Master Thesis, Department of Geosciences

Caledonian structural development on Hovedøya and Lindøya, in the inner Oslofjord

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At last I would like to thank my family and my girlfriend for believing in me and motivation.

Abstract

The study presented focuses on mapping and interpretation of the Caledonian structures on Hovedøya and Lindøya, in the inner Oslofjord. The bulk tectonic caledonian transport direction and structures within the study area are consistent with the known Caledonian structures found in the the Oslo Region.

The present study differentiate between 5 deformation stages found in the study area. Structural elements identified within the study area are displayed below:
Primary sedimentary structures, bedding parallel cleavage, bedding perpendicular cleavage ,bedding parallel shortening, axial plane cleavage, foreland directed thrusts, hinterland directed thrusts, normal faults and development intermediate NW dipping cleavage.

A new lithological and structural geological map of the study area is also presented in this thesis.

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1 Introduction

1.1 Purpose of study

The main geological features on the islands in the Oslofjord area are relatively well known, especially the lithostratigraphy and biostratigraphy of the Cambro-Silurian succession, which is the subject of this study, as well as the petrology of the younger Permian intrusives.

Although the main structural features of the Oslo Region have been known since the geological mapping done by Brøgger (1887, 1890), relatively few structural studies have focused on the Paleozoic structures in the study area. The most recent work on the Caledonian structures close to the study area were conducted by C.K. Morley (1986b, 1987a, 1994).

The focus of this thesis is to study the structural development of the Cambro- Silurian successions on two islands, Hovedøya and Lindøya in inner Oslofjord(Fig. 1.1). The study presented here focuses on mapping and interpretation of Caledonian structures, but also includes a brief description of Permian rocks and structures in order to develop a structural geological history of the study area.

1.2 Study area

The study area consists of the two islands Lindøya and Hovedøya located in the inner Oslofjord.

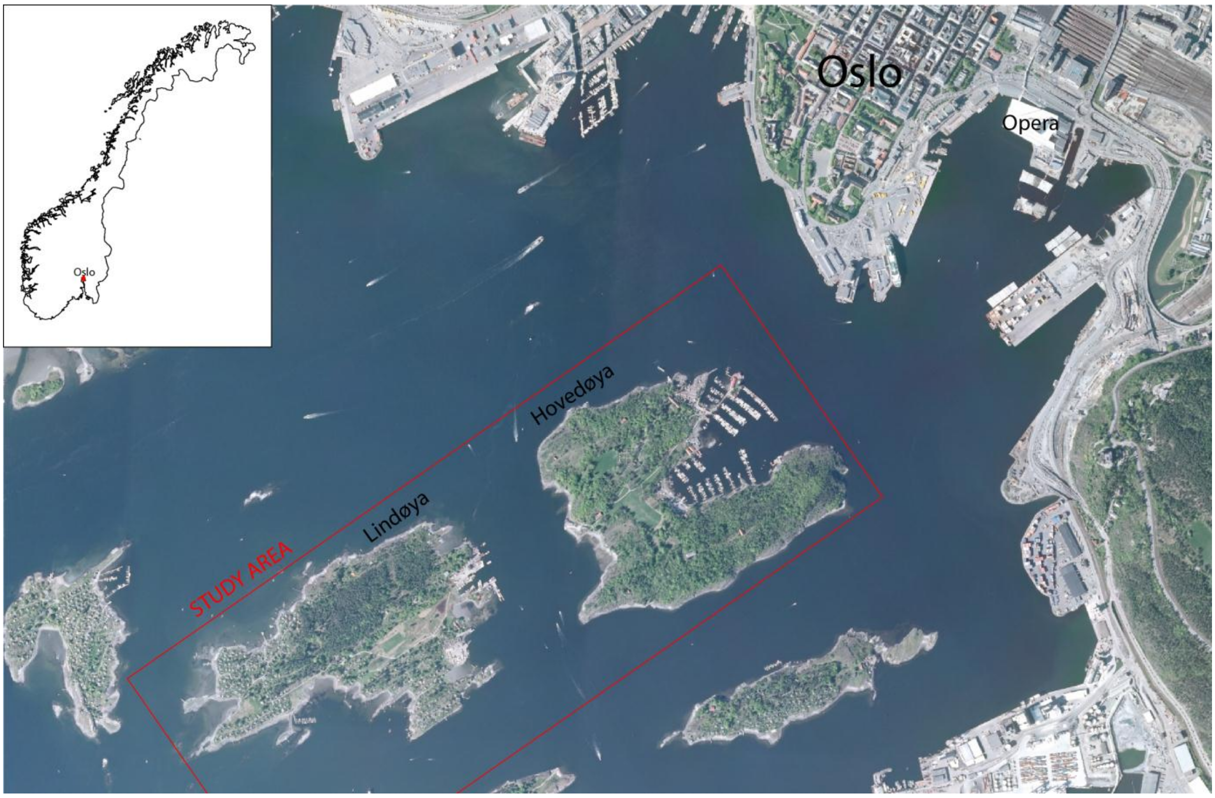


Fig. 1.1 Study area is located in Oslo, Norway. The red square indicates the two islands studied, and is located just southwest of the city center of Oslo. Satelite image taken from Statens Kartverk 2011 (kartverk, 2011).

1.3 Equipment

Equipments	General description
Compass	Suunto MC-2 Global Pro Compass Method used: Right-hand rule
Software	
GEOrient©	Stereographic projection program used to plot and display field measurements. Provides basic statistical information (Holcombe, 2011)
Adobe® Illustrator® CS5.1	Drawing program used to improve figures and pictures
ArcGis 9.3	Program used to draw geological maps of the study area.
Statens Kartverk	Maps, satellite images and position taken from (GoogleMapsTM 2011)

1.4 Methods and Terminology

Methods

The fieldwork was carried out over a period of five months, in the period April to October 2011 and involved lithological and structural mapping of the study area.

Field measurements were obtained using a Suunto MC-2 Global Pro Compass. The right-hand rule was applied while measuring planar features. For the structural analysis a stereographic projection program called GEOrient© version 9.5 (Holcombe, 2011) was used. The structural data obtained from the fieldwork include measurements of strike and dip of bedding planes, fault planes, cleavage planes and dykes, as well as the trend and plunge of slickenside lineations and fold axes. All stereographic projections in this thesis is plottet in an equal area plot (Schmidt nett).

The outcrops of the study area are well exposed along the shoreline on both islands, but with limited to no exposure in the interior due to Quaternary cover, vegetation and buildings. Lithological boundaries were mapped out from visual observation in the field following the descriptions from the modern lithostratigraphic litterature (Owen et al., 1990)and (Worsley et al., 1983). Rock samples from several Permian dykes and rock samples of the cleavage were taken for further analysis.

Terminology

Folding- with respect to lithological differences and bed thickness variations

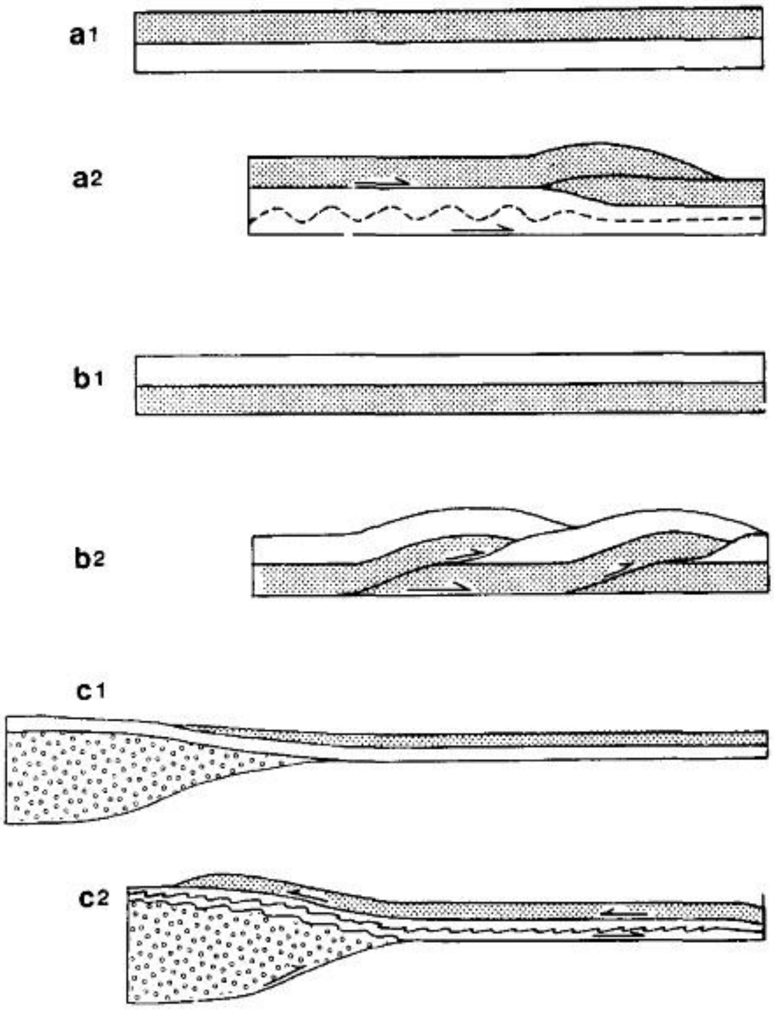


Fig. 1.2 Effects of vertical changes in competency on the deformation style in a thrust sheet. A[1] and A[2] display a possible deformation style as a competent unit deforms independently on top of an incompetent unit. Resulting in the competent unit deforms by overthrusting on a single fault plane, while the incompetent unit deforms by folding and layer – parallel thickening below. The situation in B[1] and B[2] is reversed, but the competent unit below can now exercise much stronger control the deformation style in both layers. C[1] and C[2] display a schematic cross section through the Oslo Region. Precambrian clastics displayed as the lower unit, the middle unit displaying the weaker Cambro-Ordovician unit and upper unit acting as a lid above the Cambro-Ordovician unit. Figure and text taken from Morley (1986b)

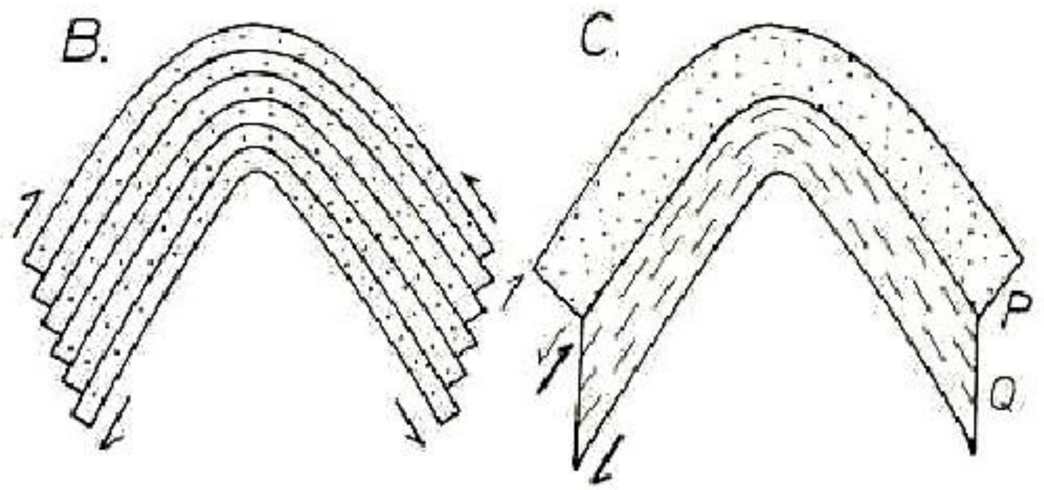


Fig. 1.3 b) display relative movement along slip surfaces in between layers with equal competence, folding due to flexural slip. c) display relative movement along slip surfaces in between layers with different competence, and shearing in the least competent layer (below), folding due to flexural slip and flexural shearing. Slickenside lineations are often found on fault surfaces.

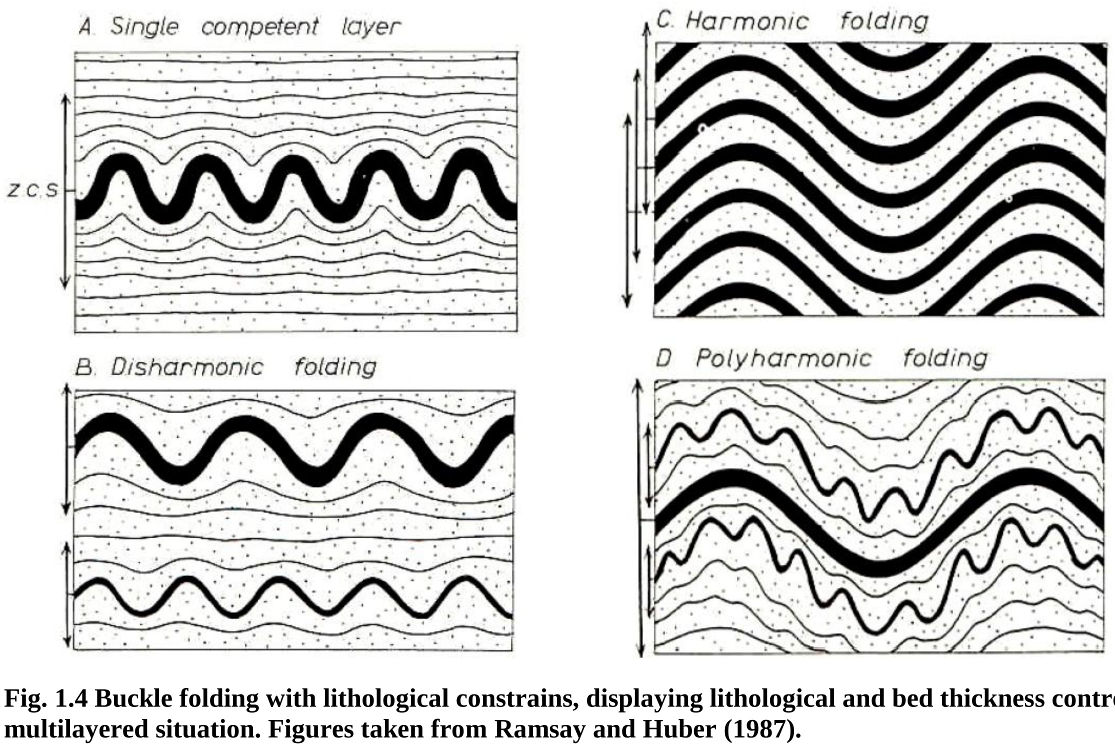


Fig. 1.4 Buckle folding with lithological constrains, displaying lithological and bed thickness control in a multilayered situation. Figures taken from Ramsay and Huber (1987).

Cleavage

A cleavage refers to the planar features of secondary origin along a body of rock which cleaves or split(Dieterich, 1969; Marshak and Engelder, 1985). Axial plane foliations are cleavage which are parallel or sub- parallel to the axial planes of folds. The relation between folding and axial plane cleavage is shown in Fig. 1.6.

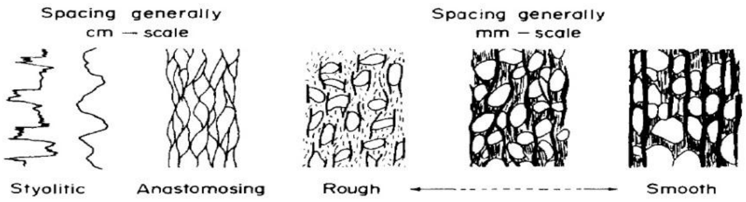


Fig. 1.5 Shape of cleavage domain: Spaced cleavage in rocks with no preexisting planar anisotropy. Figure taken from Powell (1979).

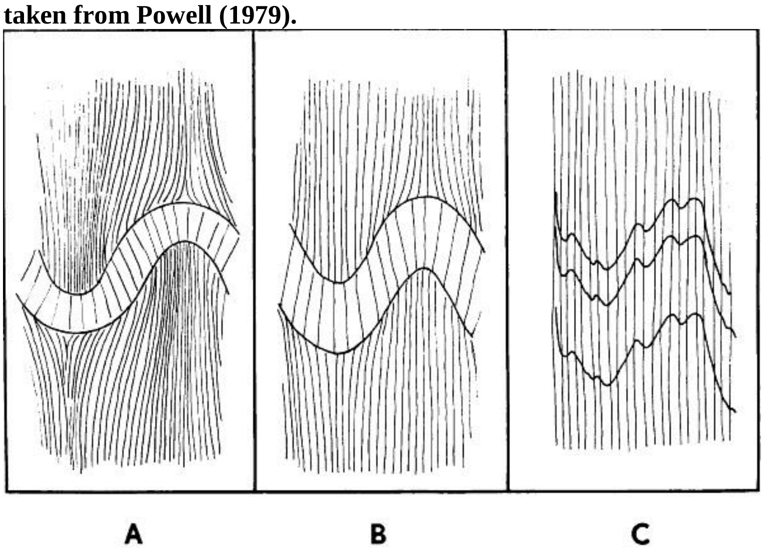


Fig. 1.6 Relation of orientation of axial plane cleavage to fold geometry. a) Concentric fold with strongly fanned and refracted cleavage. b) Intermediate to concentric and similar type fold geometry, displaying weakly fanned and refracted cleavage. c) Similar fold geometry where cleavage neither is fanned or refracted. Figure and text from Dieterich (1969).

Pressure solution cleavage can develop in a sedimentary rock if the rock is subjected to high differential stress. Pressure-solution deformation can be summarized by three processes, first dissolution at stressed grain contacts, secondly diffusion in grain-boundary fluid films toward areas of relatively lower stress such as pores and cracks, and finally precipitation in areas which display grain contacts with lower stress (Dieterich, 1969; Marshak and Engelder, 1985; Rutter, 1983).

Pencil structures can develop due to the intersection of independent fabric anisotropies, like the intersection of weak pressure solution cleavage and bedding fissility (Reks and Gray, 1982), or as in the models developed by Ramsay & Huber (1983) and Ferrel (1989)were pencil structures are formed by the intersection of bedding fissility and irregular fractures at a high angle to bedding, generally controlled by grain – alignment rather than pressure solution.

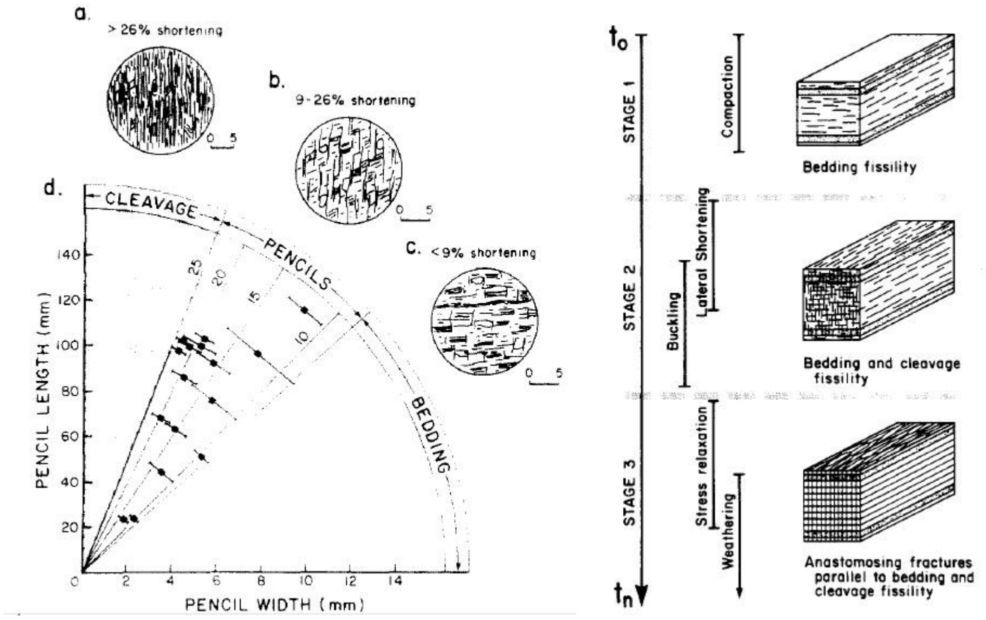


Fig. 1.7 Left: Variations in microfabric associated with progressive deformation. a) Sketch of cleavage microfabric at strains greater than 26%, b) Pencil fabric at strains between 9 and 26% shortening c) Bedding fabric with incipent cleavage at strains less than 9%. d) Pencil length (l) vs width (w), graph showing distribution of each fabric. Right: Figure illustrating the three main stages in pencil formation and their respective fabrics. Linear time sequence (t) shows the dominant process affecting the rock during each stage. Figures and text taken directly from Reks and Gray (1982 p. 172 and 173)

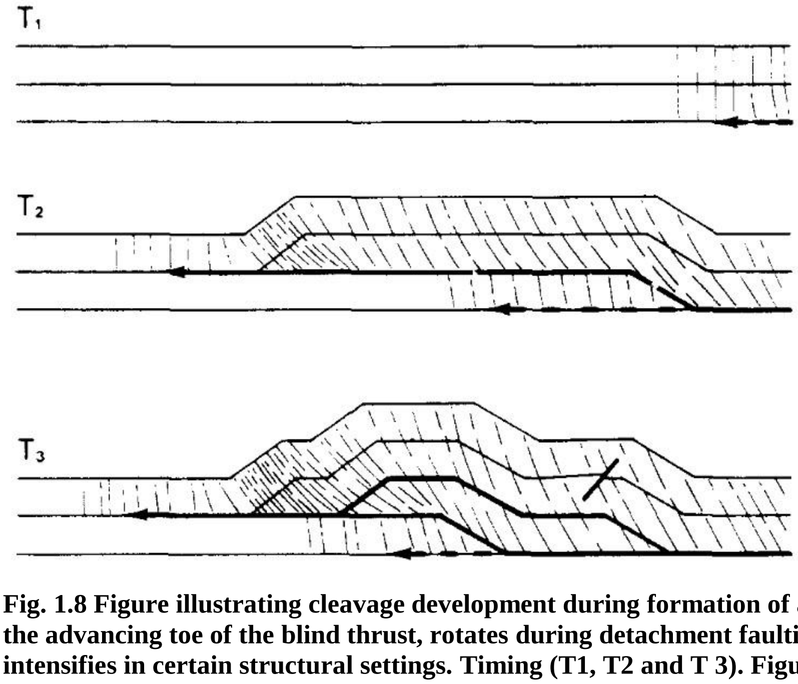


Fig. 1.8 Figure illustrating cleavage development during formation of a fold-thrust belt. Cleavage tracks the advancing toe of the blind thrust, rotates during detachment faulting and flexural slip, and locally intensifies in certain structural settings. Timing (T1, T2 and T 3). Figure and text from Marshak & Engelder ((1985)p. 356).

2 Geology of the Oslo Region

2.1 Introduction

The Oslo Region (Fig. 2.1) is a geographical term that describes an area of approximately 10,000 km2 in southeastern Norway. The width of the Oslo Region is about 80 km in the south and reduced to about 40 km in the north, trending in a NNE-SSW direction from the Langesund-Skien district to the northern Mjøsa distric. The extent from south to north is approximately 230 km (Bruton et al., 2010). The Oslo Region is located in the external frontal zone of the Caledonian Nappe system(Bruton et al., 2010) and consists of thrust and folded Lower Palaeozoic sedimentary rocks which is intruded and cut by Upper Palaeozoic lavas, sills and dykes. The Palaeozoic rocks in the Oslo Region are surrounded by Precambrian rocks (Bockelie and Nystuen, 1985).

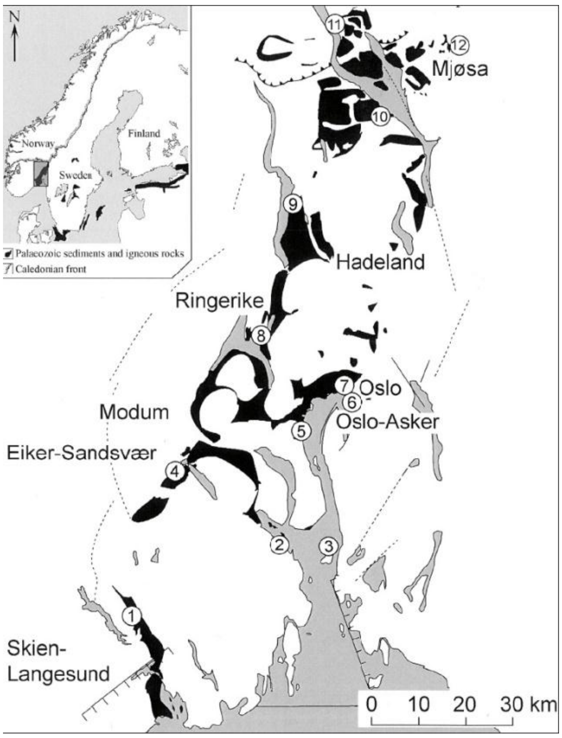


Fig. 2.1Outline of the Oslo Region, with Lower Palaeozoic deposits marked in black, figure taken from (Bruton et al., 2010).

2.2 Precambrian basement

The Precambrian basement in southern Norway consists of metasediments, granites, amphibolites and a broad variation of gneisses that is part of either the Fennoscandian or

Baltic shield. The basement has been subjected to several phases of folding and metamorphosis (Larsen and Olaussen, 2005; Nordgulen and Andresen, 2006; Ramberg and Spjeldnæs, 1978)

The Precambrian rocks of the Fennoscandian and Baltic shield are divided into three zones depending on geological structures and radiometric dating: The Saamo – Karelian Zone (3.6 – 1.9 Ba) in the northeast, the Svecofennian Zone (2.3 – 1.6 Ba) in southern Finland and northern and eastern Sweden, and the Sveconorwegian Zone (1.13 – 0.9 Ba) in south southwestern Sweden and southern Norway (Larsen and Olaussen, 2005; Nordgulen and Andresen, 2006).

The Precambrian basement in southern Norway consists of blocks of characteristic Precambrian rocks separated by shear zones oriented approximately N-S to NW-SE. Strong deformation along the shear zones can probably be related to strike – slip movement between the blocks under the Sveconorwegian Orogeny (Nordgulen and Andresen, 2006; Ramberg and Spjeldnæs, 1978).

2.3 Lower Paleozoic deposits

The Cambro - Silurian sequence in the Oslo Region was first divided into 9 stratigraphic stages (etagen) by Prof. Theodor Kjerulf and Tellef Dahll in (1857). The stratigraphy from Middle Cambrian to Early Silurian were established by Prof. Waldemar C. Brøgger (1887, 1890). The Silurian stratigraphic system was established by Prof. Johan A. Kiær (1908), when he divided the stages 6-9 in the Silurian strata into several sub – units. The Lower Cambrian were established at Ringsaker by Prof. Thorolf Vogt (Larsen and Olaussen, 2005; 1924). The etagen established by Kjerulf(1857), Brøgger (1887, 1890) and Kiær (1908) were at first based on lithostratigraphy. Subsequently the etagen was through the years used on successions elsewhere in the Oslo Region and a chronostratigraphical etasje nomenclature had developed, with a combination of litho- and biostratigraphy. This nomenclature were commonly inapplicable when used in field, and a stratigraphical revision of both the Ordovician and Silurian has been produced (Owen et al., 1990). The modern Ordovician and Silurian lithosstratigraphic system was provided respectively by Owen et. al. (1990) and

Worsley et. al. (1983). Fig. 2.2 display the modern stratigraphy of the Lower Palaeozoic deposits.

The Precambrian basement was in the Sub-Cambrian mostly eroded down to a relatively flat peneplain, the Sub-Cambrian peneplain. In the lower most Cambrian, the Oslo region were above sea level, but had low relief (Nystuen, 2006; Ramberg and Spjeldnæs, 1978).

In the Lower- to Middle- Cambrian, the sea transgressed from the north towards south, forming an epicontinental sea over the Baltic plate (Larsen and Olaussen, 2005). The relative age of the deposited sediments suggest that the sea transgressed from the north. Lower-Cambrian sediments are found as the lowermost deposits in the Ringsaker – Mjøsa area, and Middle – Cambrian sediments are found as the lowermost deposits in the Oslo area (Bjørlykke, 1974, 1983; Bockelie and Nystuen, 1985). The varying thicknesses of the sediments deposited on the Precambrian basement suggests that the Oslo region had topographical heights and depressions during deposition (Bjørlykke, 1974).

The Lower Paleozoic successions in the Oslo region were deposited in front of the Baltica – Laurentia collision and the final closing of the Iapetus Sea (Fig. 2.3), which makes up the Caledonian Orogeny (Larsen and Olaussen, 2005). According to Larsen and Olaussen (2005) the Lower Palaeozoic basin fill can be divided into four different major events. The first event was the transgression of the shallow sea from the north in Early to Middle Cambrian, secondly from Late Cambrian to Middle Ordovician, deposition in a basin with low sedimentation rate typical for epicontinental sea conditions. Foreland basin silt- and sandstones and shallow marine warm water carbonates followed in the Late Upper Ordovician and Lower Silurian. The Lower Palaeozoic deposition ended with the foreland alluvial basin fill in Late Silurian (Larsen and Olaussen, 2005; Nakrem and Worsley, 2006; Worsley et al., 1983).
The Cambrian - Silurian successions display deposition of alternating beds consisting of mudstone, limestone, nodular limestone, siltstone and sandstone. The sedimentary succession can roughly be divided into to parts, a lower part (up to 1200 meters thick) consisting mostly of marine mud-and limestone, and an upper part consisting of (up to 1250 meters thick)

continental silt- and sandstone (Bjørlykke, 1974; Bruton et al., 2010; Larsen and Olaussen, 2005; Nakrem and Worsley, 2006; Owen et al., 1990; Worsley et al., 1983).

