DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2008/7

Introduction to Principles of Structural Geology

Short course notes and exercises for the course in structural geology at Hanoi University of Mining and Geology, Vietnam, 16th – 18th January 2008

Stig A. Schack Pedersen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

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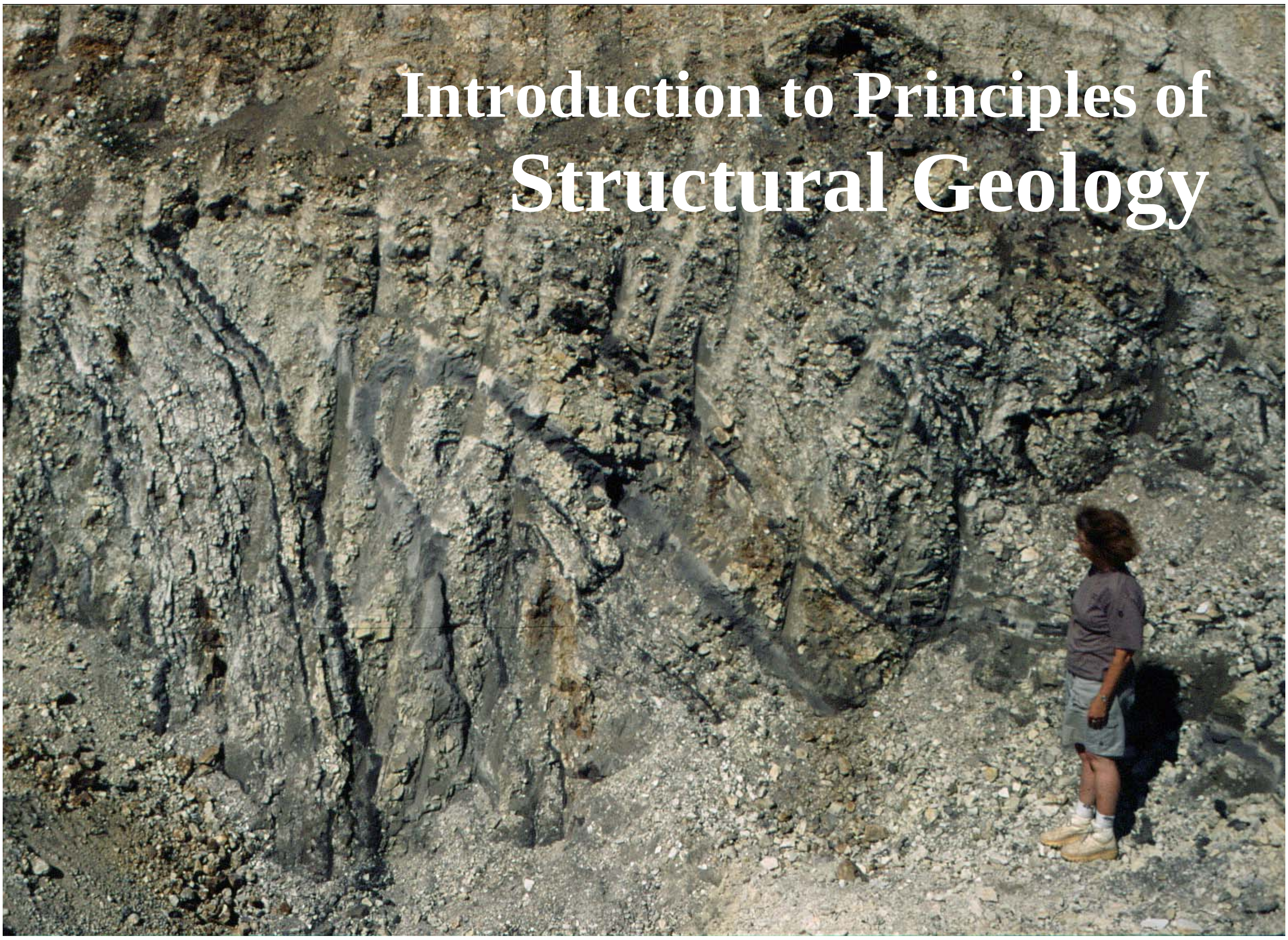

Dr. Stig A. Schack Pedersen, GEUS

Hanoi University of Mining and Geology

16th – 18th January 2008

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Geological Survey of Denmark and Greenland

Preface

This paper is a brief accumulation of notes for a short course in the introduction to principles of structural geology. The challenge of structural geology is to enables scientists to visualise the three dimensional structural features of geology and provide the scientist with a set of terms to describe these features. The interpretation and evaluation of subsurface geology may, in many cases be enhanced by the use of outcrop data. Data from outcrops closely adjacent to deep basins may often be obtained by relatively in-expensive activity compared to conventional seismic surveys and drilling. The utilisation of such data may thus be a very valuable contribution to a regional conventional data set. Structural geology provides the background and skills for describing outcrops and interpreting the data and combining the data into 3-D models which gives the possibility of predicting the subsurface geology.

The aim of this seminar is thus to exemplify how such data may be obtained by 1) The study of exposed sections, construction of cross section and measuring structural data ; 2) Interpretation of cross sections from shallow wells (bore holes); 3) Construction of 3-D models; 4) Reading and compiling geological maps; 5) Predictions from structural geological models; and 6) Describing and interpreting dynamic models for evaluating and concluding decisions concerning subsurface exploration and exploitation.

Course instructor: Dr Stig A. Schack Pedersen, GEUS

Course location: Hanoi University of Mining and Geology, 16–18th January 08

Overview of the course:

1. Introduction to the 3-D processes: Deposition, Deformation and Destruction (sedimentation, alteration and erosion)
2. Structural analysis of folds and faults
3. Extensional deformation, from normal faults to landslides
4. Compressional deformation, from thin-skinned thrust faulting to superimposed deformation.
5. Transform deformation, from pull apart basins to transpression thrusting
6. Syn-tectonic depositional systems
7. Dynamic interpretation of poly-deformational events.

Introduction

Structural geology aims at understanding the architecture of the Earth's crust, from the highest to the deepest. The science of structural geology includes the skills of structural analysis, and what is a structural analysis? Within all natural sciences the analysis of structures means description of geometrical behaviour of bodies and architectural arrangement of groups of bodies. However, within the structural geology it also includes the sequential superposition of structures and their dynamic development. The classic systematic within structural geology comprises three steps: The first step is description of geometry, the second step concerns unravelling the kinematics including the dynamic development, and the third step aims at setting up a tectonic synthesis.

The basis for dealing with structural geology is the understanding of the principles in general geology, which may be summarised in the 3-D processes: DEPOSITION, DEFORMATION AND DESTRUKTION (sedimentation, alteration and erosion). Deposition is here regarded in a broad term, not only concentrated to sedimentation but also including material supplied from magmatic origin. Deformation includes all the processes resulting in the change of shape, the target of structural geology. Finally destruction includes the erosion and removal of geological formations.

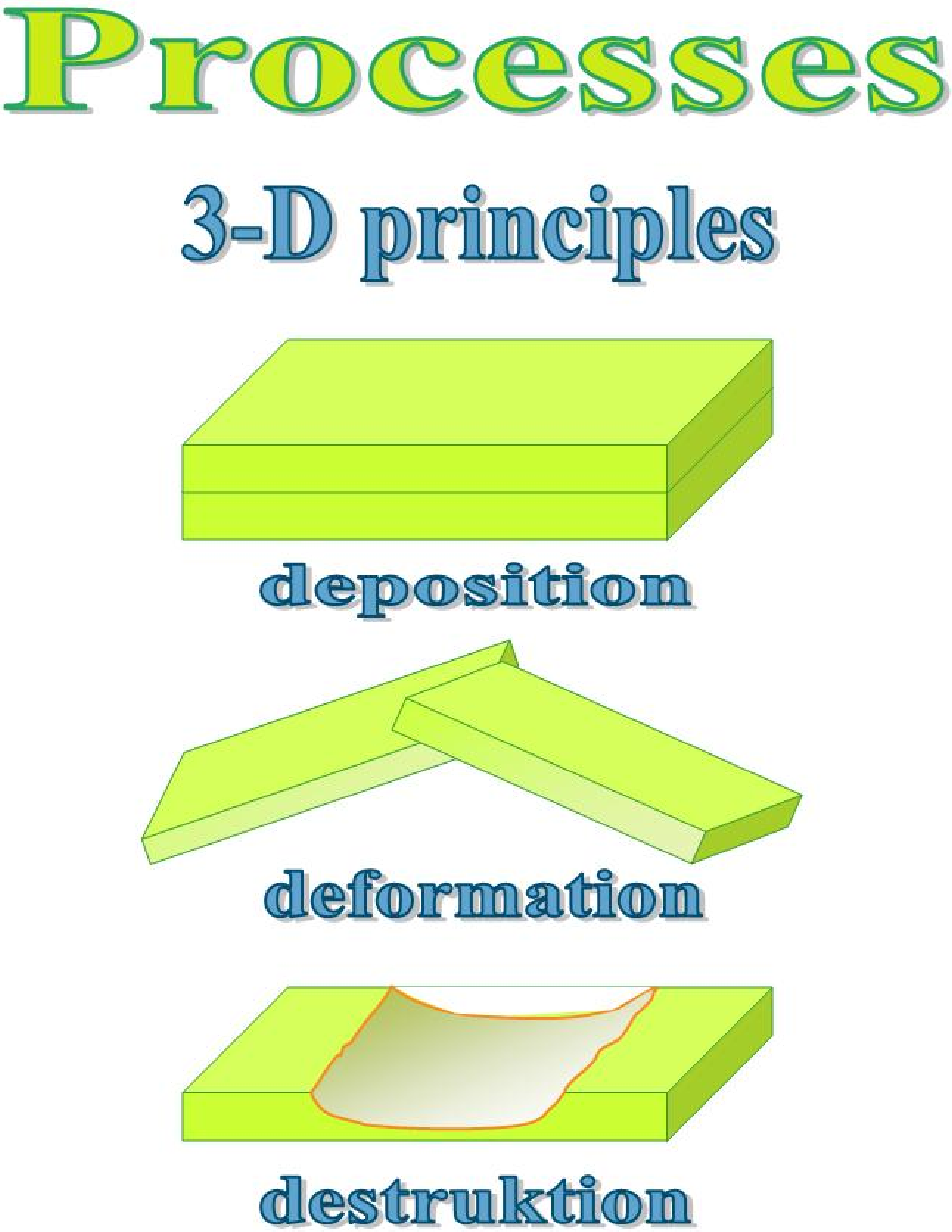
The present introduction to principles of structural geology aims at describing three different types of tectonic regimes: 1) The extensional regime, which focuses on normal faulting and subsiding basins 2) The compressional regime, which deals with structures of mountain ranges and orogenic complexes, and 3) The transtensional regimes which includes the strike-slip system and wrench fault settings.

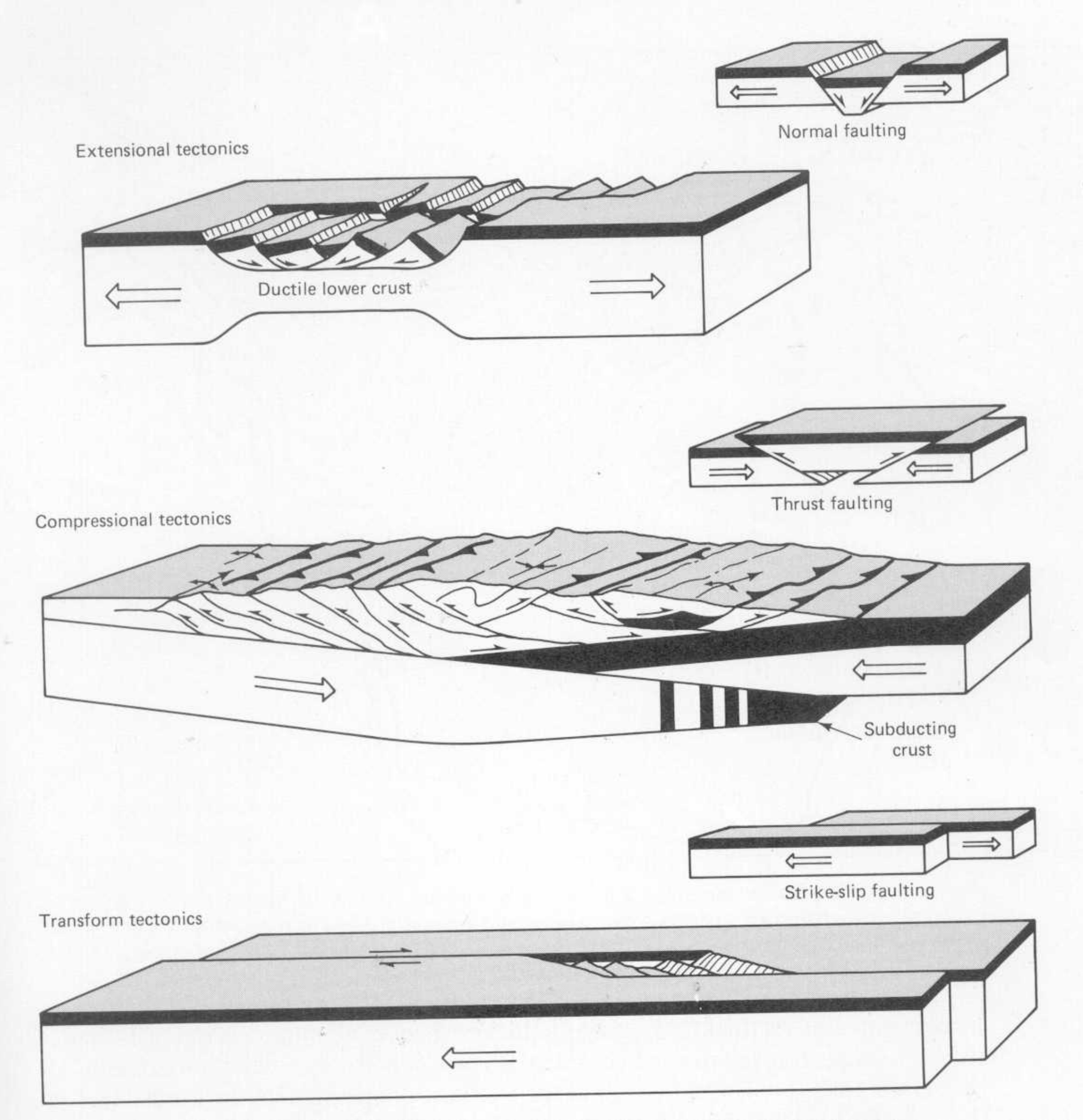
In the description of elements in structural geology one has to address the size of structures, which are classified as: megascopic, macroscopic, mesoscopic and microscopic structures.

1. The megascopic structures are elements in a scale larger than 10 km. They are included in global tectonic frameworks, and could be exemplified by the Reykjanes Ridge oceanic spreading zone, the Taiwan compressional mountain range, or the San Andreas Fault zone.
2. The macroscopic structures have the scale from hundred meters to kilometre in size and could be one long extensional fracture zone, a large hanging-wall anticline forming one mountain range ridge or a splay-fault zone in a transtension system.
3. The mesoscopic structures are the structures you can over look on an outcrop. They are in the scale from a decimetre to ten metres in size, which may include a fault breccia, parasitic folds on a larger fold, pinnace jointing on a fault surface.
4. The microscopic structures viewed with a hand lens, an optic microscope or in scanning electron microscope. The structures observed in this scale are mineralogical composition of cleavage and schistosity, rotation of mineral grains, fabric orientation, superimposed metamorphic alteration.

In the following chapters examples of structural elements are presented. The structures are grouped in relation to the structural regimes, in which they appear. Furthermore the first chapter includes the introduction to the presentation of the orientation of structural elements: the stereographic presentation and contour line maps.

