DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2001/8

Fractures and Rock Mechanics Phase 2

Description of natural and test induced fractures in chalk

Finn Jakobsen

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GEUS

EFP 98

Fractures and Rock Mechanics, Phase 2

DESCRIPTION OF NATURAL AND TEST INDUCED FRACTURES IN CHALK

Finn Jakobsen, GEUS.

DESCRIPTION OF NATURAL AND TEST INDUCED FRACTURES IN CHALK

TECTONIC DEVELOPMENT, HILLERSLEV

BACKGROUND FOR SPECIMEN DESCRIPTION, SEDIMENTOLOGY AND FRACTURES

1 Introduction

This report contains the results of the research carried out by GEUS under EFP 98, Fractures and Rock Mechanics, Phase 2 (EFP J.nr. 1313/98-0006). The study is supplementary to EFP 96, Fractures and Rock Mechanics, Phase 1 (EFP J.nr. 1313/96-0007) and the main work is related to the results, conclusions and recommendation from this primary project.

The main objective of this project is to relate geological descriptions of chalk types and fractures to rock mechanical properties. This project phase focus on the fractured chalk from the Hillerslev quarry but is supplemented with core samples from the Tyra and Valhall fields.

A detailed description on the fracture system of the Hillerslev quarry has been carried out and the sampling in the Hillerslev quarry has been guided by the fracture system. An attempt was made to associate the natural fracture system with rock mechanical properties.

GEUS' involvement in this project includes

1) Geological description of the outcrop locality Hillerslev quarry,
2) Classification and geological description of all test specimen (plug and block samples),
3) Standard core analysis for plugs taken from test specimens and block samples,
4) Fracture description.

Subsequent discussions of the relation between geological and geotechnical observations involving GEO – Danish Geotechnical Institute, Department of Geology and Geotechnical Engineering, DTU and GEUS have taken place. The results of this discussion are presented in a separate report.

This report introduces the results of the geological study, but due to the complexity in work areas the report is divided into 3 individual sections:

1) Tectonic development within the Hillerslev area
2) Lithological and fracture description methodology
3) Specimen description

Section 1 deals with the fracture distribution in the Hillerslev quarry and the relationship between fracture type and the overall tectonic development of the Thisted dome.

Section 2 is a presentation on methodologies introduced to the study and the basic ideas for examination of the various test specimens.

A fracture classification and geological description on all test specimens have been carried out and a complete description of each test specimen is included in Appendix 1.

2 Preliminary result

2.1 Tectonic history of the Thisted salt dome

The chalk sequence in the Thisted area have been buried to 500- 600 m (Japsen and Bidstrup, 1999). Uplift and doming related to salt diapirism have given rise to a complex stress system and rather divergent fracture systems within the chalk sequence in the area.

Five fracture types have been described in the Hillerslev quarry. The most common is the slightly inclined conjugate shear fracture sets oriented ENE-WSW and SE-NW. Another important fracture set comprises zones of stratabounded vertical, smooth (flexural-slip associated) fractures oriented NNE-SSW and SSE-NNW. Secondary fracture sets are related to slightly easterly dipping dip-slip fractures, sub-horizontal strike-slip fractures and horizontal bedding plane relaxation or flexural-slip fractures.

The dimension of the Thisted dome (diameter: 30 km) is slightly larger than the examined offshore chalk fields but fracturing of the Thisted dome may to some degree be compared to the fracturing within the offshore fields.

2.2 Fracture description

All test specimens have been described with respect to lithology and fracturing prior and after geotechnical test. With respect to block samples from the Hillerslev quarry the fractures are related to the regional fracture system.

The strength of a jointed rock mass depends on the properties of the intact rock pieces and also upon the freedom of these pieces to slide and rotate under different stress conditions. This degree of freedom is controlled by the geometrical shape of the intact rock pieces as well as the condition of the surfaces separating the pieces. The Geological Strength Index (GSI) introduced by Hoek & Brown (1997) provides a system for estimating the reduction in rock mass strength for different geological conditions – a system used in this project. The GSI system, however, is scale dependent. Therefore it is not possible to compare GSI values on plug size specimens and block samples.

For quantification of the intensity of fractures the scale independent areal intensity (P_{32}, Golder Associates FracMan manual, 1998) is introduced as the fracture density measurement in this project. The P_{32} is preferred since it, beside the scale independency, is invariant with respect to the distribution of fracture size.

It is anticipated that there is a close relationship between fracture roughness and shear strength. Therefore the fracture description is focussing on the fracture roughness. Initially the Q-method defined by Norwegian Geotechnical Institute (Barton et al., 1974, Løset, 1995) was applied for fracture description, but a number of conditions were not available for a full description. Therefore it was decided in this project to follow the Joint Roughness Coefficient (JRC) model defined by Barton and Bandis for fracture description (Barton & Bandis, 1990).

This model, however, also shows a number of inconsistencies for a proper description. Especially, the plug scale seems to affect the JRC figures in the way that fractures in small plug samples result in lower values than fractures in larger samples.

Fracture type and surface were described and fracture/failure plane angle determined. Based on the angle of the failure plane the friction angle was deduced. Some uncertainty in the evaluation of the fracture description is to be expected, partly because the tests have been carried out under different conditions and partly because the quality of specimen after test was not always perfect.

The fracture angle varies according to plug dimension, hardness of the test plug and test type, (including type of piston head).

The fracture surface varies from planar to rough with a preference of undulating smooth surfaces. The conformity in fracture surfaces is interpreted to be due to similarities in hardness (cementation) of the chalk. Slickensides (striation) are observed in plugs with relative large displacement (generally in large plugs)

In some of the samples hairlines have been observed. Hairlines are typically oblique to bedding planes and are formed by small-scale vertical shear. The induced fractures are partly controlled by the hairlines and parts of the fracture planes are coinciding with the hairlines.

2.3 Fracturing

The induced fractures in the samples are normally associated with a zone of weakening that varies in thickness. Within this zone micro-joints (area of cm-size) seem to develop. With increasing shear stress condition the micro-joints expand and the final fracture in the plug is formed by amalgamated joints. The fracture surfaces are often highly irregular because of a random take-over of the various micro-joints along the fracture lineament. The thickness of the fracture zone and the irregularity are dependent on block size, rock hardness and size of displacement.

In the plug samples the compression and displacement are of limited size and the fracture zone is generally less than 2 mm. During block test the compaction exceeded 3 cm and caused severe displacement. The width of the fracture zones is here recorded up to 2 cm. Along zones with large displacement shear fractures are developed, but in case of more obscure displacements no clear surfaces are seen.

TECTONIC DEVELOPMENT, HILLERSLEV

EFP 98

Fractures and Rock Mechanics, Phase 2

1 Introduction

The main objective of this project is to relate geological descriptions of chalk types and fractures to rock mechanics properties. The project comprises an establishment of a geological description and classification programme related to natural and induced fractures.
The geological description programme aims at providing the basis for correlation of data between different localities, and at illustrating the impact of various geological parameters on natural and induced fractures.

In this project a geological description of the Hillerslev quarry with respect to structural evaluation, fracture density and characterisation has been carried out. Also for the variation in sedimentology, lithology and diagenesis a description has been carried out. This description forms the framework for the fracture analysis of the block samples acquired in the quarry for geotechnical tests. A detailed description of the fracturation in the samples before and after test forms the basis for comparison with the geotechnical results.

For regional purposes the Hillerslev data are included into a regional framework related to the structural development of the Thisted dome, which gives rise to the structural development within the chalk of the Hillerslev quarry.

In this section of the report a short introduction on the regional distribution of the chalk followed by the structural development of the Thisted dome is given. (This description on the regional aspects is a minor revised copy from the phase 1 report "Geology", but included here because of the direct relationship between the structural development of the Thisted dome and the fracture distribution in the Hillerslev quarry).

The regional aspects are followed by a discussion on the impact on the chalk sequence in the Hillerslev quarry and on the fracture types present in the examined profile.

2 Chalk in northern Jutland

The Upper Cretaceous and Danian succession of the Danish area is dominated by very pure, largely biogenic limestones. In the Early Maastrichtian global sea level highstand all of the Danish territory was transgressed as the culmination of the period of 35 mill. years (Cenomanian- Maastrichtian) during which the chalk was deposited in a shallow seaway running from the Cretaceous Atlantic in the west to Poland in the east, bordered by the Fennoscandian Precambrian Shield and the Middle Europe islands (fig. 1; Håkansson et al., 1974). The near-shore areas were dominated by greensands and biocalcarenites passing into biomicrites or chalks towards the basin. In the earlier part of the Danian the marine accumulation was largely confined to the Danish Basin (Håkansson & Thomsen, 1979) and to the Central Graben in the present North Sea. Chalks in northern Jutland are basinal and occur in regions with salt induced highs as well as fault controlled inversion structures - much like the situation in the Central Graben.

The inversion took place during the Cretaceous and Early Tertiary along the Fennoscandian Border Zone, and due to subsequent regional Neogene upheaval and intensive Quaternary erosion, the location of the coastline to the north is not known. The chalk level now exposed is the result of up to 500 - 750 metres of Neogene uplift and subsequent erosion (Japsen & Bistrup, 1999). Glacial influence is largely erosional in northern Jutland with only local internal deformation of the chalk sequence. The melting of the icesheet, however, may have induced horizontal, largely bed-parallel unloading fractures of the near surface part of the chalk sequence.

Maastrichtian and Danian chalks and limestones are exposed in the sub-Quaternary surface in a zone across northern Jutland (fig. 2). The rocks are generally covered by glacial and postglacial deposits, but in a series of quarries and natural outcrops the chalks and limestones are readily accessible.

The main lithologies include a more or less continuous spectrum of biogenic carbonate sediments ranging between the two dominant end members, pelagic chalk and bryozoan limestone (Bromley, 1979). The insoluble residue content is low, suggesting a low influx of terrestrial material. The chalk is intensively bioturbated with distinct burrows indicating deposition in mainly oxic conditions (Ekdale and Bromley, 1984). Sedimentation rate has been fairly high during the Maastrichtian (Håkansson et al., 1974). As a result of low to moderate post-depositional burial most onshore chalk has suffered surprisingly mild diagenesis and has retained a very high primary porosity.

3 The Thisted Dome

The area between Thisted and Hanstholm occupies the crestal part of a broad, flat salt-induced dome. In this dome movements of the deep-lying Zechstein salt commenced in Late Triassic time, have been active in the Holocene and may still be going on today (Hansen & Håkansson, 1980; Madirazza, 1981). As a result of the very late movements, chalk and limestones of Maastrichtian and Danian age are extensively exposed at the surface, in part without a cover of glacial sediments (fig. 3). The topography of the area is dominated by a hemi-circular line of prominent hills, capped by Danian limestones, while inside the hemi-circle Late Maastrichtian chalk is the youngest pre-Quaternary deposit present. The center of the structure is believed to be situated slightly north of Nors Sø (fig. 3).

Limestones in the Hanstholm Hill, on the northern side of the dome, dip gently towards the north, as confirmed by age differences of the bryozoan limestones at the north- and south-side of the hill, respectively (Hansen & Håkansson, 1980). Limestone in the Hjardemål Hill in the north-eastern part of the dome dips towards the northeast, and the area south of the lake Vandet Sø the limestone shows a generel dip towards the south (Andersen, 1944). However, the dips rarely exceed 5 degrees.

3.1 Stratigraphy

Due to its domal nature the Thisted Dome exposes a wide stratigraphic range of chalk at the surface. Preliminary biostratigraphical investigations indicate that the entire Maastrichtian system may be present, and possibly the center of the structure exhibit chalk of Late Campanian age (E. Håkansson, pers. com. 1996). Similarly a wide range of Danian sediments are exposed in the area, particularly along the northern and eastern perimeter. The basal Danian succession is exposed intermittently all around the dome (Håkansson & Hansen, 1979; Hansen, 1979). At the northern margin of the structure the Middle Danian zone NP3 is exposed on the beach NE of Hanstholm Hill (Thomsen, 1995), while the Late Danian zones NP8 and NP9 are exposed within the Hanstholm Harbour immediately NW of Hanstholm Hill (Hansen & Håkansson, 1980; Thomsen 1995).

3.2 Structural geology

Structural data from the area have been obtained at two scales. The large scale fault pattern of the Thisted Structure has been established from stereoscopic interpretation of aerial photographs covering an area of approximately 400 sq. km, while orientation on the numerous small scale fractures has been determined in outcrops.

Most prominent faults are compatible with the systems of radiating and concentric faults expected over a rising dome. The elongated Danian limestone hills are bounded by faults belonging to a concentric fault system and the hills are separated by wide gabs and intersected by narrow gullies representing a radiating fault system. A more chaotic fault pattern is found in the center of the dome with several fault-bounded lakes, among which Nors Sø can be considered a collapse graben.

So far only a single topographically determined fault line has been documented through biostratigraphic investigation; i.e. a relative down-throw in excess of 50 m has been established for the block immediately west of Hanstholm (fig. 3; Hansen & Håkansson; 1980).

The small-scale fracture orientation has been determined at selected localities in the Thisted Structure (fig. 3). Strike orientation of fractures measured in three different localities in the area are presented as rose diagrams on figure 3. Two localities, the Thisted Quarry and Nye Kløv, are situated at the rim of the dome. In Thisted Quarry the ENE-WSW and the NW-SE orientations are easily explained as part of the overall radiating and concentric fault pattern whereas the relation of the N-S fracture orientation is less obvious. At Nye Kløv two orientations are dominating, one is following the NNE-SSW concentric faults pattern, whereas the other, NW-SE, parallels the major faults creating the gabs between the prominent hills both north and south of the locality. The dominating orientations in the Hillerslev quarry are ENE-WSW and NNW-SSE, which are in good accordance with the fault pattern detected in the immediate vicinity of the locality.

3.3 Evaluation of deformation history

During the Late Weichselian glaciation all of northern Jutland was covered by ice caps, and the topography, therefore, reflects the landscaping effects of glacier ice or melt water. However, in the Thisted Dome, Maastrichtian and Danian chalks and limestones are exposed at the surface and to a large extent devoid of tills and glaciofluvial sediments. Moreover, the present surface topography displays a number of morphological features, which are not readily compatible with glacial processes. Rather, it appears that most prominent topographic elements in the Thisted-Hanstholm area can be related to fault activities subsequent to the disapperance of the ice about 12,000 years ago.

The average upheaval of the area has been in the order of 2.5 mm/year in the center of the dome during the past 4000 years (Hansen & Håkansson, 1980). The relative magnitude of salt induced deformation has been established by comparing two previously horisontal reference surfaces, the Maastrichtian/Danian boundary (age 65 MY) and the maximum transgression surface (age 4000 years), with the present day sea level.

The Maastrichtian/Danian boundary is exposed in several localities around the margin and taking the local tilt into account, this points to a domal surface with a maximum near Nors Sø (Hansen & Håkansson 1980). Based on a conservative estimate of the local thichness of the Maastrichtian chalk, it appears that the Maastrichtian/Danian boundary level in the center of the dome has been raised approximately 300 m in relation to the margin during the last 65 MY; on average this amounts to a negligible yearly movement in the order of 0.005 mm/year or less (Hansen & Håkansson, 1980).

During the Holocene transgression the Thisted Dome was partly covered by the sea. The presence of erosive beach lines and beach ridges associated with this transgression allow the determination of the former maximum sea level over large parts of the dome. Deviation from the present sea level, therefore, provide information on deformation, which has affected the area, subsequent to the time of the maximum transgression which occured in the Thisted-Hanstholm area approximately 4000 years ago (Petersen, 1976).

In the Thisted-Hanstholm area the regional, isostatic land upheaval caused by uploading subsequent to the melting of the Late Weichselian ice cap is expected to be between 4 and 4.5 m above present day sea level (Mertz, 1924; fig. 3). However, throughout the area a substantial variation exists in the present level of the maximum Holocene transgression surface indicated by the altitude of beach lines. In most of the area the figures are significantly higher than expected, up to 15.7 m, whereas in other areas the figures are lower, down to 1.6 m (fig. 3). Thus, within this area a surface feature which was horizontal approximately 4000 years ago is now deformed with an amplitude exceeding 14 m (Hansen & Håkansson, 1980).

The fault controlled topography in combination with the deviation recorded between the actual, local levels of the maximum transgression and the expected, regional level confirms that the deep-seated salt surface in the Thisted-Hanstholm area has changed its shape significantly during Holocene. Thus, the calculated average yearly movement in the center of the dome is close 2.5 mm/year over the last 4000 years (Hansen & Håkansson, 1980).

4 Hillerslev Quarry

The outcrop locality Hillerslev quarry has been described geologically. The Hillerslev quarry is located on top of the Thisted dome in the north-western Jutland and the structural development is closely related to the stress and deformation history of the Thisted dome. A detailed fracture study was carried out in order to be able to relate geological descriptions to natural fracture patterns. In this project the sampling in the Hillerslev quarry was determined by the local fractures and not by descriptions of the global, natural fracture systems.

4.1 Hillerslev Quarry

The Hillerslev Quarry is an active chalk quarry located immediately south-west of the village Hillerslev in the eastern half of the Thisted Dome (fig. 3). Presently it provides the only good exposure within the central portion of the dome although it is located at some distance from the very center. The size of the quarry is approximately 500 x 200 metres.

A low quarry wall (approximately 4 m high and 45 m long (fig 4)) in the northern part of the quarry has been excavated and described in detail under a chalk research project. Fracture density and orientation have been determined along a horizontal line. The fracture description was associated with a series of one-inch core plugs subsequently described and analysed for porosity and permeability. In this project supplementary measurements and fracture descriptions have been carried out along new profiles as re-excavation of the same wall section took place.

4.1.1 Stratigraphy and lithology

The chalk in the quarry is of Late Maastrichtian age, belonging to the *humboldtii-stevensis* Zone (Brachiopod zone 9, E. Håkansson pers. com., 1996). It is a soft, weakly cemented mudstone/wackestone, composed almost exclusively of coccolithic material with subordinate amounts of skeletal material (foraminifera, bryozoans, echinoderms, molluscs) and a low content of silica, clay minerals and pyrite (~5%).

Horizontal bedding of the chalk is indicated by a slightly darker marly chalk and discontinuous layers of flint. The flint layers are traceable over larger areas and they are useful as marker horizons. The individual beds occur as sheet like deposits with a lateral extension exceeding the length of the profile investigated. Omission surfaces are largely overprinted by late horizontal relaxation fractures. Thickness of the individual beds ranges from 10 to 50 cm as defined by relaxation fractures and from 20 to 40 cm if based on marly intervals.

Three different lithotypes have been recognised along the profile. Burrowed massive chalk mudstone is the most common lithotype found in most of the profile. Locally burrowed laminated chalk mudstone is seen and in the eastern part of the profile pebbly massive chalk mudstone (and skeletal wackestone) is dominating.

4.1.2 Diagenesis

Analysis of the chalk samples from North Jutland indicates that the chalk is more affected by compaction (mechanical diagenesis) than chemical diagenesis. The pore volume is dominated by intra fossil (foraminifers and calcispheres) voids.

Fine euhedral and subhedral cement crystals are found scattered in the pore space. Relatively few calcite spar crystals are associated with overgrowth of shell fragments. Syntaxial calcite overgrowth on coccolith platelets is normally scarce and the size of these crystallites is typically less than 2 μm.

Flint concretions amount to a small percentage of the total sediment volume and most silica within the chalk is found as cristobalite/tridymite lepispheres.

4.1.3 Porosity and permeability

The average porosity from more than 200 samples along the horizontal profile is 47 % (with a range from 44 % to 52 %) and the average gas permeability is 8.1 mD (ranging from 5.1 mD to 13.4 mD) (Jakobsen & Madsen, 1996).

The one inch core plugs and the reference fracture data was sampled along the same line and the possible linkage between the variation in porosity and permeability and the position of fractures was investigated. However, low as well as high values of porosity and permeability are found associated with fractures and no consistency could be detected based on the present data set.

4.2 Fracture investigation

The fractures are assumed to be related to the structural growth of the Thisted dome and a discussion on structural evaluation, fracture density and characterisation has been carried out. The discussion is based on a detailed fracture study in the quarry.

4.2.1 Uplift and stress indications

The center of the Thisted dome has experienced average movements of approximately 2.5 mm/year over the last 4000 years and the growth of the structure may still be going on. The general tilt in the Hillerslev quarry is 4-5 degrees towards ESE.

The domal development of the Thisted dome gave rise to a rather complex structural system introducing a series of fracture types associated with the stress regimes (fig. 5). Bending of the chalk sequence due to doming and uplift gives rise to extensional fractures (fig. 5a), but in addition, shear fractures – dependent on effective stress direction – will be developed in different quantities (fig. 5b).

A high proportion of the measured fractures is conjugated strike-slip fractures with an ENE-WSW and SE-NW orientation, but also generally NNE-SSW and SSE-NNW oriented fracture systems are seen. The majority of the fractures are steeply dipping with a dominance of almost vertical fractures. The fracture densities were measured indicating almost random spacing of fractures.

Horizontal bedding parallel fractures are common. These fractures may be interpreted as a result of deloading, but the fractures often exhibit evidence of minor lateral displacements (the asperity along fracture indicates minimum displacements of 5 – 10 mm) and may be considered as flexural-slip fractures.

In addition to the bed-parallel fractures sub-horizontal strike-slip shear fractures are seen intersecting and displacing the chalk sequence. These sub-horizontal strike-slip faults are interpreted to be associated with the stress caused by the dip of the structure.

4.2.2 Scanlines

Detailed description and fracture measurements along scanlines have been carried out along a 25 m freshly excavated chalk profile in the Hillerslev quarry. A horizontal scanline profile, approximately 25 metres long, was sampled from the originally exposed quarry wall. This scanline has been used as reference for the additional scanline measurements. During the project period the chalk profile was further excavated 2 m into the wall with a temporary formation of a plateau (for sampling of block specimens), which makes it possible to establish a 3D picture of the sampling area (fig. 6).

As the majority of fractures are steep to very steep with a dip of 65^{o} or more the horizontal line sampling employed is considered to be at a sufficiently high angle to the overall fracture orientation. It must, however, be mentioned that the numbers of measured subhorizontal fractures/bedding planes are less than the actual appearance because of the scanline parallel occurrence. Also the measurement of wall parallel-dipping fractures are hindered by the excavation technique.

The fracture density along the scanlines has been determined. The density of fractures along the reference scanline is evident from figure 7a showing some variation along the profile. The fracture density determined from the recent scanlines also illustrates the variation along the profile, but indicates a spatial variation as well (fig. 7b).

4.2.3 Orientation

The orientations of the fractures in the quarry were measured as strike/dip and subsequently plotted in a Wulff projection (equal angle) as normals to fracture planes (fig. 8a). The fracture orientations are widely scattered, although some clustering is evident from the plot. A rose diagram of strike orientations (fig. 8b) shows that a high proportion of fractures are oriented SSE-NNW and ENE-WSW with NNE-SSW and ESE-WNW as secondary directions.

4.2.4 Dip

Dip frequency and dip direction of fractures have been plotted as histograms and rose diagrams (figs. 9a and 9b). The majority of fractures are steeply dipping with a predominance of almost vertical fractures (fig. 9a).

Based on their dip, fractures can be divided into two fairly distinct groups with little overlap:
1) a group of low angle to horizontal fractures, dipping less than 30°, and
2) a group of the much more numerous high angle fractures. The high angle fractures most likely originate from the structural growth of the dome and associated tectonic movements.

The fracture generation is interpreted to be associated with tectonic movements associated with doming, but a glaciotectonic origin cannot be excluded.

4.2.5 Fracture types

The fractures recognised in the Hillerslev quarry comprises fracture types ranging from fissures (extension fractures) over joints (negligible or absent movement) to minor faults with visible movement (more than 30 cm displacement). The various fractures can be grouped into sets with a prevailing orientation (fig. 10). Generally the fracture sets are formed simultaneously and form conjugate systems.

The fracture surfaces display delicate relief patterns (fig. 11). The essential structures of a fracture surface are the main joint face carrying hackle marks forming feather-like pattern (**plume**), the **fringe** composed of small subsidiary fringe (twist-hackle) faces offset from one another by step faces joints and **rib marks** which tend to form annular patterns. These structures are seen in different combinations but may as well be missing.

Five sets of fractures have been identified in the Hillerslev quarry:

1) Inclined conjugate shear fracture sets oriented ENE-WSW and SE-NW.
2) Vertical, smooth fracture systems oriented NNE-SSW and SSE-NNW.
3) Slightly easterly dipping slip fractures.
4) Sub-horizontal dip-slip fractures and
5) Horizontal bedding plane fractures.

Inclined shear fractures

Two sets of inclining (in the order of 60°) shear fractures oriented ENE-WSW and SE-NW appears contemporaneously and is described as conjugate sets (fig. 12).

The lengths of the fractures exceed the profile height and are expected to be more than 5 m long. Based on the excavated platform it is evident that the lateral extension exceeds 2 m (the width of the platform). The fractures intersect both horizontal and vertical fractures, but no severe vertical displacement is seen in the profile. Only in connection with the block sampling a possible contemporaneous sedimentary surface shows evidences of displacements up to 2 cm (fig. 13).

The fracture surface is undulating, smooth to rough with a relief along strike in the order of 1 cm (over 10 cm). Along dip slickensides are seen.

Vertical fractures

Along the profile, the most prominent fracture type is the vertical smooth fractures. Two conjugate sets with NNE-SSW and SSE-NNW orientations prevail. The fractures appear as more than 3 m long continuos fractures cutting the horizontal fractures (fig. 14). A detailed study, however, show that the fracture zones are composed by a series of parallel stratabounded fractures controlled by one overall stress system, where the individual fractures are bounded by the horizontal bed-parallel fractures.

The individual fractures are displaced up to 1 cm crossing the horizontal fractures and exhibit a minor variation in orientation. Passing from one bed to the neighbouring bed a conjugate fracture set may exhibit different lateral displacements in opposite directions. The off-set is most likely a result of a subsequent lateral movement along the horizontal fractures (flexural-slip movements) and the observed displacement of the conjugate fracture sets suggests movements perpendicular to the orientation of the examined wall.

The fracture surfaces are generally smooth and uncoated, but more or less indistinct plume and fringe structures can be identified (fig. 15). These structures indicate a horizontal stress.

The size of the fractures is 20 – 30 cm in height and around 50 cm from the center to fringe shoulder. The total relief of the surface is within the plume less than 1 cm.

Slightly easterly dipping strike-slip fractures.

Gently dipping (approximately 45^{o}) sliding fractures with displacement of the horizontal fractures are relative common in the upper part of the profile (fig. 16). More than 7 sliding fractures over 20 m have been recognised but a larger number cannot be ruled out.

The fractures appear as undulating, smooth (fig. 16b) with apertures of 5 mm. The surface features indicate an overall down-dip progradation. The displacement of the horizontal fractures is in the order of more than 10 cm. The fractures braid into several fractures entering softer layers (fig. 16a).

Towards the base of the profile the sliding fractures gradually divide into to sub-vertical fractures (fig. 17). This type of fracturing can be interpreted as a result of lateral progradation (Ameen, 1995)

The length of the fractures is more than 5 m whereas the width is unknown.

Sub-horizontal strike-slip fractures

Whereas the slightly inclined fractures are found in the upper part of the profile a number of sub-horizontal strike slip fractures are found in the lower part of the profile.

The fracture system is large scale undulating shear zones cutting the horizontal bed-parallel fractures along oblique angles resulting in lenticular features (fig. 17b). Movements up to 2 cm are observed. Progradation perpendicular to the profile orientation may be more prominent, but not possible to determine.

The fracture surface is undulating but smooth with apertures of 5 mm. The length of the fractures are more than 10 m. The width is unknown.

Horizontal bedding parallel fractures.

Horizontal fractures are the most common features in the chalk sequence. The distance between the sub-parallel fractures ranges from less than 10 cm to 30 cm.

The fractures are commonly interpreted to be associated with deloading during uplift and melting of the ice cap. However, displacement associated with brecciation along the fracture linement is here interpreted as flexural-slip movements

The movements are in the order of 3 cm and give rise to an open fracture system with apertures in the dimension of 1-2 cm times 5 mm (fig. 18). The fracture surface is generally smooth with wavy appearance.

4.2.6 Fracture generation

Interpretation of the origin and timing of the fracture sets in the Hillerslev quarry is hampered by the lack of clear evidences of displacement. Most fracture sets are associated with horizontal progradation in the same order and orientation and therefore difficult to differentiate.

It is however anticipated that the various fracture sets may be of different genetic origin and formed at different time.

A fracture history is suggested as follows:

Halokinesis within the Thisted area may have initiated before deposition of the chalk, but doming and uplift prevailed in Neogene after maximum depth of burial. Associated with the uplift and doming the inclined conjugate fracture sets may have formed. The dominant orientation along ENE-WSW and SE-NW indicates the presence of a minimum principal stress situation radial to the dome structure. Contemporaneously the extensional fractures with the prevailing NNE-SSW and SSE-NNW orientation were formed.

Along with the updoming the dip of the chalk sequence increases to 5^0 and the horizontal stress increases downflank. The bending of the chalk sequence gives rise to horizontal (bed-parallel) flexural-slip fractures. In addition the horizontal stress regime gives rise to the formation of the slightly dipping fracture/fault sets and the sub-horizontal shear fractures.

4.2.7 Fracture density and block sampling

In the original project planning it was decided to test plugs with different fracture density. As mentioned earlier the fracture density varies along the profile and based on these information the location of block samples have been decided.

In figure 19 the platform excavated for plug sampling are seen from above. The density of the various dipping fracture sets are indicated. According to the fracture measurements it was decided to cut 17 block samples. However, only 10 blocks were recovered successfully of which 7 have been tested (the location of test samples is indicated in figure 19).

The quality of the block samples is variable and in heavily fractured samples, the broken and missing parts were repaired with gypsum. This restoring of the samples may have some impact on the block strength measured during test and a direct relationship between fracture system and rock strength is to some degree violated.

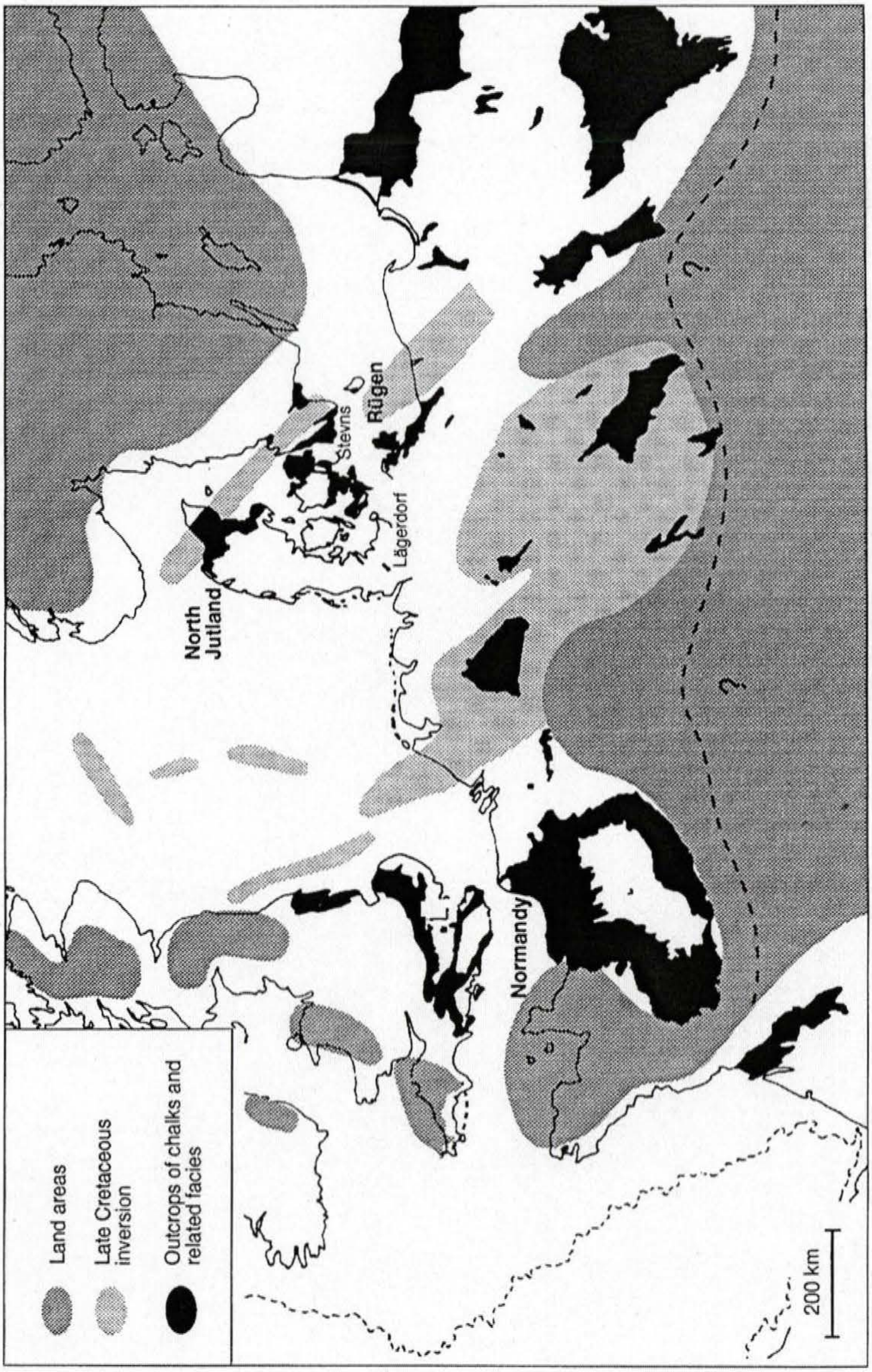
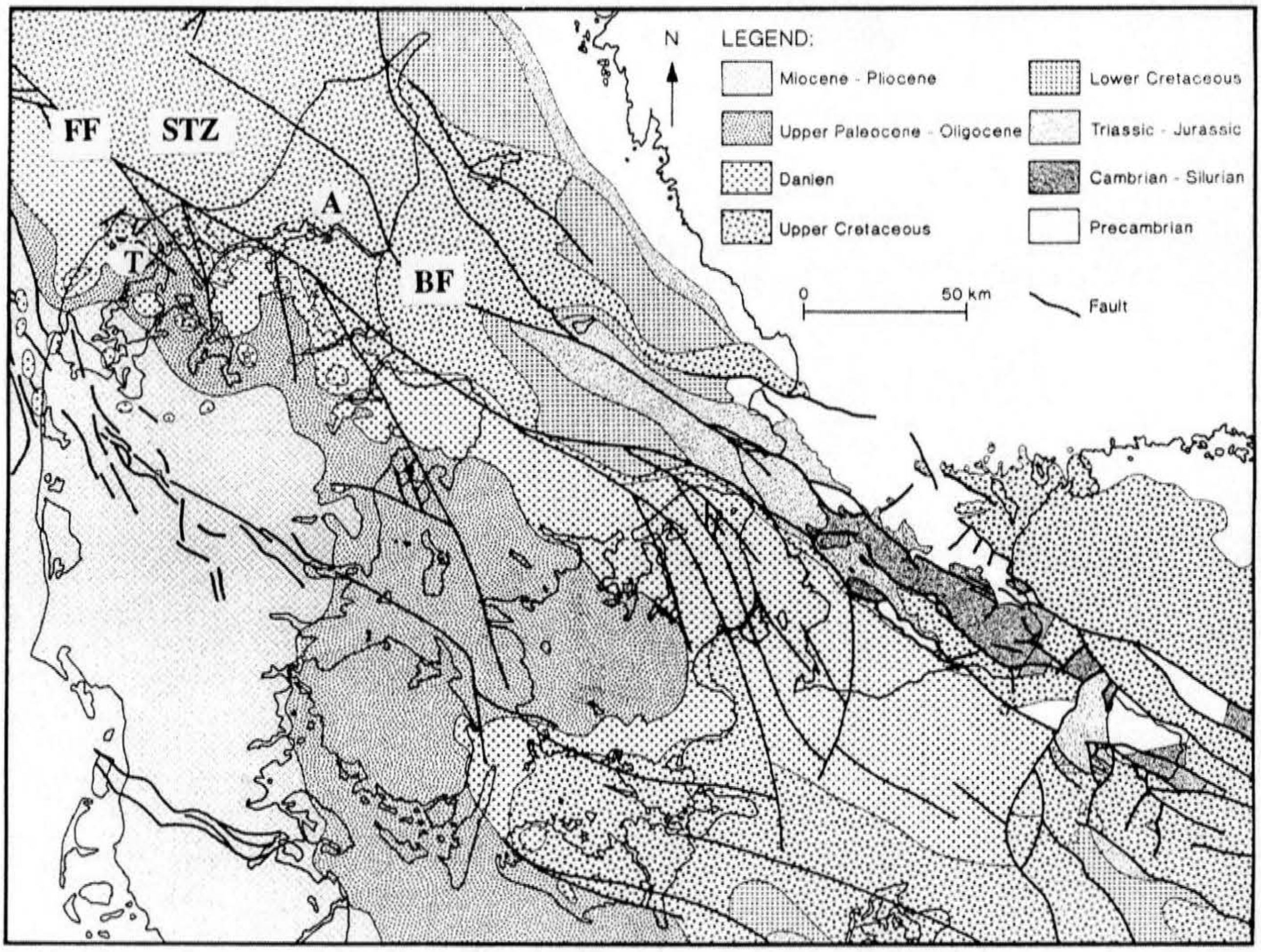


Figure 1.
Locality map showing the geological setting and maximum extension of the sea during the Upper Cretaceous. Present day outcrops of chalks and related facies are shown (after Scholle, 1974 and Hancock, 1975)



STZ: Sorgenfrei- Tornquist Zone
FF: Fjerritslev Fault
BF: Børglum Fault
A: Aalborg
T: Thisted

Figure 2.
Sub-Quaternary geological map of Denmark. (from: Håkansson & Surlyk, 1997)

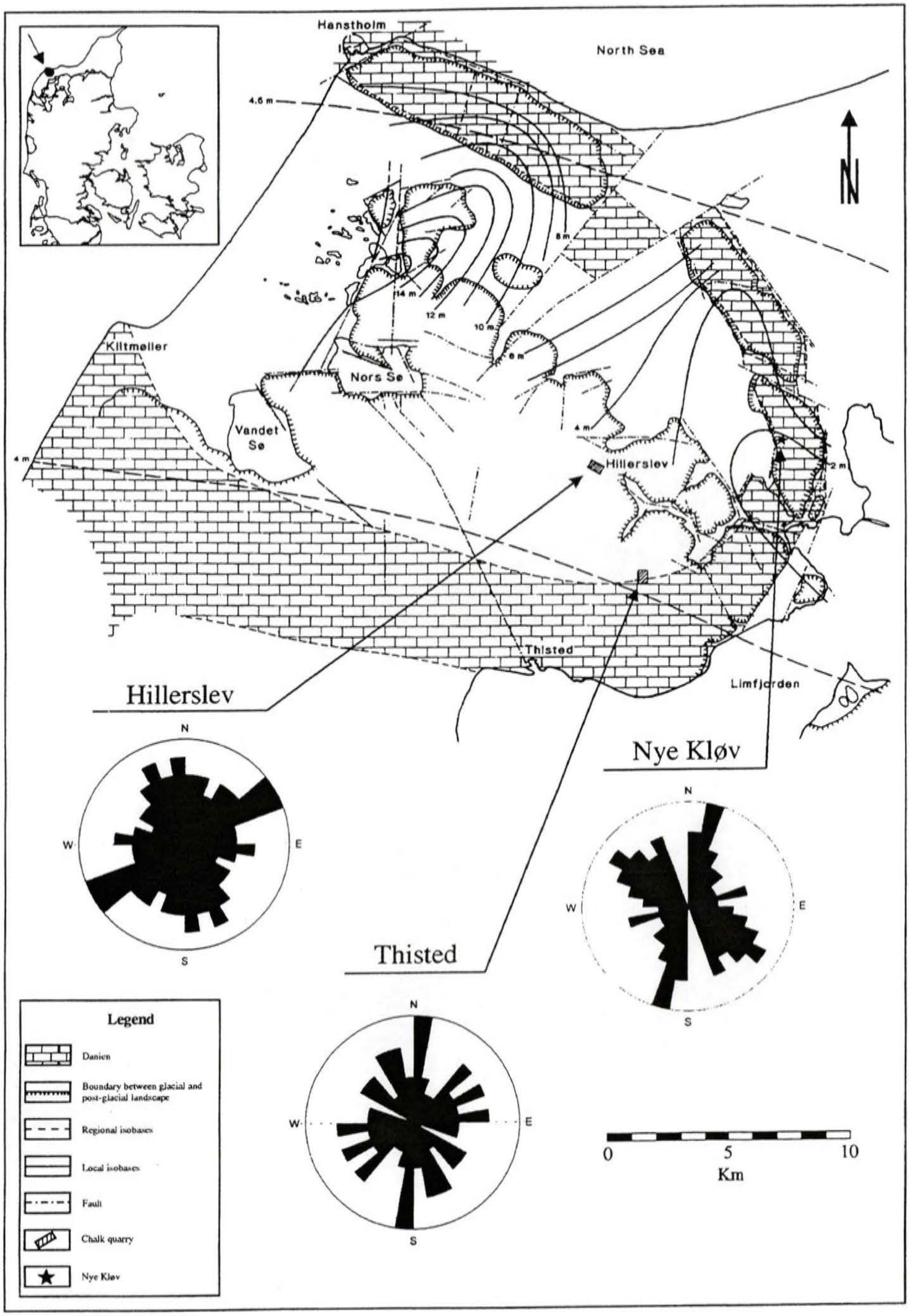


Figure 3.
Geological map of the Thisted Dome. A rim of Danian sediments surrounds Maastrichtian chalk. Rose diagram of strike orientation of fractures from three locations are included (from Madsen & Zink-Jørgensen, 1997)

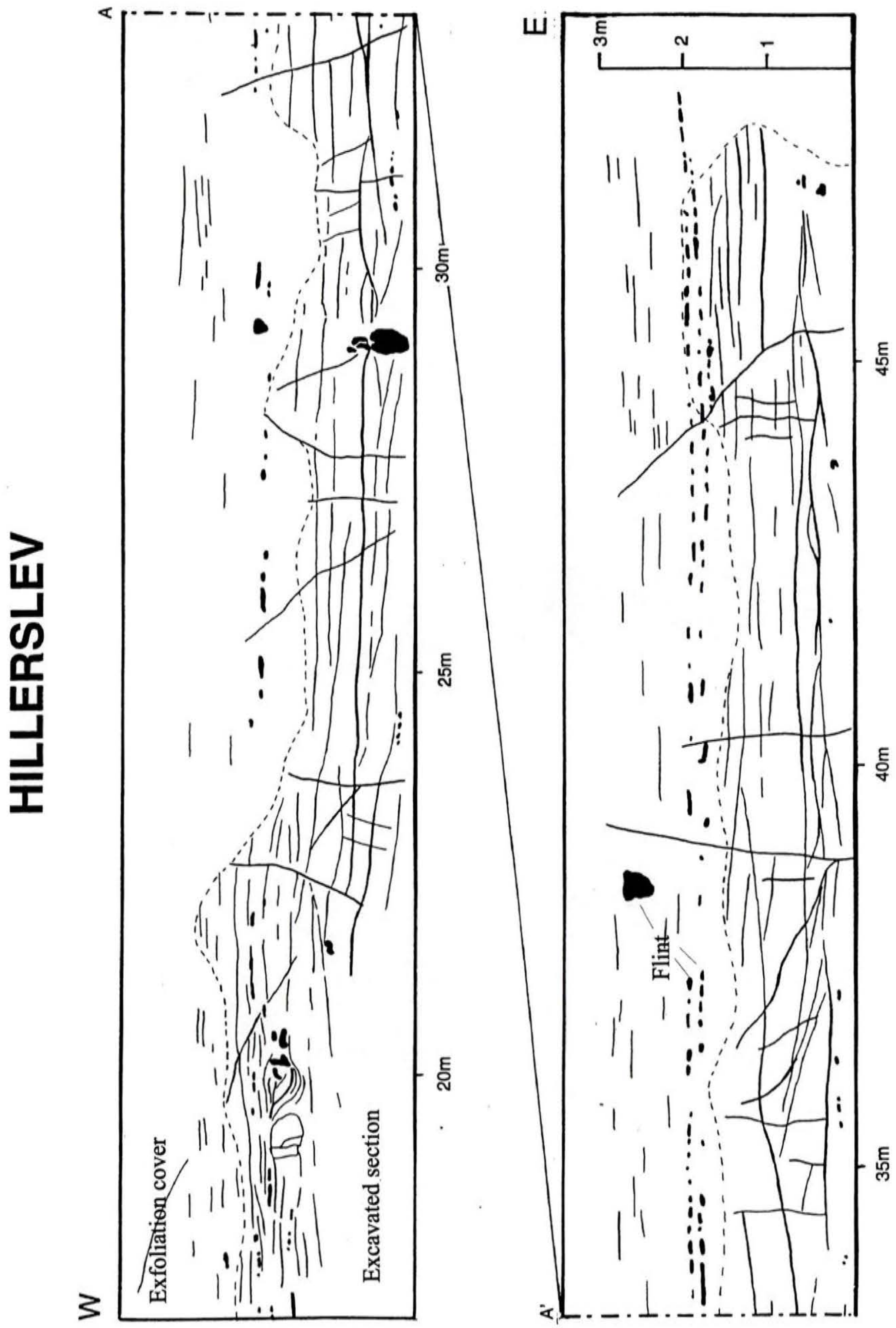


Figure 4.
Original excavated quarry wall in the northern part of the Hillerslev quarry.