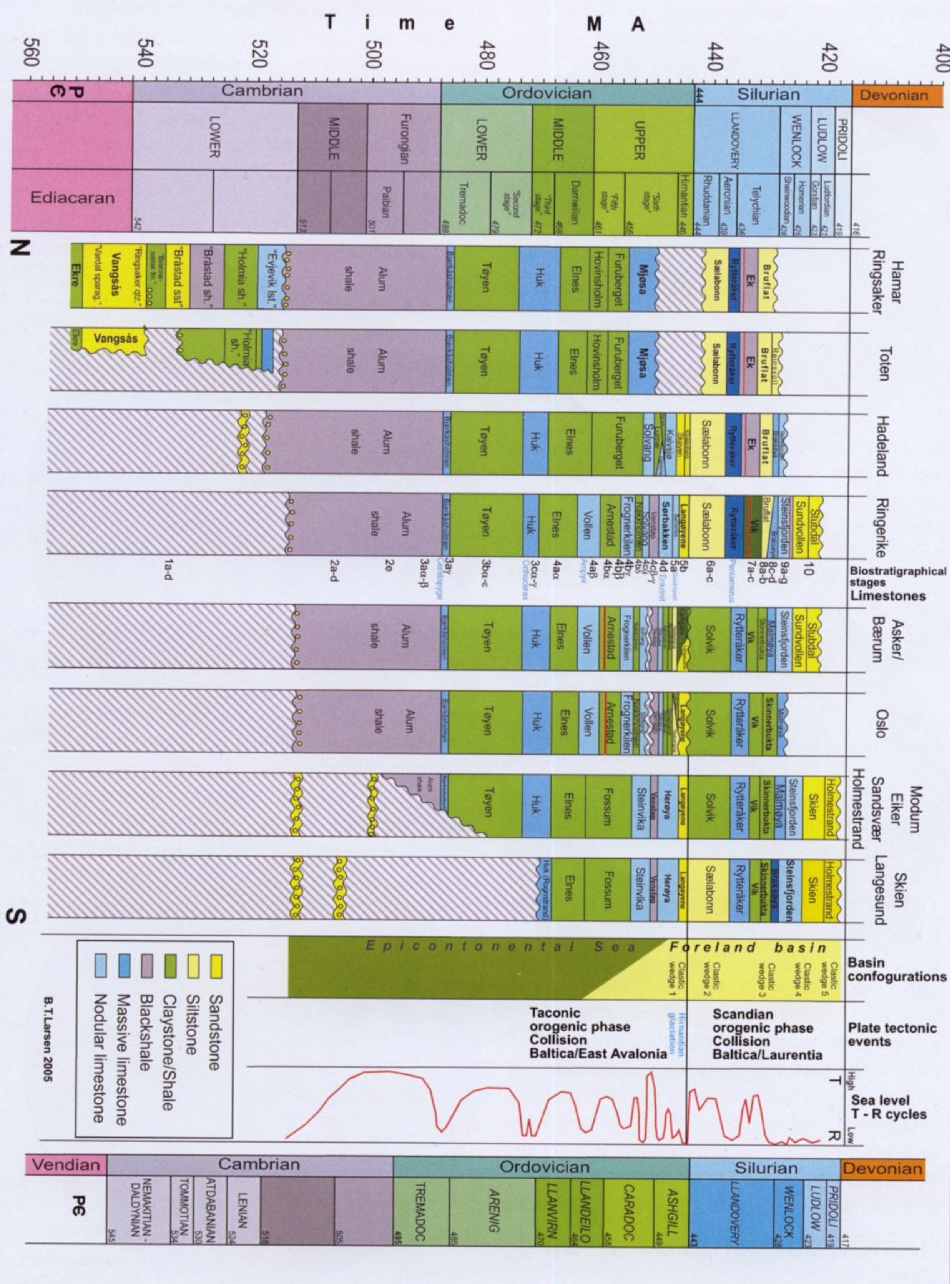


Fig. 2.2 Stratigraphy in the Oslo Region, figure display modern lithosstratigraphy (formations), time scale, lithology distribution, relative sea level, plate tectonic events, basin configuration and biostratigraphic stages (previous etagen). Figure taken from Larsen and Olaussen (2005).

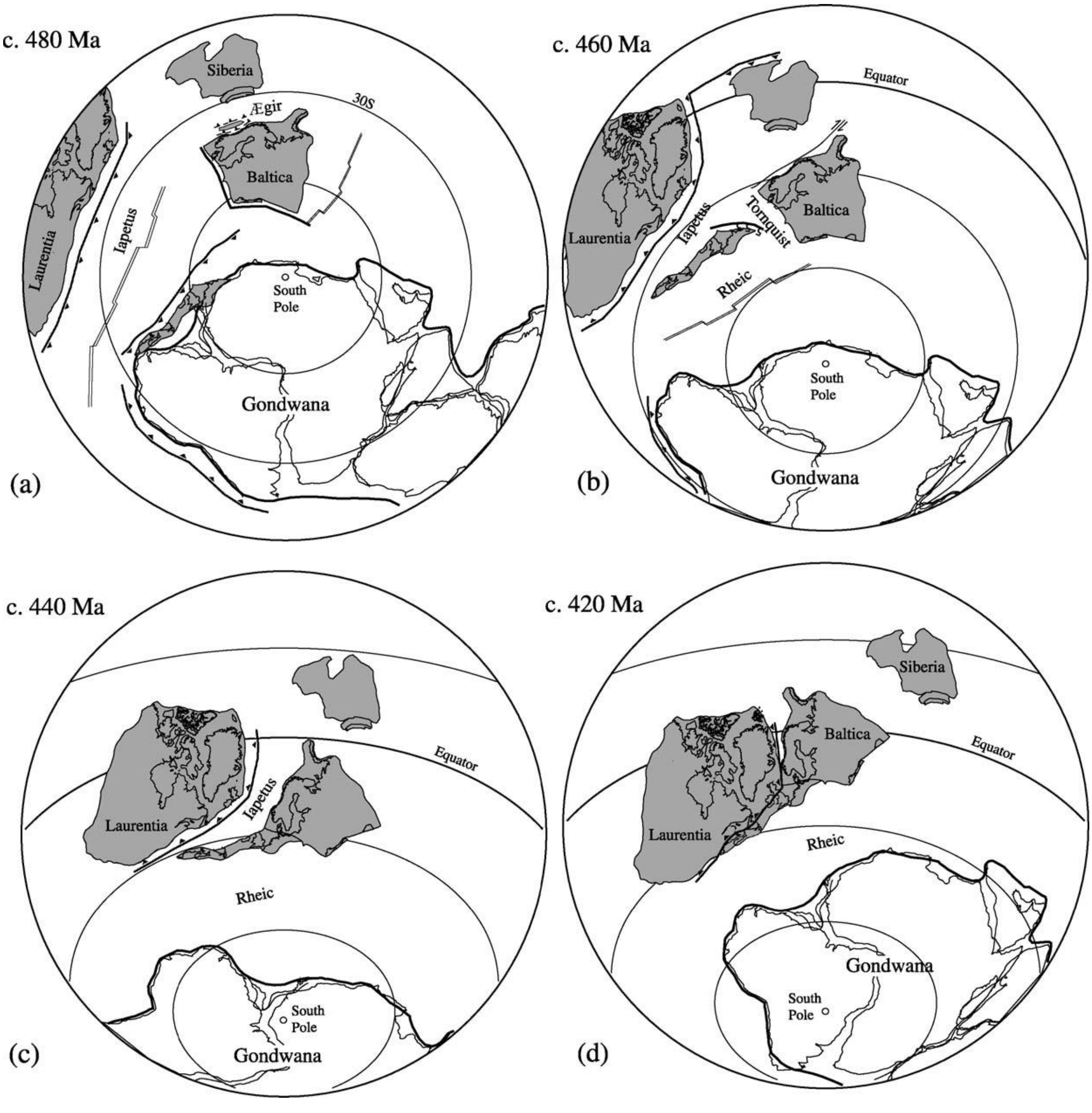


Fig. 2.3 Simplified palaeomagnetic reconstructions from Early Ordovician to Late Silurian time, with emphasis on the gradually changing positions and interaction between Baltica, Siberia and Laurentia, made by Trond Torsvik, NGU 2003. Figure taken from Roberts (2003).

2.4 The Caledonian orogeny

The Scandinavian Caledonides

The Scandinavian Caledonides are found over a total length of 1800 km and with varying width (up to 300 km) within western Scandinavia (Roberts, 2003; Roberts and Gee, 1985) and was formed during the four major compressive/ transpressive events, the Finnmarkian, the Trondheim, the Taconian and the Scandian, during the closing of the Iapetus Ocean and collision between the Baltic and the Laurentian Craton (Fig. 2.7)(Fossen, 1992; Fossen et al., 2006; Hossack and Cooper, 1986; Roberts, 2003; Roberts and Gee, 1985).

The Scandinavian Caledonian orogen is characterized by a variety of nappes that are thrusted on to the Baltoscandian craton from the west (Fig. 2.4). The nappes can be divided into four different tectono-stratigraphical units, the Lower-, Middle-, Upper- and Uppermost Allochton (Fossen et al., 2006; Hossack and Cooper, 1986; Roberts and Gee, 1985). The Lower Allocthon comprises transported and deformed Upper Precambrian and Lower Palaeozoic sedimentary rocks, consisting of structures such as imbricate fans and duplexes. Situated originally on the baltic margin, the Lower Allocthon were transported up on to the craton (Fossen et al., 2006; Hossack and Cooper, 1986; Roberts, 2003; Roberts and Gee, 1985) The Middle Allocthon consists of the same type of rocks as the Lower Allocthon, including micro – continents, but has been transported further (estimated 300 km) over the Baltic craton and therefor display a higher grade of deformation than the Lower Allocthon (Hossack and Cooper, 1986; Roberts, 2003; Roberts and Gee, 1985). The Upper Allochton composes island arcs and oceanic crust from the Iapetus ocean and is transported futher than both underlying nappes (estimated 300- 400 km) onto the Baltic craton (Hossack and Cooper, 1986; Roberts, 2003; Roberts and Gee, 1985). The Uppermost Allocthon is only present in Nordland and Troms, and exibits rocks originating from either Laurentia or micro- continents stuck between Laurentia and Baltica (Dwarko, 2010; Hossack and Cooper, 1986; Roberts, 2003)
.

The Allocthons were transported towards E – SE, but display in the Oslo region a transport direction towards SSE(Fig. 2.5) (Bruton et al., 2010; Hossack and Cooper, 1986). The structural style of the Scandinavian Caledonides changes from east to west. With the Caledonian thrust front in eastern Norway displaying thin-skinned deformation by folding and thrusting of the Lower Palaeozoic rocks due to a decollement zone in the Middle Cambrian Alum shale, the Caledonides in western Norway display thick-skinned deformation where the Precambrian basement has taken part in the deformation. The basement is increasingly deformed from east to west, displaying development of thrusting in the foreland to the east, and more ductile deformation towards the hinterland in the west (Bockelie and Nystuen, 1985; Hossack and Cooper, 1986; Roberts, 2003; Roberts and Gee, 1985).

Caledonian structuring within the Oslo Region

The most recent work done in the Oslo Region,with regards to the Caledonian deformation has been done by Nystuen (1981, 1983), Bockelie and Nystuen (1985), Morley (1983, 1986a, 1986b, 1987a, 1987b, 1989, 1992, 1994), Fjærtoft (1987),Ygre (1988), Hjelseth (2010), Bruton et. al. (2010) and Kleven (2010).

The Oslo Region is located in the Lower Allocthon, and is named the Osen – Røa nappe according to Nystuen (1981). The nappe complex is positioned within the external, frontal zone of the Caledonian fold and thrust belt (Bruton et al., 2010). Deformation of the Cambro-Silurian successions reveal a characteristic structural style with folding and thrusting related to a dècollement zone (the Osen- Røa thrust sheet) in the Cambrian Alum Shale, which undelie the entire Oslo Region. Cross – section restorations and lateral and vertical strain variation descriptions within the Oslo Region done by Morley (1983, 1986a, 1986b, 1987a, 1987b, 1989, 1992, 1994) suggest that the Cambro – Silurian stratigraphy has not been deformed uniformly. Deformation intensity is reduced along the thrust front and vertically within the Cambro-Silurian succession towards the south. This reduction in deformation intensity can be explained by contributing factors such as a decrease in transportation length to the south, vertical and latteral lithology variations and differences in bed thicknesses.

On the basis of the change in tectonic style and lithology both latteral and vertical within the Osen- Røa thrust sheet, Morley (1986b, 1987a) suggests to divide the stratigraphy into four different litho – tectonic units described by their different deformational characteristics (the Cambrian Alum shales Fm. (50 m thick), the Lower to Middle Ordovician limestone and shale of the Alum shale to end Skogerholmen Fm.(about 310 m thick), Upper Ordovician limestone, shale and sandstones of Husbergøya and Langøyene Formation(about 150 m thick), Silurian limestone, shale and the Ringerike sandstone of the Solvik to Stubdal Fm.(about 1140 m thick). Fjærtoft (1987) reviewed the deformation style in a less regional scale within the western part of the inner Oslofjord and modifies Morley's division some by dividing the stratigraphy into only three litho- tectonic units displaying different style of folding(Unit 1, Cambrian Alum shale Fm. to the Middle Ordovician Elnes Fm characterized by tight, disharmonic and asymmetrical folds. Unit 2, Upper Ordovician Vollen Fm. to the Silurian Solvik Fm. characterized by class 1C and class 2 folding (Ramsay et al., 1967). Unit 3 Silurian Solvik Fm and formations above is characterized by harmonic, near parallelle folding.) The most recent modifications in dividing the structural levels were done by Bruton et. al. (2010), where they define four structural levels associated flats whithin the Osen – Røa nappe complex based on transport direction, transport length and structural style. The basal thrust system, the middle thrust system, the third and fourth structural level (Fig. 2.6). The dominant trend of bedding and fold axis in the Oslo Region varies from NE-SW to ENE – WSW, while thrusts in the Oslo Region mainly show dipping towards NNW, which indicate transport towards the SSE (Bruton et al., 2010; Morley, 1986b). Back- thrusting with transport direction towards NNW are also present within the Oslo Region. These structures seams to post - date all other Caledonian structures (Bruton et al., 2010; Hjelseth, 2010; Kleven, 2010; Morley, 1987a).

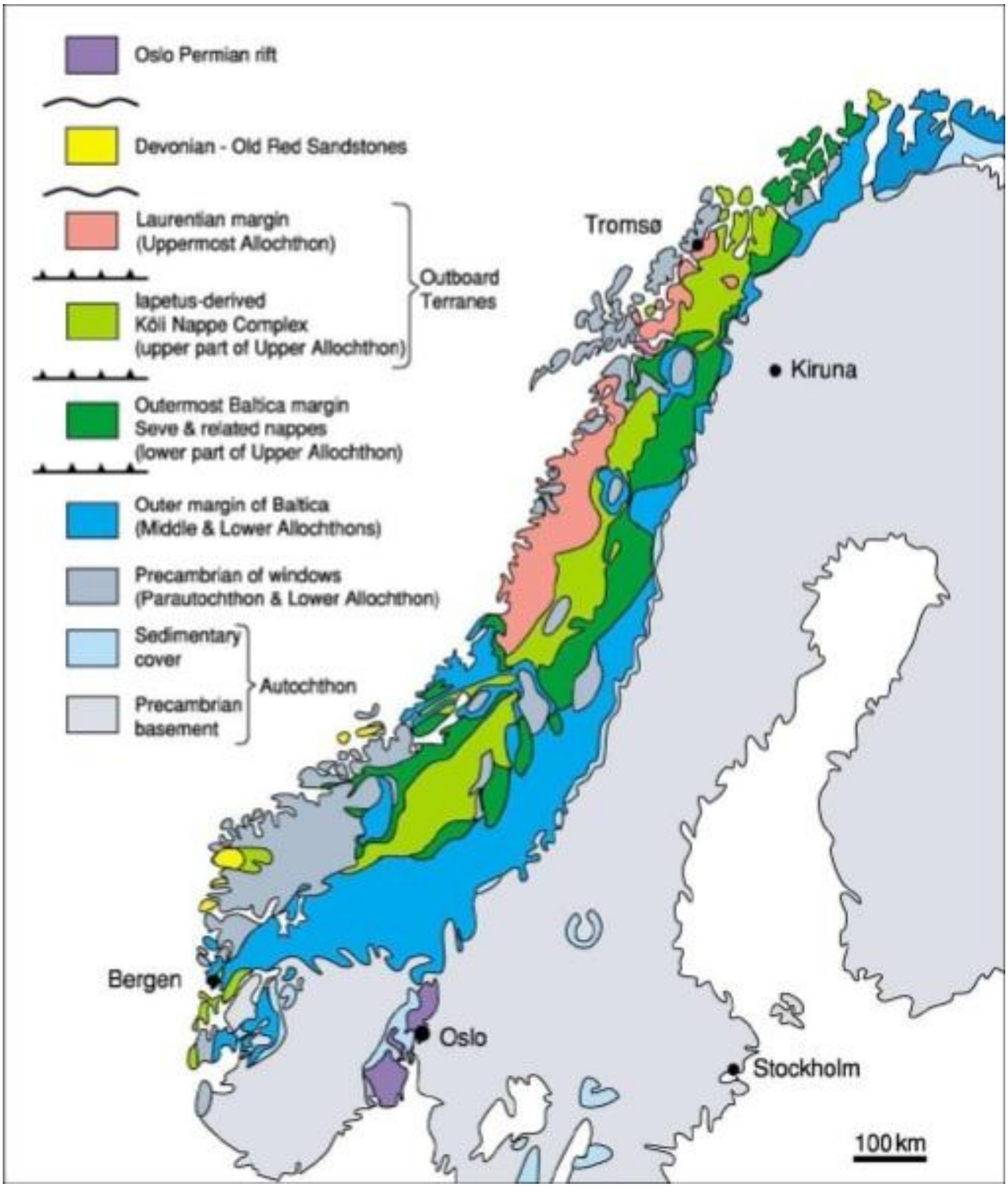


Fig. 2.4 Tectonostratigraphic map displaying the major nappe units within the Scandinavian Caledonides. Figure taken from Gee (2005).

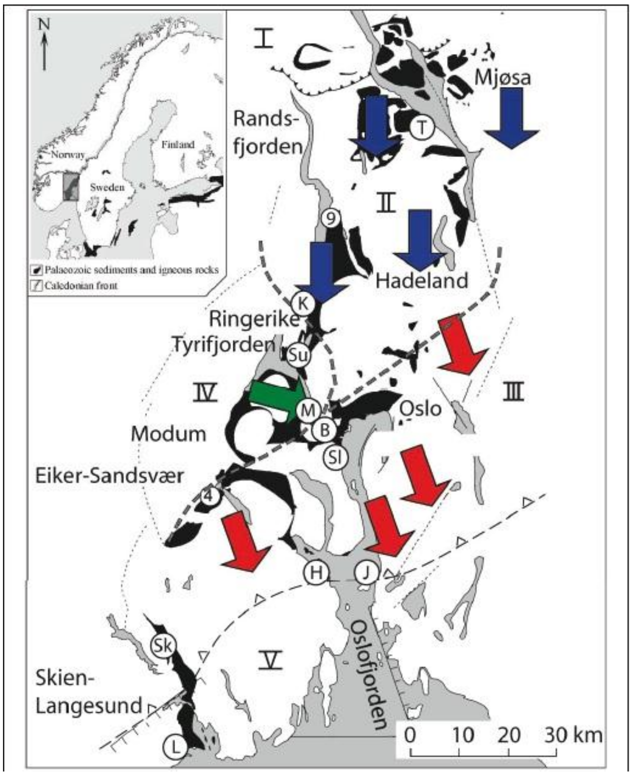


Fig. 2.5 Map of the Oslo Region displaying tectonic transport directions (shown by arrows), Lower Palaeozoic deposits (displayed in black) and the Caledonian thrust front. Figure taken from Bruton et. al. (2010).

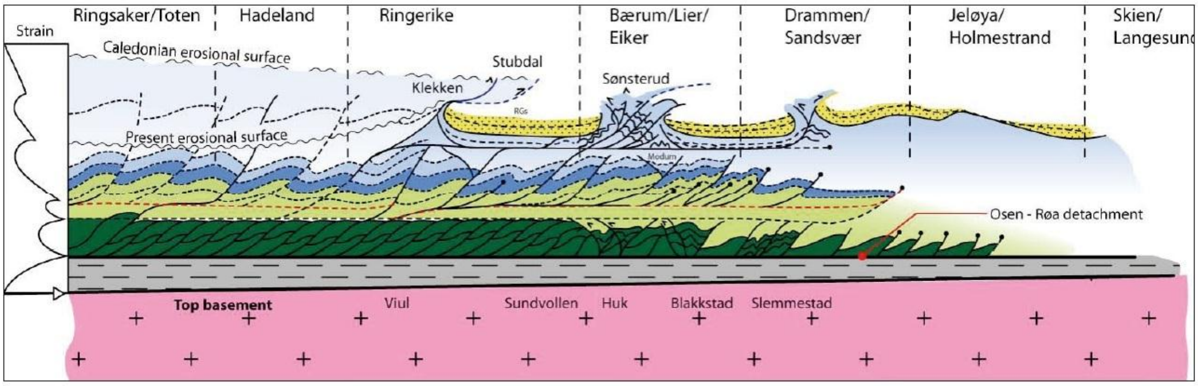


Fig. 2.6 NNW –SSE (left to right) cross – section of the Oslo Region displaying Osen – Røa detachment and the four structural levels defined by Bruton et. al. (2010). Strain intensity distribution curve to associated with each structural level are displayed in the figure to the left. Present and Caledonian erosional surface is indicated to the NNW in the figure, illustrating that the sequences to the north have not been protected by Permian volcanic rocks as in the south.

Structural level 1: The basal thrust is restricted to the Cambrian Alum Shale and display folding and imbrication with fold wavelengths of 100-300 m.

Structural level 2: The middle thrust system display structures that varies significantly in size and geometry, from meters to hundreds of meters.

Structural level 3: Display strongly folded and thrusted sequences with fold axis oriented NE-SW, characterized by steeply dipping thrust faults linked to the underlying structural level by faults ramping upwards.

Structural level 4: The master faults of structural level four are closely related to the structural level below and occur where the thrust faults have ramped through the Ringerike sandstones. The structures of this level is rarly preserved due to erosion and decreasing strain intensity upwards. Figure and text taken from Bruton et. al. (2010).

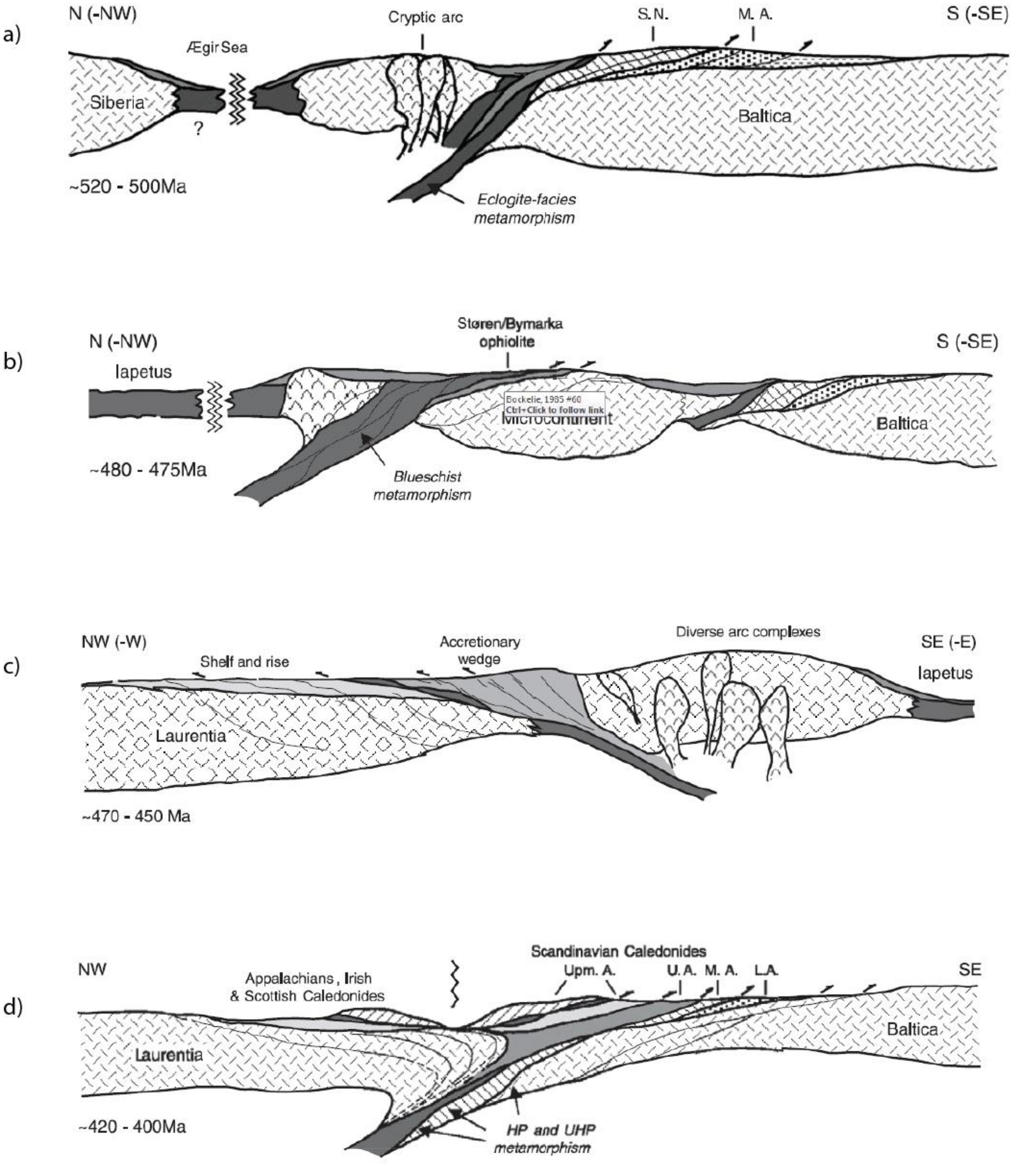


Fig. 2.7 The possible evolution of the Caledonides through the four major deformation events.

a) Schematic, composite profil illustrating the Finnmarkian accretionary event (520-500 Ma), oceanward subduction of the continental margin down to eclogite facies. S.N. –Seve Nappes; M.A. – Middle Allochton.
b) Schematic, composite profil illustrating the Trondheim event (480-475 Ma), oceanward subduction is inferred down to blueshist facies.
c) Schematic, composite profil illustrating the Taconian event (470-450 Ma), subduction and accretion, including eclogite generation and ophiolite obduction along the the continental margin of Laurentia.
d) Schematic, composite profil illustrating the Scandian event (420-400 Ma), continent–continent collision between Baltica & Laurentia. Relative motions of the two continental plates produced a major component of sinistral shear that is recorded in most parts of the Caledonian – Appalachian orogen. L.A., M.A., U.A. and Upm.A.—Lower, Middle, Upper and Uppermost Allochthons. Modified after Roberts (2003).

2.5 Late Carboniferous-Permian rocks

Due to a hiatus in the sedimentary succession between Late Silurian and Late Carboniferous, it is likely that during the Devonian and early- Middle Carboniferous, a lot of the Oslo region was exposed above sea-level. The hiatus between the Lower and Upper Palaeozoic sediments spans over a period of about 100 million years and represent a long period of erosion and low relative sea-level, and the Oslo region was probably eroded into a sub- "Permian" peneplain (Henningsmoen, 1978).

A thin package of sedimentary rocks were deposited in the Late Carboniferous. These are the only the Late Carboniferous-Early Permian sedimentary rocks whithin the Oslo Region that is preserved. These rocks are named the Asker Group, and are subdivided into three formations, Kolsås, Tanum and Skaugum. The Asker Group rests unconformably on the folded Cambro-Silurian strata, and represents a depositional environment ranging from floodplain, fluvial channel fill and shallow lake in the Kolsås Formation. Alluvial channels, floodplain and deltaic deposits in the Tanum Formation, and a volcanoclastic unit in the Skaugum Formation (Dons and Gyøry, 1967; Henningsmoen, 1978; Larsen et al., 2008; Sippel et al., 2010).

Permian rifting

The Oslo Rift was formed by extension and lithospheric stretching to the north of the Tornquist fault system and may be divided into four different graben segments, the Rendals Graben Segment in the north, the Akershus Graben Segment (north of Oslo) and Vestfold Graben Segment (south of Oslo), and the Skagerak Graben Segment to the south, with main boundary faults trending NNW-SSE to NNE-SSW (Fig. 2.8). The rifting initiated in the Late

Carboniferous and lasted for approximately 65 million years throughout the Permian (Larsen et al., 2008; Sundvoll and Larsen, 1994; Sundvoll et al., 1992; Wilson et al., 2004).
The Development of the Oslo rift can be subdivided into six different phases beginning in Late Carboniferous covering approximately 65 million years, and ending in Late Permian-Lower Triassic (Larsen et al., 2008; Neumann et al., 2004; Neumann et al., 1992; Olaussen, 1981; Sundvoll et al., 1990).

