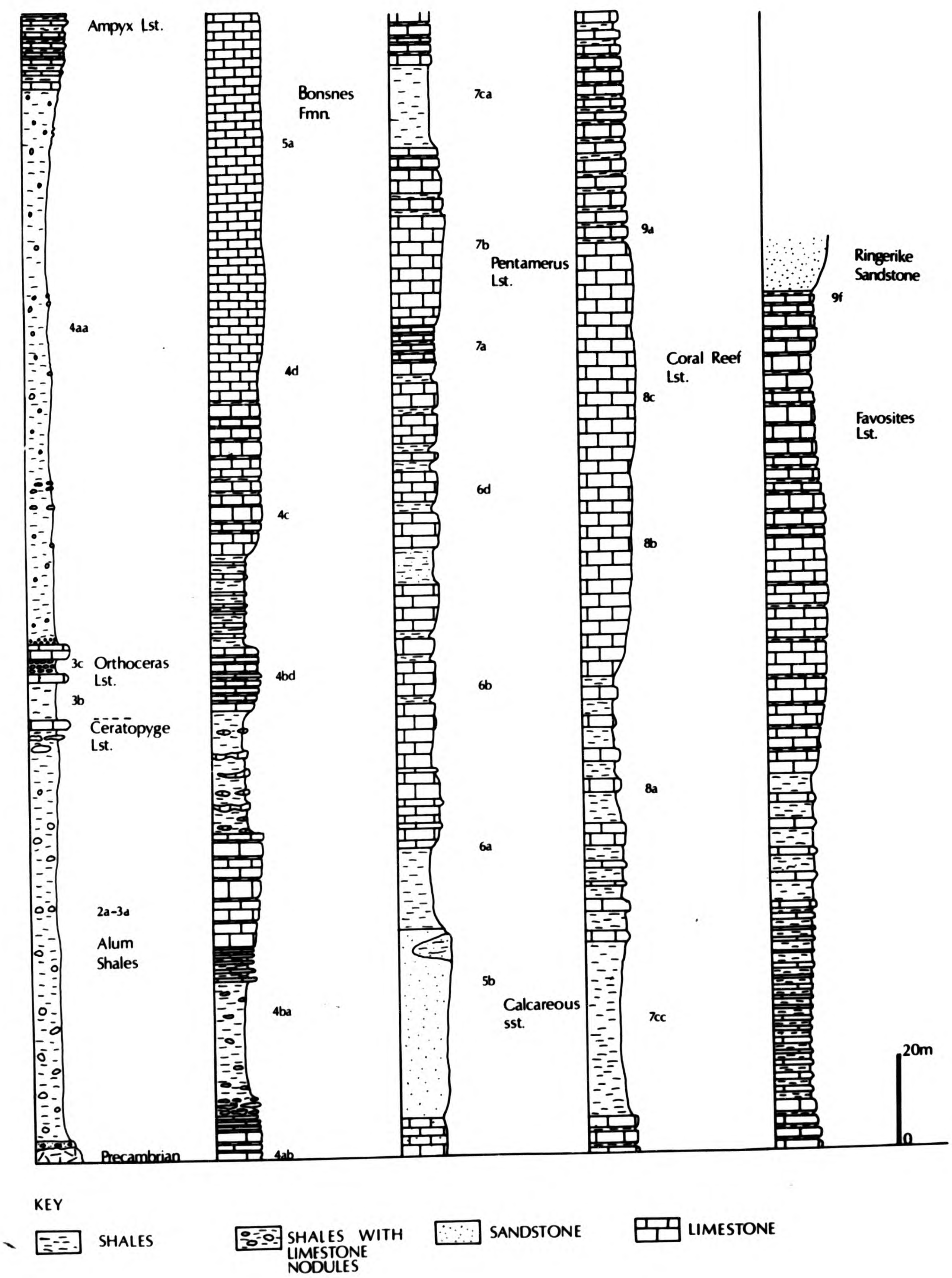
There is apparently no basal conglomerate in this area, so black alum shales with stinkstones and concretions, similar in lithology to those described in Asker, rest directly on Precambrian basement.

Ordovician.

2e-3b. Ceratopyge Shales, thickness 30m

These shales are black alum shales at the base (containing Dictyonema flabelliforme), that become a dark grey colour towards the top. Just below the base of the Ceratopyge Limestone they contain the occasional large nodule, elliptical to spherical in shape and about 30cm in diameter, otherwise no nodules are present.

Fig.2.3 The Cambro-Silurian stratigraphy of Ringerike


Ampyx Lst.
4aa
3c Orthoceras
Lst.
3b
Ceratopyge
Lst.
2a-3a
Alum
Shales
Precambrian
Bonsnes
Fmn.
5a
4d
4c
4bd
4ba
4ab
7ca
7b
Pentamerus
Lst.
7a
6d
6b
6a
5b
Calcareous
sst.
9a
Coral Reef
Lst.
8c
8b
8a
7cc
Ringerike
Sandstone
9f
Favosites
Lst.
20m
0
KEY
SHALES
SHALES WITH
LIMESTONE
NODULES
SANDSTONE
LIMESTONE

3ac. Ceratopyge Limestone, thickness 1.5m

This obvious marker band is a mid-grey, bioturbated ,fossiliferous, bedded limestone.

3b. Lower Didymograptus Shales, thickness 20-25m

These are dark grey shales containing very few nodules. They have a good bedding-parallel fissility and contain some graptolites. Unless the contact with the Ceratopyge Limestone is exposed they are very difficult to distinguish from the grey shale horizons in the Ceratopyge Shales.

3c. Orthoceras Limestone, thickness 7-9m

The three part division of massive limestone at the base, nodular limestone-shale, with massive limestone on top is again present. The nodular limestone-shale is more shale rich than in Asker and though fossils, especially orthoconic nautilloids are abundant, the many fragments of trilobite present in the Megitaspis Limestone of Asker are not as abundant in Ringerike.

4aa Upper Didymograptus Shales and Ogygiacaris Shales, thickness 80-90m

These shales are dark grey when fresh and weather in a streaky yellow-brown fashon, nodules and some limestone beds are present. The nodules are round, about 2-3cm. in diameter and weather to a yellowish-brown colour. Graptolites are abundant in some horizons.

It is difficult to obtain an accurate estimate of thickness for these beds because of folding, thrusting and poor exposure, but a thickness of 80-90m. seems a resonable estimate

4ab. Ampyx Limestone, thickness 30m

This limestone does not resemble its counterpart in Asker, in Ringerike it is a poorly fossiliferous rock with a large proportion of shale between the nodular and bedded limestone horizons. The nodules, common near the base, decrease in number upwards. At the base the nodule horizons are about 3-3.5cm thick separated by 2-3cm of shale whilst near the top limestone beds about 4-5cm thick occur between shale intervals of about 20cm. The limestone weathers in places to an ochre colour and the grey shales weather to a mid-brown.

2.2.3 North Hadeland.

The first comprehensive work on the stratigraphy of the Hadeland area was published by Holtendahl and Schetelig (1923) and includes a 1:100,000 map. Since then the Central and South Hadeland areas have attracted the great majority of workers (Kiaer 1926; Stormer 1944; Strand 1948; Hagemann 1957). The latest worker, Owen (1977, 1978) studied the geology of Central Hadeland in detail, mapping the area at 1:5000 and revised the middle Ordovician-Silurian stratigraphy, giving the units new local names.

The area north of Gran with rocks of Cambro-middle Ordovician age has largely been ignored since the time of Holtendahl and Schetelig (1923), So it was found necessary to map this area at 1:5000. The stratigraphy of the Cambrian to the top of the Orthoceras Limestone is similar to Oslo and Ringerike but a thick shale lithology dominates the middle Ordovician unlike the shale-limestone sequences of the above mentioned areas.

Cambrian.

Torella Conglomerate and Alum Shales, thickness 60m

Between the basement and the Alum Shales at Bjerke near Brandbu Brogger (1909) found the Torella Conglomerate. It is a conglomerate with fragments of basement similar to that found in Asker. Above the Torella Conglomerate are typical Alum shales within which is developed a local nodular horizon west of Royken. In the cliffs west of Nes Church the nodules are best exposed, revealing great lenses (about 1-2m in diameter) of light grey limestone which weathers light brown and contains numerous agnostid trilobite cranidia.

Ordovician.

2e-3a. Ceratopyge Series. 30m

The Ceratopyge Shales follow on from the Cambrian shales and consist of similar black alum shale lithology, but characteristically contain Dictyonema flabelliforme. After about 10m of black shales, the shales become a dark grey colour. Within the dark grey shales, about 2-4m below the base of the Ceratopyge Limestone are large, dark grey nodules (30x40cm.) and a few discontinuous limestone bands. Capping this sequence is the Ceratopyge Limestone which is well bedded, mid-grey in colour and 1-1.5m thick.

Lower Didymograptus Shales, thickness 23-28m

This dark grey shale is distinguishes from the other shales in the area by the scarcity of nodules in it. It contains a few fossils, mainly graptolites and has a sharp contact with the base of the Orthoceras Limestone

Orthoceras Limestone, thickness 7.5-8.5m

The three part division of this unit is still present in North Hadeland, where 1.5m of massive bedded limestone is followed by 3m of thinly bedded limestone nodules and shale and is capped by 2.5m of an upper massive limestone. The limestone grades into the shales above via 2-3m of transition beds, which display some continuous limestone and nodular limestone horizons. At the base of the transition zone there is about 33% shale which increases to 66% at the top.

4aa-4bc. Kirkerud Group, thickness 250m?

This great thickness of shale with nodular limestone horizons has a complex and elusive internal stratigraphy. Holtendahl and Schetelig

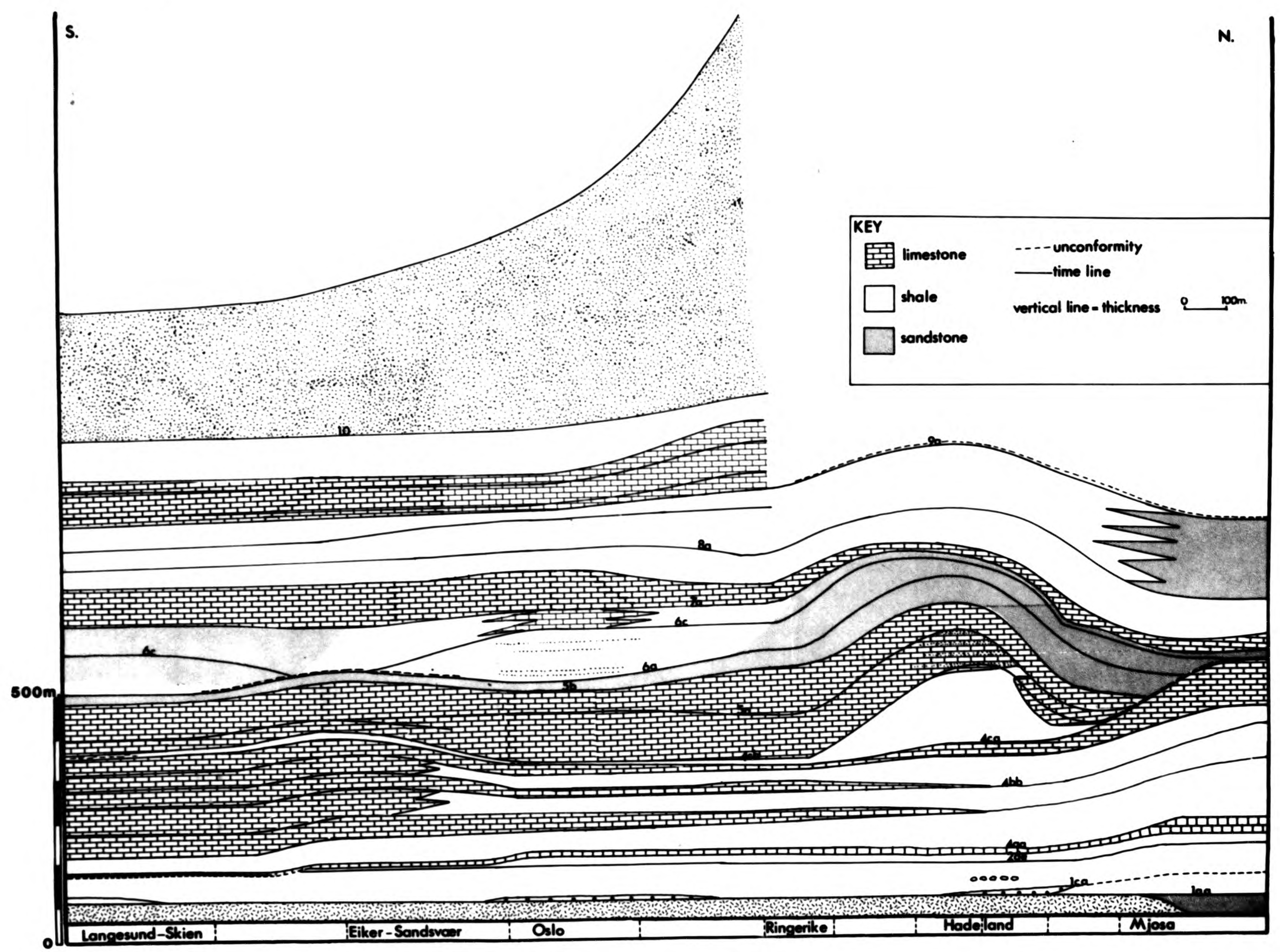
(1923) and Stormer (1953) have attempted to divide the Kirkerud Group into the Upper Didymograptus Shales, Ogygiacaris Shales, Cephalopod Shales and Lower Chasmops Shales. However these units proved difficult to apply in the field and as they form the base to the Solvang Formation of 4bd age (Owen 1978) they must also be extended in age to include the Upper Chasmops Shale. Perhaps the top 50-60m of the Kirkerud Group is distinguishable from the rest of the group by the presence of numerous limestone and calcareous sandstone bands.

The difficulties in deciphering the rest of the internal stratigraphy arise from several causes:

1. The large amount of thrusting and folding within the beds requires that long continuous sections be exposed in order to piece together the stratigraphy; these are not present.
2. Shale units with few limestone nodules present are poorly resistant to weathering and therefore only occur in small infrequent outcrops which rarely display stratigraphic contacts with more nodular horizons.
3. Detailed lithological descriptions from numerous localities in North Hadeland have not produced any usable marker horizons for detailed correlation over the whole area. Each distinctive nodular limestone horizon appears to be only locally developed.
4. Frequently the shales are very poorly fossiliferous, despite some fossil rich horizons, and therefore it is hard to correlate by this means.

Owen (pers. comm.) though unable to recognise much of the internal stratigraphy, estimates the thickness of these shales at about 250m.

Fig.2.4 Diagram of facies variations (N-S) in the Cambro-Silurian rocks of the Oslo Graben.



S.
N.
KEY
limestone
shale
sandstone
unconformity
time line
vertical line = thickness
0
100m
500m
0
10
9a
8a
7a
6c
6a
5b
4ca
4bb
4aa
2aa
1ca
1aa
Langesund-Skien
Eiker-Sandsvær
Oslo
Ringerike
Hadeland
Mjøsa

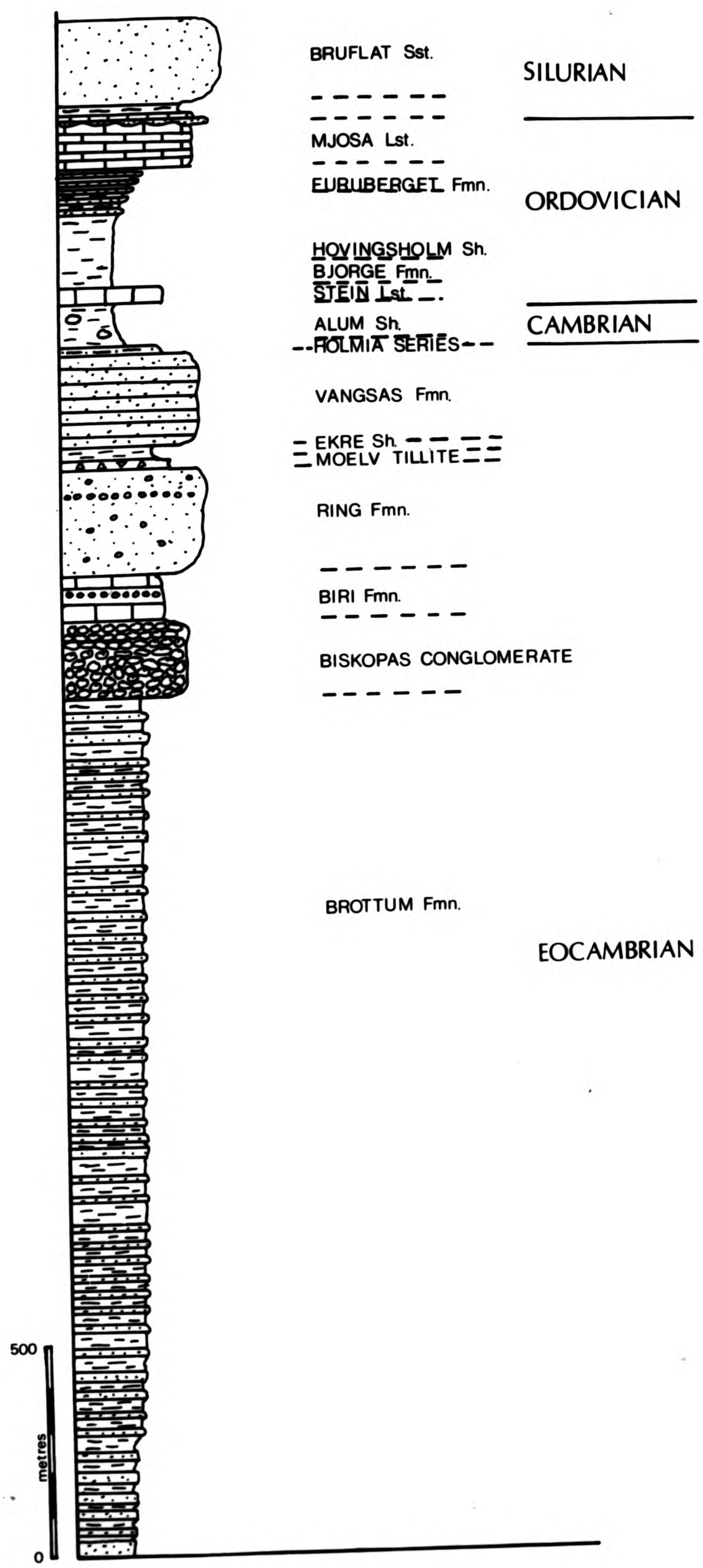
2.3 Stratigraphic variations in the Oslo Graben.

The variations in thickness and facies of the Cambro-Silurian rocks in the Oslo region are shown in Fig 2.4. It can be seen from this figure that the Cambrian sequence in all but the Mjosa area rests transgressively on Precambrian basement. At Mjosa a full Cambrian sequence is present resting on the late Precambrian (Eocambrian) Sparagmites, which are mainly coarse clastic deposits up to 3000m thick (see Fig.2.5).

The oldest Sparagmite rocks are the turbidite sandstones and shales of the Brottum Formation that were deposited in the western part of the basin (Englund 1972) and their alluvial equivalents to the east and north (Rendall Formation), (Nystuen 1981). A regional transgression followed, depositing the carbonates, shales and the phosphorites of the Biri Formation, followed by coarse, clastic marginal wedge sequences known as the Biskopas Conglomerate and Ring Formation (Bjorlykke et al. 1976). Next, the Varanger glaciation produced the basal till and glaciomarine deposits now comprising the Moelv Tillite and following the post-glacial sea rise, delta progradation resulted in the deposition of the greenish-brown Ekre Shale and fluviatile sandstone called the Vardal Sandstone Member. Shallow marine sedimentation then resumed with the deposition of the Ringsaker Quartzite Member, which could be of Lower Cambrian age (Foyn and Glaessner 1979). A minor unconformity separates this unit from the overlying Holmia Series.

Skjeseth (1963) divided the Holmia Series (comprising calcareous sandstones and shales) into a southern shaly facies and a northern more sandy facies. These are followed by the Holmia Shale which has an increasing number of arenaceous limestone bands upwards.

Fig.2.5 The Eocambrian to Silurian stratigraphy of the Mjosa area.


BRUFLAT Sst.
SILURIAN
MJOSA Lst.
EURUBERGET Fmn.
ORDOVICIAN
HOVINGSHOLM Sh.
BJORGE Fmn.
STEIN Lst.
ALUM Sh.
CAMBRIAN
HOLMIA SERIES
VANGSAS Fmn.
EKRE Sh.
MOELV TILLITE
RING Fmn.
BIRI Fmn.
BISKOPAS CONGLOMERATE
BROTTUM Fmn.
EOCAMBRIAN
500
metres
0

The oldest Middle Cambrian zone is found between Mjosa and Roykenvik in Hadeland but is missing throughout the rest of the region. In Mjosa this zone contains limestones, sandstones and some conglomerates rich in phosphorite, whilst in Hadeland the zone is represented by the thin Torella Conglomerate followed by Alum Shales. The next zone, that of Paradoxides paradoxissimus is known throughout the region, where the Alum Shale lithology is ubiquitious. The thickness of the Alum Shales usually exceeds 50m but in Langesund-Skien the Olenid Series (2a-2d) is only 12m thick, representing a regression at the end of the Cambrian.

The Upper Cambrian regression resulted in the unconformity at the base of the Ordovician in the southern areas. In the Langesund-Skien area the Ceratopyge Series and Lower Didymograptus Series are absent and the Orthoceras Limestone is only represented by the uppermost 3m. In the area to the north called Eiker-Sandsvaer, the Orthoceras Limestone is developed, but the Ceratopyge Shales are absent and the Lower Didymograptus Shales are only 2-5m thick,(25m in Oslo). The Orthoceras Limestone is generally 7-10m thick within the region but in the Mjosa area it thickens up from 15m in Toten to over 40m in Ringsaker where it is known as the Stein Limestone.

The Middle Ordovician (Llanvirn-Caradoc) is found in the southern areas as arenaceous limestones (some showing slumping) with thin shale sequences between, passing upwards into a thick bryozoan rich limestone. From Asker to Ringerike limestones alternate with shales throughout the Middle Ordovician. The sequence changes laterally northwards into a shale dominated sequence. In Hadeland and Mjosa these thick shales (in excess of 200m) become increasingly rich upwards in calcareous sandstone bands. The shales in Hadeland are capped by a limestone which thins rapidly from 70m in the south to 17m in the north part of the area. In

Mjosa too, a thick limestone (called the Mjosa Limestone) caps the shale sequence. The top of this unit is marked by a sedimentary break and a fossil karst surface indicating emergence of the area above sea level in the late Ordovician-early Silurian.

The Upper Ordovician is present everywhere in the region except in Mjosa. Generally in Hadeland there is a thin, more limestone rich facies in the north passing into a thicker, more shale rich southern facies. There then follows a thick (60-80m) nodular limestone which is capped by a thick calcareous sandstone formation. The latter formation straddles the Ordovician/Silurian boundary. In Ringerike the sequence is limestone rich throughout with calcareous sandstones (sometimes channeled) becoming frequent in the uppermost Ordovician. The rocks become of shallow water type towards Oslo and deeper again further south, where in Langesund-Skien the Upper Ordovician is developed as the nodular limestones and shales called the Heroy Limestone. This limestone is followed by calcareous sandstones forming the highest Ordovician unit.

The Silurian Stricklandia Series, (Stage 6), varies throughout the region. In Mjosa it rests unconformably on the Mjosa Limestone and only the highest part of Stage 6 is present. From Mjosa to Hadeland (where all of Stage 6 is present) a sandy facies is present, whilst in Ringerike and Oslo shales are dominant with thin bands of limestone and sandstone between. In Eiker-Sandsvaer only the upper part of Stage 6 is present and is of a limestone- shale facies whilst a more sandy facies is developed in Langesund-Skien to the south.

The traditional interpretation of the regional sedimentology from late Ordovician to Early Silurian times is of NNE-SSW trending facies belts, which swing more WSW-ENE towards Mjosa (Spjeldnaes 1957). To the west of the region a land area (called Telemark Land) has been postulated to provide a source area for the clastic sediments that show transport directions from the west (Stormer 1967).

In all districts except the Mjosa area the Silurian exhibits an increase in the amount of carbonates present upwards. One characteristic limestone is the Pentamerus Limestone which especially in Ringerike and Hadeland is packed with brachiopods. During stage 8 shallow water and continental deposits of coarse sands and marls began to invade the region, beginning in the Mjosa area as the deltaic Bruflat Sandstone. By stage 10 these deposits had reached Ringerike and Oslo forming the red beds of the Ringerike Sandstone. They can be up to 1000m thick in Ringerike and are the last of the rocks deposited during the Silurian.

CHAPTER 3

THE STRUCTURAL GEOLOGY OF ASKER-BAERUM.

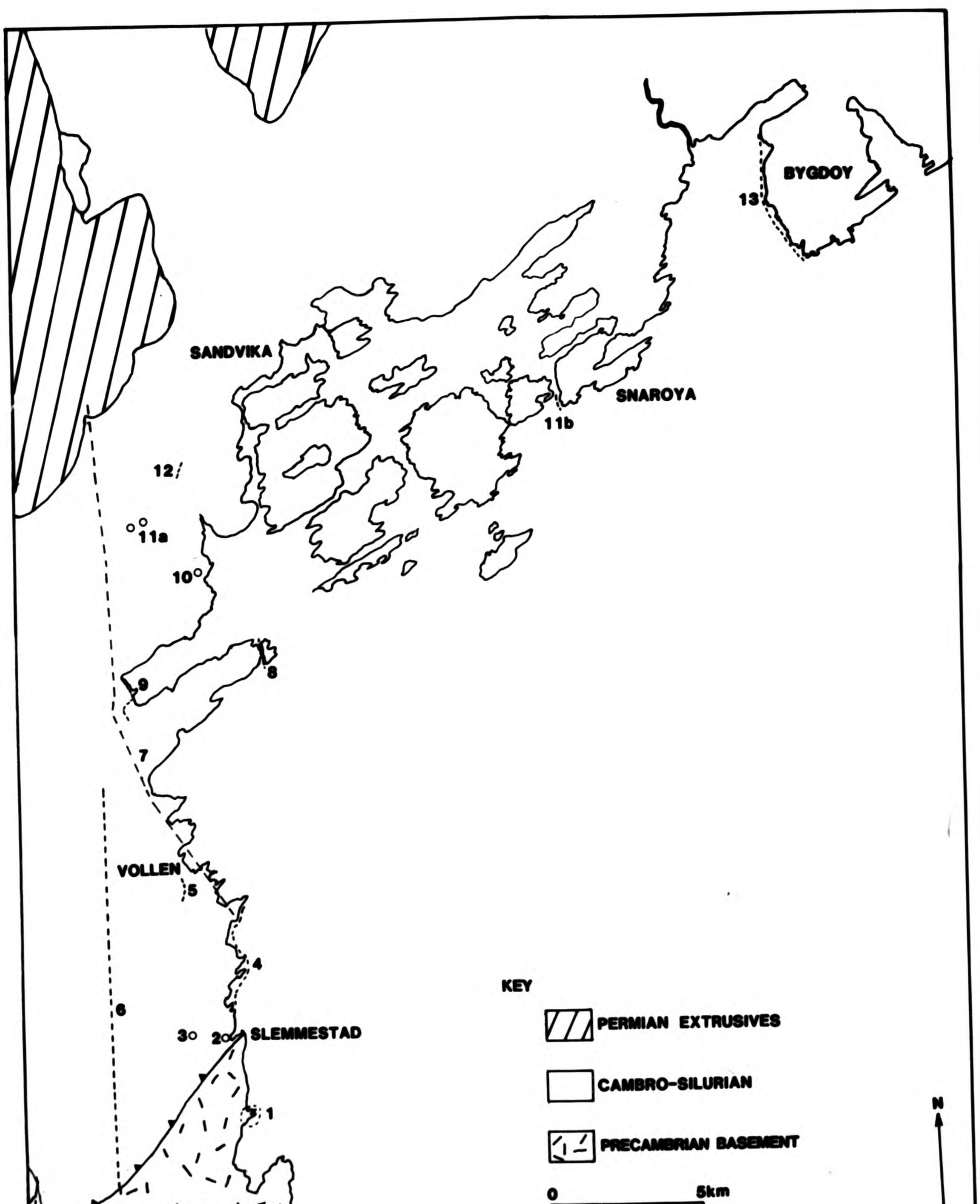
3.1 Introduction.

There is only a small amount of literature published specifically on the structural geology of the Oslo district. Brogger (1887) has described sections in the most detail, Bjorlykke (1898) mapped the eastern part of the district and Bockelie and Nystuen (in press) are currently working on a description of the structural geology of Asker. However no attempt has yet been made to construct a balanced section through the district. To enable this to be achieved I mapped at 1:5000 (see map of Asker-Baerum in Appendix 2), studyied well exposed sections to gain an understanding of the geometry of the structure, extrapolated this into the eroded and sub-surface geology and estimated how much shortening had occurred by cleavage formation and internal deformation.

The allochthonous Cambro-Silurian stratigraphy, (see Chapter 2), lies tectonically and stratigraphically above autochthonous Precambrian and lowermost Middle Cambrian rocks, separated by the Osen-Roa Detachment. Resting with an angular unconformity above the deformed Cambro-Silurian rocks, are gently tilted late Carboniferous sediments and Permian sediments and lavas. Late Permian block faulting has affected all these rocks.

Fig.3.1. Location map of the Oslo area

Locality number	Locality	Figure number
1	Grundvik (map)	3.13
2	Slemmestad cement works	3.2
3	Slemmestad bus station	3.14
4	Slemmestad coastal section	3.12
5	Vollen section along road 165	3.17
6	Foss-Blakstad section	3.5
7	Hakavik-Billingstad section	3.6
8	Konglugen (west coast)	3.7
9	Tangen section	3.11
10	Solheim 165 road section	3.10
11a	Hvalstad (two localities)	3.9
11b	Snaroya	3.9
12	E18 Motorway section, Holmen	3.4
13	Bygdoy coastal section	3.8



BYGDOY
13
SANDVIKA
SNAROYA
11b
12
11a
10
9
8
7
VOLLEN
5
4
6
3
2
SLEMMESTAD
1
KEY
PERMIAN EXTRUSIVES
CAMBRO-SILURIAN
PRECAMBRIAN BASEMENT
0
5km
N

The decollement zone near the base of the Alum Shales has long been recognised (e.g. Holtedahl et al 1934) and forms a wide zone of deformation which represents the Osen-Roa Thrust south of Mjosa. Listric contraction faults which fan off this (Osen-Roa) detachment form imbricates, pop-ups and triangle zones (Boyer and Elliott 1982; Butler 1982) which displace fold limbs related to the same episode of deformation. Lithological contrasts in the local stratigraphy (Fig.2.2) create a multilayer package in which competent and incompetent layers display different structural styles.

(Locations of structural sections referred to in the chapter are shown in Fig.3.1.)

3.2 Structurally important lithological units.

The deformation of the Osen-Roa Thrust Sheet in Asker-Baerum displays noticable changes in tectonic style vertically. This is caused by the increasing amount of competent units up the succession, which resisted deforming (by faulting and folding) more easily than the lower units. It is therefore possible to divide the stratigraphy into four broad units characterised by different deformational behaviour. These divisions do not have definite boundaries, but instead grade into each other.

The structurally important lithological groupings are as follows: the Alum Shales; lower to middle Ordovician limestones and shales; upper Ordovician limestones, shales and sandstones; Silurian limestones, shales and the Ringerike Sandstone. Their different deformational characteristics are described below.

3.2.1 Alum Shales.

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3.2.1 Alum Shales.

The Osen-Roa Detachment lies low within these shales where it is a complex zone of slip, not a discrete slip surface. It is difficult to define the width of the detachment zone because there are numerous sub-horizontal minor slip planes, up to a few meters long, present throughout much of the shales. These slip planes frequently display shiny, graphitic surfaces in the carbon rich shales, but when the carbon content of the shales is reduced the slip surfaces become hard, polished, shiny (almost nacreous) and feel porcellaneous to the touch. The polished surfaces are seen to be a thin veneer of communited micaceous and sandy sediment in thin section.

Thin sections of the highly cleaved and graphitised portions of the shales (Plate 3.1) show well developed low angled, anastamosing, pressure-solution cleavage seams. The sub-horizontal angle of the seams might be attributed to nearly vertical seams formed early on in the deformation history being rotated by slightly later movement on the sole detachment. Large amounts of sparry calcite have been deposited as products of pressure solution in small veins at right angles and in conjugate sets to this pressure-solution cleavage.

Folding within the Alum Shales ranges from tight chevron style puckering near the slip horizons, to broader disharmonic, asymmetrical folds within the rest of the shales. The larger folds have wavelengths up to 4m and amplitudes up to 3m, (see Fig.3.2).

Accommodation problems in the cores of large folds are probably responsible for the style of folding within the Alum Shales. The first important competent horizon above the Alum Shales is the Orthoceras Limestone. This is significant because when anticlines form, the beds in the crests are raised above regional bedding height, so that as the anticline grows a space develops between the base of the competent unit and a line joining the base of the competent layer in the synclines (Wiltschko and Chapple 1977). This void of course never actually develops because rock moves in to fill the space. In this case the Alum Shales probably flowed into the cores of anticlines and regions of thrusting from synclinal areas, causing the asymmetry of the folds within these shales. The exposures in the region of the cement factory at Slemmestad display this very well (Fig.3.2).

Most cleavage and slip planes are sub-horizontal indicating that the second order thrusts also probably flatten out approaching the Osen-Roa Detachment. Often the second order thrusts do not form discrete slip horizons in these shales; instead they form broad (up to a few metres wide) chaotic zones of disharmonic folds and locally intense cleavage.

3.2.2 Lower to middle Ordovician limestones and shales.

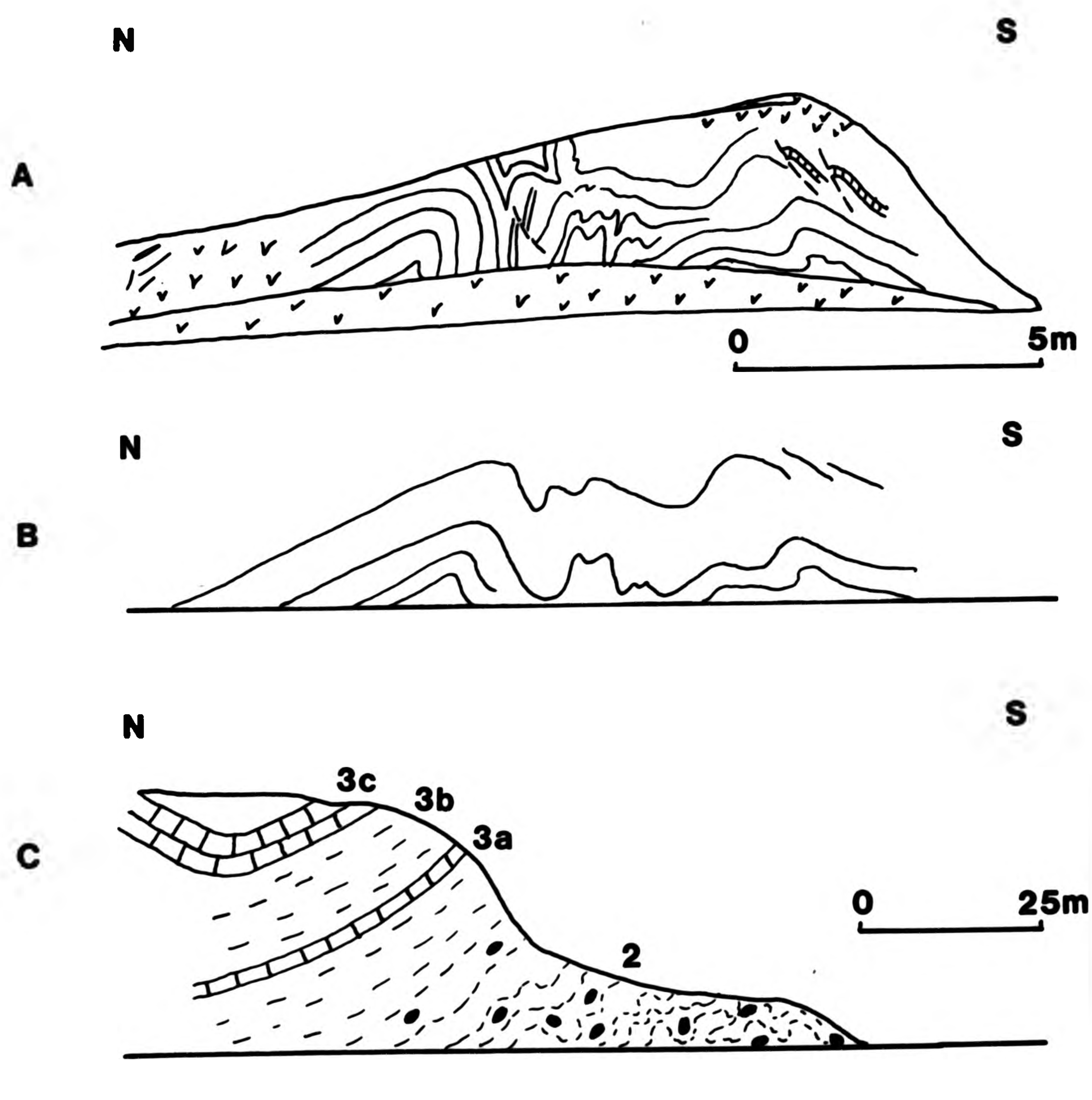
This sequence of alternating limestones and shales displays the effects of deformation by second and third order contraction faults fanning off the main detachment. In outcrop it can frequently be demonstrated that the largest folds in these rocks fold an earlier fracture cleavage or have a syn-folding fracture cleavage imposed on them (see section 3.2.5). These folds often have a limb (usually the forelimb) displaced by later imbricate thrusts. Because the forelimb is the most frequently truncated limb (see Table 3.1), the most common thrust-fold relationship is that of an anticline in the hangingwall of the thrust pushed over a syncline in the footwall.

Fig.3.2.<u>Field sketches illustrating folding within the Alum Shales near the cement factory, Slemmestad.</u>

A. Road section opposite the entrance to the cement factory (G.R.840 283).

B. Profile of folds in section A.

C. Cliff section inside the cement factory (G.R. 839 284).



N
S
A
0
5m
N
S
B
N
S
C
3c
3b
3a
0
25m
2

Plate 3.1 Thin section (x20) of stylolites forming sub-parallel to fissility in the Alum Shales, Slemmestad cement factory.

Plate 3.2 Oversteepened (almost vertical) thrust fault, with H.W.F. F.W.F. geometry at the base and H.W.R. F.W.F. geometry at the top, in Tretraspis Limestone, Nes.

1/6

Table 3.1 Thrust-fold relationships in the Slemmestad area

Thrusts which ramp through Stage 3c	Thrust geometry of the Orthoceras limestone				
	H.W.R^1	H.W.R.^{2}	F.W.R.^{1}	F.W.R.^{2}	F.W.F.
1		X			X
2	X		X		
3	X		X		
4	X		X		
5	X				X
6		X			X
7	X		?		
8	X		?		
9	X		?		
10	X		X		
11		X	?		
12	X		X		

KEY

H.W.R.^{1} = Orthoceras Limestone forms hangingwall anticline

H.W.R.^{2} = Orthoceras Limestone has hangingwall ramp geometry without anticline

F.W.R.^{1} = Footwall rocks form ramp with F.W. syncline geometry

F.W.R.^{2} = Footwall rocks have ramp geometry without syncline

F.W.F. = Footwall flat geometry below H.W.R.

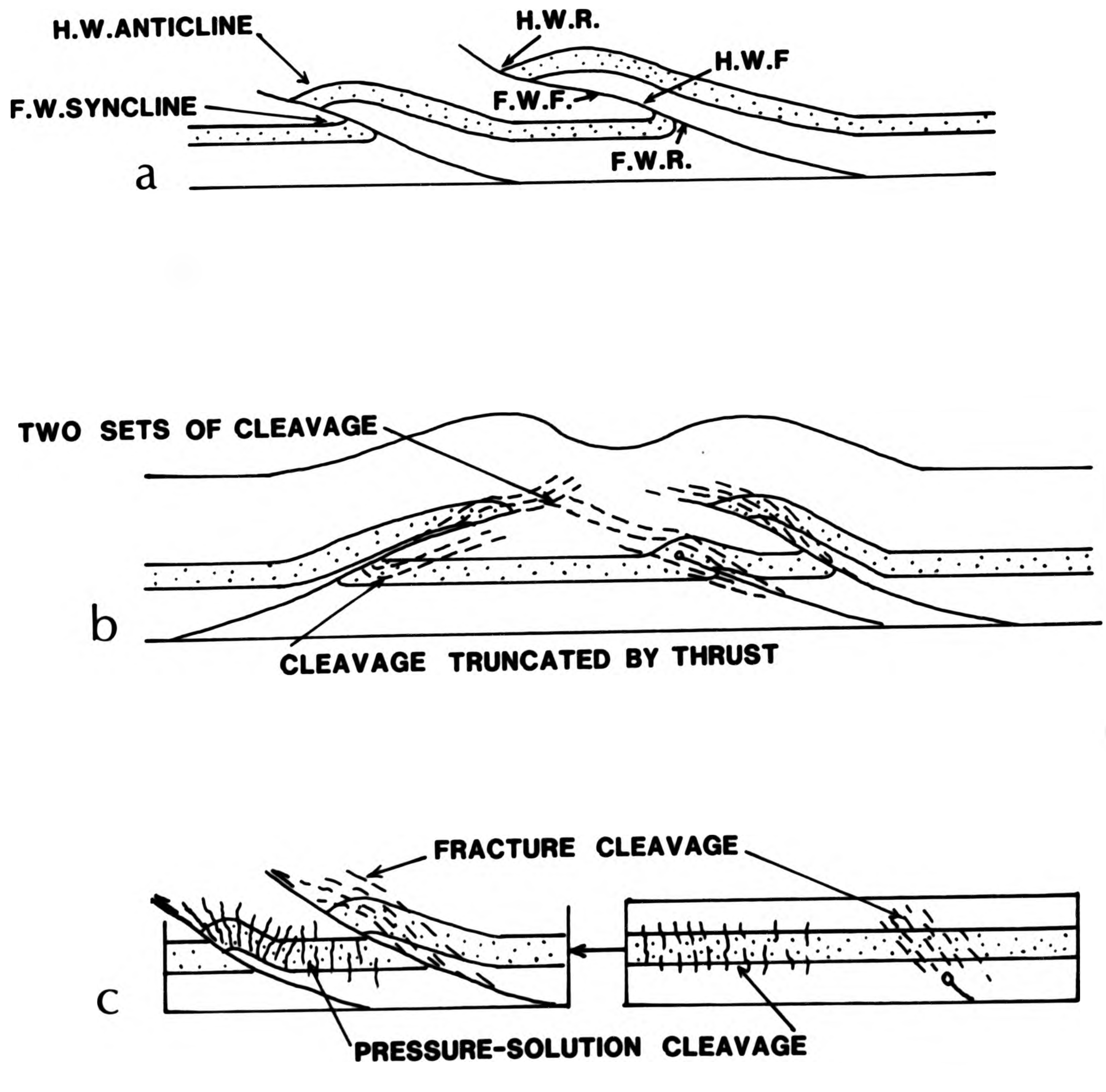
The faults are numbered 1-12 progressing from south to north along the south-eastern outcrop of Cambro-Ordovician rocks south of Slemmestad. Crosses denote the geometry of foot- and hanging- walls of an imbricate thrust as it ramps through the Orthoceras Limestone in the hangingwall.

Fig.3.3 <u>The relationships of thrusts, folds and cleavage in Asker-Baerum.</u>

a. Thrust geometry

b. Fracture and slaty cleavage forming ahead of thrust fault tip lines.

c. Thrust relationships with deformed early cleavage


H.W.ANTICLINE
H.W.R.
H.W.F
F.W.SYNCLINE
F.W.F.
F.W.R.
a
TWO SETS OF CLEAVAGE
b
CLEAVAGE TRUNCATED BY THRUST
FRACTURE CLEAVAGE
c
PRESSURE-SOLUTION CLEAVAGE

The relationship of folds, cleavage and thrusts can be explained by the folds and cleavage developing in the ductile bead, which advances ahead of propogating second and third order thrusts. When the fold has locked, or the speed of thrusting has overtaken folding, a fold limb (usually the forelimb) becomes displaced by the thrust. There are many examples in these rocks of thrust geometries displaying footwall synclines below hangingwall flats, flats on flats and hangingwall anticlines above footwall flats, formed as a result of the thrusting style described above (see Fig 3.3).

Previously, the folds and thrusts were interpreted as break thrusts in the limestones (Brogger 1887, Stormer in Holtedahl and Dons 1960), where over-tightening of folds resulted in a limb breaking and a thrust developing. However such thrusts would be localised and of small displacement, perhaps dying out into the shale horizons on either side of the faulted competent unit, and frequently of short extent along strike. This is not the case because: 1, imbricate thrusts can be traced for several kilometres along strike; 2, they are frequently found in shale horizons with F.W.F. and H.W.F. geometries; 3,they often splay ; 4, their displacements can be up to 150m along the fault plane. The characteristics of the thrusts are therefore not compatable with a break thrust interpretation (see Fig.3.17).

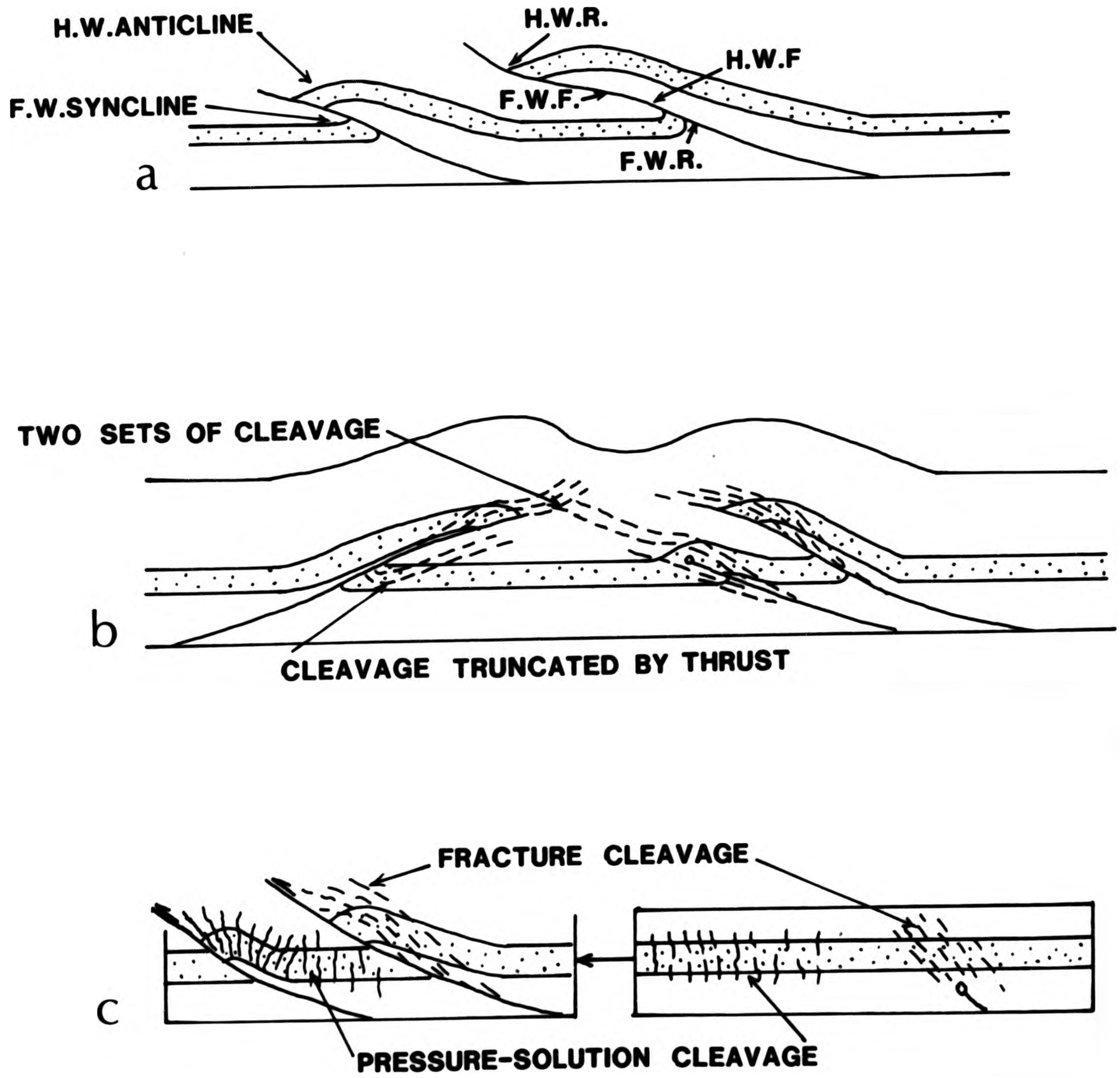
The thrusts in the middle Ordovician rocks display similar geometries to those described by American geologists for rocks in the Rocky Mountains and Appalachians (eg Bally et al 1966; Dahlstrom 1969a,b, 1970; Gwinn 1964; Jacobeen and Kanes 1974; Perry 1978).

Fig.3.3 <u>The relationships of thrusts, folds and cleavage in Asker-Baerum.</u>

a. Thrust geometry

b. Fracture and slaty cleavage forming ahead of thrust fault tip lines.

c. Thrust relationships with deformed early cleavage



H.W.ANTICLINE
H.W.R.
H.W.F
F.W.SYNCLINE
F.W.F.
F.W.R.
a
TWO SETS OF CLEAVAGE
b
CLEAVAGE TRUNCATED BY THRUST
FRACTURE CLEAVAGE
c
PRESSURE-SOLUTION CLEAVAGE

The relationship of folds, cleavage and thrusts can be explained by the folds and cleavage developing in the ductile bead, which advances ahead of propogating second and third order thrusts. When the fold has locked, or the speed of thrusting has overtaken folding, a fold limb (usually the forelimb) becomes displaced by the thrust. There are many examples in these rocks of thrust geometries displaying footwall synclines below hangingwall flats, flats on flats and hangingwall anticlines above footwall flats, formed as a result of the thrusting style described above (see Fig 3.3).

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The thrusts in the middle Ordovician rocks display similar geometries to those described by American geologists for rocks in the Rocky Mountains and Appalachians (eg Bally et al 1966; Dahlstrom 1969a,b, 1970; Gwinn 1964; Jacobeen and Kanes 1974; Perry 1978).

Fig.3.4 <u>E18 motorway section, Nesbru (G.R. 835 377).</u>

This road section displays imbricates thrusts with the following geometries: hangingwall flat (H.W.F.), hangingwall ramp (H.W.R.), footwall flat (F.W.F.), and footwall ramp (F.W.R.).

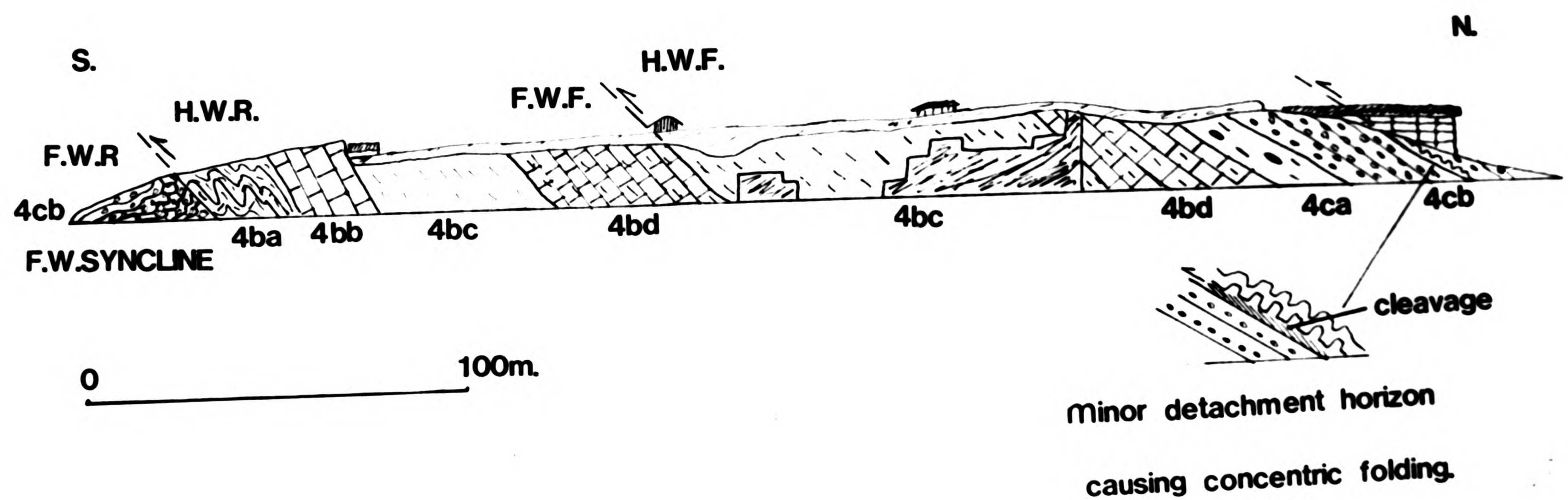
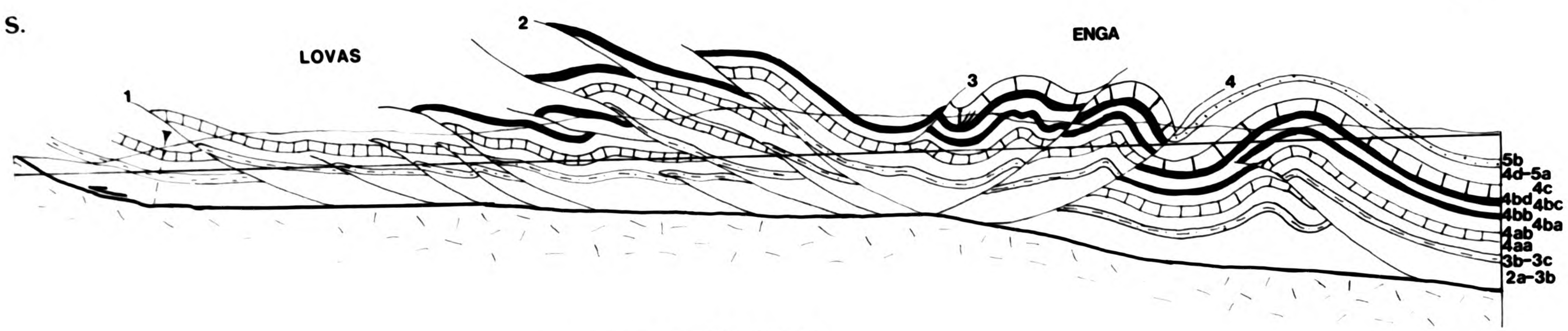
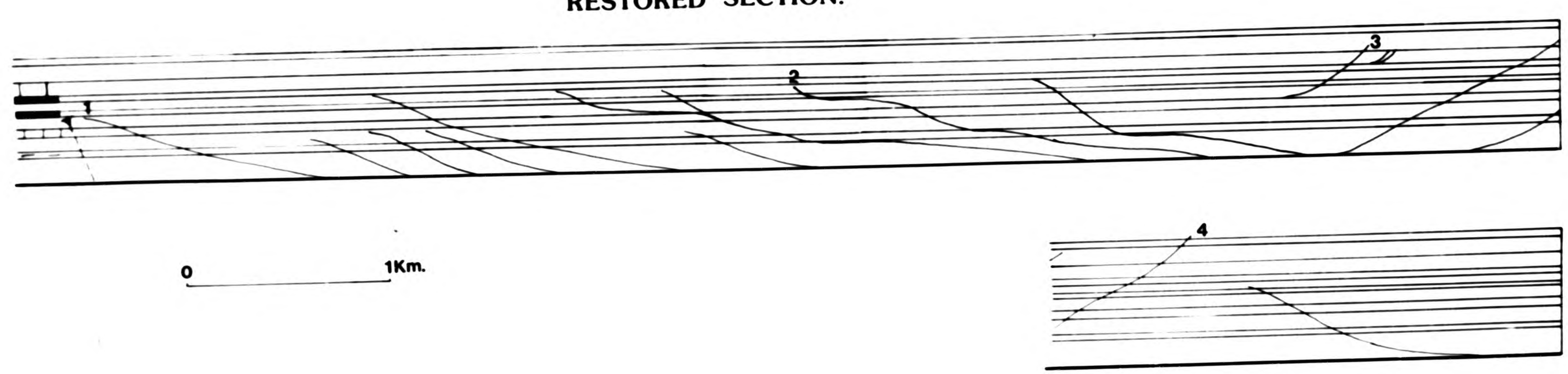

S.
H.W.R.
F.W.R
4cb
F.W.SYNCLINE
4ba
4bb
4bc
F.W.F.
H.W.F.
4bd
4bc
4bd
4ca
4cb
N.
cleavage
0
100m.
Minor detachment horizon
causing concentric folding.

Fig.3.5 A balanced cross-section from Foss to Blakstad (G.R. 835 324).

BALANCED CROSS SECTION FROM FOSS TO BLAKSTAD (G.R. 824 256 TO 822 324).



RESTORED SECTION.



The alternating middle Ordovician limestone and shale sequence frequently displays second and third order thrusts which ramp through the competent limestone units and follow bedding parallel "flats" in incompetent shale horizons. This geometry is well seen in the E18 road section at Nesbru (Fig.3.4) where thrusted shales form a hangingwall flat over the top of a limestone displaying a footwall flat geometry. Hangingwall flats on footwall flats in shales are rarely exposed but are present (see Fig 3.14). Some of the more continuous second order imbricate thrusts are present in the Sjostrand-Heggedal area (see 1:12000 Asker map and Fig.3.5) where the thrust frequently lies within the lowest Ordovician shales with a flat on flat geometry.

Thrusts in southern Asker do penetrate the middle Ordovician (Fig.3.6) but tend to die out laterally and upwards into tip line folds. In northern Asker imbrication has been stronger and some imbricates penetrate the Silurian. Generally thrusts steepen up the succession and the steepening is accentuated by successive foreland progressing imbrication (Perry 1978). Overturned thrusts which now appear as normal faults in outcrop may have been produced by this means (see Plate 3.2) or by reactivation of deformation hindewards of backthrusts (see Figs.3.7 and 3.8).

Minor decollement horizons within the Chasmops and Didymograptus Shales are rare, despite the presence of bentonite horizons in some beds which would be expected to form good glide horizons. The thin Lower Tretraspis Shale, does however form minor detachments. Frequently in southern Asker the Lower Tretraspis Shale and Limestone deforms with the rest of the middle Ordovician, but in northern Asker especially, these units have

Fig.3.6 A balanced cross-section through Asker from Hakavik to Billingstad (G.R.854 305 to 817 390). (see Appendix 3 for full size diagram).

Fig.3.7 Folded backthrust and cleavage on the west coast of Konglugen.

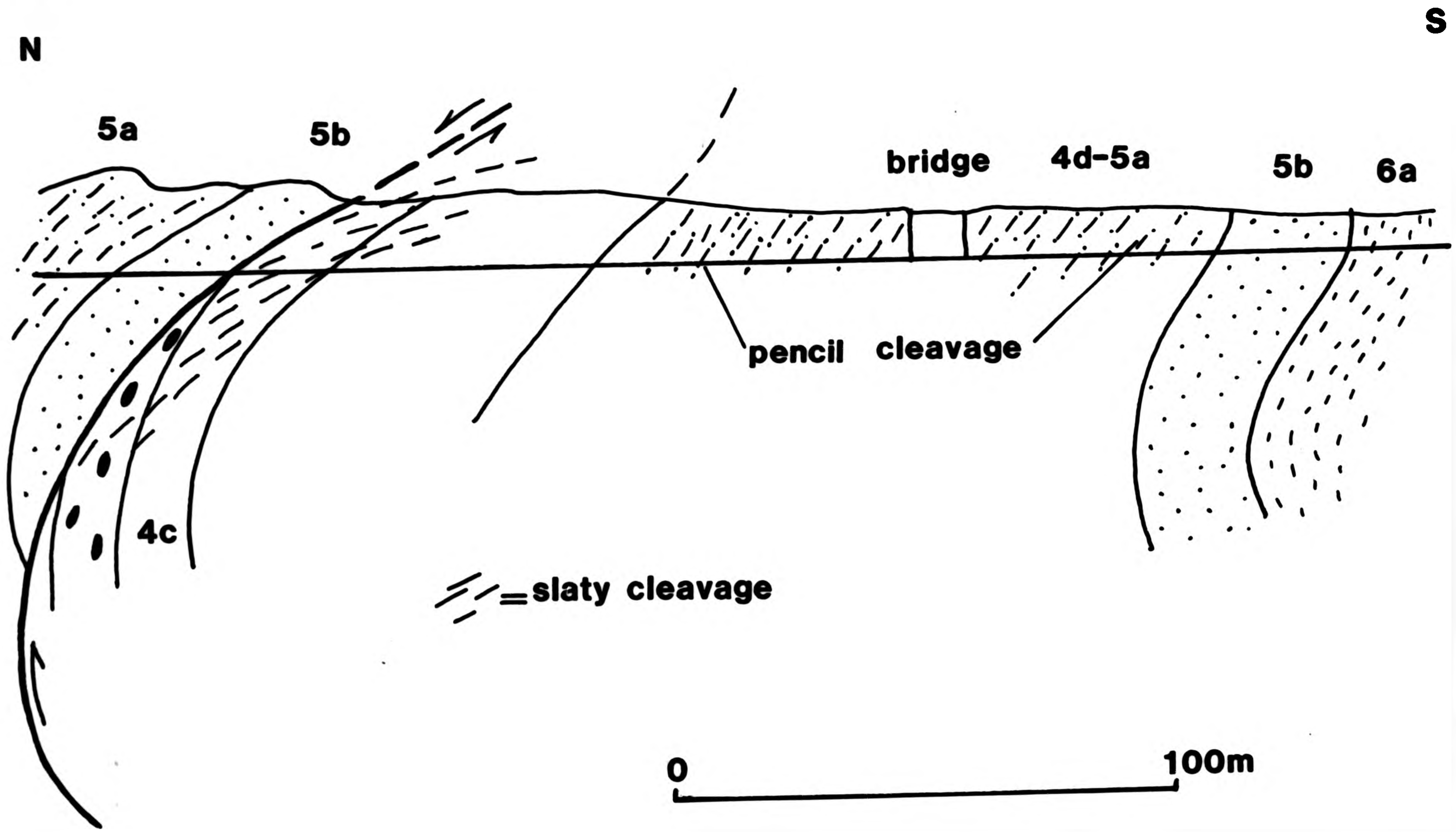
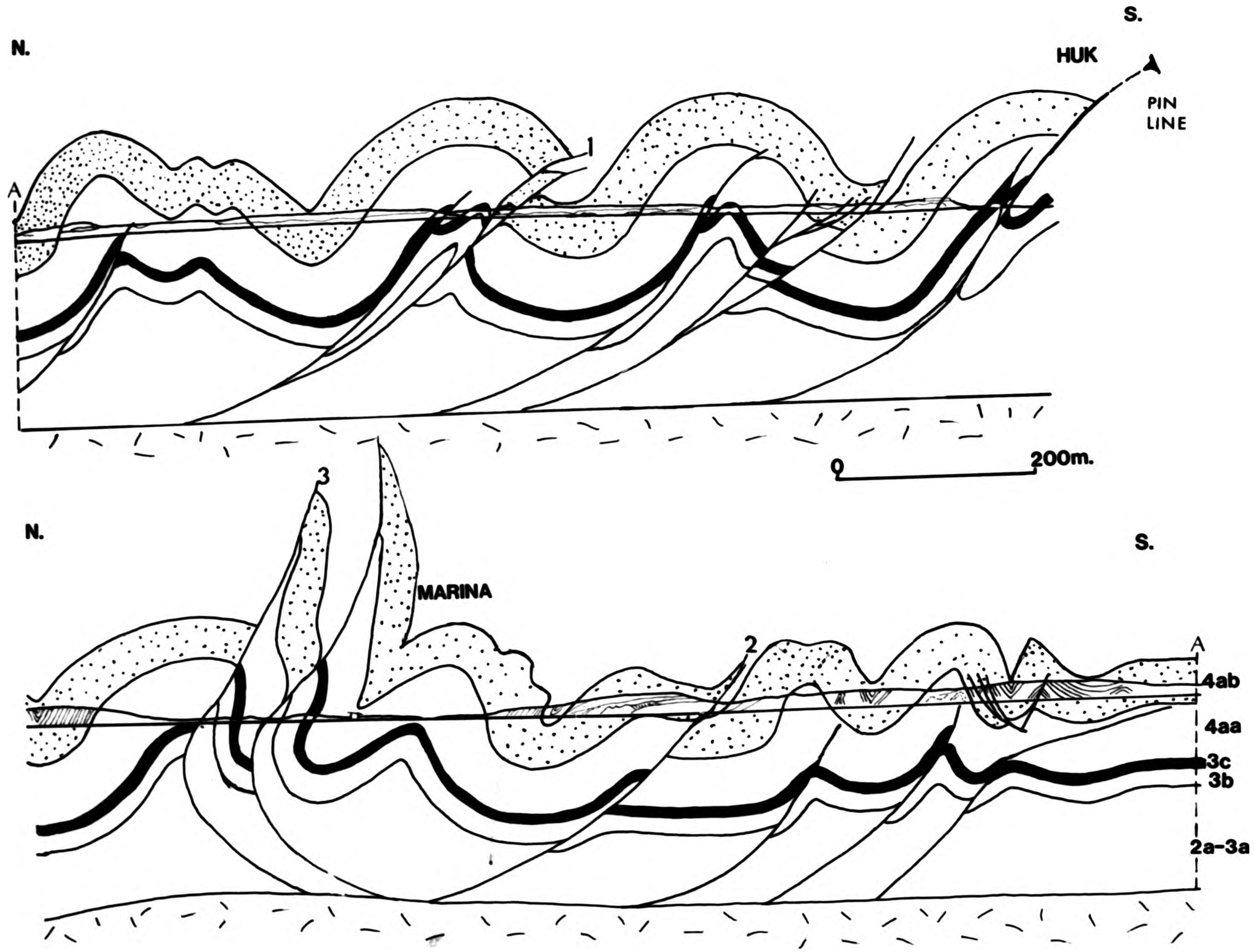
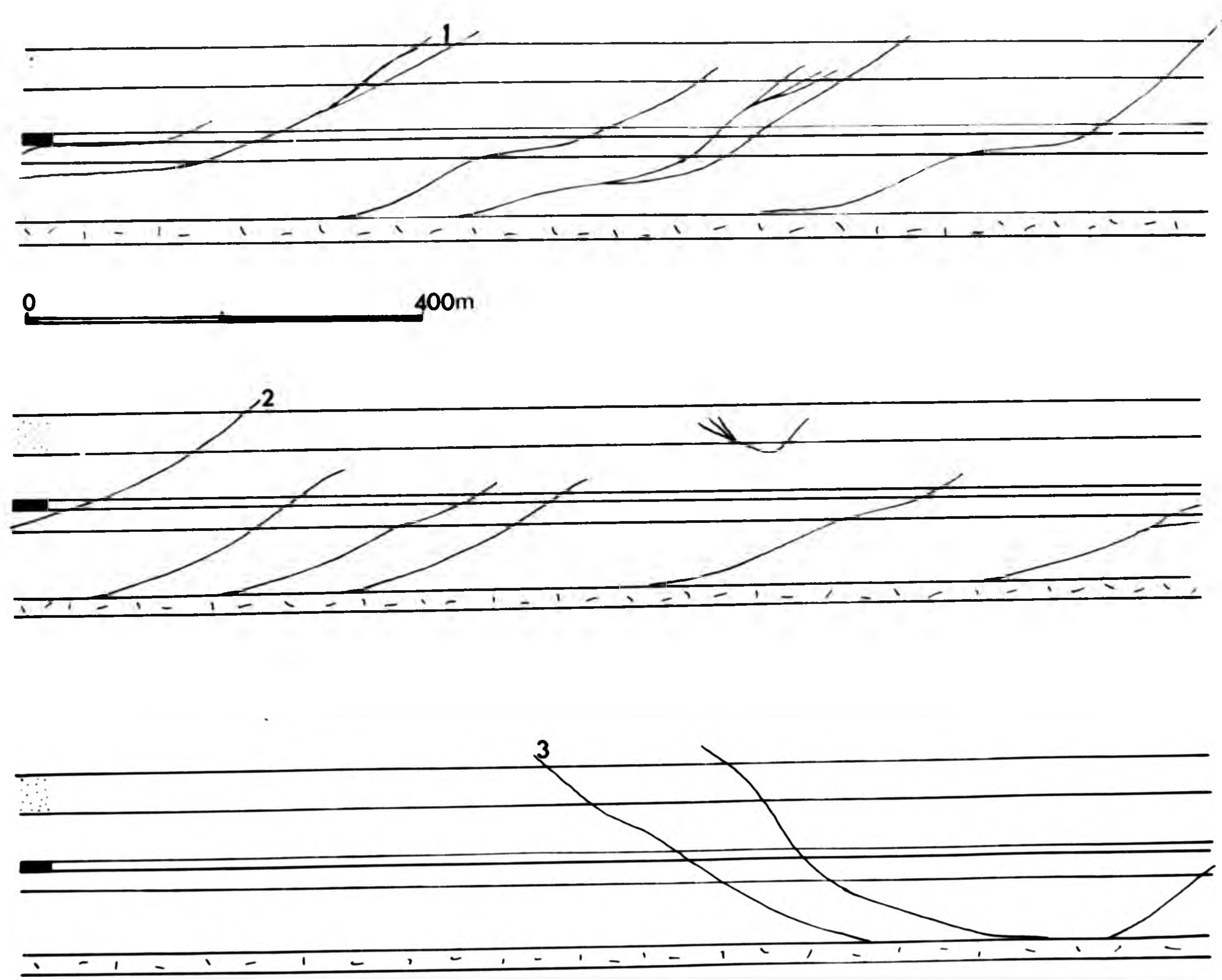

N
S
5a
5b
bridge
4d-5a
5b
6a
pencil cleavage
4c
=slaty cleavage
0
100m

Fig.3.8a A balanced cross-section along the west coast of Bygdoy, from Huk (G.R. 937 411) to Bygdoy Sjobad (G.R.931 430).

Fig.3.8b Restored section of Fig.3.8a.


N.
S.
HUK
PIN LINE
A
1
0
200m.
N.
S.
3
MARINA
2
A
4ab
4aa
3c
3b
2a-3a


1
0
400m
2
3

imbricated independantly of the rocks below (Fig.3.6). The base of the Tretraspis Limestone, characterised by small nodules, forms a good marker horizon for tracing the imbrication which is on a small, intense scale. The sections in Fig.3.9 show that in several instances the imbricates cut through both limbs of some folds, therefore cutting down section in the direction of transport. This is against the rules for simple thrusting, so folding must have preceeded thrusting. There are other sections in Asker which display unfaulted minor concentric folds in the Tretraspis Limestone formed above minor detachments (see Fig.3.4); the imbrication therefore would appear to be a later modification of these folds as they lock.

3.2.3 Upper Ordovician limestones, shales and sandstones.

These Ordovician rocks and the lower Silurian shales form the tectonic transition zone between the thrust-dominated rocks below and the fold-dominated rocks above. Many thrusts generated from the main detachment die out within the Cambro-mid Ordovician rocks and the great majority have died out once the top of the upper Ordovician is reached. The stiff, competent limestones and sandstones of 5b frequently form simple anticlines above tip lines of faults eg.the Hagastrand area (G.R.839 355). Imbricate thrusts from the minor detachments in the Tretraspis Shale also continue into the upper Ordovician rocks.

Some low-angled thrusts have been formed later than the folds. For example at Solheim (Fig.3.10) there is a road cut exposing 5a limestone folded into an anticline and syncline where three fold limbs are

Fig.3.9 Deformation within the Lower Tretraspis Limestone, caused by imbrication from minor detachment horizons in the Tretraspis Shales.

Snaroya cliff section

= bedding

= minor thrust fault

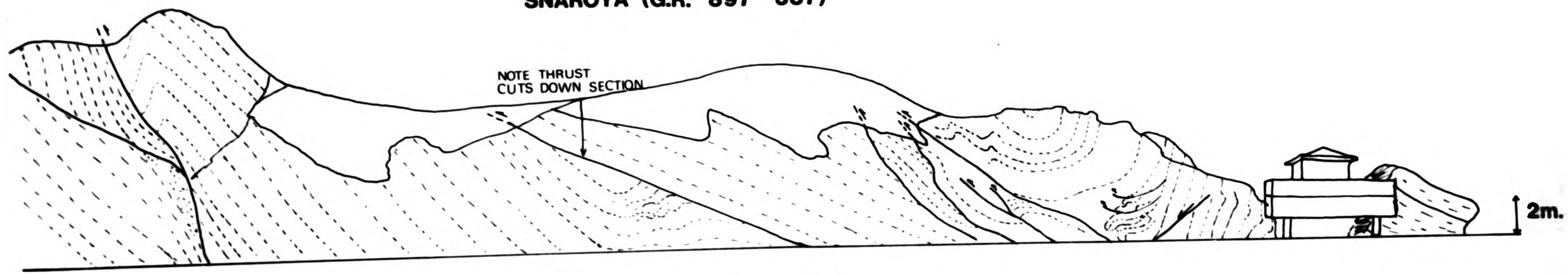
Torstadbakken and road no.91 sections

= bedding

= minor thrust fault

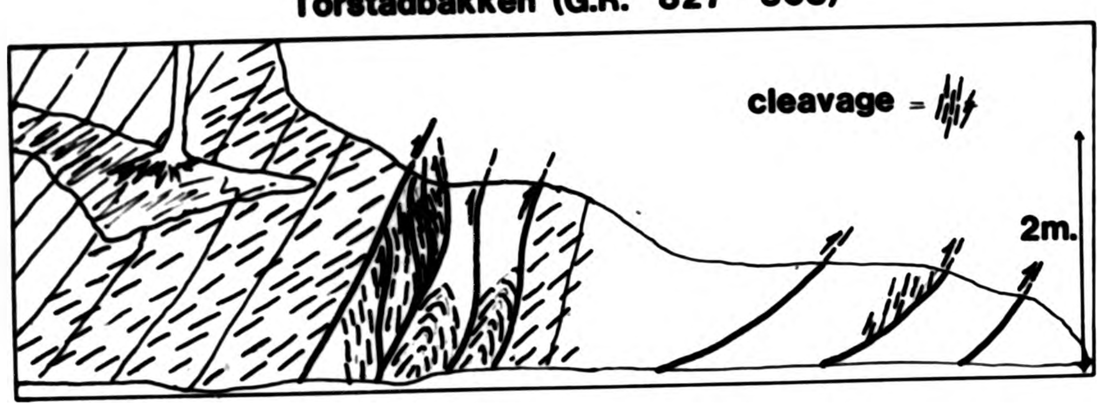
= cleavage

SNAROYA (G.R. $^{5}897\ ^{66}387$)



HVALSTAD

Torstadbakken (G.R. $^{5}827\ ^{66}368$)



Road 91 (G.R. $^{5}826^{66}367$)

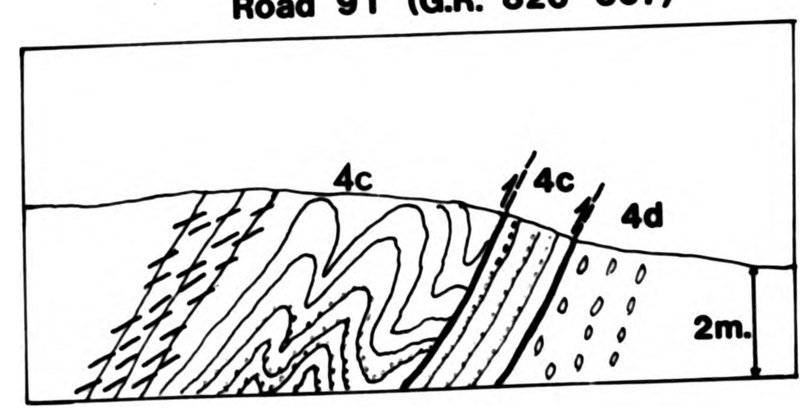
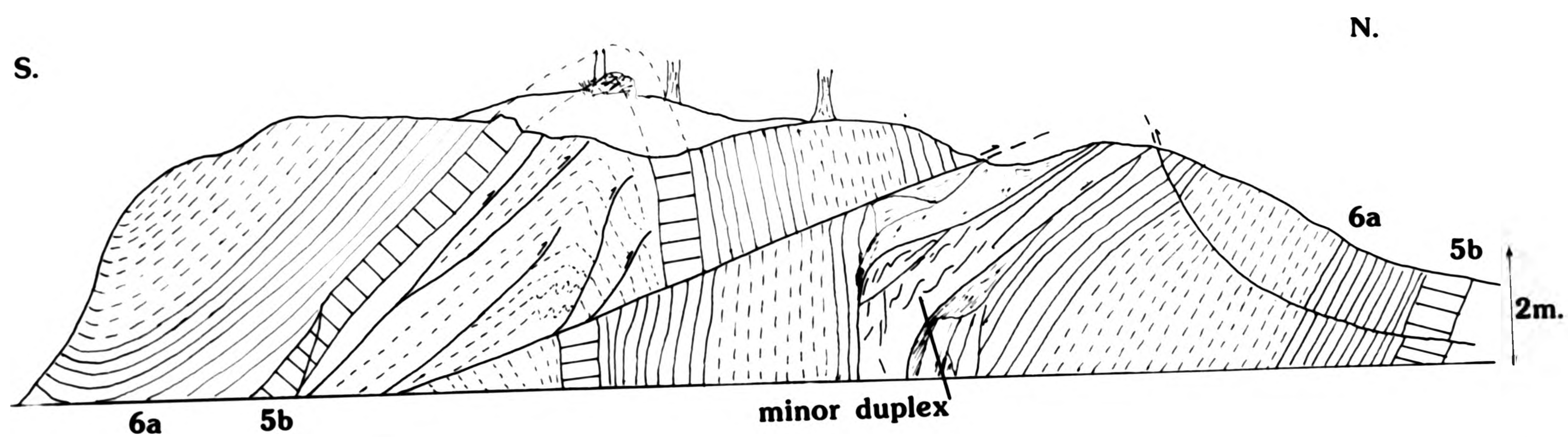


Fig.3.10 Road section along road no.165 at Solheim (G.R. 836 362) displaying thrusting in response to buckling, in upper Ordovician and lower Silurian rocks.


S.
N.
6a
5b
2m.
6a
5b
minor duplex

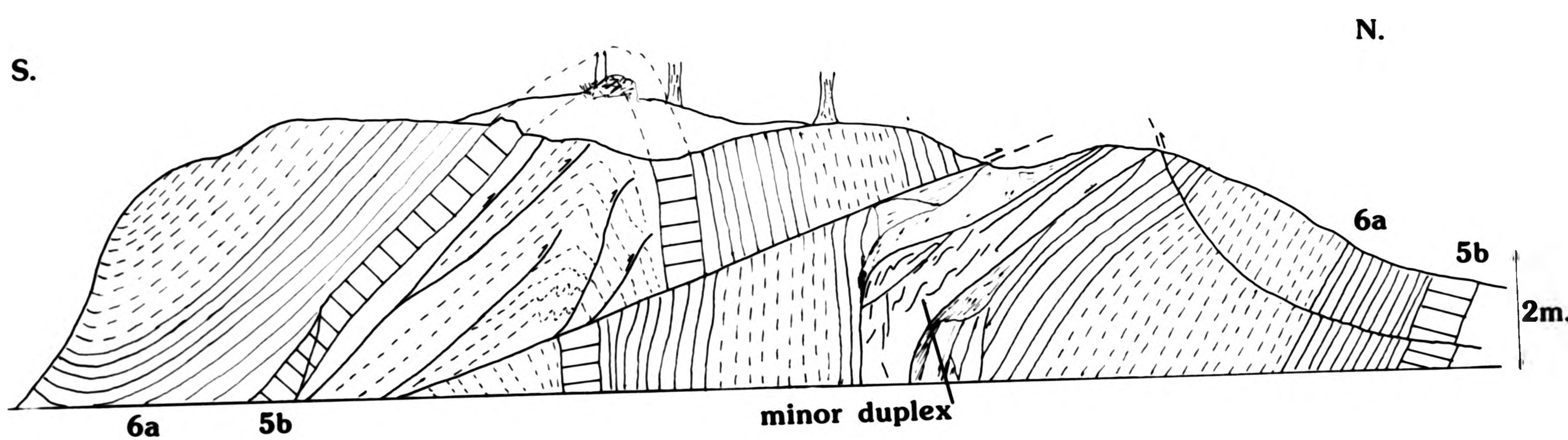
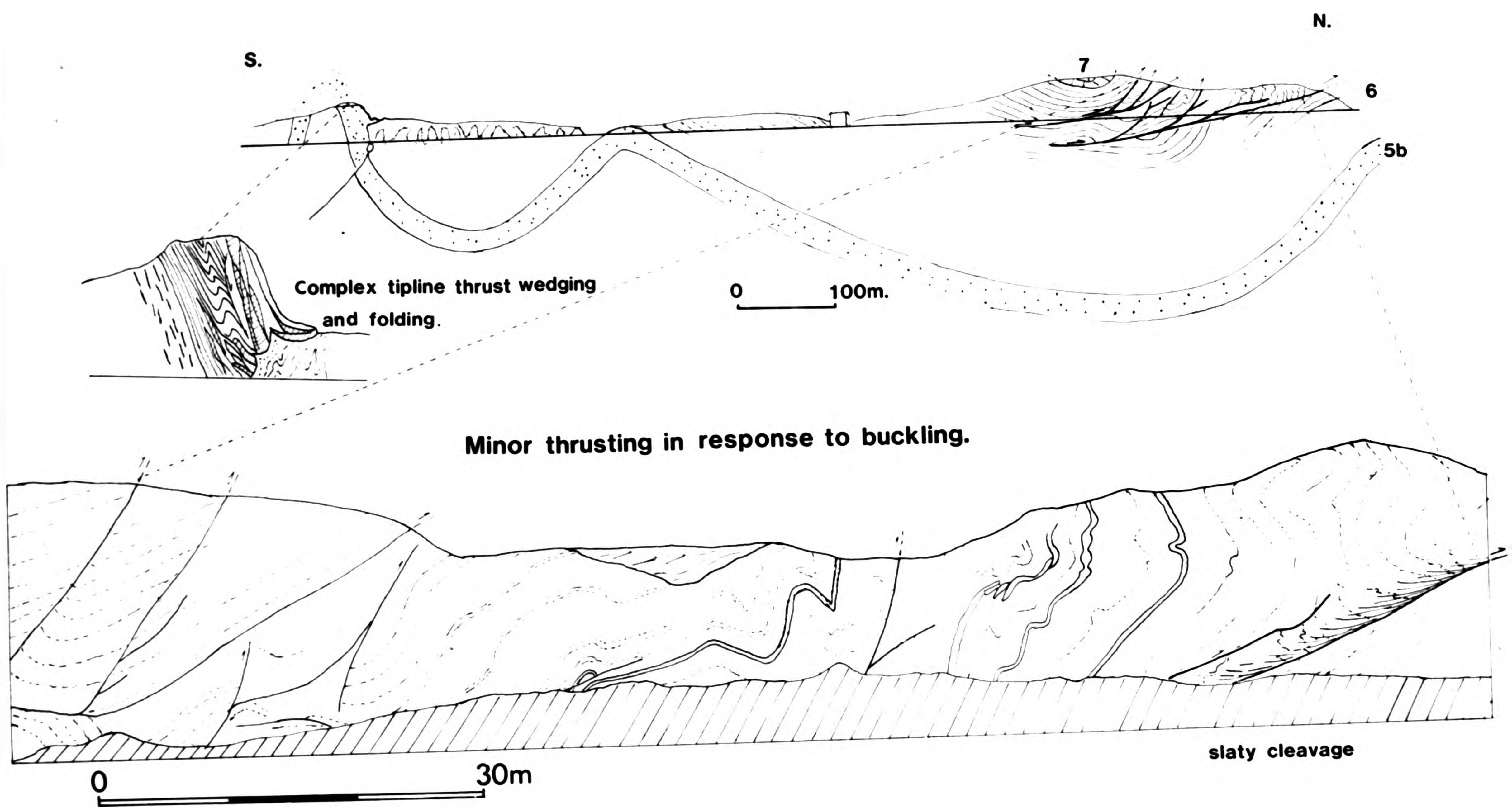

S.
N.
6a
5b
2m.
6a
5b
minor duplex

Fig. 3.11 Road section along road no.165 at Tannen (GR. 824 343 to 825 331), displaying break thrusting in response to buckling in lower Silurian rocks.

Fig.3.11 Road section along road no.165 at Tangen (G.R. 824 343 to 825 334), displaying break thrusting in response to buckling in lower Silurian rocks.



S.
N.
7
6
5b
0
100m.
Complex tipline thrust wedging
and folding.
Minor thrusting in response to buckling.
slaty cleavage
0
30m

displaced by a later, low angled, backthrust. This style differs from that in the older rocks as the folding has not been caused by the (break) thrust which displaces it.

3.13.4 Silurian shales, limestones and the Ringerike Sandstone.

The dominant mode of shortening in the Silurian is by folding. Shortening decreases upwards because the stiff, competent layers become thicker and more resistant to deformation, culminating in the 500m (minimum) thick Ringerike Sandstone. Folds become broader, with more gently dipping limbs and display less and less thrusting in rocks of younger age.

In the lower Silurian, thrusts are formed in response to accommodation problems caused by folding. They fan off locally formed detachments and they often cut up and down section through folded rocks (see Fig.3.11). These (break) thrusts rarely exhibit displacements greater than a few metres. However adjacent to the thrust planes a very localised cleavage may have been formed by the fault, which has a listric trace in outcrop, as the cleavage planes flatten out approaching the fault.

3.3 Structural elements.

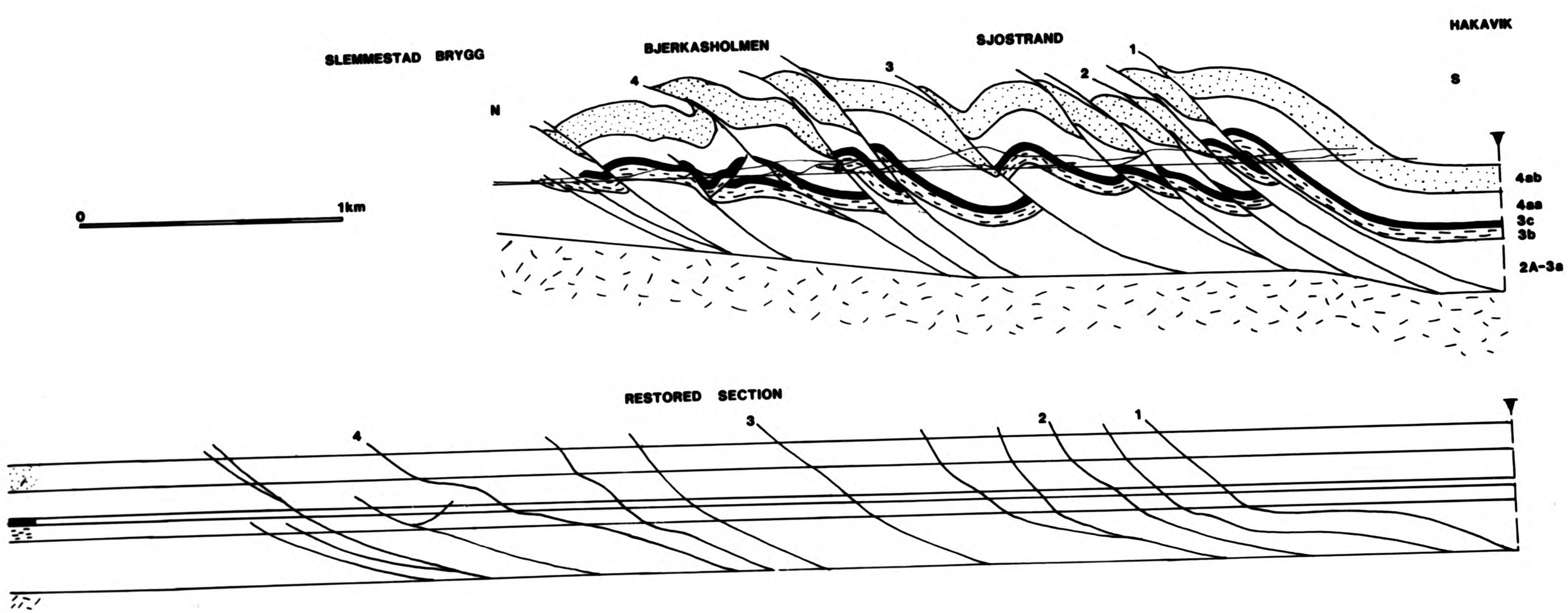
The important elements causing shortening are folds, faults and cleavage, which reflect the structural development of the area. Each structural element will be treated separately.

3.3.1 Faults

Second and third order contraction faults are structurally important in the Cambro-Ordovician rocks, producing thickening in some units and therefore the partial stratigraphic repetition of the succession. Minor flexural slip surfaces along folded bedding planes and third order contraction faults in shales are frequently filled with fibrous calcite slickensides (Durney and Ramsay, 1973; see Plate 3.3). Successively overlapping sheets of fibres display a progressive change in the direction of fault movement with a maximum angle of divergence of up to 50°. This could be due to one part of the fault sticking and ceasing movement before other parts, resulting in the rotation of the imbricate sheet about an axis centered on the sticking point.

When balanced sections through the area were constructed, in order to preserve stratigraphic thickness, it was necessary to postulate an uneven basement topography, which reflects itself in the deformation of the cover rocks moving over its surface. Although the cover rocks when unstrained do not remain in their present position with relation to the basement topography, the presence or absence of basement highs and lows

Fig.3.12 A balanced cross-section along the coast from Hakavik to the cement factory, Slemmestad (G.R. 844 306 to 842 288).


SLEMMESTAD BRYGG
BJERKASHOLMEN
SJOSTRAND
HAKAVIK
N
S
1
2
3
4
4ab
4aa
3c
3b
2A-3a
0
1km
RESTORED SECTION

may have caused three patterns of second order faults to be developed as follows.

1. Imbricate contraction faults dipping towards the hinterland. Sections through these imbricates are best seen at Slemmestad (Fig 3.12) and Bygdoy (Fig.3.8). These may have formed over horizontal or gently dipping basement surfaces.

2. Triangle and pop-up zones. The most intense backthrusting probably originated over areas of basement rises (Figs. 3.5 and 3.6). So although the Osen-Roa Detachment does not cut up section, the effect of basement rises appears to affect deformation in a similar way to a thrust ramping up section; perhaps by slowing down the thrust sheet as it moves uphill, or by causing stick. This may result in the production of backthrusts, which in this case, decrease in intensity northwards from each basement "ramp" and form triangle and pop-up zones

3. Second order faults of large displacement. There are several faults in the Oslo Graben which have much greater displacements than other second order contraction faults. Three of these occur in Asker; one runs south of Billingstad and out into Oslo Bay between Sandvika and Nesoya and is probably responsible for the E-W trend of the northern Oslo Fjord shore line. The other two are in south Asker and run from Sjostrand to Heggedal (Fig. 3.5). Their strike lengths are unknown but are at least 3km and their displacements along the fault planes are 540m and 660m respectively. The fault south of Billingstad has a strike length of at least 10km and a maximum displacement of 500m. By comparison, the size of other second order faults in the district range from 0.5-3km strike length with up to 150m

displacement along the fault plane.

The thrust south of Billingstad is notable for the deformation present in its footwall, where there are duplex structures developed (Fig.3.6). These larger faults appear to be found above basement rises ahead of zones involving backthrusts.

3.3.2 Tip lines.

Fault planes may be seen to decrease in displacement along their length. When the actual front of the propogating fault is reached displacement should be zero and this front is known as the tip line (Boyer and Elliott 1982). Deformation ahead of the tip line can be complex or simple depending on, for example, the size of the fault and the lithology involved. The brittle deformation of the tip line may pass into another type of deformation, which may be ductile folds, shear zones, zone of cleavage or a combination of these (Hossack pers comm). Examples of tip line structures found in Asker are described below.

1.Tip lines in shales.

Faults dying out in shales tend to produce a complex of small disharmonic folds. These are well displayed on the south side of the southern peninsular at Grundvik (Fig.3.13). At Slemmestad bus station (Fig.3.14) a thrust forms three splays which further dissapate slip into chevron folds.

Fig.3.13 Geological map of Grundvik.

- - - - - - - - Joins up the same synclinal core, which displays a transfer zone.

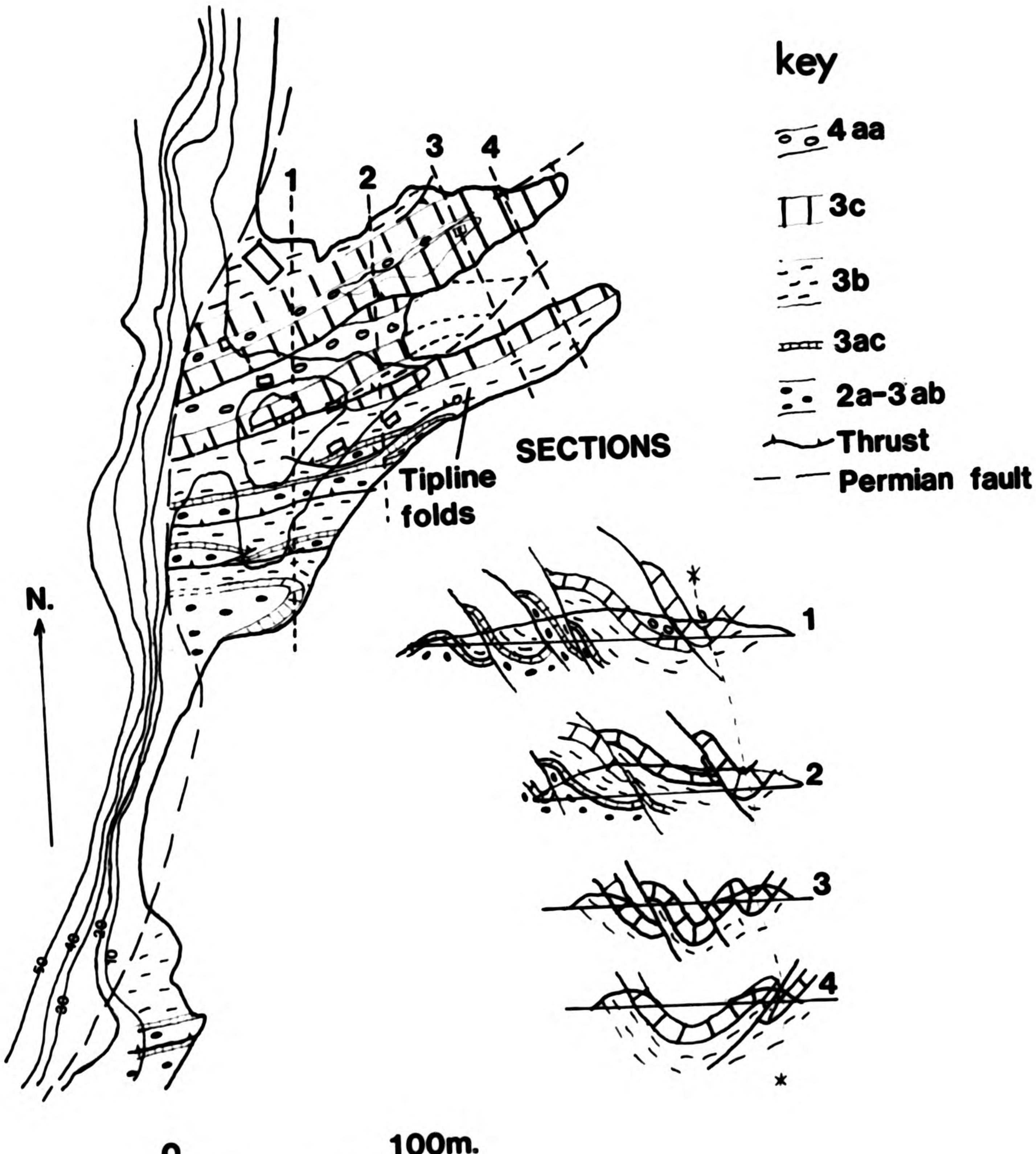
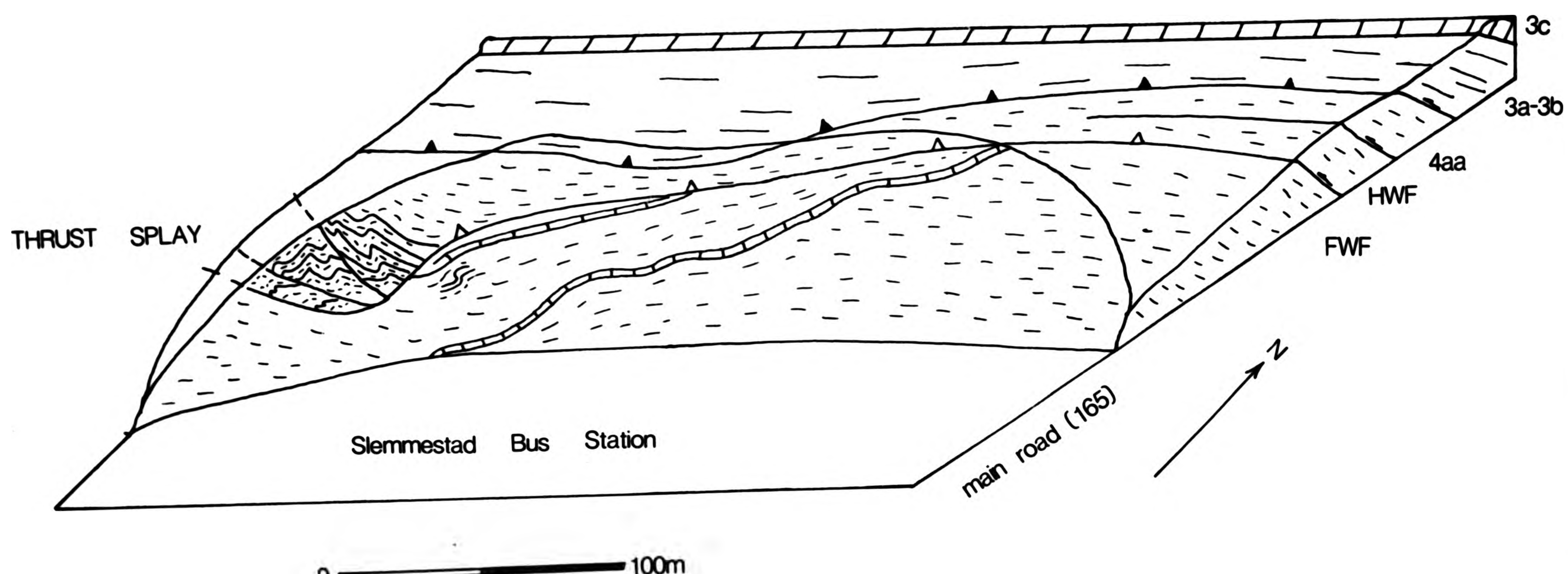

key
4 aa
3c
3b
3ac
2a-3 ab
Thrust
Permian fault
1
2
3
4
SECTIONS
Tipline
folds
N.
1
2
3
4
0
100m.

Fig.3.14 A 3d diagram showing thrust geometry and a splaying thrust tip at Slemmestad bus station.

Fig.3.14 A 3d diagram showing thrust geometry and a splaying thrust tip at Slemmestad bus station.


3c
3a-3b
4aa
HWF
FWF
THRUST SPLAY
Slemmestad Bus Station
main road (165)
N
0
100m

2.Tip lines in limestones and sandstones.

Thrust faults die out into simple anticlines, eg, the anticline north of Hagastrand (G.R.839 355) and into asymmetrical fold pairs (G.R.828 297). Faults may also die out into anticlines which pass laterally into other faults, such structures have been termed transfer zones by Dahlstrom 1970).

A simple transfer zone can be seen on the northern peninsula of Grundvik where a hinterland dipping thrust passes via an anticline into a backthrust (Fig.3.13).

3.Faults can die out into bedding surfaces. The structure on the 165 road by the Konglugen turning (Fig.3.11) might represent such a tip line.

4.There are a few examples of strained nodules and a weak slaty cleavage developed directly above, or below second order thrusts. These indicate a more intense strain resulting in slightly increased ductile behaviour ahead of the propogating thrust tip. Such structures are seen on the west side of Konglugen (see Fig.3.7) and at Bruset (G.R. 828 363, see Plate 3.4).

3.3.3 Thrust splays

Frequently in outcrop thrusts can be seen to bifurcate or splay. In Asker-Baerum this behaviour is almost entirely limited to the shale units and quite frequently occurs shortly after a thrust has exited from a limestone horizon. It therefore appears that the competent units do not favour thrust splaying.

The reason for this is probably a simple one. When a thrust propogates through an incompetent shale horizon, the zone of fracture can end rapidly in a folded zone. The transfer of displacement from a fracture into a zone of small scale folding is more difficult to achieve in the rigid, brittle, competent units. Therefore a displacement on a thin competent unit will produce a rapidly propogating fracture which is likely offset the rigid, compact unit in one deformation pulse. However a shale might absorb the displacement in several zones and require several deformation pulses for it to be completely broken through by the fault. Thus a single clean break is likely in competent units whilst a more complicated thrust propogation history is expected for incompetent units.

Sometimes brittle shear zones are formed in the shales. These are zones with a strongly foliated fabric and a width of ~10cm to 1m. Frequently polished cleavage surfaces and cleavage lamella are orientated at a steep angle to the roof and floor thrusts of the shear zone. The zone might be acting like a small duplex where the high angled slip planes transfer slip from the floor to the roof thrust.

3.3.4 Thrust wedges.

The anastamosing fractures of small thrust displacement called thrust wedges (Cloos 1961) are quite frequently displayed in narrow zones in competent rocks. For most of their length the fractures are roughly parallel to bedding and when not, cut rapidly across bedding to join another bedding parallel fracture (Fig.3.15). Many thrust wedges could be incipient thrusts which have been later rotated to their present positions (Cloos 1961). Alternatively they could represent complex tip lines or accommodation structures resulting from folding. Locally they may double the thickness of a bed and their orientations are similar to those of second and third order thrusts and bedding.

3.3.5 Folds

Two orders of folds are recognised; firstly large scale draping of the cover rocks over basement topography. For example in the Konglugen area a broad depression about 2km wide has preserved Silurian rocks between Ordovician rocks to the north and south. These folds contribute an insignificant amount of shortening. Secondly mesoscopic folds are present, which comprise the principle means of shortening above the Osen-Roa Detachment. These can be divided into two groups based on structural association and geometry as follows.

Group 1. Folds related to thrust faults.

Group 1 folds occur mainly in the Cambro-Ordovician rocks where their attitude and tightness are related to the presence of contraction faults and minor detachment surfaces.

Folds generated ahead of thrust tips (Fig.3.3) generally form tight, even chevron, symmetrical to moderately asymmetrical folds, with wavelengths of 120-280m and moderate amplitudes of 70-135m in the Orthoceras and Ampyx Limestones. These have gently plunging hinges and interlimb angles of 65-90°. The axial planes of tip line folds dip in the direction of the fault planes responsible for their formation, which is usually to the NNW or the SSE by approximately 60-90°. Their fold geometry is either 1B or 1C (Ramsay 1967).

Within the Ordovician shales, units near faults and detachment horizons display tight chevron-like polyclinal folds with multiple axial planes, diverse orientations and thickened hinges relative to the limbs. Geometries range from class 1C to 2 (Ramsay 1967). Wavelengths range from 0.1 to 3m. and amplitudes from 0.2 to 3m, with interlimb angles from 30-90°. These display bedding parallel slip and small contraction faults which transport material into the fold hinges. The folds die out a few metres away from fault surfaces and are replaced by more gentle folds which themselves eventually die out. The fold hinges of these folds may deviate up to 30° from the regional trend.

Group 2. Folds unrelated to faults.

This group of folds have formed by "active" buckling and second and third order contraction fault development is unimportant in comparison. The tightness of the folds decreases and wavelength increases higher in the stratigraphic succession reflecting the reduction in shortening going up the sequence.

These folds in the Ordovician form moderately broad, open folds with wavelengths of 270-1400m and amplitudes of 120-300m. Axial planes are steep to upright with dips of 80-90° and interlimb angles fall between 85-110°. Fold geometry is class 1B (Ramsay 1967).

In the Silurian succession this group of folds is the dominant means of shortening, forming broad, open folds with wavelengths of 800-2000m and amplitudes of 120-280m. The folds are upright or slightly inclined, with axial planes dipping to the NNW by between 70-90° and exhibit interlimb angles of 100-120°. Fold geometry is class 1B (Ramsay 1967).

The Ringerike Sandstone capping the succession forms even broader folds, with wavelengths up to 4000m and amplitudes up to 870m.

Fig.3.15 Structure maps of Asker-Baerum

A. Fracture cleavage intensity map.

Increasing density of dots denotes decreasing spacing of cleavage planes, distinguished in the field as absent,weak, moderate or strong cleavage.

B Structural map of Asker Baerum

= thrusts

= normal faults

= anticlinal axial traces

= synclinal axial traces

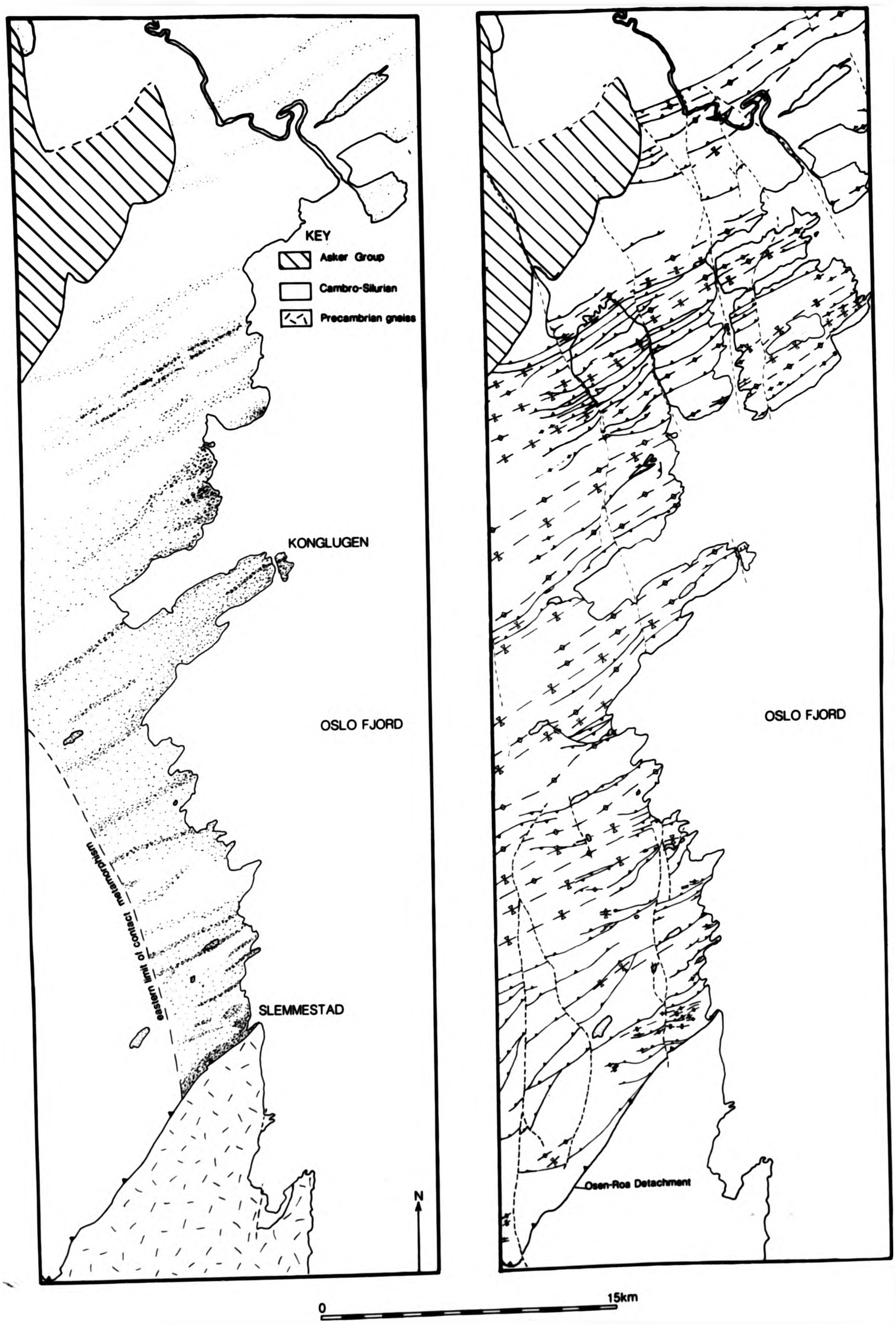
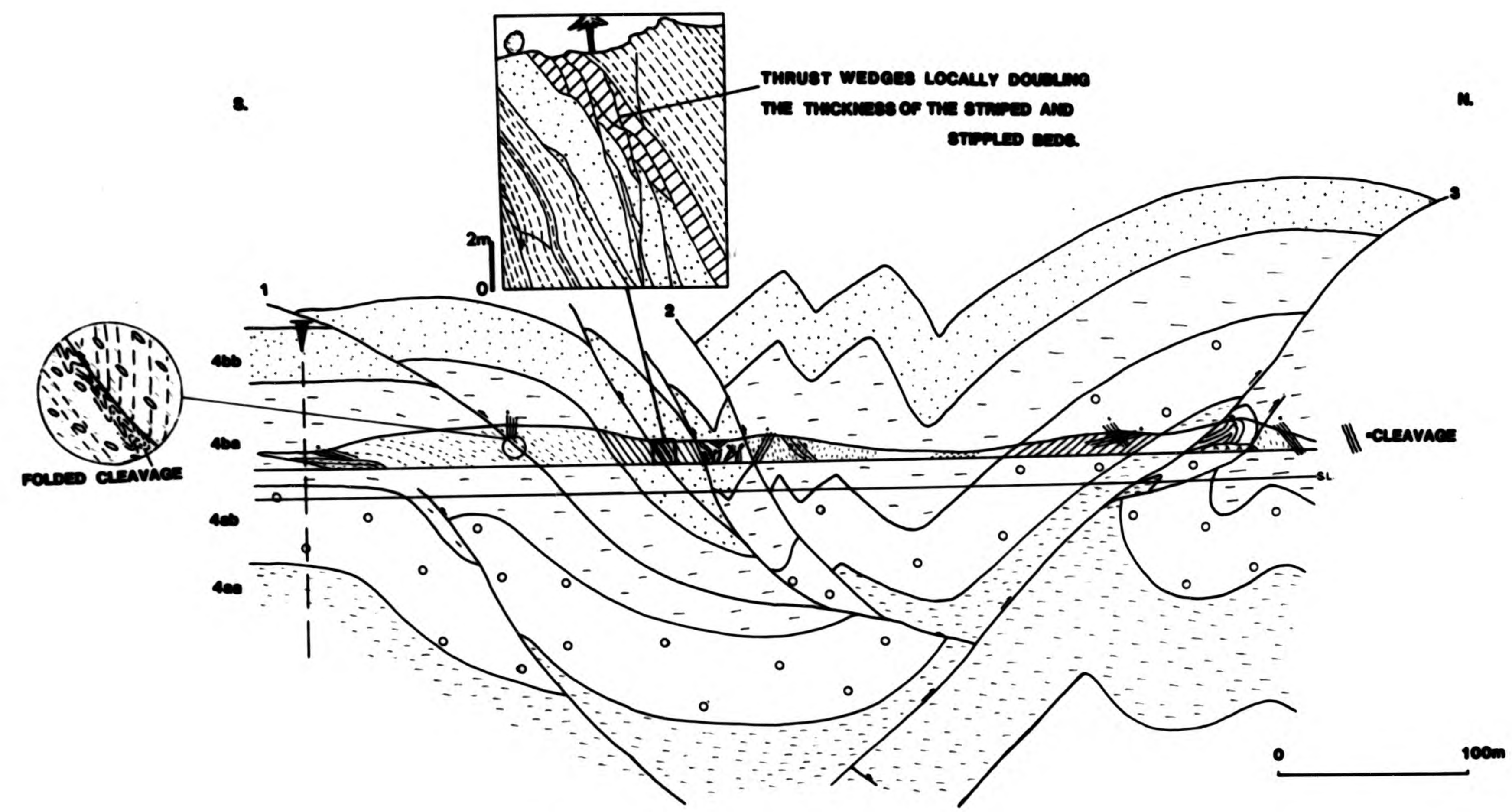
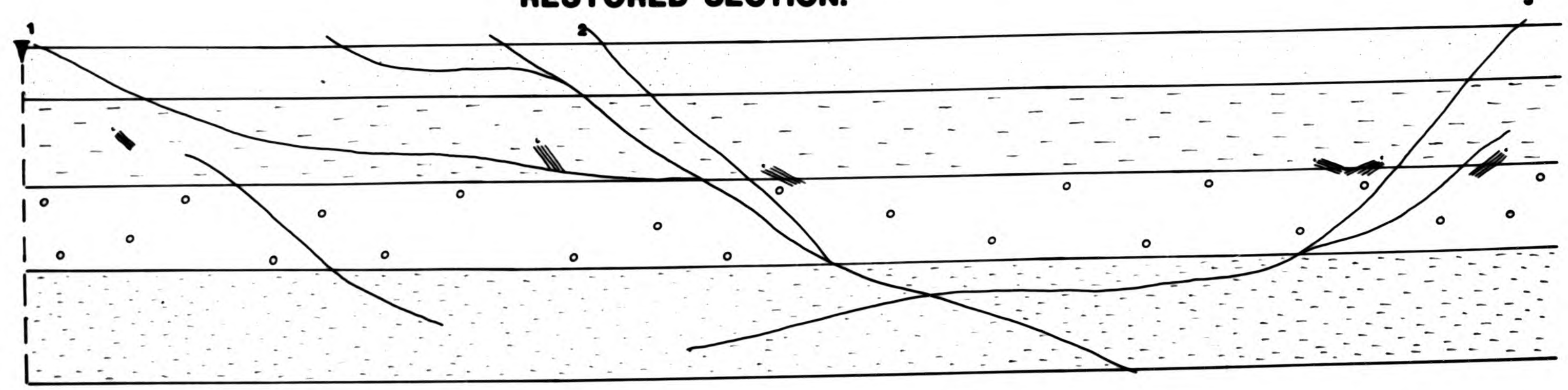

KEY
Asker Group
Cambro-Silurian
Precambrian gneiss
KONGLUGEN
OSLO FJORD
eastern limit of contact metamorphism
SLEMMESTAD
N
OSLO FJORD
Osen-Roa Detachment
0
15km

Fig.3.16 <u>Detailed road section along 0.5km of road no.165 between Vollen and Arnestad, displaying details of cleavage, thrusting and thrust wedging</u>

The restored section shows cleavage orientations in the undeformed state, which is sub-parallel to the restored fault traces.