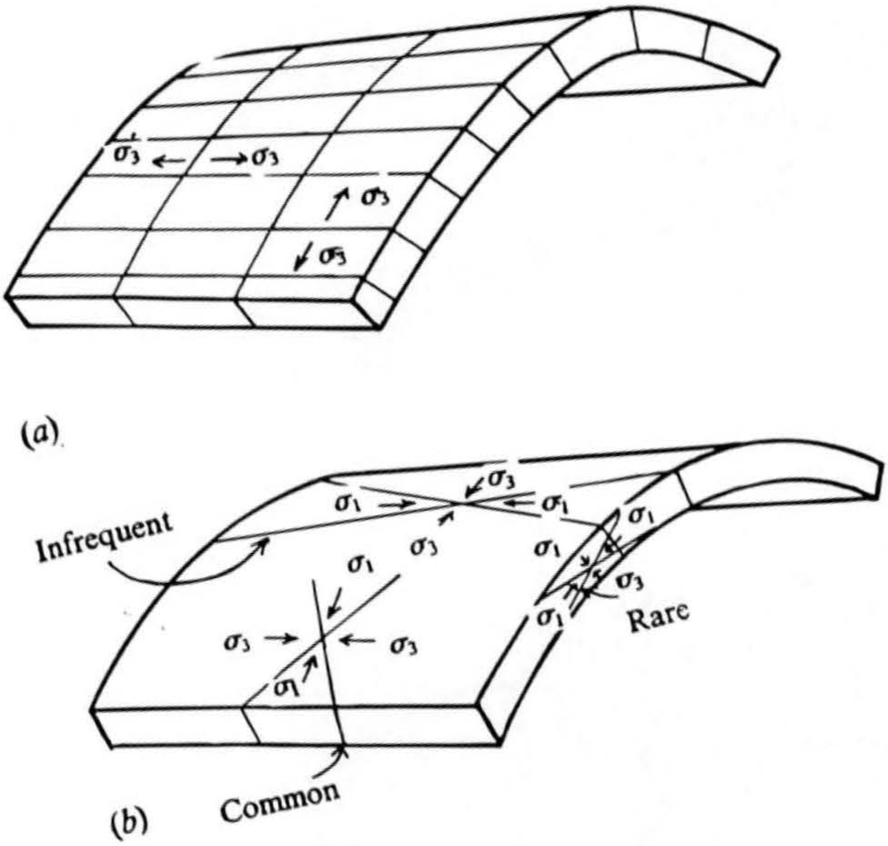
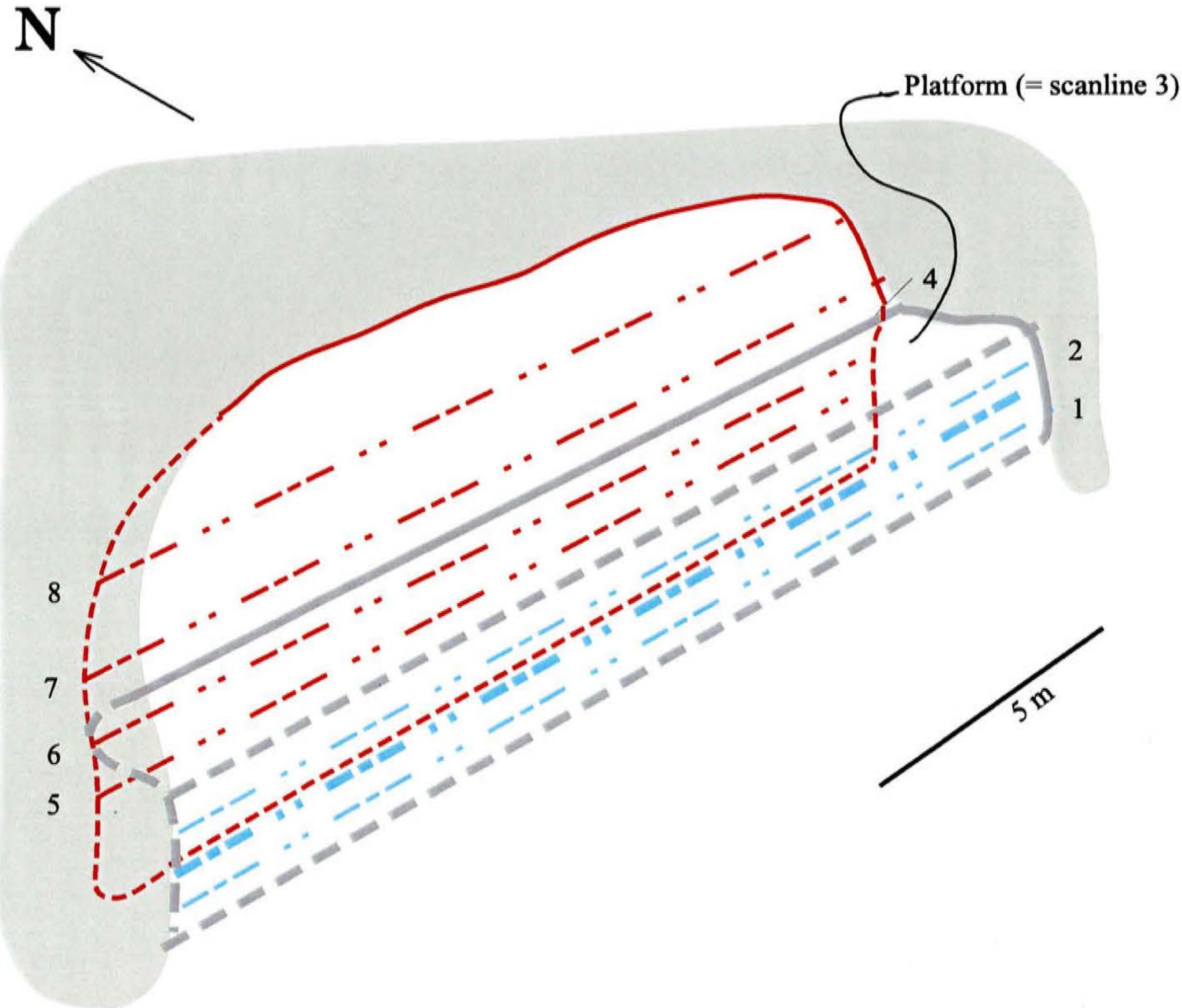
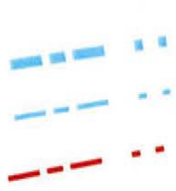


Figure 5.
Stress indications associated with doming.

Hillerslev profile with indications of scanlines

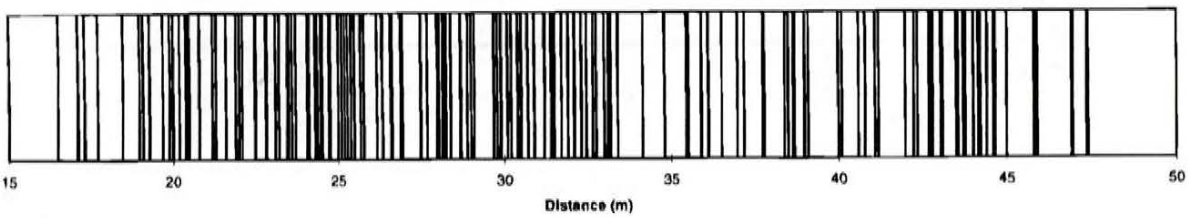


Grey color: Original profile **Red color: New profile**

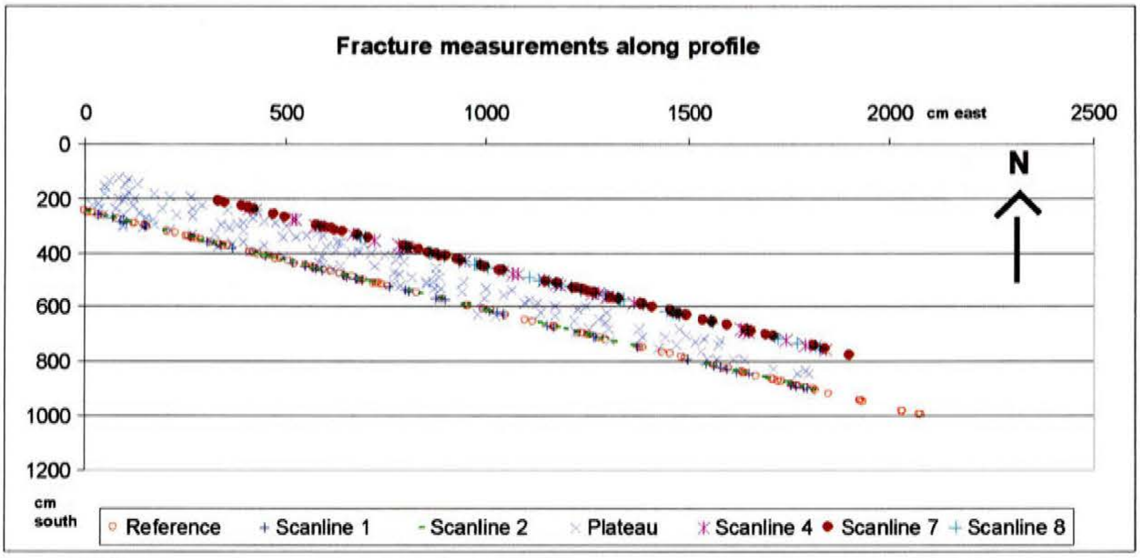


reference scanline (old profile)
scanlines (old profile)
scanlines (new profile)

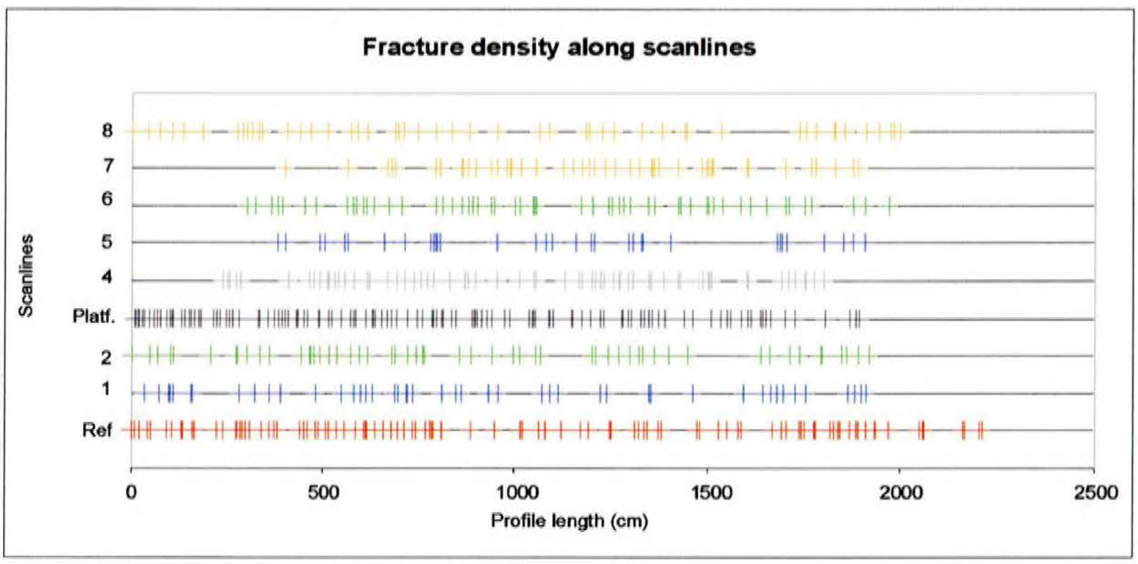
Figure 6.
Sketch of excavated profiles and the platform with indication of scanlines for fracture analysis.



A



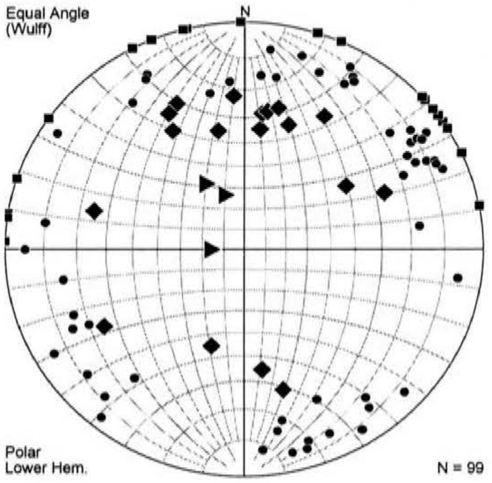
B



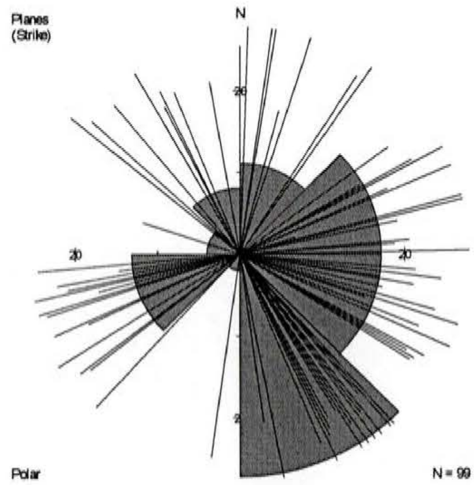
C

Figure 7.
Fracture density plots from Hillerslev quarry.
A) Fracture density along reference scanline.
B) Map plot of measured fractures (profile seen from above)
C) Fracture densities along the different scanlines.

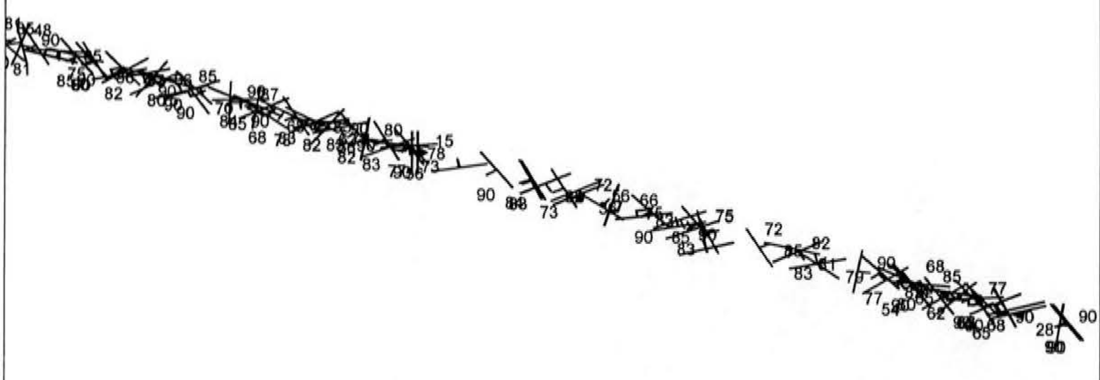
Hillerslev, Reference scanline



A:
Wulff projection of strike/dip for all fractures along reference scanline as normals to fracture planes. **Circles**: Inclined, rough. **Squares**: Assoc, smooth. **Diamonds**: Assoc, rough. **Triangles**: Strike-slip

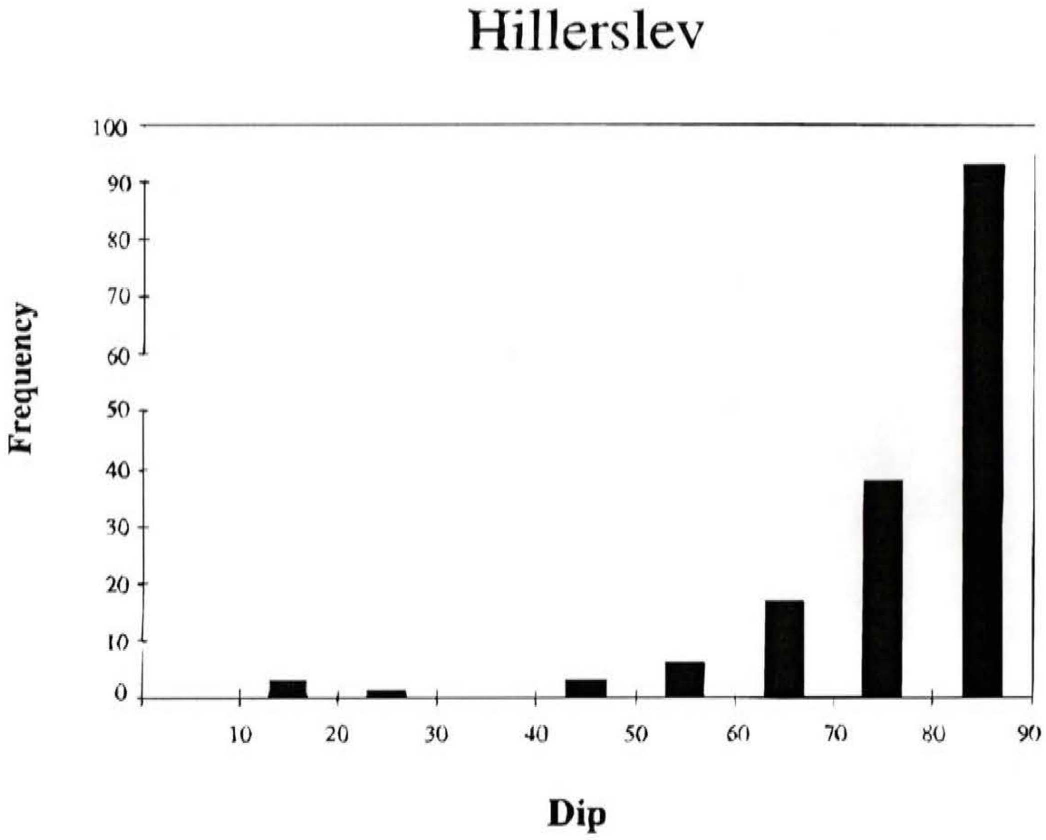


B:
Rose diagram of strike orientation for all measured fractures along reference line.



C:
Map of strike/dip measurements demonstrating the density of fractures along reference scanline.

Figure 8.
Fracture orientations from Hillerslev quarry illustrated by A) Wulff projection, B) Rose diagram and C) map plot.



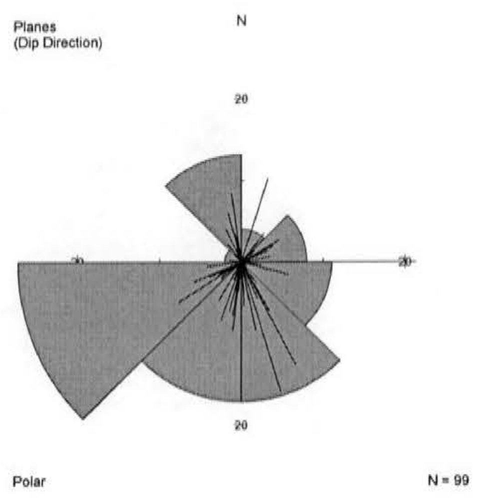
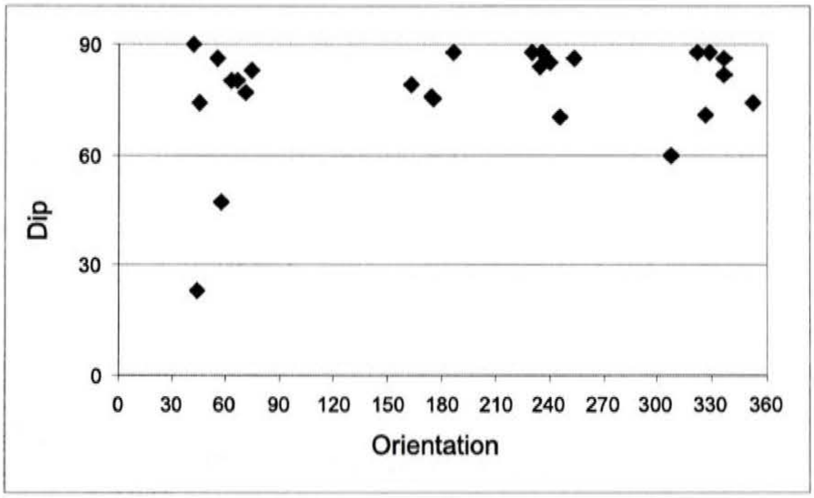
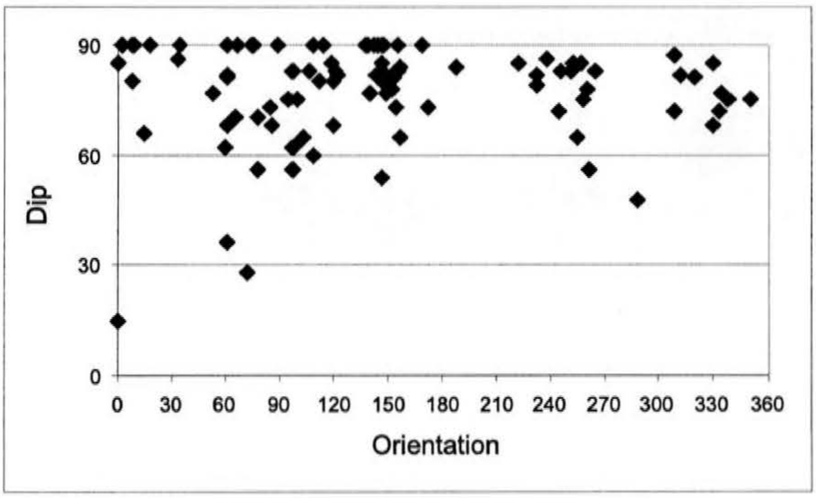


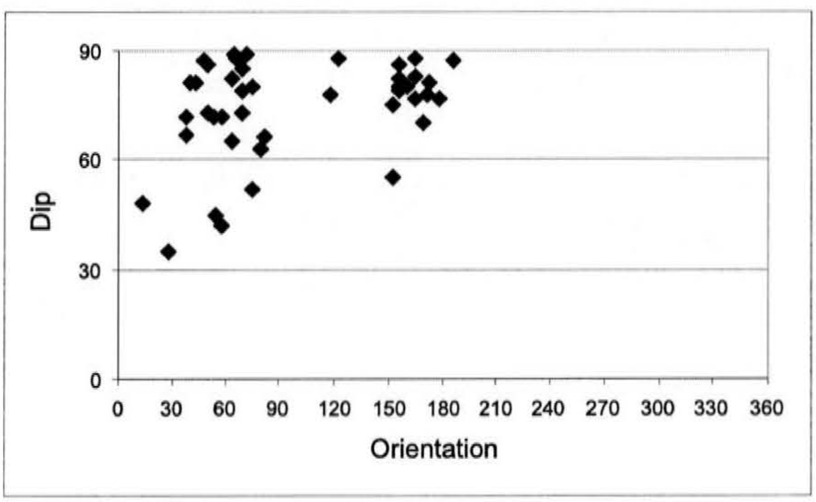
Figure 9.
Frequency histogram and rose diagram of fracture dip orientations related to fractures along the reference scanline in the Hillerslev quarry.



Orientation and dip in the upper part of the profile.



Orientation and dip along the reference scanline.



Orientation and dip in the lower part of the profile.

Figure 10.
Dip/orientation plot for various scanlines. The different fracture types seem to grouped along specific orientations

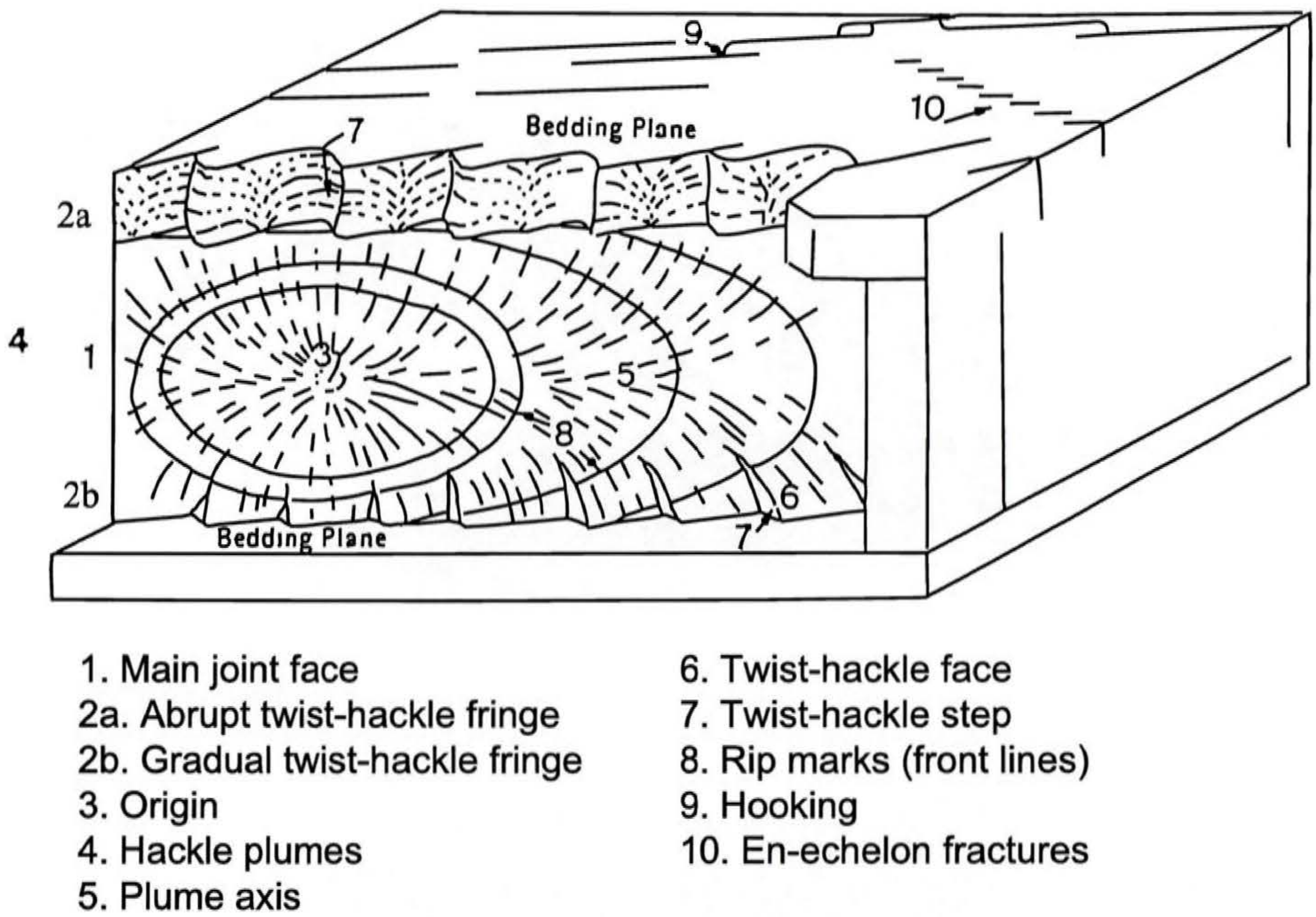


Figure 11.
Schematic diagram of joint face structures and their nomenclature

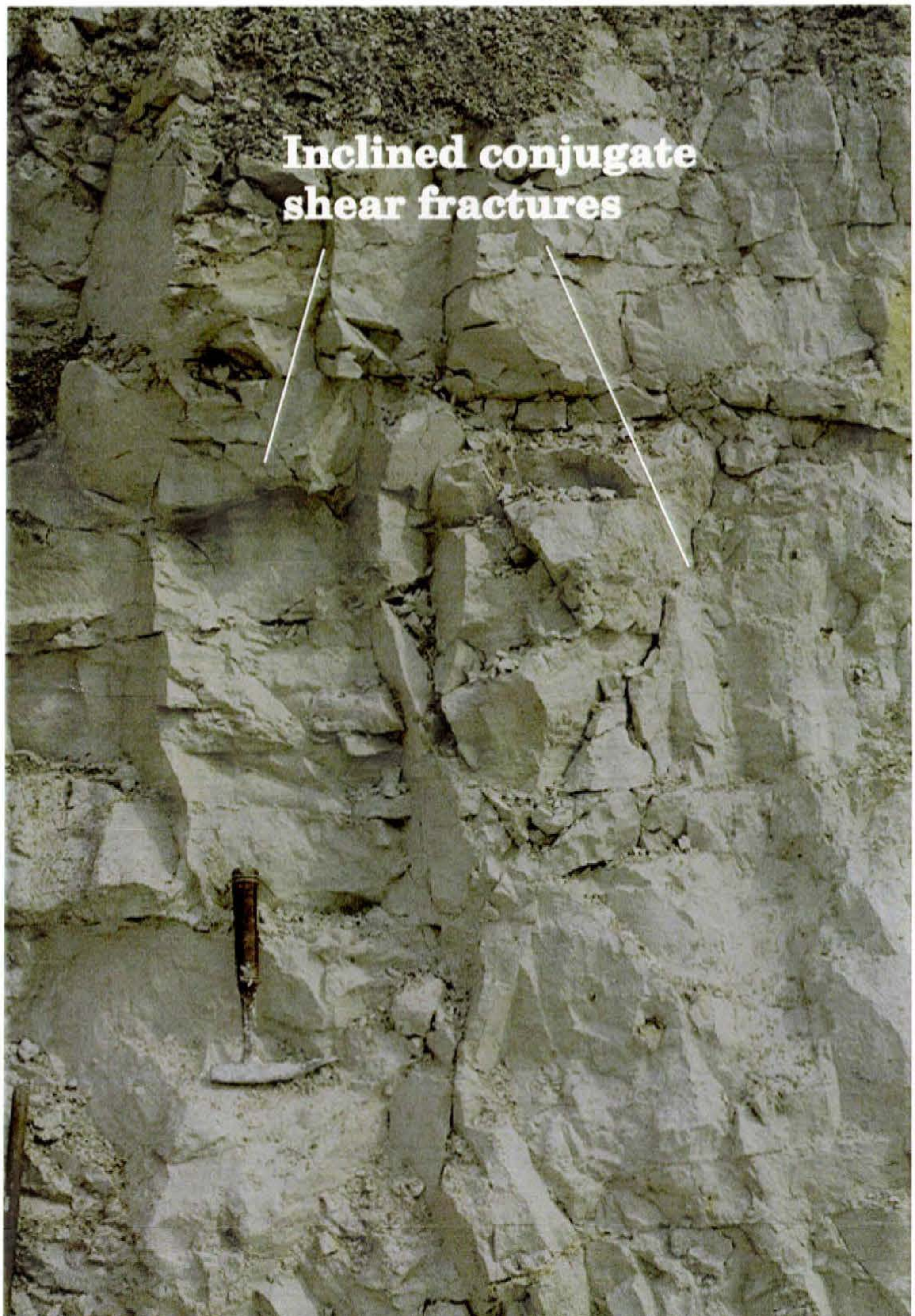


Figure 12.
Example of a conjugate set of inclined shear fractures.

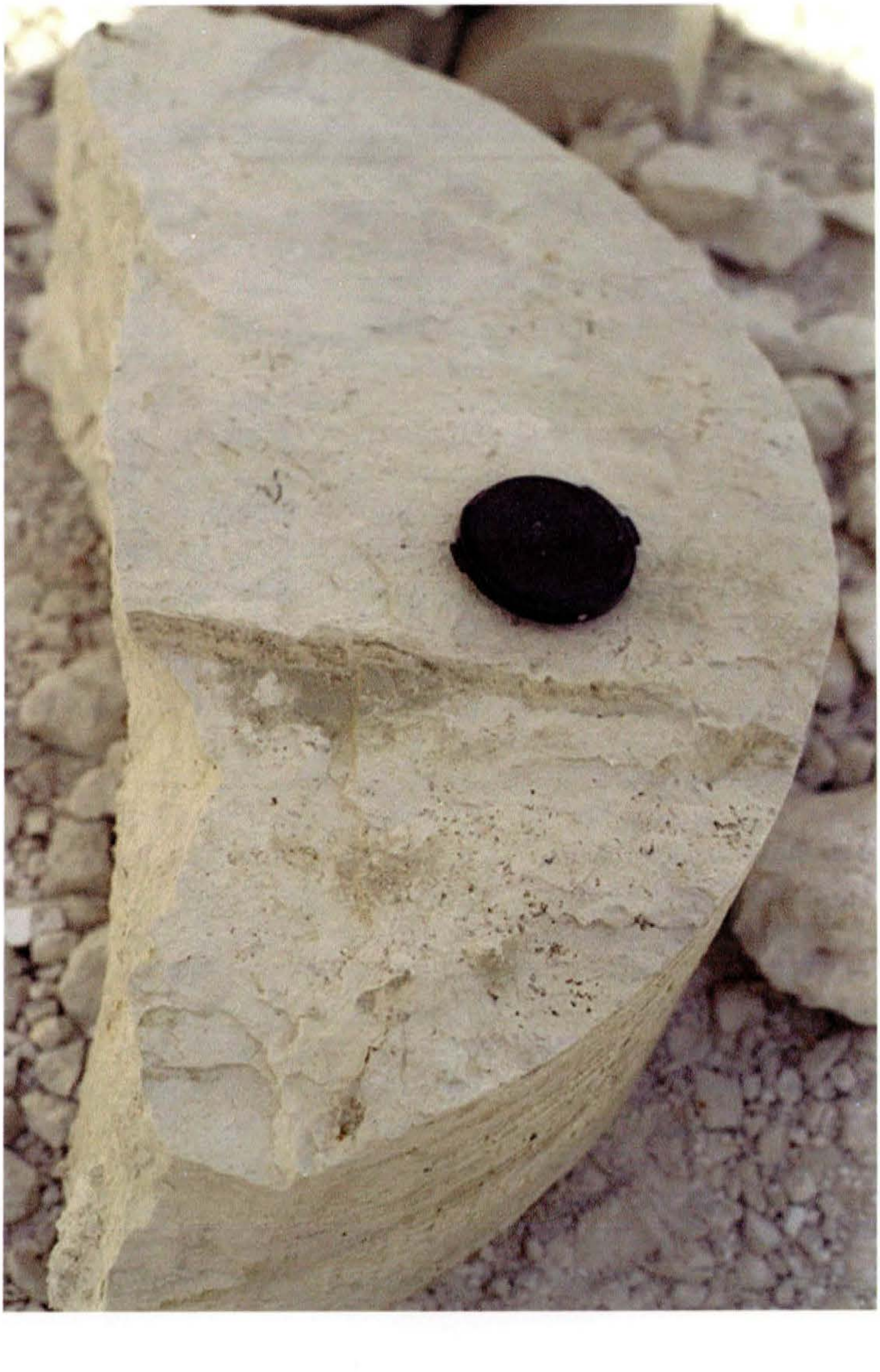


Figure 13.
Shear fracture with possible offset of 2 cm.

Figure 14.
Vertical fracture set. The fracture sets appear as continous zones, but is either cut and offset by the horizontal fractures or appear as stratabounded fractures with slightly different orientation.

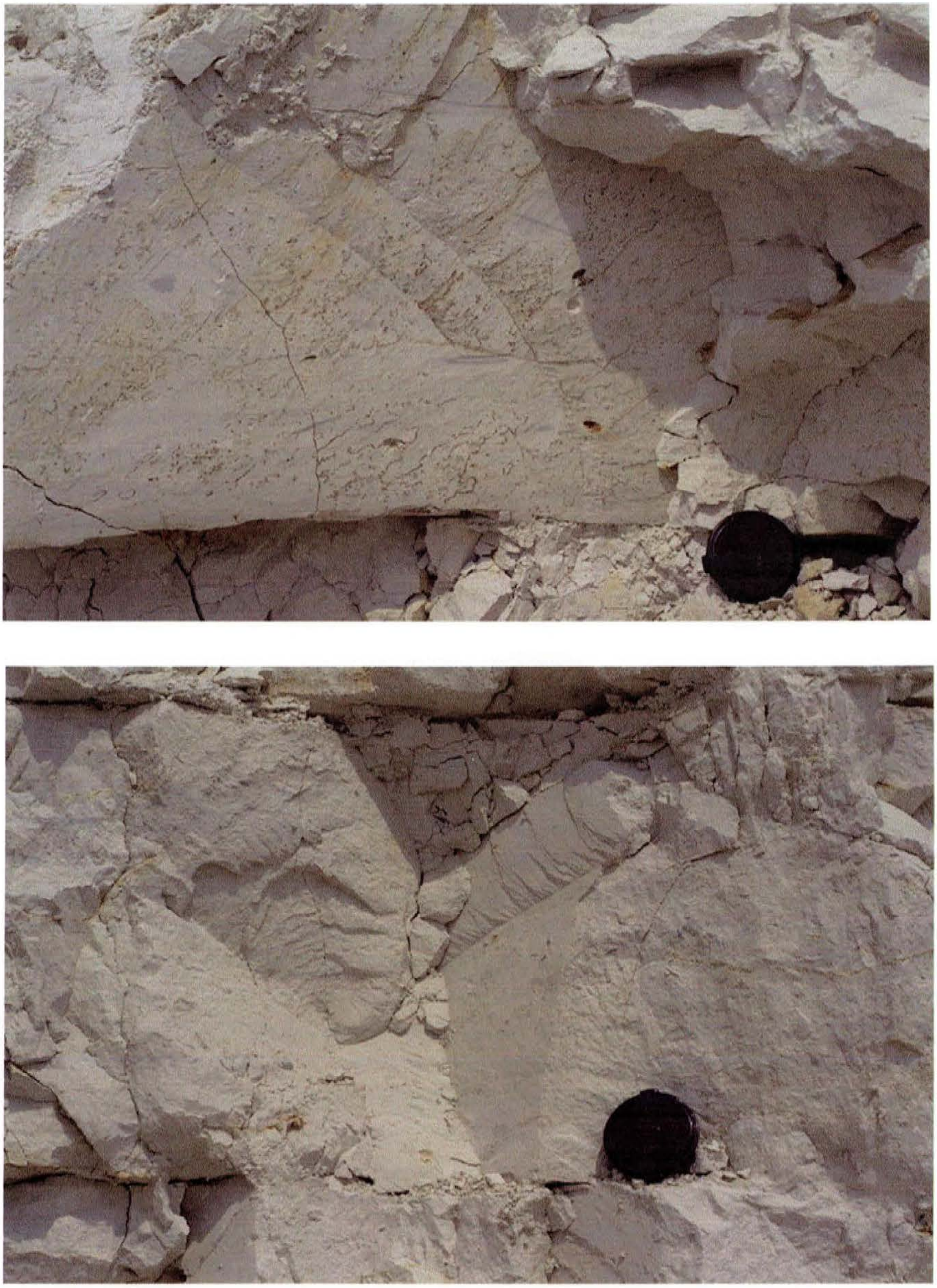


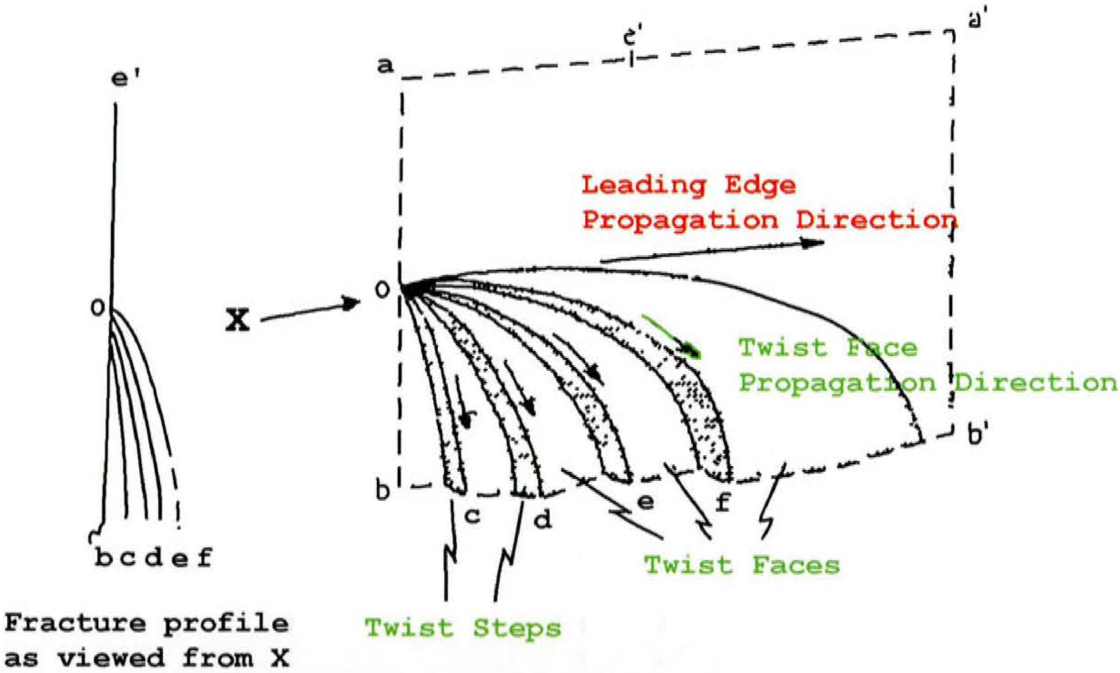
Figure 15.
Fracture surfaces associated with the smooth vertical fractures.

A

B

Figure 16.
Gentle dipping strike-slip fractures. A) Fracture along strike direction. B) Excavated surface.

A



B

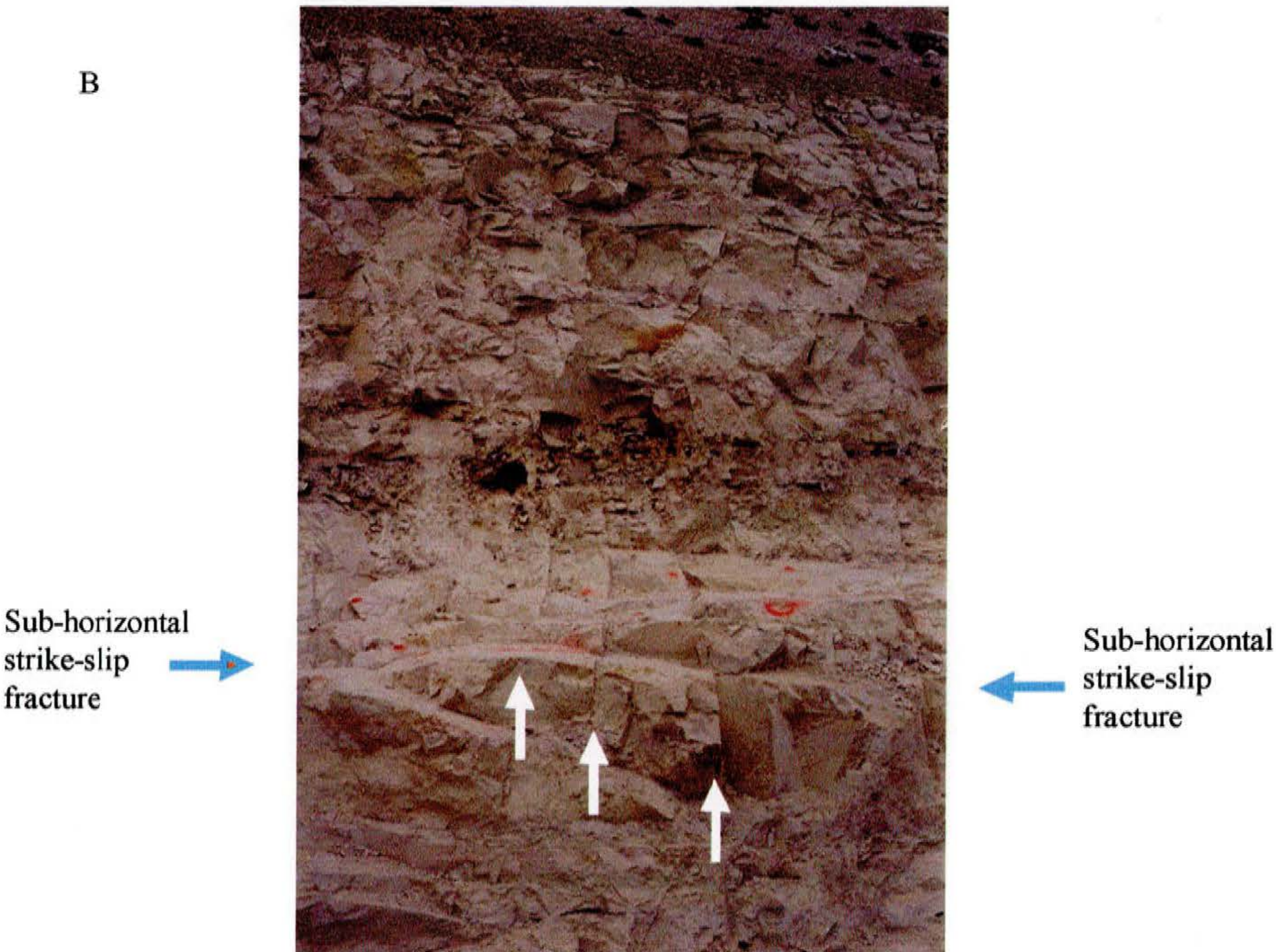


Figure 17.
Diverging strike-slip fractures (B, white arrows) with interpreted formation model (A) (after Ameen, 1995).

Figure 18.
Horizontal (bed-parallel) fracture with indication of minor off-set.

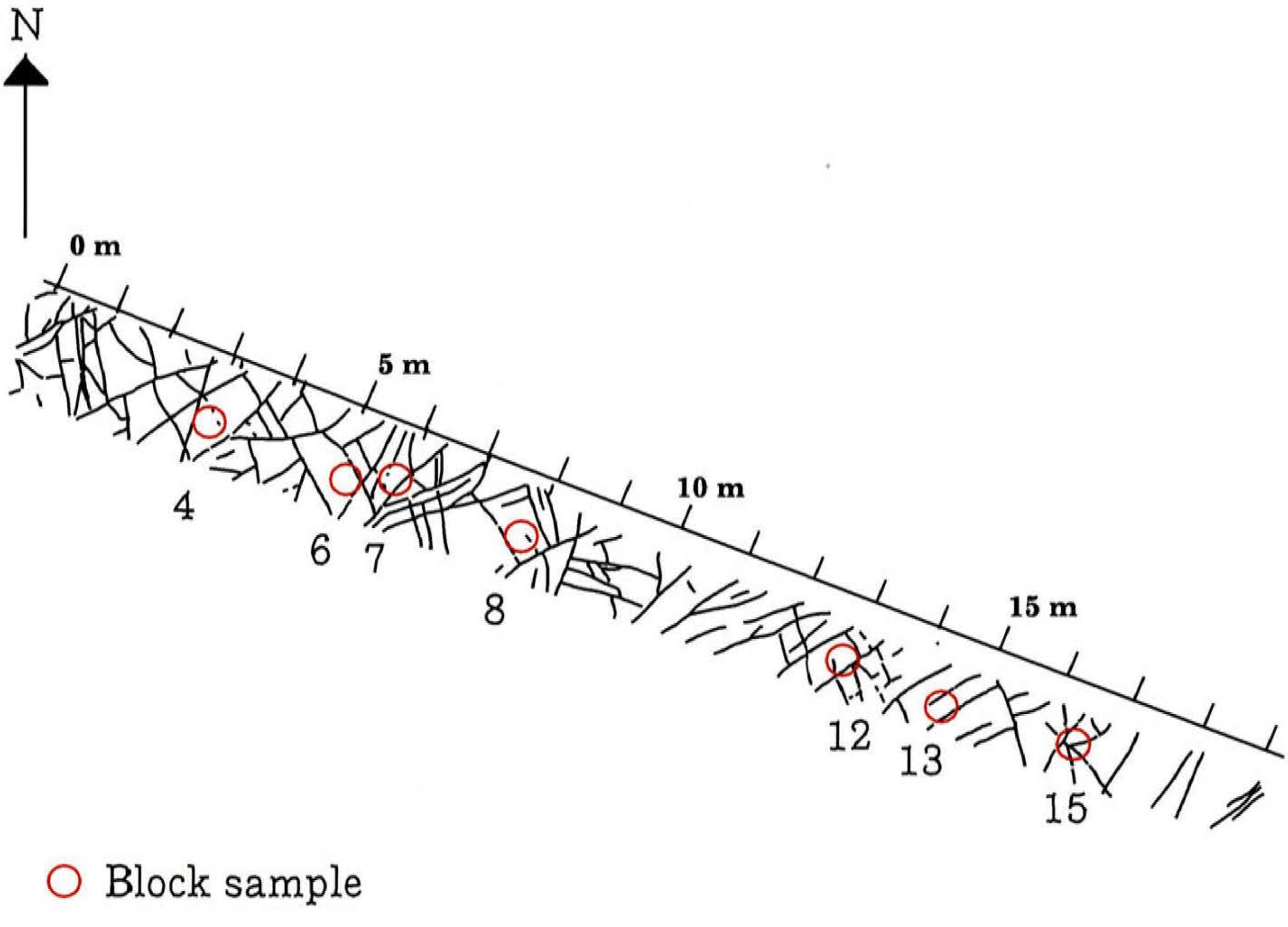


Figure 19.
Fracture pattern on excavated platform seen from above.
Red circles indicate the location of the block samples described in this report.

Background for SPECIMEN DESCRIPTION, SEDIMENTOLOGY FRACTURES

EFP 98

Fractures and Rock Mechanics, Phase 2

1 Plug description

In this project 28 plug specimens and 7 block samples have been described and tested. The description includes 1) fracture classification, 2) geological description of all samples and 3) standard core analysis prior to and after the geomechanical tests.

A complete presentation of specimen description is presented in appendix 1. In this section the basic methodologies are described and the used nomenclatures are explained.

To improve the understanding of the impact of fractures on rock mechanical properties the fracture type and fracture density are described and attempted to be associated with the geology of the chalk samples. Unfortunately no well established methodologies for fracture description within plug samples are published and at present severe uncertainties are associated with the impact of fracture type on the rock mechanical properties. Therefore a number of classifications systems have been used in order to test any correlation with the rock mechanic tests.