The 3-D processes and the main tectonic regimes

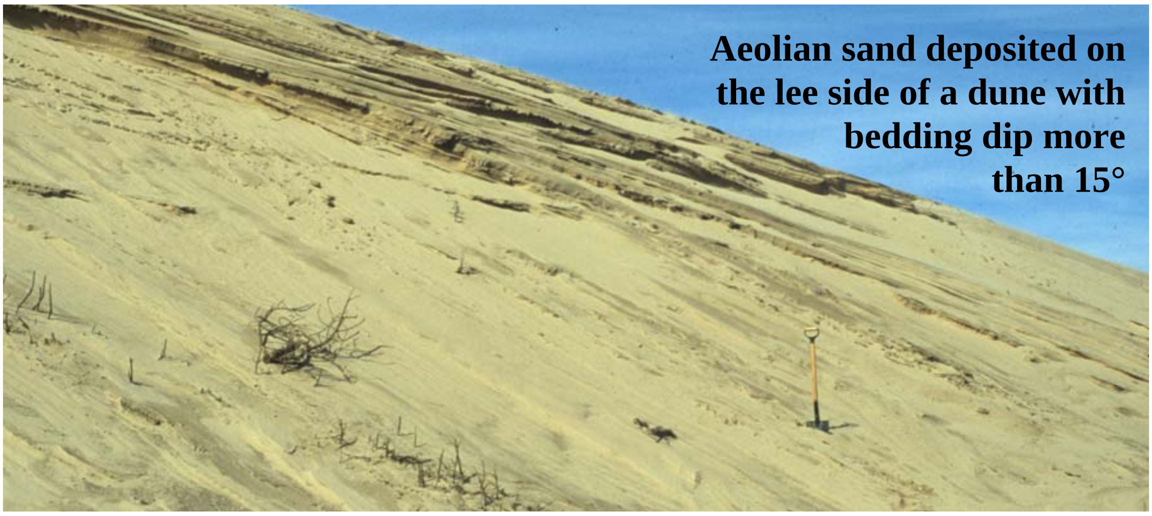




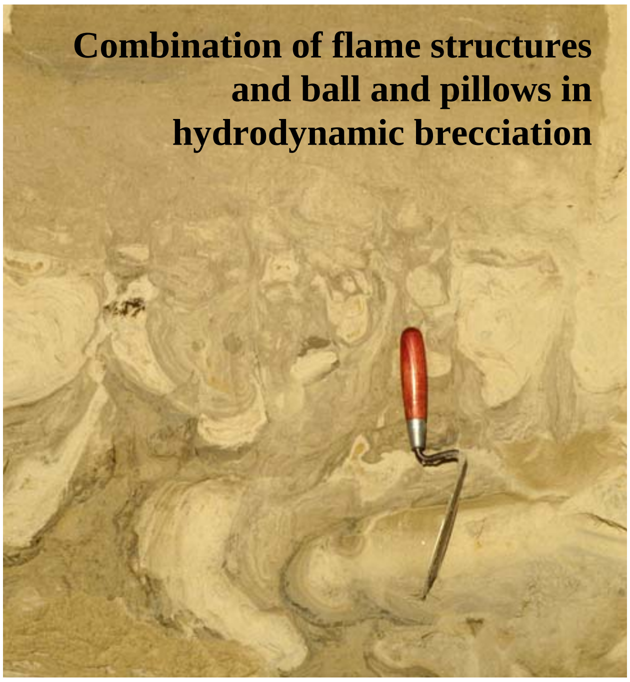
The three main tectonic regimes are here illustrated in block diagrams with their significant setting types and fundamental fault types. At the top it is illustrated, how the extensional tectonics make the lithosphere thinner and the subsidence is related to normal faulting. In the middle it is illustrated, how the compressional tectonics make the lithosphere thicker and the main fault type is thrust faulting. The transform tectonics illustrated in the lower diagram will typically link the extensional and the compressional plate boundaries and compensate for oblique plate movements.

Primary bedding and unconformities

The general principle for bedding is that particles are deposited to form a horizontal layer. This is mainly the situation in marine environment, where the sea bed form the surface upon which new strata are deposited to horizontal lamination. In continental environment the situation is a bit more complicated. Here cross bedding is a common occurrence in fluvial environment, and in aeolian dune deposits large scale cross bedding may be a dominant feature, which should not be mistaken for tilted bedding.



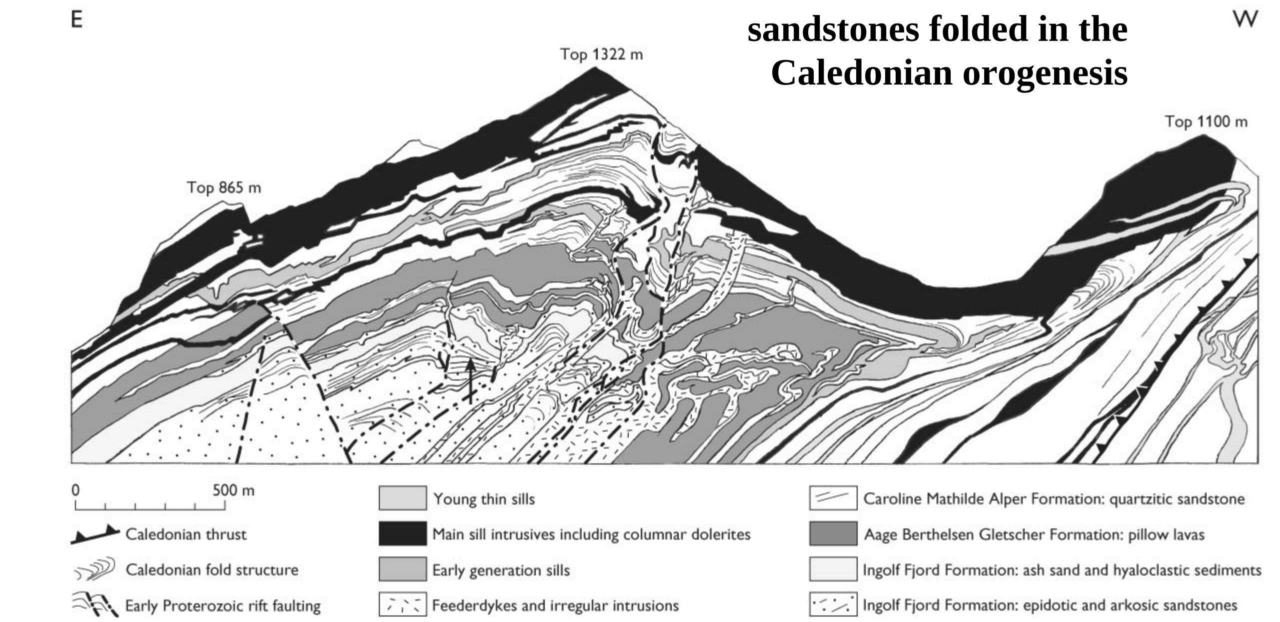
Also in the Gilbert delta settings large scale cross bedding occur, but the sedimentological setting will normally give the clue to the understanding of the tilted bed features. The sedimentological structures provide important information of the way up relationship in the tectonically deformed complexes. In cross bedding the tangential approximation to the underlying bed and the truncation of the top set provides this information, and graded bedding with the coarse grains at the base and fine grains at the top is similarly a good way up marker.



In soft sedimentary deformation the first alteration during the depositional loading and early diagenesis results in deformation in the regime between sedimentation and deformation. Especially in formations with variable water content the primary bedding is disturbed due to the density contrast. The resulting structures are flame structures, and with increasing loading ball and pillow structures, which may develop into hydrodynamic breccias or even diapirs. Deposits with high water content will often response to compaction by volume change. This is typically the case for peat deposits, which may loss up to 80% of its primary volume.

Volcanic settings will often build up a cone with dipping strata in the vicinity of the vent. More distally the lava flows form horizontally deposited pyroclastic beds. In many volcanic settings part of the erupting magma does not reach the surface, but form intrusive layers, which we name sills (horizontal) or dykes (vertical). When the sills form layers parallel with bedding they are described as concordant. If the sills cross cut the bedding with a gentle to moderate angel it is described as discordant.

Proterozoic sills in a succession of sandstones folded in the Caledonian orogenesis

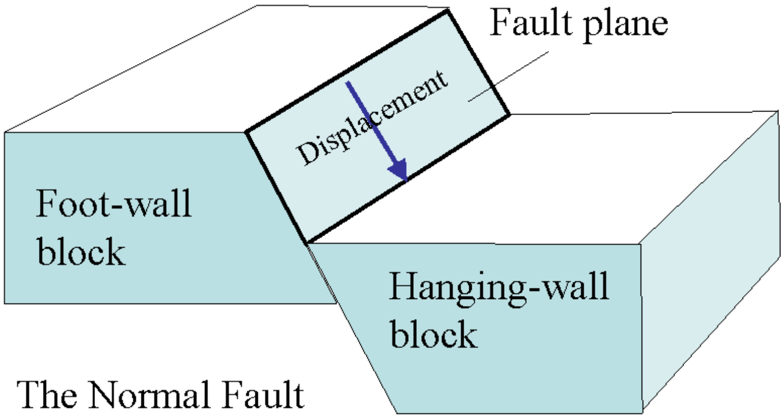


When a geological boundary in a succession represents a stratigraphic time gab, the boundary is named an unconformity. The reason for missing deposits may be due to non-sedimentation. However, in general it is due to erosion. If the erosion created an uneven surface it is referred to as an erosional unconformity, which often will be overlain by a residual conglomerate.

If a structural event has affected a geological succession the bedding will in general be tilted. In the a succeeding erosional event the tilted beds will be truncated, and a new succession will be deposited horizontally above it. This type of unconformity will also be described as discordant, and the term disconformity may also be applied.

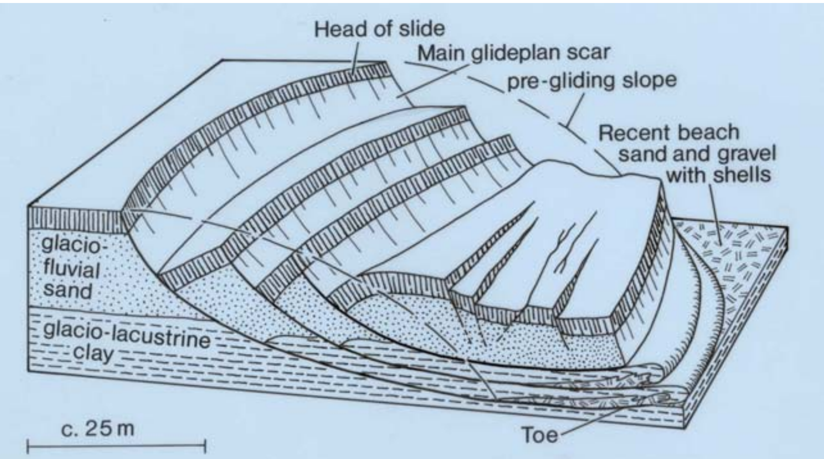
Normal faults in basin analysis

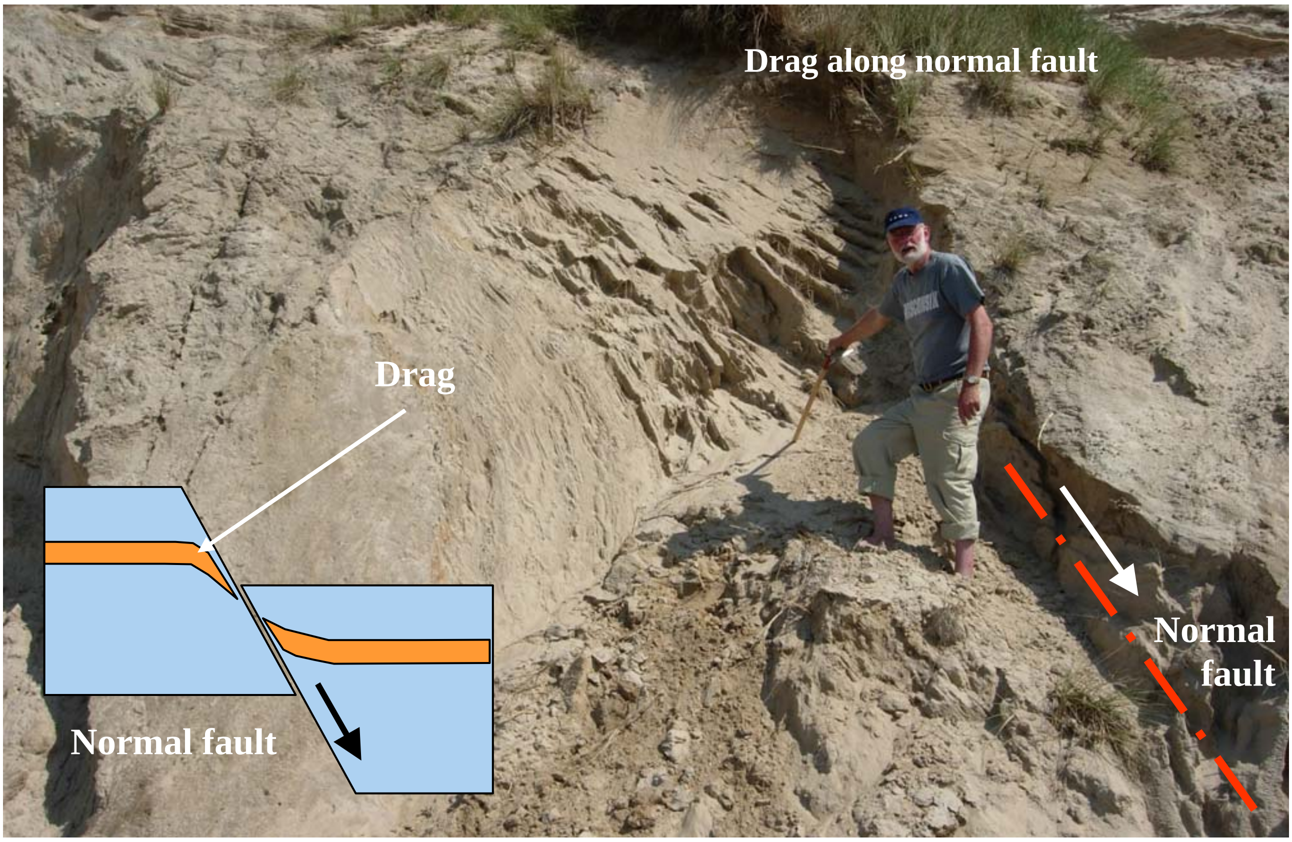
Faults are grouped into three different regimes: extensional regimes, compressional regimes and transtensional regimes. In the extensional regime the faults are typically normal faults, where one block is down thrown along a moderate to steeply dipping fault plane. In the compressional regime moving block is displaced up along a gentle dipping fault plane, which is named a thrust fault. In the transtensional regime the fault planes are steeply dipping to vertical, and the moving block may either be moving down to be a normal fault setting or moving upwards to create reverse faults. In the following we will start to look at the extensional regime dominated by normal faults.



The normal faults are related to a number of structural settings: Subsiding basins in a continental extension or continental margins. The two types of continental margins are distinguished: 1) Passive margins along which the subsidence is related to cooling and contraction combined with depositional loading, 2) active margins, which may either be: a) extensional ridges, or b) subduction zones. The extensional ridges are related to lithosphere updoming and ocean floor spreading. In the initial development of extensional ridges rift basins are formed, which are bounded by normal faults. In relation to subduction zones a number of minor extensional settings may appear during the stretching of the subducting plate, for instance in the crest above a hinge zone.

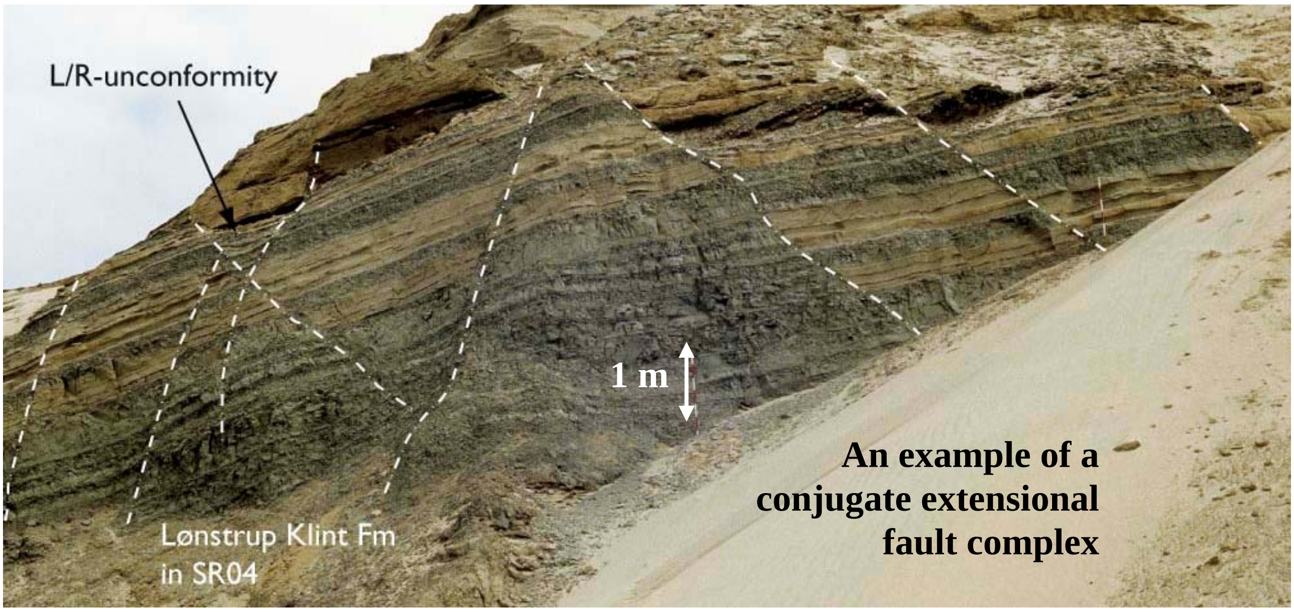
Normal faults a typically related to landslides, which is the most recent example of extensional faulting. In a landslide the following architecture elements are differentiated: The head of slide, the toe of slide, the main escarpment plane, and the translational block.

