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Hillerslev outcrop chalk

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Hillerslev Outcrop Chalk

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Preface

This report is part of the written documentation of the Ph.D. project: "Displacement of Oil by Waterflooding in Fractured Chalk". The Ph.D. project was coordinated with and partly financed by a Danish Energy Research Programme (EFP) project 2000. The title of this project is "Displacement and Deformation Processes in Fractured Reservoir Chalk" (Christensen 2003), and the main objective was to quantify the displacement processes in fractured reservoir chalk. The research partners were: Danish Geotechnical Institute (GEO), Geological Survey of Denmark and Greenland (GEUS), Department of Environment and Resources (ER), DTU and Department of Civil Engineering (BYG•DTU), DTU. The industrial partners were: BP Norway and Mærsk Olie og Gas AS.

I thank Senior Research Geologist Finn Jakobsen, GEUS, for help and supervision related to the work described in this report.

Lyngby, April 2005

Miriam M. Lykke

Abstract

A field trip was made to the Hillerslev outcrop chalk quarry located in the northern part of Jutland. Here, a (global) fracture description was carried out and twelve chalk block specimens were sampled. A (local) fracture description was carried out on eight Hillerslev outcrop chalk specimens.

The main orientation NNE-SSW and the secondary orientation NNW-SSE was found in all three fracture data sets in the Ph.D. project. A comparison of the measured Joint Roughness Coefficient (JRC) and fracture aperture for all Ph.D. fracture data shows that some of the fractures along the chalk wall were disturbed which apart from the influence of excavation may be due to weathering near the chalk wall.

Fracture description and sampling carried out in the Hillerslev chalk quarry during "Fractures and Rock Mechanics", phase 1 and 2 was compared to the work presented in this report (Ph.D. project). A comparison shows that the main orientation ENE-WSW is found in phase 1 and 2, and along the wall in the Ph.D. project. This orientation is also found as a secondary orientation behind the specimens. In all fracture data in the Ph.D. project and in phase 2, horizontal beds were observed, and horizontal bedding parallel fractures were common. The fracture density for all the measured fractures in the Hillerslev chalk quarry indicate almost random spacing of fractures, and the majority of all the fractures are steeply dipping with a dominance of almost vertical fractures.

All the specimens were fractured to a higher or lesser degree. In four of the specimens horizontal fracture planes were present. The most dominant fractures in the periphery of the specimens were very steeply dipping and seemed almost vertical. Zones with brittle chalk as seen in two of the specimens were also seen at the Hillerslev quarry.

Overall, the three fracture data sets in the Ph.D. project are evaluated to be similar. Further, it is evaluated that the fracture descriptions in the three research projects are similar. Finally, the local and the global fracture descriptions were in accordance, i.e. the fracture system in the specimens represents the major part of the Hillerslev chalk fracture pattern.

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Chapter 1

Introduction

Fractures are a great benefit to production of oil, since the matrix permeability in the oil bearing chalk reservoirs in the North Sea is low. Many of the oil fields would be marginally economic to produce without natural or induced fractures to enhance the effective permeability of the reservoirs. However, when oil is produced due to waterflooding, an important issue is the effect of fractures on the displacement processes during waterflooding.

To study the effect of fractures on the displacement processes, it is important to obtain knowledge of the fractures in the chalk, i.e. it is necessary to perform a fracture study of the chalk. A field trip was made to the Hillerslev outcrop chalk quarry located in the northern part of Jutland. Here, a (global) fracture description was carried out and twelve chalk block specimens were sampled at a chosen location in the Hillerslev quarry. A team of five including the author performed the sampling of the large specimens. However, the drilling of the specimens by use of a mobile drilling rig was performed by GEO, and staff at the Hillerslev outcrop quarry performed the rough excavation by use of a backhoe. A (global) fracture description was carried out mainly by the author with help from the group. The author performed the processing and evaluation of the fracture data. The presentation of the fracture data was carried out at GEUS with help and supervision from Senior Research Geologist Finn Jakobsen, GEUS.

For comparison of earlier work performed in the Hillerslev chalk quarry, a summary of the fracture description and sampling carried out during the earlier research project "Fractures and Rock Mechanics", phase 2 (Jakobsen 2001), and the earlier research project "Fractures and Rock Mechanics", phase 1 (Krogsbøll et al. 1997) containing even earlier work is included.

A (local) fracture description was carried out by the author on eight Hillerslev outcrop chalk specimens. One of these specimens was sampled during "Fractures and Rock Mechanics", phase 2 (Jakobsen 2001). The other seven were sampled during the Ph.D. project.

Chapter 2

Description of Hillerslev Outcrop Chalk (Earlier Work)

The Hillerslev outcrop chalk quarry is located near Thisted in the northwestern part of Jutland. The location of the Hillerslev chalk quarry is indicated on Figure 2.1.

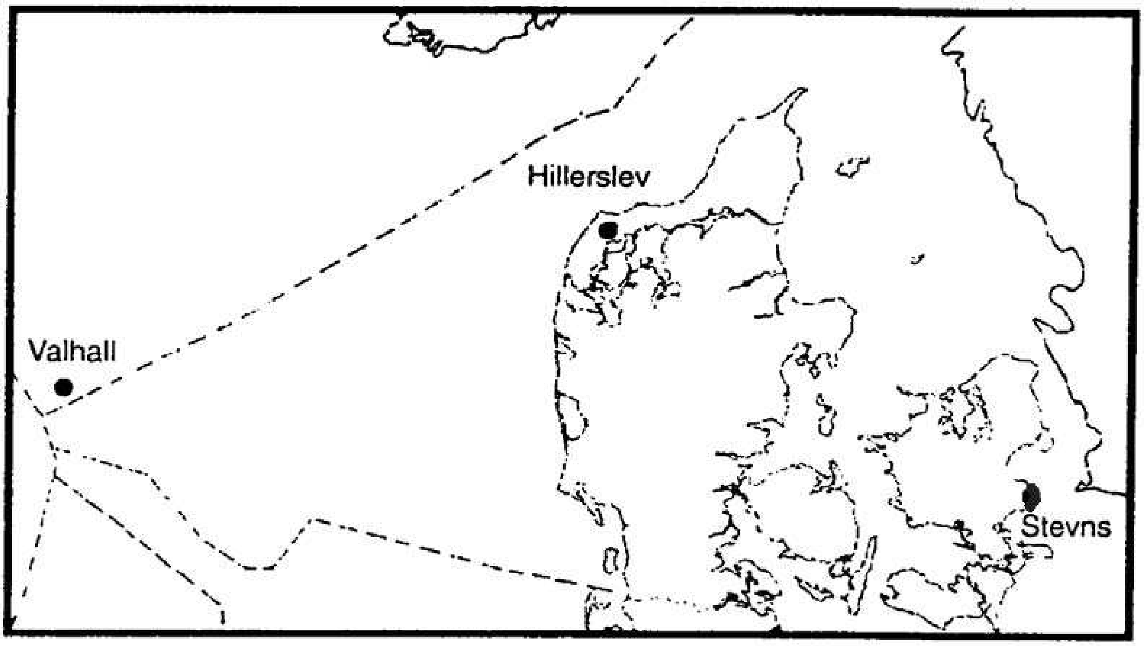

Figure 2.1 *Location of the Hillerslev chalk quarry.*

The Hillerslev chalk quarry is an active quarry located on the eastern half of the top of the Thisted dome, which is a salt-induced dome. The size of the chalk quarry is approximately 500 m $\times$ 200 m (Jakobsen 2001). The chalk at the Hillerslev quarry is heavily fractured. The fracturing of the quarry is assumed to be related to the structural growth of the dome. The general tilt in the Hillerslev area is 4 degrees towards ESE (Krogsbøll et al. 1997).

The chalk in the quarry is of Late Maastrictian age. It is a soft, greyish white, weakly cemented mudstone/wackestone. It is composed almost exclusively of coccolithic material with subordinate amounts of skeletal material (foraminifera, bryozoans, echinoderms and molluscs). The chalk has a low content of silica, clay minerals and pyrite (Krogsbøll et al. 1997).

Analysis of Hillerslev chalk specimens indicates that the chalk is more affected by compaction (mechanical diagenesis) than chemical diagenesis. Flint concretions in the chalk only amount to a small part of the total sediment volume (Krogsbøll et al. 1997).

2.1 Earlier Research Project, Phase 1

A detailed description of the fracture system of the Hillerslev chalk quarry was carried out in an earlier chalk research project, and the main conclusions from that project are given in the earlier research project "Fractures and Rock Mechanics", phase 1, geology report (Krogsbøll et al. 1997), and summarised below.

In the northern part of the Hillerslev quarry a low chalk wall (approximately 4 m high and 45 m long) was excavated and described (Figure A.1, Appendix A). Fracture density and fracture orientations were determined along a horizontal line profile (approximately 31 m long) in the wall. The fracture description was associated with a series of one inch core specimens sampled along the horizontal line.

Analysis of more than 200 specimens sampled along the horizontal profile shows a porosity variation of 44-52% with an average of 47%. The average gas permeability is 8.1 mD, ranging from 5.1-13.4 mD. The average distribution of pore throat radius is 0.6 mm. The content of insoluble residue is low, around 4%.

As the one inch core specimens and fracture data was sampled along the same line, the possible correlation between the variation in porosity and permeability and the position of fractures was investigated. However, no clear evidence of correlation was observed.

Information on fracture density and the orientations (strike/dip) of each fracture was primarily sampled along the horizontal line profile in the excavated chalk wall, see Figure A.1, Appendix A. However, the fracture data were supplemented with measurements of fracture orientations from other locations in the quarry.

The density of the fractures along the horizontal line is evident from Figure A.2, Appendix A, where each measured fracture is marked by a vertical line. The measured fracture densities indicate almost random spacing of fractures. A rose diagram of strike (Figure A.3, Appendix A) shows that a high proportion of fractures are oriented ENE-WSW with NNW-SSE as another important direction. The dip directions are shown in a rose diagram in Figure A.4, Appendix A. The number of fractures sorted by dip is plotted as a histogram in Figure A.5, Appendix A. From Figure A.5 it is seen that the majority of the fractures are steeply dipping with a dominance of almost vertical fractures.

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

2.2 Earlier Research Project, Phase 2

In the earlier research project "Fractures and Rock Mechanics", phase 2 (Jakobsen 2001) supplementary fracture descriptions were carried out along new profiles in a re-excavation of the same wall section described in "Fractures and Rock Mechanics", phase 1. The study is thus supplementary to phase 1 and the main work is related to the descriptions and conclusions from that project. Description and fracture measurements were carried out along horizontal lines along the freshly excavated originally exposed chalk wall in the Hillerslev quarry. 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.

Information on fracture density and the orientations (strike/dip) of each fracture included here was sampled along a horizontal line profile along the same horizontal line profile as described in "Fractures and Rock Mechanics", phase 1, i.e. the profiles are identical except for the length. The new line profile is only approximately 25 m of the originally approximately 31 m. The new profile is referred to as the reference profile.

The density of the fractures along the reference profile is evident from Figure B.1, Appendix B. The measured fracture densities indicate almost random spacing of fractures. The orientations of the fractures were measured as strike/dip. A rose diagram of strike (Figure B.2, Appendix B) shows that a high proportion of fractures are oriented ENE-WSW and SSE-NNW with NNE-SSW and SE-NW as secondary directions. Horizontal bedding is seen, and horizontal bedding parallel fractures are common. Dip directions of fractures are plotted in a rose diagram (Figure B.3, Appendix B). The number of fractures sorted by dip is plotted as a histogram (Figure B.4, Appendix B). From Figure B.4 it is seen that the majority of fractures are steeply dipping with a dominance of almost vertical fractures.

Ten block specimens and a number of smaller irregular blocks were sampled (Havmøller & Krogsbøll 2001).

In some of the specimens hairlines were observed. Hairlines 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.

Based on the sampled specimens, two chalk types were identified; a soft, greyish white bioturbated chalk mudstone characterized by a weakly laminated structure partly disturbed by burrowing organisms, and a sparse biomicritic chalk wackestone. The microfossil content in the wackestone is dominated by calcispheres. Foraminifera and echinoderm fragments are rare. The main component of the wackestone is the large amount of well-preserved coccoliths.

Chapter 3

Sampling of Large Hillerslev Chalk Specimens

At the Hillerslev outcrop chalk quarry, twelve cylindrical block specimens with the dimensions $D \approx 50$ cm and $H \approx 50$ cm were sampled successfully. A team of five including the author performed the sampling of the large specimens. However, the drilling was performed by GEO, and staff at the quarry performed the work done by backhoe.

Initially a location for fracture description and sampling at the Hillerslev chalk quarry was chosen, see Figure C.1 and C.2, Appendix C. The location is situated in the northern part of the quarry just west of the location used for fracture description and sampling in the earlier research projects "Fractures and Rock Mechanics", phase 1 and 2. The locations are indicated on Figure C.3, Appendix C.

A chalk wall (approximately 2.5 m high and 25 m long) was excavated at the chosen location, see Figure C.4, Appendix C. A fracture description including fracture density and fracture orientations (strike/dip) was performed along a horizontal line along the wall from a chosen start point (point 1) at the eastern end of the wall and approximately 9 m towards west (Figure D.1, Appendix D). The fracture description is included in Section 4.1.

A horizontal plateau (approximately 1.5 m high, 25 m long and 2 m deep) referred to as the chalk bench was made by further excavation (approximately 2 m) into the wall starting approximately 4 m above the ground, i.e. 2.5 m above the bench (Figure D.2, Appendix D). The bench is seen in Figure C.5, Appendix C. The bench was made for sampling of block specimens. A ramp of chalk was temporarily built in front of and beside the bench in order for the mobile drilling rig to be able to drill from the top of the bench (Figure C.6, Appendix C). The drilling rig is a 12 ton Unimog HY77 with a maximum torque of 900 kgm and a maximum speed of 50 rounds per minute.

Before drilling, the drill bit was mounted on the rig and the chalk surface of the drilling spot was levelled (Figure C.7, Appendix C). Water was added during drilling to cool the drill bit and flush away cuttings (Figure C.8, Appendix C). Drilling was performed using a light vertical pressure and at a speed lower than 50 rounds per minute. If the bit was pushed too hard onto the chalk surface, the chalk crushed immediately. After drilling to a depth of 60 cm below the surface, the bit was pulled up very slowly still rotating, while water was added. This procedure was performed in order to avoid tension cracks in the specimens.

After removal of the drill bit, a metal shield was inserted in the trace left by the drill bit (Figure C.9, Appendix C). After metal shields were inserted in twelve promising out of twenty drill traces, the success criteria was fulfilled, and the drilling was ended. Then the ramp of loose chalk in front of the bench was removed. A fracture description including fracture density and fracture orientations (strike/dip) was performed along a horizontal line along the front of the bench from a chosen start point (approximately 10 m west of point 1) and approximately 10 m towards west (Figure D.2, Appendix D). The fracture description is included in Section 4.1.

A backhoe was used to perform the rough excavation in front of and beside the specimen to a distance of approximately 20 cm from the metal shield and to a depth of 30-50 cm below the estimated location of the specimen bottom. The distance to the metal shield was maintained in order to avoid possible fracturing induced by the backhoe and to avoid dragging out thin beds of hardened chalk (Figure C.10, Appendix C). As the chalk is highly fractured, most of the chalk surrounding the specimen was removed by hand using hammer and chisel or by use of an electrical Bosch hammer.