Methods for fracture characterisation are published (Fritzen & Corrigan, 1990; Aarseth, 1997 and Ameen, 1995), but in most cases these are associated with core or field/outcrop scale. In addition many of the fracture characterisation methodologies focus on flow properties and not on rock mechanical properties. More rock mechanic related classifications are published by Barton and Bandis (1990), Løset (1995) and Hoek & Brown (1997). These classifications have in this project been modified to fit the plug scale. The classifications and modifications are described in the following sections.

A summary of data is shown in table 1.

2 Presentation of plug description

2.1 Figures

For the purpose of fracture description each plug sample was wrapped in transparent paper. Fractures and important sedimentary features were outlined on the paper. For presentation the paper was un-wrapped and the entire surface shown (fig. 20). A line and color code are associated with the various fracture sets. Red color indicates the most significant fracture type. Blue and green colors refer to decreasing significance. Grey lining is associated with subordinate fractures.

In original samples (prior to test) the surface normally is reasonably accessible for inspection, but after the test, chalk-mud and fragmentation obstruct the description. To improve the possibility for description of the fractures after test the plugs have been cut through. These cuts are presented together with the unwrapped surface description.

2.2 Description scheme

As standard for the test samples a geological description following the Joint Chalk Research nomenclature is used. Standard core analysis data have been carried out where conceivable.

In connection with the fracture description of the plugs and blocks, a standard description scheme has been established (fig. 21). The scheme makes it possible to subdivide the fracture system into fracture sets. The fracture sets are listed in decreasing order according to importance. An explanation to the various topics are given below.

GSI value: The Geological Strength Index is a figure on the strength of a jointed chalk associated with the fracture density (for more explanation, see below). The GSI values are indicated by both a letter code and a number. Normally healed hairline fractures and stylolites are not considered as active fractures and therefore not included in the basic GSI determination. However, in test specimens where these features are frequent a secondary GSI value is indicated.

P_{32} (Areal intensity of fractures). The P_{32} is defined as the total fracture area per unit volume (for more explanation, see below). In the scheme two P_{32} values are indicated; one associated with the main fracture set and one for the total fracture set.

Numbers: An alternative fracture density indication is the number of fractures. In this description the fracture density is indicated as number of fractures per fracture set. The total fracture density for the test samples is the sum of the fracture sets.
The number of fractures may be underestimated during description, especially in plugs after test where surface coating covers the minute fractures. The number of fractures is also affected by the fact that fractures cross-cutting the sample only counts as one (paired fractures

on un-wrapped surface) whereas non-paired fractures (with uncertain termination within the plug) also counts as one.

Type: The fractures are divided into five groups depending on dip: Vertical (85-90°), sub-vertical (~70- 85°), inclined (~20-~70°), sub-horizontal (< 20°) and horizontal (~0°). A system of fractures consisting of two or more sets, which appear to have formed simultaneously, is a conjugate system. During test, different types of fractures form simultaneously but a conjugate fracture set is in this classification defined as identical fracture types but with different dip orientation intersecting each other.

2θ: Intersection angle between conjugate fractures. This angle may correspond to the friction angle in a Mohr envelope following the equation: $\varphi = 90 - 2\theta$

Divergence: Divergence defines the degree of branching or division of the fracture into several fractures. Well defined fractures in the center of the plug often grades into several minor fractures near plug ends. Also where two fractures merge the transition zone may appear as a set of sub parallel fractures. The degree of branching is divided into 3 groups: low (< 3 fractures), medium (3-5 fractures) and high (> 5 fractures).
The reason for introducing this term is that the stress transfer will change going from one fracture to several fractures.

Dip: Angle from horizontal of the failure/fracture plane. Reference for measurement is the plug ends.
The dip angle is dependant of plug length and hardness. A conversion to friction angles can be calculated using following equation: $\varphi = 2\beta - 90^{\circ}$.

Length: Fracture length within plug.
In general the main fractures intersect the plug with an angle less than 90° giving a fracture length longer than plug height. Less distinct fractures often terminate within the plug.

Aperture: Maximum measurable opening of the fractures.
The opening of the fractures is highly variable ranging from closed to > 5mm aperture but in this classification scheme only the maximum opening is indicated.

Surface: The description of the fracture surface includes a determination of the roughness of the fracture surface (nomenclature based on Løset (1995), see below) and an indication of any kind of coating,

J-number: Quantification of surface roughness according to Løset (1995) (for detail see below).

Relief: Amplitude of undulating fracture surface.

JRC: Quantification of surface roughness according to Barton and Bandis (1995) (for detail see below)

3 Chalk characterisation

All the analysed samples were described geologically, prior to test (original rock) and where possible after test (test plug). The description is made both on a macroscopic and a microscopic scale carried out on block material or plug trims.

The geological description comprises determination of chalk type, origin and diagenesis which is used for a subdivision of the chalks that might explain the variation in strength properties of the chalks. The description and classification of the chalk follows the JCR nomenclature (JCR, 1996) supplemented by determination of texture variations using microscope and SEM. The nomenclature used for the texture is in this report based on the Folk (1962) and Embry and Klovan (1971) classifications.

In addition analysis of porosity (permeability) and the content of insoluble residue were carried out on a large number of the examined samples. Capillary pressure analysis has not been carried out in phase 2 but refers to measurements carried out on four samples from phase 1 (two from Hillerslev, one from Stevns and one from Valhall Hod).

Only two distinctly different lithotypes are described in this study. The most prevailing lithofacies is the Burrowed Massive chalk Mudstone encompassing the samples from the Hillerslev quarry, the Tyra field samples and a number of the Valhall field samples. The remaining samples from the Valhall field are classified as Massive chalk Mudstone with high density hairline fractures.

With respect to the Burrowed Massive chalk Mudstone there are indications of predominantly autochthonous pelagic origin. The main variation as seen from the various localities is related to compaction and cementation where the Tyra samples are the only compacted and cemented samples examined in this project. No severe compaction of the chalk has taken place in the Hillerslev quarry and only relatively sparse cementation is seen. Cement in the samples from the Valhall field is also scarce.

After test, the plugs were described with respect to fracturing. A few attempts were made to clean the samples for further geological analysis, but the samples did fall apart in a way that porosity and permeability measurements and other analyses were impossible.

4 Fracture characterisation

One important aspect in the project was to determine a possible relationship between fracture type and rock mechanical properties. Special focus was set on fracture density and fracture type. The fracture description was attempted to follow the methodologies as described in Fritzen and Corrigan (1990) and by the Q-methodology described by the Norwegian Geotechnical Institute (Løset, 1995). However, both methods are based on fracture systems on core scale or larger and require often more information than can be recovered from the scale of the test specimen. Only in connection with outcrops these methods proved applicable.

Intuitively the rock mechanical properties related to shear fractures are closely associated with the roughness of the fracture surface. It was therefore decided to focus the fracture characterisation on the roughness of the fractures. For this purpose the Joint Roughness Coefficient (JRC) methodology introduced by Barton and Bandis. The JRC classification is in this project compared with the roughness determination (J_r) defined by Løset (1995).

Other aspects are included in the specimen description and in the following the basic assumptions for the description of fractures in the test specimen are described.

4.1 Fracture roughness

Fracture roughness can be determined in two ways:

1) along the length of fracture lining
2) on the fracture surface

Only in highly irregular (exposure or specimen) surfaces fracture surfaces are measurable and in general the roughness of the fractures is related to the fracture lining.

However, it is important to determine the roughness along the dip direction of the fracture to obtain the most reliable values. As discussed below, acute angles from dip may give rise to overestimation of roughness values.

A more reliable evaluation of the roughness can be carried out on the fracture surface, but this is often restricted to samples after test.

4.1.1 J-number

The J-number refers to the roughness of the fractures and represents a single parameter set in the Q methodology as described by Løset (1995). The classification divides the fracture roughness into three main groups (plane, undulating and angular, fig. 22). These three groups are again divided into slickensided, smooth and rough. For determination of the Q-value an associated value for the various groups of roughness is given. However, some overlap in the numbers is obvious and this type of classification cannot be used as unambiguous classification methods as stand alone method.

In addition the method is more qualitative rather than quantitative and may be somewhat subjective.

4.1.2 Joint Roughness Coefficient

In this project it was decided to restrict the description of the fractures to Joint Roughness Coefficient (JRC) as defined by Barton and Bandis (1990), which is a quantitative tool for description of the fracture which can be transposed to friction.

In short the method measures the asperity along the dip direction of the fracture. A linear relationship between asperity and length of measured profile is indicated as JCR values from 0 to 20. For chalk there is a tendency that JRC for chalk is > 20, which have been verified from several measurements in chalk quarries (e.g. Lägerdorf quarry, Köstler (pers. comm., 1999)) and core examinations.

Normally the lower limit of the measured profiles in published JCR diagrams is 10 cm, but in connection with test specimens in this project the measured profiles are as short as 1 cm. Experience from this study indicates that caution should be paid on determination of the JRC along such short profiles. Figure 23 shows the variation in JRC values within different test samples and it is obvious that uncertainties are associated with the short profiles. More constant values appear when approaching a profile length of 10 cm.

The reason for this phenomena may be associated with the microfracturing in zones where the development/initiation of fracture zones on each side of the plug progrades and merges to one high amplitudal fracture during increasing stresses (fig. 30). This merging of two different microfractures may explain the non-linear fracture behaviour in some samples.

In many cases the microfractures are slightly concave resulting in higher relief along strike than in dip direction. The difference is in the order of 2 to 3 times.

4.2 Geological Strength Index

The strength of a jointed rock mass depends on the properties of the intact rock pieces and also upon the freedom of these pieces to slide and rotate under different stress conditions. This degree of freedom is controlled by the geometrical shape of the intact rock pieces as well as the condition of the surfaces separating the pieces. The Geological Strength Index (GSI) introduced by Hoek & Brown (1997) provides a system for estimating the reduction in rock mass strength for different geological conditions. This system is presented in figures 24 and 25. Figure 24 represents the lettercode for the rock mass categories whereas figure 25 are used to estimate the GSI value.

The GSI values for the entire Hillerslev profile (indicated in figures 24 and 25) are ranging from 55 – 70 (blocky-very blocky and good-very good surface quality).

The GSI values for the plug samples are more diversified and ranges from 45 –75 (blocky-disturbed blocky with very good surface quality (figures 24 and 25).

In this project an attempt has been made to classify both the exposed chalk sequence in Hillerslev and the plugs and block specimens according to the GSI. However, using the GSI classification at different scales is not straight forward because a certain GSI value on a plug sample will represent a relatively higher fracture area per volume than the same GSI value for a large block or outcrop exposure (fig. 26). In fact the plug samples taken from a larger block or volume with a certain GSI value may have a limited number of fractures expressed and therefore in a quite different GSI value, or may even have no fractures at all (fig. 26). This discrepancy makes it impossible to compare rock mechanical test results with GSI values for samples and descriptions at different scales (fig. 27).

Because the GSI system was established on large scale features it is anticipated that a relation between GSI values and rock mechanical properties is more reliable when testing large samples, mainly because large volumes are more representative and have a more homogeneous geometry of the fractures – BUT the relation seems only valid for that particular scale or volume.

As shown in figure 26 the GSI is totally depending on at which scale it is described and is useless as a measure to compare samples with different volumes. Instead it is recommended to calculate a scale-independent measure of the fracture density e.g. P_{32}.

4.3 Fracture intensity

Whereas many fracture density measures are scale dependent, the fracture area per unit volume represents a scale independent value. The **Areal Intensity (P_{32})** as described in Golder Associates' User Documentation for FracMan (1998) represents such a value.

The areal fracture intensity P_{32} defines the total area of fractures per unit volume (e.g. m^2/m^3).

$$P_{32} = A_f/V_t$$

where A_f = total area of features and V_t = Total volume.

The dimension is 1/length unit. The value is scale independent and is invariant with respect to the distribution of fracture size.

Generally it is difficult to estimate the fracture area in a plug sample. However, by introducing the measure P_{21} (Golder Associates, 1998) representing the fracture intensity on trace planes it is possible to estimate the P_{32} from determination of the length of fractures as seen on the surface of the plug and as outlined on the un-rolled tracing-paper used for the plug description.

$$P_{21} = L_f/A_t$$

Where
L_f = total length of fracture traces on a two dimensional feature, and
A_t = total area of surface

The relationship between P_{21} and P_{32} depends upon the relationship between the fracture orientation distribution and the orientation of the surface on which P_{21} is calculated.

$$P_{32} = C_{32} * P_{21}$$

Where C_{32} is a proportionality constant related to the orientation distribution of the fractures.

For most fracture geometric patterns, values for C_{32} vary between 1 and 2. C_{32}=1 if associated with horizontal fractures (perpendicular to plug orientation); C_{32} = 2 for vertical (plug parallel) fractures. For a uniform distribution of varying orientations, a value of 1.3 can be used. In plugs with of a superior horizontal or vertical fracture orientation the C_{32} value are adjusted towards 1 or 2, respectively.

The C_{32} value increases with increasing height/diameter (H/D) ratio. For plugs with a H/D ratio ranging from 1 to 2 and with a uniform distribution of fracture orientations, the C_{32} value is in the order of 1.3. In case of a H/D ratio of 5 or 10 the value of C_{32} is changing towards 2.

In this study the examined plug samples has a H/D ratio of 1 or 2. Therefore C_{32}= 1.3 has been used for estimation of P_{32} from the fracture determination on the surface traced pattern derived from the plug description.

5 Hardness

During fracturing of the chalk, a limited zone (< 1 mm) within the rock is affected and reorganisation of the particles in the matrix takes place (fig. 28). This change in matrix properties may have some impact on the hardness of the rock – either going to be softer than the unaffected matrix or in case of striation/slickensides going to be probably a harder zone.

5.1 Penetrometer

For determination of the change in hardness a series of measurements have been carried out with a pocket penetrometer on both matrix and various types of fracture surfaces.

The penetrometer is a tool for measuring the depth of penetration into the rock related to the applied pressure. It consists of a 15 mm conical tip grading into a 3mm Ø cylindrical part.

A calibration of the tool gives the following conversion values:

Tool scale	Calibrated value (applied pressure)
1.5 kg/cm^2	2.0 kg
2.5 kg/cm^2	3.8 kg
4.5 kg/cm^2	7.4 kg

No direct conversion to chalk hardness is available at present.

In this project the measurements were carried out on the same plug sample and the variation in penetration depth should be considered as relative variations in hardness.

5.2 Methodology

The textural changes of the matrix along the fracture surface do only involve a very limited thin zone. To be able to measure any impact of the change in matrix texture caused by fracturing it is essential to start measuring at pressures that do not exceed the corresponding hardness of the zone. In case of a high initial pressure the measurement would be ignored and would not measure an existing but low hardness characteristic for the surfaces.

The measurements with the penetrometer were therefore carried out at different pressures (1.5 kg/cm^2, 2.5 kg/cm^2, 3.5 kg/cm^2 and 4.5 kg/cm^2) starting with the lower pressure.

All measurements at the various pressures were carried out three time to test the reproducibility. In the various sets of measurement the uncertainty is higher than 5%. The high uncertainty is partly due to the difficulty in performing with a uniform pressure and measure with constant period of time.

To evaluate the impact of time on penetration a test were carried out. A uniform area was measured at a constant pressure of 3.5 kg/cm^2 for periods of time ranging from instant to 45 seconds. The result of this test was a 30 % deeper penetration for the 45 seconds measurement as compared with the instant measurement.

Also the quality of the surface is important for reasonable measurements. A smooth surface is the most appropriate whereas irregular flake-rich surfaces break up in a disordered way and will not give reasonable measurements.

From a fresh broken surface the hardness was measured at 15 randomly chosen points at a pressure of 4.5 kg/cm^2. The average penetration depth for the measurements was 5.6 mm with a range from 3.4 to 7.2 mm showing a high diversity in hardness within a block sample. Therefore the presented result should be considered a guidelines rather than accurate figures.

5.3 Results

The total data set from Hillerslev block 8 is presented in fig. 29a. All data are enclosed in a envelope defined by the lines

1) $H_h = 0.7 * P$
2) $H_s = 1.8 * P$

where H is hardness represented by penetration in mm, subscript s and h are soft and hard, respectively, and P is pressure (tool scale; kg/cm^2).

In general each set of measurements increases linearly within the defined envelope, but a few distinct variations are seen (fig. 29b). Curves A-D indicate a distinct softning with increasing pressure. This configuration may be due to the fact that the measurements represents fracture surfaces of a certain hardness which is exceeded when the pressure is higher than 3.5 kg/cm^2.

6 Fracturing

Examination of the artificial fractures in the plugs after the various tests indicates that the formation of fractures follows a general pathway from minor isolated shear planes (micro-joints) within a limited zone prograding and merging, giving rise to rather undulating surface with a relatively high amplitude of asperities.

The surface is often concave resulting in a higher relief along strike as compared to dip direction.

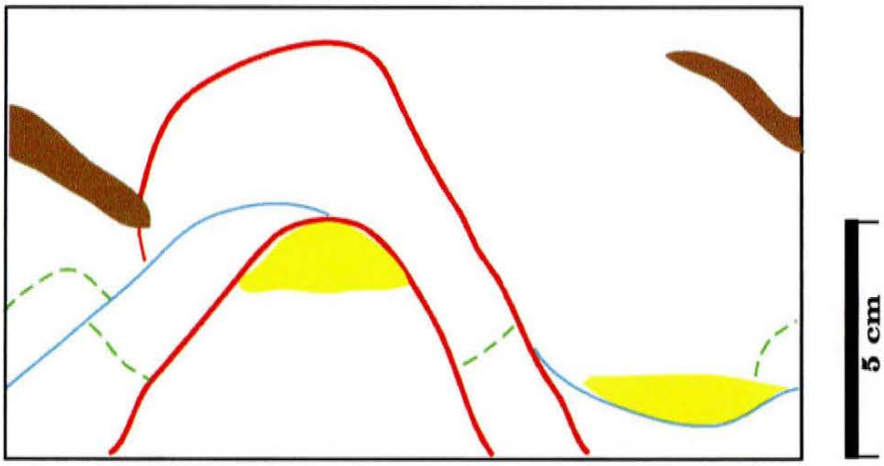
The roughness in dip direction is dependent on induration of the chalk and length of movement. Minor movements result in the most rough (stepped) surface whereas the impact of distinct movements is a more smooth and planar behaviour. Striation is common in samples with distinct shear but due to the relatively clean matrix no coated slickensides are developed.

The induced fractures in the samples are generally representing a fracture zone varying in thickness and characterised by a somewhat unclear surface following a large number of micro-joints (fig. 30). The thickness of the fracture zone is dependent on block size and displacement. In the element samples the compression and displacement is of limited size and the fracture zone is generally less than 2 mm whereas the block tests gave rise to compaction up to 3 cm and caused severe displacement. The induced fracturing is associated with a progradation of the micro-joint merging in a highly irregular way giving rise to a rough appearance along the fracture linement

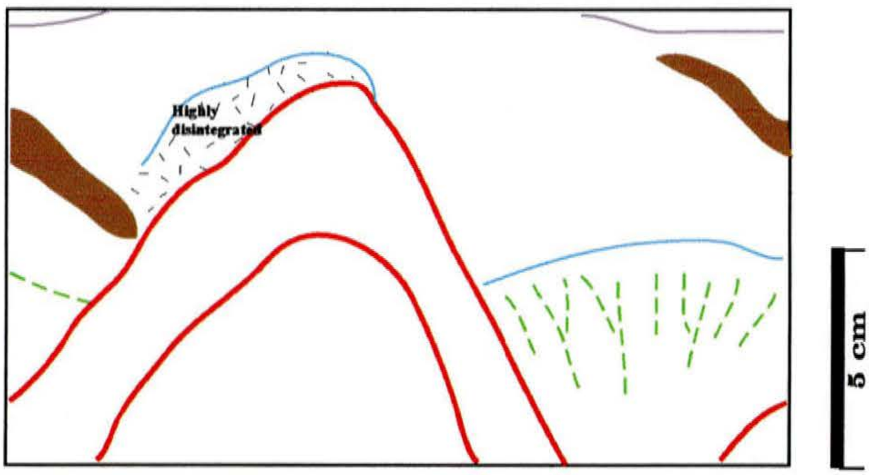
The fracture angle seems to depend on the degree of induration. In the most cemented chalk from Tyra a well defined subvertical fracture system appears with an angle of 60-70°. In the less cemented samples as Valhall Tor and outcrop samples subhorizontal fractures are dominant. In Valhall Hod the examined sample is multifractured with both subhorizontal and subvertical fracture sets.

Hillerslev, HF 9

Before test



After test



Legend:

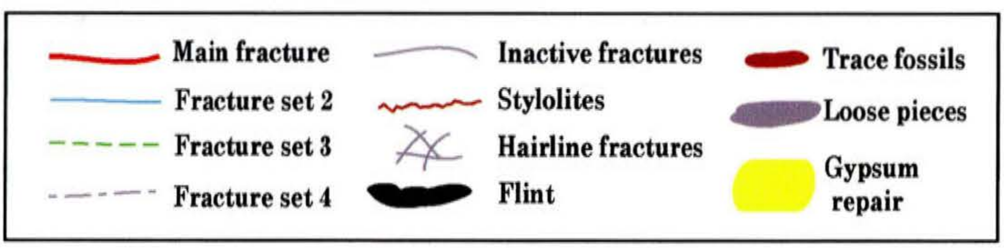


Figure 20.
The fracture description is based on surface identifications drawn on paper wrapped around the plug sample. The final presentation is the unwrapped description as shown above. Supplementary information from the core plug is shown when possible.

HU 1
Fractures (after test):

GSI	B/VG	75		
P_{32} main frac	0,22		P_{32} total	0,41
	Main fracture	Fracture 2	Fracture 3	Fracture 4
Numbers	2	3	1	
Type	Inclined	Vertical	Subhorizontal	
2θ	48			
Divergence	Medium	None	None	
Comments	Intersecting			
Dip (° from horizontal)	60-65	90	30	
Length (mm)	117	10-50		
Aperture (mm)	< 0.2	Closed		
Surface	Uncoated			
	Undulating, smooth			
J-no	2			
Relief (mm)	5	2		
JRC	13 - 15			

Figure 21.
Standard description scheme used in this report. (For explanation of the various topics see text).

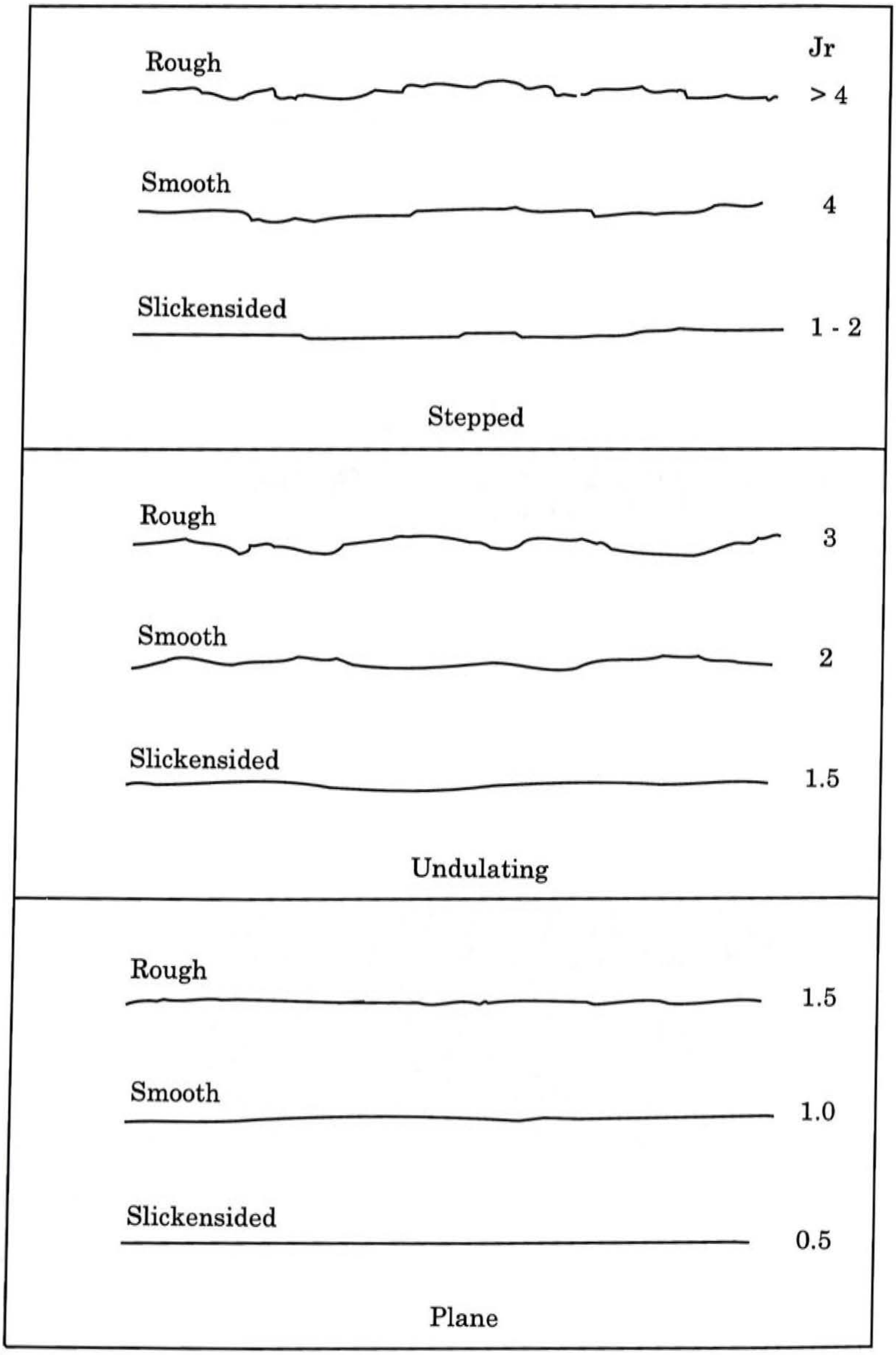


Figure 22.
Fracture surface classification and associated Jr-nomenclature (Løset, 1995)

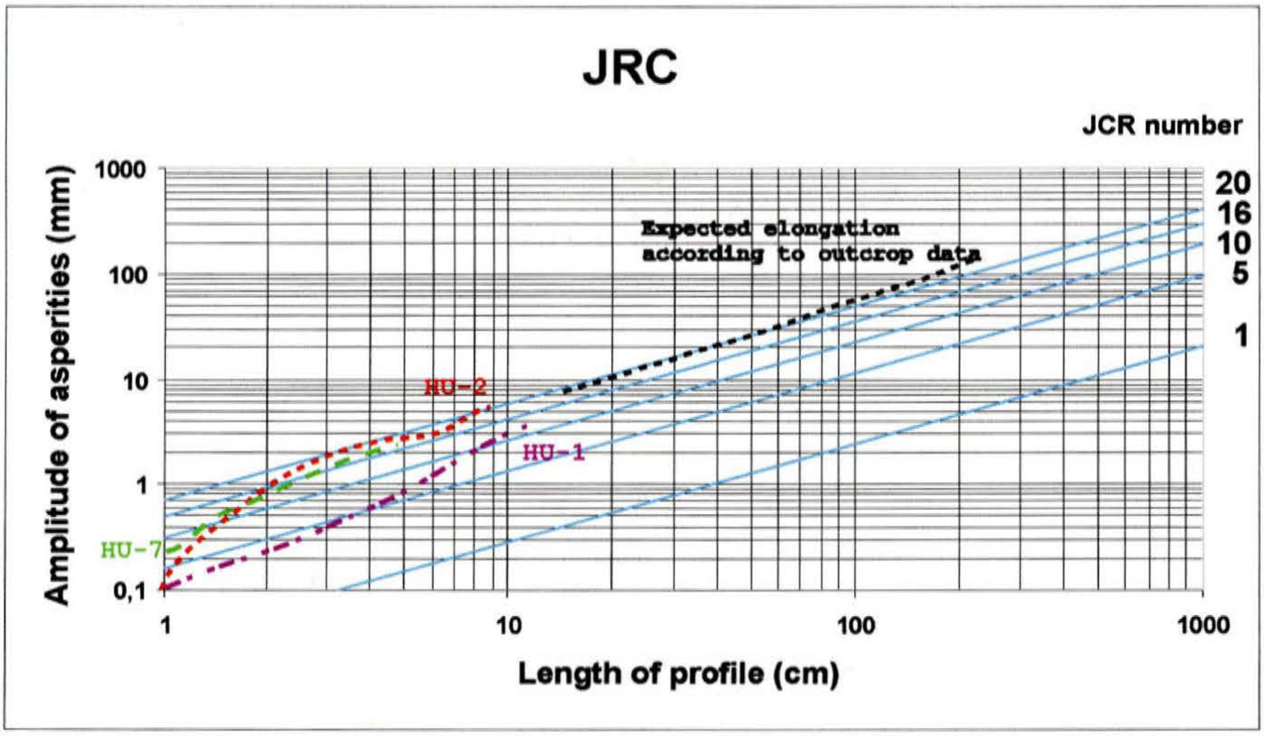


Figure 23.

Joint Roughness Coefficient (JRC) diagram. Amplitude of asperities are plotted versus length of profile and converted to JRC values.

The plot illustrates the inconsistency in determination of JRC over short intervals. The JRC for the larger intervals are based on outcrop data (Köstler, pers. comm., 1999).

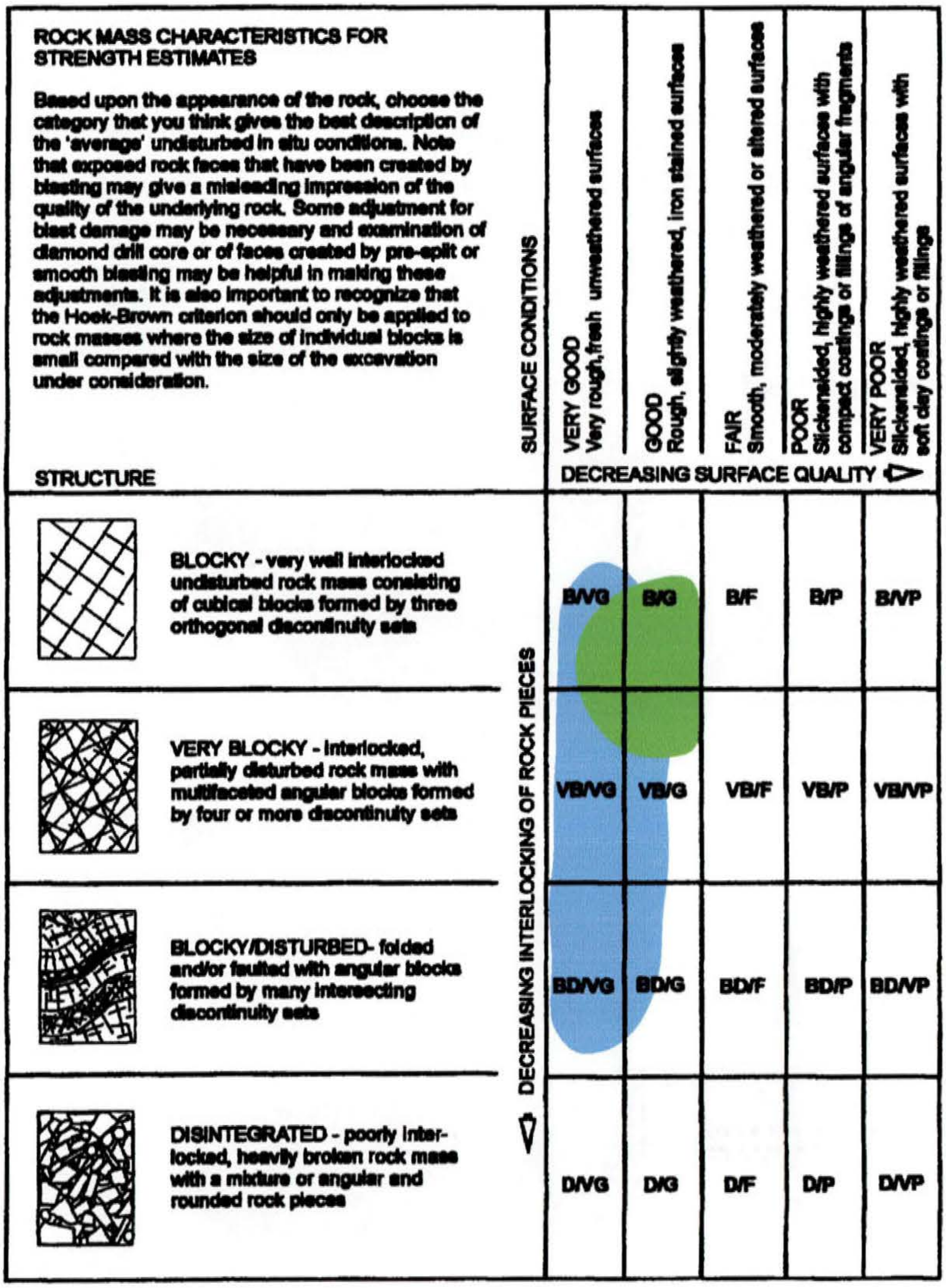


Figure 24.
Characterisation of rock masses on the basis of interlocking and joint alternation. (After Hoek & Brown, 1997).
GSI values for the Hillerslev profile are found within the green area. GSI values for the various test samples (after test) are found within the blue area.

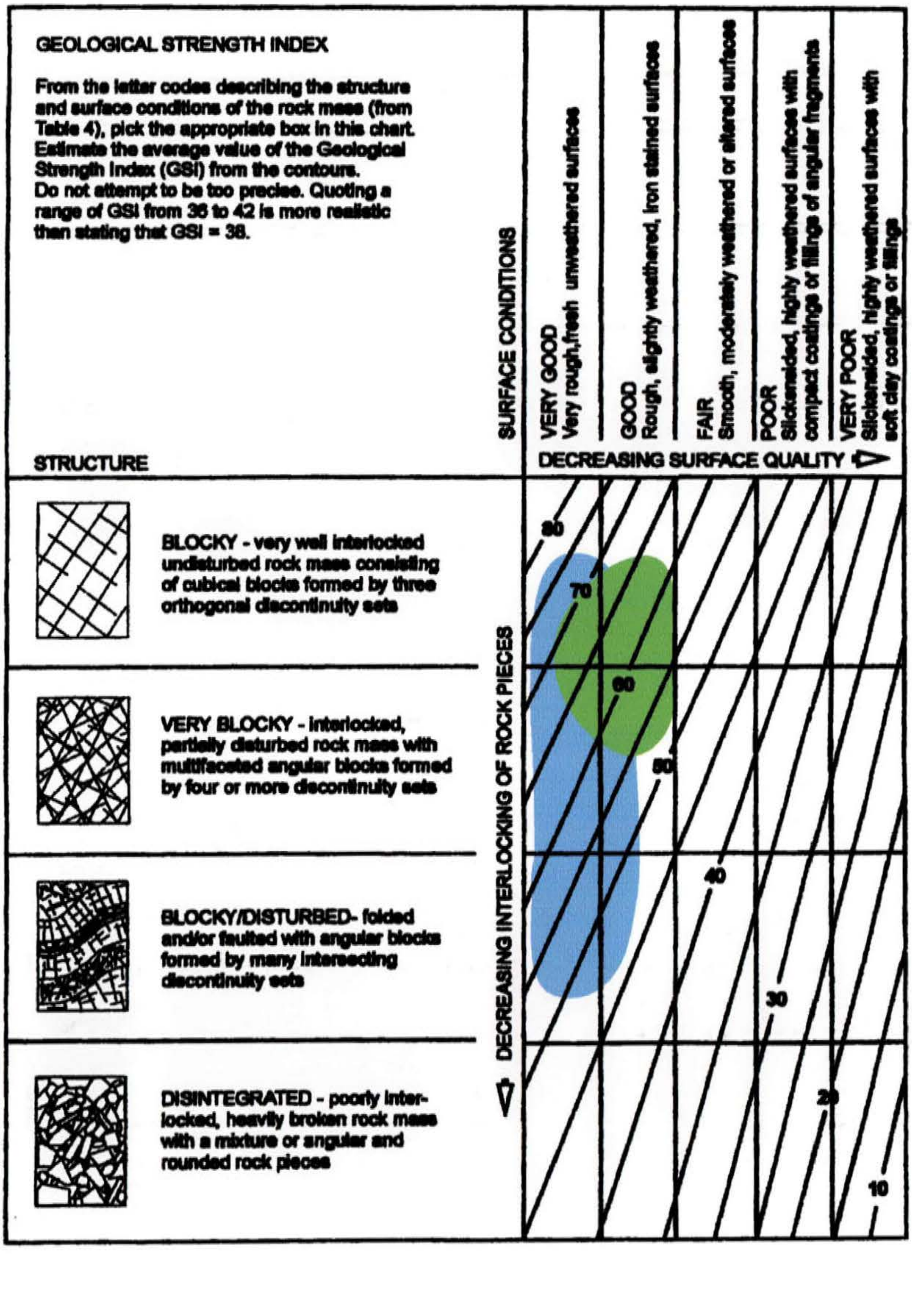


Figure 25.
Estimate of Geological Strength Index GSI based on geological description.
(After Hoek & Brown, 1997).
GSI values for the Hillerslev profile are found within the green area. GSI values for the various test samples (after test) are found within the blue area.

UPSCALING PROBLEMS

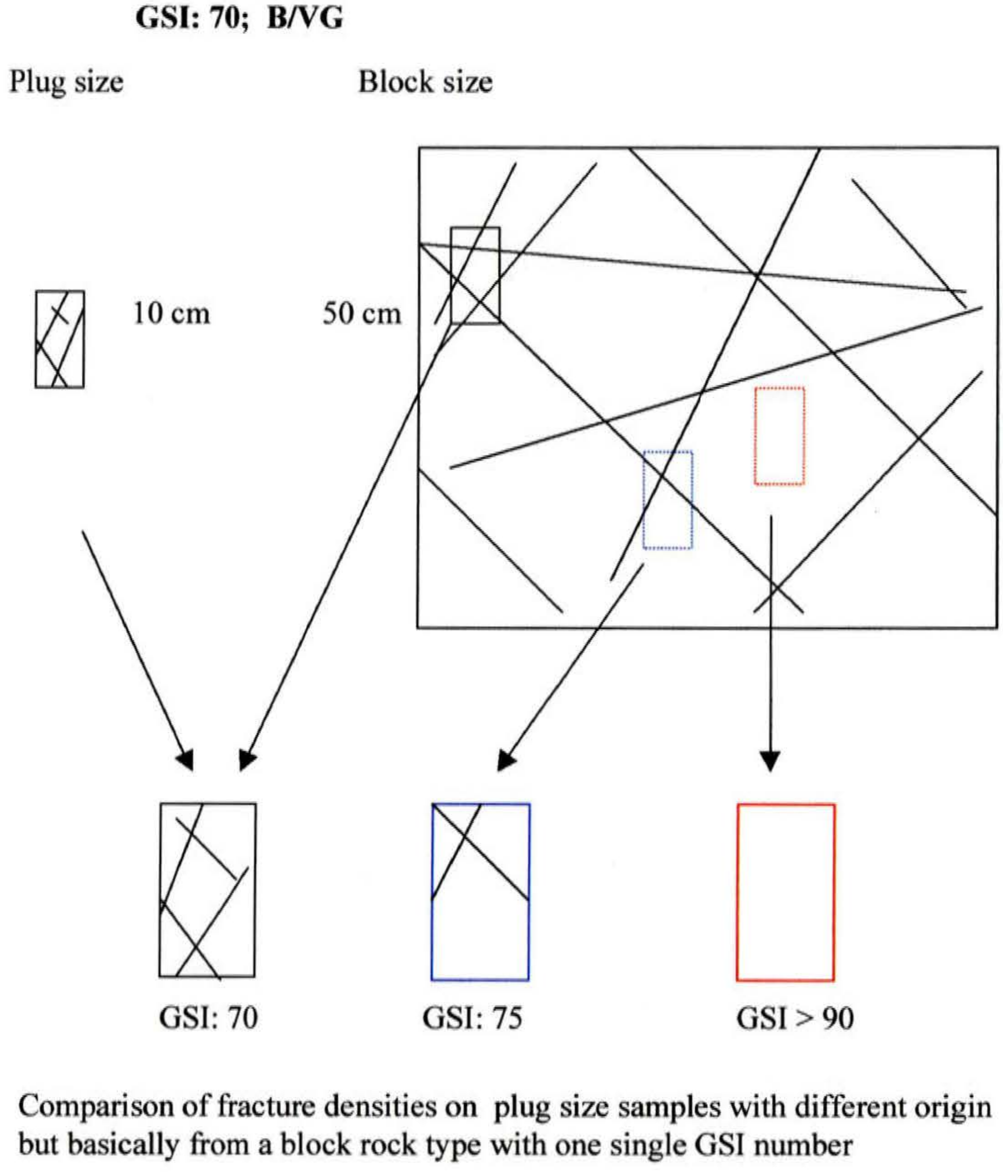


Figure 26. Different fracture densities (per volume) as a result of GSI determinations at different scale.

UPSCALING PROBLEMS

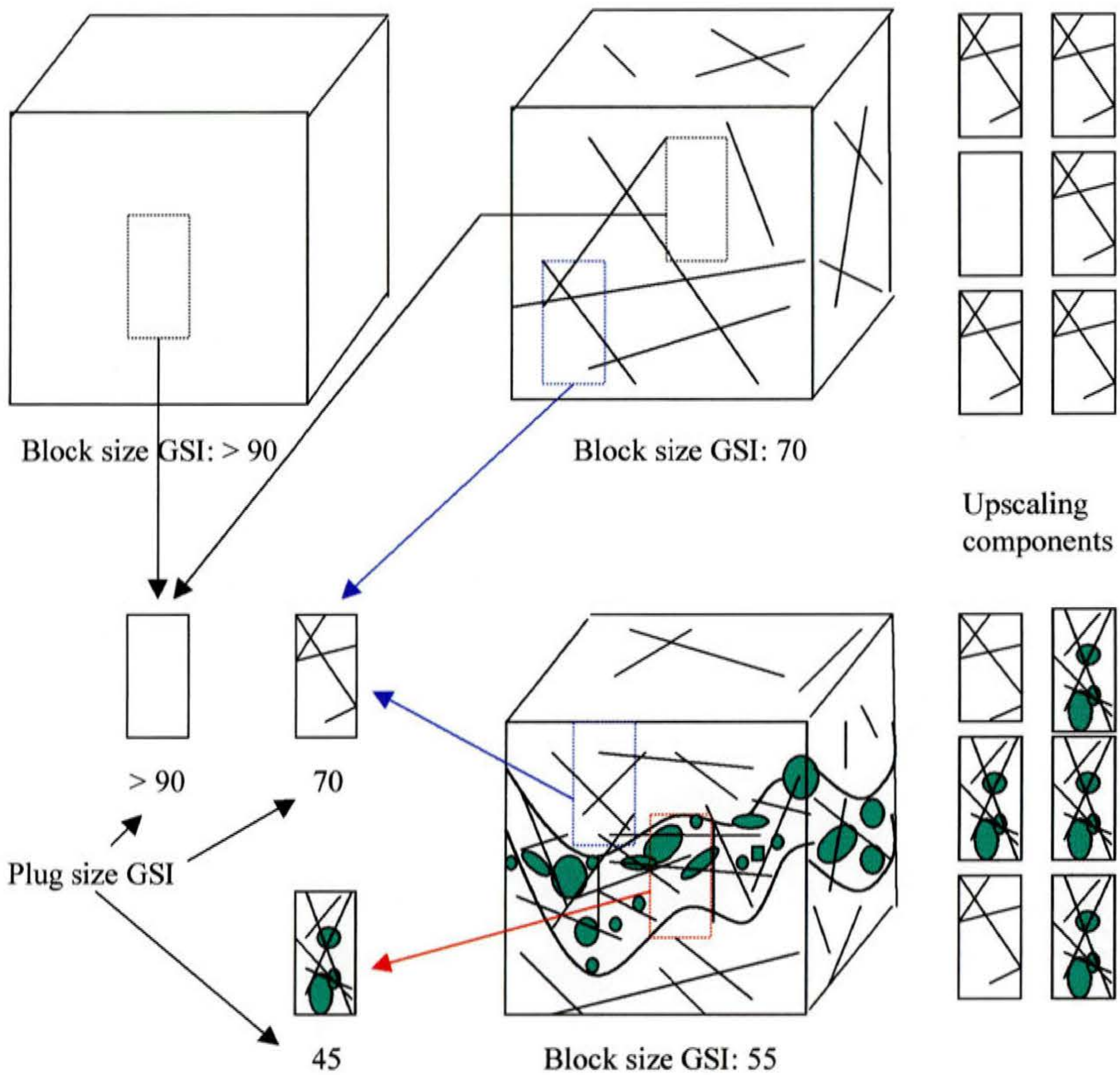


Figure 27. Plug samples with different GSI values may be a component in a large volume block. The composite appearence of the large volume blocks illustrates the difficulty in tranferring rock strength from plug samples to larger scale.