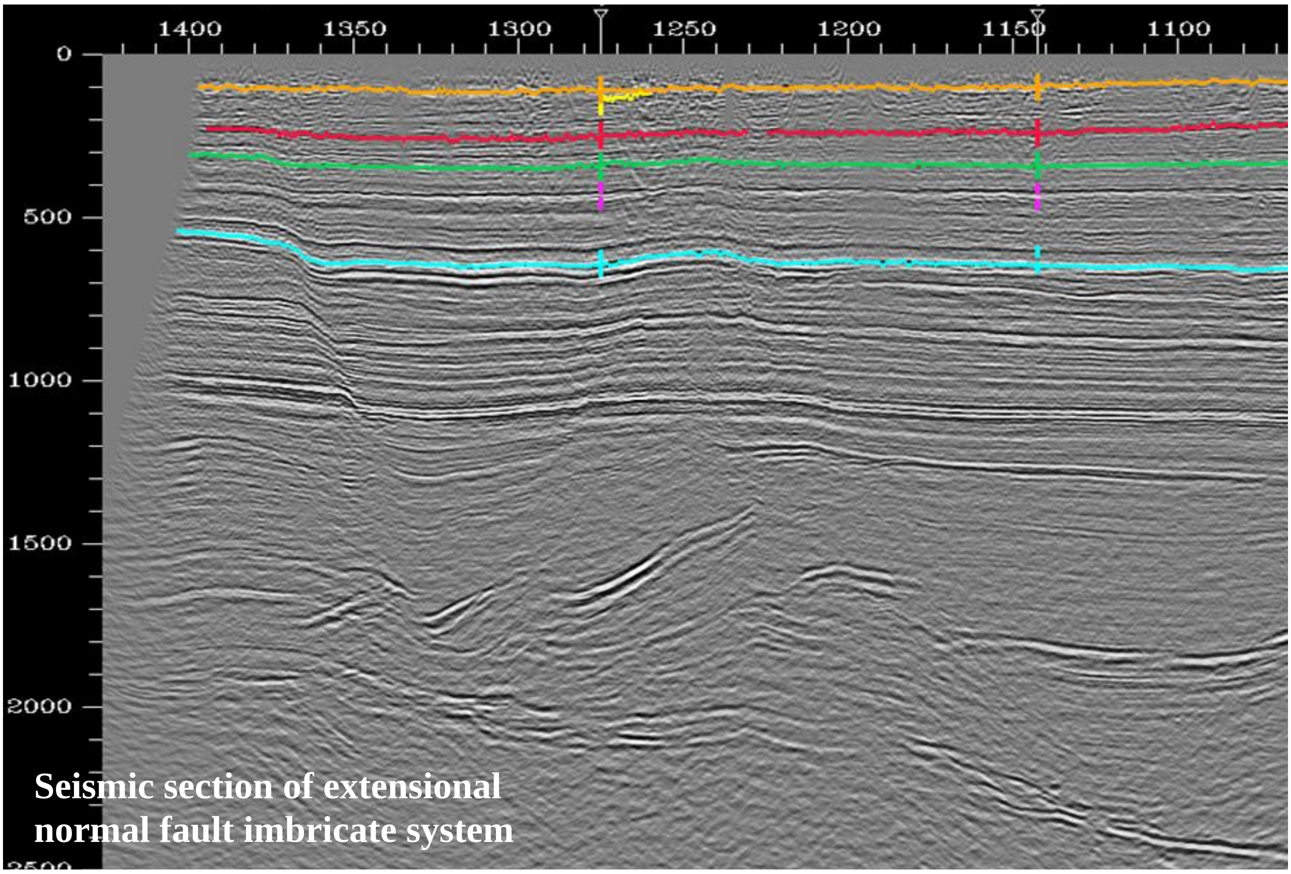


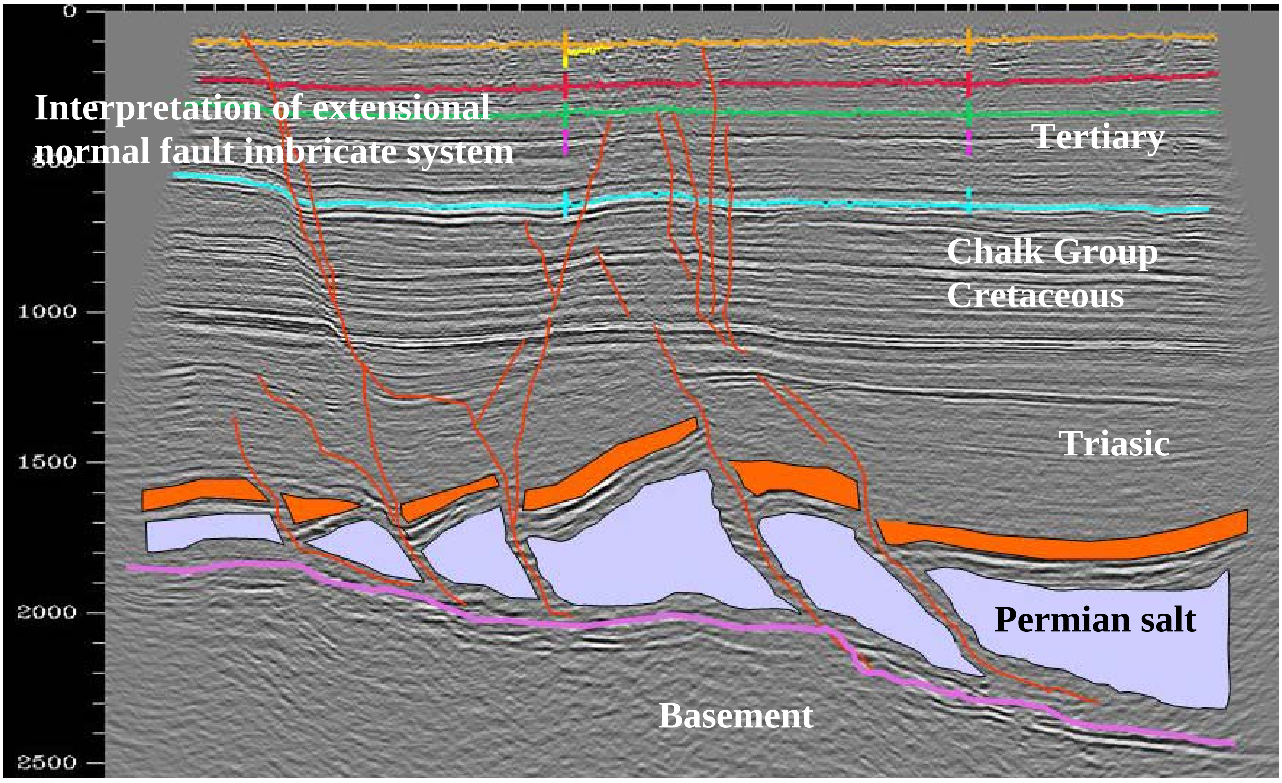


The key words for describing normal faults are:

1. Foot-wall block
2. Hanging-wall block
3. Fault plane, fault escarpment, dislocation plane,
4. Fault displacement, block separation
5. Fault drag, fault breccia, fault striation, slickenside lineation

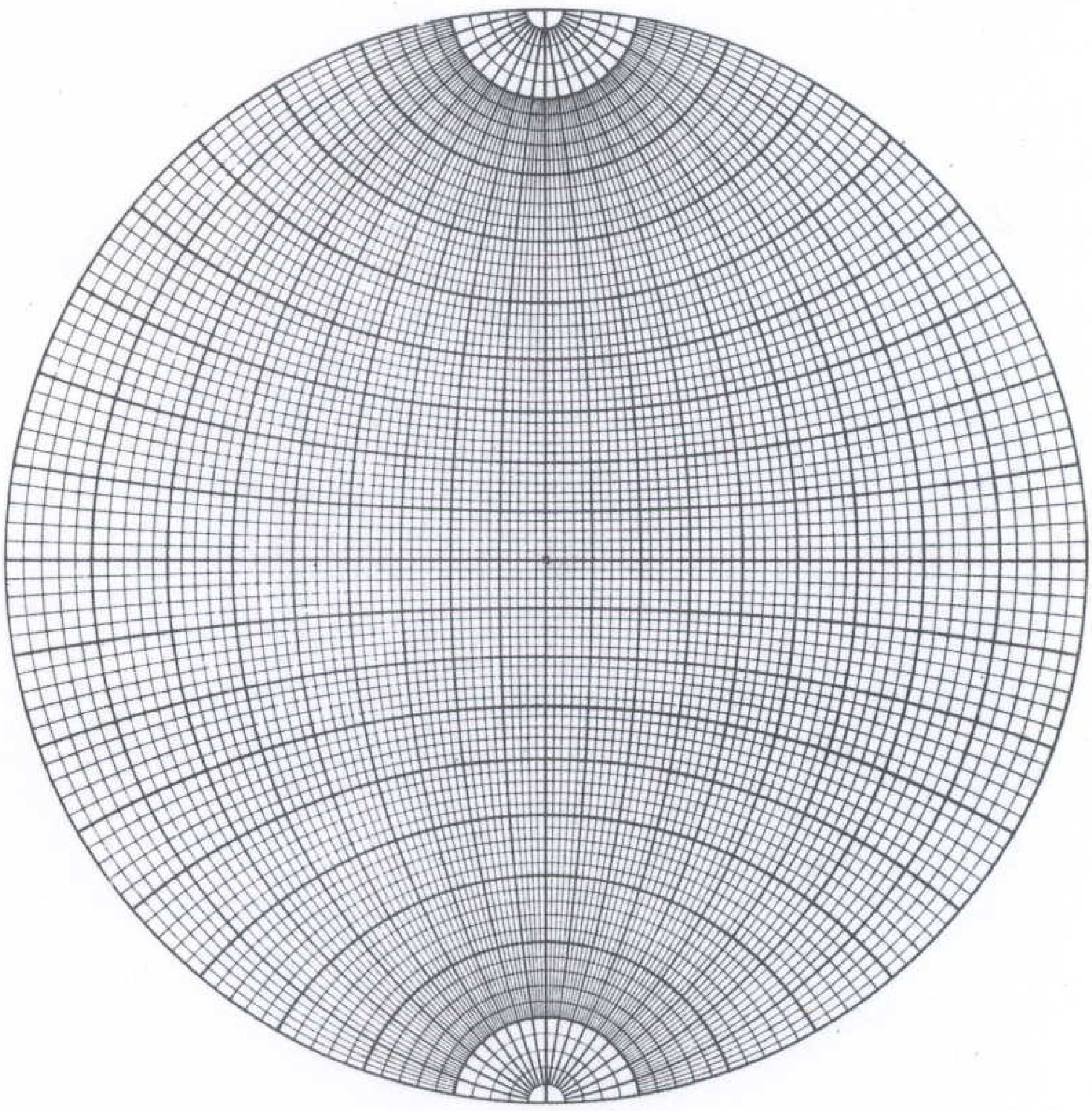






A normal fault complex may either have a series of conjugate normal faults, or it may have imbricate normal fault architecture. The extensional imbricate normal fault complex will often be associated with a roll-over anticline developed in the hanging-wall block along the fault plane.

Exercise 1: stereographic projection, strike and dip



Aim of exercise: introduction to the application of stereographic project in fault analysis, which includes plotting of strike and dip in Wulff net and presentation of orientation of faults and inclined bedding planes.

Definition: Strike is the line defined by the intersection of the dipping plane with the horizontal plane. The angle of strike is measured from north and clock wise to 180°. Dip is the angle of the bedding inclination measured perpendicular to strike from horizontal to 90° (vertical).

Exercise 2: The coal seams at Nuussuaq

In West Greenland coal is present in the Nuussuaq Basin. The central strait in this basin is the Vaigat, and on both sides of Vaigat coal bearing successions crops out. On the south side of Vaigat, the north coast of Disko, coal was mined until 1972. Several investigations have been made on the coal seams on Nuussuaq, but until now no exploitation have been started in this area. If a drill operation should be planed a number of conditions have to be considered. First of all, where will the most potential coal seam be expected to crop out, and how is it located in the underground.

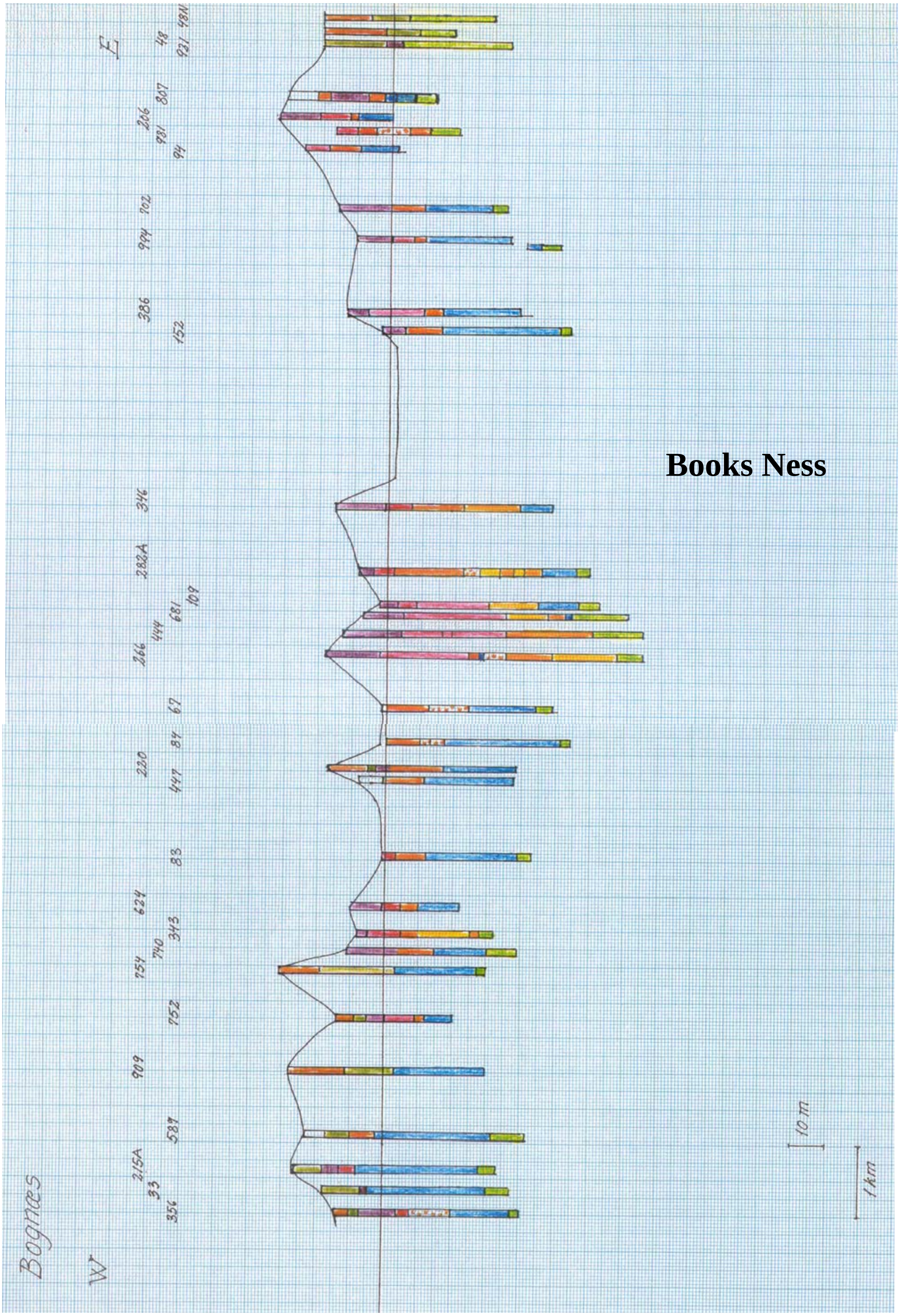
Basis for the exercise is the contour map 70 V2 J-5-1. Contour line intervals are 10 m, map scale 1:10 000. Thicknesses of individual seams are given in small numbers, and traces of exposed beds are marked. C/T is the Cretaceous-Tertiary boundary.