RESTORED SECTION.



3.3.6 Cleavage

Spaced solution (Alvarez et al 1978) and fracture cleavage occurs within the Cambro-Silurian rocks. Cleavage ranges from close spacing (0.2-1cm) to a wider spacing (1-5cm) but it is not always present. Lithological contrasts affect the intensity and type of cleavage.

Fracture cleavage is usually steeper than bedding and increases in intensity (ie. thicker cleavage and closer spacing) towards second and third order contraction faults, which modify the cleavage. Strong cleavage is localised to fault zones, though it does not necessarily display similar intensities and orientations within the hanging- and footwall blocks of an individual fault (Fig.3.3). A slaty cleavage is sometimes developed in shales close to fault planes and frequently appears to be derived from the locally intensified and puckered bedding- parallel fissility in shales.

The Wulff net plot of poles to fracture cleavage (Fig.3.18a,b) exhibit a scattering of poles along a NNW-SSE trending great circle, characteristic of folded cleavage. When bedding for each cleavage orientation is restored to horizontal, the cleavage poles cluster in two groups with opposing dips inclined in the majority of cases between 10° and 30° and dipping to the NNW or SSE. Other steeper poles to cleavage outside these clusters might represent cleavage formation related to steeper faults or to formation during folding.

The fracture cleavage is not always developed (see Fig.15A). When present it has varying orientations and sometimes two similar fracture cleavages oblique to bedding, but of opposing dip, are present in one outcrop. This suggests that the cleavage is not an early formed regional cleavage. It is therefore envisaged that the fracture cleavage formed ahead of and sub-parallel or acutely inclined to second and third order contraction fault tips. The two clusters of poles are related to hinterland-dipping and foreland-dipping thrusts (Fig.3.16) so that when thrusts of opposing dip are in close proximity to each other two sets of cleavage may be formed, dividing the rock up into pencils where neither cleavage is bedding parallel (see Field Guide, Plate 13 Appendix 1).

Pressure-solution cleavage is developed in the limestone and sandstone bands and can be seen to pass laterally into pencil cleavage developed in shales (see Plate 3.5). The strike direction of the pressure-solution cleavage and the long axis of the pencils are orientated roughly parallel to minor and regional fold hinge direction.

Pressure-solution cleavage seams vary from weak to strong and change their morphology in several ways. Weak cleavage is characterised by toothed, stylolitic surfaces. As solution-shortening increases, the wavelength increases faster than the amplitude of the teeth, resulting in the eventual elimination of the stylolitic form with higher solution-shortening (Reks and Gray 1982). Clay selvage in the solution seams may be up to 1mm thick; stylolitic seams are spaced every 4-10cm and may be up to 40cm long.

Moderate pressure-solution forms slightly wavy seams up to 20cm long with spacings from about 2-5cm. Clay selvages are about 1-2mm thick and are thickest towards the centre of the seams.

The strongest pressure-solution present in Asker-Baerum forms anastamosing seams 20-50cm long often with moderate pressure solution seams between. The clay selvage is up to 2mm thick and varies along strike.

On a Wulff net (Fig.3.18b) the poles to pressure-solution planes have a scatter along a great circle similar to those for the fracture cleavage, indicating folding of the pressure solution planes. When bedding is restored to horizontal, the pressure solution seams cluster within 15° either side of vertical, striking WSW-ESE. This shows the main pressure solution development to be prior to folding. However there is some scattering of poles which probably represents pressure-solution development during folding.

Calcite veins have been plotted on the same Wulff net and are formed at approximately 90° to the pressure-solution seams. In thin sections of minor folds the calcite veins can be seen to be folded. Pressure solution seams are orientated at about 90° to the principle stress direction (x) and the calcite veins at approximately 90° to the minimum stress direction (z). So these veins are probably the deposited products resulting from pressure-solution.

Estimates of shortening by pressure solution were achieved in three ways; by estimating the amount of insoluable material present in the rock and relating it to the amount of insoluable material present in the pressure-solution seams; by calculating how much of a fossil has been dissolved by a pressure-solution seam and by estimating the amount of redeposited calcite produced by pressure-solution. It has been estimated from these three methods that the maximum shortening produced by pressure solution is about 15%. However pressure-solution is localised and varies in intensity so the amount of shortening averaged out over the region is probably about 5% for most limestone horizons.

Pencil cleavage is characterised by two sets of parallel fractures intersecting at high angles (Fig.3.17). One set comprises fractures parallel or sub-parallel to a bedding-parallel fabric. The second set is inclined at 70-90° to the bedding and may pass laterally and upwards into pressure- solution seams in limestones.

Spacing of the fractures ranges from 0.3-1.3cm: the fractures are planar forming continuous and discontinuous traces perpendicular to bedding. Fracture traces on bedding planes display an anastamosing network which divide the rock into elongate fragments terminating in acutely triangular ends. The pencils may be 2-12cm long and their long axis parallels other cleavage strike directions and local fold hinges.

The pencils are found in shales and are best developed in areas of moderate deformation. They pass into a single cleavage as deformation increases. This can be demonstrated on Konglugen (see Fig.3.7), where slaty cleavage in the overturned hangingwall passes upwards, away from a folded backthrust, to the south into a well developed pencil cleavge.

Pencils appear to have developed initally from discontinuous bedding parallel cracks which may propogate into long, tapering, anastamosing cracks which eventually join up to form regular pencil cleavage. Increasing pencil cleavage intensity is marked by longer thinner pencils (Fig.3.17).

Occasionally, strained graptolites are present on bedding parallel surfaces, between the other steeper cleavage which defines the pencils, so that shortening within the pencils can be calculated. A two dimensional strain ellipse was calculated for four different sets of strained graptolites using construction 4a and b, Ramsay (1967, p.80-81).

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Plate 3, Fibrous calcite slickensides on bedding surface, Nesova.

Plate 4, Pressure-solution seams in limestone passing into pencil cleavage in shales, Nes.

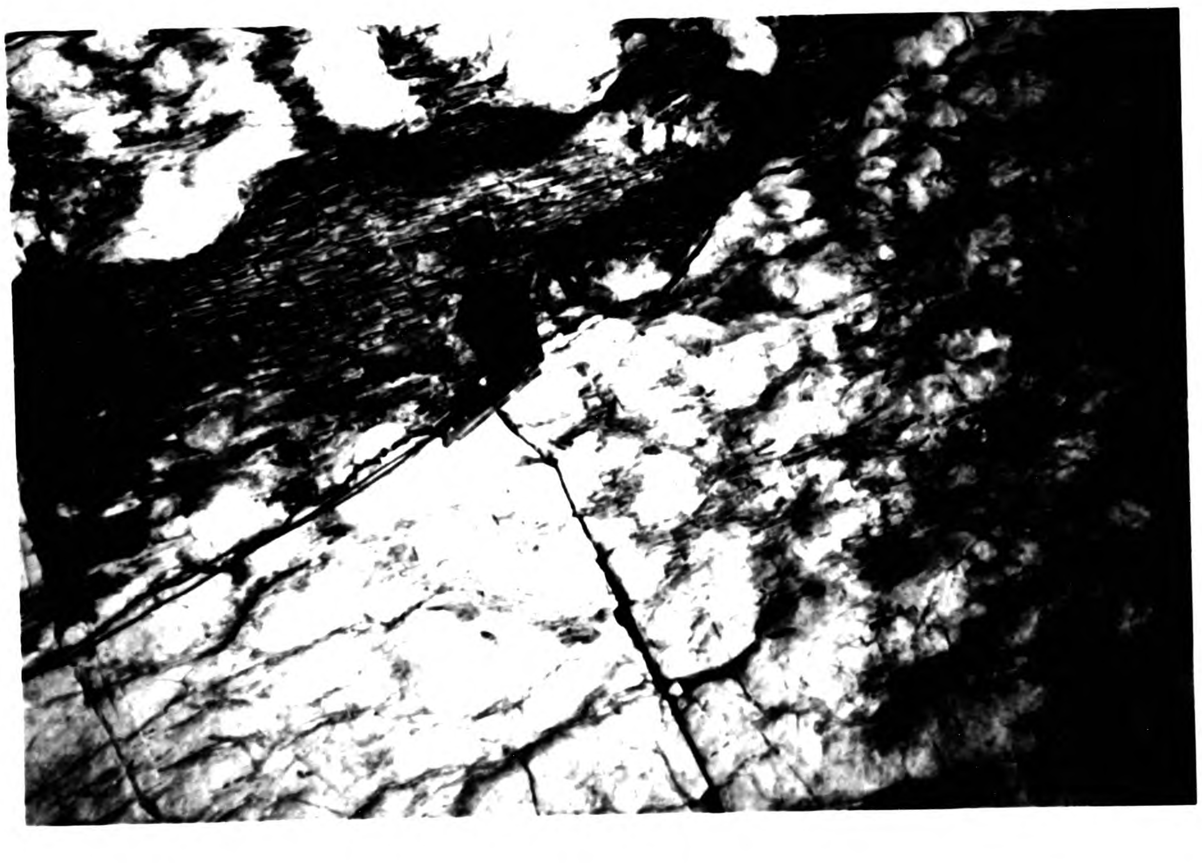


Fig.3.17 The progressive development of pencil cleavage in 4aa Shales. Biorkas. The orientation is at right angles to the long axis of the pencils.

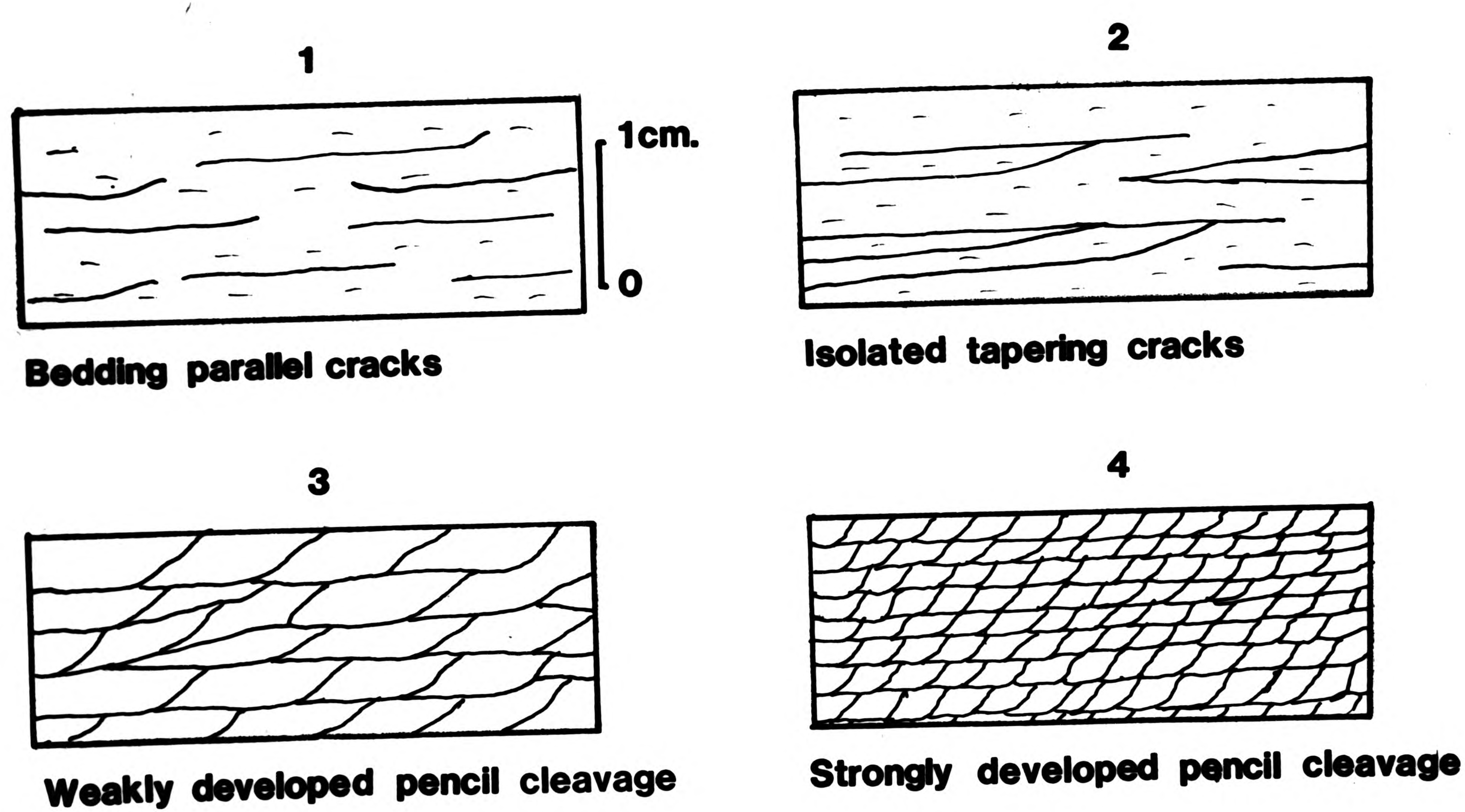

1
1cm.
0
Bedding parallel cracks
2
Isolated tapering cracks
3
Weakly developed pencil cleavage
4
Strongly developed pencil cleavage

Fig.3.18 Stereographic plots (lower hemisphere, Wulff net) of structural elements in Asker-Baerum.

KEY

A. × poles to fracture cleavage, with bedding restored to horizontal

B. • poles to fracture cleavage

C. ó poles to calcite veins

o poles to calcite veins, with bedding restored to horizontal

• poles to pressure-solution cleavage

× poles to pressure-solution cleavage, with bedding restored to horizontal

D. • bedding-cleavage intersection lineation

o pencil cleavage long axis lineation

E. ⸝ poles to second and third order contraction faults

o poles to minor fold axial planes

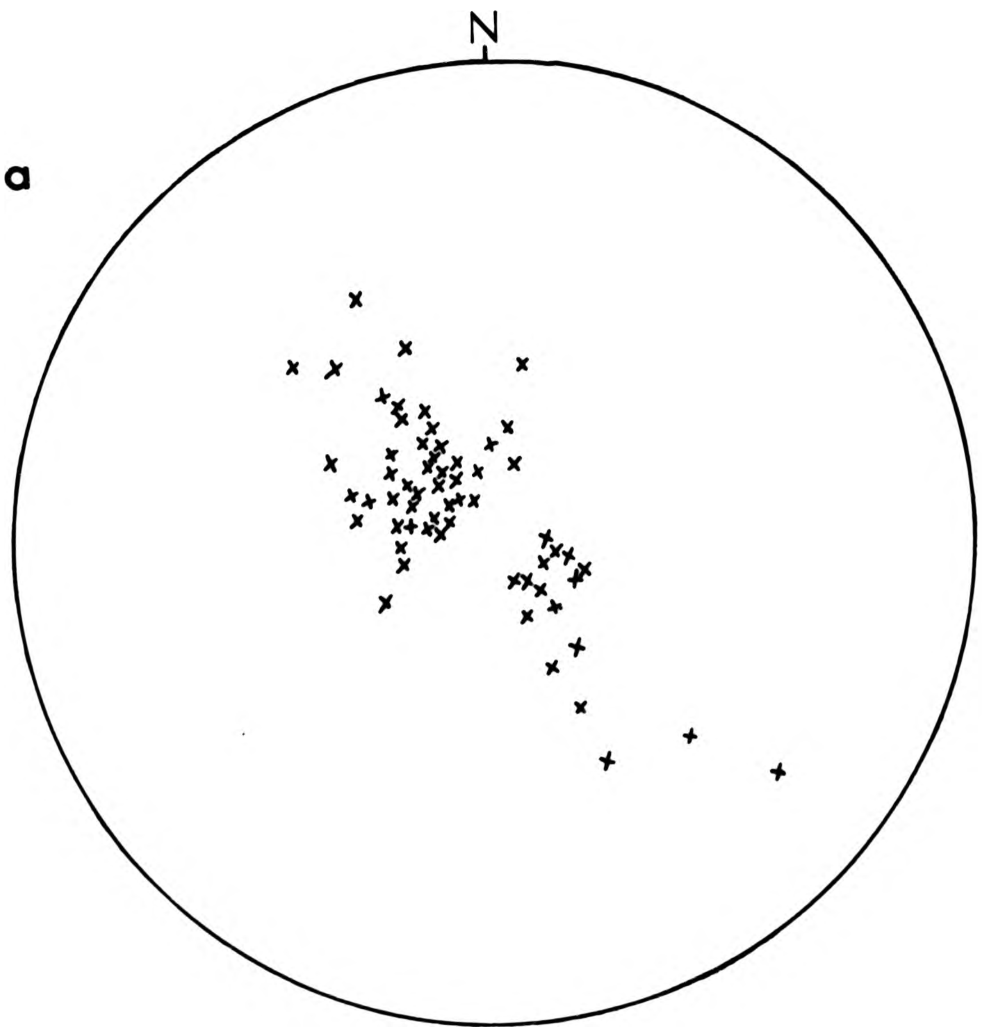
× slickenside fibre lineation

• minor fold hinge orientation

F. • poles to bedding

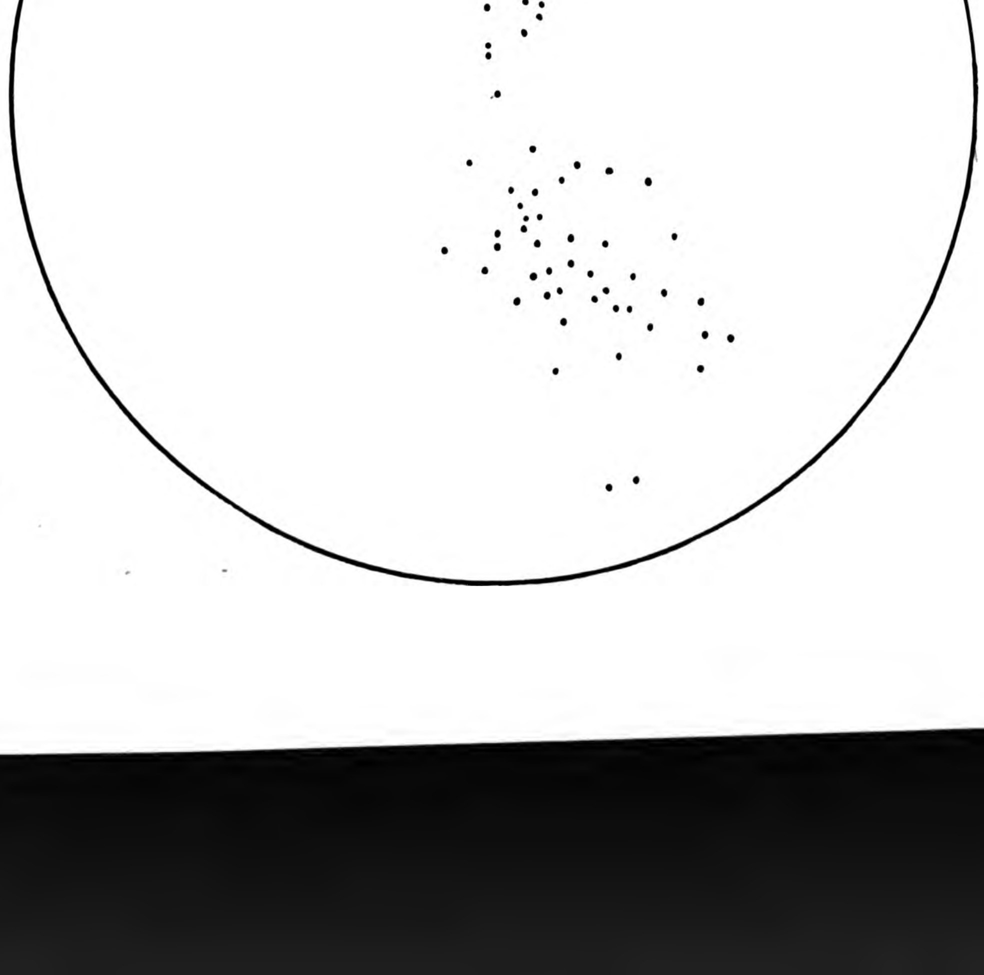
RFA = Regional fold axis orientation, derived from poles to bedding.

a



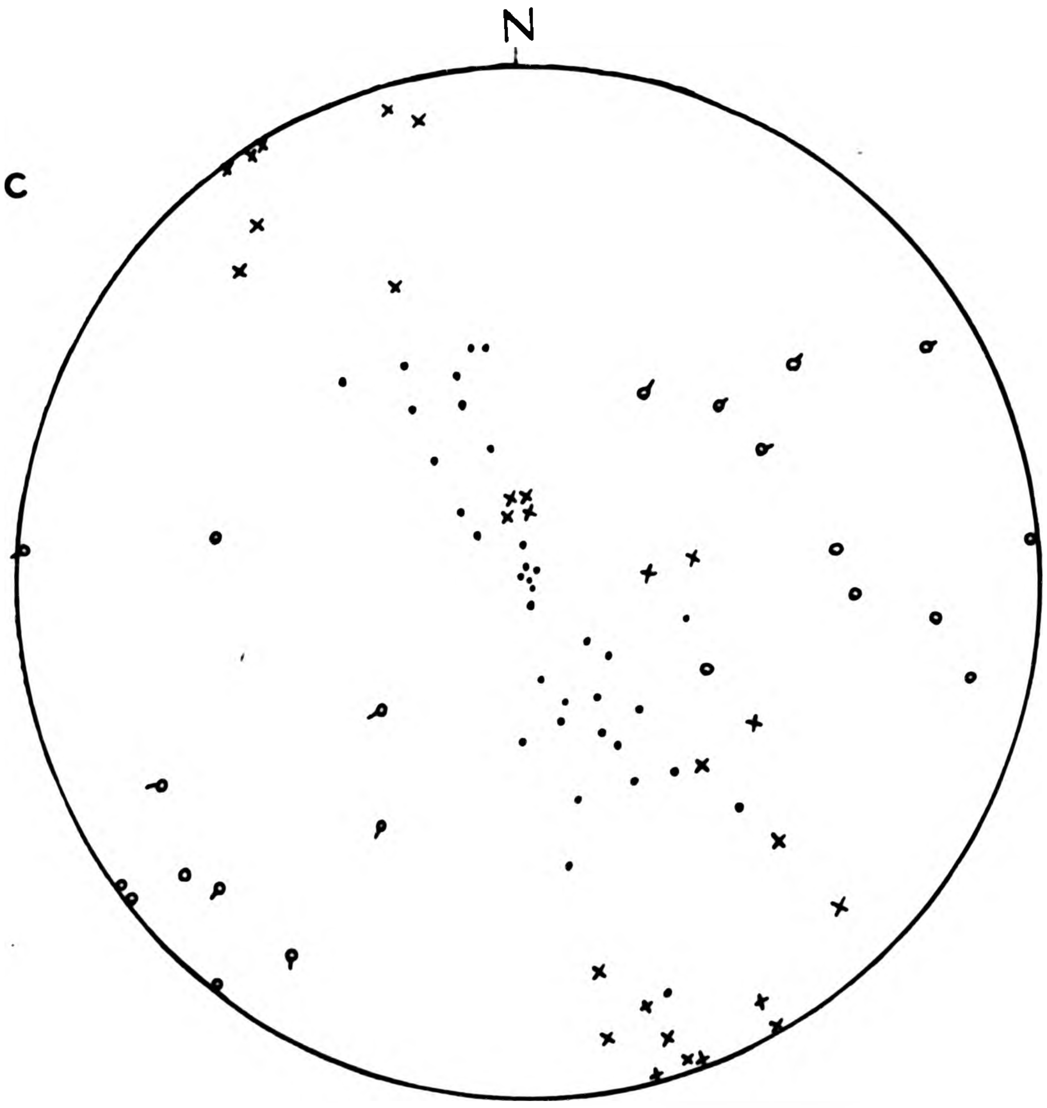
x POLES TO FRACTURE CLEAVAGE WITH BEDDING RESTORED TO HORIZONTAL

b

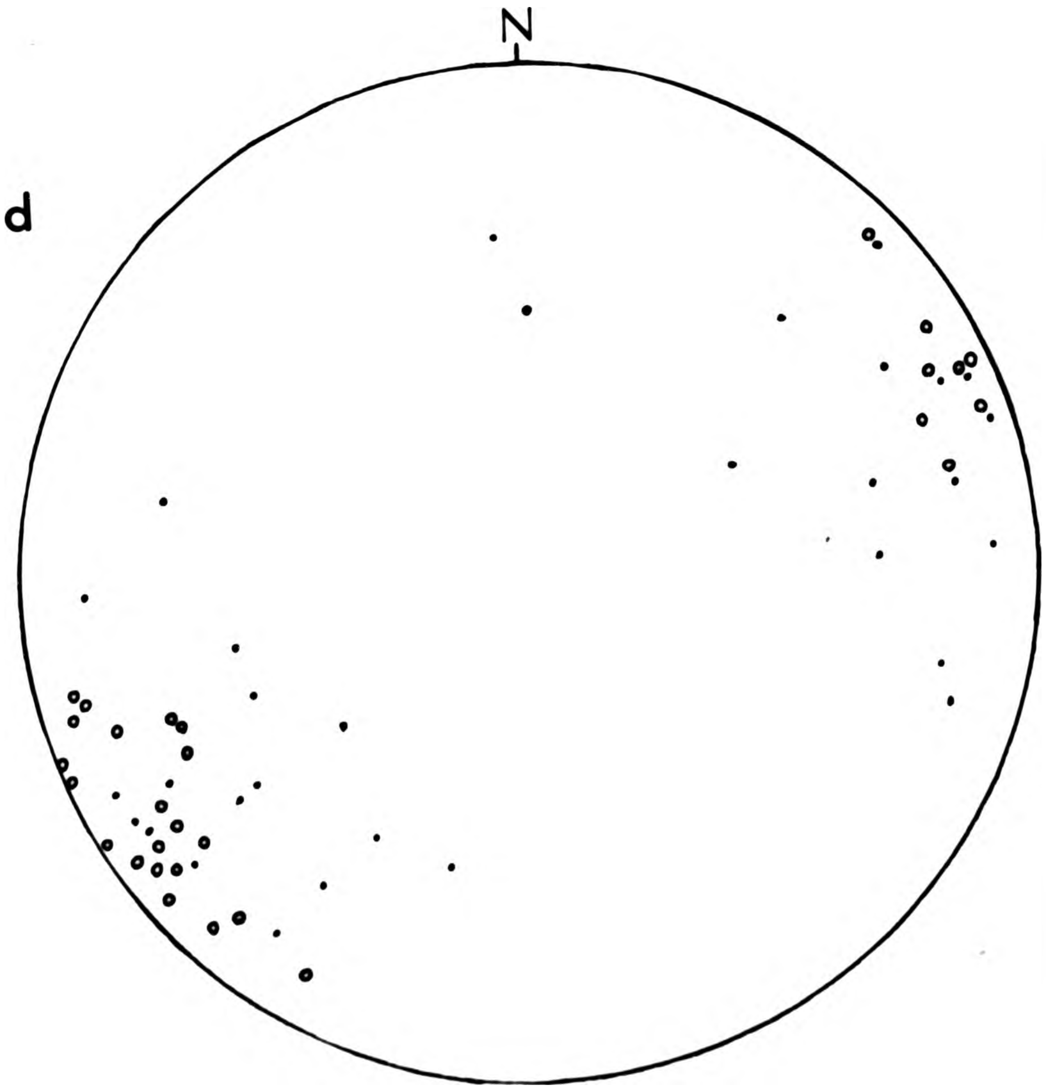


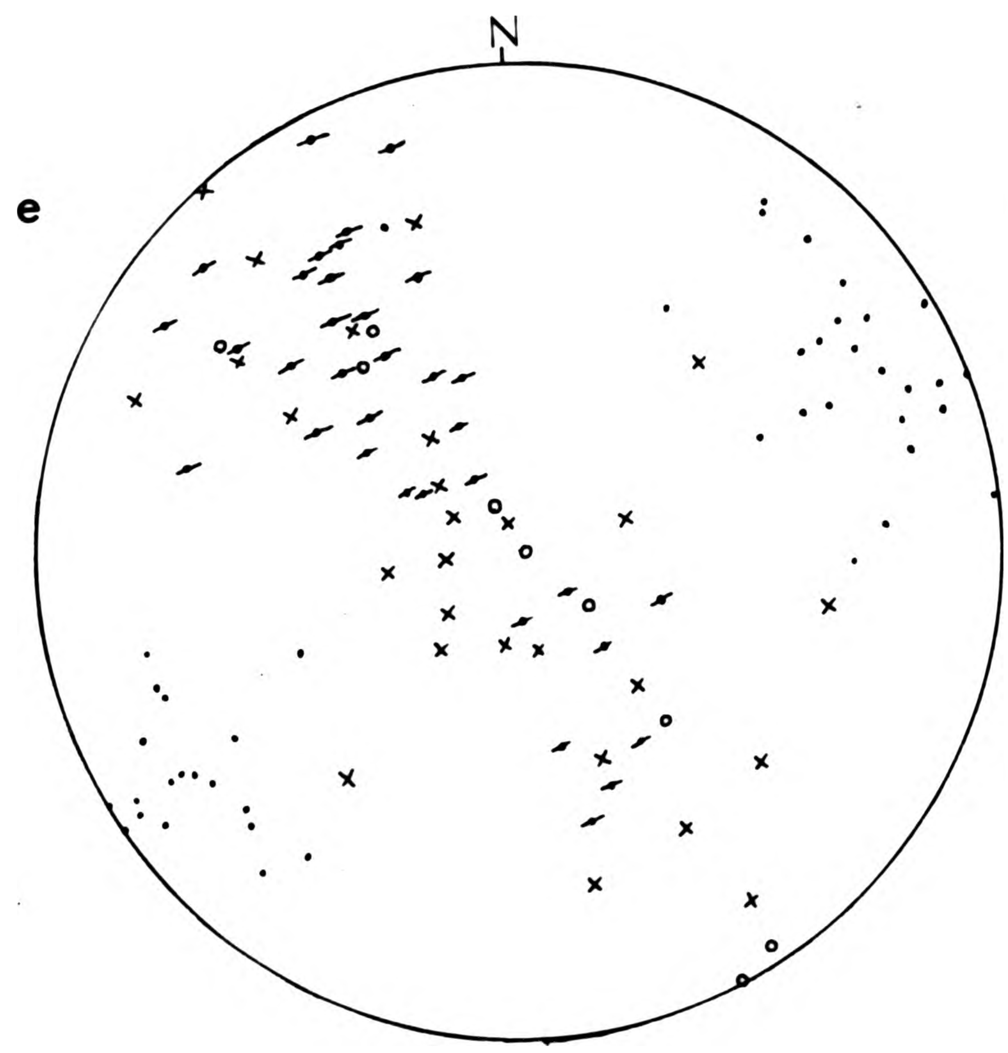
• POLE TO FRACTURE CLEAVAGE

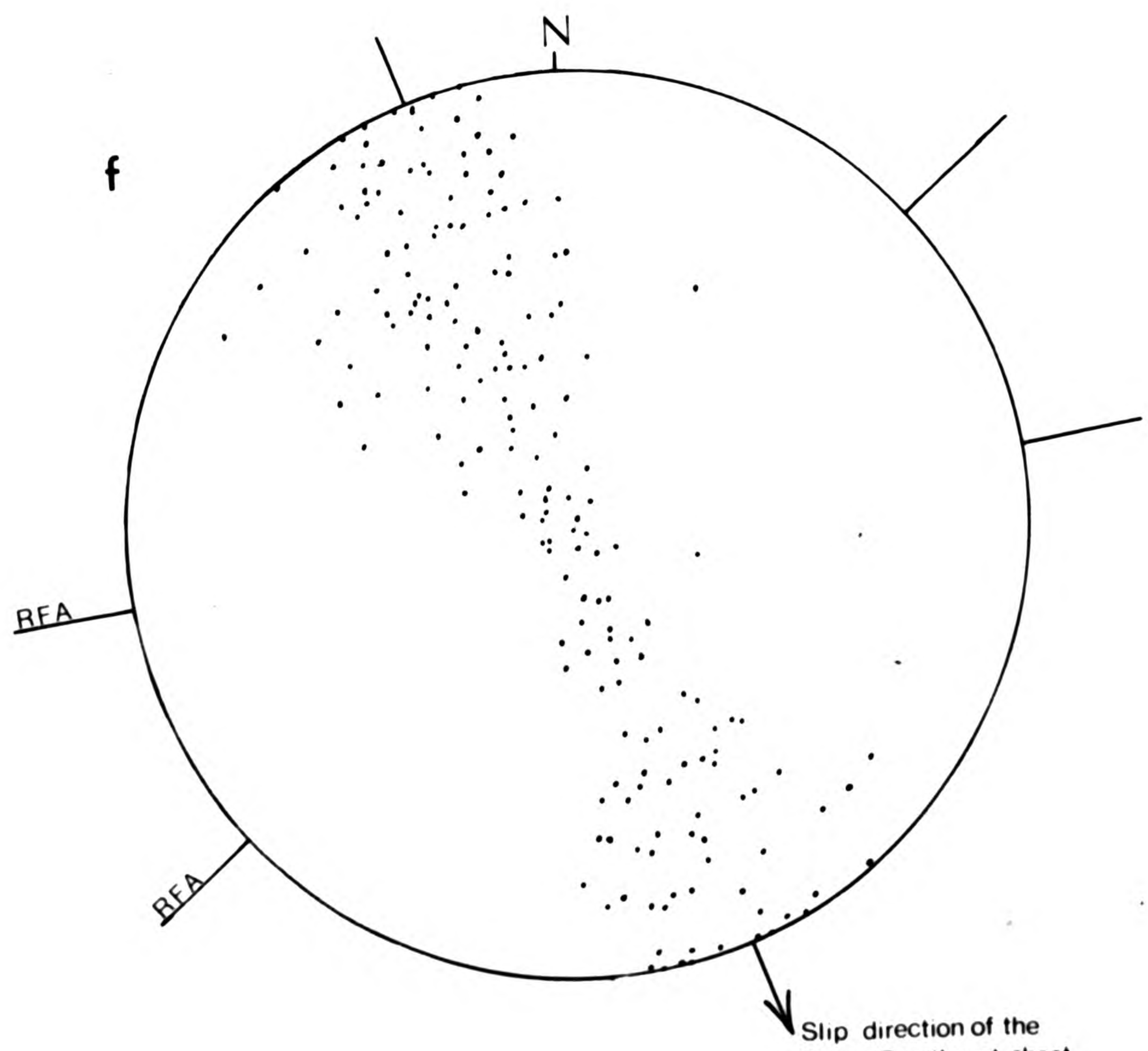
c



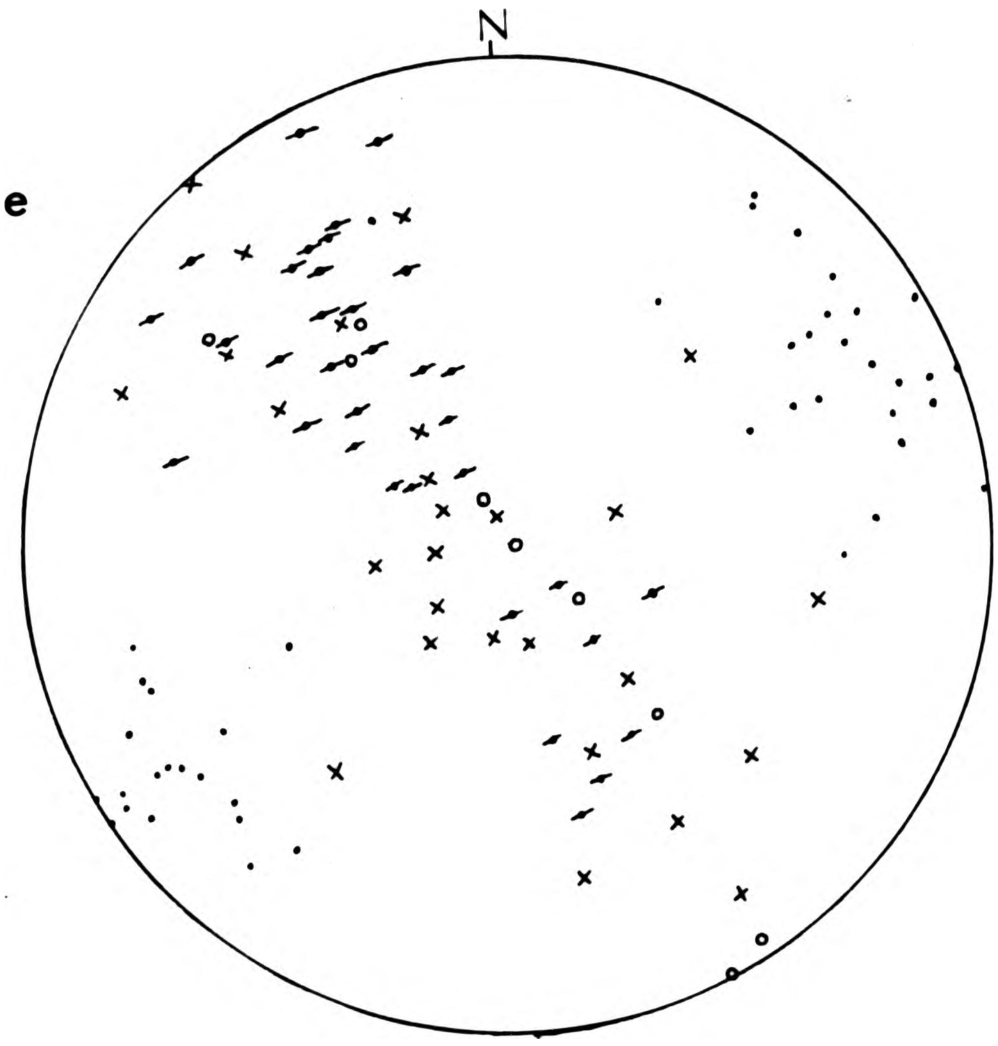
d



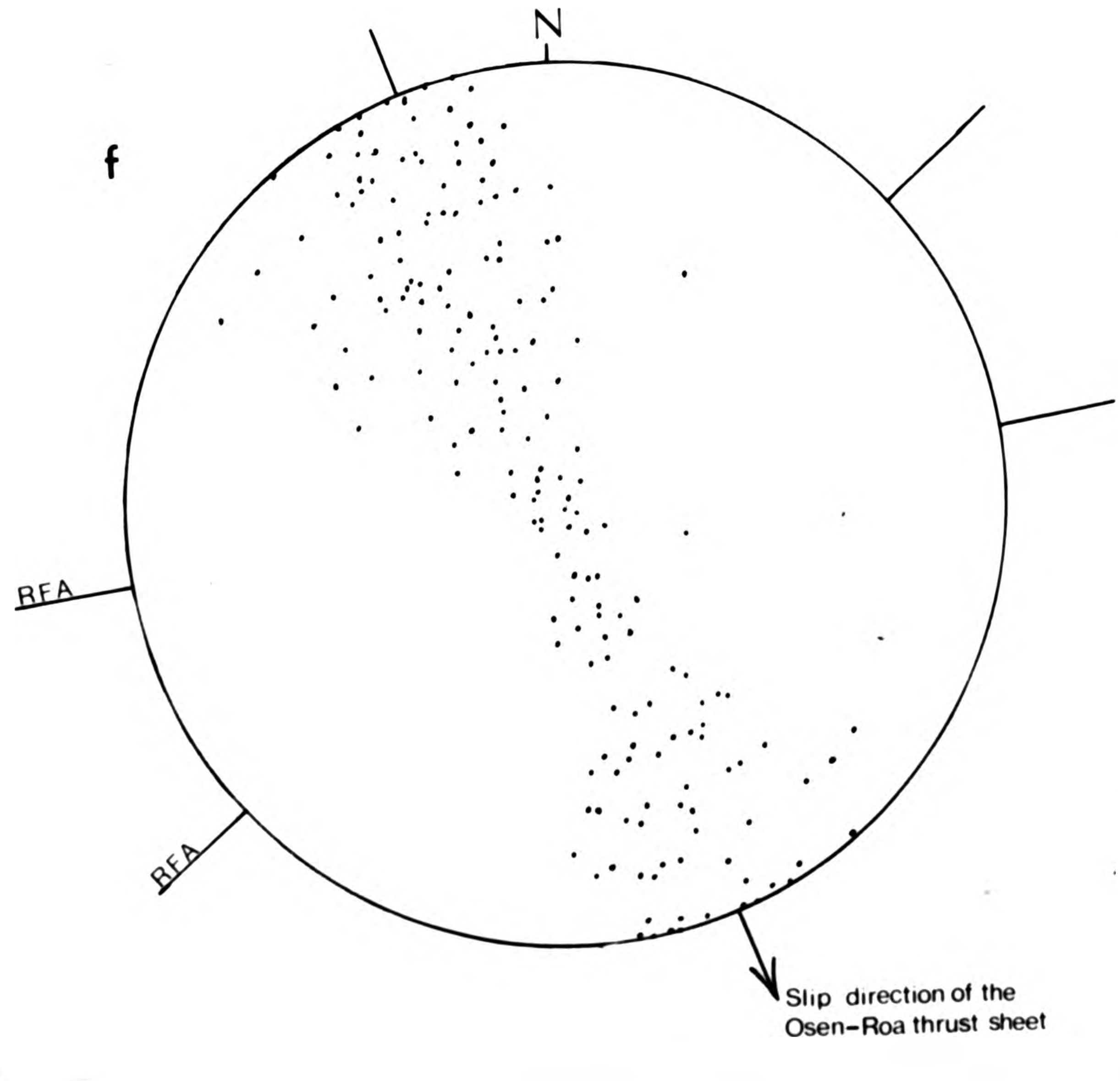

N
e


N
f
RFA
RFA
Slip direction of the
Osen-Roa thrust sheet

e



f



From these the principle extension direction (z axis) was found to be parallel to the long axis of the pencils, whilst the principle shortening direction (x axis) is parallel to the short axis of the pencils. Maximum shortening across the pencils (x axis) is 26%.

3.4 Analysis of field data (Figs.3.15).

The poles to bedding, cleavage, pressure-solution, minor fold axial planes and second and third contraction fault planes occupy similar positions on the Wulff net, with a 50° variation in strike direction of approximately NNW-SSE. The slip direction of the thrust sheet lies in the plane of the girdle of the above structures.

Lineations clustering with shallow plunges orientated at approximately 90° to the above mentioned poles are pencil cleavage lineations, minor fold hinges and bedding-cleavage intersection lineation. The bedding-cleavage intersection lineation is scattered about a small circle indicating subsequent flexural slip folding.

The orientation of shear-vein fibres is more scattered, generally trending in a NW-SE band whilst other veins with no plunge reflect shear-veins on minor wrench faults. The swinging away from regional movement direction of fibres formed late in the fault movement serve to increase the scatter of fibre orientations.

The data shows a close relationship between all the elements measured indicating one progressive phase of deformation. Some early formed elements have been deformed by later ones (eg. cleavage was formed prior to folding and faulting and so poles to cleavage instead of clustering have been scattered along a great circle). Most of the data plotted is either approximately perpendicular or lying parallel to the main movement direction of the Osen- Roa Detachment.

3.5 Strain distribution and the total amount of shortening.

Several deformation mechanisms comprise the total strain within Asker- Baerum. Strain markers used within the district are as follows.

1. Fossils, mainly graptolites, trilobites and brachiopods.

   These are distributed unevenly and frequently in insufficient numbers to enable strain to be properly calculated. In about 80-90% of the exposure the fossils are undeformed of only slightly deformed. In the lower Ordovician fossils display up to 26% shortening along the x axis, whilst for ten localities within the Silurian found suitable for measuring strain maximum shortening in the x axis direction was 32%.

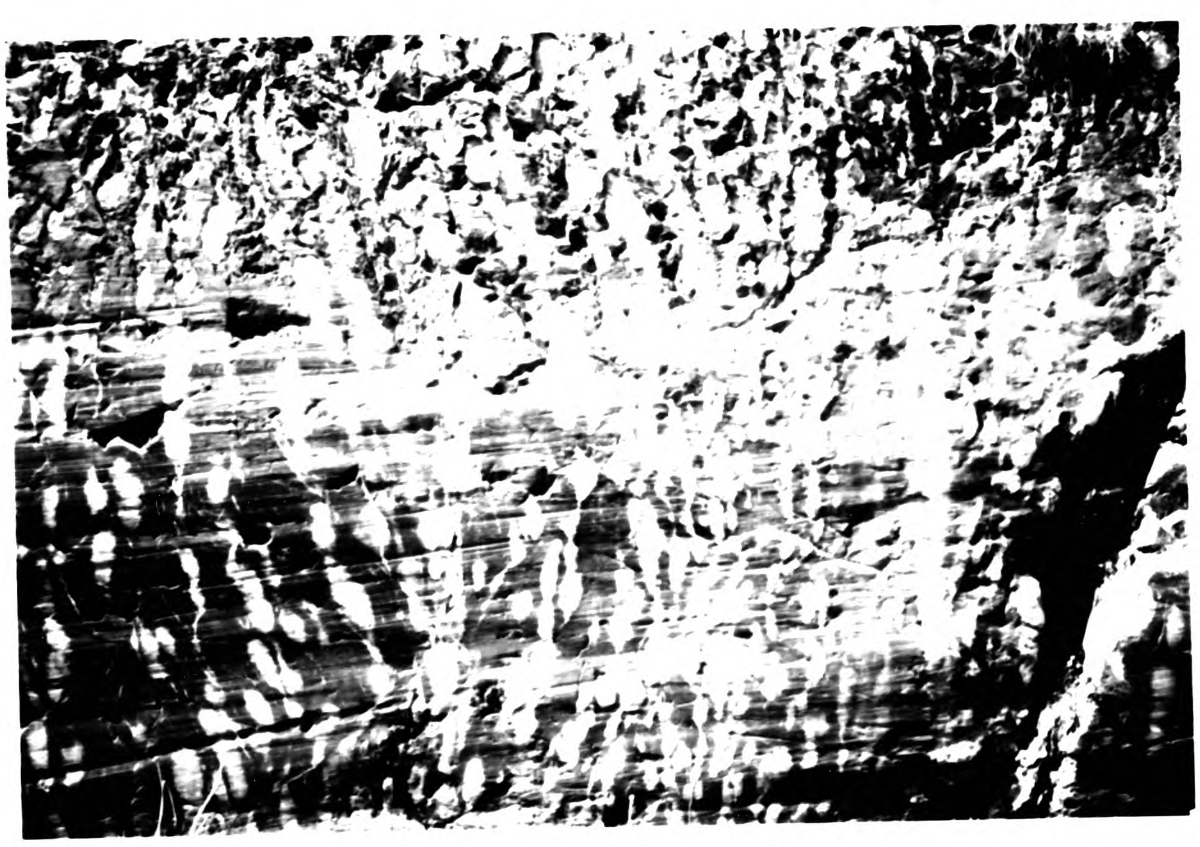
2. Strained nodules and ooliths.

   Although oolitic rocks are present in deformed localities, no significant distortion of ooliths was found. Strained nodules were found in three localities in localised zones close to faults (see Plate 3.5). The nodules accompanied by a slaty cleavage were drawn out parallel to the fault plane.

3. Pressure-solution.

   Pressure-soution produces a maximum shortening of 15%. As the products of pressure solution are removed from any section parallel to strike. The assumption of plane strain no longer applies to any section parallel to strike. The effects of pressure solution must be added onto a balanced section.

Plate 3.5 Strained nodules in Upper Ordovician beds, Bruset.



4.Folding and thrusting.

The amount of shortening achieved by folding and thrusting was calculated by constructing balanced sections through the area (Figs.3.5; 3.6; 3.8; 3.12). By comparing arc length (l_0) with deformed length (l_1), using $l_1 - l_0 / l_0$ the amount of shortening can be calculated. Simon and Grey (1982) drew attention to the possibility of fold flattening producing a slight underestimate in folded length of 1-2%. By direct measurements from the cross-section the amount of shortening achieved by thrusting and folding can be obtained.

5. Extension within the thrust sheet.

Occasionally Caledonian extensional features are locally present in Asker-Baerum. There are some strike parallel normal faults of a few meters displacement and also some features which indicate extension at right angles to the regional strike direction. The latter extension is recognised by the presence of calcite filled veins at right angles to strike and by chocolate tablet extension in limestone beds which breaks competent beds into plates about 30cm across. The local extension exhibited by these plates is from 5-10% in 10 localities.

Principal natural shortening ET=Elps+Eb+Ef+Eps

where Elps=layer parallel shortening (30 localities)

Ef =buckling strain (balanced cross-sections)

Ef =contractional faulting (balanced cross-sections)

Eps =pressure solution (43 localities)

The factors contributing to ET may vary according to lithology and position in the thrust sheet, examples are given below.

Orthoceras Limestone ET (Total natural strain)=

Eps -0.036 + Eb -0.25 + Ef -0.13 + Elps 0.0 = -0.416 = 34%

Upper Didymograptus Shale ET =

Eps -0.011 + Eb -0.25 + Ef -0.13 + Elps -0.025 = -0.416 = 34%

Lower ordovician ET =

Eps -0.025 + Eb -0.25 + Ef -0.13 + Elps -0.011 = -0.416 = 34%

Lower Silurian ET =

Eps -0.02 + Eb -0.185 + Ef -0.04 + Elps -0.056 = -0.306 = 26%

Upper Silurian ET =

Eps 0 (?) + Eb -0.160 + Ef 0 (?) + Elps -0.030 = -0.190 = 17.5%

CHAPTER 4

THE STRUCTURAL GEOLOGY OF RINGERIKE.

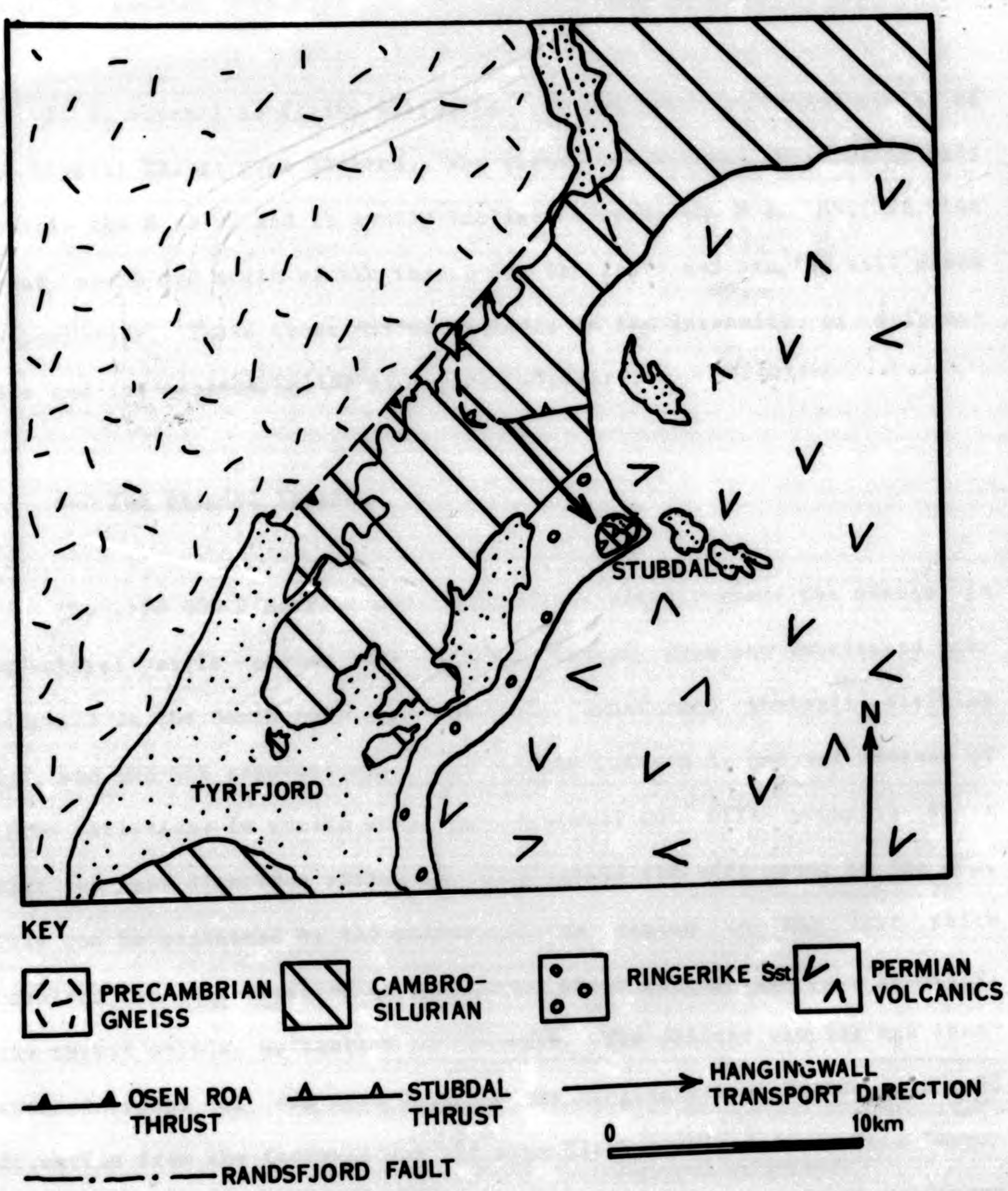
4.1 Introduction

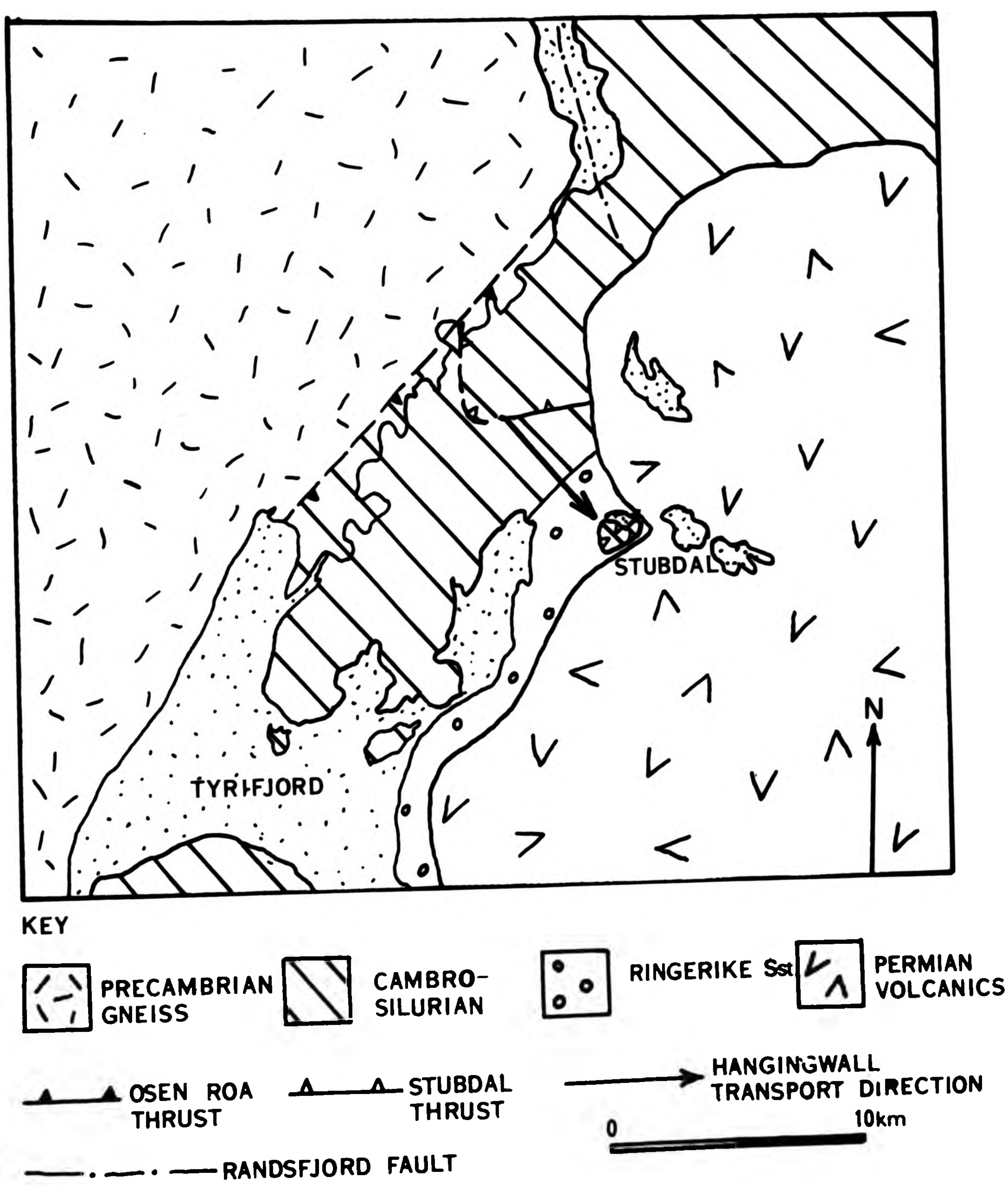
The outcrop of Cambro-Silurian rocks in Ringerike occupies a thin NNW-SSE trending strip tilted 10-20° to the ESE (see the 1:50 000 and 1:12 000 Ringerike maps, Appendix 2). The Cambro-Silurian strip is separated from the Precambrian basement to the WNW by the Osen-Roa Detachment and is overlain with an angular unconformity by Permian sediments and lavas to the ESE (see Fig.4.1). At Honerud, a Permian plug is found intruding into Cambro-Ordovician rocks and minor Permian intrusions are also abundant, frequently following Caledonian structures and trends.

Thick glacial deposits cover much of the area especially on the WNW side of the Cambro-Silurian strip where weak Cambro-Ordovician rocks have been eroded and buried under the thick outwash sands. These sands have made the Ringsaker area famous for its glass blowing industry. Where glacial sands are absent the Cambro-Ordovician forms good farm land, so that only the upper Ordovician-Silurian forms areas of substantial outcrop.

Stormer (1942) found mid-Ordovician shales resting on top of the Silurian Ringerike Sandstone at Stubdal. He regarded the tectonic position of the shales as representing a large recumbent fold of Ordovician and Silurian rocks resting on top of Ringerike Sandstone, Strand (1972) agreed with this interpretation. However, the shales have probably been emplaced by a large thrust (here called the Stubdal Thrust) which must have transported these shales at least 2.5km towards the SSE.

Fig.4.1 Generalied geological map of the Ringerike district.


STUBDAL
TYRIFJORD
N
KEY
PRECAMBRIAN GNEISS
CAMBRO-SILURIAN
RINGERIKE Sst
PERMIAN VOLCANICS
OSEN ROA THRUST
STUBDAL THRUST
HANGINGWALL TRANSPORT DIRECTION
0
10km
RANDSFJORD FAULT


STUBDAL
TYRIFJORD
N
KEY
PRECAMBRIAN GNEISS
CAMBRO-SILURIAN
RINGERIKE Sst
PERMIAN VOLCANICS
OSEN ROA THRUST
STUBDAL THRUST
HANGINGWALL TRANSPORT DIRECTION
0
10km
RANDSFJORD FAULT

This fault is a very important structure because it influences the deformation style of region. The obvious continuation of the Stubdal Thrust in the main Cambro-Silurian strip of Ringerike is the thrust found just south of Klekken (See 1:12 000 and 1:50 000 Ringerike maps, Appendix 2).

It is natural to divide Ringerike into two parts north and south of the Stubdal Thrust near Klekken. The thrust transported the hanging wall towards the S to SE and is gently inclined towards the N to NW, so the areas south and north of the thrust are the foot- and hanging wall areas respectively. These areas differ markedly in the intensity of deformation and the orientation of structural elements.

4.2 The Stubdal Thrust.

The 1:50 000 Ringerike map (Appendix 2) clearly shows the change in structural style across the Stubdal Thrust, from the imbricated hangingwall in the north into the relatively undeformed footwall striking E-W and NNE-SSW respectively. The outcrop pattern is unusual because of these variations in strike which show footwall cut offs younging in a west to east direction whilst the hangingwall cut offs young to the NNE. This can be explained by the tilting of the region to the east which resulted in the rotation of the thrust which has oblique ramp geometry, the thrust cutting up section to the east. The oblique ramping has transported rocks of 4aa age, found in the hangingwall at Stubdal, in a SE direction from the footwall cut off near Klekken (Fig.4.1). This movement direction is about 20° to the east of the regional transport direction.

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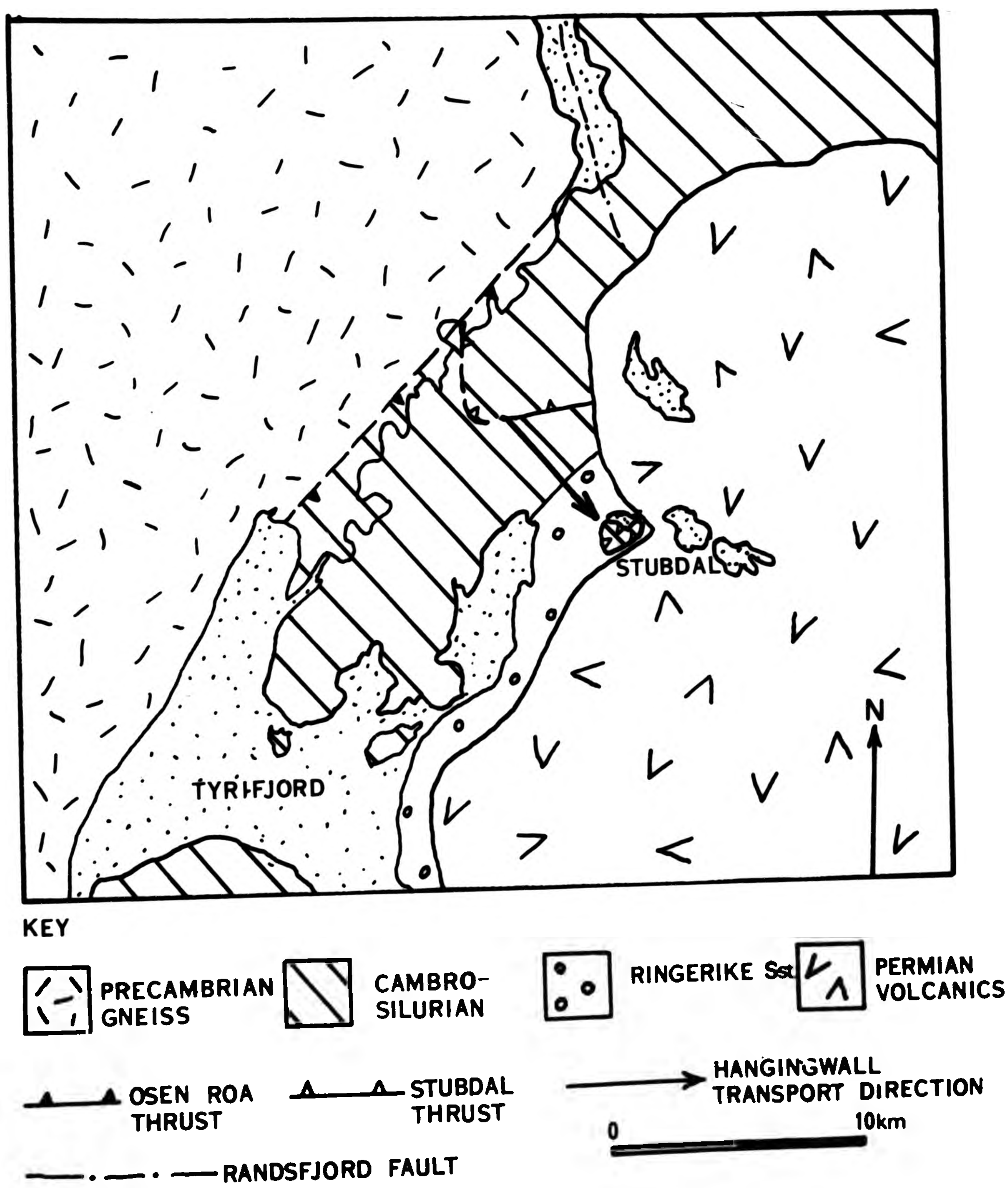
STUBDAL
TYRIFJORD
N
KEY
PRECAMBRIAN GNEISS
CAMBRO-SILURIAN
RINGERIKE Sst
PERMIAN VOLCANICS
OSEN ROA THRUST
STUBDAL THRUST
HANGINGWALL TRANSPORT DIRECTION
0
10km
RANDSFJORD FAULT

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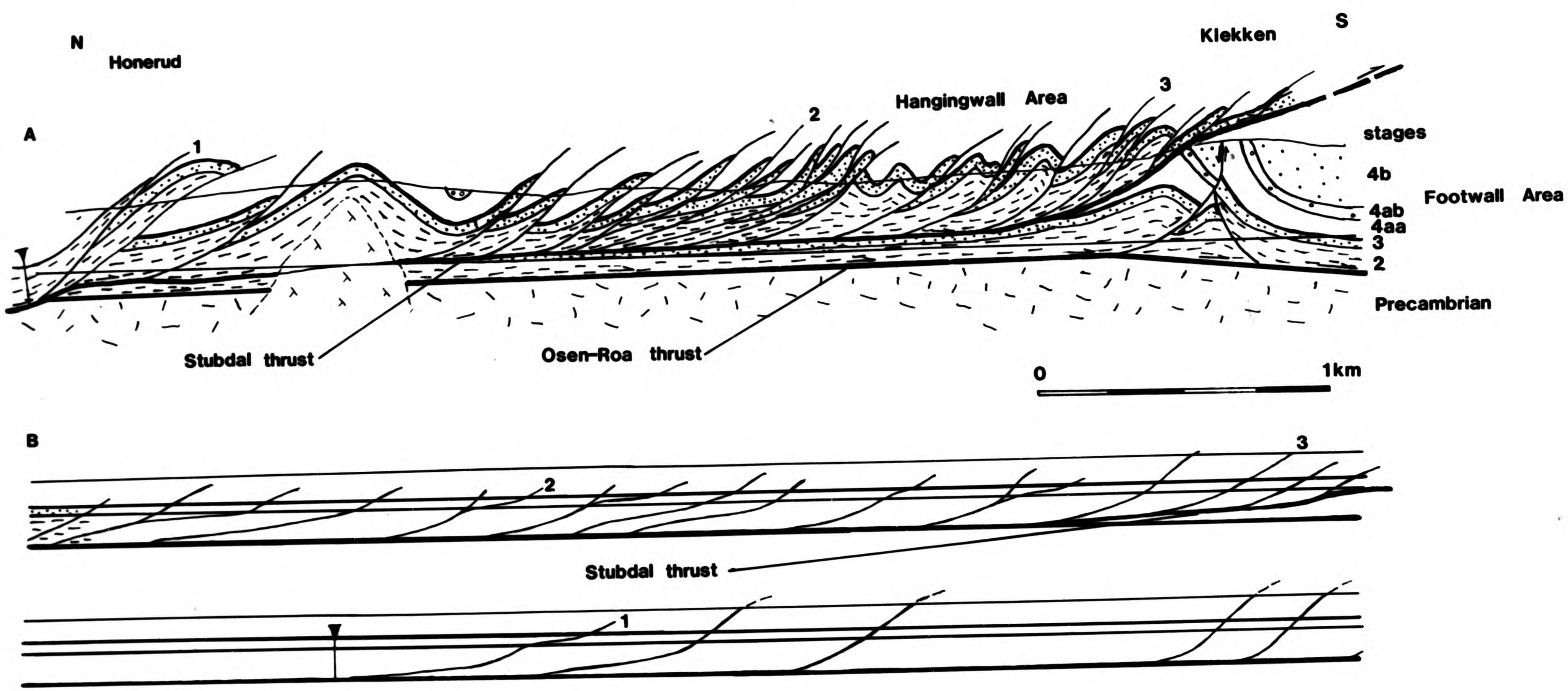
Fig.4.2 <u>A balanced section through the hangingwall area from Klekken (G.R. 735 070) to Auren (733 729).</u>


A
N
Honerud
1
2
Hangingwall Area
3
Klekken
S
stages
4b
4ab
4aa
3
2
Footwall Area
Precambrian
Stubdal thrust
Osen-Roa thrust
0
1km
B
2
3
Stubdal thrust
1

To balance the section through the area (Fig.4.2) the rocks below the 4aa shales must swing around to a more E-W orientation and form a flat below the Stubdal Thrust, in order to maintain the correct stratigraphic separation. It can be seen that the strikes of the footwall rocks do begin to swing towards this direction approaching the thrust. The length of the flat must match the 2.5km separation of the 4aa Shales in the foot- and hanging- wall blocks. This results in a thrust geometry of a flat or gently dipping ramp in the footwall of about 2.5km length, in the sequence from Alum shales to Orthoceras Limestone.

4.3 The hangingwall area.

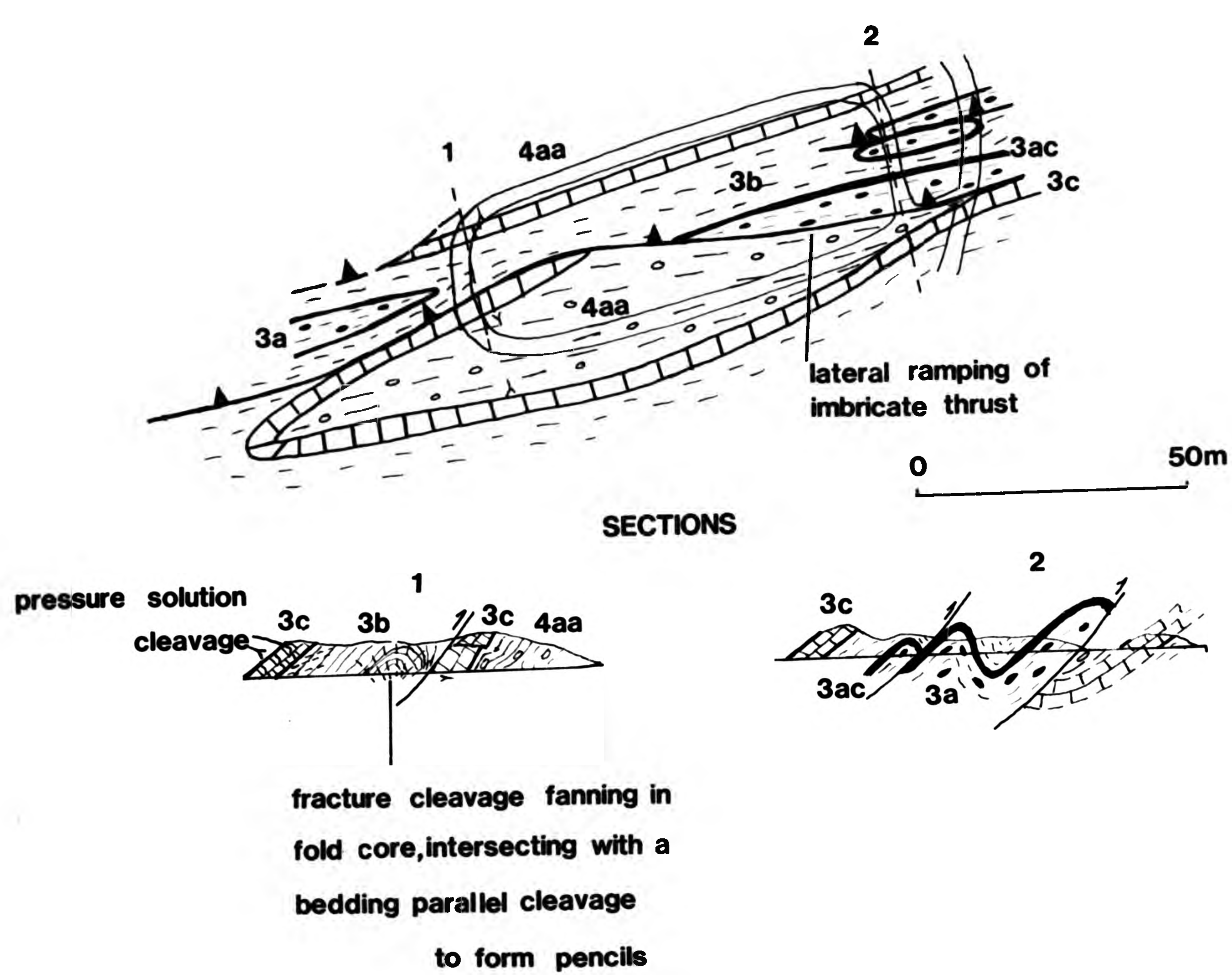
4.3.1 Introduction

The hangingwall area (see 1:12 000 Ringerike map, Appendix 2) is best exposed in the Haug and Klekken areas. Elsewhere exposure is often very poor and interpretations of the outcrop patterns are, more than ever, largely a matter of style. Even this is difficult because the better exposed areas display complex imbricate thrusting of a fairly intense nature.

The rocks in the hangingwall are of Cambro-mid Ordovician age and are almost entirely of 2a-4aa age except for a few exposures of the Ampyx Limestone (4ab). The main marker horizon is the Orthoceras Limestone (and occasionally the Ceratopyge Limestone) which is repeated by imbrication and a small amount of buckle folding.

The hangingwall sequence youngs towards the NE and is tilted eastwards by 10-20°, the structural style is similar to that found in

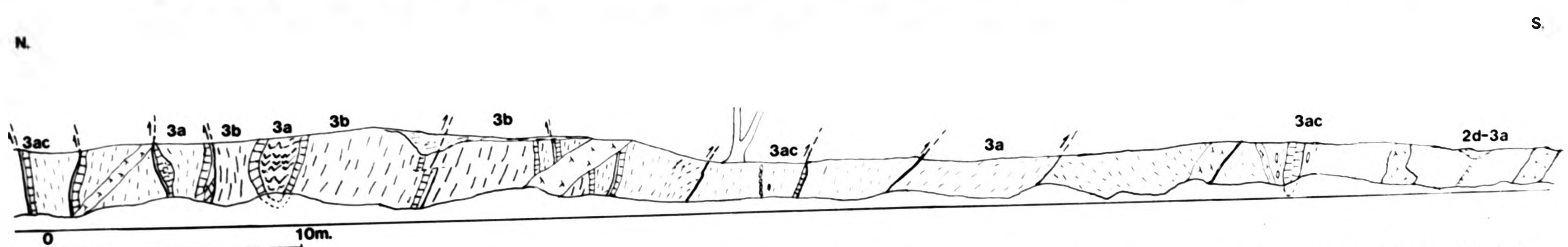
Fig.4.3 Geological sketch map showing details of imbricate thrusting, Haug (G.R. 734 718).



2
1
4aa
3ac
3b
3c
4aa
3a
lateral ramping of
imbricate thrust
0
50m
SECTIONS
1
pressure solution
cleavage
3c
3b
3c
4aa
fracture cleavage fanning in
fold core, intersecting with a
bedding parallel cleavage
to form pencils
2
3c
3ac
3a

Fig.4.4 Road section between Haug and Klekken (G.R. 734 710) displaying imbricated Cambro-lower Ordovician beds.

ROAD SECTION BETWEEN HAUG AND KLEKKEN THROUGH IMBRICATED CAMBRO-LOWER ORDOVICIAN BEDS (G.R. 734 710).



The section shows imbricate thrusts oversteepened by subsequent thrusting and squeezing of the shales laterally and vertically, which sometimes produce steeply plunging folds.

North Hadeland. However there the rocks young towards the NW and are tilted about 35° to the west. These differences are explained here by movement along the Permian, Randsfjord fault which separates the Ringerike and Hadeland areas.

4.3.2 <u>Structural style.</u>

A N-S section through the area (Fig.4.2) displays the highly imbricated style of the hangingwall area. Most of the folds are interpreted as thrust cut tip line folds which show footwall syncline and hangingwall anticline geometries. A few isolated buckle folds are present but even some of these may be unfaulted tip line folds.

Second order thrusts form hinterland dipping imbricate structures, spaced on average every 180m (unstrained every 360m), with an average displacement along the fault planes of 158m and a maximum throw of 450m. The imbricate thrusts frequently splay and display lateral, oblique and frontal ramps. Fig.4.3 shows a detailed sketch map of such an area in Haug where an imbricate thrust cuts down section along two lateral ramps of opposing dip.

In the Cambro-lower Ordovician beds complex, intense imbricate structures are present. The shales are frequently asymmetrical, disharmonically folded and appear to be locally squeezed from one area (probably synclines) into another (frequently close to thrusts). Fig.4.4 shows a road section near Klekken, through the Cambro-lower Ordovician where the Ceratopyge Limestone has been repeated by thrusts and then subsequently rotated into their present steep positions. Squeezing of the shales has rotated fold hinges into steeply plunging orientations, eg in Fig.4.4 one fold is plunging 53° to the WSW, when the regional dip is

10-20° to the ENE. Post or syn-imbrication squeezing has also folded imbricate thrusts and locally transported and folded slices of Ceratopyge Limestone.

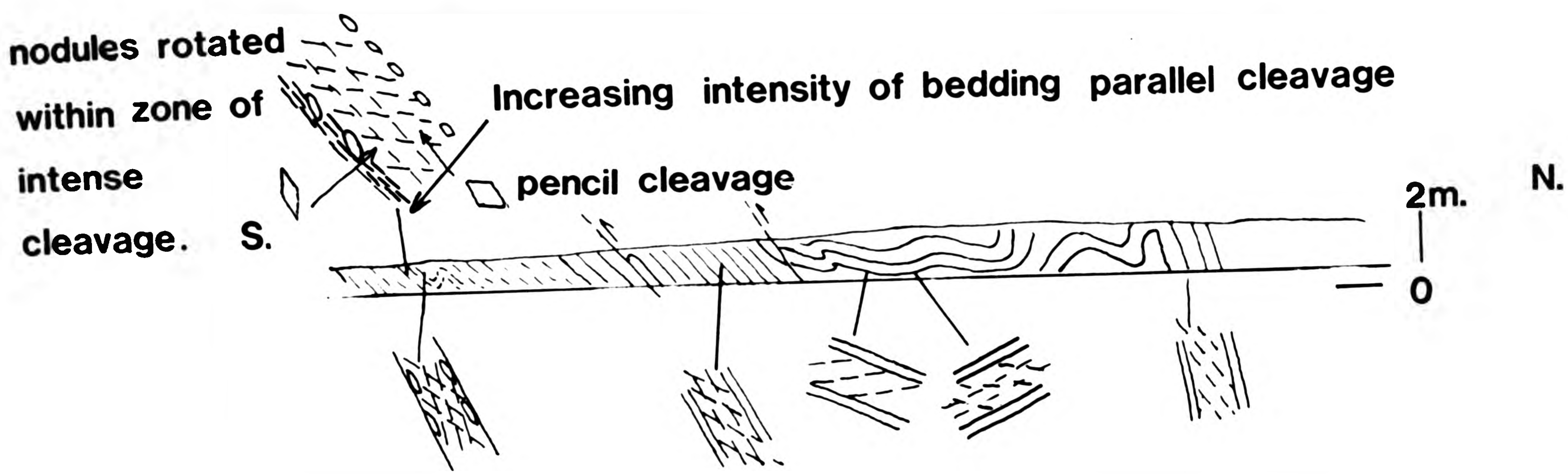
The folds in the Orthoceras Limestone display wavelengths of 40-200m and amplitudes of 40-140m. They are symmetrical to inclined with interlimb angles of 45-95°. The fold axes are frequently vertical but may be inclined up to 75° to the N. These are similar dimensions to those found elsewhere in the Oslo region

4.3.4 <u>Cleavage</u>

There is pressure-solution, fracture, pencil and slaty cleavage present in the hangingwall area. In the Cambrian shales most fabrics are folded, intensified, bedding parallel fabrics, whilst in the other shale units fracture, pencil and slaty cleavage are common. Pressure-solution cleavage is largely confined to limestones and highly deformed Cambrian shales.

Pressure-solution cleavage ranges from stylolitic to anastamosing seams and is mainly found in the Orthoceras Limestone. It is an early formed cleavage developed at about 90° to bedding, parallel to the regional strike and subsequently folded along with bedding. Pressure-solution probably does not contribute greatly to total shortening within the region.

Fig.4.5 Folded cleavage in Upper Didymograptus Shale and Ampyx Limestone, in a road section north of Auren (G.R. 738 732).



The pencil cleavage is formed by the intersection of a bedding parallel cleavage and a foreland dipping cleavage, both cleavages have been subsequently folded.

Frequently pencil cleavage is developed in the hangingwall area. Quite often it is found adjacent to imbricate faults and is always formed by the intersection of an intensified bedding parallel fabric and a cleavage formed at an angle to bedding. When pencil cleavage is adjacent to imbricate faults the cleavage at an angle to bedding is inclined parallel or sub-parallel to the thrust plane and was probably generated in the tip line region of the second and third order thrusts (see Chapter 3).

The bedding parallel fabric changes in intensity in the shales (see Fig.4.5). When it forms intense zones, nodules can be rotated within them and pencil cross-sections approaching these zones become increasingly flattened, parallel to cleavage. Bedding parallel flexural slip due to folding may be important in the bedding- parallel cleavage development, where the increasing intensity of cleavage reflects increasing amounts of slip in the horizon concerned. Alternatively bedding parallel shear during imbrication might be involved. A combination of simple shear involving the mechanisms mentioned above and by volume loss caused by increased confining pressure (perhaps by loading from higher thrusts or syn-orogenic sedimentation) might have produced this bedding parallel cleavage.

Frequently a cleavage which is inclined towards the hinterland (when the beds are restored to horizontal) is developed in the 4aa shales, forming the second cleavage in some pencils. As the pencils are modified by the later flexural slip, bedding-parallel cleavage, this hinterland dipping cleavage must be formed relatively early. The origins of this cleavage are discussed in Chapter 5.

Fracture cleavage is developed in some folds at approximately right angles to bedding where it can be seen to fan away from the fold core (see Fig.4.3.). It displays similar orientations to the pressure solution cleavage found in limestones and is also a relatively early, subsequently folded, cleavage.

4.3.5 A balanced cross-section through the hangingwall area.

The section (Fig.4.2) shows that for the Cambro-mid Ordovician in the hangingwall area shortening (e)= 50% along the line of section. To the 50% shortening in the hangingwall area must be added the amount of overthrusting on the Stubdal Thrust which represents a further 50% shortening of 5km (unstrained) length of Cambro-Silurian at right angles to the transport direction.

4.4 The footwall area.

The footwall area of Ringerike has been mapped by Kiaer (1908) and Owen (pers comm) who mapped the Silurian and Cambro-Ordovician respectively. The exposure of the Cambro-Ordovician is very poor, especially towards the older rocks, but is quite good for the Silurian.

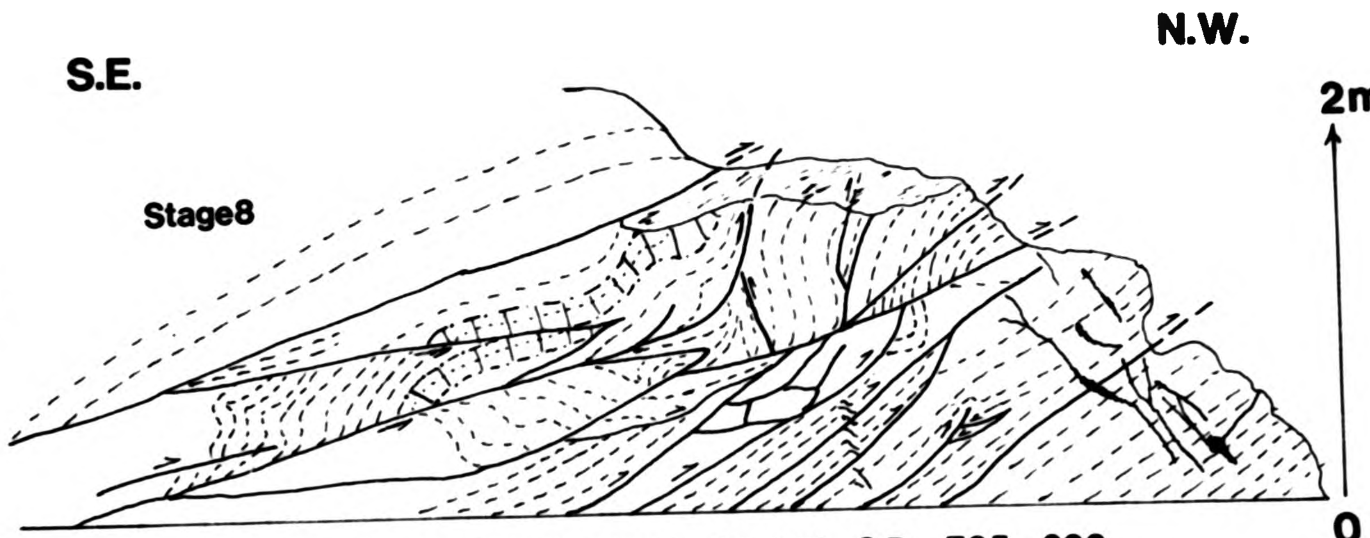
Deformation in the area increases southwards but is seen to be no more intense than gentle folds in the Silurian. The beds swing around from a NE-SW to a N-S and back to a NE-SW strike progressing southwards. Folding begins to appear in southern Ringerike and eventually the bedding strikes approach a WSW-ENE direction. In the SE part of the area the Ringerike Sandstone can be seen along an 8km road section on the west side of Tyrifjord where it is folded into two broad anticlines and two synclines. At Nes the most southerly anticline exposes Silurian in its core.

The folding of the Ringerike Sandstone, which may be 800m or more thick in this area, is gentle because the unit is so thick and competent. The broad folds have wavelengths of about 4000m and amplitudes of about 900m. Interlimb angles range from 120-145° as fold limbs tend to dip at about 20°, though steeper dips of 40-50° can be found towards the base of the sandstone near the marine-continental transition.

Deformation in the rest of the Silurian is weak and involves mainly broad folding on a variety of scales, and a small amount of minor thrusting, probably related to buckle folding. There also is some late minor thrusting (frequently backthrusts) which displace folded rocks (Fig.4.6). The difference in deformation amount and style between the hanging- and footwall areas can be seen by comparing the orientation of bedding for

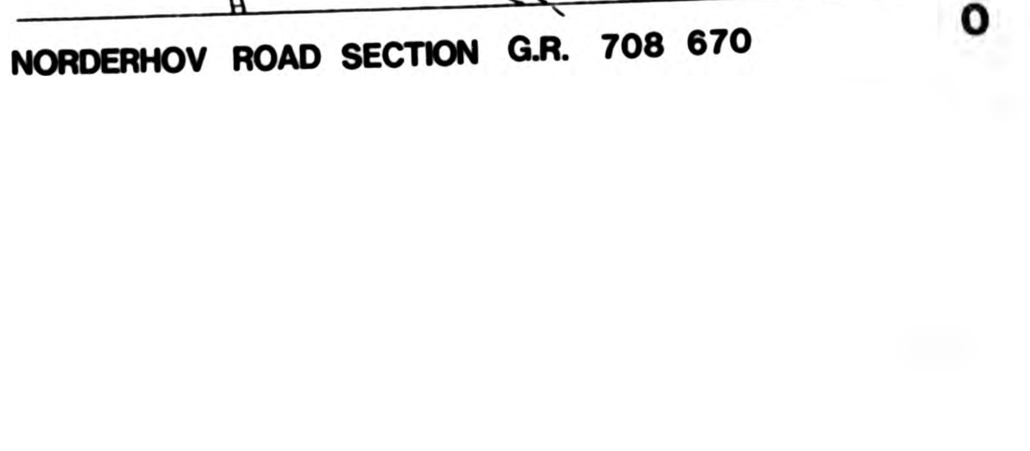
Fig.4.6 Examples of minor backthrusts (syn- or post- folding) in the footwall area of Ringerike.

A



E68 ROAD SECTION SOUTH OF VIK G.R. 725 606

B



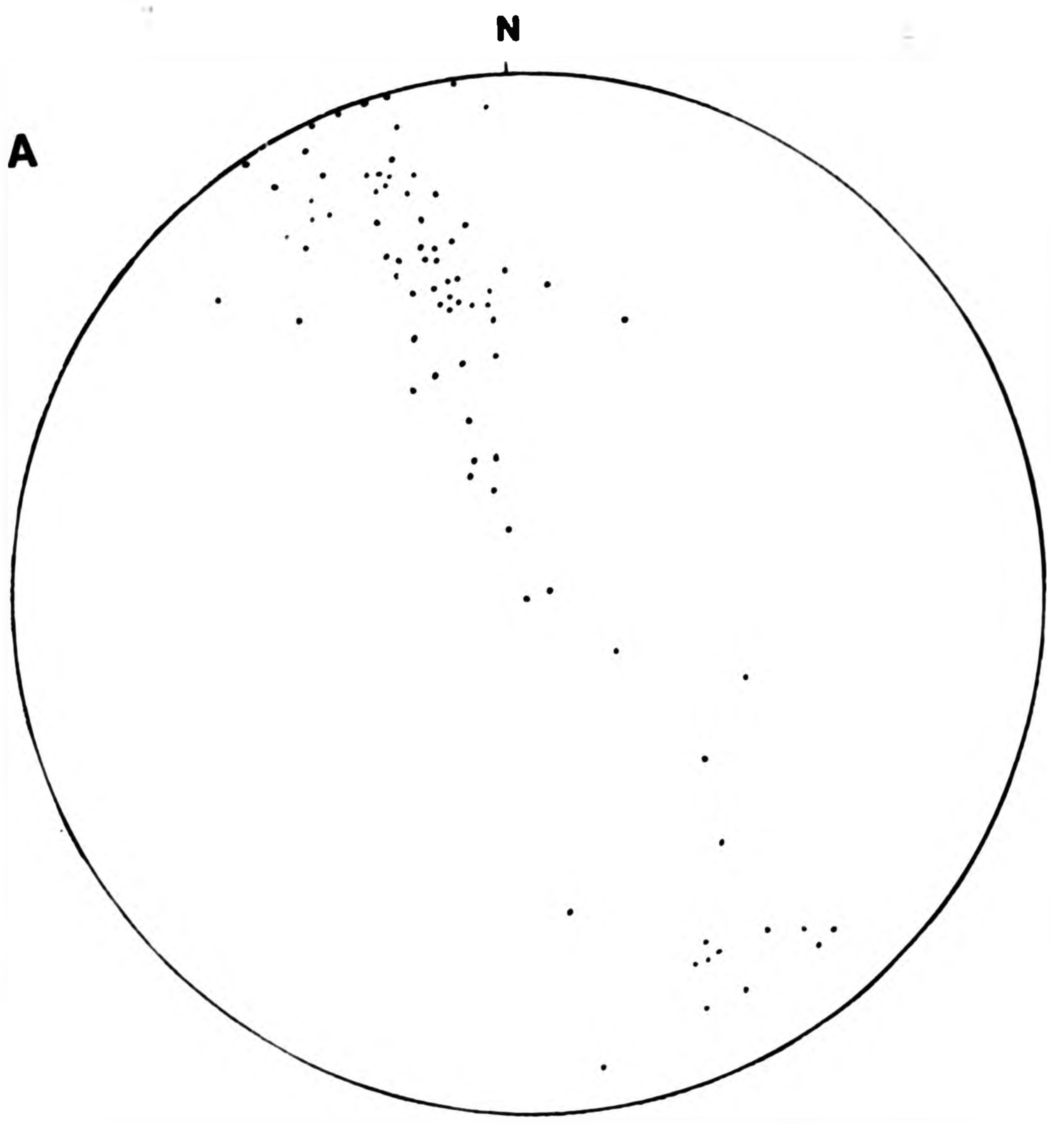
NORDERHOV ROAD SECTION G.R. 708 670

Fig.4.7 <u>Poles to bedding for the Ringerike area (Wulff net).</u>

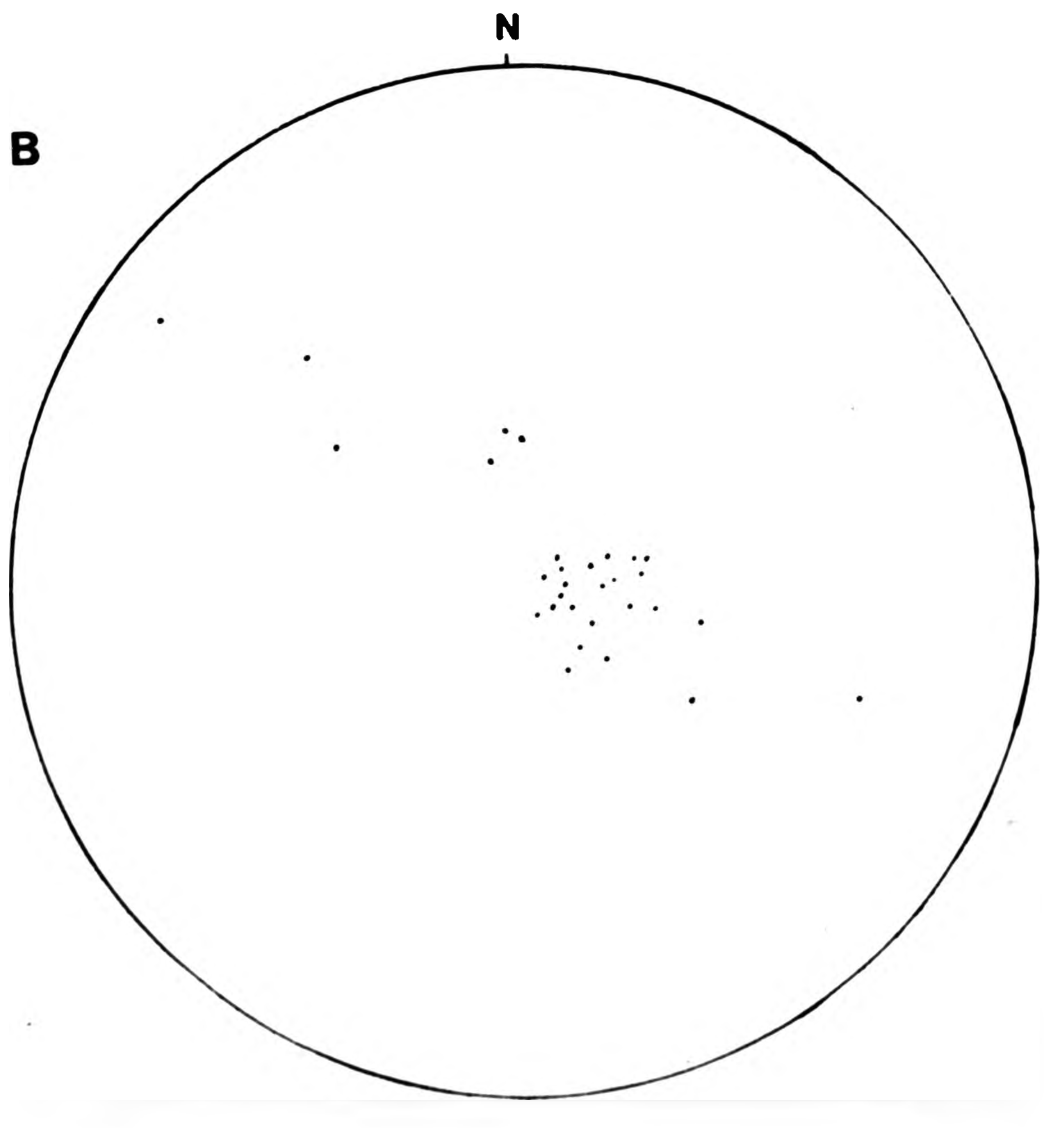
Fig.4.7A Hangingwall area

Fig.4.7B Footwall area

A



B



the two areas (see Fig.4.7). The figure shows that the poles to bedding for the hangingwall area cluster at a steep dip to the SSW, whilst the poles for the footwall area cluster at a low dip to the NW and W.

Shortening (e) in the southern part of the footwall area ranges from 10-15%.

4.5 Conclusions and discussion.

There is little deformation in the footwall area, although deformation begins to increase again towards the S. To the N in Hadeland, shortening (e) is up to 60%, to the south in Asker-Baerum it is up to 37% and in the hangingwall area in Ringerike it is about 50%. So why is there so little shortening in the footwall area of Ringerike ?

It seems most likely that the amount of regional shortening has been maintained by displacement along one thrust, ie. the Stubdal Thrust, instead of along many smaller imbricate thrusts. The footwall has remained "protected" from deformation by the shortening being taken up above it. In contractional deformation the stratigraphy is thickened and raised vertically in addition to shortening horizontally. The presence locally of an extra 1.5km of straigraphy, in the case of the Stubdal Thrust, would therefore have resulted in extra energy being expended in order to raise the thickened footwall stratigraphy vertically during shortening. Perhaps the footwall sequence remained relatively undeformed for this mechanical reason and extra shortening was achieved elsewhere to compensate.

The footwall area might also have remained undeformed because of smooth slip (Elliott and Johnson 1980) along the sole fault. It is difficult to see why, in the Oslo region where the sole thrust is always within the Alum Shales, only one area would undergo smooth slip. Perhaps it was related to the extra overburden of the rocks above the Stubdal Thrust; Gretener (1981) shows where likely overpressuring of pore waters, facilitating easy slip is likely to occur. Such a position is under a tectonically thickened sequence, so the hangingwall rocks of the Stubdal Thrust might have caused local over pressuring of the footwall area and allowed relatively friction free slip just in that area.

The Stubdal Thrust is unique in the Oslo region because of the large amount of displacement along it. There are, however, other second order thrusts in the region with unusually large displacements relative to other thrusts in the area, (see Chapters 3 and 6). Imbrication shortens and raises a sequence of rock vertically above regional height more efficiently than a single, larger thrust can do the same amount of work (Boyer 1978, unpub. thesis). It would therefore seem that an increase in propogation rate was necessary to produce the Stubdal Thrust whether a stick-slip or perturbation model is invoked to initiate ramping.

For example in the perturbation model of Knipe (in prep) it is suggested that the speed of displacement on the sole thrust and the confining pressures, constrain the amount displacement along imbricates that are formed when the main detachment hits a perturbation during propogation. This causes faulting or ramping to get around the obstruction. A slowly propogating master detachment on encountering a perturbation may first result in deformation by folding. Later the folds may be displaced by a thrust which may slow, die out and become abandoned. Therefore the detachment continues in its original horizon and repeats the process. Eventually the propogation rate might be increased or the stratigraphy thins or changes lithology so that the thrust attains a propogation rate fast enough to allow the main detachment to successfully ramp up and abandon its original horizon for a higher one.

Despite the variations in deformation styles in the Ringerike area which appear to be due to the Stubdal Thrust, the shortening (e) across the district from NNW-SSE averages about 54%. The most significant con- tibutions to shortening coming from the imbrication in the hangingwall area and the repetition of stratigraphy by the Stubdal Thrust. It is unknown whether the hanging wall sequence around Stubdal was imbricated, if it was then this is a minimum estimate of shortening.

CHAPTER 5

THE STRUCTURAL GEOLOGY OF HADELAND.

5.1 Introduction.

This chapter is divided into two parts. The first part describes the structural geology of the Cambro-mid Ordovician of North Hadeland mapped by myself, whilst the second part describes the structural geology of the mid Ordovician-Silurian rocks of Central and South Hadeland (mapped by Owen 1977) and the variations in the structural style within Hadeland.

The 1:100 000 geological map of Hadeland by Holtendahl and Schetelig (1923) is of a scale that could not possibly reflect the intensity of thrust repetitions of the Cambro-mid Ordovician, best marked by the repeated ridges of Orthoceras Limestone. It was therefore necessary to map the area at 1:5000. A 1:12000 map of this area (North Hadeland) and a 1:50 000 compilation map of Hadeland are contained in Appendix 2.

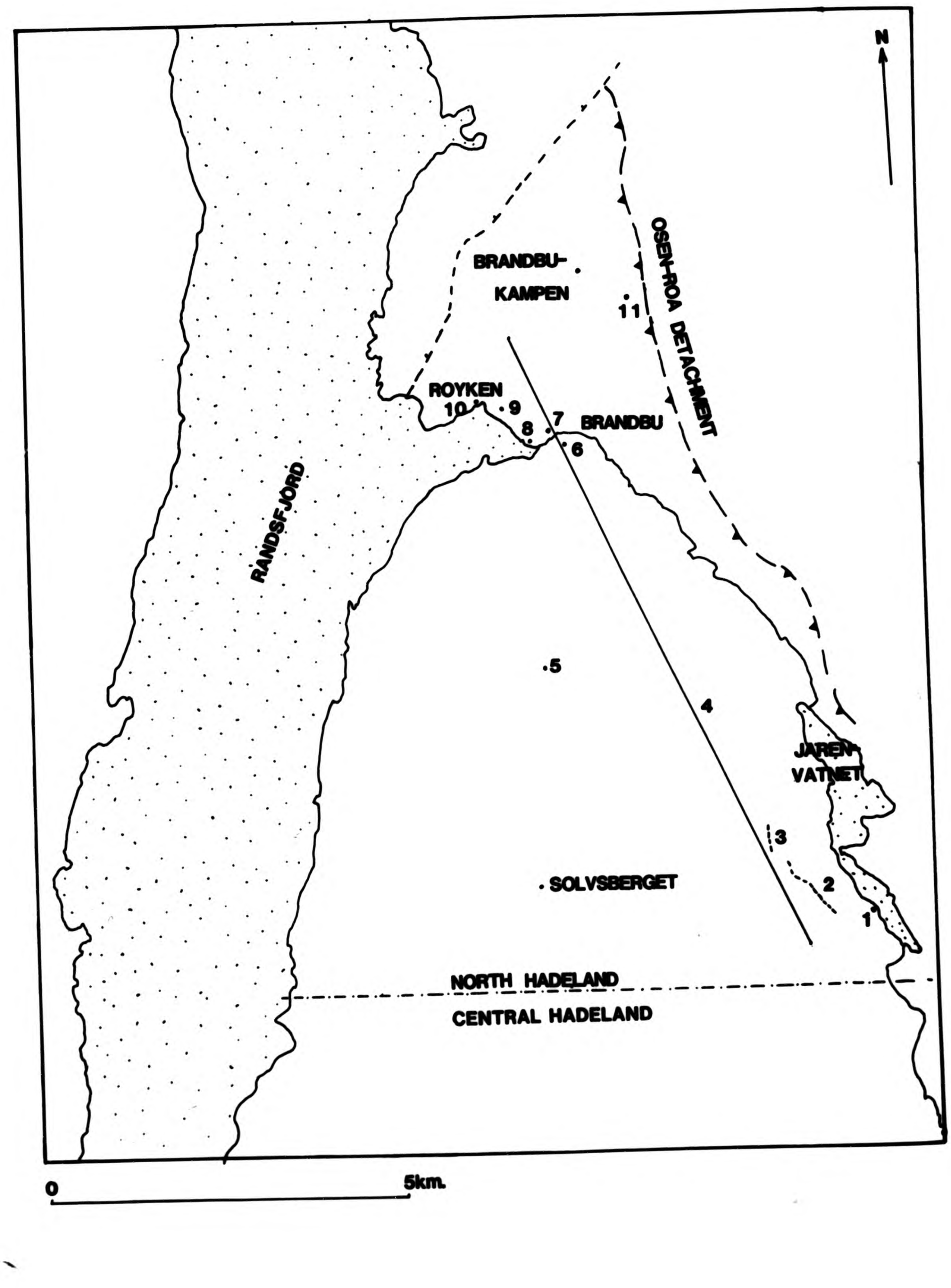
Numerous Permian intrusions penetrate the Cambro-Silurian and include two eroded volcanic plugs which form the dominant hills of Solvsberget and Brandbukampen. These plugs coincide with the southern and northern boundaries of the North Hadeland area (Fig.5:1). Dykes, some of which radiate out from the volcanic plugs, are very common and frequently follow Caledonian thrust planes and fold axes.

Exposure is frequently limited because of the cover of boulder clay. This is especially so in the western part of the area, south of Royken, where no exposure of the Cambro-Silurian was found.

Fig.5.1 <u>Location map for North Hadeland</u>

The numbered localities are as follows:

1. Jarenvalnet	Fig.5.2
2. Hjertebo to Helgaker	Fig.5.5
3. Helgaker path section	Fig.5.3
4. Rossum to Granasen section	Fig.5.4
5. Road no.35, Grindaker	Fig.5.8
6. Road section	Fig.5.3
7. Railway bridge	Fig.5.3
8. Abandoned railway line	Plate 15 (Appendix 1)
9. Road no.35, Royken	Fig.5.8
10. Old factory, Royken	Plate 5.1
11. Road section between Brandbu and Bleiker	Fig.5.2


N
BRANDBU-
KAMPEN
11
OSEN-ROA DETACHMENT
ROYKEN
10
9
8
7
BRANDBU
6
RANDSFJORD
5
4
JAREN-
VATNET
3
2
1
SOLVSBERGET
NORTH HADELAND
CENTRAL HADELAND
0
5km.

5.2 North Hadeland.

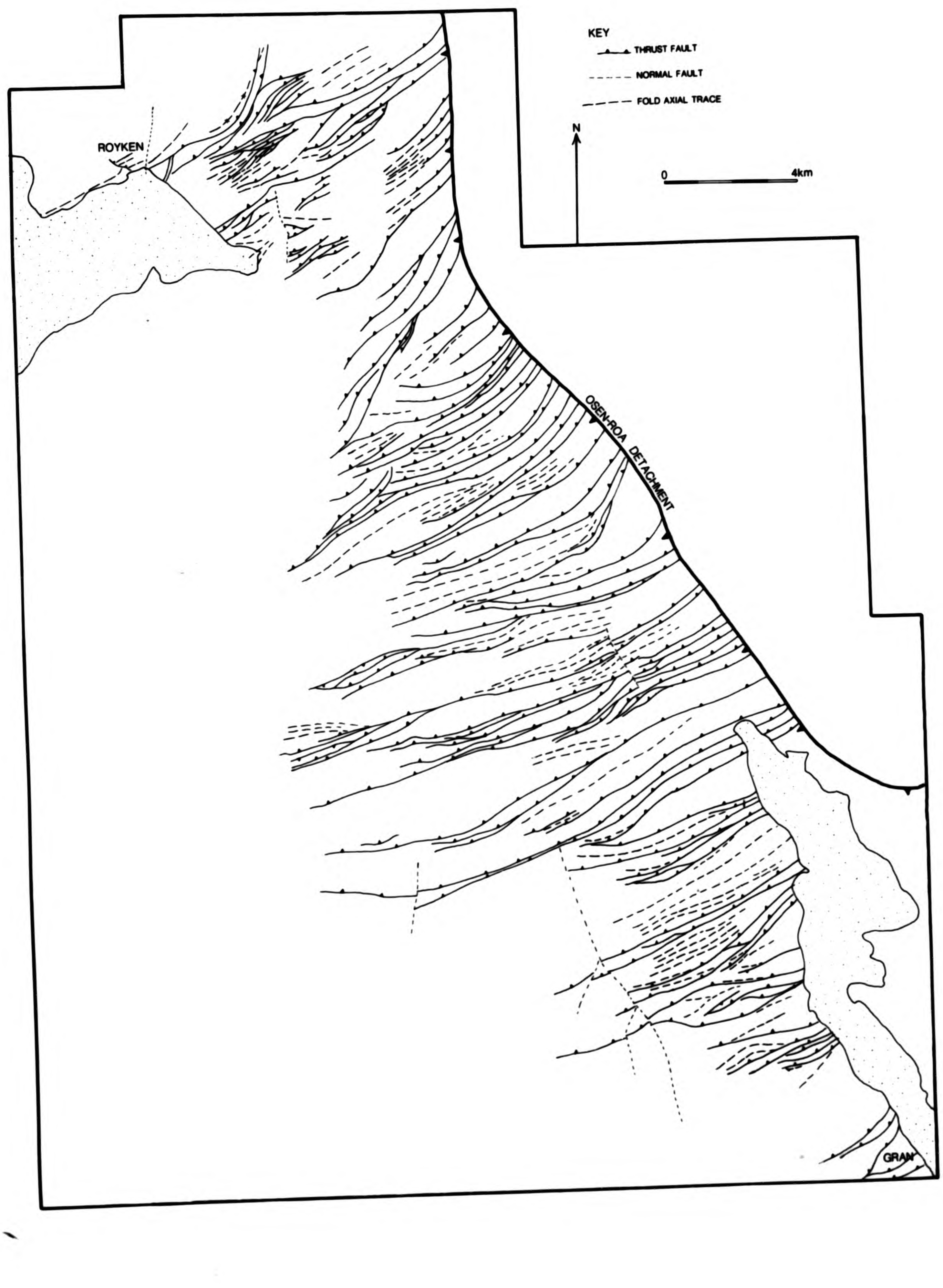
5.2.1 The effect of lithology on structural style.

It can be seen from the stratigraphy of North Hadeland described in Chapter 2, that in the Cambro-mid Ordovician there are only two thin limestone units within a dominantly shale and shale with limestone sequence. The total stratigraphic thickness is in excess of 300m. Of the two limestone units only the Orthoceras Limestone consistently forms good exposures and topographic ridges that can be used to determine the structure of the area. The Ceratopyge Limestone is only useful as a marker horizon in the eastern side of the area, in places of good exposure. As in the Oslo area the orthoconic nautiloids present in the limestones are useful way up indicators.

As the two limestone units comprise less than 3% of the total thickness of the Cambro-Ordovician up to the top of the Kirkerud Group they could not have greatly influenced the style of deformation in this sequence. Instead they acted as passive marker horizons deforming with the shales and reveal the structural style of the area (see Fig.5.2).

About 80% of the good exposure (mainly in the road and railway cuttings) which displays insight into the deformation style is confined to the Orthoceras Limestone and those shales immediately above and below it. So although a good picture of deformation style within the Orthoceras Limestone can be built up, this gives an unavoidably biased picture centered around the only thick (7-9m) competent unit in the area. Therefore the most typical deformation remains unseen in the incompetent units.