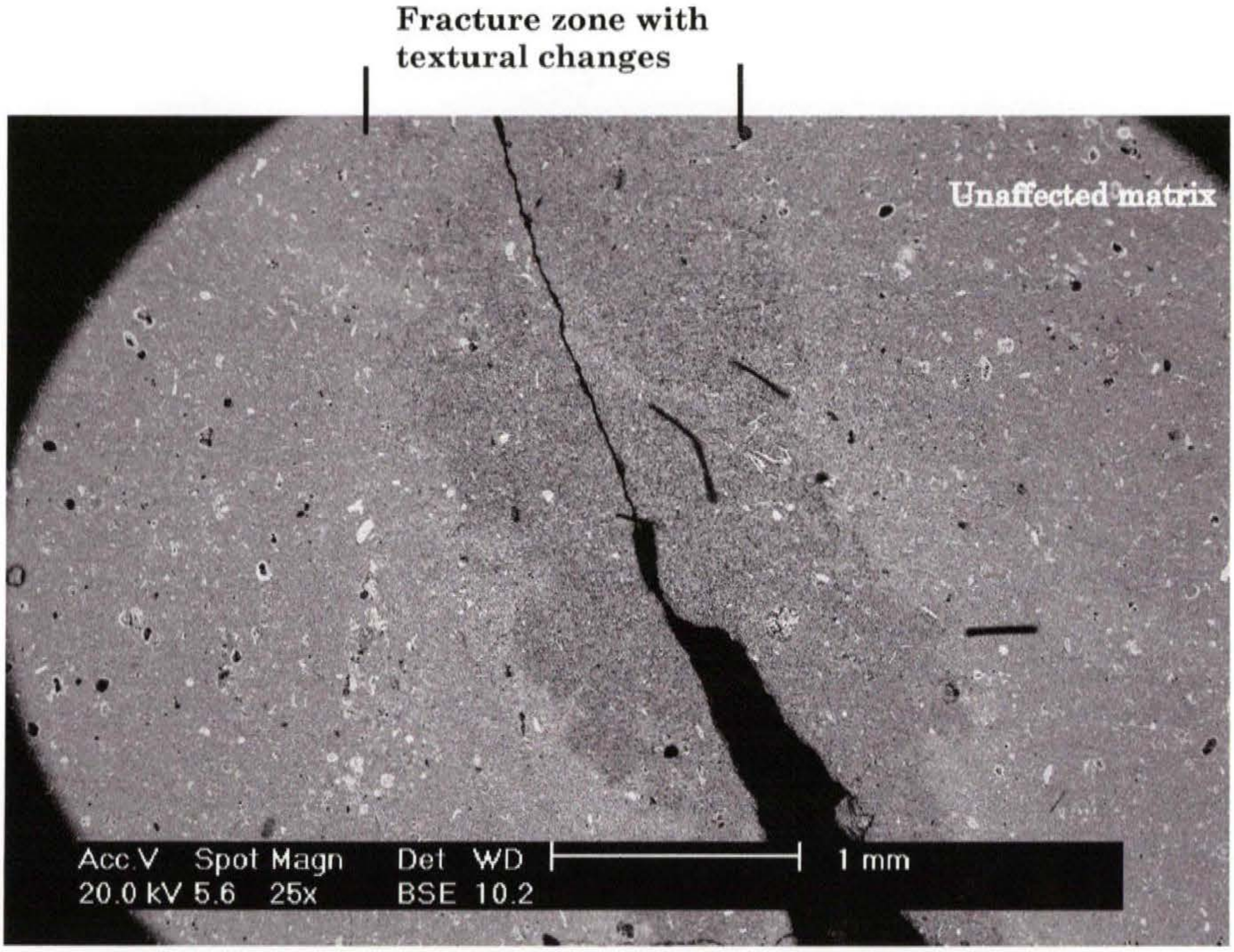
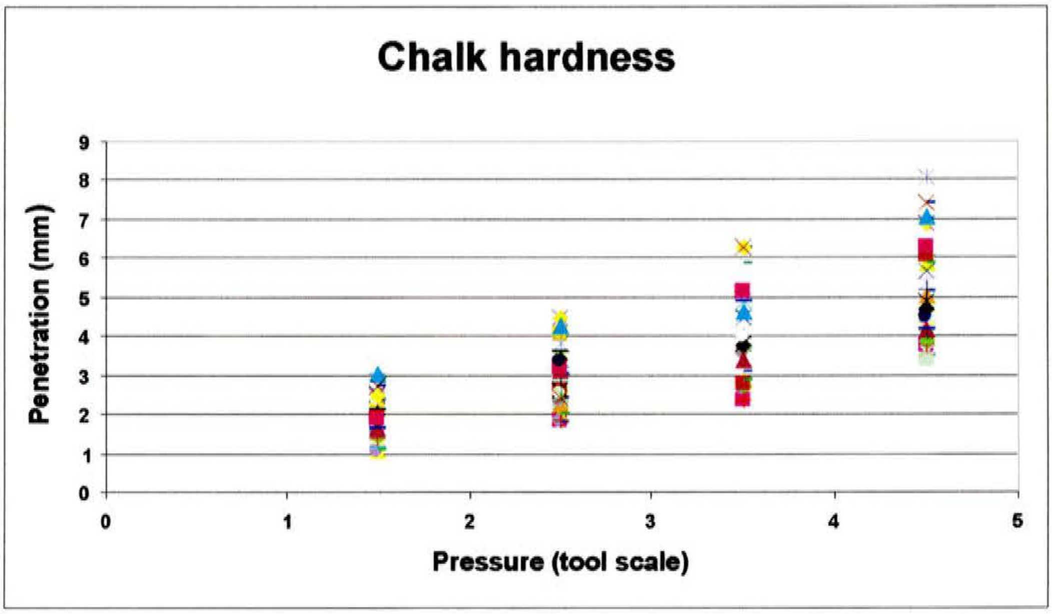


Figure 28.
Back-scatter photo of a polished sample with a fine fracture. Within a narrow zone around the fracture there is a textural change of the matrix.



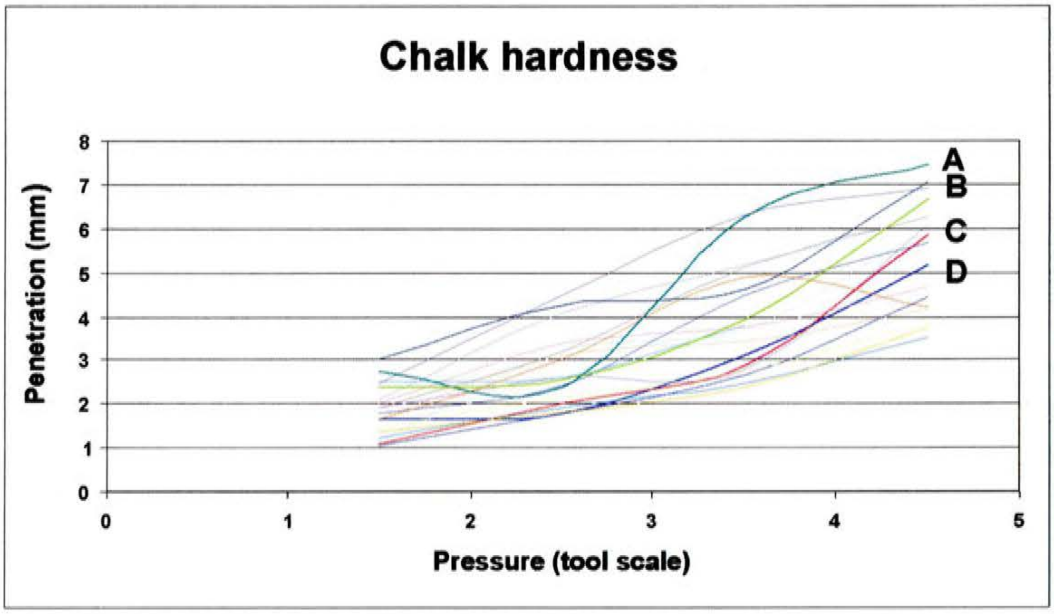


Figure 29.
Hardness measurements indicated by penetration versus pressure plots. Upper plot shows a general increase in penetration with higher tool pressure within an envelope defining a "hard" and "soft" trend. The lower plot indicates the variation with pressure at different locations.

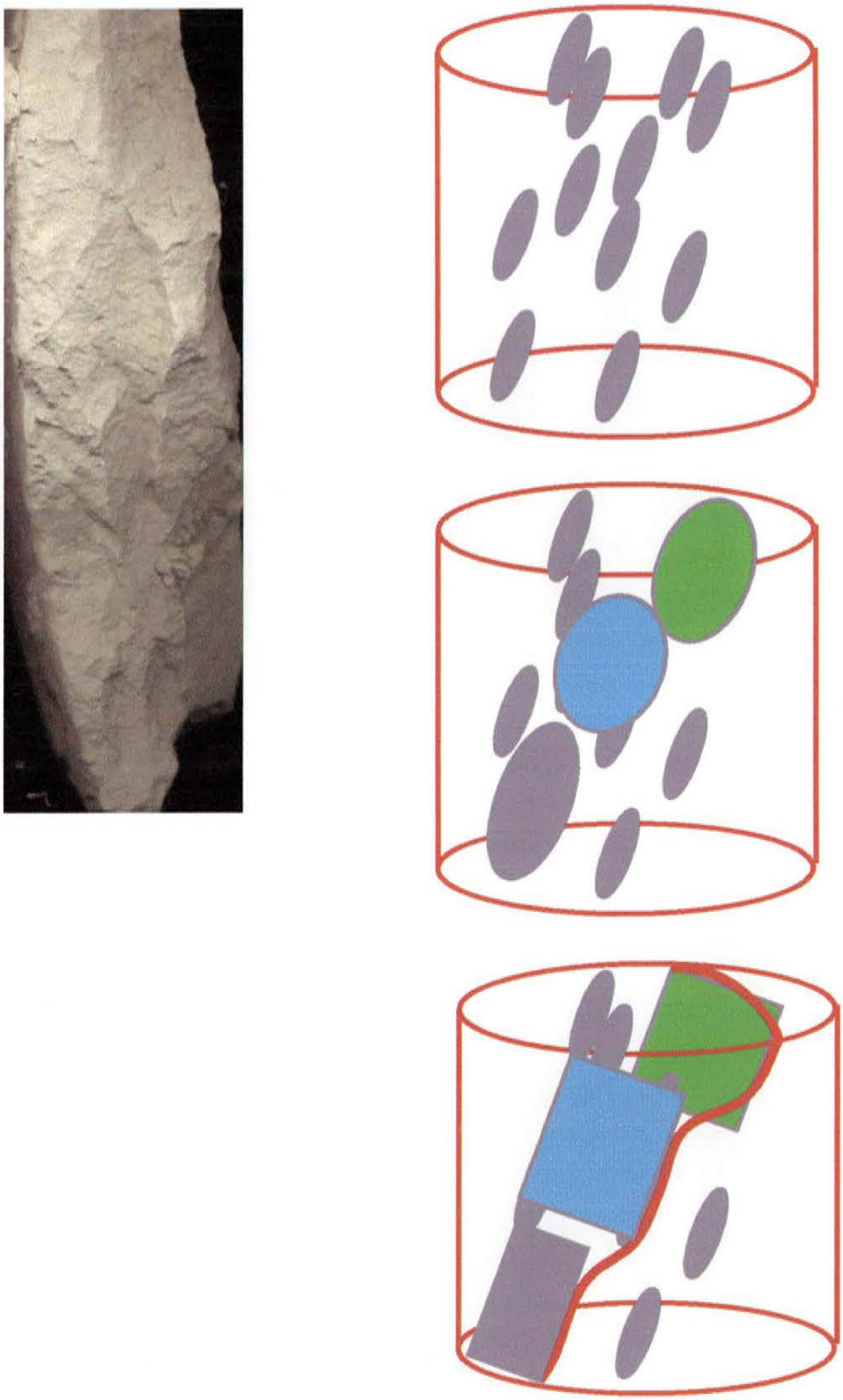


Figure 30.
Cartoon illustrating the growth of microjoints to a composite fracture within a plug sample.

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Tables

GEO projektno 16015027

	Well	Plug no	GI lab no	Height mm	Diameter mm	Height/Dia	Test type	Porosity After test	Density g/cm3	% IR	% clay of IR	% quartz of IR	Quality of sample before test	Quality of sample after test	BEFORE TEST GSI before test	BEFORE TEST Total number of fractures	BEFORE TEST P32 main fracture	BEFORE TEST P32 total rock	AFTER TEST GSI after test	AFTER TEST Total number of fractures	AFTER TEST P32 main fracture	AFTER TEST P32 total rock
Hillerslev		1A	HU1	107	54	1,98	MT3	46	2,637	7	94	6	good	fair	100	0	-	-	75	6	0,22	0,41
Hillerslev		2A	HU2	105	53	1,98	MT3	45,76	2,631	6	94	6	good	fair	100	0	-	-	70	7	0,18	0,29
Hillerslev		3A	HU3	115	54	2,12	MT3	46,93	2,627	8	95	5	good	fair	100	0	-	-	55	16	0,2	0,65
Hillerslev		4A	HU4																			
Hillerslev		5A	HU5	105	55	1,91	H	38,84	2,657	10	93	7	good	poor	100	0	-	-	-	0	-	-
Hillerslev		6A	HU6																			
Hillerslev		7A	HU7	115	53	2,17	MT3	45,72	2,68	6	92	8	good	broken	100	0	-	-	55	>14	0,19	0,69
Hillerslev		8A	HU8	95	53	1,79	U	39,03	2,644	8	92	8	good	poor	100	0	-	-	?	0	-	-
Hillerslev		9A	HU9																			
Hillerslev		10	HU10																			
Hillerslev		11	HU11																			
Hillerslev		12	HU12	70	70	1,00	MT3	-	-	-	-	-	good	fair	100	0	-	-	70	7	0,24	0,38
Hillerslev		13	HU13	70	70	1,00	MT3	47,07	2,677	6	92	8	good	poor	100	0	-	-	65	7	0,2	0,47
Hillerslev		14	HU14																			
Hillerslev		15	HU15	70	70	1,00	MT3	48,25	2,684	7	92	8	good	fair	100	0	-	-	65	3	0,22	0,5
Hillerslev		16	HU16																			
Hillerslev		17	HU17	68	69	0,99	MT3	46,94	2,656	7	92	8	good	fair	100	0	-	-	70	5	0,29	0,62
Hillerslev		18	HU18	69	69	1,00	MT3	47,39	2,642	9	93	7	good	fair	100	0	-	-	75	1	0,14	0,27
Hillerslev		kerne1	HF1					45,3	2,634													
Hillerslev		kerne2	HF2	95	53	1,79	MT3	-	-	-	-	-	fair	poor	75	4	0,16	0,31	60	8	0,16	0,51
Hillerslev		blok x	HF3	106	53	2,00	MT3	45,8	2,665	4	86	14	fair	broken	75	4	0,21	0,33	65	9	0,21	0,39
Hillerslev		10-1	HF4																			
Hillerslev		10-2	HF5																			
Hillerslev		10-2	HF6																			
Hillerslev		22B ned	HF7	100	53	1,89	MT3	46,43	2,643	6	92	8	fair	poor	80	4	0,18	0,25	65	1	0,18	0,42
Hillerslev		22B op	HF8	90	58	1,55	U	38,07	2,666	5	89	11	poor	poor	80	6	0,13	0,25	?	2	-	-
Hillerslev		26 øst	HF9	100	55	1,82	MT3	45,31	2,648	3	89	11	fair	poor	75	4	0,22	0,37	60	>14	0,24	0,5
Hillerslev		27 vest	HF10	89	53	1,68	MT3	46,67	2,651	5	93	7	fair	broken	80	4	0,09	0,29	55	8	0,33	0,76
Hillerslev		28 vest	HF11																			
Hillerslev		30 øst 1	HF12					46,58	2,651	9		6										
Hillerslev		30 øst 2	HF13																			
Hillerslev		30 øst 3	HF14																			
Hillerslev		y	HF15	65	45	1,44	H	37,2	2,665	4	87	13	fair	poor	80	1	0,2	0,35	?	Desc not pos	-	-
Hillerslev			Block 1																			
Hillerslev			Block 2																			
Hillerslev			Block 3																			
Hillerslev			Block 4	501	490		MT3								65	10	0,02	0,12	60	>14	0,04	0,14
Hillerslev			Block 5																			
Hillerslev			Block 6	502	493		MT3	ULFILLED TEST							70	10	0,05	0,15	65	>20	0,05	0,11
Hillerslev			Block 7	508	493		MT3								70	10	0,04	0,1	60	>20	0,04	0,15
Hillerslev			Block 8	502	493		MT3			6	96	4			75	8	0,03	0,09	55	>15	0,08	0,18
Hillerslev			Block 9																			
Hillerslev			Block 10																			
Hillerslev			Block 11																			
Hillerslev			Block 12	501	491		MT3								65	>20	0,03	0,17	55	>20	?	?
Hillerslev			Block 13	515	491		MT3								65	>20	0,08	0,15	60	>35	0,04	0,13
Hillerslev			Block 14																			
Hillerslev			Block 15	503	495		MT3								65	>35	0,06	0,12	50	>35	0,04	0,16
Hillerslev			Block 16																	>20		
Tyra	E-5x	22.1A	T1	89	53	1,68	MT3	28,55	2,691	2	97	3	good	good	100	0	-	-	75	2	0,28	0,28
Tyra	E-5x	22.1B	T2																			
Tyra	E-5x	22.1C	T3	89	55	1,62	MT3	28,52	2,675	8	96	4	good	good	100	0	-	-	70	>10	0,34	0,34
Tyra	E-5x	22.2A	T4																			
Tyra	E-5x	22.2B	T5	98	55	1,78	MT3	29,12	2,694	3	94	6	good	good	100	0	-	-	75	5	0,16	0,29
Tyra	E-5x	22.2C	T6	98	55	1,78	MT3	28,79	2,686	4	95	5	good	good	100	0	-	-	75	10	0,22	0,39
Tyra	E-5x	22.3A	T7	98	50	1,96	MT3	29,38	2,689	4	97	3	good	good	100	1	-	-	65	>10	0,44	0,5
Tyra	E-5x	22.3B	T8																			
Tyra	E-5x	22.3C	T9																			
Valhall	2/8 F-2	9D	V1	80	53	1,51	MT3	37,61	2,652	3	87	13	good	fair	100	0	-	-	70	>15	0,3	0,58
Valhall	2/8 F-2	10	V2	80	53	1,51	MT3	44,31	2,7	2	83	17	good	broken	90	1	-	-	70	>8	0,25	0,65
Valhall	2/8 F-2	10	V3	80	53	1,51	MT3	40,95	2,654	3	88	12	good	broken	90	1	-	-	70	10	0,23	0,73
Valhall	2/8 F-2	11	V4	75	53	1,42	MT3	42,32	2,664	2	81	19	good	broken	75	1	-	-	70	2	0,4	0,4
Valhall	2/8 F-2	11	V5	78	54	1,44	MT3	42,09	2,681	11	94	6	fair	broken	70	>3	-	-	65	8	0,35	0,55

	GI lab no	Major Vertical	Major Horizontal	2Ø	Main fracture: Fracture angle	Main fracture: Calculated Friction angle	Main fracture: J-number	Main fracture: JRC	Fracture set 2: Fracture angle	Fracture set 2: Friction angle	Fracture set 2: J-number	Fracture set 2: JRC	Fracture set 3: Fracture angle	Fracture set 3: J-number	Fracture set 3: JRC	Fracture set 4: Fracture angle	Fracture set 4: J-number	Fracture set 4: JRC	Stylolites numbers
Hillerslev	HU1	2		48	65	40	2	14	90				30						
Hillerslev	HU2	1			75	60	2-3	18	65		2		50	2					
Hillerslev	HU3	0	2		0		2	13	80	70			60		16	10-15			
Hillerslev	HU4																		
Hillerslev	HU5	0	0																
Hillerslev	HU6																		
Hillerslev	HU7	0	2		0		3	16	0				0-90						
Hillerslev	HU8	0	0																
Hillerslev	HU9																		
Hillerslev	HU10																		
Hillerslev	HU11																		
Hillerslev	HU12	2	0	70	60	30	2	20	0				80						
Hillerslev	HU13	2	0		85	80	2	16	60-90										
Hillerslev	HU14																		
Hillerslev	HU15	3	0	70	60	30	3	13	80-90		3								
Hillerslev	HU16																		
Hillerslev	HU17	2	0	48	75	60	2	13	85-90		2								
Hillerslev	HU18	1	0		80	70	3	13	60-70										
Hillerslev	HF1																		
Hillerslev	HF2	0	1		0		2	20	60	30	3			2-3					
Hillerslev	HF3	2	2		0		2	14	85		3		65	3	10-15				
Hillerslev	HF4																		
Hillerslev	HF5																		
Hillerslev	HF6																		
Hillerslev	HF7	1	0		75	60	2	12	70	50	3	16	65	3					
Hillerslev	HF8	2	0		60	30	-	15	85										
Hillerslev	HF9	2	0		60	30	3	15	40			10							
Hillerslev	HF10	2	1		0		3	-	60	30	2	15	80	3					
Hillerslev	HF11																		
Hillerslev	HF12																		
Hillerslev	HF13																		
Hillerslev	HF14																		
Hillerslev	HF15																		
Hillerslev	Block 1																		
Hillerslev	Block 2																		
Hillerslev	Block 3																		
Hillerslev	Block 4	2	1		40-70		2		75-85		2		50			0	3	25	
Hillerslev	Block 5																		
Hillerslev	Block 6	2	1		10		2		60	30	3		80	3		80-90			
Hillerslev	Block 7	2	2	30	70	50	1		0-10		2								
Hillerslev	Block 8	2	2	30	55	20			70-80				70-90			0-10	2	15	
Hillerslev	Block 9																		
Hillerslev	Block 10																		
Hillerslev	Block 11																		
Hillerslev	Block 12	4	2		10		2		50	10	3		80-90		16				
Hillerslev	Block 13	2	2	25	65	40			80-90				10	2	15				
Hillerslev	Block 14																		
Hillerslev	Block 15	3	2	35	70	50	1	16	10		2	20	80-90	2	18	70-90	1	16	
Hillerslev	Block 16	3	2	45	60-90				0										
Tyra	T1	2	0		50-70		0,5	20											9
Tyra	T2																		
Tyra	T3	5	0		50-65		1	20	80-90										8
Tyra	T4																		
Tyra	T5	1	0		75		2	18	0		2								3
Tyra	T6	1	0		65		1	20	90										4
Tyra	T7	5	0		70		1,5	18	80-90										13
Tyra	T8																		
Tyra	T9																		
Valhall	V1	3	0	40	65		2	16	45										6
Valhall	V2	1	1		40		2		10				50-80						1
Valhall	V3	1	0		60		1,5	18	20-60				80-90						1
Valhall	V4	2	0	70	40-65		2	18											
Valhall	V5	2	0		60		2	18											

MT3	Multiple triaxial test
U	Uniaxial
H	Hydrostatic

TABEL 1: Summary chart.

APPENDIX 1

Plug description

HILLERSLEV

Chalk description

The chalk at Hillerslev is a soft, greyish white bioturbated chalk mudstone characterised by a weakly laminated structure partly disturbed by burrowing organisms (*Thalassinoides*, *Planolites*, *Zoophycos* and *Chondrites*). The bioturbation is weakly discernible due to similarities in lithology and coloration of burrow fills and matrix. The chalk sequence at Hillerslev has a high frequency of horizontal, inclined and vertical fractures.

The chalk is a sparse biomicritic wackestone. The microfossil content is dominated by calcispheres. Foraminifera and echinoderm fragments are rare. The main component of the chalk is the large amount of well preserved coccoliths. Syntaxial calcite overgrowth on coccolith platelets is normally sparse and the size of these crystals is generally less than 1-2 μm.

The porosity includes both intercrystalline and intrafossiliferous pores. The calcisphere chambers are normally open. Fine euhedral and subhedral cement crystals are found scattered in the matrix. The size of the calcite cement crystals appears rather uniform with an average around 2 μm (micrite). Crystal sizes above 5 μm (microspar) are rare. Average porosity and permeability are in the order of 46 % and 8.5 mD, respectively. The average distribution of pore throat radius is ~0.6 μm.

The content of insoluble residue is approximately 4 %. The clay content is low and rarely seen in the SEM. Silica (opal) is relatively common within the chalk and appears as cristobalite aggregates.

Analyses carried out on samples from Hillerslev.

From the Hillerslev quarry different types of chalk samples have been acquired according to the different types of tests to be carried out.

In phase 2 both intact and fractured blocks were sampled. A geological description (including a lithological description following the JCR nomenclature, porosity measurements, determination of insoluble residue and SEM analysis) was carried out on the plug trims to describe the initial state of the samples. Subsequent to the geotechnical test a description of the plugs was made with respect to fracturing (angle, surface coating and roughness).

In addition to the plug samples more than 15 block samples were planned to be drilled. The location of the block samples was selected on the basis of a detailed fracture study carried out prior to the drilling campaign. The intention with the large number of block samples was to have a broad representation of fracture types and fracture densities. However, only 10 block samples were recovered successfully. 7 of these samples were subsequently tested in the geotechnical laboratory.

A pre-test geological description has been carried out on the actual test samples, but as the main emphasis in this project phase was to evaluate the impact of fractures on the geotechnical properties focus was on the fracture type and density. A later plug/sample description followed the geotechnical tests. This description was solely related to the fractures.

Test samples

Three sample types have been examined:

1) originally non-fractured plug samples (HU-samples)
2) originally fractured plug samples (HF-samples)
3) block samples (50 cm Ø) (block samples)

A complete list of analyses carried out on the various samples is shown in table H-1. In table H-1 phase 1 samples are indicated with HL.

GSI

A summary of GSI values on each sample type is attached after every group of test samples. Green numbers indicate the GSI values for the plug sample prior to test. The red numbers refer to the GSI values for the plugs after test.

Table H-1

Sample	Porosity	Permea-bility	Thin section	Capillary pressure	Insoluble residue	SEM	Geotechnical test type
HL 81A	X	AIR	X	X	X	X	Direct shear
HL 81B							Direct shear
HL 82							Unconfined uniaxial compression
HL 91							Direct shear
HL 106	X	AIR					Uniaxial strain compaction
HL 107			X	X	X		Multiple triaxial test
HU1	X		X		X	X	Multiple triaxial test
HU2	X		X		X	X	Multiple triaxial test
HU3	X		X		X	X	Multiple triaxial test
HU4							
HU5	X		X		X	X	Hydrostatic compaction
HU6							
HU7	X		X		X	X	Multiple triaxial test
HU8	X		X		X	X	Uniaxial compaction
HU9							
HU10							
HU11							
HU12							Multiple triaxial test
HU13	X		X		X	X	Multiple triaxial test
HU14							
HU15	X		X		X	X	Multiple triaxial test
HU16							
HU17	X		X		X	X	Multiple triaxial test
HU18	X		X		X	X	Multiple triaxial test
HF1							
HF2	X		X		X	X	Multiple triaxial test
HF3	X		X		X	X	Multiple triaxial test
HF4							
HF5							
HF6							
HF7	X		X		X	X	Multiple triaxial test
HF8	X		X		X	X	Multiple triaxial test
HF9	X		X		X	X	Multiple triaxial test
HF10	X		X		X	X	Multiple triaxial test
HF11							
HF12	X		X		X	X	
HF13							
HF14							
HF15	X		X		X	X	Hydrostatic compaction
Block 1							
Block 2							
Block 3							
Block 4							Multiple triaxial test
Block 5							
Block 6							Multiple triaxial test
Block 7							Multiple triaxial test
Block 8	X		X		X		Multiple triaxial test
Block 9							
Block 10							
Block 11							
Block 12							Multiple triaxial test
Block 13							Multiple triaxial test
Block 14							
Block 15							Multiple triaxial test
Block 16							

Hillerslev, HU 1

Plug description before test.

Burrowed Massive Mudstone, the chalk appears with irregular lamination, moderately hard, low consolidated, low density of trace fossils (*Thalassinoides*).

Plug description after multiple triaxial test.

Length: 107 mm Diameter: 54 mm H/D: 1.98
Plug affected by rubber slieve. Irregular and coated surface.

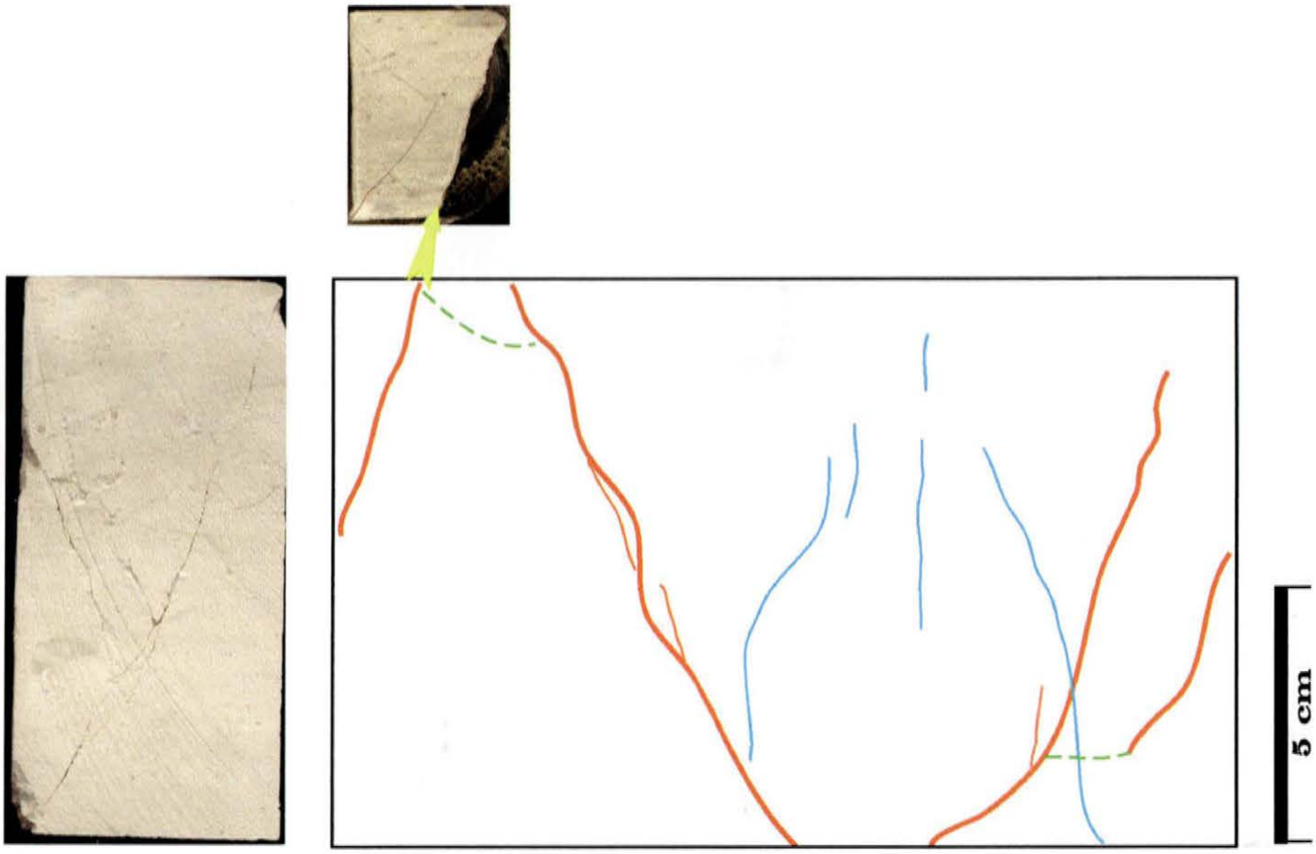
Porosity: 46.0 % Insoluble residue: 7 % (94 % clay, 6 % quartz)

The plug appears with open fractures and minor broken ends.
Due to the coated surface some of the sedimentary features cannot be described and fine fractures may have been overlooked.

HU 1
Fractures (after test):

GSI	**B/VG**	**(70) - 75**		
P_{32} main frac	**0,22**		**P_{32} total**	**0,41**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	3	1	
Type	Inclined	Vertical	Subhorizontal	
2θ	48			
Divergence	Medium	None	None	
Comments	Intersecting			
Dip (° from horizontal)	60-65	90	30	
Length (mm)	117	10-50		
Aperture (mm)	< 0.2	Closed		
Surface	Uncoated			
	Undulating, smooth			
J-no	2			
Relief (mm)	5	2		
JRC	**13 - 15**			

Hillerslev, HU 1



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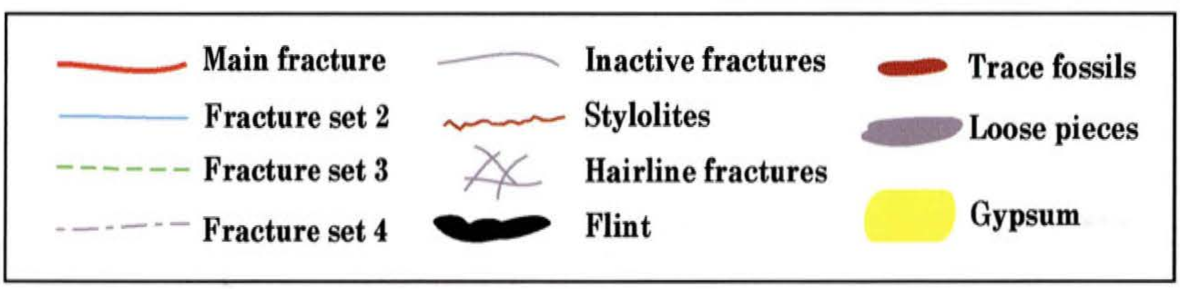


Hillerslev, HU 2

Plug description before test.

Burrowed Massive Mudstone, clean chalk, homogeneous, moderate hard, low consolidation, low density of trace fossils (*Chondrites*).

Plug description after multiple triaxial test.

Length: 105 mm	Diameter: 53 mm	H/D: 1.98
Porosity: 45.8 %	Insoluble residue: 6 %	(94 % clay, 6 % quartz)

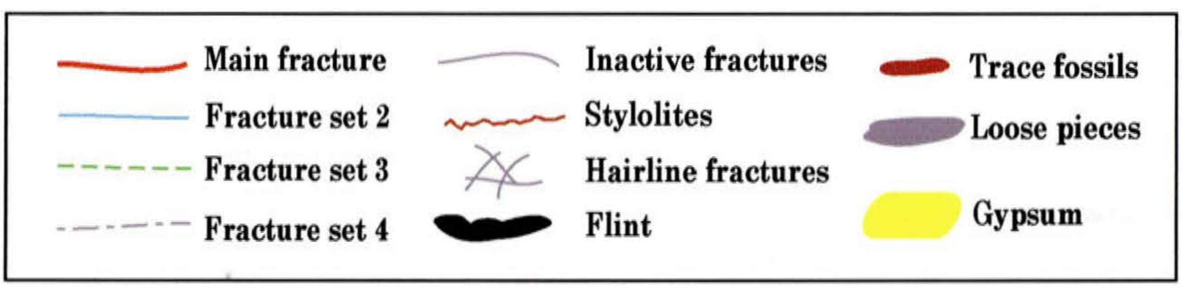
The plug appears with open fractures and severe broken ends.
Test induced fractures in top of plug caused by piston.

HU 2
Fractures (after test):

GSI	**B/VG**	**70 – (75)**		
P_{32} main frac	**0,18**		**P_{32} total**	**0,29**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	1	2	>4	
Type	Sub-vertical	Inclined	Inclined	
2θ				
Divergence	Low	None	None	
Comments			Piston induced	
Dip (° from horizontal)	75	65	50	
Length (mm)	110	40	25 – 50	
Aperture (mm)	< 0.5	< 0.5	Open (corehandling)	
Surface	Uncoated	Un-coated	Uncoated	
	Undulating, rough	Undulating, rough	Undulating, rough	
J-no	2-3	2	2	
Relief (mm)	6			
JRC	**18**			

Hillerslev, HU 2

Legend:



Hillerslev, HU 3

Plug description before test.

Burrowed Massive Mudstone, clean chalk, homogeneous, moderate hard, low consolidation, low density of trace fossils (*Thalassinoides/Zoophycos*).

Plug description after multiple triaxial test.

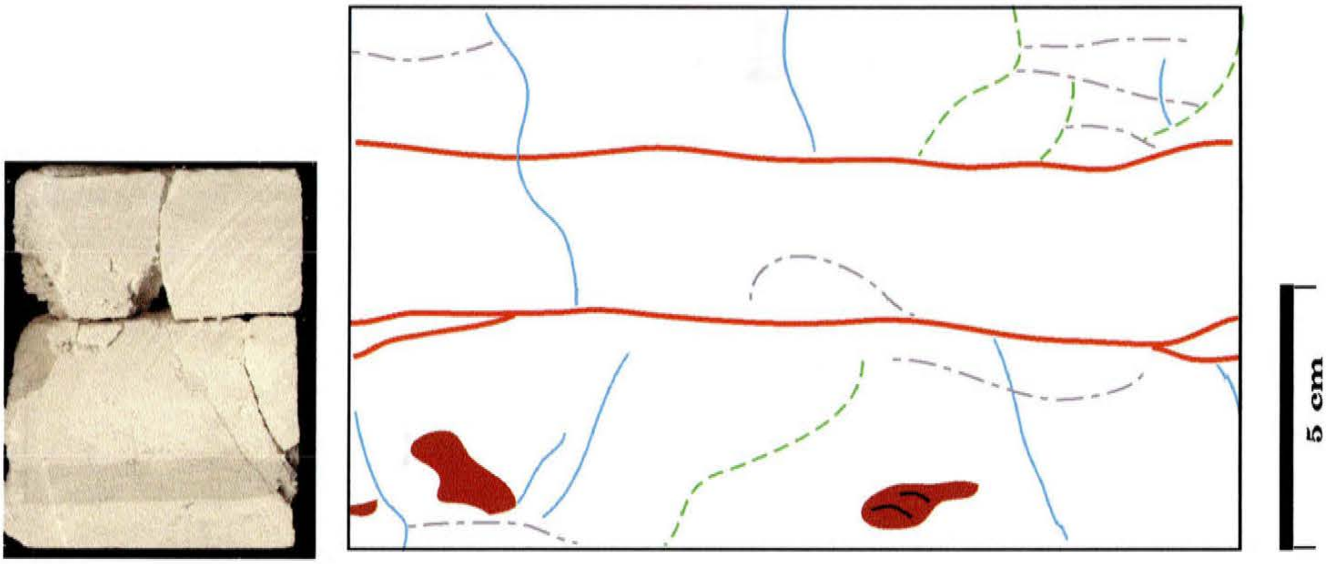
Length: 115 mm	Diameter: 54 mm	H/D: 2.12
Porosity: 46.9 %	Insoluble residue: 8 %	(95 % clay, 5 % quartz)

The plug is highly destructed after test but appears with open horizontal fractures. Test induced fractures in top of plug caused by piston.

HU 3
Fractures (after test):

GSI	**VB/VG**	**55 – (60)**		
P_{32} main frac	**0,20**		**P_{32} total**	**0,65**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	5	3	6
Type	Horizontal	Sub-vertical	Subvertical	Sub-horizontal
2θ				
Divergence	Medium	None	None	
Comments		Stratabounded		Piston frac
Dip (° from horizontal)	0	75 - 80	60	10 - 15
Length (mm)	> 54	30	50	20 - 30
Aperture (mm)	> 1	Closed	< 0.5	Open (corehandling)
Surface	Uncoated		Uncoated	Uncoated
	Undulating, smooth		Undulating, rough	Undulating, rough
J-no	2			
Relief (mm)	3	3	4	2
JRC	**13**		**16**	

Hillerslev, HU 3



Legend:

Main fracture	Inactive fractures	Trace fossils
Fracture set 2	Stylolites	Loose pieces
Fracture set 3	Hairline fractures	Gypsum
Fracture set 4	Flint	

Hillerslev, HU 5

Plug description before test.

Burrowed Massive Mudstone, clean chalk, homogeneous, biomottled, moderate hard, low consolidation, no visible trace fossils.

Plug description after hydrostatic compaction test.

Length: 105 mm	Diameter: 55 mm	H/D: 1.91
Porosity: 38.8 %	Insoluble residue: 10 %	(93 % clay, 7 % quartz)

The plug is covered by soft chalk paste which make it impossible to describe. No visible fractures are observed.

HU 5
Fractures (after test):

GSI	No fractures			
P_{32} main frac			P_{32} total	
	Main fracture	Fracture 2	Fracture 3	Fracture 4
Numbers	0			
Type				
2θ				
Divergence				
Comments				
Dip (° from horizontal)				
Length (mm)				
Aperture (mm)				
Surface				
J-no				
Relief (mm)				
JRC	-			

Hillerslev, HU 5

Plug not described

Hillerslev, HU 7

Plug description before test.

Burrowed Massive Mudstone, clean chalk, homogeneous, moderate hard, low consolidation, low density of trace fossils.

Plug description after multiple triaxial test.

Length: 115 mm	Diameter: 53 mm	H/D: 2.17
Porosity: 45.7 %	Insoluble residue: 6 %	(92 % clay, 8 % quartz)

The plug comprises a large number of broken pieces and is extremely difficult to describe due to fragmentation. The high degree of fragmentation is interpreted to be associated with open fractures.

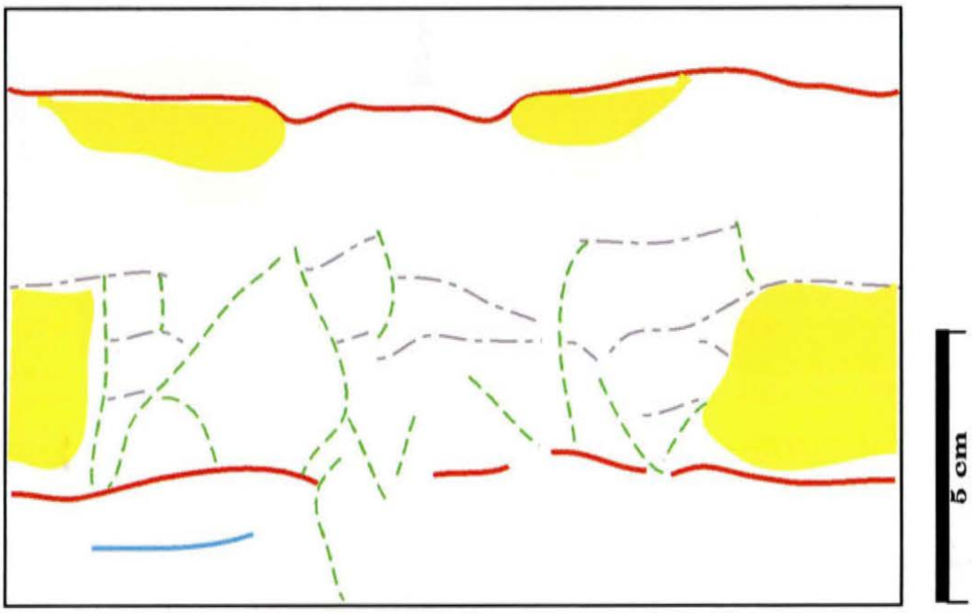
The plug is heavily fractured in the middle part and the fracturing indicate stratabounding, limited by the two horisontal fractures.

HU 7
Fractures (after test):

GSI	BD/VG	(50) - 55		
P_{32} main frac	0,19		P_{32} total	0,69
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	1	10*	
Type	Horizontal	Horizontal	Random	
2θ				
Divergence	None	None		
Comments			Complex stratabounded	
Dip (° from horizontal)	0	0	0 - 90	
Length (mm)	>53	?	10 - 50	
Aperture (mm)	> 0.5 - 1	< 0.2	Open (corehandling)	
Surface	Uncoated	Uncoated	Uncoated	
	Irregular due to vertical fractur.	Planar, rough	Undulating, rough	
J-no	(3)			
Relief (mm)	6	1.5	3	
JRC	**16**			

* Intensive fractured interval in the middle of the plug

Hillerslev, HU 7



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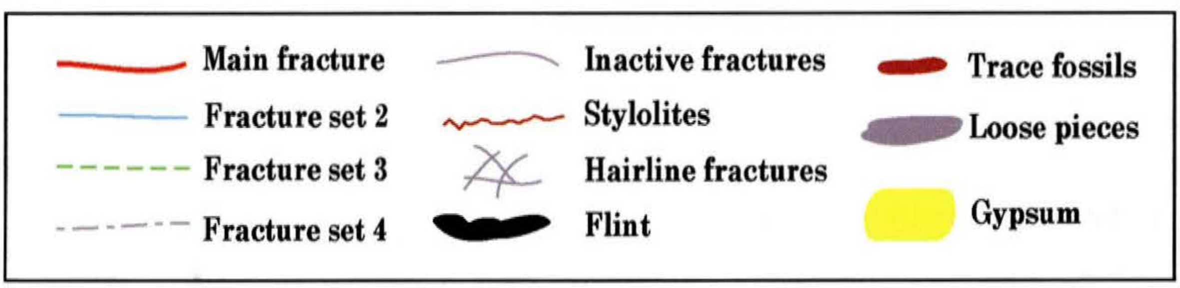


Hillerslev, HU 8

Plug description before test.

Burrowed Massive Mudstone, clean chalk, homogeneous, moderate hard, low consolidation, low density of trace fossils (*Thalassinoides*).

Plug description after uniaxial compaction test.

Length: 95 mm	Diameter: 53 mm	H/D: 1.79
Porosity: 39.0 %	Insoluble residue: 8 %	(92 % clay, 8 % quartz)

The plug is covered by soft chalk paste which make it impossible to describe. No visible fractures are observed.

HU 8
Fractures (after test):

GSI	**No fractures**			
P_{32} main frac			**P_{32} total**	
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	0			
Type				
2θ				
Divergence				
Comments				
Dip (° from horizontal)				
Length (mm)				
Aperture (mm)				
Surface				
J-no				
Relief (mm)				
JRC	-			

Hillerslev, HU 8

Plug not described

Hillerslev, HU 12

Plug description before test.

Burrowed Massive Mudstone, clean chalk, biomottled, moderate hard, low consolidation, low density of trace fossils (*Planolites*).

Plug description after multiple triaxial test.

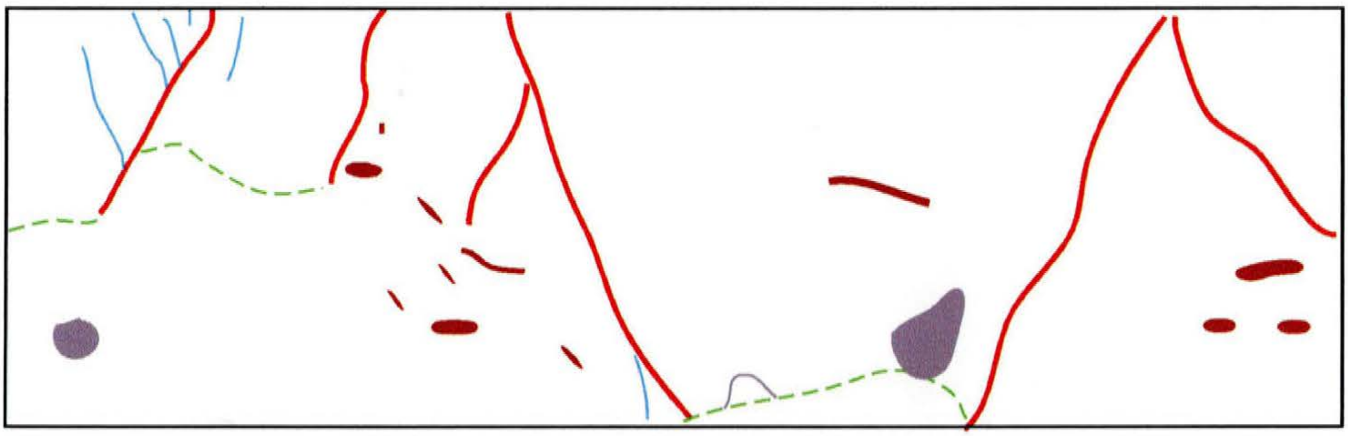
Length: 70 mm	Diameter: 70 mm	H/D: 1.00
Porosity: -	Insoluble residue: -	(% clay, % quartz)

The plug exhibits distinct, open conjugated fractures after test.

HU 12
Fractures (after test):

GSI	**B/VG**	**70 – (75)**		
P_{32} main frac	**0,24**		**P_{32} total**	**0,38**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	2	3	
Type	Inclined	Sub-horizontal	Subvertical	
2θ	70			
Divergence	High	None	None	
Comments	Intersecting			
Dip (° from horizontal)	60	0	80	
Length (mm)	80	10-50	- 40	
Aperture (mm)	< 0,5 - closed	Closed	Closed	
Surface	Uncoated	Uncoated	Uncoated	
	Undulating, smooth	Undulating, smooth		
J-no	2	1,5		
Relief (mm)	3	3		
JRC	**20**			

Hillerslev, HU 12



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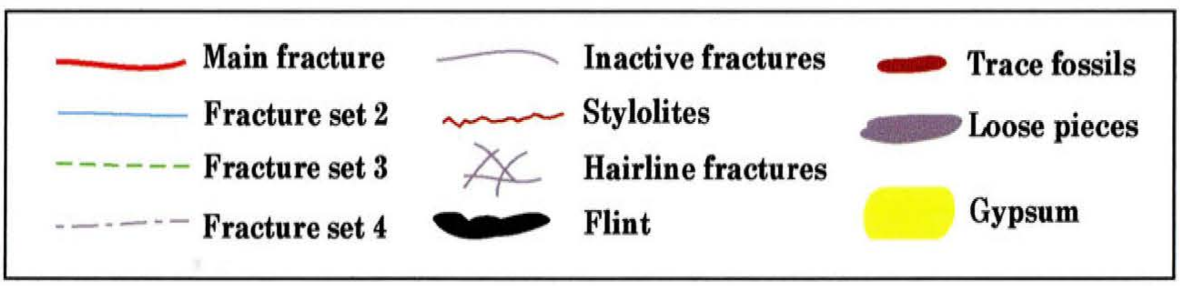


Hillerslev, HU 13

Plug description before test.

Burrowed Massive Mudstone, clean chalk, homogeneous, moderate hard, low consolidation, high density of trace fossils (*Thalassinoides/Zoophycos*), microstylolites.

Plug description after multiple triaxial test.

