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Geological investigations by drill core logging for the Rogfast tunnel project.

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REPORT

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Title:
Geological investigations by drill core logging for the Rogfast tunnel project

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Summary:

In the framework of Rogfast undersea tunnel project, the Norwegian road authorities, western region, have cored four locations along the tunnel trace. The report contains the results of the geological logging of several of these cores from drilling at four locations. The first core comes from Alstein, an island between Randaberg and Kvitsøy, and displays the typical intrusive mainly gabbroic rocks of the Karmøy Ophiolite unit. A shear zone at the bottom of the core may indicate the vicinity of the sole detachment of the Hardangerfjord Nappe. The three other cores are from Kvitsøy. They display the typical meta-volcanic and volcano-clastic greenstones outcropping on the island but also a large proportion of graphite-rich black shales which was not previously reported in the bedrock suite. The inspection of the cores drilled northward from Sauholmen, an island north of Kvitsøy, confirms the presence of a tectonic fault zone along the Boknafjord. The other cores were drilled toward the east from Krågøy and Hesteholmen, two islands east of Kvitsøy. Along these cores, quartz-rich units and cherty schists are widely present and interlayered with the black shales and greenstones. The cores show an impressive amount of large fault rock intervals and damaged host rocks toward the expected location of steep regional meridian fault zones.

Keywords:	Bedrock geology	Structural geology
Drill core logging	Scientific report	

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just north of Kvitsøy correspond to severely crushed zones/ gouge-bearing breccias. See text for further explanation. 29

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1. INTRODUCTION

The Rogfast undersea tunnel project of the Norwegian road authorities, western region, ("Statens vegvesen Region vest") is to join Randaberg to Bokn via Kvitsøy in the outer coastal area of Rogaland County.

The tunnel trace is currently investigated by several drill holes and the Geological Survey of Norway (NGU) has logged four drill cores in order to better constrain the 3D geological pattern in the surroundings of the planned Rogfast tunnel. This is the follow-up of a previous collaboration between the Geological Survey and the Norwegian road authorities which resulted in a report on regional geological and geophysical investigations for the ROGFAST project (Rønning et al., 2006). Some important geological features were identified from these investigations and consequently, refined geological models proposed.

Seven tectono-stratigraphic major units are expected to be found in the vicinity of the tunnel trace (Jorde et al. 1995, Ragnhildstveit et al. 1998; Figure 1). In tectono-stratigraphic order, they comprise:

- the Caledonian autochthon, a Precambrian granitic to dioritic gneissic basement, with some bodies of gabbro and covered by thin Cambro-Silurian phyllites;
- the lower Caledonian allochthon, the Viste Thrust Sheet mainly composed of the Cambrian – Ordovician quartz-rich Ryfylke Schists;
- the overlying Caledonian Storheia and Boknafjorden nappes which consist of Proterozoic granitic gneisses, amphibolites and mica schists with some lenses of marble;
- the uppermost Caledonian allochthon in the tunnel region, the Hardangerfjord Nappe, composed of about 20 different units, with the Lower Ordovician Karmøy Ophiolite and its Middle to Upper Ordovician supracrustal volcanic and volcano-clastic cover, the Visnes and Torvastad groups, being the two prominent units;
- the Upper Ordovician-Silurian sandstones and conglomerates (Skudenes Group) which contains pebbles of the underlying Karmøy Ophiolite;
- the Mesozoic (or Permo-Triassic) sedimentary infill of the Karmsundet fault-bounded graben (Bøe et al., 1992).

A geological study of Alstein has allowed the identification of rocks of the Karmøy Ophiolite unit, therefore located between the Visnes and Torvastad groups of Kvitsøy (i.e., the supracrustal cover of the ophiolite, respectively outcropping west and east of Kvitsøy) and the Ryfylke Schists of Randaberg (Figure 1). These rocks at Alstein are mostly gabbroic but also ultramafic and dioritic in composition and intruded by later trondhjemites and mafic dykes, i.e., they display the typical suite of the intrusive rocks of the Karmøy Ophiolite unit. One of the drill cores investigated by NGU was vertically drilled in Alstein. The second, third and fourth set of analysed drill cores are from Sauholmen, a small island north of Kvitsøy, from Krågøy and from Hesteholmen, two islands east of Kvitsøy, where the volcano-clastic rocks of the Torvastad Group crop out (Figure 1 and Figure 2). The drilling from Sauholmen was inclined at 20° and directed to the N, the ones from Krågøy and from Hesteholmen, inclined at 17° and 20°, respectively and both directed to the E. The diameter of all cores is approximately 6 cm. The Sauholmen, Krågøy and Hesteholmen drill holes are expected to intersect the large fault or/and fracture zones identified through an integrated geological and geophysical studies reported in Rønning et al. (2006).

The detailed geological core logging presented in this report is the basis for drawing updated geological profiles along the tunnel trace.