Fig.5.2 <u>Structure map of the North Hadeland area.</u>


KEY
THRUST FAULT
NORMAL FAULT
FOLD AXIAL TRACE
N
0
4km
ROYKEN
OSEN-ROA DETACHMENT
GRAN

The Orthoceras and Ceratopyge Limestones behave as brittle, competent units, within the incompetent shales. The dominant mode of deformation was by imbricate thrusts fanning off the Osen-Roa Detachment. These thrusts have cut through earlier tip line folds to produce footwall synclines and hangingwall anticline structures, described in Chapter 3 (see Figs.3.4, 5.2 and 5.3). The second and third order faults in the limestone beds often die out into minor chevron folds and kink bands in the shales. So that generally minor brittle deformation in the limestone units changes to minor ductile folding in the shale units. On a smaller scale the Orthoceras Limestone has deformed by minor faulting, both normal and reverse (Fig.5.4) and by thrust wedging (Plate 5.1).

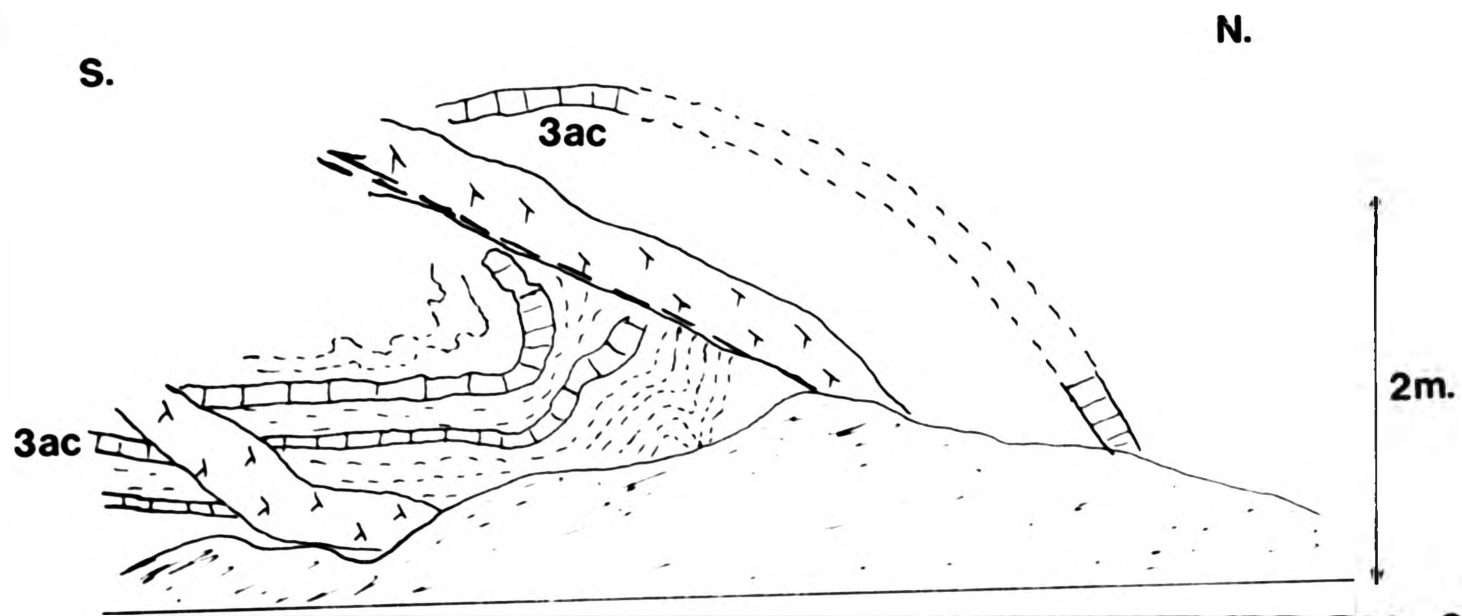
Frequently in anticlines wedge-shaped blocks up to 2m wide show minor conjugate fault movements (Fig.5.4a) within the limestone. These fractures are set up in massive limestone under similar conditions to those, where in bedded units, flexural slip would operate. The fracture sets form at about 60° to bedding and strike WSW-ENE.

Local extensional faults are often present, frequently with opposing dips to the contractional faults found in the same exposure (Fig.5.4c). No evidence has been found to date the relative ages of these sets of faults, but the similarity of the strike directions suggests that both sets of faults are of Caledonian age. The small displacements on the extensional faults (up to 5m) and the Caledonian strike directions indicates that these faults were probably developed in response to local stresses set up during imbrication and allowed bulk rotation of wedge shaped blocks. Similar strike-parallel extension by extension faulting, extensional fracturing and flow have been found in beds on fold limbs and adjacent to thrust faults in the Appalachians (Cloos 1951, Perry 1968, Perry and de Witt 1977).

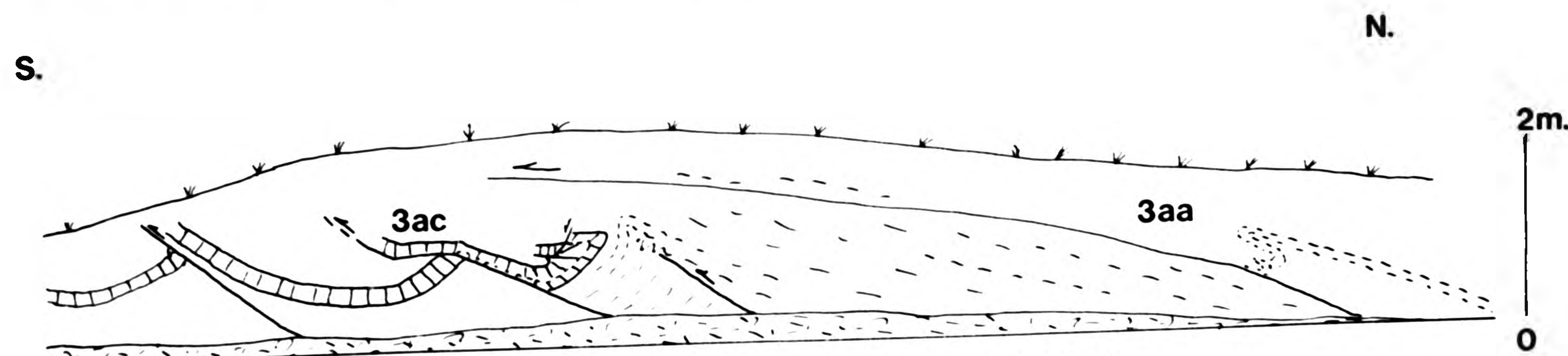
Fig. [illegible] Examples of deformation by thrusting in lower Ordovician

[illegible]

Fig.5.3 Examples of deformation by thrusting in lower Ordovician rocks.



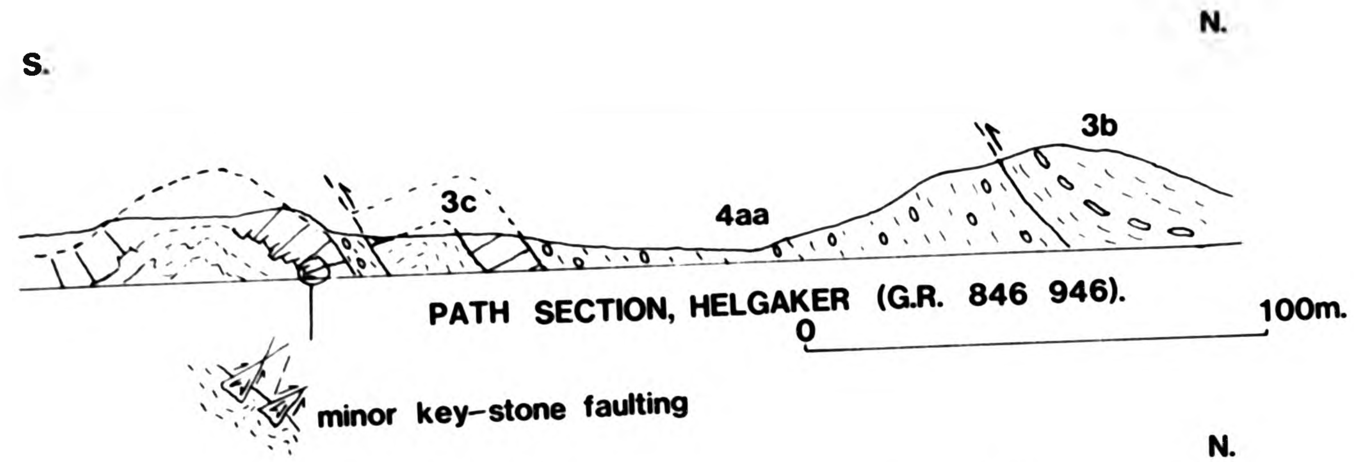
ROAD EXPOSURE ON THE WEST SIDE OF JARENVATNET (G.R. 862 936).



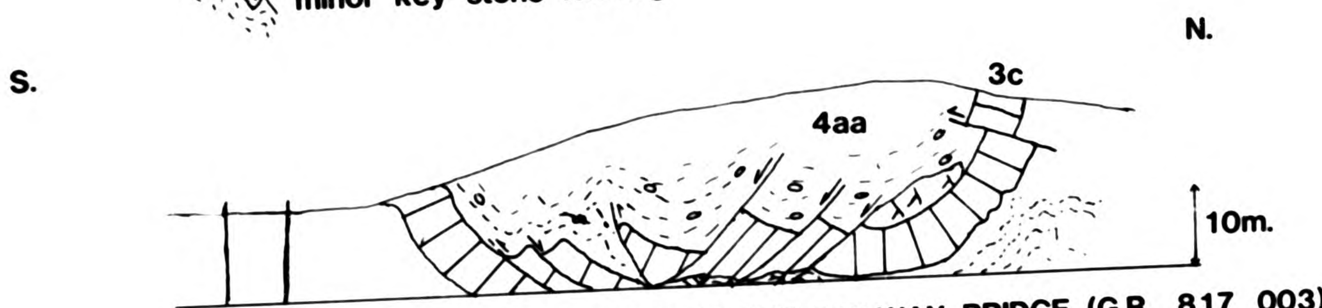
ROAD EXPOSURE BETWEEN BRANDBU AND BLEIKEN (G.R. 826 016).

Frequently footwall synclines are presen below second and third order thrusts.

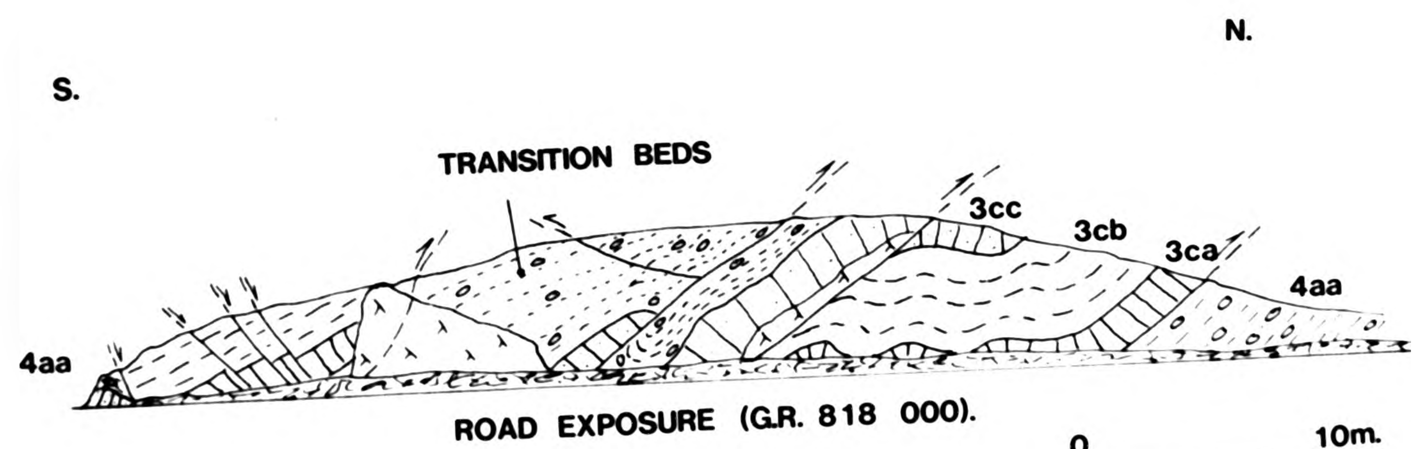
Fig.5.4 <u>Examples of deformation by folding, thrusting and normal faulting in the Orthoceras Limestone.</u>



PATH SECTION, HELGAKER (G.R. 846 946).



ROAD 35 EXPOSURE BY THE RAILWAY BRIDGE (G.R. 817 003).



ROAD EXPOSURE (G.R. 818 000).

Fig.5.5 <u>A balanced cross-section from Rossum to Granasen, North Hadeland, (see Appendix 3 for diagram).</u>

KEY

4aa Kirkerud Group

3c Orthoceras Limestone

3b Lower Didymograptus Shale

2a-3b Alum Shales and Ceratopyge Series

Osen-Roa Detachment

Precambrian basement

5.2.2 Structural elements.

Thrusts.

The density of imbricate thrusting in North Hadeland is very great. On average second order imbricate thrust faults are spaced every 140m (in restored sections every 330m). The average throw is 180m (ranging up to 300m) and of the total horizontal shortening about 50% is contributed by contractional faulting. The average strike lengths of the second order thrusts cannot be determined because of poor exposure and the consequent difficulties of tracing the thrusts into the Kirkerud Group. However the strike lengths probably in exceed 2km.

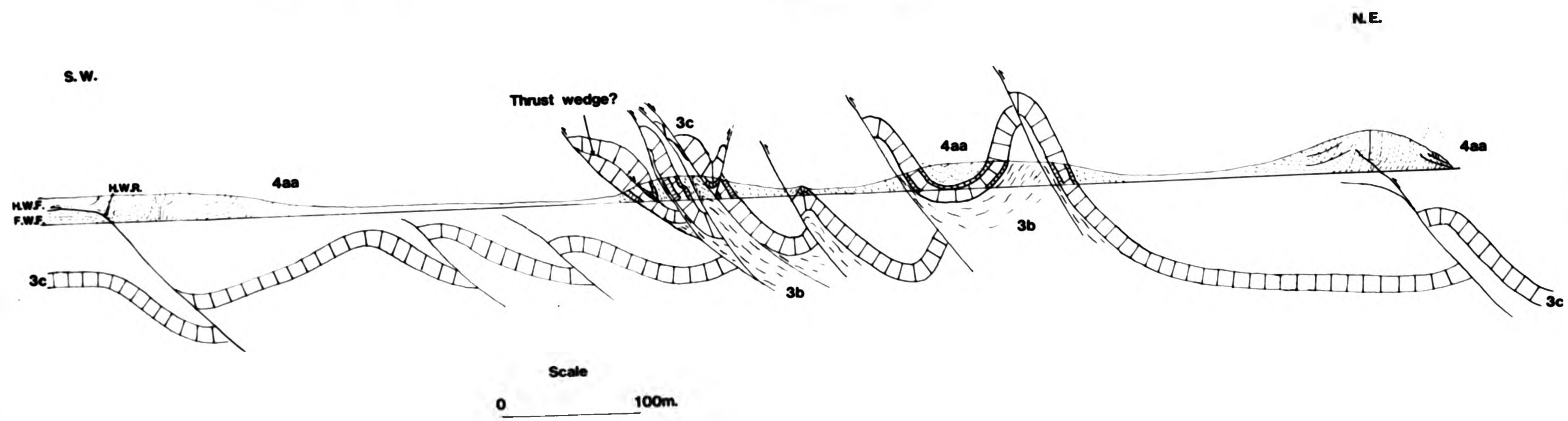
The cross-section through North Hadeland (Fig.5.5) shows just how dominant imbricate thrusting is in deforming the Cambro-mid Ordovician sequence. This style of thrusting continues into the Ringerike area (see Chapter 4) where it is present in the hangingwall area of the Stubdal Thrust. The same intensity of imbrication is not found south of the Stubdal Thrust.

On a smaller scale the imbrication is more complex. Figs.5.3 and 5.4 show details of thrusting; thrust-splays may repeat the Orthoceras Limestone with displacements up to 10m (Fig.5.6) and the occasional back-thrust is also present, but these are of small displacement and very infrequent.

Plate 5.1 Thrust wedging in Orthoceras Limestone, old factory, Royken.

Fig.5.6 Detailed road section demonstrating the structural style along the Gran to Tuv road between G.R. 854 935 and 844 943.

DETAILED ROAD SECTION DEMONSTRATING STRUCTURAL STYLE ALONG THE GRAN TO TUV ROAD BETWEEN G. R. 854 935 AND 884 943.



In several parts of Hadeland (eg.G.R. 010 830) there are individual hillocks and groups of small hills made up of Orthoceras Limestone repeated many times. Using the facing of the orthoconic nautiloid tests the vast majority of limestone slices young towards the hinterland. These slices are too numerous to be repeated in detail on the scale of the 1:12 000 map of North Hadeland (see Appendix 2). The limestone horses may be explained as the product of splays coming off a second order imbricate thrust which forms a "flat" parallel to bedding with the splays repeating the limestone and joining up to form a bedding parallel roof thrust above the limestone unit. However it is easier to explain this geometry as being caused by thrust wedging (Cloos 1961).

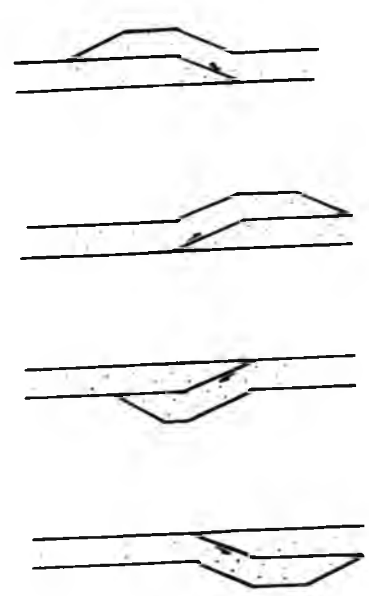
Thrust wedging in Hadeland can be seen frequently on a small scale within the Orthoceras Limestone (Plate 5.1), but it may also be present on a larger scale. The Orthoceras Limestone is the only notable competent unit in over 300m of shales. These shales could have taken up the early horizontal stresses by buckling and layer parallel thickening. The competent Orthoceras Limestone could not have deformed so easily in that manner; instead it probably fractured, locally forming thrust wedges (Fig 5.7). These may have formed a series of localised triangle and pop-up zones prior to the main deformation by imbrication.

The thrust-wedge piles could have been rotated by the later imbrication into their present orientations (Fig.5.7). The rotation of the fractures in individual wedges can produce apparent normal faults in outcrop. If an early thrust wedge moved with the sense of a backthrust and was subsequently rotated by movement on a hinterland dipping thrust, a ramp anticline formed by thrust wedging could appear in outcrop as a synform (Figs.5.6 and 5.7).

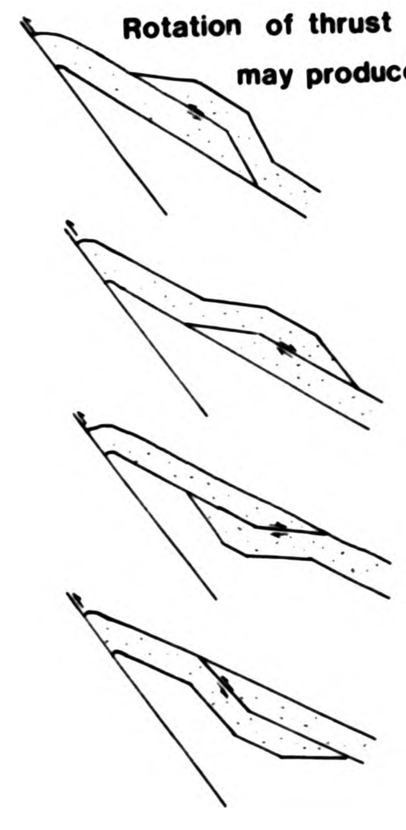
Fig.5.7 Some examples of thrust wedge geometry.

THRUST WEDGE GEOMETRY.

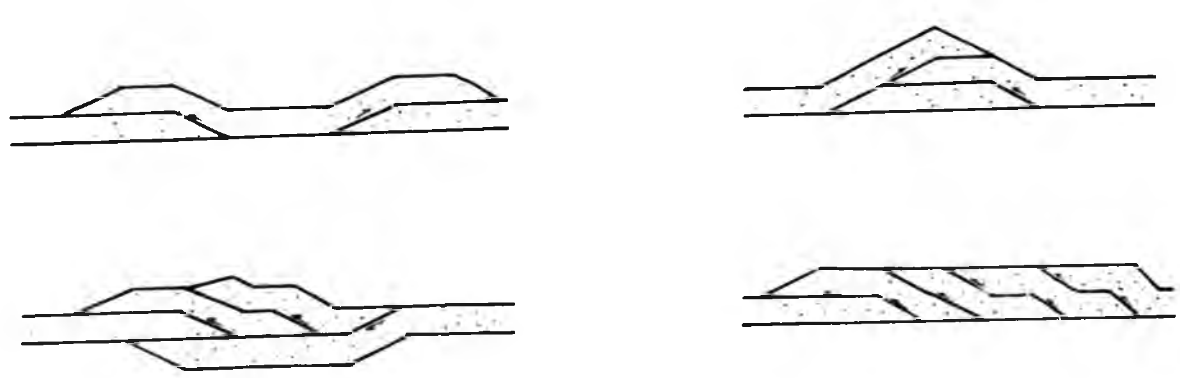
INDIVIDUAL THRUST WEDGES



Rotation of thrust wedges by later imbrication may produce apparent thrust splays or normal faults.



SOME EXAMPLES OF MULTIPLE THRUST WEDGE GEOMETRY.



A unit can be repeated by thrust wedging without involving other units.

Thrust wedging can explain rotated back- and fore-thrust geometries confined to limestone horizons with a simpler sequence of events than need be invoked for imbrication. If however shales are present in significant quantities (eg.50% limestones, 50% shales) between limestone repetitions then imbrication would be a more likely mechanism, because thrust wedges are largely confined to competent horizons.

There is evidence of out of sequence thrusting in North Hadeland. Its extent is limited, but produced some broad warping of folds and some second and third order faults that may thrust younger rocks over older rocks. The best example of this is in the vicinity of the abandoned factory at Royken (G.R. 880 006). Here a syncline is broadly refolded in the footwall of a thrust which pushed the Kirkerud Group over folded Lower Didymograptus Shale-Kirkerud Group rocks.

Folds.

Most folds in the area have one or both limbs attenuated by thrusting and are probably thrust out tip line folds. There are buckle folds with similar dimensions and orientations present, but these are not numerous enough to contribute significantly to total shortening in the area. Many of these could be an even earlier stage in the development of tip line folds, into which displacement on sub-surface thrusts has passed.

In the cores of many anticlines, below the competent Orthoceras Limestone, the shales have been transported into the anticlinal core. This is achieved by a type of flow which resulted in numerous minor bedding parallel detachments with small folds above (1-5cm amplitude and wavelength) forming during transport into the core. Also numerous minor fault planes which cut across bedding, transported material into the fold core. These faults tend to be aligned sub-parallel to the fold limbs and form small triangle zones.

The Orthoceras Limestone is the best marker for the larger folds in the area. In this unit the folds are symmetrical to moderately inclined with occasionally overturned limbs inclined towards the hinterland. The folds have wavelengths of 75-225m with amplitudes of 50-90m and interlimb angles of 35-100°. The axial planes are inclined up to 65° towards the NNW (hinderland) and no examples were found of foreland inclined axial planes.

Apart from the larger folds described above, tight polyclinal, disharmonic folds with wavelengths of a few millimeters are also present within the shale horizons. These are found in highly deformed zones in close proximity to tip lines of both thrust and normal faults, thrust splays and areas of flow within fold cores.

Cleavage.

Spaced solution and fracture cleavage occurs within the Cambro-Ordovician rocks. The spacing and intensity for both types is similar to that found in Asker-Baerum but the distribution is more akin to that found in northern Ringerike.

Pressure-solution seams are not always present, when they are they usually have slightly wavy seams with spacings of 2-8cm and clay selvages 1-2mm thick. The most intense pressure-solution, usually found in areas of multiple limestone repetitions, forms anastamosing seams tracable for 20-70cm, with clay selvages up to 2mm thick and spaced at 1-3cm intervals.

Fig.5.8 Structural orientation data for North Hadeland

Fig.5.8a

• = poles to cleavage

× = poles to cleavage with bedding restored to horizontal

Fig.5.8b

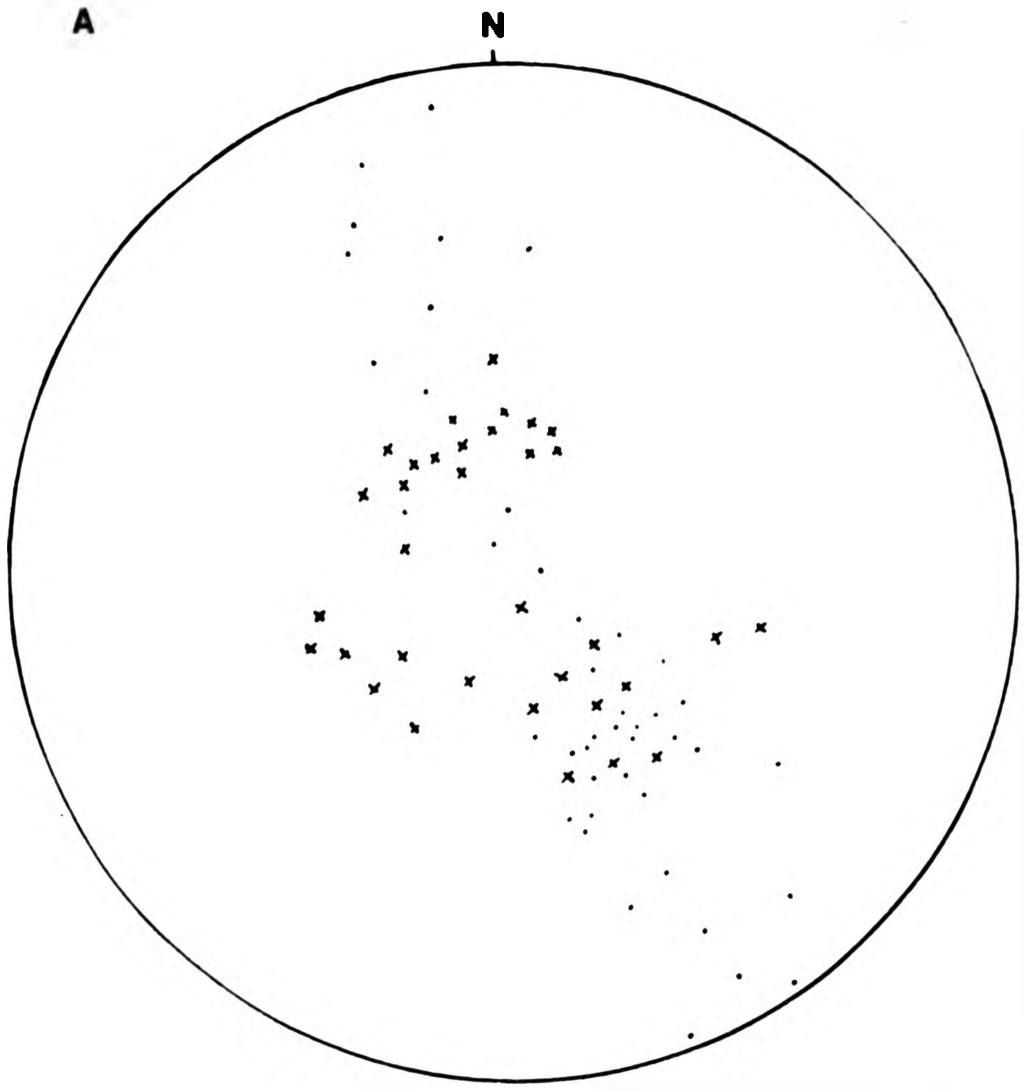
⤚ = poles to minor thrusts

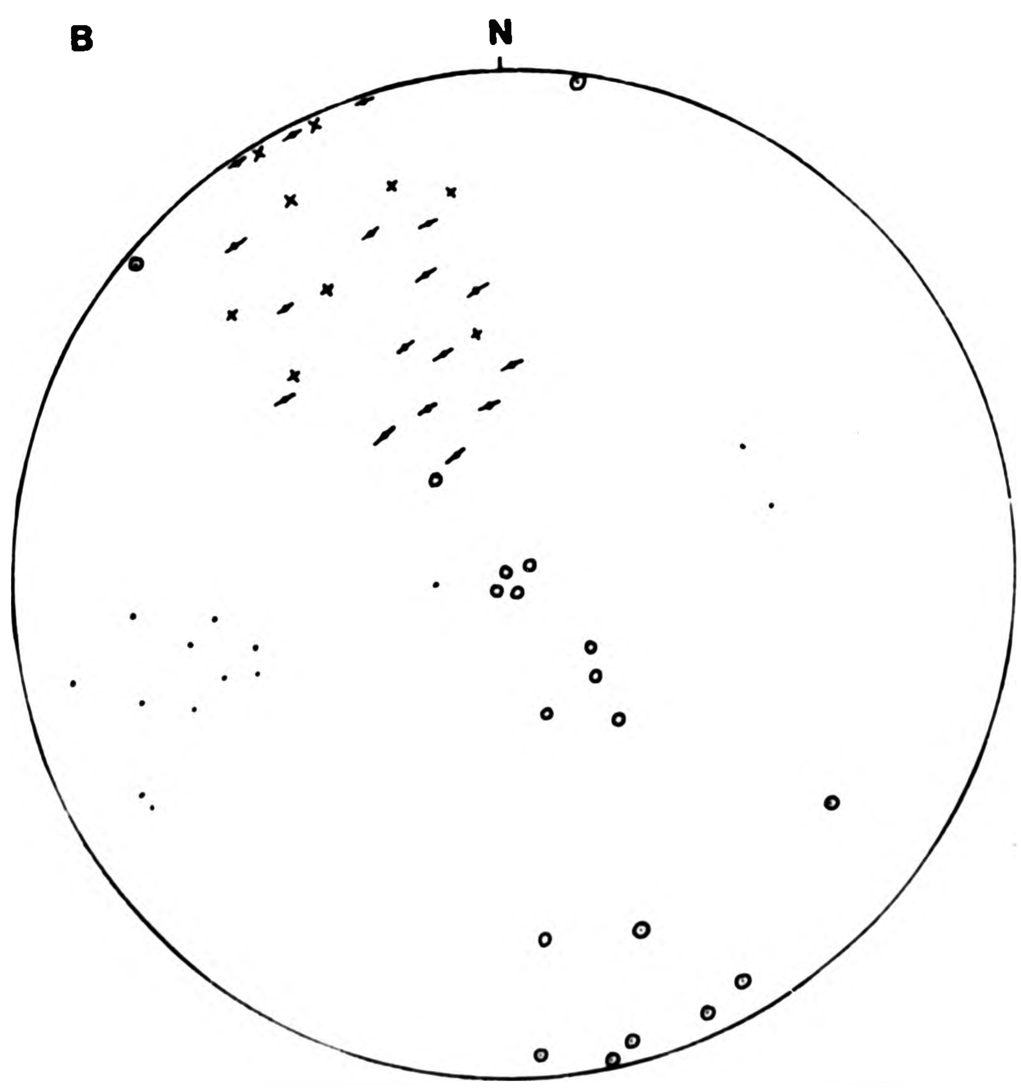
× = poles to minor fold axial surfaces

• = orientation of minor fold hinges

○ = poles to pressure-solution seams

⊗ = poles to pressure-solution seams with bedding restored to horizontal


A
N


B
N

From the Stereonet (Fig.5.8) it can be seen that the pressure-solution cleavage has been folded, distributing the poles to cleavage along a NNW-SSE trending girdle. There is a concentration of poles plunging between 0° and 40° in the NNW segment of the stereonet. The solution cleavage formed early at approximately right angles to bedding, with an E-W to ENE-WSW strike direction. When bedding is restored to horizontal the poles to solution cleavage rotate back close to vertical so the concentration of cleavage poles between 0° and 40° is an artifact reflecting the dominant orientation of bedding in the deformed state.

There therefore appears to be an early manifestation of strain in localised areas within the limestone units, represented by intense pressure-solution cleavage and thrust wedging. The main deformation later reorientated these structures.

Fracture cleavage spacing ranges from 0.2-5cm and is found in most outcrops. Sometimes fracture cleavage has not developed or it may have been obliterated by a later slaty bedding-parallel fabric. This slaty fabric, when present, is folded, whether it be intensified bedding- parallel fabric close to a fault plane or in an area of intense folding.

The stereonet (Fig.5.8) of poles to fracture cleavage displays a scatter along a NNW-SSE trending girdle, the majority of poles cluster in the SSE half of the girdle. When the bedding is restored to horizontal (Fig 5.8b) it can be seen that there is a cluster of poles in the NNW segment from 20-40° and a scattering of poles in the southern half of the stereonet.

The cluster of poles in the NNW segment represent cleavage forming ahead of the imbricate thrusts as previously described in Asker-Baerum (Chapter 3, see Fig 3.4). As almost all the second order thrusts dip towards the hinterland in North Hadeland the cluster of poles in the NNW fits in very well with the fault orientation and indicates that the cleavage was forming ahead of the tip line folds and was subsequently folded.

The cluster of foreland (SSE) dipping cleavages cannot be explained by backthrusting as in Asker-Baerum because backthrusts are so rare in this area. The foreland dipping cleavages are largely confined to the Kirkerud Group and have been folded by imbricate generated folds (Fig.5.9) showing it to be an early cleavage. One possible explanation is connected with the problem of decreasing amounts of shortening upwards in the stratigraphy.

The amount of shortening is lower in the mid Ordovician-Silurian rocks of South Hadeland than in the Cambro-mid Ordovician of North Hadeland. One method of accommodating this discrepancy in shortening is to postulate an upper detachment horizon (Fig.5.10).

The entire thickness of the Osen-Roa Thrust Sheet can be pinned in Langesund Skien (see Chapter 6). Therefore the discrepancy in the amount of shortening within the thrust sheet probably meant that the higher, competent units that deformed less, must have moved towards the hinterland relative to the footwall rocks, along a zone or plane of detachment.

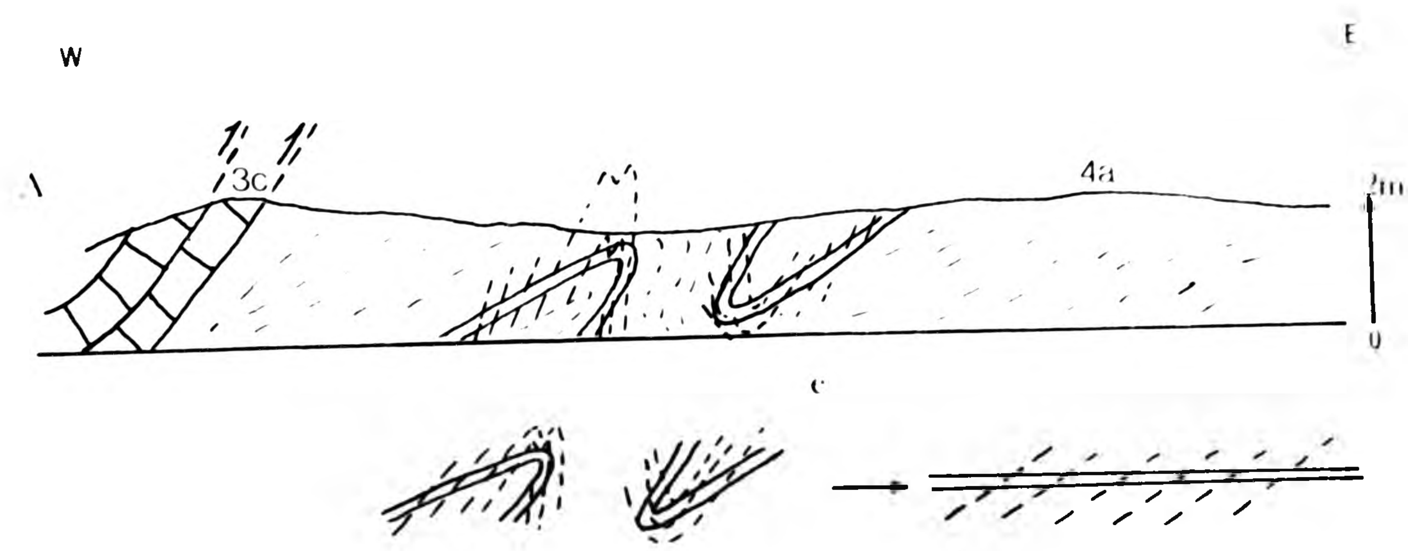
The relative sense movement in the hanging- and footwall- blocks is correct for producing a foreland dipping cleavage in the footwall and probably the imbalance in shortening within the thrust sheet caused the upper detachment horizon to migrate ahead of the propogating Osen-Roa

Fig.5.9 Folded cleavage in the Kirkerud Group.

A. Road 35, Royken

B. Road 35, Grindaker

The cleavage in both examples has been folded. When the bedding is restored to horizontal the cleavage is found to be originally inclined towards the foreland.


W
E
A
3c
4a
2m
0
c

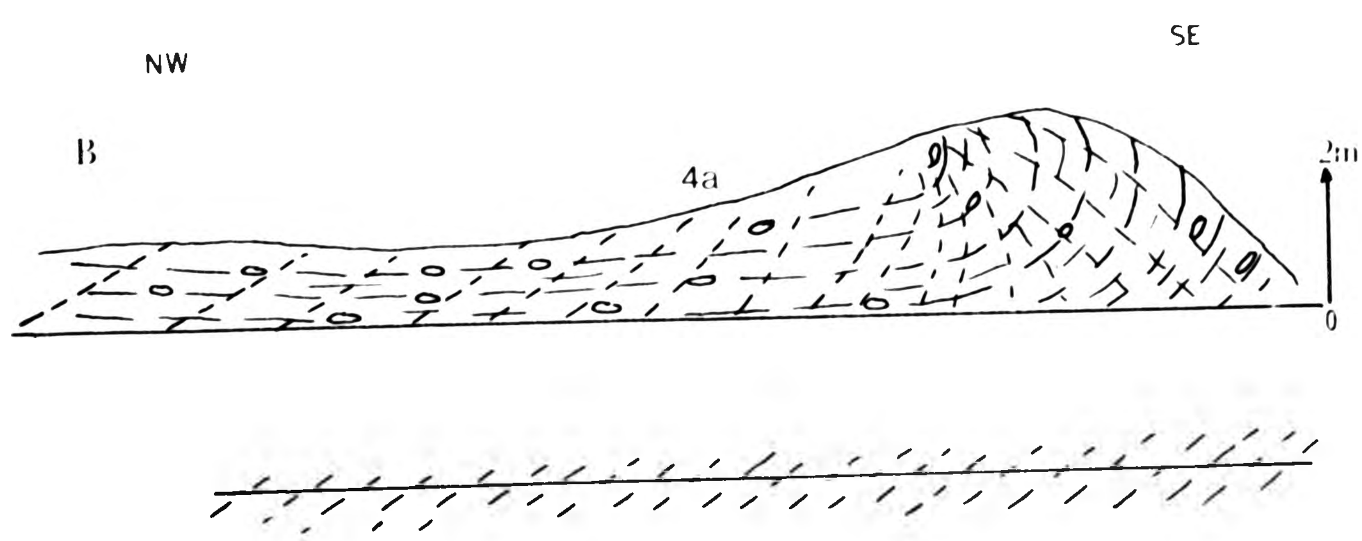
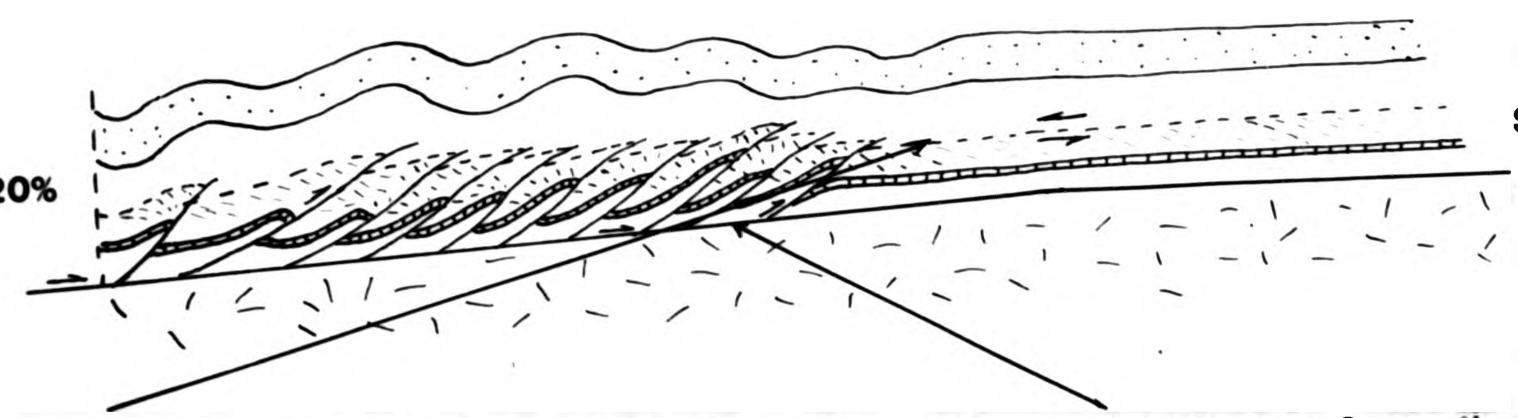

NW
SE
B
4a
2m
0

Fig.5.10 Diagram to show the probable nature of the upper detachment horizon (or zone).



Bedding parallel upper detachment proceeding ahead of lower detachment, Generating a foreland dipping cleavage, later deformed by imbrication from the lower detachment.

Detachment. The folded foreland dipping cleavage is therefore explained by generation from the upper detachment and later folding of the cleavage by tip line folds as the Osen-Roa Detachment passed through the area.

Stereonet analysis.

The stereonet of poles to bedding (Fig.5.11) shows a fairly wide scatter. The great majority (75%) of poles lie along the SSE half of a NNW-SSE trending girdle, reflecting the imbrication style. The 20% of poles lying on the NNW half of the girdle are the SW dipping limbs of the tip line and buckle folds, whilst the other 5% of scattered poles reflect the plunge of fold closures, mainly dipping up to 40° to the WSW. However some dip in the opposite direction and were probably caused by the lateral ramping of some imbricates.

The stereonet of minor structures (Fig.5.8) also reflect the general inclination of structures, eg. thrusts, bedding and axial surfaces, to the NNW and the movement direction of the Osen-Roa thrust sheet to the SSE. Poles to cleavage, pressure-solution, bedding, minor fault planes and minor fold axial surfaces all lie on similar NNW-SSE trending girdles. Minor fold hinges are at right angles to this girdle and generally plunge up to 45° to the WSW. All structures therefore appear to be related to one protracted deformation event.

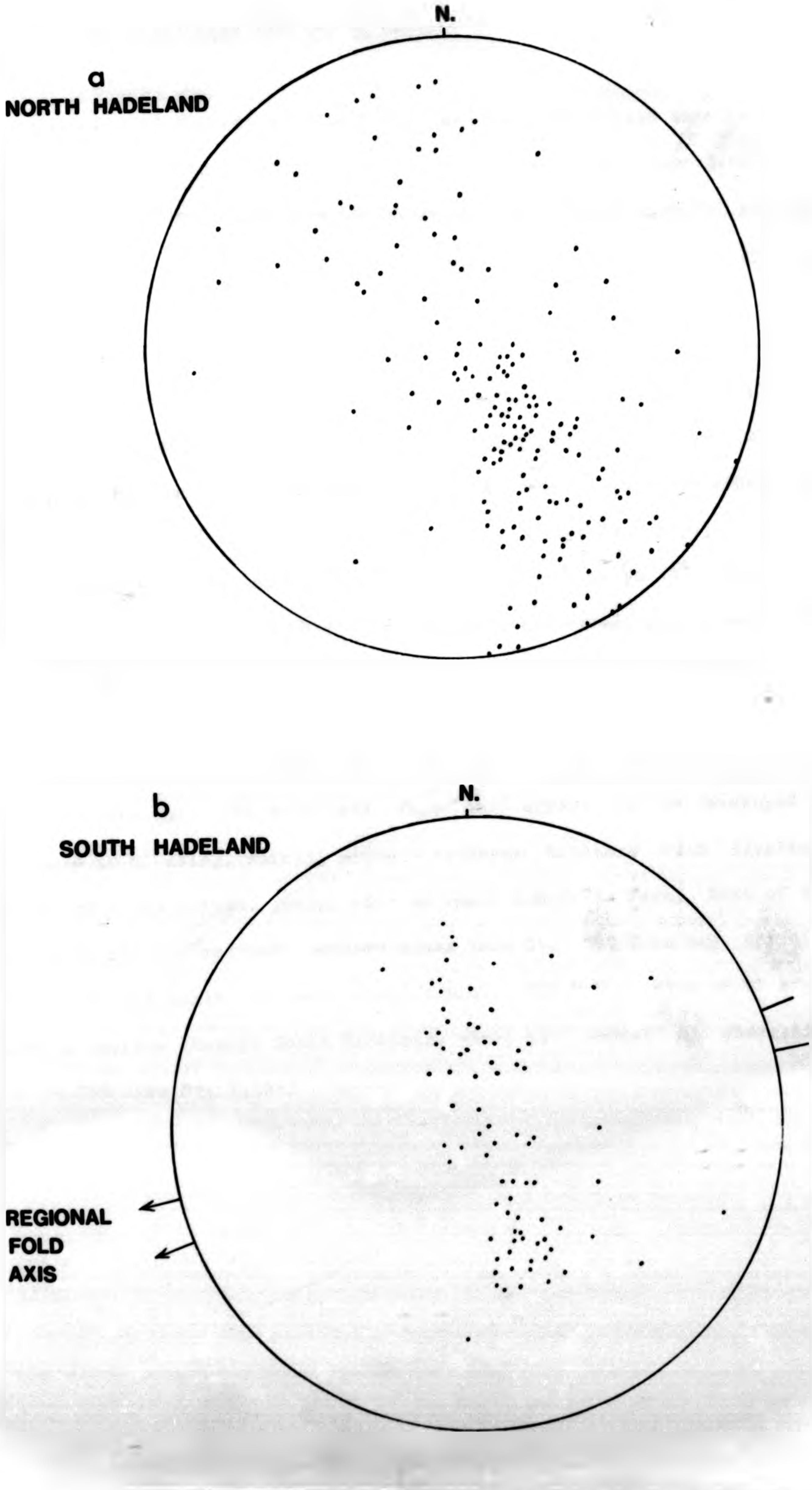
A balanced cross-section through North Hadeland.

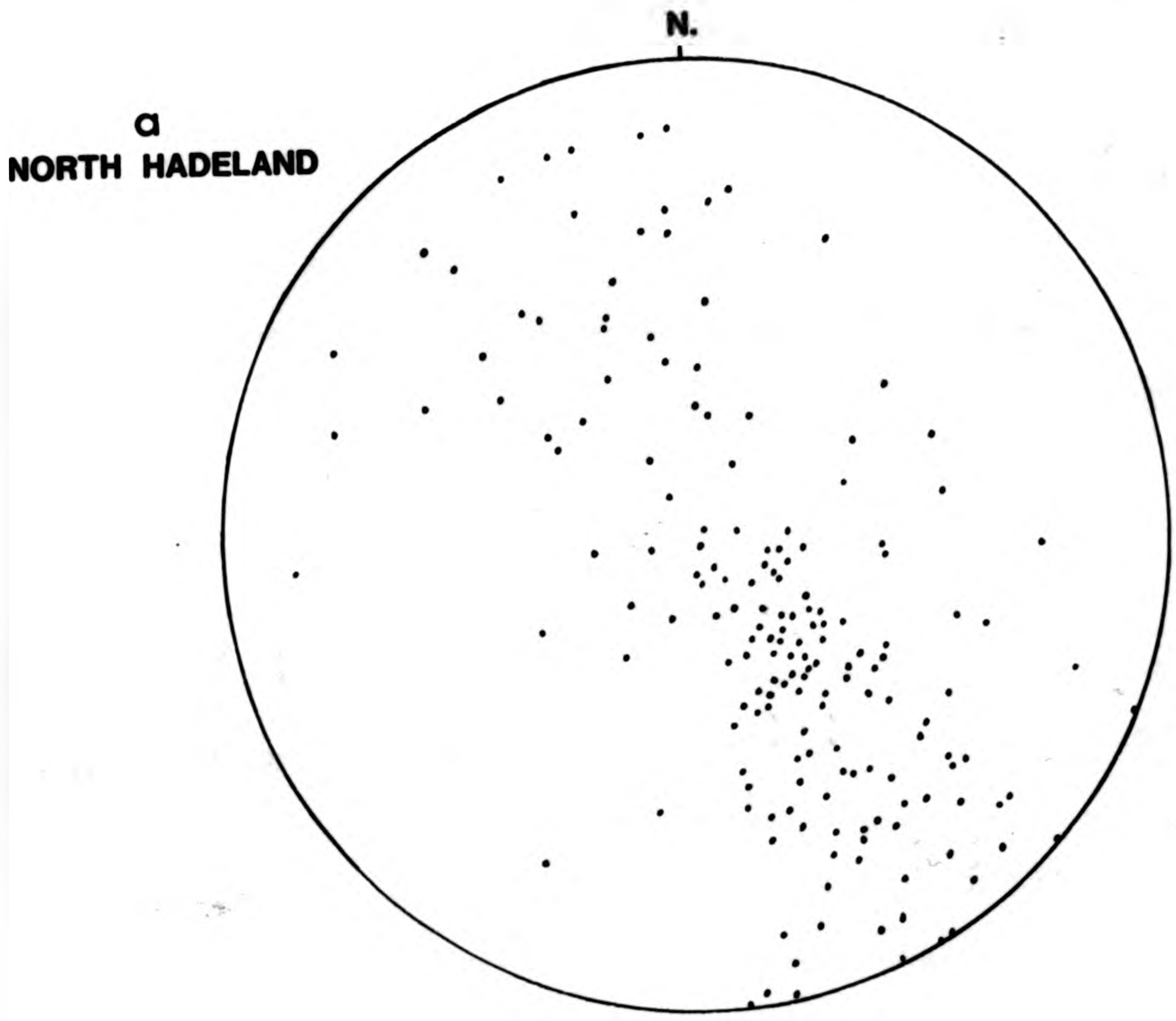
The NNW-SSE trending balanced cross-section (Fig.5.5) uses the Orthoceras and Ceratopyge Limestones as marker horizons and the restored section shows that shortening (e) along the line of section = 60%

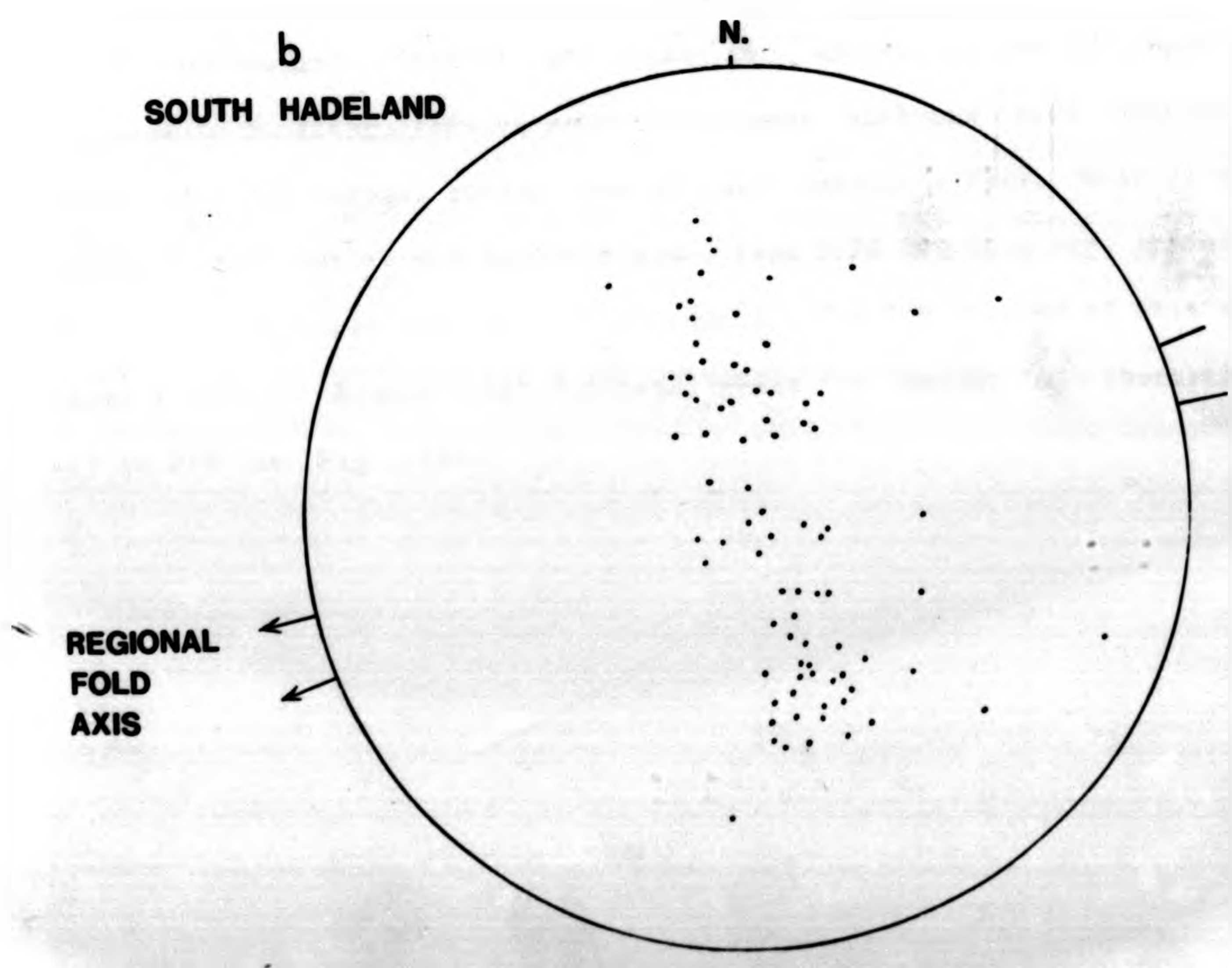
Fig.5.11 <u>Wulff nets of poles to bedding for Hadeland (north hemisphere projection).</u>

A. North Hadeland

B. South Hadeland


N.
a
NORTH HADELAND
N.
b
SOUTH HADELAND
REGIONAL
FOLD
AXIS


N.
a
NORTH HADELAND


N.
b
SOUTH HADELAND
REGIONAL
FOLD
AXIS

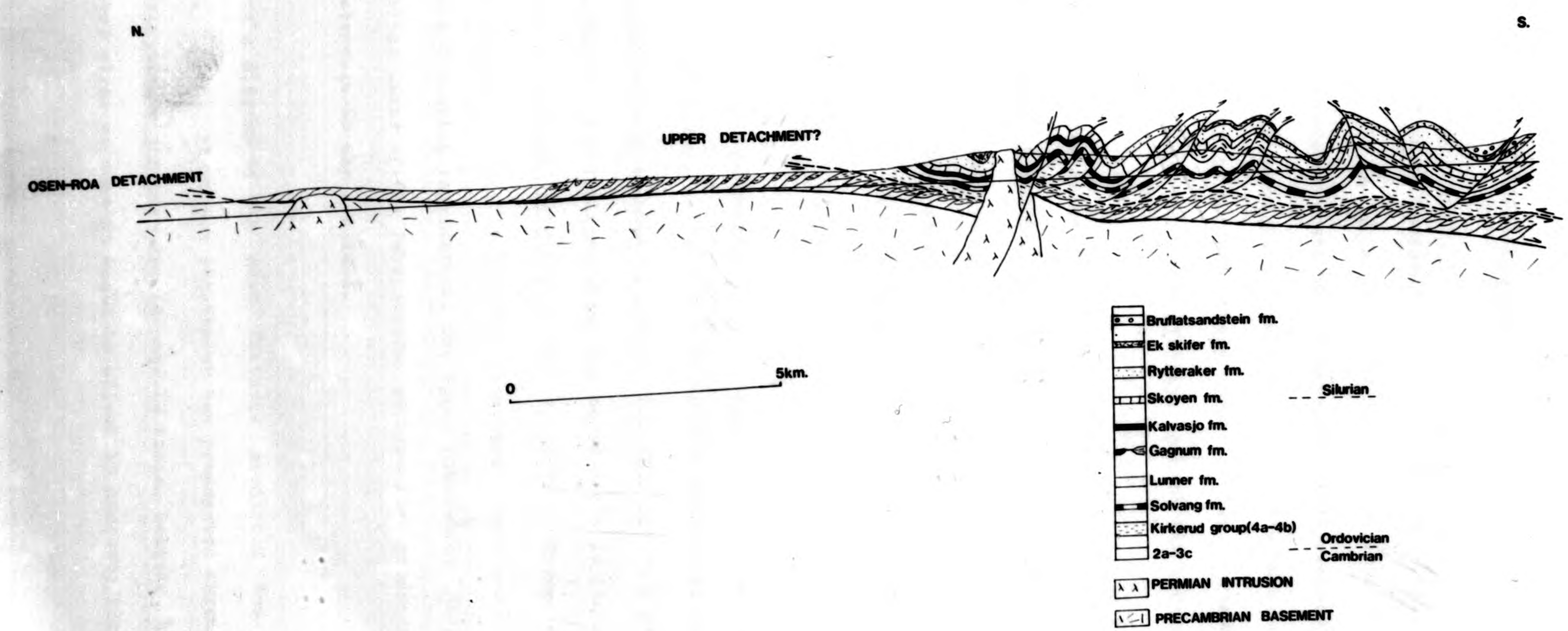
5.3 The structural geology of Central and South Hadeland.

The area of Central and South Hadeland has been mapped in detail by Owen (1977 unpublished thesis). The area comprises mid Ordovician-Silurian rocks from the Kirkerud Shales Group upwards and is folded into a broad series of anticlines and synclines, cut by high angled Caledonian and Permian faults.

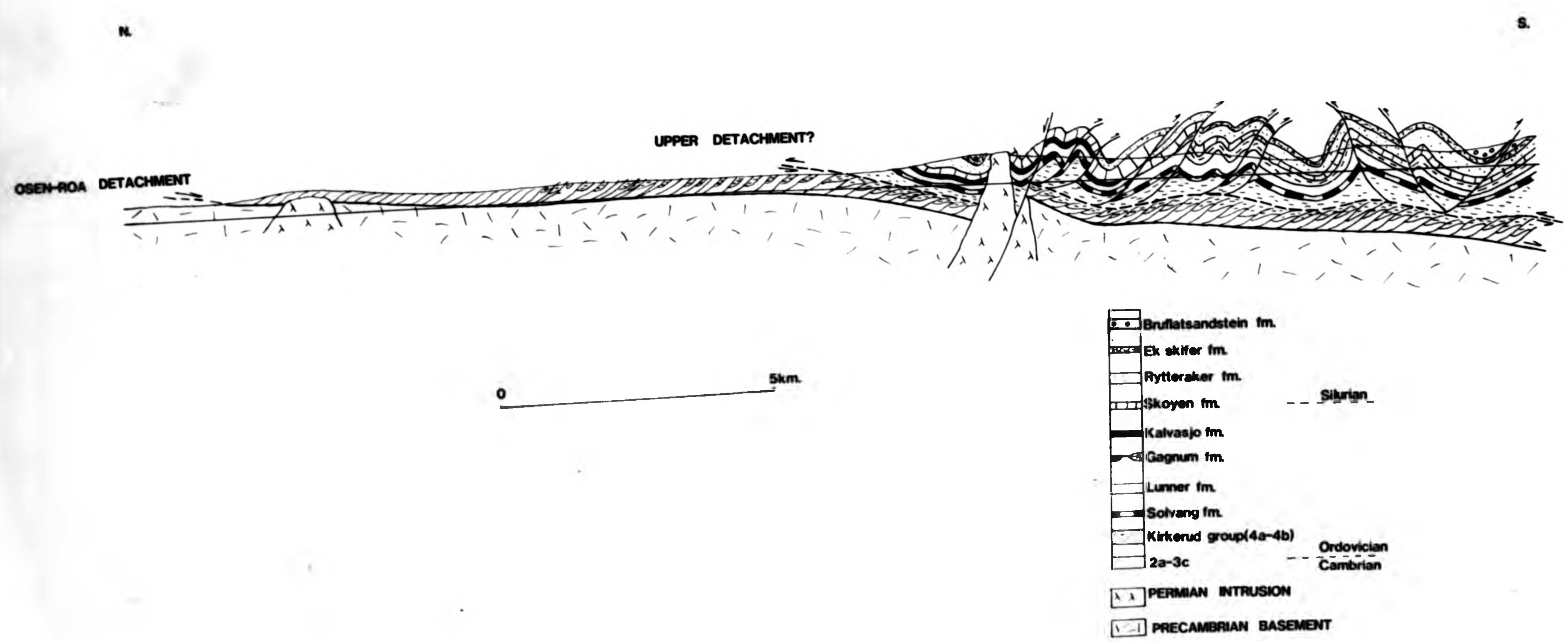
The mid Ordovician-Silurian rocks have several thick competent units (Fig.5.12) which have stiffened this sequence, producing broad symmetrical to slightly asymmetrical folds with wavelengths of 500-1650m and amplitudes of 350-800m. Interlimb angles range from 85-120° and the axial planes are inclined both to the SSE and NNW from 80-90°. The Wulff net of poles to bedding (Fig.5.12) reflects the broad, gentle nature of the folding in the scatter of poles along a NNW-SSE trending girdle.

Thrusting does not apparently contribute a significant amount to the total shortening. Thrusts are rare and appear to be developed in response to buckling, forming minor detachment horizons with displacements of a few meters, giving rise to small imbricate fans. Most of the faults in the central and southern areas (see 1:50 000 Gran map, Appendix 2) are of high angle and small displacement. The N-S section of this map shows a section through South Hadeland, where the amount of shortening (e) is 29% (see Fig.5.12).

Fig.5.11 North-south section through the 1:50,000 Gran map (see Appendix 2), Hadeland.



N.
S.
OSEN-ROA DETACHMENT
UPPER DETACHMENT?
0
5km.
Bruflatsandstein fm.
Ek skifer fm.
Rytteraker fm.
Skoyen fm.
Silurian
Kalvasjo fm.
Gagnum fm.
Lunner fm.
Solvang fm.
Kirkerud group(4a-4b)
2a-3c
Ordovician
Cambrian
PERMIAN INTRUSION
PRECAMBRIAN BASEMENT


N.
S.
OSEN-ROA DETACHMENT
UPPER DETACHMENT?
0
5km.
Bruflatsandstein fm.
Ek skifer fm.
Rytteraker fm.
Skoyen fm.
Silurian
Kalvasjo fm.
Gagnum fm.
Lunner fm.
Solvang fm.
Kirkerud group(4a-4b)
2a-3c
Ordovician
Cambrian
PERMIAN INTRUSION
PRECAMBRIAN BASEMENT

5.4 The structural style of Hadeland.

The structural style of North Hadeland varies greatly from that of Central and South Hadeland. It is not a lateral variation but a vertical one, for the Cambro-mid Ordovician rocks in northern Ringerike exhibit a similar structural style to those rocks of similar age in North Hadeland. Both are dominated by imbrication and relatively small folds. Between these two areas in South Hadeland the style displays none of the imbrication and much larger, broader folds. This is reflected in the pattern of poles to bedding for the two areas (Fig.5.11). The change in style is also apparent in the amounts of shortening in the two areas; whilst North Hadeland displays about 60% shortening (e), South Hadeland has deformed by only e = 29%. Therefore a 10km section of Cambro-mid Ordovician rock will unstrain to about 24km, whilst 10km of Cambro-mid Ordovician rock will unstrain to only 14.6km.

The discrepancy in shortening must mean that the mid Ordovician-Silurian rocks presently above the Cambro-mid Ordovician rocks were originally deposited many kilometres apart. For this reason a plane or zone of detachment is postulated which has moved rocks in the hangingwall towards the hinterland, relative to the footwall. Using this model is could be argued that as the Osen-Roa Detachment progressed from hinterland to foreland causing imbrication, the upper detachment horizon was already travelling ahead of the imbrication; perhaps also producing a foreland dipping cleavage in the footwall.

Fig.5.10 shows a diagram of the main features predicted for the upper detachment. After the upper detachment has propogated through a region, later imbrication might make the it hard to trace, because being a bedding parallel plane or zone it might be offset by numerous thrusts or folded. Alternatively the imbricates might use the upper detachment as a plane of weakness and re-activate the detachment (reversing its original sense of movement) forming a duplex. In Hadeland the exposure is too poor to prove either of these possibilities. The regional problems of the upper detachment horizon are discussed in Chapter 8..PG

CHAPTER 6

THE CALEDONIAN STRUCTURE SOUTH OF ASKER.

6.1 Introduction.

The Cambro-Silurian rocks south of Asker are preserved in a discontinuous strip on the western side of the Oslo Fjord. They are generally bounded on their eastern margin by Permian intrusions (up to 80km wide in an E-W direction) and on their western margin by Precambrian basement (see Fig.6.1). At the northern end of this area the Cambro-Silurian rocks form a semi-circular strip around complex granite intrusions (see Holtedahl and Dons 1960). Here the fullest exposures are on the western side of the Permian intrusions, whilst the exposures on the eastern side from Konnerud through Langoya to Jeloya are only of contact metamorphosed Silurian rocks.

The north-south trending Cambro-Silurian strip is interrupted for 20km by Permian intrusions in the Nordagutu area (see Holtedahl and Dons 1960). The Osen-Roa Thrust probably died out in this area because weakly folded Alum Shales are present north of this area, whilst unfolded rocks are found to the south in the Langesund-Skien area.

This chapter aims to describe the deformation style in the Eiker-Sandsvaer and Holmen areas and the ways in which the Osen-Roa Detachment could have died out in the area of missing Cambro-Silurian at Nordagutu.

6.2 The Eikeren area.

The area of Cambro-Silurian rocks around Lake Eikeren was mapped at 1:50,000 (see Fig.7.1). The Cambro-Silurian rocks have been intruded to the east by Permian granites and lie above Precambrian basement to the west, separated by a Permian normal fault which downthrows Precambrian gneisses and a strip of Cambro-mid Ordovician rocks on its western side.

At Eikeren, the largest hill in the area called Sirikjerka slopes down to the lake. The eastern portion of the hill is composed of Permian granite whilst the western portion is made up of Ordovician to Silurian rocks. These form a broad synclinal structure which is modified by minor folds and imbricates (see Fig.6.1b).

The Cambro-Ordovician rocks north of Eikeren are folded and imbricated in the deformation style typical of the Oslo Graben. The imbricates form a series of low hills, defined by repeated ridges of Ampyx and Orthoceras Limestones. Deformation of the Silurian rocks is mainly by folding with second order faults dying out in the lower Silurian units.

There is a good structural section through the Cambro-lower Ordovician exposed along the railway line, south of Vest-Fossen station, (see Fig.6.2). This section displays folding and minor backthrusting of the Orthoceras Limestone at the northern end. Further south a large imbricate thrust has emplaced Alum Shales over 4aa Shales, which are deformed into a chevron style footwall syncline. The footwall rocks are further deformed by minor thrust splays, after which the shales become sub-horizontal for a considerable distance. The southern end of the section is disturbed by thrust splays which rotate the bedding so that it dips gently hindewards. The lack of deformation in the 4aa Shales in the southern part of the section displays the difference between Asker and this area, for it reflects the increasing spacing between second order thrusts towards foreland, which reduces the amount of shortening in the lower units.

Deformation within the Alum Shales is similar to that found in Asker. It is best seen in road sections along road 35 (G.R.488 188) where small asymmetrical disharmonic folds are present, with wavelengths up to 4m and amplitudes up to 3m.

South of Eikeren there is little evidence of deformation; the most easterly outcrop of Cambro-Ordovician is separated by a Permian fault from the main western strip and is tilted up to 30° to the south west. The main western strip also displays little deformation. For example, the Ampyx Limestone forms a gentle, south-easterly dipping continuous cap to the hill west of the 286 road at Raen. The only proof of the existance of the Osen-Roa Detachment in this area is in the Alum Shales outcropping near the road side of the 286, which continue to display small asymmetrical folds. This folding can be traced along the road, (which follows the Alum Shales along strike), for a considerable distance. At Krekling the Orthoceras Limestone appears to be slightly offset by thrusts of opposing dips which displace the limbs (which dip about 10-20°) of a broad anticlinal structure.

<u>Summary</u>

The large syncline at Eikeren appears to be an important feature south of Asker because it is the southern most structure of that size in the region. It has a wavelength of about 2.5km and is therefore larger

Fig.6.1 The southern Oslo Graben area.

A. Geological map of the south-western side of the Oslo Fjord,

showing areas of Cambro-Silurian outcrop.

B. Geological map around the north end of Lake Eikeren.

Cross-section through the area along line a-b.

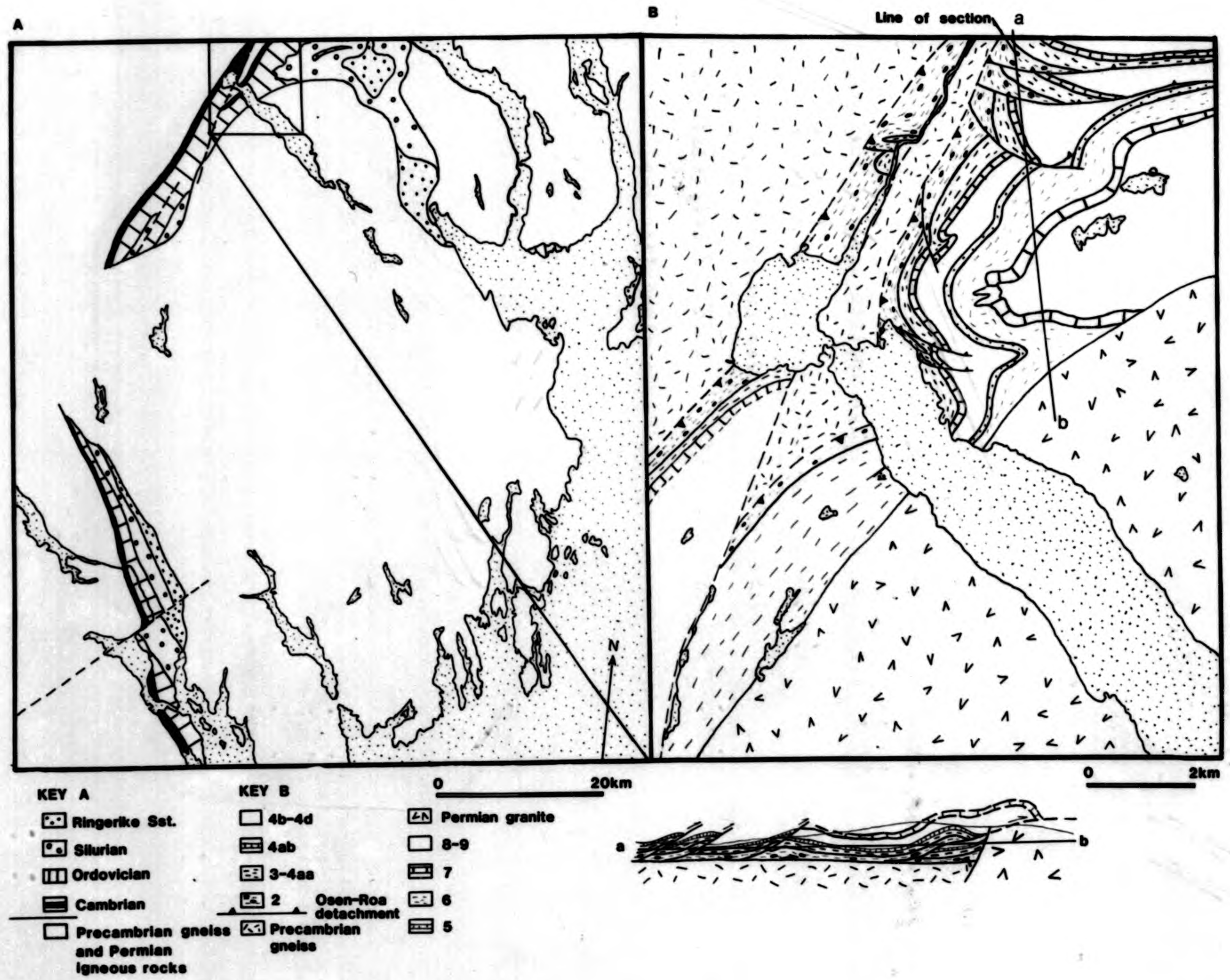

A
B
Line of section
a
b
N
0
20km
0
2km
KEY A
Ringerike Sst.
Silurian
Ordovician
Cambrian
Precambrian gneiss and Permian igneous rocks
KEY B
4b-4d
4ab
3-4aa
2
Osen-Roa detachment
Precambrian gneiss
Permian granite
8-9
7
6
5

Fig.6.2 Cross-section south west of Vest Fossen railway station. Details of sections along the railway line are shown.

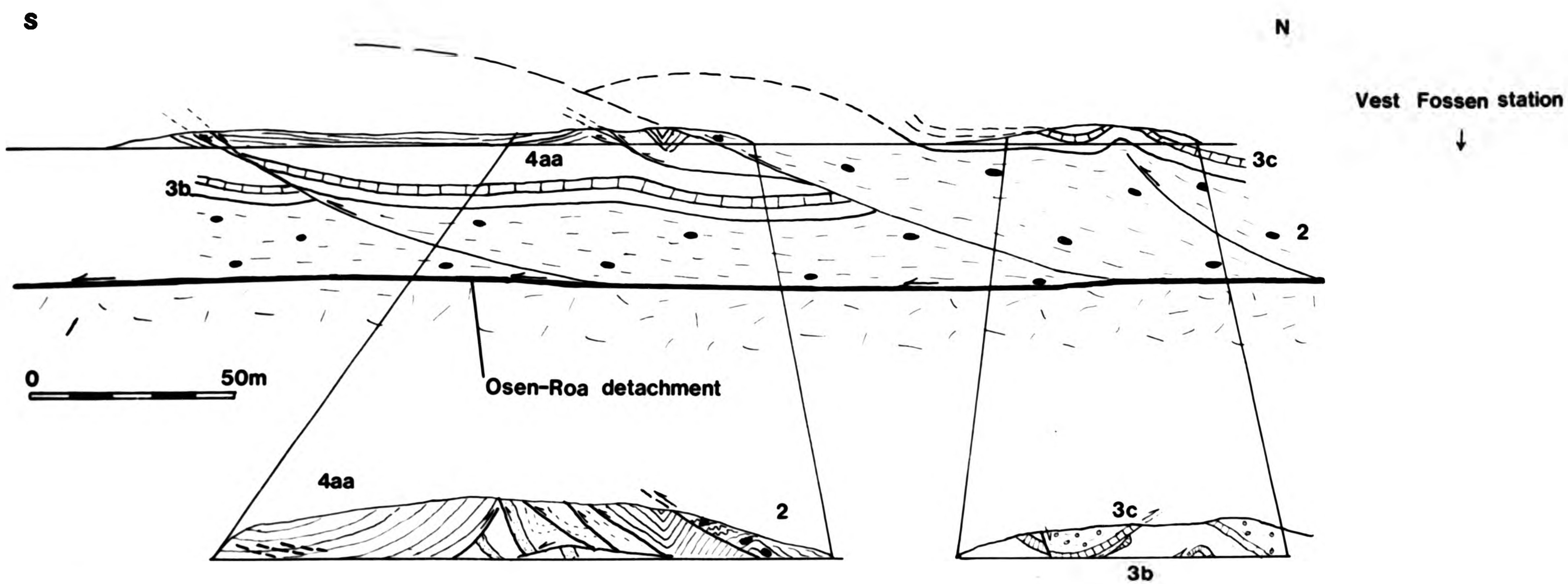
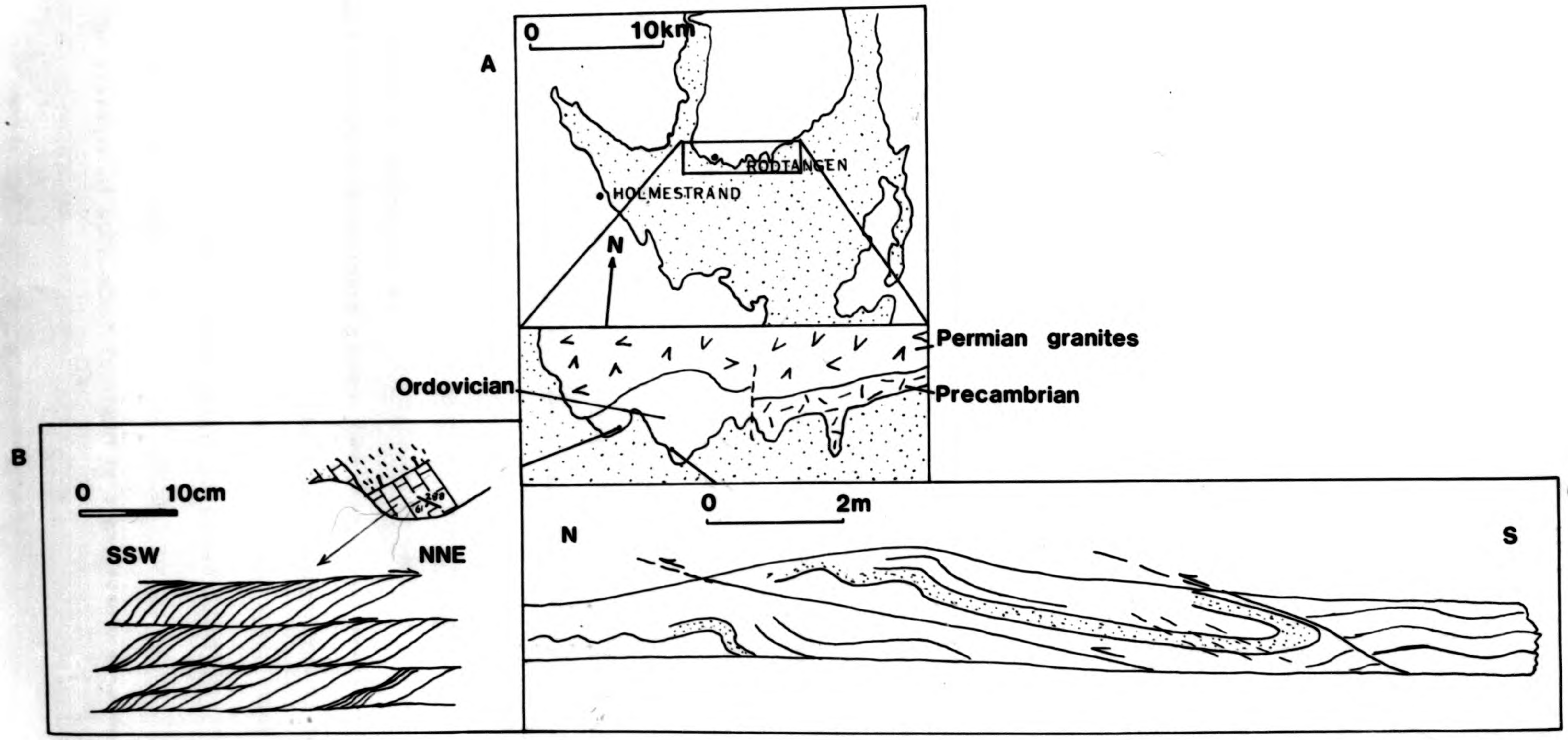

S
N
Vest Fossen station
4aa
3b
3c
2
0
50m
Osen-Roa detachment
4aa
2
3c
3b

Fig.6.3 Rodtangen

A. Location map

B. Shear zones on the western side of Rodtangen

C. Minor folding and backthrusting on the eastern side of Rodtangen


A
0 10km
HOLMESTRAND
RODTANGEN
N
Permian granites
Precambrian
Ordovician
B
0 10cm
SSW
NNE
C
0 2m
N
S

On the western side in the Upper Chasmops Limestone, shear zones are developed which have a relative sense of movement which transports successively higher beds towards the anticlinal core, (see Fig.6.3). It is likely that these shear zones were caused by flexural slip in response to the anticlinal folding. However, they are unusual because they have not been observed elsewhere in the Oslo Region, although a flexural slip origin for the bedding parallel cleavage in many shale outcrops elsewhere in the graben seems likely. This area is the one closest to the thrust front and it may be that the shear zones are related to the termination of the Osen-Roa Detachment.

6.4 Langesund-Skien

This is the most southerly area of Cambro-Silurian rock in the Oslo Graben (see Fig.2.1) and displays rocks which remained undeformed by the Caledonian orogeny. They have been tilted to the ENE between 20° and 30° and are offset by numerous Permian normal faults.

Any hint of Caledonian structures is very faint: there is no definate evidence of a Caledonian cleavage in the Cambro- Silurian rocks, although a thin limestone band just above the Alum Shales at Omborsnes (G.R. 385 457) displays a faint hinterland dipping fabric which might be a very weak cleavage. Also, some competent horizons are fractured to form incipient thrust wedges, of Caledonian trend, but along which no movement appears to have taken place. The Alum Shales which elsewhere in the southern part of the Oslo Graben were deformed even if the higher units remained undeformed, are themselves undeformed here. Therefore the Langesund-Skien area appears to be true, undeformed foreland.

The presence of undeformed foreland is significant, because as the rocks are truely autochthonous it is possible to pin a balanced section through the Southern Caledonides in this area. From this pin line progressively higher thrust sheets can be unstrained, in order to estimate the original width of the rocks comprising the thrust belt.

The actual location of the thrust front has been eroded away as the Cambro-Silurian rocks in that area formed the roof to the Permian intrusions. However it can be positioned fairly accurately as trending roughly east-west, north of Langesund-Skien and south of the deformed rocks at Rodtangen.

6.5 The probable nature of the thrust front

In Scandanavia, outside the Oslo Graben, the current eroded thrust front does not relate to the original position of the thrust front. Over the rest of southern Norway a similar relationship probably existed to that only seen today in southern Mjosa where the Osen-Roa Thrust ramps through the rocks of the Sparagmite region into the Oslo Graben,(see Chapter 7). Unfortunately even in the Oslo Graben the Cambro-Silurian rocks at the thrust front have been eroded away. Therefore it is necessary to assess the possible ways in which the detachment may have died out.

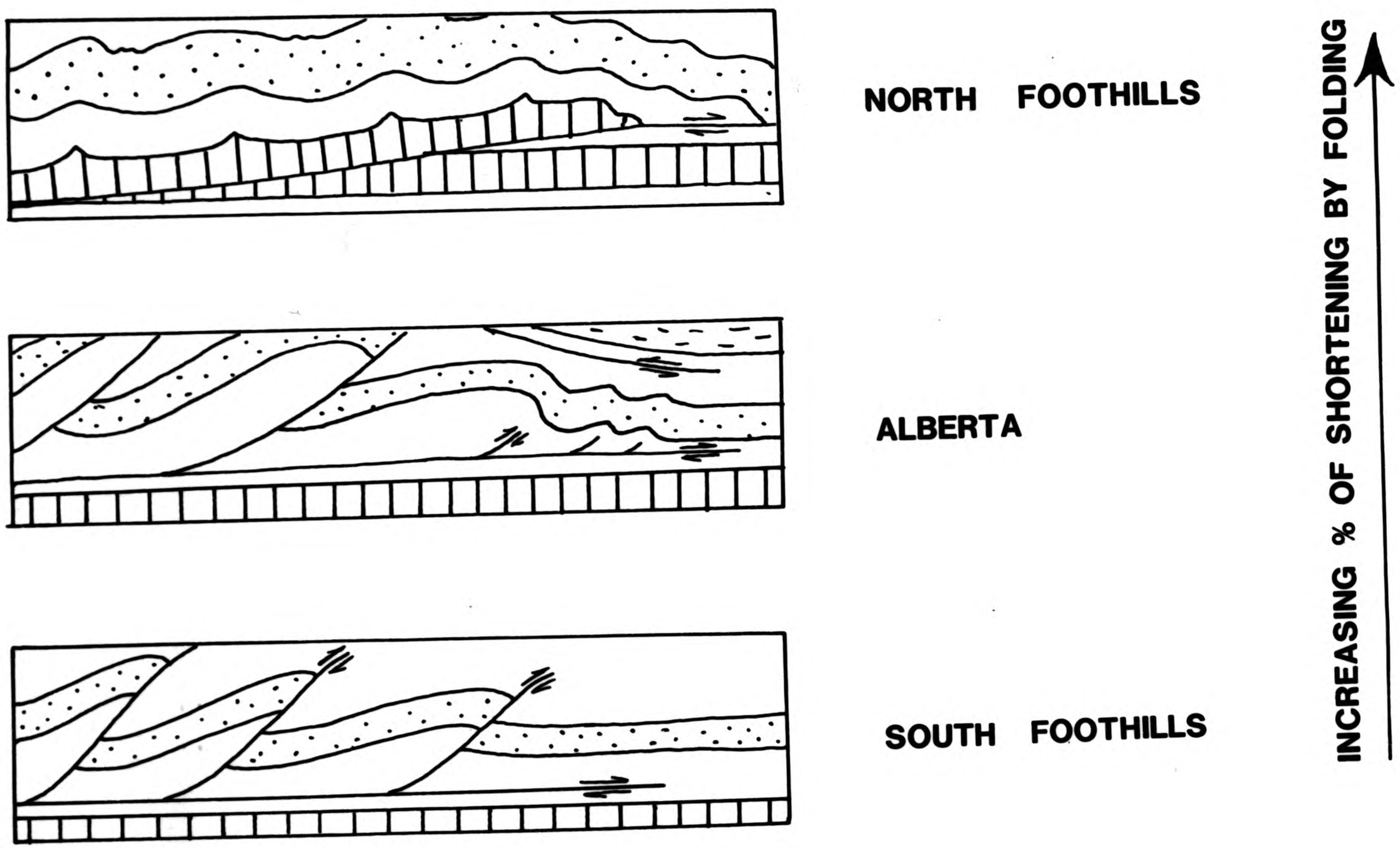
Dahlstrom (1970) outlined how the edge of the shortened and structurally thickened section of the eastern margin of the Canadian Rockies, known as the Foothills, passed into the normal, unthickened, stratigraphic succession of the Plains. From seismic, outcrop and borehole evidence he proposed two basic types of detachment end members as follows:

Fig.6.4 Typical detachment terminations in the Canadian Rocky Mountains. (after Dahlstrom 1970).

North Foothills = Concentric fold detachment

Alberta = Front fold detachment

South Foothills = Sole fault detachment


NORTH FOOTHILLS
ALBERTA
SOUTH FOOTHILLS
INCREASING % OF SHORTENING BY FOLDING

1.Concentric fold detachment (Fig.6.4a).

Concentric folding dies out against two surfaces; downwards into a lower detachment horizon and upwards into an upper detachment horizon (Dahlstrom 1969a). The latter is not normally recognised because of the simple dips involved, or because the folding reached the land surface.

Dahlstrom (1970) favours both detachment horizons forming as a geometric necessity of folding and not folding being caused by movement on the sole thrust. In the Northern Foothills of the Canadian Rockies the detachment at the leading edge cuts up section and dies out on reaching the land surface (Mountjoy 1959).

2.Sole fault detachment (Fig.6.4c).

In this end member thrusting is dominant, with second order imbricates fanning off the a sole detachment being the primary mechanism for internally deforming the thrust sheet. The sole thrust is the basic model for the Southern Foothills, and this may die out by either decreasing to zero displacement horizontally or by cutting up section to the surface.

Between the end members come the thrust sheets deformed by a mixture of imbrication at the base, which passes into folds higher in the thrust sheet, with thrusting and folding dying out horizontally towards the foreland. The Alberta thrust front displays such characteristics and involves an upper and lower detachment surface (see Fig.6.4b). A similar type of thrust front is described by Root (1973) for the Pennsylvania

Appalchians (see Fig.6.5), which involves triangle and pop-up zones spaced above a detachment horizon. These isolated thrust-folds are separated by largely undeformed rock. Such an area of low shortening may continue for tens of kilometres before the detachment eventually dies out.

The detachment end members proposed by Dahlstrom (1970) all involve thrusts decreasing in deformation towards foreland. However this is not necessarily the case. Loss of relatively friction free slip may cause the thrust tip to stop propogating and result in stresses building up at the thrust tip. This will cause a regional pattern of decreasing severity of deformation towards the foreland, but then a sudden increase in deformation actually at the tip line. The Hercynian thrust front at Amroth, (Dyfid, Wales) could be such an example where complex imbrication is met approaching the thrust front (see Fig.6.6).

It is important to decide which of the above examples is most likely to apply to the Oslo Graben. If the sole thrust frontally ramped, the thrust front cannot be pinned accurately because an unknown quantity of displacement has occurred over the top of the Langesund-Skien area. If however the sole thrust died out horizontally in the Alum Shales then the Cambro-Silurian rocks can be pinned in the Langesund-Skien area quite accurately.

Fig.6.5 <u>Highly generalised cross-section across the folded Appalachians. (after Root 1973).</u>

Dashed pattern indicates Precambrian rocks

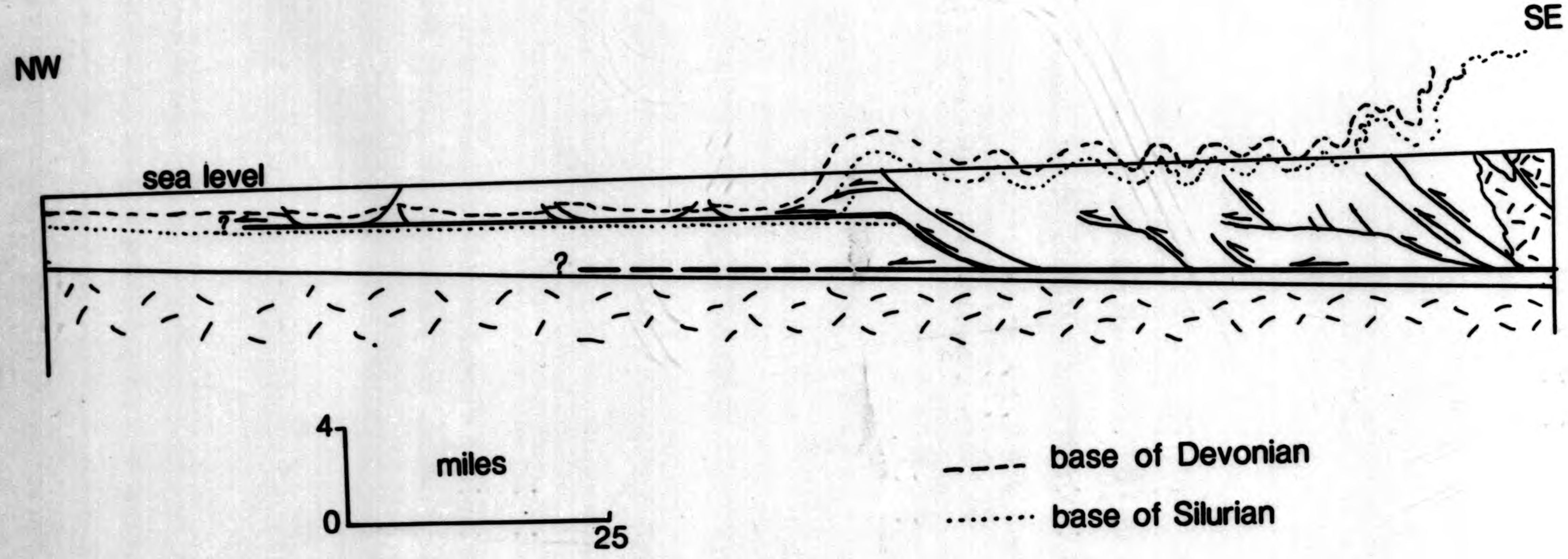
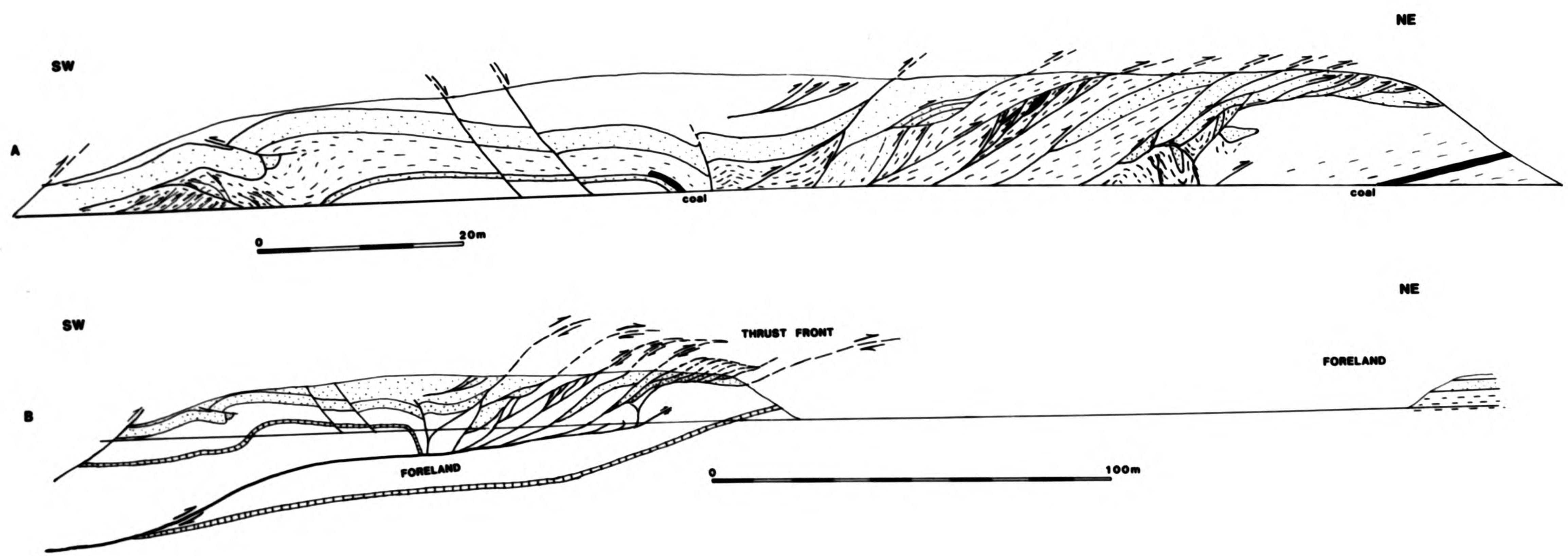

NW
SE
sea level
?
?
4
0
miles
25
base of Devonian
base of Silurian

Fig.6.6 <u>The Hercynian thrust front at Amroth (Wales).</u>

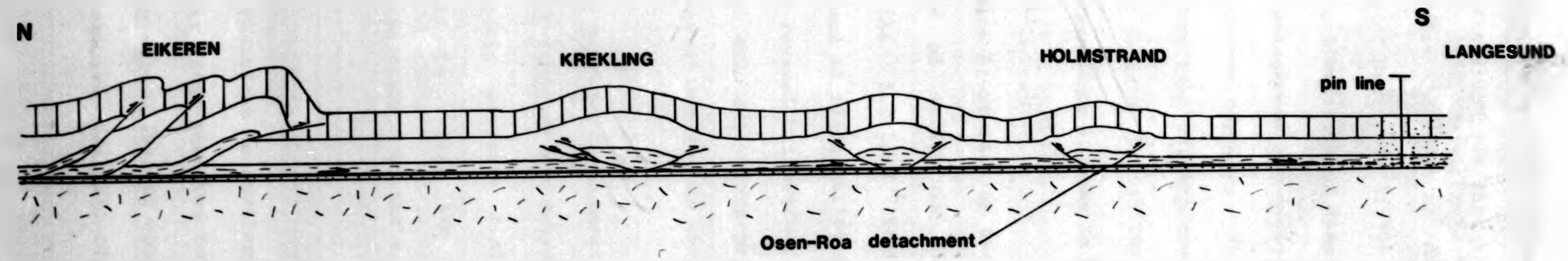
A. Cliff section showing numerous imbricate thrusts approaching the thrust tip.

B. Interpretation of the structure at depth as the sole thrust cuts up section by a series of frontal ramps.



A
SW
NE
coal
coal
0
20m
B
SW
NE
THRUST FRONT
FORELAND
FORELAND
0
100m

Fig.6.7 Idealised section through the southern Oslo Graben to show the structural style above the Osen-Roa Detachment as it dies out into foreland.


N
EIKEREN
KREKLING
HOLMSTRAND
S
LANGESUND
pin line
Osen-Roa detachment

The Caledonian deformation in the Oslo Graben displays second order contraction faults which die out upwards into tip line and buckle folds. It is therefore more akin to the Alberta or Amroth models and falls between the two end members of Dahlstrom (1970). The amount of shortening is small (~10%) for about 30km south of Eikeren, so it is unlikely that stick on the Osen-Roa Detachment could build up large stresses near the tip, as required in the Amroth example. Therefore the Alberta or Pennslyvania examples probably best display the way the Osen-Roa Detachment died out. An idealised section through the southern part of the Oslo Graben, to the thrust front can be seen in Fig.6.7.

In areas where the thrust front cuts up section to the surface, frequently there is evidence of strain in the foreland rocks of the footwall. At Amroth the foreland rocks display Hercynian pressure-solution seams formed at right angles to the bedding. These are present in the foreland for several kilometres ahead of the Hercynian thrust front before they die out. This probably represents a thrust front which ends with the thrust cutting up section at its leading edge.

In the Oslo Graben the Osen-Roa Detachment probably died out horizontally. As the horizontal limit of the detachment represents precicely where the influence of orogenic stresses finished, (unlike a ramping thrust which may be able to stress the footwall) the limit of the Caledonian deformation is constrained by the extent of the detachment tip line.

A cleavage front may therefore be developed in the foreland rocks ahead of the current thrust front when the lowest thrust sheet has frontally ramped at its leading edge. This of course means that the thrust sheet has travelled a unknown distance over the cleavage front after frontally ramping. However, a cleavage front may coincide with, but not extend beyond, a detachment which dies out horizontally. For example in the Oslo Graben cleavage has (except very locally) died out before the actual thrust front is reached.

CHAPTER 7

THE STRUCTURAL GEOLOGY OF MJOSA AND THE SPARAGMITE REGION.

7.1 Introduction

The Mjosa and Sparagmite regions (see Fig.7.1) comprise allochthonous sediments of late Precambrian (Eocambrian) to Silurian age which rest on structurally autochthonous Precambrian basement gneisses and thin Eocambrian to Cambrian sediments. Some Permian intrusions are also present, especially in the south of the Mjosa area, though they are not as extensive as those in the southern part of the Oslo Graben.

Traditionally the Caledonian thrust front has been positioned in the southern Mjosa area along a line separating the northern imbricated Quartz-Sandstone Nappe units from a southern, folded Cambro-Silurian sequence which rests on Precambrian basement (Skjeseth 1963). The Sparagmite region was thought to be parautochthonous by Schiotz (1902) who proposed that there were local, fault bound basins within the Eocambrian sequence, (called the Hedmark Group by Bjorlykke et al 1967). Schiotz's view dominated thought about the development of the region into the 1970's e.g.Strand (1972). However Oftedahl (1943) had proposed an autochthonous model involving transport distances for the Eocambrian rocks of up to 300km. This model has at last been gaining favour amongst workers in the Sparagmite region e.g. Nystuen (1981).

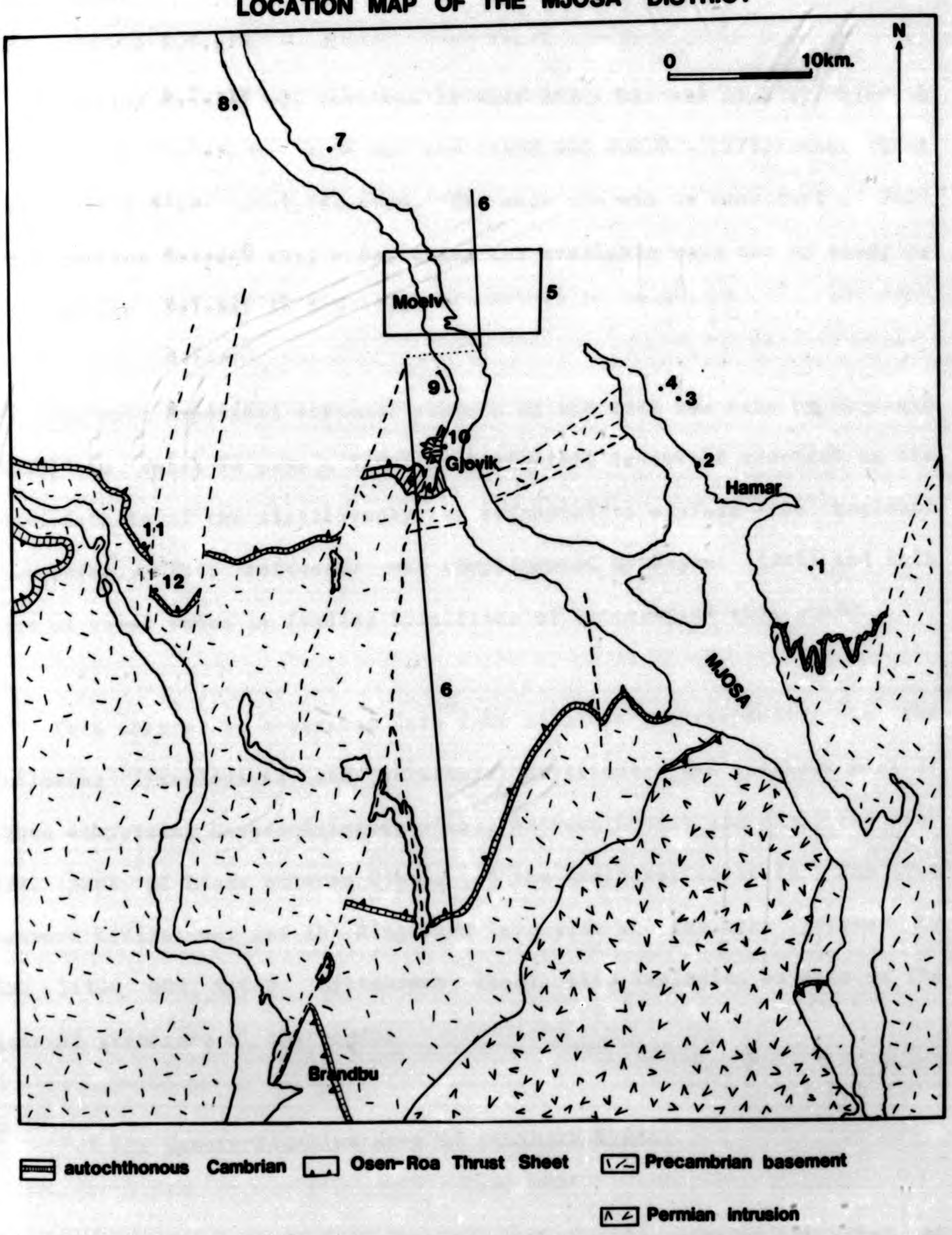
In this chapter the traditional position of the thrust front in Mjosa is contested and it is proposed that the Osen-Roa Thrust, which lies at the base of the Quartz Sandstone Nappe (or Osen-Roa Nappe) continues into the Oslo Graben. A series of ramps and flats are cited as

Fig.7.1 Location map for the Mjosa region

Localities

1. Ottestad-Hamar road section		Fig.7.2
2. Steens Kalkbrenneri		Fig.7.4
3. Berg road section		Fig.7.3
4. Sollerud	(see Appendix 1)	Plate 19
5. Moelv Duplex (map)		Fig.7.8
6. Section from Lundehogda to Eina		Fig.7.9
7. Dehli		Fig.7.6
8. Vingrom		Fig.7.6
9. Darlsjordet		Fig.7.5
10. Furuset		
11. Fluberg		
12. Loken Farm		

LOCATION MAP OF THE MJOSA DISTRICT



the means by which the Osen-Roa Thrust cuts up section to eventually form the detachment beneath the Cambro- the Oslo Graben. Hence the imbricate stacks of the Oslo region are the logical extension of the Osen-Roa Thrust Sheet.

No major mapping was involved in this study because maps by Skjeseth (1963), 1:50,000 N.G.U. maps and the 1:100,000 N.G.U. Lillehammer sheet were available for interpretation. The main aim was to construct a balanced section through this area, using the available maps and by studying well exposed sections in the area.

The most important regional summary of the area was made by Skjeseth (1963) in which he gave a detailed historical review of research in the area, details of the stratigraphy and attempted to explain the regional structures. This reference was complimented by Bryhni (1981) and both were of great value in finding localities of interest to this study.

This chapter is separated into four sections corresponding to the following lithological and structural divisions: the southern part of Mjosa comprising Cambro-Silurian rocks, between Gjovik and Eina; the central part of Mjosa between Gjovik and the Ringsaker inversion; the area between Lillehammer and the Ringsaker inversion and the area covered by the 1:100 000 N.G.U. Lillehammer sheet, also including aspects of the general structure of the region.

7.2 <u>The Cambro-Silurian area of southern Mjosa.</u>

The Cambro-Silurian stratigraphy of Mjosa is similar to that of Hadeland (see Chapter 2). Both areas have predominantly incompetent Cambro-mid Ordovician rocks below competent mid Ordovician-Silurian rocks.

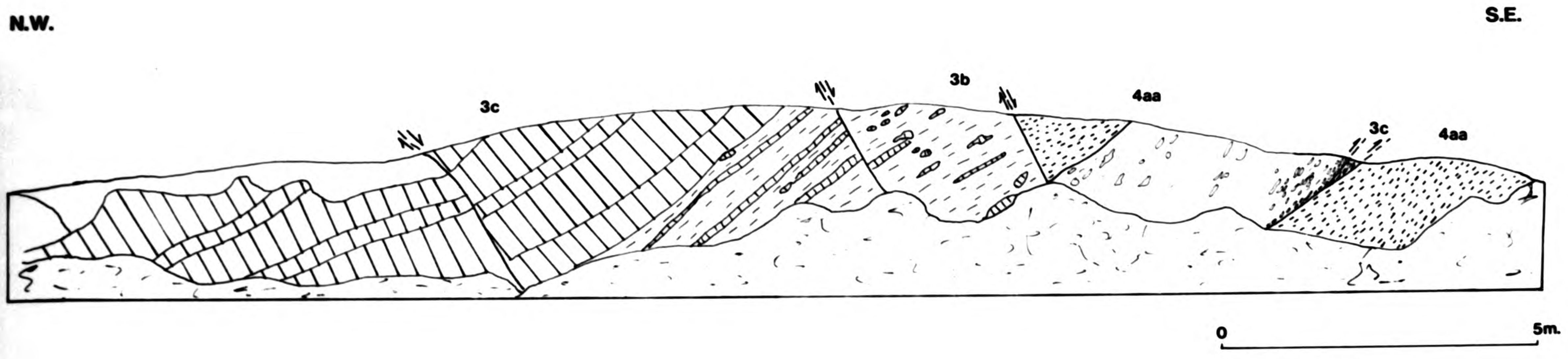
Briefly, the Mjosa stratigraphy from the base upwards is as follows (see Fig 2.5): Incompetent Cambro-mid Ordovician, Alum Shales (100m), Stein Limestone (15-40m),4aa-4b shales divided into the Bjorg Formation (70m), Hovingsholm Shales (150m) and the Furuberget Formation (50m). Competent mid Ordovician-Silurian, Mjosa Limestone (100m), Helgoya Quartzite (6-10m), Limovnstangen Formation (10-20m), Ek Shale (20m) and Bruflat Sandstone (200m). At the top of the Mjosa Limestone there is an unconformity spanning the age of upper 4c-6b.

The similarities in stratigraphy between the Mjosa and Hadeland areas have resulted in similar deformation styles in the two areas. However erosion has separated the Hadeland area into an imbricated northern part and a folded southern area, whilst in Mjosa it is possible to trace folds in the higher units laterally eastwards into imbricated lower units.

The importance of imbrication in the lower units of Mjosa has in the past largely been ignored and key sections (eg. the Ottestad section, Skjeseth 1963, fig.41 and page 96 :see Fig.7.2 for comparison) have been misinterpreted. Skjeseth (1963, p.96) does, however, mention one section where thrusting and folding have repeated the Orthoceras Limestone twenty times in 400m.

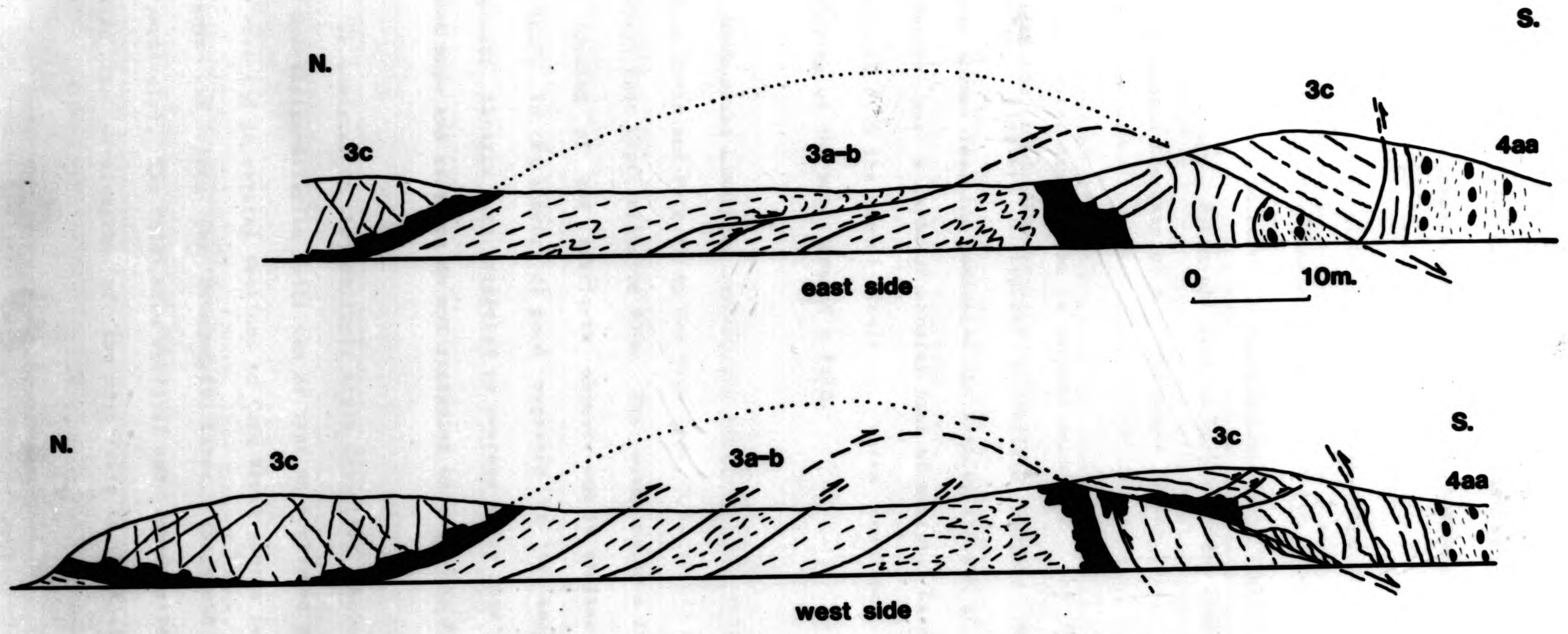
An important feature of the deformation of the Cambro-mid Ordovician is the folding of imbricate thrust planes, not just by foreland progressing sequential imbrication, but by "active buckling". As the later buckling masks the inital shortening by imbrication, the amount of shortening in poorly exposed sections can be easily underestimated. The section at Berg (Fig.7.3) shows how difficult it is to judge the style of deformation from poor outcrops. With less outcrop it would be easy to

Fig.7.2 Faulted Ordovician rocks along the main road north of Ottestad Church (G.R. 165 384).



N.W.
S.E.
3c
3b
4aa
3c
4aa
0
5m.

Fig.7.3 <u>Road sections either side of the E6 at Berg (G.R. 081 480)</u>



The west side profile has been reversed to enable direct comparison of the two sides.

interpret the Berg area as having deformed just by simple folding, but the good exposure reveals a folded imbricate thrust.

The Berg section also displays conjugate sets of fractures forming in the folds at a steep angle to bedding. These structures are explained as accommodation structures in massive limestones where flexural slip is unable to function. Minor off-sets in keystone-like limestone blocks are produced around the base of the limestones in the fold.

Imbricates can be seen in several sections: the Ottestad section (Fig.7.2) displays a typical hinterland dipping imbricate thrust. However normal faulting dominates the section and one of these extensional faults has a throw of several tens of metres. Later folding may be associated with the normal faulting, which developed in response to stretching on the outer arc of a fold.