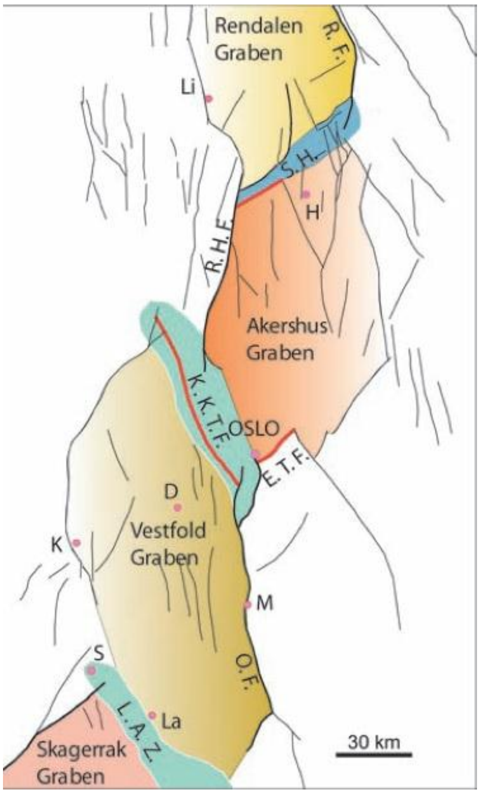


Fig. 2.8 Displaying the different graben segment and master faults in the Oslo Rift. (R.F = Rendalen Fault, S.H = Solberg Horst, R.H.F = Randsfjorden – Hunnselv Fault, K.K.T.F = Krokkleiva – Kjaglidalen Transfer Fault, E.T.F = Ekeberg Transfer Fault, O.F = Oslofjord Fault, and L.A.Z = Langesund Accommodation Zone. Li = Lillehammer, H = Hamar, D = Drammen, K = Kongsvberg, M = Moss, S = Skien, La = Larvik.)

The First rifting stage or proto-rift started with the deposition of the thin clastic and evaporitic sediments which make up the Asker Group. These sediments were deposited in a shallow basin, unconformable on top of the folded and thrusted Cambro-Silurian sedimentary succession. Magmatic activity started between 304 -294 Ma, with the intrusion of sills made up of a syenitic composition (Larsen et al., 2008; Olaussen, 1981; Sundvoll and Larsen, 1994; Sundvoll et al., 1992; Sundvoll et al., 1990). The initial rifting started in the southern part of the Oslo region with the production of basaltic lava flows. Radiometric U/Pb-dating show ages of approximately 300 Ma (Corfu and Dahlgren, 2008). According to fault-slip data, the initial rifting stage was controlled by two continuous strike-slip paleostress regimes. The first one with σ1 oriented in a NNE-SSW direction and a second one with an σ1 oriented N-S (Fig. 2.9)(Heeremans et al., 1996; Sippel et al., 2010). Main rifting phase is established by an intensive volcanic phase followed by extensive vertical movements along master faults. Intensive eruptions of trachyandesitic rhomb porphyry lavas markes the volcanic phase. These rocks are dated by using Rb/Sr dating to be approximately 294-283 Ma in the southern part, and approximately 290-276 Ma in the northern part of the Oslo graben (Larsen et al., 2008; Sippel et al., 2010). The main extrusive periode produced the central volcanoes which at the beginning formed basalts for then erupt explosively due to residual felsic melt products, forming calderas (Larsen et al., 2008; Neumann et al., 2004; Sippel et al., 2010). Numerous striated normal faults and tensile fractures are correlated with the main rifting phase. The faults display a tensional stress regime (vertical σ1) with horizontal NW–SE to WSW–ENE oriented σ3 (Fig. 2.9)(Heeremans et al., 1996; Sippel et al., 2010). The last stages of the Oslo rifting are characterized by the emplacement of the alkali syenitic to granitic batholiths dated to 265-255 Ma and emplacement of the granitic intrusions is dated to 251-241 (Larsen et al., 2008; Neumann et al., 1992; Sundvoll et al., 1990).

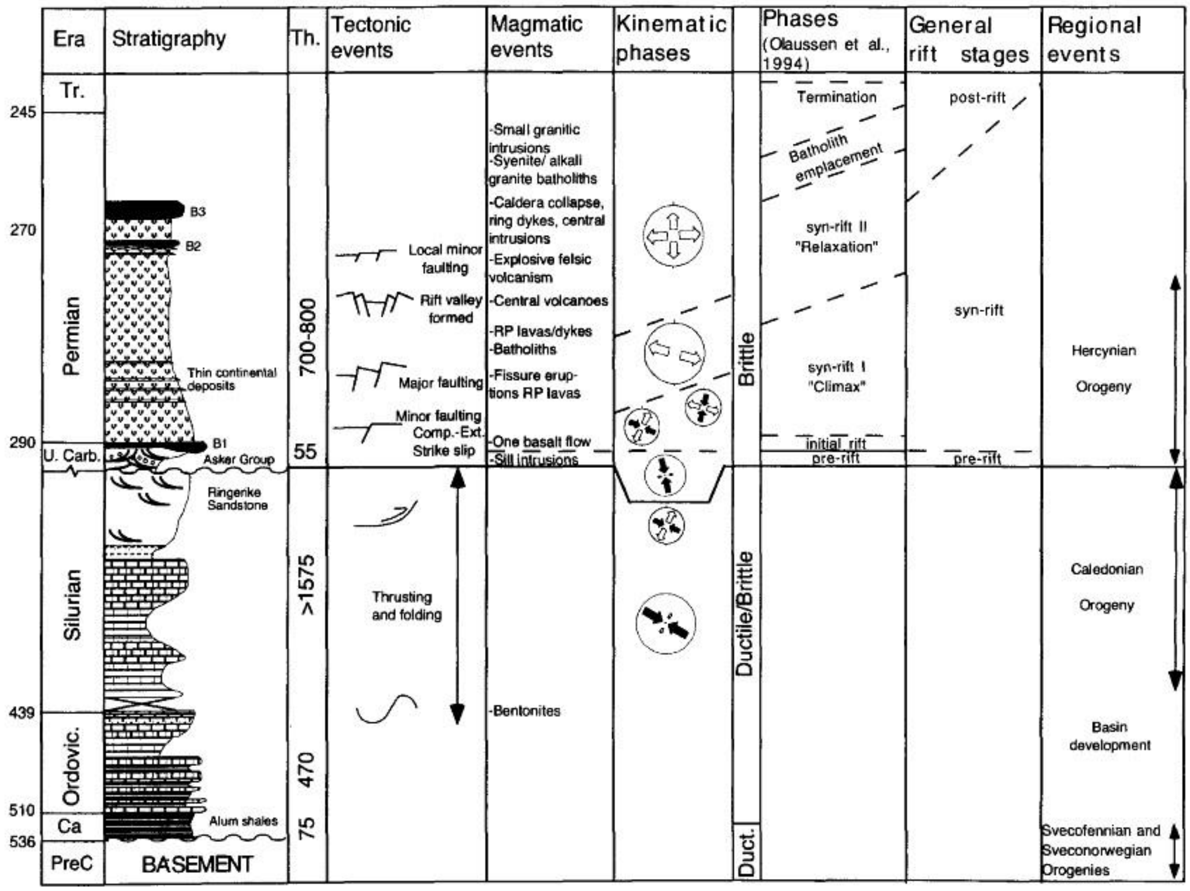


Fig. 2.9 Stratigraphy, tectonics and related magmatic activity in the Ringerike – Oslo area in association with calculated stress regimes. (Ca = Cambrian, B1, B2 and B3 are first, second and third basalt flow respectively. Figure and figure text taken directly from Heeremans et. al. (1996).

2.6 Post-Permian exhumation

It is estimated that a total volume of about 60,000 km3 of magmatic rocks was generated by the tectonomagmatic activity in the Oslo Graben area during the Permian rifting (Neumann et al., 2004). Although huge amount of Permian magmatic rocks already have been eroded a total volume of 28,000 km3 of magmatic rocks is still preserved within the Oslo Graben. Since the end of the Permo-Carboniferous rifting, the Oslo region has been affected by two periods of strong uplift and erosion, the first period was a result of rift margin erosion during Triassic-Jurassic (220-160 Ma) and the second period was the result of domal uplift in Neogene (30 Ma). Combined, these two phases of uplift and erosion removed a minimum of 2.8 km and a maximum of 6.0 km of Precambrian basement, Lower Palaeozoic sedimentary deposits and Permian magmatic rocks (Gabrielsen et al., 2010; Ramberg, 1974; Rohrman et al., 1995). Besides from the two periods of uplift, no tectonic activity or magmatic episodes has been recorded in the Oslo region (Gabrielsen et al., 2010; Heeremans et al., 1996; Sippel et al., 2010).

3 Lithostratigraphy of the study area

The modern lithostratigraphy of the sedimentary rocks found within the study area were established by Owen et. al. (1990) for the Ordovician sections and Worsley et. al. (1983) for the Silurian sections (Fig. 2.2).

The islands comprising the study area,Hovedøya and Lindøya, consist of Upper Ordovician to Early Silurian sedimentary rocks and are composed of alternating units of mudstone, limestone, siltstone and sandstone. Present within the study area there are eleven formations that will be described from stratigraphic older toyounger. Arnestad, Frognerkilen, Nakkholmen, Solvang, Venstøp, Grimsøya, Skjerholmen, Skogerholmen, Husbergøya and Langøyene Formation of Upper Ordovicium age, and the Solvik Formation of Early Silurian age. Below follows a summorized description of the lithology and formations found at Hovedøya and Lindøya. The descriptions is from the modern lithostratigraphy done by Owen et. al. (1990) and Worsley et. al. (1983).

Arnestad Formation

Description is taken from Owen et. al. (1990).
The main lithology of the Arnestad Formation (Fig. 3.1) consists of dark mudstone with thin limestone beds. The base of the formation is marked by thich dark shales with minor limestone horizons. Shale horizons are generally between 30-70cm thick. The nodular and bedded limestone horizons are almost continuously less than 10cm thick. Volcanic ash sediments called bentonite, are developed at various localities in Oslo region. The thickness of the formation is estimated by Brøgger to be about 45 m, while a study by Kvingan in 1986 estimated a thickness of about 22 m.

Frognerkilen Formation

Description is taken from Owen et. al. (1990).

The main lithology of the Frognerkilen Formation (Fig. 3.2) consists of bedded limestone and shale. The base of the formation is marked by a sudden change from the shale dominated Arnestad Formation into 10 cm thick limestone horizons passing into nodular and to the end bedded limestone and shales, up to 10 cm and 35 cm respectively. The formation thickness is between 10-12 m in the study area, and thinning towards the east.

Nakkhomen Formation

Description is taken from Owen et. al. (1990).

The main lithology of the Nakkholmen Formation (Fig. 3.3) is thick dark shale. The shale horizons are known to be more than 1 m thick in the eastern part of Oslo. Some isolated limestone nodules are found at various levels being up to 30 cm thick in the lower parts. While in the upper part these limestones form distinct 10 cm thick horizons. The thickness of the formation is estimated to be around 12-14 m in the study area and thickening westward to about 30-40 m in the Asker area.

Solvang Formation

Description is taken from Owen et. al. (1990).

Nodular and bedded limestone interbedded with calcareous shale make up the lithology of the Solvang Formation (Fig. 3.4). The formation is marked both at the base and above by dominantly shale units. At Nakkholmen, Bygdøy and Fornebu, the formation is composed of nodular limestone up to 20cm thick with intervening calcareous shales up to 60cm thick. On Raudskjer, such a development is only seen between 1-7m below the top of the formation. The thickness of the formation are estimated to be between 10 and 15 m thick in the study area.

Venstøp Formation

Description is taken from Owen et. al. (1990).

The Venstøp formation (Fig. 3.4) is composed of dark shale with dispersed limestone concretions. In the Oslo it is bounded below by a phosphoritic conglomerate and above by the Grimsøya limestone. The thickness of the formation is estimated to be 7-10 m in the study area.

Grimsøya Formation

Description is taken from Owen et. al. (1990).
The main lithology of the formation is alternating limestone and shale units. The base and the lower most part of the Grimsøya formation (Fig. 3.5) are med up of very thin nodular limestone horizons with shale separations. The upper part of the formation is made up of alternating bedded limestones and shales. The formation thins eastwards from above 46 meters in the Asker area to as little as 10m in the study area.

Skjerholmen Formation

Description is taken from Owen et. al. (1990).

The Skjerholmen Formation (Fig. 3.6) consists of alternating calcareous shale, silty nodular limestone and calcareous silt- and sandstone, where the shale horizons thickness vary from 10-50 cm, while the sandstone, siltstone and limestone usually are thinner than 10 cm. The siltstones and sandstones increases towards the top of the formation and some exhibits cross-bedding. The thickness of the formation varies considerably, but is by Brøgger estimated to be about 35-43 m in the study area.

Skogerholmen Formation

Description is taken from Owen et. al. (1990).

Limestone, shale and siltstone make up the main lithologies of the Skogerholmen Formation (Fig. 3.7). The Formation comprises two members called Hovedøya member and Spannslokket member. The base of the formation and base of the Hovedøya member marks a change to a nodular limestone dominated succession from the lime-silt and shale succession of the Skjerholmen Formation. The Hovedøya member is made up of alternating limestone, siltstone and shale beds. The Spannslokket member can be divided into a distinct 6-9 m thick dark shale unit at its base, while the second unit bear a strong resemblance to the underlying Hovedøya member with alternating limestones, siltstones and shales. Brøgger estimated on Hovedøya, that the Spannslokket member and the entire Skogerholmen Formation have thicknesses of 27.4 m and 43 m respectively.

Husbergøya Formation

Description is taken from Owen et. al. (1990).

The main lithology of the Husbergøya Formation (Fig. 3.8) is shale with an increase of sandstone towards the top. The base of the formation show a sudden change from nodular limestones to a shale dominated succession. At the top of the formation an up to 5 m thick bedded sandstone horizon has been developed. The thickness is estimated to be between about 15-20 m in the study area, with an overall decrease in thickness towards the west.

Langøyene Formation

Description is taken from Owen et. al. (1990) and Brenchley & Newall (1975).

The main lithology of the Langøyene Formation (Fig. 3.9) is sandstone, but the base of the formation is defined as the shales, laminated sandstones and limestone which overlie the top of the Husbergøya Formation. Increasingly more coarse grained calcareous sandstone (Fig. 3.10) is found towards the top of the formation. The thickness of the formation varies in East-West direction with a maximum thickness of about 60 m. In the study area, the thickness decrease to about 40-50 m.

Solvik Formation

Description is taken from Worsley et. al. (1983).

The main lithology of the Solvik Formation (Fig. 3.12) is shale, with increasing siltstone and limestone horizons. The base of the formation (Fig. 3.11) is marked in the study area by the sharp contact between the underlying calcareous sandstones and pale brown weathered sandstone at the top of the Langøyene Formation, and a 60 cm-thick nodular limestone overlying the dark grey silty shale. The basal stratotype of the Solvik Formation is actually defined on the south coast of Hovedøya. The thickness of the formation is estimated to be about 190 m thick at Malmøya, but due to faulting, an exact thickness determination is very difficult.

Fig. 3.1 Display the dark mudstone with thin limestone horizons of the Arnestad Formation. The outcrop is located on the northeast side of Hovedøya.

Fig. 3.2 Display the dense bedded and nodular limestone of the Frognerkilen Formation, with the boundary to the Arnestad Formation situated on the right side. The outcrop is located on the western shoreline of Hovedøya and displays

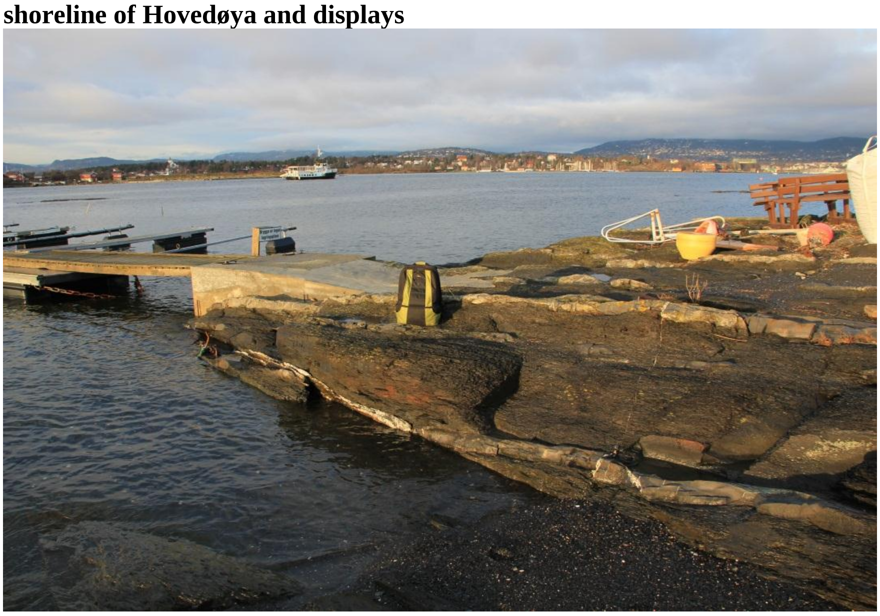


Fig. 3.3 Display the dark mudstone of the Nakkholmen Formation located on the western side of Lindøya

Fig. 3.4 Display the boundary between the bedded and nodular limestone of the Solvang Formation to the right, and the dark mudstone of the Venstøp Formation to the left in the picture. The outcrop is located on the western shoreline of Hovedøya

Fig. 3.5 Display the Grimsøya Formation. The outcrop is located on the western shoreline of Lindøya, and marks the abrupt change from bedded lime-, and siltstone of the Grimsøya Formation, to the dark mudstone of the Venstøp Formation towards the photo

Fig. 3.6 Display folded beds of the bedded limestone and siltstone of the Skjerholmen Formation. The outcrop is located near the soccer field on Hovedøya (in the middle of the island), photographer looking towards southwest.

Fig. 3.7 Display vertical dipping beds of the Skogerholmen Formation. The outcrop is located on southwestern side of Hovedøya. The backpack is situated on a approximately 2,5 meters wide shale unit which marks the beginning of the Spannslokket member.

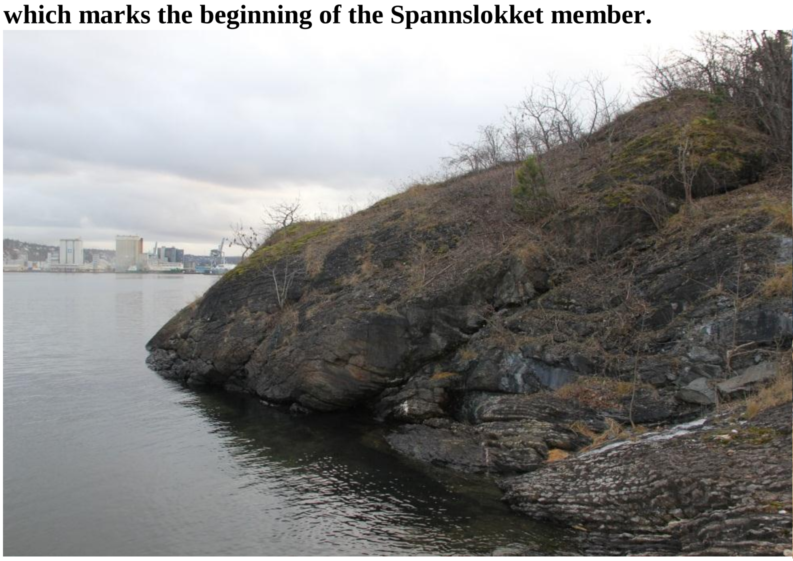


Fig. 3.8 Left picture: Displays the boundary between the underlying nodular limestone of the Skogerholmen Formation (Spannslokket member) and the mudstone dominated Husbergøya above. The

outcrop is located on the northeastern shoreline of Hovedøya. Right picture: Displays the same boundary, except the outcrop is located on the southwestern shoreline of Hovedøya.

Fig. 3.9 Left picture: Display slumping within silt-, lime- and sandstone beds of the Langøyene Formation. Right picture: Bedded lime-, silt- and sandstone within the Langøyene Formation. The outcrop is located near the shoreline, on the southernmost tip of Hovedøya.

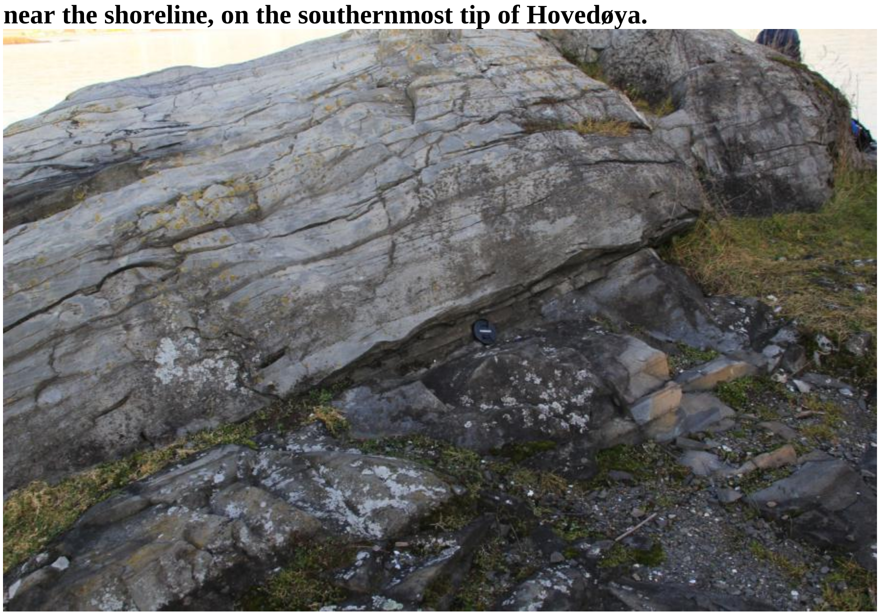


Fig. 3.10 Display cross-bedded coarse grained sandstone of the Langøyene Formation. The outcrop is located on the northwestern shoreline of Hovedøya.

Fig. 3.11 Display the Ordovician Silurian boundary with four distinct lithologies. The bedding is inverted. Top of the picture display the cross-bedded coarse grained sandstone of the Langøyene Formation. The Ordovician Silurian boundary is defined by a sharp contact between the brown weathering lime - and siltstone which marks the end of the Ordovician period and the grey nodular limestone below (stratigraphically above).

Fig. 3.12 Both pictures display the small scale folding within the Silurian Solvik Formation which comprises thin (~5-10 cm) siltstone beds within a dark mudstone. The outcrops are located on the southeastern shoreline of Hovedøya.

Conglomerate (incised Valley fill)

The Upper Ordovician Langøyene Formation at southern and northeastern tip of Hovedøya display a conglomerate unit (Fig. 3.13) consisting of calcareous sandstone and limestone boulders at the base and interbedded limestone, silt and sandstone in the upper part. Detailed studies of the on the Upper Ordovician deposits have been conducted by Brenchley and Newell (1975, 1979, 1980), and Bockelie (1978; 1982). Bockelie (pers.com.) suggest that the large channels in the area have been developed as incised valleys by incising the sediments as uplift exposed the Uppermost Ordovician successions above sea level, towards the end of the Ordovician. These incised valleys can be traced over large areas within Oslo, Bærum and Asker.

Fig. 3.13 Pictures display valley fill conglomerate consisting of calcareous sandstone and limestone boulders from the coarse grained calcareous sandstone of the Upper Ordovician Langøyene Fm. Boulders at the base overlain by interbedded limestone, silt and sandstone in the upper part. a) Located on the northeastern tip of Hovedøya, b) Located on the southeastern tip of Hovedøya, c) Same location as b)

4 Structural geology of the study area

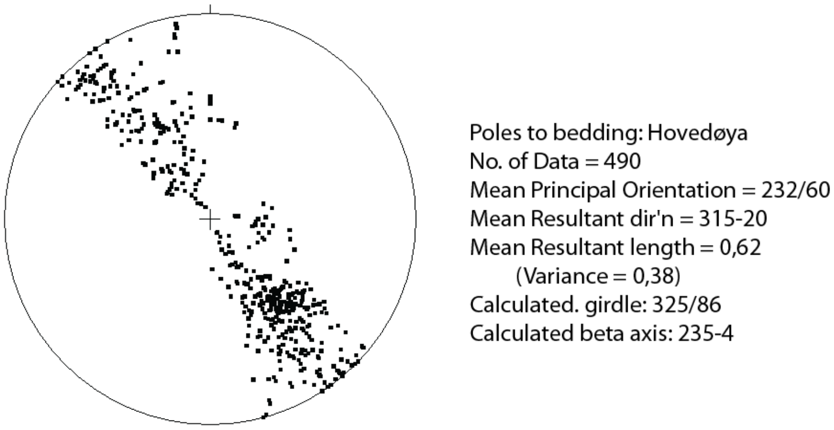
4.1 Main structural elements of the study area

The structural elements within the study area reflects in particular two different phases of deformation, the Caledonian Orogen and the Permian rifting. From these two phases, we can define the Caledonian contractional structures and the Permian extensional structures. The geological maps of the study area (Appendix A- Geological maps) show that the Lower Paleozoic deposits are folded in both macroscopic and mesoscopic scale. Observations made from field measurements (Fig. 4.1) and geological mapping (Appendix A- Geological maps), supports the theory that a macroscopic anticline covers the entire study area. Mesoscopic folding and thrusting, as well as cleavage development also occures in several formations and with differences in scale.

Permian extensional structures within the study area can by seen in the geological maps (Appendix A- Geological maps), by normal faulting accompanied by intrusion of Permian dykes. The Permian structures display a general N – S trend within the study area.

The orientations of bedding planes (Fig. 4.1) within the study area display a NE – SW strike, with dip towards NW and SE respectively. There is a predominance of bedding planes within the study area which have dip towards the NW, aspecially at Hovedøya, were the macroscopic fold is overturned with vergence towards the SE (Appendix A2: Geological map of Hovedøya).
The overturned folding towards SE and bedding planes with dip towards NW indicate that the direction of the maximum stress axis is oriented NW – SE, with a transport direction towards SE, which is in accordance with previous work in the Oslo area.

The study area consists of Lower Paleozoic deposits with alternating lithologies such as shale, bedded limestone, nodular limestone, siltstone and sandstone, and comprises ten formations of the Upper Ordovicium age ,Arnestad, Frognerkilen, Nakkholmen, Solvang, Venstøp, Grimsøya, Skjerholmen, Skogerholmen, Husbergøya and Langøyene, and one formation of the Early Silurian age, the Solvik Formation. Primary sedimentary structures such as cross-stratification, loading structures and trace fossils are also found within the study area.



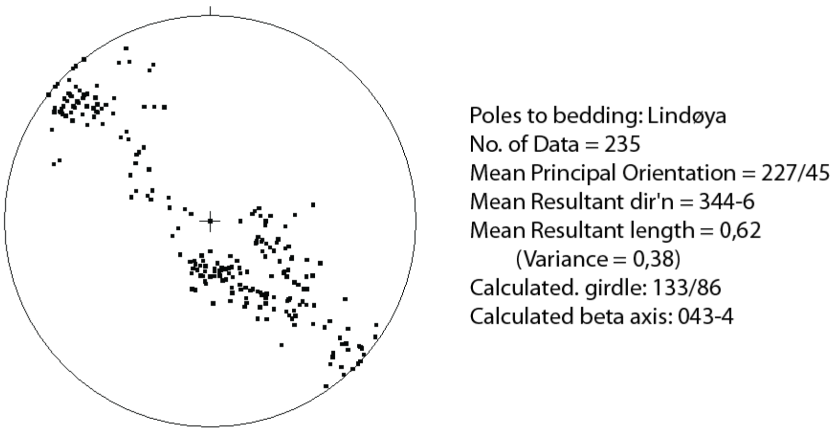


Fig. 4.1 Stereographic projections displaying all bedding planes measured in the field of the two islands (Hovedøya, n=490 and Lindøya, n=235) within the study area.

Description of geological maps and cross-sections

The geological maps of the study area found in Appendix A- Geological maps, and is based on the lithological field observations made in the study area. The formations from the modern lithostratigraphy established by Owen et. al. (1990) for the Ordovician sections and Worsley et. al. (1983) for the Silurian sections (Fig. 2.2) make up the basis for recognizing the different lithologies and lithological boundaries in the field.

From the geological maps (Appendix A- Geological maps), the macroscopic structures of the study area can be interpreted, as the same formations are found on opposite sides of the islands, with older Lower Paleozoic deposits towards the center. The macroscopic structure of the study area are interpret to be a macroscopic overturned anticline with southeasterly vergence on Hovedøya and a upright

There were also constructed two cross-sections across the study area, one for Hovedøya and one for Lindøya. The Hovedøya profile is oriented NW (322˚) to SE (142˚), and the Lindøya profile is oriented NW (322˚) to SE (142˚), which is perpendicular to the mean strike of the bedding planes in the area.

4.2 Caledonian contractional structures

The Caledonian contractional structures are described separately in different sub-chapters according to their assumed time relationship based on previous structural work in the Oslo Region, displaying Early formed bedding parallel structures, folds, foreland directed thrusts and reverse faults, hinterland directed thrusts and reverse faults and cleavage development.

The cleavage chapter display three uniqe cleavages with different development in relation to timing , and is because of this placed as the last sub-chapter in the Caledonian contractional structures.