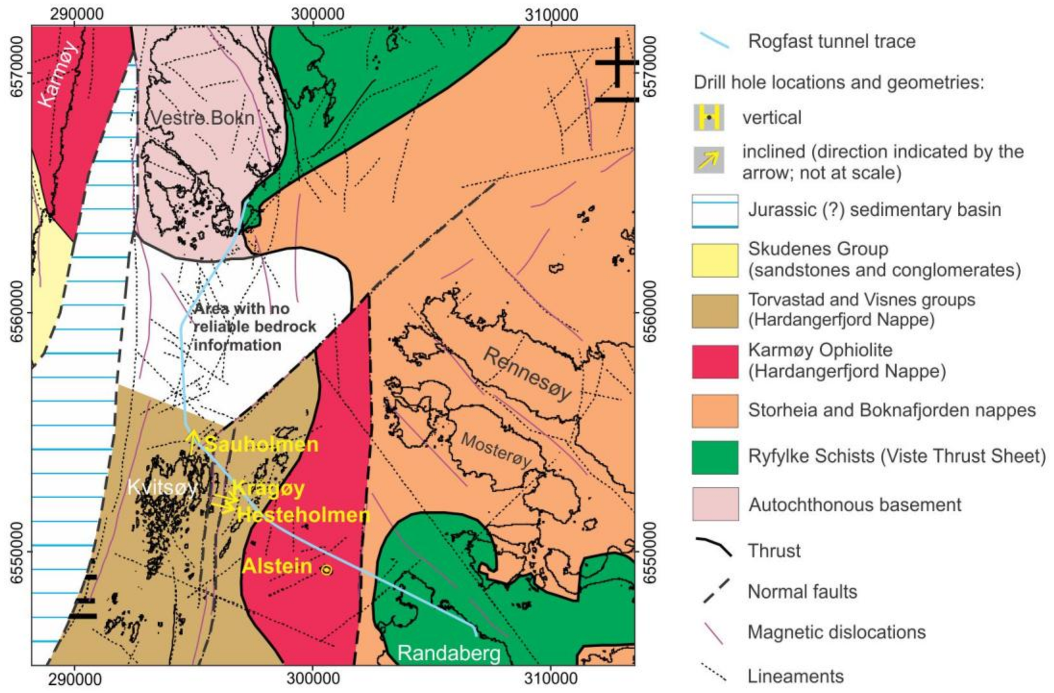

Figure 1. Tectonic map of the Rogfast tunnel region from Rønning et al. (2006) with locations of the four analysed Alstein, Sauholmen, Krågøy and Hesteholmen drill cores.

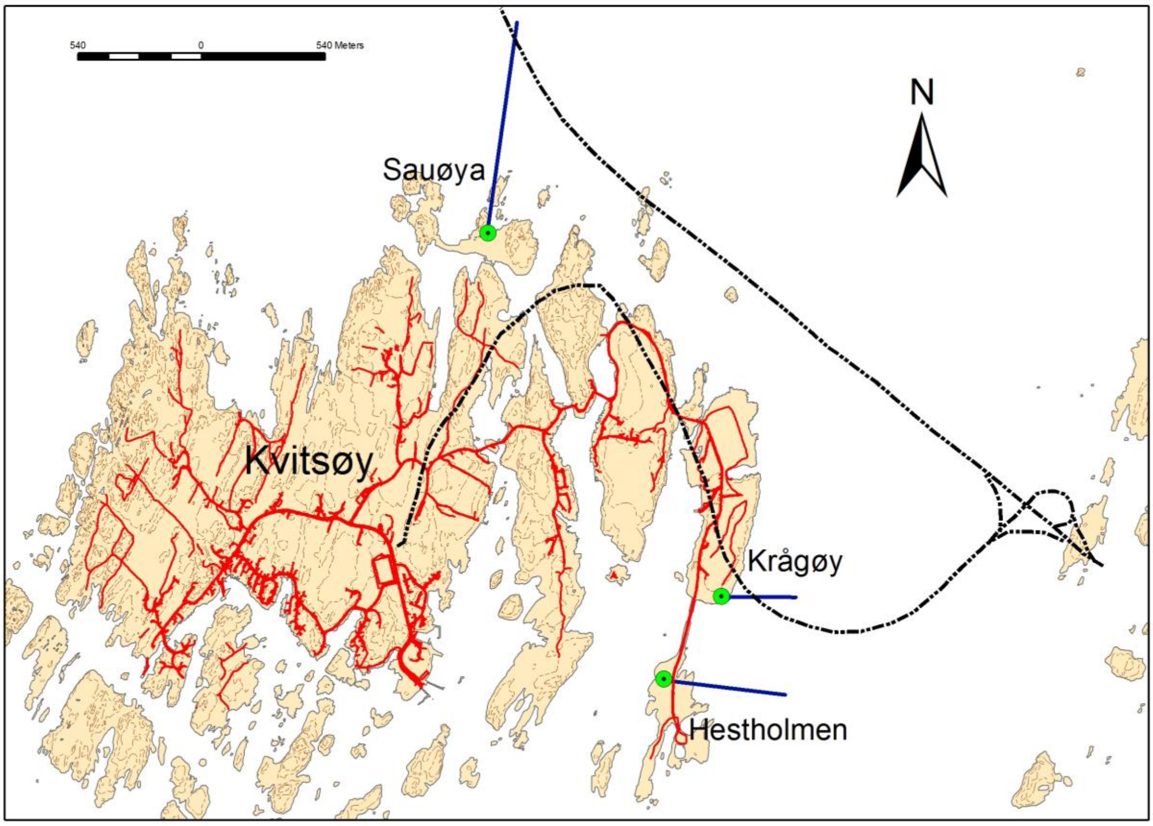

Figure 2: Detailed overview of drill holes investigated next to Kvitsøy.

2. GEOLOGICAL LOGGING OF ALSTEIN DRILL CORE

The vertical drilling at Alstein (UTM 32V coordinates: 300588 E, 6549227 N, 7.8 m a.s.l.; Figure 1) aimed at better determining the thickness and geometry of the intrusive rocks of the Karmøy Ophiolite. It was drilled to confirm the result of a magnetic modelling that indicated a possible basal shear contact with an underlying unit at a depth of 200–300 m below Alstein (Rønning et al. 2006). The available core for geological logging is 300 m long. For a better characterization of the rock properties, a geophysical logging of the drill hole was performed and reported in Elvebakk (2011).

2.1 Geological logging of Alstein drill core

The main core length intervals are defined on distinct geological characteristics identified during the logging. A detailed geological logging illustrated by pictures of chosen core bits is available in Appendix A.

0 – 21 m: mixed unit: inter-layered fine-grained mafic rocks, plagioclase-rich gabbro, feldspar-rich granitic unit (migmatitic texture) and amphibolite, slightly foliated.

21 – 69 m: fine-grained gabbro. Plagioclase can be visible. Veins (of epidote, calcite, zeolites?) are present. The gabbro can be biotite-rich. Chloritization, alteration (sericitization and/or saussuritization?) of plagioclase is observed.

69 – 87 m: medium to coarse grained gabbro with few fine-grained inter-layered gabbros; some intervals are foliated.

87 – 98 m: fine-grained foliated gabbro, sulphides.

98 – 103.5 m: plagioclase-rich coarse gabbro, not foliated, alteration (sericitization and/or saussuritization?) of plagioclases, garnets.

103.5 – 127 m: mixed unit, granitic, fine- to coarse-grained gabbro, plagioclase-rich, pegmatitic granite, no real foliation in this interval. The felsic intervals give a strong signal on the gamma log (Elvebakk, 2011).