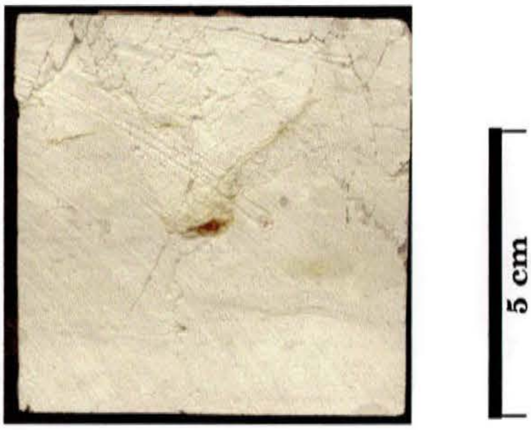
Length: 70 mm	Diameter: 70 mm	H/D: 1.00
Porosity: 47.1 %	Insoluble residue: 6 %	(92 % clay, 8 % quartz)

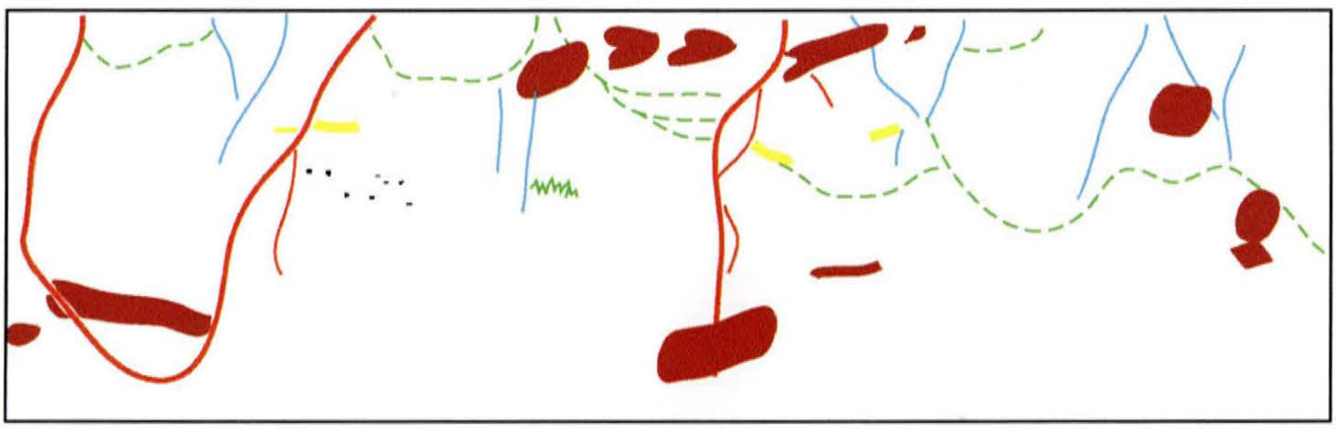
The plug appears with open fractures and broken ends.
Test induced fractures in top of plug caused by piston compression.

HU 13
Fractures (after test):

GSI	VB/VG	65 – (70)		
P_{32} main frac	0,20		P_{32} total	0,47
	Main fracture	Fracture 2	Fracture 3	Fracture 4
Numbers	2	5	> 25	
Type	Sub-vertical	Inclined - subvertical	Random	
2θ				
Divergence	Medium	None		
Comments			Piston induced	
Dip (° from horizontal)	80 - 90	60 - 90		
Length (mm)	- 60	< 30		
Aperture (mm)	< 0.5	< 0.2		
Surface	Uncoated			
	Undulating, wavy			
J-no	2			
Relief (mm)	3	3		
JRC	16			

Hillerslev, HU 13





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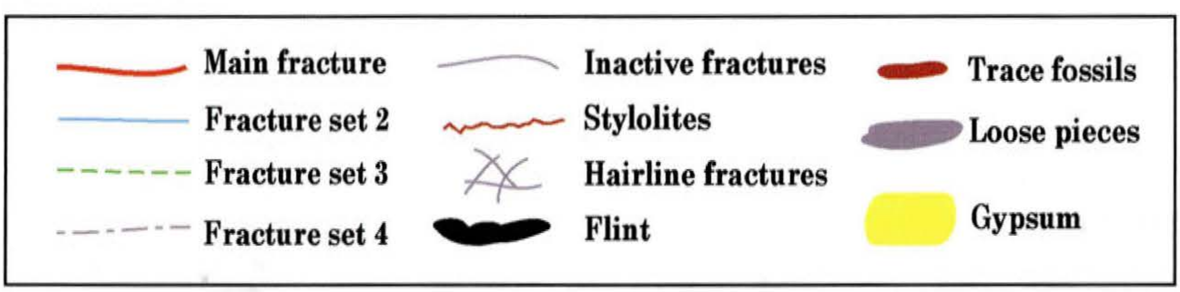


Hillerslev, HU 15

Plug description before test.

Burrowed Massive Mudstone, clean chalk, homogeneous, moderate hard, low consolidation, low density of trace fossils (*Thalassinoides*).

Plug description after multiple triaxial test.

Length: 70 mm	Diameter: 70 mm	H/D: 1.00
Porosity: 48.3 %	Insoluble residue: 7 %	(92 % clay, 8 % quartz)

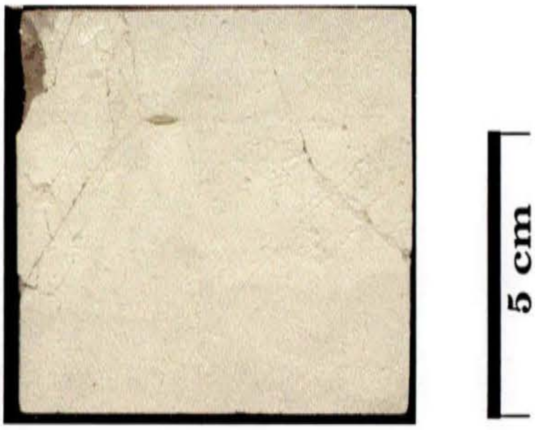
The plug appears with open fractures and broken ends. Test induced fracture system in top of plug caused by piston compression.

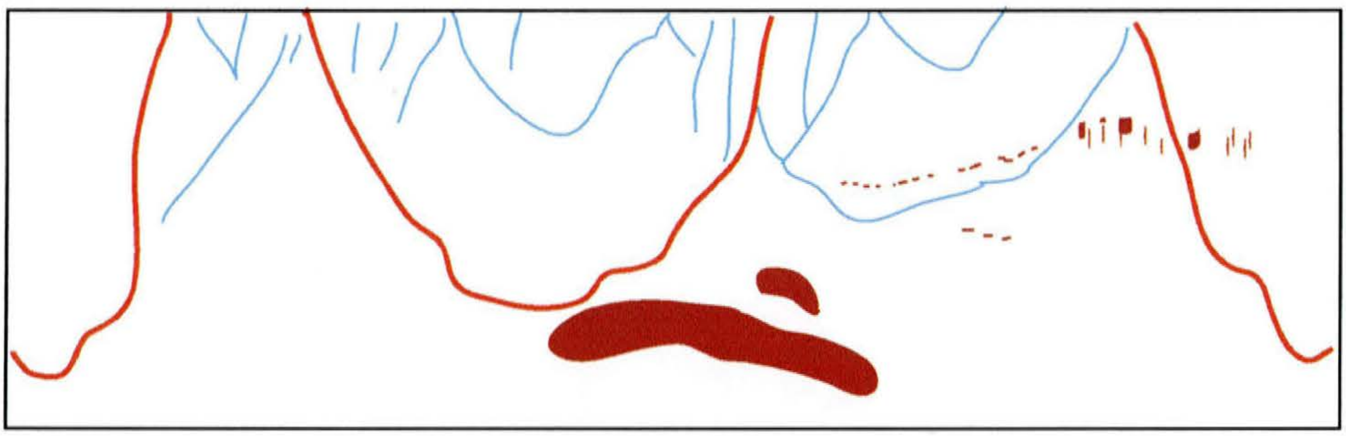
HU 15
Fractures (after test):

GSI	**B/VG**	**65 – (70)**		
P_{32} main frac	**0,22**		**P_{32} total**	**0,50**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	> 5		
Type	Conjugate	Sub-vertical		
2θ	70			
Divergence	Medium	None		
Comments				
Dip (° from horizontal)	60	80 - 90		
Length (mm)	- 50	20 – 30		
Aperture (mm)	< 0.5 - 1	Open		
Surface	Uncoated	Uncoated		
	Undulating, rough	Undulating, rough		
J-no	3	3		
Relief (mm)	4			
JRC	**13**			

Fracture type 2 are test induced fracture system in top of plug caused by piston compression.

Hillerslev, HU 15





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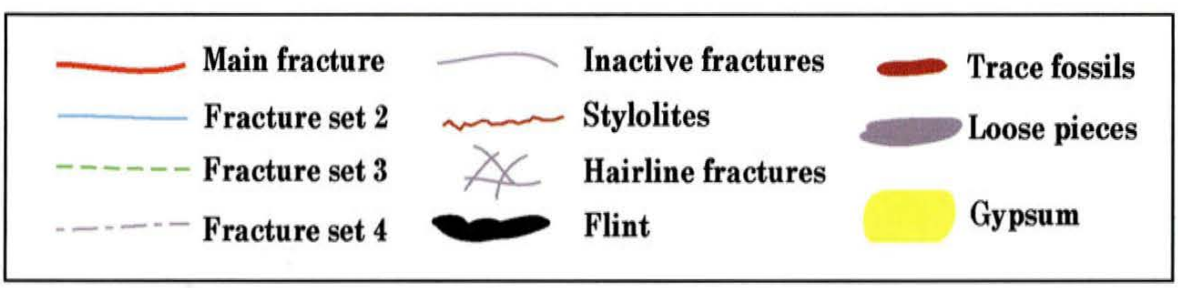


Hillerslev, HU 17

Plug description before test.

Burrowed Massive Mudstone, clean chalk, homogeneous, moderate hard, low consolidation, low density of trace fossils (*Thalassinoides*).

Plug description after multiple triaxial test.

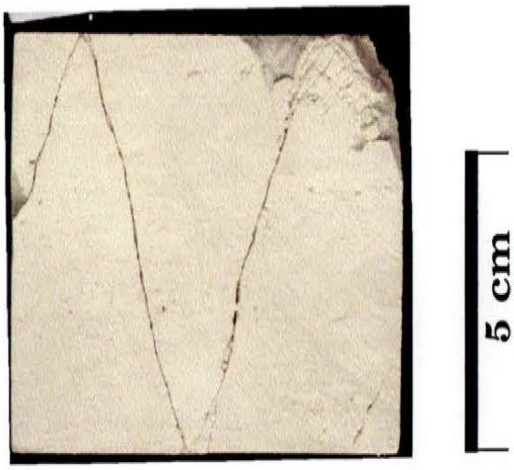
Length: 68 mm	Diameter: 69 mm	H/D: 0.99
Porosity: 46.9 %	Insoluble residue: 7 %	(92 % clay, 8 % quartz)

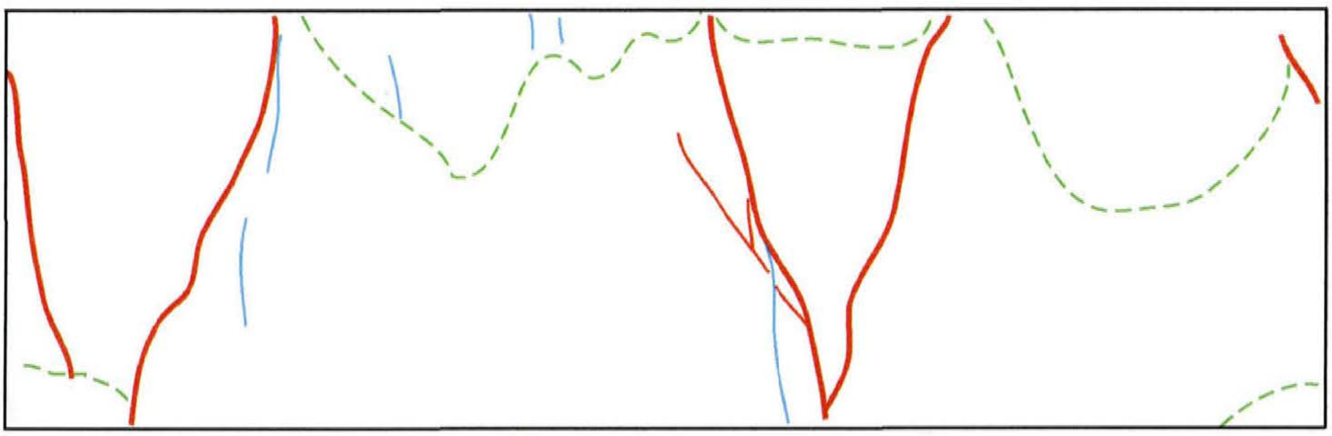
The plug appears with open fractures and broken ends. Piston induced fractures in the upper part of the plug.

HU 17
Fractures (after test):

GSI	**B/VG**	**(65) – 70**		
P_{32} main frac	**0,29**		**P_{32} total**	**0,62**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	3	>5	
Type	Conjugated	Sub-vertical	Random	
2θ	48			
Divergence	High	None		
Comments			Piston frac	
Dip (° from horizontal)	70 - 75	85 - 90		
Length (mm)	70	10 - 50		
Aperture (mm)	< 0.5	< 0.2		
Surface	Uncoated	Uncoated		
	Undulating, rough	Undulating, rough		
J-no	2	2		
Relief (mm)	3			
JRC	**13**			

Hillerslev, HU 17





Legend:

Main fracture	Inactive fractures	Trace fossils
Fracture set 2	Stylolites	Loose pieces
Fracture set 3	Hairline fractures	
Fracture set 4	Flint	Gypsum

Hillerslev, HU 18

Plug description before test.

Burrowed Massive Mudstone, clean chalk, homogeneous, moderate hard, low consolidation, high density of trace fossils (*Thalassinoides*) cross-cutting plug, bryozoan fragments.

Plug description after multiple triaxial test.

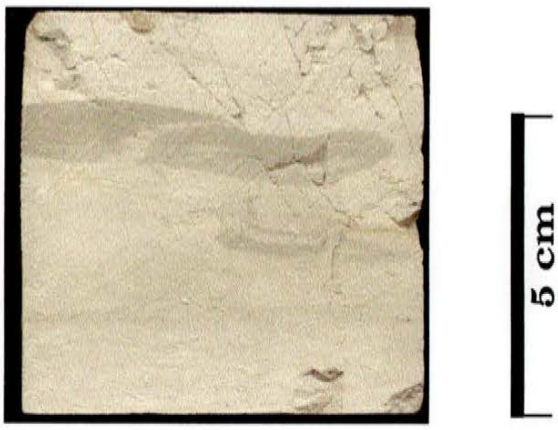
Length: 69 mm	Diameter: 69 mm	H/D: 1.00
Porosity: 47.4 %	Insoluble residue: 9 %	(93 % clay, 7 % quartz)

One distinct open fracture dominates the plug efter test, but is associated with piston induced fractures in top of plug.

HU 18
Fractures (after test):

GSI	**B/VG**	**75**	**Non-uniform** distribution	
P_{32} main frac	**0,14**		**P_{32} total**	**0,27**
	Main facture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	1	> 5		
Type	Sub-vertical	Random		
2θ				
Divergence	Low			
Comments		Piston frac.		
Dip (° from horizontal)	80	60 - 70		
Length (mm)	70	40 –50		
Aperture (mm)	< 0,5	< 0.5		
Surface	Uncoated			
	Undulating, rough			
J-no	**3**			
Relief (mm)	2			
JRC	**13**			

Hillerslev, HU 18



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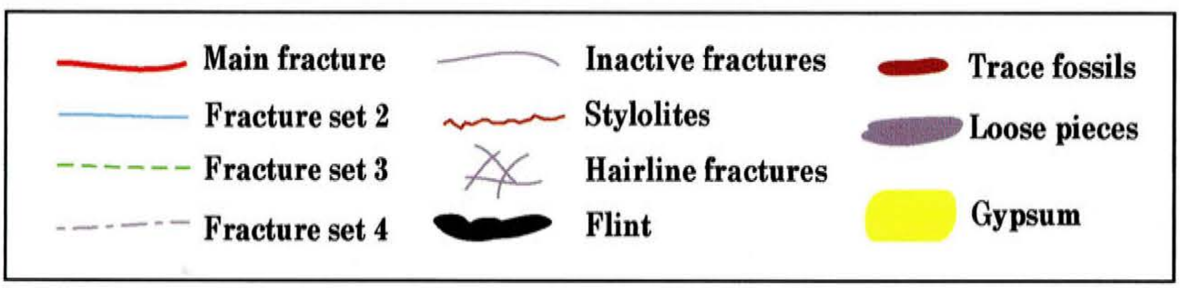
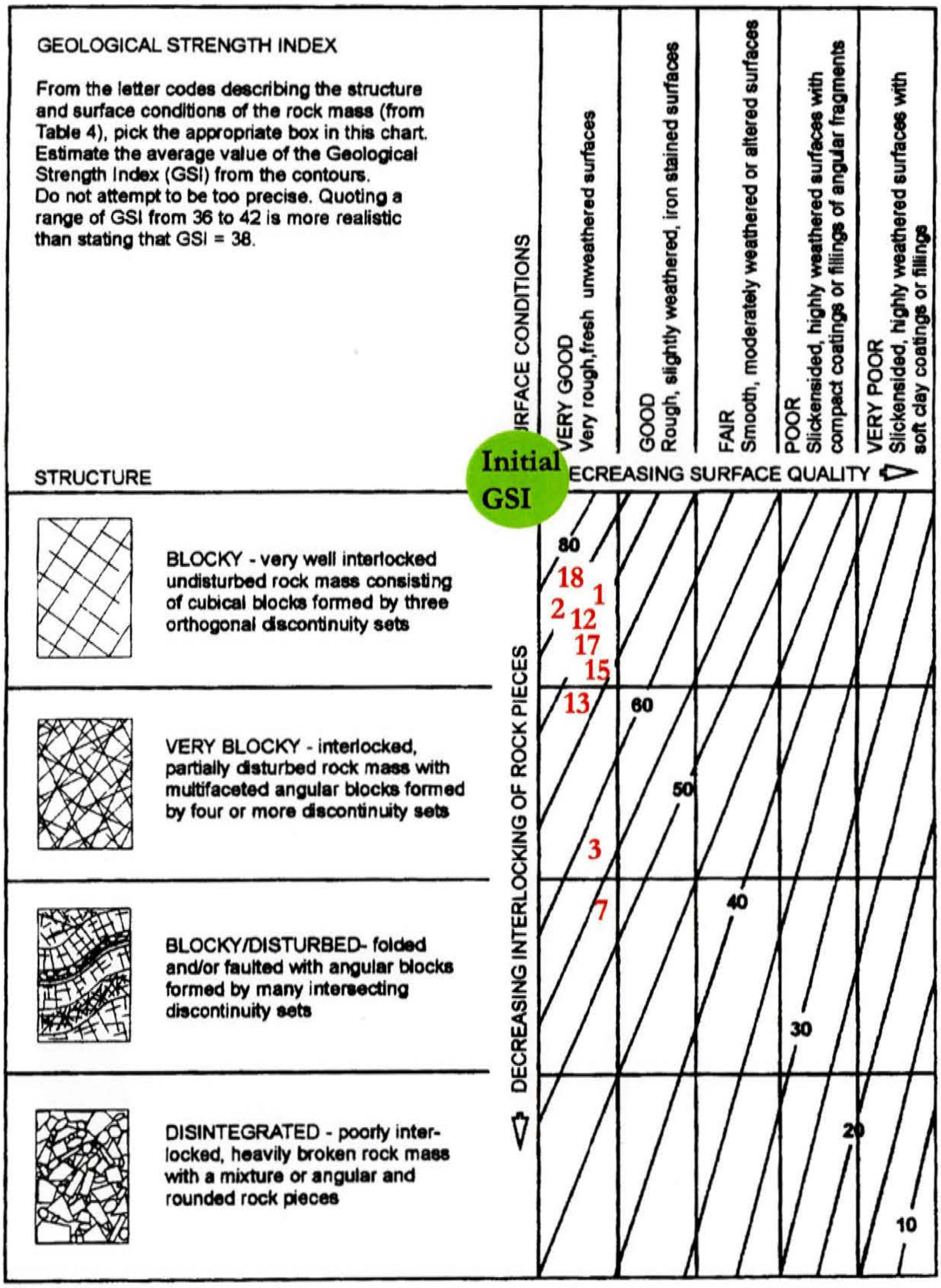


HU samples



Estimate of Geological Strength Index GSI for the HU samples based on plug description. Green: initial GSI values. Red number: Plug sample GSI after test

Hillerslev, HF 2

Plug description before test

Burrowed Massive Mudstone, clean chalk, homogeneous, medium hard, medium consolidated, low density of trace fossils (*Thalassinoides*).
One highly diverging, open horizontal fractures

Plug description after multiple triaxial test.

Length: 95 mm	Diameter: 53 mm	H/D: 1.79
Porosity: -	Insoluble residue: -	(% clay, % quartz)

Not a perfect plug (un-even sides). Double slieve has caused bacterial growth on plug, hindering a perfect description.

HF 2 fractures:

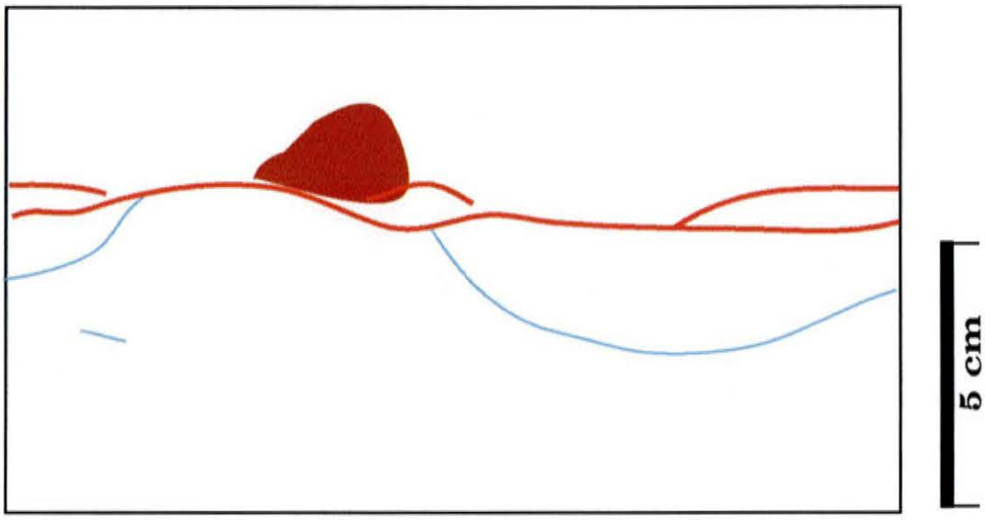
Before test

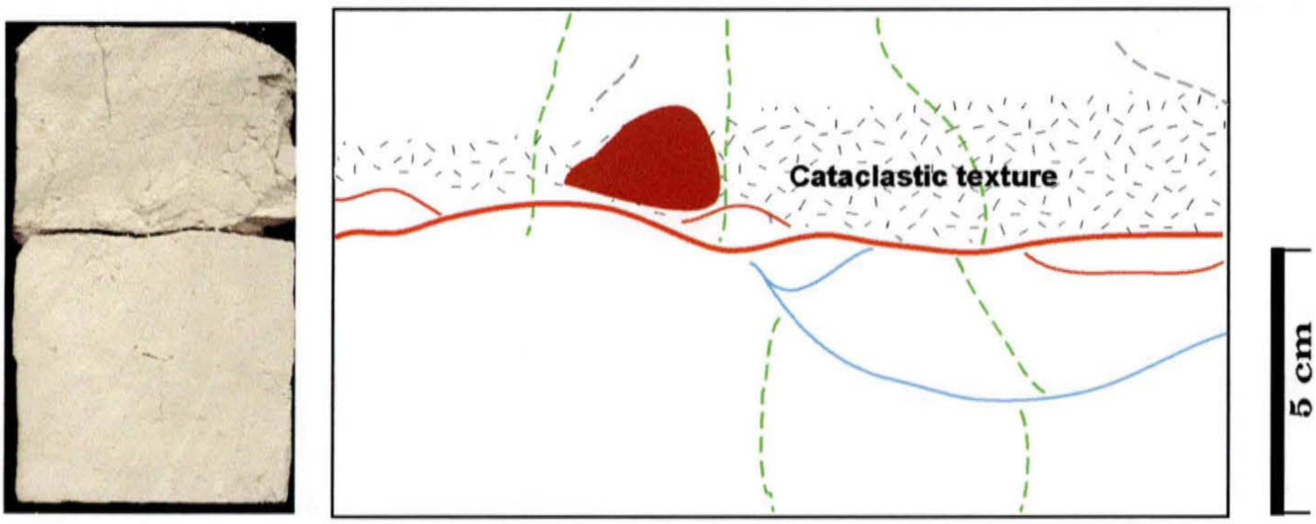
GSI	B/VG	75 – (80)		
P_{32} main frac	0,16		P_{32} total	0,31
	Main fracture	Fracture 2	Fracture 3	Fracture 4
Numbers	1	3		
Type	Horizontal	Sub-vertical		
2θ				
Divergence	High	None		
Comments				
Dip (° from horizontal)	0	60		
Length (mm)	> 5.3	50		
Aperture (mm)	> 0,5	Closed		
Surface	Uncoated	Uncoated		
	Undulating, smooth	Undulating, smooth		
Jr-no	2	2		
Relief (mm)	7			
JRC	18			

After test

GSI	VB/VG	60 – (65)		
P_{32} main frac	0,16		P_{32} total	0,51
	Main fracture	Fracture 2	Fracture 3	Fracture 4
Numbers	1	1	> 5	> 10
Type	Horizontal	Sub-vertical	Vertical	Cataclastic zone
2θ				
Divergence	High	None	Low	
Comments			Stratabounded	
Dip (° from horizontal)	0	60	70 - 90	
Length (mm)	> 5.3	50	10 - 20	
Aperture (mm)	> 0.5	< 0.5	< 0.5	
Surface	Uncoated	Uncoated	Uncoated	
	Undulating, smooth	Undulating, rough	Undulating, smooth -rough	
J-no	2	3	2 - 3	
Relief (mm)	7			
JRC	> 20			

Hillerslev, HF 2





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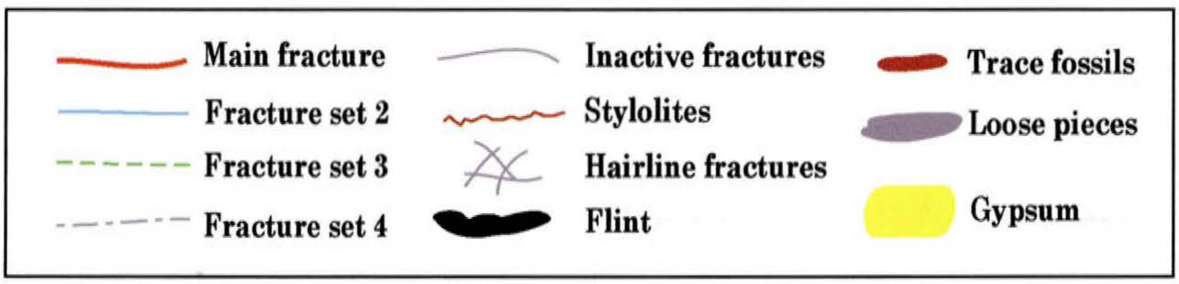


Hillerslev, HF 3

Plug description before test

Burrowed Massive Mudstone, clean chalk, homogeneous, moderate hard, low consolidation, low density of trace fossils (*Thalassinoides*).
2 open horizontal fractures

Plug description after multiple triaxial test.

Length: 106 mm	Diameter: 53 mm	H/D: 2.00
Porosity: 45.8 %	Insoluble residue: 4 %	(86 % clay, 14 % quartz)

Double slieve and fragmented sample.

HF 3 fractures:

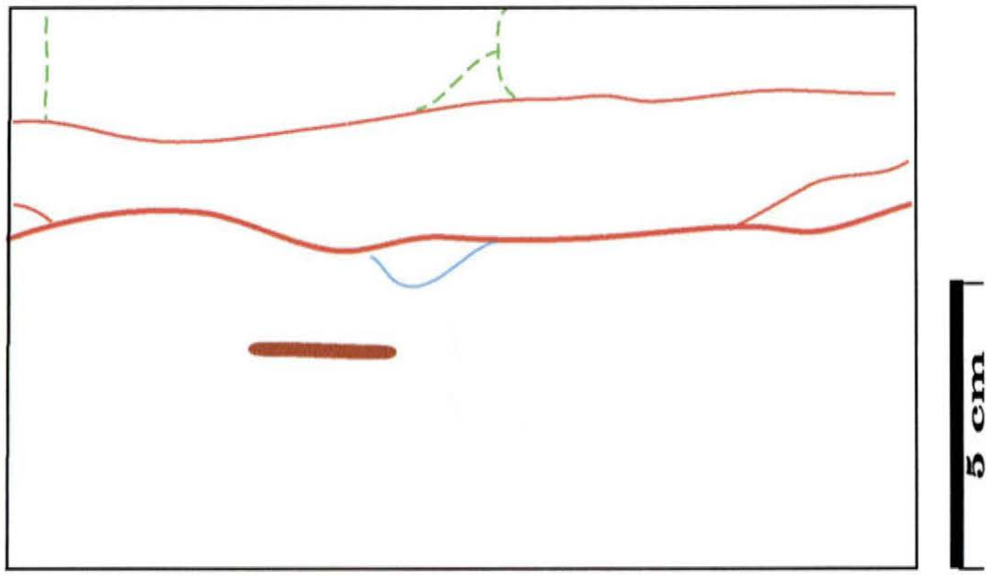
Before test

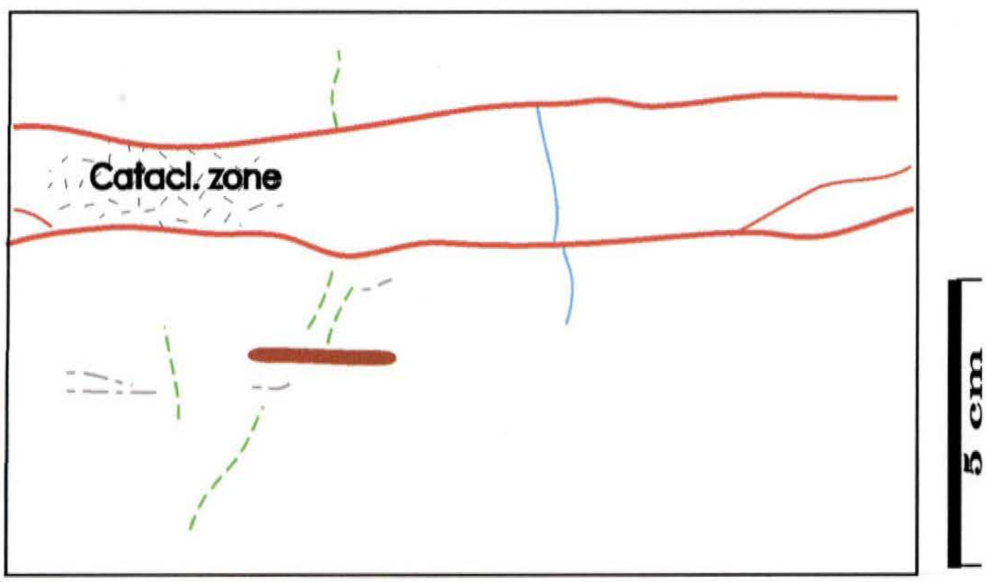
GSI	B/VG	75 – (80)		
P_{32} main frac	0,21		P_{32} total	0,33
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	2		
Type	Horizontal	Vertical		
2θ				
Divergence	Medium	None		
Comments				
Dip (° from horizontal)	0	90		
Length (mm)	> 53	10		
Aperture (mm)	< 0,5	Closed		
Surface	Uncoated			
	Planar-undul., smooth-rough			
J-no	1-3			
Relief (mm)	5			
JRC	**13**			

After test

GSI	VB/VG	(60) – 65		
P_{32} main frac	0,21		P_{32} total	0,39
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	1	5	1
Type	Horizontal	Vertical	Inclined	Horizontal
2θ			50	
Divergence	Medium	High	None	
Comments	High amplitude		Intersecting, statabounded	
Dip (° from horizontal)	0	85 - 90	65	
Length (mm)	> 53	10 - 20	30 - 50	
Aperture (mm)	< 0.5	< 0.5	< 0.2	
Surface	Uncoated	Uncoated	Uncoated	
	Undulating, smooth	Undulating, rough	Undulating, rough	
J-no	2	3	3	
Relief (mm)	5			
JRC	**14**		**10 - 15**	

Hillerslev, HF 3





Legend:

- Main fracture
- Fracture set 2
- Fracture set 3
- Fracture set 4
- Inactive fractures
- Stylolites
- Hairline fractures
- Flint
- Trace fossils
- Loose pieces
- Gypsum

Hillerslev, HF 7

Plug description before test

Burrowed Massive Mudstone, clean chalk, homogeneous, medium hard, medium consolidation, biomottled, trace fossils (*Thalassinoides, Chondrites, Planolites*). 1 inclining open fracture.

Plug description after multiple triaxial test.

Length: 100 mm	Diameter: 53 mm	H/D: 1.89
Porosity: 46.4 %	Insoluble residue: 6 %	(92 % clay, 8 % quartz)

Double slieve, pasty plug surface.

HF 7 fractures:

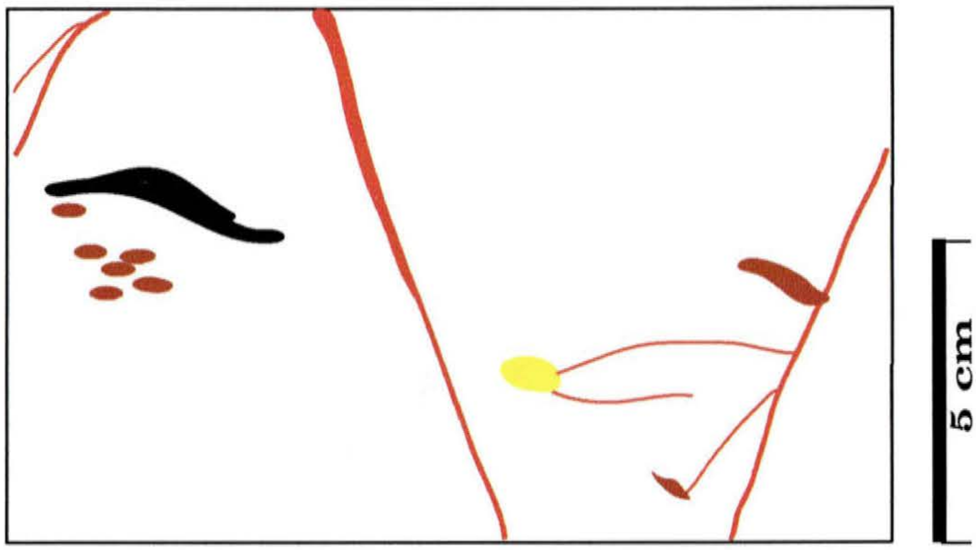
Before test

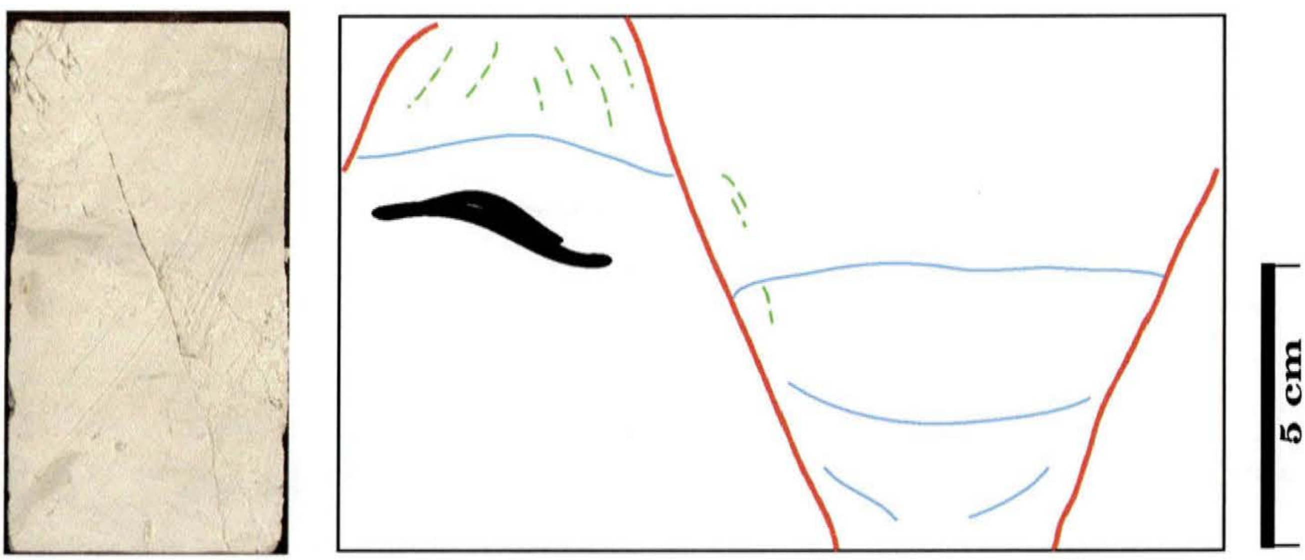
GSI	**B/VG**	**(75) - 80**		
P_{32} main frac	**0,18**		**P_{32} total**	**0,25**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	1	3		
Type	Sub-vertical	Sub-horizontal		
2θ				
Divergence	Low	None		
Comments		Drying fract.		
Dip (° from horizontal)	70 -75	0 – 10		
Length (mm)	100	50		
Aperture (mm)	> 1.0	< 0.5		
Surface				
J-no				
Relief (mm)				
JRC				

After test

GSI	**B/VG**	**65 – (70)**	**Non-uniform** distribution	
P_{32} main frac	**0,18**		**P_{32} total**	**0,42**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	1	> 3	> 10	
Type	Sub-vertical	Crush zone	Crush zone	
2θ				
Divergence	Low	Low	High	
Comments				
Dip (° from horizontal)	70 - 75	65 – 75	65	
Length (mm)	100	50	20 – 30	
Aperture (mm)	< 0.5	< 0.5	< 0.2	
Surface	Uncoated	Uncoated	Uncoated	
	Undulating, smooth	Undulating, rough	Undulating, rough	
J-no	2	3	3	
Relief (mm)	5			
JRC	**12**	16		

Hillerslev, HF 7





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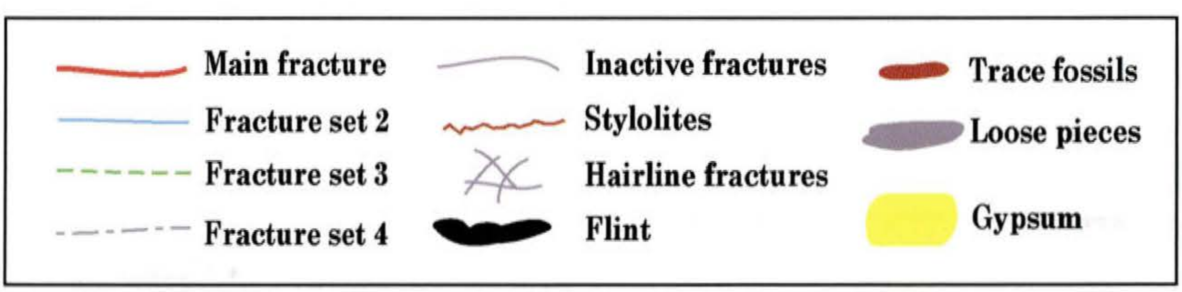


Hillerslev, HF 8

Plug description before test

Burrowed Massive Mudstone, clean chalk, homogeneous, medium hard, low consolidation, biomottled, trace fossils (*Chondrites, Planolites*).

Conjugated open fractures

Plug description after multiple triaxial test.

Length: 90 mm	Diameter: 58 mm	H/D: 1.55
Porosity: 38.1 %	Insoluble residue: 5 %	(89 % clay, 11 % quartz)

Pasty plug surface, not to be described properly

HF 8 fractures:

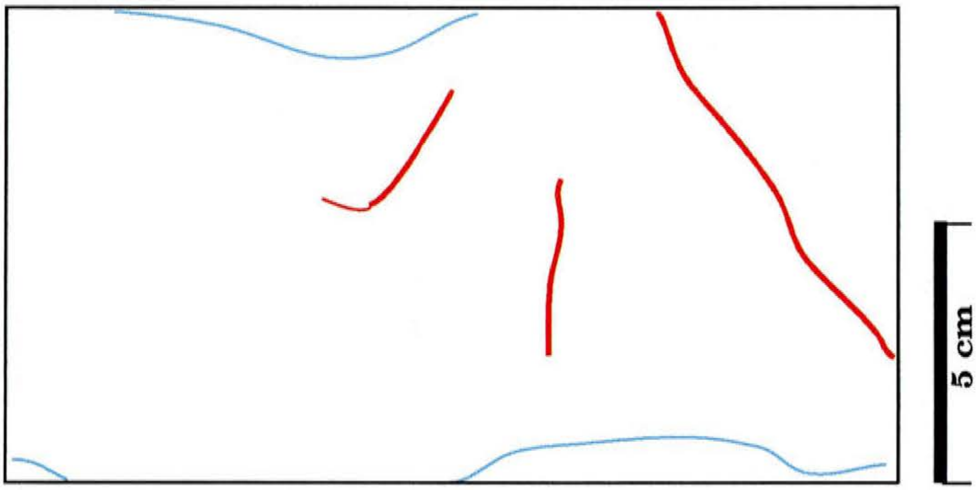
Before test

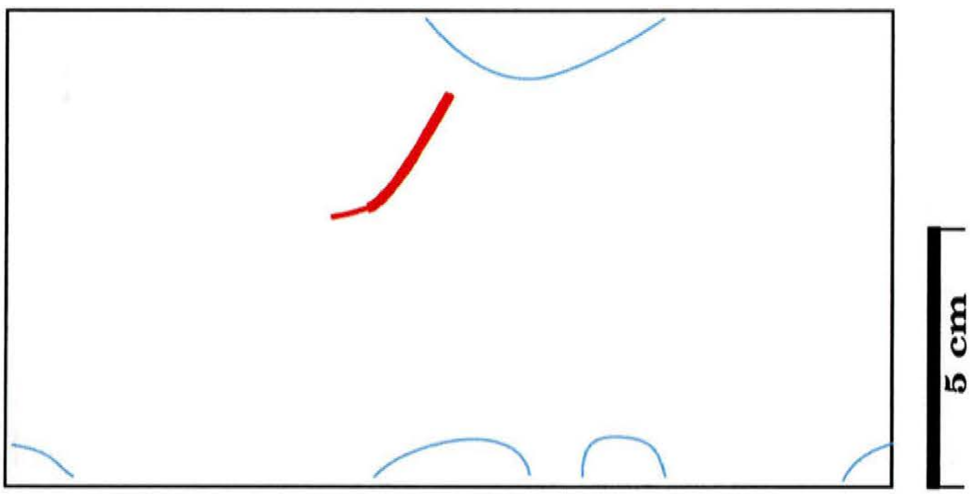
GSI	B/VG	80		
P_{32} main frac	0,13		P_{32} total	0,25
	Main fracture	Fracture 2	Fracture 3	Fracture 4
Numbers	2	3	1	
Type	Sub-vertical	Sub-vertical	Sub-horizontal	
2θ	48			
Divergence	None	None	None	
Comments				
Dip (° from horizontal)	60 - 65	90	30	
Length m(m)	117	10 - 50		
Aperture (mm)	< 0.2	Closed		
Surface	Uncoated			
	Undulating, smooth			
J-no	2			
Relief (mm)	10			
JRC	**13**			

After test

GSI	?			
P_{32} main frac			P_{32} total	
	Main fracture	Fracture 2	Fracture 3	Fracture 4
Numbers	1	1		
Type	Inclined	Sub-vertical		
2θ				
Divergence	None	None		
Comments				
Dip (° from horizontal)	60	85		
Length m(m)	100	> 40		
Aperture (mm)	< 0.5	Open		
Surface	Uncoated	Uncoated		
	Undulating	Undulating, smooth		
J-no				
Relief (mm)				
JRC	**14 – 15**			

Hillerslev, HF 8





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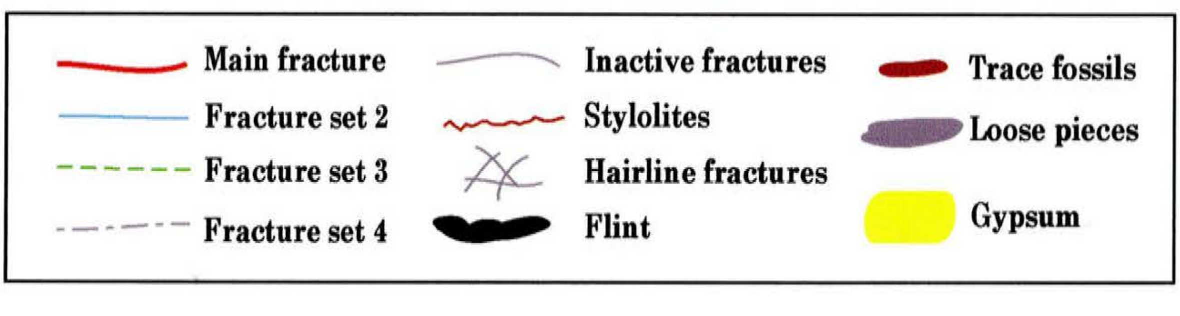


Hillerslev, HF 9

Plug description before test

Burrowed Massive Mudstone, clean chalk, homogeneous, medium hard, medium consolidation, trace fossils (*Thalassinoides*).
3 parallel open fractures

Plug description after multiple triaxial test.

Length: 100 mm	Diameter: 55 mm	H/D: 1.82
Porosity: 45.3 %	Insoluble residue: 3 %	(89 % clay, 11 % quartz)

Pasty surface.