Thrust are presented as "*Foreland directed thrusts and reverse faults*", displaying fault planes dipping towards NW, with thrusting towards SE, and "*Hinterland directed thrusts and reverse faults*", displaying fault planes dipping towards SE, with thrusting towards NW. This is because of the location of the Oslo Region with respect to the Caledonian fold and thrust belt and the bulk transport direction within the Oslo Region (Fig. 2.5).

Fold and thrusts- bedding parallel shortening

Three different localities within the study area display bedding parallel shortening structures. The structures are belived to be early formed structures, which means that they are belived to have been formed before the macroscopic and mesoscopic folding and thrusting of the study area. The different locations of the described outcrops supports this conclusion, since the layers which the structures are in have been later folded and tilted.

Locality A1: Fold and thrusts- bedding parallel shortening

The outcrop is located towards the southeastern side of Badebukta, which lies on the southwestern shoreline of Hovedøya. The outcrop display shallow dipping beds made up of bedded shale, limestone and siltstone of the Skjerholmen Formation. The thrusting were confined to single layers of competent limestone and siltstone.

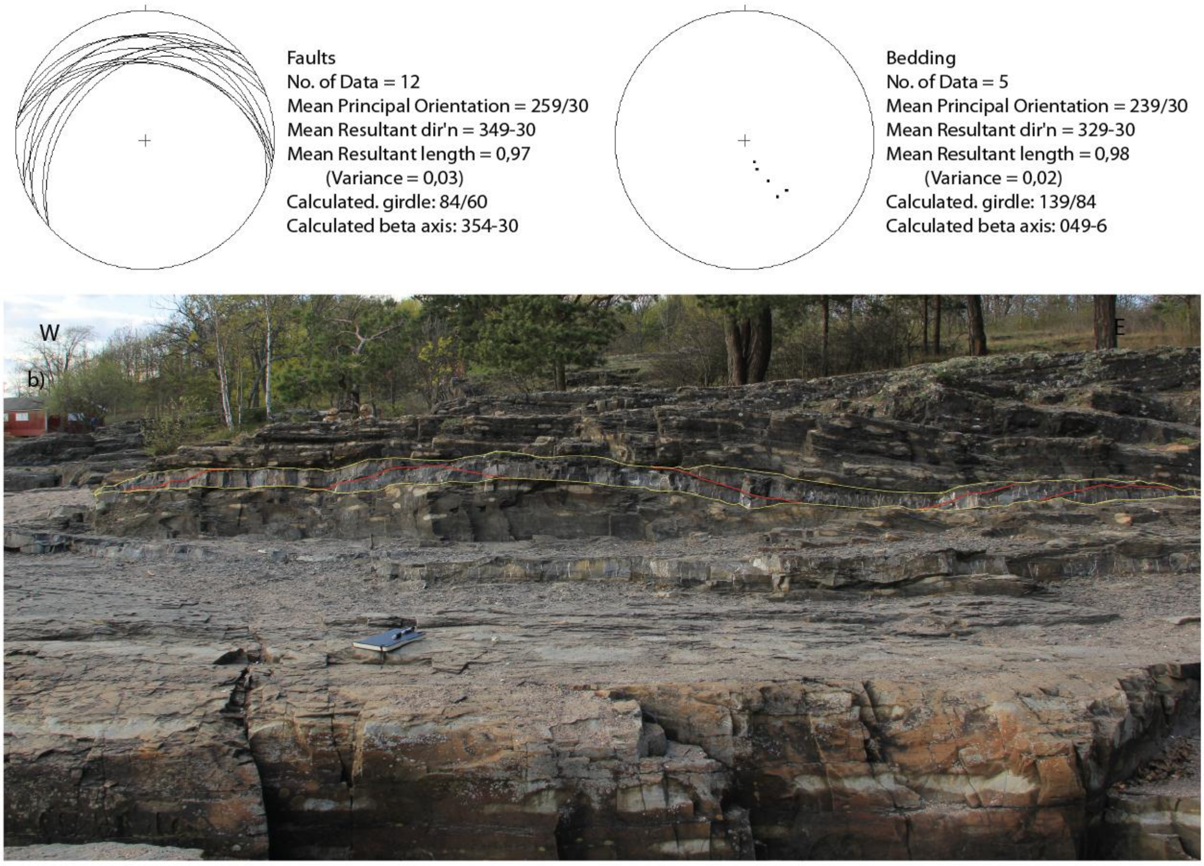


Fig. 4.2 Location A1 displays low angle thrust faults(red lines) confined to a single limestone layer(yellow lines). Stereoplot and statistics of bedding and thrust faults displayed above. (N 59° 53.595', E 10° 43.671')

Locality A2: Fold and thrusts- bedding parallel shortening

The outcrop is located on the southern tip of Hovedøya. The outcrop display beds made up of bedded limestone, siltstone and sandstone of the Upper Ordovician Langøyene Formation. The thrusting is confined to a single layer of competent limestone and siltstone and show a mean orientation of 252/47 (Fig. 4.3, stereographic projection Fault plane). The bedding is striking NE-SW and display an intermediate to steep dip (Fig. 4.3, stereographic projection bedding).

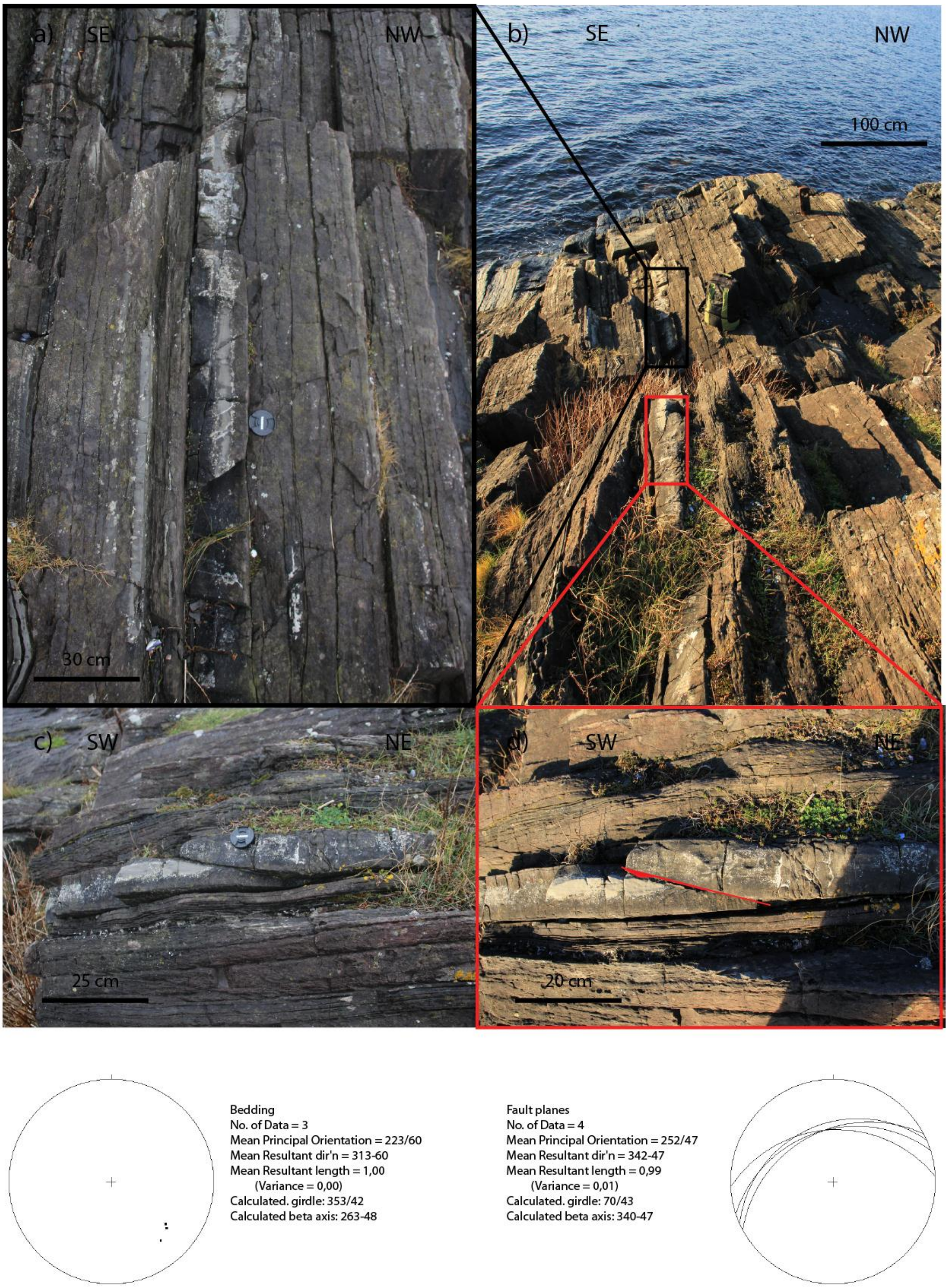


Fig. 4.3 Locality A2 display small thrusts confined within a single bed (10-20 cm thick) of limestone and sandstone within the Langøyene Formation at the south tip of Hovedøya (N 59° 53.464', E 10° 43.591'). The bedding is inverted and display a mean orientation of 223/60. Stereographic projection of bedding and fault planes are displayed below.

Locality A3: Fold and thrusts- bedding parallel shortening

Locality A3 is located on the SE side of Badebukta and comprises the Skogerholmen formation which consists of an interlayered bedded and nodular limestone and shale sequence, with bed thicknesses ranging from 5 to 20 cm. The thicknesses of the beds are comparable.

The locality displays folding and low angle thrusting with relation to bedding, in an interlayered nodular limestone and shale sequence, and three fold folds axes were calculated from strike and dip measured within the same limestone layer.

FA 1 is a gentle symmetrical fold with a recumbent attitude. The calculated beta axis from strike and dip measurements displays a trend and plunge of 224/21 (Fig. 4.4, FA1). FA 2 and 3 displays a tight asymmetrical z-fold with a gently inclined and gently plunging attitude. The calculated beta axis is measured to be 221/0 for FA2 and 046/0 for FA3 (Fig. 4.4b, FA2 and FA3).

The fault (Fig. 4.4, F1) displayed in the picture are consistent with bedding parallel thrusting when if rotated back to horizontal. The thrusting develops in a thicker limestone layer than the small scale folding (FA1, FA2 and FA3) and thereby develops in the brittle regime as low angle to bedding thrust, rather than the ductile small scale contractional folding in thinner shale beds.

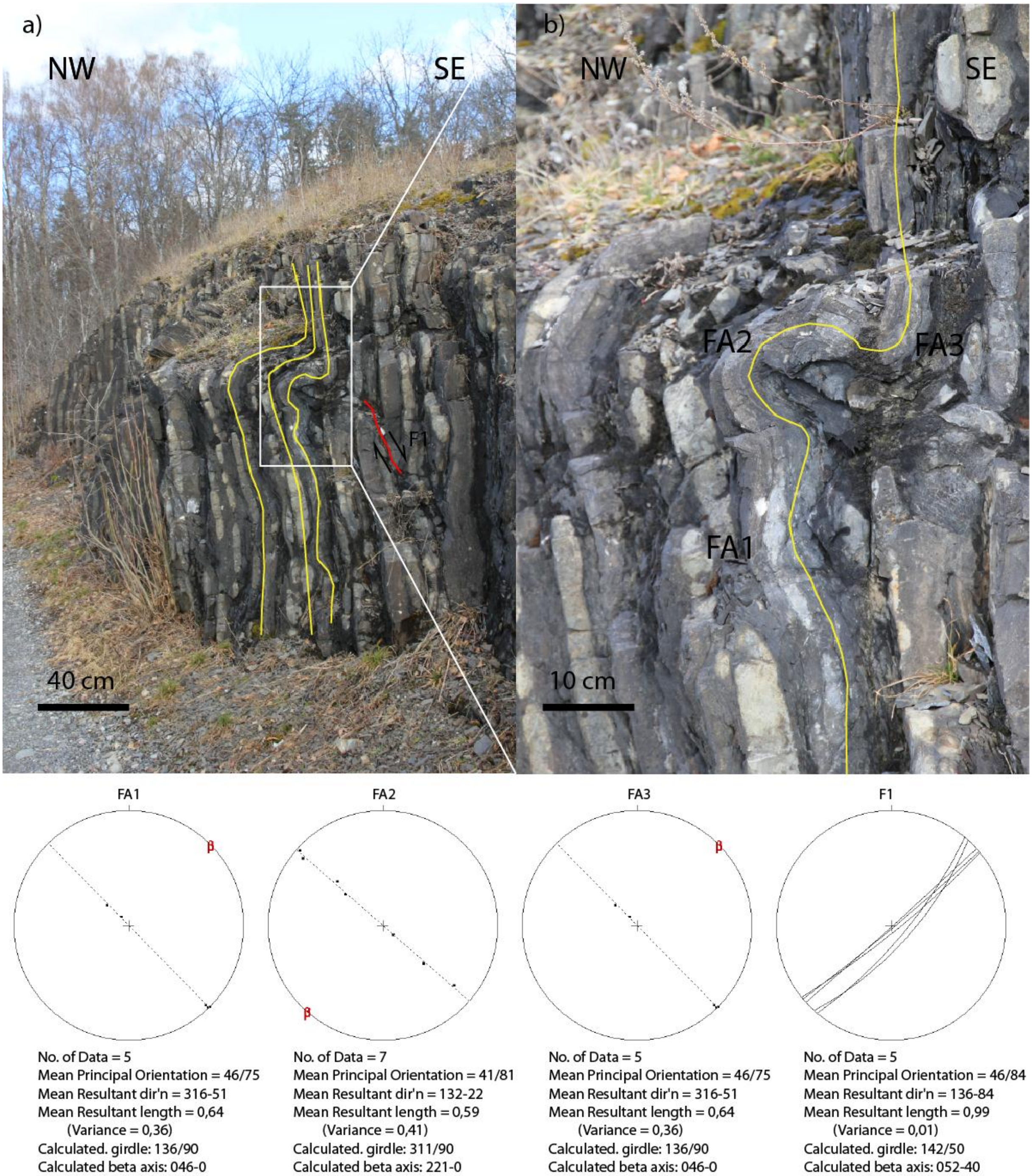


Fig. 4.4 Locality A3: Outcrop displaying small scale folding and a thrust fault. Stereoplot of folded beds are displayed as F1-F3, and the thrust fault is displayed as F1. Calculated statistics is displayed below each stereoplot. (N 59° 53.571', E 10° 43.674')

Folds

Folding is one of the main structural elements found in the study area. Bedding planes within the study area (Fig. 4.1) display a macroscopic folding which covers the entire study area. Most bedding planes display dip towards NW, this can be related to the fact that most of the thrusting and folding in the study area display vergence towards SE, which is in complience with previous work within the Oslo Region (Fig. 2.5).

Measurements of bedding planes (n= 725) have been plotted in stereographic projections (Fig. 4.5, equal area, Schmidt net) and display a regional fold axis of 231/1.

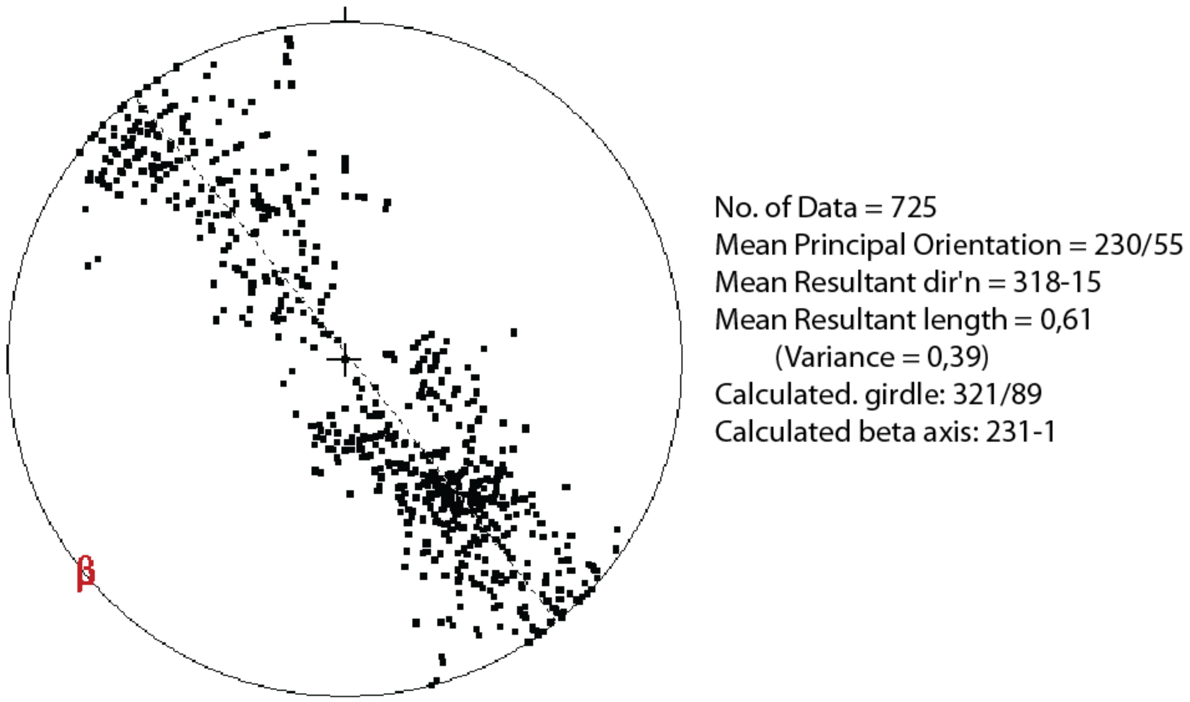


Fig. 4.5 Stereographic projections displaying all bedding planes (n = 725) measured in the study area.

Locality B1 – Folds

Locality B1 is located on the eastern tip of Hovedøya and comprises the Upper Ordovician Langøyene Formation which consists of calcareous sandstone, limestone and shales subsequently. The locality is characterized by a large synclinal fold structure shown in Fig. 4.6a, with a normal fault cutting the bedding in the southern corner (Fig. 4.6a, b).

The Ordovician Silurian boundary is found on the southeastern limb of the syncline, near the shoreline (displayed in Fig. 4.31). The lithology is displayed with the Silurian shale on top of Upper Ordovician sandstone indicating locality position within the fold structure. Bedding planes measured within the locality are displayed in stereoplot (Fig. 4.6, stereographic projection 1), and show a calculated beta axis of 224/11.

Fault desription

A normal fault cutting through bedding planes are shown in (Fig. 4.6a, b), with fault plane measurements shown in stereoplot (Fig. 4.6, stereographic projection 2).

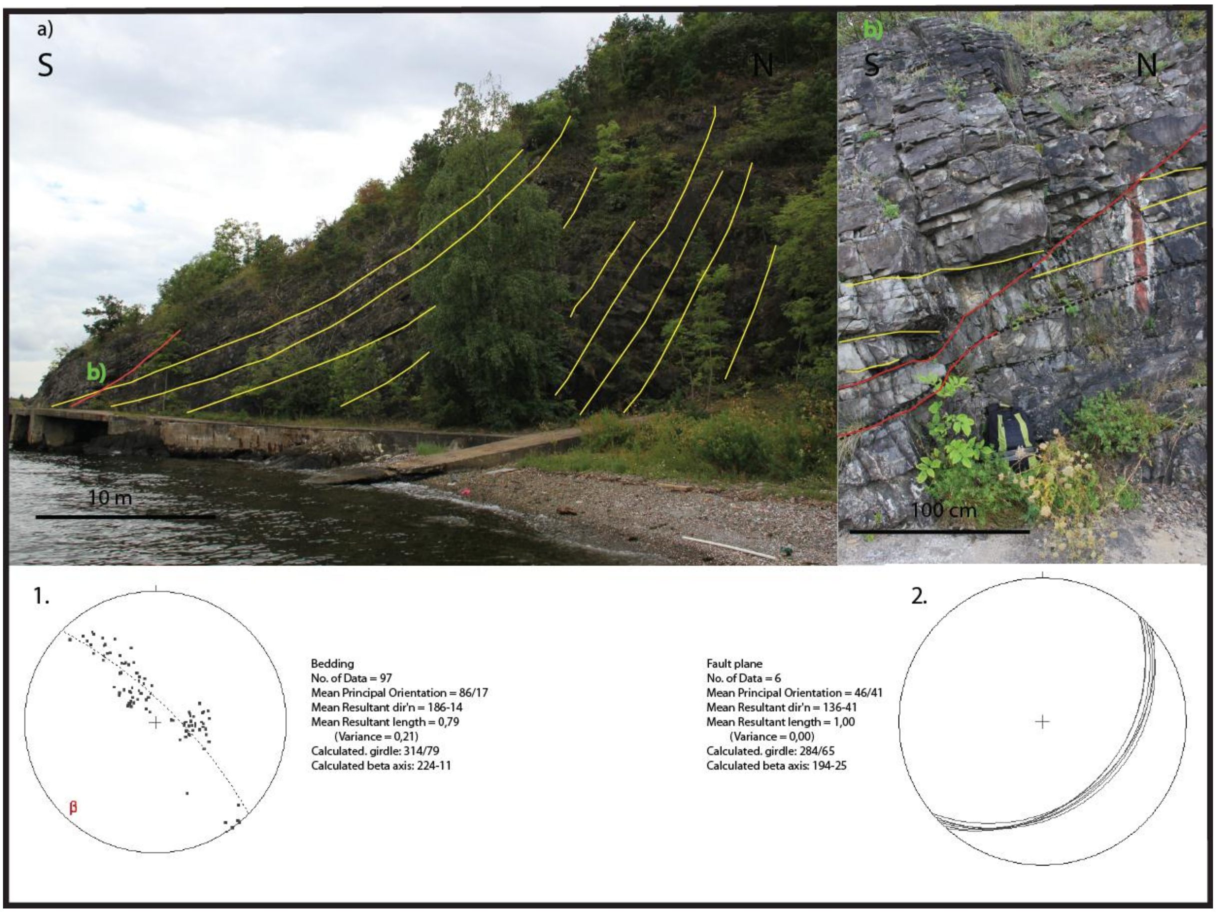


Fig. 4.6 Locality B1: a) Large fold structure displayed by change in bedding plane (yellow lines) dip. b) Small section within figure a showing a normal fault (red lines) with a displacement of approximately 10-50 cm. Stereoplot of bedding and fault planes and associated calculated statistics displayed below. (N 59° 53.759', E 10° 44.516')

Locality B2 – Folds

Locality B2 is located on the southeastern shoreline of Lindøya in the Upper Ordovician Frognerkilen Formation. The locality displays a single fold in an interlayered nodular limestone and shale sequence, with limestone beds ranging from 5 to 20 cm and shale beds ranging from 2 – 15 cm. The limestone and shale beds are comparable.

Towards the northwest of the fold, bedding planes display an average strike and dip of 237/40 (Fig. 4.7, stereographic projection 2). On the southeast side of the fold, bedding planes shift to an average strike and dip of 049/74 (Fig. 4.7, stereographic projection 3). The Fold is an open symmetrical anticline with a steeply inclined horizontal attitude. Strike and dip measurements from the fold limbs give a calculated beta axis of 243/0 (Fig. 4.7, stereographic projection 1).

The orthogonal thickness is constant in the limestone layers from hinge to limbs and is characterized as a class-1B fold. The shale layers can be described as class 3 folds. The classification of the multilayered fold is a class 2 fold. The fold was not fully exposed so the wavelength and the amplitude could not be recorded. However, the minimum wavelength and amplitude must be greater than 4 and 2 meters subsequently.

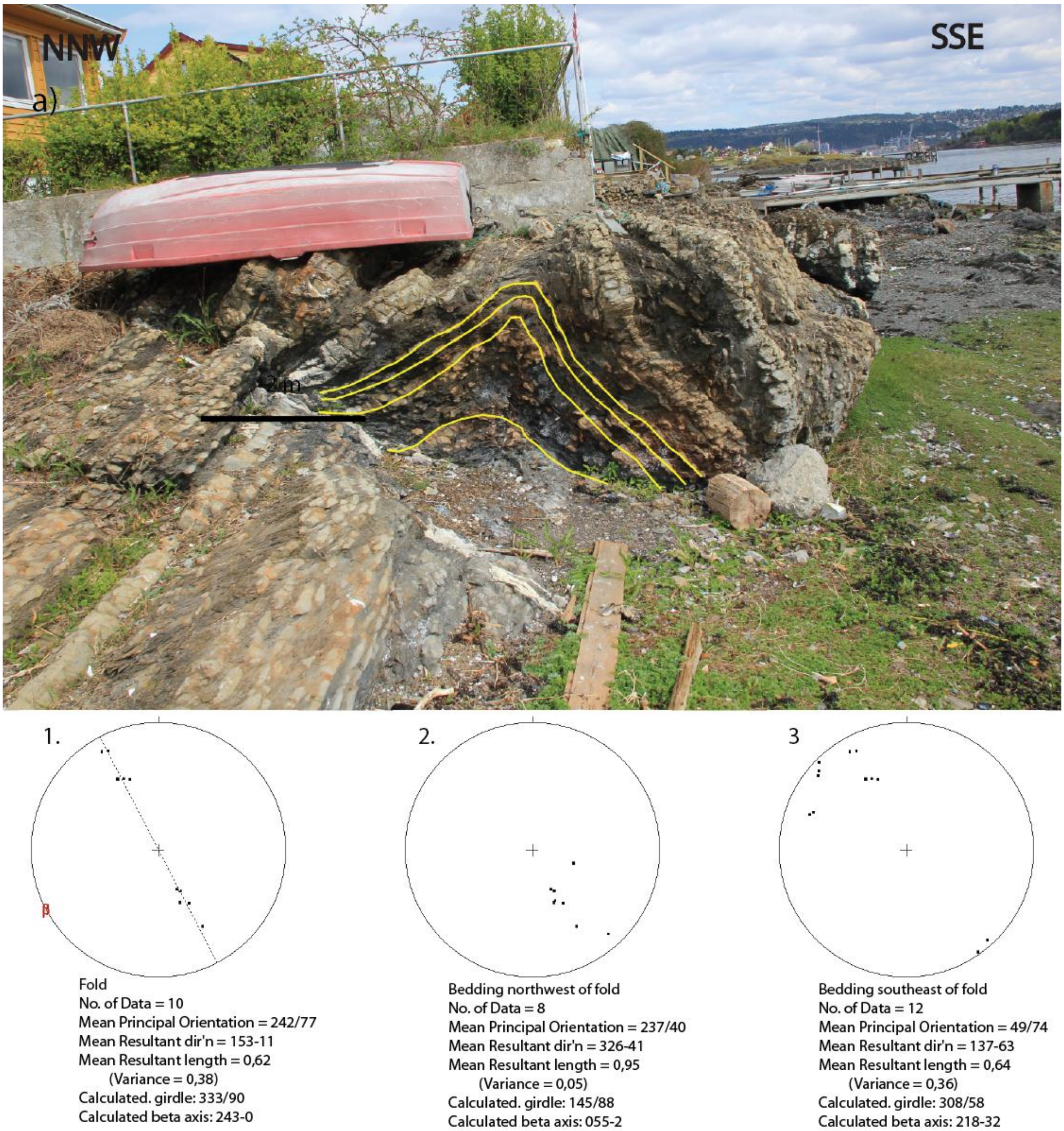


Fig. 4.7 Locality B2; Displaying an open symmetrical anticline with a steeply inclined horizontal attitude. 1) Stereographic projection calculated fold axis. 2) Stereographic projection of bedding planes measured within a proximity of 50 meters NW of the fold. 3) Stereographic projection of bedding planes measured within a proximity of 15 meters SE of the fold. (N 59° 53.198', E 10° 42.276')

Locality B3 – Folds

Locality B3 is located on the southern shoreline of Lindøya in the Upper Ordovician Frognerkilen Formation. The locality displays a single fold in an interlayered nodular limestone and shale sequence, with thicknesses of each bed ranging from 5 to 20 cm (Fig. 4.8). The the limestone and shale beds are comparable and have approximately the same thickness. The competent limestone beds seems to controll the folding and display a shallow NE plunging, open upright anticline, classified as a Class 1B fold after Ramsey (1967)

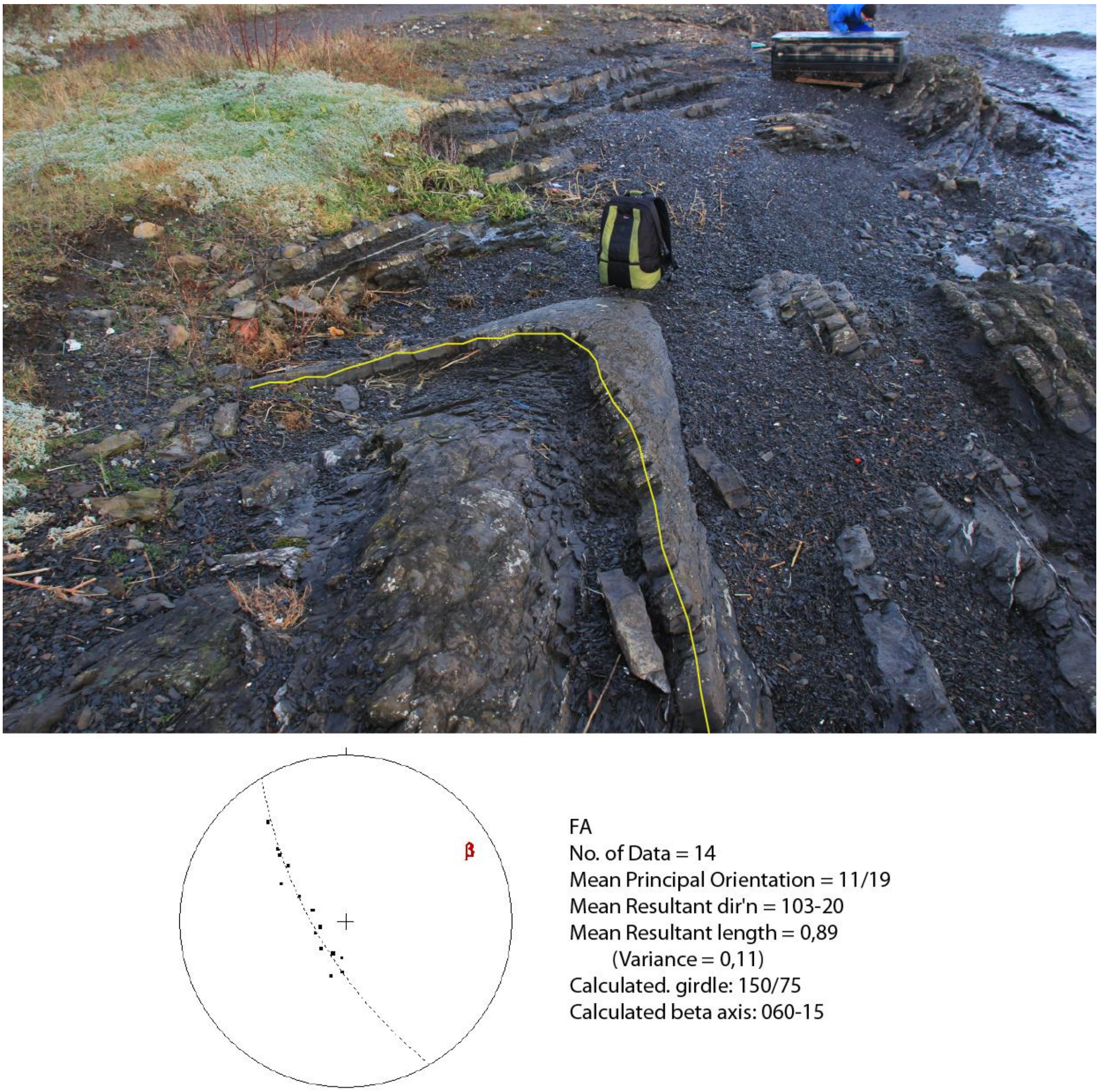


Fig. 4.8 Locality B3 displays folding in the limestone and shale of the Frognerkilen Formation. Backpack as scale. Stereographic projection display poles to bedding. (N 59° 53.246', E 10° 42.471')

Locality B4 – Folds

Locality B4 is located on the southwestern shoreline of Lindøya in the Upper Ordovician Arnestad Formation. The locality displays two separate folds in an interlayered bedded lime- and siltstone and shale sequence, with thicknesses of each bed ranging from 5 to 45 cm (Fig. 4.9). The the limestone beds display thicknesses of 5-10 cm and shale beds display thicknesses of 15-45 cm. The folding may be controlled by a blind thrust surface assumed to be within 5-40 meters towards NW. The folds (Fig. 4.9 & Fig. 4.10) demonstrates horizontal to shallow NE plunging, open synclines, with consistent bed thicknesses classified as a Class 1B fold after Ramsey (1967).