After removal of the surrounding chalk, the metal shield was removed, and the specimen was inspected. Often it was necessary to wrap blue tape around the specimen to ensure that parts of the fractured specimen did not fall of. A specimen secured with blue tape is seen in Figure C.11, Appendix C. A rubber membrane was pulled over the specimen. This is seen in Figure C.12, Appendix C. Then an additional rubber blanket and the metal shield were wrapped around the specimen. Two steel belts were fastened around the shield. The top surface was trimmed roughly by use of a chain saw. A piece of blue tape was placed on the trimmed top surface to indicate the direction of north. A plastic cap was placed on the top surface of the specimen. The top of the membrane was fitted around the cap, and a steel belt was fastened around the membrane (Figure C.13, Appendix C).

The backhoe was used to hold onto the specimen via lifting equipment fastened around the specimen while the specimen was cut free at the bottom by use of a chain saw, see Figure C.13, Appendix C. The backhoe was then used to lift up the specimen and move it from the ground and turn it upside down for a rough trimming of the bottom surface (Figure C.14, Appendix C). The trimming was performed by use of a chain saw. A plastic cap was placed on the bottom surface after trimming. The specimens were trimmed to a height a little higher that 50 cm, since the final trimming should be performed in the laboratory. The bottom of the membrane was fitted around the cap, and a steel belt was fastened around the membrane (Figure C.15, Appendix C).

The specimen was then placed upside down on a wooden pallet. The first successfully sampled specimen is shown in Figure C.15, Appendix C.

View of the bench and wall with indication of the location of the twelve specimens by yellow numbering on the wall behind the specimens is seen in Figure C.16, Appendix C. At this stage the first specimen is sampled and the surrounding chalk in front of and beside eight of the specimens is more or less removed. A sketch of the location of the twelve specimens on the bench is shown in Figure D.3, Appendix D.

A fracture description including fracture density and fracture orientations (strike/dip) was performed approximately 75 cm behind all twelve specimen stumps, i.e. the area below the bottom of the specimens, where the specimens were cut free by use of a chain saw. The fracture description is included in Section 4.1.

Finally the specimens were transported to the laboratory at DTU on a lorry (Figure C.17, Appendix C). A number of smaller chalk blocks with fractures were also brought to the laboratory.

Chapter 4

Description of Hillerslev Outcrop Chalk (Additional Work)

4.1 Ph.D. Project

In the Ph.D. project, the fracture description was carried out along horizontal profiles in the northern part of the quarry just west of the location used for fracture description and sampling in "Fractures and Rock Mechanics", phase 1 and 2. The author mainly carried out the fracture description in the Ph.D. project with help from the group, and the author performed the processing and evaluation of the fracture data.

The fracture description includes fracture density (no. and position), fracture orientations (strike/dip), fracture roughness (JRC) and fracture aperture.

Fracture No.: The fractures are numbered for identification. The number of fractures is an alternative fracture density indication.

Strike: Strike is the orientation of the intersection line between the fracture plane and a horizontal plane, i.e. the compass orientation of the horizontal line, which can be drawn on the fracture plane. Strike is indicated in Figure 4.1.

Dip: Both dip and dip directions are included in the fracture description. Dip is the angle between the fracture plane and the horizontal plane, i.e. the angle between the vertical line that can be drawn of the fracture plane and the horizontal plane. A determination of dip direction is necessary as the fracture plane can dip to either side of the strike for the fracture plane. Dip direction is perpendicular to strike. Dip and dip direction is indicated in Figure 4.1.

Roughness: Joint Roughness Coefficient (JRC) is a quantification of fracture surface roughness (Barton 1976). A linear relationship between asperity along the dip direction and length of the measured profile is indicated as JRC values from 0-20. In this project, the fracture roughness is evaluated on basis of characteristic JRC-profiles (Appendix F).

Aperture: Maximum measurable opening of the fractures.

Position: Intersection with measuring tape (measured towards west with point 1 as zero). The position of the fractures gives opportunity to map the fracture density.

The density of the fractures and the orientations (strike/dip) are graphically represented in density maps and rose diagrams made by use of a program called SpheriStat.

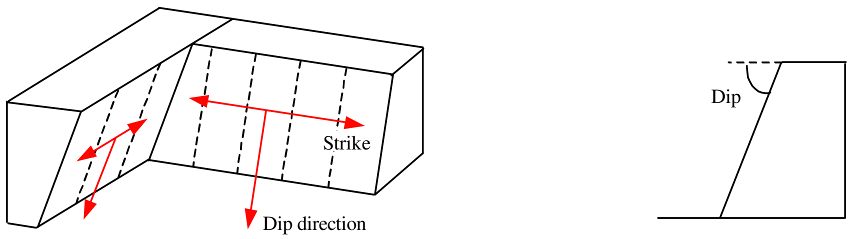

Figure 4.1 *Fracture planes with indication of strike, dip and dip direction.*

In a rose diagram strike and dip direction of a fracture can be represented. A rose diagram is seen in Figure 4.2.

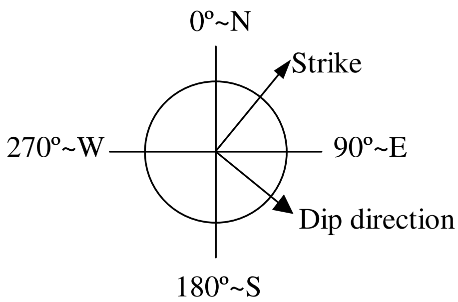

Figure 4.2 *Rose diagram with strike and associated dip direction indicated.*

The fracture density maps are based only on the measured horizontal position of the fractures, as the vertical position was not measured.

Fracture descriptions were performed along a horizontal profile along the freshly excavated chalk wall, along a horizontal profile along the front of the chalk bench made by further excavation into the chalk wall, and finally along twelve horizontal profiles - one behind each of the sampled specimens. Horizontal bedding was seen with beds of hardened chalk and horizontal bedding parallel fractures were seen along all the horizontal profiles. These fractures may be surface parallel tensional fractures due to unloading since the area has been subjected to uplift and subsequent erosion during the geological history (Jakobsen 2001). Fractures due to frost were also present since the Hillerslev formation is situated in the top of the geological profile, but such fractures were not seen and actually not expected since the fracture description is performed at least 10 m below the top of the ground, and at least 1 m of chalk material was removed in the depth, when the chalk wall was excavated. Conjugate shear fracture sets were also seen along all the horizontal profiles. "Crushing zones", i.e. zones with brittle chalk were seen as well. The chalk at the location was identified as chalk mudstone.

Chalk Wall

The chalk wall is approximately 2.5 m high and 25 m long. A fracture description was performed along a horizontal line along the wall from a chosen start point (point 1) at the eastern end of the wall and approximately 9 m towards west (Figure D.1, Appendix D).

A map of strike/dip indicating the density of the fractures along the profile is evident from Figure E.1, Appendix E. The measured fracture densities indicate almost random spacing of fractures. A rose diagram of strike (Figure E.5, Appendix E) shows that a high proportion of fractures are oriented NNE-SSW and ENE-WSW with NNW-SSE and WNW-ESE as secondary directions. Dip directions of fractures are plotted in a rose diagram (Figure E.6, Appendix E). The number of fractures sorted by dip is plotted as a histogram (Figure E.7, Appendix E). From Figure E.7 it is seen that the majority of fractures are steeply dipping with a dominance of almost vertical fractures.

Chalk Bench

The chalk bench is approximately 1.5 m high, 25 m long and 2 m deep. The wall behind the bench is approximately 4 m above the ground, i.e. 2.5 m above the bench. A fracture description was performed along a horizontal line along the front of the bench from a chosen start point (approximately 10 m west of point 1) and approximately 10 m towards west (Figure D.2, Appendix D).

A map of strike/dip indicating the density of the fractures along the profile is evident from Figure E.2, Appendix E. The measured fracture densities indicate almost random spacing of fractures. A rose diagram of strike (Figure E.8, Appendix E) shows that a high proportion of fractures are oriented NNE-SSW and ESE-WNW with NNW-SSE as a secondary direction. Dip directions of fractures are plotted in a rose diagram (Figure E.9, Appendix E). The number of fractures sorted by dip is plotted as a histogram (Figure E.10, Appendix E). From Figure E.10 it is seen that the majority of fractures are steeply dipping with a dominance of almost vertical fractures.

Chalk Specimens

Twelve cylindrical specimens with the dimensions $D \approx 50$ cm and $H \approx 50$ cm were sampled successfully. The location of the specimens on the bench is indicated in Figure D.3, Appendix D.

Behind the Chalk Specimens

A fracture description was performed on horizontal line profiles of 0.5-2 m length approximately 75 cm behind each of the twelve specimen stumps.

A map of strike/dip indicating the density of the fractures along the line with the twelve horizontal line profiles is evident from Figure E.3, Appendix E. The measured fracture densities indicate almost random spacing of fractures. A rose diagram of strike (Figure E.11, Appendix E) shows that a high proportion of fractures are oriented NNE-SSW and ESE-WNW with ENE-WSW and NNW-SSE as secondary directions. Dip directions of fractures are plotted in a rose diagram (Figure E.12, Appendix E). The number of fractures sorted by dip is plotted as a histogram (Figure E.13, Appendix E). From Figure E.13 it is seen that the majority of fractures are steeply dipping with a dominance of almost vertical fractures.

The location of the horizontal line profile along the wall, along the front of the bench and the location of the horizontal line along which the twelve horizontal line profiles behind the specimens are situated are sketched in Figure D.4, Appendix D.

A map of strike/dip indicating the density of all the measured fractures are shown in Figure E.4, Appendix E. In Figure E.4, the location of the centres of the twelve specimens are indicated.

Strike vs. JRC is plotted in a Schmidt projection (equal area) for measured data both for the wall, the bench and behind the specimens. The projections are seen in Figure E.14-E.16, Appendix E. The JRCs are mainly between 5-15. No clear correlation is seen between strike and JRC. However, experience from "Fractures and Rock Mechanics", phase 2 indicates that caution should be paid on determination of the JRC along fracture profiles shorter than 10 cm, which many of the measured fractures had. Further, it is important to determine the roughness along the dip direction of the fracture to obtain the most reliable values (Jakobsen 2001).

The number of fractures sorted by JRC is plotted as a histogram for measured data both for the wall, the bench and behind the specimens. The histograms are seen in Figure E.17-E.19, Appendix E. For the fractures along the chalk wall, no clear picture of JRC is seen, as all the JRCs are represented and no one more distinct than the other. For the fractures both along the chalk bench and behind the specimens, the JRC is around 9 and no smooth (JRC: 0-2) or rough (JRC: 18-20) fractures are represented.

The number of fractures sorted by aperture is plotted as a histogram for measured data both for the wall, the bench and behind the specimens. The histograms are seen in Figure E.20-E.22, Appendix E. For the fractures along the wall, apertures between $\leq$ 0.1 to 0.5 mm and 1 to 2 mm were seen, i.e. both closed to very narrow fractures and very open fractures were seen. The closed to very narrow fractures were dominating, but some very open fractures were seen. For the fractures both along the chalk bench and behind the specimens, primarily apertures $\leq$ 1 mm, were seen, i.e. the number of closed fractures were dominant and only very few very open fractures were observed.

Chapter 5

Comparison of Hillerslev Work

A comparison of the data from the "Fractures and Rock Mechanics", phase 1 and 2, and the Ph.D. project is included. In addition, a comparison of the three different sets of fracture data found in the Ph.D. project is included.

The main and secondary orientations of the measured fractures (strike) for the three research projects are included in Table 5.1.

A comparison of the main orientations of the fractures (strike) for the three research projects shows that the orientation ENE-WSW is found in "Fractures and Rock Mechanics", phase 1 and 2, and along the horizontal profile along the wall in the Ph.D. project. The orientation is also found as secondary orientation behind the specimens. It is expected to have some correlation between the measured fracture orientations from "Fractures and Rock Mechanics", phase 1 and 2, since the horizontal profile used in phase 2 is a re-excavation of the horizontal profile used in phase 1. However, the fracture data represented in phase 1 are supplemented with data from other locations in the quarry.

A comparison of the main orientations found along the wall, the bench and behind the specimens in the Ph.D. project shows that the orientation NNE-SSW is found along all three profiles, this orientation is also found as secondary orientation for phase 2. A comparison of the secondary orientations shows that the orientation NNW-SSE is found along all three profiles in the Ph.D. project. Again, it is expected to have some correlation between the measured fracture orientations from the three horizontal profiles, since the horizontal profile used is from the same location (displaced only in the northern and vertical direction).

Overall, similar fracture orientation were found along the wall, the bench and behind

	"Fractures and Rock Mechanics"				Ph.D. project					
	Phase 1		Phase 2		Wall		Bench		Behind specimens	
Main orientations	ENE-WSW	NNW-SSE	SSE-NNW	ENE-WSW	NNE-SSW	ENE-WSW	NNE-SSW	ESE-WNW	ESE-WNW	NNE-SSW
Secondary orientations	-	-	SE-NW	NNE-SSW	NNW-SSE	WNW-ESE	NNW-SSE	-	ENE-WSW	NNW-SSE

Table 5.1 *Main and secondary fracture orientations for the research projects "Fractures and Rock Mechanics", phase 1 and 2 and the Ph.D. project.*

the specimens.

The measured fracture densities indicate almost random spacing of fractures for all the measured fractures in the Hillerslev outcrop chalk quarry. The number of fractures sorted by dip is plotted as histograms for all the measured fractures in the research projects (Figure A.5, Appendix A, Figure B.4, Appendix B and Figures E.7, E.10 and E.13, Appendix E). A comparison of the histograms shows that the majority of all the measured fractures in the Hillerslev quarry are steeply dipping with a dominance of almost vertical fractures.

In both the Ph.D. project and phase 2, horizontal bedding parallel fractures are common.

The correlation between JRC and aperture for the three different sets of fracture data found in the Ph.D. project (Figures E.17-E.22, Appendix E) is interpreted as follows: The measured JRC and aperture is of the same order and distribution for the fractures both along the chalk bench and behind the specimens. This consistency indicates that the fractures here were not disturbed by etc. the excavation performed by use of a backhoe. However, when comparing the measured JRC and aperture for all three sets of fracture data, it is evaluated that the fractures along the chalk wall were disturbed. This evaluation is mainly based on the fact that some very open fractures were observed along the chalk wall, while only very few very open fractures were observed along the chalk bench and behind the specimens. Some of the included data with apertures of 1.5 to 2 mm may thus be fractures opened or induced by the backhoe. The fact that the variance in JRC for the chalk wall differs from the JRCs measured along the chalk bench and behind the specimens also supports a disturbance, which apart from the influence of excavation may be due to weathering near the chalk wall.

Chapter 6

Hillerslev Chalk Specimens

A (local) fracture description was carried out on eight Hillerslev outcrop chalk specimens used in the Ph.D. thesis. One of these specimens (specimen 11) was sampled during the "Fractures and Rock Mechanics", phase 2. The other seven (specimens 2, 3, 5, 7, 8, 9 and 10) were sampled during the Ph.D. project. For the purpose of a local fracture description, fractures, voids at the surface, gypsum and crushed zones were indicated on pieces of plastic matching the top, the bottom and the periphery of the specimens. Photos of the pieces of plastic are included in Appendix G. The location of the seven sampled specimens is indicated in Figure D.3 in Appendix D.