127 – 186 m: medium-grained gabbro, still veining, felsic magmatic pockets, plagioclase-rich, not foliated.

186 – 187 m: granitic interval, well detected by a strong amplitude signal on the gamma log (Elvebakk, 2011).

187 – 208 m: plagioclase-rich medium-grained gabbro, no foliation, more plagioclase-rich (white) parts or more dark (amphibole, biotite) parts, alteration (sericitization and/or saussuritization?) of plagioclase, sulphides, garnet.

208 – 217 m: gabbro, very dark, very fine-grained, foliated, calcite vein network.

217 – 231.5 m: medium- and fine-grained plagioclase-rich gabbro.

231.5 – 232.8 m: medium- to coarse-grained gabbro.

232.8 – 246.8 m: fine-grained gabbro, some intervals are plagioclase-rich.

246.8 – 264.7 m: porphyritic plagioclase-rich mafic rock (gabbro to diorite), some foliated intervals, pyrite-rich.

264.7 – 274.3 m: alternating plagioclase-rich –dark mineral-rich, fine-grained and medium grained gabbro/diorite. Some intervals display very small garnets.

274.3 – 283 m: sheared granitic layer, mylonitic texture, and porphyroblasts of K-feldspars (Figure 3).

283 – 301 m: chlorite-rich altered-biotite gabbro and fine grained foliated mafic rocks (Figure 3).

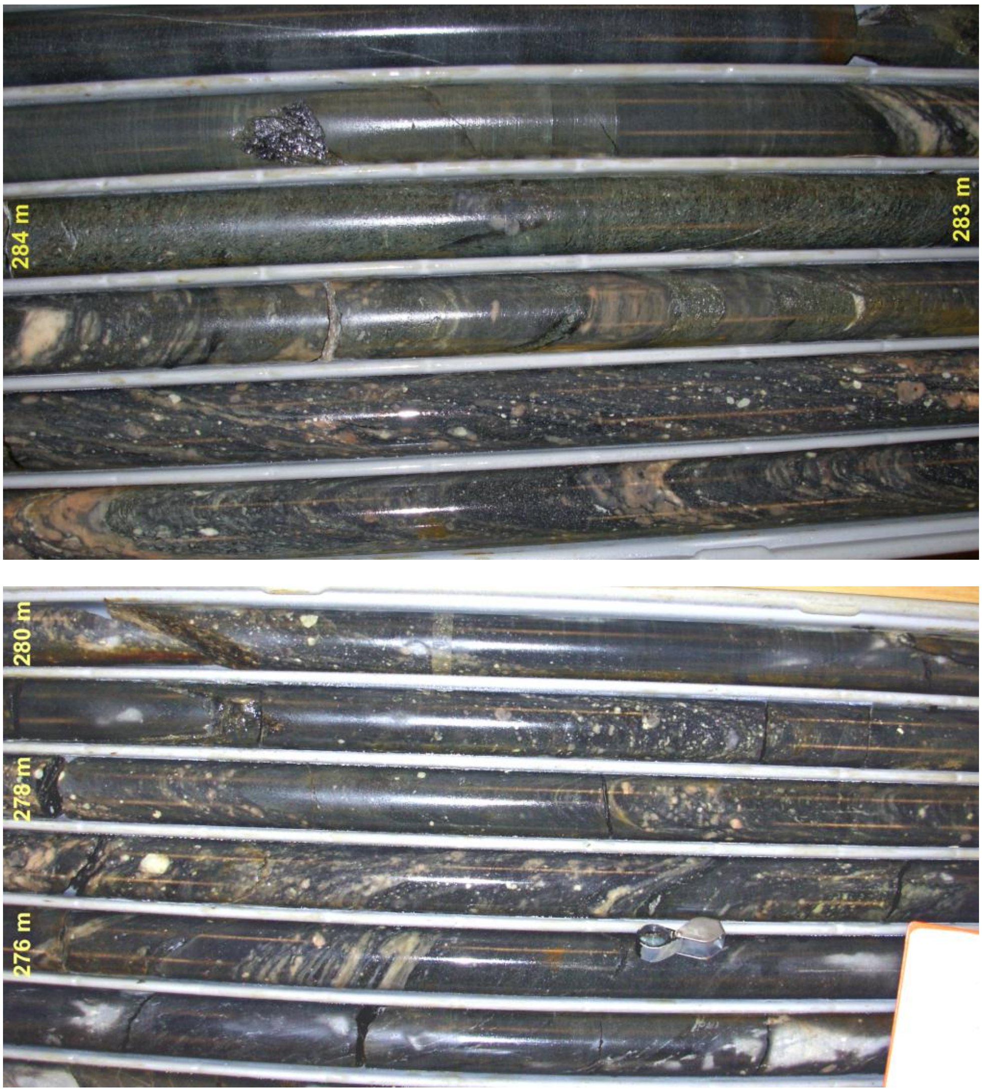

Figure 3. Sheared granitic layer, mylonitic texture, and porphyroblasts of K-feldspars in the 274.3 – 283 m core interval.

2.2 General remarks on Alstein drill core inspection

The olivine component of a typical gabbro is not observed. If the gabbro is poor in olivine, it is a ferrogabbro although the olivine may be only detectable on microscope.

The sheared zone at the bottom of the core (see Figure 3) may indicate the proximity of the sole detachment of the Hardangerfjord Nappe.

2.3 Geophysical and geological profile along Alstein drill hole

Figure 4 summarizes the geophysical and geological investigations of Alstein drill hole and core. Further explanations for the significance of the geophysical signals can be found in Elvebakk (2011).