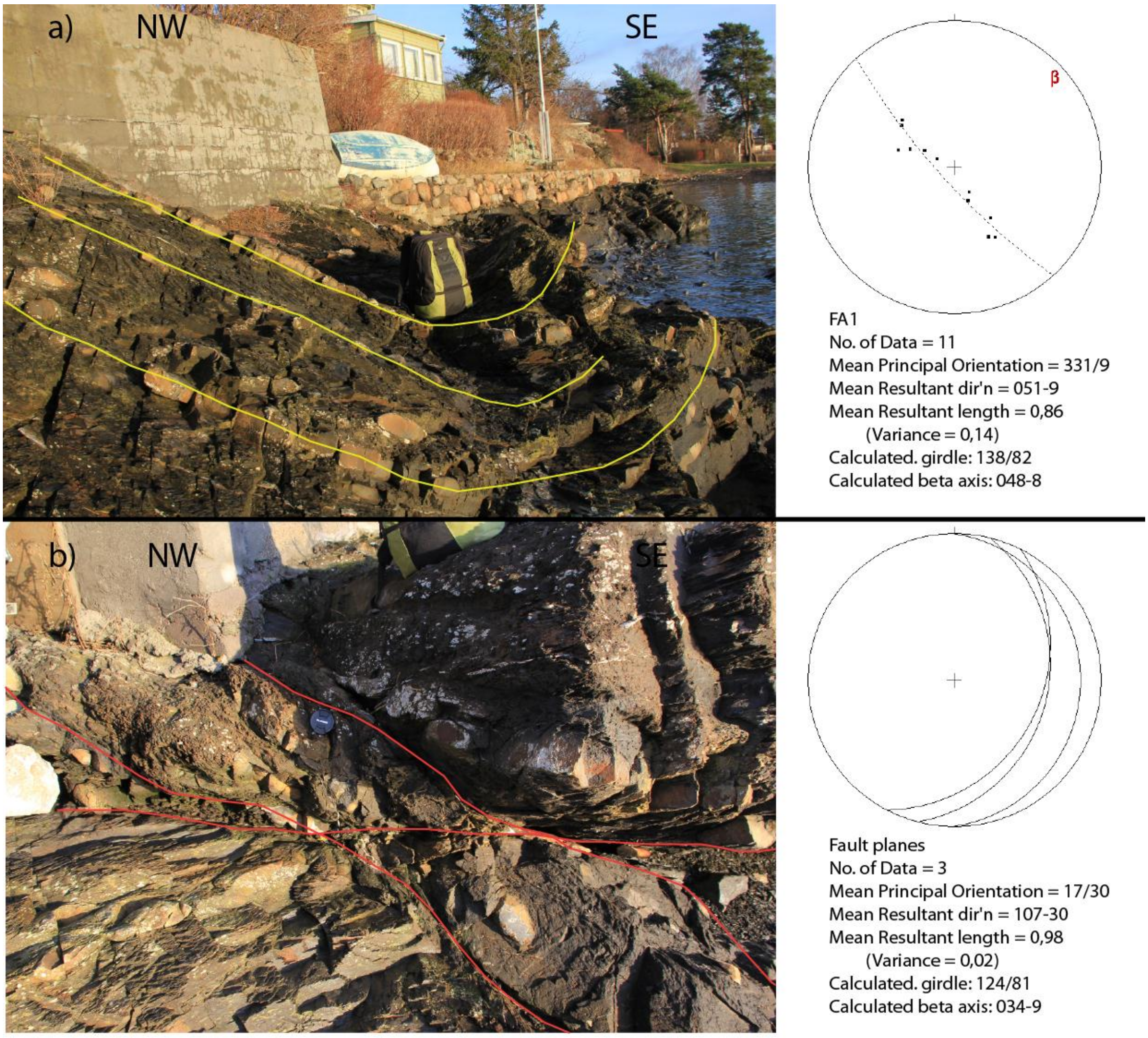


Fig. 4.9 Locality B4a: a) Display folding of bedding. b) Display calcite filled faults cutting through the beds in the shale and limestone succession of the Arnestad Formation. Backpack and lens cap as scale. Stereographic projections of fold axis and fault plane are shown to the right of the figures. (N 59° 53.274', E 10° 42.251')

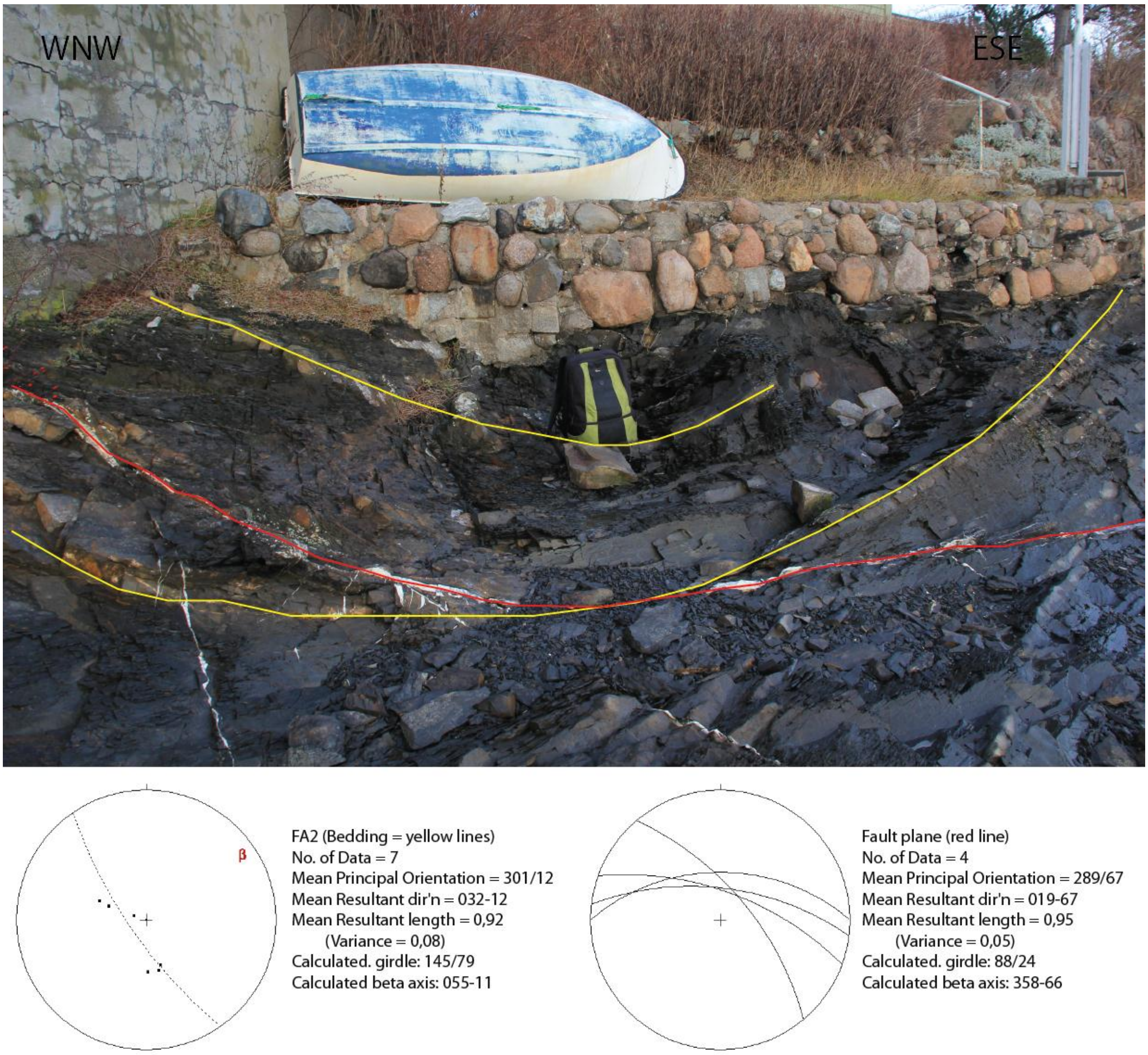


Fig. 4.10 Locality B4b displaying folding of bedding with a calcite filled fault cutting through the beds within the shale and limestone succession of the Arnestad Formation. Backpack as scale. Stereographic projections of fold axis and fault plane are shown below. (N 59° 53.274', E 10° 42.251')

Locality B5 – Folds

The outcrop is located on the southwestern shoreline of Hovedøya, in the middle of the beach area. The outcrop displays the intensely folded limestone, shale and siltstone of the Skjerholmen Formation. The folding consists of limestone, shale and siltstone beds, with bed thicknesses ranging from 5 to 30 cm (Fig. 4.11). The fold demonstrates a horizontal NE plunging, open synclines, parallel fold classified as a Class 1B fold after Ramsey (1967).

Fig. 4.11 Location B5 displays intensely folded limestone and siltstone of the Skjerholmen Formation. Backpack as scale. Bedding is marked as yellow lines. The Stereographic projection display poles to bedding, and the calculated beta axis for the fold. (N 59° 53.605', E 10° 43.655')

Locality B6 – Folds

The outcrop is located on the southwestern side of the soccer field in the middle of the island on Hovedøya, and display the intensely folded limestone, shale and siltstone of the Skjerholmen Formation. The fold consists of limestone, shale and siltstone beds, with bed thicknesses ranging from 5 to 15 cm (Fig. 4.12). The fold demonstrates a horizontal NE plunging, open parallel fold in the limestone and shale units classified as a Class 1C folds, and similar folds classified as Class 2 in the shaleunits, after Ramsey (1967).

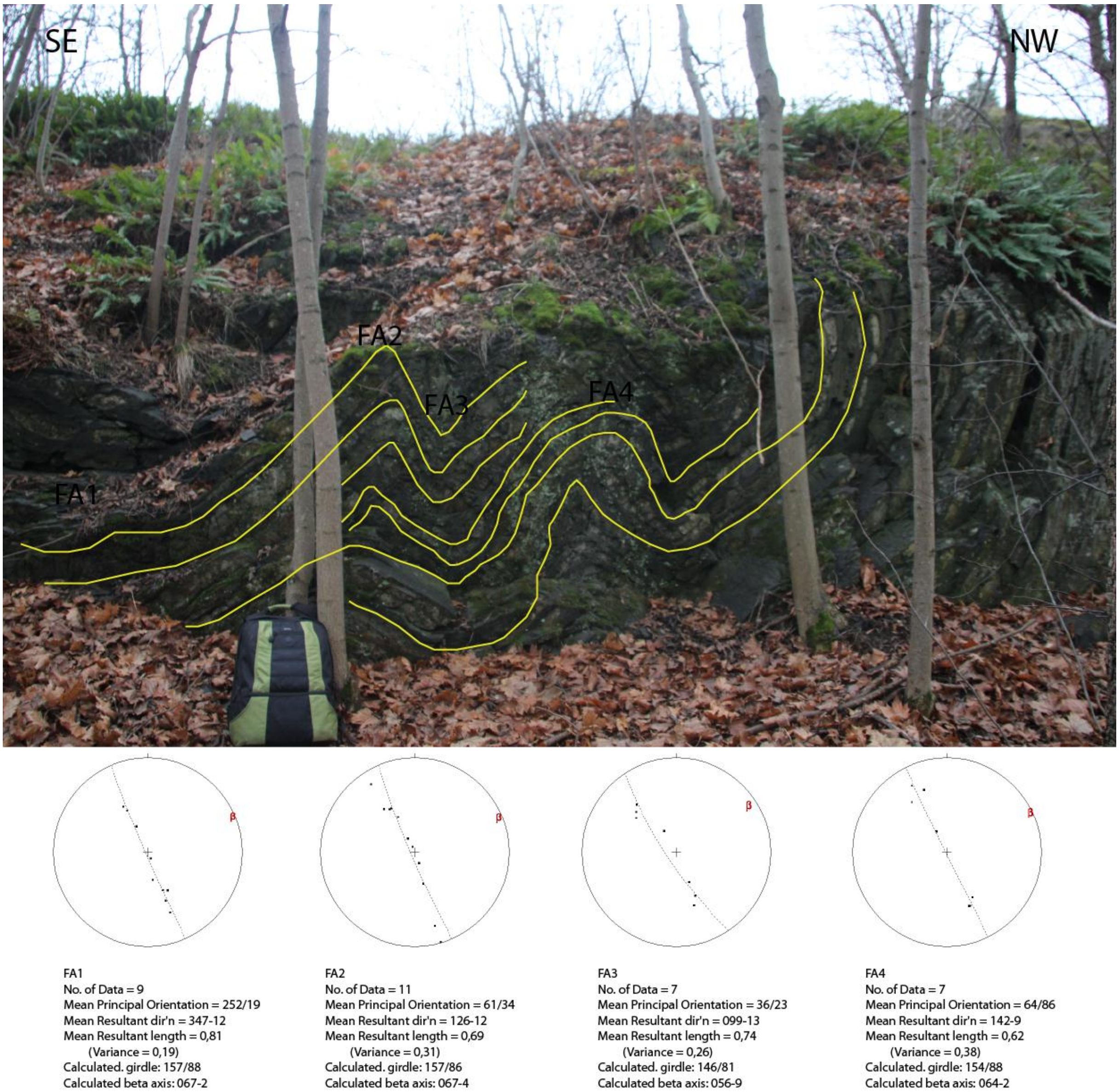


Fig. 4.12 Location B6displays intensely folded limestone and siltstone of the Skjerholmen Formation. Backpack as scale. Bedding is marked as yellow lines. The Stereographic projections display poles to bedding, and the calculated beta axis for the folds. (N 59° 53.650', E 10° 43.781')

Locality B7 – Folds

Locality B7 is located on the southeastern side of Hovedøya and comprises the Upper Ordovician Langøyene formation which consists of calcareous sandstone, limestone and shales subsequently. The locality is made up of two different outcrops located approximately 100 meters apart.

The first outcrop (Fig. 4.13,a) displays a single fold in a sequence made up of bedded limestone and siltstone, with thicknesses of each bed ranging from 10 to 20 cm.
The Fold is an open symmetrical fold with a recumbent attitude. Strike and dip measurements from the fold limbs give a calculated beta axis of 048/2 (Fig. 4.13,FA1).
The orthogonal thickness is constant in the layers from hinge to limbs and is characterized as a class-1B fold. The fold was not fully exposed so the wavelength and the amplitude could not be recorded.
The second outcrop (Fig. 4.13,b) displays a single fold in a sequence made up of bedded siltstone, with thicknesses of each bed ranging from 5 to 20 cm.
The Fold is a close asymmetrical fold with a recumbent attitude. Strike and dip measurements from the fold limbs give a calculated beta axis of 048/1 (Fig. 4.13, FA2).
The orthogonal thickness in the layers varies from hinge to limbs and is characterized as a class-2 fold (similar fold). The fold was not fully exposed so the wavelength and the amplitude could not be recorded.

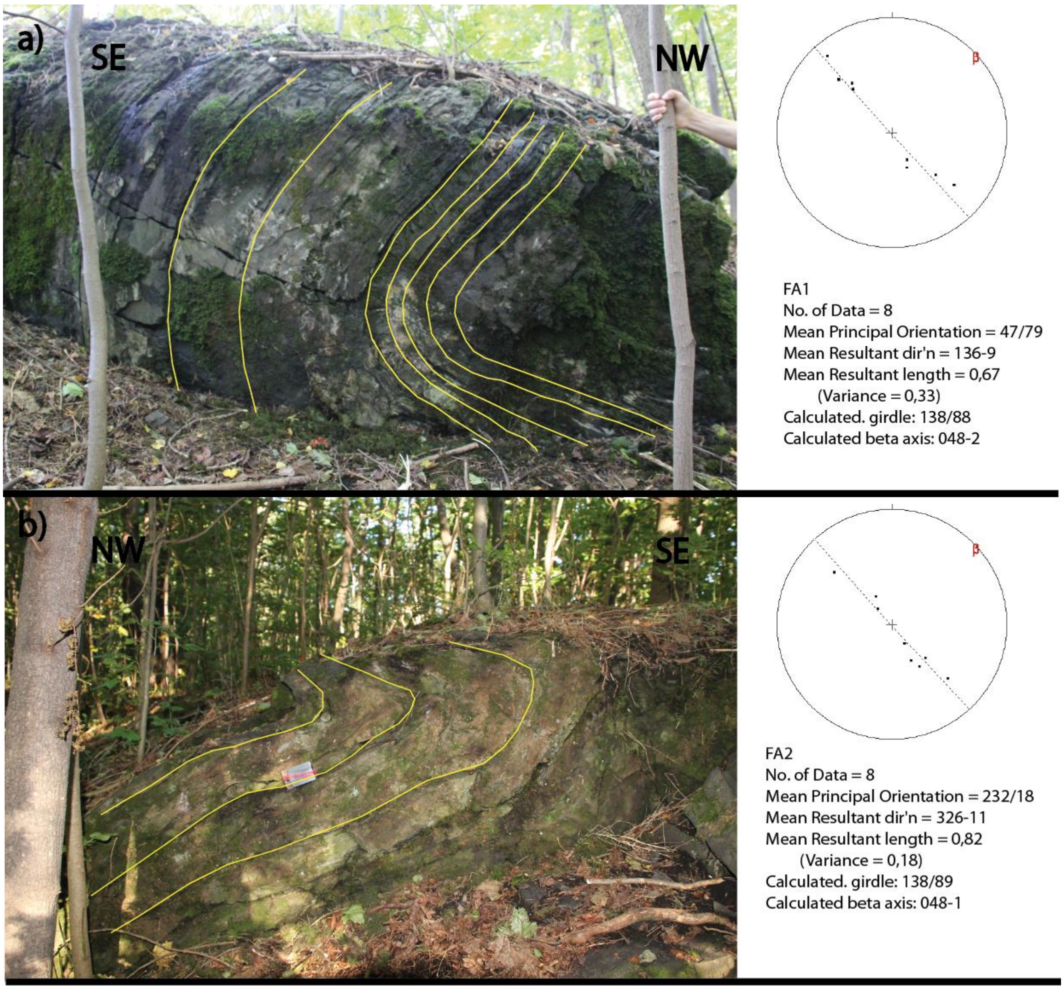


Fig. 4.13 Locality B7: a) Folded bedding (yellow lines), with associated calculated statistics (FA1) displayed to the right (hand as scale)(N 59° 53.608', E 10° 44.102'). b) Folded bedding (yellow lines), with associated calculated statistics (FA2) displayed to the right (compass as scale)(N 59° 53.576', E 10° 44.050').

Locality B8 – Folds

Locality B8 consists of numerous small scale folds within the Silurian Shale along the entire SE shoreline of Hovedøya. The folds consists of thin competent siltstone beds (0-15 cm thick) that display tight to isoclinal parallel class 1B folding within the siltstone beds, and

The Stereographic projection displays the trend and plunge of the fold axis of 15 folds.

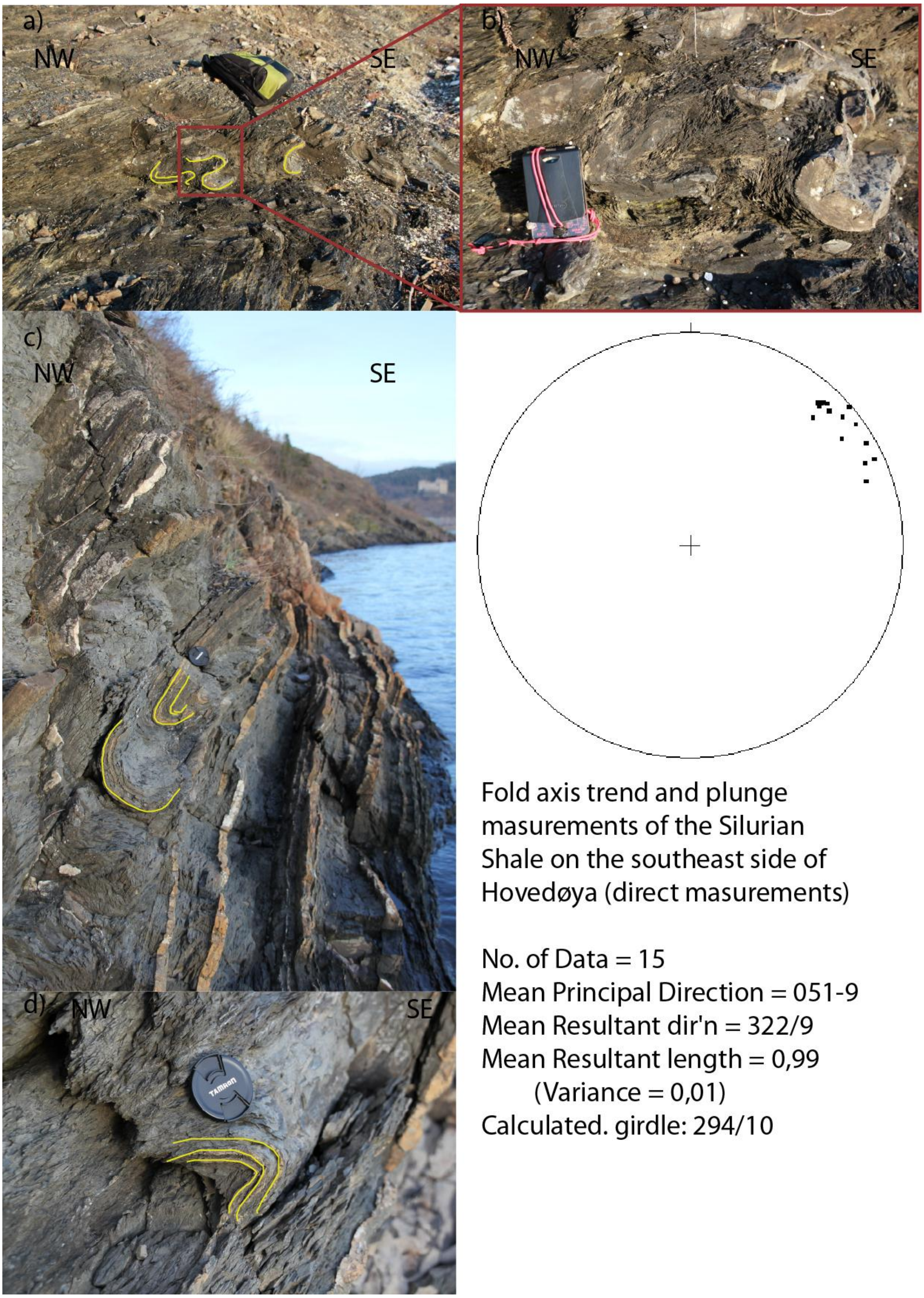


Fig. 4.14 Locality B8 consists of numerous small scale folds within the Silurian Shale along the entire SE shoreline of Hovedøya. Bedding is illustrated as yellow lines. Backpack, compass and lens cap as scale. The Stereographic projection displays the trend and plunge of the fold axis of 15 folds.

Foreland directed thrusts and reverse faults

Locality C1 – Foreland directed thrusts and reverse faults

Locality C1 is located on the western shoreline of Hovedøya and comprises both the Skjerholmen and Skogerholmen Formations. The locality displays section which is characterized by several fault slip surfaces oriented parallel to the bedding planes. The section is displayed from the northwestern tip of Hovedøya towards the south-southeast, measuring approximately 80 meters across. Slickenside lineations are evident on several of the fault slip surfaces. Measurements are taken from two outcrops (Subarea A & B) within the section, and the two subareas are located on opposite sides of the section.

Subarea A, located to the SSE consists of a sedimentary sequence with variations of interlayered nodular limestone and shale. Bed thicknesses range from 5-35 cm, with increase in shale dominance towards SSE. Strike and dip of bedding planes are consistent in the outcrop and display an average strike of NE-SW, with an average dip of 48 degrees (Fig. 4.15, stereographic projection 3). Subarea B is located to the NNW and consists of interlayered bedded limestone and shale with thicknesses ranging from 10- 50 cm. Bedding planes are consistent and display an average strike and dip of 226/41 (Fig. 4.15, stereographic projection 5).

Fault planes within both subareas are parallel to the orientation of bedding planes, but are concentrated within bed boundaries which display high competence contrasts, for example competent limestone beds and less competent shale beds. Slickenside lineations measured on fault planes at the outcrop to SSE display an average trend and plunge of 301/48 (Fig. 4.15, stereographic projection 4). From stereographic projection in we can observe that most slickenside lineations have a plunge close to 90 degrees within the fault planes, indicating that most of the movement is dip-slip, with some oblique-slip. The slickenside lineations found in the outcrop to NNW, display two distinct slip directions (Fig. 4.15, stereographic projection 8). First one displays a dip-slip component, the other showing an oblique-slip component with slip closer to strike-slip.

The faults are seems to have been formed by flexural slip at the boundaries between competent and incompetent layers, and is interpreted to be related to the development of the macroscopic anticline structure displayed in the study area.