The specimens were described as light grey (chalk mudstone) with areas of a darker grey color (clay). Spots of rust were seen on the surfaces. There were marks on the periphery of the specimens due to the drill. There were voids at the surface (material missing) on all the specimens to a higher or lesser degree.

Small pieces of flint were seen in specimens 2, 3, 7 and 8. Few fossils were found in specimen 2 and many were found in specimen 8.

Due to the long period of storage of the specimens, long treads of fungus/roots were seen on the surface of the specimens. Further, there were traces of mould and a mouldy smell. The longer the storage, the mouldier the specimens were.

All the specimens were fractured to a higher or lesser degree. Specimen 8 was in a very good condition (the best of them all). This is due to that many of the fracture apertures were narrow (fine), and that only few voids were seen at the surface. Specimen 2 was in a very bad condition (the worst of them all) due to the many fractures and the almost brittle state of the chalk. The specimen had been cast with gypsum on the top at the Hillerslev quarry. Specimen 5 contained so-called crushed zones where the chalk was brittle, and almost plastified (reworked). In these zones, it was difficult to see fractures. This, and the many fractures were responsible for the bad condition of specimen 5 (almost as bad as specimen 2). Zones with brittle chalk as seen in specimen 2 and 5 were also seen along all the horizontal profiles at the Hillerslev quarry.

For the two best specimens 7 and 8, the fracture density was the highest observed, see Figure E.4 in Appendix E. One reason for this is that the chalk in this area does not contain crushed zones. Often, only few fractures were indicated in the crushed zone, as it was difficult to see the fractures.

It was observed that fractures opened in the specimens after being unwrapped and exposed to air (drying), and due to the handling of the specimens.

Six of the specimens were cast with gypsum during preparation due to filling of voids at the surface (specimens 7 after drying) and due to stabilizing of the specimens (specimens 2, 3, 9 and 10 before drying). Specimen 11 had been cast with gypsum in an earlier project (Larsen 2000).

In four of the specimens horizontal fracture planes were present, two continuing ones in specimen 8, a continuing one in specimen 5, two in specimen 7 and one in specimen 9. This is in accordance with the global fracture observations.

The most dominant fractures in the periphery of the specimens are very steeply dipping and seem almost vertical. This is consistent with the overall picture from the global fracture description concluding that the majority of fractures are steeply dipping with a dominance of almost vertical fractures. The fracture density in the specimens are similar to the observations in the Hillerslev outcrop chalk quarry indicating almost random spacing of fractures.

Overall, the local and the global fracture descriptions are in accordance, i.e. the fracture system in the specimens represents the major part of the Hillerslev outcrop chalk fracture pattern.

Chapter 7

Conclusions

A field trip was made to the Hillerslev outcrop chalk quarry. Here, a global fracture description was carried out and twelve chalk block specimens were sampled. A local fracture description was carried out on eight Hillerslev outcrop chalk specimens. One of these was sampled during "Fractures and Rock Mechanics", phase 2. The other seven were sampled during the Ph.D. project. For the purpose of a local fracture description, fractures, voids at the surface, gypsum and crushed zones were indicated on pieces of plastic matching the top, bottom and periphery of the specimens.

A comparison of the main orientations found along the wall, the bench and behind the specimens shows that the orientation NNE-SSW was found in all three fracture data sets in the Ph.D. project. A comparison of the secondary orientations shows that the orientation NNW-SSE was found in all three fracture data sets.

The measured Joint Roughness Coefficient (JRC) and fracture aperture is of the same order and distribution for the fractures both along the chalk bench and behind the specimens. This indicates that the fractures here were not significantly disturbed by for instance the excavation performed by use of a backhoe. However, when comparing the measured JRC and aperture for all three sets of fracture data, it is evaluated that the fractures along the chalk wall were disturbed. The fact that the variance in JRC for the chalk wall differs from the JRCs measured along the chalk bench and behind the specimens supports a disturbance, which apart from the influence of excavation may be due to weathering near the chalk wall.

For the fractures along the wall, apertures between ≤ 0.1 to 0.5 mm and 1 to 2 mm are seen, i.e. both closed to very narrow fractures and very open fractures are seen. The closed to very narrow fractures are dominating, but some very open fractures are seen. For the fractures both along the chalk bench and behind the specimens, primarily apertures ≤ 1 mm were seen, i.e. the number of closed fractures were dominant and only very few very open fractures were observed.

Fracture description and sampling carried out in the Hillerslev chalk quarry during "Fractures and Rock Mechanics", phase 1 and 2 was compared to the work presented in this report (Ph.D. project). A comparison shows that the main orientation ENE-WSW was found in the "Fractures and Rock Mechanics", phase 1 and 2, and along the wall in the Ph.D. project. This orientation was also found as a secondary orientation behind the specimens. The main orientation NNE-SSW found in all three fracture data sets in the

Ph.D. project is also found as a secondary orientation in "Fractures and Rock Mechanics", phase 2.

In all three fracture data sets in the Ph.D. project and in "Fractures and Rock Mechanics", phase 2, horizontal beds were observed, and horizontal bedding parallel fractures were common. The fracture density for all the measured fractures in the Hillerslev chalk quarry indicate almost random spacing of the fractures. A comparison of the number of fractures sorted by dip shows that the majority of all the measured fractures in the Hillerslev chalk quarry are steeply dipping with a dominance of almost vertical fractures. Based on the comparison it is evaluated that overall, the fracture descriptions for the three research projects are similar.

All the specimens were fractured to a higher or lesser degree. In four of the specimens horizontal fracture planes were present, two continuing ones in specimen 8, a continuing one in specimen 5, two in specimen 7 and one in specimen 9. This is in accordance with the global fracture observations. The most dominant fractures in the periphery of the specimens are very steeply dipping and seemed almost vertical. This is consistent with the global fracture description. The fracture density in the specimens are similar to the observations in the Hillerslev outcrop chalk quarry indicating almost random spacing of fractures.

Zones with brittle chalk as seen in specimen 2 and 5 were also seen along all the horizontal profiles at the Hillerslev quarry.

Overall, the three fracture data sets in the Ph.D. project are evaluated to be similar. Further, it is evaluated that the fracture descriptions carried out in the three research projects are similar. Finally, the local and the global fracture descriptions are in accordance, i.e. the fracture system in the specimens represents the major part of the Hillerslev outcrop chalk fracture pattern.

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Appendix A

Fracture Description of Hillerslev Chalk (EFP-96)

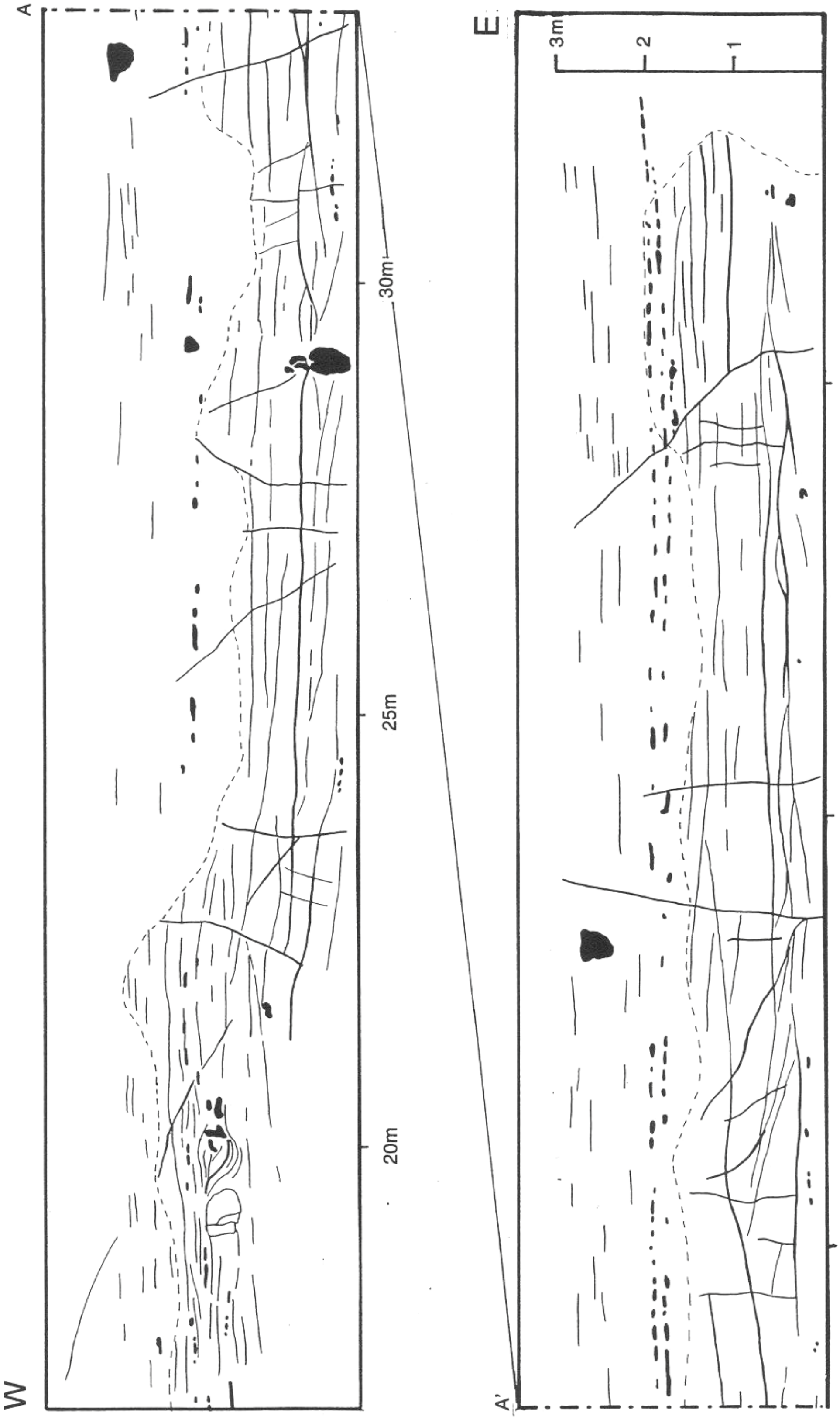

Figure A.1 *Excavated chalk wall in the northern part of the Hillerslev quarry (Krogsbøll et al. 1997).*

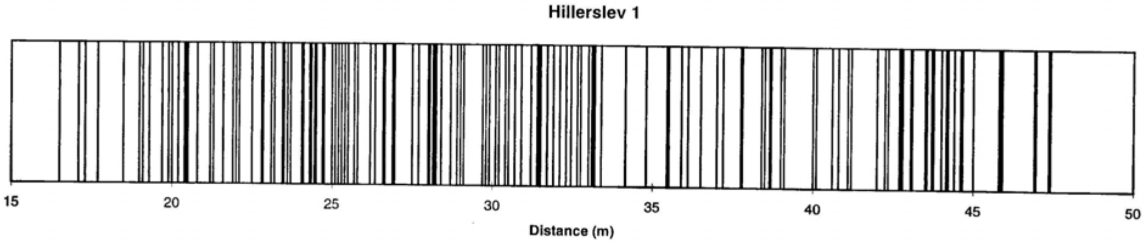

Figure A.2 *Fracture density along the horizontal line (Krogsbøll et al. 1997).*

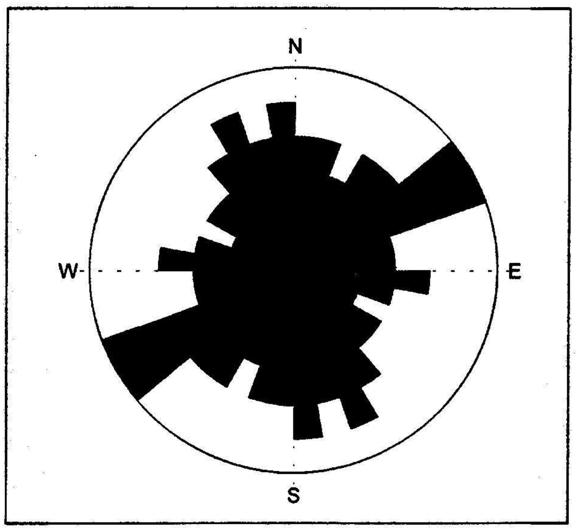

Figure A.3 *Rose diagram of strike for all measured fractures from the Hillerslev quarry (Krogsbøll et al. 1997).*

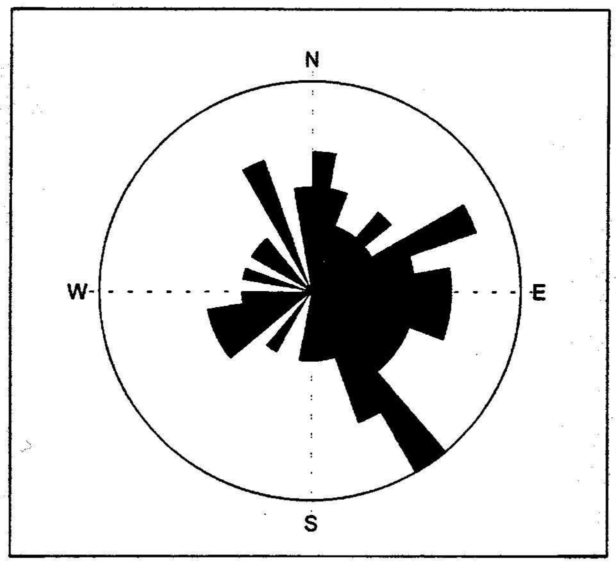

Figure A.4 *Rose diagram of dip directions for all measured fractures from the Hillerslev quarry (Krogsbøll et al. 1997).*

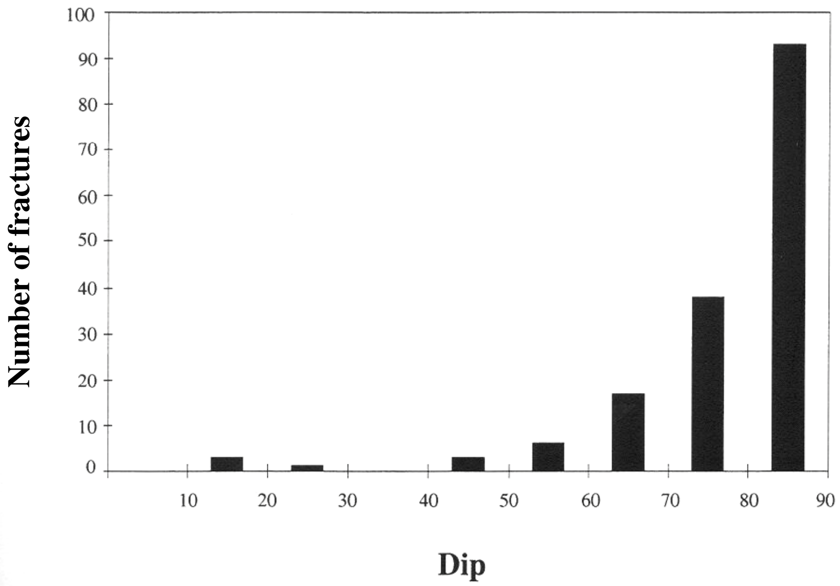

Figure A.5 *Histogram of dip for all measured fractures from the Hillerslev quarry (Krogsbøll et al. 1997).*