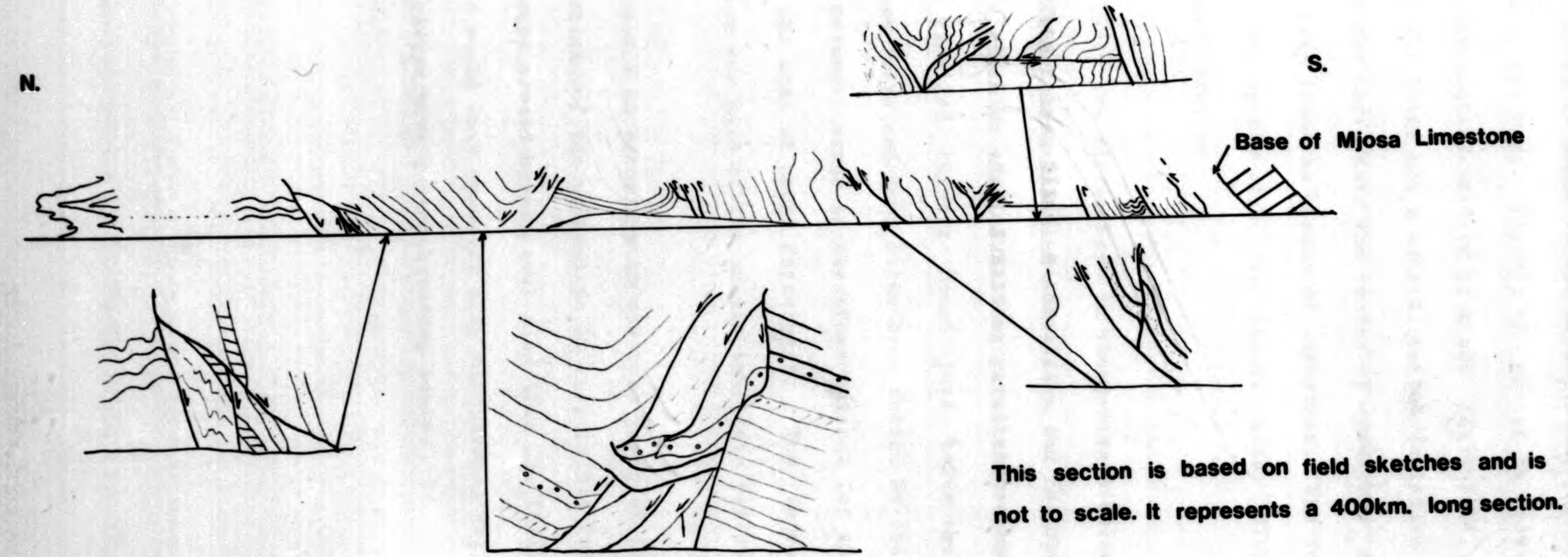
Orthoceras Limestone repetitions can also be seen in a section between Hamar and Berg along the main road (G.R.103 476 to 106 475) which displays four repetitions in 500m. This seems to be a fair reflection of the spacing of the imbricate thrusts and is similar to that found in Hadeland. In the absence of good exposure it is suggested that the imbricate thrusts are repeated on average every 150m and that the published maps and sections do not recognise this density of thrusting.

In contrast to the imbricate style described above, the competent mid Ordovician-Silurian units can be seen on published geological maps of the area and in several sections to form broad gentle folds eg. Bruflat, Helgoya and along the Brumundelv River, (Skjeseth 1963, p.81,97,83, respectively). The folds have vertical and sub-vertical axial planes, whilst the wavelengths of the main folds in the Mjosa Limestone range from 275-1000m,(averaging 500m). However in the northern part of the area, above imbricated rocks (including the Vangsas Formation at the base), the wavelength increases to an average of 1000m. Amplitudes for the whole area range from 150-500m with interlimb angles ranging from 100 to 130°. The amount of shortening (e) achieved by folding is about 28%.

The discrepancy in the amount of shortening above and below the base of the Mjosa Limestone, shown by the contrasting deformation styles described above appears to be similar to that described for Hadeland (see Chapter 5). Whilst the amount of shortening (e) within the lower units is probably 50% or more, the upper units have only shortened by about 28%. Therefore the discrepany in the amounts of shortening means that the upper detachment in the Hadeland area probably continues into the Mjosa area at about the same stratigraphic level.

At Steens Kalkbryenneri, Furuberget there is a N-S section through the 4a-4b shales and the Mjosa Limestone. This section (see Fig.7.4) shows the junction between the tightly folded and imbricated Cambro-mid Ordovician rocks and the broadly folded mid Ordovician-Silurian rocks at the proposed level of the upper detachment. The mid Ordovician shales in this section display early tight folds, rotated by the syncline in the Mjosa Limestone up to 90° from their intial positions so they now have horizontal axial planes. In the shales on the northern side of the syncline numerous minor faults and folds can be seen. Most faults are sub-parallel or parallel to bedding and have splays of minor thrusts. At the northern end of the section minor thrusts have transported material towards the synclinal core, whilst progressing southwards the thrusts have a dominant transport direction away from the core.

Fig.7.4 Deformation within the Hovingsholm Shale and Furuberget Formation, Steens Kalkbrvenneri, Furuberget (G.R. 092 442)



This section is based on field sketches and is not to scale. It represents a 400km. long section.

The change in sense of the almost bedding parallel thrusts can be explained in two ways. Firstly the change in sense of slip can be due to crossing the neutral surface of a concentric fold. Ideally flexural slip in synclinal folds has a slip direction (relative to the underlying bed) away from the core, near the centre of curvature and towards the core further away from the centre of curvature. The idealised structure corresponds very neatly with the thrust sense displayed by the Steins Kalkbrenneri section.

Secondly the differences in shortening between the incompetent lower part of the Cambro-Silurian succession and the competent upper half must lead to a plane or zone of bedding parallel detachment being formed. The bedding parallel thrusts found just below the Mjosa Limestone have a backthrust sense and have later been folded by the syncline. Their timing and movement sense is therefore correct for these faults to represent part of the zone of upper detachment. The thrusts of opposite sense below them are part of the normal imbricate pattern.

It would be necessary to see both limbs of the syncline in order to prove which of the mechanisms is responsible for the thrusting. If the faults were caused by flexural slip then the thrusts on either limb of the fold would have opposite slip directions, whilst the upper detachment should always have a backthrusting sense.

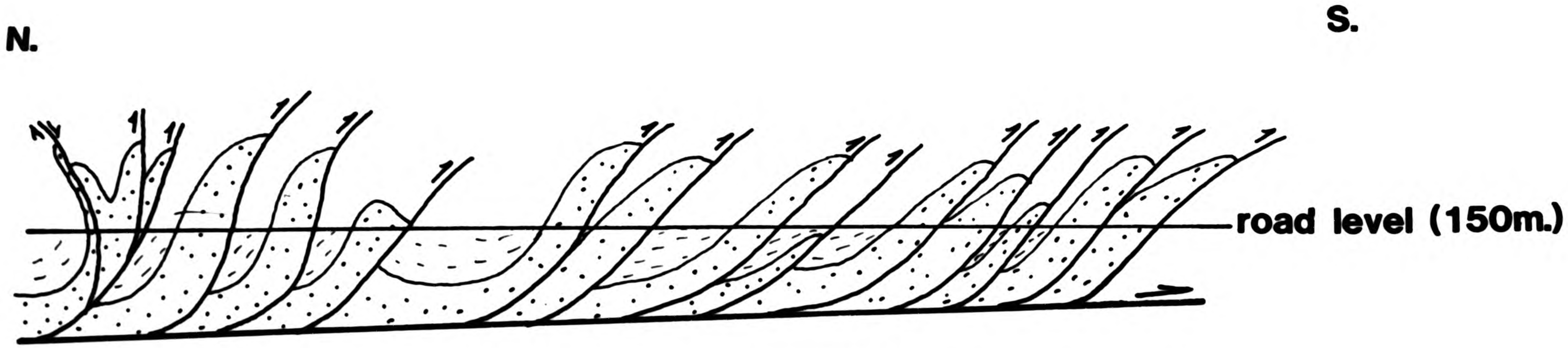
7.3 The area between Gjovik and the Ringsaker inversion.

The area just north of Gjovik on the west side of Lake Mjosa and just north of Berg on the east side of Lake Mjosa is the most southerly extension of Eocambrian rocks in Norway. There is a ragged E-W boundary to this area which is separated from the Cambro-Silurian rocks of the Oslo Graben by a thin strip of Precambrian basement (see Fig.7.1).

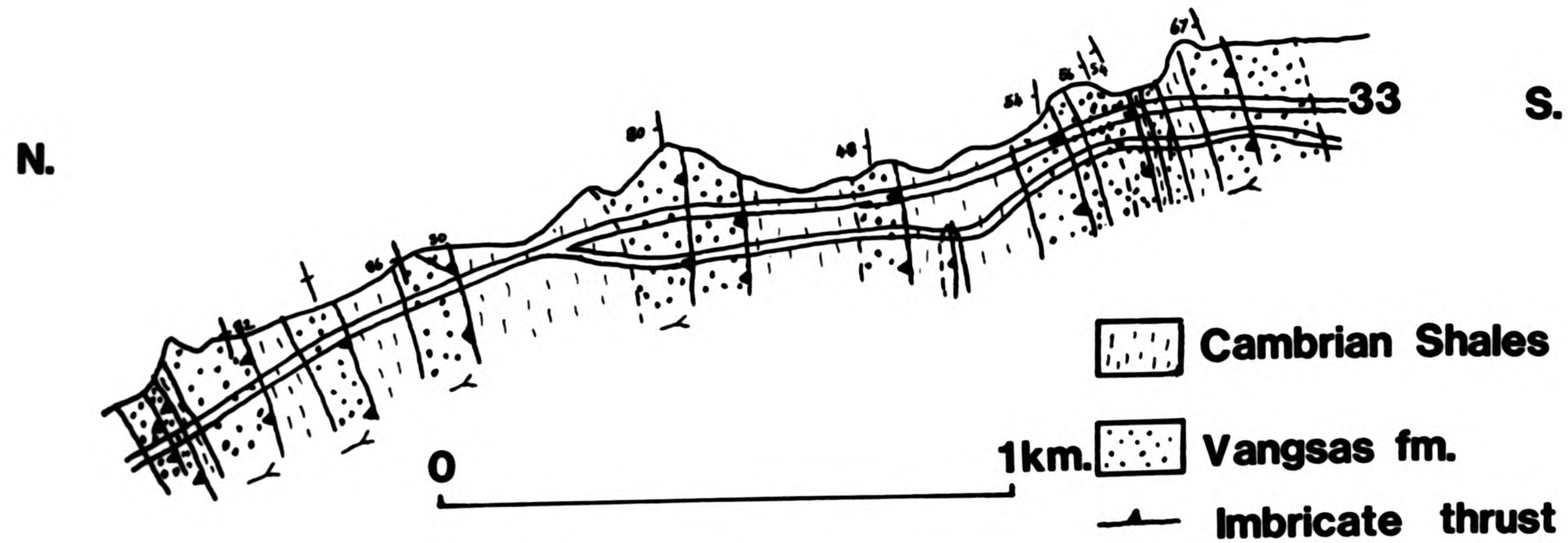
The present eroded outcrop pattern has given rise to the spurious position of the (traditional) thrust front. Evidence that the Osen-Roa Thrust should pass into the Oslo region can be found on the eastern side of Lake Mjosa where there is no erosion separating the Eocambrian from the Cambro-Silurian rocks. The younger rocks lie at first on top of, and are deformed together with, the Eocambrian whilst further south they lie allochthonously on Precambrian basement.

The base of the Osen-Roa Thrust Sheet is exposed in several hillside and Mjosa shoreline outcrops. At Furuset, 1km north of Gjovik the base of the thrust sheet is exposed, where Ekre Shales at the base can be seen to be overthrusting younger, folded, para-autochthonous Vangsas Formation and Cambrian shales. The Furnes section must display the most southerly extent of the Sparagmite basin because the Alum Shales are the only autochthonous sediments found elsewhere along the traditional thrust front and no Eocambrian sediments are found south of this area. In the Gjovik area the Vangsas Formation is present in the autochthonous footwall of the Osen-Roa Thrust , the thrust sheet was transported over the footwall from the NNW to the SSE. Therefore the absence of the Vangsas Formation in the hangingwall of the Osen-Roa Thrust Sheet south of Gjovik must be tectonic and not due to sedimentary thinning (see Fig.7.9).

Fig.7.5 Road section through imbricated Vangsas Formation and Cambrian shales, Darlsjordet (G.R. 919 570 to 924 490).



Cross-Section constructed from the outcrop along road 33.

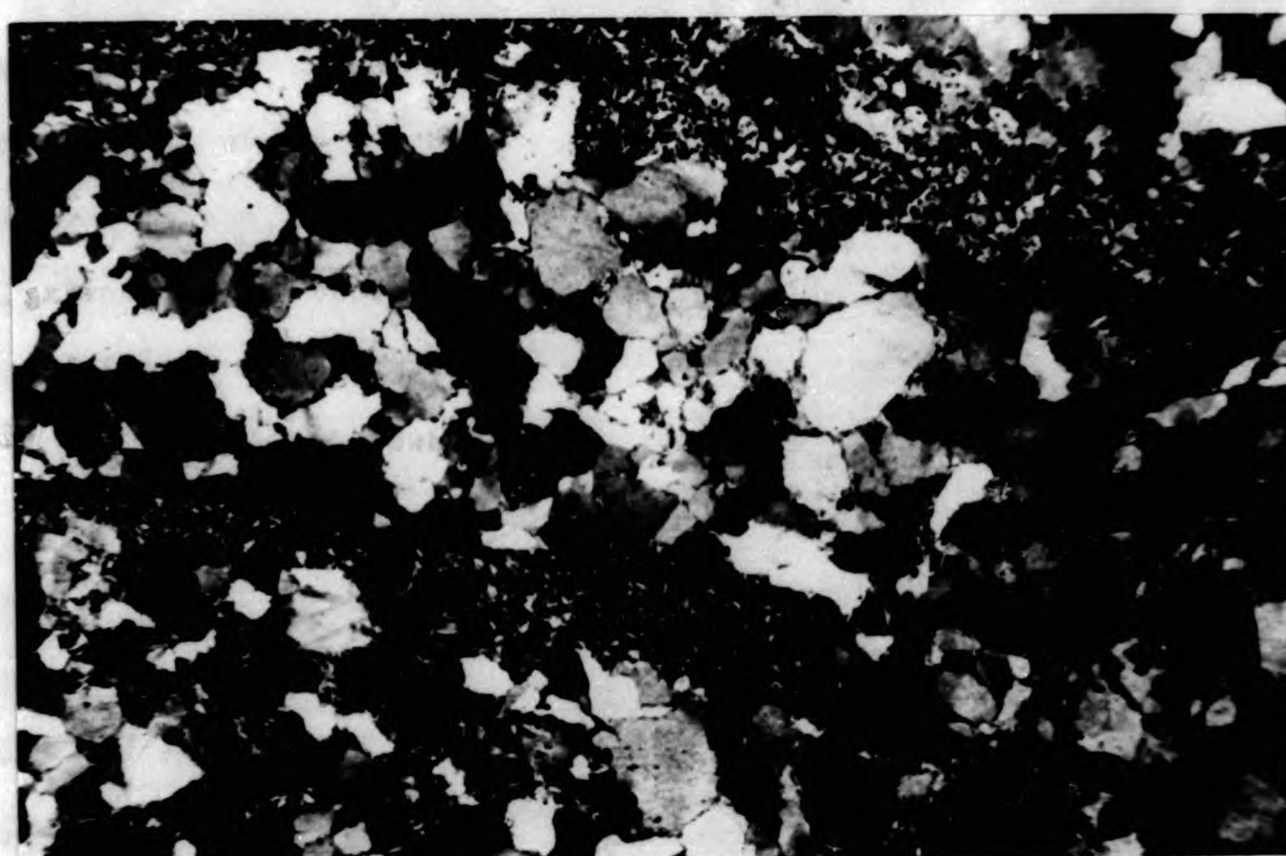


Geological sketch map

Plate 7.1 Thin section of Vangsas Formation sandstone (x20) showing pressure solution of grain boundaries and discrete zone of dislocation and creation of sub-grains, Darlsjordet.

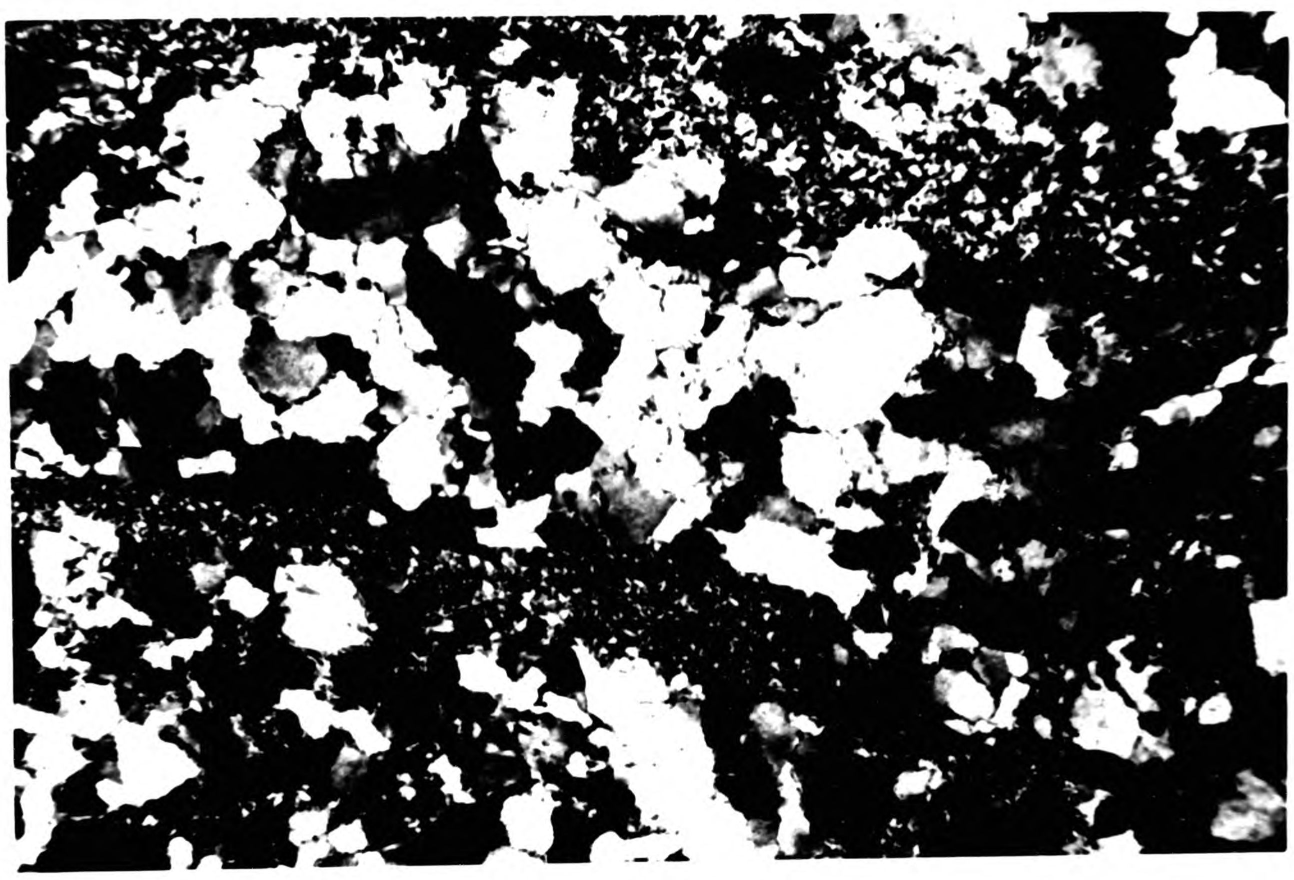
Plate 7.2 Thin section of Vangsas Formation sandstone (x20) showing advanced formation of sub-grains, obliteration of original stylolitic grain boundaries and amalgamation of dislocation-creep zones, base of Osen-Roa Thrust sheet, Fluberg.

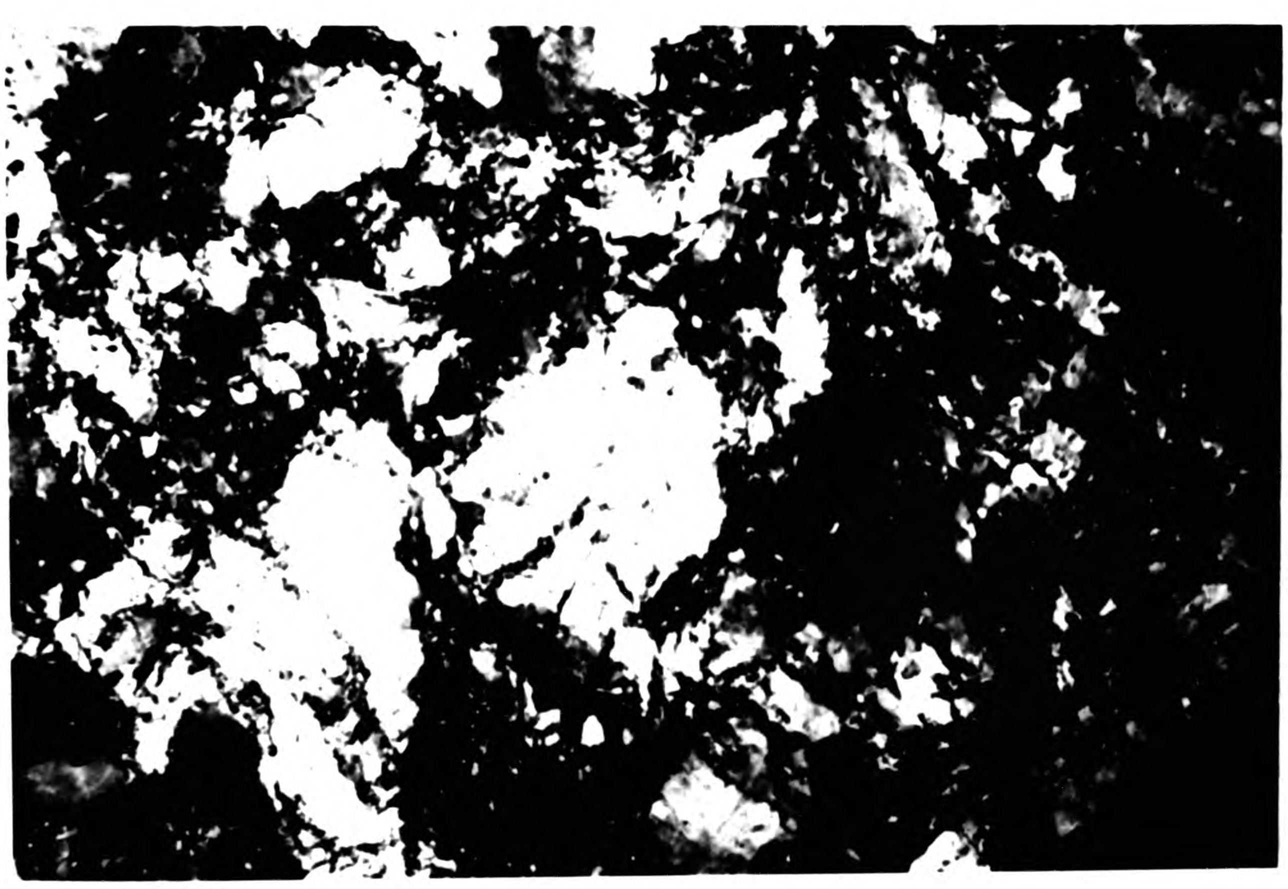
Fisherig (N.H.688 392) the Dørn-Hoe Thrust Sheet can be seen over Precambrian basement in the surrounding hillsides (see Hol-

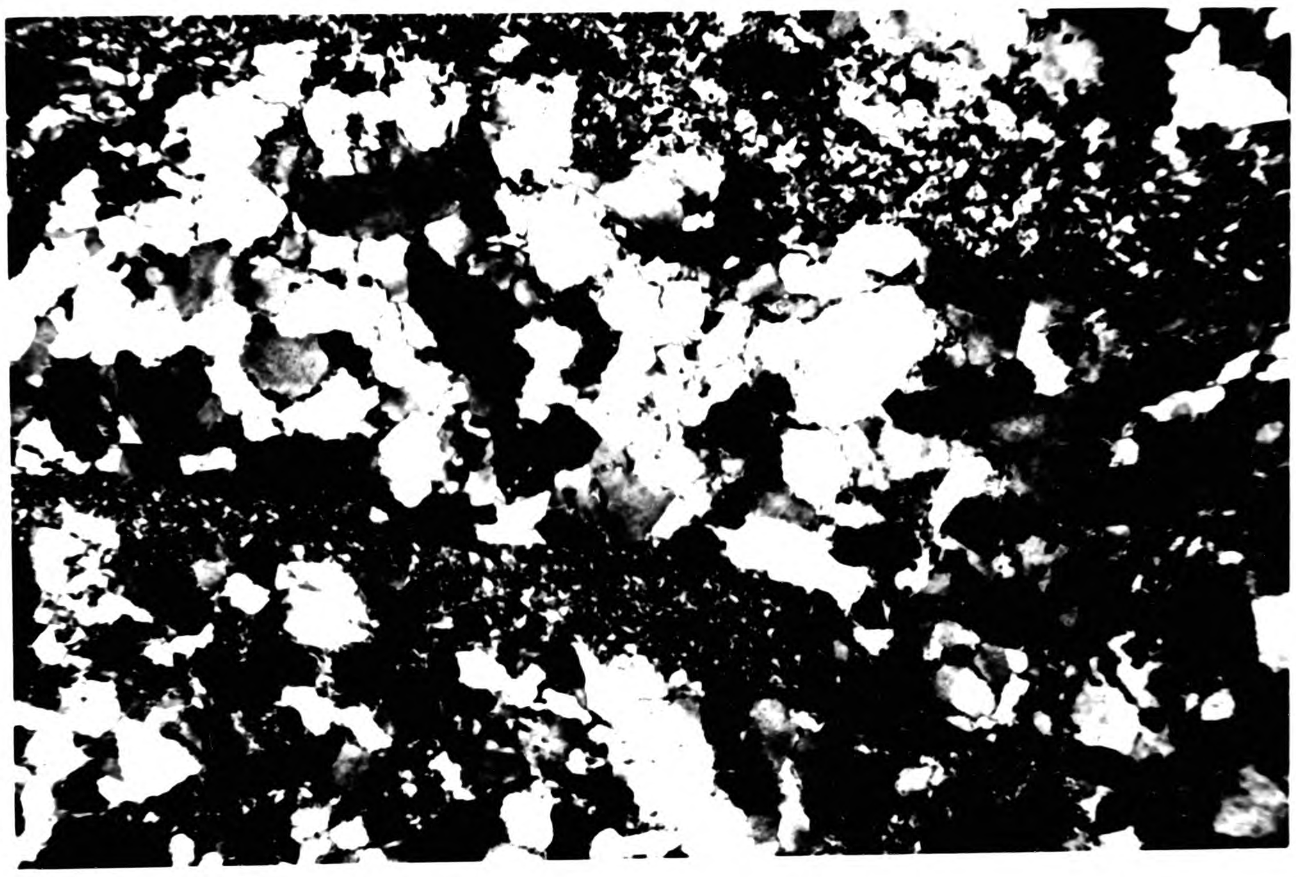


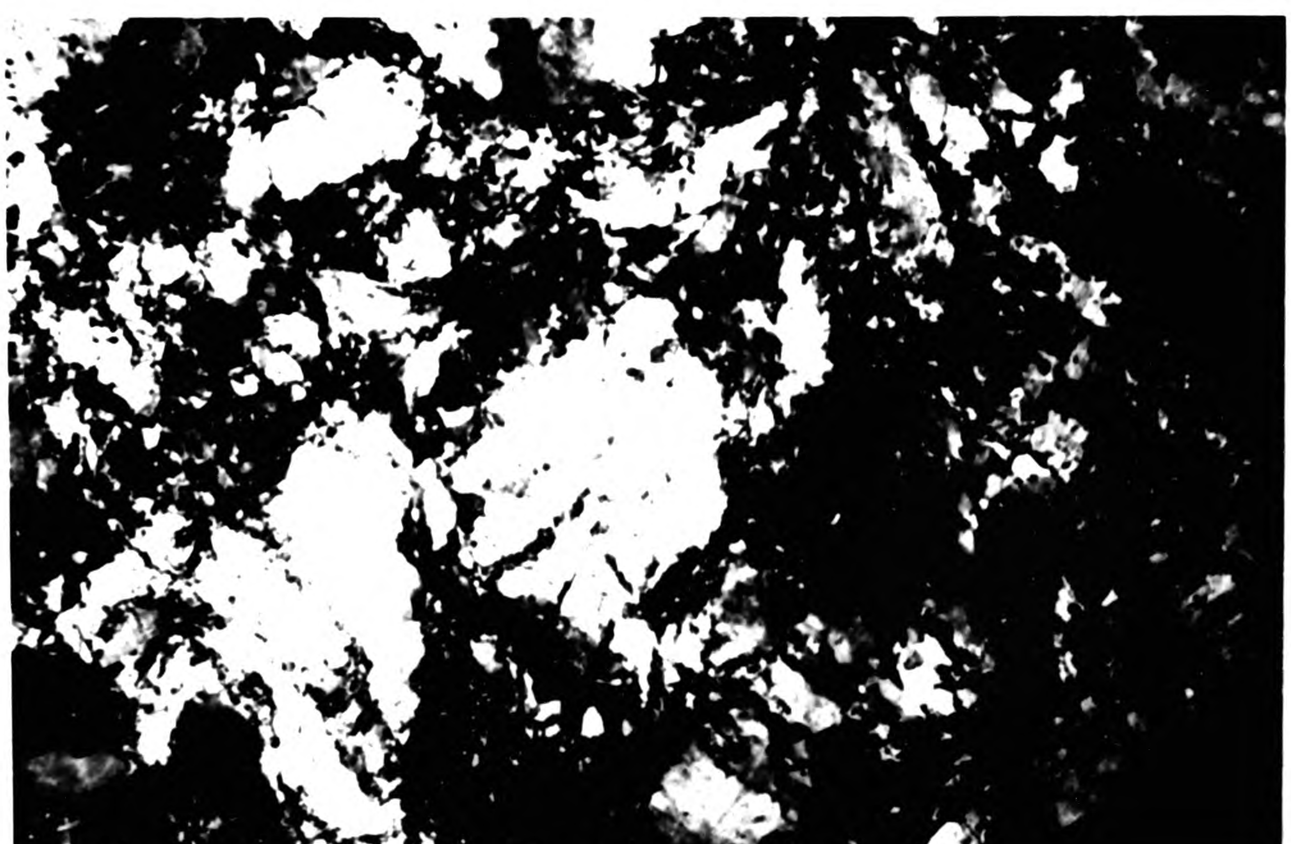
of Vangsas Formation and Cambrian shales in 2km. The spacing of imbricates along the section averages one every 165m with displacement along the thrust plane up to 200m. The northern part of the section shows that some thrust planes within the thrust sheet have been ... by subsequent foreland propagation imbrication. Shortening

Whilst in thin section all grain boundaries can be seen to be









At Fluberg (G.R.688 392) the Osen-Roa Thrust Sheet can be seen thrust over Precambrian basement in the surrounding hillsides (see Holtendahl 1915). Also at this point by the road side there is a small exposure of Vangsas Formation which has been thrust over Alum shales. The thrust plane has therefore cut up section between the Furnes and Furuberget exposures in order for the Ekre Shale to be absent at Furuberget.

The outcrop pattern of the Vangsas Formation and Ogyiacaris Shales on the 1:50 000 Gjovik sheet is typical of numerous imbricate thrust repetitions. This deformation style within the thrust sheet is well displayed at Darlsjordet and Vinju. At Darlsjordet a section along the main Gjovik-Lillehammer road (see Fig.7.5) displays thirteen imbricate repetitions of Vangsas Formation and Cambrian shales in 2km. The spacing of the imbricates along the section averages one every 165m with displacements along the thrust plane up to 200m. The northern part of the section shows that some thrust planes within the thrust sheet have been oversteepened by subsequent foreland progressing imbrication. Shortening (e) estimated by line length balancing along the road section is 55%.

The shoreline section at Vinju (G.R.935 525 to 940 516) also involves imbrication of the Vangsas Formation and Cambrian shales, but the imbrication is more complicated here than at Darlsjordet. The section displays in places steep, northwards-plunging folds probably produced by rotation above later lateral and oblique ramps.

Internal deformation within the Vangsas Formation increases approching imbricate thrusts. In the field this can be seen by an increasing number of pressure-solution seams and minute shear zones adjacent to a thrust. Whilst in thin section all grain boundaries can be seen to be stylolitic except where new sub-grains have been created (Plate 7.1). Usually these new grains form linear zones of more intense deformation varying laterally in thickness and displacement. The most intense deformation was found in the Vangsas Formation directly above the Osen-Roa Thrust, where in thin section the sandstone displays relic stylolitic grain boundaries surrounded by wide areas of sub-grain formation, probably representing amalgamated linear dislocation-creep zones (Plate 7.2).

Summary of the geology from Gjovik to Ringsaker inversion.

The Eocambrian at the base of the Osen-Roa Thrust Sheet youngs towards the south; the Moelv Tillite is found at the base of the thrust sheet in the north whilst Ekre Shale or Vangsas Formation forms the base in the south of the area. The thrust sheet is deformed internally by hinterland dipping imbrication and associated folding and occasionally by backthrusting and thrust wedging. In thin section the sandstones have deformed by intense pressure solution and varying degrees of dislocation-creep which increases in intensity towards thrust planes.

7.4 The structural geology from Ringsaker to Lillehammer.

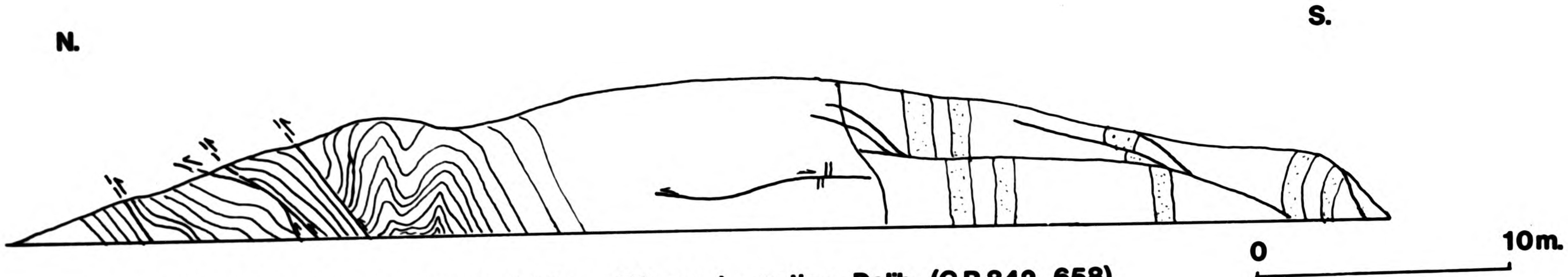
In this area the full sequence of Eocambrian rocks is present and so is conciderably thicker than in the area from Gjovik to Ringsaker . At the base of the Osen-Roa Thrust Sheet in this area is the thick (2000m), turbiditic Brottum Formation which is followed by the Biri Limestone, Biskopas conglomerate, Ring Formation, Moelv Tillite, Ekre Shale and Vangsas Formation. Of these units only the Ekre Shale (40m thick) is incompetent. The sequence thins from north to south from over 3000m of Eocambrian rocks plus an unknown thickness of overlying, eroded Cambro-Silurian rocks in the north to only 750m of Cambro-Silurian south of Gjovik. Therefore a change tectonic style might be expected between the thick, competent sequence in the north and the thin, fairly incompetent sequence in the south. Resistance to deformation in the north might have led to increased deformation in the south, to enable the stresses to remain in equilibrium.

Deformation in the Brottum Formation differs from that found in the rocks south of the Ringsaker inversion, appearing chaotic in comparison with the imbrication displayed to the south. The most informative sections through the Brottum Formation that demonstrate deformation style are along the E6 between Brottum and Lillehammer. Two good road sections are to be found along the E6 near Delih (see Figs.7.6 and 7.7) where the Brottum Formation displays tight folding, thrusting and thrust wedging.

The thrusts found in these sections are fore- and back thrusts which sometimes truncate tip line folds (see Fig.7.6). There is also a set of more horizontal, later thrusts which displace folded beds and usually have a backthrust sense with only minor displacements (less than 2m).

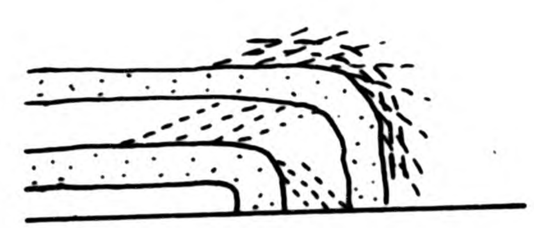
Thrusts are secondary in importance to buckle folds which form broad open folds of class 1b (Ramsay 1967), with interlimb angles up to 120°; to tight angular folds with interlimb angles down to 45° which display the thickened hinges and thinned limbs of class 2 folds (Ramsay 1967).

Fig.7.6 <u>Examples of deformation within the Brottum Formation</u>



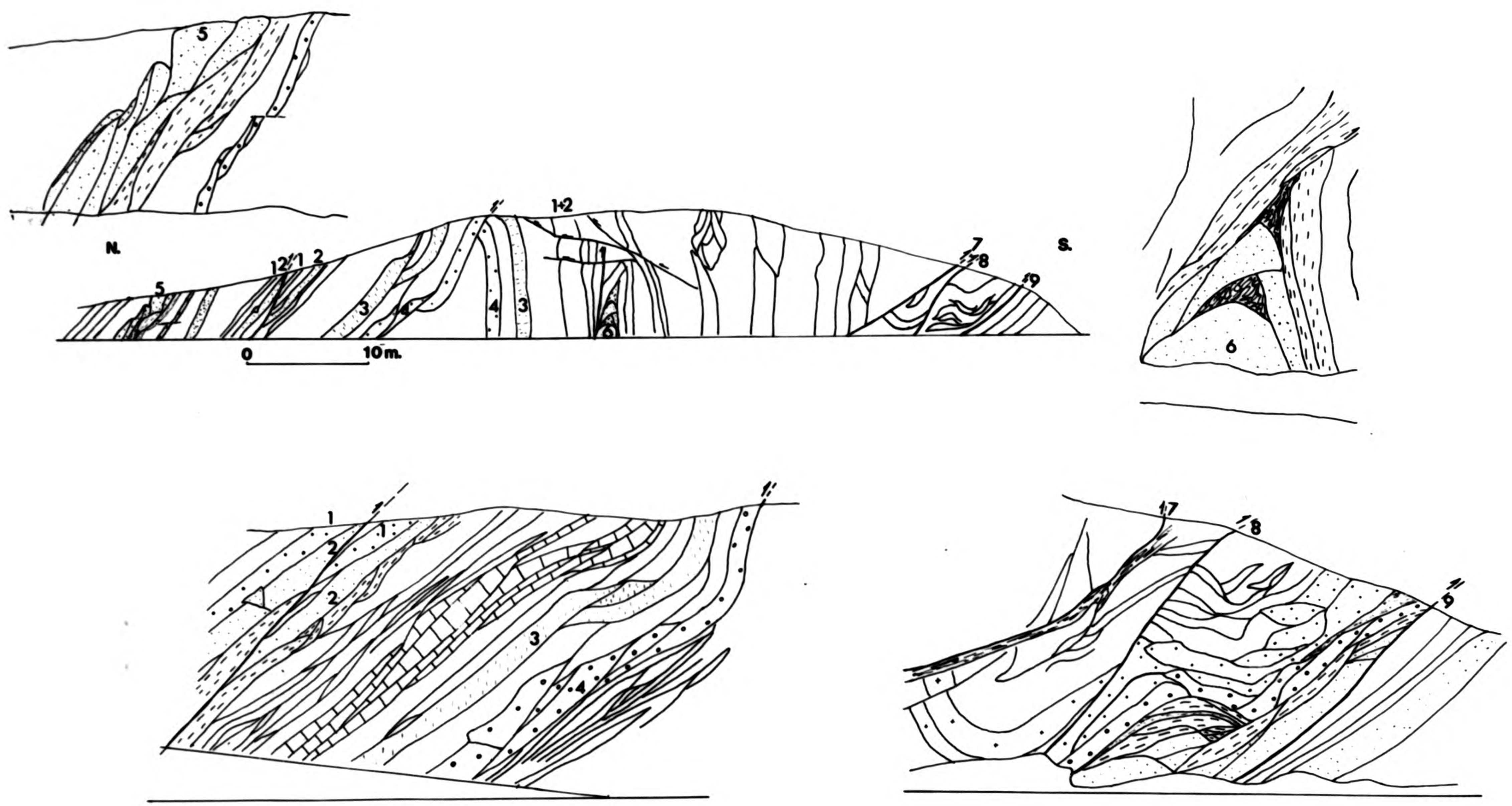
Back thrusting and associated folding, E6 road section Delih (G.R.842 658).

Pencil cleavage,Vingrom (G.R. 775 693



Pencils are formed by the intersection of a hinderland dipping cleavage and a bedding parallel cleavage.

Fig.7.7 Deformation within the Brottum Formation, road E6, Dehli (G.R. 842 658)



The alternating sandstone and shale bands have been folded and thrusted. Complex thrust wedging produced significant amounts of shortening in the competent units (see detailed sketches of portions of the main section).

The tight buckle folds have complex patterns of thrusts and thrust wedging associated with them. The shales between the competent silt and sandstone layers have undergone flow towards the fold cores, whilst the competent layers have experienced thrust wedging. Two associations of thrust wedges can be recognised. Thrust wedging can be localised, because individual thrust wedge faults join up to form a single fracture, (similar to a roof thrust of a duplex), which has a throw equal to the sum of the displacements on the individual thrust wedges, eg. the thrust affecting beds 1 and 2, Fig.7.7. Elsewhere thrust wedging may be distributed more evenly along a competent bed which is evenly divided up by a series of fractures eg. bed 4, Fig 7.7.

Thrust wedging may contribute up to 50% shortening (e) along a single bed in the Dehli road sections, which is far greater than can be explained by the formation of thrust wedges during flexural slip folding. Cloos (1961) made similar observations on thrust wedges in the Appalachians and explained the thrust wedges as early structures which formed sub-horizontally and were subsequently folded and rotated. A similar origin is proposed for the thrust wedges in the Brottum Formation.

Pencil cleavage may also be strongly developed within the Brottum Formation. Long, thin pencils indicating intense cleavage formation (Reks and Gray 1982) are formed by the intersection of a bedding parallel (flexural slip?) cleavage and a hinterland dipping cleavage (Fig.7.6). Both sets are seen to have been subsequently folded.

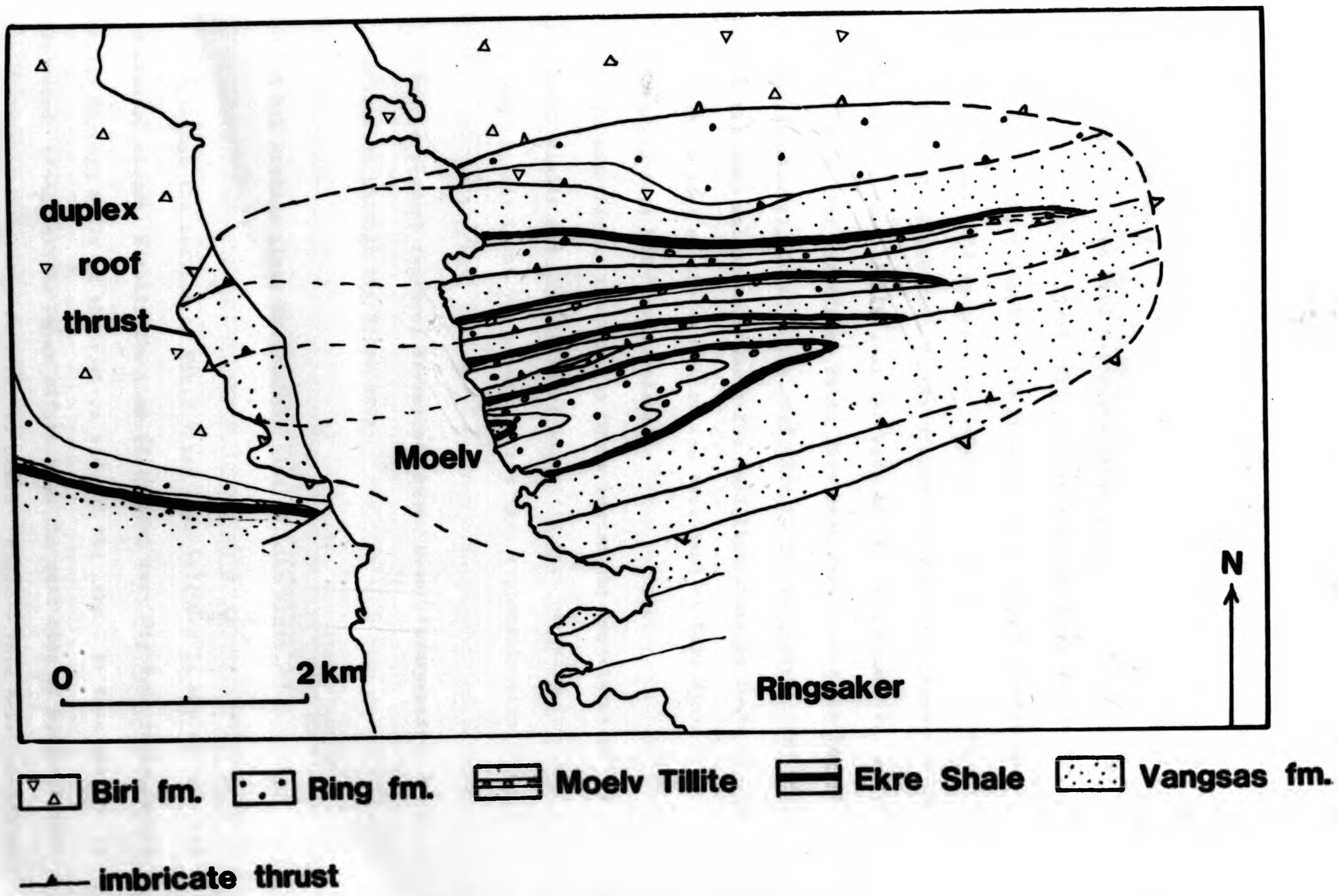
7.5 The important structures of the Lillehammer-Giovik area

The deformation within the Osen-Roa Thrust Sheet though still strong, decreases in intensity south of Lillehammer. This is associated with the sequence thinning rapidly south of the Ringsaker inversion. Rather than internally deforming the thick Eocambrian sequence it was probably easier for shortening to be achieved by extra movement on the sole thrust in order to take up the shortening in the thin incompetent rocks to the south.

The important structural features of the Lillehammer-Gjovik area which have been considered when trying to construct a balanced cross-section are as follows:

1. The rocks found at the base of the Osen-Roa Thrust Sheet become progressively younger southwards.
2. The disappearance of the thick Brottum-Ring Formation sequence is rapid (too rapid to be sedimentary) and coincides with the line of the Ringsaker inversion. The disappearance of the Vangsas Formation in the hangingwall north of Gjovik is also achieved over a short distance and cannot be due to sedimentary thinning because there is autochthonous Vangsas Formation in the footwall below the thrust sheet in this area.
3. The lowest Cambrian shales form the autochthon resting in most places on Precambrian basement or, occasionally, on autochthonous Vangsas Formation. These shales have been over-ridden by the Osen-Roa Thrust Sheet so that as the Vangsas Formation dissappears from the thrust sheet the Osen-Roa Thrust must pass into the (Cambrian) Alum Shales which form part of both the allochthon and autochthon within the Oslo Graben.

Fig.7.8 Geological map of the Moelv Duplex window (based on Vogt 1953)


duplex
roof
thrust
Moelv
Ringsaker
0
2 km
N
Biri fm.
Ring fm.
Moelv Tillite
Ekre Shale
Vangsas fm.
imbricate thrust

4. The Moelv area has been the subject of much discussion concerning the recognition and importance of tectonic units. Vogt (1953) described the geology on both sides of Mjosa at Moelv-Biri (Fig.7.8)and introduced the terms Biri Nappe and Moelv window for what he recognised as an allochthonous and autochthonous series respectively.(The Biri Nappe was later renamed the Sparagmite Nappe by Skjeseth, 1954). The section drawn by Vogt (1953) through the Moelv window displays the geometry of a duplex (though the term was not used at the time). Imbricate thrusts repeat the Ring-Vangsas Formations in the window, so the floor thrust to the imbricates probably lies at the base of the Ring Formation. The Biri Formation and higher units have been thrust over the top of the imbricates, forming the roof thrust. The hangingwall cut off of the ramp culmination above the roof thrust can be found at the southern edge of the window on the west bank of Lake Mjosa trending in a ENE-WSW direction.

In any section through the Mjosa region the importance of the Moelv window and the Ringsaker inversion must be evaluated. Are they of only local importance or are they regionally significant?

The structural features discussed have been incorporated into a cross-section through the Mjosa area.

A N-S section along the western side of Lake Mjosa.

Although the section in Fig.7.9 has been balanced it may contain two sources of error. Firstly the line of section (see Fig.7.1) in the north passes through Moelv on the eastern side of the lake. It then has to be projected along strike on an offset onto the west side of Mjosa so that the the section does not continue in water. However this does not affect the amount of shortening displayed in the section, nor the interpretation because the structures on both sides of the lake are similar and the distance from the Ringsaker inversion can be kept constant in the projection along strike.

Secondly, the southern part of the section is drawn through the Cambro-Silurian rocks between Gjovik and Eina, mapped by Skjeseth (1963). Although this work quite accurately shows the folding in the Silurian rocks the scale is too large to reflect the deformation within the Cambro-mid Ordovician. Imbrication marked by the Orthoceras Limestone is intense and considering the deformation seen in north Ringerike and North Hadeland, it is likely that the Cambro-Silurian rocks have shortened by at least 50%. This will not be reflected in a section drawn through Skjeseth's map (1963), however no other map is available.

The section, from Lundehogda to Eina, explains the structural features of the Mjosa area listed above by showing the trajectory of the Osen-Roa Thrust plane as a series of ramps and flats. The Brottum-Ring Formation is cut out by a hangingwall ramp just north of the Ringsaker inversion. In Chapter 1 it was shown that hangingwall anticlines (or culminations) can be produced above ramps, where the thrust cuts rapidly up section. In such a model applied to the Mjosa area, the Ringsaker inversion (which is a synclinal structure with a overturned northern limb of Vangsas Formation and Cambrian Shales) is the overturned fore-limb of a frontal culmination. This large fold has undergone deformation, probably during transport, so that it has been modified by structures of local significance which include the Moelv Duplex and the Biri Nappe.

Fig.7.9 Balanced cross-section from Lundehogda to Eina (see Appendix 3 for diagram).

South of the Ringsaker inversion the Osen-Roa Thrust forms a flat, at first lying below the Moelv Tillite, which is then cut out by a minor ramp so that the thrust lies at the base of the Ekre Shale. This now much thinned Eocambrian to Lower Palaeozoic sequence is imbricated- a style which is continued into the Oslo Graben.

Just north of Gjovik the Osen-Roa Thrust ramps through the Ekre Shale and Vangsas Formation. It then forms a flat so that the thrust lies within the Alum Shales and continues to do so throughout the Oslo Graben. The autochthonous Alum Shales in the footwall must therefore extend under the Osen-Roa Thrust Sheet, towards the hinterland, by a distance equal to the amount of shortening in hangingwall Cambro-Silurian rocks;ie. from undeformed foreland in Langesund-Skien to the hangingwall ramp which cuts out the Vangsas Formation at Gjovik. The palinspastic reconstruction using the relationships described above can be found in Chapter 8.

Fig.7.10 Two sections illustrating important ramps within the Osen-Roa Thrust Sheet (see fig.7.11 for location of sections and Appendix 3 for diagram).

7.6 An overview of the Sparagmite region.

It is not intended to summarise the structure of the Sparagmite region. Instead I want to discuss the consequences of structures in the Mjosa area which extend into this region and some interesting features of the region that have not been fully explained in the literature.

The Sparagmite region (see Fig.7.10) is a broadly rectangular area of thrusted, Eocambrian rocks of conciderable thickness. Two main thrust sheets have been recognised, the lowest is the Osen-Roa Thrust Sheet which comprises the great majority of the current outcrop. Its stratigraphy may be in excess of 3000m thick, comprising mainly Eocambrian rocks with a thin discontinuous covering of Cambro-mid Ordovician rocks on top, whilst in the north of the basin thin basement slices also become incorporated into the thrust sheet. The Kvitvola Thrust Sheet lies structurally above the Osen-Roa Thrust Sheet and is composed of Eocambrian rocks and some slices of basement.

The Sparagmite region is bound by the structurally higher units of the Trondheim thrust sheets and Valdres Thrust Sheet to the north and west respectively. To the east and south erosion has removed the frontal areas of the thrust sheets to reveal Precambrian basement below, except where the region passes into the Cambro-Silurian of the Oslo Graben. Nystuen (1981 and in press) has described the structural geology of the region most recently.

The consequence of the geology featured in the Lundehogda-Gjovik section (Fig.7.9) for the main Sparagmite region can be seen in Fig.7.11b. Underlying the Osen-Roa Thrust Sheet are autochthonous rocks, which in the south of Mjosa are usually Alum Shales resting on Precambrian basement. However, the autochthonous sequence must eventually include Eocambrian rocks which form the footwall cut offs to the hangingwall ramps in the Vangsas and Brottum-Ring Formations of Fig.7.9. These ramps will be separated by the unstrained distances of the Ekre Shale and Moelv Tillite flats.

The minimum displacement undergone by the Vangsas hangingwall cutoff from its footwall cutoff can be estimated by using the basement windows at the northern end of the Sparagmite region. Autochthonous Vangsas Formation and Moelv Tillite can be seen in places around the Atnasjoen window (and other windows too), 130km north of the hangingwall cutoff of Vangsas Formation at Gjovik. This gives a minimum displacement of 130km.

The Osen-Roa Thrust has the geometry of a flat, lying within in the Ekre Shale between the Ringsaker inversion and Gjovik. Then the Ekre Shale and Vangsas Formation are ramped through by the Osen-Roa Thrust at Gjovik, so the corresponding footwall geometry should also be a ramp. In the windows however, the autochthonous Vangsas Formation is exposed as a flat. As this cannot be the correct geometry (the flat should occur in the footwall Ekre Shale), the autochthonous Alum Shales probably originally covered the Vangsas Formation in the windows and were subsequently removed. This prediction is supported by the presence of small, intense folding and graphitisation of the autochthonous Alum Shales in south Mjosa. Therefore the absence of the Alum Shales in the windows can be explained by the Osen-Roa Thrust Sheet "rucking up" the uppermost part of the autochthon and dragging it a few tens of kilometers southwards. This has in effect caused a branch line to migrate, where the branch line is the junction of the Osen-Roa Thrust (ramping through the Alum Shales) and the thrust at the base of the "rucked up" parautochthonous Alum Shales.

7.6.1 Ramp structures in the Sparagmite region.

The margins of the Sparagmite basin were thought by Schiotz (1906) to have been coincident with the post-Caledonian Rendal, Osen and Engerdal faults in the east and hypothetical faults in the south and west. This idea has prevailed in explaining the current boundaries of the Sparagmite region, except for the thrust front to the south (e.g. Skjeseth 1963 and Strand 1972). However because interpretation of balanced cross-sections and basement windows demonstrates that the Sparagmite region is allochthonous,the limits of the region are likely to be related to its emplacement history. Here it is proposed that lateral, oblique and frontal ramps define the southern, eastern and western margins of the Sparagmite region.

The Ringsaker inversion is an important structure marking the hangingwall cut off of the Brottum to Ring Formation sequence. It can be seen from Fig.7.10 that the lateral extent of the Ringsaker inversion (marked Brottum hangingwall cutoff in Fig.7.10) is considerable. The Ringsaker inversion is for most of its length a frontal culmination but its WSW-ENE trend does alter towards the east and west sides of the Sparagmite region, indicating oblique ramping.

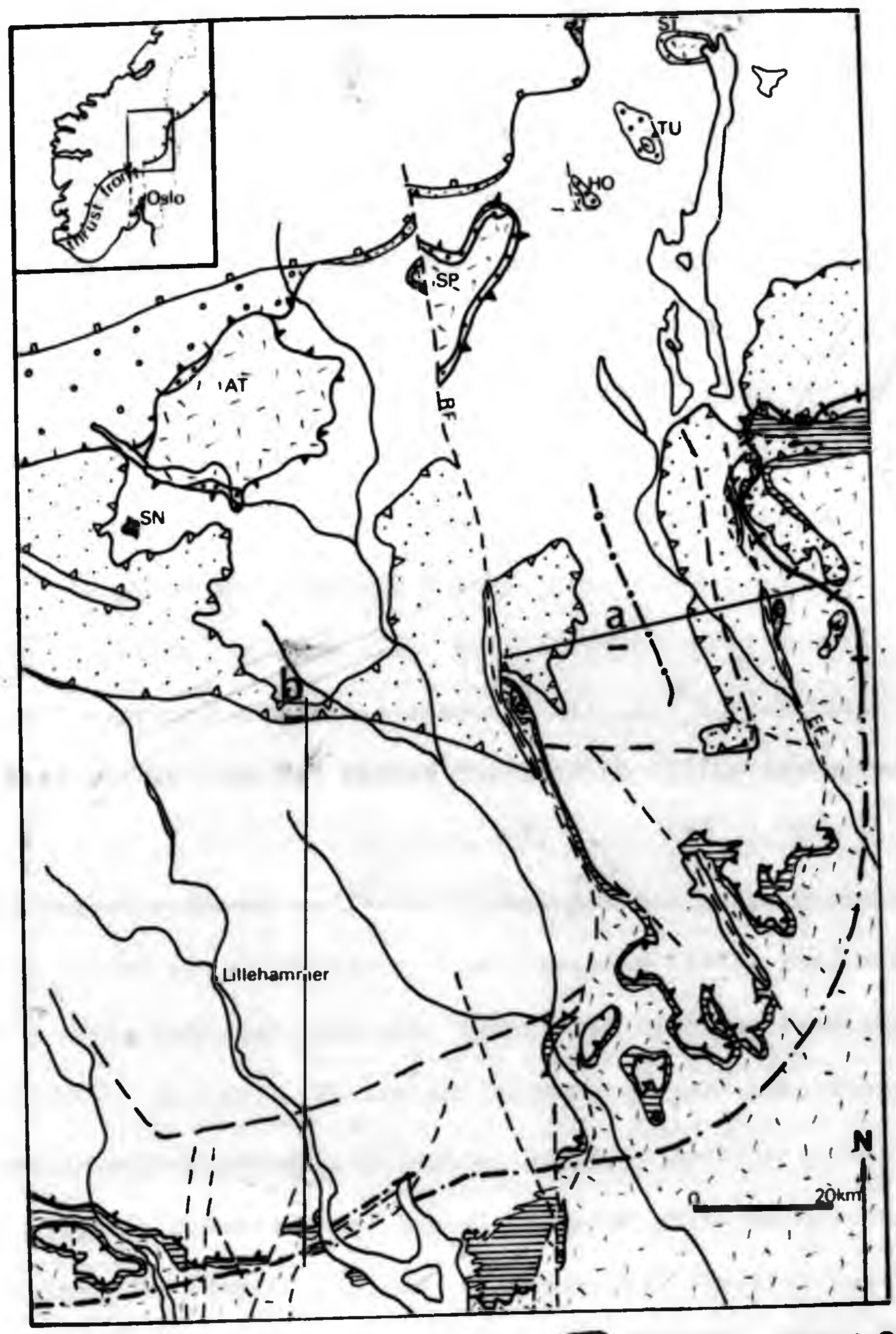
Loberg (1970) for example, recorded the Ringsaker inversion as trending NW-SE, just east of Dokka. There it could be responsible for the "christmas tree" like outcrop pattern seen in the Follebu area of the 1:100 000 N.G.U. Lillehammer sheet. This pattern is caused by the intersection of NE-SW trending structures of the Aurdal Thrust Sheet to the west and the NW-SE trending structures on the eastern side of the Osen-Roa Thrust Sheet. If the Ringsaker inversion were a late structure in this area, it could account for the outcrop pattern as the re-orientation of structures within the Aurdal Thrust Sheet by the oblique ramping of the Osen-Roa Thrust Sheet towards the SW, or by intersection of the structures produced by the oblique ramping with earlier Aurdal imbricates. The oblique ramping could also be responsible for forming the late cleavage which strikes with a sense that is always clockwise to bedding in the Dokka area (Hossack pers. comm.).

It can be seen from the structural map of the Sparagmite region by Nystuen (in press) and the 1:50 000 Engeren (2018 11) and Elvedal (2018 111) N.G.U. sheets that the eastern boundary of the Osen-Roa Thrust Sheet has undergone lateral ramping. The thick Osen-Roa Thrust Sheet on the western side of the section displays a full Eocambrian stratigraphy, which then thins dramatically eastwards untill just east of the Engerdalen Fault it is absent. This causes the Kvitvola Thrust Sheet to rest directly on autochthonous basement further east. Also in this area the Osen-Roa Thrust Sheet and the Kvitvola Thrust Sheet have been folded along a large, broad anticline which swings from a WSW-ENE to a NNE-SSW trend northwards. This NNE-SSW trend indicates movement on the thrust sheet to the ESE.

The lateral disappearance of the Osen-Roa Thrust Sheet eastwards can be explained by lateral ramping of the Osen-Roa Thrust which eventually cuts out the whole of the Osen-Roa Thrust Sheet and reactivates the Kvitvola Thrust Sheet which was carried "piggy back" style on top. The large gently folded NNE-SSW trending anticline is explained as a passive fold caused by the thrust sheets being draped over the footwall cut off of the Brottum-Vangsas Formation. This footwall sequence must also wedge out eastwards due to sedimentary thinning, because it is not seen on the eastern margin of the Sparagmite region (see Fig.7.10).

Fig.7.11 Structural map of the Sparagmite region

Line of section in Fig.7.10 marked "a" for Engeren-Elvdal and "b" for Ringsaker-Rodfjellet.



Cambrian

Autochthonous Sparagmite

Precambrian basement

Post Caledonian faults

EF-Engerdalen fault

RF-Rendalen

Osen-Roa Thrust Sheet

Kvitvola Thrust Sheet

Windows

AT Atnasjoen SP Spekedalen

HO Holoydalen TU Tufsingdalen

ST Steinfjellet SN Snodola

Approx. line of H.W.cutoff for the Vangsas fm.

Approx. line of H.W.cutoff for the Brottum fm.

Approx. line of F.W.cutoff for the Brottum fm.

Osen-Roa leading branch line.

In Fig.11a and b the actual position of the footwall ramps and flats predicted could vary depending on whether an autochthonous or allochthonous model is adopted. If it is assumed that the footwall is autochthonous then by unstraining the Osen-Roa Thrust Sheet from undeformed foreland to the footwall cut off in question the autochthonous position of the footwall can be calculated. The Brottum Formation footwall cut off, using this model, should be situated under the southern portion of the Trondjheim thrust sheets. However it is likely that the Kvitvola and Osen-Roa Thrust Sheets have undergone out-of-sequence thrusting (Nystuen in press). Part of this out-of-sequence thrusting could have involved the frontal ramping of the Eocambrian during the emplacement of the Osen-Roa Thrust Sheet south of the Atnasjoen window.

The out-of-sequence model is strongly supported by evidence from the structure known as the Elstad window. Englund (1973) recorded the presence of a shale and sandstone unit below the Brottum Formation in the Gudbrandsdalen Valley. He called these lower rocks the Elstad Unit and suggested that they either represented an older Sparagmite unit, or were younger Vangsas Formation and Cambrian shales with the Brottum Formation thrust over the top. Englund favoured the second interpretation, although he imagined that the structure was caused by only a fairly minor thrust. Hossack and Garton (pers com.) have recognised a thrust plane at the base of the Brottum Formation in the Elstad window, which supports Englunds interpretation. Here it is thought that the Elstad window reveals the abandoned leading edge of the Osen-Roa Thrust Sheet, represented by the Elstad Unit, which has been overthrust by later out-of-sequence thrusting by the Osen-Roa Thrust Sheet after it had already moved a conciderable distance.

The out-of-sequence, allochthonous model, is shown in Fig.7.10b, where the southern edge of the broad depression preserving the Kvitvola Thrust Sheet on the western side of the basin is envisaged to be caused by passive folding of the thrust sheet as it moved up the footwall ramp of the abandoned portion of the Osen-Roa Thrust Sheet.

On the eastern side of the region (see Fig.7.10) it is hard to imagine an autochthonous model because the folds and imbricates are orientated in a NNE-SSW direction and have not been modified or had other structures superimposed on them. If lateral ramping had been early then subsequent transport to the south is likely to have imposed E-W trending folds and imbricates over the area. Therefore the allochthonous footwall model as seen in Fig.7.11a is more likely to apply.

Lateral ramps have thrust the Osen-Roa Thrust Sheet to the WSW and east on the western and eastern margins of the thrust sheet, respectively, indicating variations in transport directions of up to 180°. The lateral ramps probably have less than 20km separation between the foot- and hanging- wall cut offs compared with 135km at the frontal ramp. The cause of the ramping might be explained by gravity spreading of the thrust sheet in a variety of directions. However this mechanism was probably secondary to a "push from the back" mechanism because of the significantly larger displacement of the frontal hangingwall ramp. Dramatic thinning of the thrust sheet (which is not in evidence), would be required to produce 135km of displacement by gravity spreading of the thrust sheet alone.

7.6.2 The relative timing of events in the lower thrust sheets.

The relationship of the Kvitvola Thrust Sheet with the Osen-Roa Thrust Sheet displays complex problems as to the timing of events (Nystuen 1981 and in press). The northern edge of the Kvitvola Thrust Sheet is frequently displaced by Osen-Roa imbricates, whilst the southern edge of the Kvitvola Thrust Sheet lies over truncated Osen-Roa folds.

The relationships mentioned above are well displayed on the eastern margin of the Sparagmite region. In the southern part of the eastern margin the Osen-Roa Thrust Sheet thins out by the basal thrust cutting up section to the east, which then passes into the Kvitvola Thrust Sheet above (see Fig.7.11a). To the west of this area the Kvitvola Thrust apparently cuts down section in all directions by truncating folded footwall Orthoceras Limestone, Ogygiacaris Shales and Eocambrian rocks.

Further north along the eastern margin the relationships between the two thrust sheets change. The Engerdal 1:50 000 sheet shows that the Orthoceras Limestone of the Osen-Roa Thrust Sheet is imbricated together with the Kvitvola Thrust Sheet and that the Osen-Roa Thrust lies at the base of a thin sequence of Vangsas Formation resting on top of Kvitvola rocks. To the west of this area, in Minstra, Nystuen (in press) shows Osen-Roa basement rocks thrust over the northern margin of the Kvitvola Thrust Sheet. Therefore the broad syncline in which the Kvitvola rocks are preserved could have derived its northern limb by imbrication from the Osen-Roa Thrust Sheet "jacking up" the northern end of the thrust sheet.

In any model which attempts to explain the Osen-Roa and Kvitvola Thrust Sheet deformation history, the following relationships have to be explained.

1. Osen-Roa rocks have been locally thrust over Kvitvola rocks whilst the overlying Kvitvola Thrust Sheet rests on truncated Osen-Roa folds.
2. In the Osen-Roa Thrust Sheet and Aurdal Duplex the youngest rocks

preserved are the Ogygiacaris Shales (4aa). However the Ogygiacaris Shales are more extensively preserved in the Aurdal Duplex, which is the lateral continuation of the Osen-Roa Thrust Sheet. This indicates that the overlying thrust sheets (the Synnfjell and Kvitvola respectively) must have frontally ramped to leave the Synfjell Thrust forming a flat within the 4aa shales (and the Aurdal Duplex subsequently developed). The Kvitvola Thrust, perhaps, also formed a sub-horizontal thrust (or flat) that passed through already folded beds.

3. The Kvitvola Thrust Sheet is overlain to the west by the Jotun Thrust Sheet, where there are problems with the geometry of the trailing edge. These are discussed later in the section.

The possible explanations for the geometries described above are as follows:

1. The Kvitvola Thrust Sheet could be a late out-of-sequence gravity slide or surge zone (Coward 1982) emplaced on the Osen-Roa Thrust Sheet which was already deformed and eroded. Then later out-of-sequence thrusting imbricated both thrust sheets (see Fig.7.12a).
2. The Kvitvola Thrust Sheet could have been a late out-of-sequence thrust formed after stick on the Osen-Roa Thrust. This could have caused a new thrust to be generated further towards the hinterland, which transported a former part of the Osen-Roa Thrust Sheet over the abandoned Osen-Roa Thrust Sheet, forming the Kvitvola Thrust Sheet.The new thrust sheet after cutting up section formed a sub-horizontal thrust which truncated structures in the abandoned part of the Osen-Roa Thrust Sheet. (This leading part of the Kvitvola Thrust Sheet has subsequently been eroded). Eventually movement ceased on the Kvitvola Thrust and resumed along the reactivated Osen-Roa Thrust.This would lead to out-of-sequence imbrication at the north

end of the current Kvitvola outcrop.

The reactivation of the Osen-Roa Thrust may have formed the proposed ramps in the hangingwall sequence at Moelv (see Fig.7.10a) when thrusting resumed slightly north of the original sticking point. This later movement by the Osen-Roa Thrust would account for the relationships with the Kvitvola Thrust Sheet seen on the eastern margin of the Sparagmite basin (see Fig.7.12b).

3. The Kvitvola Thrust Sheet could have been thrust over the Osen-Roa Thrust Sheet and carried by the latter "piggyback" style (Fig.7.12c). Towards the northern end of the Osen-Roa Thrust Sheet imbrication is very intense and passes into the Kvitvola Thrust Sheet above. This could have raised the northern end of the Kvitvola Thrust Sheet higher than achieved by subsequent imbrication to the south. As imbrication progressed southwards it could have transferred slip to lower horizons, eventually passing slip into the Kvitvola Thrust. If enough imbricates transferred slip into the Kvitvola Thrust reactivation of the thrust could be significant enough to move the Kvitvola Thrust Sheet over the folded Osen-Roa rocks further south, truncating these folds.

The first model has a problem with position of the trailing edge of the Kvitvola Thrust Sheet, which, although not recognised below the Trondheim thrust sheets, has been traced under the Jotun and Valdres Thrust Sheets. The Kvitvola Thrust Sheet has therefore been part of a "piggy back" sequence of thrusting, with the thrust sheets on the western side of the Sparagmite region and so cannot be a late gravity slide.

Fig.7.12 <u>Models explaining the structural relationships of the Kvitvola and Osen-Roa Thrust Sheets</u>

A. Erosion of the Osen-Roa Thrust Sheet and later gravity sliding of the Kvitvola Thrust Sheet.

B. Out of sequence thrusting of Kvitvola Thrust Sheet over the already deformed Osen-Roa Thrust Sheet followed by reactivation of the Osen-Roa Thrust Sheet.

C. In sequence thrusting and reactivation of the Kvitvola Thrust by imbricates from the Osen-Roa Thrust Sheet.

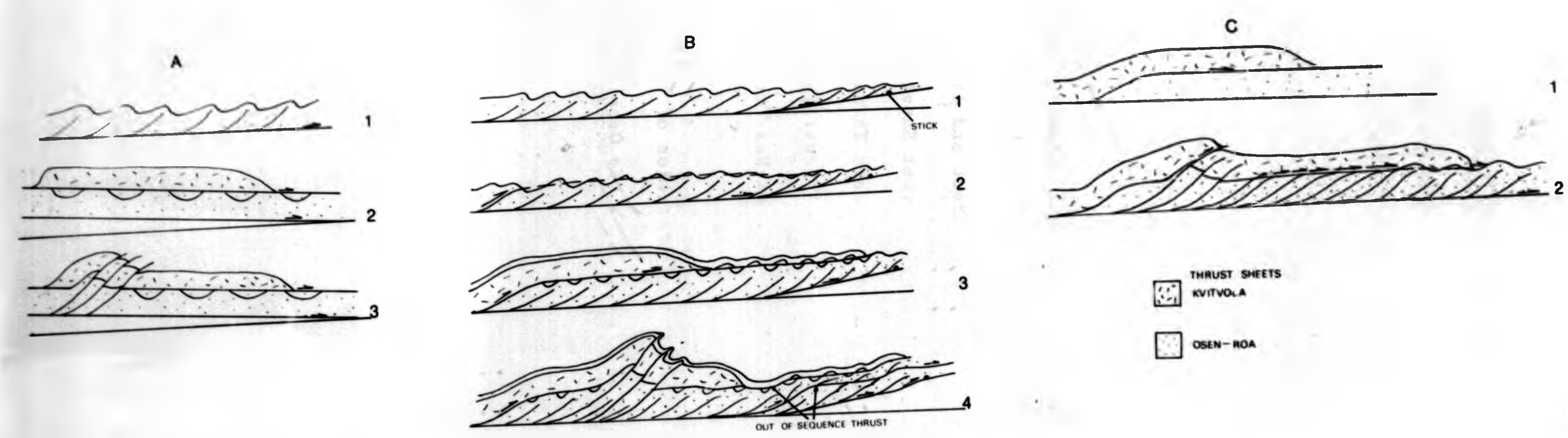
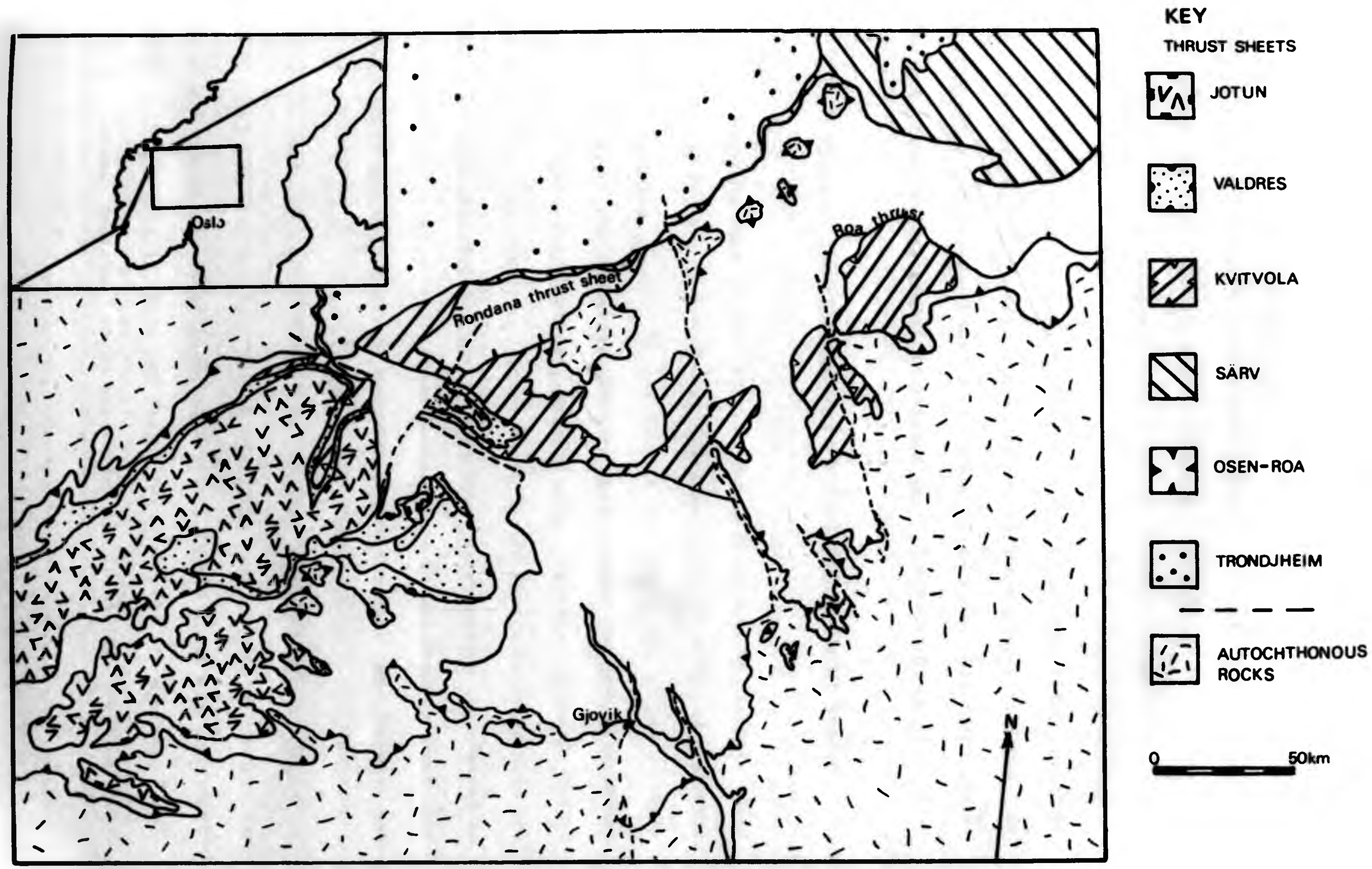

A
1
2
3
B
1
STICK
2
3
4
OUT OF SEQUENCE THRUST
C
1
2
THRUST SHEETS
KVITVOLA
OSEN-ROA

Fig.7.13 Map of structural units in the southern Caledonides



Oslo
Rondana thrust sheet
Roa thrust
Gjovik
N
KEY
THRUST SHEETS
JOTUN
VALDRES
KVITVOLA
SÄRV
OSEN-ROA
TRONDJHEIM
AUTOCHTHONOUS ROCKS
0
50km

The third model requires reactivation of 50km displacement along the Kvitvola Thrust by 50km in order to truncate the folds currently exposed and probably would involve excessive stretching of the thrust sheet. It is concidered impossible that over the short distance of the current width of the Kvitvola Thrust sheet imbricate thrusting could generate such significant and necessary slip along the Kvitvola Thrust.

The second model appears to account for all the conditions listed at the beginning of the section and so is the most acceptable solution. In the following discussion about the trailing edge of the Kvitvola Thrust Sheet the mode of emplacement is assumed to follow model 2.

7.6.3 Where is the trailing edge of the Kvitvola Thrust Sheet?

The trailing edge of the Kvitvola Thrust Sheet can be traced under the Jotun and Valdres Thrust Sheets (Iverson in Brynhi 1981 and Siedlecka in press), see Fig. 7.13. Whilst Nystuen (in press, Fig 1) has attempted to project the Kvitvola Thrust Sheet under the Trondheim Thrust Sheets, for the western Kvitvola outcrop only. Earlier Asklund (1961) attempted to link the Sarv and Kvitvola Thrust Sheets together into one unit. He also regarded the Sarv Thrust Sheet as extending into Norway as the unit now called the Leksdals-Remskleppe Thrust Sheet. Since this thrust sheet has been recently correlated with the Sarv by Roberts and Wolff 1981, the name seems an unnecessary complication.

Indirectly the Kvitvola Thrust Sheet has been projected under the Trondheim thrust sheets because the Kvitvola Thrust Sheet has been correlated with the Valdres, Sarv and Tannas Thrust Sheets by Nystuen (1981, fig.1), whose trailing edges pass under the Jotun and Trondheim thrust sheets respectively.

In the Trondheim region the lowest thrust sheet is the Leksdal-Remskleppe Thrust Sheet (Roberts and Wolff 1981) which is thought to be the lateral equivalent of the Sarv and Tannas Thrust Sheets. It can be seen from the maps of the region by Roberts and Wolff (1981) and Nystuen (in press) that below the leading edge of the Skjotingen-Essandsjo Thrust Sheet (the lateral equivalent of the Seve) there is a thin discontinuous outcrop of Leksdal-Remskleppe Thrust Sheet. It could therefore be argued that the southern boundary of the Leksdal-Remskleppe Thrust Sheet is the ragged leading edge. Whether the Leksdal-Remskleppe Thrust Sheet is totally separate from, or is a continuation of the Kvitvola Thrust Sheet leads to important conclusions about the evolution of the Southern Caledonides as follows:

1. The Kvitvola Thrust Sheet does pass northwards into the Leksdals-Remskleppe thrust sheet.

   The current outcrop pattern of the Leksdals-Remskleppe leading edge could be discontinuous because the exposure is too poor to follow the boundary continuously or because the weight of the thrust sheets above and internal shearing might have thinly and discontinuously spread the trailing edge of the Kvitvola Thrust Sheet. Also out-of-sequence thrusting could separate a thrust sheet into small, discontinuous horses.

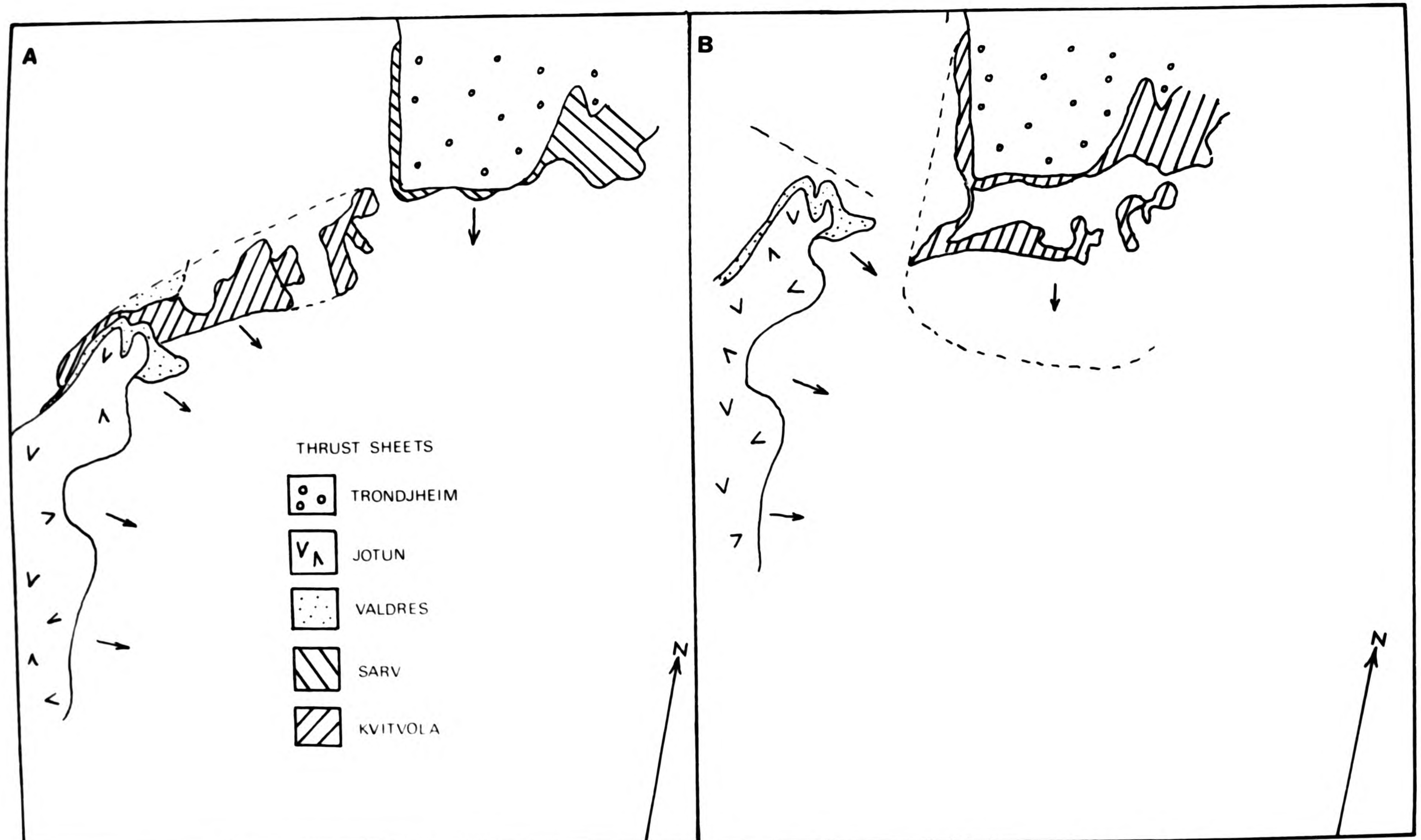
Fig.7.14 Models for the relationships of the Jotun, Valdres and Trondheim Thrust Sheets with the Kvitvola Thrust Sheet.

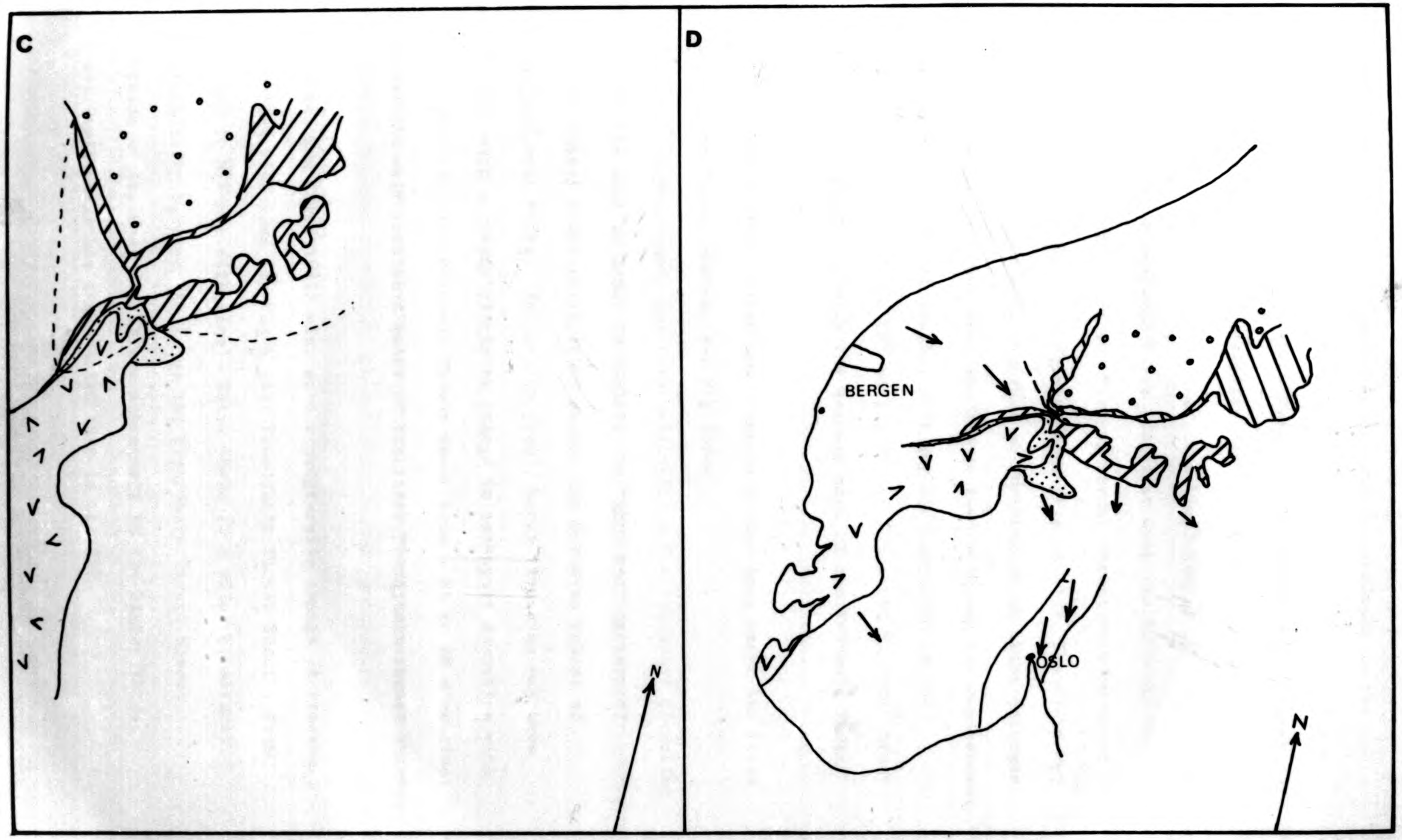
A. Kvitvola, Jotun and Valdres Thrust Sheets move first and are later overridden by the Trondheim Thrust Sheets.

B. Kvitvola and Trondheim Thrust Sheets move first and are later overridden by Jotun and Valdres Thrust Sheets.

C. Kvitvola, Trondheim, Jotun and Valdres Thrust Sheets move together.

D. Present day position of thrust sheets. Arrows indicate transport directions of the thrust sheets.


A
B
THRUST SHEETS
TRONDJHEIM
JOTUN
VALDRES
SARV
KVITVOLA
N
N


C
N
D
BERGEN
OSLO
N

If the Kvitvola Thrust Sheet was originally connected to the Leksdal-Remskleppe Thrust Sheet the interpretation of the relative timing of the emplacement of the Jotun and Trondheim thrust sheet piles is open to all the possibilities: 1. tectonic events in the two areas occurred at the same time (see Fig.7.14a).2. The Trondheim thrust sheets were emplaced first (together with the Kvitvola Thrust Sheet) and later the Jotun and Valdres Thrust Sheets were emplaced and overthrust the Kvitvola Thrust Sheet (Fig.14.).3. The Jotun and Valdres Thrust Sheets were emplaced on foreland which later deformed to form the Osen-Roa and Kvitvola Thrust Sheets during the emplacement of the Trondheim thrust sheets. This may have resulted in the clockwise rotation of the ENE margin of the Jotun and Valdres Thrust Sheets which were overlying the western edge of the Kvitvola Thrust Sheet.

2. The Kvitvola Thrust Sheet has a trailing-edge only under the Jotun and Valdres Thrust Sheets,(see Fig.7.14c).

The Jotun Thrust Sheet may have originally had a transport direction towards the east in order to explain the "shoe box" pattern of lateral thrust ramps which later became the Devonian basins of Sunnfjord west Norway (Hossack in prep). Later thrusting may have proceded with a steady clockwise change in transport direction with time, emplacing the Kvitvola Thrust Sheet from a NW to SE direction, across the main transport paths of the later Trondjheim Thrust Sheets.

(Roberts and Wolff 1981) also note a progressive change in transport direction with time for the higher Trondjheim Thrust Sheets, from WNW-ESE to NNW-SSE with time). Hence there is a major structural discontinuity between the Jotun and Trondjheim Thrust Sheets. Movement on the Osen-Roa Thrust subsequent to the higher thrust sheet emplacement has transported them to the SSE.

It should not be surprising that thrust sheets alter their movement directions either by a progressive change in orientation or in a zig zag path. This is because thrust sheets are so very long that it would be unreasonable to expect constant rates of slip along the whole length of the thrust sheet. If one part sticks or moves at a slower rate then depending on its position to the rest of the thrust sheet, the transport of the thrust sheet will be modified in one of a variety of ways. Lower slip rates on the end of a thrust sheet will cause it to rotate in towards about the axis of stick. Lower slip rates within the thrust sheet may cause portions of the trailing- and leading-edges to advance at different rates resulting in curved branch lines and lateral ramps; whilst if stick or lower slip rates occur in different places at different times in the thrust sheet a zig-zag transport path might result.

7.6.4 The significance of the Rondane Thrust Sheet.

Also pertinent to the choice of model described above is the Rondane Thrust Sheet. This minor thrust sheet is situated in the NW corner of the Sparagmite region and is thrust over the Kvitvola and Osen-Roa Thrust Sheets, whilst having the lowest Trondjheim rocks thrust over it (Nystuen in press).

The geometry of the Rondane Thrust Sheet can be explained in two ways. Firstly the Rondane Thrust Sheet could be part of the Osen-Roa Thrust Sheet which has overthrust the Kvitvola Thrust Sheet as in Fig.7.11b. Secondly the Rondane Thrust Sheet are identical to Valdres Group sediments (Hossack pers comm.), and could be part of the Valdres Thrust Sheet which has been thrust over the Kvitvola and overthrust in turn by later thrusting in the Trondjheim thrust sheets.

At present I favour the second choice, linking the Rondane Thrust Sheet to the Valdres Thrust Sheet for reasons of timing (see Chapter 8) geometry and lithological correlation. There are modifications to this model because Asklund (1960 fig.2 and 1961) shows a thrust klippe which he recognised as part of the Sarv Nappe which has subsequently been joined to the Kvitvola Thrust Sheet by Norwegian mapping (Nystuen in press). This shows the similarity between Sarv and Kvitvola rocks, although the Kvitvola Thrust Sheet does not contain the vast dyke swarms of the Sarv. Also the considerable lateral extent of the Kvitvola Thrust Sheet to the east, makes it hard to imagine it being pushed from the WNW as the transport direction would have been oblique to the longest extent of the thrust sheet. (Although this problem can be partly overcome however by proposing stick on the western side of the moving thrust sheet which would cause the eastern side of the thrust sheet to rotate in a clockwise direction). Therefore if the Kvitvola Thrust Sheet is the lateral equivalent of the Sarv Thrust Sheet out of sequence thrusting must be proposed to allow the lowest Trondheim thrust sheet, which is the Sarv Thrust Sheet, to overthrust the Rondane Thrust Sheet, which itself overthrusts the Kvitvola Thrust Sheet.

CHAPTER 8

THE STRUCTURAL EVOLUTION OF THE SOUTHERN CALEDONIDES

8.1 Introduction

This chapter aims to draw together information from previous chapters and published literature in order to describe the deformation history and style of the Osen-Roa Thrust Sheet. From the balanced cross-sections drawn through the different areas of the Oslo Graben a palinspastic reconstruction of the region has been made. Balanced cross-sections have been constructed through the thrust belt in the Jotunheimen and Trondheim regions and into the Osen-Roa Thrust Sheet where the sections can be pinned in undeformed foreland. By using the palinspastic reconstructions and identifying syn-orogenic sedimentation, (which frequently is manifest as a series of clastic wedges which young towards foreland), it is possible to identify the direction and timing of overthrusting events and to obtain a time averaged estimate of the rate of thrusting. From this the influence of the higher thrust sheets on the timing and deformation style of the Osen-Roa Thrust Sheet is evaluated.

On a regional scale the southern Caledonides display a conciderable amount of out-of-sequence thrusting, within a thrust belt that has broadly developed by in-sequence, piggy back thrusting. Several different causes of out-of-sequence thrusting have been identified to explain such occurrences.

When balanced cross-sections were constructed through the Jotunheimen and Trondheim regions it was noticed that there was a large amount of continental crust that had to be present in the restored sections, below the thrust sheets, whilst only half the area of continental crust was present in the deformed section. In order to explain 'missing' crust a much larger and more tentative section has to be drawn across the whole Caledonian Orogenic Belt by applying evidence from Greenland, NW Scotland and Norway, which can be crudely restored.

The size of the thrust sheets of southern Norway do not appear to conform to the ratios of lengths and thicknesses proposed for thrust sheets emplaced by gravity sliding by Hubbert and Rubey (1959) and others, unless pore fluid pressures of 1.0 are proposed. Therefore other mechanisms of emplacement and for driving the thrust belt are examined. The Osen-Roa Thrust Sheet is a good test for overthrust models as it probably represents a thrust sheet which has stopped mid-development when the driving mechanisms of the orogenic belt finally stopped operating.

8.2 Variations in structural style within the Oslo Graben.

The deformation of the Cambro-Silurian rocks within the Oslo Graben is broadly characterised by imbrication or pop-up and triangle zones within the Cambro-Ordovician and by buckle folding in the mid Ordovician and Silurian rocks. These structures vary in dimensions within the Oslo Graben (see Table 8.1) but they generally reflect the decreasing amount of shortening to the south, approaching the thrust front. It can be seen from Table 8.1 that the dimensions and displacements along second order contraction faults decrease to the south of the area, whilst buckle and tip line folds increase in wavelength and interlimb angle, and decrease their amplitude southwards.

Shortening (e) within the Osen-Roa Thrust Sheet is fairly constant between Mjosa and Hadeland (50-60%) but then declines for the 80km of the

Table 8.1 <u>The dimensions of faults and folds in the districts of the Oslo Graben</u>

(Shortening estimates derived from balanced cross-sections. The dimensions of structures were taken from field observations and the maps in Appendix 2).

Area	Eiker	Oslo	N.Ringerike	Hadeland	S.Mjosa	N.Mjosa
2nd order thrusts						
ave. strike length	?	3km	in excess of 2km	In excess of 2km	?	5km
ave. displacement	100m	150m	158m	180m	?	185m
ave. spacing strained	1000m	280m	180m	160m	150m?	165m
ave. spacing unstrained	1150m	400m	360m	330m	305m?	375m
tipline folds						
wavelength	20-40m	120-280m	40-200m	75-225m		
amplitude	20-30m	70-135m	40-140m	50-90m		
interlimb angle	65-140°	65-90°	45-95°	40-100°		
buckle folds						
wavelength		800-2000m		500-1650m	275-1000m	
amplitude		120-280m		350-800m	150-500m	
interlimb angle		100-120°		85-120°	100-130°	
ave. %shortening(e)						
lower Ordovician	15%	37%	50%	60%	55%	60% (Eocambrian)
lower Silurian	15%	27%	?	29%	28%	

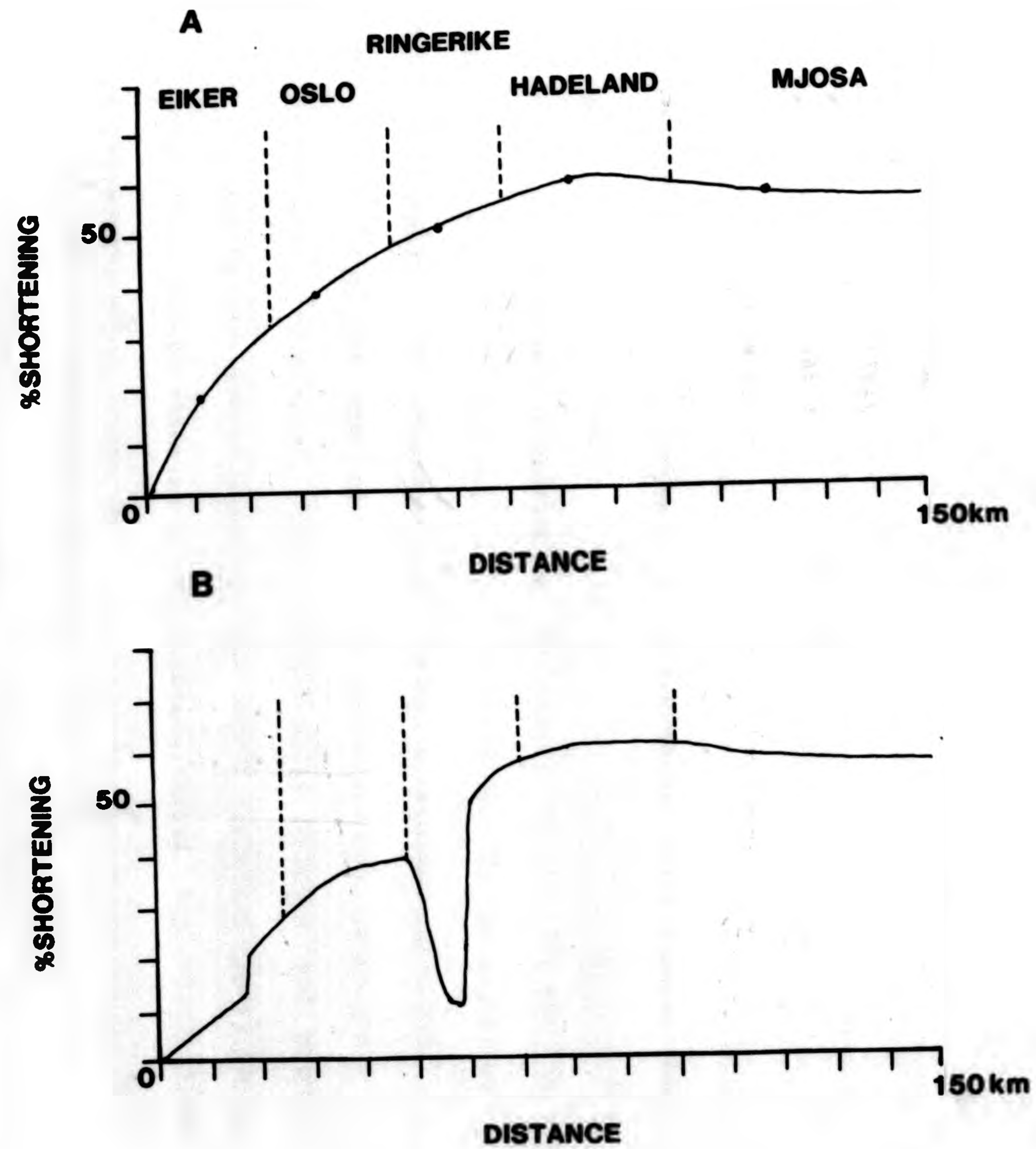
Fig.8.1 <u>Graphs of distance from foreland (north to south), plotted against the amount of shortening in each district</u>

a. Average amount of shortening for each district.

b. Variations in amount of shortening within each district. Large variations in shortening coincide with a drop in the amount of shortening in the footwall of large second order thrusts.

1 = Stubdal Thrust

2 = Eikeren Thrust



A
RINGERIKE
EIKER
OSLO
HADELAND
MJOSA
%SHORTENING
50
0
150km
DISTANCE
B
%SHORTENING
50
0
150km
DISTANCE

Oslo Graben north of the undeformed Langesund-Skien area,(see Fig.8.1a). Although the average amount of shortening for each district, plotted against distance shows a steady decline in the amount of shortening (Fig.8.1a); in more detail it can be seen that shortening varies markedly near second order thrusts of large displacement (see Fig.8.1b), mainly at the Stubdal Thrust and at Eikeren. In the footwall areas of these thrusts the amount of shortening is markedly less than in the hangingwall. This suggests that these thrusts are significant in reducing the displacement on the Osen-Roa Detachment and help it to die out. The second order thrusts may achieve this by taking up significant amounts of regional stresses themselves in hangingwall deformation and in an unknown amount of slip along the thrust planes.

The deformation style within the Osen-Roa Thrust Sheet changes once the amount of shortening begins to decrease. In the northern part of the region, which has undergone shortening (e) between 50% and 60%, the lower part of the thrust sheet has deformed by imbrication. To the south, with decreasing amounts of shortening (reaching a maximum of 37% in Asker-Baerum) triangle and pop-up zones become common, though areas of imbrication are still present. The introduction of triangle and pop-up zones in the deformation of a thrust sheet would therefore appear to be related to lower strain rates as the propogating thrust tip slows down towards foreland.

8.3.1 Why do backthrusts develop?

It is possible for triangle and pop-up zones to develop in the following ways:

(a)in response to accommodation problems in the cores of folds, so that when the folds overtighten break thrusts (Gwinn 1964) are formed (see Chapter 1,). (The slowing down of a sole thrust could produce conditions favourable to buckling by stressing the rocks over a longer period of time than that which produced imbrication).

(b) It has been demonstrated in the field e.g. Jacobeen and Kanes (1974), Sierra (1977) and by experiment (Morse 1977) that backthrusts develop by stick or by lower movement rates over ramps, these are called chisel faults by Jacobeen and Kanes (1974).

In the Oslo region the backthrusts seem to have developed their own tip line folds and cleavage, therefore in many cases they do not appear to be the result of accommodation problems in the cores of folds. However stick or decceleration of the thrust sheet as it passes over basement topographical rises may be responsible for some of the backthrusts developing in a similar manner to chisel faults.

In addition low stresses on their own might be responsible for producing triangle and pop-up zones. This can be seen on a small scale in Alvarez et al (1978, fig.3), where minor brittle chert beds deformed to triangle and pop-up zones in areas of weak pressure-solution cleavage and progress to imbricated beds (with all the fractures inclined in one direction) with strong cleavage. If stresses are built up slowly in a rock, deformation would be expected to progress from weak to strong ie. from triangle and pop-up zones to later imbricated thrusts, which would truncate earlier structures. However imbricate zones do not appear to display earlier backthrusts, which indicates that either the subsequent deformation has disguised earlier structures of the progressive deformation, or that the rocks quickly respond to the maximum stresses in an area. The latter case is valid for the chert beds in the example from

Alvarez et al (1978).

The orientation of the principle stress trajectories (eg. Hubbert 1951, Mandl and Shippam 1981) may be used to explain why hinterland dipping imbricate thrusts are preferentially formed at higher amounts of shortening. Traditionally, stress trajectories have been calculated using an oblong outline to represent the thrust sheet boundaries in cross-section. However shortening probably proceeds as a migrating bulge where the ductile bead at the thrust tip represents the inital zone of shortening, at the thin edge of a wedge of deformed rock which tapers towards the foreland. This wedge shape is defined by a foreland dipping syn-orogenic surface and a hinterland dipping sole thrust, where the acute angle between these converging surfaces may be up to 10° (Davis, Suppe and Dahlen 1983). As the compressive deformation involves an increase in vertical height of the thrust sheet there must be a foreland dipping slope on the top surface of the thrust sheet between the raised, deformed rocks towards the hinterland and the undeformed rocks ahead of the ductile bead. As deformation is actively taking place around the thrust tip it will be the stress trajectories around the sloping thrust sheet roof that will be important in determining the orientation of the thrust planes not the stresses in the main oblong outline of the rest of the thrust sheet.

Stress trajectories are distributed qualitatively in the following manner. On the upper boundary of an idealised thrust sheet the normal stress is at atmospheric pressure and the shear stresses are at zero. Therefore along the upper boundary one of the stress trajectories must terminate perpendicularly, whilst the other is tangental to the surface (Hubbert 1951). A foreland dipping syn-orogenic surface may therefore significantly influence the distribution of stress trajectories.

As the ductile bead migrates through the foreland rocks so the stresses favourable for producing hinterland dipping minor thrusts will remain the same untill the the angle of the slope changes. The position of the stress trajectories predicts which orientation of a conjugate set of faults is most likely to form under a given set of stresses. If one set of conjugate fault planes under varying conditions becomes rotated to lie at an increasingly acute angle to the main direction of basal shear stress, then that set becomes increasingly likely to form (at the expense of the other set). Therefore the more inclined a foreland dipping surface slope becomes, the higher the probability of a hinterland dipping thrust developing.

As a thrust slows down and the amount of shortening decreases, the foreland slope will have a gentler gradient. This will result in the rotation of the conjugate faults predicted for the slope area, so that the acute angle between the hinterland dipping set of faults and the basal thrust becomes incresingly larger; whilst the angle between the basal thrust and the other (foreland dipping) set of faults begins to decrease (Fig.8.2). Eventually the surface slope may become small enough to exert little influence on the stress trajectories, in which case there would be a 50% chance of either conjugate set developing.

If there is little or no deformation above a propogating thrust plane, which then sticks, producing a thickened zone of layer parallel shortening (see Fig.8.2d), then a bulge is produced with a foreland and hinterland dipping slope. The stress trajectories produced for this geometry favour backthrusts developing below the hinterland dipping slope and a forethrust developing below the foreland slope, thus producing an isolated pop-up structure.

Fig.8.2 Diagram showing supplimentary stress systems imposed on a thrust sheet of varying shape (partly after Hafner 1951, and Attewell and Farmer 1976).

Diagrams a1, b1, etc.

---- = trajectory of minimum principal stress σ min

= trajectory of maximum principal stress σ max

(σ max will be parallel to pressure-solution cleavage)

Diagrams a2, b2, etc.

= position of possible thrust fault surfaces

= boundaries of areas of stablity for various ratios of constants a/c

Fig.8.2 Diagram showing supplimentary stress systems imposed on a thrust sheet of varying shape (partly after Hafner 1951, and Attewell and Farmer 1976).

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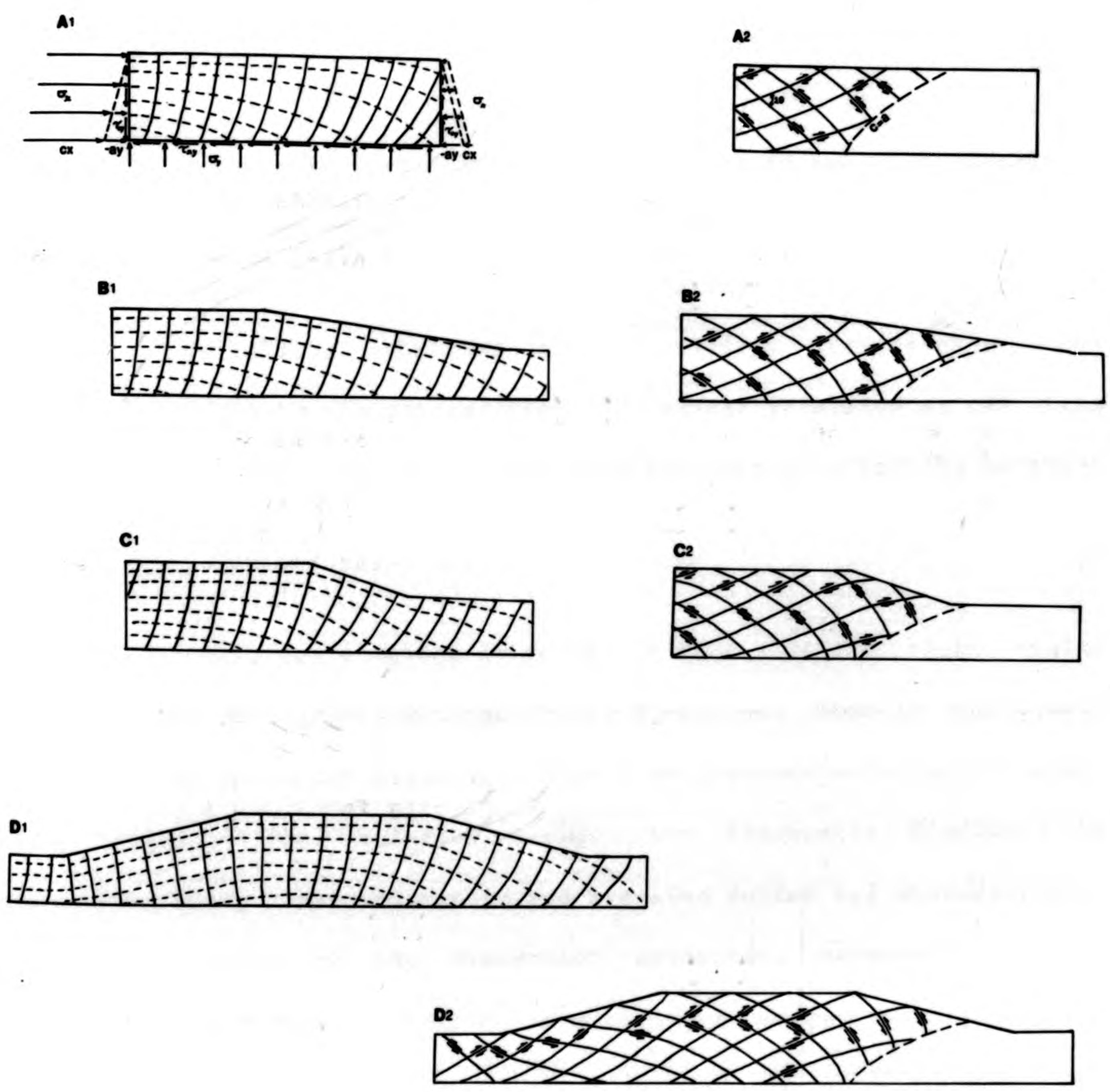
Diagrams a2, b2, etc.

= position of possible thrust fault surfaces

= boundaries of areas of stablity for various ratios of constants a/c


A1
A2
B1
B2
C1
C2
D1
D2

8.2.2 Cleavage

The types of cleavage found in the Oslo Graben are fracture, pencil, slaty and pressure-solution. The fracture cleavage appears to be developed in three ways: ahead of, or at the tip lines of thrust faults, as a foreland dipping cleavage below the upper detachment zone and where pressure solution seams in limestones pass into shales.

Pencil cleavage is formed by the intersection of one (or more) of the types of fracture cleavage described above with a bedding parallel fracture cleavage. This bedding parallel cleavage may be related to flexural slip folding enhancing shaly fissility. Occasionally pencil cleavage is formed by the intersection of cleavage generated at the tips of thrusts of opposing dips, and does not involve a bedding parallel fracture cleavage.

Pressure-solution cleavage is formed at approximately right angles to the local or regional maximum stress direction. Locally significant shortening (e) up to 20% might be achieved by pressure-solution of limestone units. The solution seams are frequently displaced by dislocation-creep zones and faults and are also folded and therefore must have formed early in the protracted sequential deformation of the Osen-Roa Thrust Sheet.