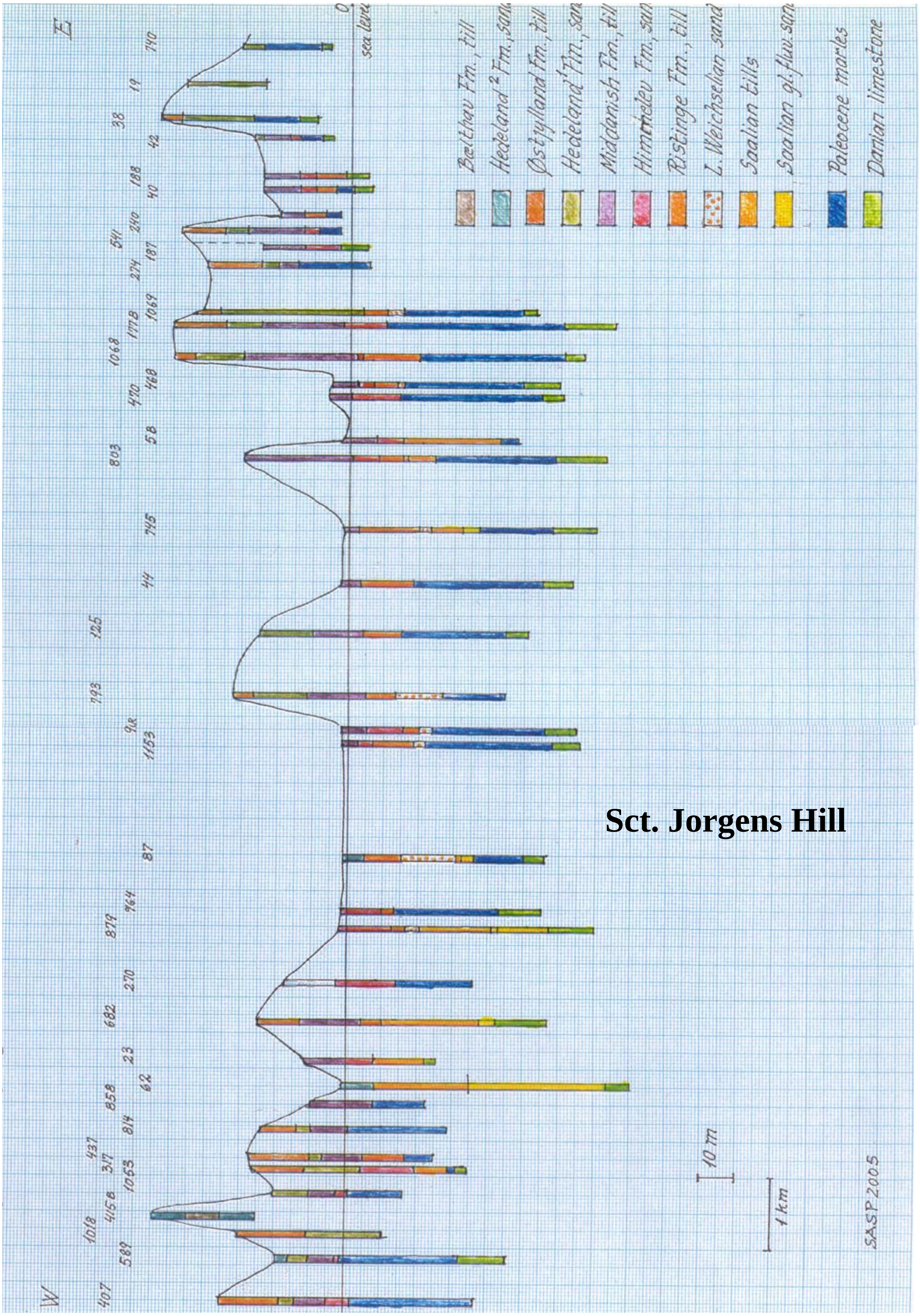
1) Make an estimate of the most reliable strike and dip of the coal seam strata.
2) Make a construction of the structural contour lines for the coal seam 165 cm thick. Draw in on the topographic contour map the outcrop of the two beds 165 and 275.
3) Trace the C/T boundary, eventually by making a new set of structure contours based on the same country dip.
4) Draw cross section across the valley slope and indicate the position of the coal seams.
5) How deep should the well be planned to be, if the coal seams 165 and 275 have to be penetrated?
6) Make a calculation of the vertical displacement along the fault zone trending east – west in the lower part of the map sheet.

Exercise 3: Roskilde Fault complex – cross sections correlation

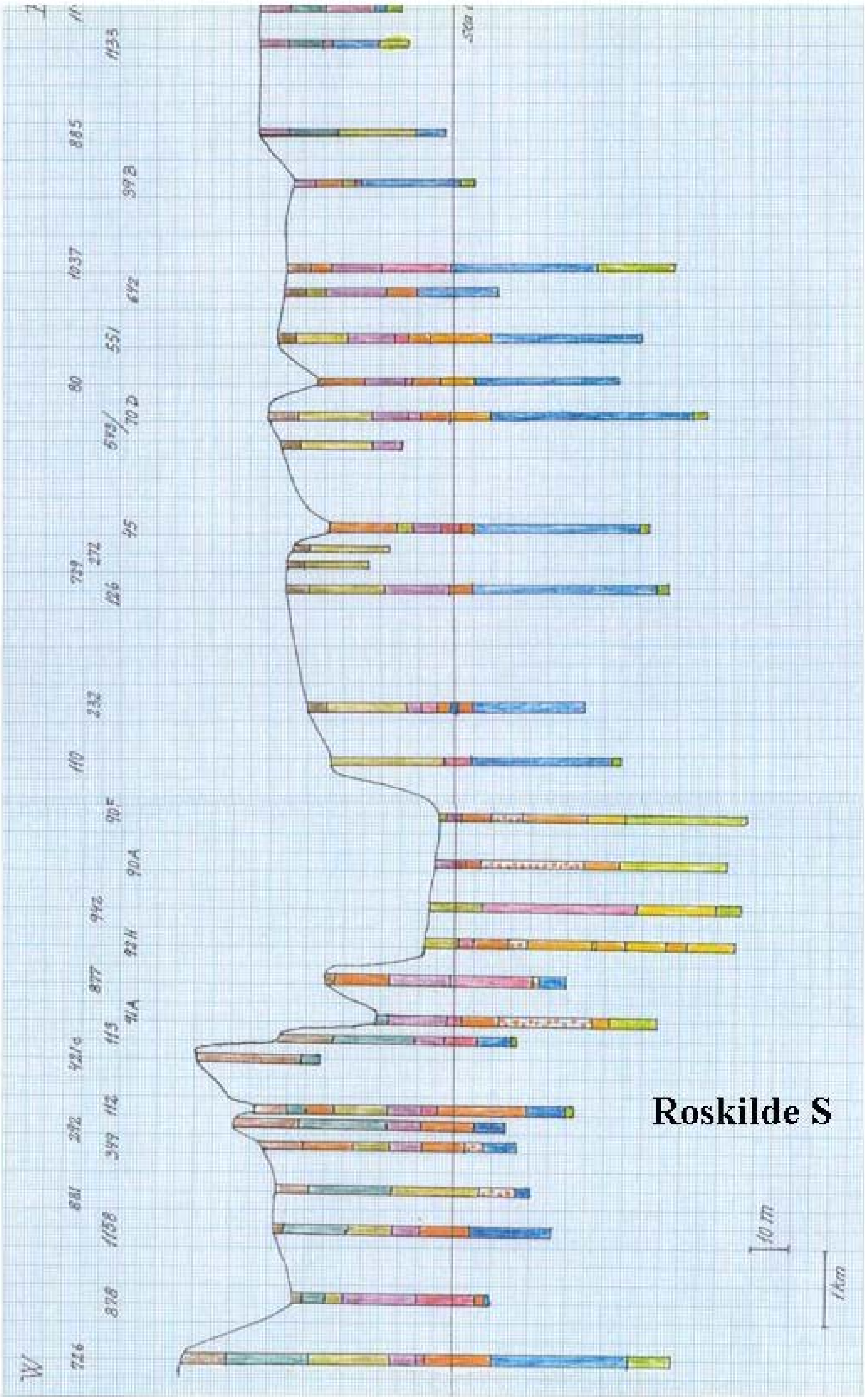
This exercise is training in interpretation and construction of geological cross sections. In the area near Roskilde three cross sections have been selected and the topography and the wells along the cross sections will be handed out at the beginning of the exercise. The geology includes the lower Paleogene Danian limestone, the overlain Palaeocene Lellinge greensand and Kerteminde marl, and above the pre-Quaternary unconformity two Saalian formations and eight Weichselian units occur. Correlate the stratigraphy from well to well and make a compiled cross section. Start with the boundary between the Danian limestone and the Palaeocene marl.

Colour pencils can be very helpful for indicating the different stratigraphic levels.


Books Ness
Bognæs
W
E
10 m
1 km



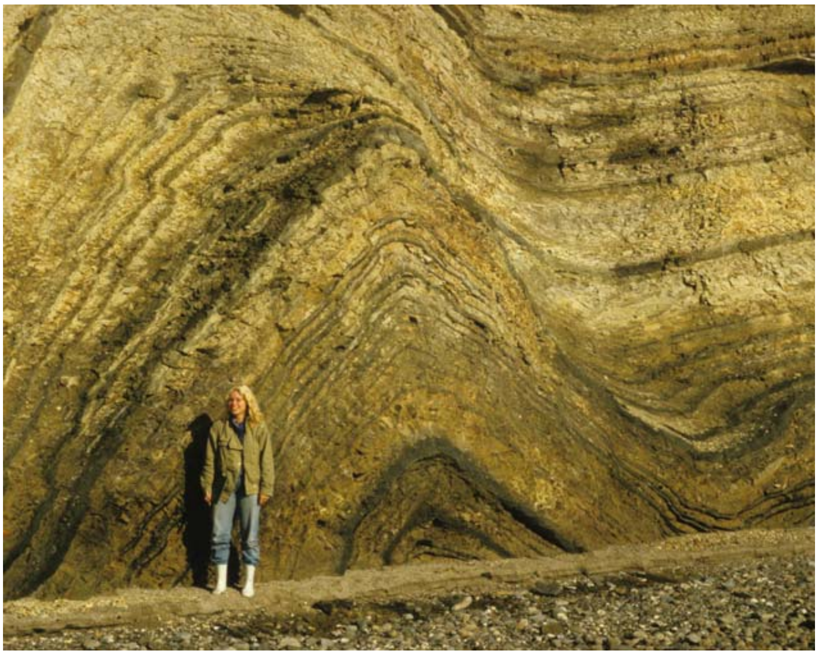
Sct. Jorgens Hill



W
Roskilde S
10 m
1 km

Folding and thrust faulting

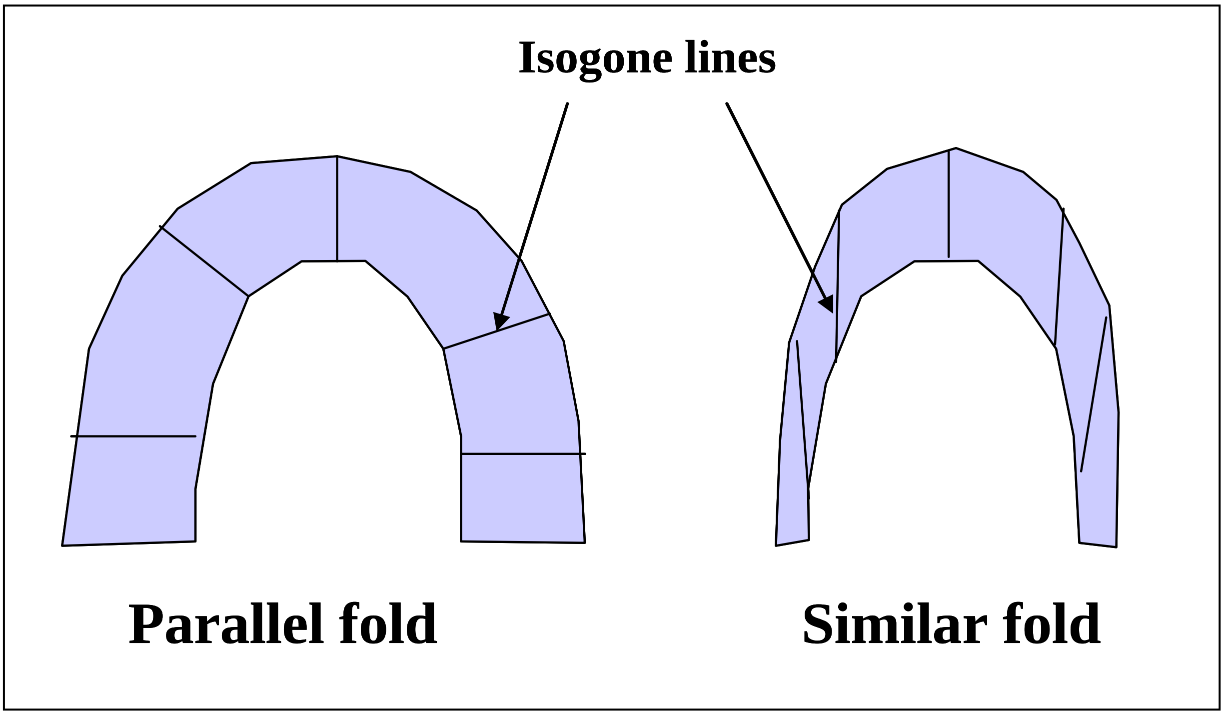
Folds are the most aesthetic features in structural geology. Their variation and occurrences are numerous. However, at set of systematic and descriptive classifications enables us to describe and work with folds. The first thing is to differentiate between anticlines and synclines.



An ANTICLINE folded in volcanic ash layers in clayey diatomite. The deposit is an early Eocene marine formation

A SYNCLINE folded in the same volcanic ash layer bearing early Eocene marine diatomite formation

A monocline is a fold bend only consisting “half” of the syncline, or to put it in an other way, it only contains one limb, the normal fault drag on page 8 could be classified as a monocline.



To simple types of folds are classified due to their thicknes of the limbs, namely the parallel folds and the similar folds. The isogones, which are a lines of equal distance, helps to define the differentiation between the two different types. In the parallel folds the equal distance of the isogones are perpendicular to the bedding, whereas the isogones are more or less parallel with the axial plane of the folds in the similar folds. The folds on page 15 a parallel folds, whereas the folds below are typically similar type of folds.

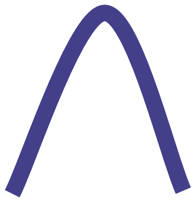
Classification of folds according to the limb configuration

The inclination and the angle between the limbs of the folds are an additional way of differentiations, which can define the fold geometry.

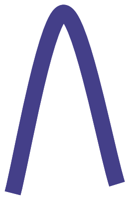
The general inclination of the limbs may simply be symmetrical dipping to each side on the vertical acial plane, this we call an upright fold. If the inclination of the fold limbs start to be asymmetric we call it an turned or even overturned fold. When the limbs are more or less horizontally orientated we call it a recumbent fold.

The shape of the fold can also be described according to the angle between the fold limbs: When the angle is more than 90° it is referred to as an open fold. With an angle of 90° and decreasing to about 30° it is referred to as a close fold. When the angle between the limbs is smaller than 30° the fold becomes a tight fold, and it the limbs tend to be parallel the fold is named an isoclinal fold (iso = the same, clinal = dipping).

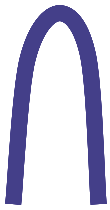
Open



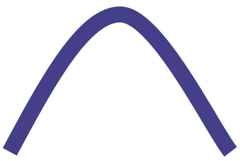
Close



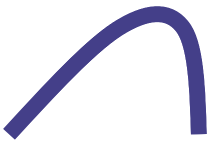
Tight



Isoclinal



Upright

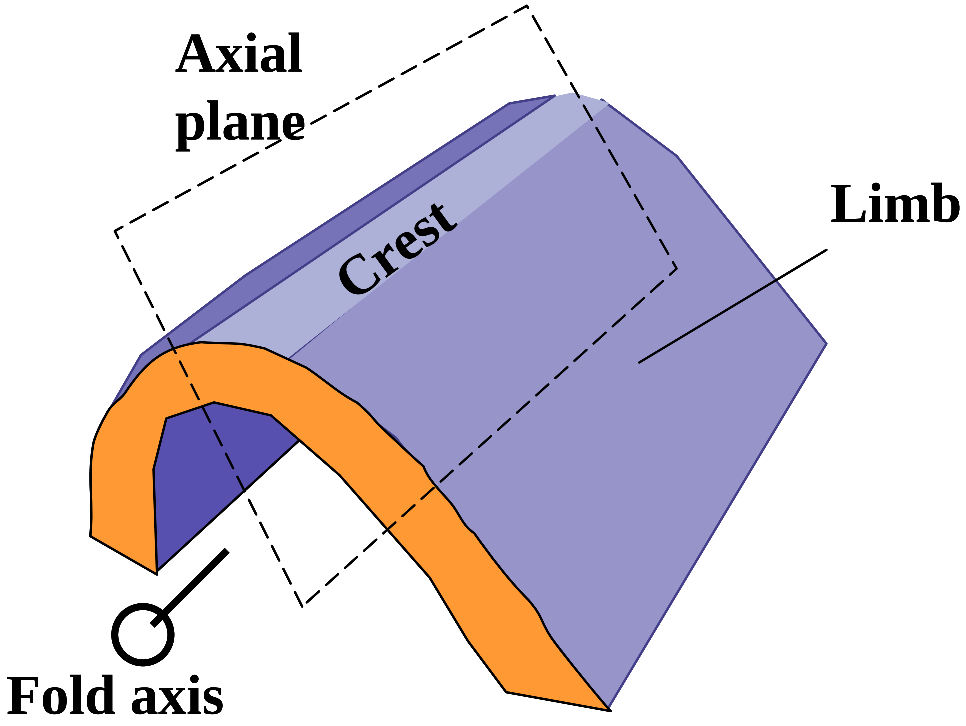


Turned

Overturned

Recumbent

Architectural elements of a fold



The orientation of a fold is defined by its fold axis and its axial plane. The fold axis is defined by the line in which the limbs intersect. The orientation of the fold axis is measured clockwise all the 360° around the compass rose. If the fold axis is plunging, the plunge is measured like the dip for the bedding plane, from horizontal to vertical.