Appendix B

Fracture Description of Hillerslev Chalk (EFP-98)

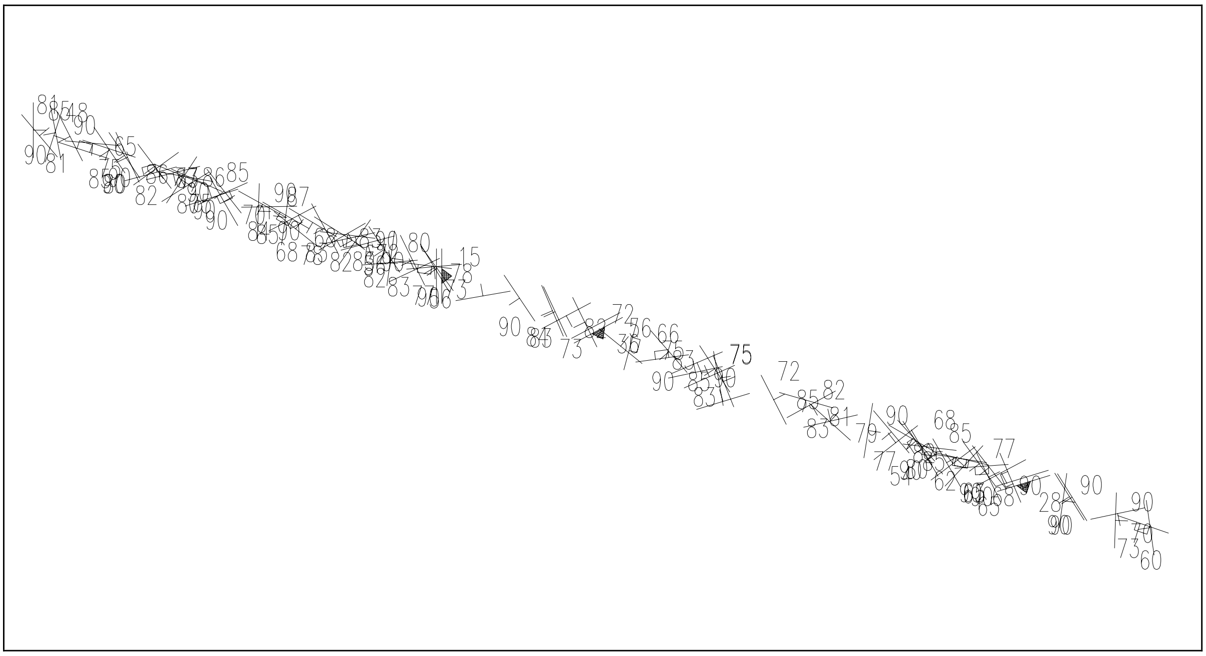

Figure B.1 *Map of strike/dip indicating the density of fractures along the same horizontal profile as described in "Fractures and Rock Mechanics", phase 1 and here referred to as the reference line (Jakobsen 2001).*

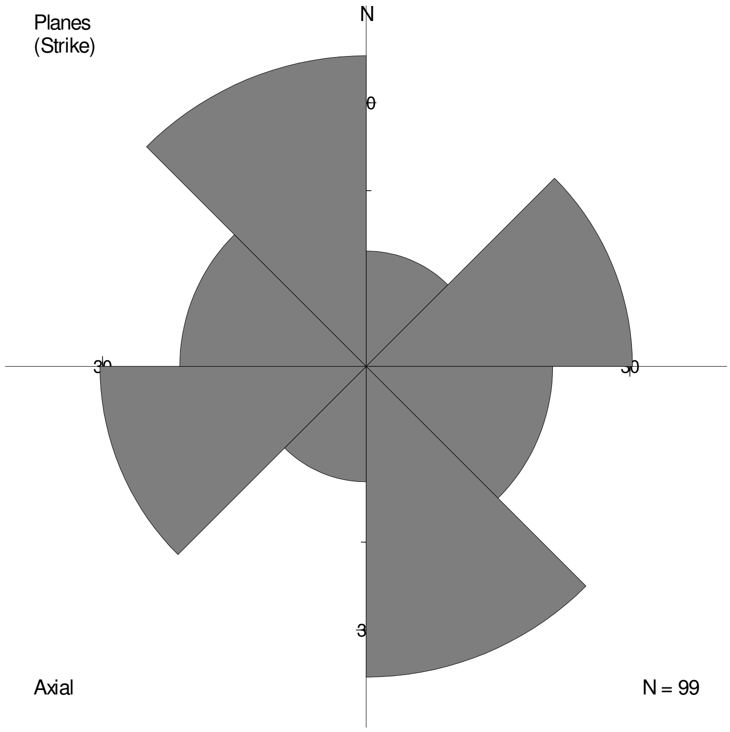

Figure B.2 *Rose diagram of strike for all measured fractures along the reference line (Jakobsen 2001).*

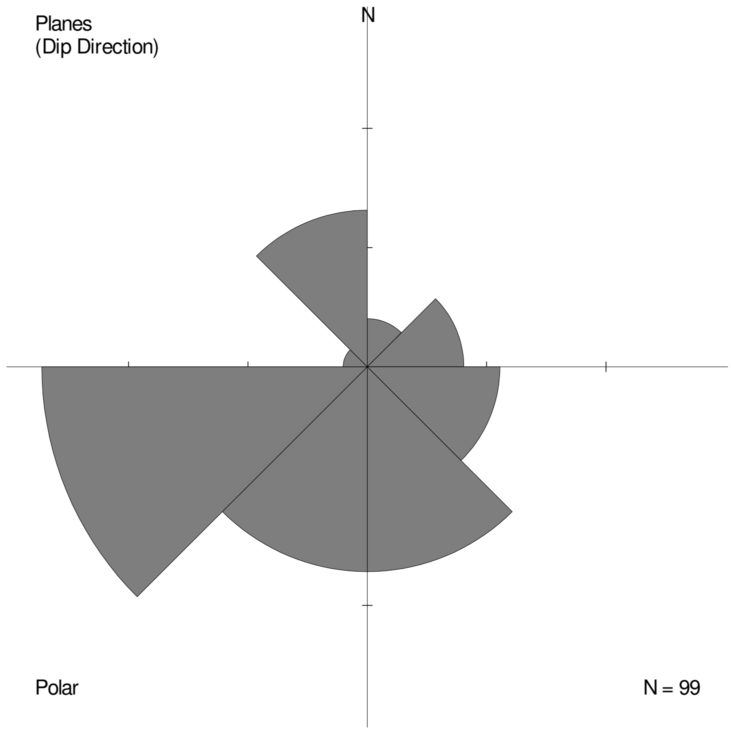

Figure B.3 *Rose diagram of dip directions for all measured fractures along the reference line (Jakobsen 2001).*

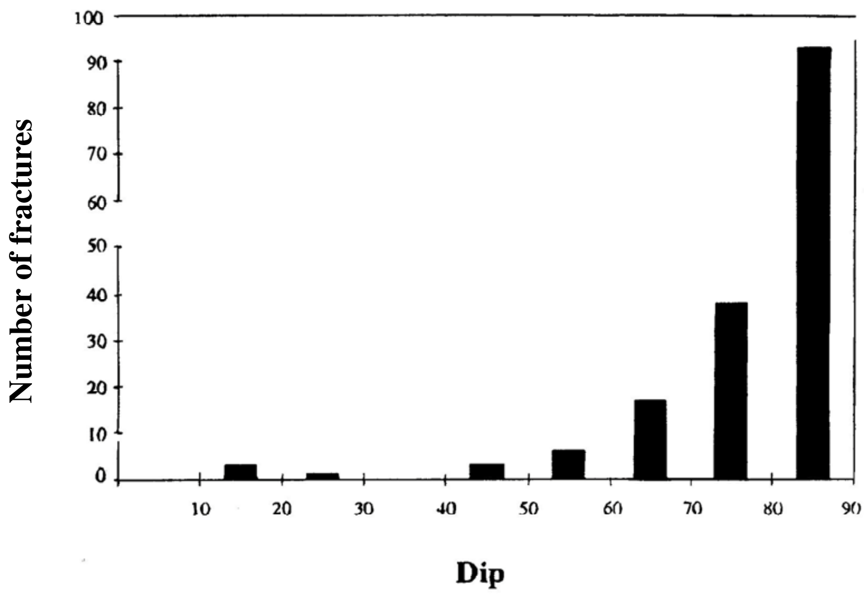

Figure B.4 *Histogram of dip for all measured fractures along the reference line (Jakobsen 2001).*

Appendix C

Field Trip to the Hillerslev Chalk Quarry (Ph.D. Project)

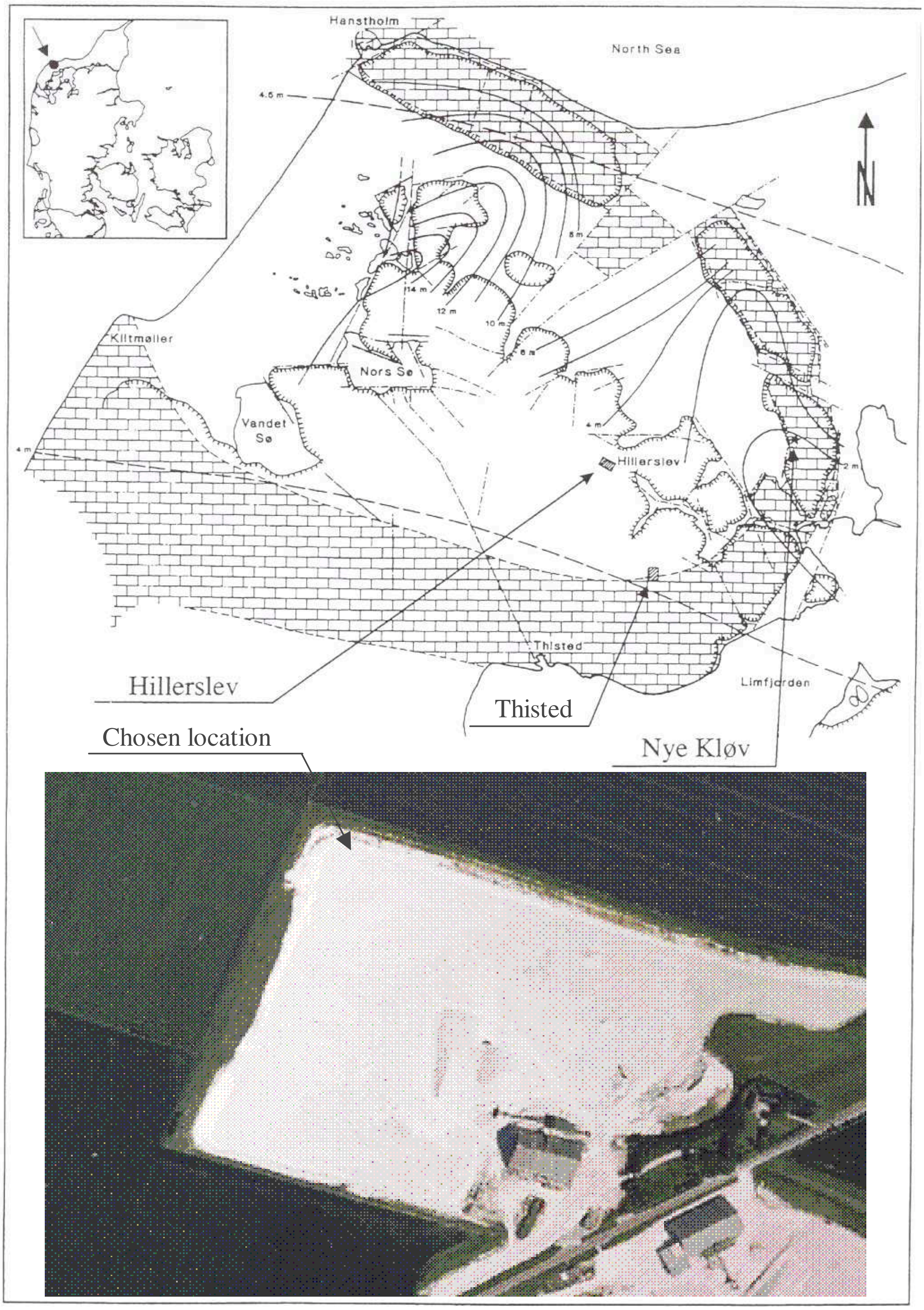

Figure C.1 *Map showing the location of the Hillerslev chalk quarry in the northern part of Jutland (Jakobsen 2001), and air photo with indication of the chosen location for fracture description and sampling in the quarry.*

Figure C.2 *Location for fracture description and sampling at Hillerslev chalk quarry.*

Figure C.3 *The area for fracture description and sampling is located just west of the area used in the earlier research projects "Fractures and Rock Mechanics", phase 1 and 2 (west ←).*

Figure C.4 *Excavated chalk wall (approximately 2.5 m high and 25 m long).*

Figure C.5 *Chalk bench (approximately 1.5 m high, 25 m long and 2 m deep).*

Figure C.6 *The mobile drilling rig on the chalk bench.*

Figure C.7 *The drill bit is mounted on the drilling rig.*

Figure C.8 *Water was used to cool the drill bit and flush away cuttings during drilling.*

Figure C.9 *Insertion of metal shield in the drill bit trace.*

Figure C.10 *Rough excavation in front of and beside the specimen performed by use of the backhoe. The excavation is supervised to prevent fracturing.*

Figure C.11 *Blue tape wrapped around the specimen to keep the fractured specimen together.*

Figure C.12 *A rubber membrane is pulled over the specimen.*

Figure C.13 *The specimen is cut free at the bottom by use of a chain saw.*

Figure C.14 *The specimen is turned upside down for a rough trimming of the bottom.*

Figure C.15 *A successfully sampled specimen placed upside down on a wooden pallet.*

Figure C.16 *View of the specimens, the bench and the wall behind. Yellow numbering on the wall indicates the location of the twelve specimens.*

Figure C.17 *Transportation of the chalk specimens to DTU by lorry.*

Appendix D

Location for Sampling at the Hillerslev Quarry (Ph.D. Project)

Chalk Wall

The chalk wall is approximately 2.5 m high and 25 m long, see Figure D.1.

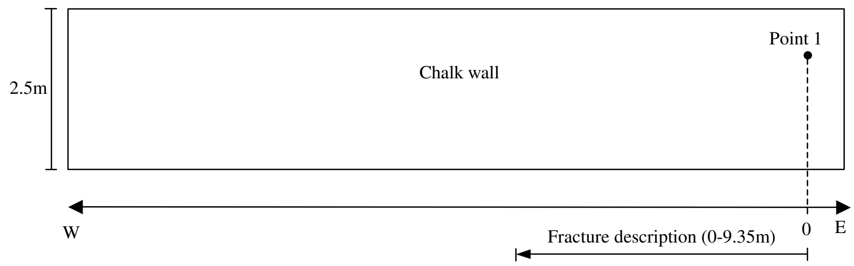

Figure D.1 *Sketch of the excavated chalk wall (2.5 m high and 25 m long).*

A fracture description was performed along a horizontal line along the wall from point 1 and 9.35 m towards west.