8.2.3 Thrust wedging (Fig.8.3).

The most severe deformation by thrust wedging of the Osen-Roa Thrust Sheet rocks is achieved by those thrust wedges which formed early on in the deformation, in thin competent units enclosed by incompetent units. These thrust wedges have been subsequently folded and rotated by thrusting. Less localised, layer parallel thickening and shortening probably deformed the incompetent shale units, instead of thrust wedging and pressure-solution. The appearance of telescoped beds caused by thrust wedging and pressure-solution is prior to the main deformation by imbrication and folding. This indicates that there was an early compressional phase as the stresses built up within the foreland rocks which were perhaps related to the ductile bead advancing ahead of the Osen-Roa Detachment. These early structures formed either at right angles to the maximum principle stress direction (pressure-solution cleavage) or parallel/sub-parallel to it (thrust wedges).

Later thrust wedging was produced by flexural slip folding and by thrusts dying out into tip line thrust wedges. Shortening (e) along individual beds by this later thrust wedging is significantly less than in the early formed thrust wedges, it being up to 25% in the former and 50% in the latter.

It can be seen from the summary of the types of thrust wedges given in (Fig.8.3) that the early formed thrust wedges are likely to be folded and rotated resulting in an apparent normal fault sense of movement in outcrop. Cloos (1961) suggested that these early thrust wedges might form the nucleation sites for future anticlines to develop. However in the Oslo Graben the folds in areas of thrust wedging are not usually formed by "active buckling", but instead are tip line folds, which would not be governed by the position of weakened, thickened, layers in the same way as buckle folds might be. For this reason intense thrust wedging was not found extensively in the region of anticlinal cores.

Fig.8.3 Thrust wedges

a. Early formed thrust wedges. When these are folded some thrust wedges may become rotated and consequently appear to cut down section is the transport direction.

b. Early thrust wedges combining to form one fracture.

c. Thrust wedges formed by tangental shear during folding.

d. Thrust wedges at the tip line of a thrust.

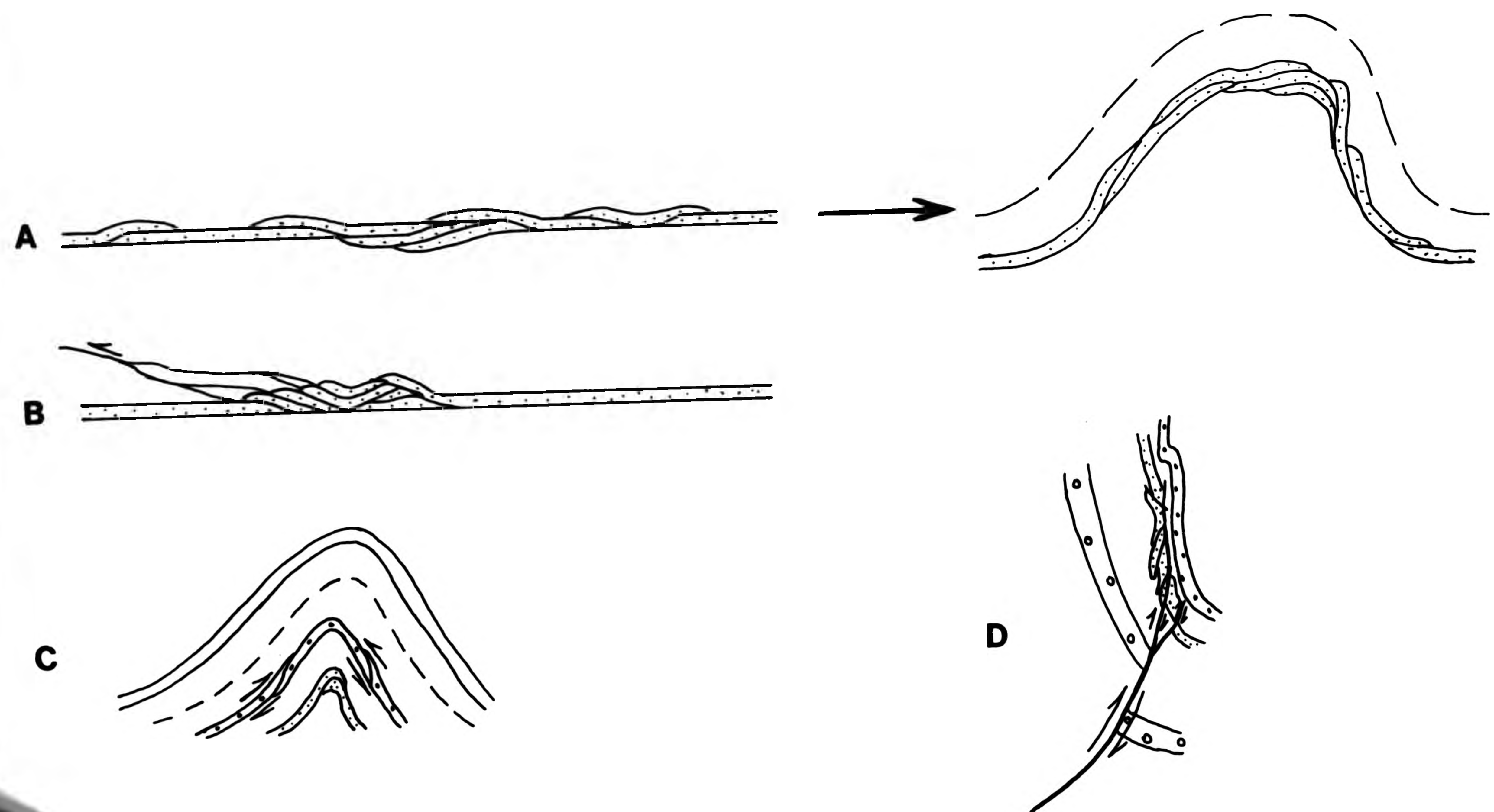

A
B
C
D

Fig.8.4 <u>The development of an upper detachment horizon</u>

A. Uniform shortening of a thrust sheet by the presence of subsiduary low angled thrusts.

B. Non-uniform shortening of a thrust sheet resulting in an upper detachment horizon being required to balance the restored section.

C. Upper detachment developing backthrusts, foreland dipping cleavage and triangle zones ahead of sole detachment. Imbricates from the sole detacment produce numerous off-sets of the upper detachment.

D. Imbricates from the sole detachment use the upper detachment zone as a zone of weakness and reverse its original sense of movement, forming a duplex zone with an opposed dip complex on top.
its sense of movement, forming a duplex zone with an opposed dip complex on top.

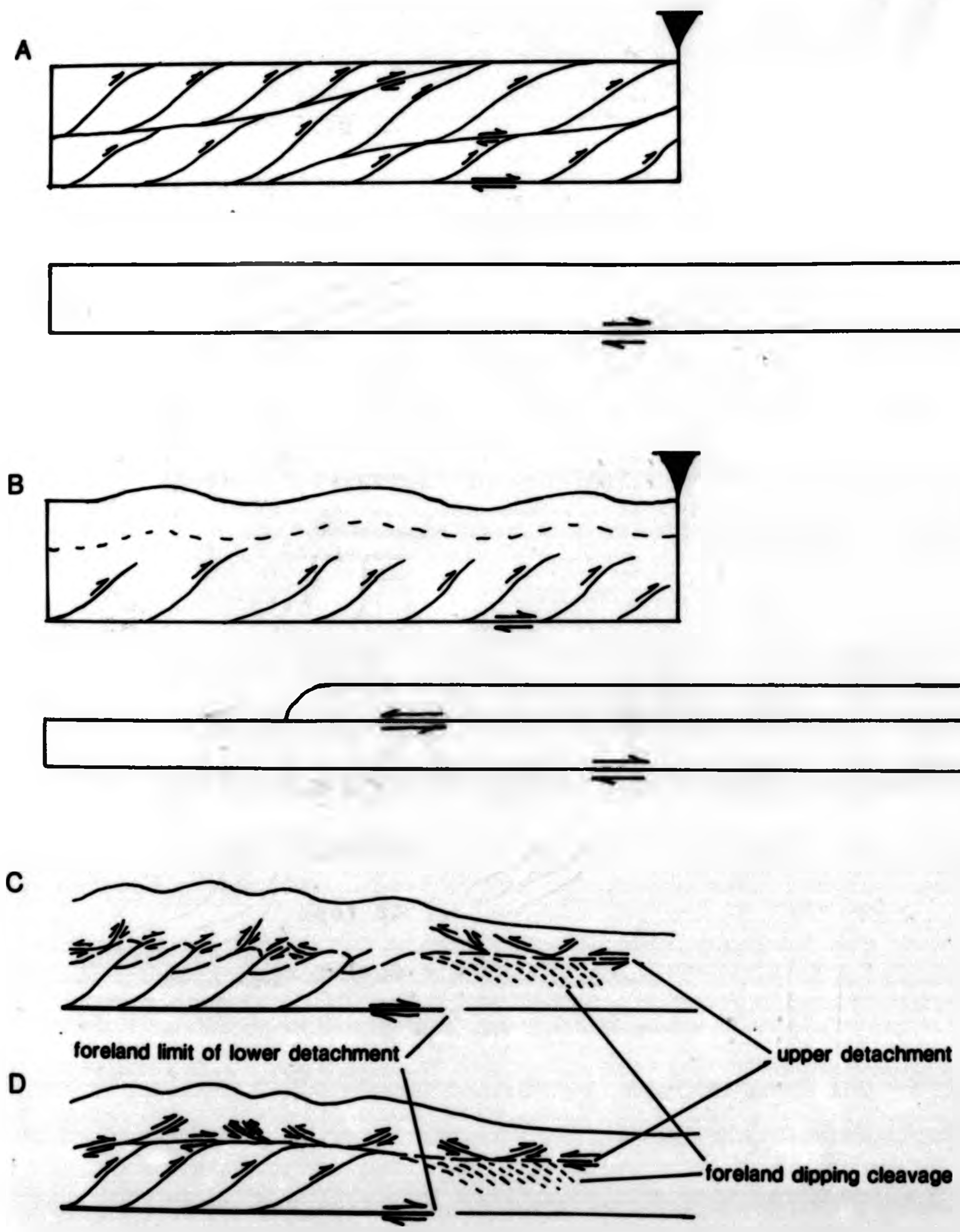

A
B
C
foreland limit of lower detachment
upper detachment
D
foreland dipping cleavage

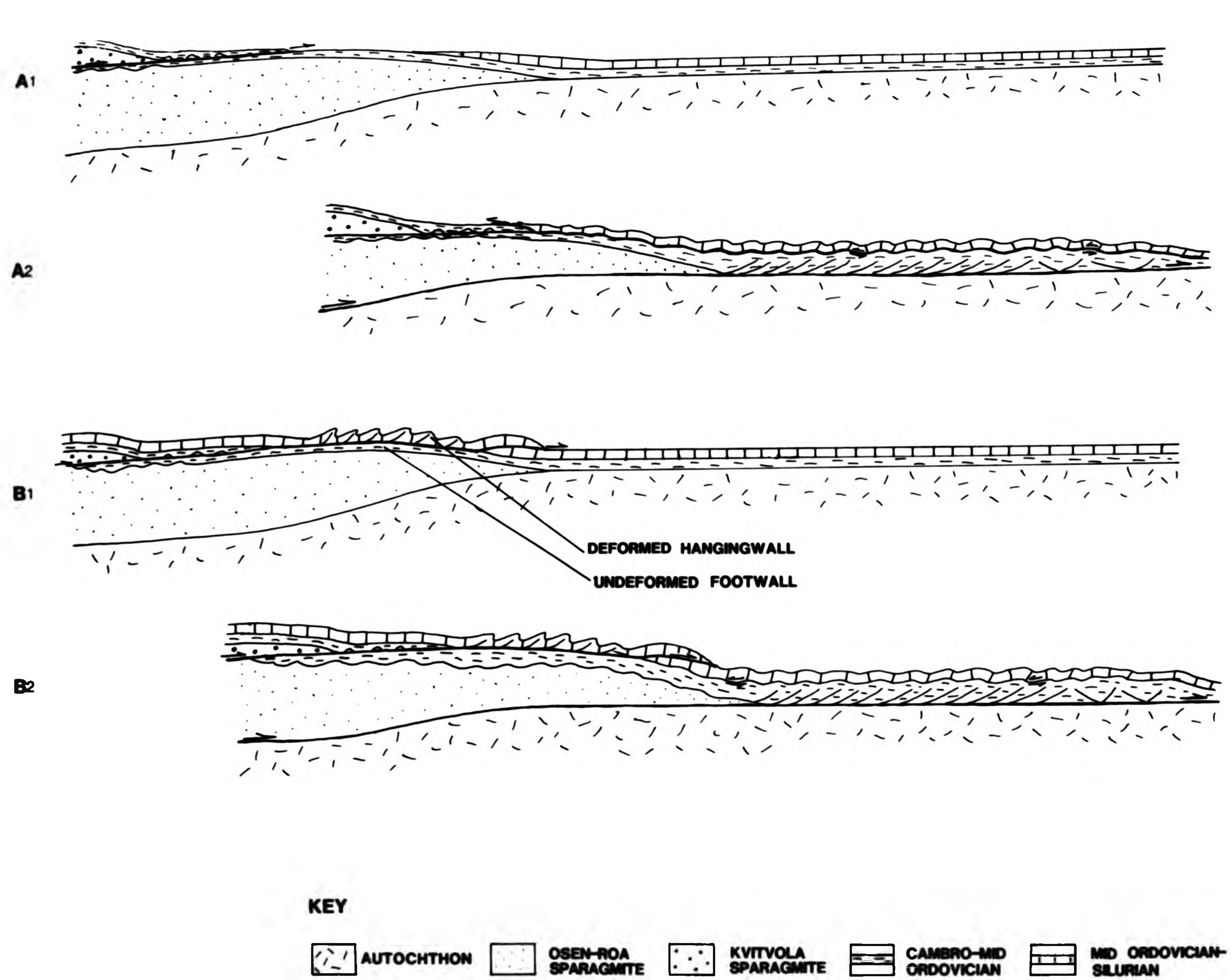
Fig.8.5 <u>The possible development of the upper detachment zone in the Osen-Roa Thrust Sheet.</u>

A1. Emplacement of the Kvitvola Thrust Sheet.

A2. Movement on the Osen-Roa Thrust Sheet, results in the active overthrusting of the hangingwall towards the Kvitvola Thrust Sheet.

B1. The Kvitvola Thrust passes into the Silurian of the Osen-Roa Thrust Sheet, leaving the Cambro-Ordovician rocks underneath undeformed.

B2. Later movement on the Osen-Roa Thrust Sheet underthrusts the mid Ordovician-Silurian rocks.



A1
A2
B1
DEFORMED HANGINGWALL
UNDEFORMED FOOTWALL
B2
KEY
AUTOCHTHON
OSEN-ROA SPARAGMITE
KVITVOLA SPARAGMITE
CAMBRO-MID ORDOVICIAN
MID ORDOVICIAN-SILURIAN

8.2.4 The upper detachment zone.

The local problems concerning the lower amounts of shortening in the upper part of the Osen-Roa Thrust Sheet compared with the lower units has been discussed in Chapter 5. It is how an upper detachment zone can be fitted into a regional picture that concernes this section.

Many thrust sheets are too thick for the imbricate thrusts, which fan off the sole thrust, to penetrate the whole thrust sheet and reach the surface (or higher thrust sheets). Therefore to achieve uniform shortening within the thrust sheet subsidiary low angled thrusts with imbricate splays may develop and sub-divide the thrust sheet (Fig.8.4a).

However in the Osen-Roa Thrust Sheet of the Oslo Graben, uniform shortening has not happened. The imbricate thrusts were unable to penetrate the competent upper units of the thrust sheet, which instead deformed by buckle folding. Therefore the amount of shortening decreases upwards in the thrust sheet (see Fig.8.4b,c,d). The upper part of the thrust sheet (mid Ordovician and Silurian) unstrains to about 215km original length, whilst the lower part (Cambro-mid Ordovician) unstrains to 270km.

In order to compensate for the smaller amount of shortening in the higher units, assuming that all beds are pinned at the same point in the foreland, the upper detachment zone could have developed in the following ways:

1. The mid Ordovician and Silurian hangingwall rocks were transported above the upper detachment zone towards the hinterland relative to the footwall (see Fig.8.5a).
   The hangingwall rocks could either have moved horizontally

into an area where the Silurian was absent or been forced to slide over the top of the Kvitvola Thrust Sheet.

2. The Kvitvola Thrust Sheet was probably emplaced along an out-of-sequence thrust(see Chapter 7). As the Kvitvola Thrust ramped through the Osen-Roa Thrust Sheet (Fig.8.5b) it probably passed from deformed into undeformed mid Ordovician rocks and formed a flat so that the mid Ordovician and Silurian hangingwall rocks were deformed whilst the footwall rocks remained undeformed. Later shortening of the Osen-Roa Thrust Sheet corrected this imbalance by deforming the excess Cambro-mid Ordovician below the Kvitvola Thrust and transported it towards the foreland. The footwall rocks of the upper detachment zone therefore actively underthrust the hangingwall rocks.

It is not possible at this stage to state which of the models is likely to apply. However this kind of structure can be seen on an outcrop scale, where a competent unit has remained rigid, whilst imbricate thrusts have shortened imbricate shales to a much greater extent below.

8.2.5 Palinspastic restorations of the Oslo Graben.

Using the balanced cross-sections drawn through the Eiker-Sandsvaer, Asker-Baerum, Ringerike-Tyrifjord, Hadeland and Mjosa areas (for a summary see Fig.8.6), a palinspastic restoration of the Cambro-Silurian of the Oslo Graben from foreland up to the Vangsas Formation hangingwall cut off has been made (see Fig.8.7). The distance from the predicted limit of the thrust front to the Vangsas Formation hangingwall cut off in the present strained state is 140km and in the unstrained state is about

275km. Therefore the average shortening (e) within the region is about 50%.

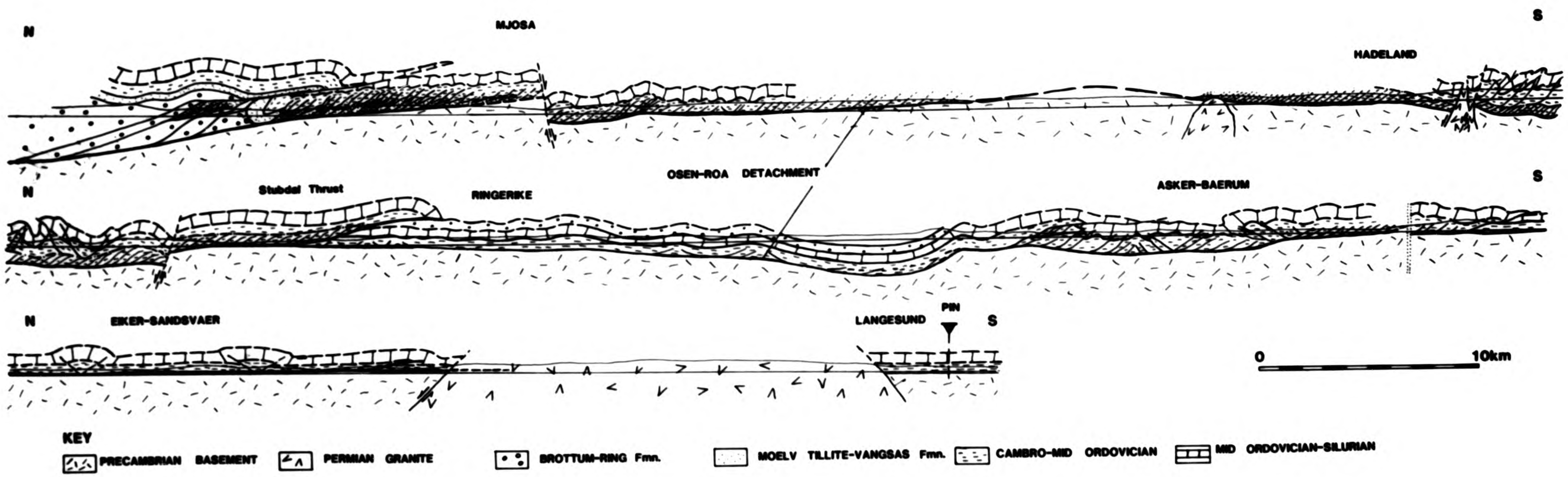
Using this estimate for shortening, the Vangsas hangingwall cut off has travelled a minimum distance of 135km. This figure can be tested to prove whether it is valid or not because the basement windows at the northern end of the Sparagmite region display autochthonous Vangsas Formation and Moelv Tillite, with occasional patches of Alum Shales, resting on Precambrian basement. Therefore the Vangsas Formation hangingwall cut off must restore to a line north of the basement windows when unstrained.

Assuming a minimum of 50% shortening for the Osen-Roa Thrust Sheet north of the Vangsas Formation hangingwall cut off, the 140km wide sparagmite region unstrains to 280km. Therefore the original length of the whole Osen-Roa Thrust Sheet is 275km for the Oslo Graben and 280km for the Sparagmite region, making a total of 555km. This figure is probably a minimum estimate and a 20% error margin should be allowed. This means that the most northerly third of the Sparagmite region at least, was originally deposited NNW (of its present position) off the present Norwegian coast.

Nystuen (1981,p.73-75) summarised the two tectonic models for the Osen-Roa Thrust Sheet which are currently being applied to the Sparagmite region. These are a parautochthonous model (Skjeseth 1963, Strand 1972) and an allochthonous model by Oftedahl (1943).

The parautochthonous model requires a detachment of the Ekre Shales from the underlying rocks and the transport of the Osen Nappe (previously the "Quartz Sandstone Nappe") by about 50km to the south. The remainder

Fig.8.6 __The structure of the Osen-Roa Thrust Sheet in a N-S section through the Oslo Graben.__



N
MJOSA
S
HADELAND
N
Stubdal Thrust
RINGERIKE
OSEN-ROA DETACHMENT
ASKER-BAERUM
S
N
EIKER-SANDSVAER
LANGESUND
PIN
S
0
10km
KEY
PRECAMBRIAN BASEMENT
PERMIAN GRANITE
BROTTUM-RING Fmn.
MOELV TILLITE-VANGSAS Fmn.
CAMBRO-MID ORDOVICIAN
MID ORDOVICIAN-SILURIAN

Fig.8.7 <u>Palinspastic restoration of the Oslo region.</u>

The boundaries represent the northern limit of each area in the deformed and restored state.

1,1' = Eikeren

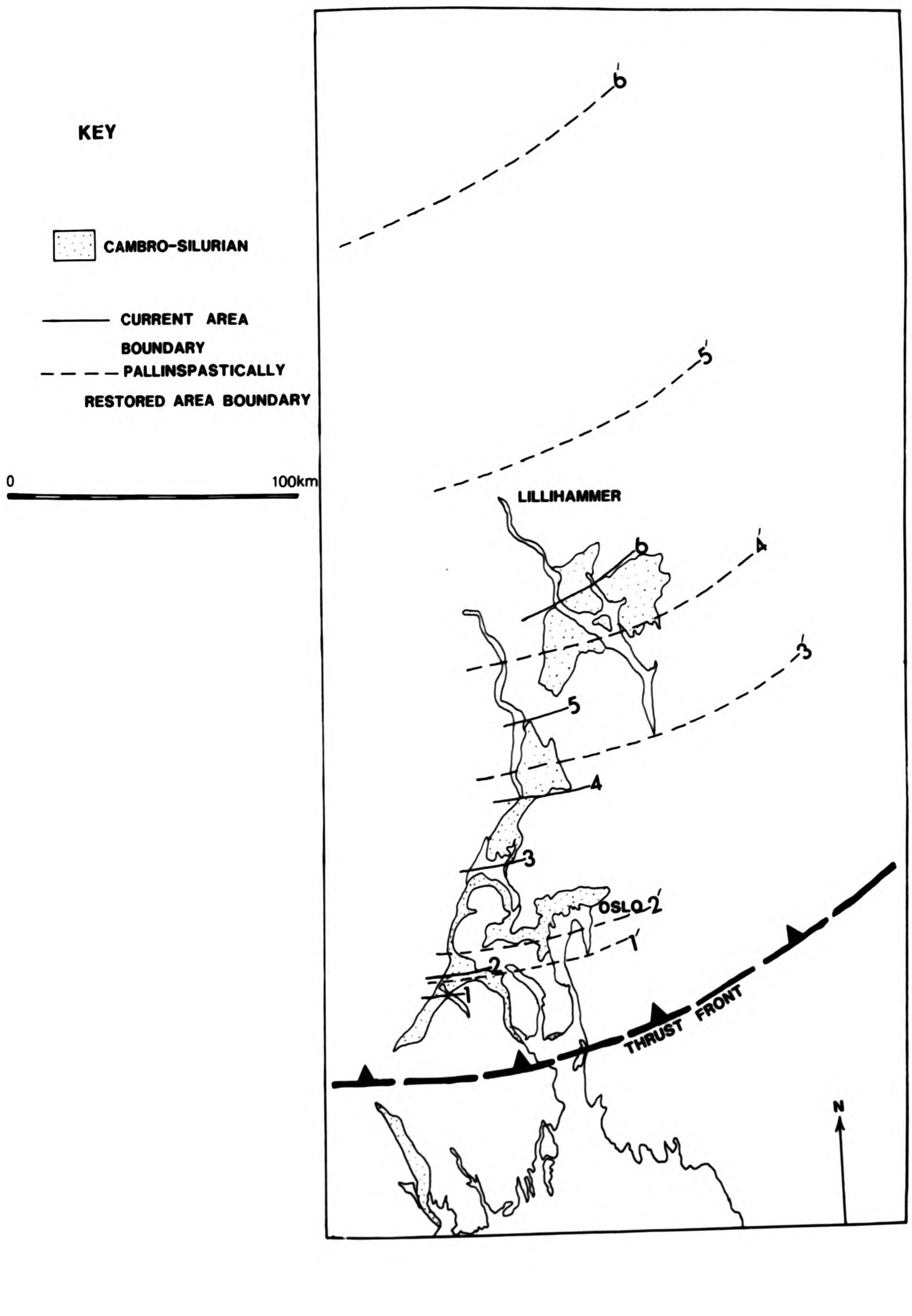
2,2' = North Drammen

3,3' = Asker-Baerum and Tyrifjord

4,4' = Ringerike

5,5' = Hadeland

6,6' = Vangsas Formation hangingwall cut off


KEY
CAMBRO-SILURIAN
CURRENT AREA BOUNDARY
PALLINSPASTICALLY RESTORED AREA BOUNDARY
0
100km
LILLIHAMMER
OSLO
THRUST FRONT
N

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

The allochthonous model proposes that the Sparagmite sequence was a thrust sheet transported from a depositional area north of the current basement windows. Thrust distances of 300km were originally suggested by Oftedahl (1943) and later models (Oftedahl 1954 a,b; Holmsen and Oftedahl 1956) also placed the main depositional area north of the basement windows. An intermediate model with basins on the northern and southern sides of the windows was proposed by Prost (1977).

One of the main aims of this thesis is to demonstrate the relationship between the Sparagmite region and the Oslo Graben. By using the frontal ramping model (see Fig.7.9) to explain the progressive cutting up section of the Osen-Roa Thrust until it passes into the Oslo Graben as a detachment within the Alum Shales, the parautochthonous model can be shown to be invalid. This is because by unstraining the Cambro-Silurian of the Oslo Graben the Vangsas Formation in the hangingwall is placed north of the basement windows, which involves transport distances of at least 135km and therefore supports the allochthonous model.

8.3 The timing of structural events in the Southern Caledonides.

Evidence for the timing of tectonic events comes from the structural relationships within and between thrust sheets and from tectonically influenced sedimentation (Armstrong and Oriel 1965). The concentration will be mainly on the sedimentary evidence here.

Sedimentation rates are low in the Cambro-lower Ordovician of the Oslo Graben (about 1mm/1000 years) but increase to about 30mm/1000 years in the lower Silurian, (Bjorlykke 1974). So there is little evidence for material being eroded off rising thrust sheets and reaching the Oslo Graben until the late Ordovician and Silurian.

Notable in the distribution of the upper Ordovician and lower Silurian rocks of the Oslo Graben are NNE-SSW trending facies belts which change from sandy to calcareous to shaley-nodular limestone facies from E-W (see fig.5 in Brenchley and Newall 1980). This distribution of clastics away from the old Baltic shoreline, with sediments becoming finer towards the shoreline led to the postulation of the emergence of the western edge of the platform during the Arenig by Skjeseth (1952). Later Stormer (1967) suggested a mid-Caradoc belt of shallows, which was referred to a "Telemarkland". The facies belts trend at right angles to the the movement directions of the southern Norwegian thrust sheets, which is probably no coincidence.

However it is unlikely that any direct link can be made between sedimentation and the emplacement of the southern Norwegian Storhei and Busdals Thrust Sheets of Sigmond (1978). Never-the-less, the emplacement of one or both of these thrust sheets during the upper Ordovician and lower Silurian could explain the sandy facies as either forming ahead of the forebulge or in the foredeep formed in isostatic response to the loading of the crust by a thrust sheet (Price 1973; Gretener 1981). The increase in the amount of Fe,Mg,Ni,Cr and chlorite that has been detected by Bjorlykke (1974) in the upper Ordovician rocks in Oslo could also be due to the erosion of the metamorphic rocks of the Storhei Thrust Sheet. More direct evidence for Ordovician thrust movements is the mid Ordovician deformation and metamorphism of the Bergen Arcs district (Nicholson 1974,p182).

Syn-orogenic sediments are thought to exist in the central part of the Southern Caledonides. The lowest of these units is the Phyllite Division of Strand (1938, 1951) which is found in the Synnfjell Thrust Sheet (Nickelsen et al in press). The latter authors concider the Phyllite Division to be a flysch deposit. The unit is difficult to date because of the lack of fossils, but Bjorlykke (1905) found Arenig fossils near the base of the division in its eastern extent. As the Phyllite Division follows on from Tremadoc shales (Garton pers. comm.) its stratigraphic position would support this age. This flysch deposit is of great lateral extent and can be traced from beneath the leading- to the trailing edge of the Valdres Thrust Sheet which has overridden it.

There are two main areas of outcrop of the Phyllite Division. The western most lies above the Synnfjell Thrust Sheet rocks and are the middle(?)-upper Ordovician turbidites of the Strondafjord Formation (Nickelsen et al, in press). These deposits have been interpreted as a clastic wedge deposited in front of a moving thrust sheet by Hossack (in Brynhi 1981) and Hossack et al (in press). A similar clastic wedge sequence called the Gausdal Formation has been correlated with the Strondafjord Formation by Englund (1973), who interpreted the Gausdal Formation as a flysch deposit, which contains detritus similar to the Jotun Thrust Sheet rocks.

The ages of the sandy and turbiditic facies rocks youngs to the SSE from the Arenig Phyllite Division in the NNW, through the mid-upper Ordovician (and Silurian ?) Strondafjord and Gausdal Formations to the upper Ordovician-lower Silurian sandy facies of the Oslo Graben and Jamtland (Gee 1974) areas, (see Fig.8.8), which might indicate the progression of a series of clastic wedges towards the foreland as they were deposited ahead of a moving thrust sheet.

Additional evidence for tectonic activity during these times comes from the Mjosa area where perthitic feldspars derived from charnocitic rocks, similar to the rocks of the Jotun Thrust Sheet, are present in the 6c sandstones (Strand in Holtedahl 1960,p.152). This could indicate that the Jotun Thrust Sheet was moving and being eroded at this time. The 6c sandstones rest on the Mjosa Limestone separated by an unconformity which represents stages 4c-6b, it could be explained as erosion during the passage of a forebulge through the Mjosa area.

The youngest clastic wedge deposits in the Oslo Graben are the molasse sediments representing the marine to continental transition towards the end of the Silurian. The oldest of these deposits is found in the Mjosa and Hadeland area as the deltaic deposits of stage 8 called the Bruflat Sandstone. Further south in the Ringerike area, and partly correlatable with the Bruflat Sandstone, are the red marl and sandstone deposits of the Ringerike Sandstone unit. Spjeldnaes (1966) deduced from fossil evidence that the basal beds are oldest in Ringerike and young southwards to Jeloya. This base youngs over a period of 5-10my, whilst the actual sedimentation lasted for 10-20my (Bjorlykke 1974).

The earlier clastic wedges represent the emplacement of the Jotun and Valdres Thrust Sheets from the WNW or NW direction, whilst the Bruflat and Ringerike Sandstones probably represent the emplacement of the Trondjheim thrust sheets. This is reflected in the different orientation of the facies belts for the two events (see Fig.8.8) that both perpendicular to the main transport directions of the thrust sheets.

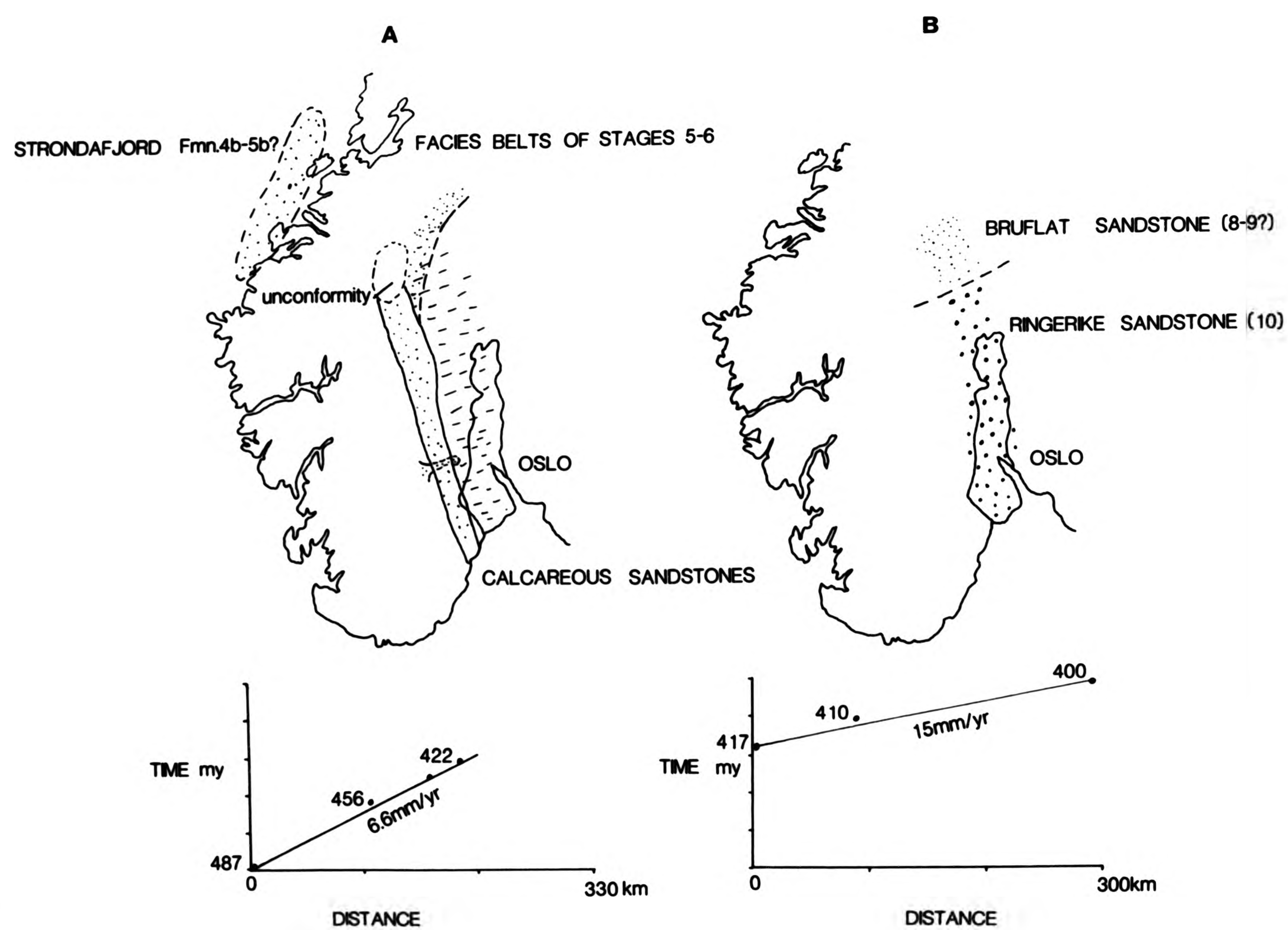
By plotting graphs of the age of the flysch or molasse deposits against the unstrained distance between the deposits, a time averaged estimate for the rate of advance of the thrust sheets can be obtained

Fig.8.8 Syn-orogenic sedimentation

A. Mid Ordovician syn-orogenic areas of sedimentation (palinspastically restored).

B. Mid-upper Silurian molasse sedimentation.

The graphs are plotted as distance from the earliest to the latest clastic wedge deposits, against geological time. This gives a time averaged rate of advance for the clastic wedges.


A
STRONDAFJORD Fmn.4b-5b?
FACIES BELTS OF STAGES 5-6
unconformity
OSLO
CALCAREOUS SANDSTONES
TIME my
487
456
422
6.6mm/yr
0
330 km
DISTANCE
B
BRUFLAT SANDSTONE (8-9?)
RINGERIKE SANDSTONE (10)
OSLO
TIME my
417
410
400
15mm/yr
0
300km
DISTANCE

(see Fig.8.8) of 6.6mm/yr for the Jotun and Valdres Thrust Sheets and 15mm/yr for the Trondheim thrust sheets.

8.4 A balanced cross-section from Fluberg to Lom.

The structural geology of the Southern Norwegian Caledonides has been investigated by numerous workers including Strand (1938, 1951a,b, 1958), Hossack (1968, 1972, 1976, 1978), Loeschke and Nicholson (1968) and Nicholson (1967, 1974). By using information from these papers and from Hossack and Garton (pers. comm.) a balanced cross-section from Fluberg to Lom was constructed (see Fig.8.9a,b). In the construction of the cross-section the following problems and relationships were taken into account:

1. The thrust sheets intersected by the line of section proceding from SSE to NNW (also from youngest to oldest) are the Aurdal, Synnfjell, Valdres and Jotun Thrust Sheets.
2. There is a branch line of the Aurdal and Synnfjell Thrusts half way along the Aurdal valley (Hossack in Brynhi 1981). This branch line needs to be projected into the line of section.
3.The Beito window displays a stratigraphy described by Hossack (1976) proceding up section from autochthonous Precambrian basement of Synnfjell, Valdres and Jotun Thrust Sheet rocks.
4. The Phyllite Division of the Synnfjell Thrust Sheet is found below the leading and trailing edges of the Valdres Thrust Sheet. At the trailing edge the Phyllite division and lower Synnfjell Thrust Sheet units are found resting on a thin covering of Cambrian(?) clastics. The basal conglomerate to these clastics is reported in Holtedahl (1960) to be autochthonous and infills fissures in the underlying Precambrian basement. Despite the highly sheared nature of the

trailing edge rocks the whole sequence has been regarded as autochthonous (eg Holtedahl 1960, Strand 1972), however Twist (1979) regardes the contact between basement and cover at the northern end of the Jotun Thrust sheet as being separated by a thrust plane.

5.The leading edge of the Valdres Thrust sheet at Rossjokollane and Djuptjernskampen comprises thin discontinuous basement slices deformed together with Eocambrian Valdres Sparagmite into large overturned folds truncated by the Valdres Thrust (Loeschke and Nicholson 1968). Progressing NW the thrust sheet thins from 4km to about 1km but the imbricated, sheared and folded Valdres basement appears to have been originally more continuous than at the leading edge. Twist (1979) regards the Valdres Thrust Sheet rocks below the trailing edge of the Jotun Thrust Sheet as forming discontinuous blocks, so the original trailing edge of the Valdres Thrust Sheet is in close proximity to its current position.

6. The footwall cut off of the hangingwall, leading edge Valdres folds cannot be located and has probably been eroded away. The likely location for this branch line between the Synnfjell and Valdres Thrusts is between the Bergen Arcs and the main mountain belt.

7.Arguments about the depth to which the Jotun Thrust Sheet is present in the centre of the mountain belt are numerous (see Smithson et al.1974). Therefore the line of section was chosen to avoid these problems by passing through the large half window in the Bessheim area, which reveals Valdres Thrust Sheet rocks and Phyllite Division below the Jotun Thrust Sheet. This enables a thin thrust sheet to be drawn in the line of section, with the dip of the thrust plane estimated from regional sheet dips measured by Garton (pers. comm.). Smithson et al (1974) estimate the thickness of the Jotun Thrust Sheet to be between 7 and 15km by gravity measurements. An arbitrary thickness of 10km is used here.

8. Data from a seismic profile across the More gneiss region by Mykkeltveit et al (1980) has revealed a low velocity zone 4km thick at a depth of about 14km. This was interpreted as oceanic crust and accompanying sediments subducted under the gneisses.

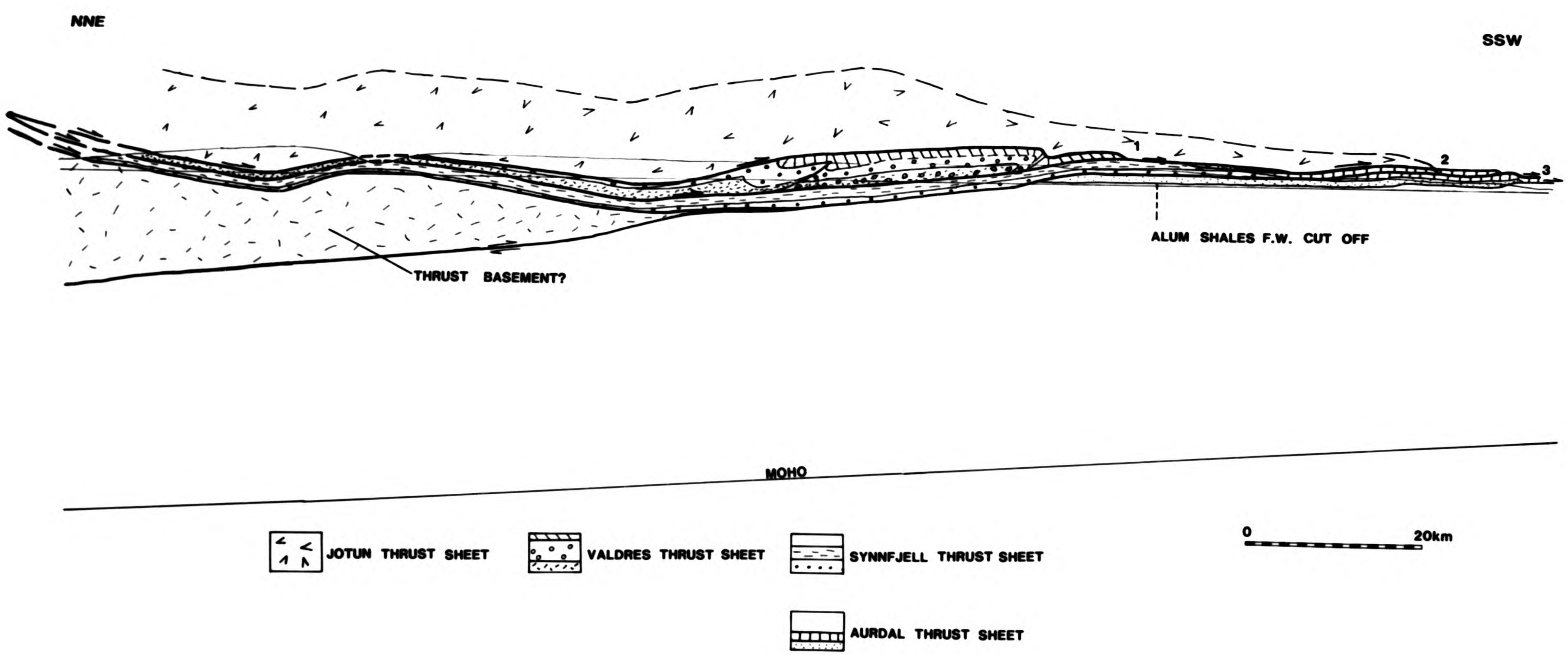
Using this information a generalised cross-section has been drawn through the Southern Caledonides from Fluberg in the SSW to Lom in the NNW (see Fig.8.9a). Only the major thrusts can be accurately positioned at the scale of Fig.8.9, so any internal stratigraphic division of the thrust sheets has been made to illustrate where ramps, flats and hanging-and footwall cut offs are located. This enables the section to be balanced using the relationships between thrust sheets, but not on the scale of structures within the thrust sheets (see Fig.8.9b). The important features of the cross-section progressing to the NNW are listed below.

1.The Aurdal Duplex Sole Thrust must have ramped into Cambro-Silurian rocks (now eroded), just south of the current thrust front. The footwall cut off must lie somewhere under the mountain belt.

2. The Synnfjell Thrust must cut up section south of its current most southerly outcrop in order to form the roof thrust to the 4aa shales in the Aurdal Duplex. The rocks younger than 4aa which originally lay on top of the Aurdal Duplex stratigraphy must have been transported to the SE and subsequently eroded . A distinct facies change must have existed between the limestone-shales of the Oslo region and the Phyllite Division further NW.

Fig.8.9a Cross-section through the Jotunheim, from Fluberg to Lom.

Fig.8.9b Restored section of Fig.8.8a.


NNE
SSW
1
2
3
ALUM SHALES F.W. CUT OFF
THRUST BASEMENT?
MOHO
JOTUN THRUST SHEET
VALDRES THRUST SHEET
SYNNFJELL THRUST SHEET
AURDAL THRUST SHEET
0
20km

However it is interesting to note that in the Hadeland and Mjosa areas the 4aa and 4b stages are dominated by a thick (about 270m) shale formation which might represent the distal end of the Phyllite Division.

3. The variations in thickness of the Valdres Thrust Sheet can largely be explained by ramping of the Jotun Thrust and partly by shearing and flattening under the confining load of the higher thrust sheets. The Jotun Thrust footwall cut offs at the trailing edge of the Valdres Thrust Sheet indicate that the corresponding hangingwall cut offs at the leading edge of the Jotun Thrust Sheet extended (WSW) at least to Fluberg, before erosion.

A similar relationship probably existed between the Valdres and Synnfjell Thrust Sheets, where the truncated hangingwall folds at Mellane had footwall cut offs in the Synnfjell Thrust Sheet just north of the current trailing edge.

4. If the trailing edge of the Synnfjell Thrust Sheet stratigraphy is autochthonous with Precambrian basement (Strand 1972), whilst the leading edge is allochthonous, then a thrust ramping up from basement has to be postulated. The low velocity zone in the More Gneiss region could represent a deep thrust which must appear somewhere under the Southern Caledonides. In this section it has been joined up with the Synnfjell Thrust.

If, however, subsequent research shows that the Synnfjell stratigraphy is allochthonous at the trailing edge the Synnfjell Thrust does not have to pass into basement.

Although the allochthonous and autochthonous More Gneiss models vary in the position of the sole thrust the amount of shortening in the line of section remains similar.

5. Assuming 50% shortening for the Synnfjell, Aurdal and Valdres Thrust Sheets and no shortening for the rigid Jotun Thrust Sheet (except at the leading edge) the section restores from 150km at present to 800km when unstrained. This is a minimum estimate because the Valdres Thrust Sheet has probably undergone more than 50% shortening (Garton pers. comm.) and the Jotun Thrust Sheet has deformed internally to some extent.

8.5 The structural history of Osen-Roa and Trondheim Thrust Sheets

A brief examination of the structural history of the Trondheim thrust sheets is important at this point because of the complex relatio-ships of the thrust sheets in southern Norway described in Chapter 7.

The Osen-Roa Thrust Sheet and its lateral continuation as the Aurdal Duplex have been regarded as having simple sequential thrust relation-ships with the overlying Synnfjell Thrust Sheet. The relationship between the Osen-Roa Thrust Sheet and Trondheim thrust sheets is not so simple.

Movement of the Jotun Thrust Sheet (and slightly later the Valdres Thrust Sheet) probably have began in Arenig or pre-Arenig times in order to produce the Phyllite Division flych. This has yielded graptolites of 3a age near the base and 4a age in the upper part (Strand, in Holtedahl 1960). East of Valdres in Vestre-Gausdal Lapworth (1905) identified 3b-4a graptolites in the Phyllite Division.

In the Trondheim area the Storen Thrust Sheet also moved in Arenig times (Roberts and Wolff 1982). However the Storen Thrust Sheet probably represents obducted ocean floor and has a North American fauna, whilst the Jotun Thrust Sheet probably represents Baltic continental crust (Hossack and Cooper in press).

The presence of exotic thrust sheets such as the Storen and Koli Thrust Sheets in the Trondheim thrust sheet pile (Hossack and Cooper in press) complicates a restored cross-section. However, using a simplified balanced cross-section, (assuming 50% internal shortening for the thrust sheets), pinned in Langesund-Skien, the undeformed length of the Trondheim region is about 1400km (see Fig.8.10), which is much greater than the length calculated for the Jotun region (Fig.8.9).

It is therefore apparent that if deformation began in both areas during the Arenig and proceded at the same rate in both areas, then the Trondheim thrust sheets would be finally emplaced later that the thrust sheets in the Jotunheimen area, at their respective positions on the trailing edge of the Osen-Roa Thrust Sheet. The final movement direction of the Osen-Roa Thrust Sheet to the SSE coincides with the final movement direction of the southern Trondheim thrust sheets, not the Jotun region thrust sheets which moved to the SE. This and the timing and distribution of syn-orogenic sediments (see 8.8) all suggest that the final emplacement of the Trondheim thrust sheets was later than the Jotun region thrust sheets.

The emplacement event of the Trondheim thrust sheet also apparently caused the greatest deformation in the Osen-Roa Thrust Sheet. This can be seen by comparing the distance of the footwall cut offs of the autochthonous Alum Shales of the two regions from the hangingwall cut off marked by the ramping through of the Vangsas Formation. In the Jotun region the autochthonous Alum Shales can be traced away from the Vangsas Formation for a minimum distance of 50km up the Aurdal valley, the maximum distance is 70km because autochthonous Alum Shales are absent in the Vang and Beito windows. In the Trondheim region the footwall cut off to the Alum Shales can be projected for 130-140km N of the Vangsas Formation hangingwall cut off to just pass under the southern edge of the Trondjheim thrust sheets. Hence much more shortening of the Cambro-Silurian appears to have been achieved in the eastern part of southern Norway.

Here it is proposed that the Jotun and Valdres Thrust Sheets moved from Arenig to early Silurian times and probably later still, "piggy back" style on the Synnfjell Thrust Sheet. The Trondheim thrust sheets moved from Arenig to Downtonian times and later, thrusting progressed into the Oslo Graben, probably during the early Devonian. As the Trondheim thrust sheets were moving, lateral ramping of the Osen-Roa Thrust produced interference in the Dokka area with earlier(?) imbricates in the Aurdal Thrust Sheet produced by the same emplacement event as the Jotun, Valdres and Synnfjell Thrust Sheets.

region the autochthonous Alum Shales can be traced away from the Vangsas Formation for a minimum distance of 50km up the Aurdal valley, the maximum distance is 70km because autochthonous Alum Shales are absent in the Vang and Beito windows. In the Trondheim region the footwall cut off to the Alum Shales can be projected for 130-140km N of the Vangsas Formation hangingwall cut off to just pass under the southern edge of the Trondjheim thrust sheets. Hence much more shortening of the Cambro-Silurian appears to have been achieved in the eastern part of southern Norway.

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Fig.8.10 Simplified cross-section and restored section from Langesund Skien (SSE) to Vallersund (NNW), through the Oslo Graben and Trondheim region.

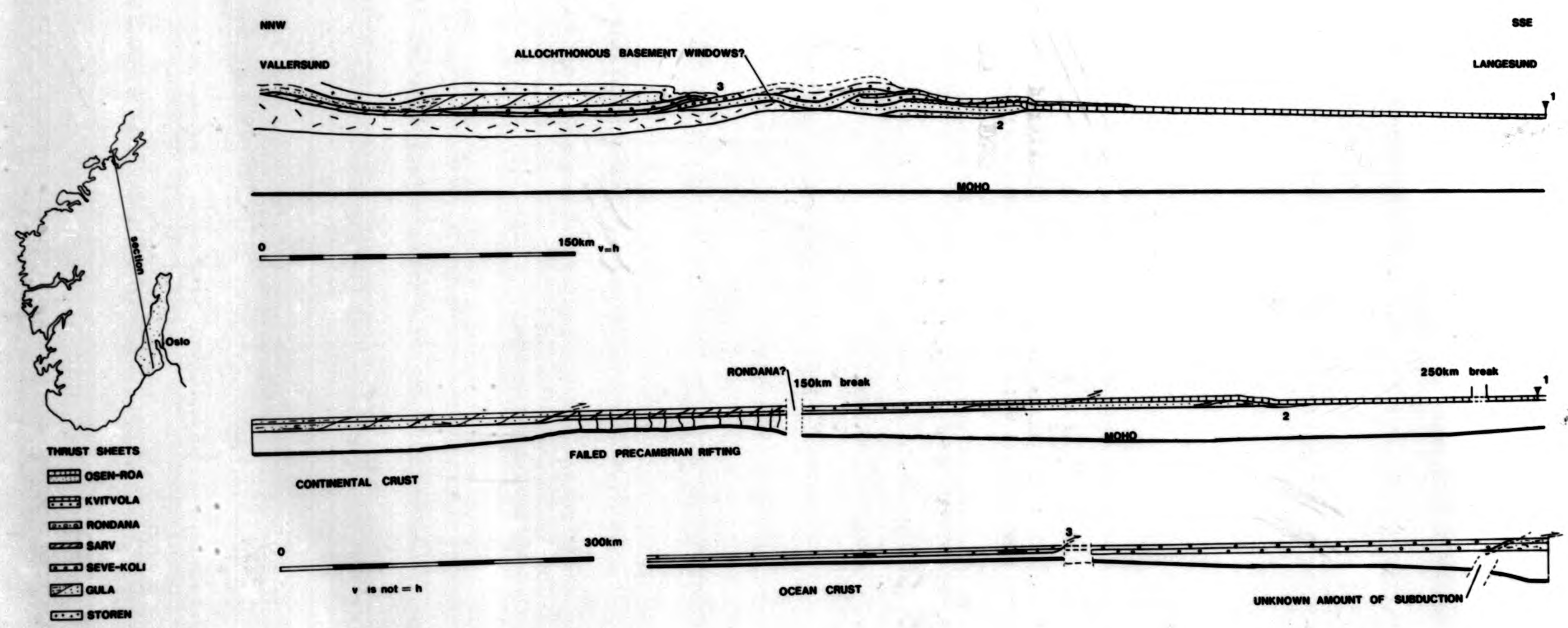

NNW
SSE
VALLERSUND
ALLOCHTHONOUS BASEMENT WINDOWS?
LANGESUND
3
2
1
MOHO
0
150km v=h
section
Oslo
RONDANA?
150km break
250km break
1
2
MOHO
FAILED PRECAMBRIAN RIFTING
CONTINENTAL CRUST
THRUST SHEETS
OSEN-ROA
KVITVOLA
RONDANA
SARV
SEVE-KOLI
GULA
STOREN
0
300km
v is not = h
3
OCEAN CRUST
UNKNOWN AMOUNT OF SUBDUCTION

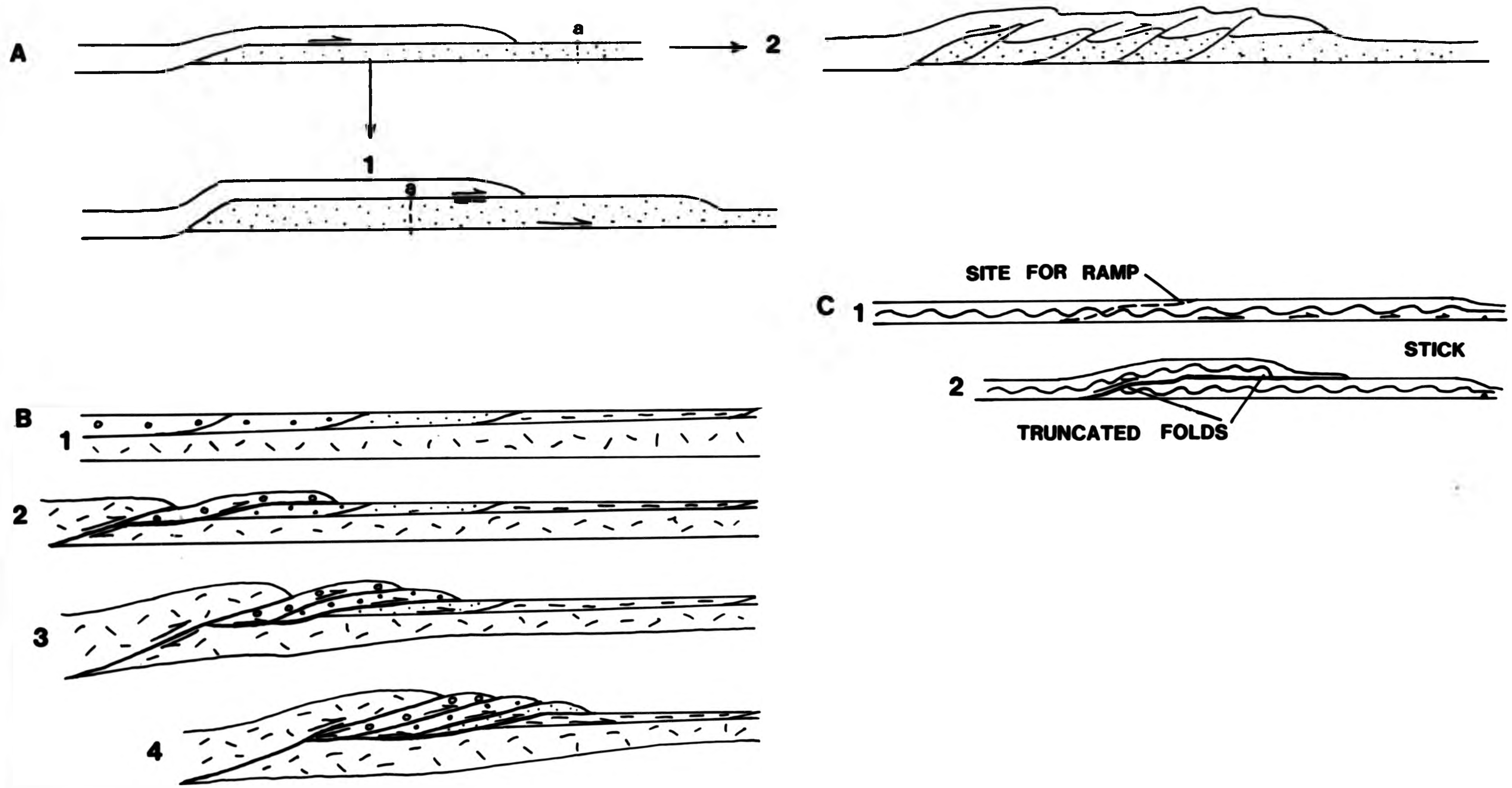
Fig.8.11 Different causes of out-of-sequence thrusting.

A1. With the thrust sheet pinned at the ramp, point "a" in the newly deforming thrust sheet moves relatively towards the hinterland. Thus the higher thrust sheet is reactivated because the lower thrust sheet contracts below it.

A2. Imbricates form the newer, lower thrust sheet deform the higher thrust sheet, producing apparent out-of sequence thrusting.

B. Sequential deformation of a thrust belt, with the lowest thrust sheet being the youngest. Stresses transferred to the deforming thrust sheet pass through the older thrust sheets which may repeatedly unstick and move as a result.

C. Stick on a thrust may result in a thrust ramping hindewards of its sticking point, truncating older structures.


A
a
2
1
a
B
1
2
3
4
C
1
SITE FOR RAMP
STICK
2
TRUNCATED FOLDS

8.6 Out-of-sequence thrusting.

Thrusts are thought to usually develop in a foreland progressing sequence (Dahlstrom 1970). This applies to major thrusts and to second and third order thrusts. In the former, in-sequence thrusting results in "piggy back" thrusting sequences, where older thrust sheets are carried passively on top of successively younger ones. In the latter, in-sequence thrusting may result in older imbricates being rotated and oversteepened by foreland progressing imbrication (Perry 1978).

Thrusts which do not form within such a sequence of thrusting usually truncate earlier structures and are known as out-of-sequence thrusts. In southern Norway there are several examples of large out of sequence thrusts and they may be classified into several groups as follows:

1. In a sequence of piggy back thrusting, a deformed thrust sheet is usually emplaced on either an undeformed sequence of rock or on a newly forming thrust sheet. In both cases the underlying thrust sheet is likely to deform at a faster rate than the already deformed and emplaced overlying thrust sheet. For simplicity I will assume that the overlying thrust sheet has ceased to move and is resting passively on top of an undeformed sequence of rock. As the the sole thrust propogates through the undeformed sequence, the rocks in the newly formed hangingwall are shortened by folding and minor thrusting. This means (assuming that both thrust sheets are pinned together at the lowest thrust sheets trailing edge) that if the overlying thrust sheet was (as in Fig.8.11a1) lying originally over point 'a' at its leading edge, the corresponding point 'a' in the higher thrusts footwall, once the footwall becomes deformed will shift towards the hinterland relative to the hangingwall, therefore reactivating the old thrust.

Therefore piggy back thrusting may by its own nature produce reactivation of old thrusts and cause out-of-sequence thrusting. Probably most major thrust planes in the Southern Caledonides have been reactivated by this process.

2. If instead of deformation restricting itself to the lowest thrust sheet in a piggy back sequence, the thrusts from the lowest thrust sheet penetrate higher thrust sheets, then apparent out-of-sequence thrusts in the higher thrust sheet may be produced (see Fig.8.11a2). Thrusts penetrating higher thrust sheets will cut the older structures present in the earlier formed thrust sheet. The Kvitvola Thrust Sheet is a good example because it is cut by later imbricate thrusts from the Osen-Roa Thrust Sheet. In this example the Osen-Roa Sole Thrust laterally ramps up section as well and passes into the Kvitvola Thrust Sheet which was reactivated and thrust over Precambrian basment.

3. If a thrust belt is deforming by a push mechanism from behind then stresses are transmitted through older to younger, newly deforming thrust sheets, because the thrust sheets overlap like tiles (see Fig.8.11b). That the push mechanism is not sufficient to line up the trailing edges of thrust sheets in a vertical plane can be seen in the Norwegian Caledonides, where the trailing edge branch line of lower thrust sheets usually lie part way under higher thrust sheets.

As the stresses causing the foreland propogation of thrust sheets must be transmitted through all the previously emplaced thrust sheets, to the newest, actively deforming thrust sheet(s) more and more thrust sheets are required to stick with time. However it is likely that these thrust sheets are not stuck permanently and that many out-of-sequence events occur during the evolution of a thrust belt as the higher thrust sheets are shuffled by repeated sticking and unsticking.

4. Stick on a newly deforming thrust may produce sufficiently increased stresses in the rocks towards the hinterland to cause a major new thrust sheet to develop hindwards of the sticking point. Thus a new thrust sheet may be formed from part of an older one (see Fig.8.11c).

One good example of this is the Kvitvola/Osen-Roa Thrust Sheet relationship. The Osen-Roa Thrust Sheet appears to have deformed first and then stuck some distance north of the Ringsaker inversion. The Kvitvola Thrust then formed in order to take up the stresses, and truncated folds in the Osen-Roa Thrust Sheet as the leading edge of the thrust cut up to the surface. Later, when the Kvitvola Thrust Sheet stopped moving, the Osen-Roa Thrust resumed movement, abandoning part of the original leading thrust sheet area. This can now be seen below the main Osen-Roa Thrust Sheet in the Elstad window (Englund 1973b).

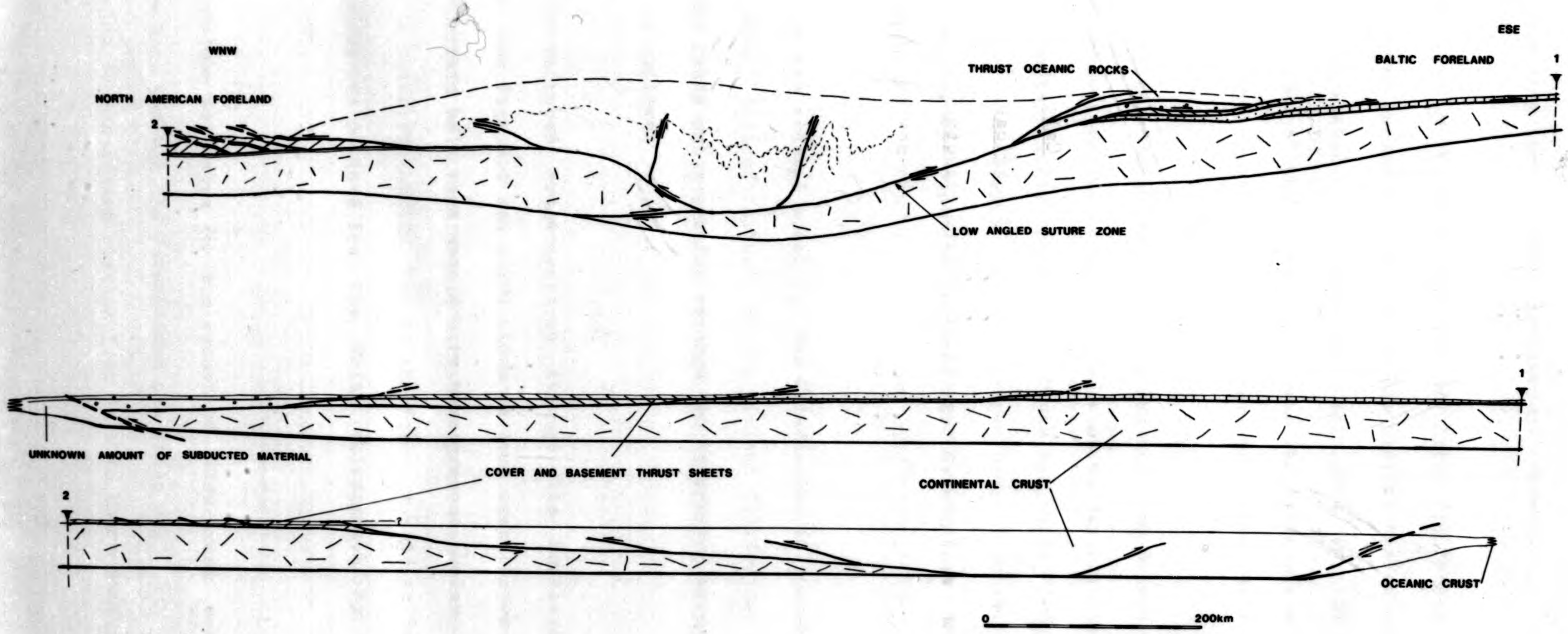
5. Truncated fold limbs formed early on in the history of a thrust sheet might suggest out-of-sequence thrusting when they are actually complex tip line folds. The folds in the Valdres Thrust Sheet at Mellane (Loeskhe and Nicholson 1968) might be such an example.

6. Thrust sheets can die out horizontally so that the sole thrust passes laterally into a higher thrust sheet, reactivating that part of it which overlaps the thrust sheet below. This can be caused either by tectonic ramping or by sedimentary thinning in the thrust sheet laterally. For example, a tectonic thinning might be represented by the the Osen-Roa Thrust which ramps up laterally to pass into the Kvitvola Thrust Sheet on the eastern margin of the Sparagmite region. The Valdres Thrust Sheet might represent the sedimentary thinning of a thrust sheet,

where it thins out to the west, so that eventually the Valdres Thrust Sheet forms a lateral branch line with the Jotun Thrust above.

Fig.8.12 Idealised cross-section through the Caledonian orogen, showing the overthrusting of the North American Plate over the Baltic Plate, to produce a crustal pop-up structure.

This model does not display the strike slip movements which may have occurred before, during and after the main Caledonian deformation, which may modify, but not drasically change its geometry or sense.


WNW
ESE
NORTH AMERICAN FORELAND
BALTIC FORELAND
THRUST OCEANIC ROCKS
LOW ANGLED SUTURE ZONE
1
2
1
UNKNOWN AMOUNT OF SUBDUCTED MATERIAL
COVER AND BASEMENT THRUST SHEETS
CONTINENTAL CRUST
2
OCEANIC CRUST
0
200km

8.7 A reconstruction of the Caledonian orogenic belt.

The collision of the North American and Asian (including the Baltic) continental plates probably produced similar crustal thrust geometries to those seen in comparable collision zones today such as the Himalayas, where the overriding of the Indian plate over the Asian plate has doubled the thickness of the crust under the mountain belt (Bird 1978).

However the Caledonian mountain belt has had a much longer time to become modified by a variety of processes; erosion has exposed a very low level of the mountain belt, the Atlantic Ocean has split the Caledonian mountains apart and wrench fault systems have further complicated attempts to realine the opposite parts of the Caledonides in Greenland and Scandanavia.

Therefore any crustal model for the Caledonides is somewhat conjectural. However various features in the present Caledonides can help to construct the crude cross-section through the Caledonian orogenic belt in Fig.8.12. as follows:

1.In the balanced cross-sections through the Southern Norwegian Caledonides (see Figs.8.9 and 8.10) there is less crust below and included in the mountain belt than should have been present below the thrust sheets in a restored section down to the Moho. A similar lack of basement thickening was noticed for the Welsh Caledonides by Coward and Siddans (1979).

Even minimum estimates for the amount of extra crust needed for a restored section through the Jotunheimen are large eg.

Length of unstrained section from Oslo to Lom = $1000km^2$

Original continental crust thickness = 25km^2

Amount of continental crust in line of section = 25000km^2

Length of present day line of section 300km^2

Present day depth to Moho = 30-40km6^2

Amount of crust in present line of section =12000km^2

Amount of crust in the Jotun Thrust sheet = 1000km^2

Amount of crust in the Valdres Thrust sheet =60km^2

Total crust in present line of section = 13060km^2

Amount of crust missing in the "balanced section" (Fig.8.10a) =25000 - 13060 = 11940km^2

This amount of missing crust must have been located towards the centre of the mountain belt which is now lost.

2. Hossack and Cooper (in press) currently think that the Precambrian gneiss domes along the north west coast of Norway are allochthonous and emplaced along fairly low angled thrusts over Baltic and exotic thrust sheet terranes in Norway. In Greenland gneiss domes form a substantial part of the eastern side of the Caledonide mountain belt forming the root zone dipping under the cover rocks (Haller 1971). A significant amount, if not all of the "missing" basement must be accounted for by shortening in the gneiss domes and by crustal thrusting.

3 There is a large difference in the amount of shortening in the mountain belts which transport thrust sheets to the north west compaired with the Norwegian thrust belt which transports thrust sheets to the south east. In NW Scotland and in Greenland the thrust belt might unstrain up to a width of 250km whilst in Southern Norway the unstrained

width is probably 900-1400km. This suggests that the North American plate overrode the Asian plate so that the direction of maximum push was to the south east. The pattern of shortening is therefore asymmetrical in a cross-section through the orogenic belt, with structures like the Moine Thrust in North West Scotland forming a crustal backthrust, in a gigant pop-up structure.

8.8 The development of thrust belts.

The thrust sheets of southern Norway are remarkable because they are so long, thin and have travelled long distances when compared with the Alps, Rockies and Appalachians. This section examines the various theories on the emplacement of thrust sheets, which have largely been developed in the latter thrust belts and tries to apply them to the Norwegian Caledonides. Some approximate dimensions are given for the southern Norwegian thrust sheets below.

NAME AND OF THRUST SHEET	LENGTH	STRAT. THICKNESS	DISTANCE TRAVELLED	LENGTH/THICKNESS RATIO STRAINED:	UNSTRAINED	%INTERNAL SHORTENING
Jotun	250km	10km	250km(min)	25:1	30:1	20%(max)
Valdres	130km	1-4km	130km	32:1(min)	70:1(min)	60%(min)
Synfjell	200km	2km	60km	100:1	200:1	50%
Osen-Roa	300km	2-4km	250km(max)	150:1(max)	300:1(max)	50%

Estimates of the maximum length for a thrust sheet have been made assuming a foreland dipping slope, or horizontal surface, down which the the thrust sheet gravity slides or is pushed (e.g.Hubbert and Rubey 1959, Hsu 1969, Forristall 1972). Hubbert and Rubey (1959) were the first to prove that abnormally high pore fluid pressures could enable a thrust sheet to be transported for the long distances observed, without breaking up. The variables in the equation predicting the maximum length of a thrust sheet were, thickness of the thrust sheet, pore fluid pressure and the angle of slope. However Forristall (1972) suggested that too much emphasis was placed on the thickness of the thrust sheet and that basal shear stress should be built into the equation. From his new equation Forristall (1972) concluded that Hubbert and Rubey (1959) had over-estimated the maximum length of thrust sheets in their equations by up to 50%. However Davis, Suppe and Dahlen (1983) now suggest that Hubbert and Rubey (1959) underestimated the maximum length of thrust sheets.

The link made between pore fluid pressures and gravity sliding is unfortunate because it is unlikely that the sole thrust in many mountain belts is gently dipping towards the foreland at the time of orogeny (e.g. Laubscher 1973, Price 1973, Bucher 1953). In southern Norway the sole thrust to the Jotun Thrust Sheet would require an elevation in excess of 5km before any movement could begin by gravity sliding. However most sedimentary evidence is of thrust belts building up underwater, causing syn-orogenic marine flysch deposits and only in the final stages emerging to produce continental molasse deposits.

It is likely that isostatic adjustment to the load of the thrust sheet pile would cause a hinterland dipping sole thrust to develop (Chapple 1978). The shape of the sedimentary prism would also favour a hinterland dipping sole thrust in the more external zones of a mountain belt because the sedimentary prism tends to thicken up towards the centre of a mountain belt. A hinterland dipping base to the sedimentary pile would result from this loading of the crust.

Many push from the back models for thrust sheets (e.g.Price 1973, Price and Mountjoy 1970, Bucher 1953) are driven by gravity spreading from the rear whilst Elliott (1976b) applied this glacier analogy further. He assumed that because of rock mass weakness, horizontal compression is of small importance for the formation of thrust belts and that gravity can cause enough horizontal spreading of the rocks to drive a thrust belt. This is mainly depedent on the topographic surface slope.

In Norway gravity spreading seems difficult to apply because of the large transport distances involved in emplacing the thrust sheets. This may have required the collapse of a huge centre of rock, perhaps 600km wide and 5km above sea level by about 50% to drive the thrust belt, which seems excessive. Gravity spreading of the thrust sheets themselves to power their transport is also usually difficult to apply. Most of the deformation in the Osen-Roa, Synnfjell, Aurdal and Kvitvola Thrust Sheets involves imbrication, this would actually conciderably raise and thicken the thrust sheets, which is the opposite result of gravity spreading. Whilst the Jotun Thrust Sheet also appears to have behaved fairly rigidly (shortening by perhaps up to 20%). The Valdres Thrust Sheet does however have several elements that may be attributable to gravity spreading e.g. the structures within the thrust sheet are more ductile involving low angled second order thrusts and a flattening fabric (Garton pers. com.). The flattening fabric is particularly well known at Bygdin where flattening appears to have occurred after the emplacement of the Jotun Thrust Sheet which also displays a flattening fabric (Hossack 1968a).

Probably some degree of gravity spreading has operated during the emplacement of the Norwegian thrust sheets. The thickened collision zone envisaged in (Fig.8.12) is likely to have spread laterally to some extent, and some higher thrust sheets may have undergone flattening. But the sliding of one continent over another to produce a low angled suture seems the best way of explaining the long transport directions of the Norwegian thrust sheets and the asymmetry in the amounts of shortening on either side of the orogenic belt.

8.8.1 <u>The evolution of a thrust belt</u>

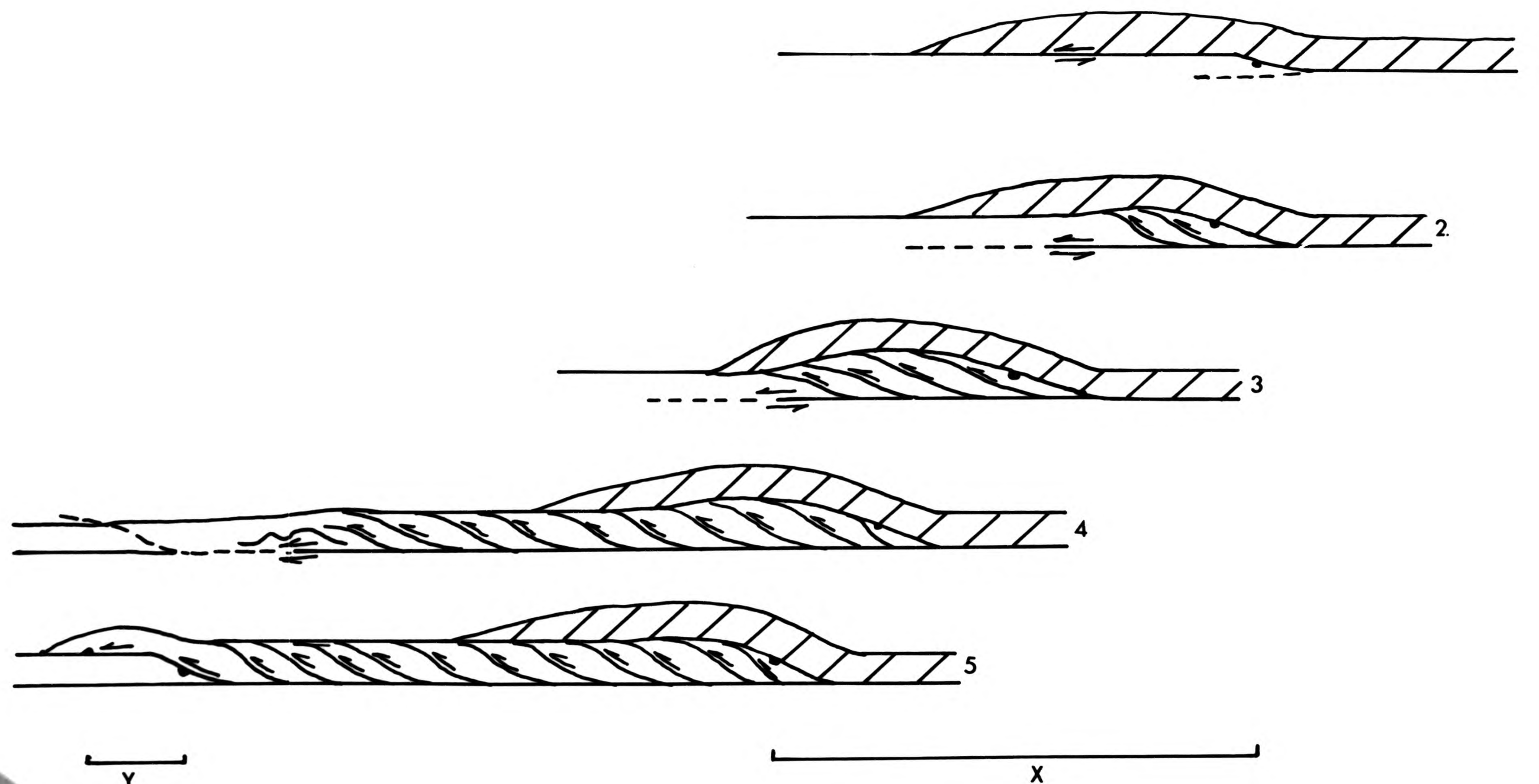
In a plate tectonic framework the continent/continent collision (Dewey and Bird 1970) involves one or several intra-crustal detachent zones which cut up towards the surface and decollement zones in cover sediments. These detached wedges are the light, shallow rocks that have been scraped off an overriding continental plate (Laubscher 1970). This progressive deformation involves new thrust sheets developing into former foreland as the foreland lithosphere progressively moves into the oregenic zone. How does this deformation progress, do thrust sheets form (geologically) instantaneously and deform as they move, or do they develop over a long time period before they actually move as one overthrusting sheet?

Many models have regarded thrust sheets as rigid blocks (e.g. Hubbert and Rubey 1959, Forristall 1972, Hsu 1969), which implies that movements at the back of a thrust sheet will instantly be translated into a similar displacement at the leading edge. A pre-requisite for this to happen is for the thrust fault to be developed in order to define the thrust sheet geometry before it is actually moved. However this does not seem likely. For example, assuming a fast terminal velocity for the collision of two continents of 8cm/yr, on collision one plate may continue to override the other plate, pushing the upper part of the subducting plate ahead of it, forming a thrust sheet. This thrust sheet may be pushed at the most 8cm/yr. Frequently in the field more than 8cm of movement on a thrust can be seen to die out into zero displacement within a few metres. Therefore it seems likely that instead of the 8cm of displacement being translated all the way to the surface, the thrust sheet will slowly and progressively increase its length at the fault tip (Elliott 1976b). This mechanism for developing a thrust sheet is best seen where deformation has finally ceased in a mountain belt, during the development of a thrust sheet. The best place to look therefore, is in the lowest thrust sheet of a thrust belt.

In some thrust belts the lowest thrust sheet has developed as far as ramping and overthrusting before movement has ceased, whilst in others movement has ceased before the thrust sheet has progressed that far. The latter case is true of the Oslo Graben and the Appalachians (Root 1973, fig.5) where the lowest thrust sheet passes into a detachment horizon which dies out without reaching the surface. Deformation of the thrust sheet is never-the-less typical of the higher thrust sheets, involving imbrication and folding along most of its length, frequently resulting in shortening (e) of about 50%, until close to the foreland where deformation dies out. The thrust sheet development has therefore progressed by increments, beginning at the trailing edge and slowly advanced into undeformed foreland, accreting former foreland rocks onto the leading edge (see Fig.8.13). This implies that all the transport at the trailing edge has been achieved without the leading edge moving; for the Osen-Roa Thrust Sheet this is probably about 250km maximum transport. Had the deformation of the Osen-Roa Thrust Sheet continued then eventually the leading edge may have cut up section to the surface and only then would the bulk transport of the whole, thickened thrust sheet have begun.

Therefore the deformation of a thrust belt might be envisaged as progressing over a long time period (perhaps up to 100my) beginning as wide deformation zones of cataclastic and plastic flow in the deeper hinterland parts. Structures in these zones tend to be more sub-horizontal than in the external zones and frequently involve recumbent folds developed by rolling frontal hinges which transport a comparitively competent upper limb towards the foreland, over a sheared

Fig.8.13 The growth of a thrust sheet by the accretion of foreland rocks results in the trailing edge travelling further (x) than the leading edge (y), which may not move at all.


1
2
3
4
5
Y
X

and thinned lower limb which is frequently thrust out. This in effect is a very large and fairly ductile thrusted out tip line anticline, which produces a large footwall syncline, hangingwall anticline geometry. This type of structure is probably best seen in the Alps e.g. the Aar Massif in basement rocks and in the Morcles-Doldenhon Nappes (Lugeon 1940, Ramsay 1980) in the internal cover sheets. The Valdres Thrust Sheet in southern Norway displays such structures and is the most internal cover thrust sheet. Eventually the rolling hinges become smaller (and more common?) and pass into decolement (Laubscher 1973), although on a smaller scale recumbent folds may still be present at the tip line. Such structures are well documented for the McConnel Thrust in the Canadian Rockies (Elliott 1976b).

8.8.2 Is a push from the back mechanism possible?

The Norwegian thrust sheets are very long and thin and it has been argued that many thrust sheets are too thin to transfer stresses all the way to their leading edges. Instead it would be more likely that there would be several shorter thrust sheet formed. Therefore mechanisms such as gravity sliding and spreading have been proposed. These however have their own problems as outlined above. Therefore assuming that the Norwegian thrust sheets have formed by a push from the back caused by the overriding of the North American Plate over the Baltic Plate, how were the stresses transferred?

It can be seen from the dimensions of the thrust sheets given at the beginning of this section that the thrust length to thickness ratios of the thrust sheets decreases towards the foreland. This could be the result of three factors which are considered below.

Firstly the overburden of higher thrust sheets may exert a concider- able confining presure on the lower thrust sheets. Therefore the tendancy for a long thin thrust sheet to split up into smaller thrust sheets is resisted by the overburden, opposing the vertical component of the ramping movement that would be involved. This is demonstrated in Fig.8.14. Using a simple thrust belt model a 10km thick thrust sheet has been emplaced and a 2km thick thrust sheet is forming below it. The thrust can either ramp up under the thrust sheet or ahead of it . By calculating the centre of gravity H for a series of regularly spaced com- partments dividing up the thrust sheet before and after thrusting the energy required to emplace the thrust sheet can be calculated (Elliott 1976b).

The cumulative volume $V=\sum_0^j V$

Has a centre of gravity $H= \sum_0^j V_j H_j /V$

The difference in the centre of gravity between the original H and final H' states for a particular rock the volume is

$$\Delta H=H_0-H'$$

The work accomplished against gravity Wg for an equivalent volume V in the original and final states is

$$W'g = pgV\Delta H$$

where p = rock density and g = gravitational acceleration.

Using the model of a thrust sheet in Fig.8.12 assuming a width of 100km for the thrust sheet, the work required to emplace the thrust dep- icted in Fig.8. b is $4.8\ 10^{12}$J, whilst the work required to emplace Fig.814c is $6.17\ 10^{13}$J. Therefore despite the increased volume of rock it requires less energy for a thrust sheet to ramp ahead of an overlying thrust sheet than ramp under it.

The first formed thrust sheet does not have the aid of a thick overburden of other thrust sheets, therefore it must be thick and have a low length to thickness ratio. As soon as this thrust sheet is lying on top of a future thrust sheet, the new thrust sheet can be much thinner, as it is strengthened by the piggy back thrust sheet. This is the case in the southern Norwegian Caledonides, where the balanced cross section from Lom to Fluberg (Fig.8.8) shows that position of frontal ramps in the major thrust sheets is positioned slightly towards the foreland of the overlying thrust sheet. This might be due to ramping developing when the overburden from the overlying thrust sheet is reduced.

Secondly if the thrust sheets thicken themselves up incrementally and progressively towards foreland then a thickened, strained block of rock will be more capable of tranferring stresses towards the foreland than an unstrained thin block. To imagine an unstrained thrust sheet of 200km length and 3km thickness moving in one sheet as a coherent block is very difficult, but to imagine the block progressively shortening by 50% to produce a thrust sheet 100km long and 6km thick, which then overthrusts with a confining load of thrust sheets on top is much easier to envisage.

The large distances of transport and low length:thickness ratios observed in the southern Norwegian thrust sheets can be explained by the emplacement of the thick Jotun Thrust Sheet which provided a large overburden and enabled long, thin thrust sheets to develop underneath it. On reaching the limit, or thin part of the leading edge of the Jotun Thrust Sheet (and other higher thrust sheets) the lower thrusts began to frontally ramp due to the decrease in confining pressure. The Osen-Roa Thrust frontally ramps at this point, but did not cut out the whole of the thrust sheet, instead it continued into the Alum Shales of the Oslo Graben. The deformation of the Cambro-Silurian sequence in the

Fig.8.14 <u>The energy expended by ramping in a thrust sheet carrying a thrust sheet piggy back style.</u>

A. Situation before ramping, numbers 1 and 2 represent the positions of the two ramps concidered.

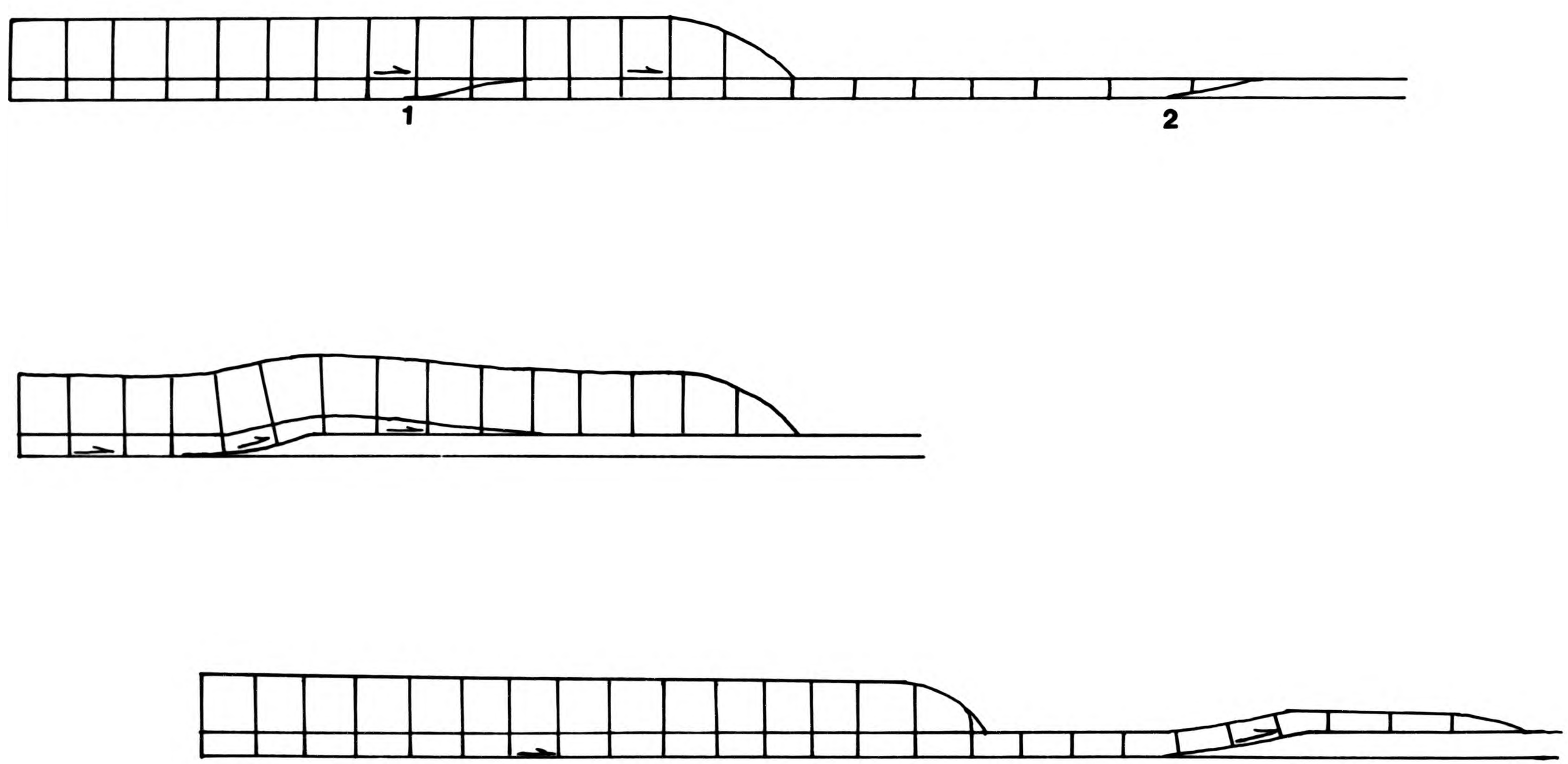
B. Ramping under the piggy back thrust.

C. Ramping ahead of the piggy back thrust.

A

B

C



Oslo Graben presents some difficulties to this model because the Osen-Roa Thrust Sheet there is still long, thin and with little overburden.

The actual transfer of stresses may solve this problem. Models for deformation may assume either slow incremental deformation, or rapid or slow bulk transport of the whole thrust sheet. The latter model has been used to estimate the maximum length to thickness ratios of a thrust sheet. However another method of transferring displacement along a thrust sheet may be possible.

Assuming that the thrust sheet rocks behave elastically, a push at the back will not be transferred instantaneously to movement at the leading edge. Rather, the stresses will build up first at the trailing edge and cause a displacement along the sole thrust there and then pass progressively towards the foreland. The form of this pulse of deformation may be likened to the movement of a wave or a catepillar. Therefore the stresses set up to deal with a rigid sheet e.g. Hubbert and Rubey (1959) may not apply, as only a fraction of the whole thrust sheet is moving at one time. The actual stress pulse will probably diminish as it moves along the thrust sheet towards the leading edge, by non-elastic folding, thrusting, out-of-sequence thrusting and (the resulting) friction.

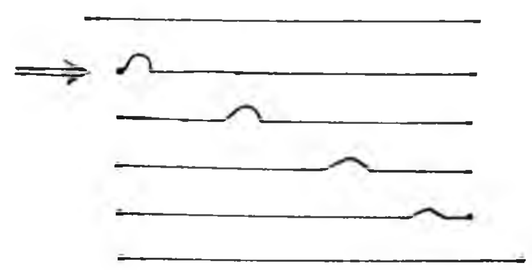


Diagram illustrating the way a deformation pulse may only displace one part of a thrust sheet at a time.

The speed at which this pulse may move through the thrust sheet is variable. It will try to move at the speed of sound through a solid material, which will be in excess of 1000km/hour. However this pulse may be slowed down in rocks which have a more viscous behaviour, or when it encounters areas of resistance like perturbations or sticking points (high spots), where a build up of stress is needed to overcome resistance. For example Nason and Weertman (1971) measured creeps of about 2-3km/hour along faults currently active in California. As the pulse is likely to be weakened during its passage, towards the foreland several pulse events may be needed to overcome a particular high spot.

8.9 Summary of the main point of the thesis

New mapping of the North Hadeland, northern Ringerike, Asker-Baerum and Eiker areas and a detailed study of other selected areas in the Oslo Graben, have enabled the most continuous balanced section possible to be drawn through the Oslo Graben. From this study the following additions to the interpretation of the southern Norwegian Caledonides have been drawn.

1. The traditional thrust front in Norway is not the original Caledonian thrust front. Only in the Oslo Graben can the original position of the thrust front be traced, where it lies between the districts of Langesund-Skien and Eikeren, trending in a WSW-ESE direction. This position has not been recognised in the literature, where the thrust front is placed in southern Mjosa.

2. It has been traditional to regard the Mjosa area as autochthonous or parautochthonous, despite recognising the Sparagmite area immediately to the N as being allochthonous (e.g. Nystuen in press). This view is incorrect as pallinspastic reconstructions of the Oslo Graben (pinned south of the thrust front in Langesund-Skien) show the

northern boundary of the Cambro-Silurian rocks in Mjosa as having been transported at least 135km to the S or SSE to lie in their present position.

3.The Osen-Roa Thrust Sheet has been regarded as ending at the traditional thrust front. However in view of the similarity in deformation style, amounts of shortening and by interpretation of the outcrop pattern, it seem most likely that the Osen-Roa Thrust by at least two frontal ramps, cuts out the Sparagmite stratigraphy and continues into the Alum Shales of the Oslo Graben. By unstraining the whole of the Sparagmite region and the Oslo Graben rocks the trailing edge of the Osen-Roa Thrust is restored to a distance of about 560km away from the thrust front. This represents an average shortening (e) of ~50% at right angles to the strike direction.

4.The eastern and western boundaries of the Osen-Roa Thrust Sheet are also probably determined by the presence of oblique and lateral ramps. These ramps may have developed by gravity spreading of the Osen-Roa Thrust Sheet, which was of secondary importance as an emplacement mechanism to a "push from the back".

5. The deformation history of the southern Norwegian Caledonides began with the movement of the Jotun and later the Valdres Thrust Sheets in Arenig times (if not earlier). In the Trondheim region the obduction of the Storen Thrust Sheet took place at a similar time. Movement on the Jotunheim thrust sheets continued until early Silurian times as indicated by the presence of clastic wedge deposits and then prabably ceased. The transport directions on these thrust sheets began from W to E but later may have swung to NW to SE.

Later the effects of movement on the Trondheim thrust sheets reached the area, and a second phase of syn-orogenic sediment was deposited in the Oslo Graben from mid to late Silurian times. Transport directions during this event were from the NNW-SSE, the final thrusting event in this episode was that which formed the Osen-Roa Thrust Sheet.

6. The thrust sheets that were derived from Baltic continental crust and overlying cover rocks were probably emplaced as the North American continental plate overrode the Baltic continental plate. This accounts for the larger amounts of shortening on the WSW side of the Iapetus, and may have given rise to a crustal pop-up system. The thrust sheets were probably emplaced by a push from the back mechanism, provided by the North American continent and to a much lesser degree by gravity spreading.

7. The Osen-Roa Detachment probably terminated within the Alum Shales. Therefore it represents a thrust sheet frozen in mid-development, which did not progress to the stage of overthrusting rocks at its leading edge. This gives an insight into the way a thrust sheet develops. It deformed by incremental deformation slowly adding more deformed rock onto the leading edge. Only later if the thrust tip line eventually reached the surface could the then, internally deformed and thickened thrust sheet begin to overthrust rocks at its leading edge.

8. The resistance of competent rocks, high in the thrust sheet, to this incremental deformation resulted in the formation of an upper detachment zone. Above this zone the hangingwall rocks were transported towards the hinterland, relative to the footwall.

8.10 Suggestions for new research

1. It would be interesting to know in detail how fracture, pencil and pressure-solution cleavages intensities and orientations are related to the second and third order thrusts and folds in Asker-Baerum (this area has the best exposure). Detailed measurements of strain can be made using graptolites, brachiopods and other fossils, ooliths and nodules. How much shortening was achieved by layer parallel shortening and thickening thrust wedging and pressure-solution before the main deformation by imbrication and buckling began?

2. How has the Osen-Roa Detachment really behaved during deformation: are the sub-horizontal pressure-solution seams, graphitised slip surfaces and highly polished slip surfaces more fitting a detachment moving plastically, viscously, due to high pore fluid pressures or to another mechanism?

3. A detailed investigation needs to be made into the discrepancy in the amount of shortening between the upper and lower parts of the Cambro-Silurian thrust sheet. Is the upper detachment a discrete plane or a zone, or several zones, and how did the detachment develop?

4. The Cambro-mid Ordovician of the southern Mjosa area needs to be remapped to decide on the importance of imbrication in the area.

5.The southern boundary of the Trondheim region needs to be carefully mapped to determine the relationships between the Leksdals-Remskleppe, Kvitvola and Rondana Thrust Sheets. Most important is whether the Leksdals-Remskleppe Thrust Sheet represents the discontinuous leading edge in this area, which means that the Kvitvola Thrust Sheet is a separate unit or whether it represents the Kvitvola Thrust Sheet passing under the higher Trondheim thrust sheets.

6. The stratigraphy of the Kirkerud Group in the Hadeland area needs to be determined. There are frequent fossiliferous horizons so a stratigrapher with a detailed knowledge of the fauna may be able to locate the presence of imbricates within the monotonous shale and nodular limestone sequence.

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APPENDIX 1

FIELD GUIDE TO THE STRUCTURAL GEOLOGY OF THE OSLO GRABEN

Introduction

This field guide aims to describe the changes in structural style within the Oslo Graben and demonstrate the application of current thrust belt terminology and geometric rules to the deformation of the southern Norwegian Caledonides.

The localities described begin in the foreland of the southern part of the Oslo Graben and progress northwards to the Mjosa area. Grid references are taken from 1:50,000 NGO maps, giving the N-S co-ordinates first and the E-W co-ordinates second.

LANGESUND-SKIEN

This is the only area of undeformed Cambro-Silurian rocks in southern Norway. Because looking for an absence of deformation is very negative, it is recommended that only one locality is visited and that the regional ENE dip of 20-30° be viewed whilst travelling through the area. The only noticable deformation is that by Permian normal faults.

OMBORSNES

Undeformed foreland rocks.

Locality: (G.R.) South side of Midtfjordskjer.

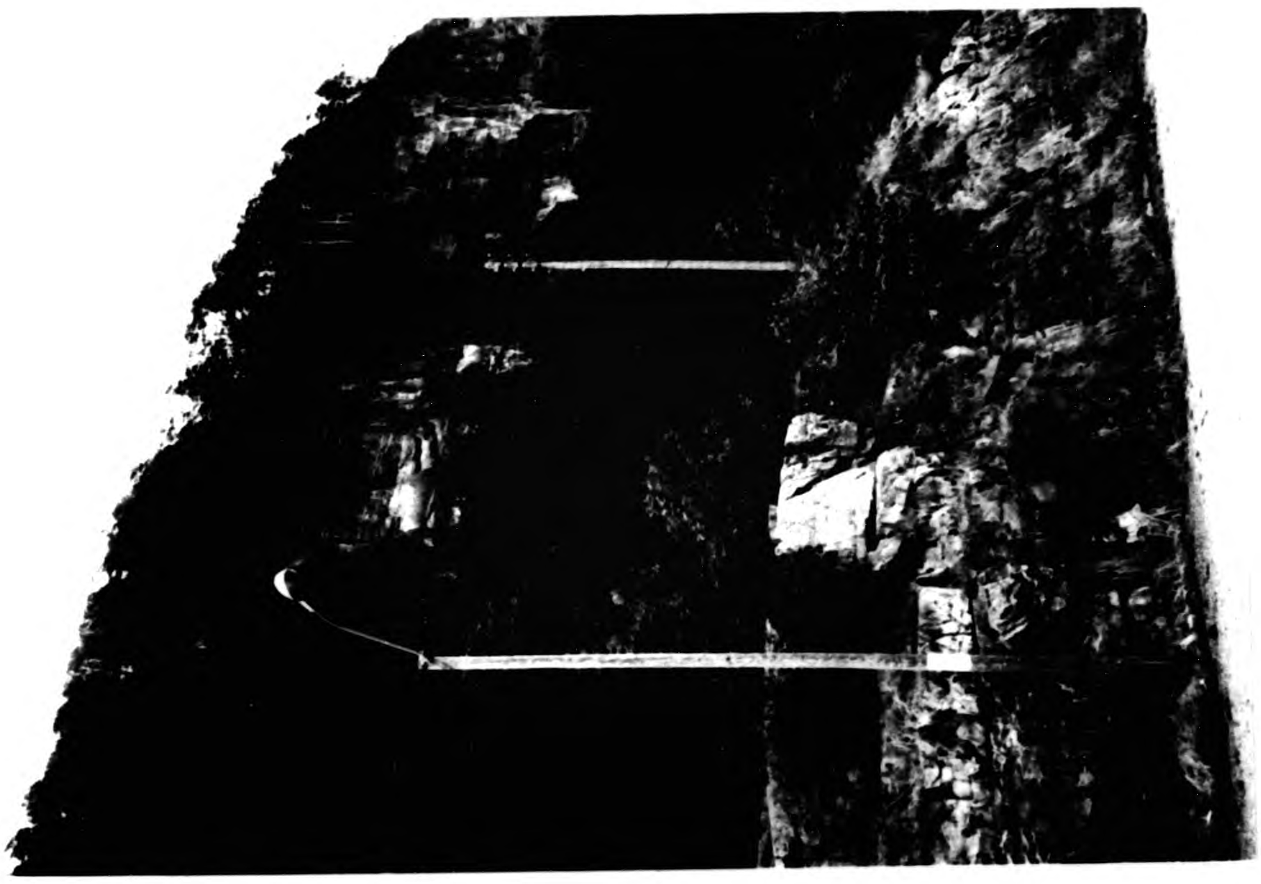
M 711 1713 ii Porsgrunn.

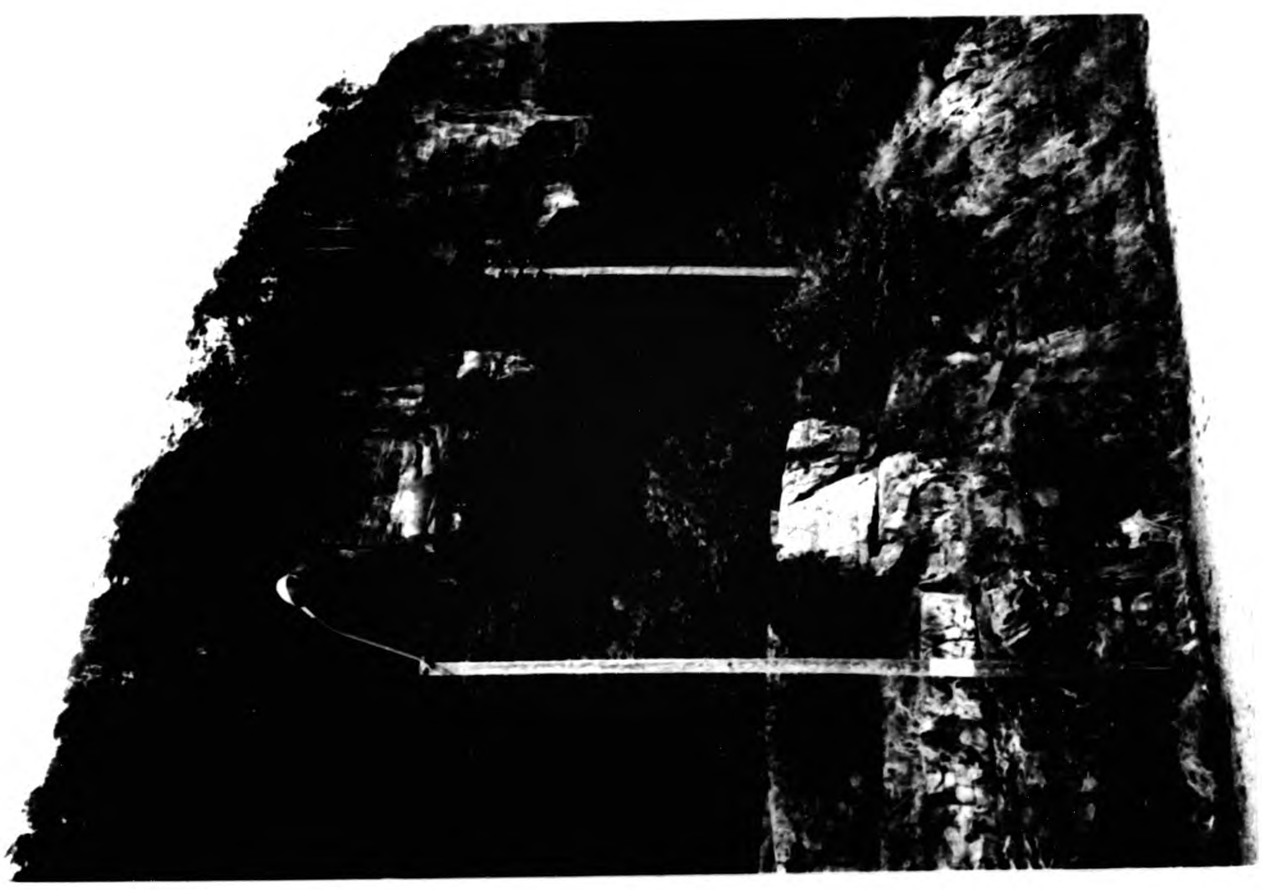
Description: The base of the Cambrian can be seen in this area by the side of the local road. The cliff section displays tilted, undeformed rocks (see Plate 1), which on closer inspection, reveal at the base, a Permian sill intruded between Precambrian gneisses and Lower Cambrian sandstone. Above the sandstone unit are undeformed Alum Shales (Cambrian) which are streaked by veins of calcite "beef".

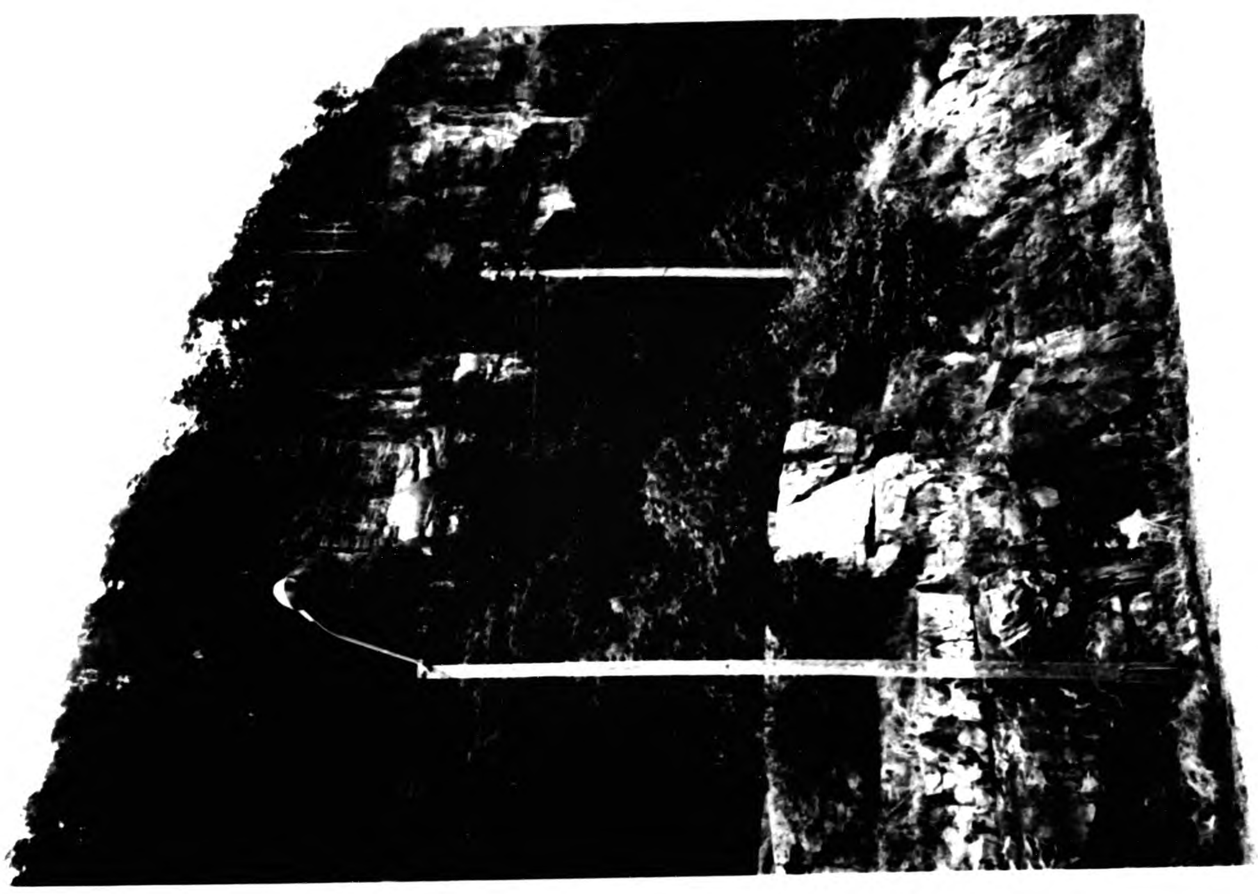
The Cambro-lower Ordovician sequence is thinner here than elsewhere in the Oslo Graben because of an unconformity which spans the late Cambrian and early Ordovician in this area. Resting unconformiably on Alum Shales is a thin (3m) Orthoceras Limestone unit followed by shales. Above these (Upper Didymograptus) Shales, is the competent Ampyx Limestone. This can be seen 150m further north-east along the local road. In it is a thin band of rock fractured along Caledonian trends, but along which no displacement has occurred. A later listric normal fault displaces the fracture zone.

Plate 1, Undeformed foreland rocks, Ormborsnes.

Plate 2, Ramping backthrust at the base of the Orthoceras Limestone, Vest Fossen railway station, Eikeren.







EIKER-SANDSVAER

Passing along the road no.286, the route passes into rocks deformed by the Caledonian orogeny, and deformation increases in intensity towards the north of the area.

ROAD 8, KREKLING.

Folded Alum Shales above the Osen-Roa Detachment.

Location: (G.R. 417 127) Road under railway bridge south of Krekling.

Description: The long hill running parallel to the west of road 8 displays the gently dipping Orthoceras Limestone capping the hill, below which are Alum Shales. Examining these shales in a road cut by the Railway bridge it can be seen that they are folded and puckered, indicating the presence of the Osen-Roa Detachment in this area.

EIKEREN

Examining the hills to the south and north of Lake Eikeren reveals a jump in the intensity of deformation to the north.

RAEN

Folded Alum Shales and view across Eikeren.

Location: (G.R. 458 177) Local Krekling-Sundhaugen road at Raen.

M711 1714 ii Kongsberg

Description: Alum Shales in the road cuts are intensely deformed by small folds whilst the Ampyx Limestone which caps the prominent hill to the east is largely undeformed. Looking across the lake to the north side, the Ordovician Limestones forming the large hill, can be see to be folded and imbricated. The next stop provides a good section through thrust faulted Cambro-mid Ordovician rocks.

VEST FOSSEN RAILWAY STATION.

Deformed Cambro-middle Ordovician rocks.

Location: (G.R. 485 211 to 485 219) Section along railway line south of Vest Fossen railway station.

M711 1714 ii Kongsberg

Description: Just south of Vest-Fossen railway station, on the west side of the railway line, are two good sections which display the deformation style of the area very well (see Fig.1). The northern section reveals folded Orthoceras Limestone, with Ceratopyge Limestone appearing in the anticlinal core. In one place there is a minor backthrust which is beginning to cut up section through the Orthoceras Limestone (see Plate 2).