The axial surface is defined by the hinge lines in the fold or the fold closure. In common speaking we regard the axial plane as a plane. However, the axial plane will in general behave as an irregular surface due to the actual deformation of the fold structures and the development of the fold closure.

120	33NW
66	80SW
90	40N
85	40N
20	37W
10	44W
15	54NW
28	50NW
25	50NW
37	37N

Measurements on a fold in one side of a clay pit, **Clay Hill 1**

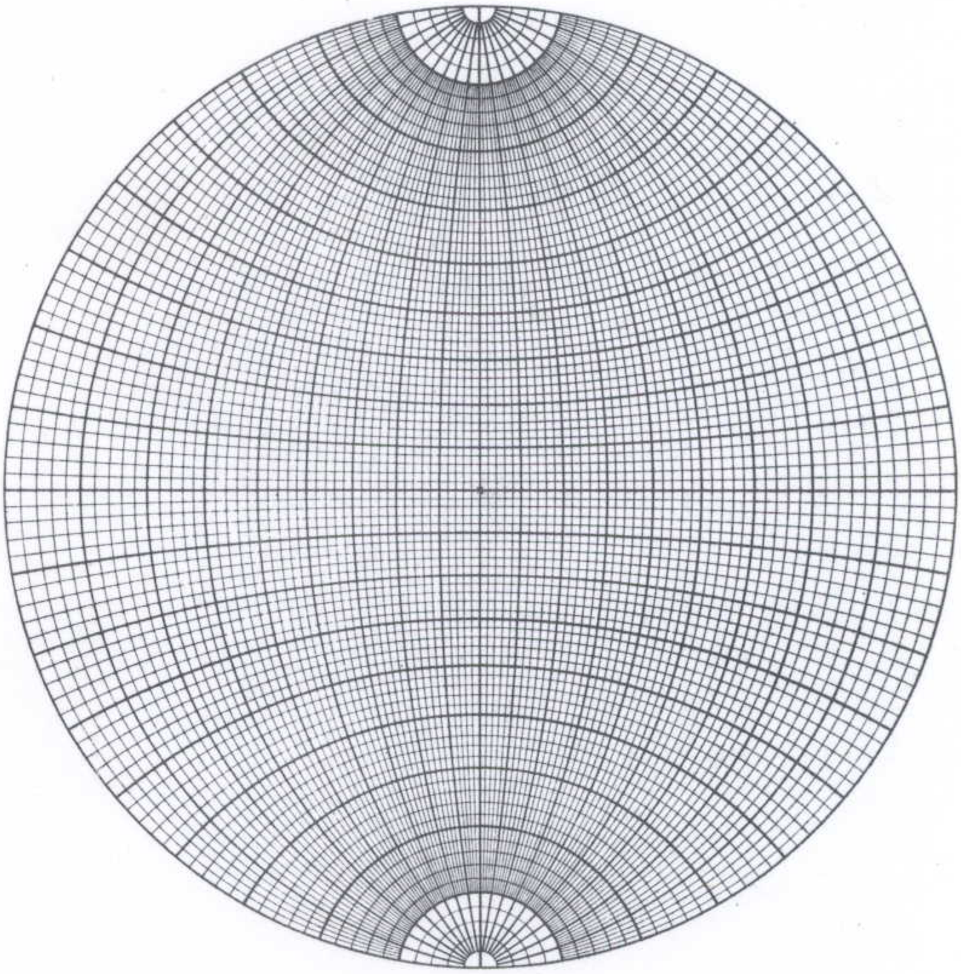
72	42N
77	37N
98	30S
88	70S
85	80S
60	43NW
122	66SW
164	50W
155	66SW
122	75SW
130	30NE
88	60S
110	85N
110	80S
102	85N
105	30N
120	10NE
150	45NE

Measurements on a fold in an other side of a clay pit, **Clay Hill 2**

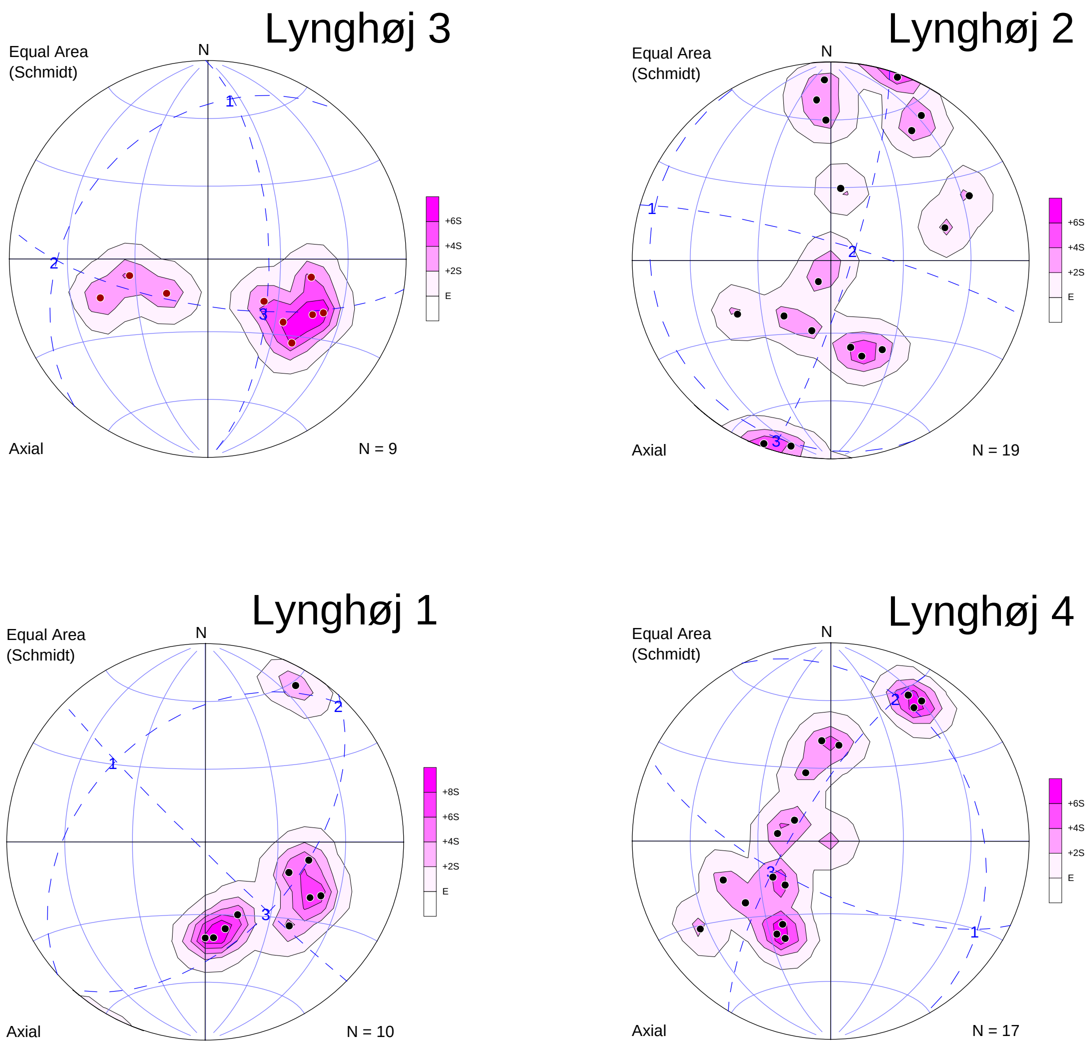
168	33E
140	22NE
37	29NW
40	41NW
45	50NW
28	50NW
25	54NW
10	44W
158	48E
162	38E

Measurements on a fold in the third side of a clay pit, **Clay Hill 3**

Exercise 4: Plot the strike and dip data for the various folds in the clay pit and construct the fold axis.



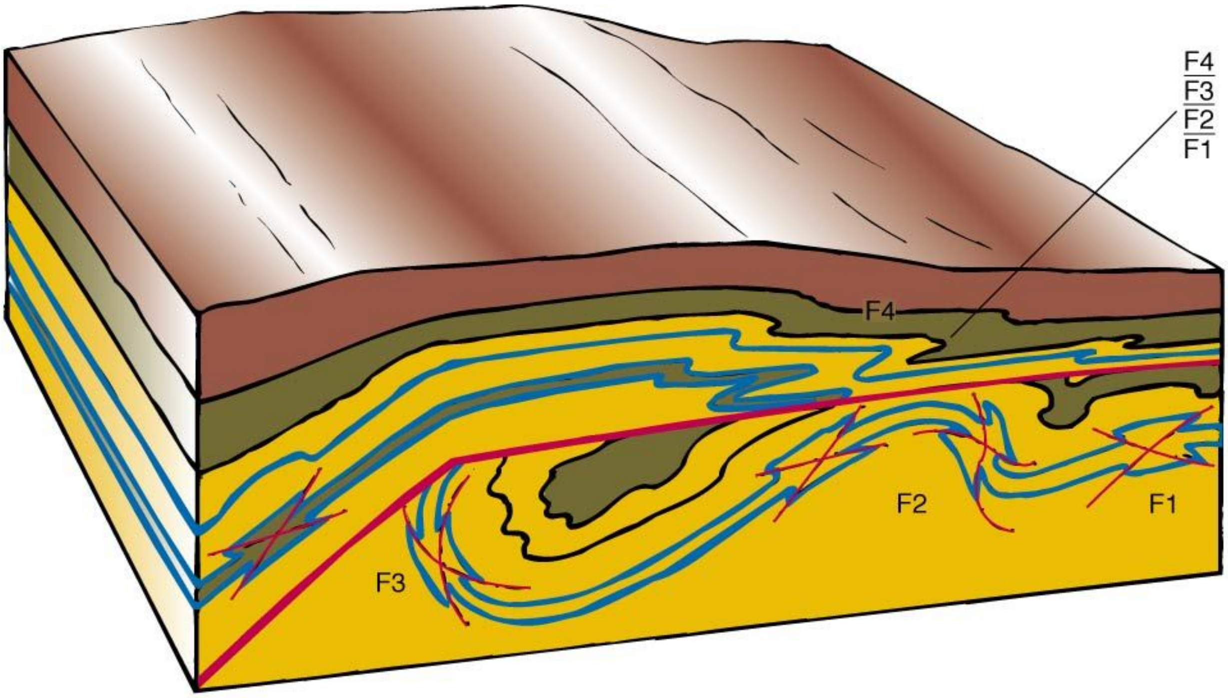
Stereographic projection net for fold axes construction



Four examples of computer program plotting and statistic density analysis of structural data.

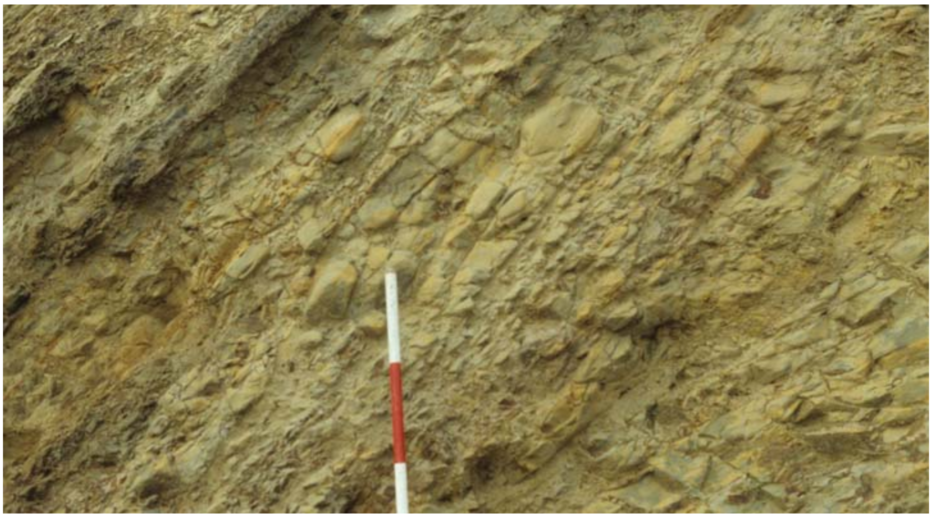
Superimposed folding and sequential deformation

When a fold complex is deformed by a new event of compression it becomes a superimposed fold complex. The deformations are named orogenic events or deformation events. An orogenic belt may thus comprise more than one orogeny (oro = mountain, gen = creation). However, with a single deformation event several phases may have developed. When the sequential deformation development can be differentiated they are named deformations phases (F1, F2, F3 …).



The block diagram illustrates four deformation phases, which are superimposed on each other. The first deformation phase is a low angle jointing and conjugate faulting (F1). The next phase is folding and listric thrust faulting (F2), and the third phase is deeper rooting thrust faulting and ramp and flat propagation (F3). The forth (F4) phase is a new deposition which should rather have been annotated D2.

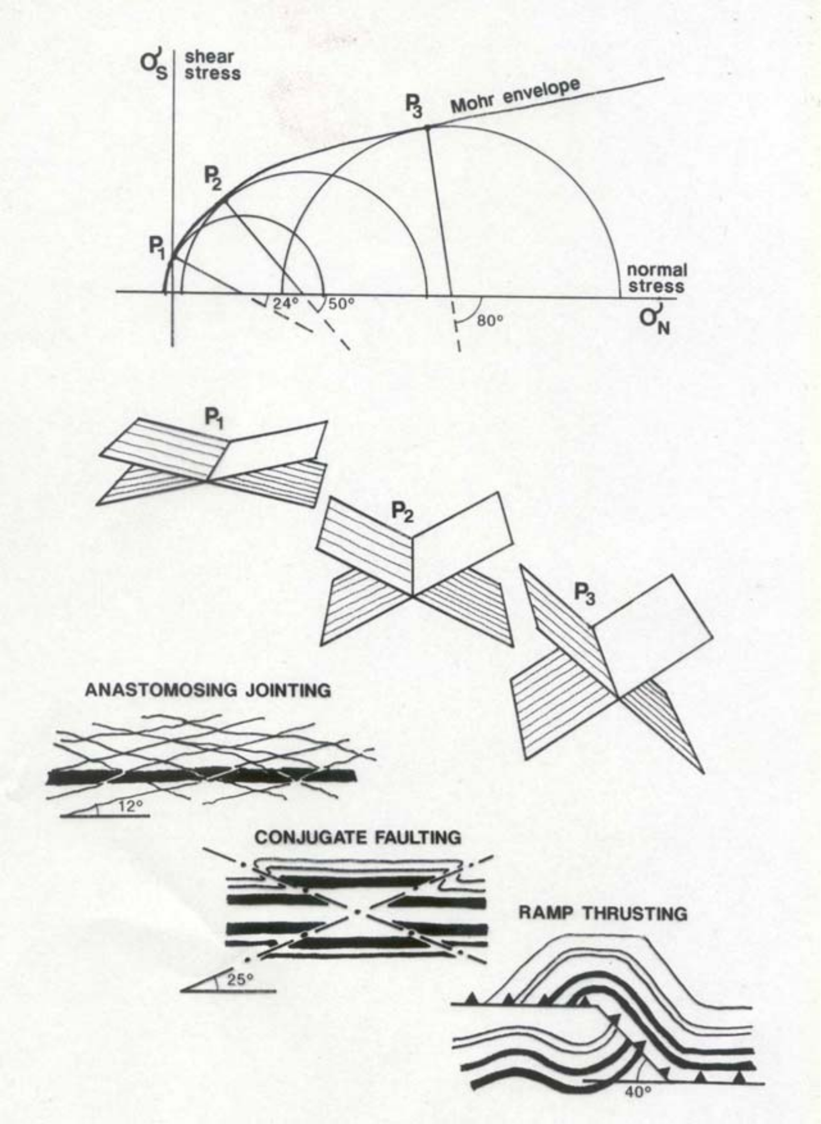
In the following a brief presentation will be given of first three deformations to illustrate the sequential development with one deformation event.