Chalk Bench

The chalk bench is approximately 1.5 m high, 25 m long and 2 m deep. The wall behind the bench is approximately 4 m above the ground, i.e. 2.5 m above the bench, see Figure D.2.

A fracture description was performed along a horizontal line in front of the bench from 10.35 m to 20.55 m measured from point 1 towards west.

Specimens

Twelve cylindrical specimens with the dimensions $D \approx 50$ cm and $H \approx 50$ cm were sampled successfully. The location of the specimens on the bench is indicated in Figure D.3.

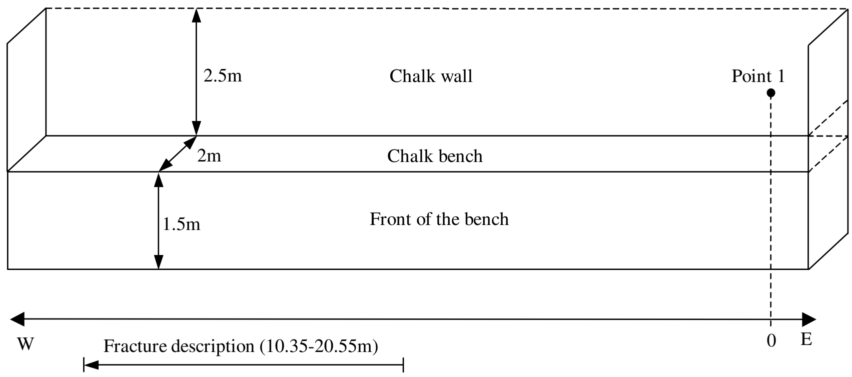

Figure D.2 *Sketch of the bench (1.5 m high, 25 m long and 2 m deep).*

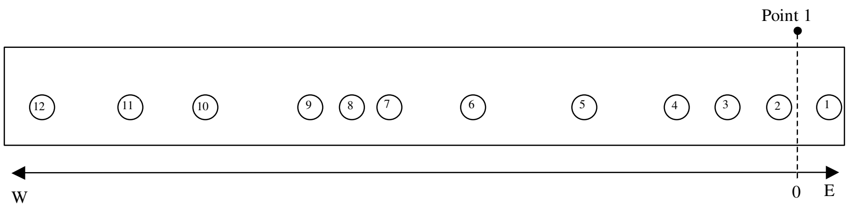

Figure D.3 *A sketch of the location of the twelve specimens in the bench.*

A fracture description was performed on horizontal line profiles of 0.5-2 m length approximately 75 cm behind each of the twelve specimen stumps, and on the stumps.

The location of the horizontal line profile along the wall, along the front of the bench and the twelve horizontal line profiles behind the specimens are sketched in Figure D.4.

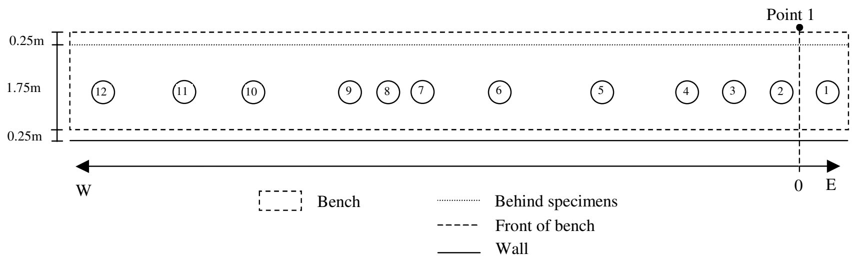

Figure D.4 *Location of the horizontal line profiles along the wall, along the bench and behind the specimens.*

Appendix E

Fracture Description of Hillerslev Chalk (Ph.D. Project)

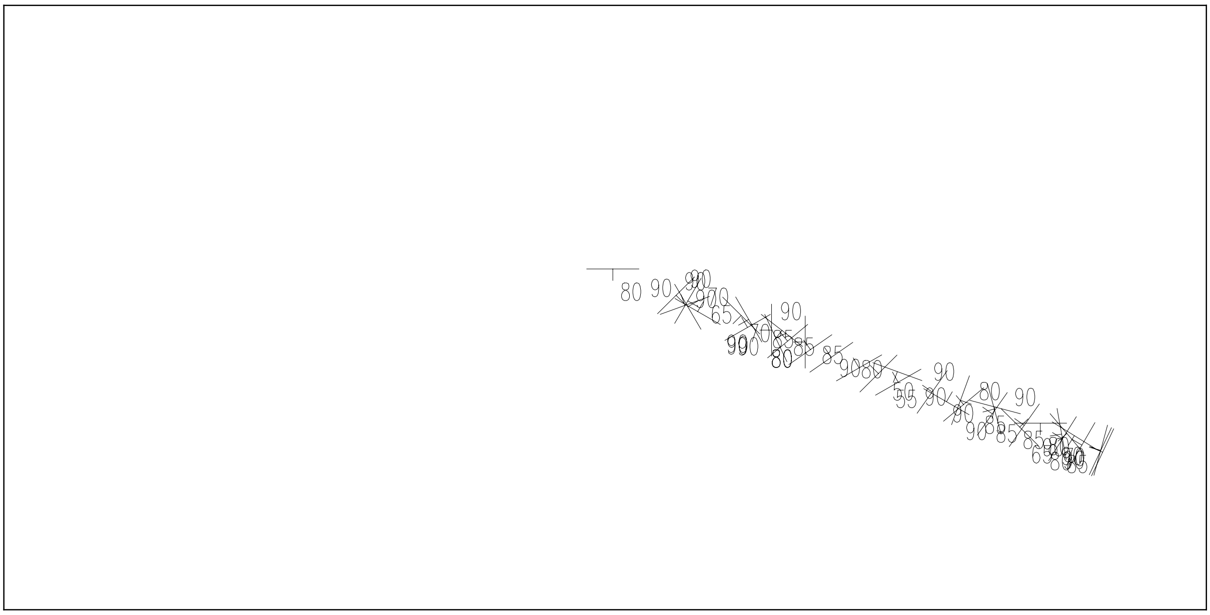

Figure E.1 *Map of strike/dip indicating the density of fractures along the horizontal profile along the chalk wall.*

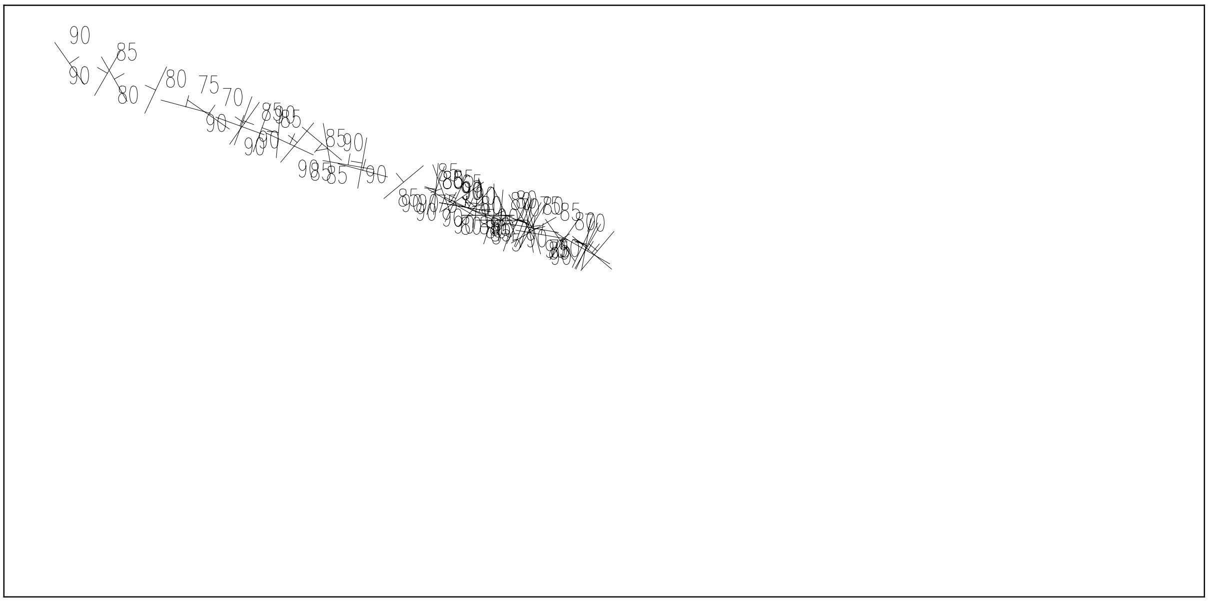

Figure E.2 *Map of strike/dip indicating the density of fractures along the horizontal profile along the chalk bench.*

Figure E.3 *Map of strike/dip indicating the density of fractures behind each of the twelve sampled specimens.*

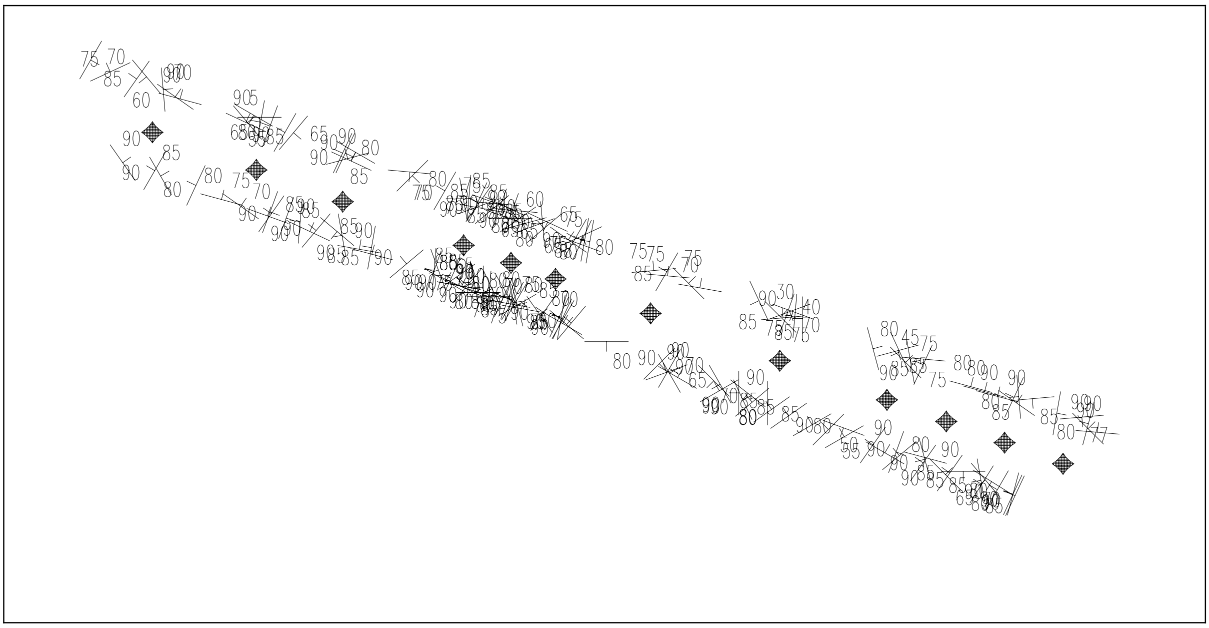

Figure E.4 *Map of strike/dip indicating the density of fractures along the profiles along the wall and the bench and behind each of the twelve sampled specimens. The centers of the specimens are indicated.*

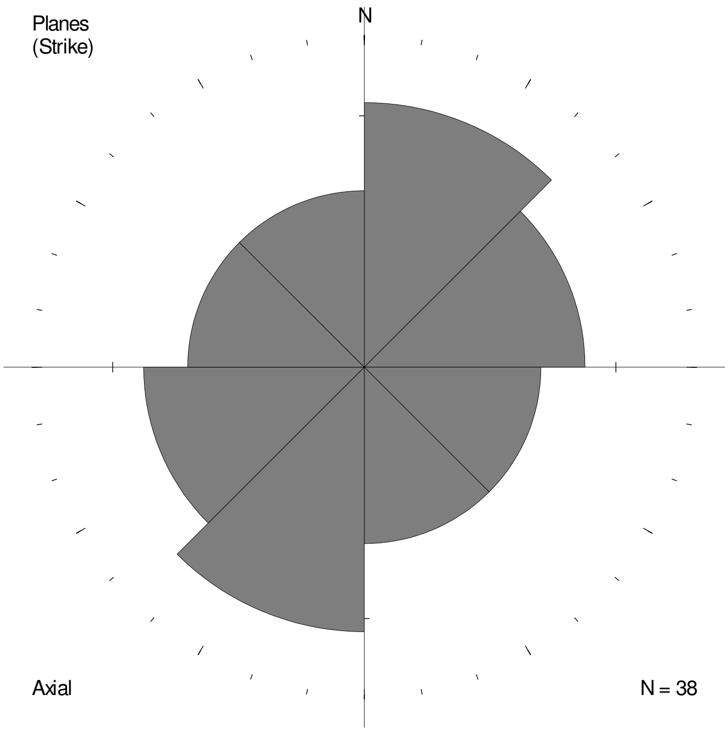

Figure E.5 *Rose diagram of strike for all measured fractures along the horizontal profile along the chalk wall.*

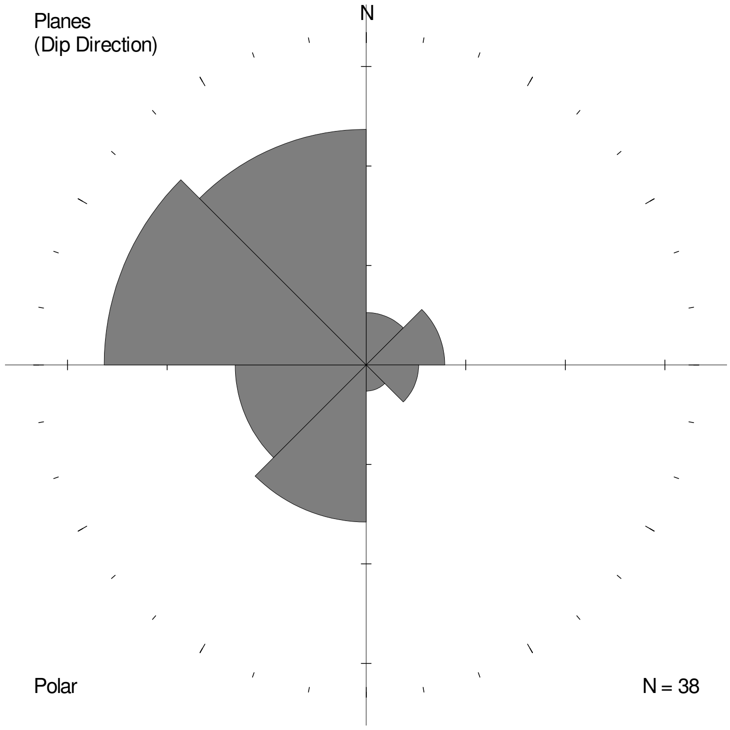

Figure E.6 *Rose diagram of dip directions for all measured fractures along the horizontal profile along the chalk wall.*