HF 9 fractures:

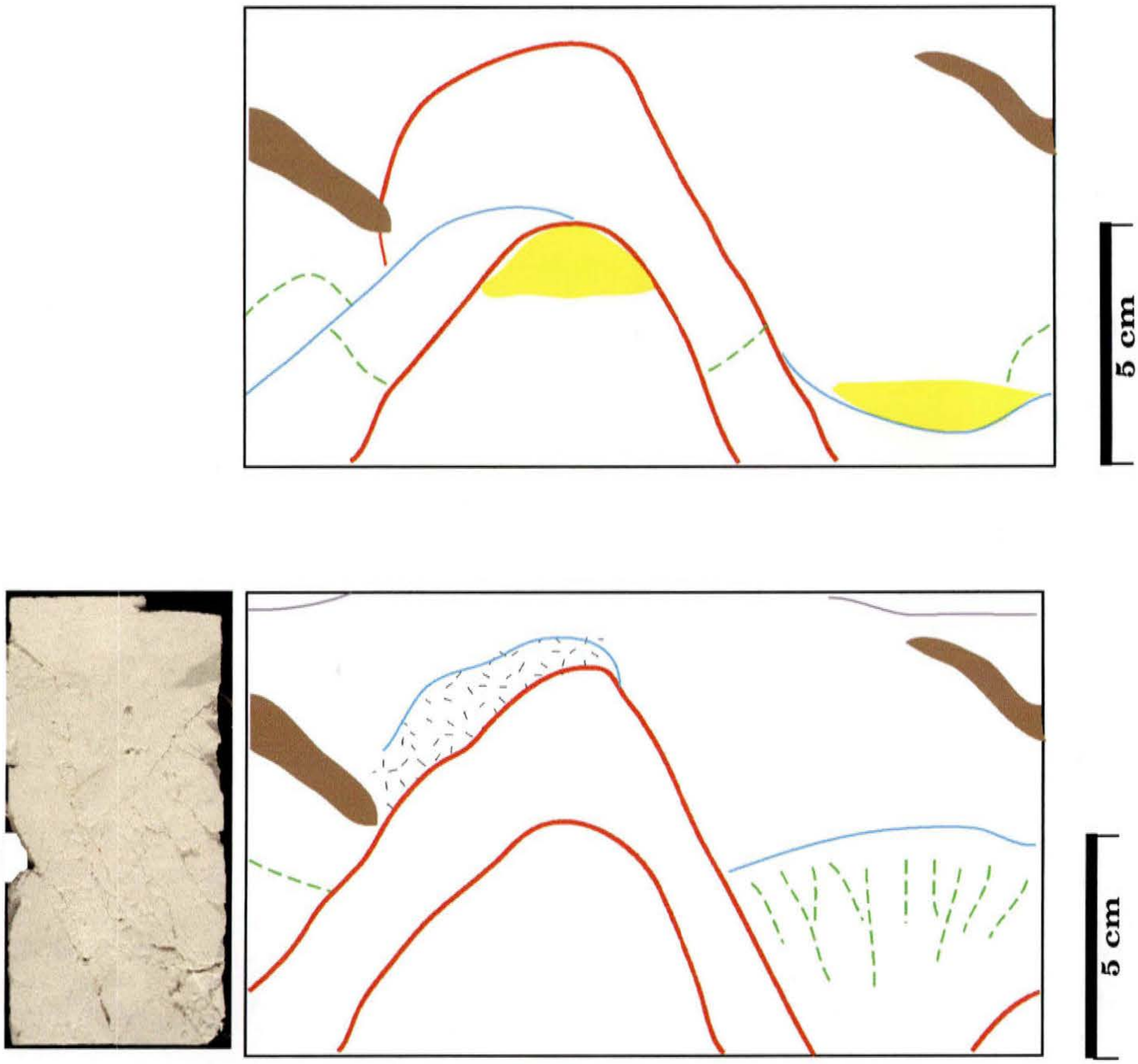
Before test

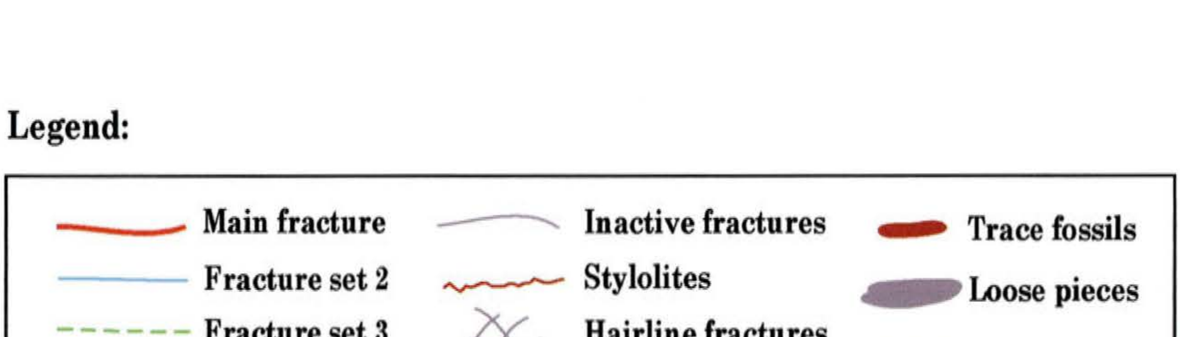
GSI	**B/VG**	**(70) - 75**		
P_{32} main frac	**0,22**		**P_{32} total**	**0,37**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	2	2	
Type	Sub-parallel, inclined	Inclined		
2θ				
Divergence	None	None		
Comments				
Dip (° from horizontal)	60 – 70	45		
Length (mm)	100	20		
Aperture (mm)	< 0.2 – closed	< 0.2		
Surface	Uncoated			
	Undulating, smooth-rough			
J-no	2 – 3			
Relief (mm)	5			
JRC	**20**			

After test

GSI	**VB/VG**	**(55) - 60**		
P_{32} main frac	**0,24**		**P_{32} total**	**0,50**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	3	1	> 10	
Type	Inclined	Inclined	Cataclastic zone	
2θ		60		
Divergence	Low	None	High	
Comments	Parallel dipping	Conjugated to main fracture		
Dip (° from horizontal)	60	40	60	
Length (mm)	60 – 100	50	10	
Aperture m(m)	< 0.2	< 0.2	< 0.1	
Surface	Uncoated	Uncoated		
	Undulating, rough			
J-no	3			
Relief (mm)	5			
JRC	**13 – 15**	10		

Hillerslev, HF 9





Hillerslev, HF 10

Plug description before test

Burrowed Massive Mudstone, clean chalk, homogeneous, medium hard, medium consolidation, low density of trace fossils.

Plug description after multiple triaxial test.

Length: 89 mm	Diameter: 53 mm	H/D: 1.68
Porosity: 46.7 %	Insoluble residue: 5 %	(93 % clay, 7 % quartz)

Highly fragmented in top.
Fractures terminates at horizontal fracture indicative of stratabounding.

HF 10 fractures:

Before test

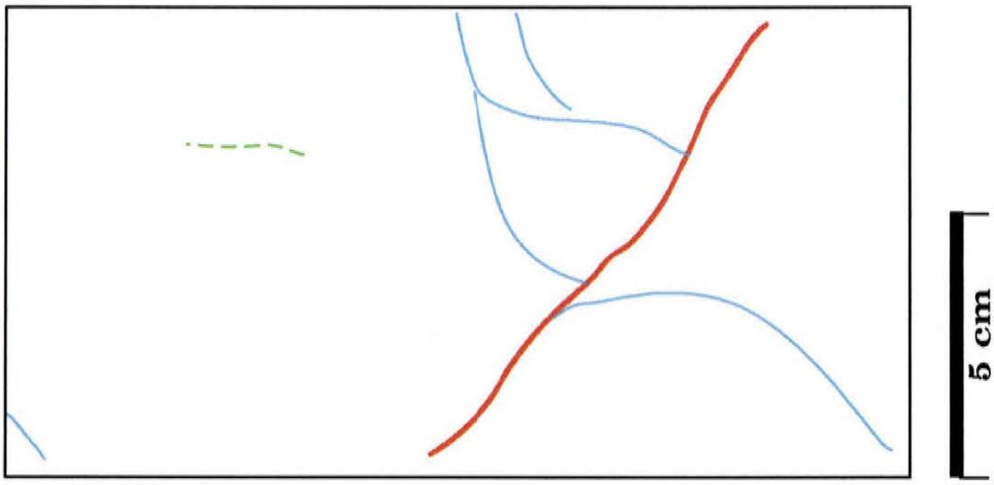
GSI	B/VG	(75) - 80		
P_{32} main frac	0,09		P_{32} total	0,29
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	1	4		
Type	Inclined	Weak horizontal		
2θ	60			
Divergence	Low	None		
Comments	Intersecting			
Dip (° from horizontal)	80	0		
Length m(m)	100	> 53		
Aperture (mm)	< 0.2	Closed		
Surface	Uncoated			
	Undulating, smooth			
J-no	2			
Relief (mm)	4			
JRC	**15**			

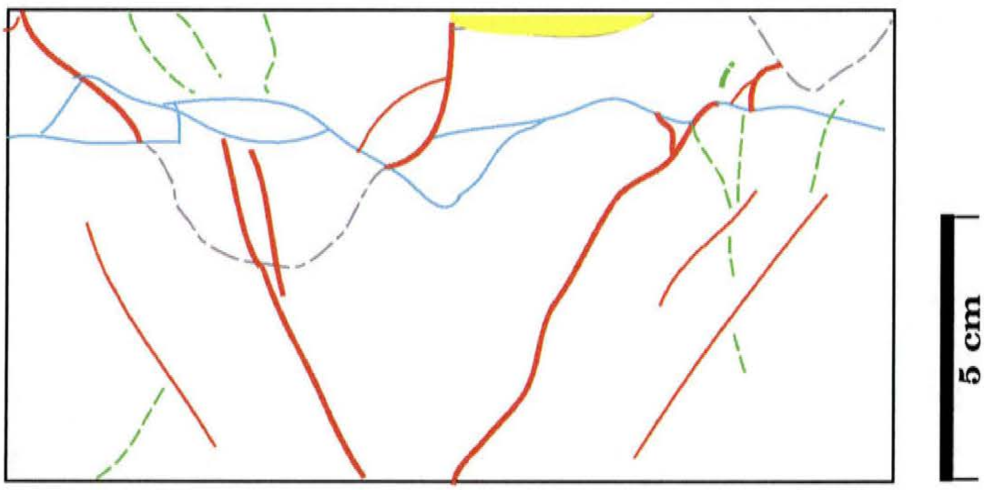
After test

GSI	VB/VG	55 – (60)		
P_{32} main frac	0,33		P_{32} total	0,76
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	3	4	> 5	2
Type	Parallel, inclined	Horizontal	Sub-vertical	
2θ				
Divergence	None	High	None	
Comments	Stratabounded			
Dip (° from horizontal)	50 – 60	0	80	
Length m(m)	110	> 53	10 - 30	
Aperture (mm)	< 0.5	> 0.5	Open, corehandling	
Surface	Uncoated	Uncoated	Uncoated	
	Undulating, smooth	Undulating, rough	Undulating, rough	
J-no	2	3	3	
Relief (mm)	4	10		
JRC	**15**			

Fracture type 3 is test induced caused by the piston.

Hillerslev, HF 10





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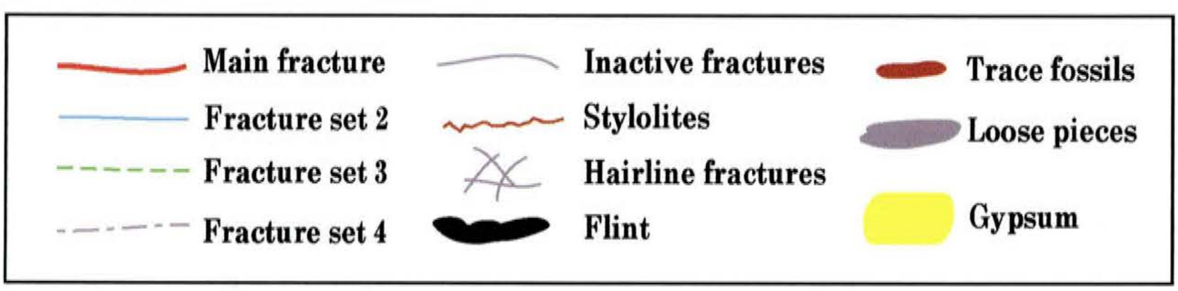


Hillerslev, HF 15

Plug description before test

Burrowed Massive Mudstone, clean chalk, homogeneous, medium hard, low consolidation, biomottled, trace fossils.
1 vertical fracture.

Plug description after hydrostatic compation test.

Length: 65 mm	Diameter: 45 mm	H/D: 1.44
Porosity: 37.2 %	Insoluble residue: 4 %	(87 % clay, 13 % quartz)

Very soft sample with pasty surface. Double slieve and hourglass shape.
NOT POSSIBLE TO DESCRIBE

HF 15 fractures:

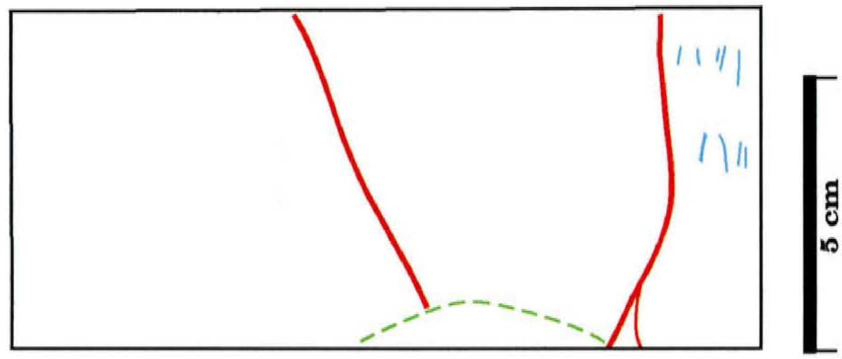
Before test

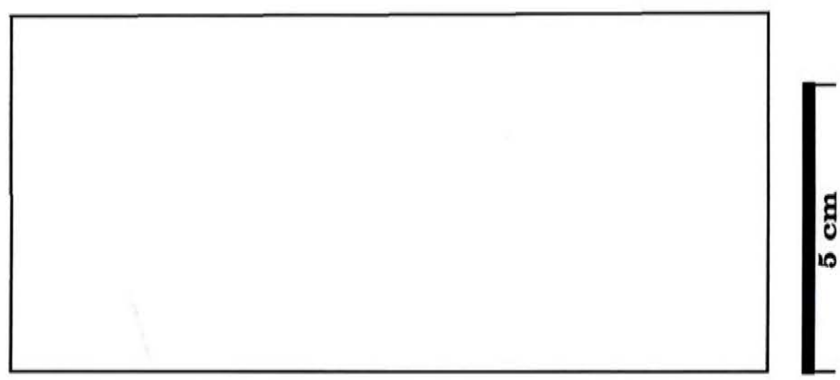
GSI	B/VG	80		
P_{32} main frac	0,20		P_{32} total	0,35
	Main fracture	Fracture 2	Fracture 3	Fracture 4
Numbers	1			
Type	Inclined			
2θ				
Divergence	Low			
Comments				
Dip (° from horizontal)	60			
Length (mm)	75			
Aperture (mm)	< 0.2			
Surface	Uncoated			
	Planar, smooth			
J-no	1			
Relief (mm)	5			
JRC	**20**			

After test

GSI	?			
P_{32} main frac			P_{32} total	
	Main fracture	Fracture 2	Fracture 3	Fracture 4
Numbers	-			
Type				
2θ				
Divergence				
Comments				
Dip (° from horizontal)				
Length (mm)				
Aperture (mm)				
Surface				
J-no				
Relief (mm)				
JRC				

Hillerslev, HF 15





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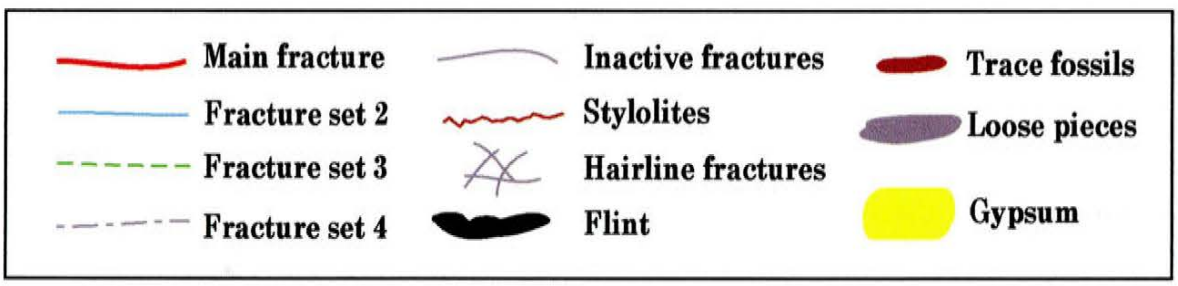
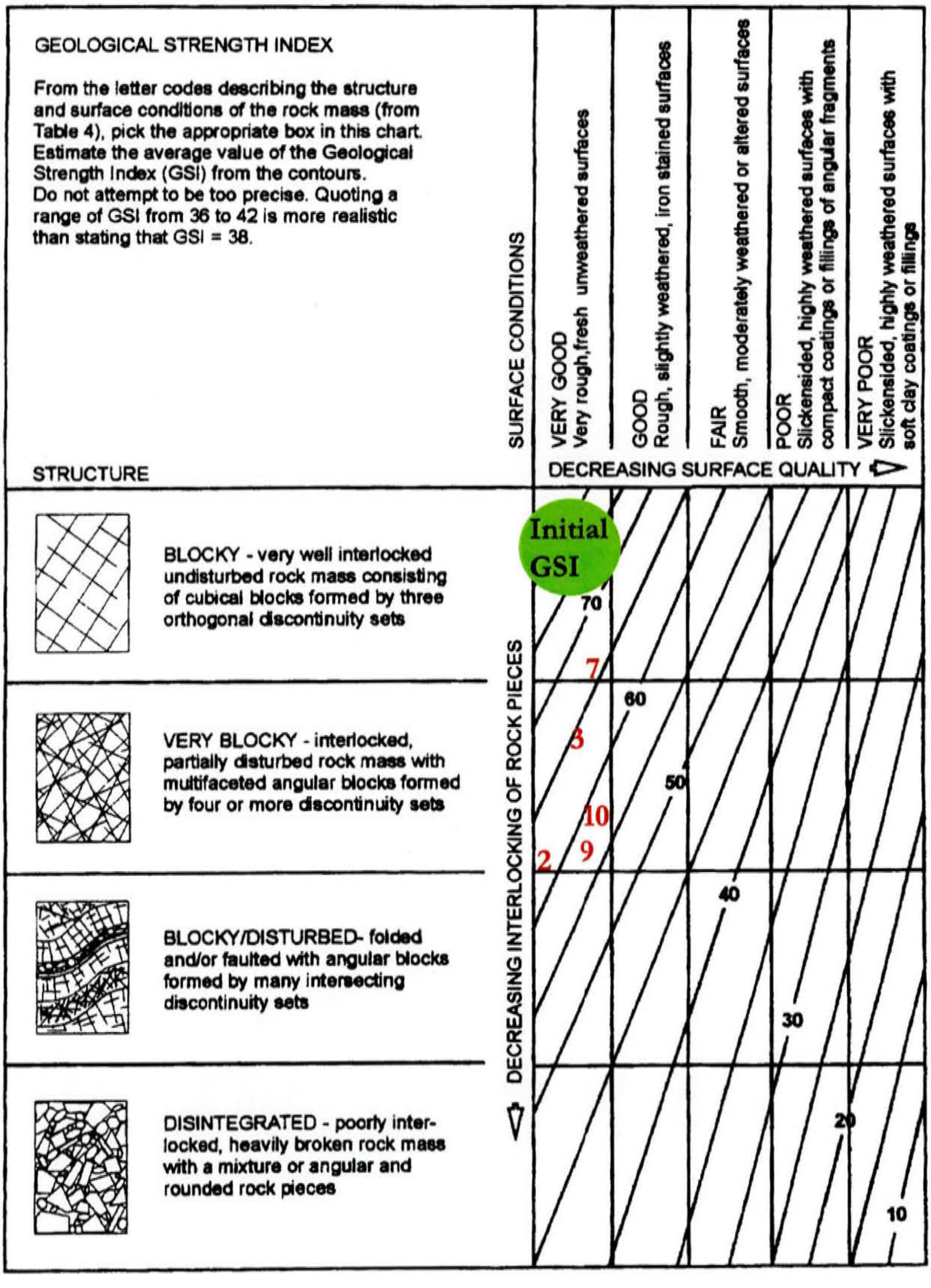


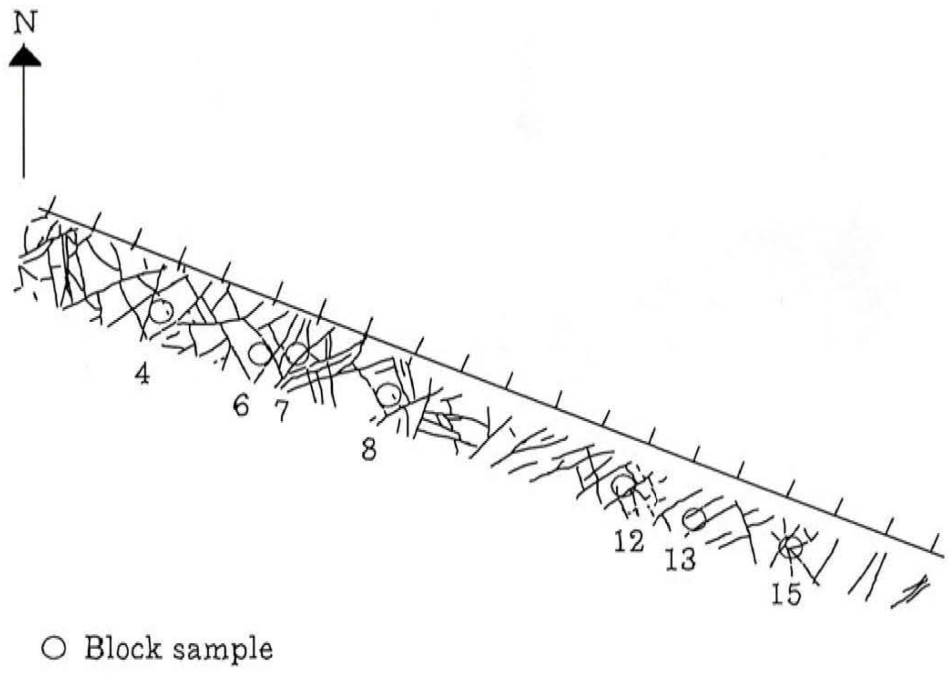
HF samples



Estimate of Geological Strength Index GSI for the HF samples based on plug description. Green: initial GSI values. Red number: Plug sample GSI after test

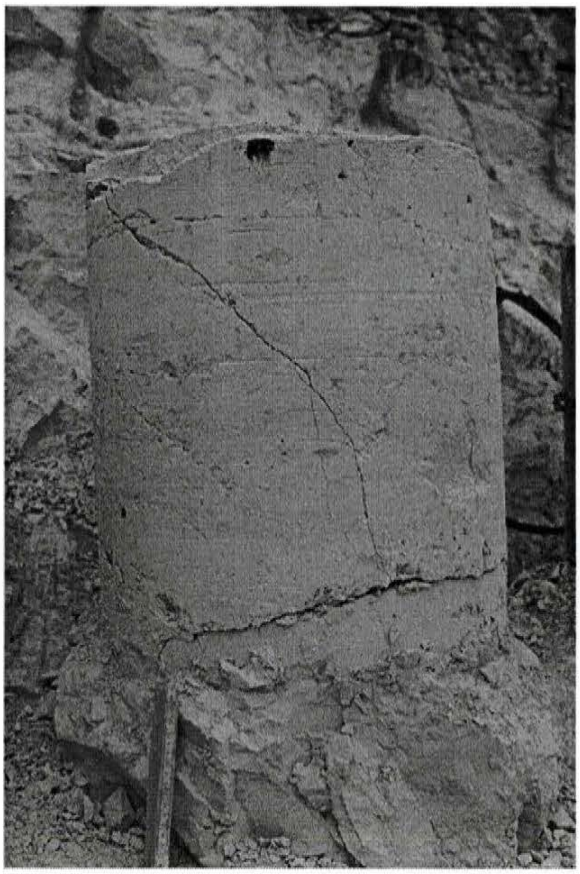
Block samples
Hillerslev

Block samples



Block samples have been drilled at locations with different fracture density and fracture types. The block locations are indicated in the map above showing the platform fracture system from above.

HILLERSLEV, BLOCK 4



HILLERSLEV, BLOCK 4

Field description:

Burrowed Massive Mudstone, clean chalk with silica sponges, thick bedded, moderate hard, low density of trace fossils (*Thalassinoides*), highly fractured.

15-20 cm bedding with fractured bedding planes. Two distinct horizontal fractures are observed in the upper and lower part whereas a less distinct fracture is present in the central part of the block. Offset along the horizontal fractures is not observed. The surfaces of the horizontal fractures are undulating, rough (Jr= 3) with a JRC of 15-20.

The block is cut by a major inclined fracture ($30^{o}/65^{o}$E), slightly converging, uncoated and open (> 1 mm) with a surface roughness of 5. Associated with the major fracture 4 converging (open to closed) sub-parallel ($50^{o} - 70^{o}$) fractures are found. Offset in the order of 4 cm along these fractures can be determined from the sedimentary features.

One set of sub-vertical closed shear fractures are seen in the upper part of the block. These fractures are associated with an offset of 2 cm.

Sampling and preparation:

During sampling the block broke along the lower horizontal fracture and was levelled out with gypsum. Also the highly fragmented upper part was plastered with gypsum prior to test.

Description after multi-triaxial test:

During test a combined block-setting took place. Movements took place along the distinct inclining fracture ($30^{o}/65^{o}$E) and the sub-parallel fractures but due to comtemporanous movements of the sub-vertical fractures new orientations of fractures was formed. Offset along the main fracture of 1 cm is seen. Also new sets (> 7) of sub-vertical fractures (70^{o}) were formed.

The horizontal fractures are only slightly affected, but appear more undulating than prior to test.

Fractures: Block 4

Before test

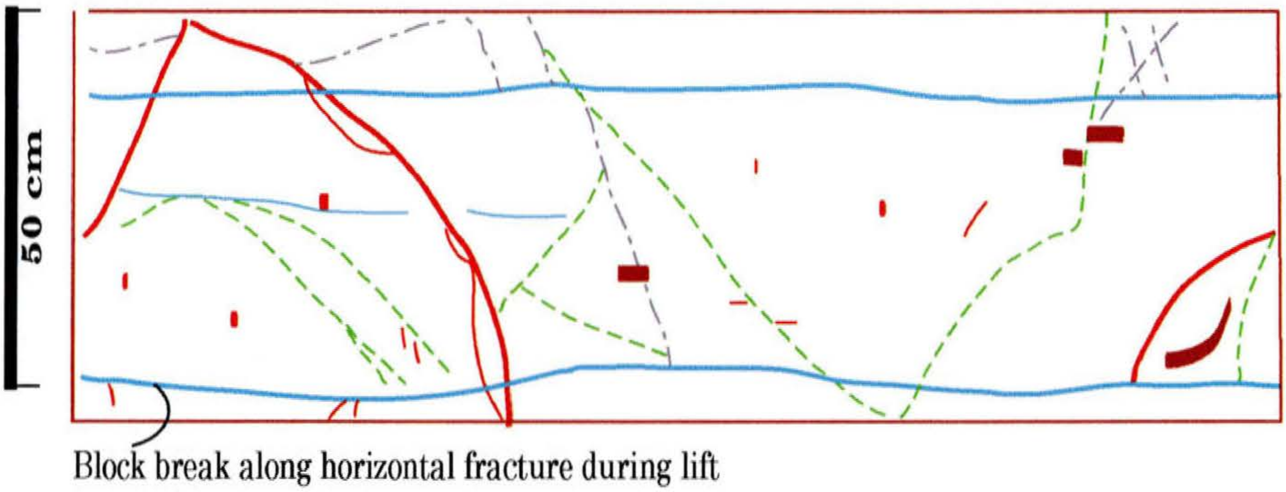
GSI	B/VG	65 – (70)		
P_{32} main frac	0,02		P_{32} total	0,12
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	1	3	>5	2
Type	Inclined	Horizontal	Inclined shear	Sub-vertical
2θ			70	
Divergence	Medium	None	Low	None
Comments			Intersecting	
Dip (° from horizontal)	50 -60	0	50-70	-85
Length (mm)	>600	>500	300-600	>400
Aperture (mm)	> 1	< 0.2	< 0.5-closed	< 0.2 - closed
Surface	Uncoated	Uncoated		
	Undulating, smooth	Undulating, rough		
J-no	2	3		
Relief (mm)				
JRC	**16 - 20**	**16 – 20**		

After test

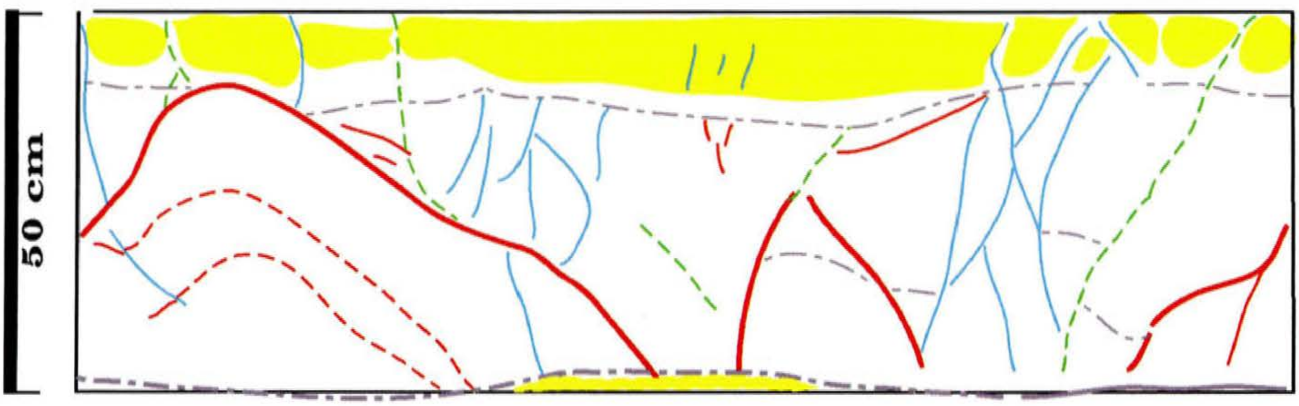
GSI	VB/VG	(55) - 60		
P_{32} main frac	0,04		P_{32} total	0,14
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2 (+ 2)	> 7	3	2
Type	Inclined shear	Sub-vertical	Inclined	Horizontal
2θ				
Divergence	None	Low	None	None
Comments				
Dip (° from horizontal)	40-70	75-85	50	0
Length (mm)	>600	>550	>300	100-500
Aperture (mm)	< 0.2	< 0.2	closed	Closed
Surface	Uncoated	Uncoated	Uncoated	Uncoated
	Undulating, smooth	Undualting, smooth	Undulating, smooth	Undulating, smooth
J-no	2	2		3
Relief (mm)				
JRC				**25**

Hillerslev, Block 4

Field description



After test



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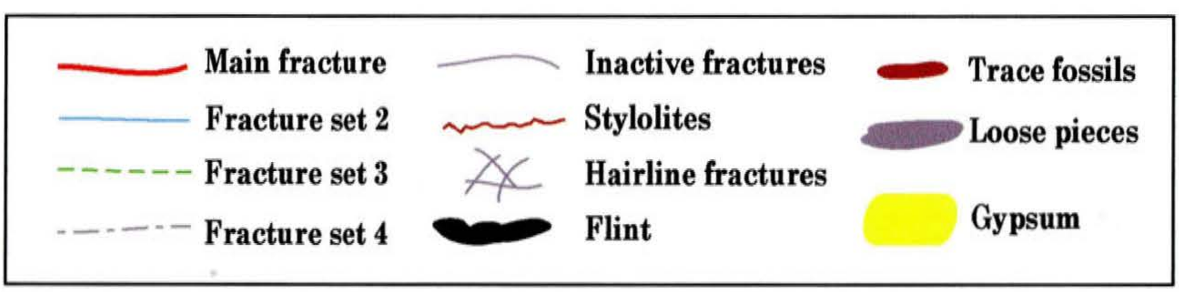


HILLERSLEV, BLOCK 6

Field description:

Burrowed Massive Mudstone, clean chalk with silica sponges, thick bedded, moderate hard, low density of trace fossils (*Thalassinoides*), highly fractured.

15-20 cm bedding with fractured bedding planes. One distinct horizontal fracture is observed in the upper part, whereas 2 less distinct fractures are present in the central and lower part of the block. Offset along the horizontal fractures is not observed. The surface of the horizontal fractures is undulating, rough (Jr= 3) with a JRC of 15-20.

The block is cut by two major inclined fractures (50°/64°SE and 135°/55°S) and two sub-vertical fractures (10°/80°N and 330°/82°NE). Less distinct vertical fractures are seen. All fractures are only slightly converging, uncoated and open (aperture 0.5 – 3 mm).

Sampling and preparation:

Due to the periferal situation of the fractures, hollows and loose fragments are dominating at the surface of the block and plastering with gypsum over large areas has taken place. This coating hampers in some degree the description of the block after test.

Description after multiple triaxial test:

During test the horizontal fractures seem to be activated and form the most distinct change in the fracture pattern. All the existing vertical fractures seem to be slightly re-activated but a few new vertical fractures have been formed.

NB: The test was not completed due to leakage of oil.

Fractures: Block 6

Before test

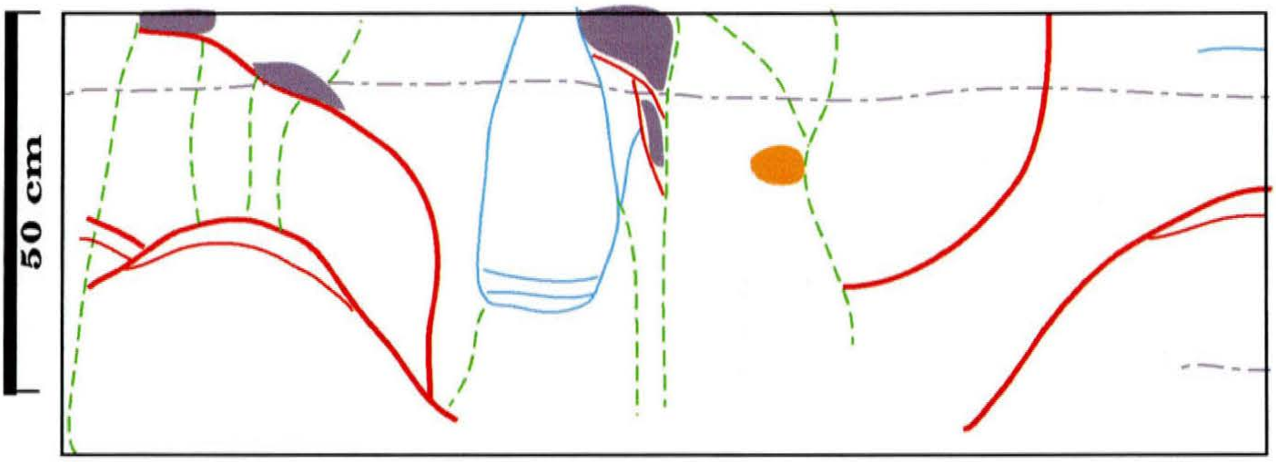
GSI	B/VG	(65) - 70		
P_{32} main frac	**0,05**		P_{32} total	**0,15**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	4	2	> 5	1
Type	Inclined	Sub-vertical	Sub-vertical	Sub-horizontal
2θ	45			
Divergence	Low	Low	None	
Comments	Intersecting			
Dip (° from horizontal)	64 / 55	80	70 – 90	0
Length (mm)	400 – 600	- 550	> 500	
Aperture (mm)	> 1	< 0.2	Closed	< 0.5
Surface	Striation	Uncoated, striation		Uncoated
	Undulating, rough	Undulating, rough	Planar, smooth	Undulating, smooth
J-no	3	3	1	2
Relief (mm)				
JRC	**16**		**18 - 20**	**15 – 20**

After test (not fulfilled)

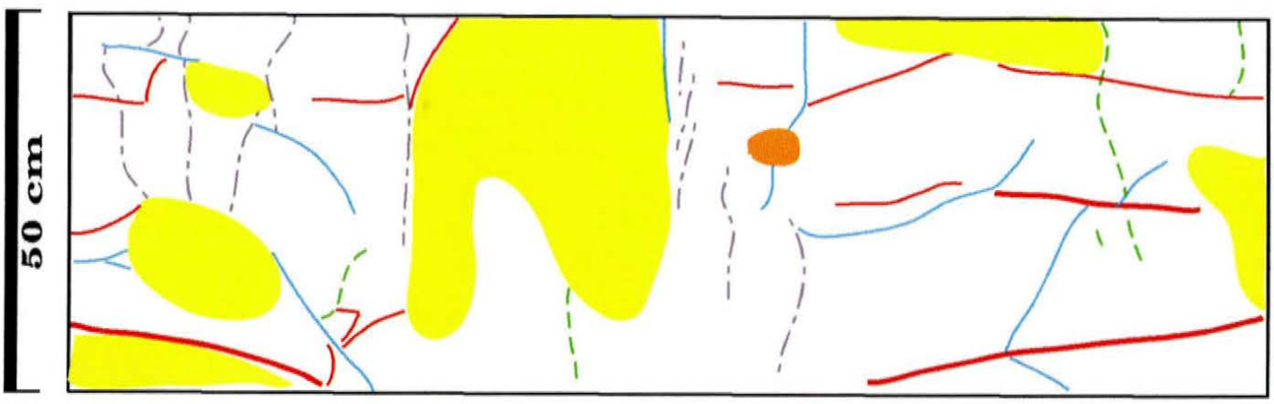
GSI	VB/VG	65 – (70)		
P_{32} main frac	**0,05**		P_{32} total	**0,11**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	3	4	2	> 10
Type	Sub-horizontal	Inclined, intersecting	Sub-vertical	Vertical
2θ		45		
Divergence	None	Low	Low	None
Comments				En-echelon
Dip (° from horizontal)	10	64 / 55	80	80 - 90
Length (mm)	> 500	400 – 600	- 550	100 - 400
Aperture (mm)	< 0.5	< 0.5	> 0.5	Closed
Surface	Uncoated	Uncoated	Uncoated	
	Undulating, smooth	Undulating, rough	Undulating, rough	
J-no	2	3	3	
Relief (mm)				
JRC				

Hillerslev, Block 6

Field description



After test



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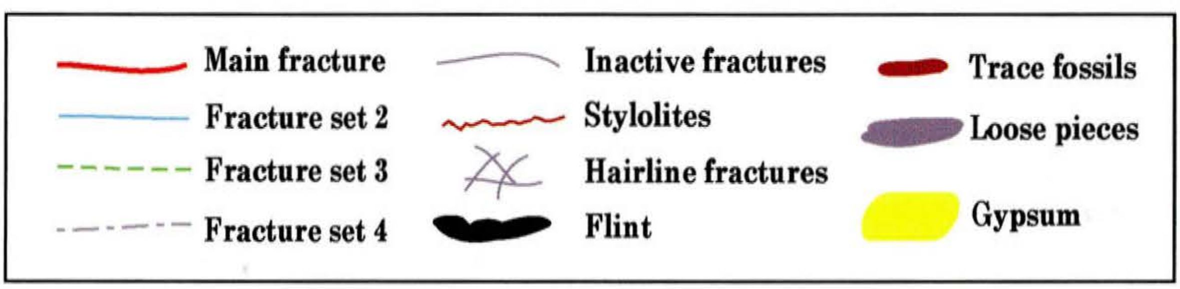


HILLERSLEV, BLOCK 7

Field description:

Burrowed Massive Mudstone, clean chalk with flint nodules, thick bedded, moderate hard, low density of trace fossils (*Thalassinoides*), medium fractured.

15-20 cm bedding with fractured bedding planes. One distinct horizontal fracture is observed in the lower part and one in the central part of the block. Offset along the horizontal fractures is not observed. The surface of the horizontal fractures is undulating, rough (Jr= 3) with a JRC of 15-20.

The block is cut by two conjugate sets of fractures and a few minor sub-vertical fractures. All fractures are slightly converging, uncoated and open (aperture 0.5 – 1 mm).

Sampling and preparation:

During sampling the block broke along the lower horizontal fracture. The block was subsequent levelled out with gypsum. Minor hollows on the block surface have been plastered with gypsum.

Description after multiple triaxial test:

During test the central horizontal fracture was activated and seems to divide the block into an upper and a lower part. Reactivation of the inclined fractures give rise to open fractures along the existing fractures and closed fractures when induced during test. The fracture pattern indicate a slight stratabounding with the highest density in the upper part and a slightly lower density in the lower part. The is a minor indication of an offset of the horizontal fracture by the inclined fractures.

Fractures: Block 7

Before test

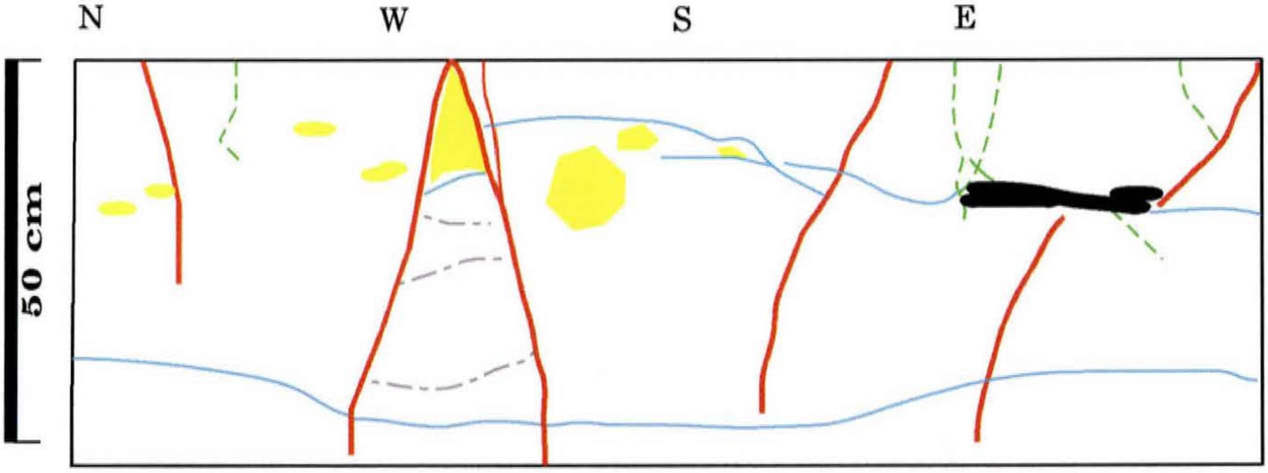
GSI	B/VG	70 – (75)		
P_{32} main frac	**0,04**		P_{32} total	**0,10**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	3	2	2	3
Type	Inclined, intersecting	Horizontal	Sub-vertical	Inclined
2θ	30			
Divergence	Middle	None – low	Low	
Comments				Terminating along main frac
Dip (° from horizontal)	70	0 – 10		60 ?
Length (mm)	> 550	> 500	> 200	
Aperture (mm)	1 – 2	< 0.5 - > 1	< 0.2	
Surface	Uncoated, striation		Uncoated, striation	
	Plane, smooth	Stepped, rough	Undulating, smooth	
J-no	1	4	2	
Relief (mm)				
JRC	**10 - 15**	**20**	**10**	

After test

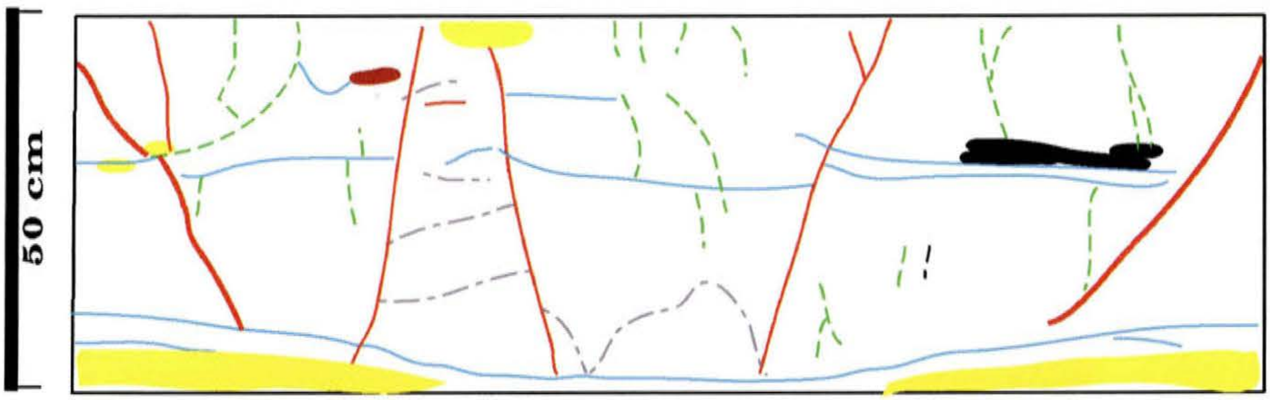
GSI	VB/VG	60 – (65)		
P_{32} main frac	**0,04**		P_{32} total	**0,15**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	3	2	> 10	3
Type	Inclined, intersecting	Horizontal	Sub-vertical	Inclined
2θ	30			
Divergence	None	Low		
Comments			Stratabounded	
Dip (° from horizontal)	70	0 - 10	75 – 90	60 ?
Length (mm)	> 550	> 500	100 –300	
Aperture (mm)	> 1	< 0.5	Closed	
Surface	Uncoated			
	Plane, smooth	Undulating, rough		
J-no	1	2		
Relief (mm)				
JRC				

Hillerslev, Block 7

Field description



After test



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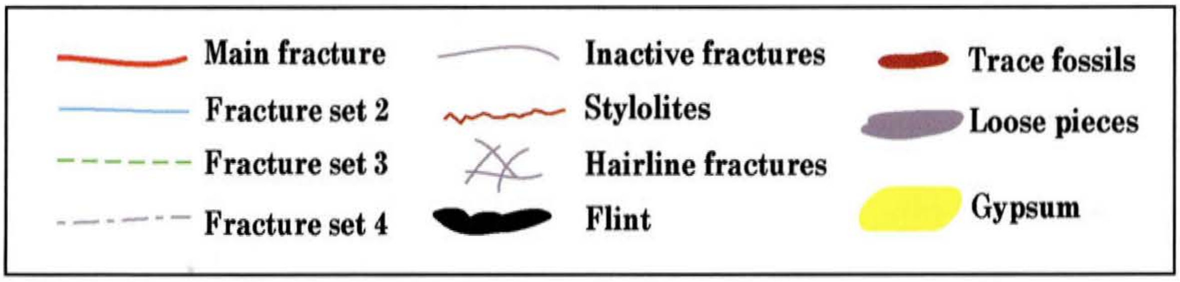


HILLERSLEV, BLOCK 8

Field description:

Burrowed Massive Mudstone, clean chalk with flint nodules, thick bedded, moderate hard, low density of trace fossils (*Thalassinoides*), low fractured.

15-20 cm bedding with fractured bedding planes with a distinct horizontal fracture located in the central part of the block. Offset along the horizontal fractures is not observed. The surface of the horizontal fractures is undulating, smooth with an amplitude of more than 5 mm and a wave length of 5 cm. (Jr= 2 and JRC = 20).

The block is cut by one major inclined fractures (*$50^o/64^o$SE*) and a series of less distinct vertical to sub-vertical fractures. All fractures are slightly converging, uncoated and open (aperture 0.5 – 1 mm). The distribution of fractures indicate a low degree of stratabounding.

Sampling and preparation:

The top and bottom of the block has been plastered with gypsum for levelling purposes. This distinct amount of gypsum seems to have some impact on the fracturing of the block (not all fractures can be followed through the plastered interval.

Description after multiple triaxial test:

A large number of vertical and sub-vertical fractures have been formed during test. The swarms of vertical/sub-vertical fractures are located around the natural fractures. During test the horizontal fractures seem to be activated and many of the induced fractures terminates at the horizontal fracture. Associated with the compaction the gypsum "caps" seems to have acted as one homogeneous unit and have caused the formation steep dipping fractures associated with the expulsion of the block juxtapositioned to the caps.

The vertical fracture surfaces are rather complex and rough due to the cross-cut/termination of minor shear fractures.