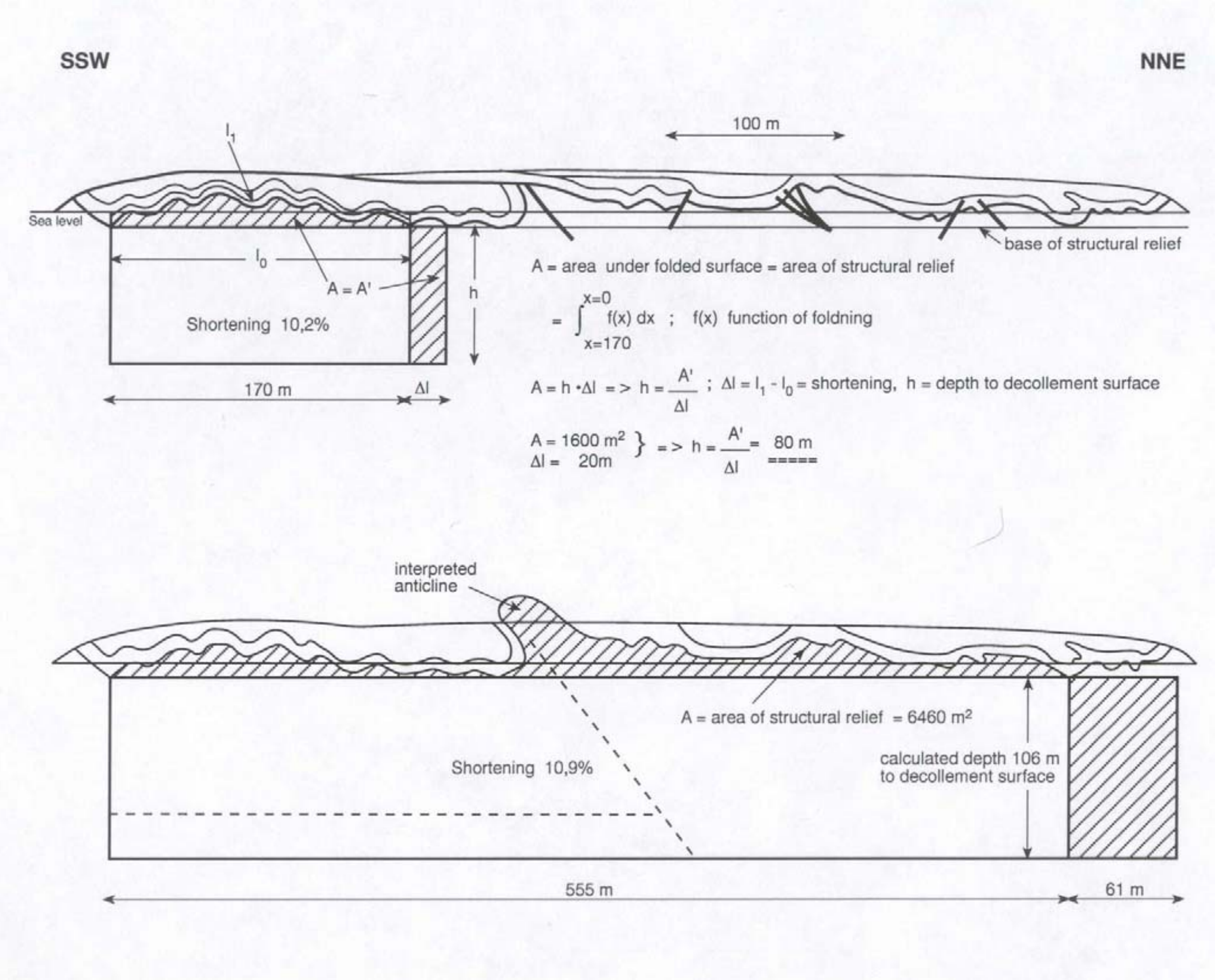
Low angle jointing, anastomosing jointing and small scale faulting affecting clayey diatomite.

Conjugate faulting and bow folding, slightly overturned to the left, folded ash layers in clayey diatomite. Divisions on pole is 20 cm

Listric thrust faulting displacing the volcanic ash layers in the clayey diatomite.

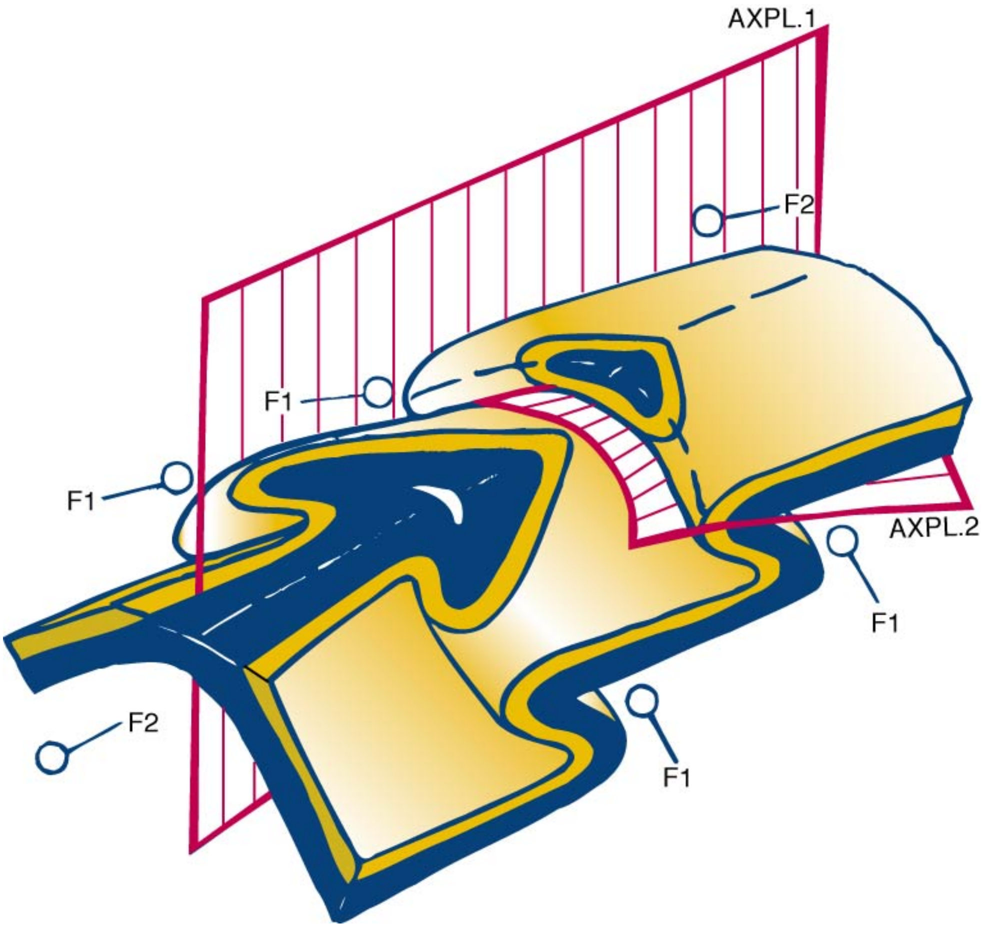


The structural model, which links the different structural elements into a chain of development phases dependent on the increasing deformational push from the hinterland. The Mohr diagram at the top explains the increasing angle of jointing and faulting in the system.



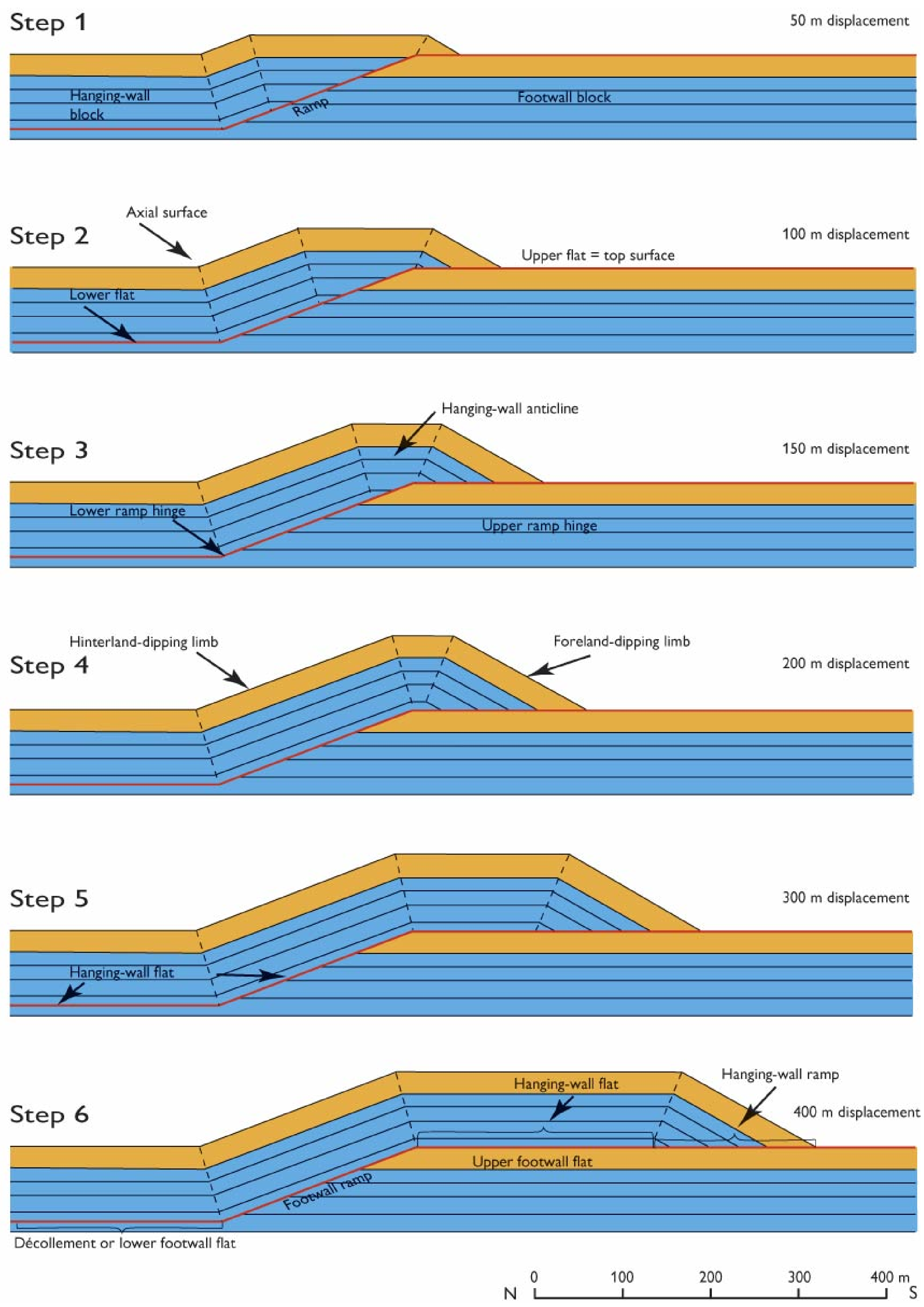
Construction of the balanced cross section for the Feggeklit profile. The construction is a help for the exercise 5: area balance of a structural profile.

Exercise 4: Make a structural analysis of the Feggeklit profile. Identify the various structure types appearing, and try to calculate the depth to the décollement surface with help of area balance.

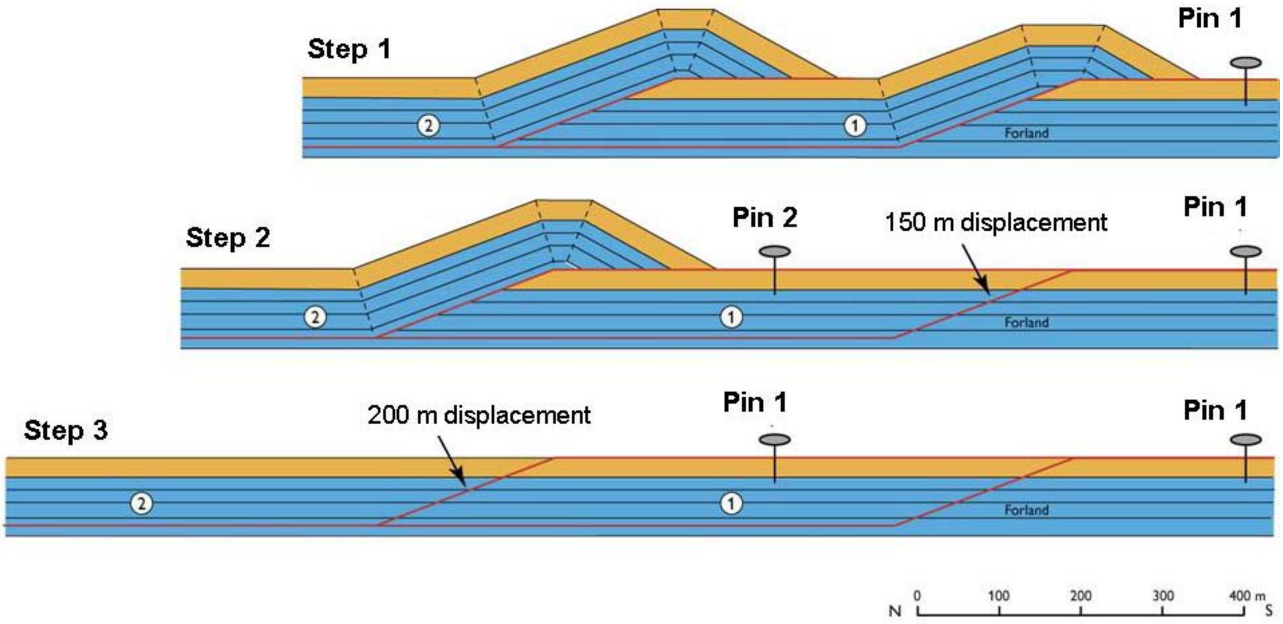


In superimposed deformation plunging fold axes will appear. The analysis of the structures focuses on the behaviour of the axial planes and the plunge of the fold axes.

Thrust faulting and hanging-wall anticline



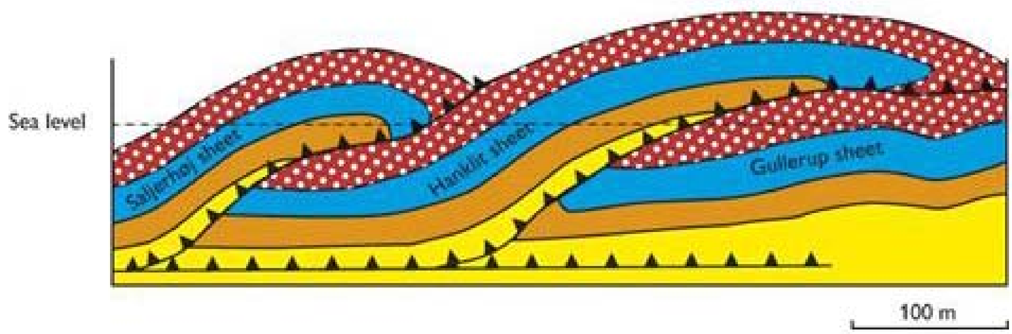
On the page above the displacement development of a thrust fault system is illustrated and the relationship between the size of displacement and the shape of the hanging-wall anticlines can be followed. An example of hanging-wall anticlines developed in thrust fault systems are shown below. First example is the volcanic ash layers in clayey diatomite, and second example are Ordovician sedimentary rocks thrust faulted in the North Greenland Fold Belt.

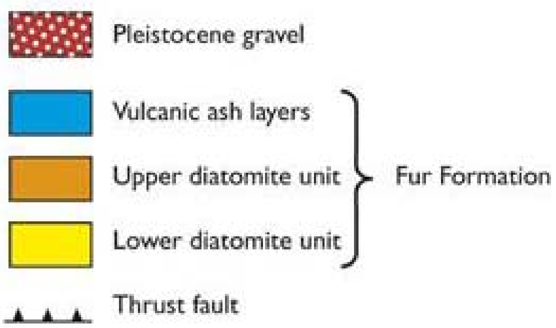


The construction of balanced sections is based on the principles of pull the last thrust sheet back first by putting a “pin” in the foreland, and then displacing the deformation complex back one step by the other. First step is to pull the complex back the amount of displacement the last thrust sheet was moved over the foreland. The next step is to put a new “pin” in this sheet and then regarding this as the foreland and pulling the rest of the complex back its back. In this way the balanced construction continues all the way through the deformational complex.

The overturned hanging-wall anticline in the nose of the Hanklit thrust sheet, which is the target for balance in exercise 5.

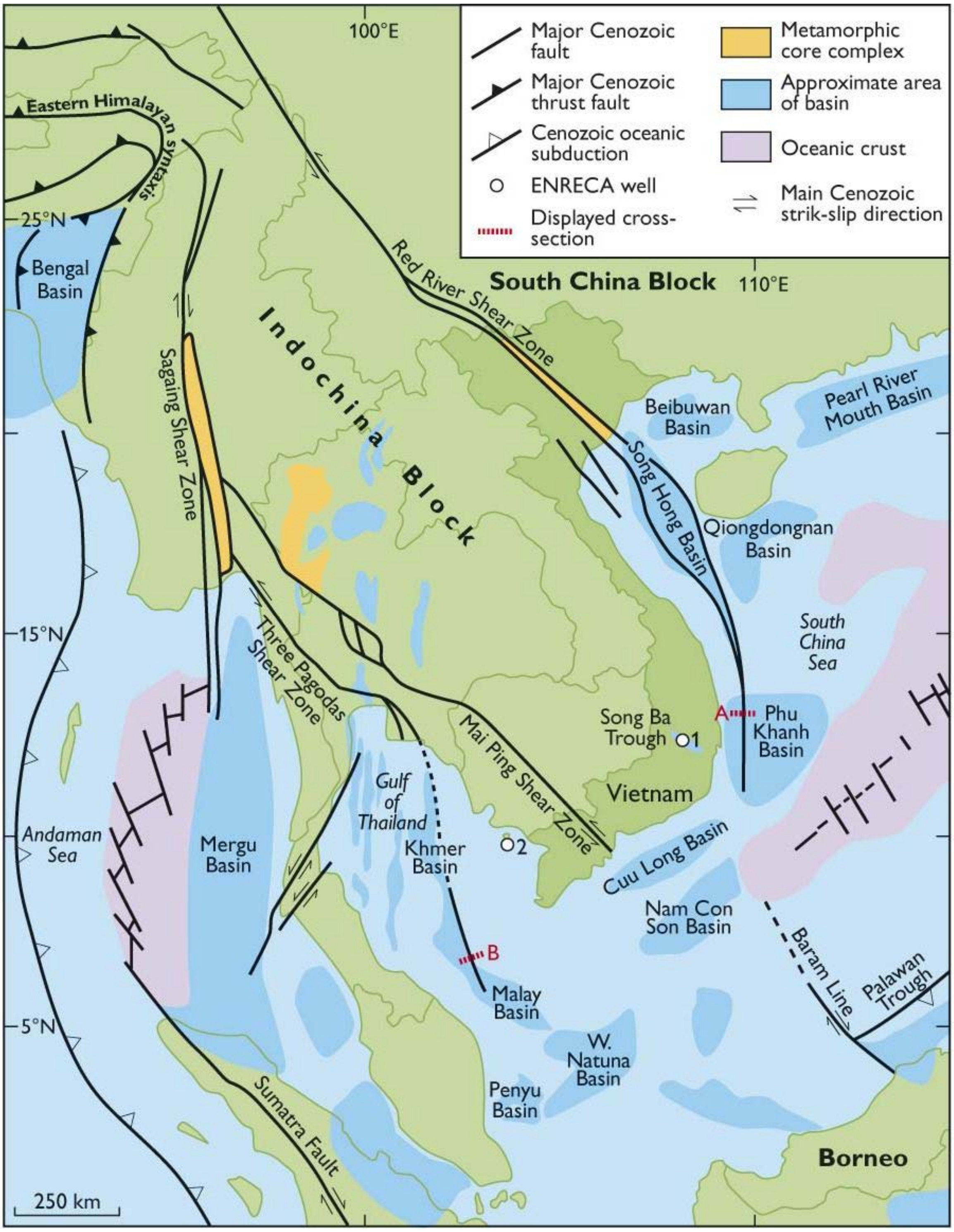
Exercise 5: Make a balanced construction of the Hanklit thrust fault system based on the measured structural cross section provided below.