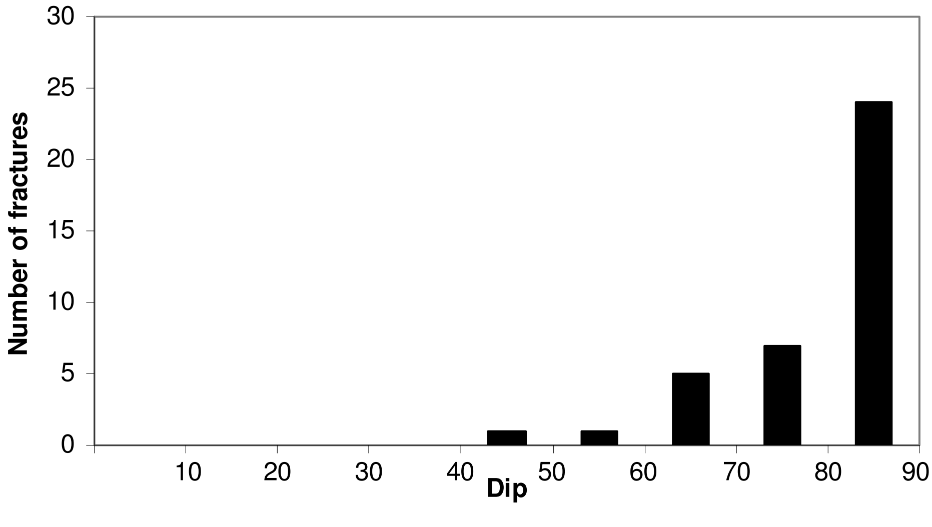

Figure E.7 *Histogram of dip for all measured fractures along the horizontal profile along the chalk wall.*

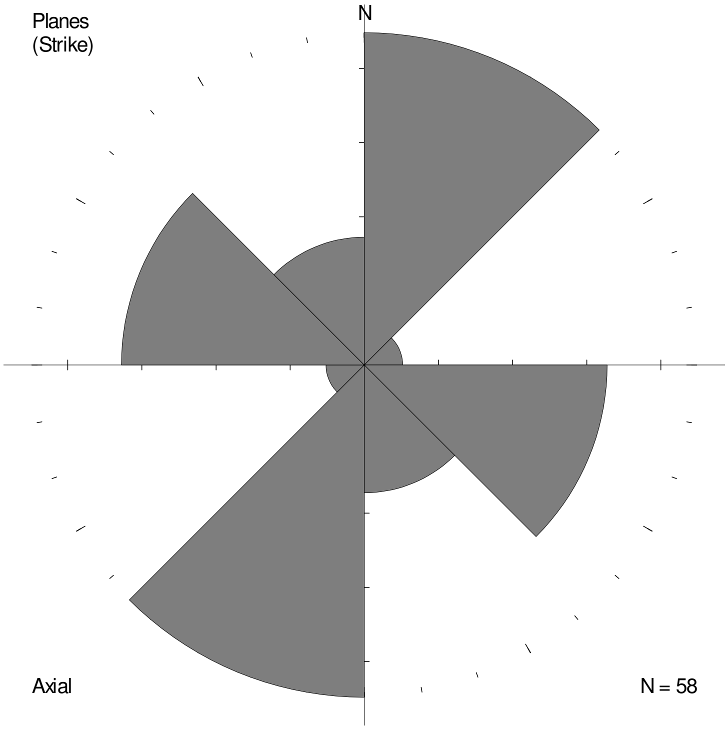

Figure E.8 *Rose diagram of strike for all measured fractures along the horizontal profile along the chalk bench.*

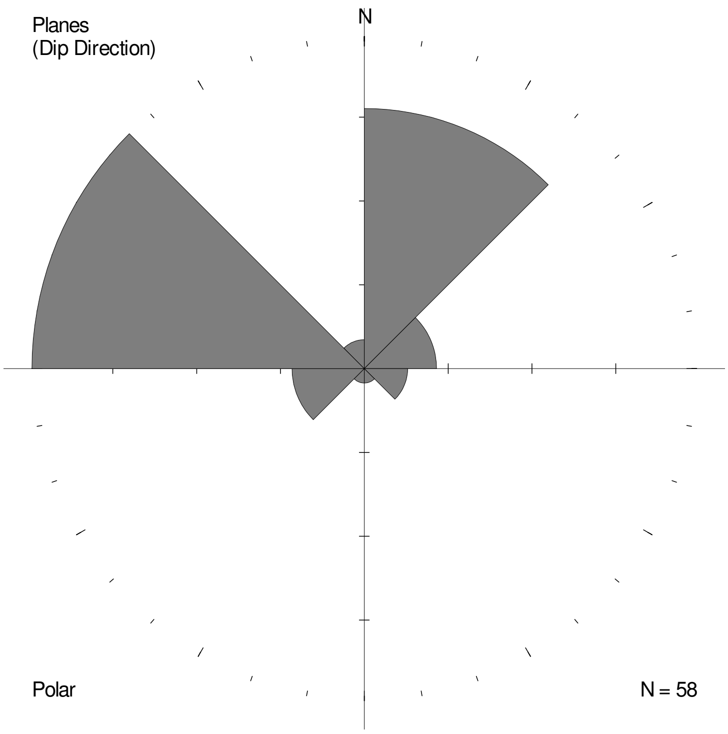

Figure E.9 *Rose diagram of dip directions for all measured fractures along the horizontal profile along the chalk bench.*

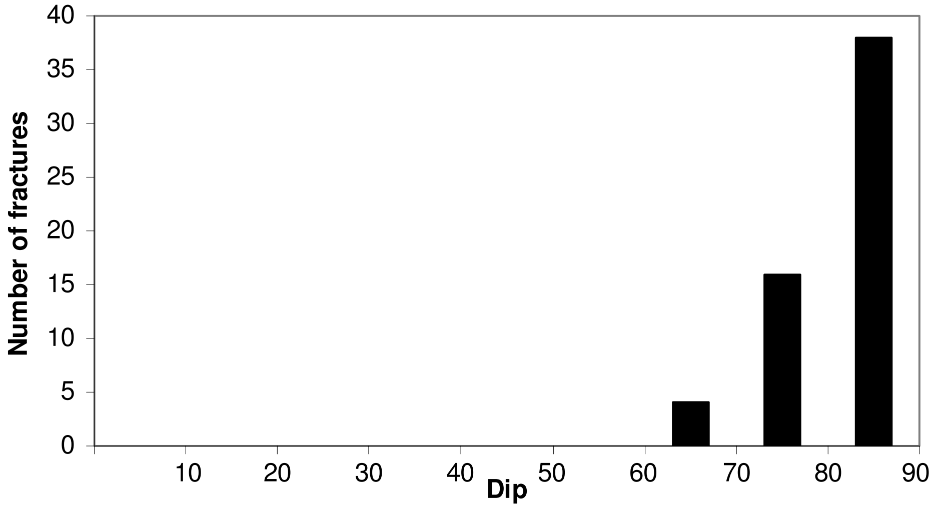

Figure E.10 *Histogram of dip for all measured fractures along the horizontal profile along the chalk bench.*

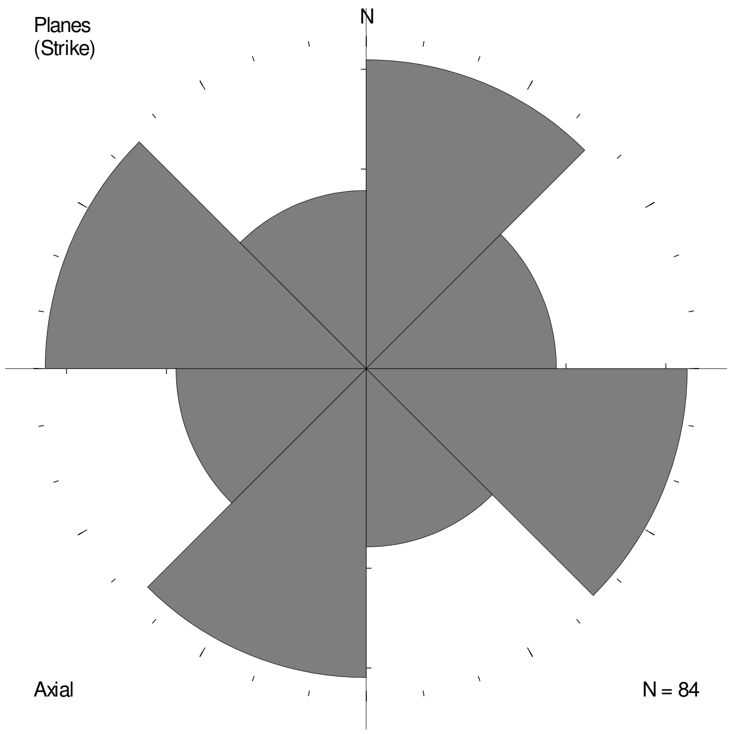

Figure E.11 *Rose diagram of strike for all measured fractures behind the twelve specimens.*

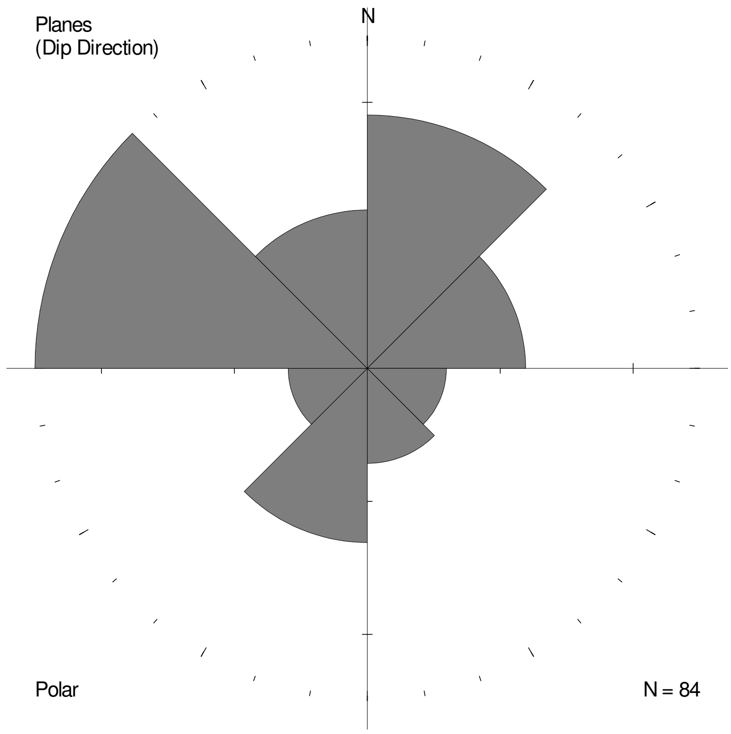

Figure E.12 *Rose diagram of dip directions for all measured fractures behind the twelve specimens.*

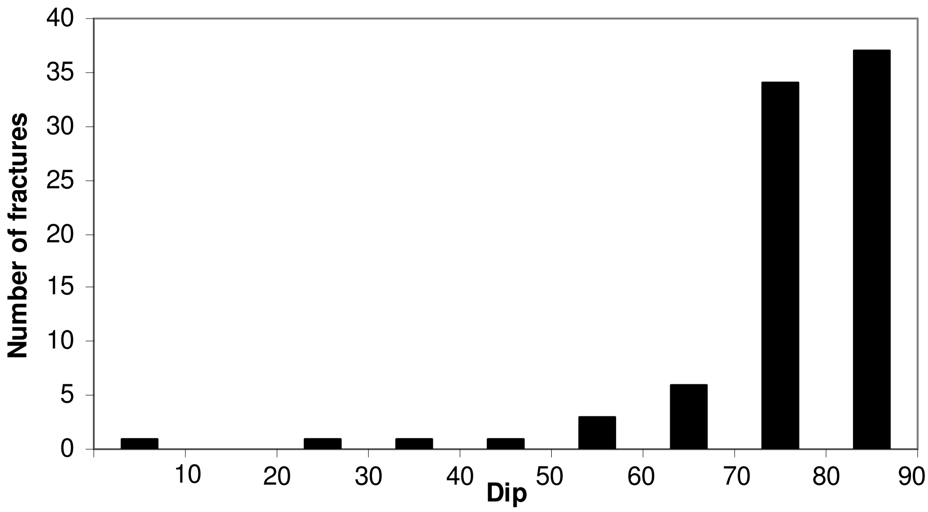

Figure E.13 *Histogram of dip for all measured fractures behind the twelve specimens.*

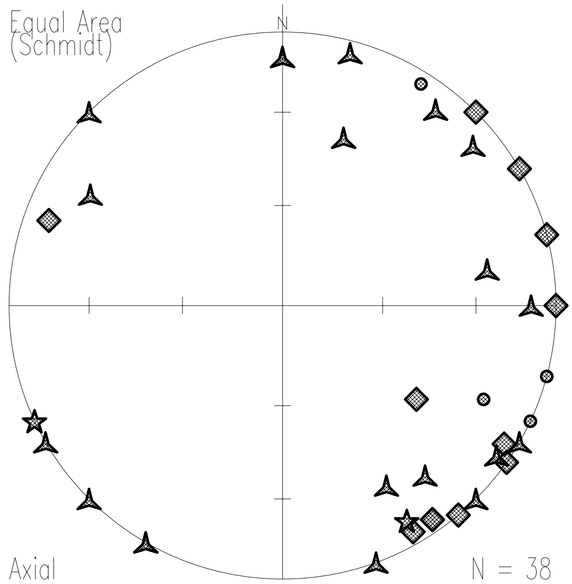

Figure E.14 *Schmidt projection of strike vs. JRC for the measured fractures along the horizontal profile along the chalk wall. Circle: JRC 0-4. Triangle: JRC 5-9. Diamond: JRC 10-15. Star: JRC > 15.*

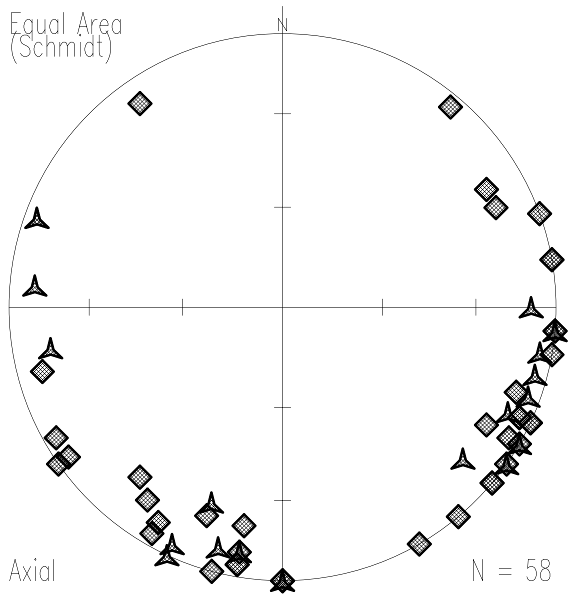

Figure E.15 *Schmidt projection of strike vs. JRC for the measured fractures along the horizontal profile along the chalk bench. Circle: JRC 0-4. Triangle: JRC 5-9. Diamond: JRC 10-15. Star: JRC > 15.*