After a break of about 30m the southern section is reached. At the northern end of this section black Alum Shales with large stinkstone nodules are present. These are thrust over (4aa) Upper Didymograptus Shales (which contain limestone and sandstone bands), (see Plate 3). The Upper Didymograptus Shales form a chevron style footwall syncline below the thrust, whilst the Alum Shales above are folded into a hangingwall anticline. The geometry of the thrust here is that of a F.W.R. and H.W.R.

The southern limb of the footwall syncline is complicated by thrust splays and minor thrusts in opposing dip structures (see Plate 4). These are followed to the south by a very long, broad, syncline which is again complicated by minor thrusting at its southern limb. A hinterland dipping fracture cleavage is developed on the northern limb of this syncline.

Fig.1, N-S cross-section through Cambro-mid Ordovician rocks. south west of Vest Fossen railway station. Details of sections along the railway line are shown.

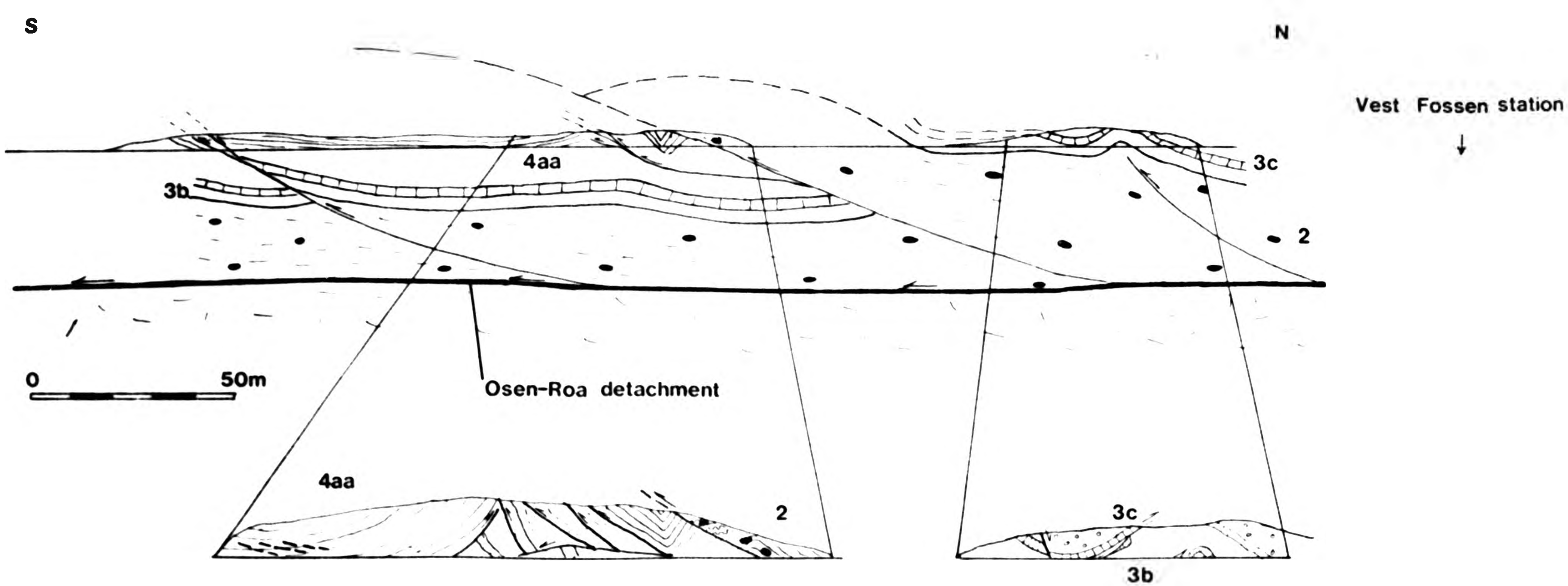
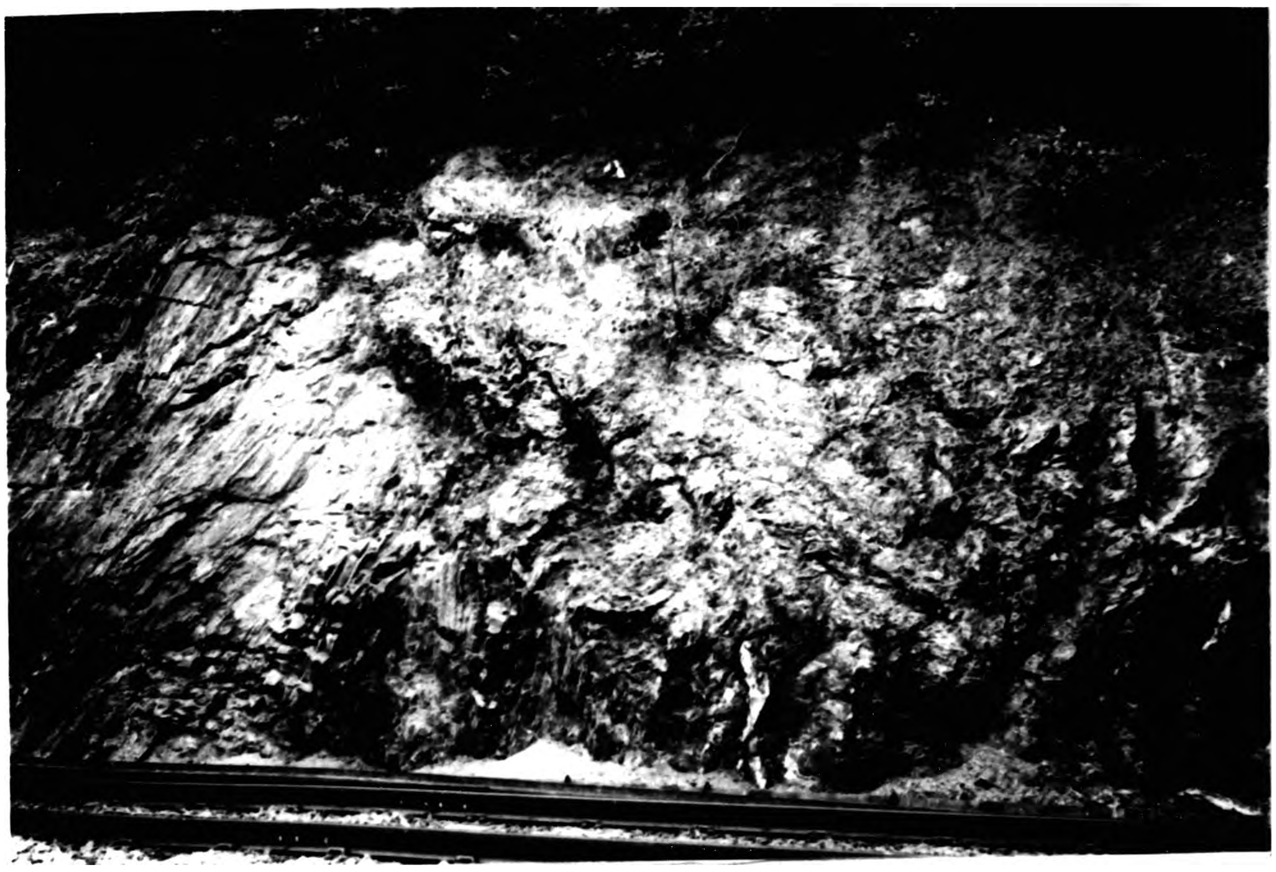
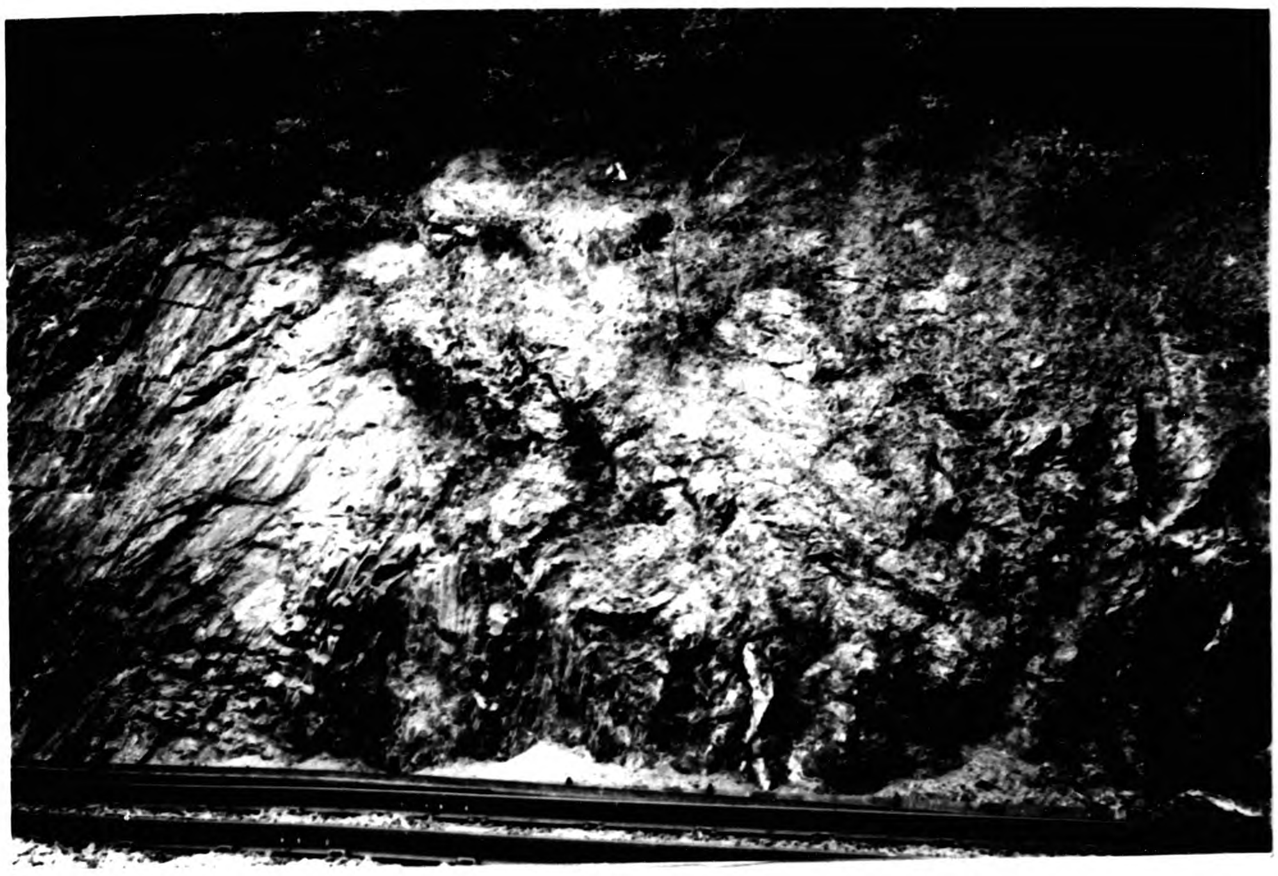
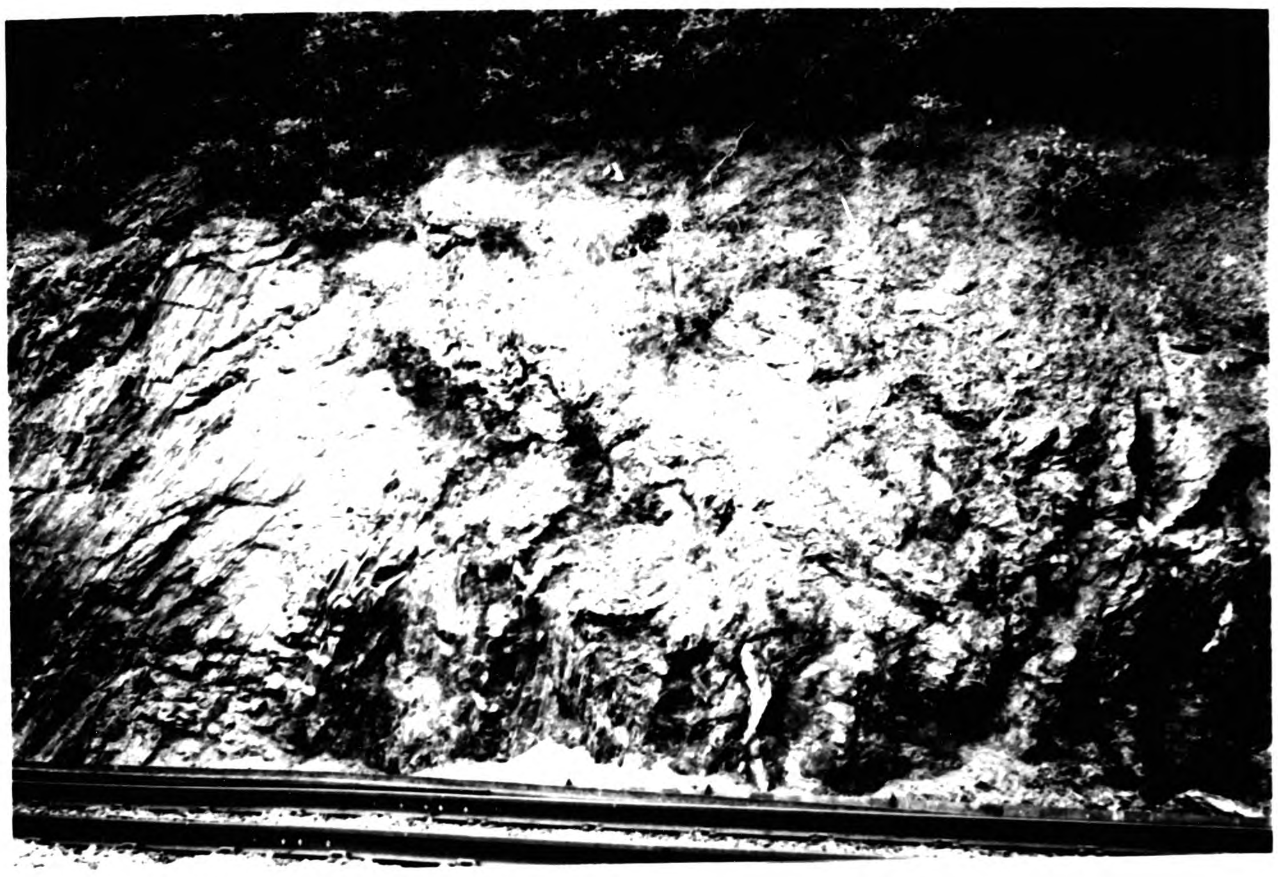

S
N
Vest Fossen station
4aa
3b
3c
2
0
50m
Osen-Roa detachment
4aa
2
3c
3b

Plate 3, Hangingwall ramp (anticline) in Alum Shales and footwall ramp (syncline) in Lower Didymograptus Shales, Vest Fossen railway station.

Plate 4, Triangle zone in Lower Didymograptus Shales, Vest Fossen railway station.







1.0 ASKER-BAERUM

This area provides numerous sections around the Oslo Fjord and the full stratigraphy of Cambro-Silurian rocks is better exposed here than in any other area in the Oslo Graben. Therefore it is worth visiting many exposures in this area. Traditional places for field trips to visit are Slemmestad, Huk (on Bygdoy), Kolsas Hill and Gjettum (Holtedahl et al 1934, Holtedahl and Dons 1957, Bockeli, in Bryhni 1981). I hope to introduce some new equally interesting localities and expand on the localities visited in the traditional places.

The proposed itenary, if fully covered will take several days to complete. The localities are listed in order, progressing northwards up the west side of the Oslo Fjord, towards Oslo.

GRUNDVIK

Folded and imbricated Cambro-middle Ordovician rocks.

Location: (G.R. 845 271)

M711 1814 i Asker

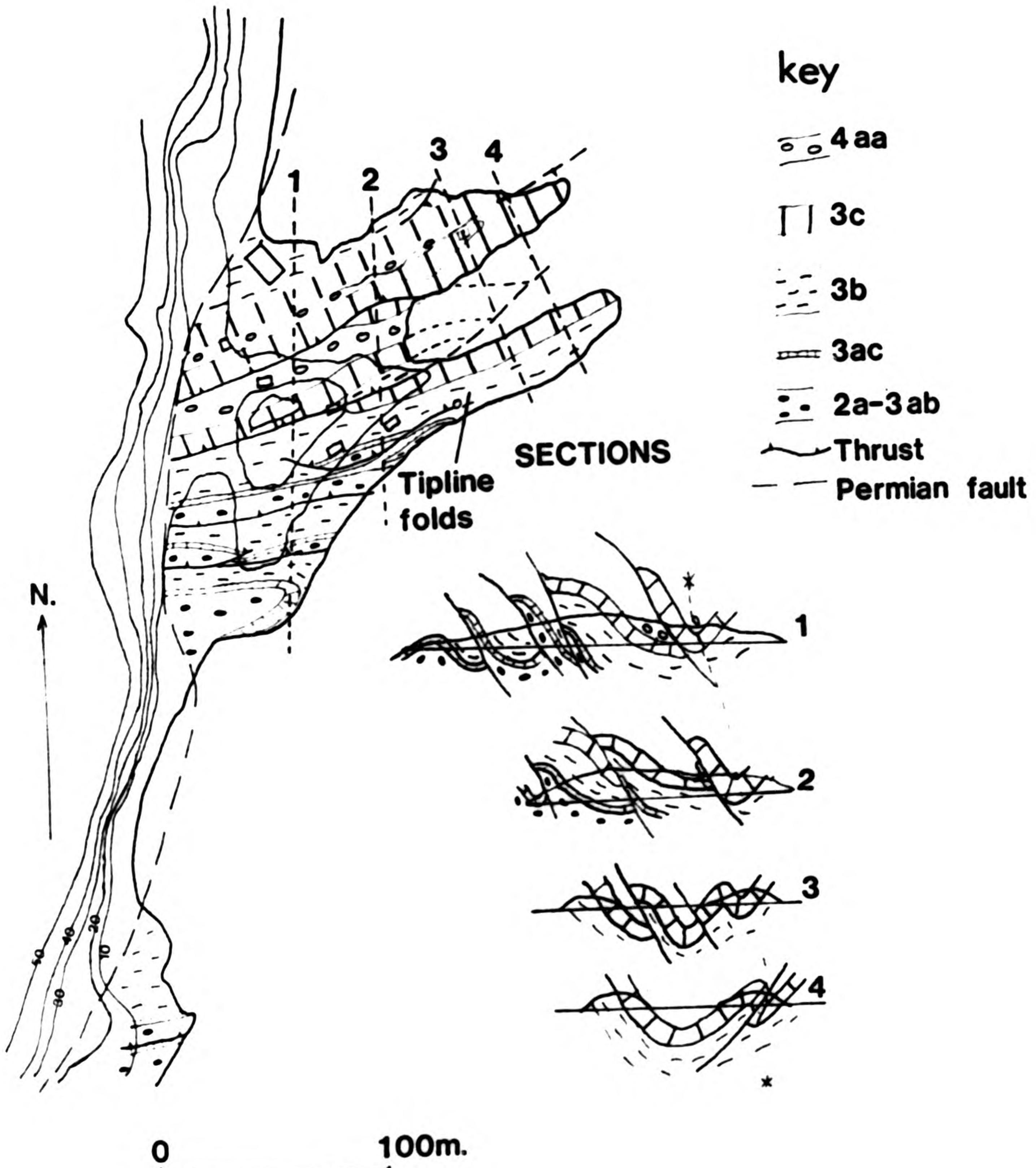
Description: The Grundvik Peninsula is accessable by foot only, any vehicles can be parked a few hundred yards away near the Slemmestad-Naersnes road.

The age of the rocks exposed on Grundvik ranges from Alum Shales (Cambrian) to Upper Didymograptus Shales (4aa Ordovician). Many horizons in these rocks are fossiliferous, but here the Ceratopyge Limestone is particularly rich in trilobites. The Cambro-Ordovician rocks have been downfaulted against Precambrian rocks to the west during the Permian.

Fig.3 Geological map of Grundvik

Joins up a syncline,which

displays a transfer zone


key
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1
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0
100m.

Plate 5, Splaying thrust in Ceratopyge Series rocks (3a), south Grundvik

Caledonian deformation is particularly well exposed here and is predominantly related to second order thrusts, some are visible in outcrop. A map of Grundvik, sketches and photographs of the structures and their locations can be seen in Fig.3.

Important structural features are as follows:

Transfer zone. The northern end of Grundvik (second peninsula) displays a hinterland dipping thrust which passes into an anticline and then into a backthrust to the east along strike.

Tip line folds. The asymmetrical and chaotic folding on the southern side of the first peninsula might be attributed to deformation ahead of the tip of a blind thrust, just below the outcrop.

Second order thrusts. There are many thrusts exposed on Grundvik and frequently the folding can be shown to be earlier than the thrusts, because the thrusts truncate a fold limb. Sometimes one thrust splays into several smaller thrusts along strike (see Plate 5).

SLEMMESTAD

The Slemmestad area is excellent for demonstrating imbrication of the Cambro-mid Ordovician and a day can easily be spent just in this one area. The Orthoceras Limestone is the most obvious marker horizon and because the majority of the abundant orthoconic nautiloid shells were buried with their siphuncle downwards, the way up of the bedding can be demonstrated. The shale horizons are also very fossiliferous; small horny brachiopods and agnostid trilobites are abundant in some horizons in the Alum Shales, whilst the Lower and Upper Didymograptus Shales can be distinguished by their graptolite faunas of Phyllograptus elongatus, Didymograptus spp. and Tetragraptus spp. in the former and Didymograptus geminus, D. bifidus, Glyptograptus teretiusculus and

Fig.4, Geological map of south-eastern Asker

KEY

2a-3a Alum Shales and Ceratopyge Shales

3ac Ceratopyge Limestone

3b Lower Didymograptus Shales

3c Orthoceras Limestone

4aa Upper Didymograptus Shales

4ab Ampyx Limestone

4ba Lower Chasmops Shales

4bb Lower Chasmops Limestone

4bc Upper Chasmops Shales

4bd Upper Chasmops Limestone

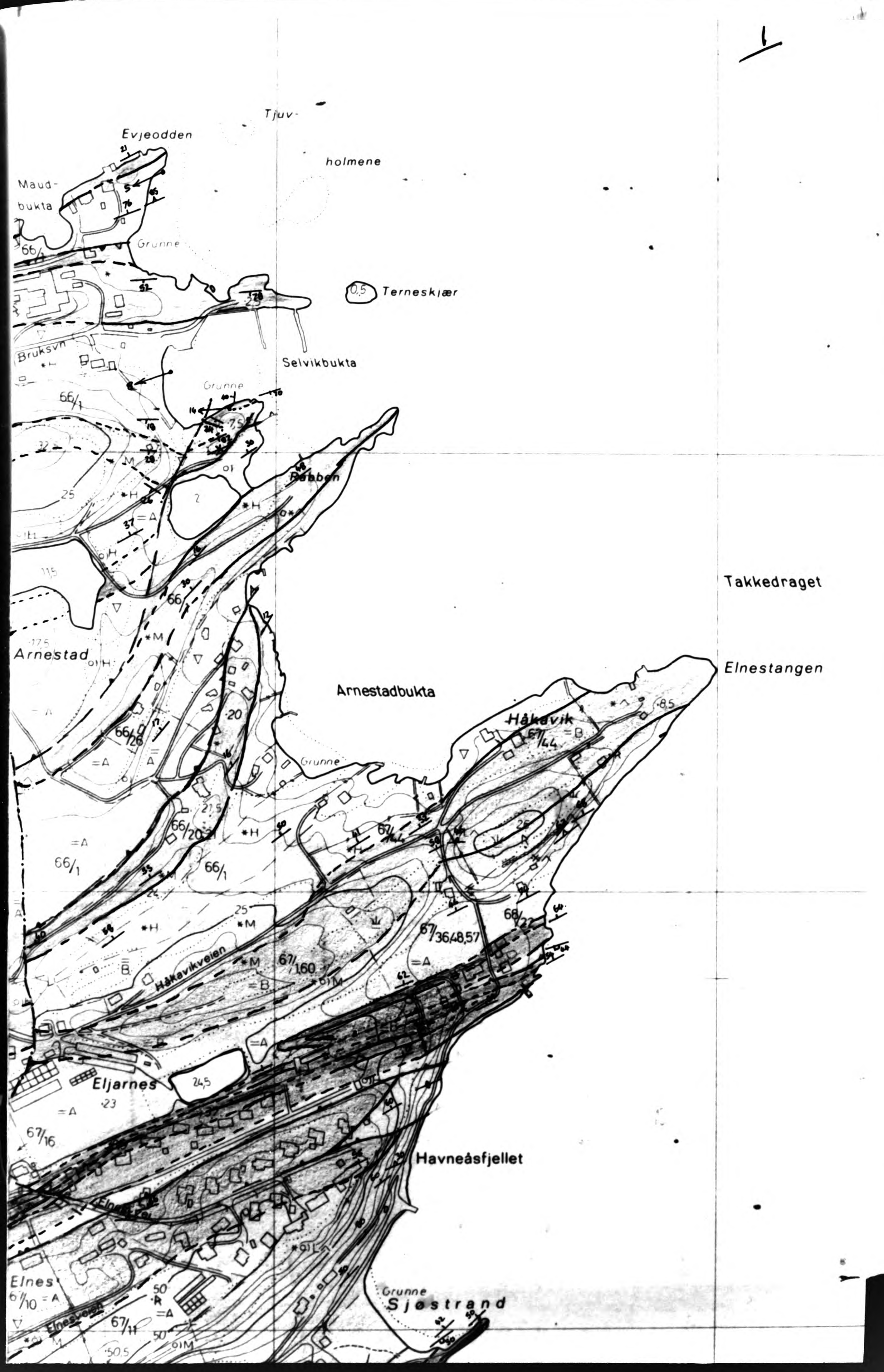
Thrust fault

Normal fault

Bedding

PAGE 13

1


Evjeodden
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holmene
Maud-
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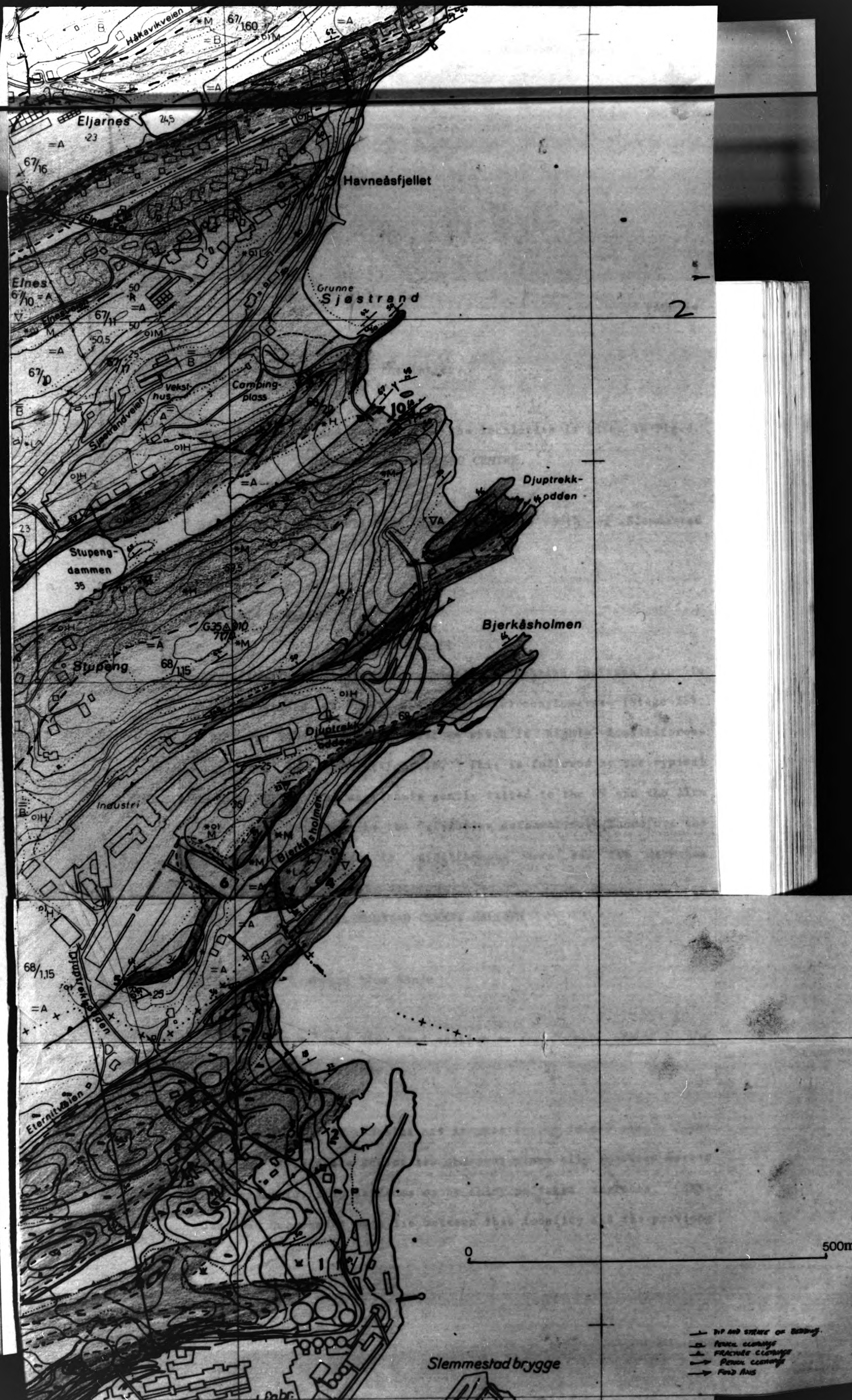
Grunne
Terneskjær
Bruksvn
Selvikbukta
Grunne
Røbben
Takkedraget
Arnestad
Elnestangen
Arnestadbukta
Håkavik
Grunne
Håkavikveien
Eljarnes
Havneåsfjellet
Elnes
Grunne
Sjøstrand


Håkavikveien
Eljarnes
Havneåsfjellet
Elnes
Grunne
Sjøstrand
Vekst-hus
Sjøstrandveien
Camping-plass
Djuptrekk-odden
Stupeng-dammen
Bjerkåsholmen
Stupeng
Industri
Eternitveien
Slemmestad brygge
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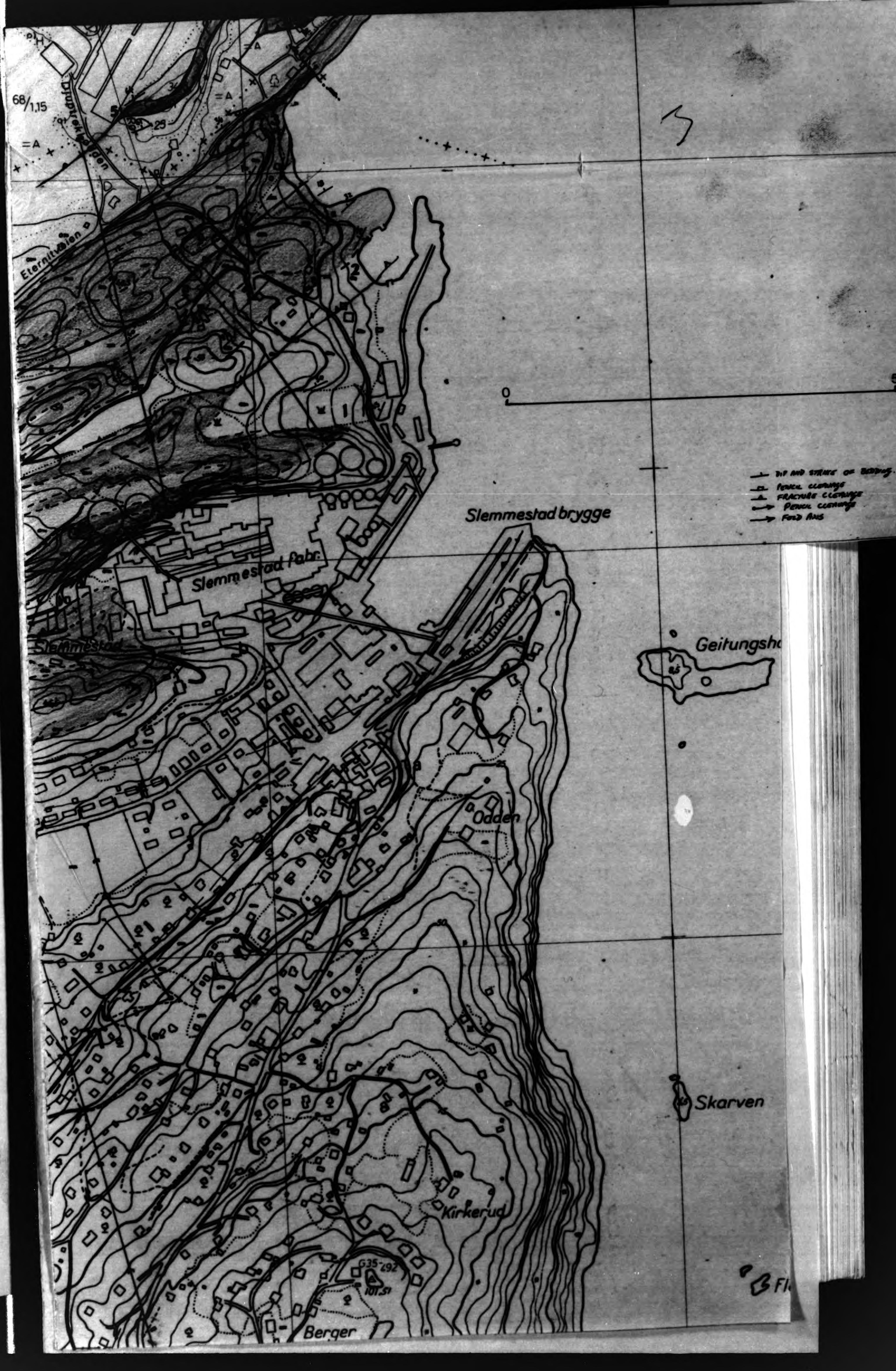
DIP AND STRIKE OF BEDDING.
PENCIL CLEAVAGE
FRACTURE CLEAVAGE
PENCIL CLEAVAGE
FOLD AXIS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Berger
0
DIP AND STRIKE OF BEDDING.
PENCIL CLEAVAGE
FRACTURE CLEAVAGE
PENCIL CLEAVAGE
FOLD AXIS

Climacograptus scharenbergi in the latter.

A map of the area and positions of the localities is given in Fig.4.

A SLEMMESTAD SHOPPING CENTRE.

Location: (G.R. 842 282) Side road to Naersnes south of Slemmestad market place.

M 711 1814 1 Asker

Description: The underlying, weathered, Precambrian gneisses are in contact with Middle Cambrian basal (arkosic) conglomerate (Stage 1c). This is followed by a hard dark limestone which is highly fossiliferous especially with agnostid trilobites. This is followed by the typical Cambrian Alum Shale. The section is gently tilted to the NW and the Alum Shales are not deformed by the Caledonian deformation. Therefore the lowest part of the Cambrian is autochthonous here and the Osen-Roa Detachment must lie above this section.

B SLEMMESTAD CEMENT FACTORY

Folded Upper Cambrian Alum Shale

Location: (G.R. 839 289) Road section on the corner, opposite the entrance to the Cement Factory.

Description: The Alum Shales are asymmetrically folded into a minor anticlinorium. Within the shales are numerous minor slip surfaces marked by highly graphitic, slip surfaces or by shiny polished surfaces. Thus the Osen-Roa Detachment must lie between this locality and the previous one.

SLEMMESTAD BUS STATION

Thrusted lower Ordovician rocks

Location: (G.R.834 283) Road section and Bus Station, west side of road 165 near turning to Slemmestad.

Description: Thrusting has transported Lower Didymograptus Shales over the lower part of the Upper Didymograptus Shales (see Fig.5, Plate 6). In the road section the thrusts display a H.W.F. on F.W.F. geometry and are marked by intensified cleavage close to the fault planes. The thin, grey limestones at the base of the Lower Didymograptus Shales are exposed in the road section and display pseudomorphs after barytes. Capping the section to the north is the Orthoceras Limestone.

In the Bus Station, the north side is a section along strike, with the thrust transport directions coming straight out of the section to the south. The western side of the section shows the lowest thrust splaying, which causes a series of tight chevron folds to be developed between the splays. This is probably a complex fault tip line.

Fig.5 3d diagram demonstrating thrust geometry and a splaying thrust tip at Slemmestad bus station

Fig.5 3d diagram demonstrating thrust geometry and a splaying thrust tip at Slemmestad bus station

Plate 6, Splaying thrust in Upper Didymograptus Shales, Slemmestad bus station

SLEMMESTAD INDUSTRIAL ESTATE AND SHORELINE ALONG THE OSLO FJORD.

Imbricated Cambro-mid Ordovician rocks

Location: (G.R. 842 284 to 842 298) Sections in the industrial estate are first examined then the section proceeds along the shore of the Oslo Fjord to Sjostrand.

Description: This long and very instructive section is well known to Scandanavian geologists, unfortunately some good exposures may be lost to new buildings on the industrial estate. The peninsulas and local ridges in the area are caused by the Orthoceras Limestone which is repeated several times in this section by imbricate thrusts, whilst the bays are developed in the Lower and Upper Didymograptus Shales and the Alum Shales.

Walk south from Tajet along the shore to the beginning of the section (see Fig.4 for localities) at the Cement Factory.

Locality 1. The Slemmestad Cement Factory. Just north of the cement factory is a pit dug into Alum Shales, these shales can be traced into the grounds of the cement factory, where they are disharmonically and asymmetrically folded. The Orthoceras Limestone forms a syncline capping the southern ridge of the pit, though it is not visible from the shore.

Travelling northwards again the section passes into the Ceratopyge Series at locality 2 and upwards into the Lower Didymograptus Shales and Orthoceras Limestone. This section therefore passes through the normal stratigraphic section. However on top of the Orthoceras Limestone are

Lower Didymograptus Shales, this indicates a thrust contact between the two units, where older rocks in the hangingwall have been pushed over younger rocks in the footwall. As the dips of the two units are similar the thrust relationship here is of a F.W.F and H.W.F.

Continuing north the Orthoceras Limestone follows on conformably, but the limestone is broken by a thrust at locality 3 (see Plate 7). This locality reveals an inital stage in the propogation of a fault through the limestone. The limestone forms a F.W.R. and a H.W.F. below and above the thrust, but further up the cliff face the hangingwall is folded over into an anticline, whose forelimb has been thrust out, forming a H.W.R. The displacement along the thrust is only a few metres and probably represents a tip line fold which has only just been displaced by the thrust before it died out.

Locality 4. The Orthoceras Limestone forms an oval outcrop by the side of the Bjerkasholmen road. An anticline is well exposed by the road side and has well developed slickenside calcite veins on the bedding surfaces indicating flexural slip during folding (see Plate 8). This outcrop is interpreted as being bound by thrust faults of opposing dips, which form a triangle zone.

Locality 5. This locality is 100m to the SW of the previous locality, by the side of the Eternite Factory. Here there is an exposure of Orthoceras Limestone thrust over Upper Didymograptus Shales. The thrust geometry is of a H.W.R. over a F.W.R. (see Fig.6a). In the next two localities the same Orthoceras Limestone ridge will be followed down to the Bjerkasholmen Peninsula in order to demonstrate that the thrust is laterally ramping ie. passing into younger rocks in the hangingwall along strike.

Fig.6a Orthoceras Limestone (H.W.R.) thrust over Upper Didymograptus Shales (F.W.R.), Eternite Factory, Slemmestad industrial estate.

Fig.6b Geological map of Djuptrekkodden.

A

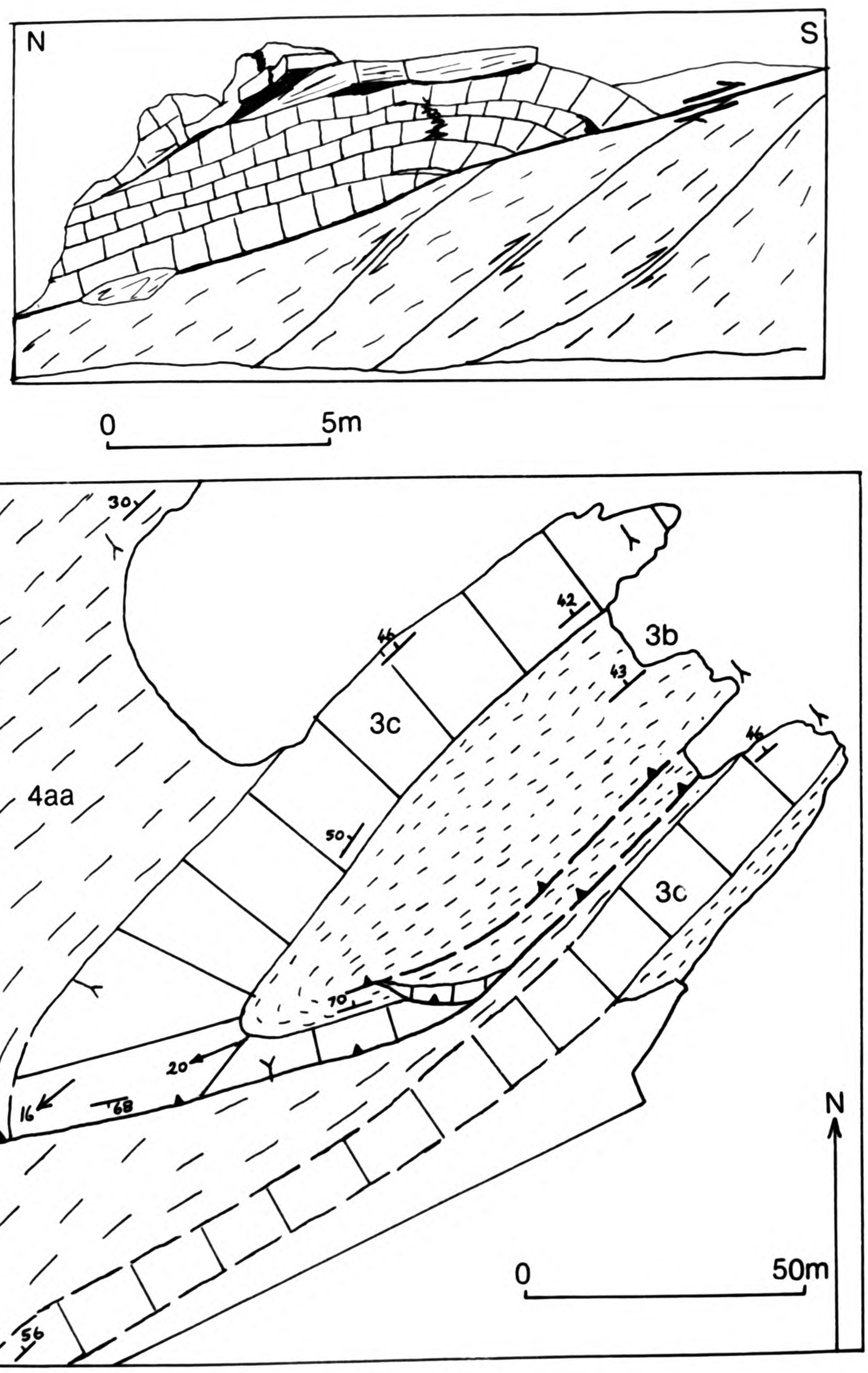


Plate 7, Thrust in Orthoceras Limestone (H.W.F., F.W.R. geometry) Slemmestad industrial estate.

Plate 8, Anticline in Orthoceras Limestone, with calcite fibre slickensides on the bedding planes, indicating flexural slip folding. Slemmestad industrial estate

This locality represents the thrust ramping having reached the stage of cutting out half the Orthoceras Limestone, whilst the other localities show the thrust in progressively older hangingwall rocks.

Locality 6. Between the factories the ridge of Orthoceras Limestone is breached and the thrust contact is revealed between the complete Orthoceras Limestone unit and the Upper Didymograptus Shales below. This time a F.W.F. and H.W.F. geometry is displayed.

Locality 7. Bjerkasholmen. The Orthoceras Limestone on the northern side of the peninsula rests conformably on lower Didymograptus Shales and Ceratopyge Limestone. On the southern side of the peninsula is a anticlinal structure in Alum Shales which has been thrust out. This thrust is the continuation of the thrust seen at Localities 5 and 6 within and at the base of the Orthoceras Limestone and has therefore cut down section to the east along strike.

Locality 8. Often thrust faults in shales are not discrete planes, but chaotic zones of deformation. This locality displays such a chaotic zone between Upper Didymograptus Shales in the footwall and Lower Didymograptus Shales in the hangingwall (see Plate 9).

Locality 9. At Djuptrekkodden a large hangingwall anticline is well exposed (see Fig.6b)

Locality 10. The walk over to this locality passes over a long exposure through the Upper Didymograptus Shales and passes into the base of the Ampyx Limestone. At locatity 10 the Ampyx Limestone is folded into a footwall syncline, pressure solution cleavage is intense here and has deviated around the limestone nodules to divide it up into mullion like elements. The small outcrop of limestone to the north of this exposure is an overturned fragment of Orthoceras Limestone which forms the southern limb of a large hangingwall anticline structure. The northern limb forms a good exposure on the pier at Sjostrand.

Other imbricate repetitions are present further north (see Fig.4)

VOLLEN

Deformation in the middle Ordovician rocks

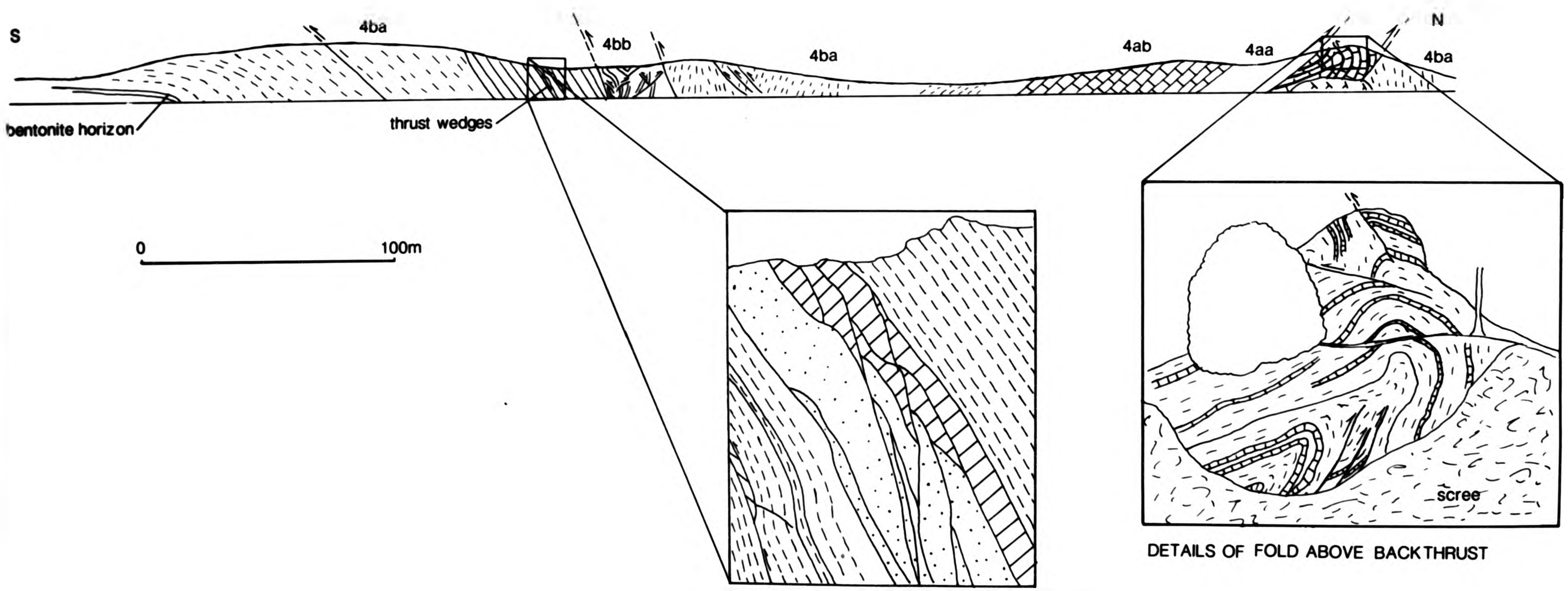
Locality: (G.R. 835 306) Section on the western side of road no.165.

M711 1814 i Asker

Description: The southern part of the section is in gently dipping Lower Chasmops Shale and has a conspicuous green bentonite horizon within the shales. Progressing northwards the dips become steeper with minor thrusting occurring in the shales. The Lower Chasmops Limestone follows on conformably, and within this unit there is a good example of thrust wedging. Thrust wedges usually occur in competent rocks, which are well bedded or which alternate in thin beds with incompetent rocks. They can produce a significant amount of shortening in restricted horizons, for example here the beds affected by thrust wedging have shortened by 50%.

Fig.7. displays the thrusting and folding which occurs in this section. It involves both fore- and back- thrusting indicating deformation in a triangle or pop-up zone (see Fig.3.- for an interpretation of the structure).

Fig.7, Section on road no.165, Vollen



BEDS AFFECTED BY THRUST WEDGING
STIPPLED AND STRIPED

DETAILS OF FOLD ABOVE BACKTHRUST

Plate 9, Chaotic fault zone between Upper Didymograptus Shales (left) and Ceratopyge Shales (right).

Plate 10, Folded Lower Tretraspis Limestone, Hvalstad.

TANGEN

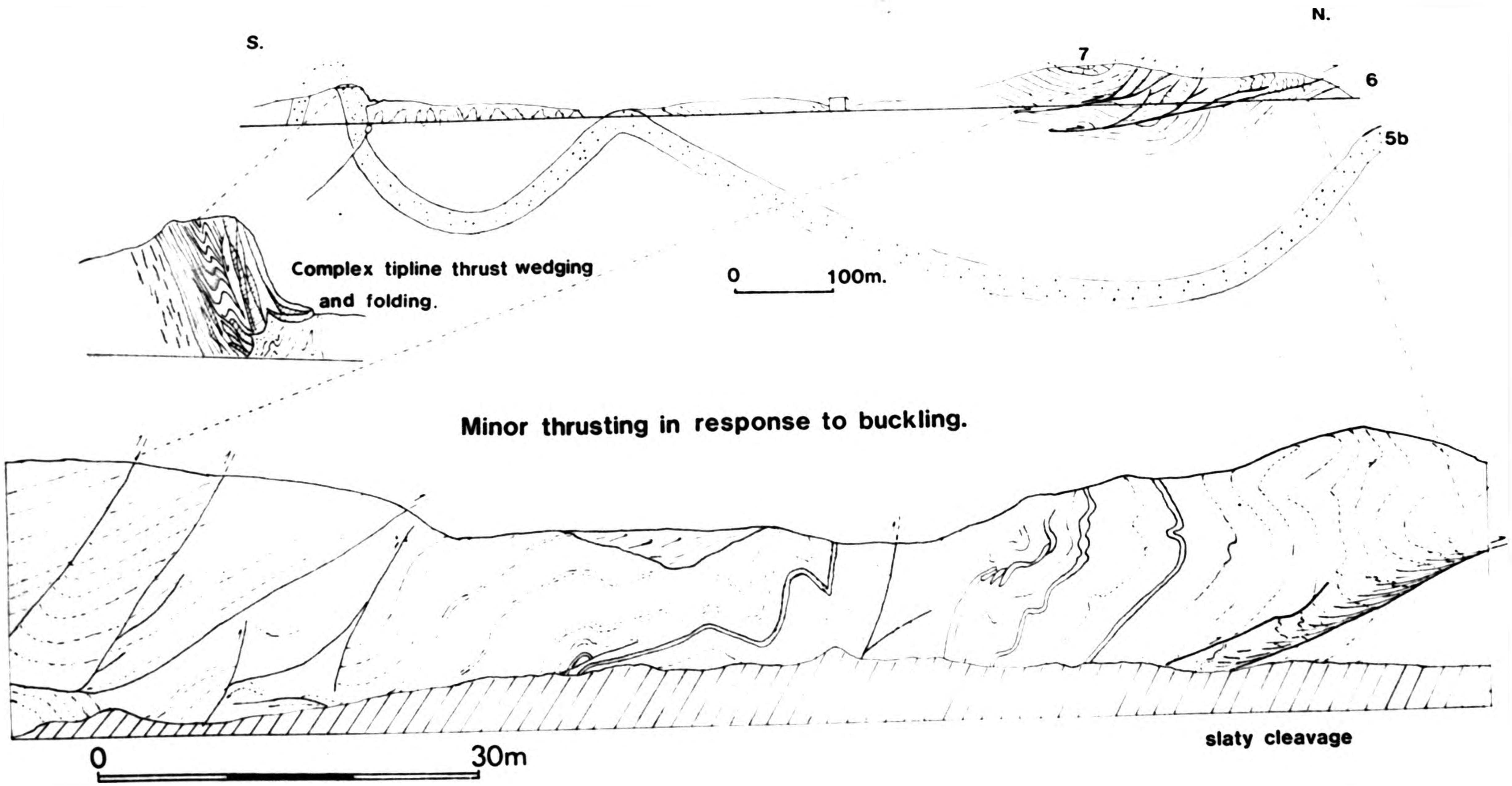
Folding and thrusting in the lower Silurian

Locality: (G.R. 825 342) Road section on the western side of road no.165.

Description: This locality is by the side of a busy road and is not suitable for large parties. The deformation of the very fossiliferous Stricklandia Series (Stage 6a-c) is different to that of the previous localities. The whole section is situated on a large syncline which has Pentamerus Limestone in its core. The northern limb of this syncline is described here (see Fig.8).

The rocks are deformed by backthrusts which cut up and down section in the direction of transport. This indicates that they formed later than the inital phase of deformation, which was by folding. In previous localities the folds had frequently been formed ahead of fault tips, however here buckle folding is dominant and when the folds oversteepened, break thrusts occurred. These thrusts may still join up into minor, sub-horizontal detachment horizons, some of which can be seen at the base of the section. Such horizons often involve complex fracture zones and thrust wedging.

Fig.8, Section on road no.164 at Tangen, in lower Silurian limestones and shales.


S.
N.
7
6
5b
Complex tipline thrust wedging
and folding.
0
100m.
Minor thrusting in response to buckling.
0
30m
slaty cleavage

SOLHEIM

Locality: (G.R. 837 361) Road section of the western side of road 165.

Description: Folding, thrusting and a small-scale duplex in Upper Ordovician Palaeoporella Beds.

The uppermost Ordovician (Stage 5b) has complex facies changes and was interpreted as a tidal bar sequence by Brenchley and Newall (1975). Here Stage 5b is represented by a limestone which is packed full of a tubular coral called Palaeoporella.

Similar post or late folding thrusting to that seen at Tangen is present here. Two limbs of the prominant anticline-syncline structure are displaced by a later thrust (see Fig.9). However the most interesting feature is a small scale duplex which has formed in shaly beds containing thin limestone bands. A balanced section of the duplex is given in Fig.10. Because more and more duplex structures are being inferred or interpreted in modern structural geology, it is useful to be able to recognise small scale structures which may help understanding of the larger structures, as well as proving that duplexes exist in nature!

The example at Solheim displays the essential features of a Duplex, that is sub-parallel roof and floor thrusts joined by numerous high angled reverse faults. The imbricate pattern caused by these reverse faults is marked by two prominant limestone bands. The Solheim Duplex is modified by a later low angled fault which displaced some of the earlier formed imbricates (see Fig.10, partially restored section).

Fig.9. Section in road no.165 through upper Ordovician and lower Silurian rocks at Solheim (G.R. 837 361).

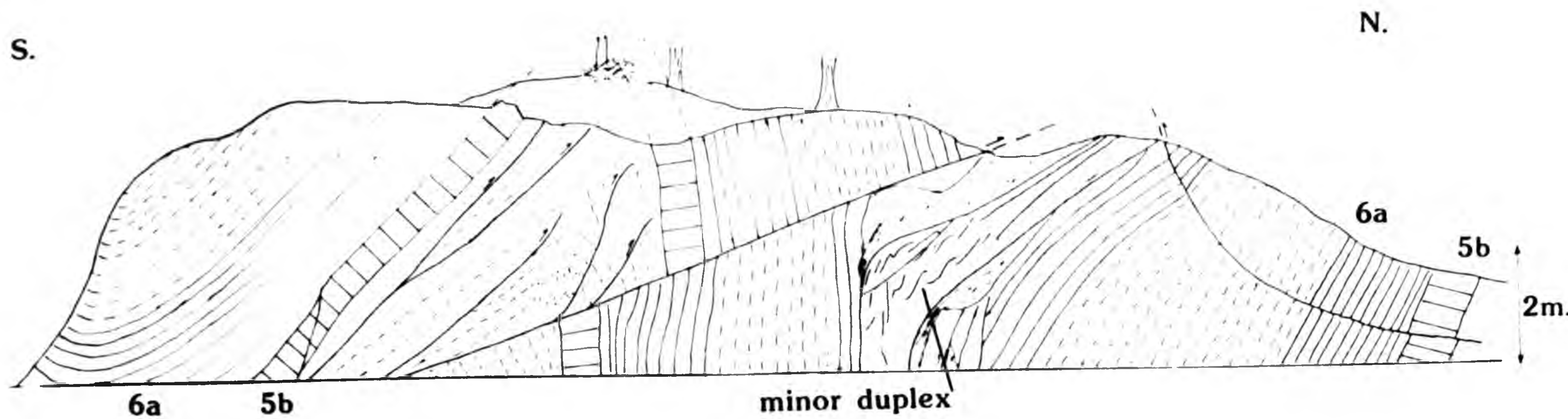

S.
N.
6a
5b
2m.
6a
5b
minor duplex

Fig.10, Detail of small scale duplex at Solheim

SOLHEIM DUPLEX

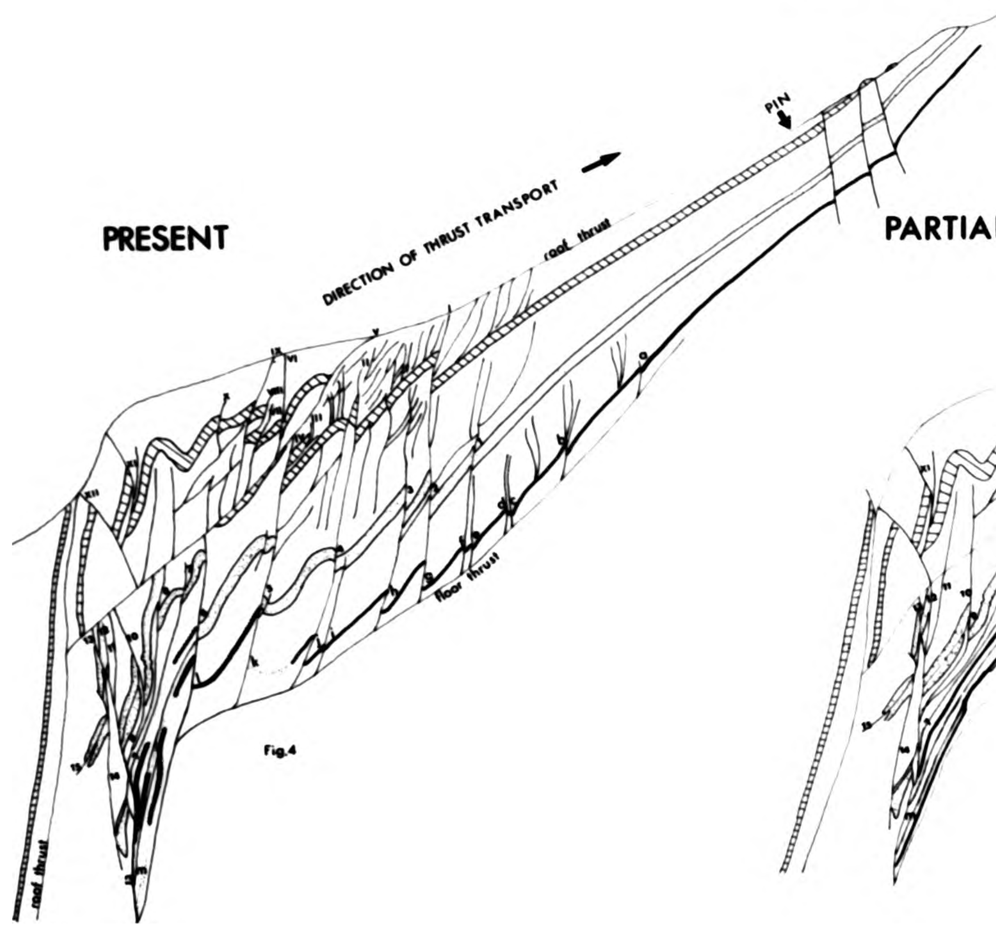


Fig.4

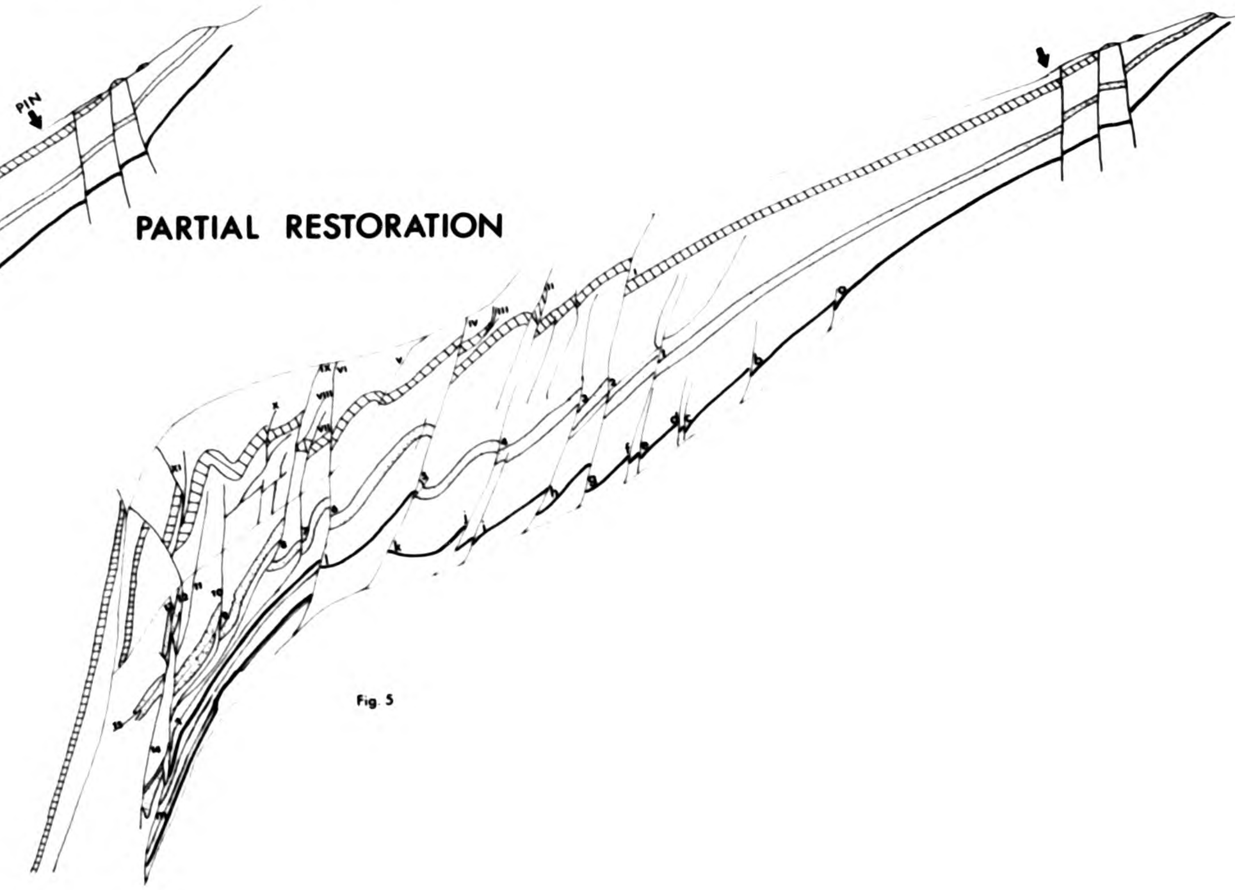


Fig. 5

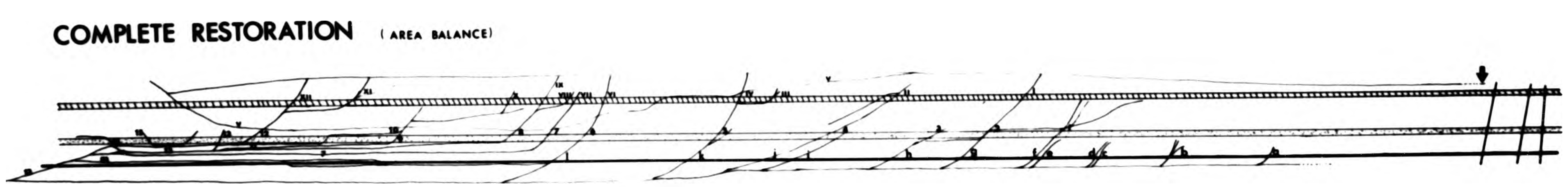


Fig.6

The present section has been restored, via a partial restoration which removes the effects of a later fault, and a full restoration which unstrains the main duplex deformation. In addition to shortening by imbrication the limestone beds have buckled whilst the shales have undergone layer parallel thickening.

HOLMEN

Locality: (G.R. 834 377) NW side of the E18.

Description: Imbricated middle Ordovician shales and limestones.

The section is viewed from the southern side of the E18 Motorway. The eastern end of the section begins with small concentric folds developed above a minor detachment horizon at the base of the Tretraspis Limestone. Further west the Chasmops Series is repeated by several imbricate thrusts (se Fig.11).The section ends in Tretraspis Limestone again, which is deformed into a footwall syncline. Obvious horizons in this section are the Lower Tretraspis Limestone with its very small nodules, the dark grey Lower Tretraspis Shale which is only 7-10m thick and contains large nodules, and the Upper Chasmops Limestone which towards the top has prominent bedding and a characteristic stark white colour.

HVALSTAD

Locality: (G.R. 830 365 to 827 367) Road section on northern part of E18 junction.

Description: Folded and imbricated Lower Tretraspis Limestone.

The Lower Tretraspis Limestone in the northern part of the

Asker-Baerum district is frequently imbricated and folded above minor detachment horizons which developed in the Lower Tretraspis Shale. In Hvalstrand there are several exposures which demonstrate this deformation.

The lowest 10m of the Lower Tretraspis Limestone is characterised by small tightly packed nodules, which pass upwards into larger less characteristic nodules. The small nodules therefore form a distinctive marker horizon and stratigraphic younging direction indicator (passing up into large nodules and down into dark shales), which enables recognition of the closely spaced imbricate slices.

At the NE side of the motorway junction to Astad (G.R. 830 365) the Lower Tretraspis Limestone is folded into an anticline. This structure is possibly a large fold developed above a detachment horizon in the Lower Tretraspis Shale.

At (G.R. 827 367) east and NW of the shopping center at Hvalstrand the intense imbrication of the Lower Tretraspis Limestone can be seen. Frequently the imbricate thrusts can be seen to cut up and down section which indicates that folding above the detachment occurred before thrusting (see Plate 10). Also cleavage is locally developed which appears to have formed during the thrusting as it is only present locally, adjacent to thrusts.

BYGDOY

Locality (G.R. 938 411 to 931 430) West coast of Bygdoy - a S-N traverse.

Description A section along imbricated and folded Cambro-mid Ordovician rocks demonstrating folded backthrusts, cleavage relationships and thrust geometries.

This is a long coastal section that should be seen by boat as well as by walking the section. The section begins in the south at Huk (see Fig.12) and finishes just north of the marina at Bygdoy Sjobad. The rocks range in age from Cambrian Shales to middle Ordovician Lower Chasmops Shales (Stage 4ba). The geology of the coastal section is sketched in Fig.13, (see Fig.3. for the interpretation) and the numbered localities marked on that section are described below.

1.Huk. The Orthoceras Limestone forms a prominant ridge on Huk. Its tectonic position is that of a modified hangingwall anticline which is thrust over Upper Didymograptus Shales (see Fig.12). The thrust splay which is seen to affect the limestone (see cross sections in Fig.12) probably originated in fault number 1 forming first, followed by fault number 2, (i.e. the newer thrust formed hindewards of the older thrust). This is because the hangingwall anticline forelimb appears to have over-steepened, and was then truncated by the first thrust. As the structure tightened, the second (backlimb) thrust splayed off the first thrust to produced a later less tightened hangingwall anticline at its tip line. The development of the normal fault seems to have occurred at a similar time because it appears to join the thrust planes and does not displace them (it might

Fig.12 **Deformation on Huk, Bygdoy**

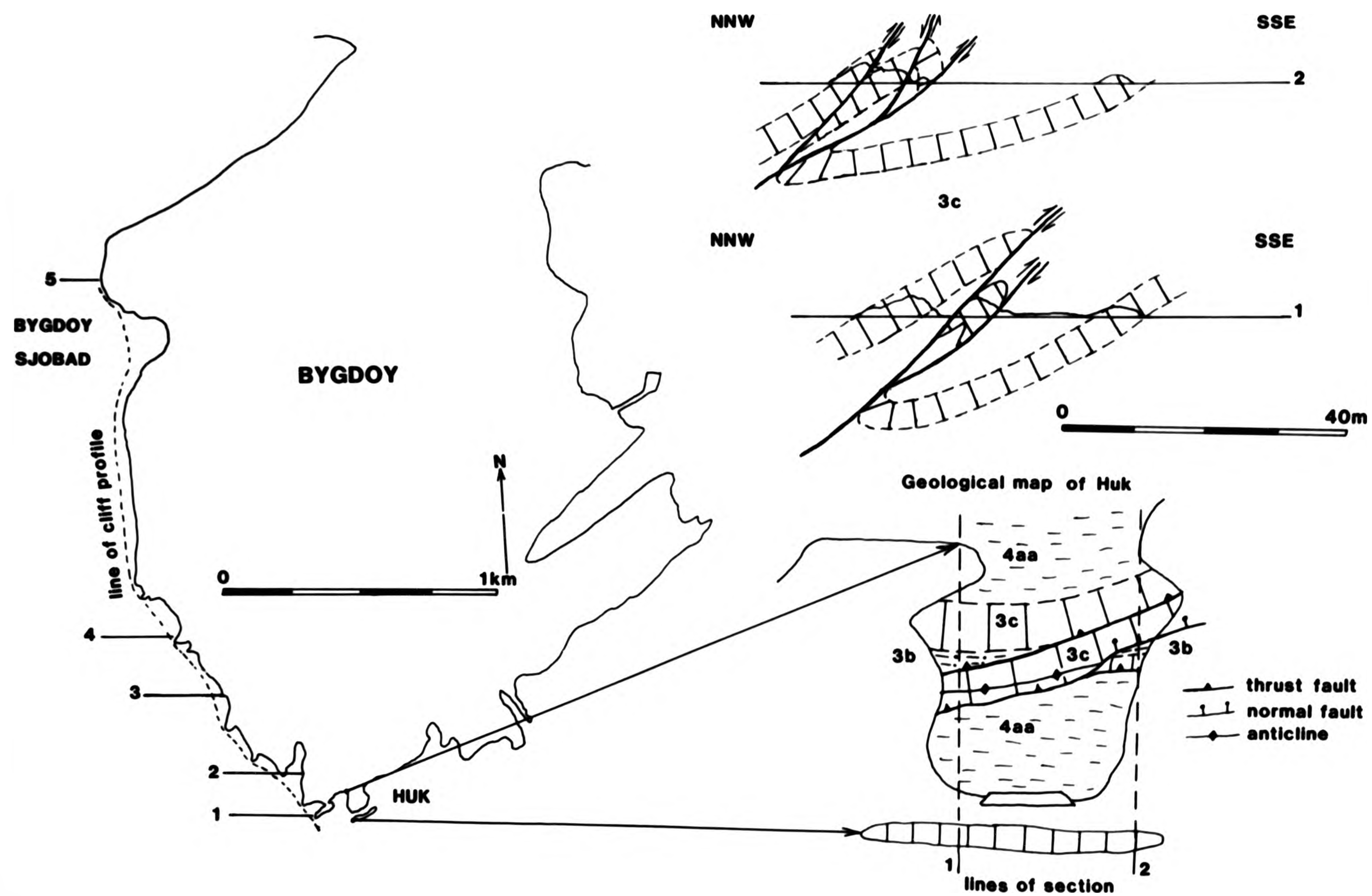

NNW
SSE
2
3c
NNW
SSE
1
0
40m
5
BYGDOY
SJOBAD
BYGDOY
line of cliff profile
N
0
1km
4
3
2
1
HUK
Geological map of Huk
4aa
3c
3b
3c
3b
4aa
thrust fault
normal fault
anticline
1
2
lines of section

Fig.13 <u>Sketch section of the geology along the west coast of Bygdoy</u>

KEY

Alum Shales and Ceratopyge Shales

Ceratopyge Limestone

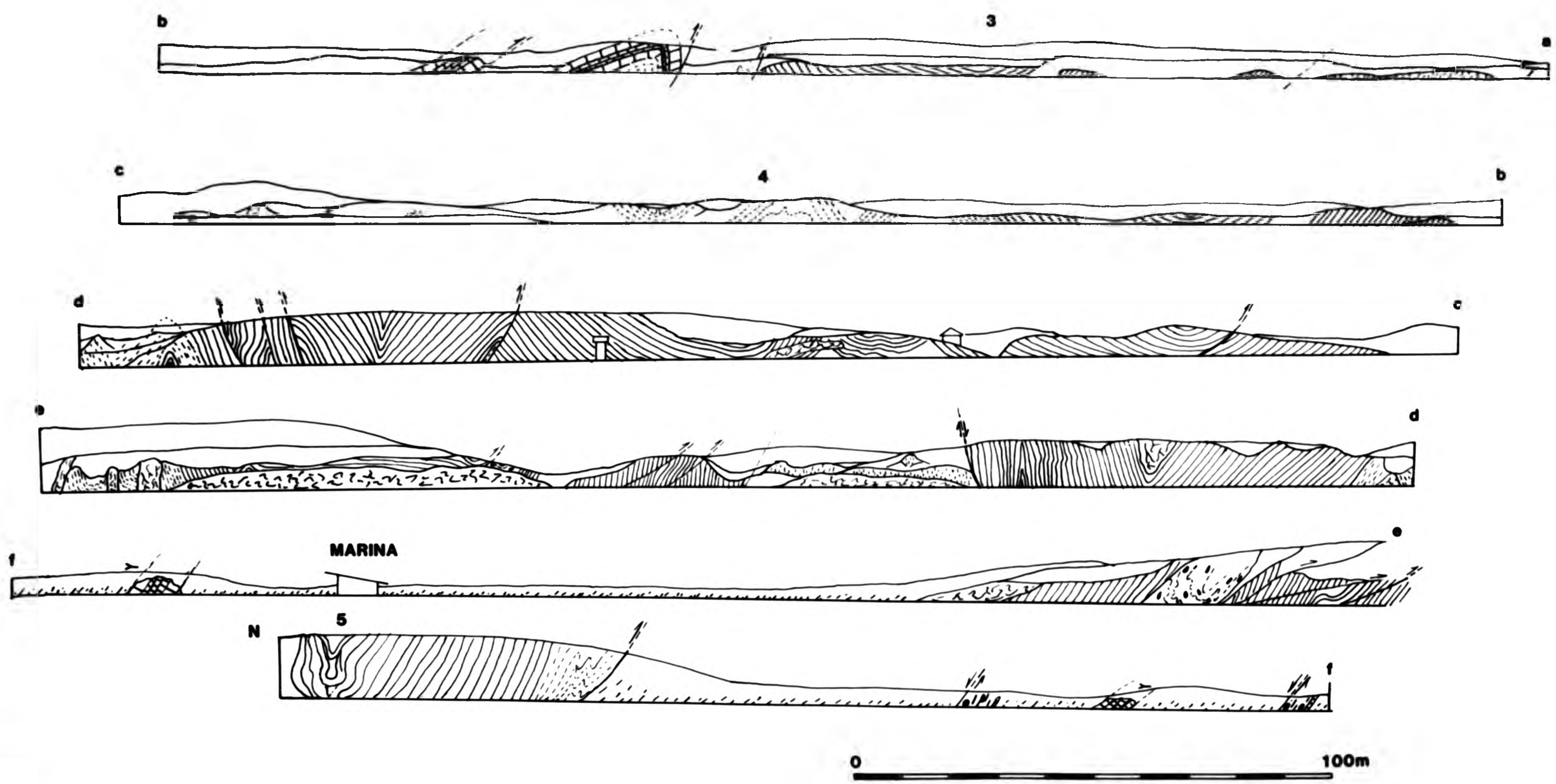
Lower Didymograptus Shales

Orthoceras Limestone

Upper Didymograptus Shales

Ampyx Limestone

Lower Chasmops Shales


b
3
a
c
4
b
d
c
e
d
f
MARINA
e
N
5
f
0
100m

also be an earlier structure). Other interpretations of this fault could explain it as a folded, overturned backthrust or that it is a lag fault.

2. North of the Cafe near Huk there is an excellent example of a footwall syncline below a hangingwall flat. The Ampyx Limestone of the hangingwall is thrust over the Lower Chasmops Shales in the footwall (see Plate 11).

3. In the broad syncline of Ampyx limestone two evenly spaced fracture cleavages are present, they are of similar strike but of opposite dips and formed at an oblique angle to bedding (see Plate 12). This relationship has been interpreted (in this thesis) as interference of two tip line cleavages produced by blind fore- and back- thrusts below the Ampyx Limestone.

4. The Orthoceras Limestone and the Ceratopyge Limestone form prominant ridges at the northern end of the section. The sequence of 4aa Shales to Alum Shales which incorporates these limestones can be seen to be overturned north of the Marina and repeated by faulting. As the beds are overturned the faults appear to be normal faults. However when the beds are restored to horizontal the faults appear to be backthrusts which have been later folded along with the bedding. Although neither a normal fault or backthrust interpretation can be conclusively proven, there is a large overturned syncline on the south side of Bygdoy Sjobad. This has the correct rotational sense on its northern limb for the folded backthrust to be formed, and it is this interpretation which I favour.

Plate 11, Footwall syncline, with Ampyx Limestone (H.W.F.) overthrusting Lower Chasmops Shales (F.W.R.), Bygdoy.

Plate 12, Two evenly spaced fracture cleavages of opposing dips in Ampyx Limestone, Bygdoy.

2.0 RINGERIKE

Introduction.

There is generally poor exposure in Ringerike except along the Tyrifjord shore line. The sections described are designed to illustrate the change in tectonic style between the southern and northern parts of Ringerike as defined in Chapter 4. The southern area displays a full Cambro-Silurian stratigraphy whilst the northern area is only composed of Cambro-mid Ordovician rocks.

The drive along the E68 from Oslo to Ringerike passes from the Ringerike Sandstone on the outskirts of Oslo into the Permian igneous complex which forms the high hills north of Oslo. Eventually near Nes the upper Silurian marine limestones and shales, which pass up into the red, continental, O.R.S. facies Ringerike Sandstone, appears by the road side again. Capping the hills above the road are the Permian extrusives and sediments which unconformably overly the Cambro-Silurian rocks.

Driving between Nes and Kroksund the thick, competent Ringerike Sandstone can be seen to be gently folded (with wavelengths of several kilometres) in the road side cuttings, with limbs dipping gently between 10° and 20°. Shortly after crossing the bridge at Sundvollen the transition between the grey marine limestones and the red sandstones and marls marking the beginnings of late Silurian molasse sedimentation can be seen.

Continuing along the E68 to Norderhov several small road side exposures near Vik display broad, gentle anticlinal folds in Pentamerus Limestone (Silurian, Stage 7c). To the east of the road between the Vik

Plate 13. View west from the E68 between Vik and Norderhov, over flat farm land in Ordovician rocks towards the main Silurian outcrop, which forms the prominent hills.

campsite and Norderhov is a long prominant hill (see Plate 13). This feature is caused by the upstanding, resistant mid Silurian limestones which are little affected by Caledonian deformation. The hill is offset in several places which reflicts the position of Permian normal faults. A gentle tilt to the ENE has been given to the district by displacement on large Permian normal faults.

NORDERHOV

Locality (G.R. 708 670) Road section on the east side of E68.

Description: Weakly deformed mid Ordovician rocks.

M711 1815 iii Honefoss

This section displays mid Ordovician limestones and shales that are little affected by Caledonian deformation. There is one minor fold and associated backthrusts in the section and some weak stylolitic pressure-solution in the limestones (normal to bedding), illustrating how weak the deformation of the Cambro-Silurian rocks is in southern Ringerike.

STUBDAL

Locality:

Description: 4aa Shales thrust over the Ringerike Sandstone.

At Stubdal after a long uphill drive over Ringerike Sandstone, a small outcrop of Ordovician phyllitic shales (4aa age, Stormer 1938) is present around the lake near the termination of the road. These have been overthrust from the NW at least 2km from their footwall cutoff near campsite and Norderhov is a long prominant hill (see Plate 13). This feature is caused by the upstanding, resistant mid Silurian limestones which are little affected by Caledonian deformation. The hill is offset in several places which reflicts the position of Permian normal faults. A gentle tilt to the ENE has been given to the district by displacement on large Permian normal faults.

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Klekken. They are fairly flat lying and display little internal folding or thrusting except for a phyllitic folliation. The thrust which emplaced these shales is called the Stubdal Thrust and its continuation in the main Cambro-Silurian strip of Ringerike separates the relatively undeformed rocks in the footwall as seen at Norderhov from the imbricated hangingwall rocks of northern Ringerike. Two localities are now described from the hangingwall area.

An excellent view of Ringerike and Tyrifjord is afforded at several points along the road down from Stubdal.

KLEKKEN

Locality: (G.R. 734 710) Local road section between Haug and Klekken.

Description: Imbricated Cambro-lower Ordovician Shales.

The Cambro-lower Ordovician sequence which was so poorly exposed in western Ringerike is here much better exposed. The regional strike of the northern area is E-W.

The section at Klekken exposes imbricated, folded and squeezed Alum and Lower Didymograptus Shales (see Fig.14). The best marker in this predominantly shaly section is the thin Ceratopyge Limestone which is repeated several times by thrusts.

HAUG

Imbricated and folded Ordovician rocks.

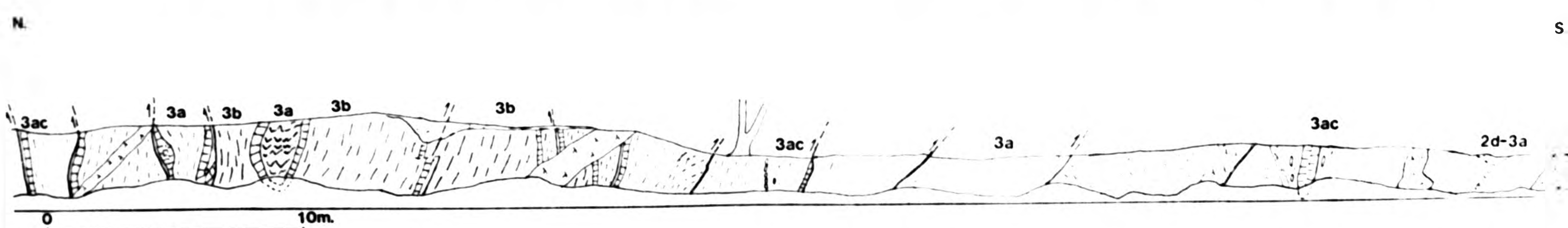
Locality: (G.R. 734 718) Housing estate in north Haug, turn west off Haug-Klekken road.

Description: The deformation of the Ceratopyge Limestone, Lower Didymograptus Shales, Orthoceras Limestone and Upper Didymograptus Shales is well displayed around a new housing estate. The following features should be noted in this locality (see Fig.15).

1. A lateral ramp in an imbricate thrust.
2. Pressure-solution cleavage parallel to strike and normal to bedding in the Orthoceras Limestone.
3. The younging direction of the Orthoceras Limestone can be determined by orthoconic nautiloids.
4. A strong localised fracture cleavage in the shales.

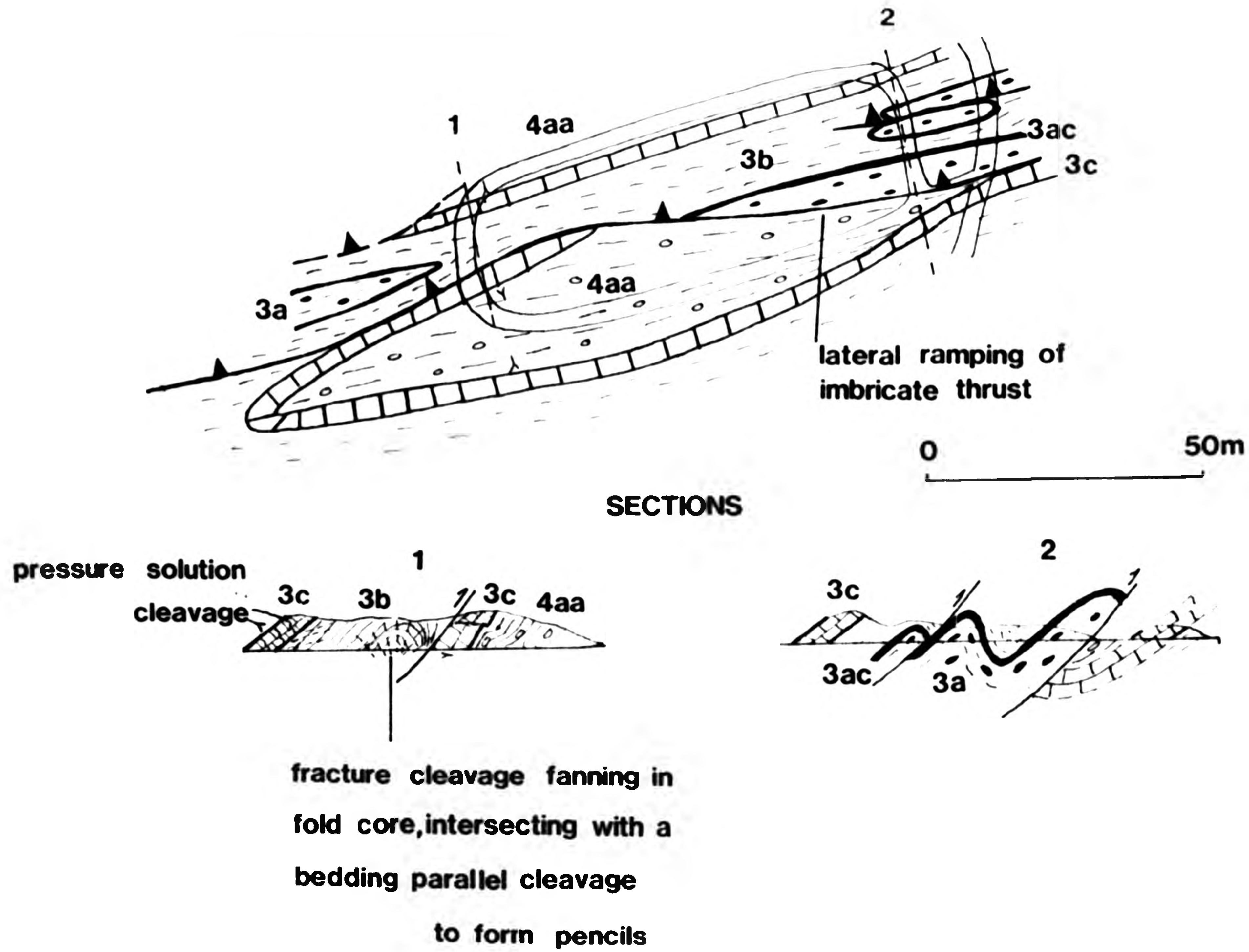
Fig.14 Road section between Haug and Klekken (G.R. 734 710) displaying imbricated Cambro-lower Ordovician beds

ROAD SECTION BETWEEN HAUG AND KLEKKEN THROUGH IMBRICATED CAMBRO–LOWER ORDOVICIAN BEDS (G.R. 734 710).



The section shows imbricate thrusts oversteepened by subsequent thrusting and squeezing of the shales laterally and vertically, which sometimes produce steeply plunging folds.

Fig.15 Geological sketch map showing details of imbricate thrusting. Haug (G.R. 734 718).


2
1
4aa
3ac
3b
3c
4aa
3a
lateral ramping of
imbricate thrust
0
50m
SECTIONS
pressure solution
cleavage
1
3c
3b
3c
4aa
2
3c
3ac
3a
fracture cleavage fanning in
fold core,intersecting with a
bedding parallel cleavage
to form pencils

3.0 HADELAND

Introduction

The imbricated Cambro-mid Ordovician rocks of northern Ringerike are upfaulted against Silurian rocks to the north, by the Permian Randsfjord Fault, in the vicinity of Jevnaker. Driving north through Hadeland the middle Ordovician-Silurian rocks by the roadside are deformed by a series of broad folds. As the style of folding is on a large scale it is hard to demonstrate in outcrop. Therefore there are no localities given for South Hadeland. The next stops are in the imbricated Cambro-middle Ordovician of North Hadeland.

The Cambro-middle Ordovician rocks are deformed by imbricate thrusting, tip line folds and thrust wedging. This is demonstrated in several well exposed sections.

ROAD AND PATH SECTION TO HELGAKER

Location: (G.R. 854 935 to 846 946) Section on the local road between Gran and Tuv, turning off road for path section to Helgaker.

Description: Folding and imbrication

This is a long, discontinuous section which excellently displays the deformation in the Ordovician rocks. The description begins at the southern end of the section and works northwards (see Fig.16).

1. There is an obvious ramping imbricate thrust in the Kirkerud Group Shales (see Plate 14). The geometry of this thrust is of a footwall flat, whilst the hangingwall is folded, and passes from a H.W.R.

3.0 HADELAND

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at the base to a H.W.F. at the top of the section. Minor chisel faults are present in the hangingwall rocks. The thrust rises at an angle from the bottom of the section and then flattens off. However the footwall rocks always have a F.W.F. relationship with the fault. Therefore the thrust plane has later been kinked to form its present geometry.

2. Complex repetitions of slices of Orthoceras Limestone and adjacent shales are displayed here. There may be an example of an early thrust wedge, later overturned, by being rotated by about 70°. Its position is indicated on Fig.16. Some minor pop-up structures in the limestone are also present.

Helgaker path section (G.R. 846 946)

3. A well exposed anticline is present here. Minor offsets in the base of the Orthoceras Limestone can be seen. These offsets are linked to a set of conjugate fractures which accommodate the varying stresses of buckle folding in massive limestone by displacing "key stone" blocks of limestone. The Stage 3b shales below the limestone display minor thrust planes which form a triangle zone, which enabled material to be transported into the fold core.

ROAD SECTION SOUTH-EAST OF ROYKEN

Location: (G.R. 818 000) Turn off Royken-Brandbu road SE over bridge, section of hairpin bend.

Description: Thrusting, folding and normal faulting in the Orthoceras Limestone.

The Orthoceras Limestone is thrust over the Kirkerud Group and repeated by imbrication and minor backthrusting (see Fig.17c). At the northern end of the section are a series of minor normal faults. The thrusts and normal faults have similar strike directions, so the latter may represent local extension during thrusting, perhaps caused by stretching of the hangingwall as it passed over a ramp.

RAILWAY BRIDGE.

Location: (G.R. 817 003) Railway bridge over road and stream section on Brandbu-Royken road.

Description: Deformation of the Orthoceras Limestone

Here there is a good exposure of a syncline in Orthoceras Limestone which has been intruded by a Permian dyke. The syncline has a steep northern limb and gently dipping southern limb. The southern limb is offset by several normal and thrust faults (see Fig.17b).

About 15m away on a bend in the river is an outcrop of Orthoceras Limestone that has been much thickened by repetition along ramping imbricate thrusts (see Fig.17a).

OLD RAILWAY LINE.

Location: (G.R. 810 002) east along railway cutting where railway and farm tracks intersect.

Description: Footwall syncline and thrust wedging.

Walking down the old railway track, which is being turned into a new road, are some exposures first described by Holtedahl and Schetelig (1923). There is a good example of a footwall syncline in Kirkerud Group

Shales, which have been over thrust by Orthoceras Limestone in the hangingwall. The Orthoceras Limestone is internally deformed by flat lying thrust wedging (see Plate 15).

Fig.16 Road section along Gran to Tuv local road from G.R. 854 935 to 846 946 at Helgaker, demonstrating the imbricate deformation of the region.

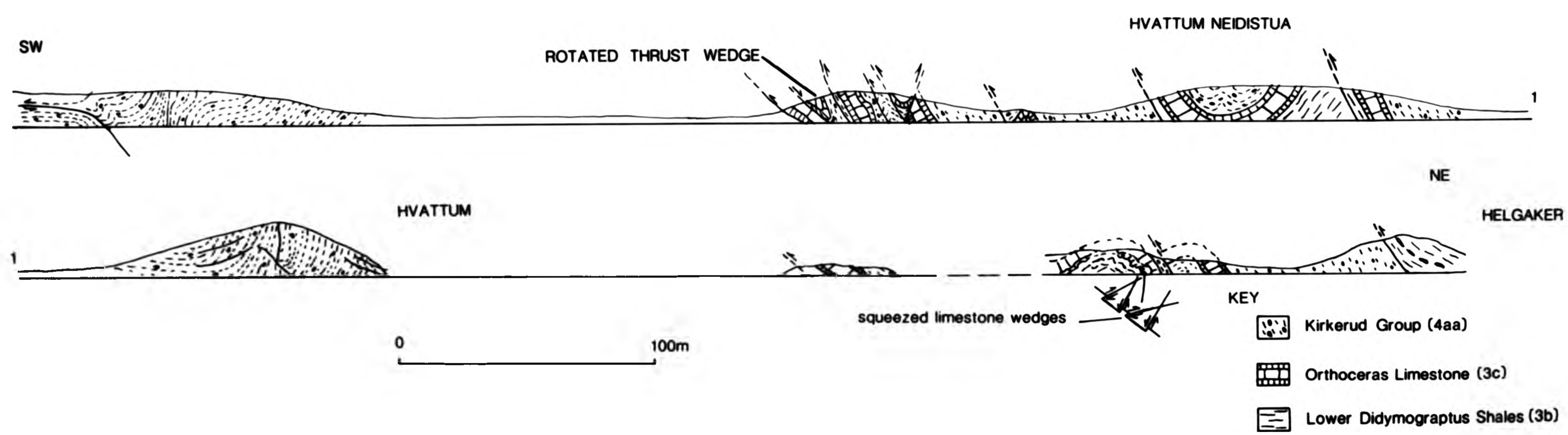

SW
ROTATED THRUST WEDGE
HVATTUM NEIDISTUA
1
NE
HVATTUM
HELGAKER
1
squeezed limestone wedges
0
100m
KEY
Kirkerud Group (4aa)
Orthoceras Limestone (3c)
Lower Didymograptus Shales (3b)

Fig.17 Examples of deformation style within the Orthoceras Limestone

A. River section (G.R. 818 002)

B. Railway bridge (G.R. 817 003)

C. Road section SE of Royken (G.R. 818 000)

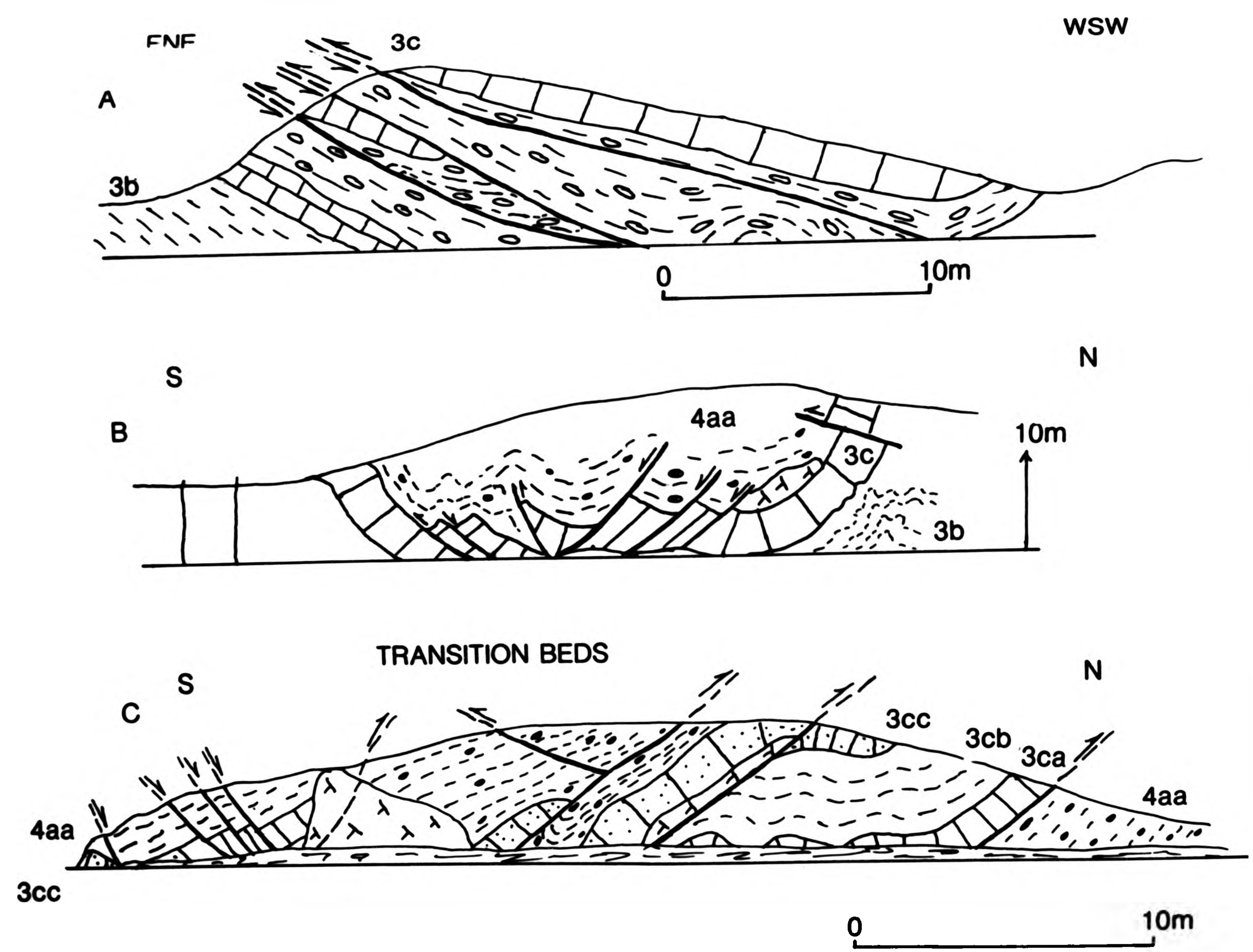
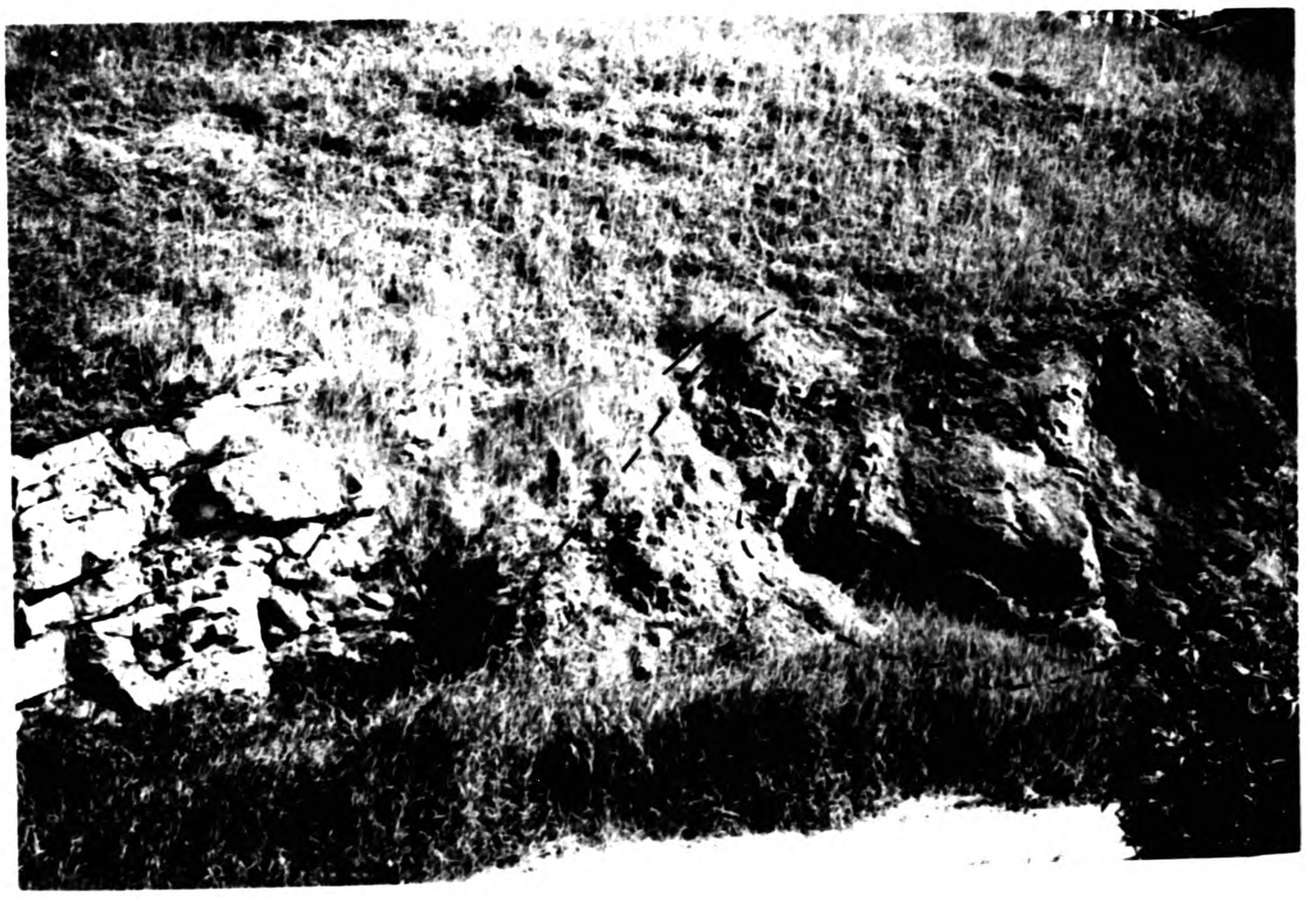

A
ENE
3c
WSW
3b
0
10m
B
S
N
4aa
3c
10m
3b
TRANSITION BEDS
C
S
N
3cc
3cb
3ca
4aa
4aa
3cc
0
10m

Plate 14. Details of kinked thrust plane with a F.W.F. and H.W.R. geometry. in Kirkerud Group Shales. on Gran-Tuv local road G.R. 854 935.

Plate 15, Orthoceras Limestone thrust over Kirkerud Group Shales (footwall syncline geometry), old railway line, Royken (G.R. 810 002).



4.0 MJOSA

The localities described for this area are designed to demonstrate several important aspects about the geology of the Mjosa area. Starting in the south, on the eastern side of Lake Mjosa, several localities are described to illustrate that imbrication of the Orthoceras Limestone is similar in Mjosa to the areas described to the south. Perhaps the most important point is that the Osen-Roa Thrust Sheet continues into the Oslo Graben. Evidence for the ramping of the Osen-Roa Thrust Sheet is shown in several localities.

The Cambro-Silurian south of Hamar has always been described in the literature as autochthonous or parautochthonous. However the deformation already described in the Oslo Graben, when unstrained allows transport distances of 100km to be estimated for south Hadeland. Therefore the region is allochthonous.

OTTESTAD-HAMAR ROAD

Location: (G.R. 165 384) Main road north of Ottestad Church.

Description: This section displays Orthoceras Limestone downthrown by normal faults against the transition bed above the Orthoceras Limestone (see Fig.18). The black shales at the southern end of the section were interpreted by Skjeseth (1963) as Cambrian Shales overthrust by 4aa Shales. However this would involve thrusting younger rocks in the hangingwall over older rocks in the footwall. Unless the tectonics are more complicated than they appear to be, either the footwall rocks are 4aa Shales and not Alum Shales (a similar shale lithology can be seen in the hangingwall) or the fault is a normal fault. At present I favour the former view.

Fig.18 Normal and thrust faulting in lower Ordovician rocks, Ottestad-Hamar road (G.R.165 384).

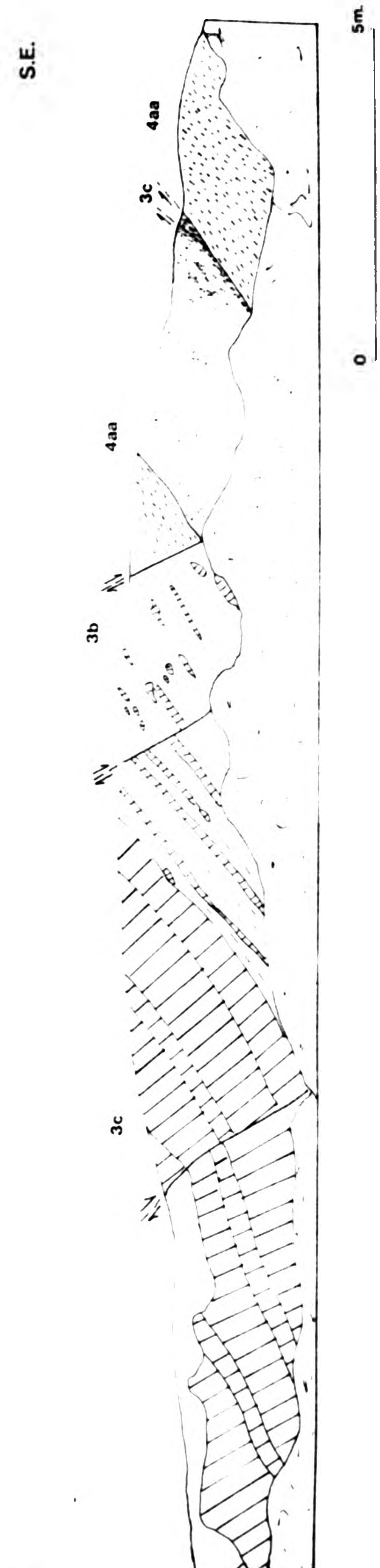

N.W.
S.E.
3c
3b
4aa
3c
4aa
0
5m.

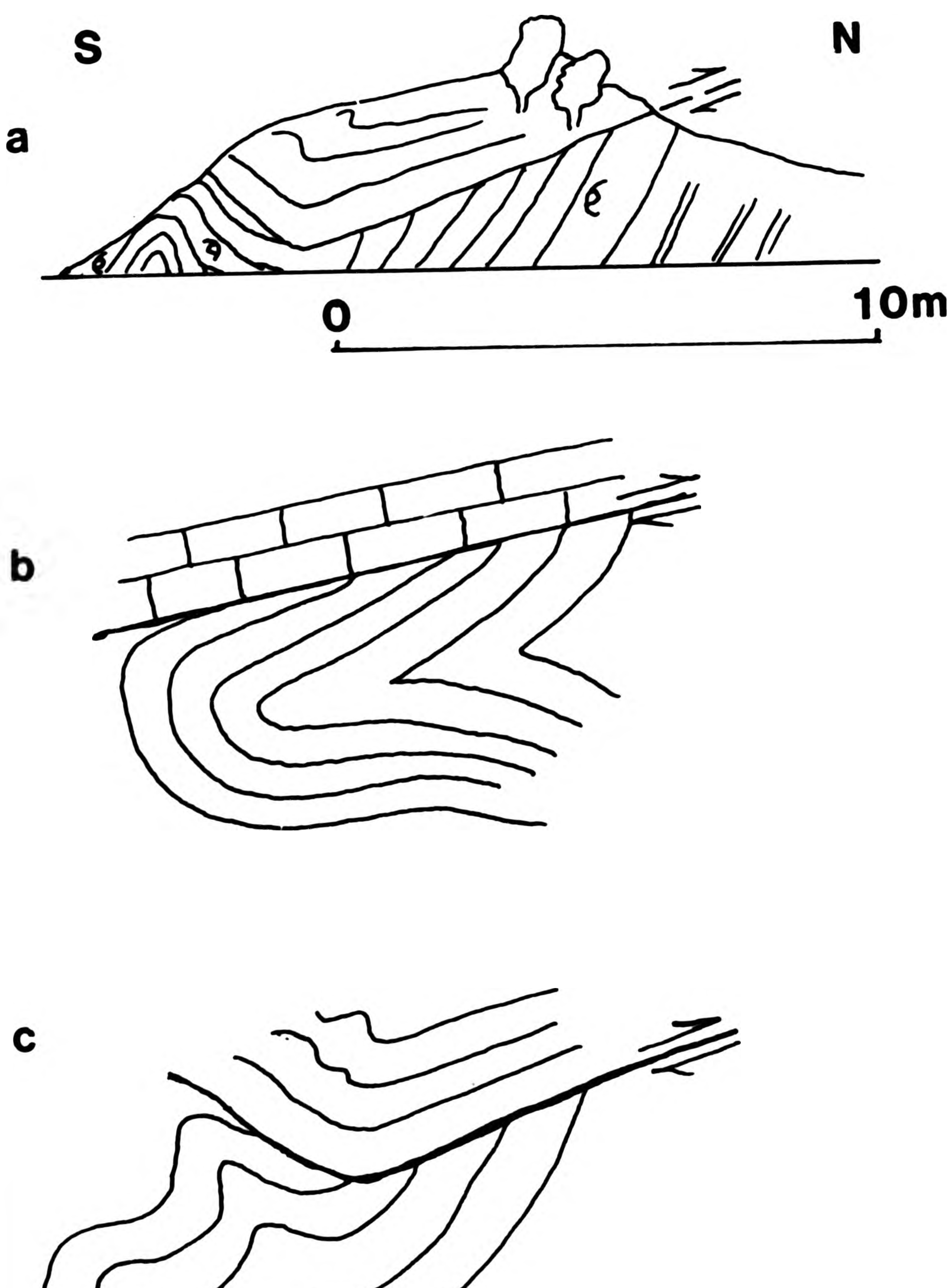
Fig.19 Sandvika

A. Sketch of section in Orthoceras Limestone showing facing directions from nautiloids (6 = ≻)

B and C deformation sequence to produce the present structure

B. Thrusting of H.W.F. over F.W.R.(syncline)

C. Later folding of the syncline to produce an antiformal syncline.


S
N
a
0
10m
b
c

SANDVIKA

Location: (G.R. 160 412) West turning off Hamar-Ottestad road to Sandvika, about 300m south of 222 to Hamar.

Description: Folded imbricate thrust.

The Orthoceras Limestone forms a prominent outcrop by the roadside (see Fig.19, Plate 16). The thrust is folded into a broad v shape and the nautiloid younging direction in the footwall at the northern end of the outcrop shows this part of the section to be overturned. A synclinal antiform is below the kinked thrust plane at the southern end. The structure is interpreted as a refolded footwall syncline (see Fig.19). Numerous shear vein slickensides, calcite veins and stylolites are also present.

Plate 16, Folded thrust in Orthoceras Limestone, Sandvika.