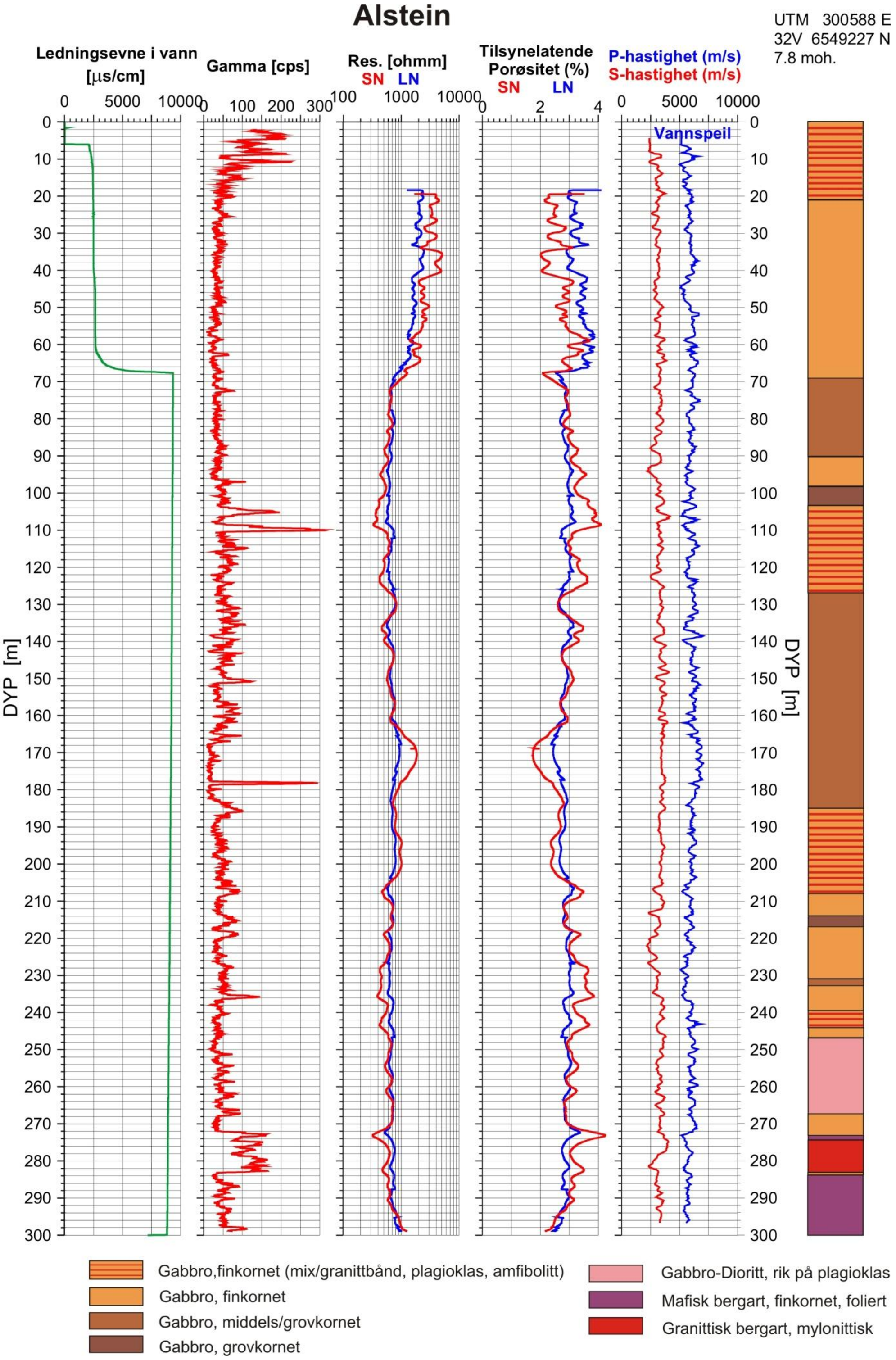

Figure 4. Geophysical and geological log of the Alstein drill hole. (From Elvebakk 2011).

3. GEOLOGICAL LOGGING OF SAUHOLMEN DRILL CORES

The drilling from Sauholmen (UTM 32V coordinates: 294861 E, 6553957 N), a small island north of Kvitsøy was across the volcano-clastic rocks of the Torvastad Group and expected to intersect sub-vertical NE-SW large fault/fracture zones (Figure 1). Hence, the drilling was inclined at 20° and directed to the N and slightly oblique to the strike of the foliation on Kvitsøy. At 670 m of drilling, the hole collapsed and the drilling was stopped. The core obtained from the first hole is labelled Sauholmen Bh01.10. A second drilling slightly deviated from the first one, was performed from c. 469 m of the first hole length to a final length of c. 970 m. The core from the second hole is labelled Sauholmen Bh01.10B.

The geological logging of these two cores is described in the next two sub-sections and led to define main core length intervals based on distinct geological characteristics. The detailed geological logging illustrated by pictures and which comprises description of sub-intervals is available in Appendix B.

3.1 Geological logging of Sauholmen Bh01.10 drill core

1 – 184.7 m: chlorite-rich, epidote-bearing schists - greenstones (metamorphosed volcanic and volcano-clastic succession) - calcite veins, folded.

183.3 – 184.7 m: fault core filled with gouge at the boundary between greenstones and black (i.e. graphite-rich) shales.

184.7 – 383 m: Black shales with a lot of quartz and pyrite. The structural pattern of the black shale significantly differs from the structural pattern of the greenstones.

383 – 492 m: greenstones with characteristics as in the 1 – 183.3 m interval.

492 – 494 m: alternating sheared layers of both greenstones and black shales, gradual transition between the two types of rocks.

494 – 571 m: black shales, with the typical structures as observed in the interval 184.7 – 383 m, i.e. ptygmatitic folds, sheared, strongly deformed, pyrite-rich unit.

571 – 588 m: a lot of thick quartz layers in the black shales with inter-layered greenstones.

588 – 679 m: black shales with the same typical structures as in the other intervals of the same units. The core displays crushed zone and breccias (Figure 5).

3.2 Geological logging of Sauholmen Bh01.10B drill core

The drilling of Bh01.10B is slightly deviated from the first one, Bh01.10, and was performed from c. 469 m of the first hole length to a final length of c. 970 m. The two drill cores from Bh01.10 and Bh01.10B overlap for c. 210 m.

469.4 – 495 m: greenstones with the structural pattern as in Bh01.10, foliated.

495 – 794 m: black shales with typical sheared layers and ptygmatitic folds, sulphides (pyrite and chalcopyrite) and green Cu-rich coating of fracture surfaces are common. Layers are more or less quartz-rich and/or graphite-rich. Calcite is common. Three meter-scale fault rock intervals are observed (Figure 6).