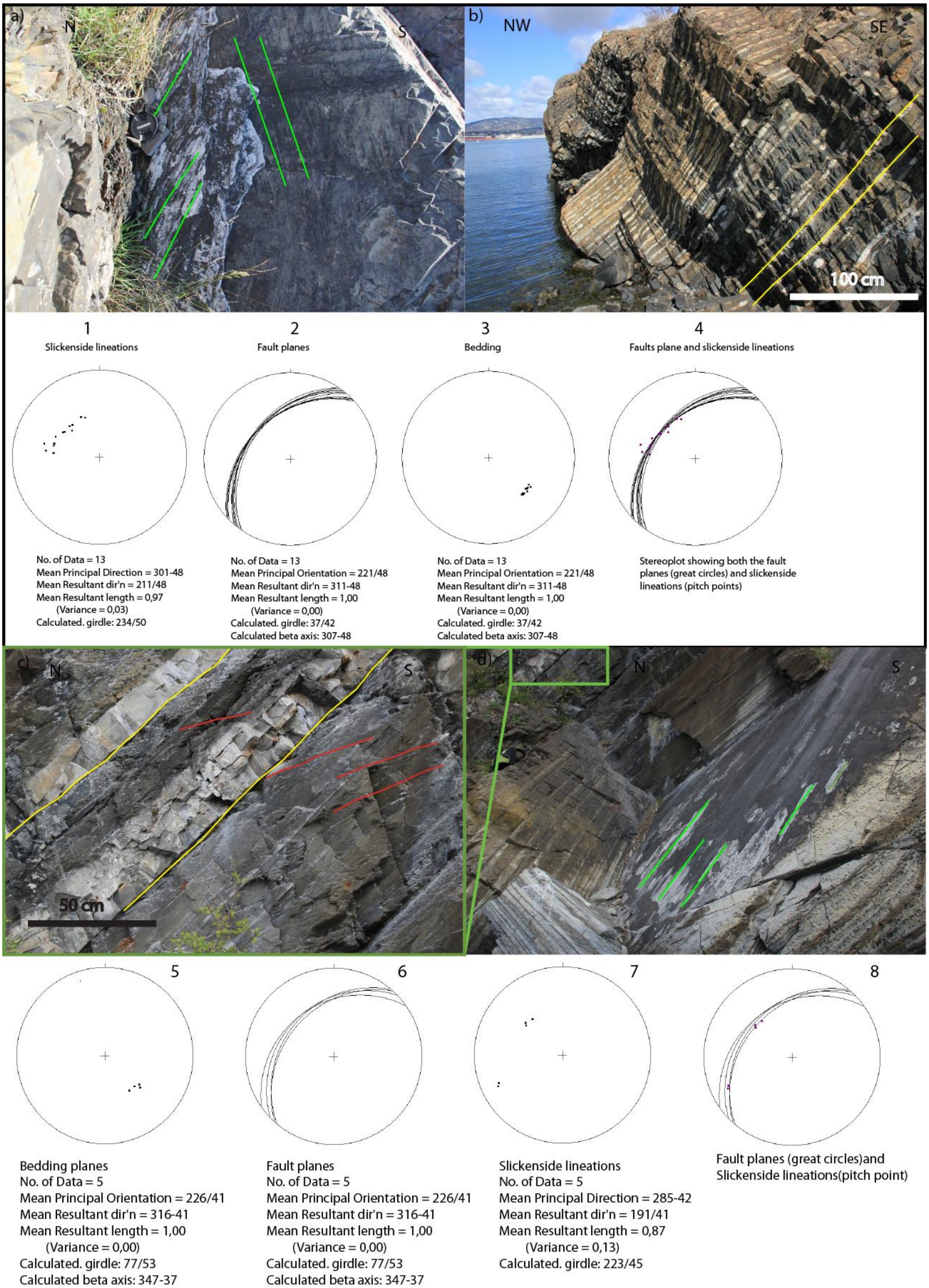

a)
N
S
b)
NW
SE
100 cm
1
Slickenside lineations
2
Fault planes
3
Bedding
4
Faults plane and slickenside lineations
No. of Data = 13
Mean Principal Direction = 301-48
Mean Resultant dir'n = 211/48
Mean Resultant length = 0,97
(Variance = 0,03)
Calculated. girdle: 234/50
No. of Data = 13
Mean Principal Orientation = 221/48
Mean Resultant dir'n = 311-48
Mean Resultant length = 1,00
(Variance = 0,00)
Calculated. girdle: 37/42
Calculated beta axis: 307-48
No. of Data = 13
Mean Principal Orientation = 221/48
Mean Resultant dir'n = 311-48
Mean Resultant length = 1,00
(Variance = 0,00)
Calculated. girdle: 37/42
Calculated beta axis: 307-48
Stereoplot showing both the fault
planes (great circles) and slickenside
lineations (pitch points)
c)
N
S
50 cm
d)
N
S
5
6
7
8
Bedding planes
No. of Data = 5
Mean Principal Orientation = 226/41
Mean Resultant dir'n = 316-41
Mean Resultant length = 1,00
(Variance = 0,00)
Calculated. girdle: 77/53
Calculated beta axis: 347-37
Fault planes
No. of Data = 5
Mean Principal Orientation = 226/41
Mean Resultant dir'n = 316-41
Mean Resultant length = 1,00
(Variance = 0,00)
Calculated. girdle: 77/53
Calculated beta axis: 347-37
Slickenside lineations
No. of Data = 5
Mean Principal Direction = 285-42
Mean Resultant dir'n = 191/41
Mean Resultant length = 0,87
(Variance = 0,13)
Calculated. girdle: 223/45
Fault planes (great circles)and
Slickenside lineations(pitch point)

Fig. 4.15 Locality C1; Fault planes are parallel to bedding across the entire locality. Subarea A: a) Slickenside lineations (green lines) on fault plan. b) Tilted bedding planes. Assosiated stereoplot and calculated statistics are displayed below. Subarea B: c) Cleavage (red lines) displaying a more gently dip than bedding. d) Slickenside lineations (green lines) on fault plane. Assosiated stereoplot and calculated statistics are displayed below. Figure a and b is located at N 59° 53.727', E 10° 43.396', while figure c and d is located at (N 59° 53.770', E 10° 43.378').

Locality C2 – Foreland directed thrusts and reverse faults

Locality C2 is located in the interior of the southeastern side of Hovedøya (N 59° 53.637', E 10° 44.162'). The outcrop is a well exposed section measuring approximately 4 meters in height and 10 meters in width. The outcrop is characterized by intermediate dipping beds, cut by a fault zone. The rocks consist of calcareous sandstone, limestone and shales subsequently of the Langøyene Formation.

The locality is characterized by a thrust fault (Fig. 4.16a, thrust planes marked as red lines) with associated slickenside lineations, fault breccia and lenses. The fault plane is oriented NE-SW, with an average dip of 55 degrees towards northwest (Fig. 4.16, stereoplot projection 2). Slickenside lineations are found on the fault surface and display a mean principal direction of 290/53 (Fig. 4.16, stereoplot projection 3). Bedding marked as yellow lines are oriented NE-SW, with an average dip of 41 degrees towards northwest (Fig. 4.16a, stereoplot projection 1). The calculated measurements of fault plane and slickenside lineations indicate that the motion is dip-slip (Fig. 4.16,stereoplot projection 4).

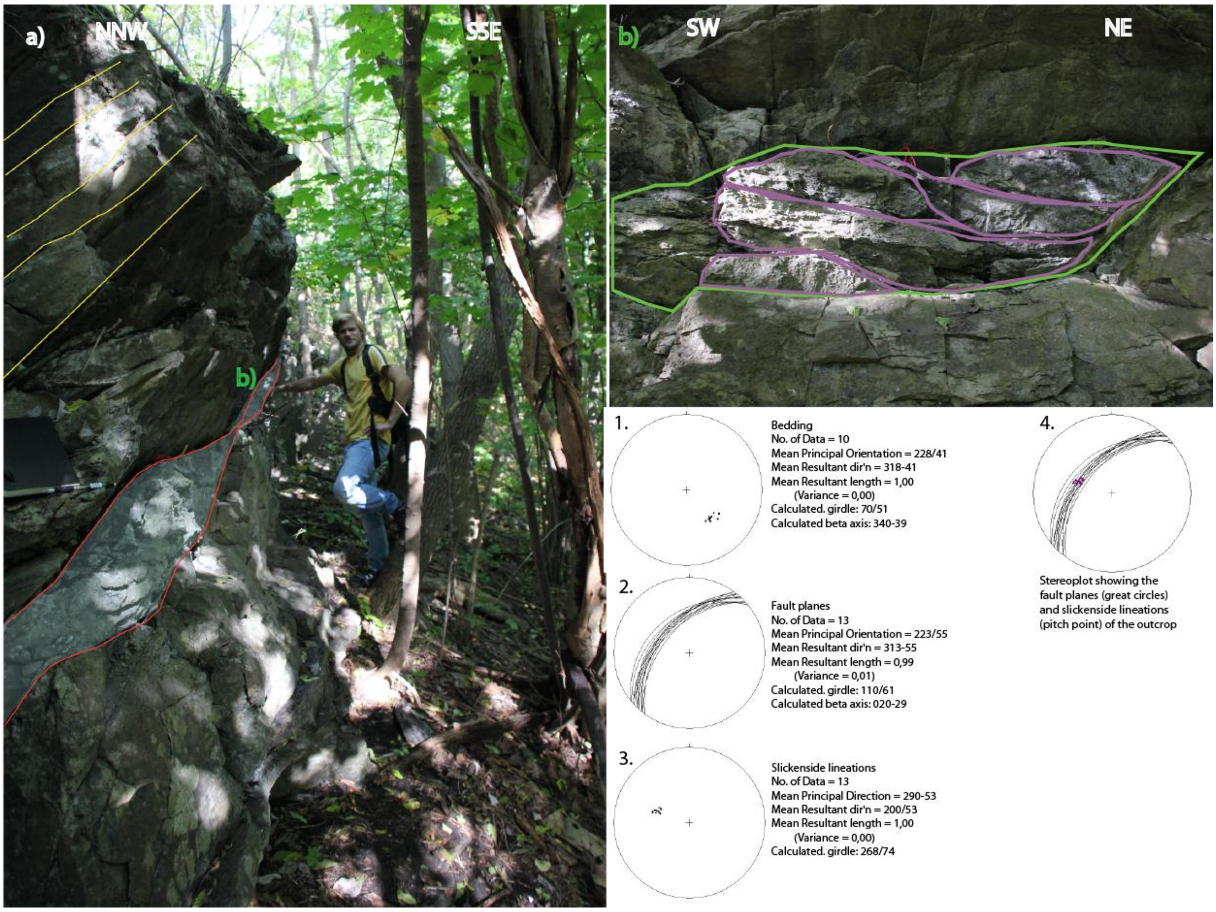


Fig. 4.16 Locality C2; a) Thrust planes (red lines) showing a low angle to bedding (yellow lines in hanging wall), but a steep angle to the horizontal. Assosiated fault breccia are displayed as shaded blue. (Geologist as scale). Assosiated stereoplot and calculated statistics are displayed to the right. b) Lenses within the fault breccia (compass as scale). (N 59° 53.637', E 10° 44.162')

Locality C3 – Foreland directed thrusts and reverse faults

Locality C3 is located on the southeastern side of Hovedøya and comprises the lower part of the Upper Ordovician Langøyene formation which consists of calcareous sandstone, limestone and shale's subsequently. The locality is characterized by thrusting and folding with bedding and thrust planes dipping towards the NW (Fig. 4.17, stereographic projections), which indicate tectonic transport with a vergence towards the SE. The thrusts seem to cut the folding at close to the fold hinges

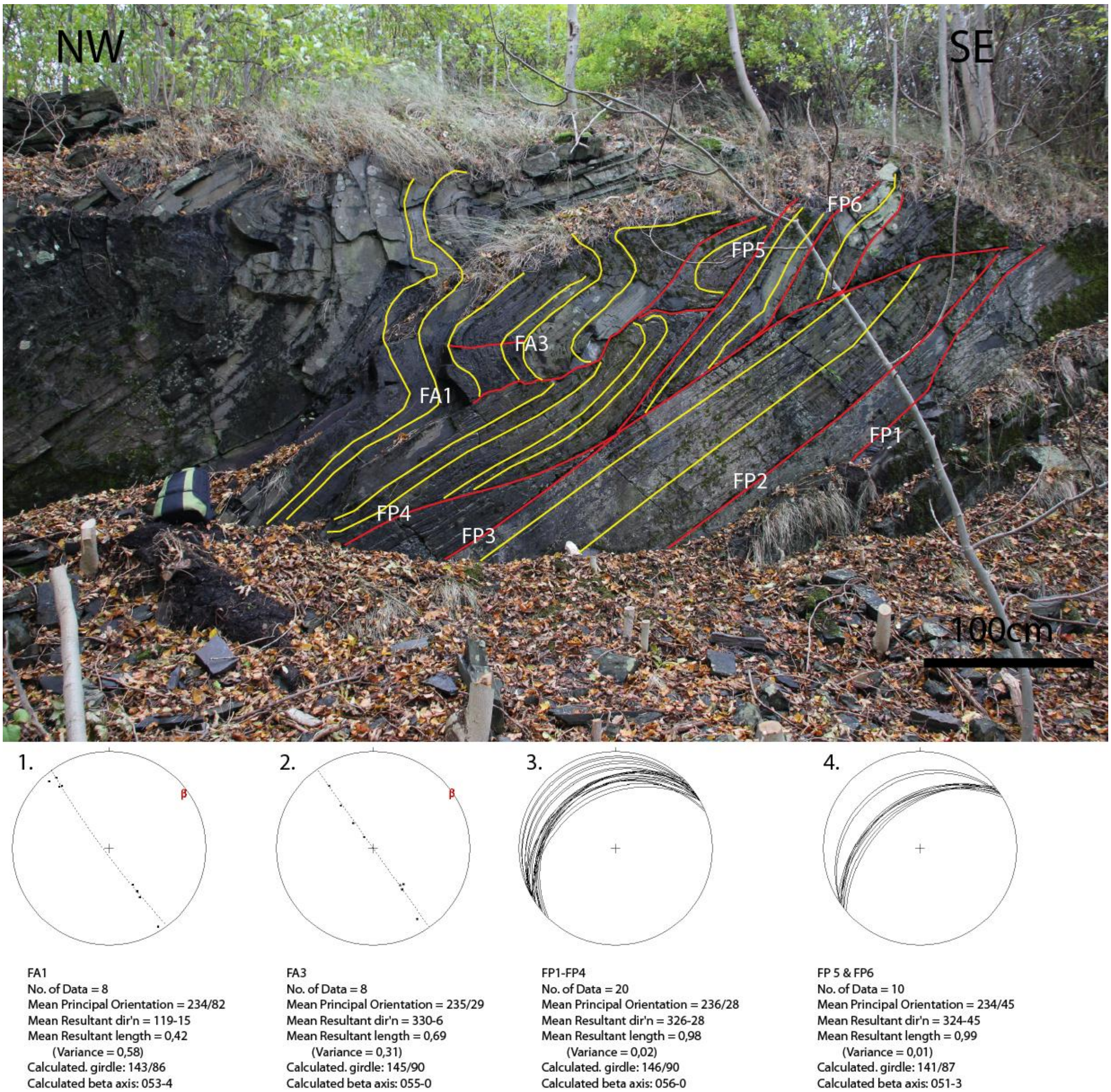


Fig. 4.17 Locality C3; Outcrop displaying bedding parallel thrusts, imbricated horses (dipping down towards NW) and folding. FP3 seams to be the detachment surface which separates the thrusting from the imbricated horses and folding. Stereoplot and associated calculated statistics displayed below. (N 59° 53.532', E 10° 43.918')

Hinterland directed thrusts and reverse faults

Locality D1 – Hinterland directed thrusts and reverse faults

The outcrop is located on the southwestern shoreline of Hovedøya and is a well exposed outcrop with intermediate to steep dipping beds of the Solvang and Venstøp Formations. A steep wall measuring maximum 3 m in height and 20 m in length make out the described locality.

The locality is characterized by faulting exibiting with numerous slickenside lineations. The fault plane display dip towards the SE.

The lithology in the outcrop consist of the boundary between the Solvang formation to the NW and the Venstøp formation towards SE. The boundary marks the abrupt change from bedded limestone horizons (5-15 cm) and grey shale (10-20 cm) in the Solvang Formation to dark shale in Venstøp Formation.

Bedding planes display an average strike orientation of ENE-WSW with intermediate to steep dipping beds towards northwest, dipping from 44 to 60 degrees (Fig. 4.18, stereographic projection bedding).

Two different fault plane orientations were plotted in stereoplot, the first fault plane direction displaying a fault plane orientation averaging 281/17, while the second fault plane orientation averaging 055/62 (Fig. 4.18, stereographic projection fault planes). Associated slickenside lineations were measured to average 098/3 and 134/60 subsequently (Fig. 4.18, stereographic projection slickenside lineations).

Combining fault plane and slickenside measurements (Fig. 4.18, stereographic projection showing fault planes and slickenside lineations) conclude a dip-slip motion on the fault plane averaging 055/62, and a strike-slip motion on the fault plane averaging 281/17.

The displacement across the fault is not possible to determine when no stratigraphic separation is visible, but the fault is interpreted to be a back – thrust due to space problems within the core of the macroscopic overturned anticline.

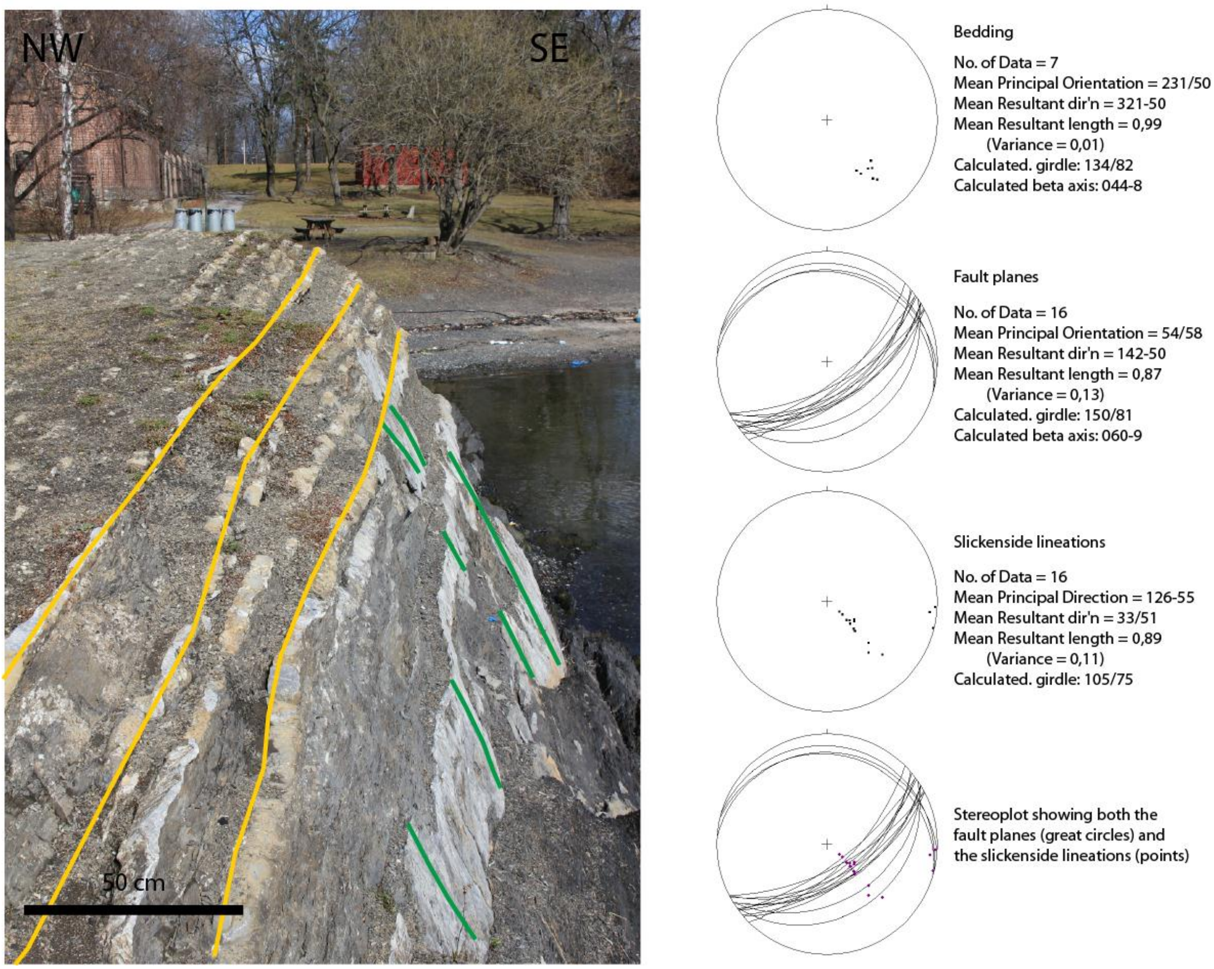


Fig. 4.18 Locality D1: Outcrop displaying bedding planes (yellow lines) and fault plane. The fault plane is covered by slickenside lineations (green lines). Stereoplot and statistics of bedding, fault planes and slickenside lineations are displayed to the right. (N 59° 53.623', E 10° 43.556')

Locality D2 – Hinterland directed thrusts and reverse faults

Locality D2 is located on the northeastern shoreline of Hovedøya and comprises variations of bedded and nodular limestone, interbedded with shale and siltstone, with bed thicknesses varying from 5-50 cm of the Skjerholmen Formation. The locality displays an approximately 50 meters wide section with thrusting and associated folding. Structurally, the locality is situated in the core of the macroscopic overturned anticline which covers the entire study area.

The locality is divided up in two outcrops which both display folding and faulting. Outcrop D2.1 is located approximately 50 meters SW of Sjømannsskolen. The outcrop is 2 meters long and 2 meters high and comprises a thrust fault with associated small scale folding (Fig. 4.19)

The displacement of the thrust could not be measured as no beds are linked across the fault surface. The faults are interpreted to be associated with back - thrusting with an average orientation of NE-SW, with an average dip of 57 degrees towards southeast (Fig. 4.19, stereographic projection 1).
Bedding planes display a change in orientation moving across the outcrop from west towards east. West of the fault zone the calculated mean principal orientation is 236/77, displaying bedding planes dipping towards NW (Fig. 4.19, stereographic projection 2). Crossing the fault zone to the east the bedding planes mean principal orientation changes to 051/80, displaying dip towards SE and (Fig. 4.19, stereographic projection 3).

Outcrop D2.2 is located approximately 10 meters W of Sjømannsskolen and show a 4 meters long and three meters high sections which display a fault with associated fold structures. A cleavage is also observed in the outcrop within the shale dominated beds. Bedding planes in the outcrop display an average orientation of NE-SW, with steep dipping beds towards northwest, with an average dip of 67 degrees (Fig. 4.20, stereographic projection 1)

The fault is interpreted to be a back – thrust, since the faults display reverse movement and the fault plane is dipping towards SE. The fault plane displays an average orientation of NE-SW, with an average dip of 46 degrees towards the southeast (Fig. 4.20, stereographic projection 2).

Two folds were measured in the outcrop and interpreted as fault propagation folds associated with the back - thrusting. Stereoplots and calculated statistics of the folds are shown in Fig. 4.20

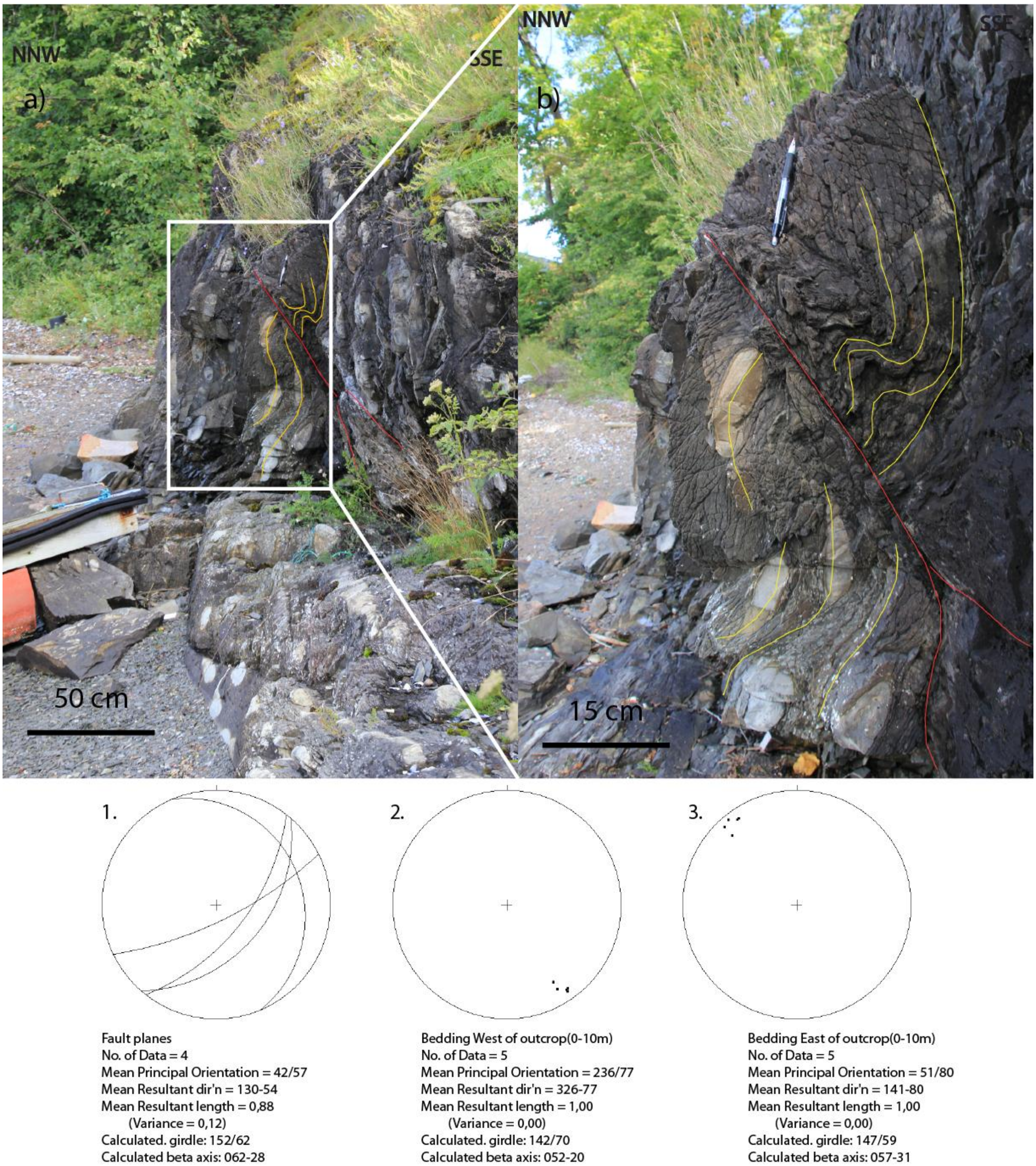


Fig. 4.19 Outcrop D2.1; a, b) The outcrop displays a back-thrust (red lines) which cut the steeply dipping bedding (yellow lines), Bottom: Numbered stereoplot of fault (1.) and bedding planes (2. and 3.) with calculated statistics below. (N 59° 53.739', E 10° 44.235')

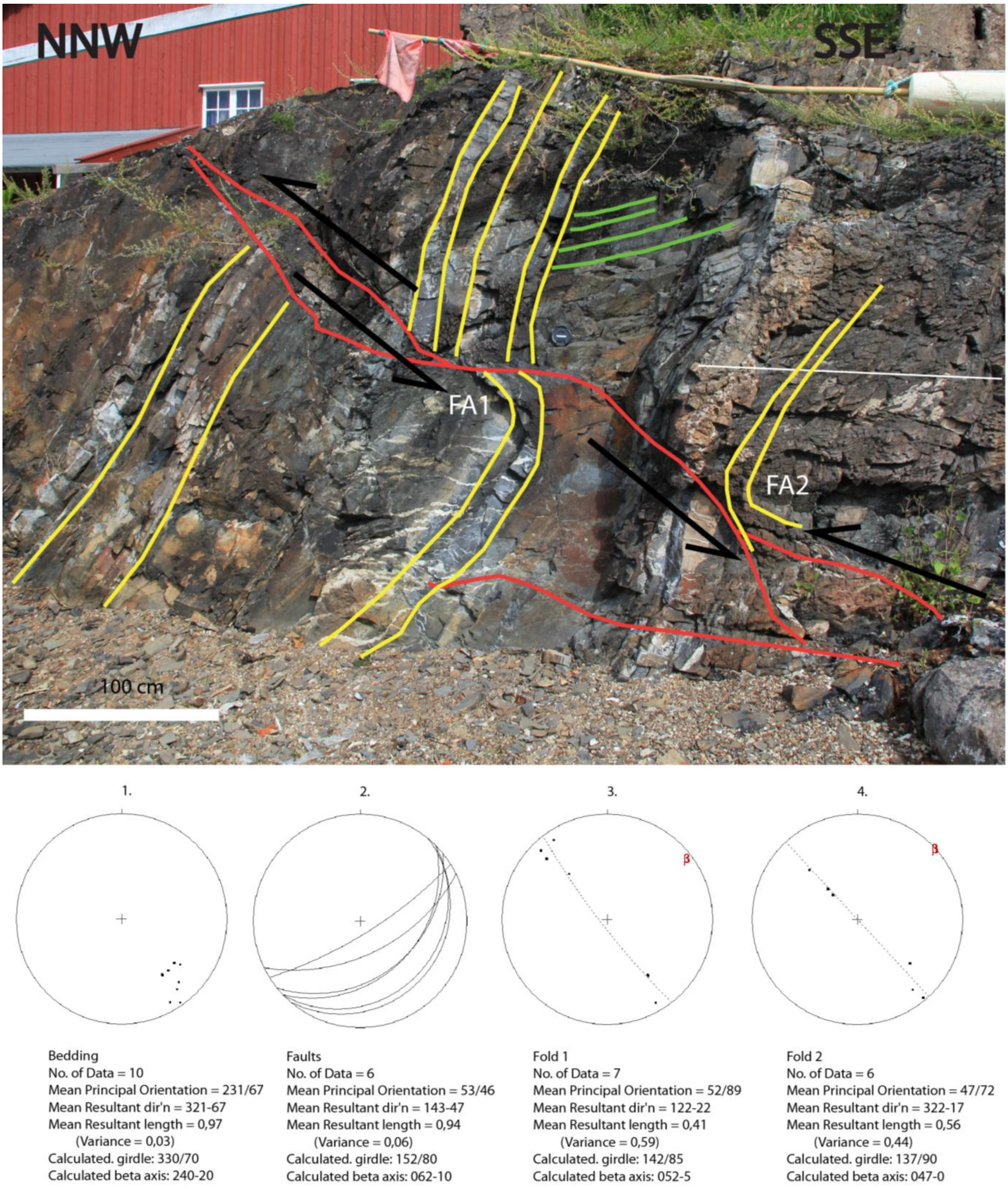


Fig. 4.20 Outcrop D2.2 a) Outcrop displaying drag folds (FA1 and FA2), with fault planes (red lines), bedding (yellow lines) and developed cleavage (green lines). Assosiated stereoplot and calculated statistics are shown below. (N 59° 53.749', E 10° 44.251')

Cleavage development

Four different kinds of cleavage are found within the study are. One cleavage are oriented parallel or sub – parallel to bedding and display pressure solution seams in the cross bedded calcareous sandstone of the Upper Ordovician Langøyene Formation. Pressure solution seams developed perpendicular to or at a very high angle to bedding are also present in the same cross bedded calcareous sandstone of the Upper Ordovician Langøyene Formation The cleavage are displayed as stylolitic to wiggly cleavage. A third cleavage development is observed in only one locality in the northeastern part of the study area, this cleavage display two cleavage directions and the development of pencil structures. The last cleavage observed within the study area display a consistent cleavage across the islands where bedding display a shale lithology. The cleavage have approximately the same NE- SW orientation as bedding planes, but display a consistent horizontal to intermediate dip towards northwest.