BERG

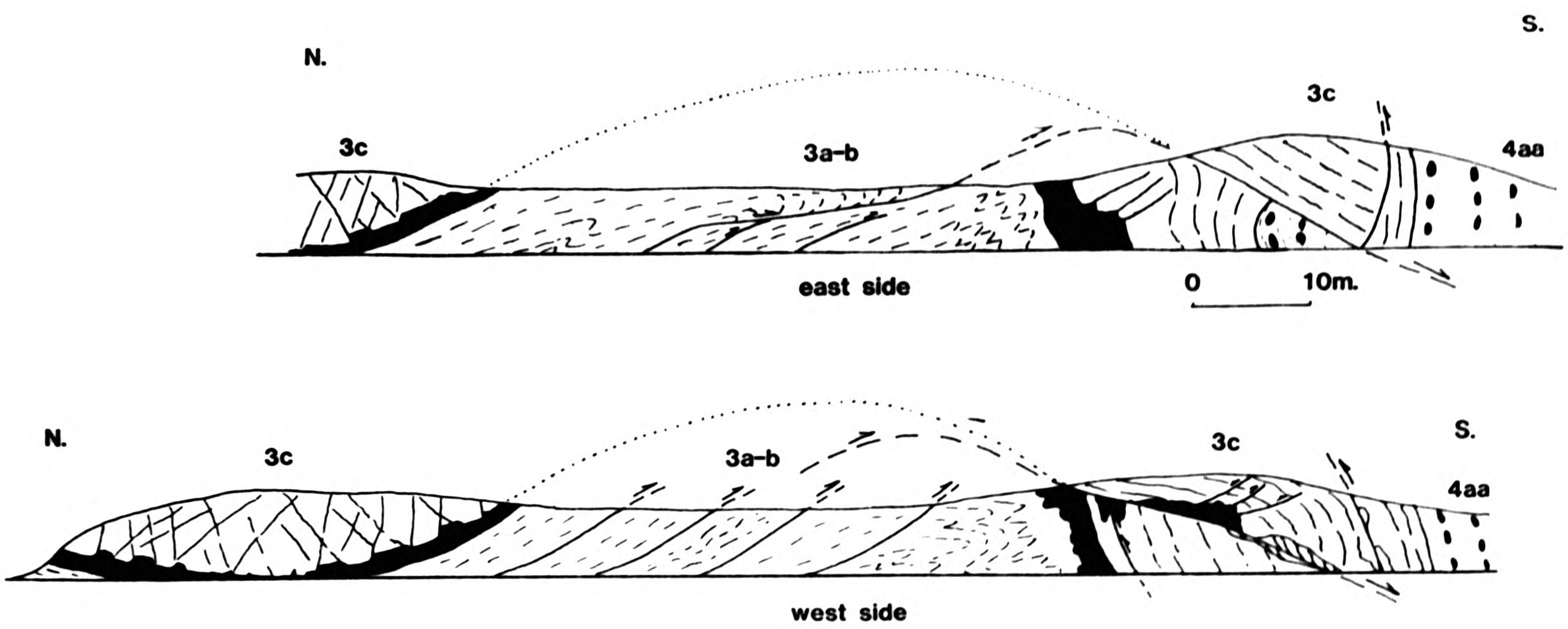
Folded and imbricated lower to middle Ordovician shales and limestones

Location: (G.R. 081 484) The E6 road section is best viewed for safety reasons on either side of the top of the cutting, looking down into the 10m deep trench. M 711 1916 iv Hamar

Description: The E6 section cuts through a folded and thrust sequence which comprises the following lithostratigraphic units.

iv top	Bjorge formation, Llanvirn-Llandeilian
iiib	Helskjaer Shale Member
iiia	Stein Formation
ii	Black Shale
i bottom	Grey Shale, Arenig

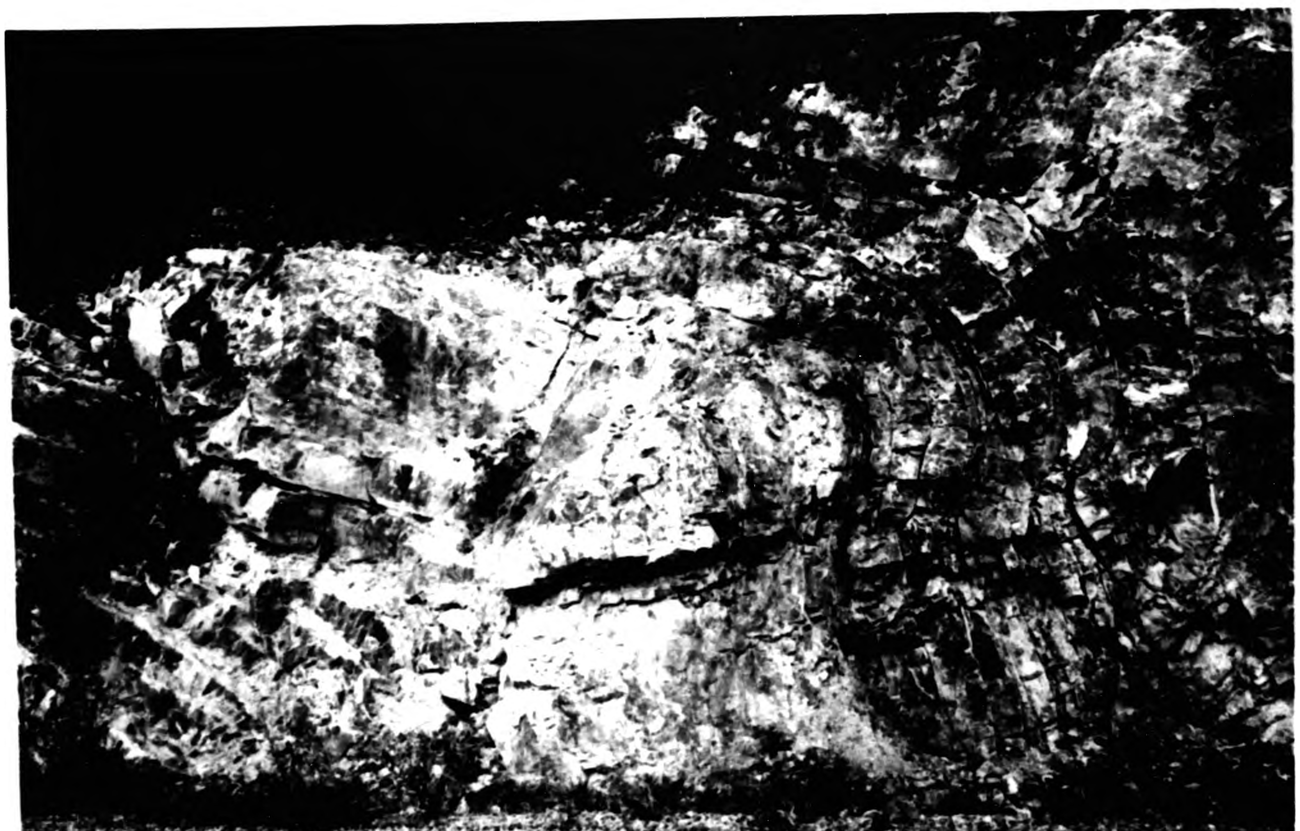
Fig.20 Road profile through folded and thrust lower Ordovician rocks, E6, Berg.

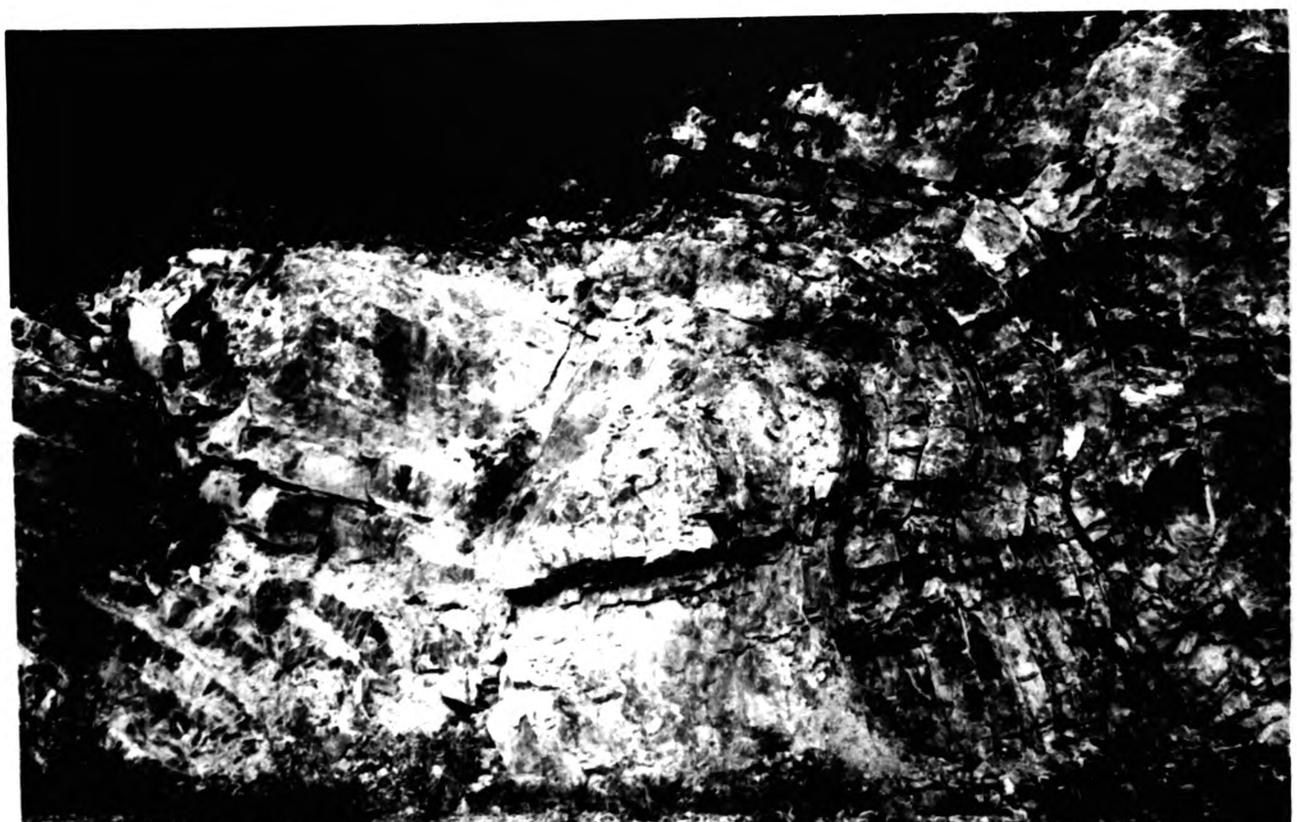


The west side profile has been reversed to enable direct comparison of the two sides.

Plate 17. Conjugate fracture sets caused by folding in massive limestone, E6, Berg.

Plate 18, Folding above a minor thrust, Sollerud.



A simplified profile of the structure is given in Fig.20. The south-western side is reversed so that both sides of the section can be directly compaired. The syncline at the NW end of the section displays numerous conjugate sets of fractures (see Plate 17) which are the result of buckling stresses in an isolated, competent, massive horizon, where bedding plane slip was unable to function. Offsets are produced on the fractures which produce wedge shaped blocks of limestone. These blocks have in places, been down faulted into the shales below and were probably formed by extension in the outer arc of a fold.

The shales between the two Orthoceras Limestone exposures are folded and imbricated. The anticline of Orthoceras Limestone at the southern end of the section is intensely folded and cut by thrust and shear planes. The main thrust affecting the anticline is inclined to the SE, whilst the footwall is apparently the upthrow side in this orientation. Therefore either the fault is a normal fault or it is a folded thrust. The latter interpretation is the more probable because there is so much evidence of compressional tectonics in the section, and because the anticline appears to be oversteepened by later folding, which would have folded earlier thrusts.

STEENS KALKBRENNERI: FURUBERGET

Folded and thrust middle Ordovician shales, calcareous sandstones and limestones.

Location: (G.R. 092 442) Road section and limestone quarry east of the railway, 1.7km south of Jessnes railway station.

M 711 1916 iv Hamar

Description: The road cut passes through the upper part of the Hovinsholm Shale, Furuberget Formation and the Mjosa Limestone. The beds at the beginning (north) of the section have been folded with originally vertical axial planes, that have subsequently been rotated to a horizontal position. The section reveals complex minor thrusting events that frequently involve sub parallel-bedding thrusts which produced minor thrust splays (see Fig.21). When the competent Mjosa Limestone is reached (in the quarry) the deformation becomes simple, with the limestone forming a broad syncline.

The discrepancy in the amount of shortening in the higher competent units when compared with the lower predominantly incompetent units has led to the postultion of an upper detachment zone between the two tectonic units (this Thesis). In Mjosa the upper detachment zone is likely to be just below the Mjosa Limestone, so this section might represent the upper detachment zone where the more resistant, less deformed, competent units in the hangingwall have moved above this zone, towards the hinterland relative to the more highly deformed rocks in the footwall. The upper detachment zone could be represented here by the numerous sub bedding-parallel faults in the shale units.

SOLLERUD

Location (G.R. 068 492) Section in the local Jessnes-Brumunddal road, about 100m north of the E6 bridge over the local road.

M 711 1916 iv Hamar

Description: The section is through the Ringsaker Quartzite member (Vangsas Formation), which is a quartz-arenite, followed by a Lower Cambrian greenish grey mudstone. The two units are deformed together here, whilst the Cambro-Silurian rocks were deformed directly above basement to the south. Further north successively older Eocambrian units are present, hence the sole thrust to the area, the Osen-Roa Thrust is cutting up section (frontally ramping) to the south. Proof that this is not sedimentary thinning is presented in the locality at Furnes on the western side of the fjord.

The rocks here display thrusting, folding above thrusts and thrust wedging (see Plate 18).

EVJEVIKS

Location: (G.R. 919 542) Path from Veikroa, E6, along southern side of Evjevika.

M711 1816 i Gjovik

Description: On a small road (200m) down to the shore of Mjosa, the overturned Eocambrian-Ordovician rocks of the Ringsaker inversion can be seen. This is the classic locality for the basal contact of the Lower Cambrian beds with the Ringsaker Quartzite Member, in Mjosa. The structure has been interpreted in this Thesis as the overturned forelimb of a hangingwall ramp anticline.

MOELV

Location

Description: The structure at Moelv is difficult to demonstrate because the exposure is only good along the shore, and the imbricates are widely spaced and not too well exposed. However the industrial estate exposure quite good. This exposure has been described in Bryhni (1981) as displaying an inverted sequence (from N to S) of Ring Formation, Moelv Tillite and Vangsas Formation with the Ekre Shale present between the latter formations squeezed to only 0.5m (from 30-40m) along a thrust zone.

However the sedimentary structures indicate that the section is the right way up. It is proposed here that the shale interpreted as the Ekre Shale is just one of the shale horizons present in the Vangsas Formation and that the imbricate thrust in this section is between the Ring Formation and Moelv Tillite.

A walk along the Mjosa shoreline at Moelv traverses several imbricate thrust repetitions. On the opposite shore line around Kremmerodden, is the continuation of the Moelv imbricate structure (see Fig.22). The imbricates on the western shore are overridden by a thrust sheet called the Biri Nappe by Vogt (1952). Because there must be a sole thrust to the imbricates at Moelv and the roof thrust to the imbricates lies on the western shore, the whole structure has the geometry of a duplex, which is tilted gently to the west.

DEHLI

Location:

Description: Two road cuts are examined which expose the Brottum Formation, which is the lowest stratigraphic unit in the Osen-Roa Thrust Sheet.

The southern section displays, at its southern end, late minor thrusts of small displacement. These thrusts die out laterally along the section into various types of tip line (see Fig.23). The way in which a fault can die out varies, it may die out into a zone of cleavage, splay into several smaller faults (horsetail), pass into folds or just end abruptly. In some of the faults exposed here decreasing displacement towards the fault tips can be traced by measuring marker horizons. In one of these faults both tips can be seen. This supports the idea that faults can grow from one point and spread in all directions, so that the thrust plane is elliptical or circular in plan. This type of fracture is called a somigliana dislocation.

At the northern end of the section a backthrust with a hangingwall anticline forms the main structure. A few later minor thrusts are also present (see Fig.23)

The northern section displays complex thrust wedging and folding (see Fig.24). Thrust wedging in the competent beds (which are between shales that are easily squeezed), is intense and responsible for a considerable amount of shortening (up to 50%) in these folded beds.

The thrust wedging at the southern end of the section has produced a structure with the geometry of an antiformal duplex. This is a duplex structure where the horses (rock slices entirely bound by fault planes) have been rotated by transport over a ramp to an inverted position.

Fig.22 Geological map of the Moelv Duplex.

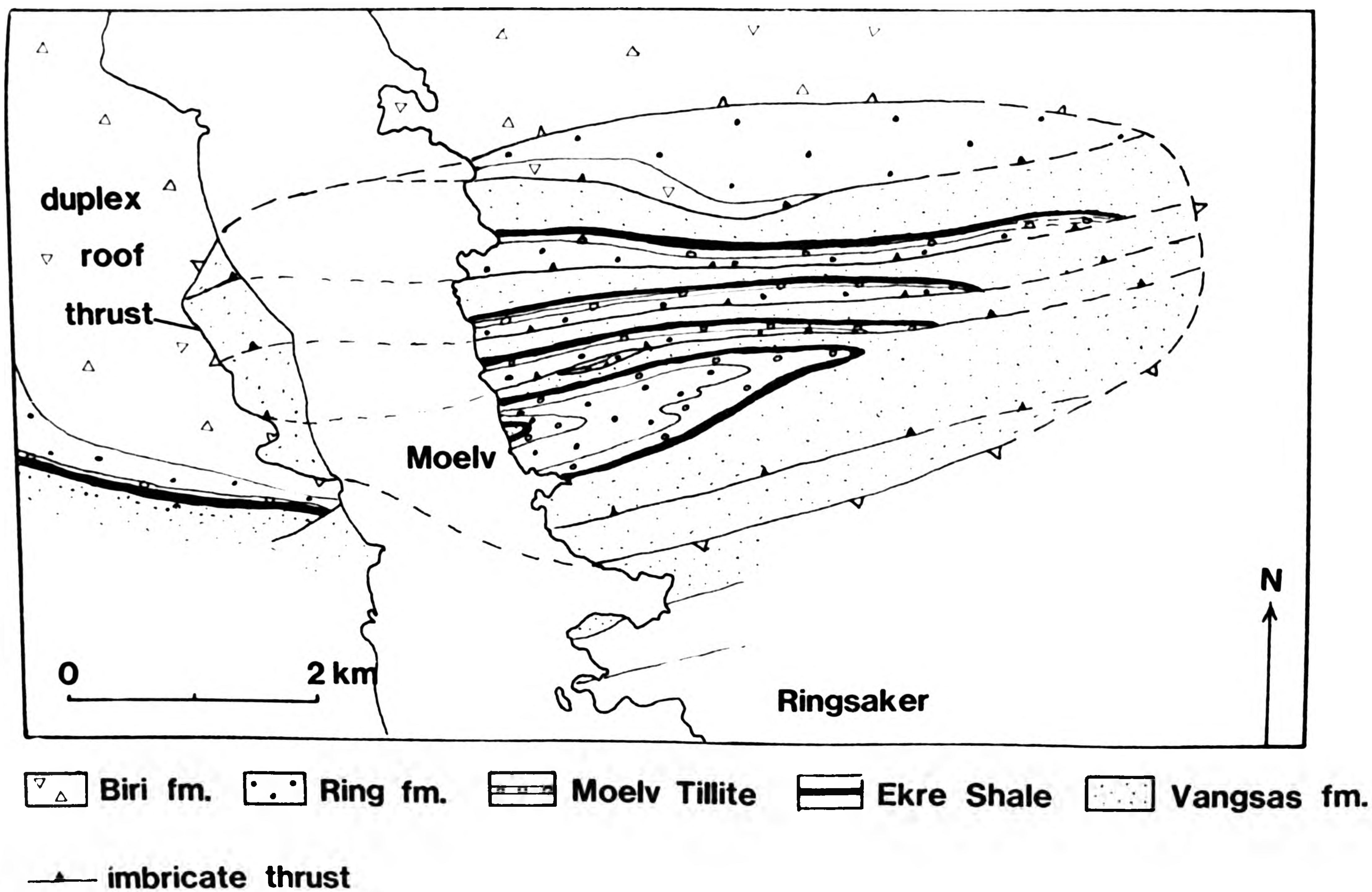

duplex
roof
thrust
Moelv
Ringsaker
0
2 km
N
Biri fm.
Ring fm.
Moelv Tillite
Ekre Shale
Vangsas fm.
imbricate thrust

Fig.23 Tip lines in the southern E6 road section at Dehli. Details of the tips of a somigliana dislocation are ringed.

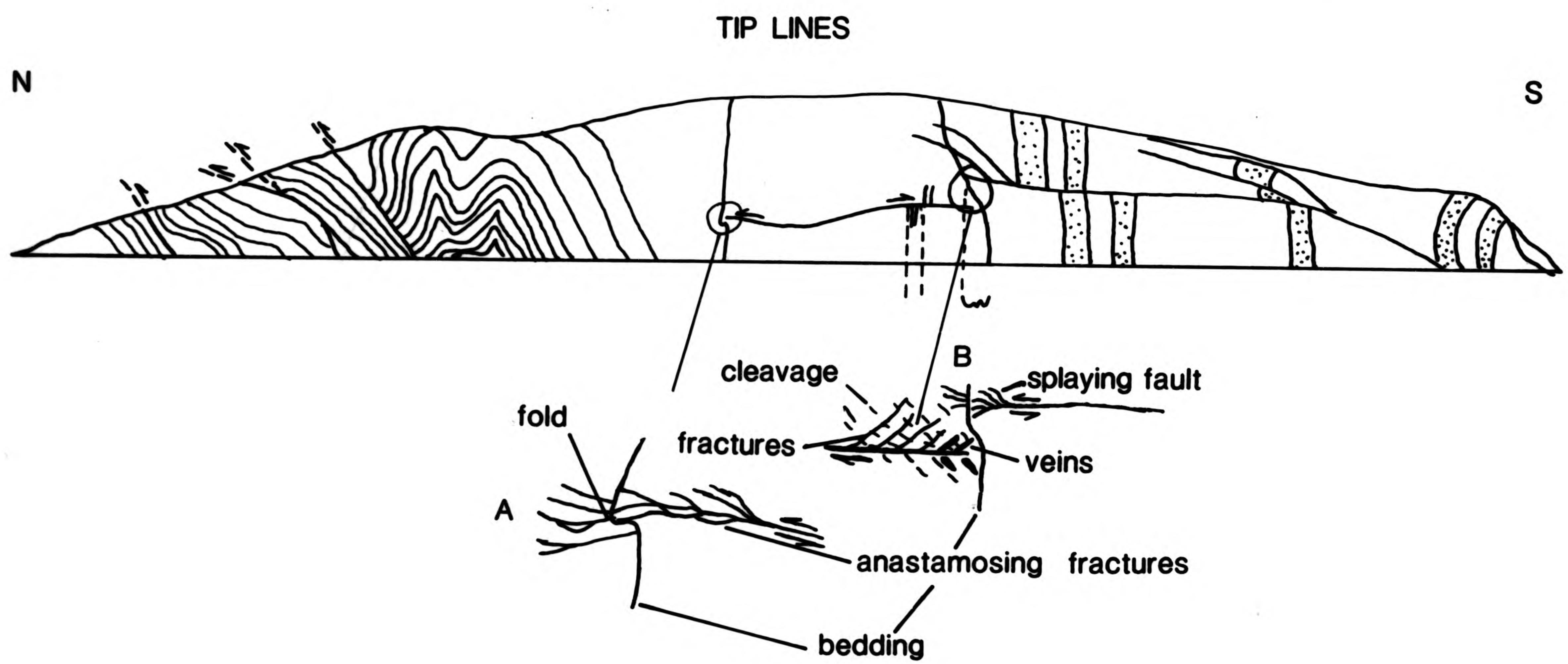
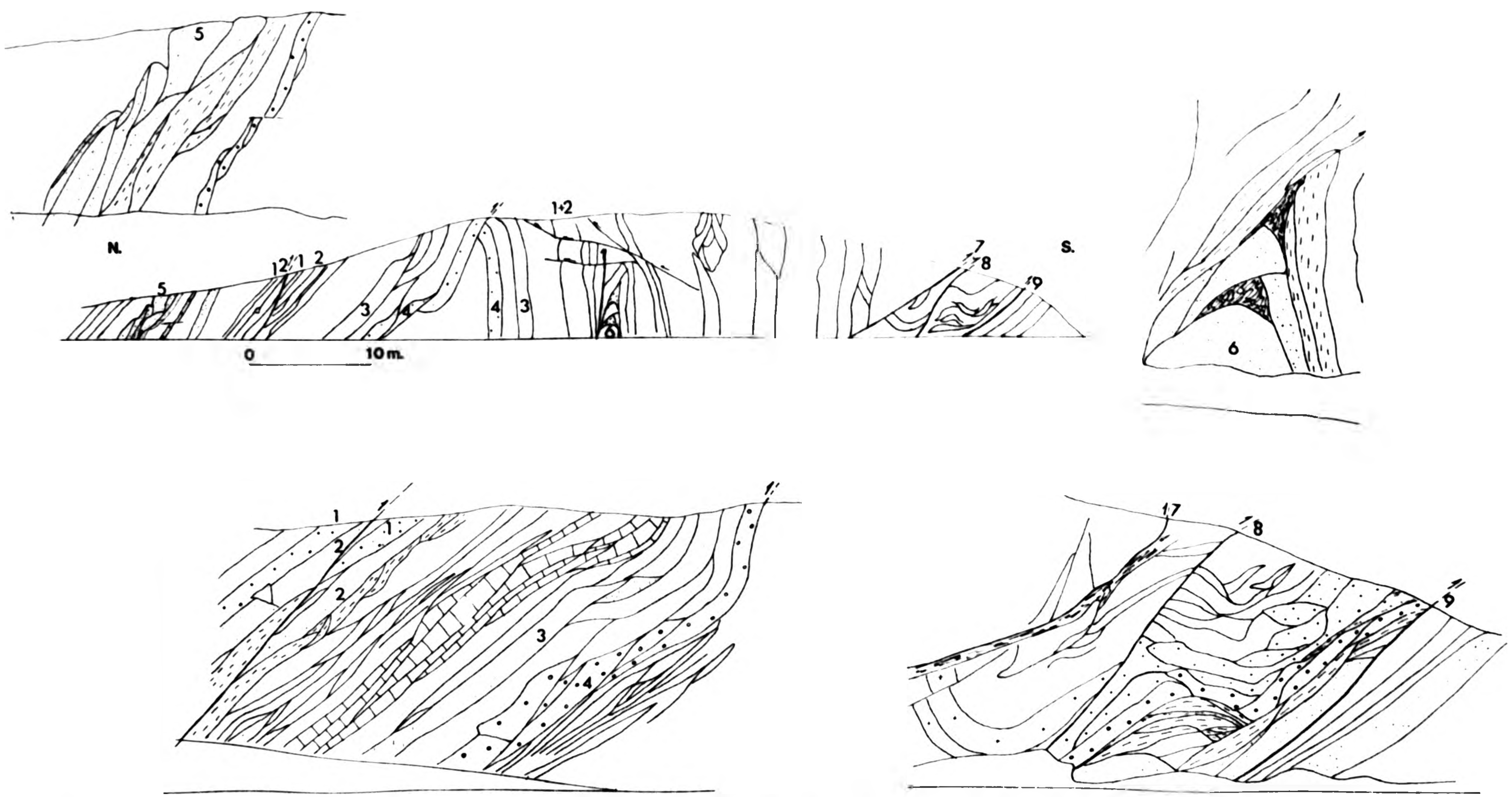

TIP LINES
N
S
B
cleavage
splaying fault
fold
fractures
veins
A
anastamosing fractures
bedding

Fig.24 Details of thrust wedging and folding in the Brottum formation in the northern E6 road section at Dehli.



The alternating sandstone and shale bands have been folded and thrusted. Complex thrust wedging produced significant amounts of shortening in the competent units (see detailed sketches of portions of the main section).

The western side of Lake Mjosa

Driving down the west side of Lake Mjosa the age of the rocks which outcrop young to the south. Just south of Kremmerodden (G.R. 889 585) the Biri Formation has been thrust above the Vangsas Formation and forms a large anticlinal fold nappe (Vogt 1952). This structure has been interpreted in this Thesis as forming the roof thrust to a duplex. The imbricates of the duplex are seen around Moelv.

DARLSJORDET

The Ringsaker Quartzite Member and tectonic imbrication

Location: (G.R. 923 493) Road section in main road No.4.

Description: The Ringsaker Quartzite Member and Lower Cambrian Shales are repeated several times along the road section. The dip of the sandstone units steepens up towards the north, untill the thrusts are vertical and overturned at the northern end of the section (see Fig.25). Oversteepened imbricate thrusts are a common consequence of sequential, foreland progressing imbrication as the higher imbricates are tilted by the younger, newly developing ones. At the northern end of the section intense irregularly spaced fracture cleavage is adjacent to several thrusts. The consistent repetition of the same units by imbrication indicates that the sole thrust below the area has a hangingwall flat geometry.

FURUSET

Location: (G.R. 914 437) Take east turning off E4 at Bjornsvea and walk to shoreline and walk north.

The western side of Lake Mjosa

Driving down the west side of Lake Mjosa the age of the rocks which outcrop young to the south. Just south of Kremmerodden (G.R. 889 585) the Biri Formation has been thrust above the Vangsas Formation and forms a large anticlinal fold nappe (Vogt 1952). This structure has been interpreted in this Thesis as forming the roof thrust to a duplex. The imbricates of the duplex are seen around Moelv.

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FURUSET

Location: (G.R. 914 437) Take east turning off E4 at Bjornsvea and walk to shoreline and walk north.

Description: The Mjosa shoreline at Furuset displays parautochthonous Cambrian Shales and Vangsas Formation in the footwall of the Osen-Roa Thrust below Ekre Shale and Vangsas Formation (to the north) in the Hangingwall, (which is actually the Osen-Roa Thrust Sheet). The Vangsas formation in the hangingwall has been transported from the NNW over the Vangsas Formation in the footwall. Therefore the absence of Vangsas Formation in the hangingwall, south of Gjovik cannot be due to sedimentary thinning, and is probablt instead due to tectonic ramping of the sole thrust. This is important because it means that the Osen-Roa Thrust continues at the base of the Cambro-Silurian rocks in the Oslo Graben, and does not override them.

FLUBERG

Autochthonous Cambrian beds and the Osen-Roa Thrust.

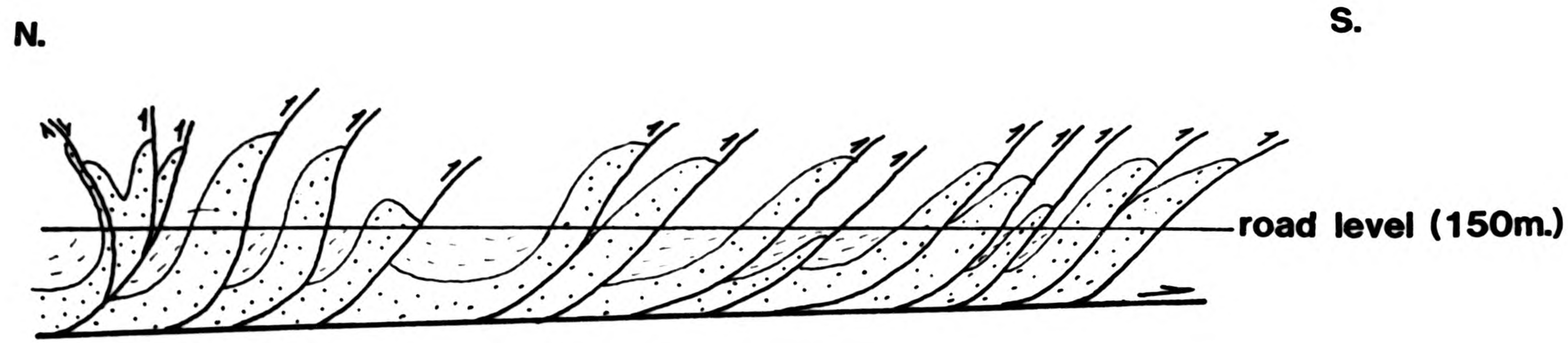
Location (G.R. 688 392) Road section in main road No.33 and view to the west.

M 711 1816 iv Dokka

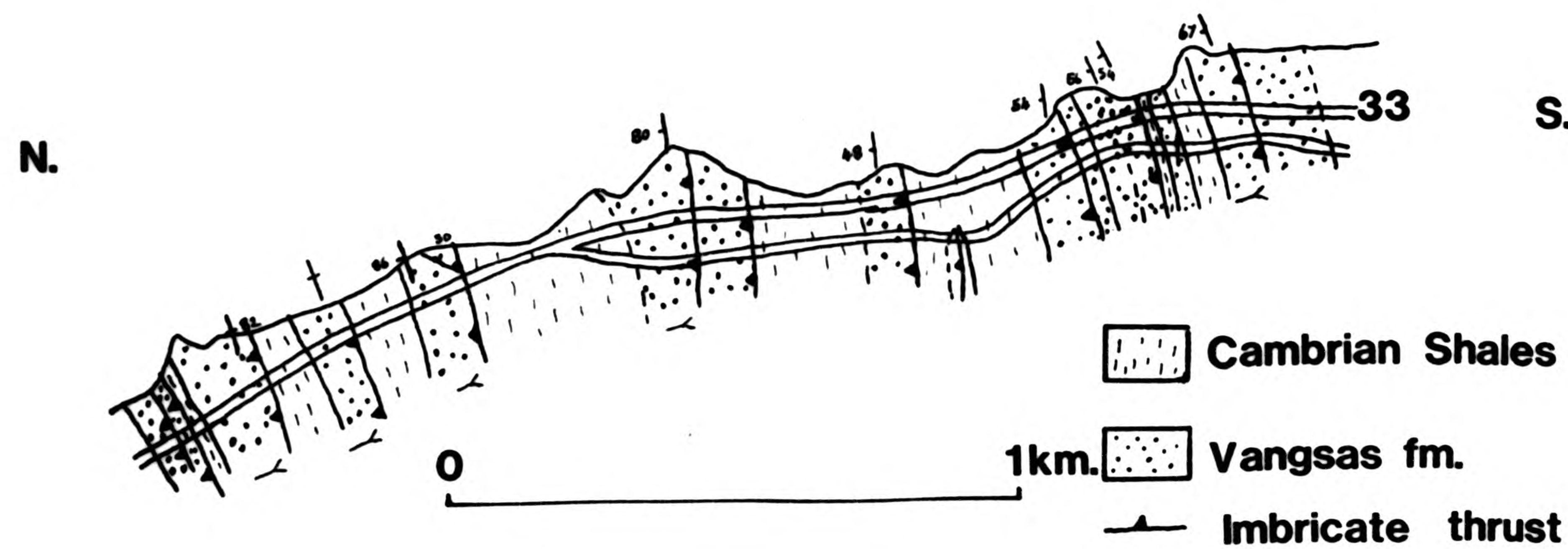
Description: The road crosses the Osen-Roa Thrust at an altitude of 280m. In a small quarried exposure thin, phyllitic and graphitic Lower Cambrian Shale occurs below the allochthonous Vangsas Formation. From this exposure towards the WNW there is a fine view of the sub-Cambrian peneplane and the Osen-Roa Thrust Sheet in the hillside north and south of the Randsfjord (see Plate 19).

The Osen-Roa Thrust has ramped to lie in the Vangsas Formation here, in relation to the previous locality, where the thrust lay within the Ekre Shale.

Fig.25 Imbricate thrusting in the Vangsas Formation and Cambrian shales on main Lillehammer-Gjovik road no.4 at Darlsjordet.

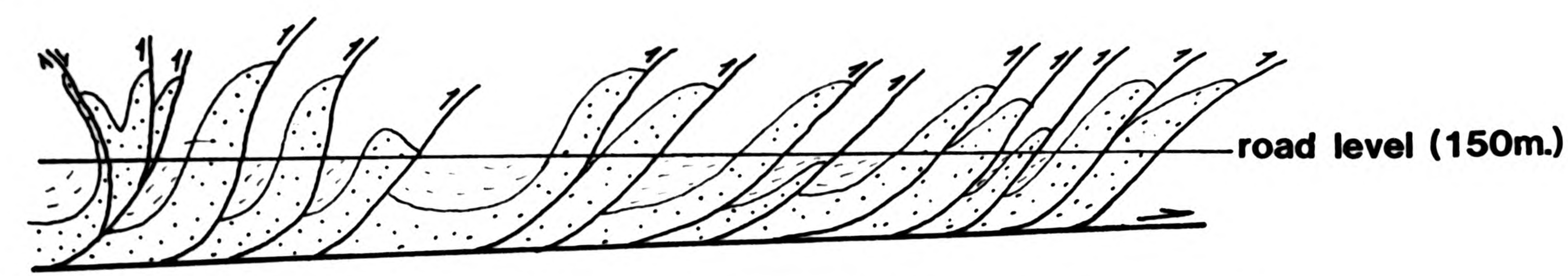


Cross-Section constructed from the outcrop along road 33.

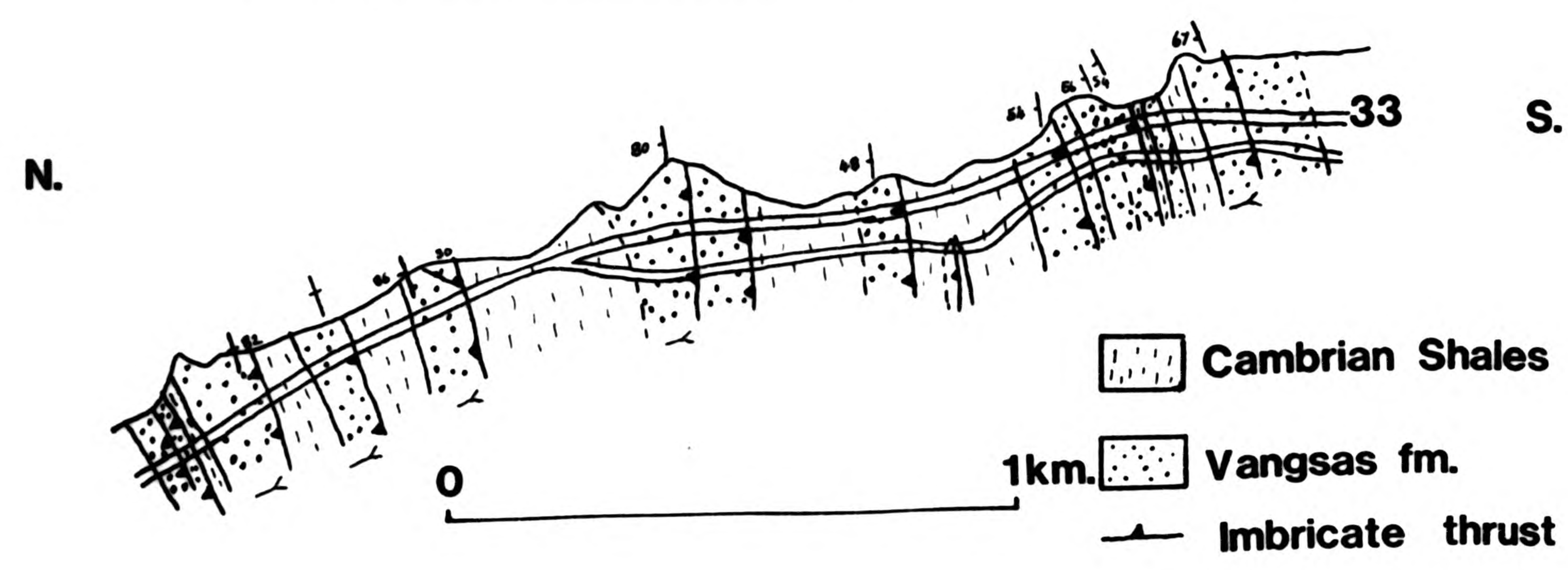


Geological sketch map

Fig.25 Imbricate thrusting in the Vangsas Formation and Cambrian shales on main Lillehammer-Giovik road no.4 at Darlsjordet.



Cross-Section constructed from the outcrop along road 33.

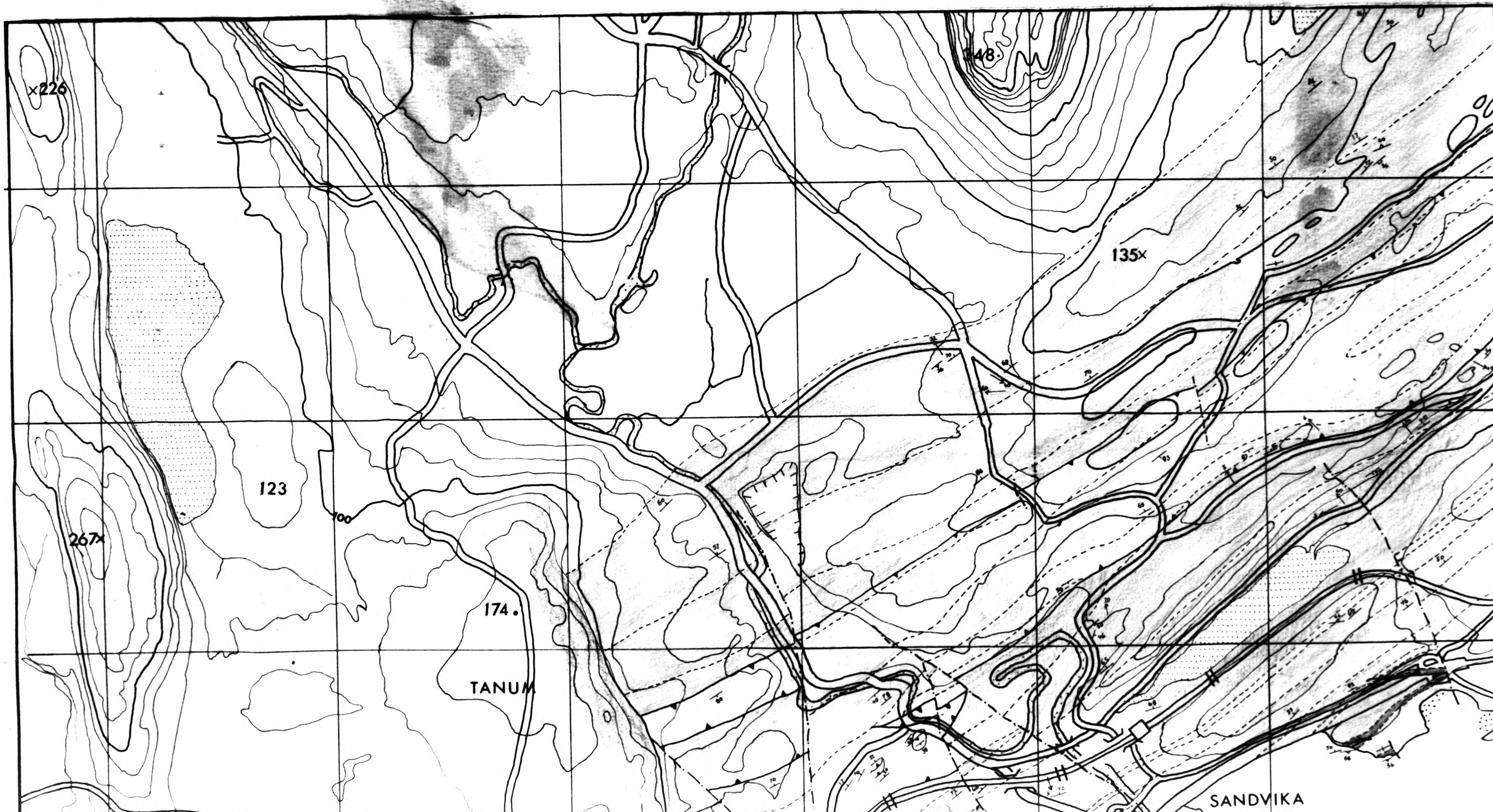


Geological sketch map

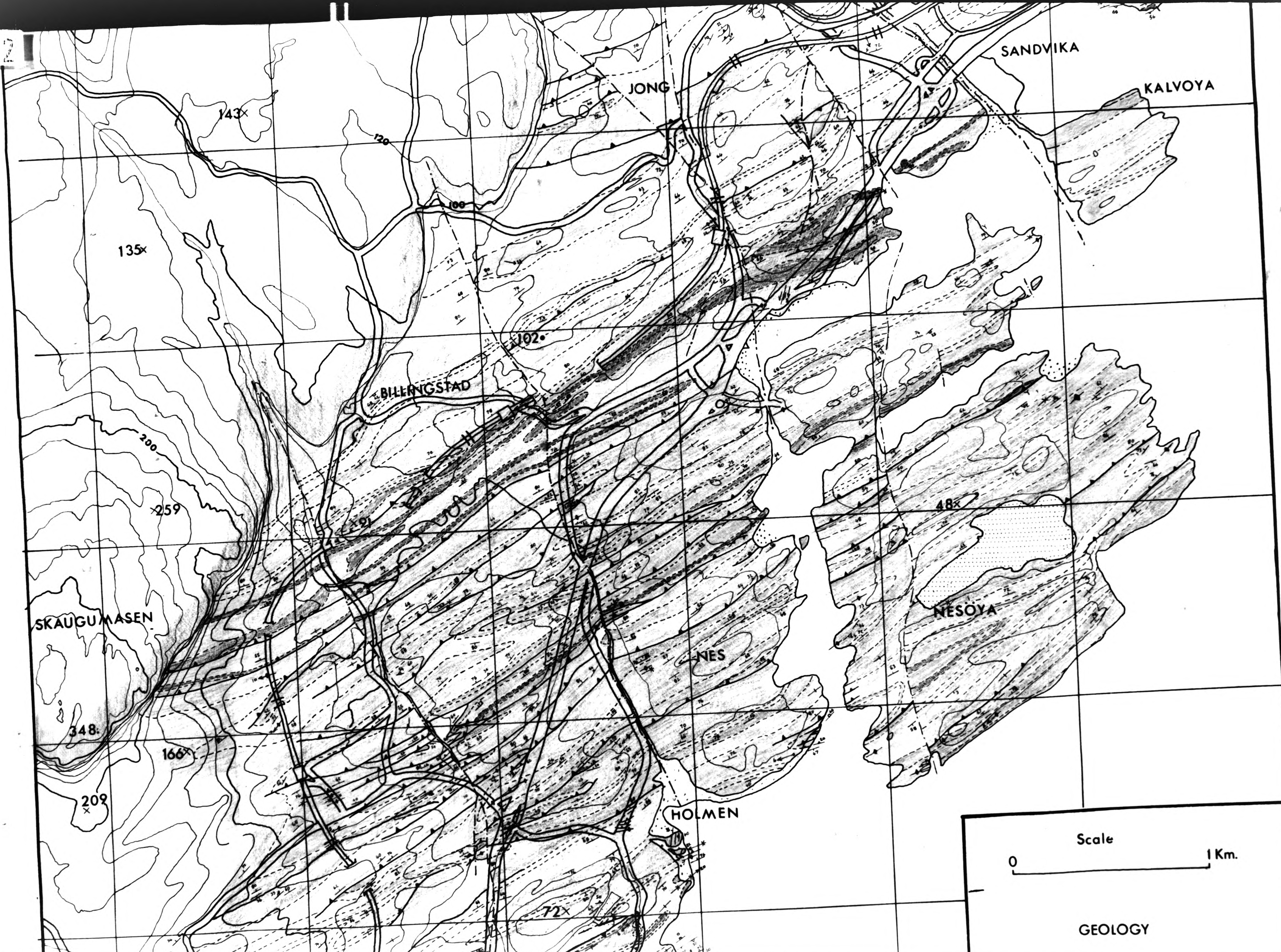
Plate 19 View westwards at Fluberg towards the Osen-Roa Thrust Sheet (forming the hillside) which is thrust over Precambrian basement.

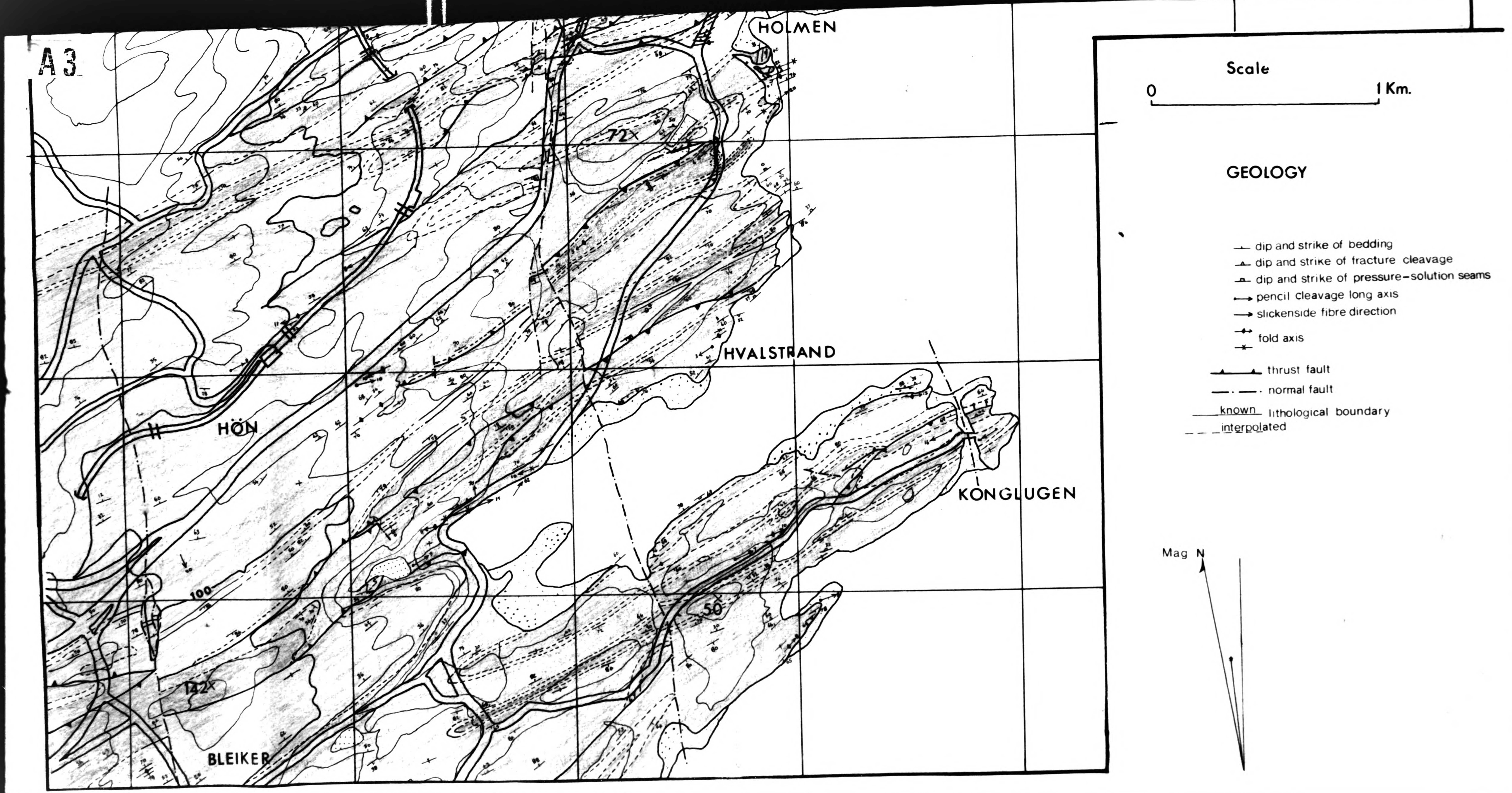
A1

ASKER — BÆRUM



A2


SANDVIKA
KALVOYA
JONG
143
120
100
135
102
BILLINGSTAD
200
259
91
48
SKAUGUMASEN
NESOYA
NES
348
166
209
HOLMEN
72
Scale
0
1 Km.
GEOLOGY



A3
HOLMEN
HVALSTRAND
HÖN
KONGLUGEN
BLEIKER
Scale
0
1 Km.
GEOLOGY
dip and strike of bedding
dip and strike of fracture cleavage
dip and strike of pressure-solution seams
pencil cleavage long axis
slickenside fibre direction
fold axis
thrust fault
normal fault
known lithological boundary
interpolated
Mag N

A1

1815 I GRAN

GE - NORWAY 1:50000

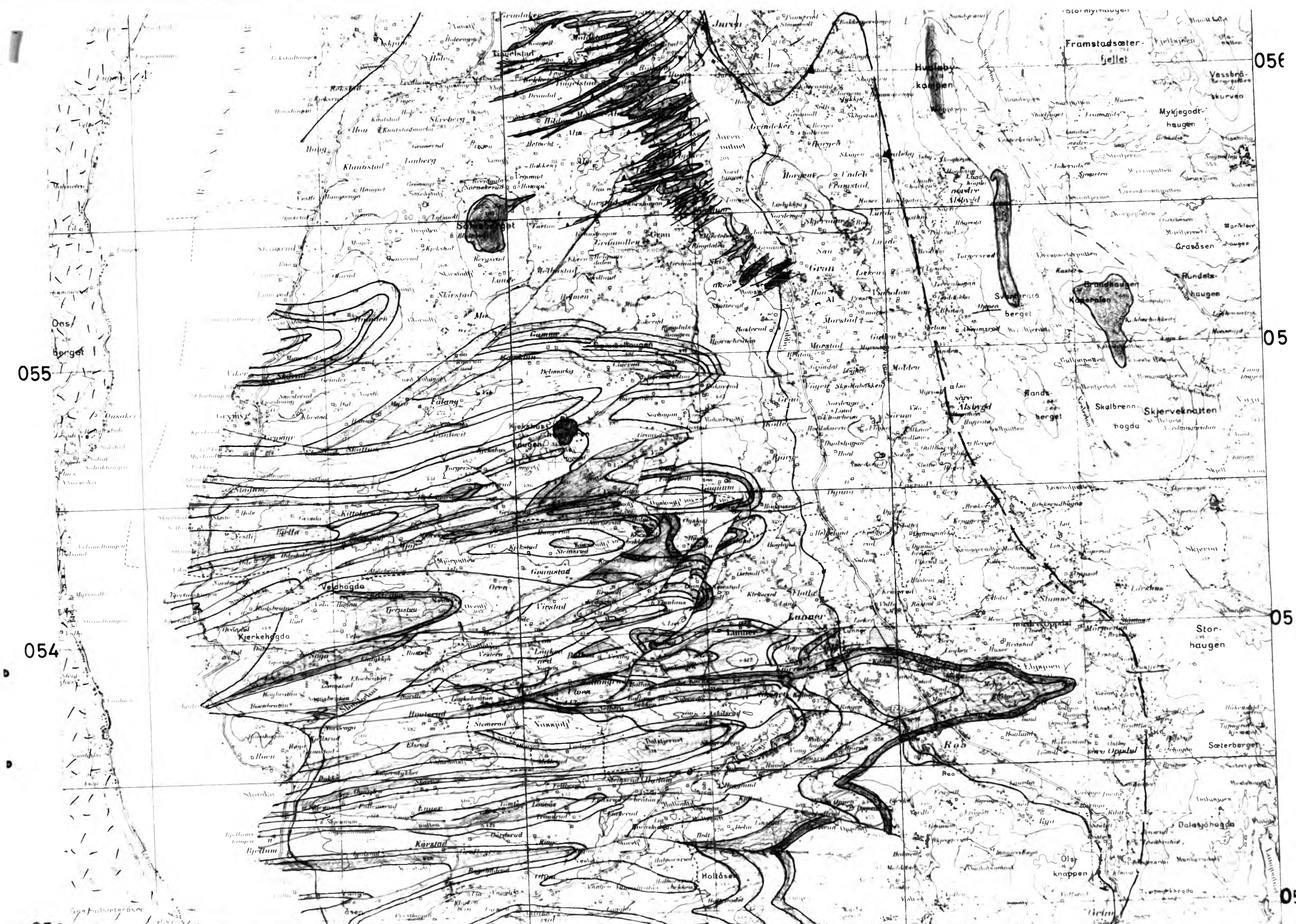
A1

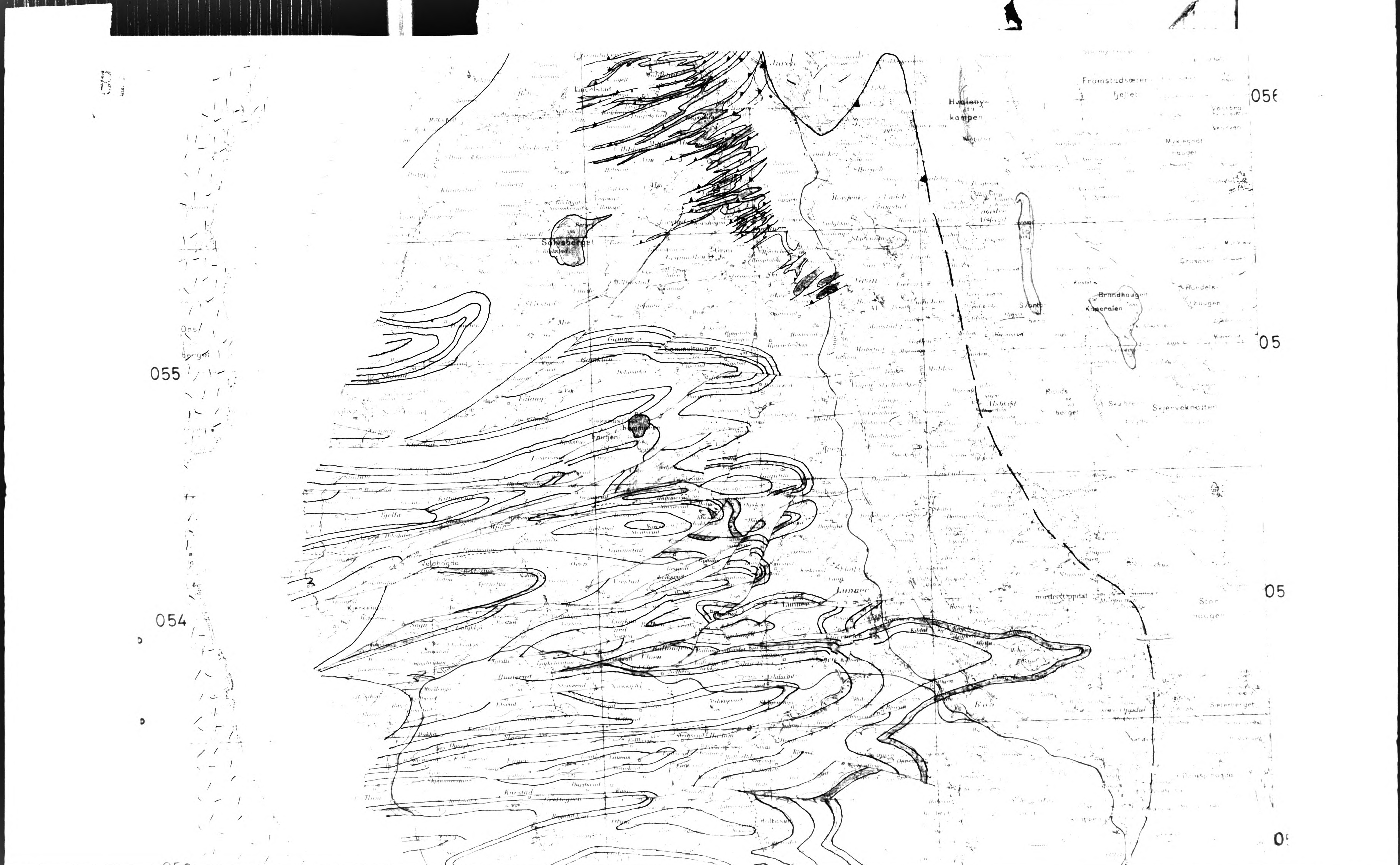
1815 I

1815 I GRAN

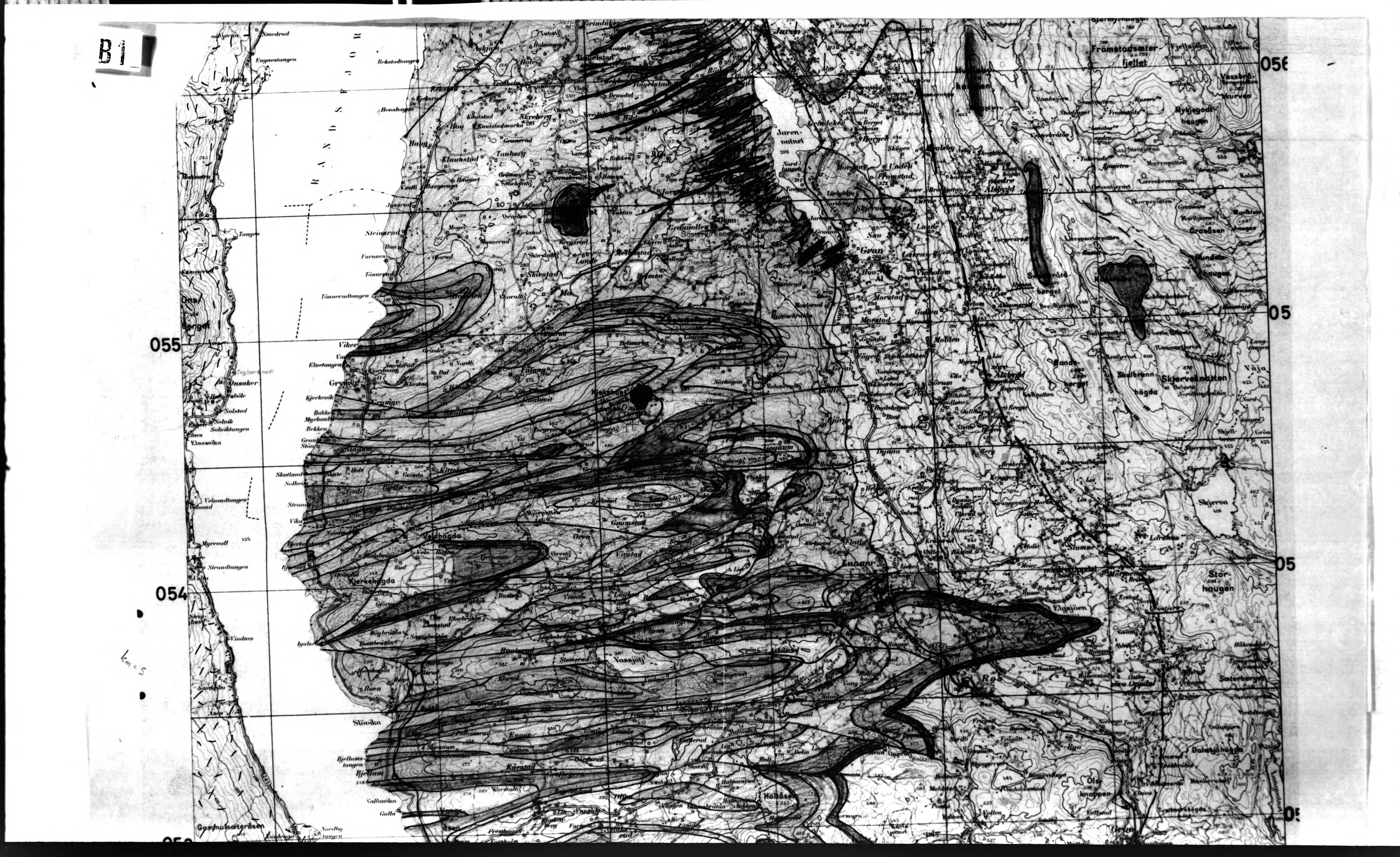
GE - NORWAY 1:50 000

B1

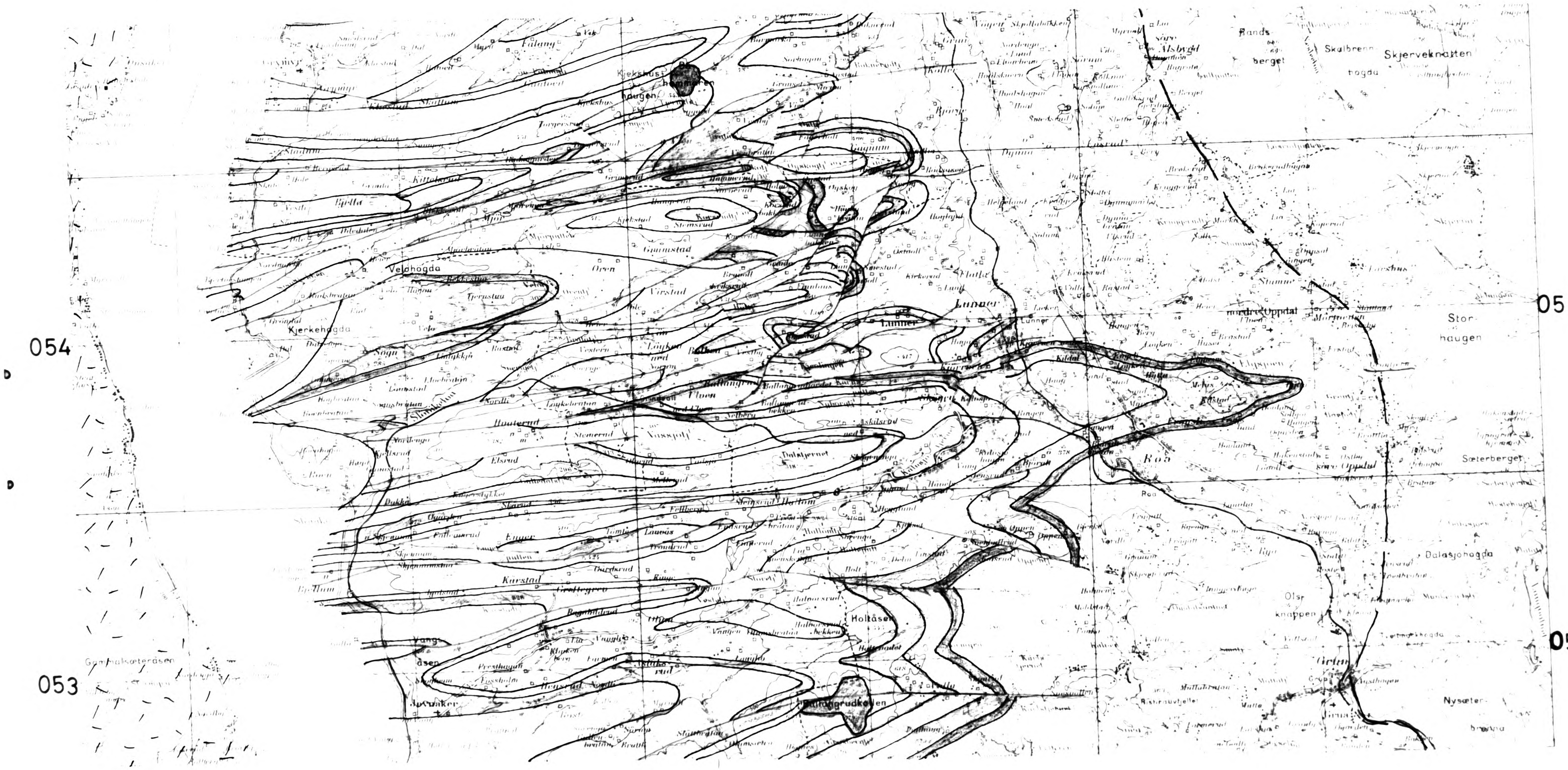

056
055
054
Ons/
berget
Framstadsæter-
fjellet
Vassbrå-
skurven
Mykjegodt-
haugen
Grasåsen
Rundals-
haugen
Rands-
berget
Skalbrenn-
hogda
Stor-
haugen
Ols-
knappen
Kjerkehogda
Veldhogda
Gran
Lunner
Roa
Hollåsen



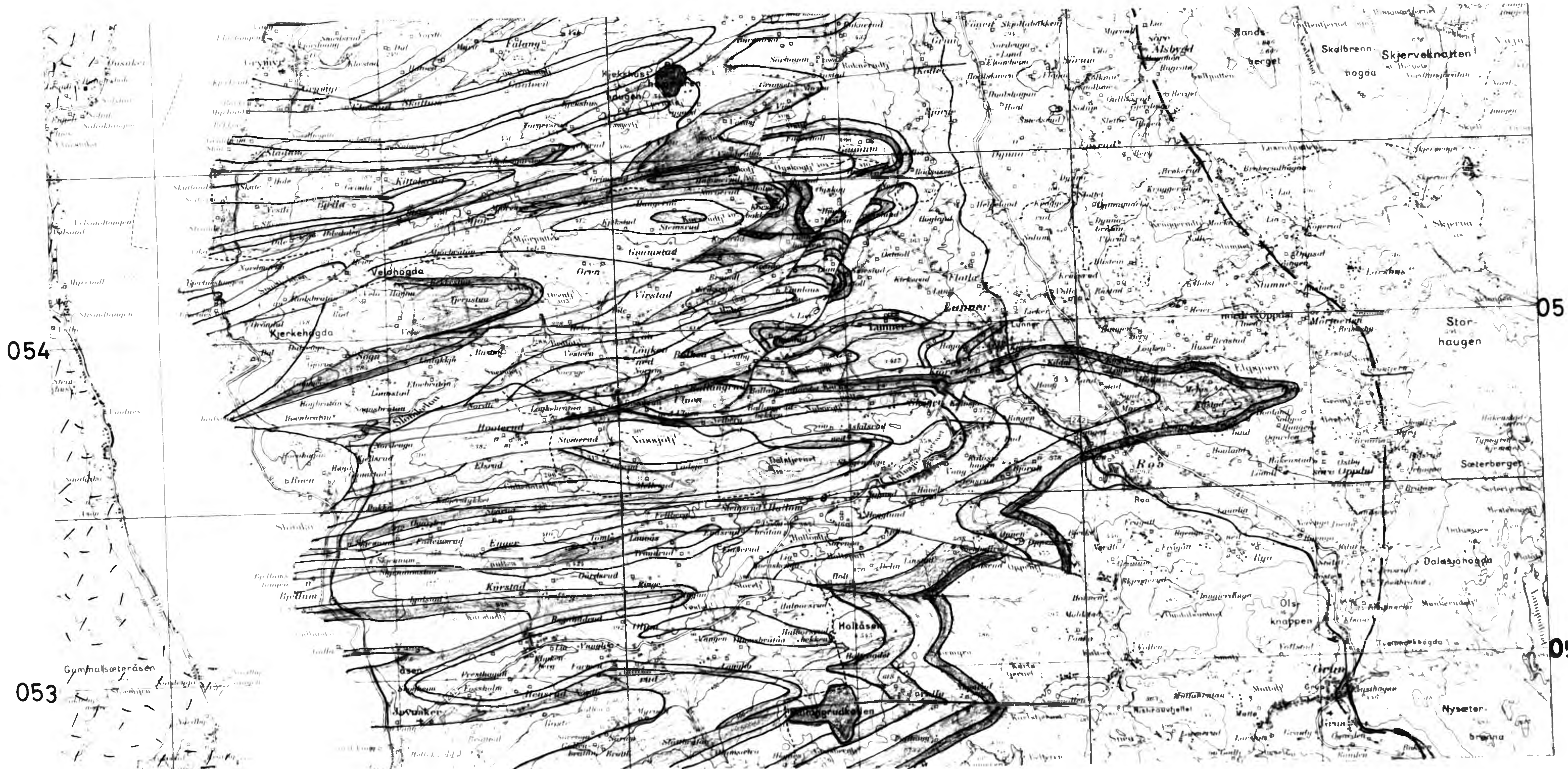
056
055
054
Sølvberget
Hvaleby-kampen
Framstadsæter
Brandhaugen
Skjerveknatten


B1
056
055
054
05
Gran
Jaren
Randsfjorden
Framstadsæter-fjellet
Skjervelknatten
Skjerva
Storhaugen
Kjerkehøgda
Vardhøgda
Dalsåshøgda
Sæterbergen
Onsaker

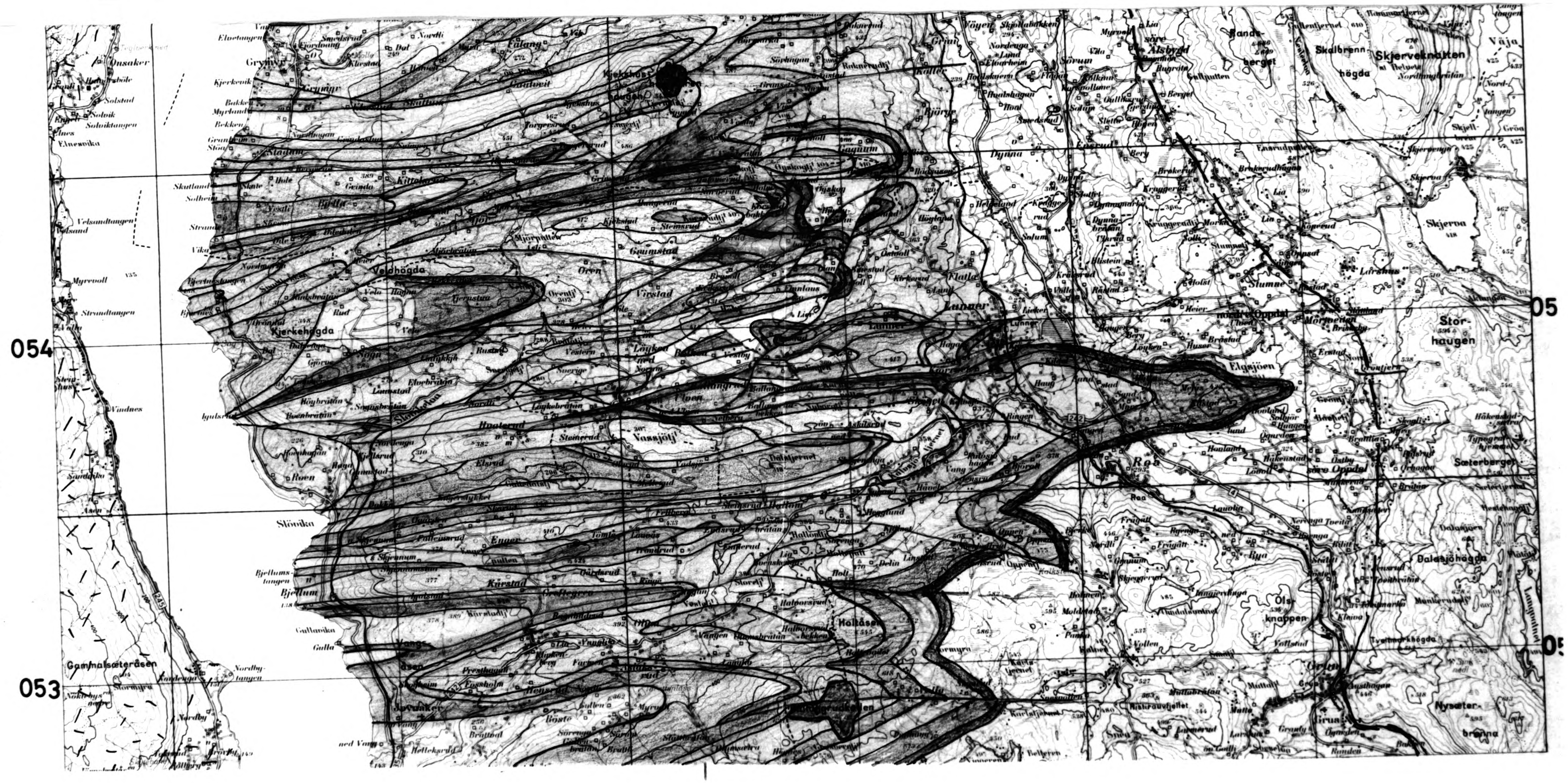
C 1


054
053
05
Skjerveknatten
Kjerkehogda
Velohogda
Holtåsen
Sæterberget
Dalasjøhogda

G1



C 1


054
053
05
Skjervekollen
Skjerva
Storhaugen
Kjerkehøgda
Gammalsæteråsen
Sæterberget
Dalesjøhøgda

A1

ASKER

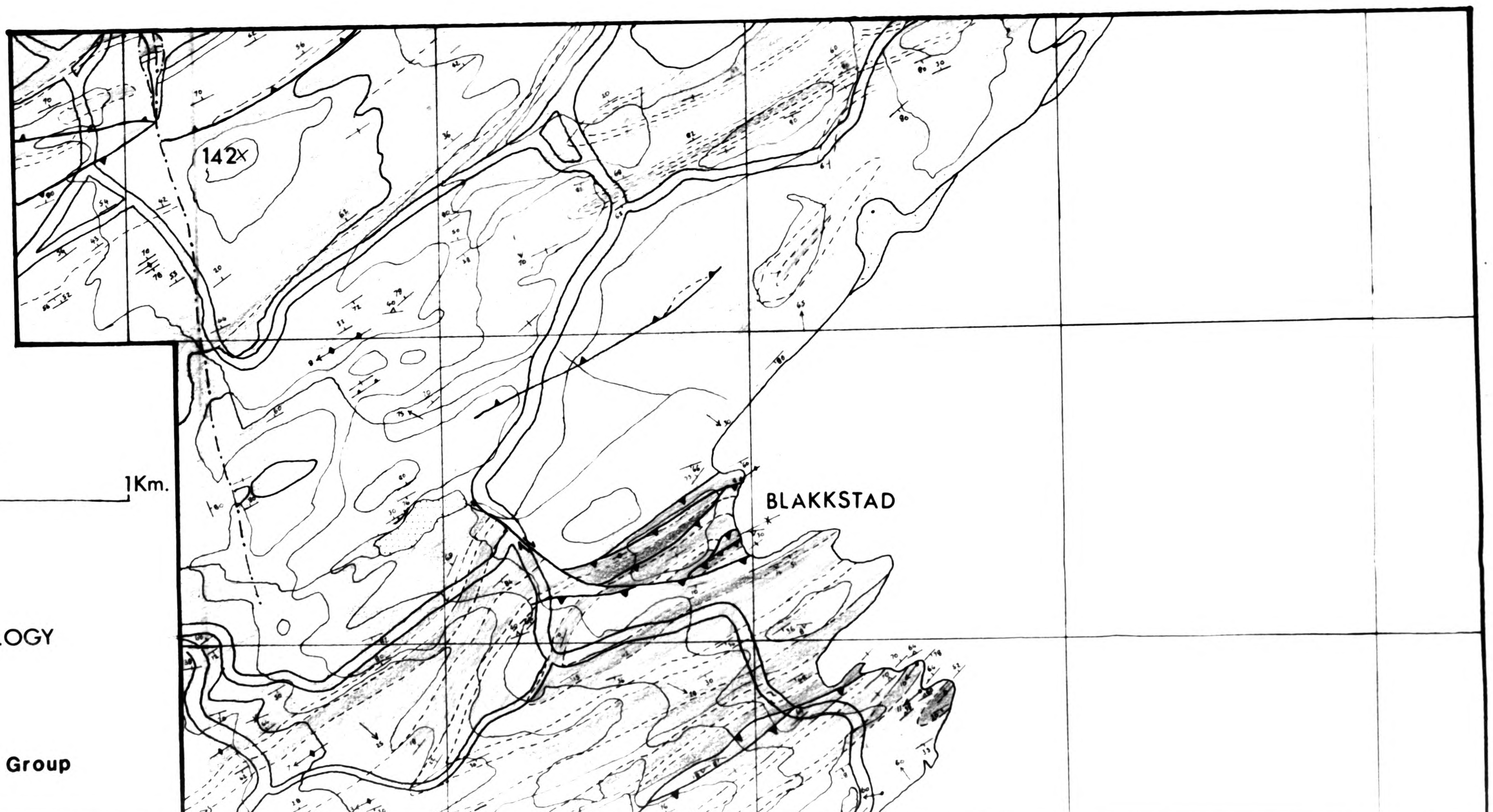
Scale

0 1Km.

GEOLOGY

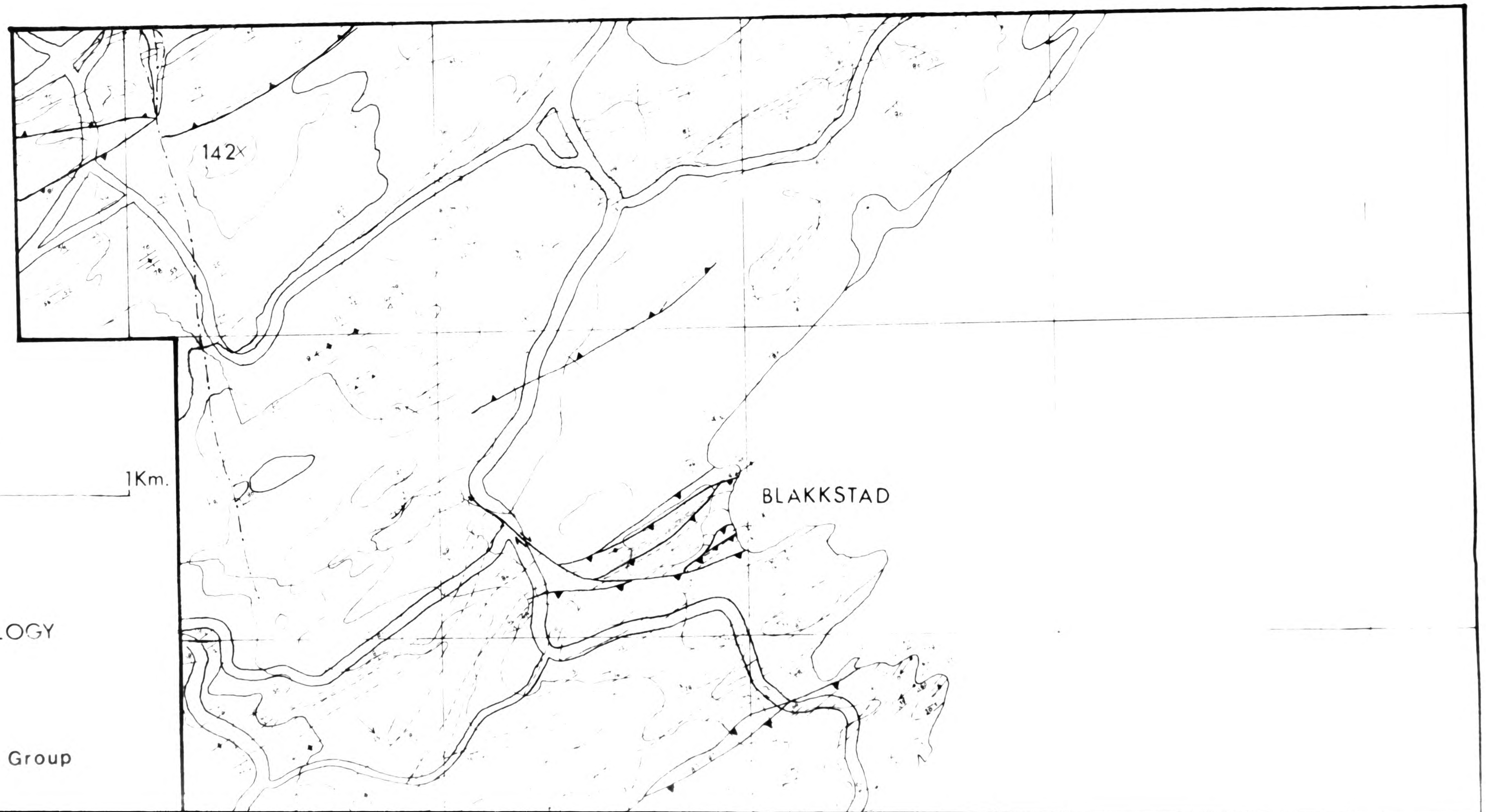
Asker Group

Stages



A1

ASKER



Scale

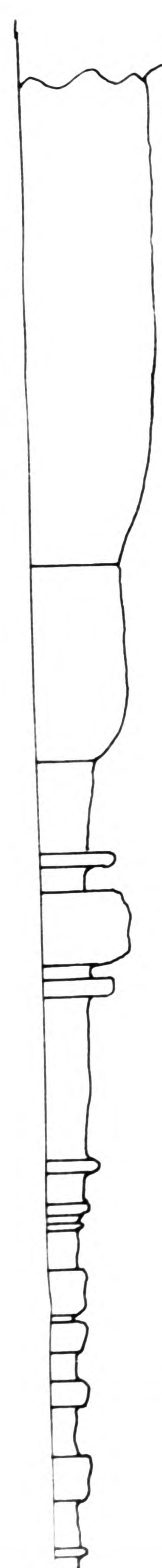
0 1Km.

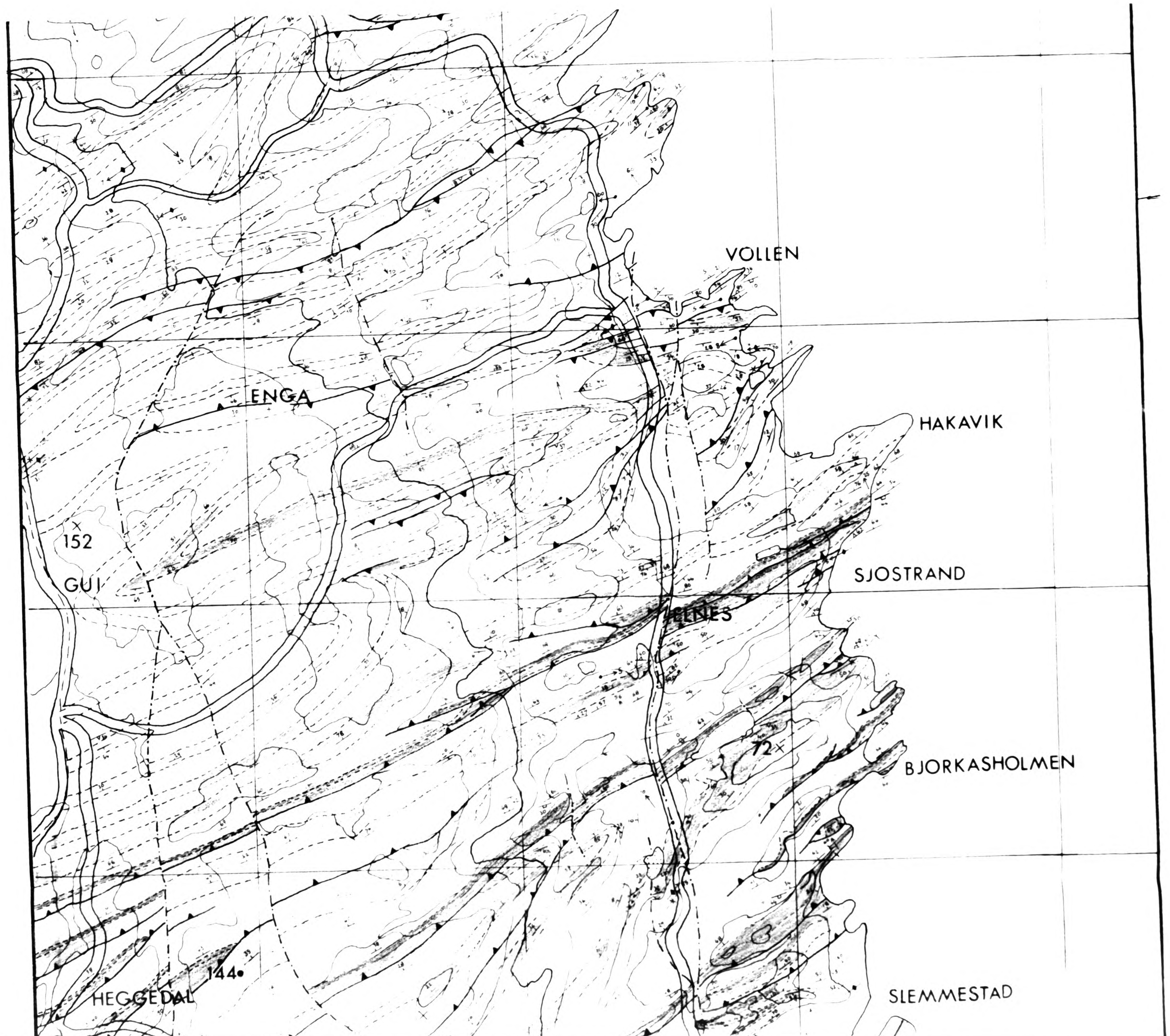
GEOLOGY

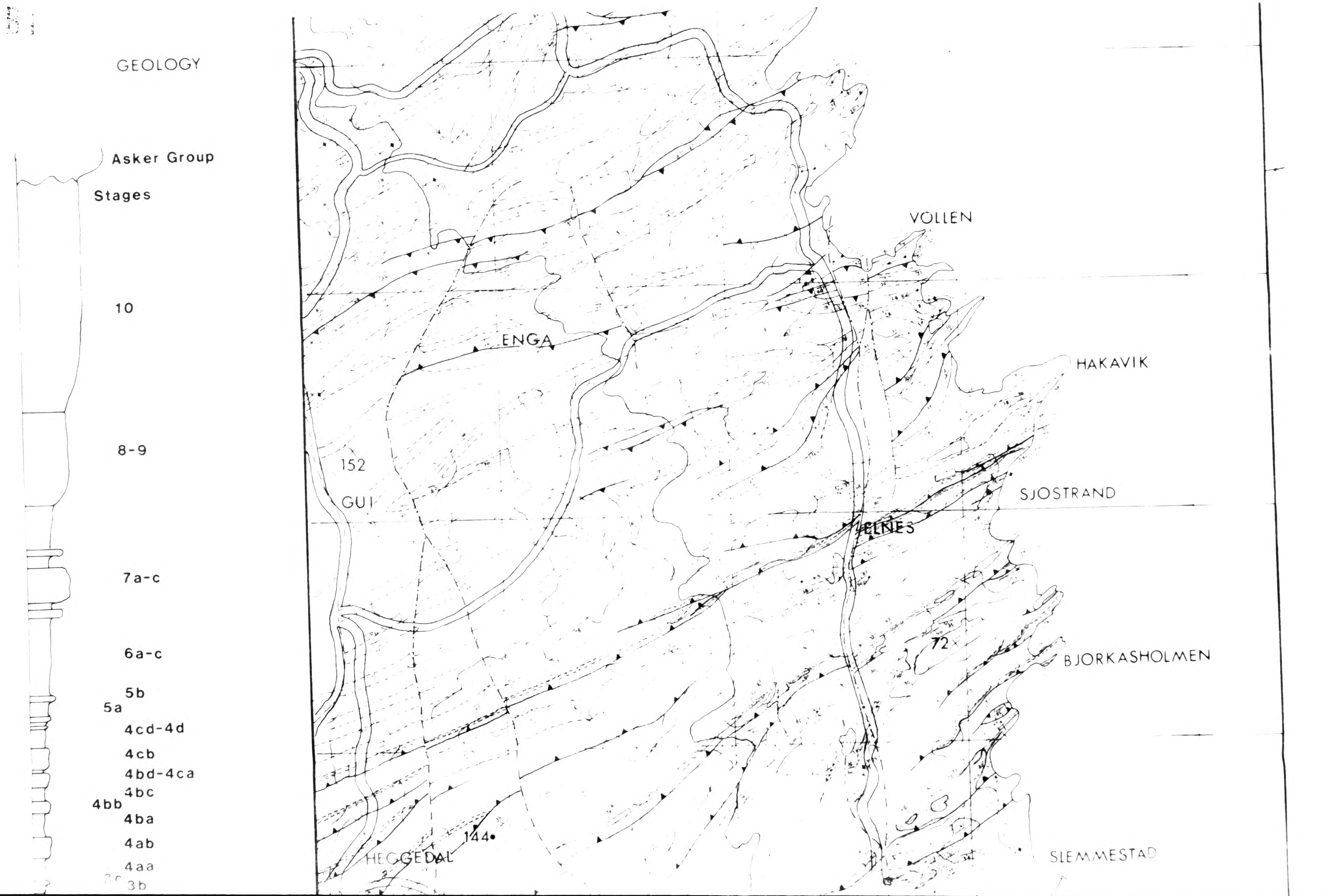
Asker Group

Stages

GEOLOGY

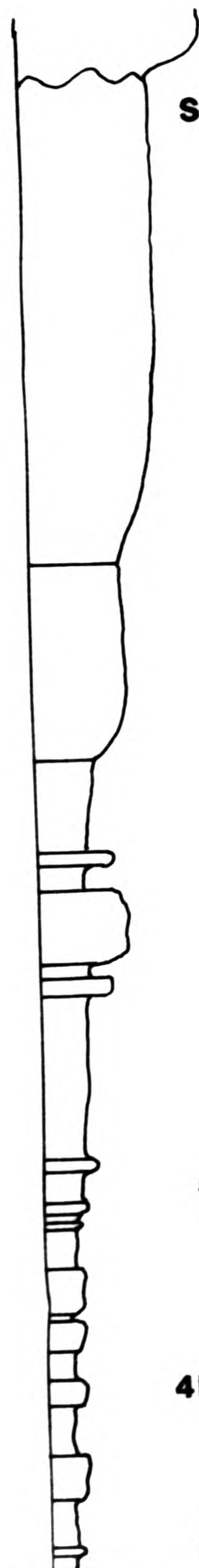

Asker Group
Stages
10
8-9
7a-c
6a-c
5b
5a
4cd-4d
4cb
4bd-4ca
4bc
4bb
4ba
4ab
4aa
3c
3b


VOLLEN
ENGA
HAKAVIK
152
GUI
SJOSTRAND
ELNES
72
BJORKASHOLMEN
144
HEGGEDAL
SLEMMESTAD


GEOLOGY
Asker Group
Stages
10
8-9
7a-c
6a-c
5b
5a
4cd-4d
4cb
4bd-4ca
4bc
4bb
4ba
4ab
4aa
3b
VOLLEN
ENGA
HAKAVIK
152
GUI
SJOSTRAND
ELNES
72
BJORKASHOLMEN
144
HEGGEDAL
SLEMMESTAD

B1

GEOLOGY



Asker Group
Stages
10
8-9
7a-c
6a-c
5b
5a
4cd-4d
4cb
4bd-4ca
4bc
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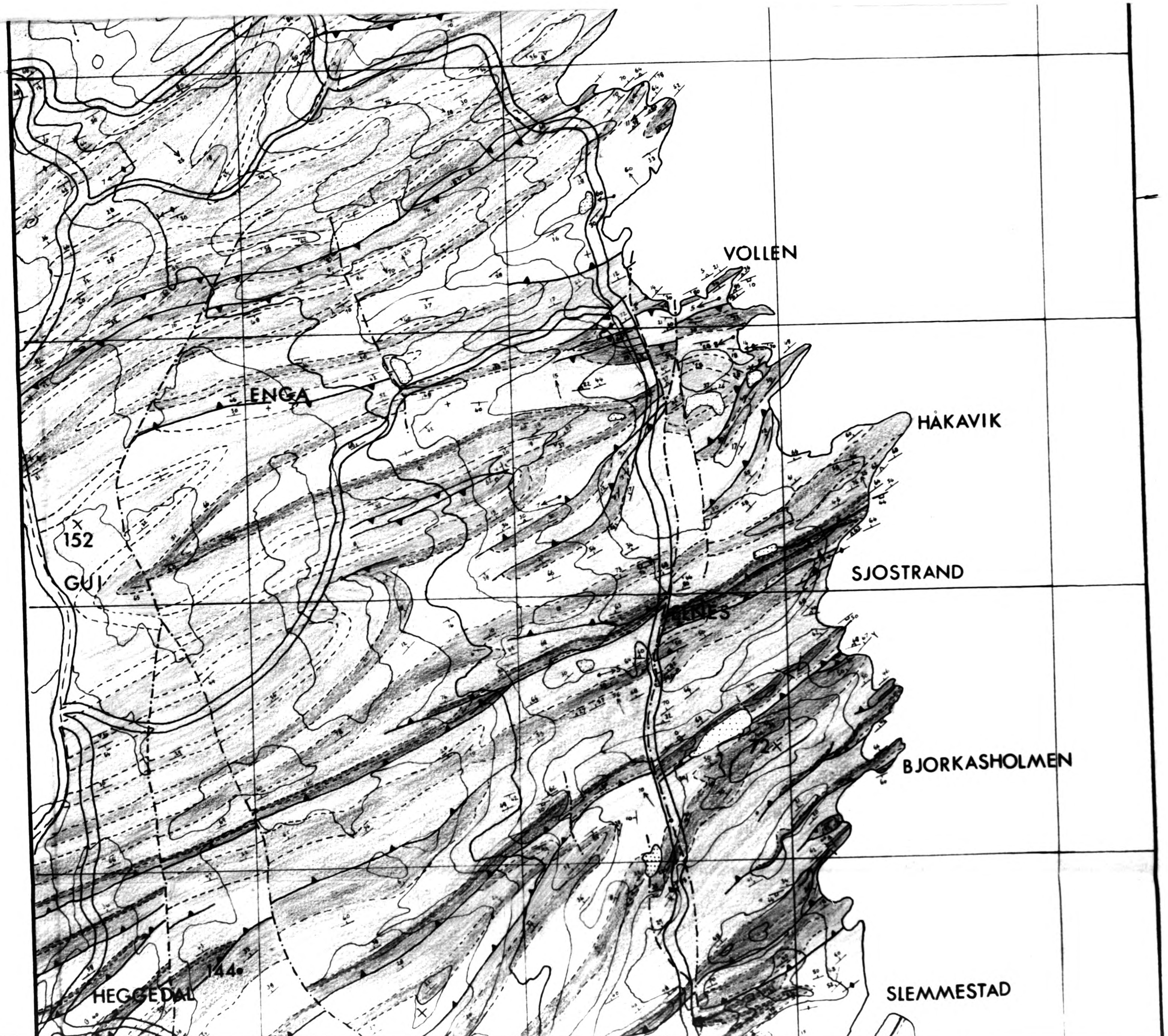
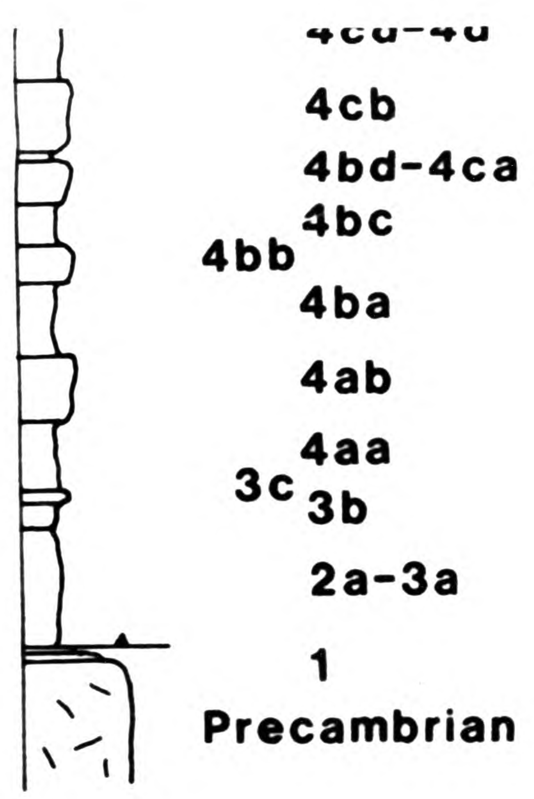
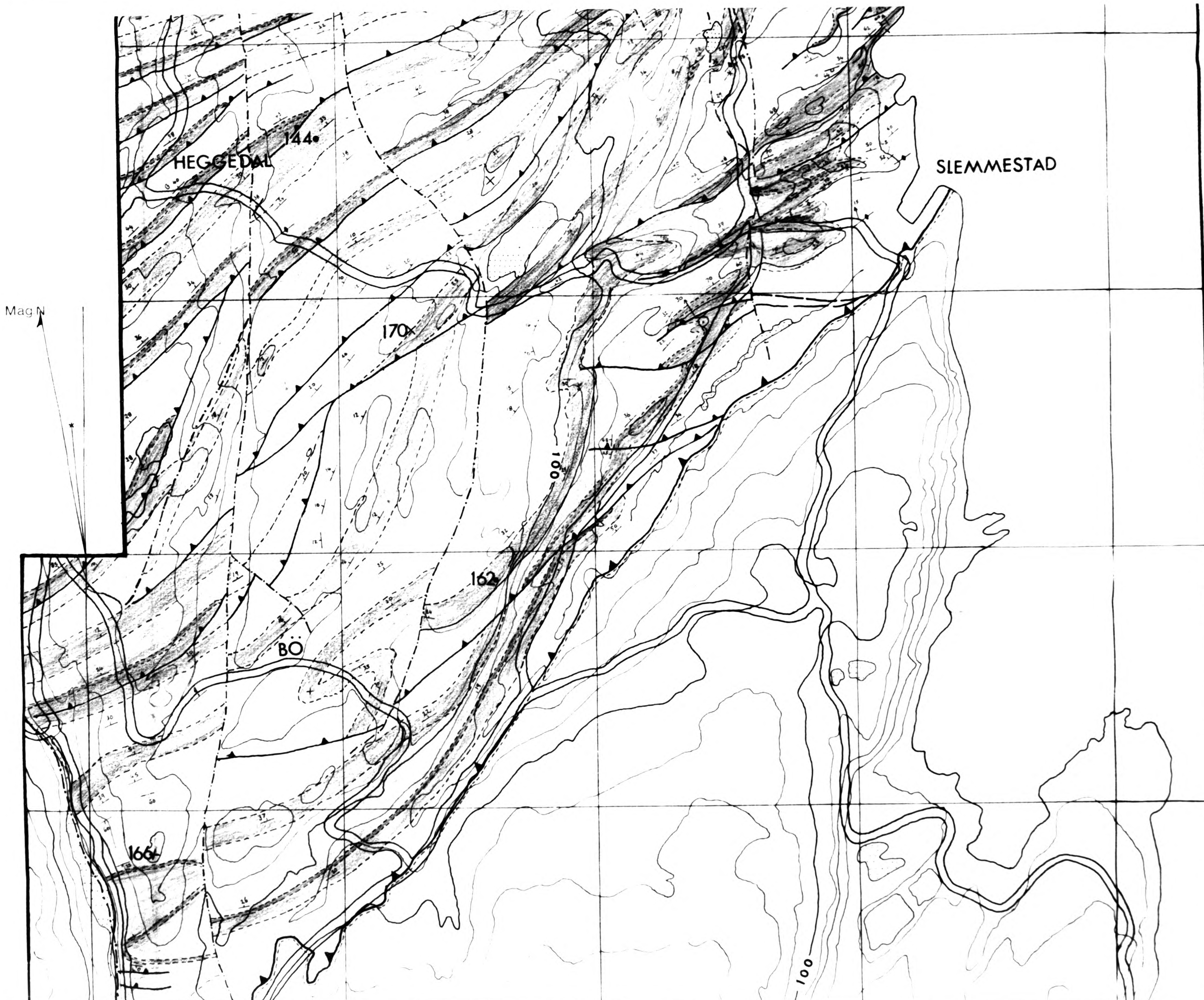
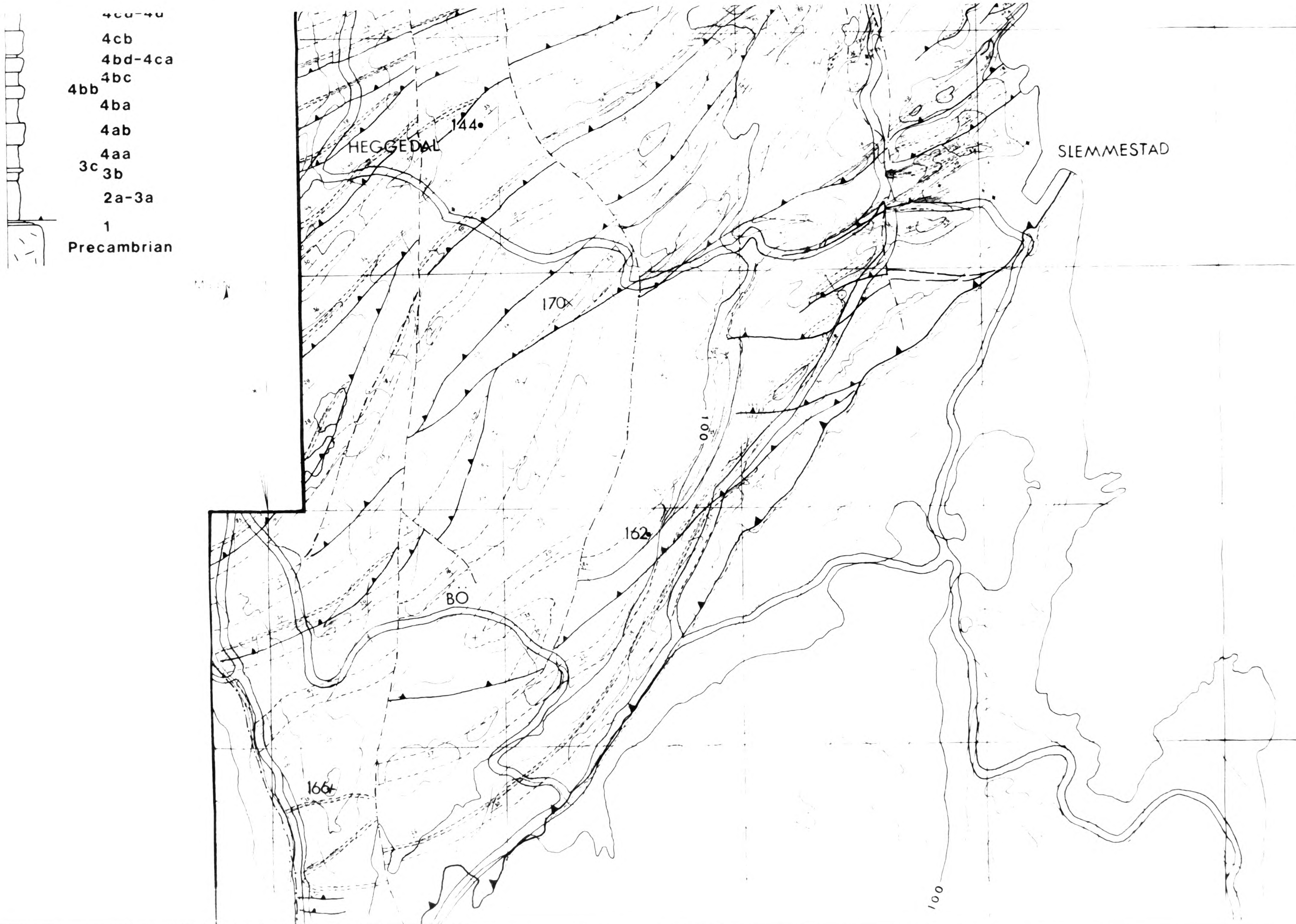
4ab
4aa
3c
3b



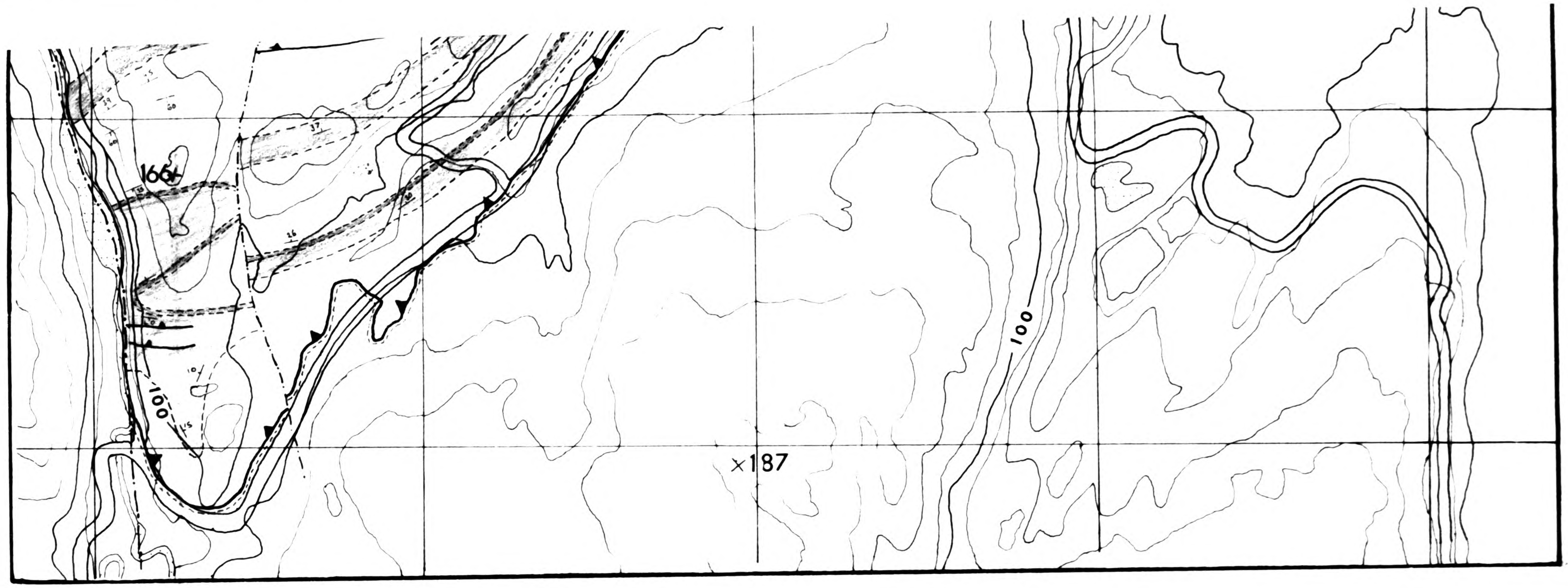
VOLLEN
ENGA
HÅKAVIK
152
GUI
SJOSTRAND
BJORKASHOLMEN
144
HEGGEDAL
SLEMMESTAD


4cd-4d
4cb
4bd-4ca
4bb
4bc
4ba
4ab
4aa
3c
3b
2a-3a
1
Precambrian

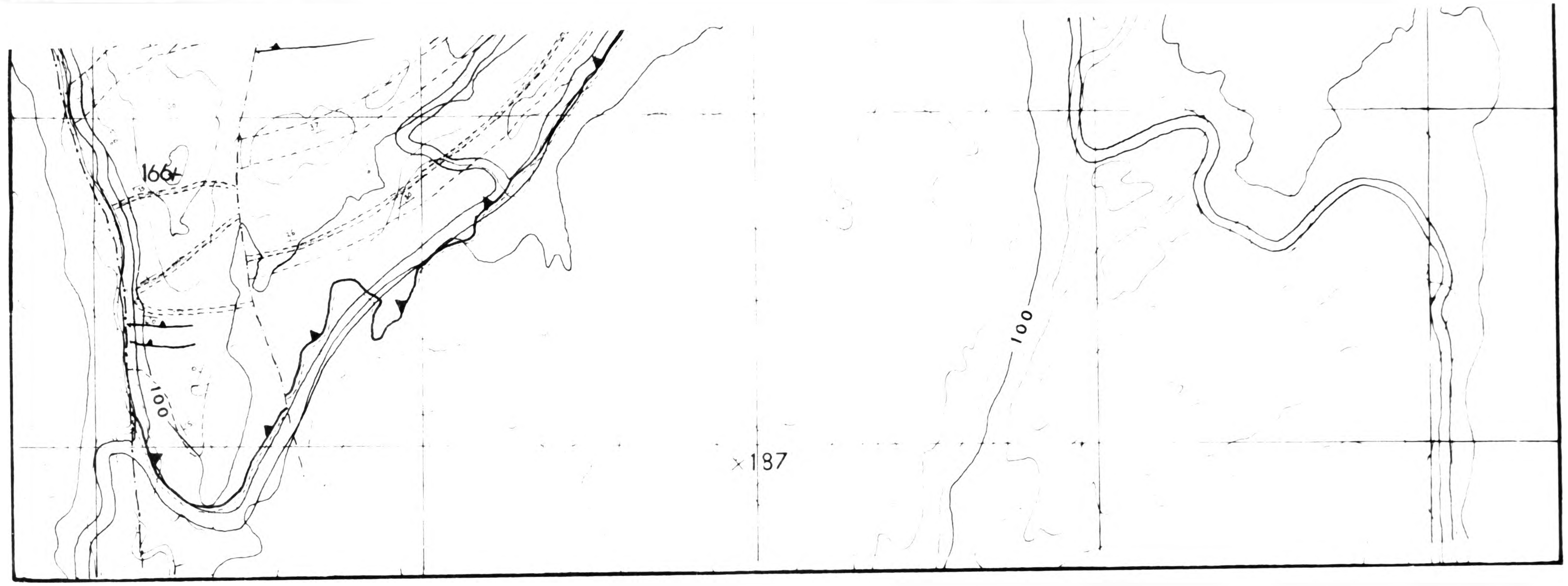

Mag N
HEGGEDAL
144
SLEMMESTAD
170
100
162
BÖ
166
100


4cb
4bd-4ca
4bc
4bb
4ba
4ab
4aa
3c
3b
2a-3a
1
Precambrian
HEGGEDAL
144
SLEMMESTAD
170
100
162
BØ
166
100