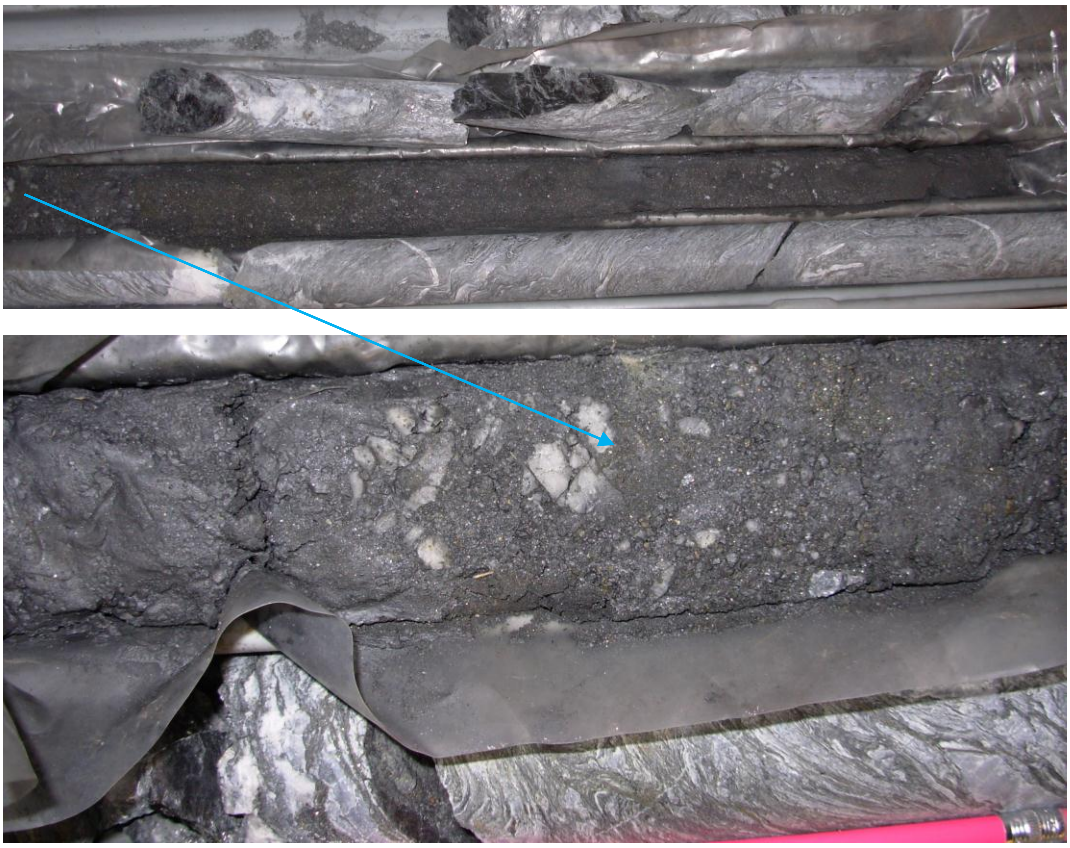

Figure 5. Approximately 1 m of breccia, i.e. crushed graphite (silty to sandy grain size; top picture) with brecciated quartz (bottom picture) at 678.5 m within the black shales. This section of the hole collapsed and the drilling was aborted, due to poor rock quality.

Figure 6. Silty to sandy grain size breccias in the graphite-rich black shale layer of the 665.8 – 668 m core interval.

794 – 850 m: less graphite in the schists, with a max total thickness of 2 m in this interval. The boundary between the two graphite-rich and graphite-poor black shale units is sharp at 794 m.

850 – 961.4 m: graphite is not so abundant but still present, muscovite, quartz, chlorite and less pyrite. Garnets have probably been dissolved but some very small grains still remain. The structures of the unit in this interval remain the same as in the other black shale intervals.

3.3 General remarks on Sauholmen Bh01.10 and Bh01.10B drill cores

The inspection on the cores from Sauholmen has led the discovery of layers of graphite-rich shales (or black shales) in the rock suite of the Torvastad Group that was primarily expected to consist only of the greenstones outcropping on Kvitsøy (Ragnhildstveit et al., 1998). Pyrite is associated with the graphite-rich layers, the greenstones and the black shales are highly fractured. In addition, the black shales display crushed intervals characterized by mm-scale grains. The fragmented/brecciated quartz grains in the crushed zones testify for tectonic faulting, i.e. breccia formation due to friction, and the surrounding clays are fault gouges. The crushed zones are breccias (non-cohesive fault rocks; see Figure 5 and Figure 6). The content of clays and, above all, of the talc in the brecciated zones may have been enhanced by deep weathering which is facilitated along damaged/faulted zones.

3.4 Geological profiles along Sauholmen drill holes

The black shales were not reported in the rock suite of the Torvastad Group outcropping on Kvitsøy (Ragnhildstveit et al., 1998). With the geological log reported along the profile of the drill holes of Sauholmen, it is possible to infer that they actually form the major part of the rock suite in this region (Figure 7).