Locality E1 – Pressure solution cleavage

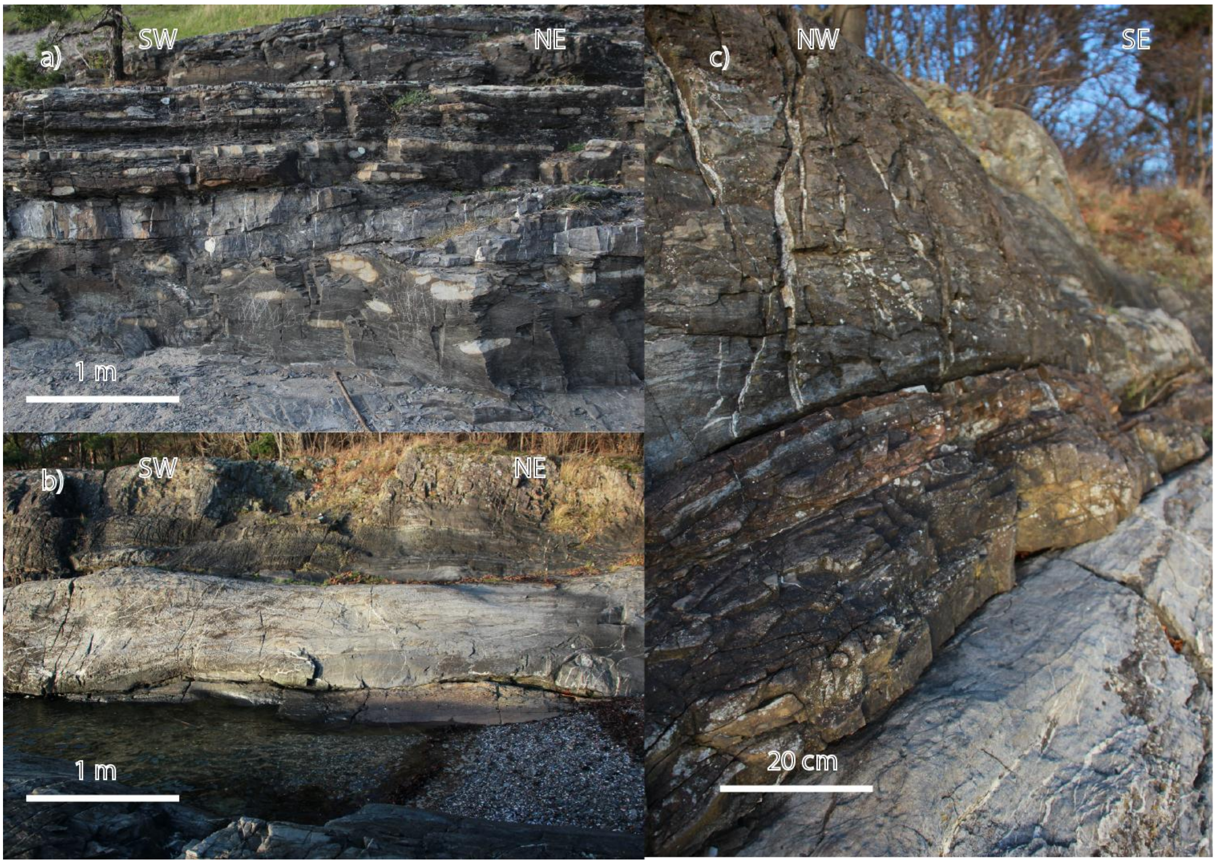


Fig. 4.21 Pictures display various pressure solution seams oriented perpendicular and parallel to bedding. Picture a) display weak to moderate wiggly cleavage constricted to a single layer of competent limestone which display small scale low angle to bedding thrusting, same location as (Fig. 4.2**). Picture b) and c)**

display weak stylolitic cleavage within the competent cross – bedded calcareous sandstone of the Langøyene Fm.

Locality E2 – Pencil cleavage

The locality comprises the Early Silurian Solvik Formation which in the study area consists of dark shale with thin siltstone layers (up to 10 cm thick). The locality is characterized by a pencil cleavage observed in the Silurian shale. An outcrop of the inverted Ordovician Silurian boundary is found 60 m towards WNW. The Ordovician Silurian boundary is also found due ESE, close to the shoreline, but here the boundary is not inverted and the Silurian shale lies on top of Upper Ordovician sandstone.

The locality consists of two outcrops displayed 5 meters apart. The outcrops display bedding planes oriented ENE-WSW, with dipping towards both SSE and NNW, ranging from 42 to 86 degrees. The different orientations within the outcrop and the presence of the Ordovician Silurian boundary both towards WNW and ESE suggest that we are situated in the core of a macroscopic syncline structure (Fig. 4.22, stereographic projection 3).

Two cleavage orientations are present in the outcrop characterize the pencil cleavage (Fig. 4.22b, cleavage orientation1 = green lines, cleavage orientation2 = red lines). From stereographic projection 1 and 2 in Fig. 4.22, cleavage orientation1 have a mean principal orientation of 255/07, while cleavage orientation2 have a mean principal orientation of 078/77.

Bedding planes and the two cleavage orientations are plotted together as great circles in a stereographic projection (Fig. 4.22, stereographic projection 4)

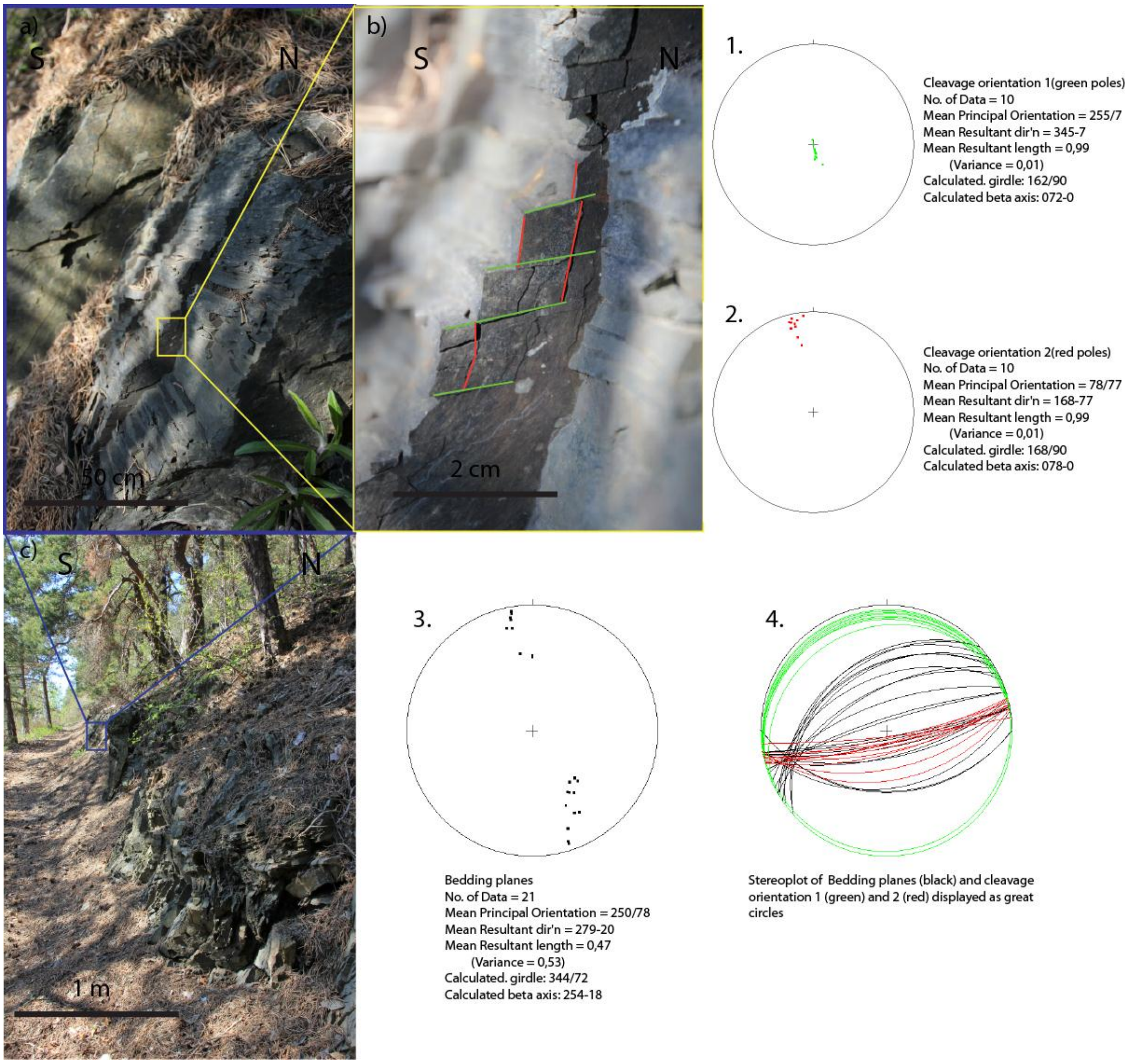


Fig. 4.22 Locality E2; a) Pencil cleavage. b) Two different cleavage directions measured in the outcrop, cleavage direction 1 (green lines) and cleavage direction 2 (red lines). Stereoplot and calculate statistics of cleavage shown to the right. c) Overview of locality, stereonett and calculate statistics of bedding shown to the right. (N 59° 53.737', E 10° 44.487')

Locality E3 – Consistent horizontal to intermediate NW dipping cleavage

Cleavage development is observed in the more shale dominated successions of the Skjerholmen Formation. The strike of the developed cleavage is parallel to the strike of the bedding planes, and displays a strike orientation of NE – SW (Fig. 4.23). The cleavage display a more gently dip than the bedding, and is consistent with a dip direction towards NW. The cleavage has a mean dip of 37 degrees towards the NW in the location area (Fig. 4.23).

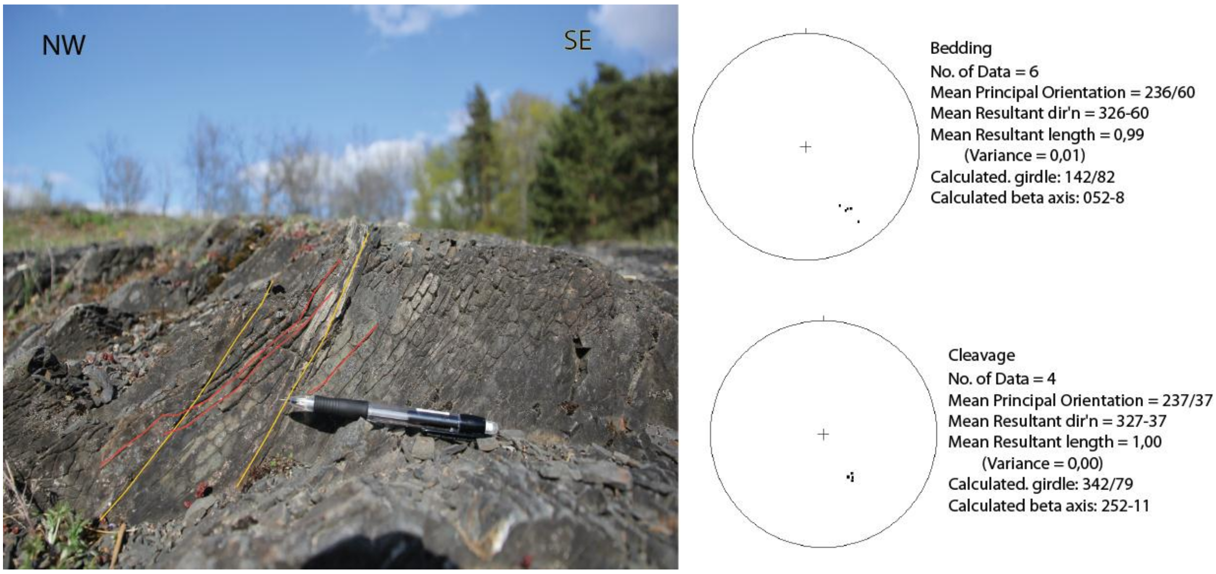


Fig. 4.23 Locality E3 display bedding and cleavage relationship (yellow lines= bedding, red lines= cleavage) with associated stereoplot and statistics to the right. (N 59° 53.615', E 10° 43.654')

Locality E4 – Consistent horizontal to intermediate NW dipping cleavage

In the outcrop towards NNW a cleavage direction is displayed in the shale dominated layers. The cleavage is observed as more gently dipping than the bedding. Stereographic projections presented in Fig. 4.24 show that cleavage displays an average strike and dip of 231/16, while bedding display a strike and dip averaging 226/41.

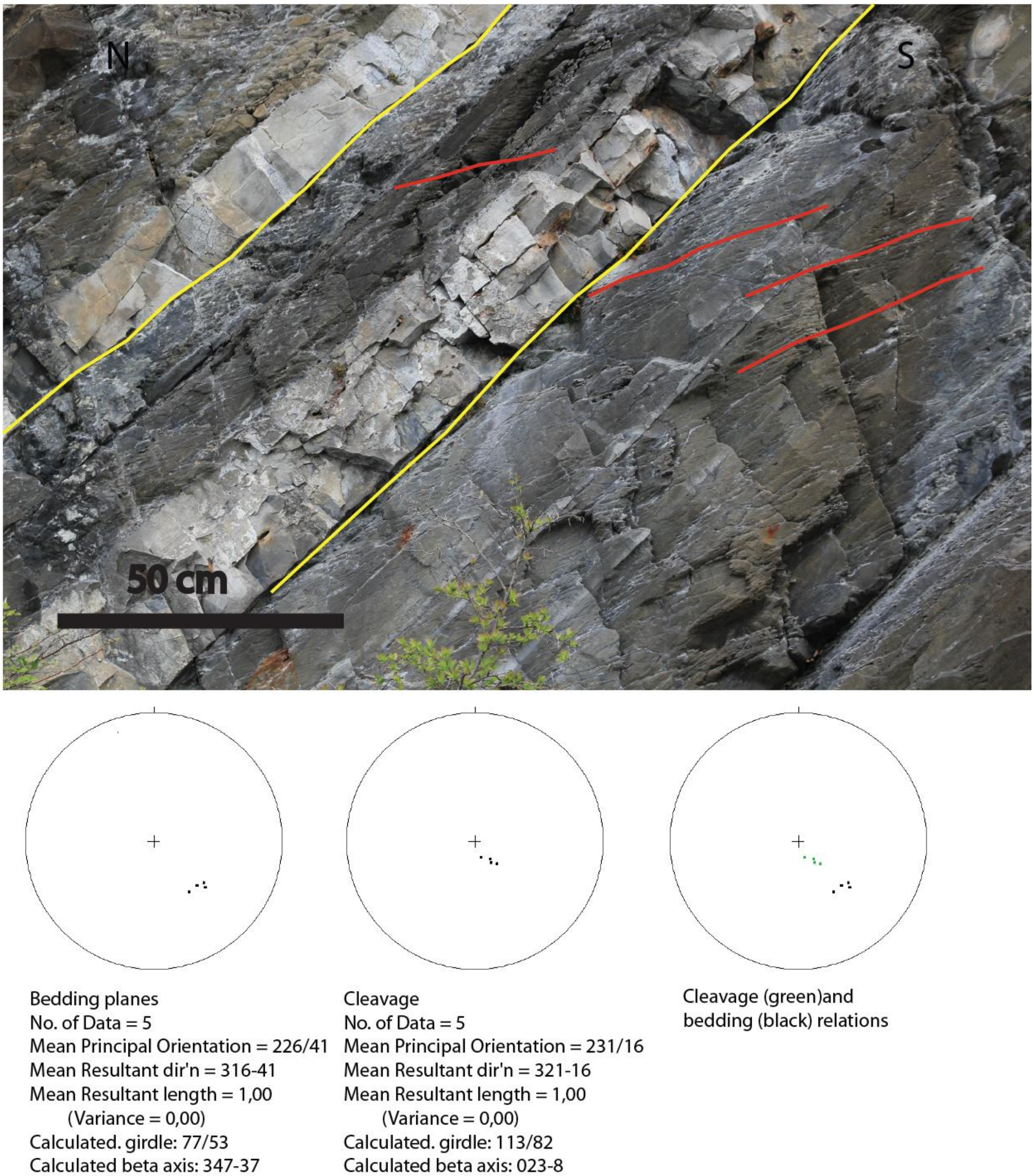


Fig. 4.24 Locality E4 display cleavage (red lines) and bedding(yellow lines) relation in limestone and shale beds at the western tip of Hovedøya (WGS 84: N 59° 53.770', E 10° 43.378').

Locality E5 – Consistent horizontal to intermediate NW dipping cleavage

Locality E5 is located on the southeastern tip of Hovedøya and comprises the Upper Ordovician Langøyene formation which consists of calcareous sandstone, limestone and shales subsequently. Bedding is overturned and displayed as steep to vertical dipping towards the NW. The locality is located on the southeastern fold limb of the large overturned anticline covering the study area.

The locality displays bedding planes oriented NE-SW, with dip ranging from 70 to 90 degrees, averaging 80 degrees (Fig. 4.25, stereographic projection, bedding as black poles). The locality is characterized by a cleavage observed in the siltstone and limestone layers (Fig. 4.25, red lines display cleavage orientation). The cleavage is oriented ENE-WSW, with dip ranging from 12 to 20 degrees, averaging 15 degrees (Fig. 4.25, stereographic projection, cleavage as green poles).

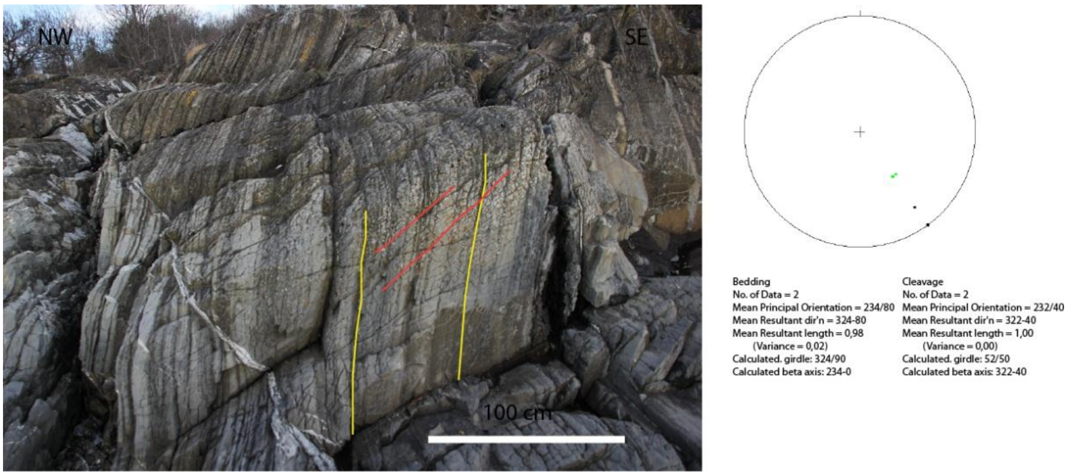


Fig. 4.25 Locality E5; Outcrop showing cleavage(red lines) and bedding(yellow lines) relation. Stereoplot of bedding planes and cleavage with associated calculated statistics displayed to the right. (N 59° 53.472', E 10° 43.576')

Locality E6 – Consistent horizontal to intermediate NW dipping cleavage

Locality E6 is located on the southeastern shoreline of Hovedøya and comprises the Ordovician Silurian boundary, displayed by the Ordovician Langøyene formation and the Silurian Solvik Formation which consists of calcareous sandstone and shales subsequently. Inverted strata displaying younger Silurian rocks down towards southeast. The locality is located on the overturned southeastern fold limb of the macroscopic overturned anticline covering the study area.

The locality displays bedding planes oriented NE-SW, with dip ranging from 22 to 73 degrees, averaging 43 degrees (Fig. 4.26, stereographic projection bedding). The locality is characterized by a cleavage observed in the shale layers (Fig. 4.26b, red lines mark cleavage direction). The cleavage is oriented ENE-WSW, with dip ranging from 12 to 20 degrees, averaging 15 degrees (Fig. 4.26, stereographic projection cleavage).

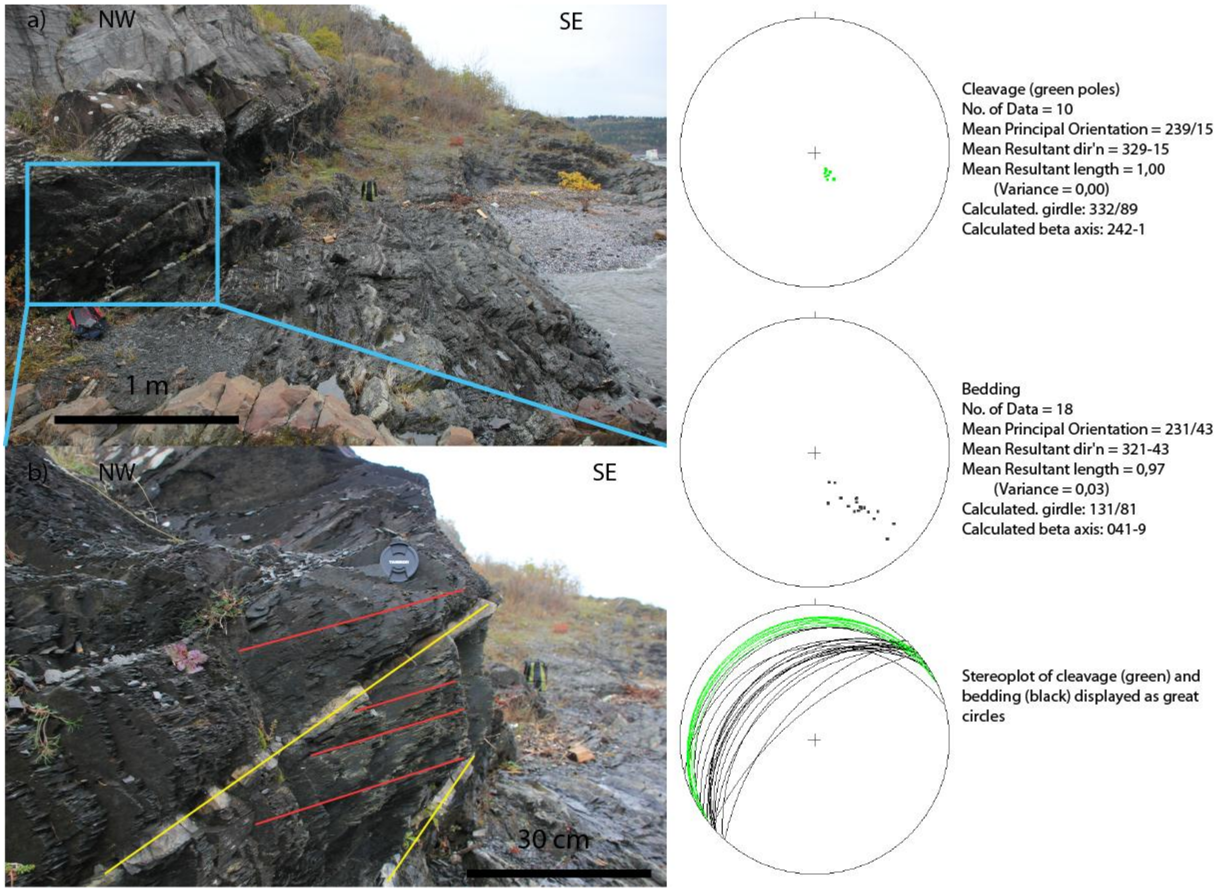


Fig. 4.26 Locality E6; Outcrop showing cleavage (red lines) and bedding (yellow lines) relation. Stereoplot of bedding planes and cleavage with associated calculated statistics displayed to the right. (N 59° 53.503', E 10° 43.889')

Locality E7 – Consistent horizontal to intermediate NW dipping cleavage

The outcrop locality is the same as Locality D2 – Hinterland directed thrusts and reverse faults (Fig. 4.20). Cleavage display a strike and dip averaging 206/14 (Fig. 4.27, stereoplot), while bedding display a strike and dip averaging 231/67 (Fig. 4.20, stereoplot 1).

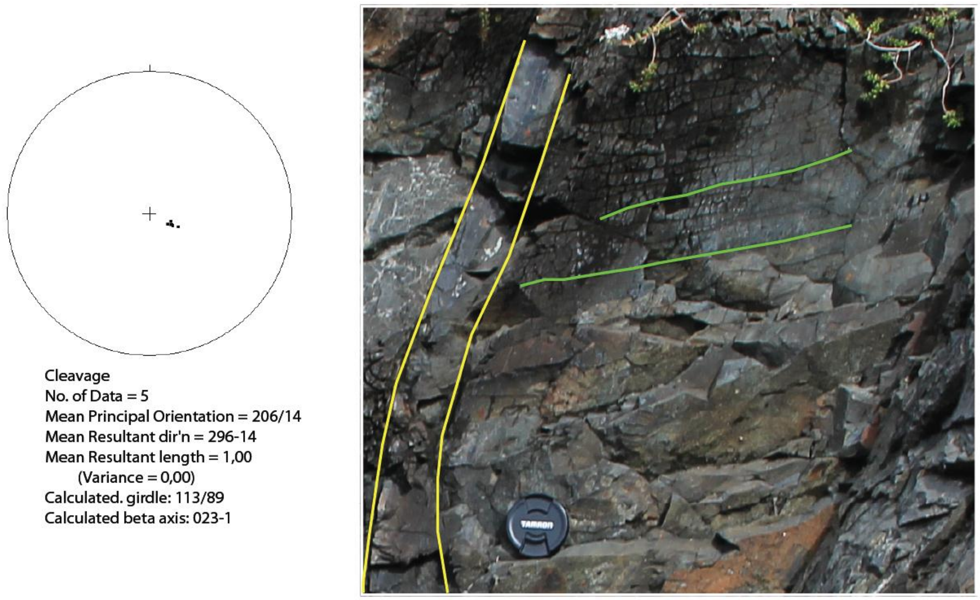


Fig. 4.27 Outcrop displaying cleavage as green lines and bedding as yellow lines (lens cap as scale). The locality is the same as Locality D2 – Hinterland directed thrusts and reverse faults (Fig. 4.20)

4.3 Permian extensional structures and intrusions

The Permian extensional structures are described briefly in the chapter below.

Normal faults and dikes

Permian structures such as normal faults and dykes are shown in Fig. 4.29a, b and c) The Permian faults in the study area are associated to the rifting of the Oslo region and display a normal fault configuration. Permian intrusions within the study area are often associated with normal faulting. Stereoplot and calculated statistics of dykes (Fig. 4.29d) show a mean orientation striking NNW-SSE, with an average steep to vertical dip.

Width measurements along strike of the bedding were taken of the dykes in the study area for calculating the elongation and β-factor (Fig. 4.28). The northwestern section of Lindøya comprises 7 dykes displaying a minimum combined thickness of 14 m. The length of the northwestern section is measured to be 1150 m. On the SE side of Lindøya a total of 10 dykes were measured, with a combined minimum thickness of 10,8 m. The length of the southeastern section is measured to be 990 m.

Along the northwestern shoreline of Hovedøya, a total of 9 dykes was observed and measured. The combined minimum thickness of the dykes is measured to be 31, 2 m. The length of the northwestern section is 568 m. On the SE side of Hovedøya a total of 14 dukes were measured, with a combined minimum thickness of 41,6 m. The length of the southeastern section is measured to be 1077 m.