Fractures:

Block 8

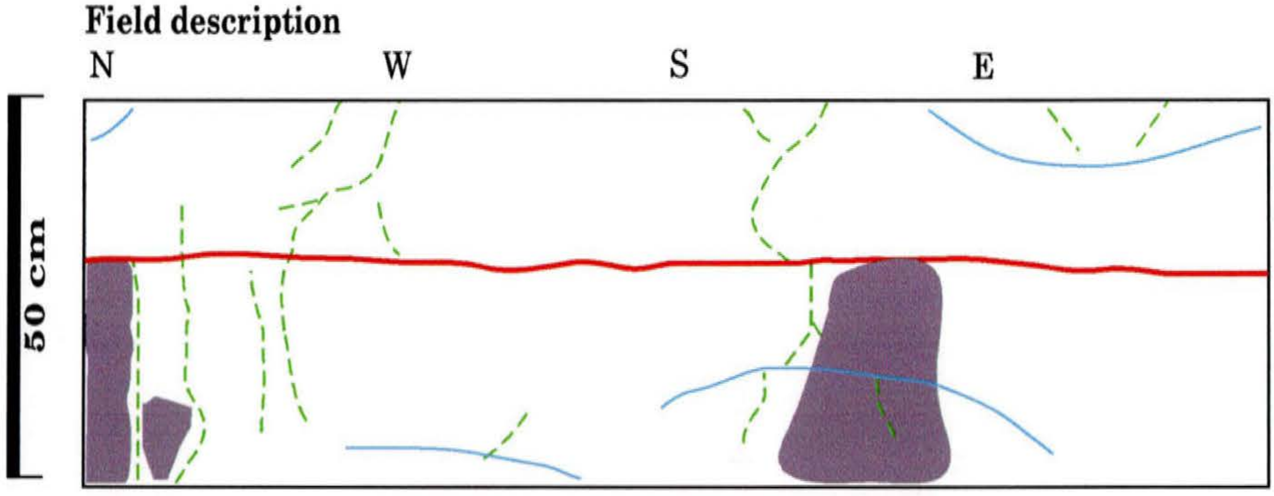
Before test

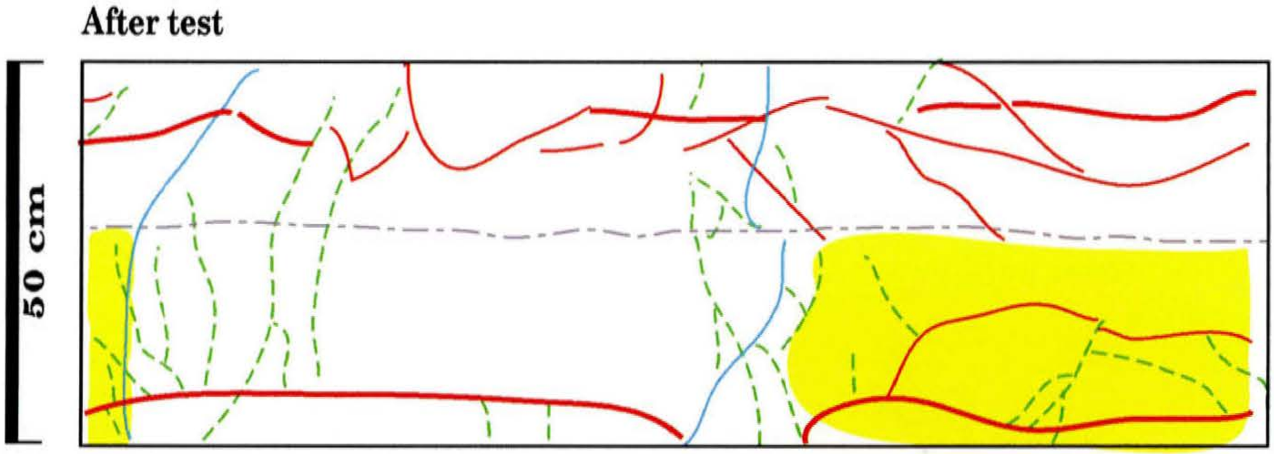
GSI	B/VG	75 – (80)		
P_{32} main frac	0,03		P_{32} total	0,09
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	1	1	> 6	
Type	Horizontal	Inclined	Sub-vertical	
2θ				
Divergence	None	None	Low	
Comments			Stratabounded	
Dip (° from horizontal)	0 – 10		70 – 90	
Length (mm)	> 500		> 350	
Aperture (mm)	> 1		< 0.5	
Surface				
	Undulating, smooth		Undulating, smooth- rough	
J-no	2			
Relief (mm)				
JRC	**10**		**10**	

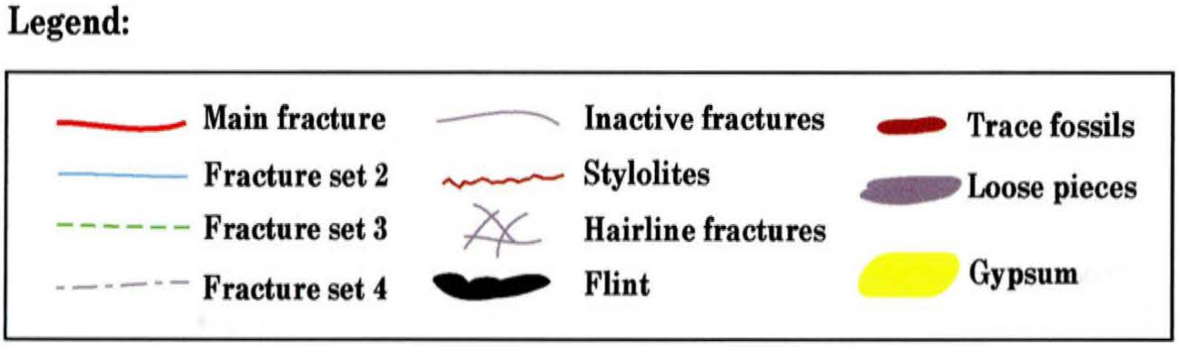
After test

GSI	VB/VG	55 – (60)		
P_{32} main frac	0,08		P_{32} total	0,18
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	1	> 10	1
Type	Sub-horizontal	Sub-vertical	Sub-vertical, intersecting	Horizontal
2θ	30		30	
Divergence	Low	None	High	None
Comments	Piston impact	Stratabounded	Stratabounded	
Dip (° from horizontal)	50 – 60	70 – 80	70 – 90	0 – 10
Length (mm)		> 500	100 – 400	> 500
Aperture (mm)		> 0.5	Closed	> 1
Surface	Complex	Complex		
				Undulating, smooth
J-no				2
Relief (mm)				
JRC				**15**

Hillerslev, Block 8







HILLERSLEV, BLOCK 12

Field description:

Burrowed Massive Mudstone, clean chalk, thick bedded, moderate hard, low density of trace fossils (*Thalassinoides*), highly fractured.

15-20 cm bedding with weakly to indistinct fractured bedding planes. One gently dipping sub-horizontal fractures (15° S) is observed in the lower part. Offset along the horizontal fractures may have occurred and many of the vertical and sub-vertical fractures terminates at the fracture. The block appears with stratabound fracturation with the highest density in the upper part. The surface of the sub-horizontal fracture is undulating, smooth (Jr= 2) with a JRC of 20.

A conjugate set of fractures (70°/65°) and a major open undulated rough fracture (265°/70° NW) are cut by both distinct and indistinct vertical fractures. All distinct fractures are slightly converging, uncoated and open (aperture 0.5 – 1 mm).

Sampling and preparation:

Due to the periferal situation of the fractures, hollows and loose fragments are dominating at the surface of the block and plastering with gypsum over large areas has taken place. This coating hampers to some degree the description of the block after test. During the lift of the block the sample broke along the sub-horizontal fracture and gypsum was used for levelling.

Description after multiple triaxial test:

During test the main activity was associated with shear-movements along the major sub-vertical fracture (265°/70° NW) and a series of new induced fractures are introduced. The shear movements gave rise to slickensided surfaces. The induced fractures are undulating, rough with a relief of up to 3 mm. Possible movements along the remaining fractures is not possible to determine due to gypsum cover.

Fractures: Block 12

Before test

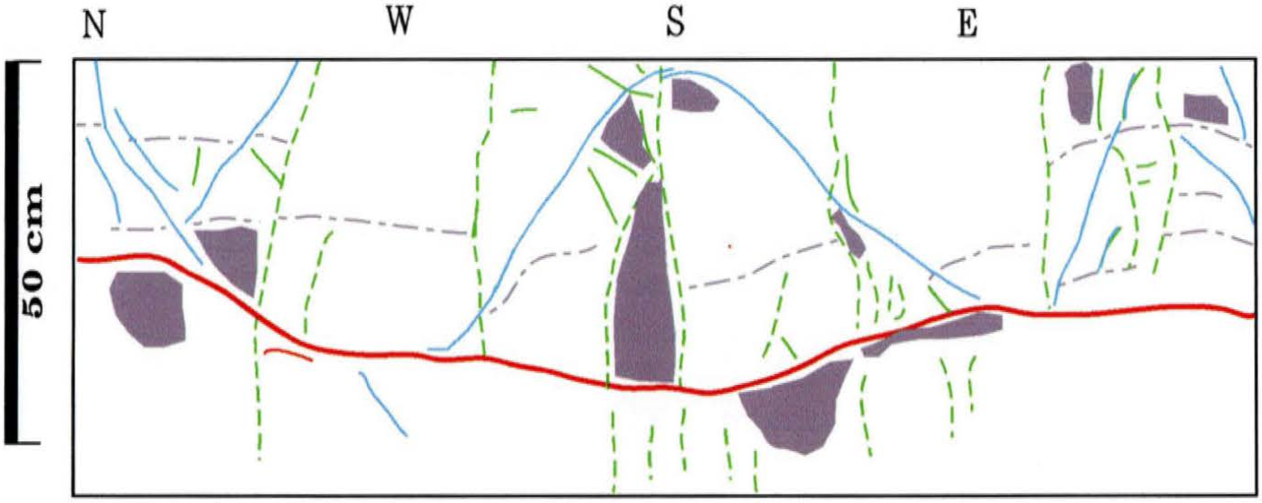
GSI	VB/VG	(60) - 65		
P_{32} main frac	0,03		P_{32} total	0,17
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	4	4	> 10
Type	Sub-horizontal	Inclined, intersecting	Sub-vertical	Associated fractures
2θ		70		
Divergence	None	Low	High	
Comments	Upper fracture, indistinct	Terminates at horizontal fract	Stratabounded	Stratabounded breccia zone
Dip (° from horizontal)	10	50	80 – 90	
Length (mm)	> 500	< 300	100 – 400	- 300
Aperture (mm)	> 5	< 0.5	< 0.5	
Surface	Uncoated	Uncoated, striation	Uncoated	Uncoated
	Undulating, smooth	Undulating, smooth	Undulating, smooth	
J-no	2	2	2	
Relief (mm)		3		
JRC	**20**			

After test

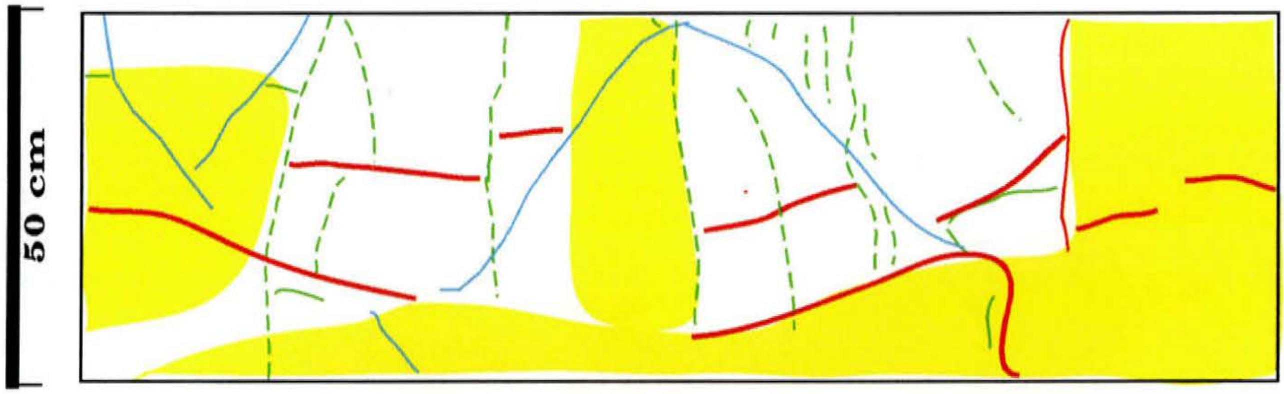
GSI	VB/VG	55 – (60)		
P_{32} main frac	?		P_{32} total	?
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	3	> 10	
Type	Sub-horizontal	Inclined, intersecting	Sub-vertical	
2θ		70		
Divergence	None	Low	Medium	
Comments			Affected by horizontal frac	
Dip (° from horizontal)	10	50	80 – 90	
Length (mm)	> 500	< 400	> 500	
Aperture (mm)	> 5	< 0.5	< 0.5	
Surface	Uncoated	Slickensided		
	Undulating, smooth	Undulating, rough	Undulating, rough	
J-no	2	3		
Relief (mm)				
JRC			**16**	

Hillerslev, Block 12

Field description



After test



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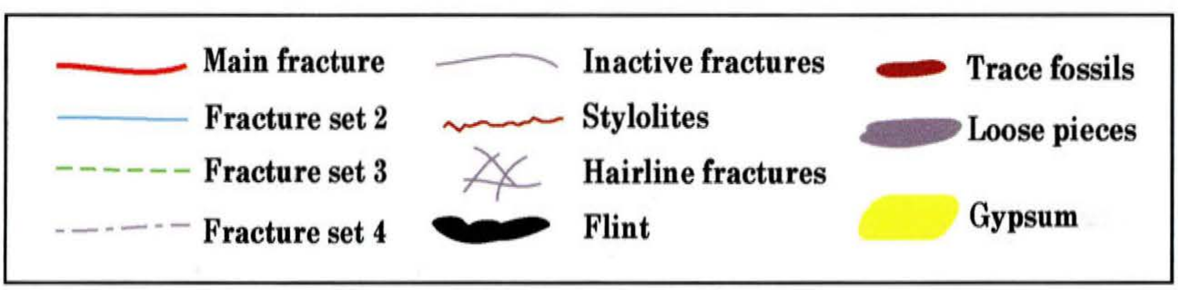


HILLERSLEV, BLOCK 13

Field description:

Burrowed Massive Mudstone, clean chalk, fine bedded, moderate hard, low density of trace fossils (*Thalassinoides*), moderate stratabounded fractured.

5-10 cm bedding with fractured bedding planes. Three distinct sub-horizontal fractures are observed in the middle part of the block. Minor offset along the horizontal fractures is observed. The surface of the horizontal fractures is undulating, smooth (Jr= 2) with a JRC of 15-20.

One cross-cutting vertical fracture is seen in the block whereas more than five sub-vertical fractures can be seen in the upper part of the block. Below the sub-horizontal fractures only one sub-vertical fracture can be seen.

Sampling and preparation:

Due to the periferal situation of the fractures, hollows and loose fragments are dominating at the surface of the block and plastering with gypsum over large areas has taken place. This coating hampers in some degree the description of the block after test.

Description after multiple triaxial test:

During test the horizontal fractures was activated as gliding planes but no difference between gliding plane and fracture surfaces is seen. Movements along the sub-vertical natural fractures are associated with the formation of induced sub-parallel fractures located in swarms around the natural fractures. There is no clear evidence of sub-vertical fractures cross-cutting the horizontal fracture zone. The horizontal fractures may have an offset of more than 2 cm.

Some of the induced fractures appears as en-echelon fractures with an offset of 1 cm. Also striation is seen in the vertical fractures. The sub-vertical fractures appear with vertical striation, are undulating and rough (plane in separate fractures). The fracture length is ranging from 30-50 cm, the aperture is 0.5 mm, amplitude < 1cm and the wave length 5 cm.

Fractures:

Block 13

Before test

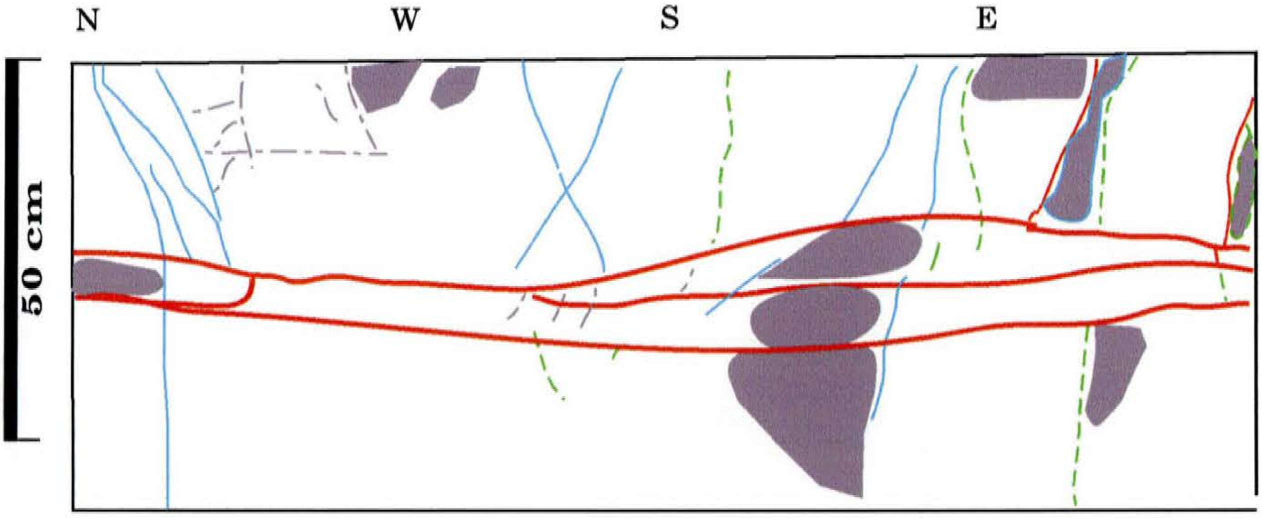
GSI	VB/VG	(60) - 65		
P_{32} main frac	0,08		P_{32} total	0,15
	Main fracture	Fracture 2	Fracture 3	Fracture 4
Numbers	3	> 10	2	> 5
Type	Sub-horizontal	Inclined, intersecting	Vertical	Random
2θ		40		
Divergence	Low	Low	None	Low
Comments	Sub-parallel	Stratabounded	Cross-cut + termination	Stratabounded
Dip (° from horizontal)	10	60 – 70	85	0 – 70
Length (mm)	> 500	> 200	> 500	100 – 250
Aperture (mm)	- 0.5		< 0.2	
Surface		Uncoated		
	Undulating, smooth	Undulating, smooth		
J-no	2	2		
Relief (mm)				
JRC	15	10 - 15		

After test

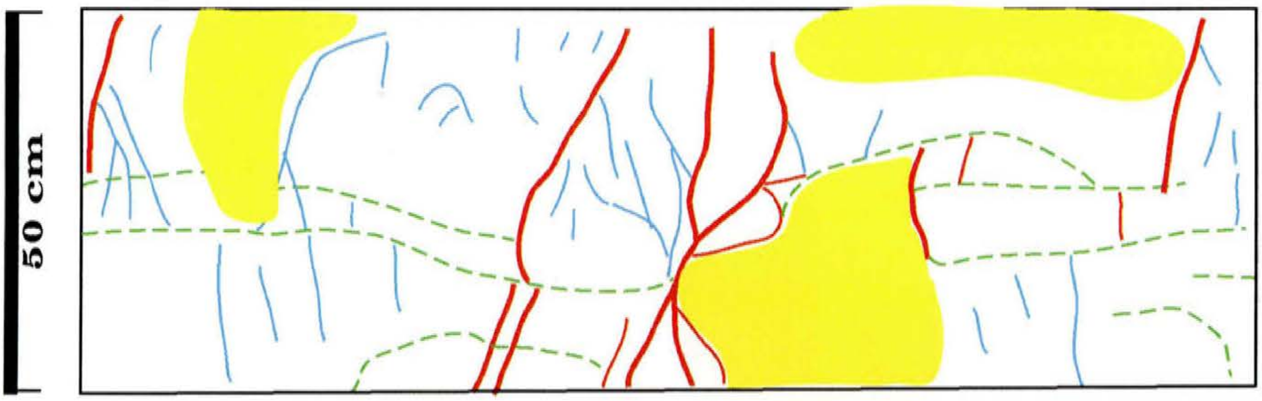
GSI	BD/VG	(55) - 60		
P_{32} main frac	0,04		P_{32} total	0,13
	Main fracture	Fracture 2	Fracture 3	Fracture 4
Numbers	4	> 10	3	> 20
Type	Inclined, intersecting	Sub-vertical, intersecting	Sub-horizontal	Associated fractures
2θ	25	30		
Divergence	Low	Medium	None	
Comments	Cross cut + horizontal fract	En-echelon, stratabounded	Bedding plane fractures	Piston induced
Dip (° from horizontal)	60 – 70	80 - 90	10	
Length (mm)	> 500	< 300	500	< 100
Aperture (mm)			- 0.5	
Surface		Striation		
			Undulating, smooth	
J-no			2	
Relief (mm)				
JRC			15	

Hillerslev, Block 13

Field description



After test



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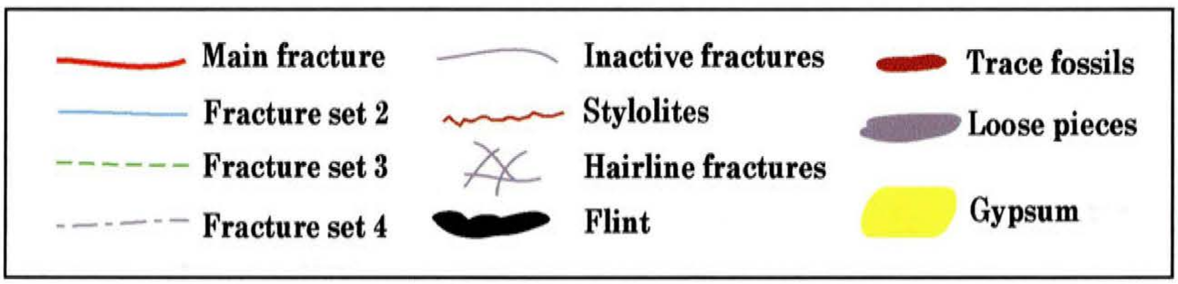


HILLERSLEV, BLOCK 15

Field description:

Burrowed Massive Mudstone, clean chalk, thick bedded, moderate hard, low density of trace fossils (*Thalassinoides*), highly stratabound fracturation.

10-30 cm bedding with fractured bedding planes in the central part of the block. The upper bedding plane is less distinct than the lower one, which appears as breccia zone.

A distinct vertical and a sub-vertical fracture is seen in the upper part and cross-cut and offsets the upper bedding plane, but terminates at the lower fracture zone. A few 10-20 cm vertical fractures in-between the bedding planes are seen, terminating at the bedding planes. Below the lower fracture zone 4-5 vertical fractures occur.

Sampling and preparation:

The block is extremely blocky and is held together with tape and plastered with gypsum – especially along the brecciated zone.

Description after multiple triaxial test:

During test the horizontal fractures seem to be activated and an additional fracture has been added. All the existing vertical fractures seem to be slightly re-activated but a high number of new vertical fractures have been formed. The horizontal fractures divides the block into three and the density of induced vertical fractures varies in the different intervals.

Fractures: **Block 15**

Before test

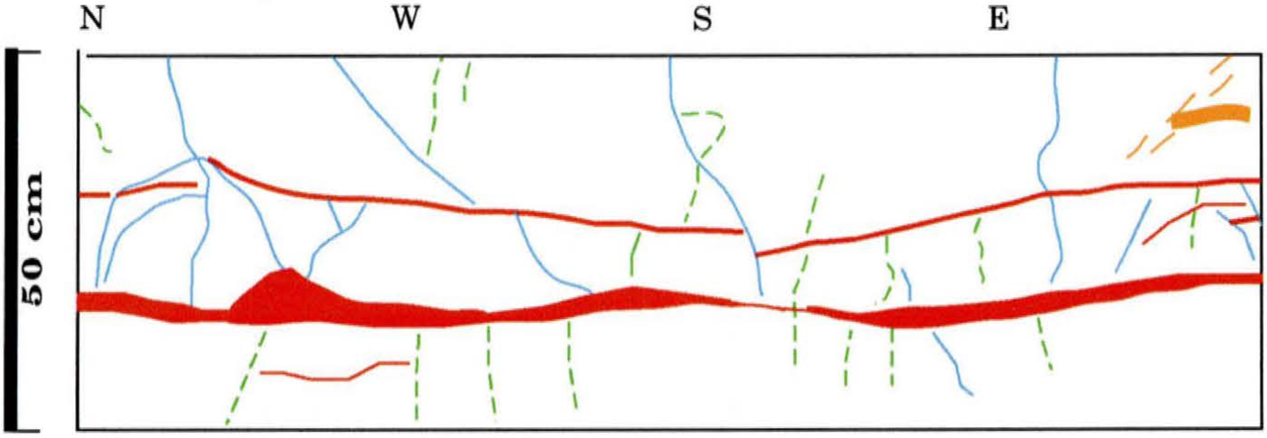
GSI	VB/VG	(60) - 65		
P_{32} main frac	0,06		P_{32} total	0,12
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	> 10	> 20	
Type	Sub-horizontal	Inclined, intersecting	Sub-vertical	
2θ		35		
Divergence	Low	Low	None	
Comments				
Dip (° from horizontal)	0-10	60 - 80	70 - 90	
Length (mm)	> 500	100 - 400	50 - 300	
Aperture (mm)	- 5	< 0.2	< 0.2	
Surface	Uncoated	Uncoated	Uncoated	
	Undulating, smooth	Planar, smooth	Smooth, planar	
J-no	2.0	1.0	1.0	
Relief (mm)				
JRC	**20**	**16**	**16**	

After test

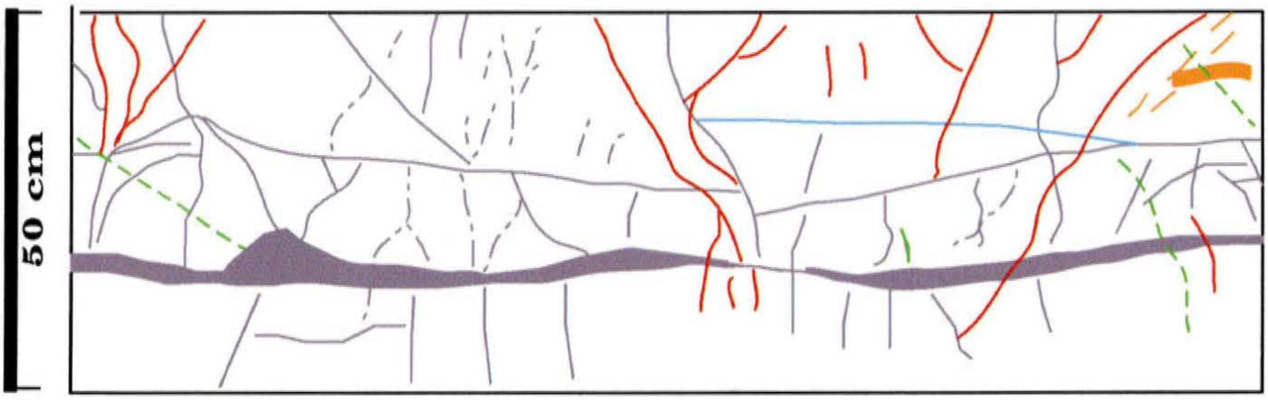
GSI	DB/VG	50 – (55)		
P_{32} main frac	0,04		P_{32} total	0,16
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	> 10	3	2	> 20
Type	Inclined, intersecting	Sub-horizontal	Vertical	Sub-vertical
2θ	30 - 40			
Divergence	Low	Low	Medium	None
Comments	Parallel with old inactive	2 fract. inactive		
Dip (° from horizontal)	60 - 80	0-10	80 - 90	70 – 90
Length (mm)	50 - 500	> 50	40	5 – 30
Aperture (mm)	< 0.2	- 5	0.2 – 0.5	< 0.2
Surface	Uncoated	Uncoated	Uncoated	Uncoated
	Smooth, planar	Smooth, undulated	Smooth, undulated	Planar, smooth
J-no	1.0	2.0	2.0	1
Relief (mm)				
JRC	**16**	**20**	**18**	**16**

Hillerslev, Block 15

Field description



After test



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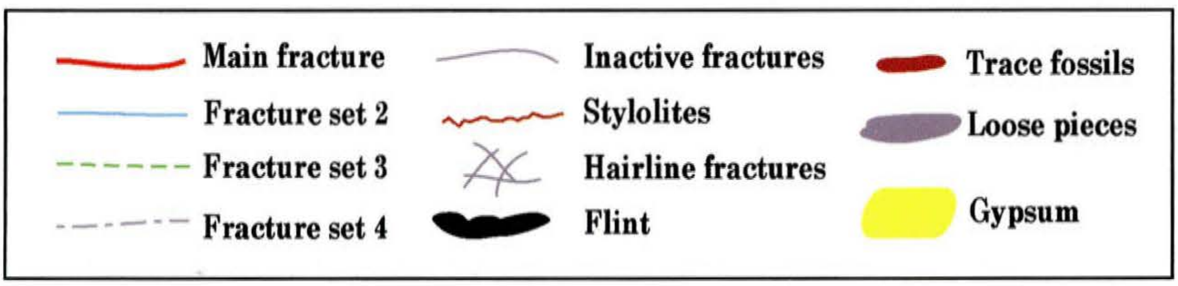
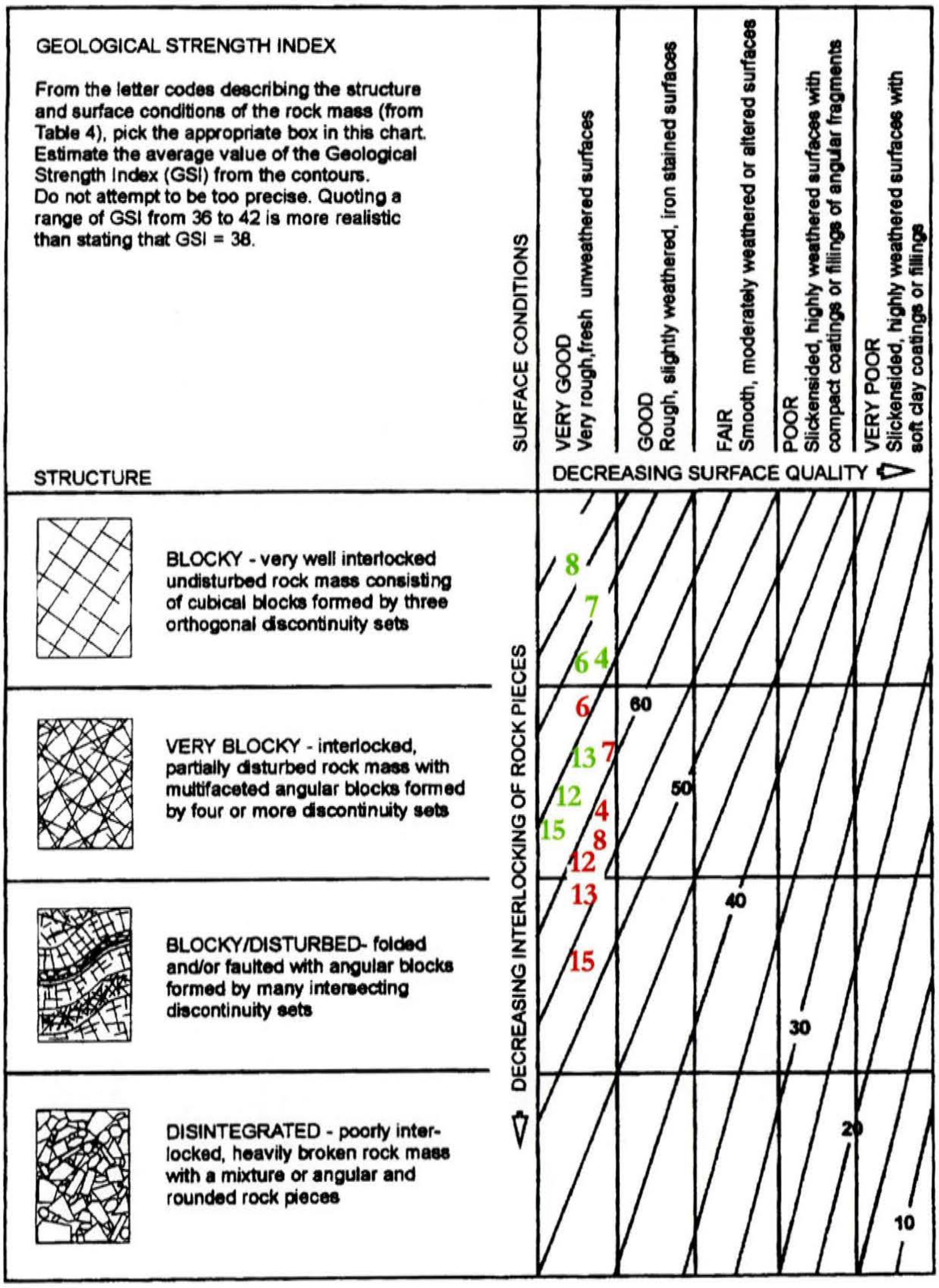


Hillerslev block samples



Estimate of Geological Strength Index GSI for the block samples based on plug description. Green number: Initial GSI values. Red number: Block sample GSI after test

TYRA FIELD

In September 1996 a 150 ft core interval from a Tyra well was inspected at Mærsk core laboratory. The core interval was described in some detail and a number of samples were taken for rock mechanical analyses.

A summary of the core description is shown on figure T-1. Sample intervals are indicated with arrows.

The examined interval is bioturbated but in varying intensity. In the upper 10' of the interval the chalk is relatively clayish indicated by lamination, primary as well as secondary (pressure dissolution seams). Downward the chalk becomes massive with a high density of hairline fractures. The pressure dissolution seams grade slightly into thin, low amplitude stylolites.

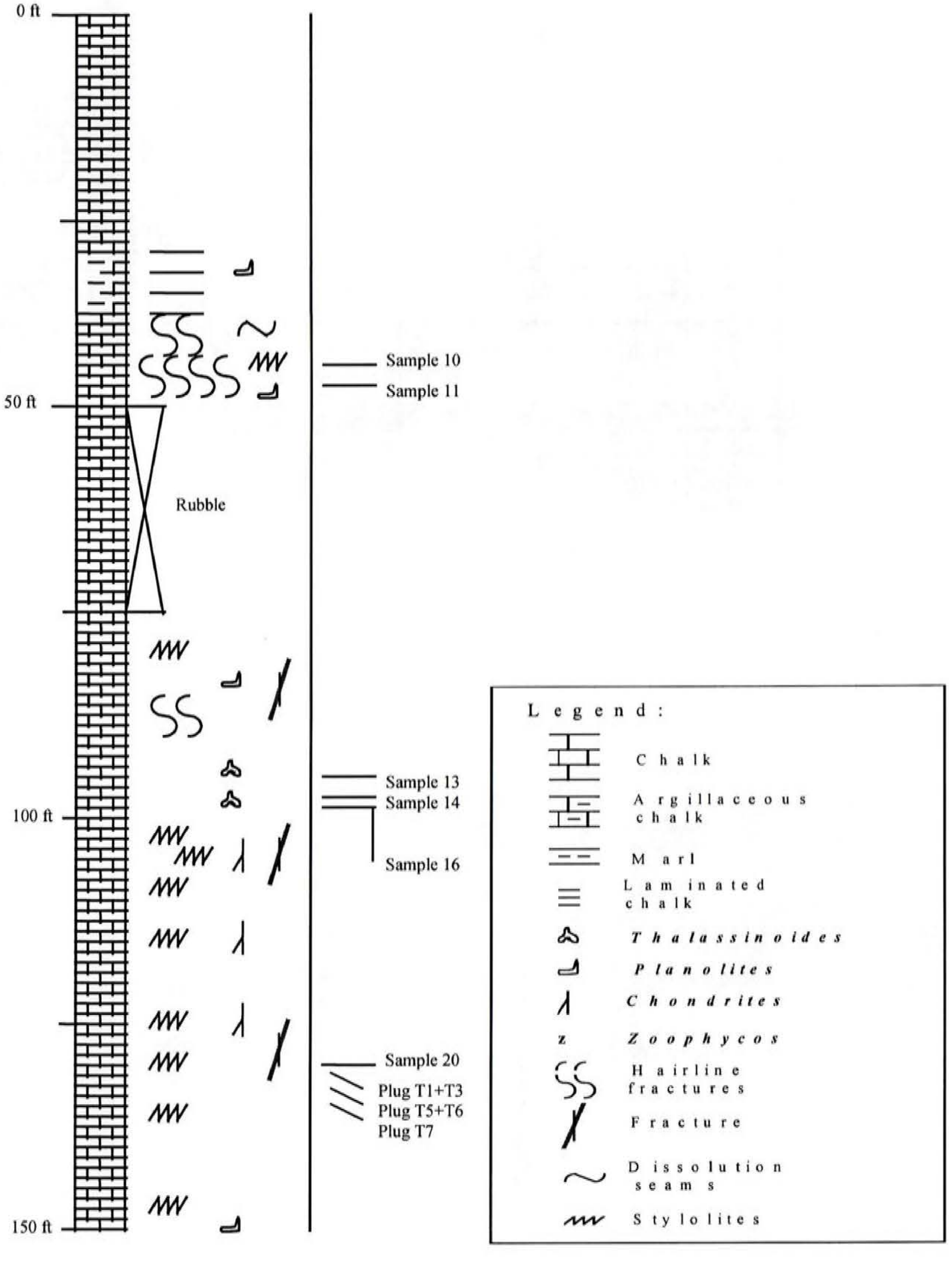
The interval from 80' to 100' is characterised by a rather homogeneous chalk. Burrows of *Thalassinoides* are seen but no stylolites or dissolution seams are observed. The interval is heavily affected by shearing and up to 1 cm wide shear fractures are seen. The shear fractures are often filled with brecciated clasts in a fine grained matrix.

From 100' to 170' the massive chalk is dominated by high amplitude stylolites.

The presence of stylolites and dissolution seams is indicative of severe dissolution of the chalk with subsequent recrystallisation giving rise to hard well cemented chalk. Due to some variation in the diagenesis in the core interval some variation in the cementation is seen and the samples are described separately.

The chalk in the examined core interval is characterised by a biogenic wackestone texture. The chalk is highly cemented. In the upper part calcite cement crystals are in the order of 1-2 μm. Microspar crystals (> 5 μm) are rare in the matrix but common in the foraminifera chambers. In the lower part microspar crystals are more common in the matrix which may be a result of a higher intensity of stylolitization.

Tyra well


0 ft
50 ft
100 ft
150 ft
Rubble
Sample 10
Sample 11
Sample 13
Sample 14
Sample 16
Sample 20
Plug T1+T3
Plug T5+T6
Plug T7
Legend:
Chalk
Argillaceous chalk
Marl
Laminated chalk
Thalassinoides
Planolites
Chondrites
Zoophycos
Hairline fractures
Fracture
Dissolution seams
Stylolites

Analyses carried out on Tyra core samples

Sample	Porosity	Permea-bility	Thin section	Capillary pressure	Insoluble residue	SEM	Geotechnical test type
10	**X**	**-**	**X**		**X**	**X**	**Direct shear test**
11A	**X**	**AIR**	**X**		**X**	**X**	**Direct shear test**
11B						**X**	**Direct shear test**
13A	**X**	**AIR**	**X**		**X**	**X**	**Multiple triaxial test**
13B						**X**	**Multiple triaxial test**
14A	**X**	**AIR**					**Multiple triaxial test**
16	**X**	**AIR**				**X**	**Multiple triaxial test**
16B	**X**	**AIR**	**X**		**X**	**X**	**Uniaxial strain compaction**
20A						**X**	**Direct shear test**
20B	**X**	**-**	**X**		**X**	**X**	**Direct shear test**
T1	**X**						**Multiple triaxial test**
T2							
T3	**X**						**Multiple triaxial test**
T4							
T5	**X**						**Multiple triaxial test**
T6	**X**						**Multiple triaxial test**
T7	**X**						**Multiple triaxial test**

Tyra Field, T1

Plug description before test.

Burrowed Massive Mudstone, chalk, hard and well consolidated, high density of trace fossils (*Chondrites, Zoophycos and Thalassionoides*), accumulated stylolites with more than 4 seams in one stylolite. 6 major stylolites evenly distributed in the plug giving a stylolite density of 1.5/cm. 1. order relief up to 1.5 cm with amplitudes of up to 5 mm.

Fine closed fractures cross-cut the stylolites and offset the stylolites in the order of 5 mm. Also indistinct highly converging hairline fractures can be observed.

Plug description multiple triaxial test.

Height: 9 cm,	Diameter: 5.3 cm	
Porosity: 28.6 %	Insoluble residue: 2 %	(97 % clay, 3 % quartz)

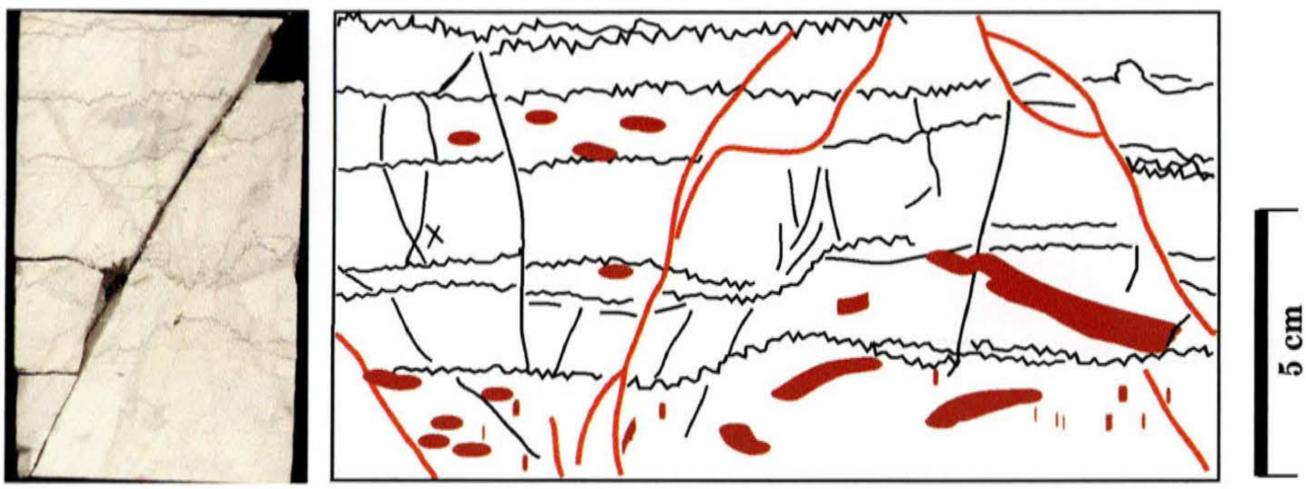
After test the plug was fractured along one major converging fracture (70^o). The fracture is parallel with an indistinct zone of weakness but oblique to a distinct vertical natural fracture. The fracture surface is an undulating concave slickensided surface (Jr:1.5). The relief along a strike line is 4 mm/ 4 cm (JRC > 20) whereas the roughness along the dip direction is 4 mm/ 10 cm (JRC: 15).

T 1
Fractures:

After test

GSI	**B/VG**	**75**	**Incl. Styl+cem.frac**	**BD/VG 55**
P_{32} main frac	**0,28**		**P_{32} total**	**0,28**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	1	> 20		
Type	Inclined	Sub-vertical shear		
2θ				
Divergence	Medium- high			
Comments	New, uninfluenced by earlier fractures	Natural fractures, stratabounded		
Dip (° from horizontal)	50 - 70			
Length (mm)	> 100	Stylolite dependent		
Aperture (mm)	> 0.5	Closed		
Surface	Striation			
	Planar, slickensided			
J-no	0.5			
Relief (mm)	4			
JRC	**20**			

Tyra Field, T 1



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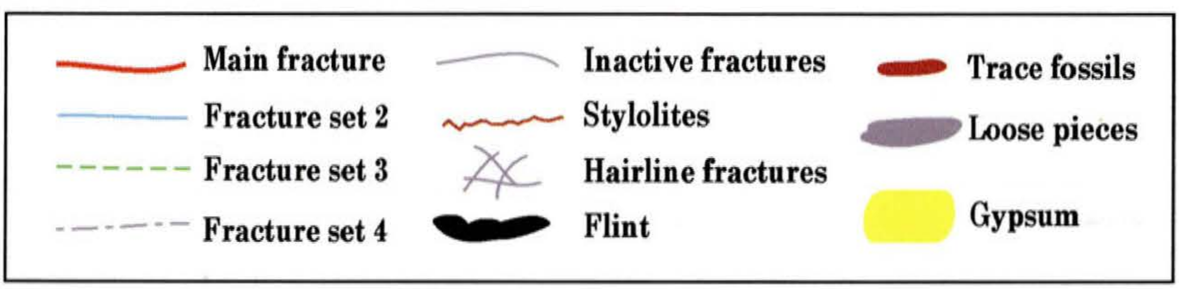


TYRA , T3

Plug description before test.

Burrowed Massive Mudstone, chalk, hard and well consolidated, high density of trace fossils (*Chondrites, Zoophycos and Thalassionoides*), accumulated stylolites with more than 3 seams in one stylolite. 15 major stylolites un-evenly distributed in the plug (10 in the upper half and 5 in the lower half, density 2 stylolites/cm).
1. order relief up to 1.5 cm with amplitudes of up to 5 mm.

Fine stratabounded closed fractures are found in between the stylolites. Minor offsets of the stylolites are seen along zones of weakness. Also indistinct highly converging hairline fractures can be observed.

Plug description after multiple triaxial test.

Height: 8.9 cm, Diameter: 5.5 cm

Porosity: 28.5 % Insoluble residue: 8 % (96 % clay, 4 % quartz)

After test the plug was fractured along two merging highly converging fractures ($75^{o}/65^{o}$). The fracture crosses a zone of weakness dominated by vertical hairline fractures. Associated with the main fracture minor sub-parallel and stratabounded fractures are formed.

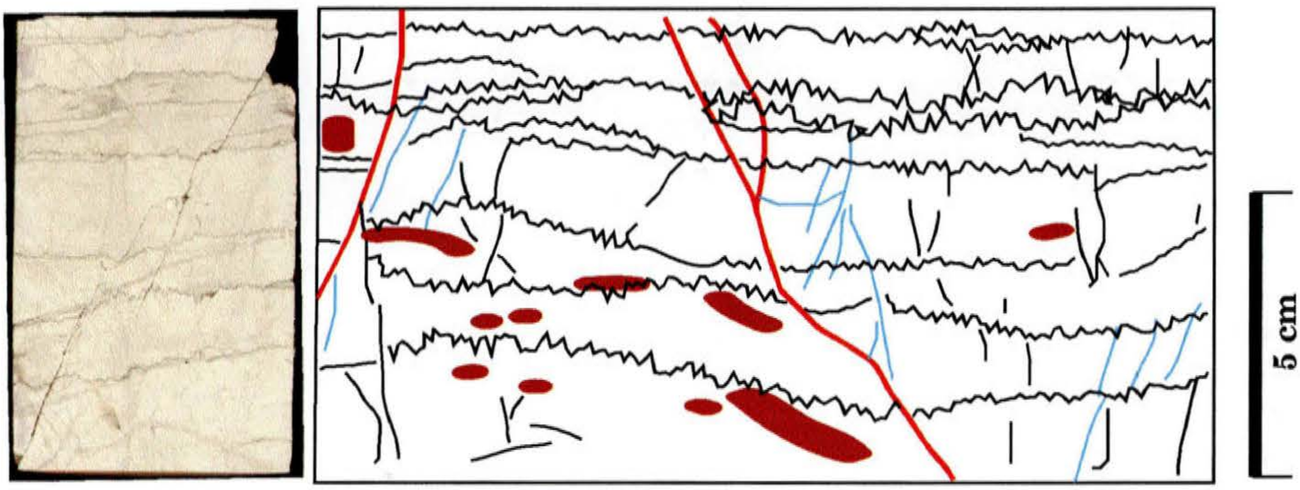
The fracture surface is planar smooth to slickensided (Jr: 1.5). The relief along the dip direction is 2 mm /4 cm (JRC: 15).