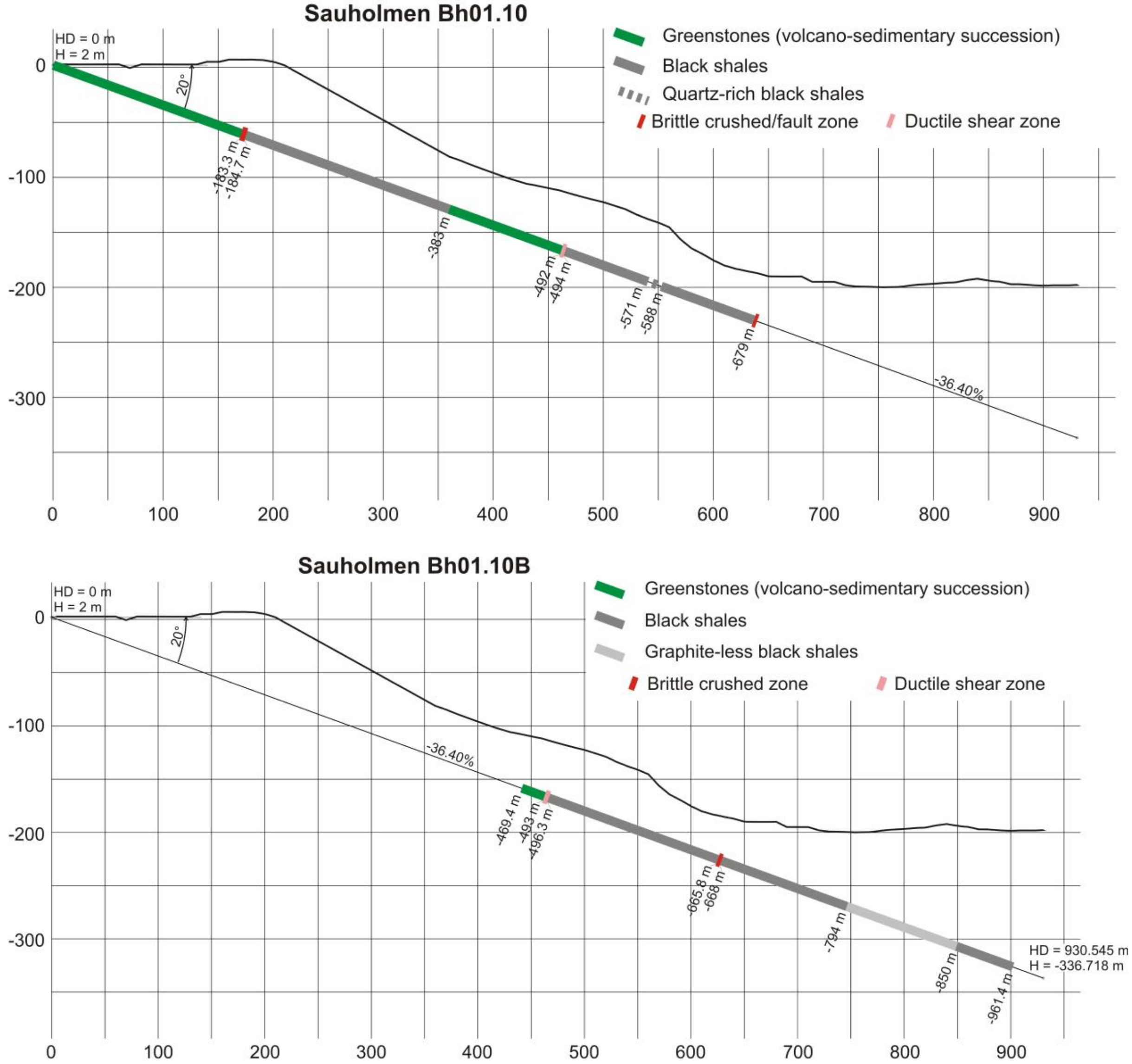

Figure 7. Geological logs along the profiles of the drill holes of Sauholmen: Bh01.10 (top) and Bh01.10B (bottom). H, elevation relative to 0 m altitude; HD, horizontal distance from the point of drilling at the topographic surface. The thicknesses of brittle crushed zones/breccias and ductile shear zones are exaggerated along the profile for a better visualization.

3.5 NGU sampling of black shales along Sauholmen Bh01.10B drill core

NGU sampled three intervals of black shales in order to check for their radioactivity, these rocks being known to concentrate heavy metals. The sample labelled Sauholmen 1 is from 749.2 – 749.3 m (Figure 8), Sauholmen 2, from 540.20 m (Figure 9) and Sauholmen 3, from 661.5 m (Figure 10).

Figure 8. Sauholmen 1 NGU sample. Top picture: before sampling; bottom picture: after sampling.

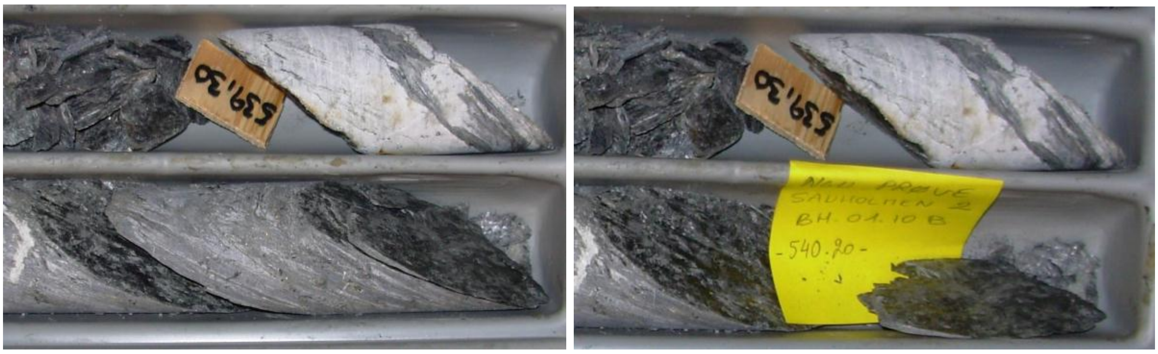

Figure 9. Sauholmen 2 NGU sample. Left picture: before sampling; right picture: after sampling.

Figure 10. Sauholmen 3 NGU sample. Top picture: before sampling; bottom picture: after sampling.

4. GEOLOGICAL LOGGING OF KRÅGØY DRILL CORES

The drilling from Krågøy (UTM 32V coordinates: 295884 E, 6552356 N), an island east of Kvitsøy, was inclined at 17° to the E across the volcano-clastic rocks of the Torvastad Group and quasi-perpendicular to the strike of the foliation measured on Kvitsøy. It was expected to intersect regional N-S fault or/and fracture zones (Figure 1).

The planned drilling was to obtain a c. 650 m long core. However, despite the repetitive attempts of drilling the longest core reached the length of c. 315 m, and the different holes systematically collapsed between 300 and 315 m. Geological logging was carried out on three cores labelled Hull 1, Bh01.11 and Bh01.11C and is described in the three next sub-sections. The main intervals are defined by distinct geological characteristics observed during the logging. A detailed geological logging is available in Appendix C. It includes description of sub-intervals and pictures of chosen core bits.

4.1 Geological logging of Krågøy Hull1 drill core

0 – 95 m: massive greenstones with quartz and calcite veins. Some intervals display a well-developed foliation.