Sea level
Saljerhoj sheet
Hanklit sheet
Gullerup sheet
100 m


Pleistocene gravel
Vulcanic ash layers
Upper diatomite unit
Lower diatomite unit
Fur Formation
Thrust fault

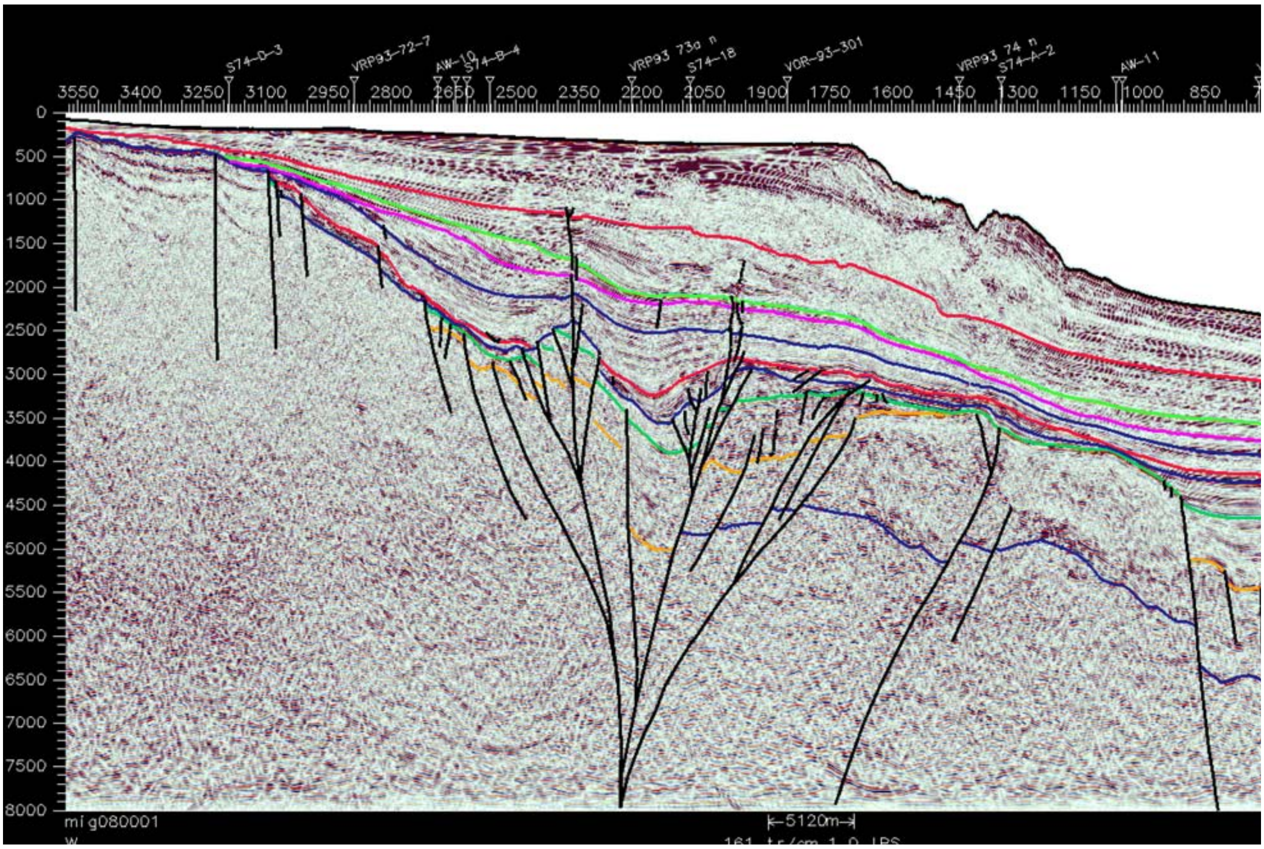
The strike-slip fault system

The strike-slip system and wrench faulting related to large scale trans-tensional – trans-pressional system created by the lateral plate-tectonic movements is probably the most important structural system for Vietnam. Two large transform shear zones crosses Vietnam, to the east The Red River shear Zone create ranges and basins (Song Hong Basin is one of them), and to the west the Mai Ping Shear Zone is a strong sinistral intra-plate fault zone. The main tectonic reasons for the transform movements are the opening of the ocean ridges in the South China Sea and Andaman Sea.



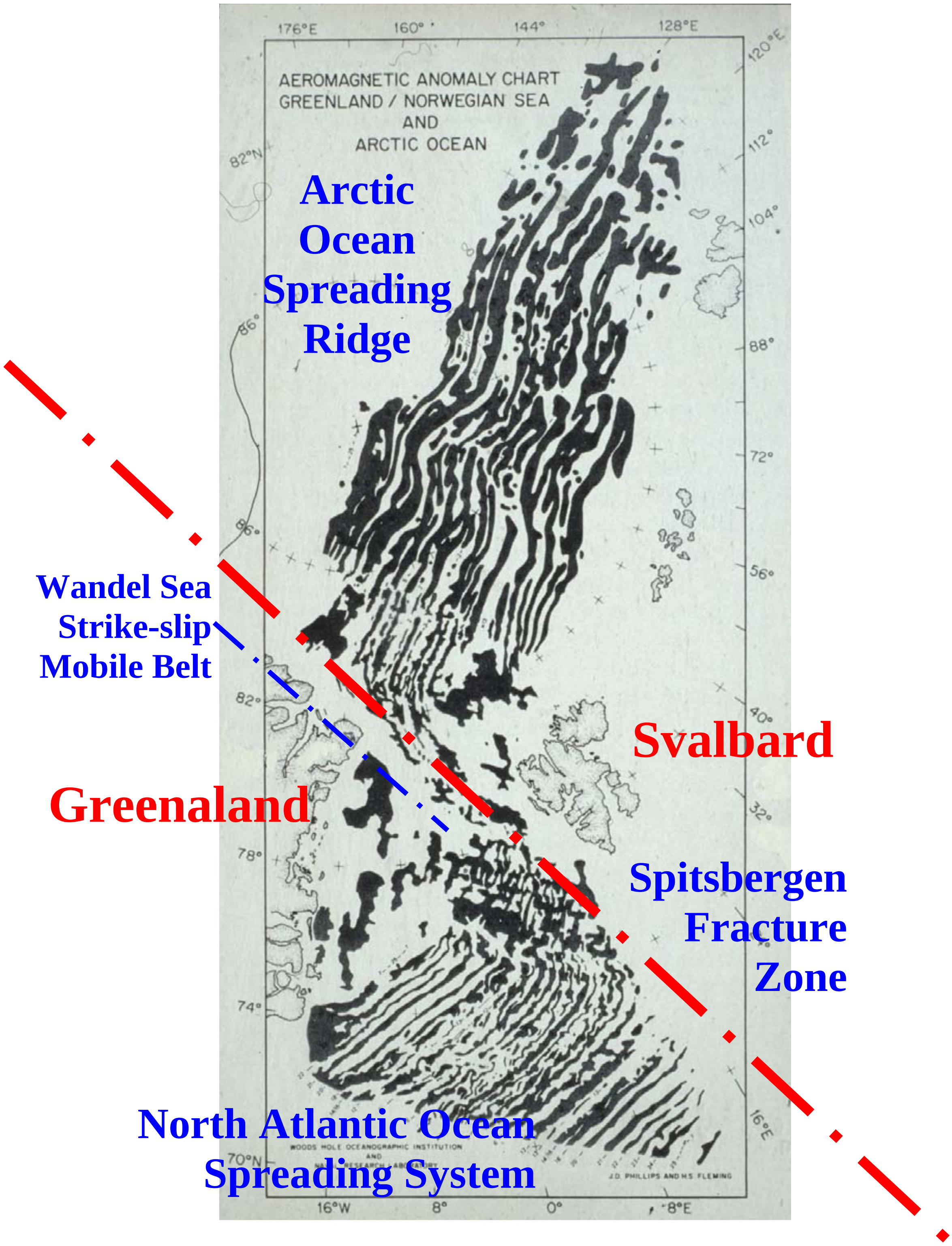
The transform fault lineaments take up all the oblique movements a create displacements between the continental segments, which compensate for the extensional space created along the ocean ridges.

In a transform fault system there will be two types of movement, either a transpression creating domes and mountain ridges, or a transtension creating pull-apart basins. A structural cross section across the two complexes results in a flower structure architecture. Two types of flower structures are differentiated: 1) the positive flower structure, in which the stratigraphic units pop up, and 2) the negative flower structure, in which a pull-apart basin is created due to the subsidence and down faulting of block in the depocenter.

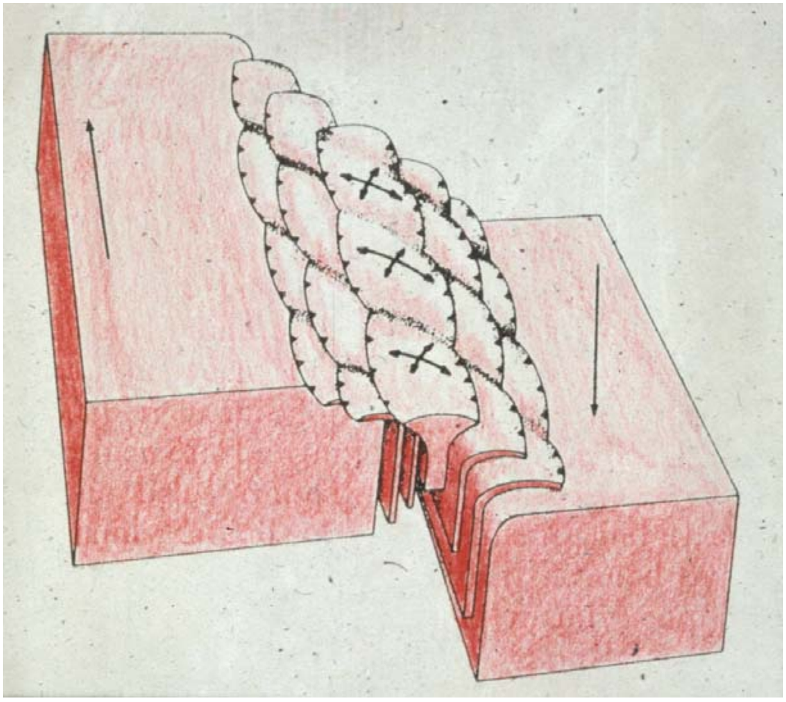


The example above shows a cross-section or the northern Phu Khanh Basin, a flower structure created along the Red River Shear Zone. Note that the flower structure is mainly a negative “flower”, however, the left side of the structure shows a positive satellite “flower”.

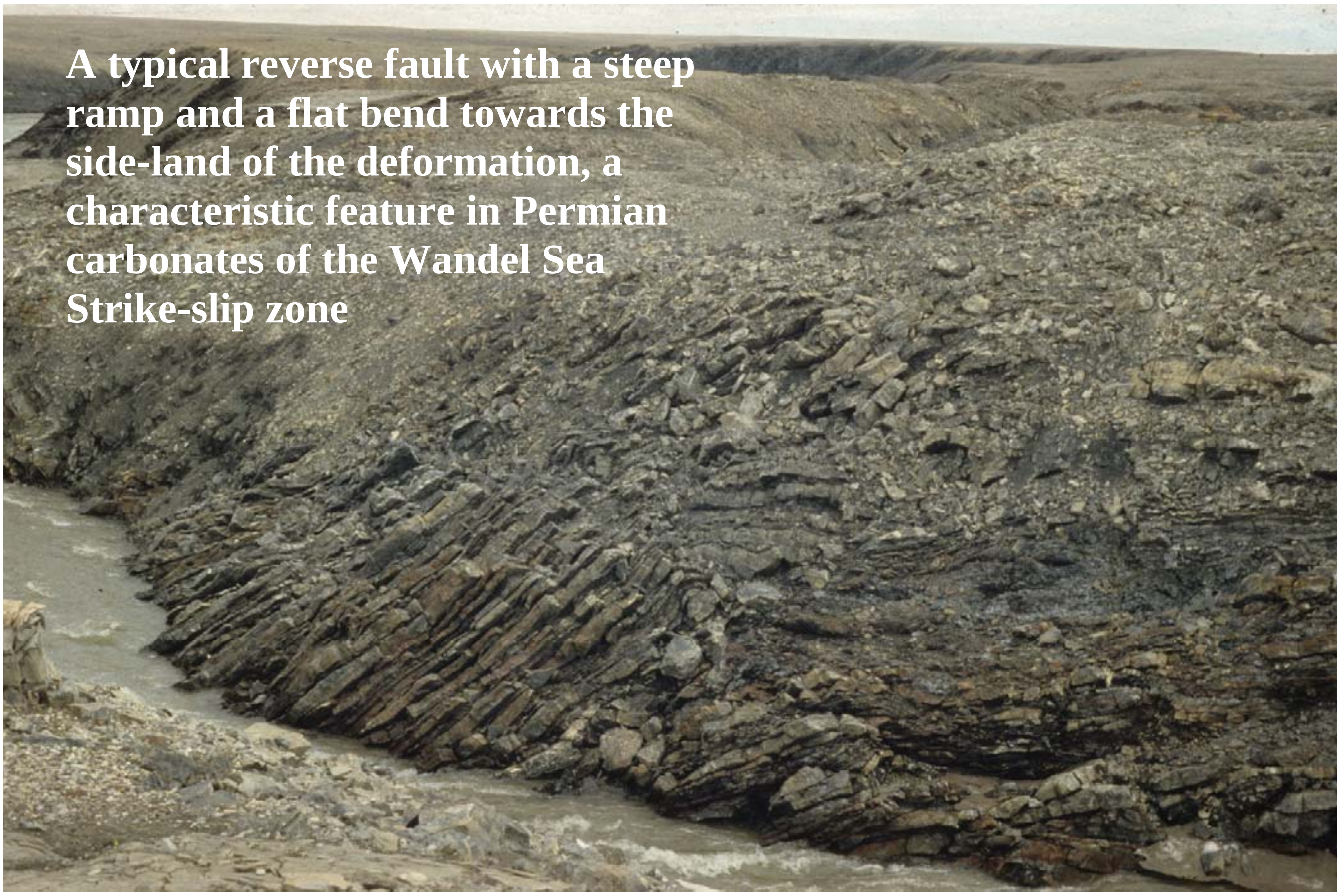
A well exposed example of a strike-slip orogenic belt is found in the north-east Greenland. Here a long lived transform fault system has affected the NE-corner of Greenland for many millions of years.