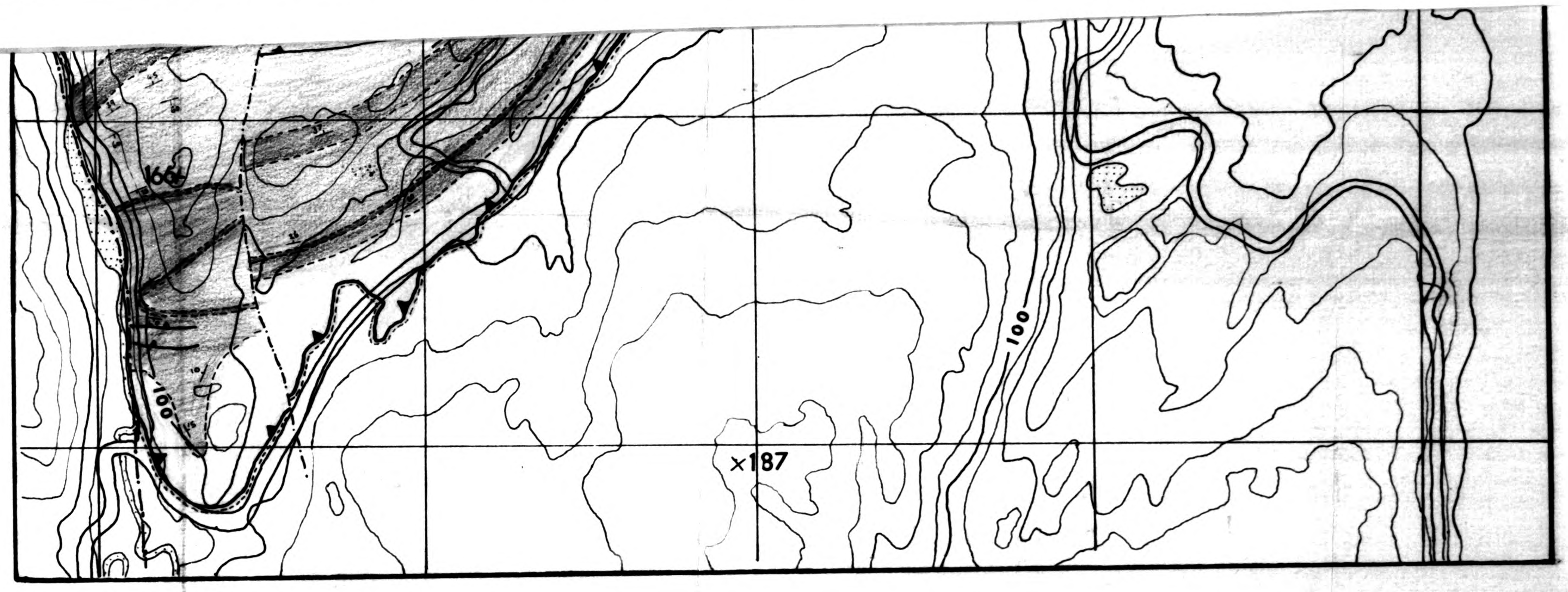
D1



D1

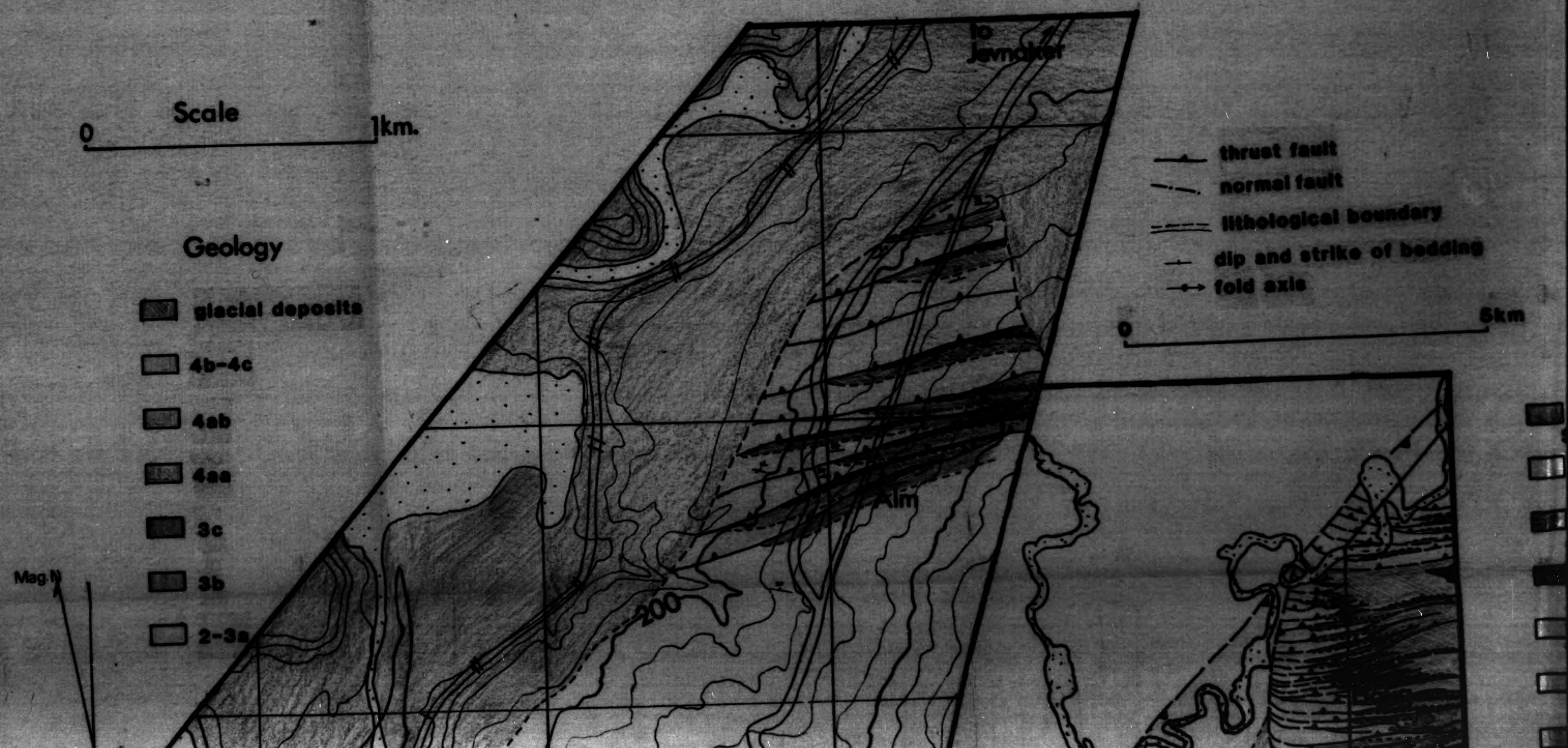


D1



A1

RINGERIKE

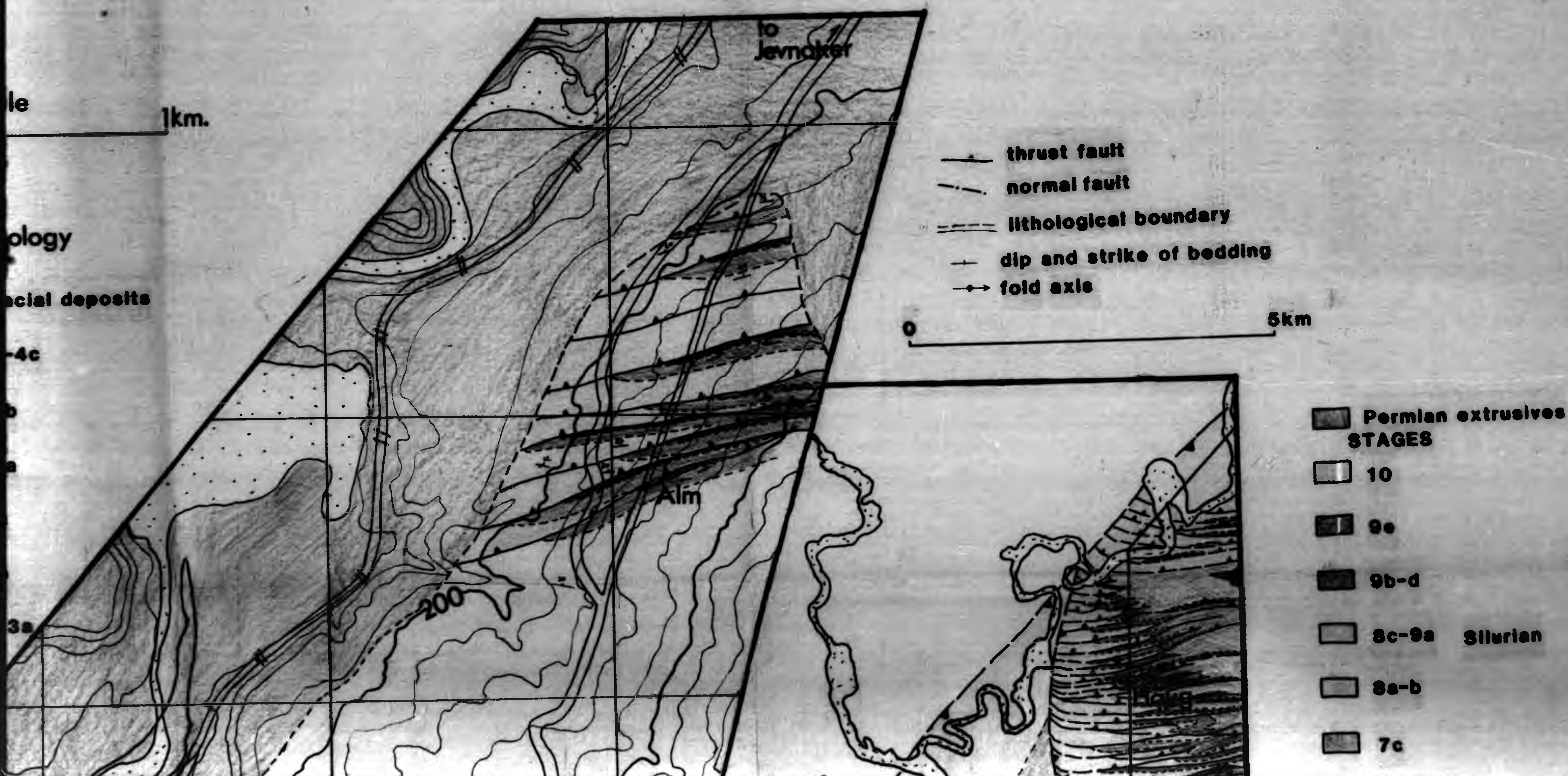


A1

RINGERIKE

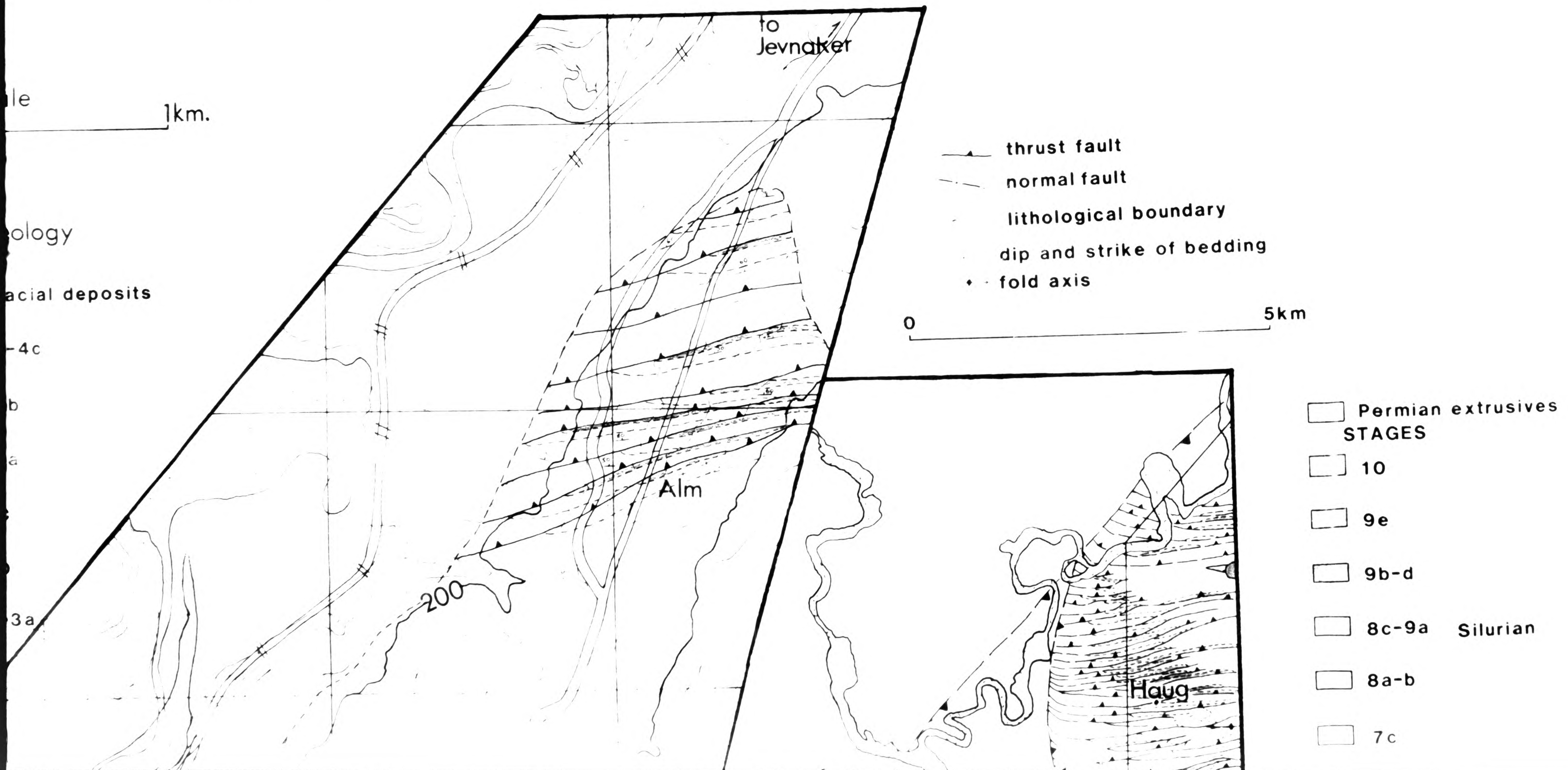
RINGERIKE

RINGERIKE



le
1km.
ology
acial deposits
-4c
3a
to Jevnaker
Alm
200
thrust fault
normal fault
lithological boundary
dip and strike of bedding
fold axis
0
5km
Permian extrusives
STAGES
10
9e
9b-d
8c-9a
Silurian
8a-b
7c

RINGERIKE



to
Jevnaker
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1km.
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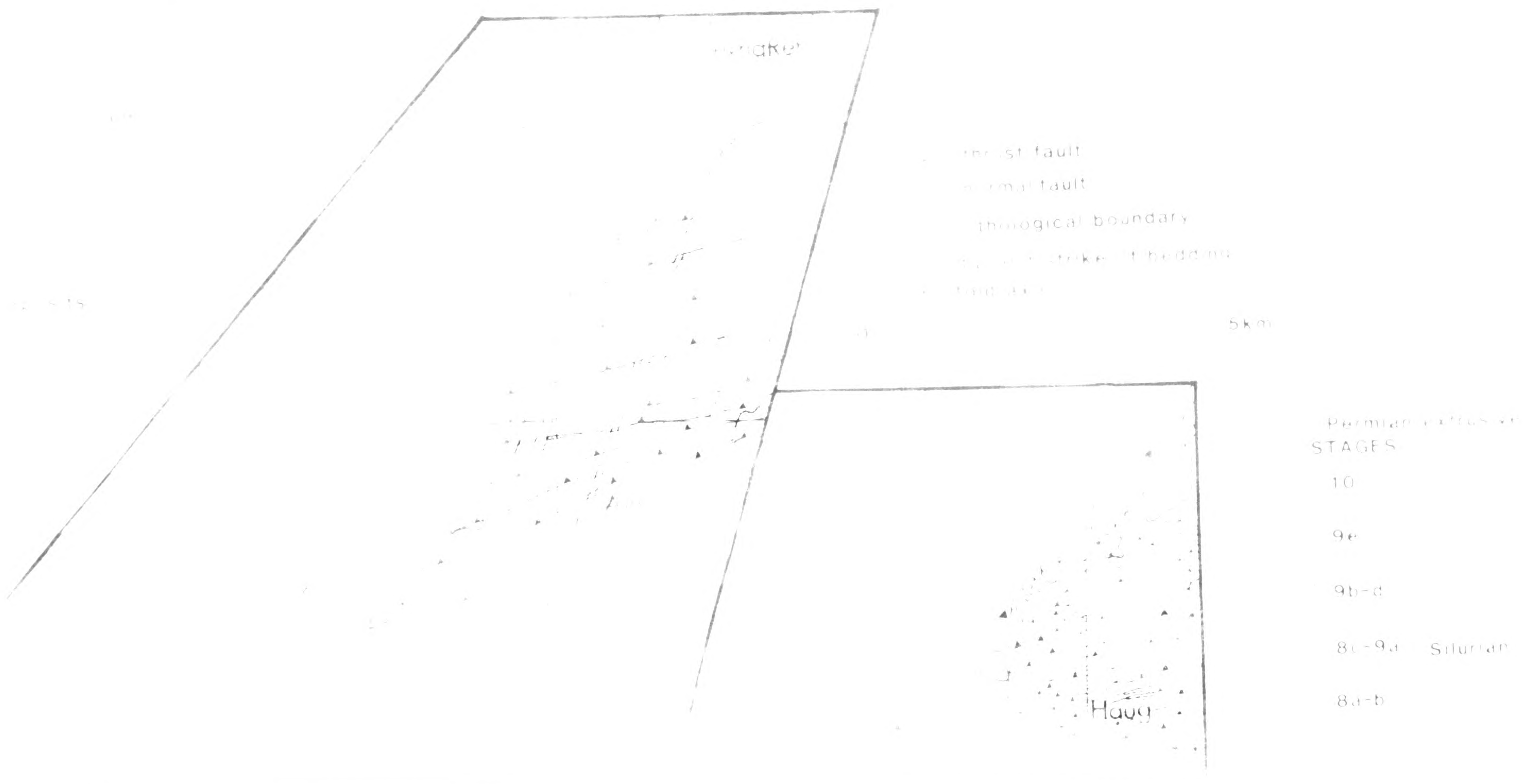
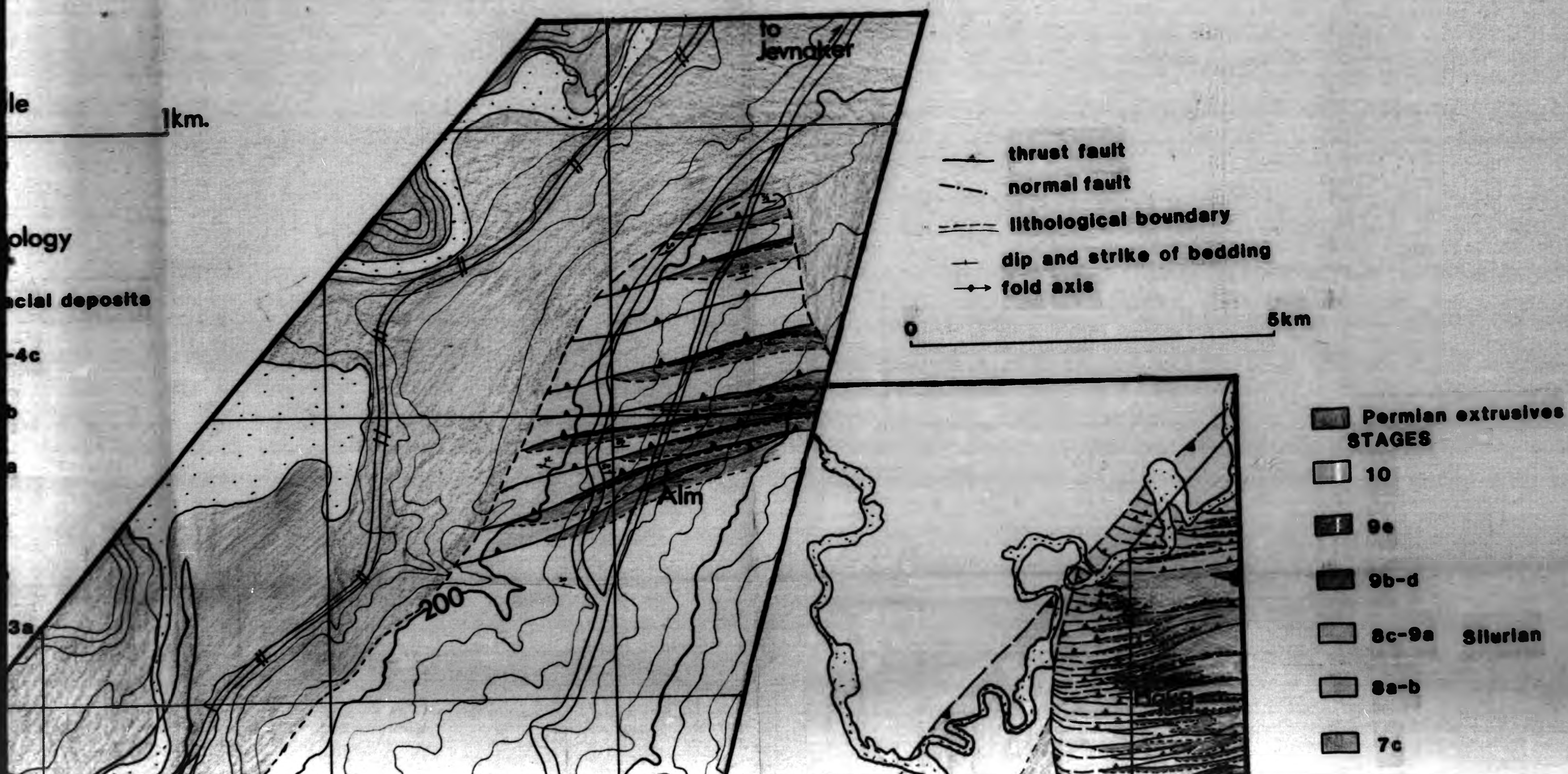
acial deposits
-4c
b
a
3a
Alm
200
Haug
thrust fault
normal fault
lithological boundary
dip and strike of bedding
fold axis
0
5km
Permian extrusives
STAGES
10
9e
9b-d
8c-9a
Silurian
8a-b
7c

RINGERIKE



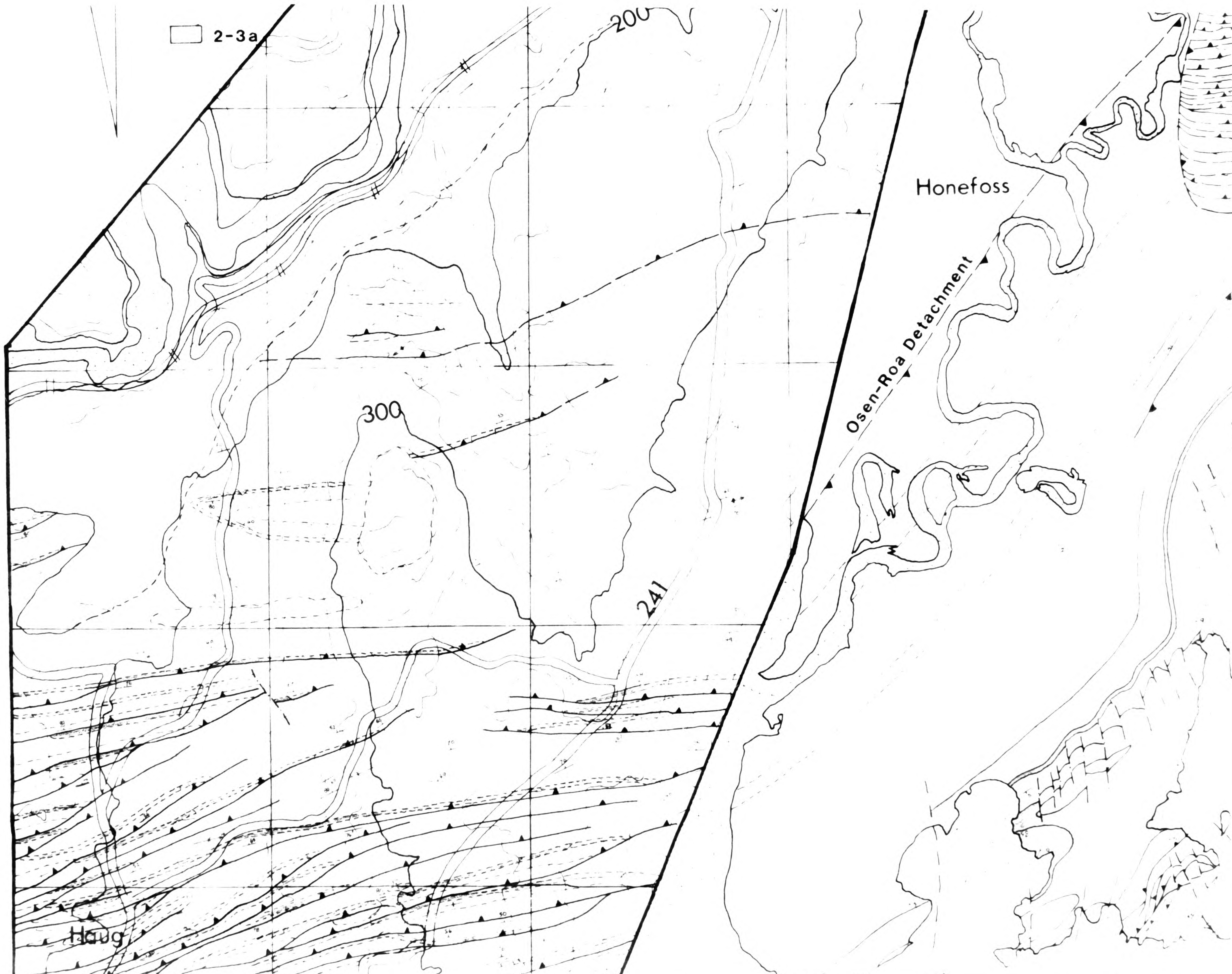
A2

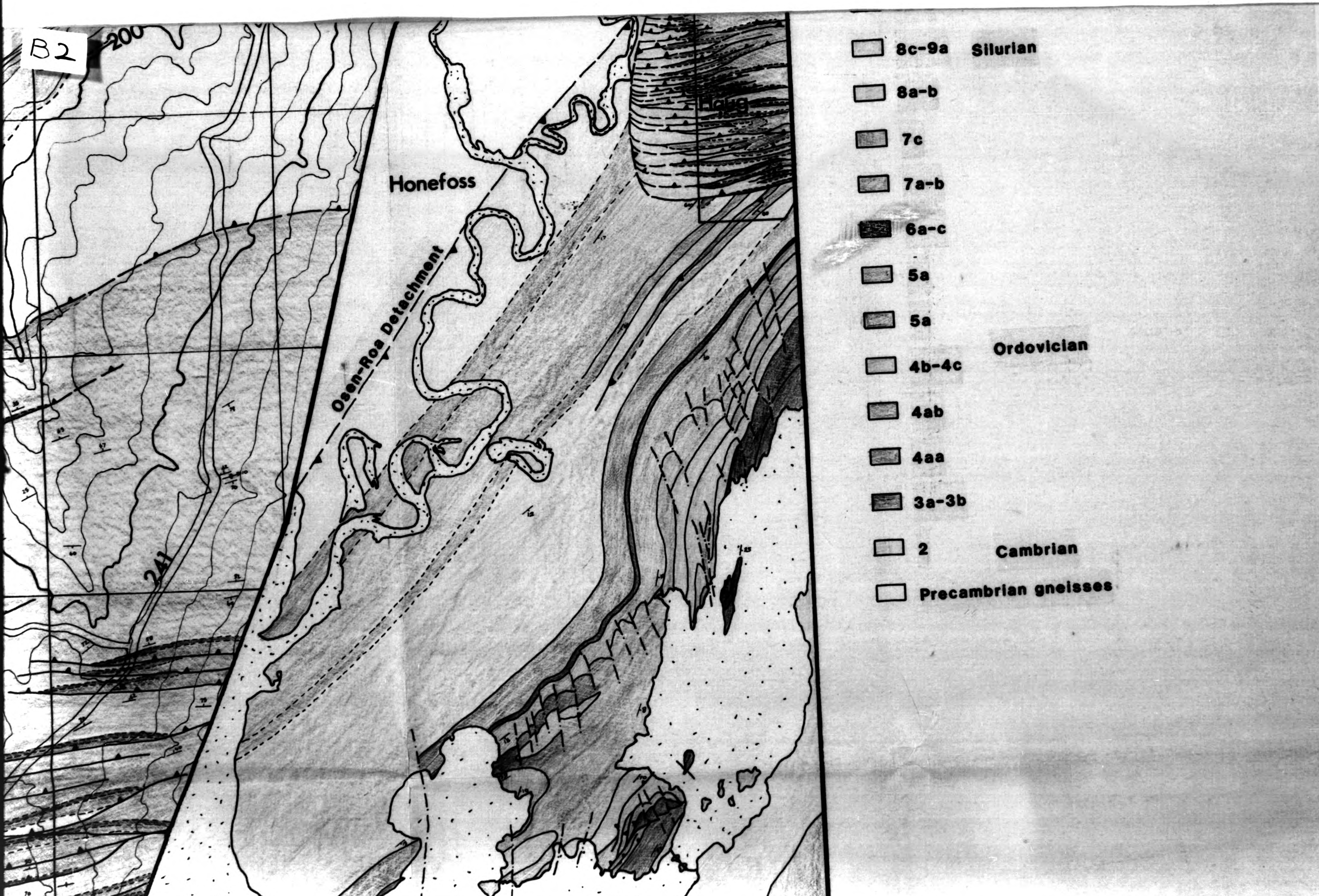
RINGERIKE

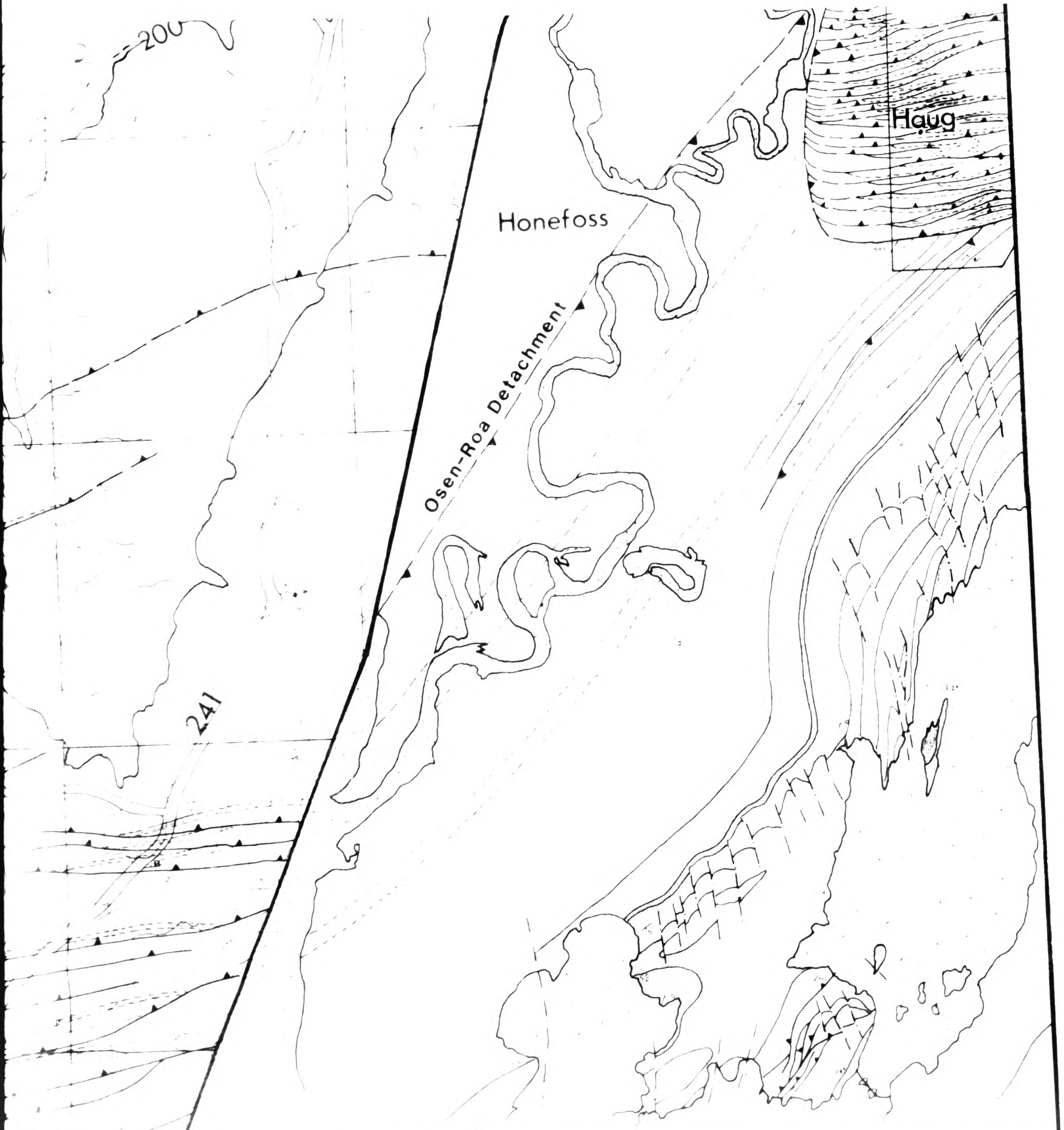


B1

B1

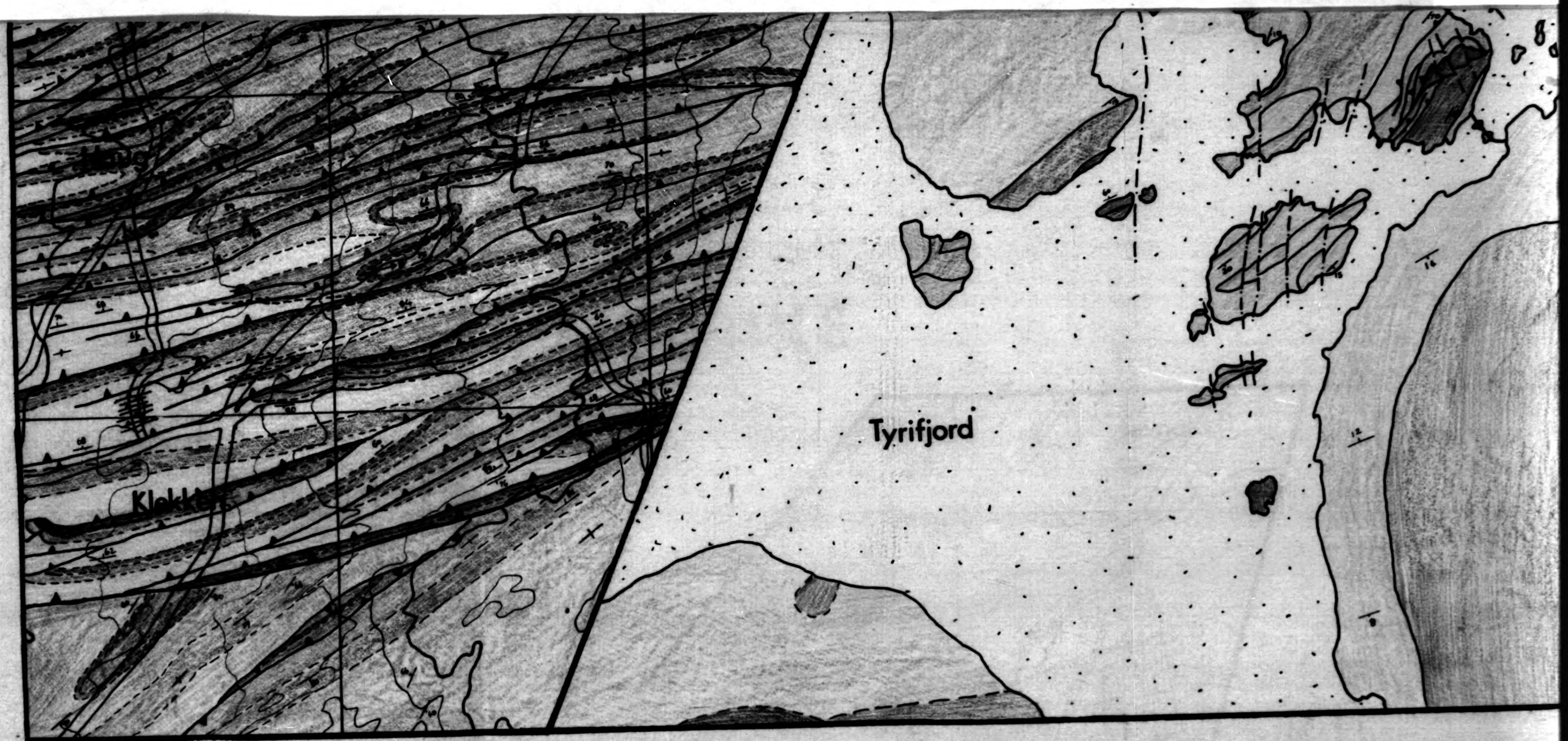



B2
200
Honefoss
Osen-Roa Detachment
241
8c-9a Silurian
8a-b
7c
7a-b
6a-c
5a
5a
Ordovician
4b-4c
4ab
4aa
3a-3b
2 Cambrian
Precambrian gneisses

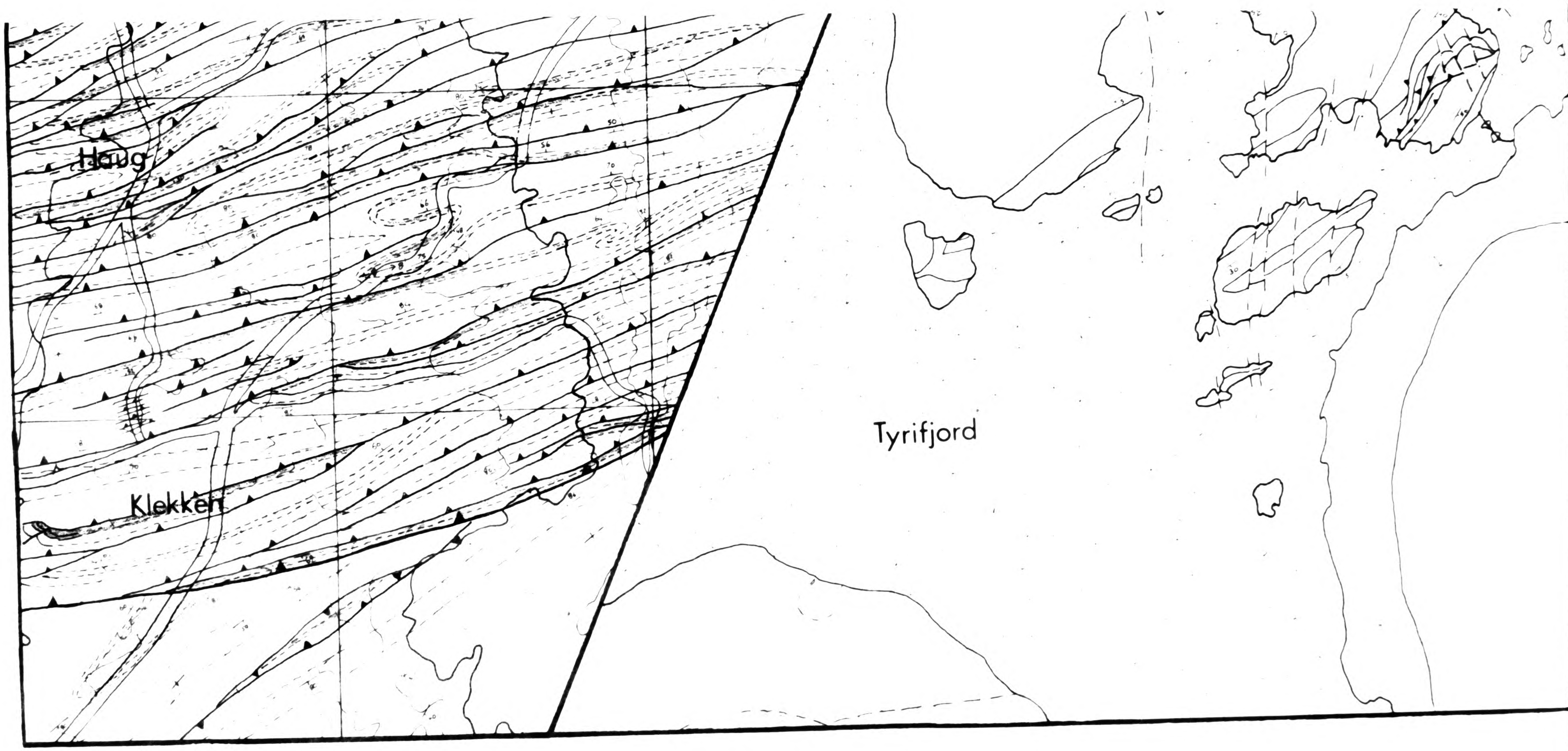


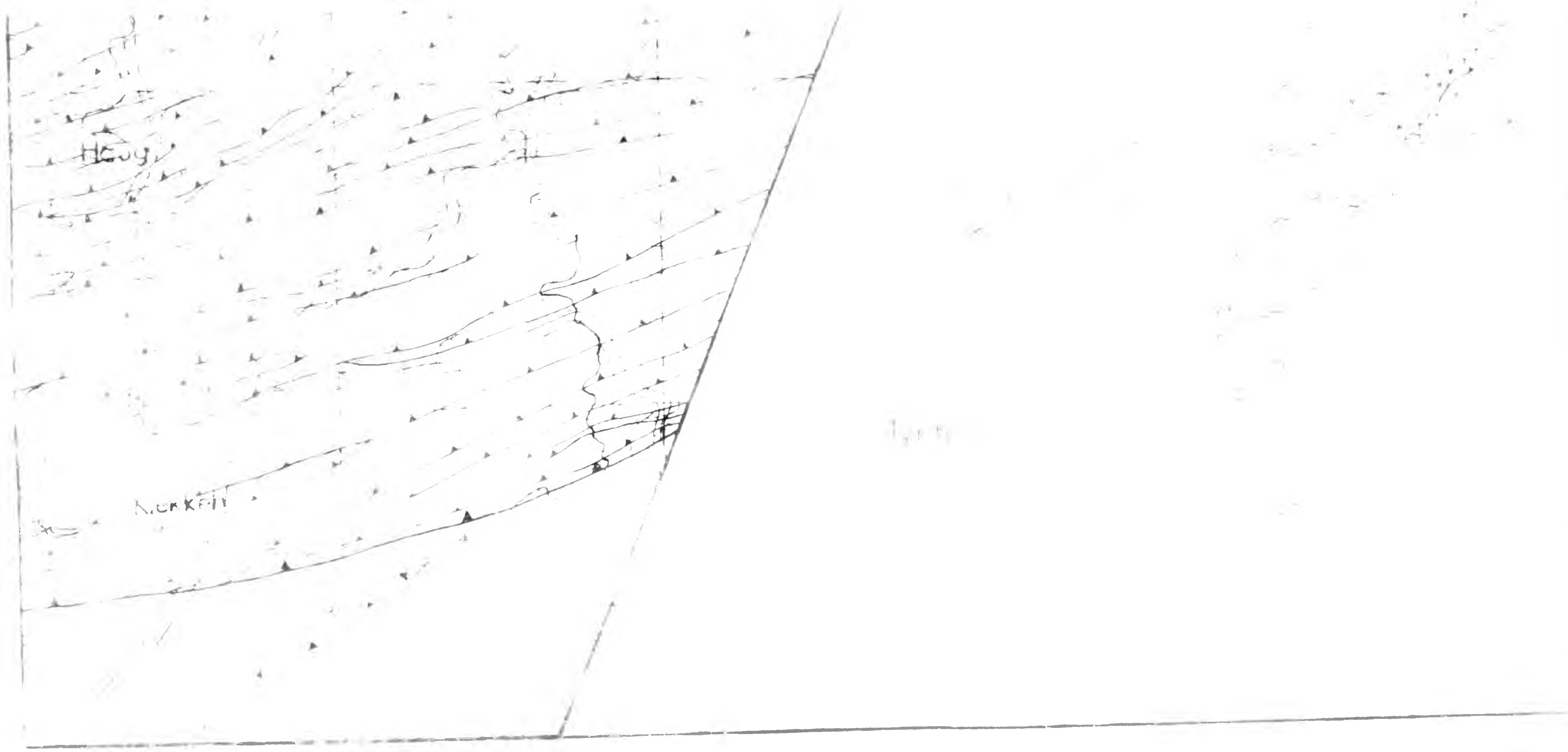
☐	8c-9a	Silurian
☐	8a-b	
☐	7c	
☐	7a-b	
☐	6a-c	
☐	5a	
☐	5a	Ordovician
☐	4b-4c	
☐	4ab	
☐	4aa	
☐	3a-3b	
☐	2	Cambrian
☐	Precambrian gneisses	

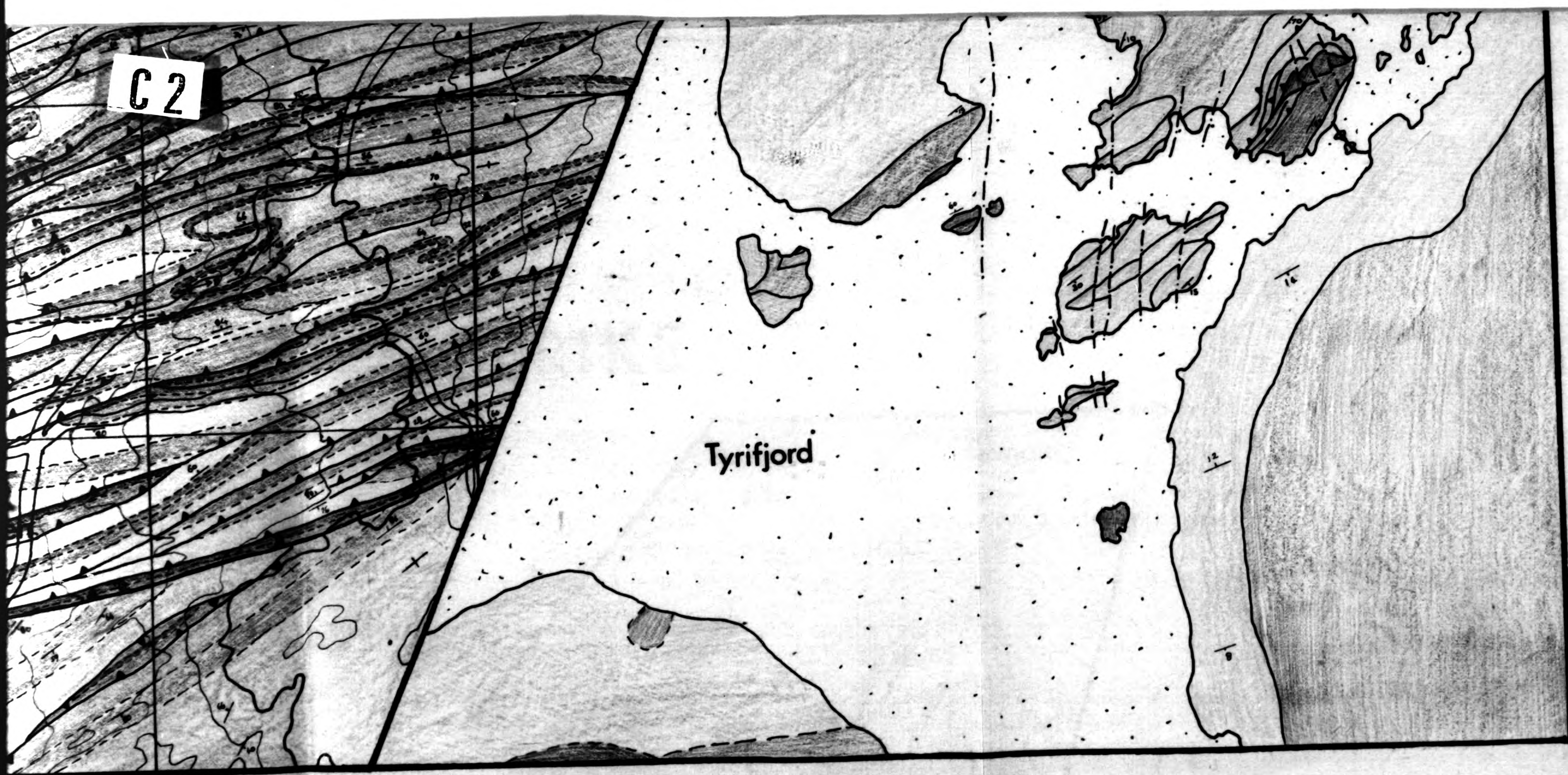
C 1



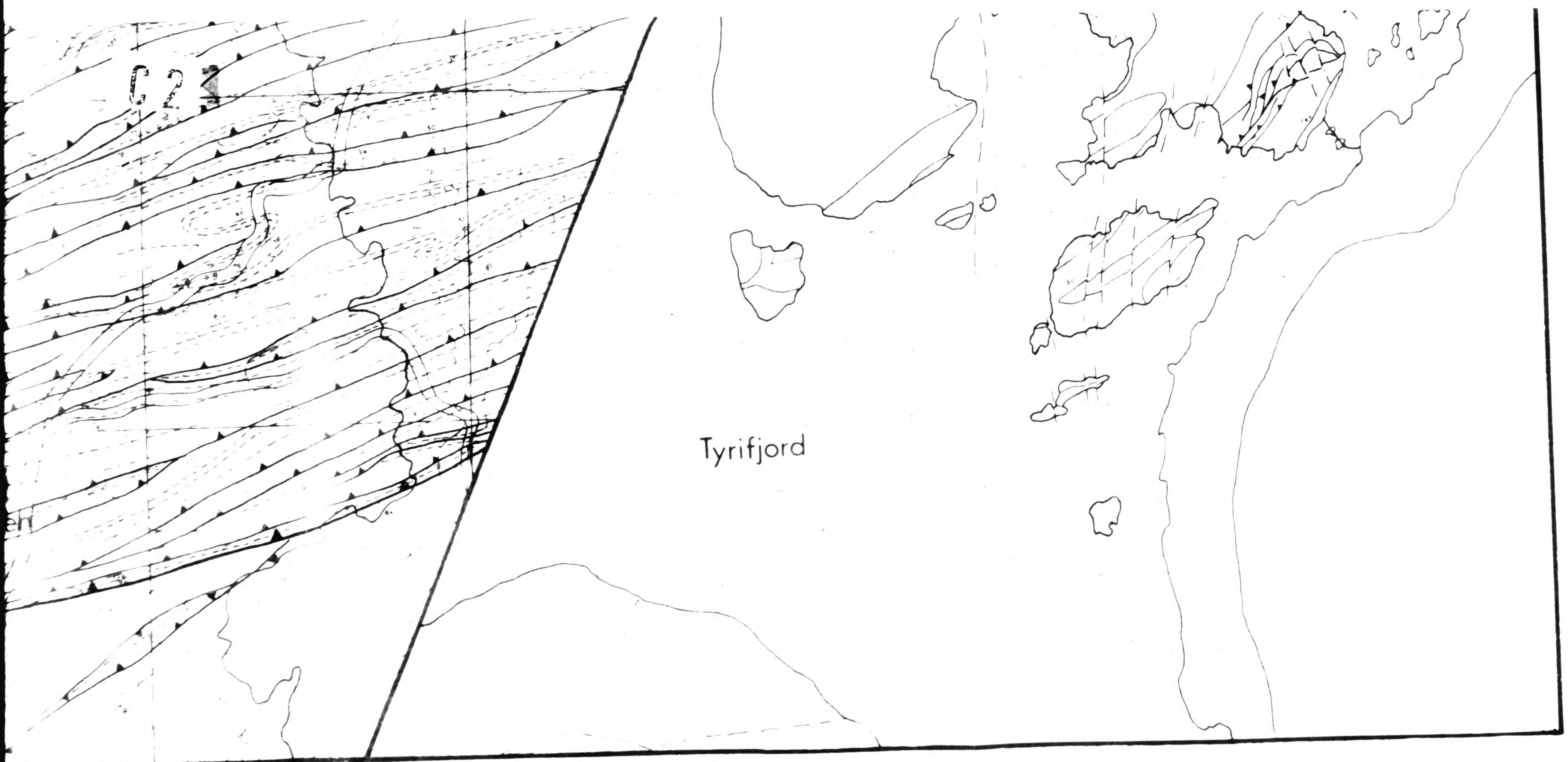
C 1





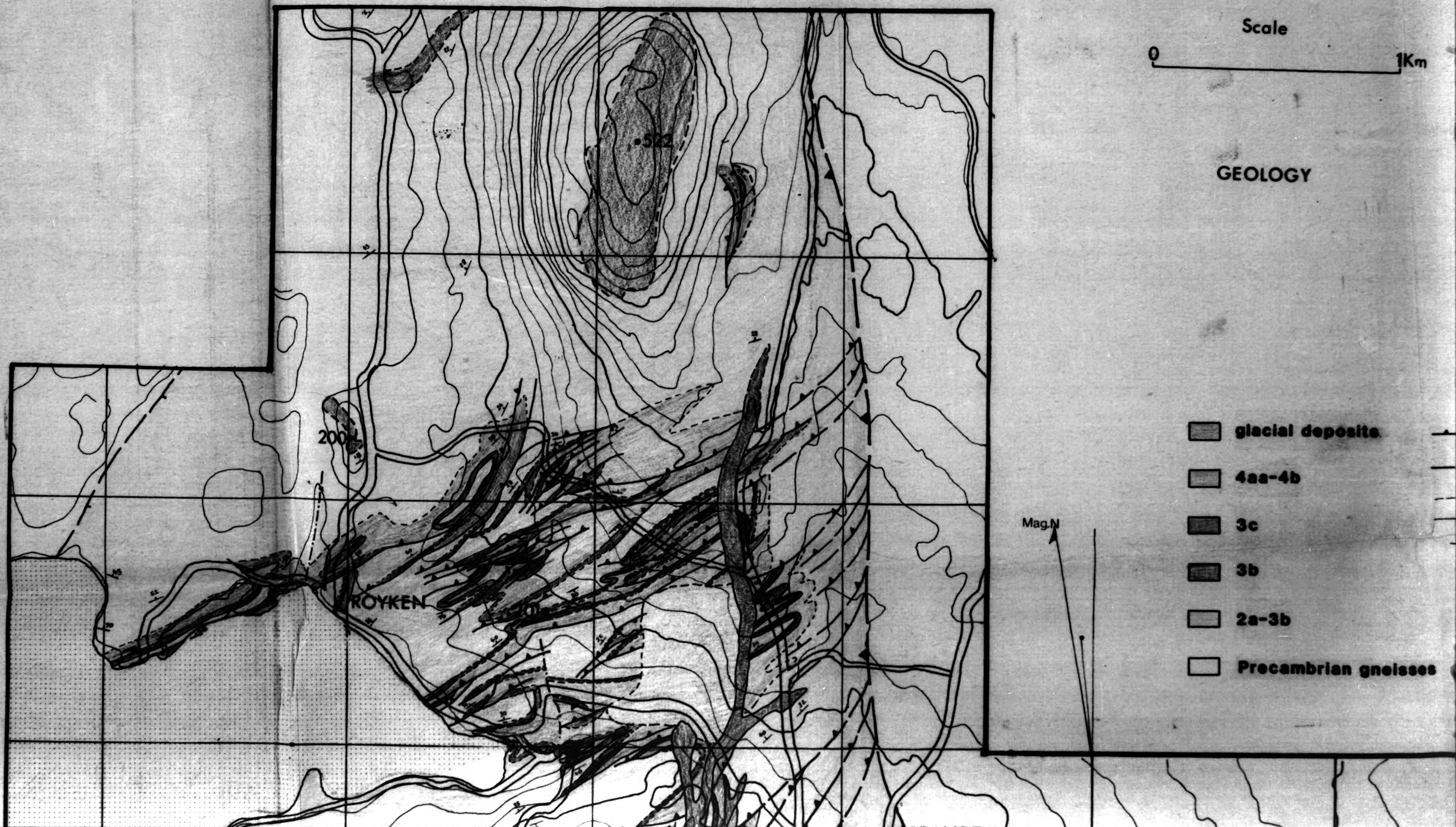


C 2
Tyrifjord


Tyrifjord

A1

HADELAND


Scale
0
1Km
GEOLOGY
glacial deposits
4aa-4b
3c
3b
2a-3b
Precambrian gneisses
Mag.N
RØYKEN
200
522

A1

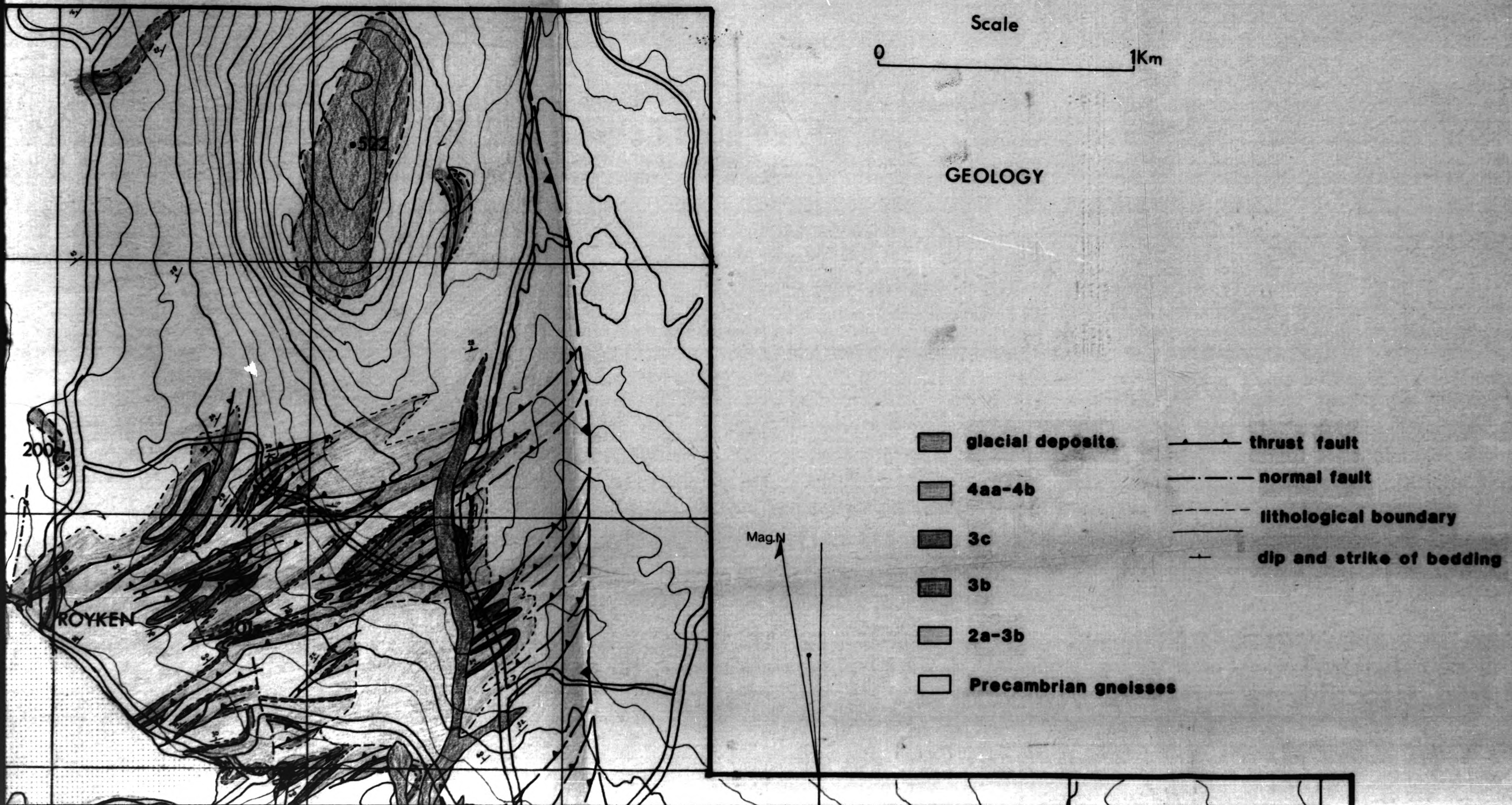
HADELAND

522
200
ROYKEN
201
Scale
0
1Km
GEOLOGY
glacial deposits
4aa-4b
3c
3b
2a-3b
Precambrian gneisses

HADELAND

A2

HADELAND


Scale
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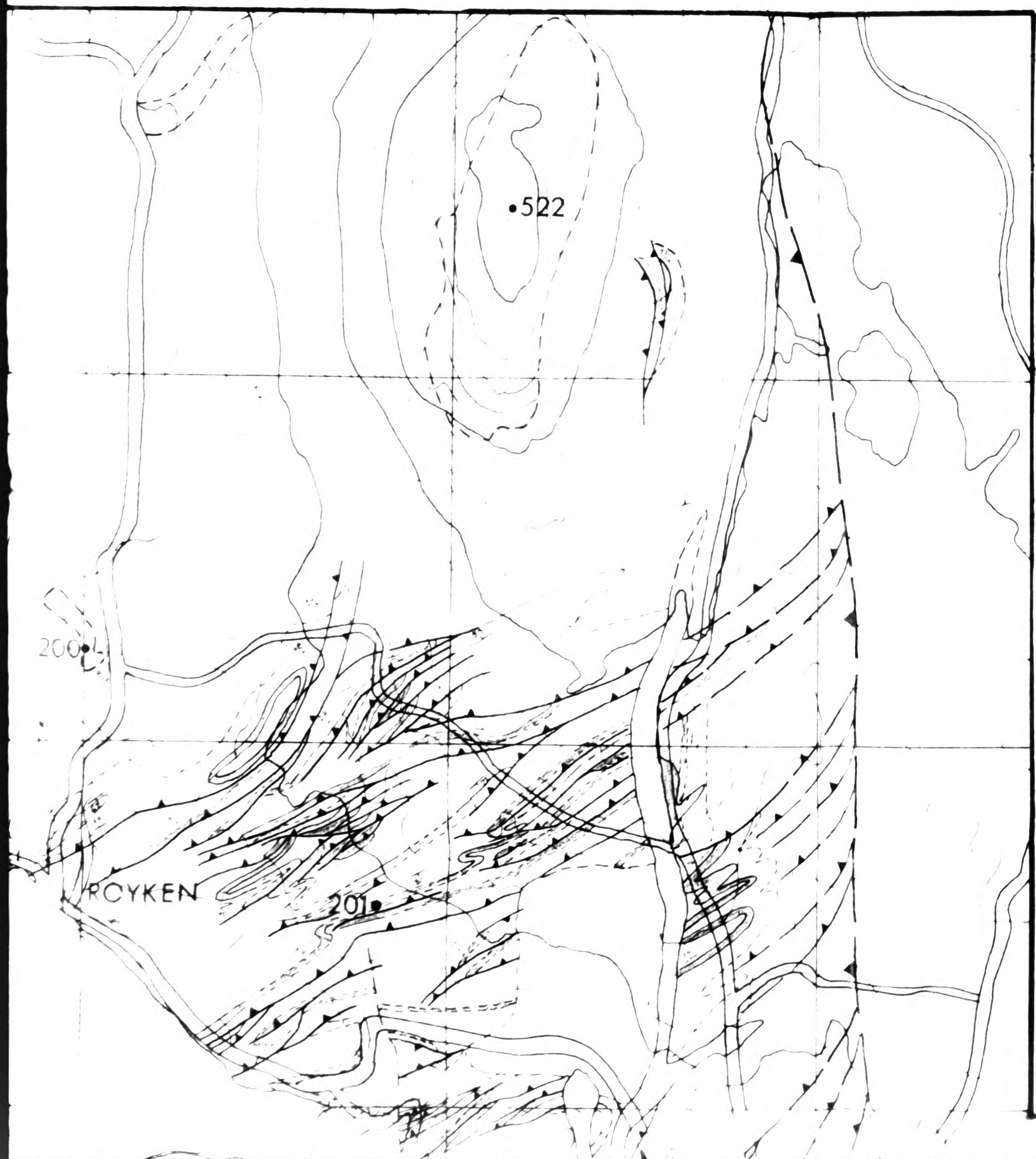
1Km
GEOLOGY
glacial deposits
4aa-4b
3c
3b
2a-3b
Precambrian gneisses
thrust fault
normal fault
lithological boundary
dip and strike of bedding
Mag.N
522
200
ROYKEN

A2

HADELAND



Scale

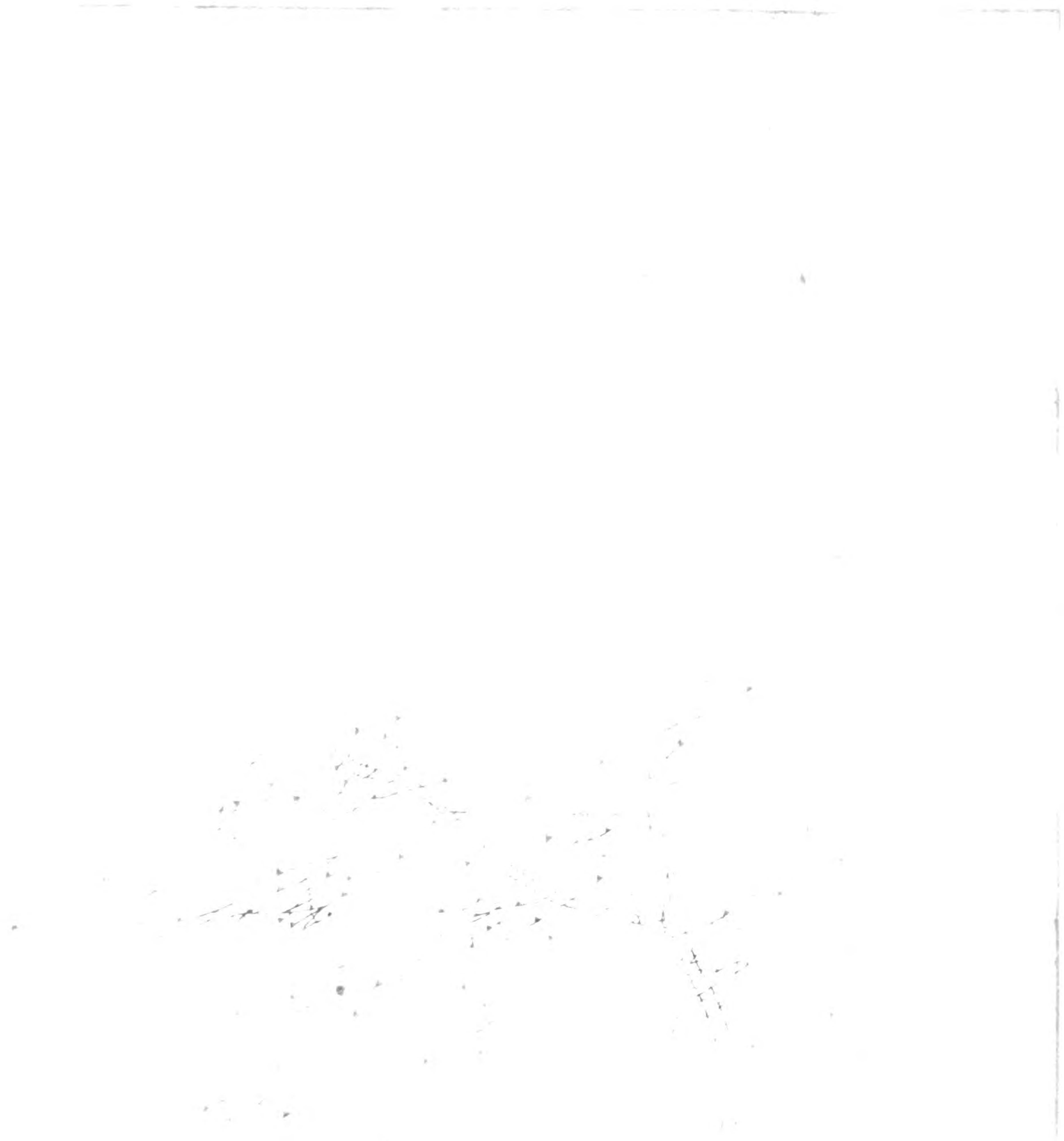
0 1Km

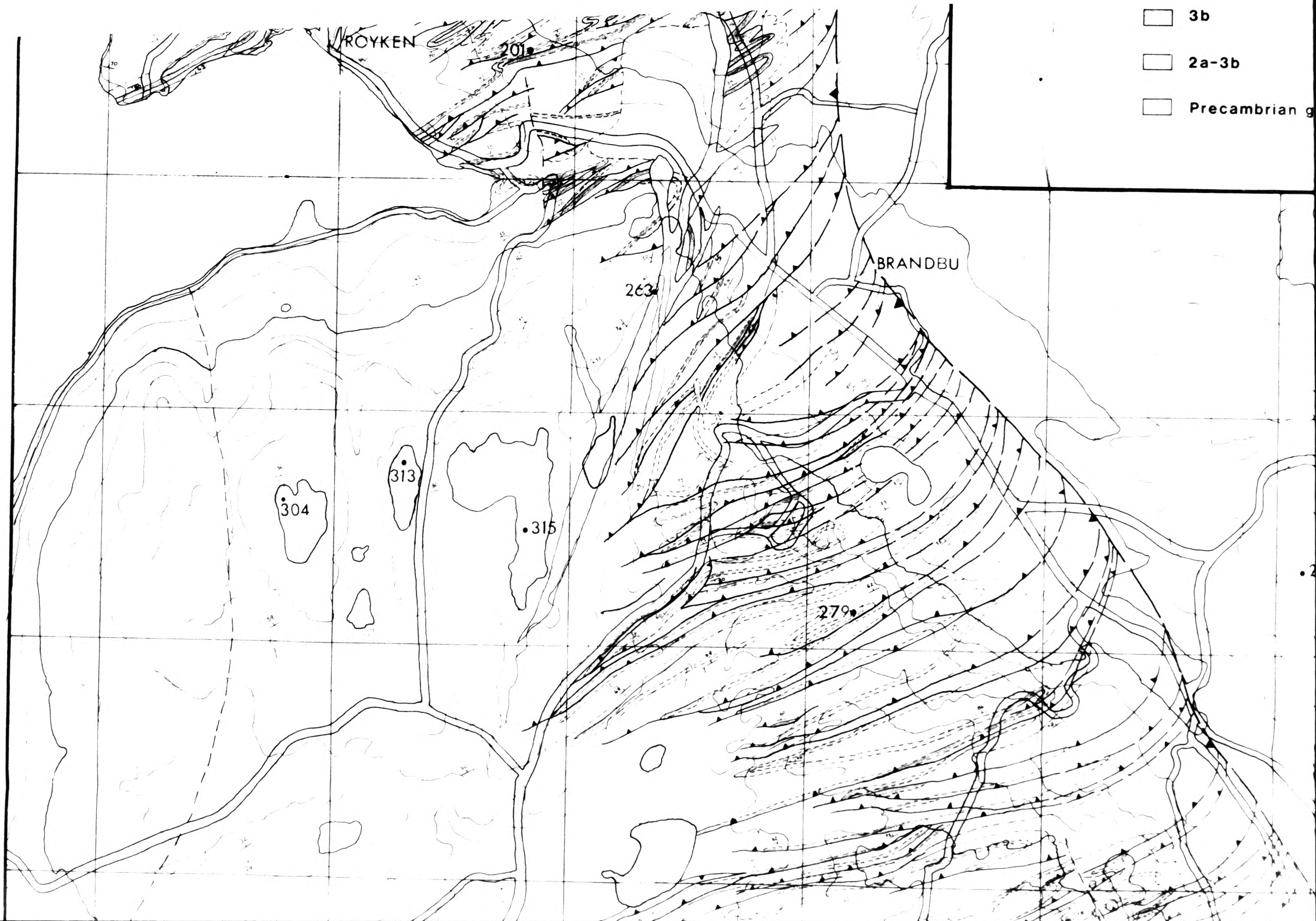
GEOLOGY

- glacial deposits
- 4aa-4b
- 3c
- 3b
- 2a-3b
- Precambrian gneisses

- thrust fault
- normal fault
- lithological boundary
- dip and strike of bedding

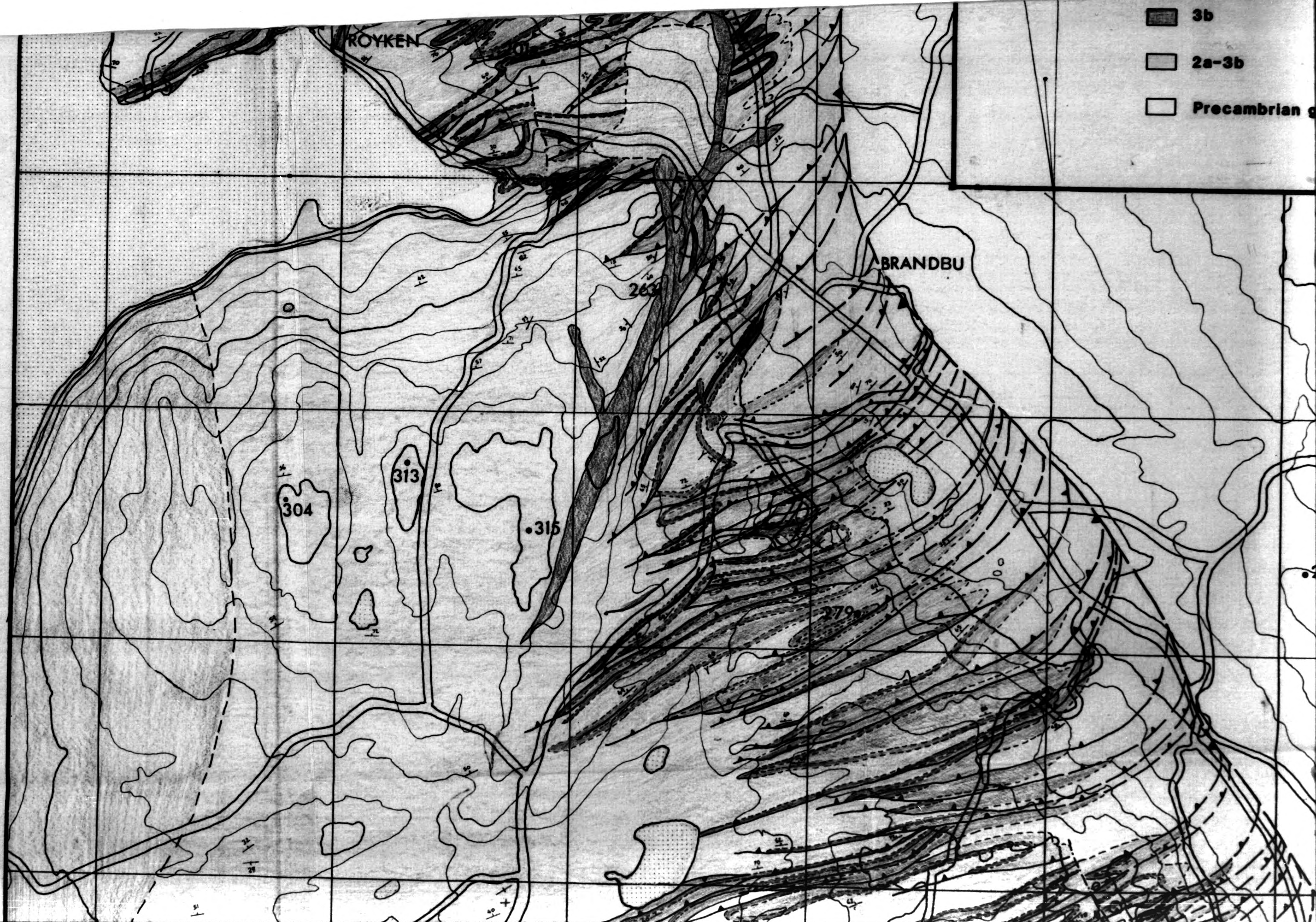
HADELAND

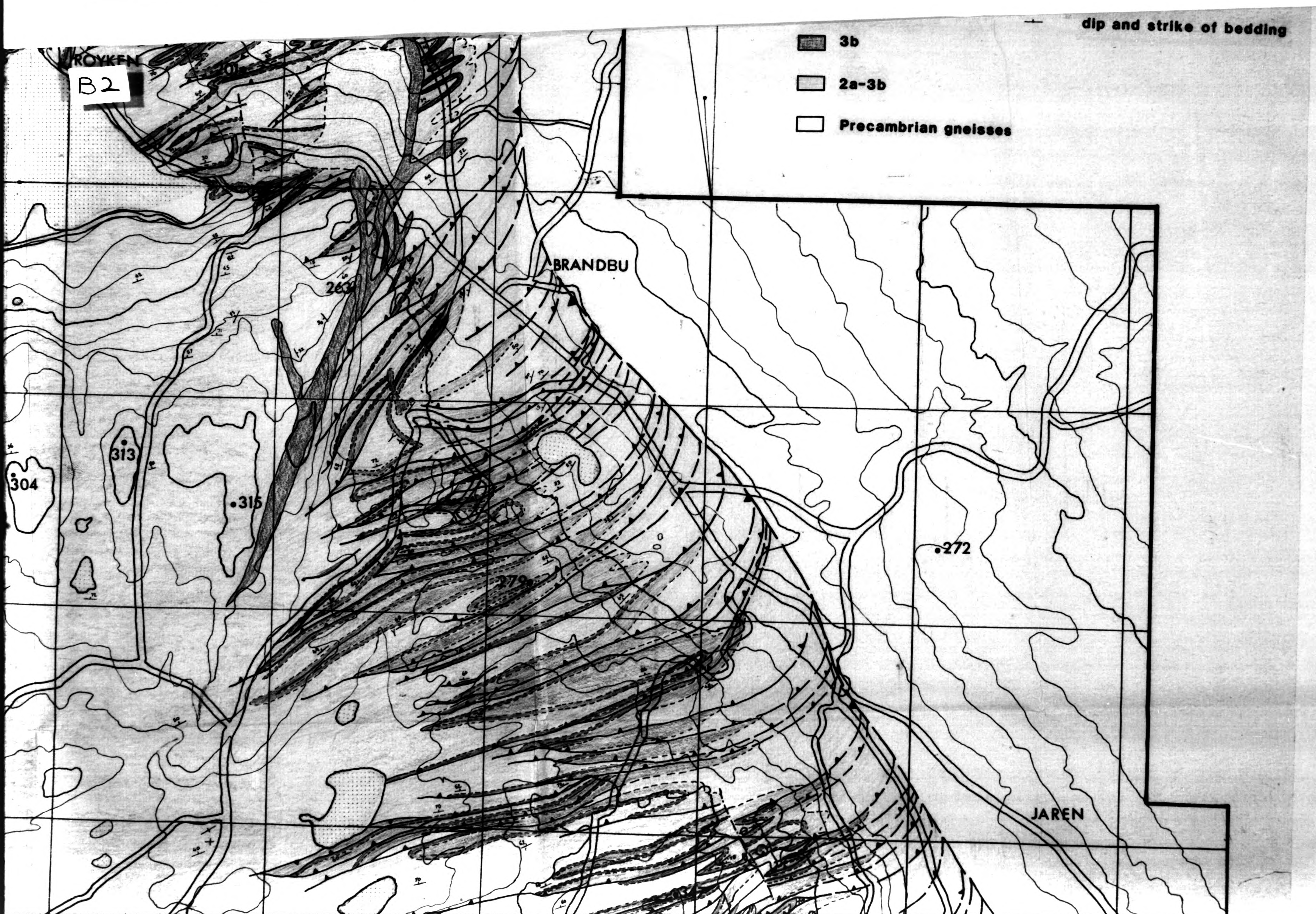




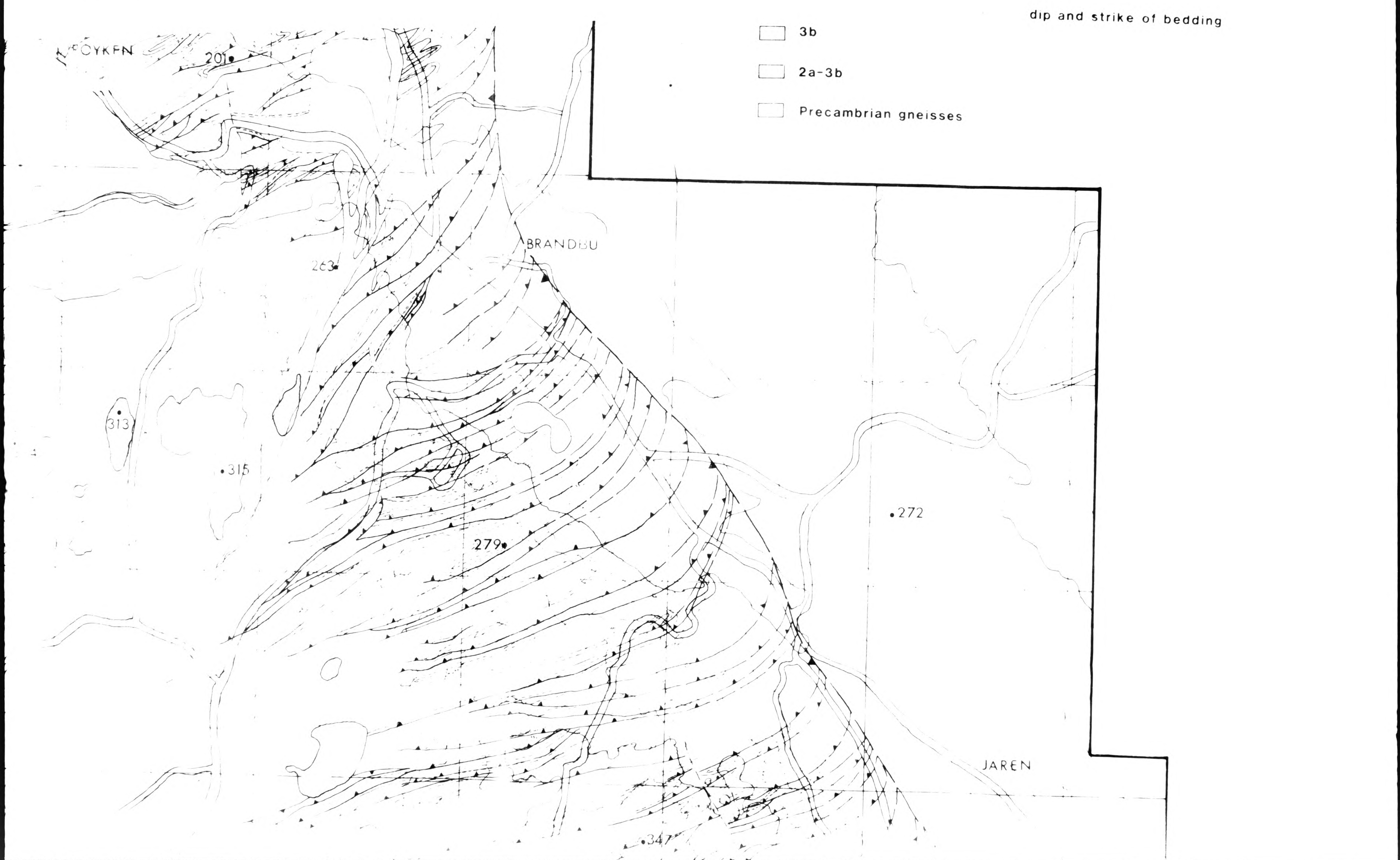
RØYKEN
201
BRANDBU
263
313
304
315
279
3b
2a-3b
Precambrian g

B1

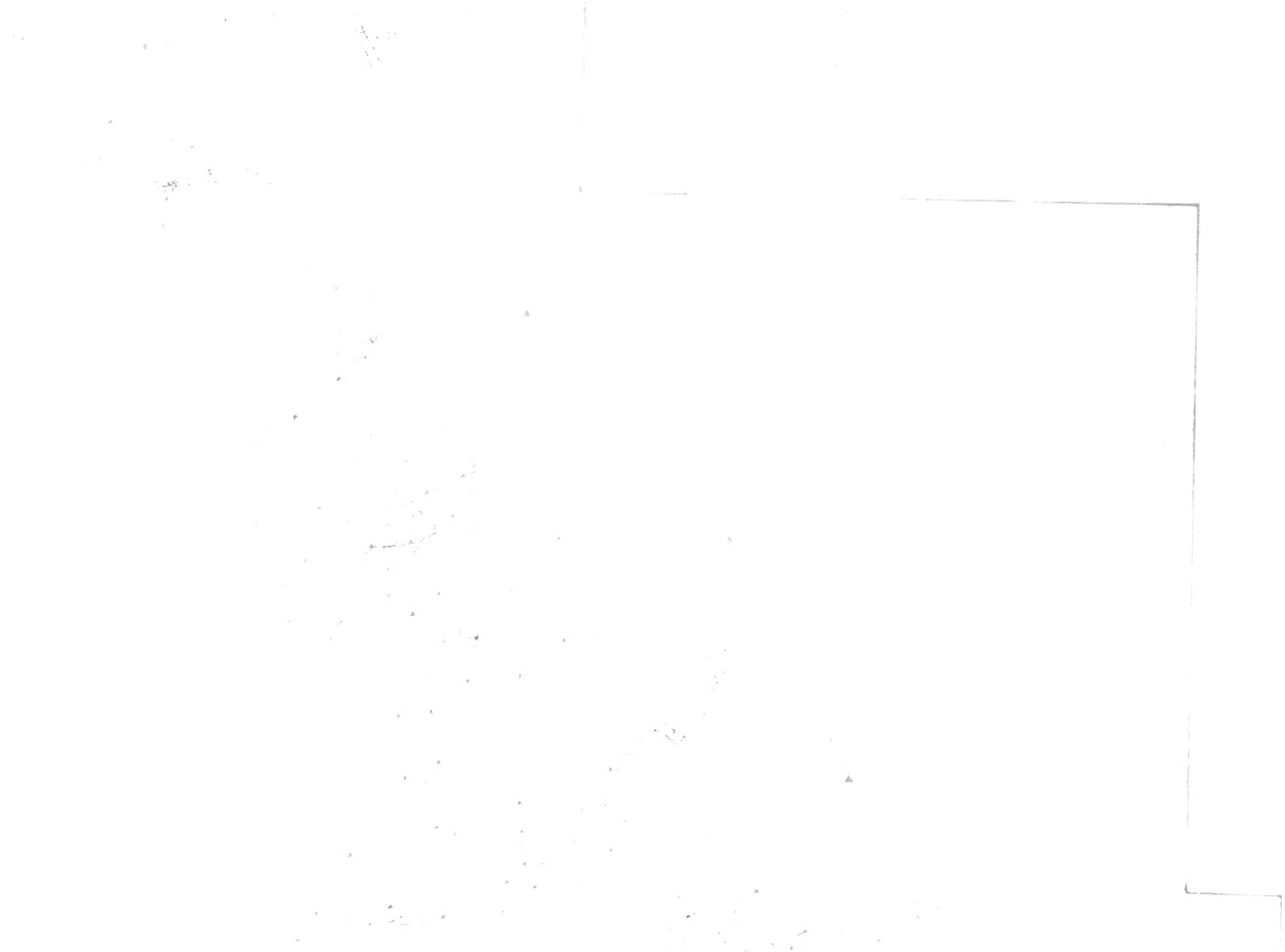




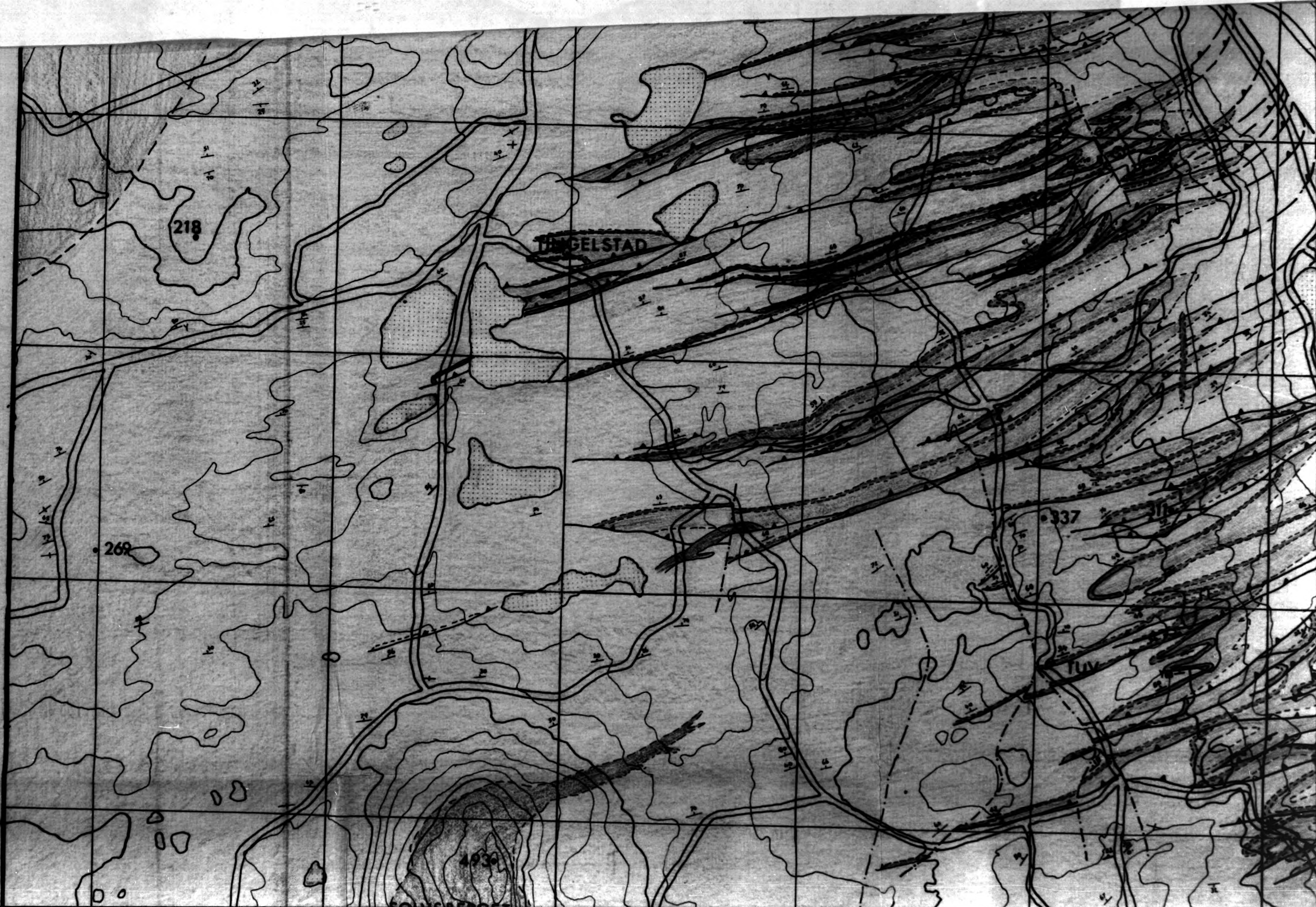
dip and strike of bedding
3b
2a-3b
Precambrian gneisses
RØYKEN
B2
BRANDBU
263
313
304
315
272
JAREN



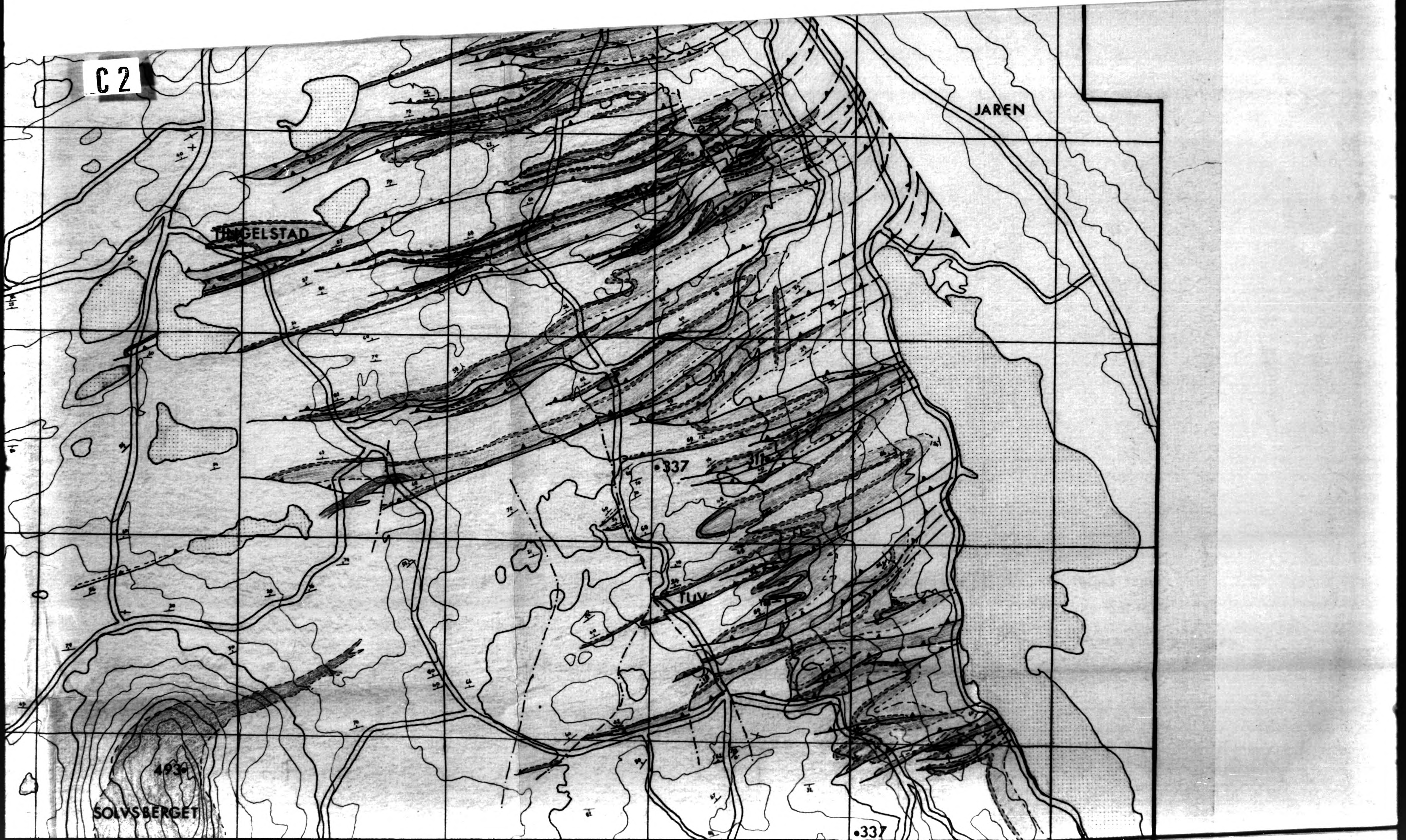
dip and strike of bedding
3b
2a-3b
Precambrian gneisses
BRANDBU
JAREN
201
263
313
315
279
272
347

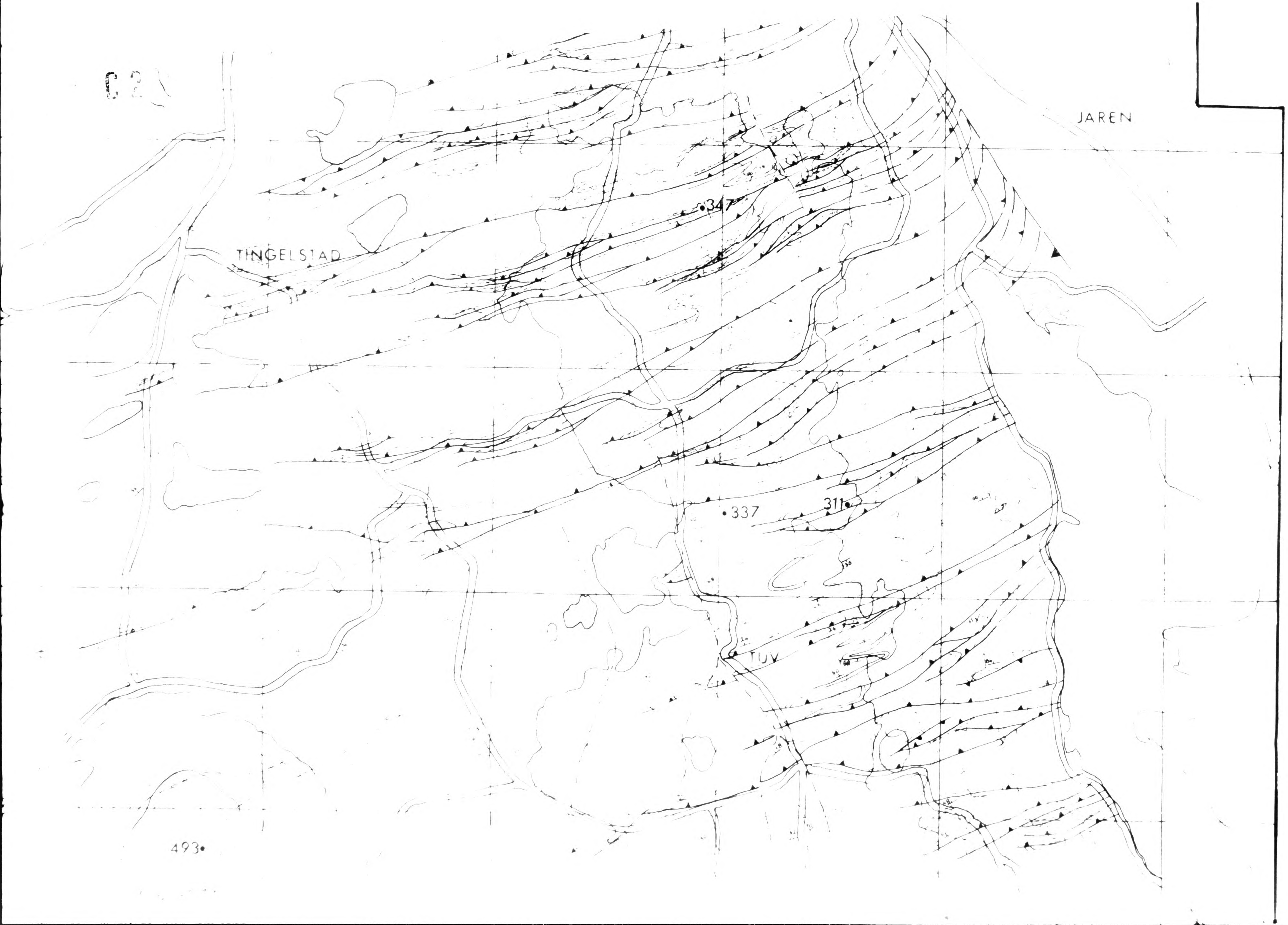


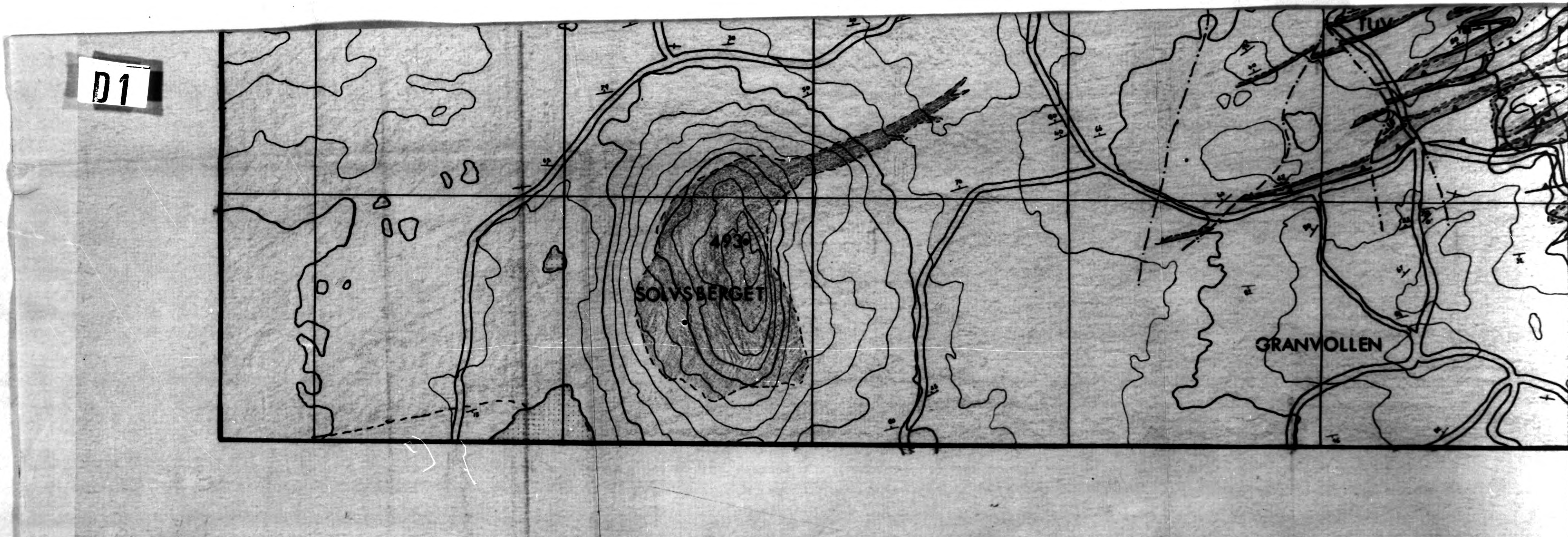
C 1



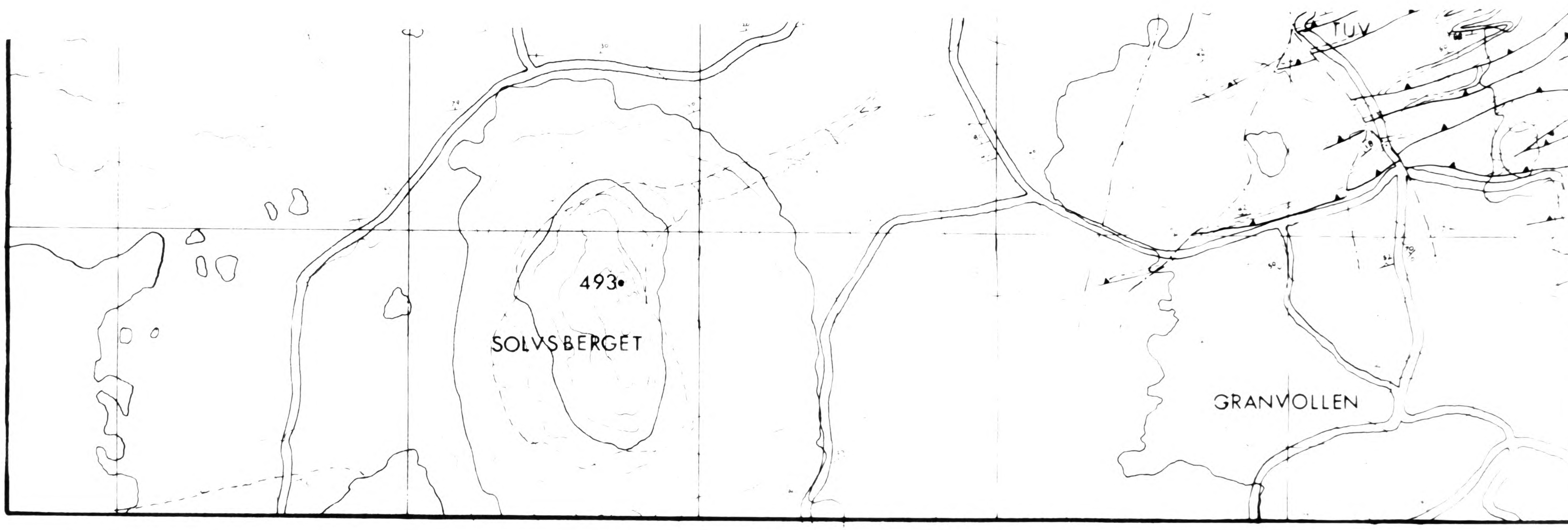
C 1

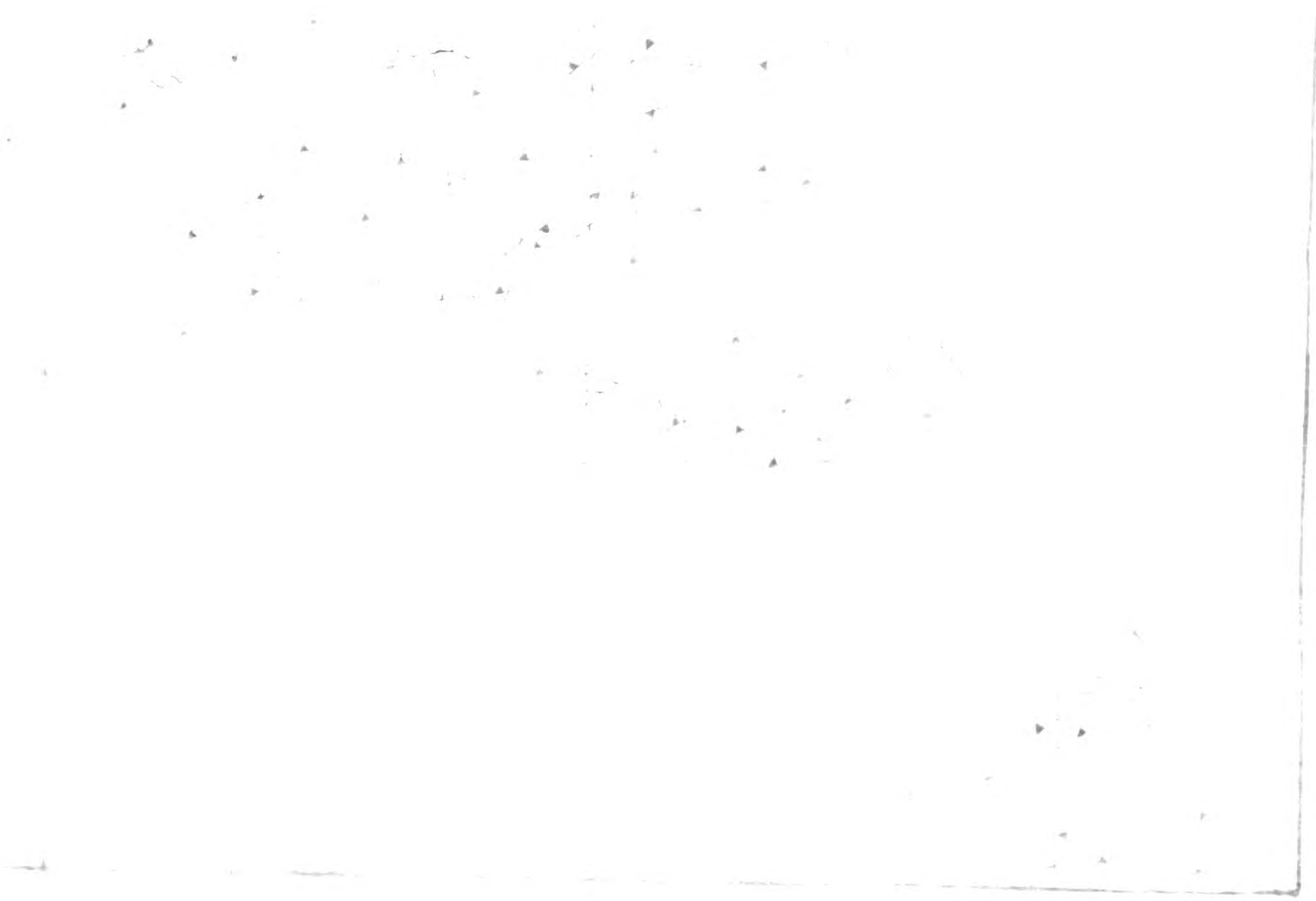

C 2
JAREN
TINGELSTAD
337
TUV
493
SOLVSBERGET
337

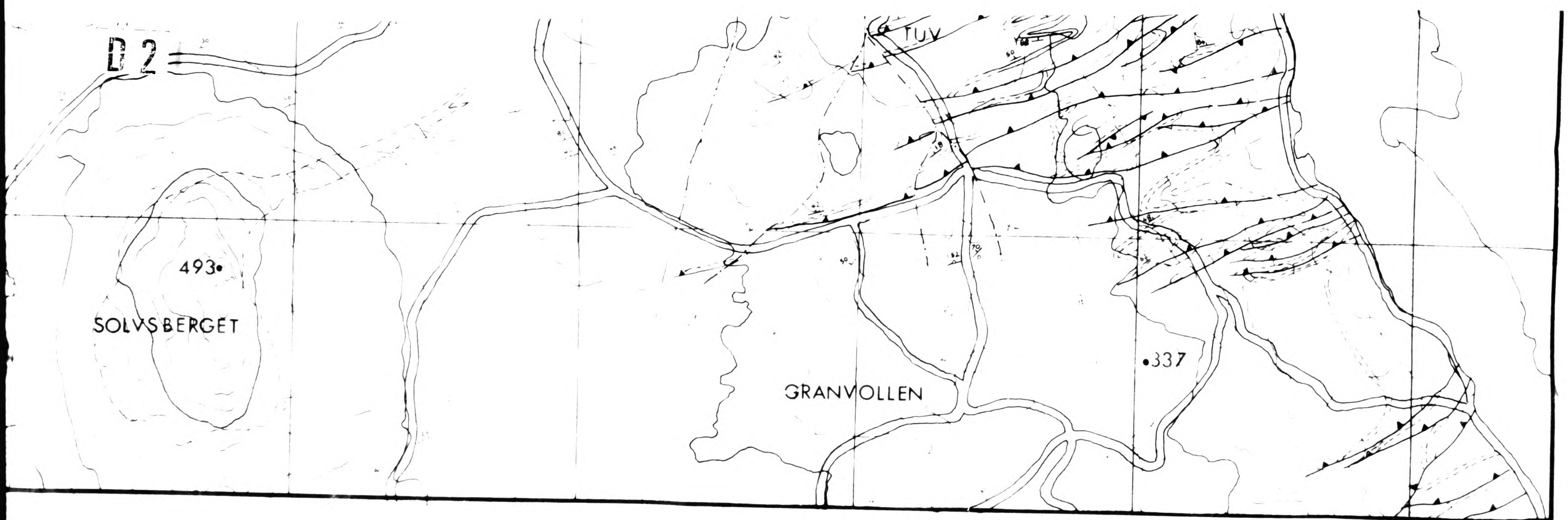

JAREN
347
TINGELSTAD
337
311
TUV
493

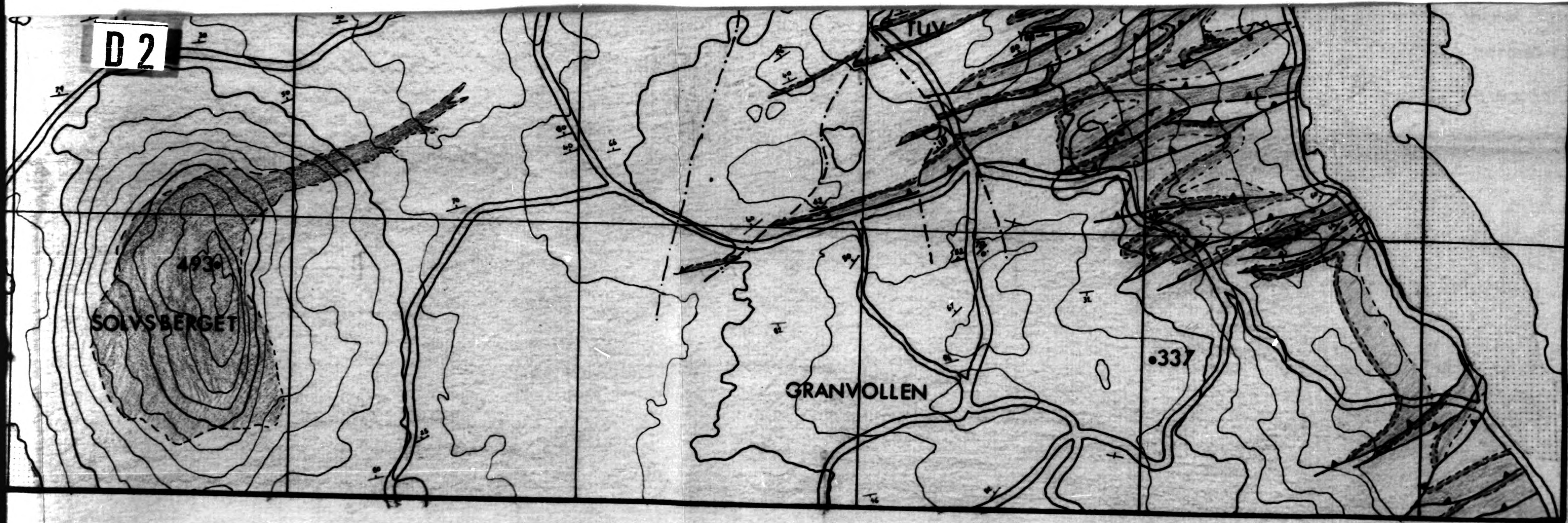

D1
SOLVSBERGET
GRANVOLLEN
Tuv

D1






D 2
TUV
493•
SOLVSBERGET
GRANVOLLEN
•337


D 2
TUV
493
SOLVSBERGET
GRANVOLLEN
337

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VOL 1
END