95 – 123 m: foliated and folded quartz-rich greenstones with conspicuous epidote-rich bands.

123 –131 m: alternating graphite-bearing black shales and greenstones.

131 –148 m: Folded and foliated black shales with a high frequency of fractures and intervals of several cm-scale rock fragments. The latter are not clay or fine-grained fault rock- or gouge-bearing.

4.2 Geological logging of Krågøy Bh01.11 drill core

151.8 – 181.8 m: well foliated mixed greenstones and black shales every 3 – 4 m intercalated.

181.8 – 188.5 m: foliated and banded greenstones with quartz bands.

188.5 – 203 m: foliated mixed greenstones and black shales.

203 – 249.4 m: foliated and folded greenstones with some graphite-rich and quartz-rich schist layers.

249.4 – 313.3 m: abundant thick crushed zones (breccias) characterized by angular fragments of quartz and by clays/gouges in severely fractured quartz-rich and graphite-rich schists/black shales (Figure 11). Quartz pegmatitic intervals are common.

Figure 11. Picture of a clay-rich, silty to sandy grain size crushed zone, i.e. gouge-bearing breccias, of the 297 – 308 m interval (here, box of the 297.6 – 305 m core interval with top of drill core to the left).

4.3 Geological logging of Krågøy Bh01.11C drill core

65.3 – 96 m: foliated greenstones characterized by quite massive intervals and a high density of quartz and calcite veins. Chalcopyrite is abundant.

96 – 120 m: very quartz-rich folded and well foliated greenstones and schists with abundant epidote veins.

120 – 129 m: greenstones.

129 – 227 m: quartz-rich schists with some graphite-rich and greenstone intervals. Fold hinges are commonly observed. Foliation is well developed.

227 – 315.5 m: severely damaged/fractured black shales and crushed zones with clays, i.e., gouge-bearing breccias (Figure 12).

4.4 General remarks on Krågøy Hull1, Bh01.11 and Bh01.11C drill cores.

The inspection of the drill cores from Krågøy, like from Sauholmen, has led to the identification of layers of graphite-rich shales (or black shales) in the rock suite of the Torvastad Group, while the latter was primarily expected to only comprise the greenstones outcropping on Kvitsøy (Ragnhildstveit et al., 1998). The greenstones predominate in the top intervals of the inspected cores and the black shales, mainly in the bottom intervals. They both display very quartz-rich layers which are not so conspicuous along the cores from Sauholmen. The non-cohesive breccias with fragmented angular quartz grains and gouges infill are very abundant in the bottom intervals, i.e. in the black shales. This led to the systematic stoppage of the successive drilling due to collapse of the holes. The fault rocks span core intervals of several meters to 20 m where the drilling stopped.

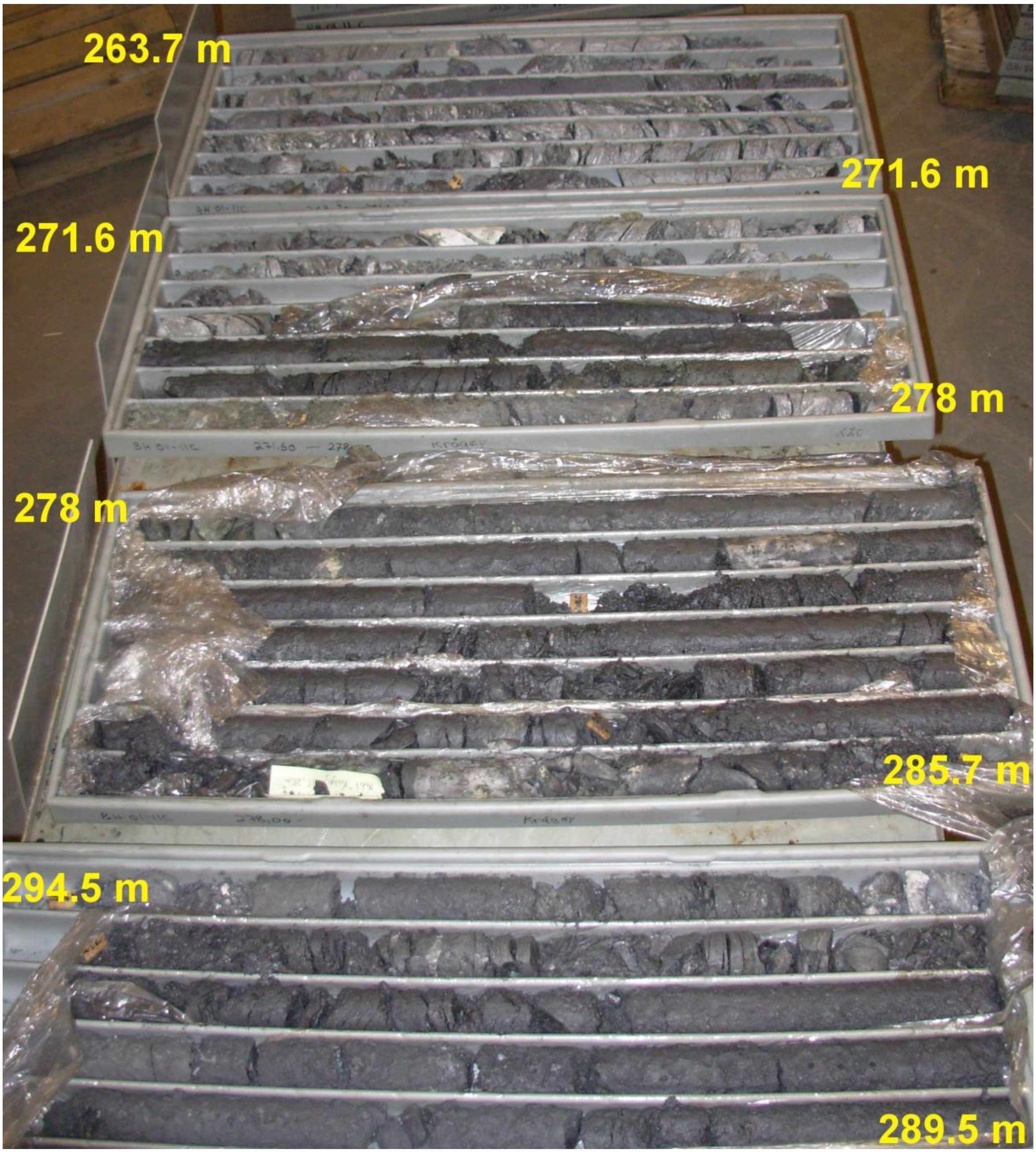

Figure 12. Picture of the 263.7 – 294.5 m core interval with the large fine-grained clay-rich crushed zone/fault gouge-bearing breccia, typical of the 275– 295 m core interval.