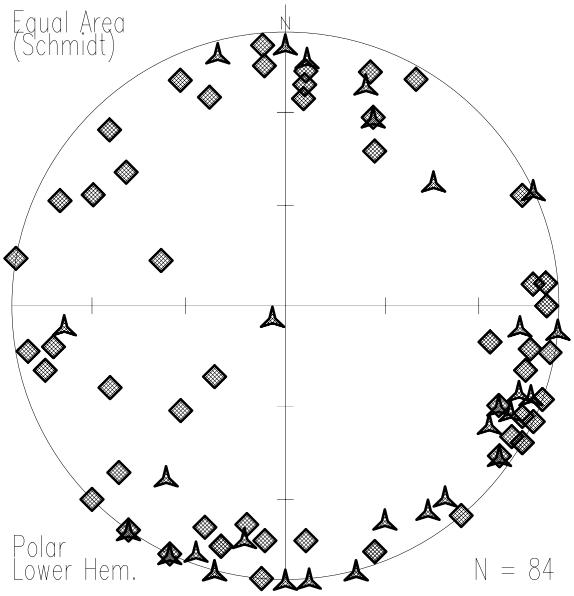

Figure E.16 *Schmidt projection of strike vs. JRC for the measured fractures behind the twelve specimens. Circle: JRC 0-4. Triangle: JRC 5-9. Diamond: JRC 10-15. Star: JRC > 15.*

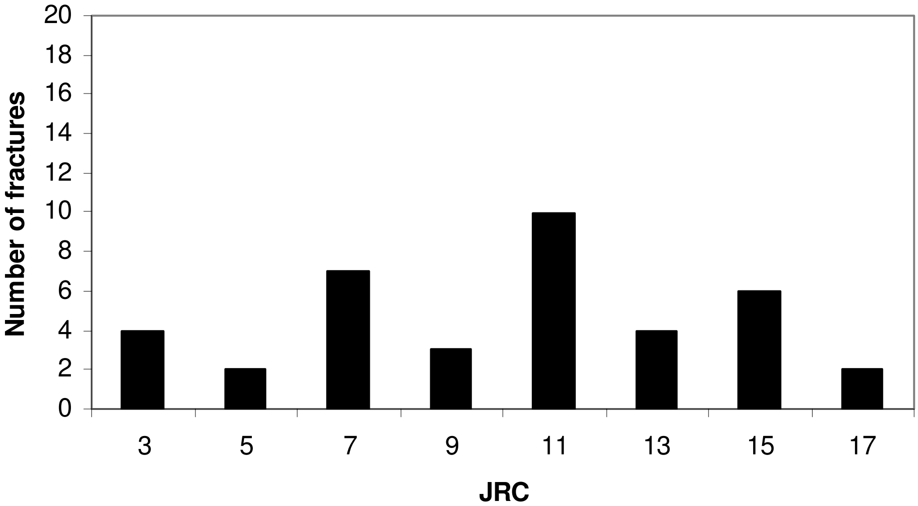

Figure E.17 *Histogram of JRC for all measured fractures along the horizontal profile along the chalk wall.*

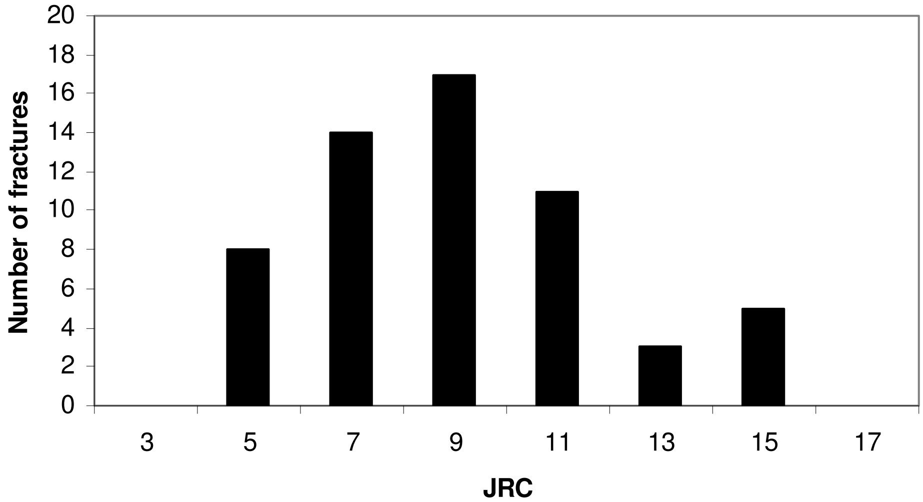

Figure E.18 *Histogram of JRC for all measured fractures along the horizontal profile along the chalk bench.*

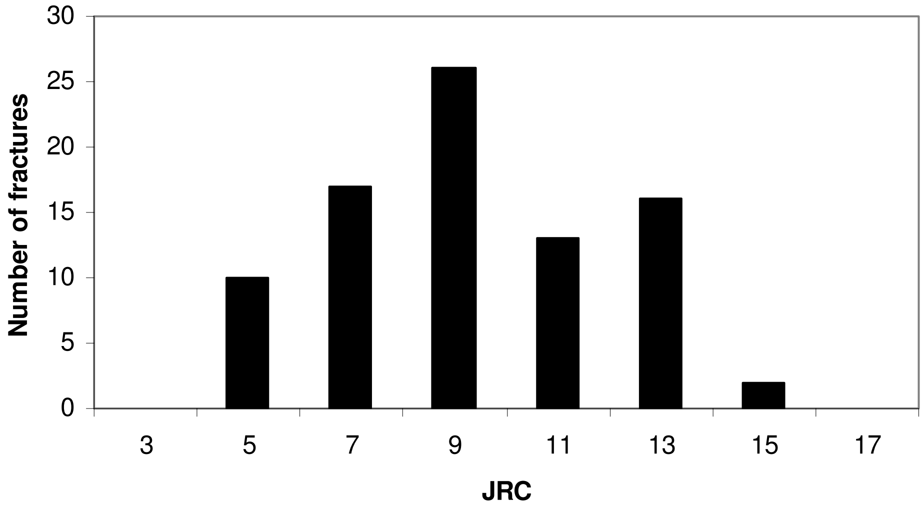

Figure E.19 *Histogram of JRC for all measured fractures behind the twelve specimens.*

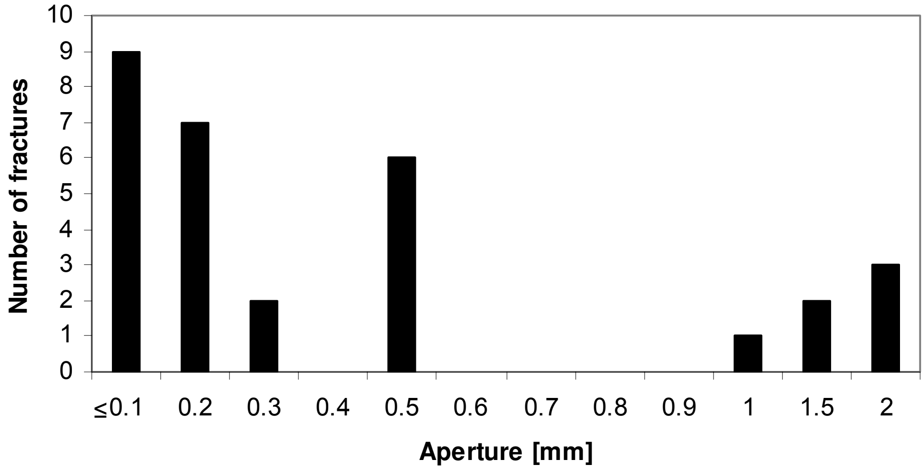

Figure E.20 *Histogram of aperture for all measured fractures along the horizontal profile along the chalk wall.*

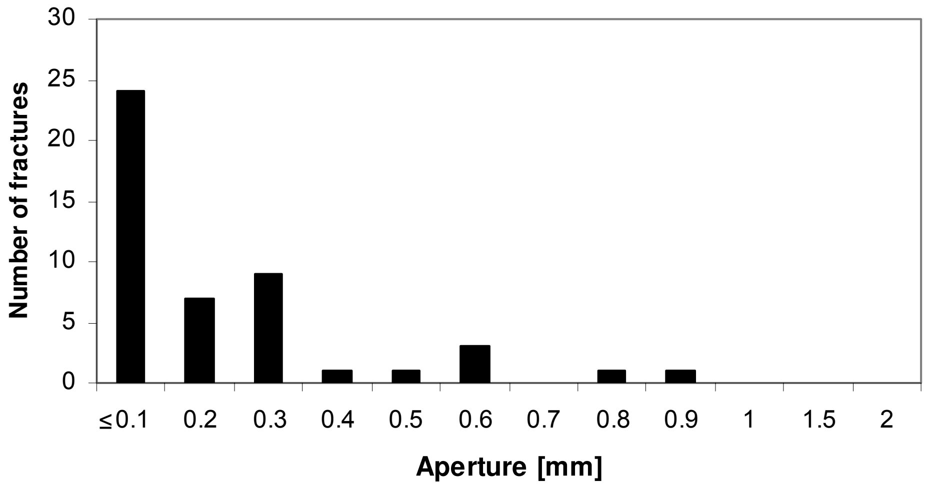

Figure E.21 *Histogram of aperture for all measured fractures along the horizontal profile along the chalk bench.*

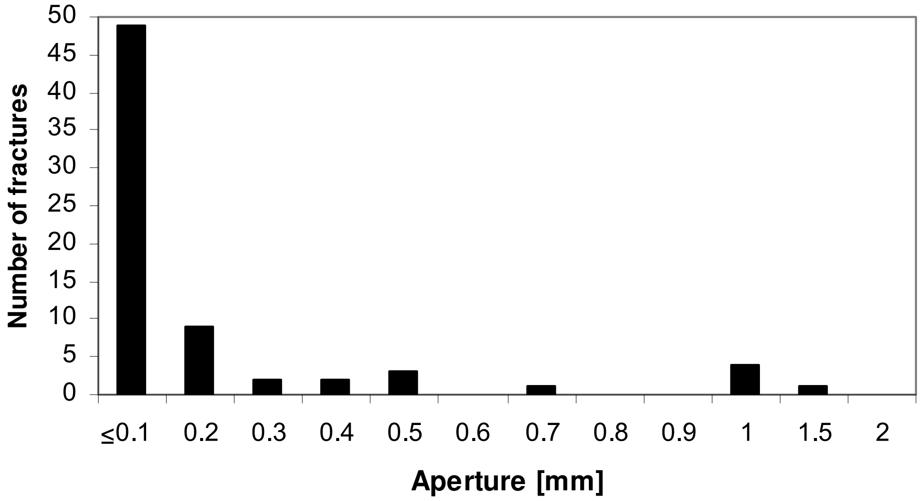

Figure E.22 *Histogram of aperture for all measured fractures behind the twelve specimens.*

Appendix F

Characteristic Joint Roughness Coefficient (JRC) Profiles

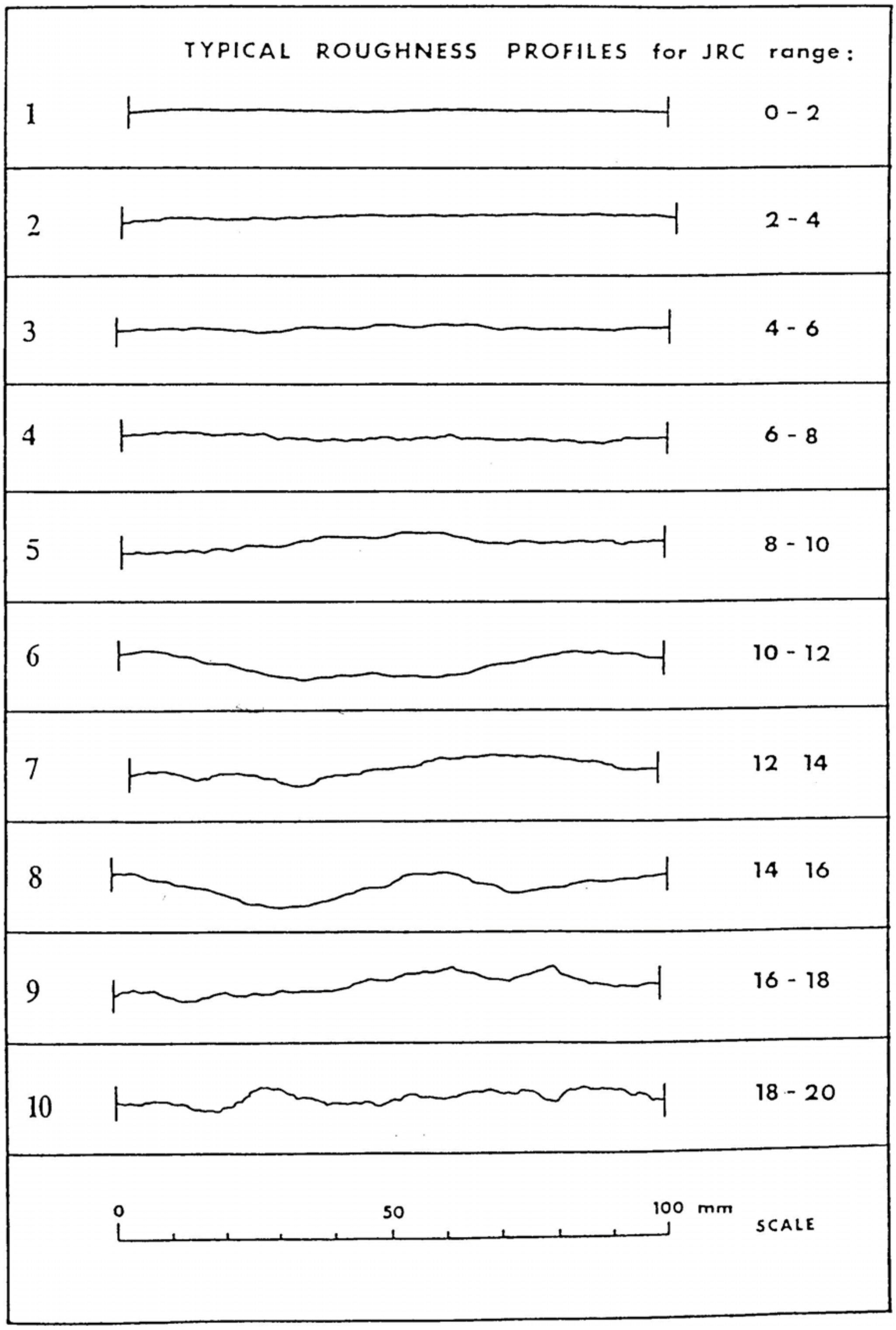

Figure F.1 *Characteristic JRC-Profiles (Løset 1995).*

Appendix G

Photographs of Fractures, Voids, Crushed Zones and Gypsum

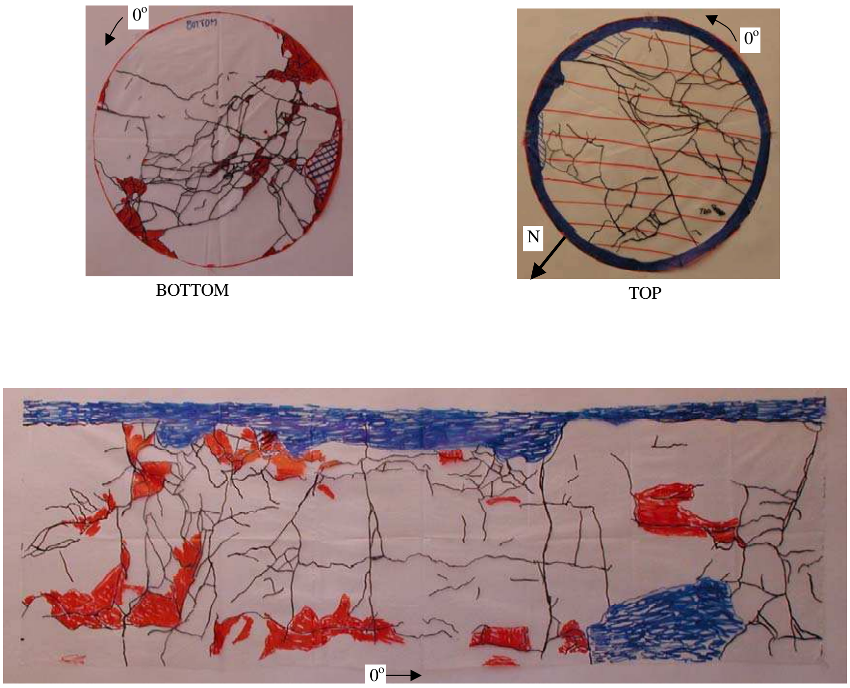

Figure G.1 *Fractures (black lines), voids at the surface (red) and gypsum (blue) indicated on plastic for specimen 2.*