Section	Length 1 (m)	Total length of dykes (m)	Length 0 (m)	Elongation	B-factor
Lindøya NW	1150	14	1136	0,0123239	1,0123239
Lindøya SE	990	10,8	979,2	0,0110294	1,0110294
Hovedøya NW	568	31,2	536,8	0,0581222	1,0581222
Hovedøya SE	1077	41,6	1035,4	0,0401932	1,0401932
Study area$_{mean}$	3785	97,6	3680,4	0,0265188	1,0265188

Fig. 4.28 Calculated elongation and β-factor for the study area from width of Permian dykes

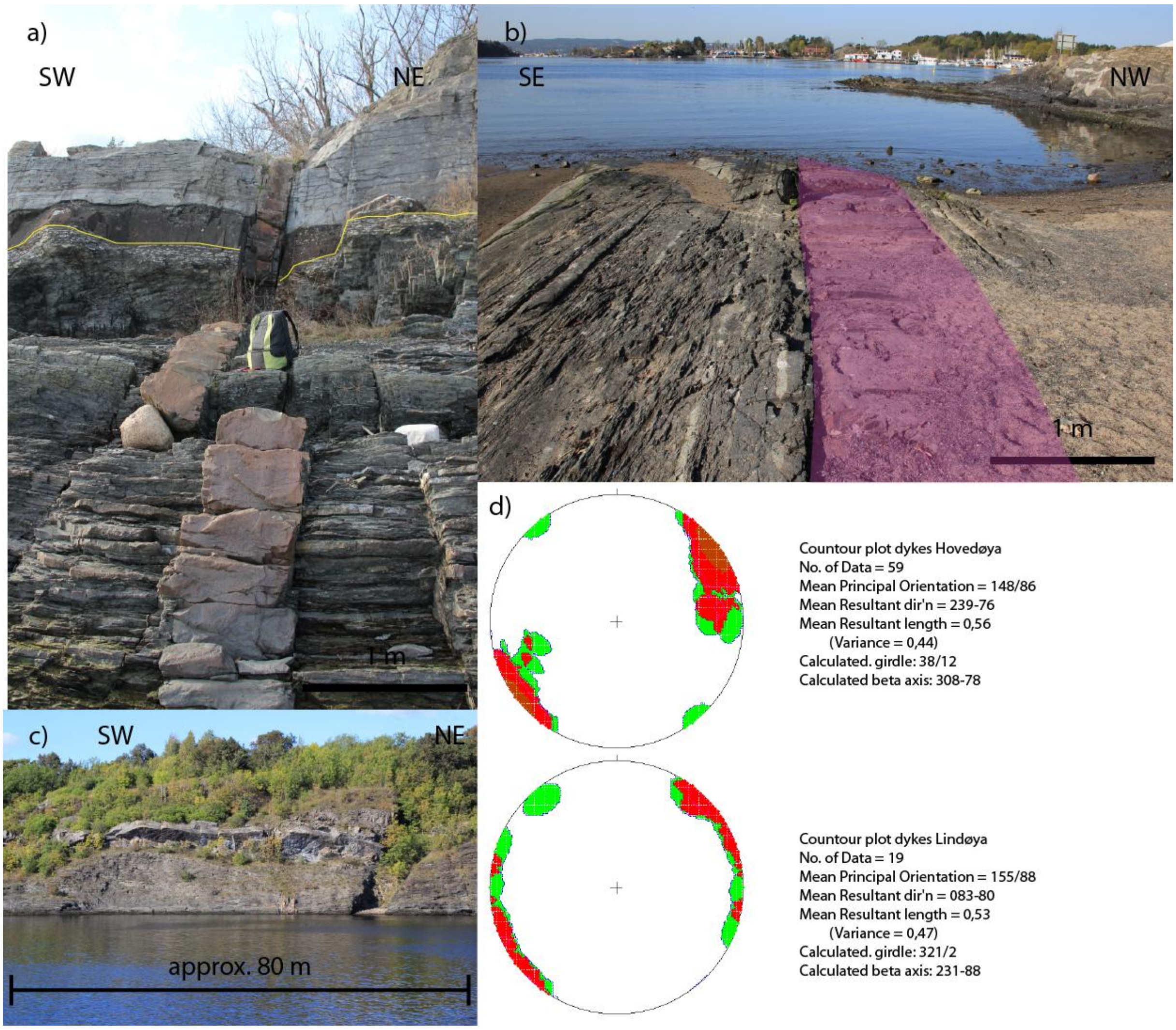


Fig. 4.29 Permian rift structures ; Figure showing typical structures associated with the Permian rifting found within the study area. a) Locality 3.2 Diabase dyke cutting through the Ordovician-Silurian boundary (yellow line), inverted strata. b) Locality 1.2 Dyke intrusion parallel with vertical bedding. c) Section of the SE shoreline of Hovedøya showing a mined Permian dyke, a typical feature in the study area. d) Contoured stereoplots displaying all measured strike and dip data of dikes on Hovedøya and Lindøya subsequently.

Locality F1 – Normal faults and dikes

Outcrop is located on the southeastern shoreline close to the southern tip of Hovedøya and display a normal fault intruded by a Permian diabase dyke. The fault planes are oriented NW – SE and display vertical dips. The lithology faulted is that of the Ordovician Silurian boundary displayed in Fig. 3.11 and Fig. 4.30, and display a general strike orientation of NE – SW, with dipping towards the NW. The beds are inverted as the outcrop lies on the southeaster limb of the macroscopic southeasterly overturned anticline of the study area. The displacement of the fault is measured to be between approximately 8 meters. The Permian dyke display a width of 2.6 meters.

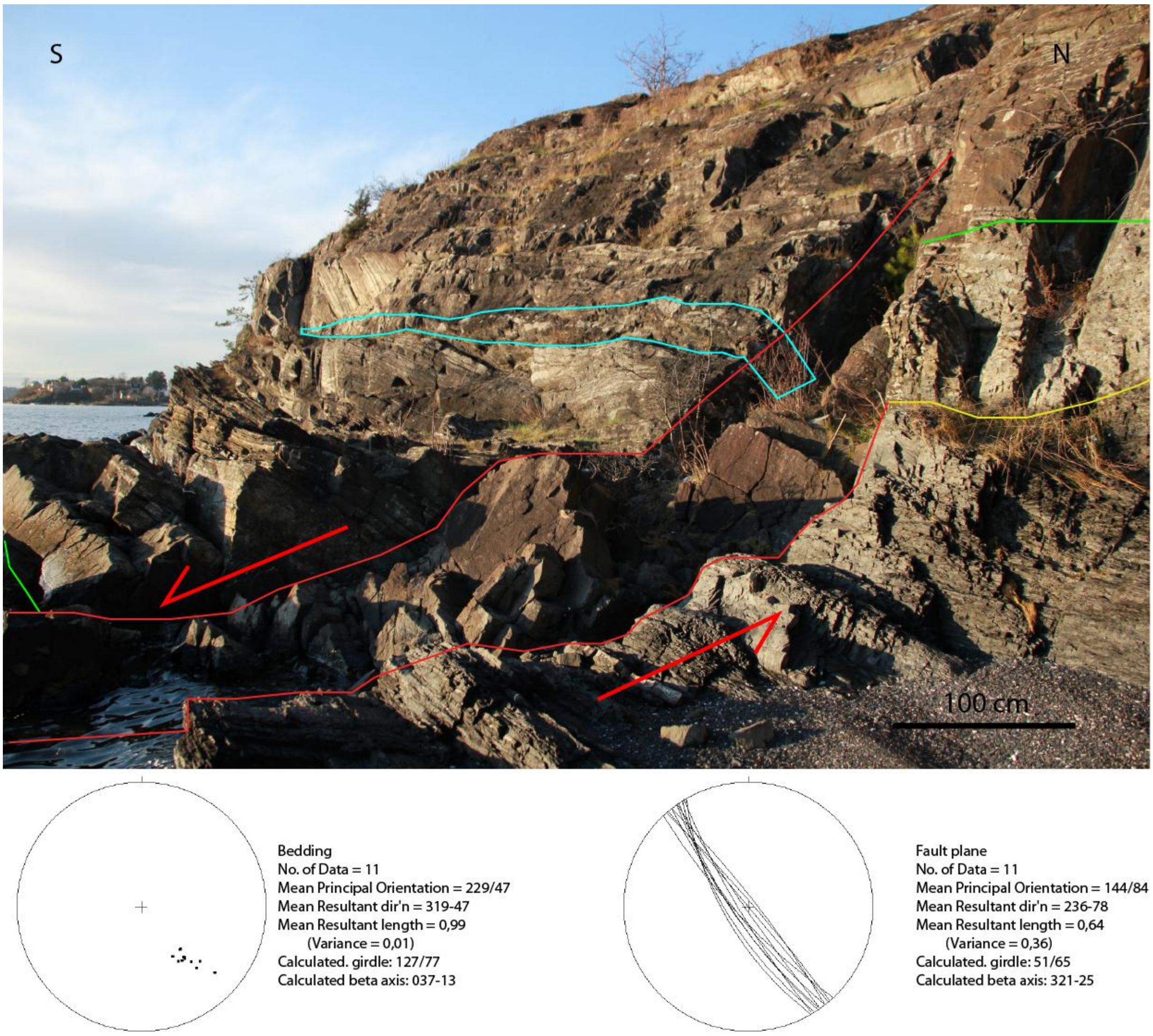


Fig. 4.30 Locality F1 displaying a normal fault with a displacement of approximately 8 meters. The fault (red lines) has been intruded by a 2.6 meters wide dyke. The green line represent the Ordovician - Silurian boundary. The blue outline represents the valley fill conglomerate which is present on the south tip of Hovedøya. Stereographic projections of bedding and fault plane are presented below the figure. (N 59° 53.497', E 10° 43.711')

Locality F2 – Normal faults and dikes

Outcrop is located on the easter tip of Hovedøya and display several normal faults with associated slickenside lineations. The fault planes are oriented NNW – SSE and display intermediate dips towards ENE. The lithology faulted is that of the Ordovician Silurian boundary displayed in Fig. 3.11 and Fig. 4.31. Four different fault planes (Fig. 4.31, red areas) with associated slickenside lineations have been measured. By comparing slickenside lineations (Fig. 4.31, stereographic projection 4) with fault planes (Fig. 4.31, stereographic projection 5), it is indicated that the motion of the faults is dip-slip. The displacement of each single fault is measured to be between 100 cm and 150 cm. The bedding is shown in Fig. 4.31 as yellow lines, with associated measurements shown in stereographic projection 3.

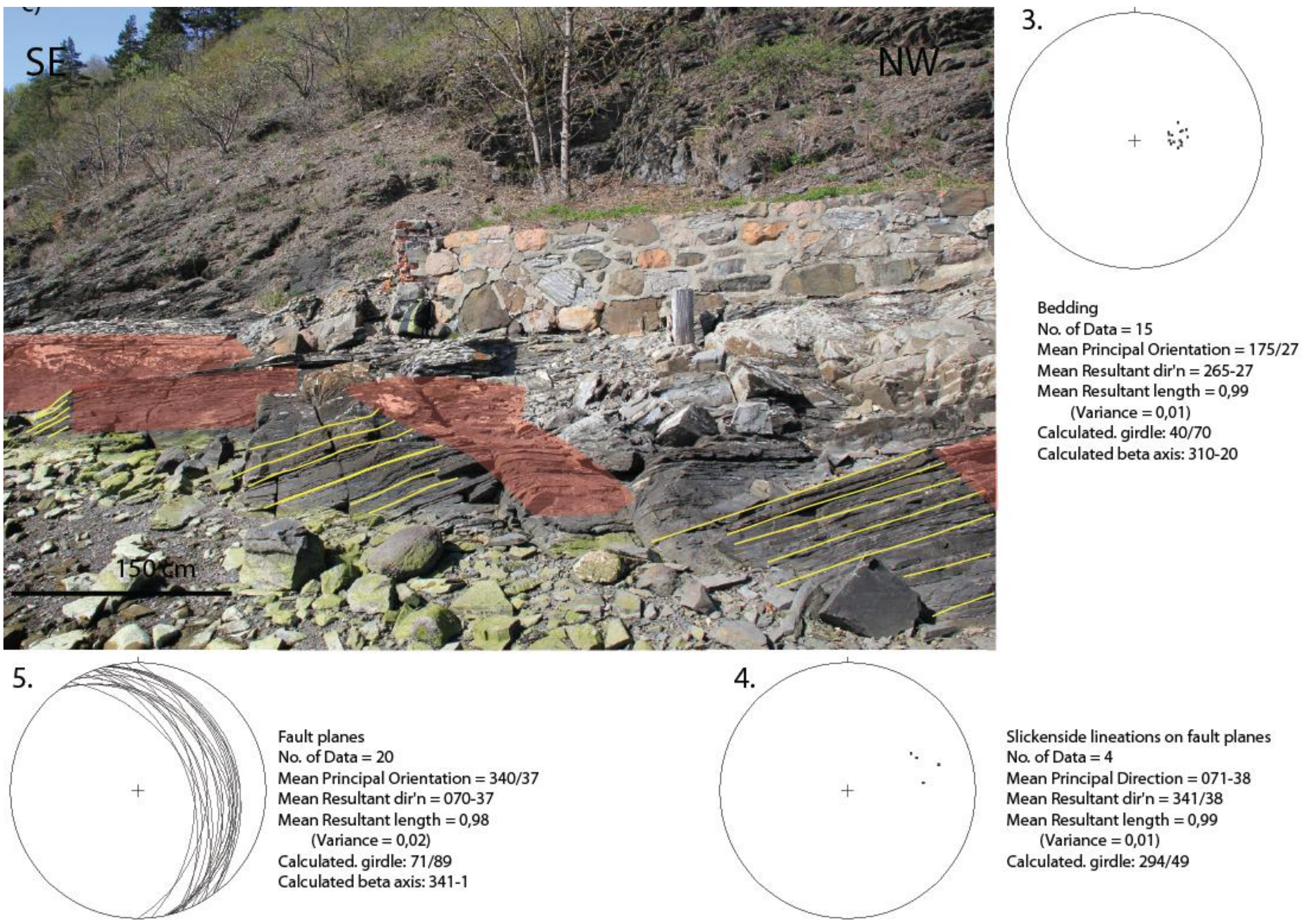


Fig. 4.31 Locality F2: Several normal fault planes with associated slickenside lineations (red areas) characterize this section. Yellow lines show bedding. Stereoplot of fault and bedding planes with associated calculated statistics displayed below and to the right. (N 59° 53.696', E 10° 44.468')

5 Discussion

Structures observed and described in the field and in preceding chapters include Fold and thrusts- bedding parallel shortening, Folds, Foreland directed thrusts and reverse faults, Hinterland directed thrusts and reverse faults, Cleavage and Permian extensional faults and will be discussed with respect to their formation and development as well as a relative age difference between the structures will be discussed at the end of the chapter.

5.1 Structures within the study area

Primary structures

The first structures developed are the primary sedimentary structures such as trace fossils, bedding lamination and cross-stratification during deposition and compaction of sediments. At some localities in the study area we got a distinct cross-stratification. These structures have been used during the field work to determine the stratigraphic right way up, and have been useful since we have overturned beds at the southeaster side of Hovedøya. Trace fossils are also found in the study area.

Fold and thrusts- bedding parallel shortening

Several localities within the study area (Fig. 4.2, Fig. 4.3, Fig. 4.4) display structures associated with bedding parallel shortening. These structures were formed due to early horizontal shortening before the main folding and thrusting event as they are found in various locations within a larger folded structure. The maximum stress ($\sigma1$) were oriented NNW-SSE (Fig. 4.2). In Fig. 4.4 we can see the litological control on deformation as thin layers with shale and limestone has been folded, while a thicker more competent limestone layer has been thrusted. Both structures are related to the same kind of bedding parallel shortening event.

Folds

The presence of broad macroscopic folds in the Upper Ordovician and Silurian rocks within the Oslo area have been discussed by Morley (1986a, 1986b, 1987a, 1994), Fjærtoft (1987), Ygre (1988) and Bruton et.al.(2010). Observations and measurements taken in the field (Fig. 4.5 and Fig. 4.6), as well as geological mapping (Appendix A1: Geological map of Hovedøya and Lindøya,) verifies the presence of a large scale anticlinal structure covering the study area.

The style of folding in the study area is influenced by several factors. Morley (1986b, 1987a, 1994) discuss how the stratigraphy influences the vertical and lateral change in deformational style. Interactions between changes in lithology, and thickness variations of the formations, produce complex changes in deformational style within the Oslo Region. The latter applies to both the macroscopic and the mesoscopic structures within the study area, were alternating units of competent and incompetent beds with varying thicknesses are present.

As mention in chapter 2.4 (Caledonian structuring within the Oslo Region), there is a general increase in competent units upwards in the Lower Palaeozoic stratigraphy within the Oslo region, culminating in the Silurian Ringerike sandstone. The Ringerike sandstone is believed to have played a vital role in the development of folds in the Oslo Region due to its high competence and vertical thickness (Morley, 1986b, 1987a, 1994)(Fig. 2.2)(Fig. 1.2).

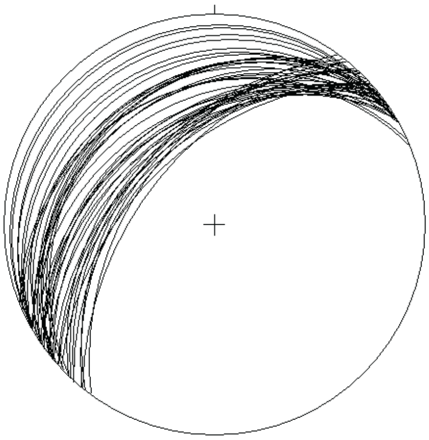
Most folds within the study area display folding of multiple layers, with competence differences between layers. This implies that we often will see differences in style of folding also within the folds. Fig. 1.4 (Ramsay and Huber, 1987) display different lithological and bed thickness control in a multilayered folding situation.

When a layered sequence of competent and incompetent units deform by layer parallel shortening, the sequence will fold due to flexural slip between the layers (Fig. 1.3). Flexural slip surfaces are developed at various locations within the study (Fig. 4.15), and are associated with calcite slickenside lineations on the slip surfaces.

Mesoscopic folds described from the study area display parallel (class 1B) folding within the competent limestone, siltstone and sandstone layers, while the incompetent shale layers display either similar (class 2 or 3) folds or parallel folds(class 1B). When shale layers exhibits parallel folding, there is also parallel folding in the competent layers. Folding of rocks exhibiting thin incompetent layers with respect to thick competent may not develop similar (class 2 or 3) folds in the incompetent layer, but must be thought of as folding of a single unit of rocks (Ramsay and Huber, 1987).

Foreland directed thrusts and reverse faults

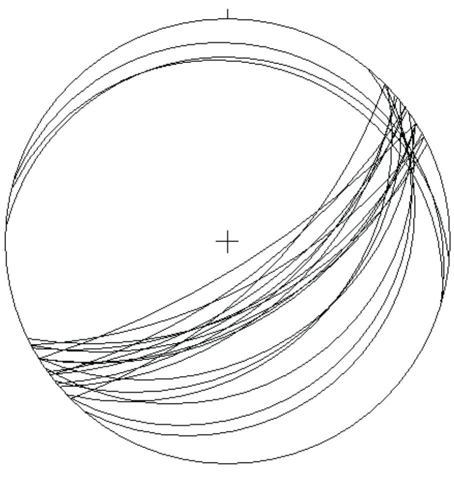
Most thrusts within the study area are interpreted to be foreland directed thrusts and reverse fault. From field measurements we observe that the main orientation of the foreland directed



thrusts and reverse fault, are oriented NE-SW or ENE- WSW, indicating a maximum stress orientation (σ1) directed NW-SE to WNW-ESE. The thrusts display an intermediate dip towards NW, inferring a main transport direction towards SE-SSE, which are in compliance with previous work done in the Oslo area.

Hinterland directed thrusts and reverse faults

Hinterland directed thrust and reverse faults or back- thrusts are described at two localities within the study area. The back thrusts within the study area are located in the core of the



macroscopic southeastern verging anticlinal structure which covers the entire study are. The back thrust are interpreted to be splay fault from earlier foreland directed thrusts, as we get space problems in the anticline core as the anticline folds. From field measurements we observe that the main orientation of the hinterland directed thrusts are NE-SW. The thrusts display an intermediate to steep dip to the SE, inferring a transport direction towards NW. The maximum stress is orientation (σ1) directed NW.

Cleavage

The main processes related to cleavage formation within the Lower Paleozoic sedimentary rocks in the study area are the relation between the sedimentary rock and water, in combination with mechanical influence (Marshak and Engelder, 1985; Ygre, 1988), which include processes such as pressure solution, free- face dissolution and diffusion and advection. Morley(1986b) and Ygre (1988) claims a burial depth of the Cambro-Silurian sediments of approximately 2 km from conodont coloration indices, and say that no metamorphic conditions are present due to low pressure and temperature. They thereby limit themselves by putting up boundaries for the mechanisms and processes related to cleavage development. From a more recent paper by (Heeremans et al., 1996), it is stated that regional metamorphic conditions with temperatures up to 200^{o}C could have been present in the sediments, due to burial estimated to be 3-5 km.

Bedding parallel cleavage

The bedding parallel cleavage within the study area is only found within the coarse-grained calcareous sandstone of the Upper Langøyene Formation. The layer parallel cleavage is defined by a preferred orientation of grains parallel to bedding planes. The cleavage is formed from vertical differential stress due to overburden during burial (Ramsay and Huber, 1983), which implies that maximum stress (σ1) was oriented vertical. The cleavages are always parallel to the bedding and are therefore interpreted to have been developed before the main folding and thrusting events.

Bedding perpendicular cleavage

The bedding perpendicular cleavage within the study area is also found within the coarse-grained calcareous sandstone of the Upper Langøyene Formation. The cleavage display a vertical to sub vertical cleavage normal to bedding planes within the study area, which relate the bedding perpendicular cleavage to have been development as a result of layer parallel shortening (Ramsay and Huber, 1987), with maximum stress (σ1) oriented horizontally, before the main folding and thrusting events.

Intermediate NW dipping cleavage

A strong intermediate NW dipping cleavage is found in various locations within the study area, always displaying the approximately the same orientation in strike and dip. The observed cleavage display no pressure solution seams or preferred mineral orientation, indicating that there has not been any other influence on cleavage formation other than mechanical influence. The cleavage can be observed across the entire macroscopic fold structure on Hovedøya, and display the same orientations on the northwestern limb, within the core of the anticline structure, on the southeastern overturned limb and on the core of the macroscopic syncline structure on the northeastern side of the island, suggesting that the intermediate NW dipping cleavage may have been developed after the main folding and thrusting event. Fig. 5.1 display cleavages planes found at Hovedøya. Green and Red poles to cleavage display the two direction of pencil cleavage found at the macroscopic syncline structure found at the northeaster side of Hovedøya. Note that cleavage direction 1 of the pencil cleavage display simmilar orientation as the intermediate NW dipping cleavage.

A possible development of the cleavage overprinting the study area can have been formed by overburden stress, rotating fault blocks and burial depths of 3-5 km during the Permian (Heeremans et al., 1996).

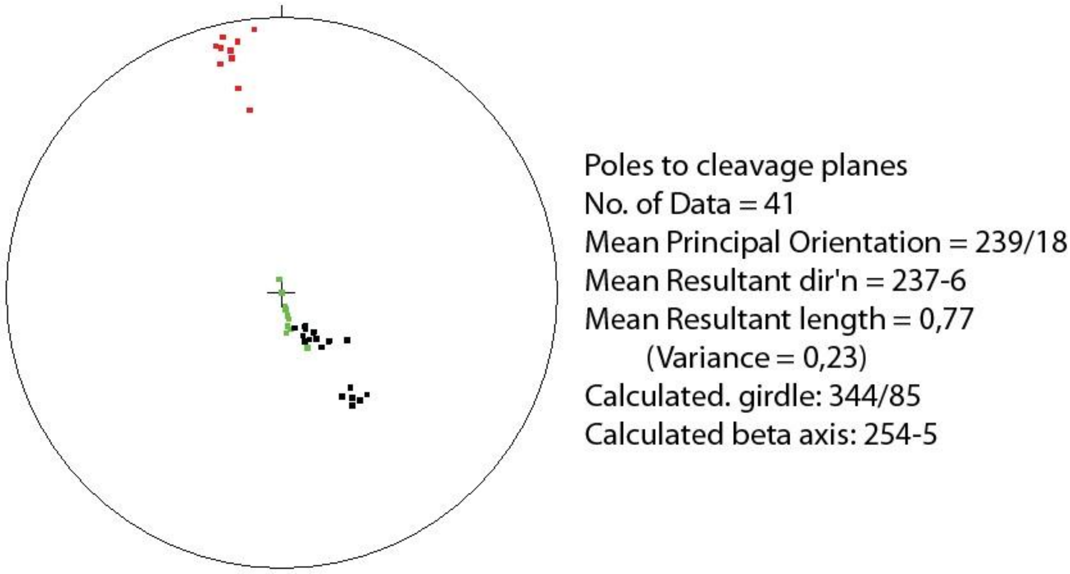


Fig. 5.1 The figure displays all cleavage planes on Hovedøya. Black: poles to the intermediate NW dipping cleavage. Green poles: Pencil structure, direction 1. Red poles: Pencil structure, direction 2.

Pencil cleavage

Reks and Gray ((1982)p. 173) states that “*pencil structures are made up of two independent anisotropy directions, bedding fissility and cleavage fabric*”.

Two possible models in how to develop the pencil structures observed in the study area. Also Reks and Gray (1982) states that to produce pencil structures, the rocks must have been deformed within the intervall 9-26 % (see Fig. 1.7 and Terminology chapter for more information)

Model 1:

The pencil structures can possibly have been developed by an early bedding fissility in the Silurian shale (pre-folding), then folding and later intersected by an axial plane cleavage.

Model 2:

The development of pencil structures can also possibly be interpreted to be an intersection of, an axial plane cleavage that developed in the macroscopic syncline and the intermediate NW dipping cleavage transecting the entire study area at a later stage, possibly cleavage development due to later overburden and rotated fault blocks in the Permian. Fig. 5.1 display the relationship directions between the the intermediate NW dipping cleavage and the axial plane cleavage.

Since the preservation of a bedding fissility needs less than 26% shortening and shortening and deformation is highest within the cores of folded rocks (Reks and Gray, 1982, 1983). The first model need less than 26 % internal deformation to be possible. Morley (1986b) states that in the lower Ordovician, strained graptolites in zones of pencil cleavage have been shortened up to 26%. A vertical decrease in internal deformation up in the strata, from a 34 % shortening in the cambrian to mid- Ordovician sequence to 17 % in the Ringerike sandstone, From folding and thrusting calculations (Morley, 1986b)p. 631, the lower Silurian have been subjected to 26% shortening, and makes model 1 possible, but not probable. Model 2 is therefor interpreted to be more likely than model 1.

Permian extensional faults

Extension and rifting in Permian resulted in the development of normal faults and graben segments (2.5 Late Carboniferous-Permian rocks). Normal faults and dyke intrusions cutting the Lower Paleozoic depoits are common within the study area. These structures are the latest developed tectonic structurs seen in the field as they cut through all other structures.

The normal faults show an orientation of N-S to NNW-SSE, with steep to vertical dips. The maximum stress orientation were oriented vertically during the Permian rifting, which is normal for extentional regimes.

5.2 Relative age of structures

Based on observations from the study area, the relative age relationship between the different structural elements can be determined by cross-cutting properties and are as follows:

Deformation stage zero (D_0)

- Primary sedimentary structures were developed during sedimentation and compaction.
- Later bedding parallel cleavage were formed due to overburden during burial

Deformation stage zero (D_1)

- Bedding perpendicular cleavage development as a result of layer parallel shortening
- Folding and low angle thrusting associated with bedding parallel shortening

Deformation stage zero (D_2)

- Folding by buckling and flexural slip between layers with differences in competence. Bedding planes and fold axis display a NE-SW orientation, with bedding planes and fold often displaying vergens toward SE, indicate maximum stress (σ1) directed towards SE
- Axial plane cleavage development in folded shale units
- Foreland directed thrusts and reverse fault, oriented NE-SW or ENE- WSW, indicating a maximum stress orientation (σ1) directed towards SE-ESE.

Deformation stage zero (D_3)

- Hinterland directed thrusts are oriented NE-SW, with indicating a maximum stress orientation (σ1) directed NW

Deformation stage zero (D_4)

- Normal faults show an orientation of N-S to NNW-SSE, with steep to vertical dips. The maximum stress (σ1) oriented vertically during the Permian rifting
- Development of possible intermediate NW dipping cleavage due to 3-5 km vertical overburden (Permian rocks) on rotated fault blocks containing the Lower Palaeozoic rocks.

6 Conclusion

Based on the discussion, five deformational stages were identified within the study area.

Structures related to compaction

Deformation stage zero (D_0)

- Primary sedimentary structures were developed during sedimentation and compaction.
- Later bedding parallel cleavage were formed due to overburden during burial

Caledonian structures

Deformation stage zero (D_1)

- Bedding perpendicular cleavage development as a result of layer parallel shortening
- Folding and low angle thrusting associated with bedding parallel shortening

Deformation stage zero (D_2)

- Folding by buckling and flexural slip between layers with differences in competence. Bedding planes and fold axis display a NE-SW orientation, with bedding planes and fold often displaying vergens toward SE, indicate maximum stress ($\sigma 1$) directed towards SE
- Axial plane cleavage development in folded shale units
- Foreland directed thrusts and reverse fault, oriented NE-SW or ENE- WSW, indicating a maximum stress orientation ($\sigma 1$) directed towards SE-ESE.

Deformation stage zero (D_3)

- Hinterland directed thrusts are oriented NE-SW, with indicating a maximum stress orientation ($\sigma 1$) directed NW

Permian structures

Deformation stage zero (D_4)

- Normal faults show an orientation of N-S to NNW-SSE, with steep to vertical dips. The maximum stress ($\sigma 1$) oriented vertically during the Permian rifting

- Development of possible intermediate NW dipping cleavage due to 3-5 km vertical overburden (Permian rocks) on rotated fault blocks containing the Lower Palaeozoic rocks.

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8 Appendix

8.1 Appendix A- Geological maps

Appendix A1: Geological map of Hovedøya and Lindøya

Appendix A2: Geological map of Hovedøya

Appendix A3: Geological map of Lindøya