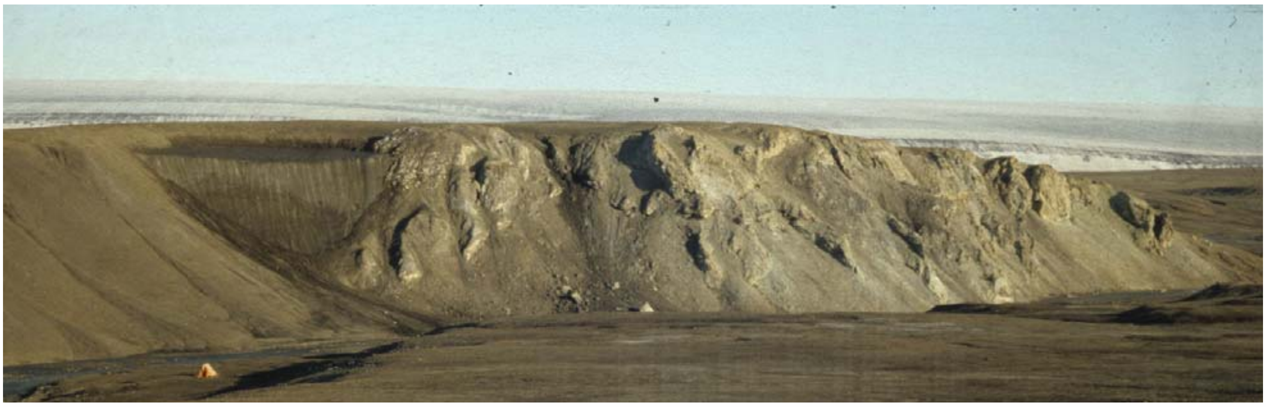
The position of the Wandel Sea Strike-Slip Mobile belt is here located in the general plate tectonic setting. Note that the sinistral displacement of the Midt Ocean Ridges is about 500 km sinistral displacement, whereas Svalbard relative to Greenland was off sat 500 km dextral.

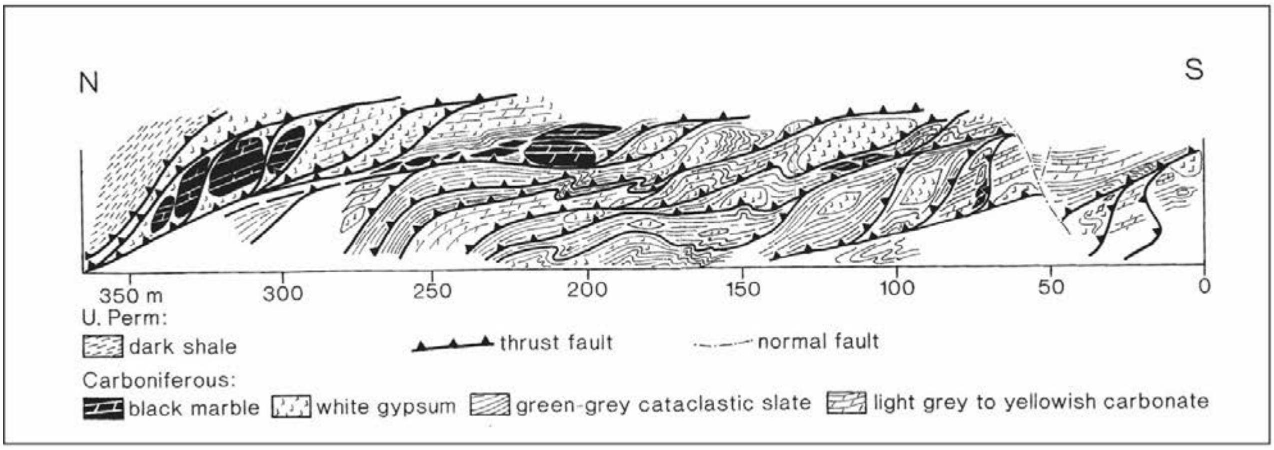


James Lowells block diagram of the Spitsbergen fracture zone and related positive flower structure, which he publiced in 1972

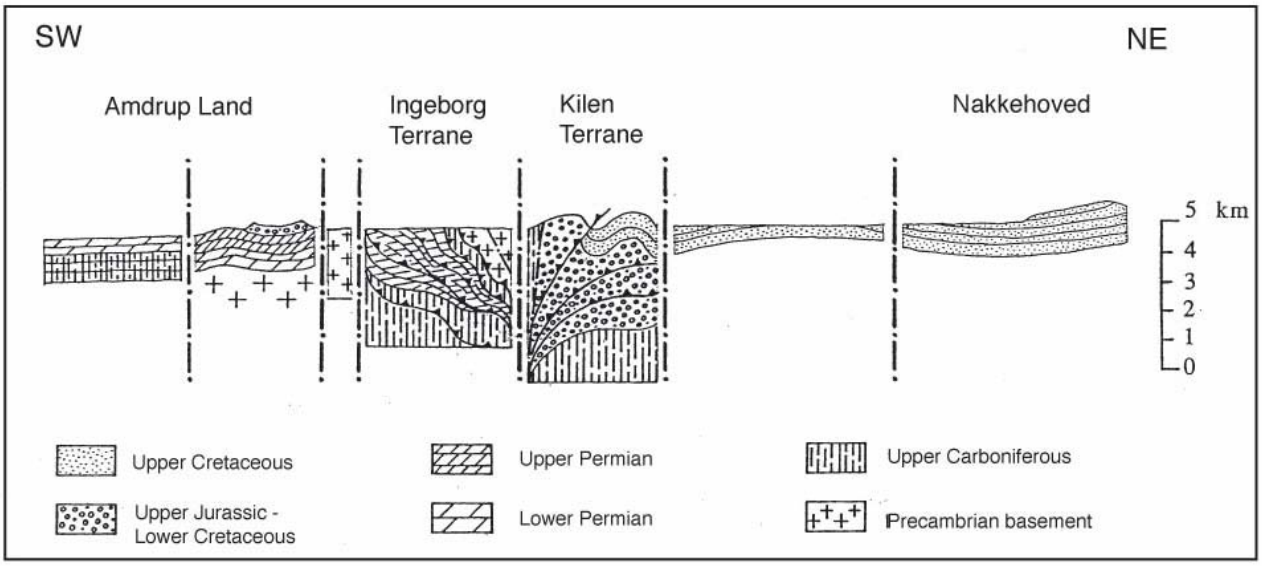


A typical reverse fault with a steep ramp and a flat bend towards the side-land of the deformation, a characteristic feature in Permian carbonates of the Wandel Sea Strike-slip zone





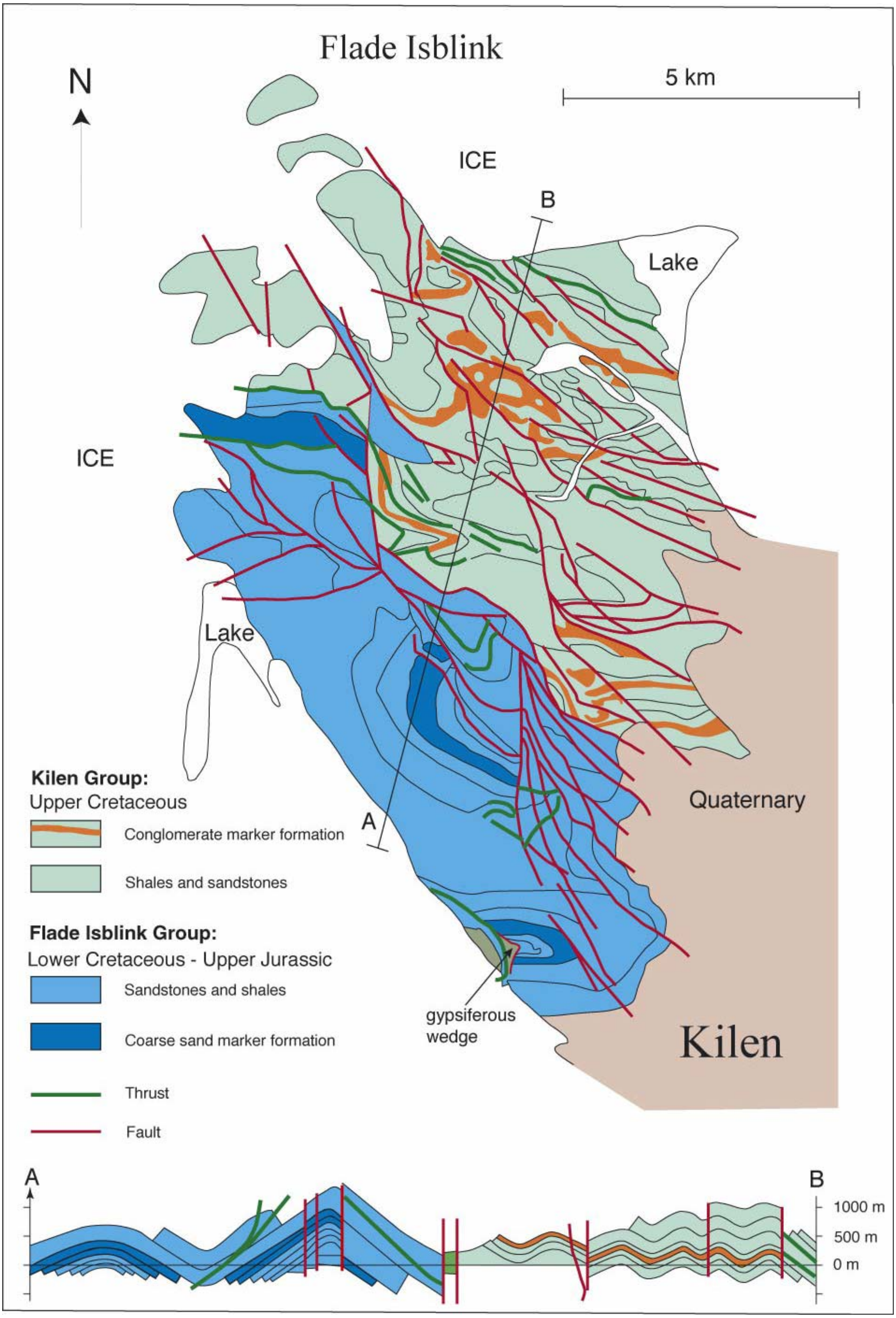
Kronprins Christian Land Orogeny

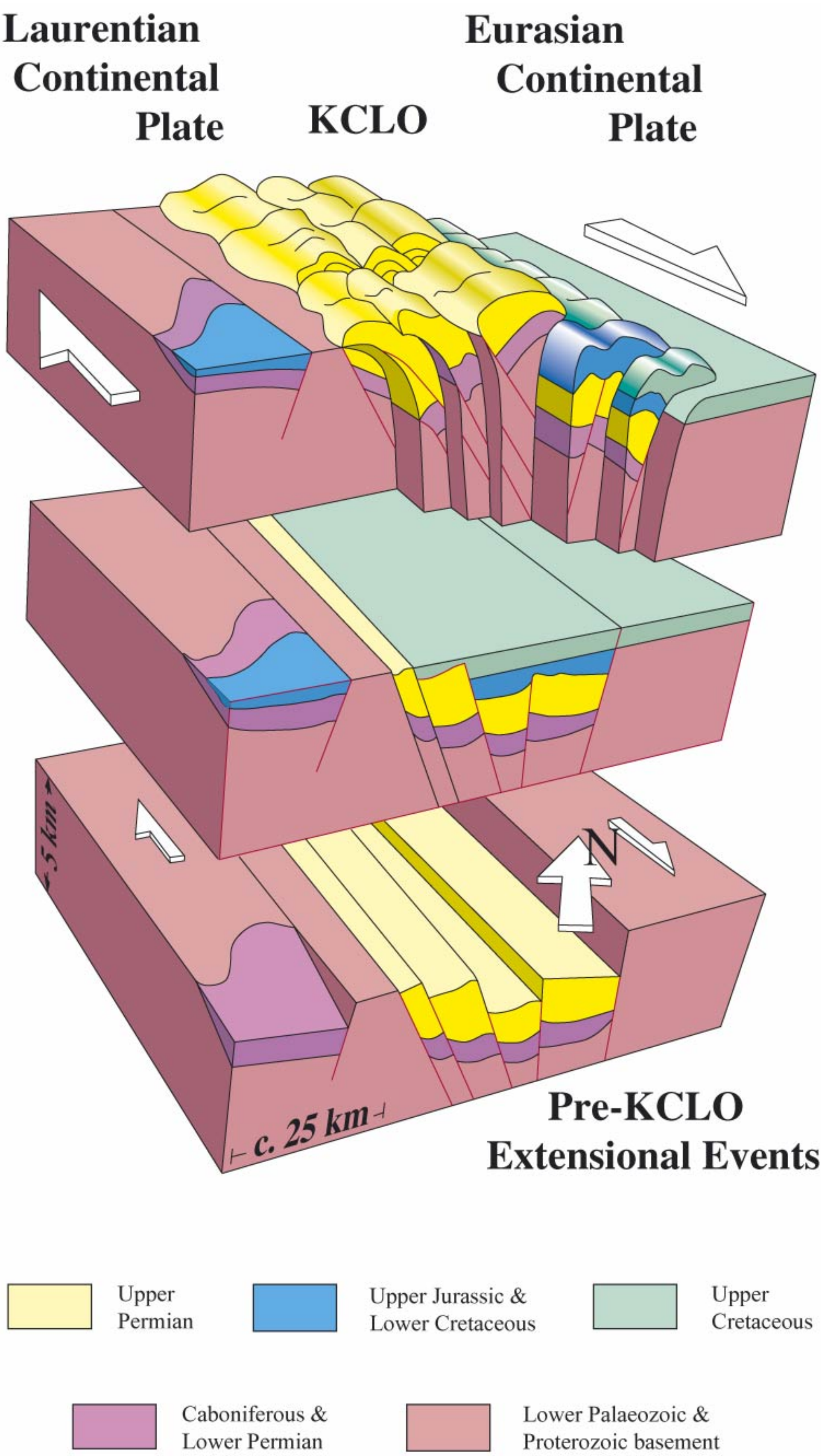


Cross-section of a detail of the fault structure and a cross-section traversing the entire mobile belt.

Dome fold in the dextral shear deformed Wandel Sea Strike-Slip Mobile Belt. The cross-section across one of the domes are shown below.

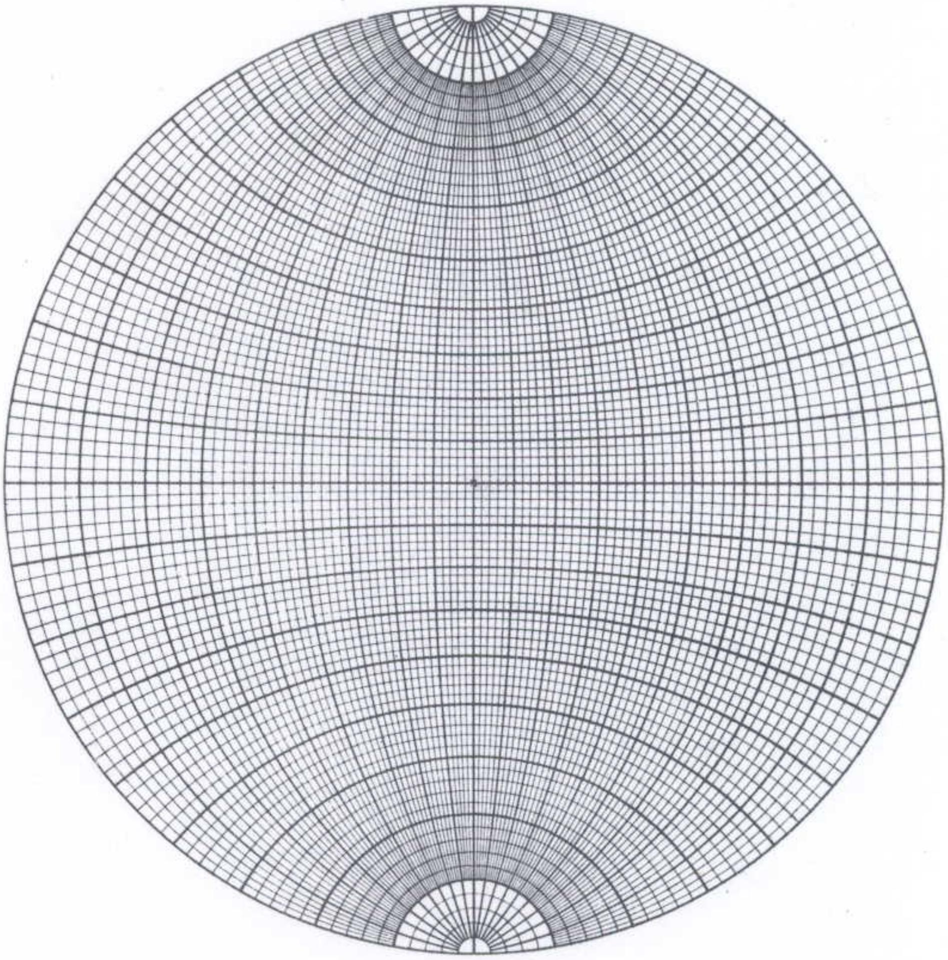
The map below shows the geological terrain for the dome folds and the flower structures.


Flade Isblink
N
5 km
ICE
B
Lake
ICE
Lake
A
Quaternary
gypsiferous
wedge
Kilen
Kilen Group:
Upper Cretaceous
Conglomerate marker formation
Shales and sandstones
Flade Isblink Group:
Lower Cretaceous - Upper Jurassic
Sandstones and shales
Coarse sand marker formation
Thrust
Fault
A
B
1000 m
500 m
0 m



The block diagram shows the development from a pull-apart basin into an inversion flower structure in the strike slip system of the Wandel Sea Strike-Slip Mobile Belt.

For notes and comments.



Wulff net

An extra Wulff Net for exercises with the stereographic projection.