T 3
Fractures

After test

GSI	**B/VG**	**(65) - 70**	**Incl. Styl+frac**	**BD/VG 50 - 55**
P_{32} main frac	**0,34**		**P_{32} total**	**0,34**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	1	> 10	> 20	
Type	Inclined	Sub-vertical	Sub-vertical	
2θ				
Divergence	High	Low		
Comments		Fracture associated, stratabounded, partly cross-cutting stylolite zones	Stratabounded, inactive to partly reactivated	
Dip (° from horizontal)	50 - 65	80 - 90	80	
Length (mm)	> 100	< 30	Stylolite dependant	
Aperture (mm)	> 0.5	< 0.2		
Surface	Striation			
	Planar, smooth-slickensided			
J-no	1.0			
Relief (mm)	2			
JRC	**> 20**			

Tyra Field, T 3



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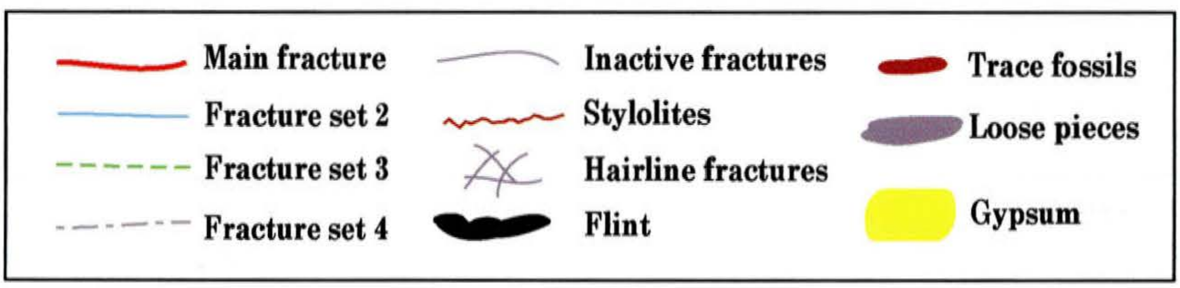


Tyra Field, T5

Plug description before test.

Burrowed Massive Mudstone, chalk, hard and well consolidated, low density of trace fossils (*Chondrites and Zoophycos*), accumulated stylolites with more than 2-3 seams in one stylolite. 3 major stylolites un-evenly distributed in the plug (2 in the upper half and 1 in the lower half, density is 0.5 stylolite/cm).
1. order relief up to 1 cm with amplitudes of up to 5 mm.

A few fine indistinct closed fractures are found off-setting the stylolites.

Plug description after multiple triaxial test.

Height: 9,8 cm, Diameter: 5,5 cm

Porosity: 29.1 % Insoluble residue: 3 % (94 % clay, 6 % quartz)

After test the plug was broken and a large piece was lost when removing the rubber membrane.

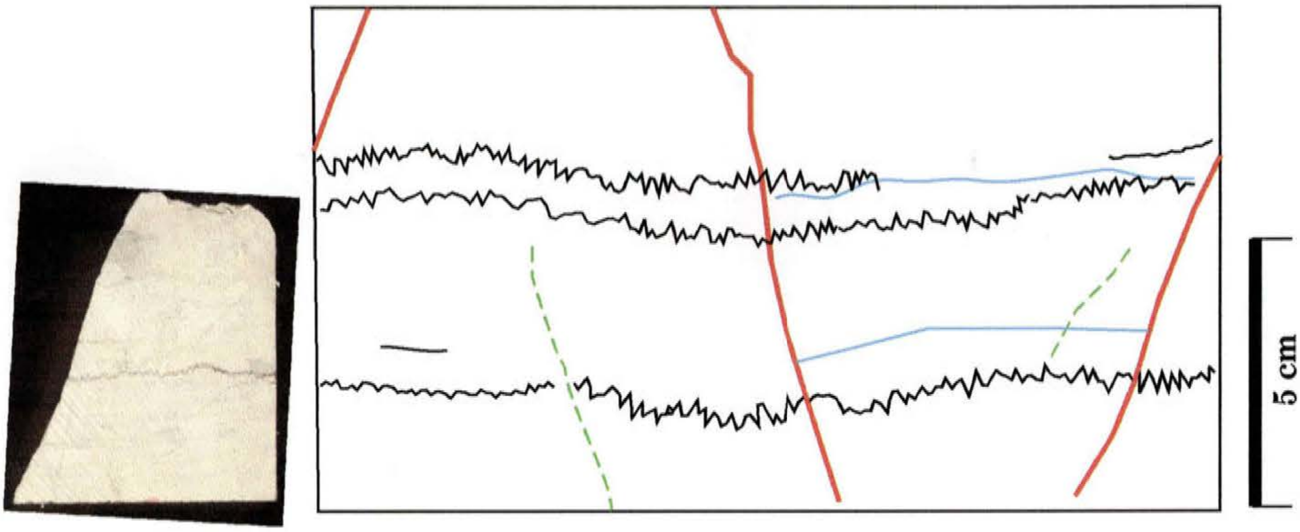
The plug was fractured along one major open fracture (75^o). The fracture is associated with two horizontal fractures corresponding to zones of weakness caused by stylolites.
The fracture surface is an undulating concave smooth surface (Jr: 2). The relief along a strike line is 6mm/5cm (JRC > 20) whereas the roughness along the dip direction is 2 mm /4 cm (JRC = 18).

T 5
Fractures

After test

GSI	B/VG	75 – (80)	Incl. Styl.+frac	B/VG 70
P_{32} main frac	0,16		P_{32} total	0,29
	Main fracture	Fracture 2	Fracture 3	Fracture 4
Numbers	1	2	2	
Type	Sub-vertical	Horizontal	Sub-vertical	
2θ				
Divergence	None	None	None	
Comments		Weakness zone parallel with stylolite	Partly stratabounded, inactive	
Dip (° from horizontal)	75	0	75	
Length (mm)	> 90	< 25	< 60	
Aperture (mm)	-	< 0.2		
Surface	Uncoated	Uncoated		
	Undulating, smooth	Planar, rough		
J-no	2	1.5		
Relief (mm)	2	2		
JRC	**18**			

Tyra Field, T 5



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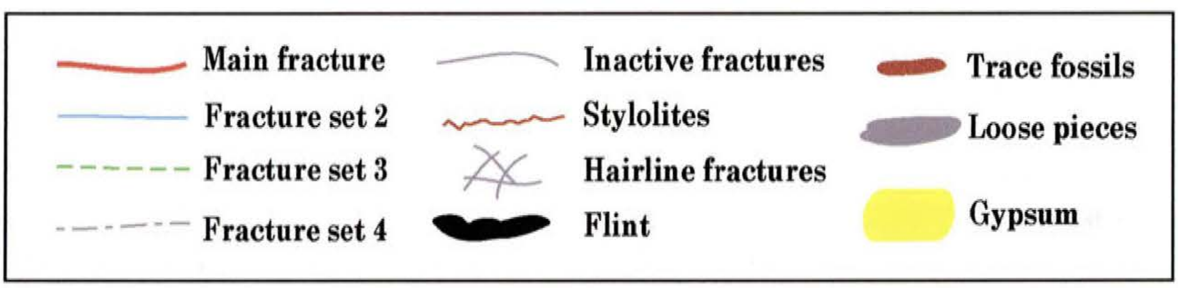


Tyra Field, T6

Plug description before test.

Burrowed Massive Mudstone, chalk, hard and well consolidated, low density of trace fossils (*Chondrites and Thalassionoides*), accumulated stylolites with more than 2 seams in one stylolite. 3 major stylolites un-evenly distributed in the plug (1 in the upper half and 2 in the lower half, density < 0.5 stylolite/cm).
1. order relief up to 1cm with amplitudes of up to 5 mm.

Closed vertical and inclined fractures are found offsetting the stylolites (2-3 mm). Also indistinct highly converging and conjugated hairline fractures can be observed.

Plug description after multiple triaxial test.

Height: 9.8 cm,	Diameter: 5.5 cm	
Porosity: 28.8 %	Insoluble residue: 4 %	(95 % clay, 5 % quartz)

After test the plug was broken and a number of small pieces were lost during removal of the rubber membrane.

Two sub-parallel converging fractures (65^o) cross-cut the plug. In addition re-activation of the vertical fracture has taken place.

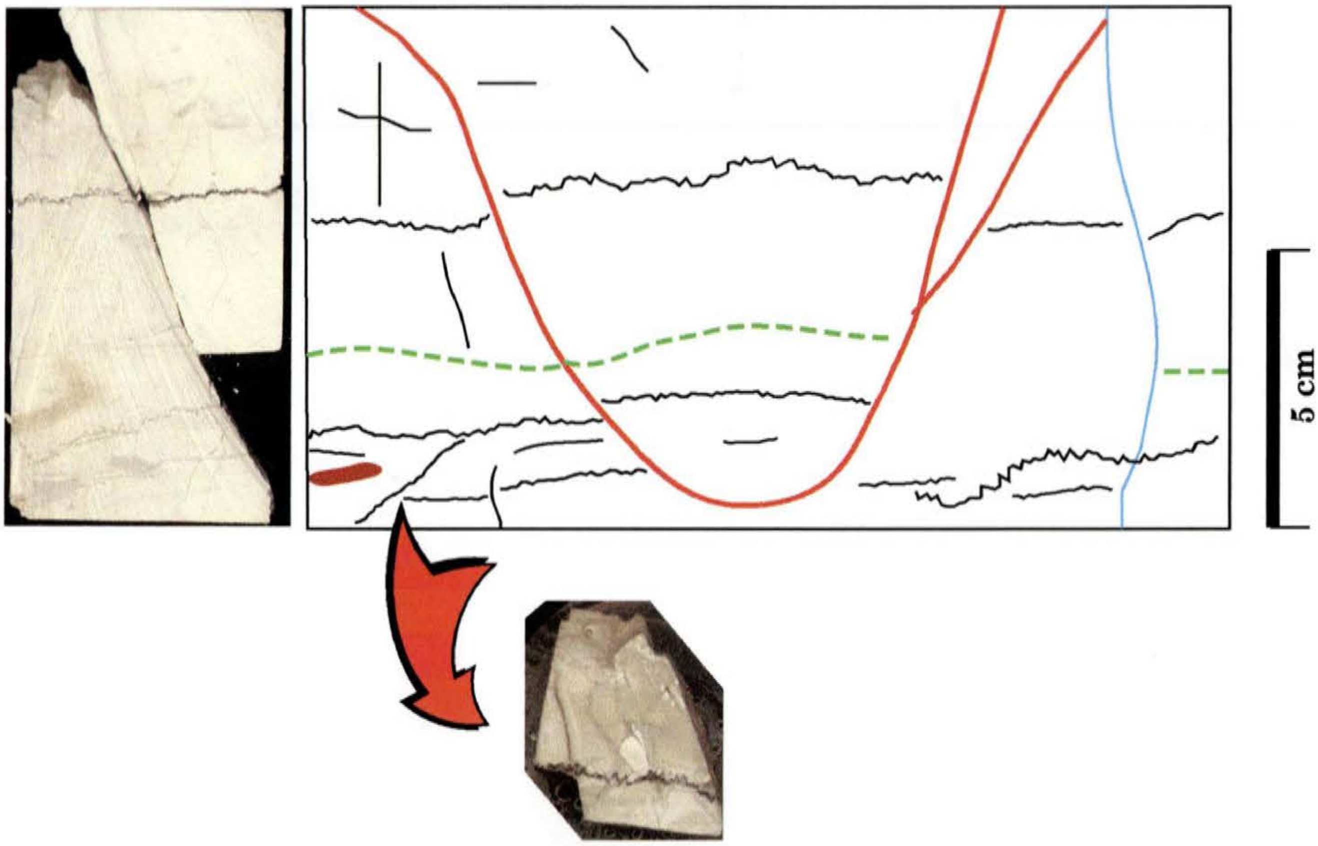
The fracture surface is an undulating concave slickensided surface (Jr:1.5). The relief along a strike line is 1mm/3.5 cm (JRC: 10) whereas the roughness along the dip direction is 2 mm /5 cm (JRC : 16).

T 6
Fractures

After test

GSI	B/VG	75	Incl. Styl.+frac	VB/VG 65
P_{32} main frac	0,22		P_{32} total	0,39
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	1	1	> 5
Type	Inclined	Vertical	Horizontal	Random
2θ				
Divergence	Low	None	None	Low
Comments				Natural, stratabounded
Dip (° from horizontal)	65	85 - 90		
Length (mm)	> 100	> 90		< 30
Aperture (mm)	- 1	< 0.2		
Surface	Uncoated			
	Planar, smooth			
J-no	1.0			
Relief (mm)	3			
JRC	**20**			

Tyra Field, T 6



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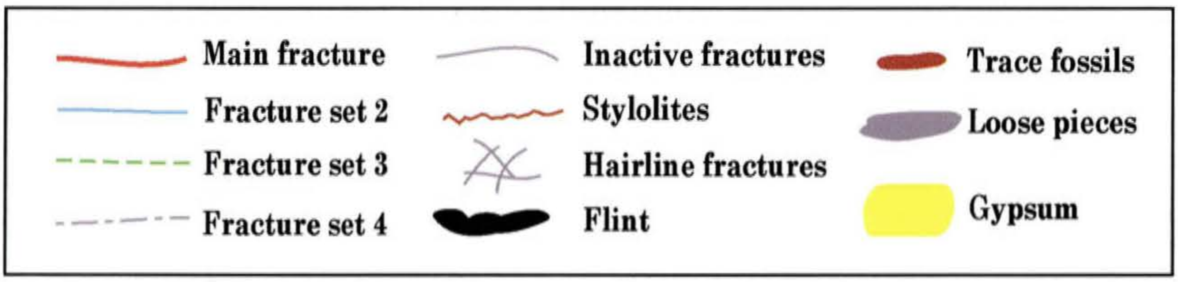


TYRA , T7

Plug description before test.

Burrowed Massive Mudstone, chalk, hard and well consolidated, high density of trace fossils (*Chondrites, Zoophycos and Thalassionoides*), accumulated stylolites with more than 3 seams in one stylolite. 15 major stylolites un-evenly distributed in the plug (distance between stylolites ranges from less than 5mm to 2 cm, density: > 2 stylolites /cm).
1. order relief less than 1 cm with amplitudes of up to 3 mm.

Fine stratabounded closed fractures are found in between the stylolites. Minor offsets of the stylolites are seen along zones of weakness. Also indistinct highly converging hairline fractures can be observed.

Plug description after multiple triaxial test.

Height: 9,8 cm,	Diameter: 5 cm	
Porosity: 29,4 %	Insoluble residue: 4 %	(97 % clay, 3 % quartz)

After test the plug was fractured along a series of sub-parallel converging fractures ($75^o/65^o$) with minor indication of conjugated fracturing. The fracture zone is highly irregular and is partly controlled by re-activation of natural fractures

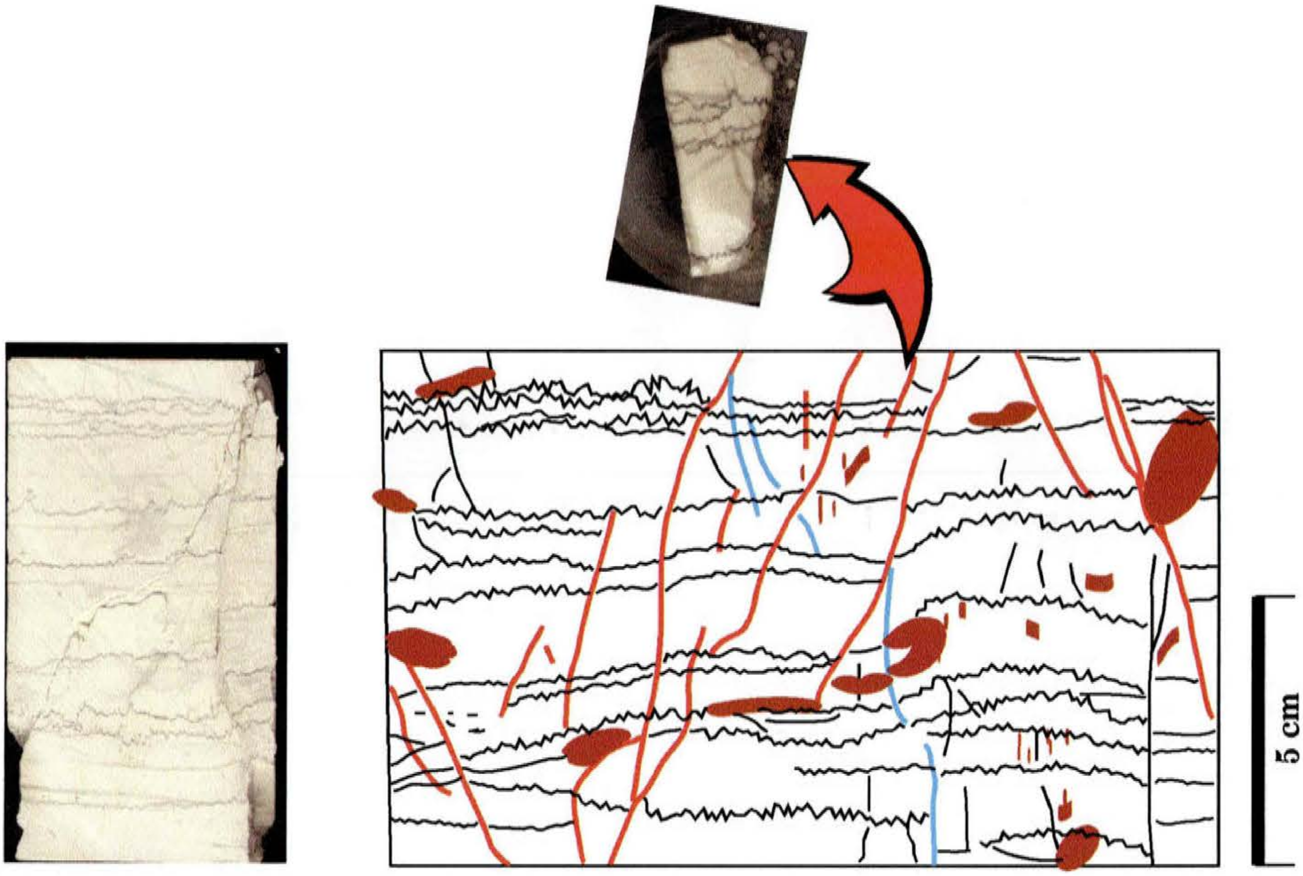
The fracture surface is an undulating slickensided surface (Jr:1.5).

T 7
Fractures

After test

GSI	**VB/VG**	**65 – (70)**	**Incl. Styl.+frac**	**BD/VG 50**
P_{32} main frac	**0,44**		**P_{32} total**	**0,50**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	4	> 7	> 10	
Type	Inclined	Associated conjugated fracture	Sub-vertical	
2θ		40		
Divergence	Low	None	None	
Comments	Sub-parallel	Partly stratabounded	Natural, inactive stratabounded	
Dip (° from horizontal)	65 – 75	80 - 90	80 - 90	
Length (mm)	> 100	< 30	Stylolite dependant	
Aperture (mm)	< 0.5	< 0.2	Closed	
Surface	Striation			
	Undulating, slickensided			
J-no	1.5			
Relief (mm)	5			
JRC	**18**			

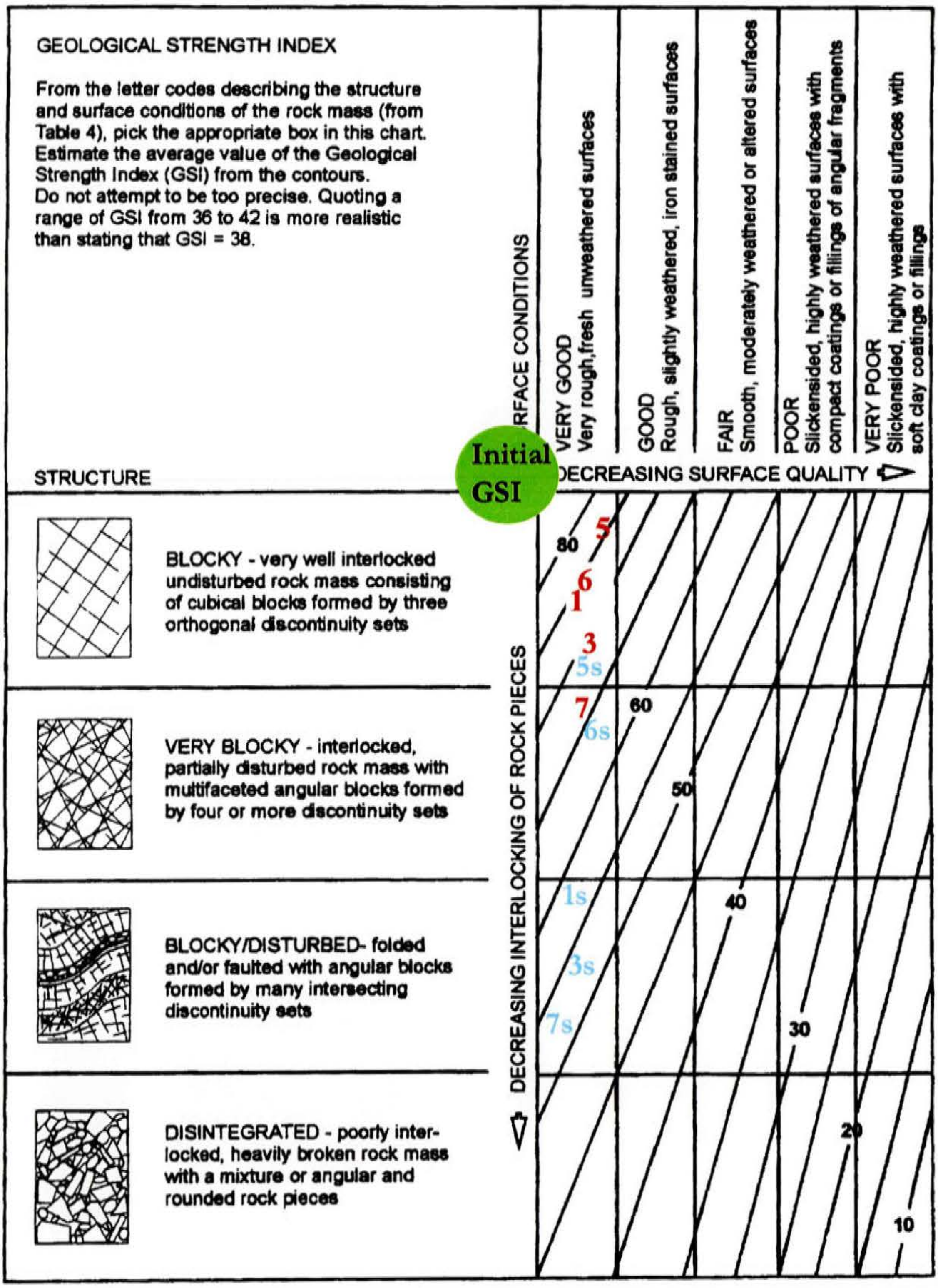
Tyra Field, T 7



Legend:

- Main fracture
- Fracture set 2
- Fracture set 3
- Fracture set 4
- Inactive fractures
- Stylolites
- Hairline fractures
- Flint
- Trace fossils
- Loose pieces
- Gypsum

Tyra field plug samples



Estimate of Geological Strength Index GSI for the Tyra samples based on plug description.
Green: initial GSI values. Red number: Plug sample GSI after test.
Blue number: GSI including stylolites

VALHALL

Valhall Field, V1

Plug description before test.

Burrowed Massive Mudstone, chalk, soft, high density of trace fossils (*Planolites*), accumulated low amplitude stylolites with more than 2 seams in one stylolite. 6 stylolites unevenly distributed in the plug (distance between stylolites ranges from less than 5 mm to 2 cm, density: 1 stylolite/cm). 1. order relief less than 0,5 cm with amplitudes of up to 1 mm. The stylolites represent a gradual transition to dissolution seam associate with shear zones.

The plug comprises sub-horizontal shear zones and indistinct multidirectional closed highly converging hairline fractures.

An open fracture associated with a stylolite located in the middle of the plug may represent an artificial break of the sample.

GSI
Undisturbed rock mass consisting of blocks separated by one indistinct fracture and a high number of stylolites. The fracture surface is not examined but is expected to be fresh, unweathered and rough to smooth.

Based on the low interlocking and the anticipated high surface quality the GSI value is estimated to be

80 or higher (low blocky/very good; LB/VG)

Plug description after multiple triaxial test:

Height: 8 cm		Diameter: 5.4 cm

Porosity: 40,14%		Insoluble residue: 3 %		(87 % clay, 13 % quartz)

A conjugated set of open highly irregular converging fractures (65°/65°) dominates the plug after test. The number of fractures are highest in the upper part of the plug. Associated with the main fractures 5-7 minor closed fractures are found in the central part of the plug.

GSI
Blocky to very blocky with very good rough and fresh surfaces

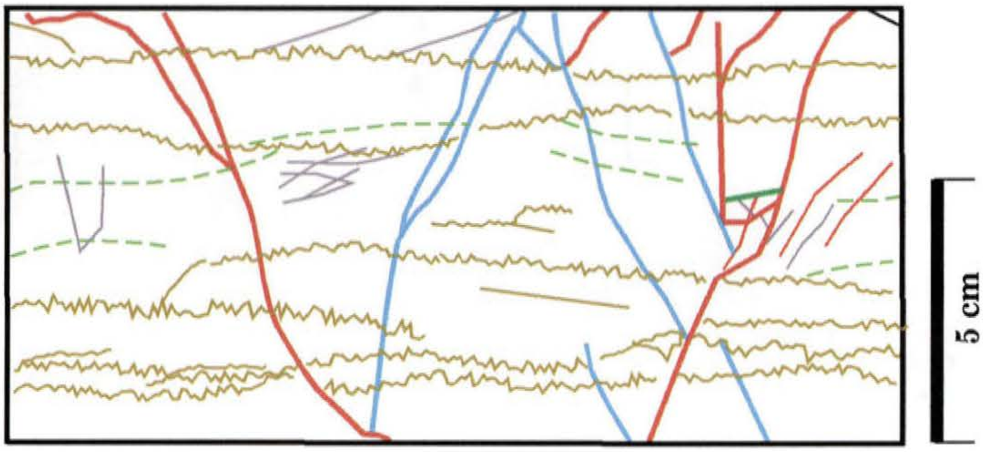
65-70 (B-VB/VG-G)

V 1
Fractures

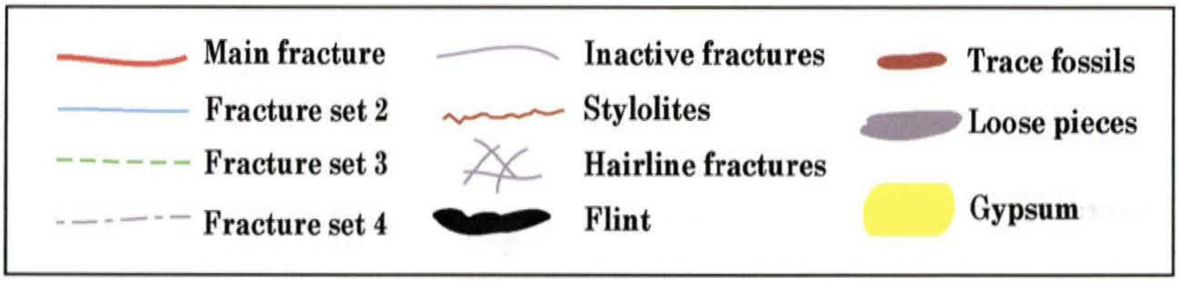
After test

GSI	**B-VB/VG**	**65-70**	**Incl. Styl + hairline frac**	**BD/VG 50**
P_{32} main frac	**0,30**		**P_{32} total**	**0,58**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	3	> 5	> 5	
Type	Inclined	Random, inclined	Random	
2θ	40			
Divergence	Medium-high	None		
Comments	Intersecting	Natural fract, partly stratabounded, intersecting main fractures	Hairline related	
Dip (° from horizontal)	65	45		
Length (mm)	> 100	< 30		
Aperture (mm)	1	< 0.2		
Surface	Uncoated			
	Undulating, smooth			
J-no	2			
Relief (mm)	3			
JRC	**16**			

Valhall Field, V 1



Legend:



Valhall Field, V2

Plug description before test.

Deformed Massive Mudstone, clean chalk, shear deformation, medium hard, medium consolidated, low density of visible trace fossils but comprises dark areas of distorted burrows, one horizontal stylolite in the middle of the plug with amplitudes of up to 1 mm.

A very high density of multidirectional closed highly converging hairline fractures appears in the plug.

Two open vertical and an inclined fracture are found initially in the plug. An offset of the vertical fracture of 3 mm crossing the stylolite is seen.

GSI
Undisturbed rock mass consisting of blocks separated by one indistinct fracture and one stylolite. The fracture surface is not examined but is expected to be fresh, unweathered and rough to smooth.

Based on the low interlocking and the anticipated high surface quality the GSI value is estimated to be

80 or higher (low blocky/very good; LB/VG)

Plug description after multiple triaxial test.

Height: 8 cm Diameter: 5.3 cm

Porosity: 44.3 % Insoluble residue: 2 % (83 % clay, 17 % quartz)

The plug is highly disordered fractured during test. Re-activation of parts of some of the natural fractures are associated with fracturing along hairline fracture zones. Both sub-vertical and horizontal directions prevail.

GSI
Blocky (to indistinct very blocky including hairline fracturing) with very good, rough-smooth and fresh surfaces

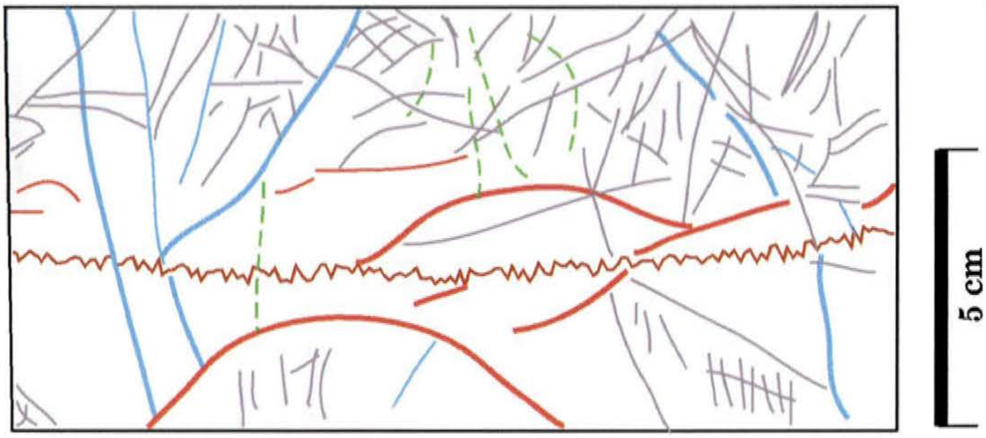
70 (B-VB/VG-G)

V 2
Fractures.

After test

GSI	B/VG	70	Including hairlines	VB/VG 60
P_{32} main frac	0,25		P_{32} total	0,65
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	1	> 3	> 5	
Type	Inclined	Sub-horizontal	Sub-vertical – inclined,	
2θ			45	
Divergence	None	None	None	
Comments	Reactivated		Hairline affected, intersecting	
Dip (° from horizontal)	40	- 10	50 - 80	
Length (mm)	< 30	< 40	< 50	
Aperture (mm)	-			
Surface	Uncoated			
	Undulating, smooth			
J-no	2			
Relief (mm)				
JRC	-			

Valhall Field, V 2



Legend:

Main fracture	Inactive fractures	Trace fossils
Fracture set 2	Stylolites	Loose pieces
Fracture set 3	Hairline fractures	Gypsum
Fracture set 4	Flint	

Valhall Field, V3

Plug description before test.

Deformed Massive Mudstone, clean chalk, shear deformation, medium hard, medium consolidated, low density of visible trace fossils (*Planolites*) but comprises dark areas of distorted burrows, stylolites density: 0.5/cm, two merging sub-horizontal stylolites in the middle of the plug with amplitudes less than 0,5 mm.

A very high density of multidirectional closed highly converging hairline fractures appears in the plug.

Thin microfractures partly open are found associated with the stylolites as well as vertical fractures.

GSI
Undisturbed rock mass consisting of blocks separated by one indistinct fracture and a few stylolites. The fracture surface is not examined but is expected to be fresh, unweathered and rough to smooth.

Based on the low interlocking and the anticipated high surface quality the GSI value is estimated to be
80 or higher (low blocky/very good; LB/VG)

Plug description after multiple triaxial test.

Height: 8 cm Diameter: 5.3 cm

Porosity: 41.0 % Insoluble residue: 3 % (88 % clay, 12% quartz)

One main fracture cross-cuts the plug. A set of secondary fractures conjugating the main fracture is seen. Re-activation of some of the open micro-fractures is seen.

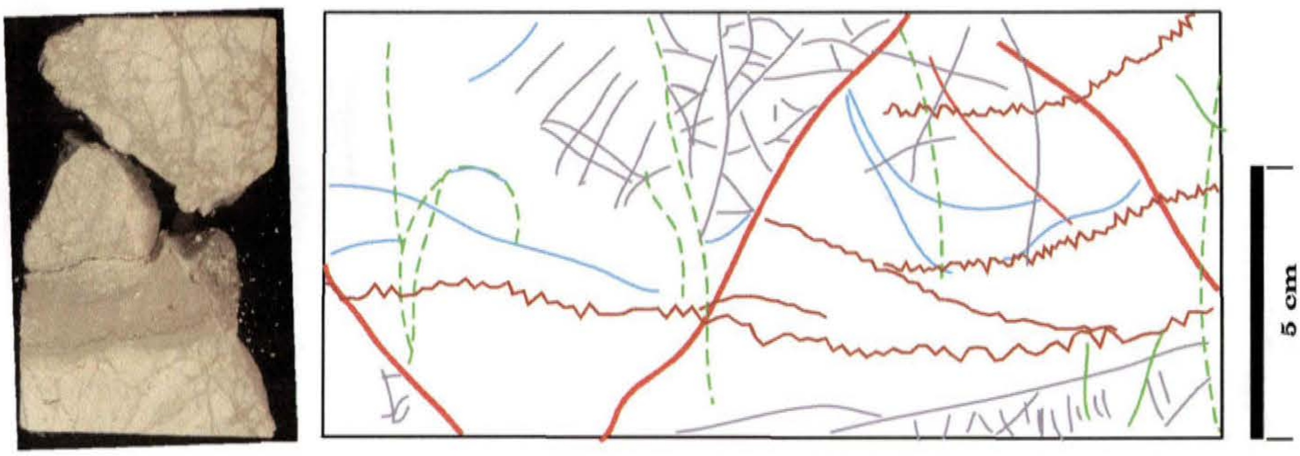
GSI
Blocky (in fractures hairline zone) with very good rough and fresh surfaces
70-75 (B/VG)

V 3
Fractures

After test

GSI	**B/VG**	**70 – (75)**	Including styl. and hairlines	VB/VG 55 - 65
P_{32} main frac	**0,23**		**P_{32} total**	**0,73**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2	5	3	
Type	Inclined	Inclined	Sub-vertical	
2θ		60		
Divergence	Low	Low	Medium	
Comments	Shear fracture	Intersecting main fracture, affected by hairlines	Partly hairline affected NOT DAMAGE ZONE AFFECTED	
Dip (° from horizontal)	60	20 - 60	80 - 90	
Length (mm)	> 80	> 50	> 90	
Aperture (mm)	> 1	< 0.2	< 0.2	
Surface	Striation			
	Undulating, slickensided			
J-no	1.5			
Relief (mm)	5			
JRC	**18**			

Valhall Field, V 3



Legend:

Main fracture	Inactive fractures	Trace fossils
Fracture set 2	Stylolites	Loose pieces
Fracture set 3	Hairline fractures	Gypsum
Fracture set 4	Flint	

Valhall, V4

Plug description before test.

Deformed Massive Mudstone, clean chalk, shear deformation, medium hard, medium consolidated,medium density of hairline fractures, major open fractures.

The plug comprises sub-horizontal shear zones and a high density of multidirectional closed highly converging hairline fractures.

GSI
Undisturbed rock mass consisting of blocks separated by two distinct fractures. The fracture surfaces are not examined but are expected to be fresh, unweathered and rough to smooth.

Based on the low interlocking and the anticipated high surface quality the GSI value is estimated to be

80 (blocky/very good; B/VG)

Plug description after multiple triaxial test.

Height: 7,5 cm Diameter: 5,3 cm

Porosity: 42,3 % Insoluble residue: 2 % (81 % clay, 19 % quartz)

A conjugated set of open converging fractures ($65^o/65^o$) dominates the plug after test. There is evidence of some offset of one of the main fractures.

GSI
Blocky (to very blocky) with very good rough and fresh surfaces

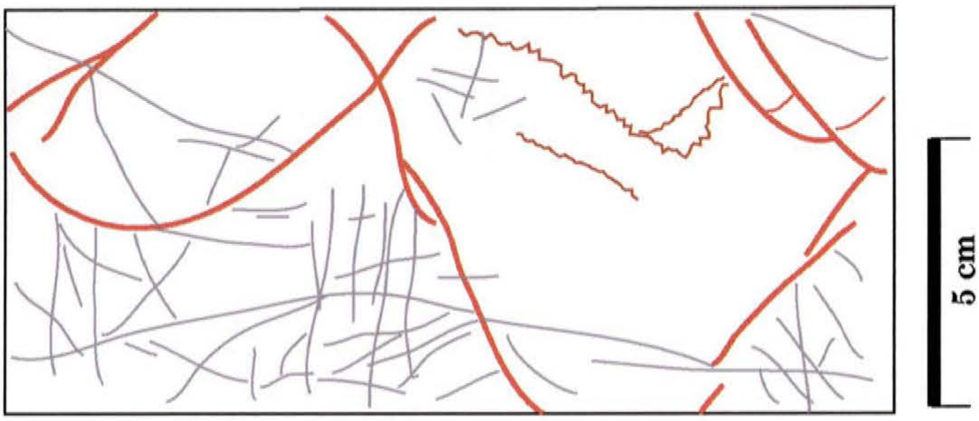
70 (B/VG-G)

V 4
Fractures

After test

GSI	**B/VG**	**70**	Including hairlines	VB/VG 60 - 65
P_{32} main frac	**0,40**		**P_{32} total**	**0,40**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	2			
Type	Inclined			
2θ	70			
Divergence	Medium			
Comments	Intersecting			
Dip (° from horizontal)	40 – 65			
Length (mm)	> 75			
Aperture (mm)	> 1			
Surface	Uncoated			
	Undulating, smooth			
J-no	2			
Relief (mm)	2			
JRC	**18**			

Valhall Field, V 4



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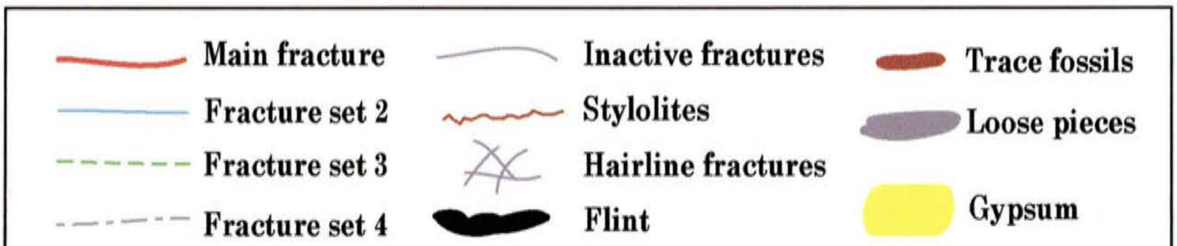


Valhall Field, V5

Plug description before test.

Deformed Massive Mudstone, clean chalk, shear deformation, medium hard, medium consolidated, low density of visible trace fossils (*Planolites*) but comprises dark areas of distorted burrows.

The plug comprises sub-horizontal shear zones and a medium density of multidirectional closed highly converging hairline fractures.

GSI
Disturbed rock mass consisting of blocks separated by distinct fractures. The fracture surfaces are not examined but are expected to be fresh, unweathered and rough to smooth.

Based on the low interlocking and the anticipated high surface quality the GSI value is estimated to be

70 (blocky/good; B/G)

Plug description after multiple triaxial test.

Height: 7.5 cm Diameter: 5.4 cm

Porosity: 42.1 % Insoluble residue: 11 % (94 % clay, 6 % quartz)

The sample was highly destructed after test and only the upper part of the plug was possible to describe.

Two inclined fractures and a sub-horizontal fracture were formed under test. The fracture surfaces are undulating and smooth (Jr= 1,5) with an aperture of 1 mm.

GSI
Blocky with very good, rough-smooth and fresh surfaces

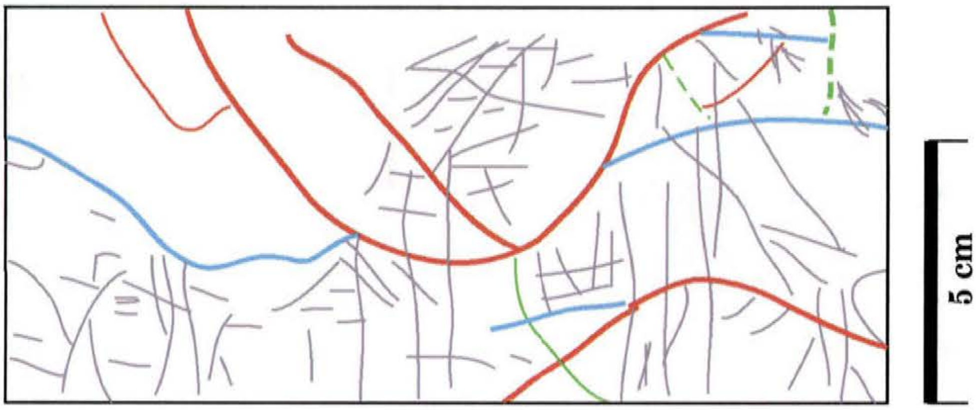
60 (B/VG-G)

V 5
Fractures

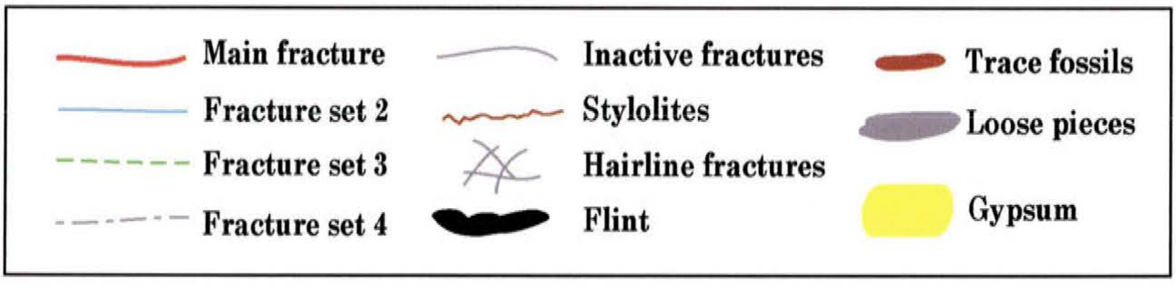
After test

GSI	**B/G-VG**	**(60) – 65**	Including hairlines	VB/G-VG 55 - 60
P_{32} main frac	**0,35**		**P_{32} total**	**0,55**
	Main fracture	**Fracture 2**	**Fracture 3**	**Fracture 4**
Numbers	3	2	> 3	
Type	Inclined	Sub-horizontal	Associated random	
2θ				
Divergence	Low	Low		
Comments	Fractures from the plug ends appears as intersecting fractures		Piston affected	
Dip (° from horizontal)	60	20	80 – 90	
Length (mm)	< 60	> 53		
Aperture (mm)	1	< 0.5	< 0.2	
Surface	Uncoated			
	Undulating, smooth			
J-no	2			
Relief (mm)	2			
JRC	**18**			

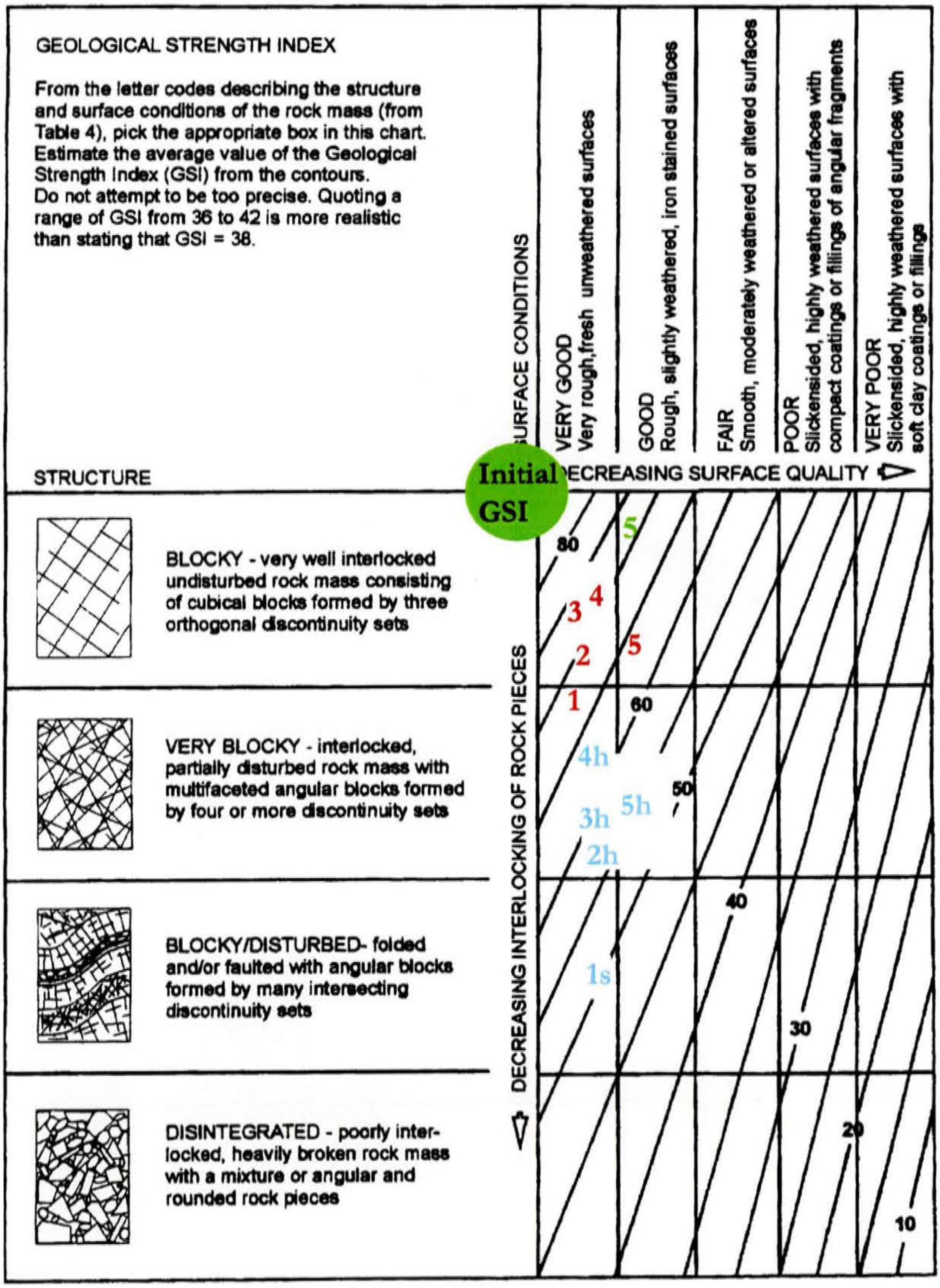
Valhall Field, V 5



Legend:



Valhall field plug samples



Estimate of Geological Strength Index GSI for the Tyra samples based on plug description.
Green: initial GSI values. Red number: Plug sample GSI after test.
Blue number: GSI including stylolites (s) or hairline fractures (h).