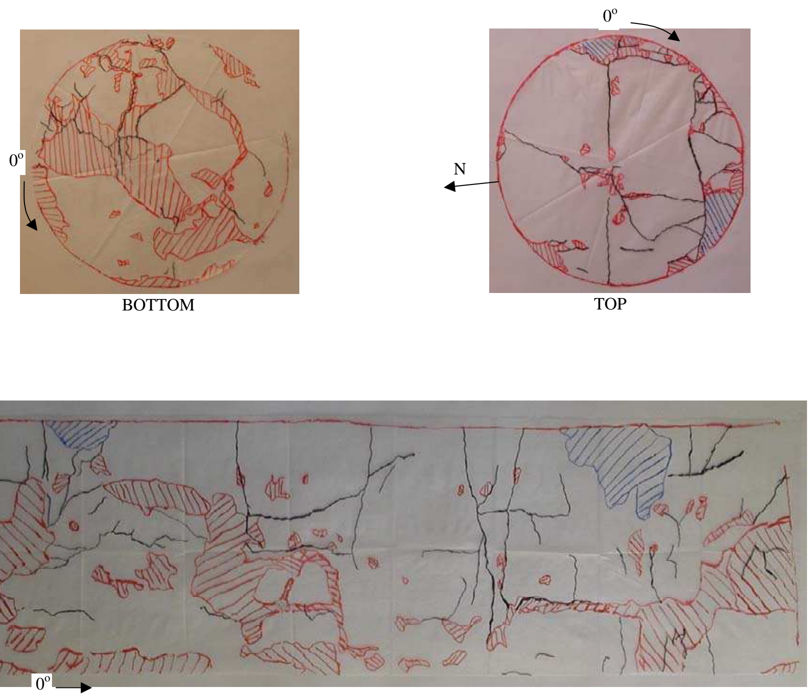

Figure G.2 *Fractures (black lines), voids at the surface (red) and gypsum (blue) indicated on plastic for specimen 3.*

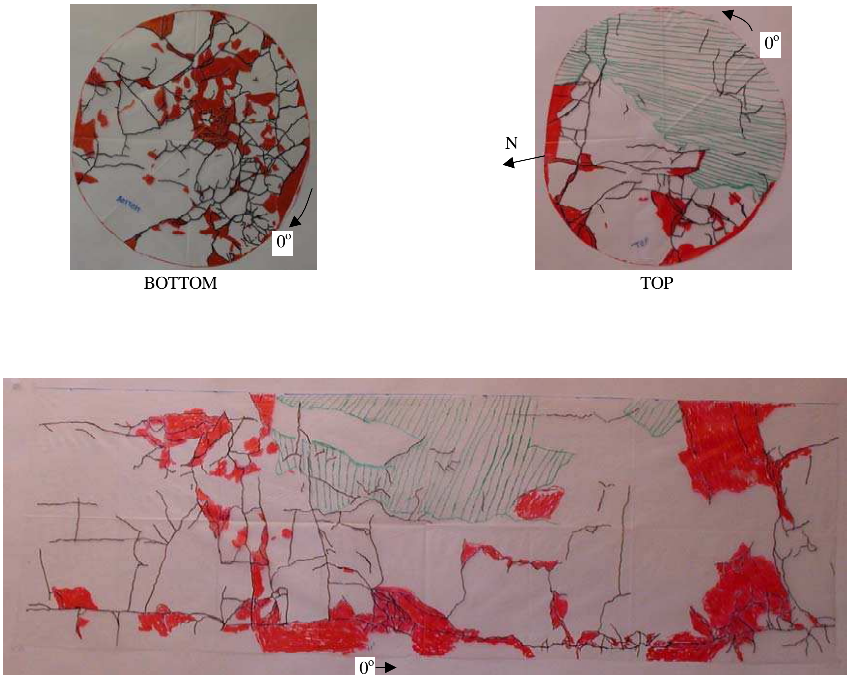

Figure G.3 *Fractures (black lines), voids at the surface (red) and crushed zones (greee) indicated on plastic for specimen 5.*

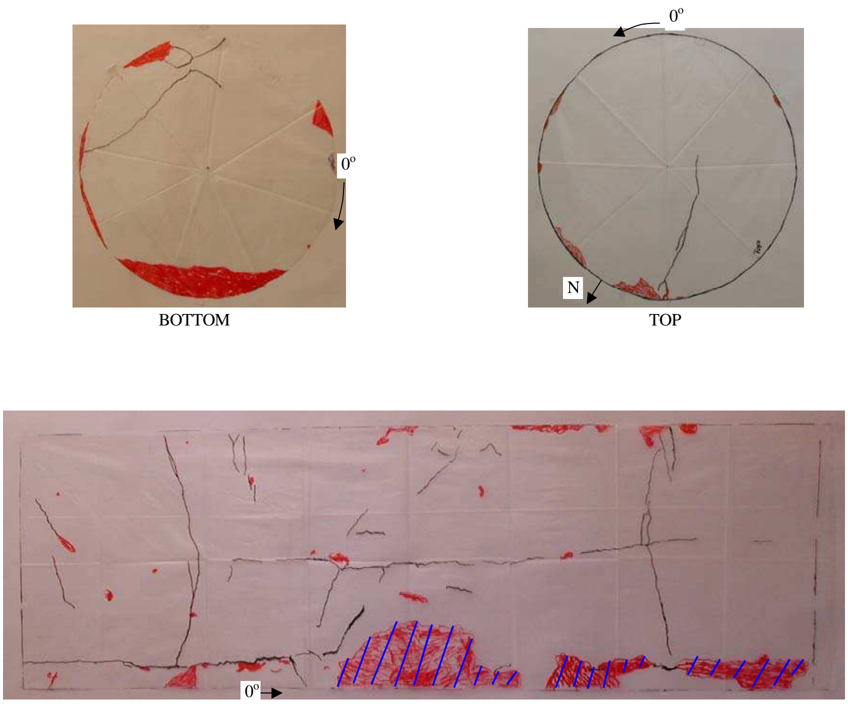

Figure G.4 *Fractures (black lines), voids at the surface (red) and gypsum (blue) indicated on plastic for specimen 7.*

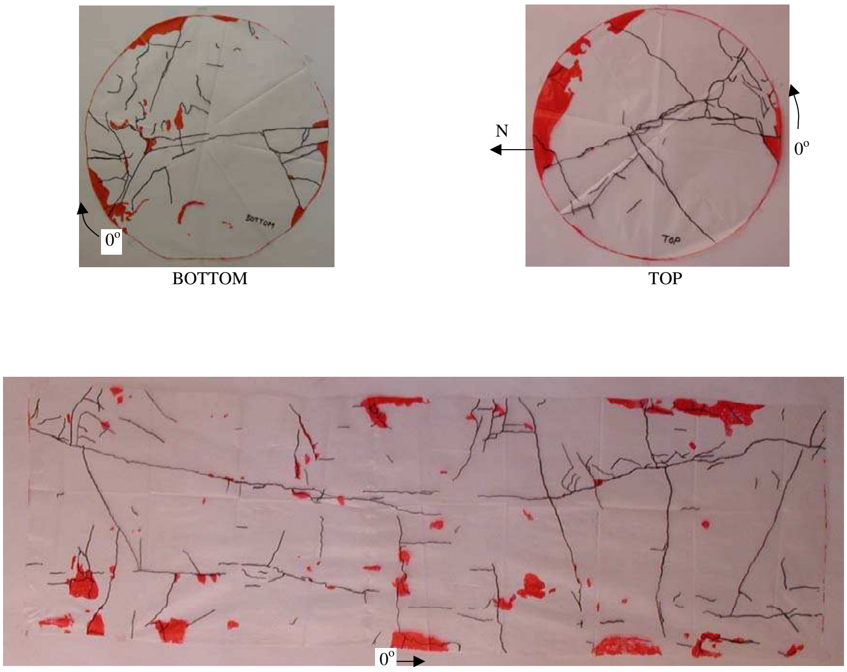

Figure G.5 *Fractures (black lines) and voids at the surface (red) indicated on plastic for specimen 8.*

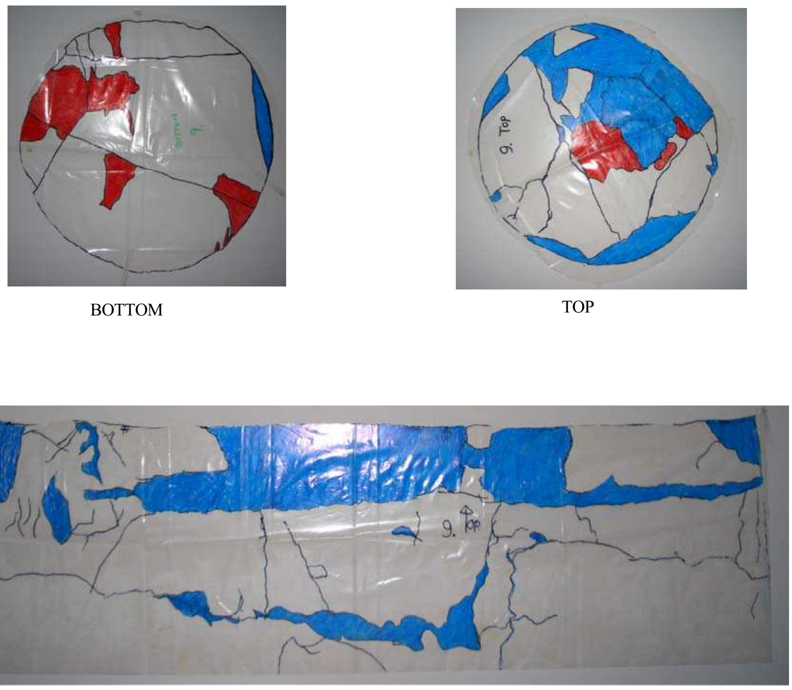

Figure G.6 *Fractures (black lines), voids at the surface (red) and gypsum (blue) indicated on plastic for specimen 9.*

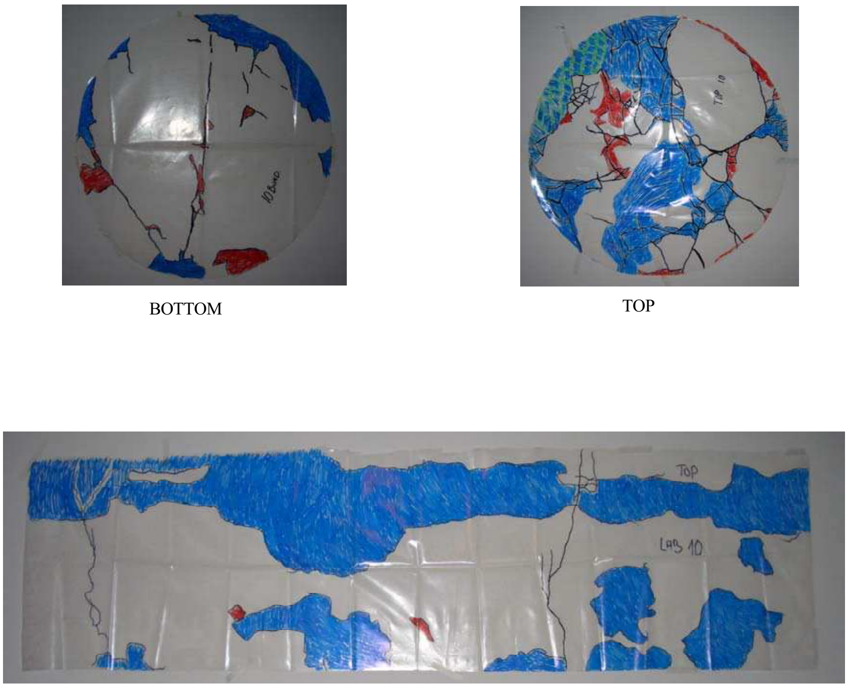

Figure G.7 *Fractures (black lines), voids at the surface (red) and gypsum (blue) indicated on plastic for specimen 10.*

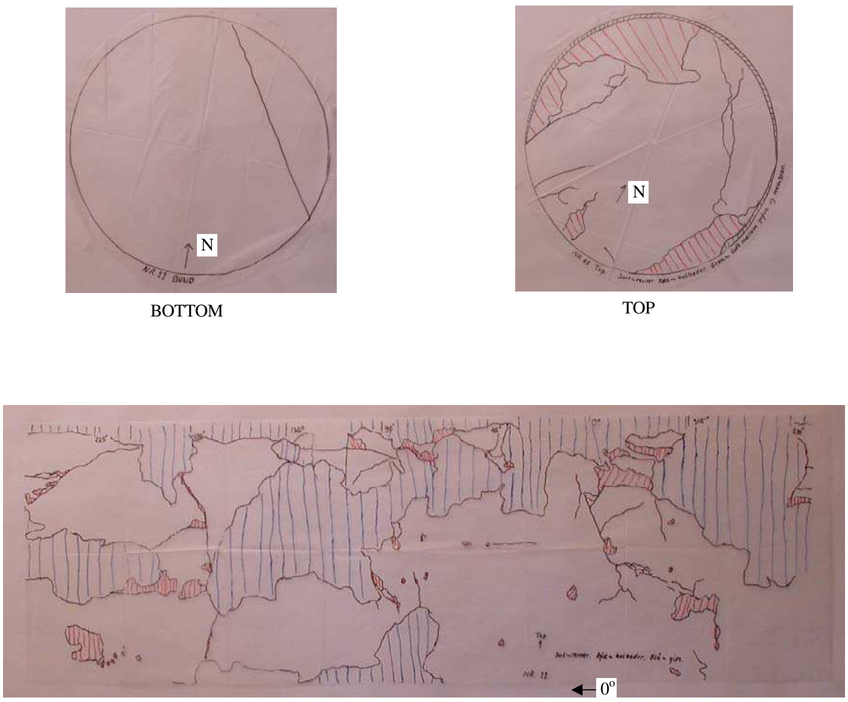

Figure G.8 *Fractures (black lines), voids at the surface (red) and gypsum (blue) indicated on plastic for specimen 11. Gab between membrane and specimen (green).*