4.5 Geological profile along Krågøy drill holes

The geological logs along the Krågøy drill holes show the high content of quartz-rich intervals in the graphite-rich black shales and the greenstones (Figure 13). The large amount of fault rock intervals (Figure 13) likely confirms the vicinity of the mapped regional N-S faults (see Figure 1).

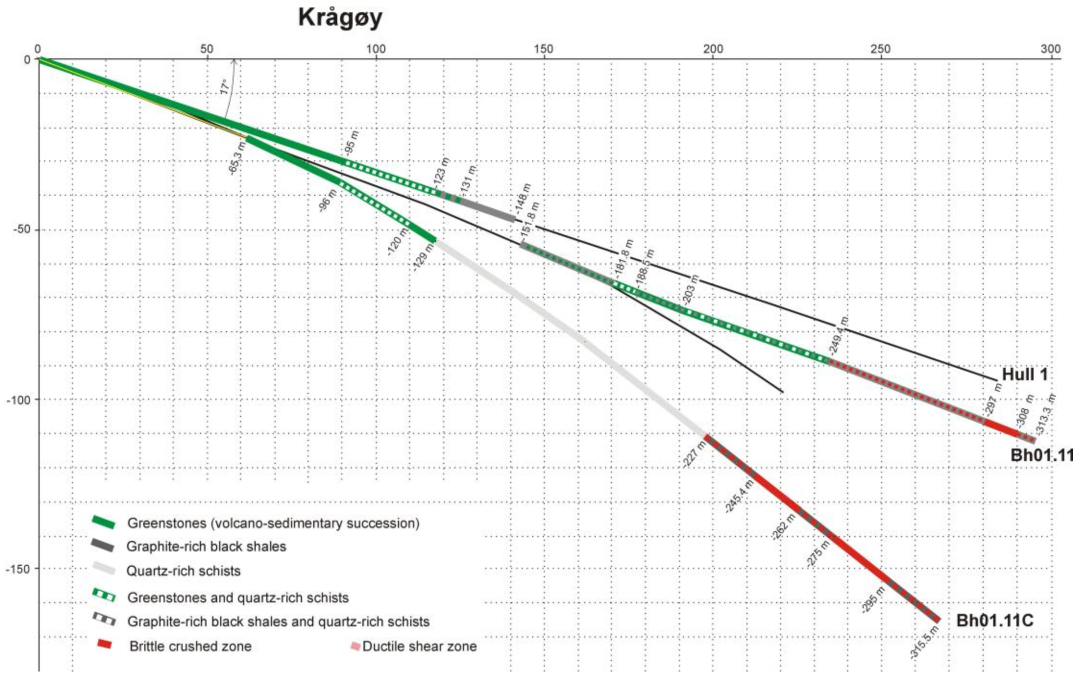

Figure 13. Geological logs along the profiles of the drill holes of Krågøy.

5. GEOLOGICAL LOGGING OF HESTEHOLMEN DRILL CORES

Like from Krågøy, only one drilling was primarily planned from Hesteholmen (UTM 32V coordinates: 295633E, 6551992N), an island east of Kvitsøy. The aim was to obtain a core of c. 750 m long, inclined at c. 20° toward the E, i.e., quasi perpendicular to the strike of the foliation of the volcano-clastic rocks of the Torvastad Group and intersecting mapped regional N-S fault or/and fracture zones (Figure 1). Like for the drilling from Krågøy, successive attempts of drilling failed before reaching the aimed core length due to collapse of the holes. The geological logging was carried out on two of the cores labelled Bh02.11A and Bh02.11B. The latter is the longest core drilled from Hesteholmen with a length of c. 520 m. The geological logging of the two cores is described in the two next sections. The detailed geological logging including description of sub-intervals and illustrated by pictures of chosen core bits is available in Appendix D.

5.1 Geological logging of Hesteholmen Bh02.11A drill core

0 – 51 m: Foliated banded greenstones with quartz-rich intervals. Calcite veins, epidote-rich layers and pyrite-coated fractures are common. Some intervals display a thin foliation.

51 – 60 m: abundance of massive layers (suspected to correspond to metamorphosed lava flows) in contrast with the banded and foliated greenstones, volcano-clastic in origin. These massive layers were not so obvious and frequent along Sauholmen and Krågøy cores (see sections 3 and 4).

60 – 130 m: foliated banded deformed greenstones with epidote-rich intervals, abundant quartz veins and some massive layers.

130 – 137 m: massive greenstones.

137 – 257 m: alternating massive greenstones up to some meters scale with foliated, banded and folded greenstones. Massive layers display a thin foliation. Talc is obvious in the foliated and banded intervals.

257 – 271 m: quartz-rich black shales with ductile sheared intervals.

271 – 291 m: alternating greenstones and quartz-rich schists with foliation varying along the core from shallow to steep (for example at c. 278 m) relatively to the axis of the core. This testifies for the occurrence of folds in the units. Quartz-rich veins and pegmatites 1-2 to 10-20 cm thick are frequent.

291 – 300 m: quartz-rich schists/chert-like rocks.

300 – 337 m: alternating greenstones and quartz-rich schists.

337 – 347 m: graphite-rich black shales alternating with quartz-rich schists. Pyrite is conspicuous.

347 – 356 m: quartz-rich schists.

356 – 359 m: crushed zone/silty to sandy grain size breccias in a unit of mixed black shales and quartz-rich schists. Core lost at the bottom of the interval.

359 – 364.5 m: quartz-rich schists and black shales with a high content of graphite.

364.5 – 380 m: quartz-rich schists.

380 – 394 m: greenstones with dark secondary minerals (garnets?).

394 – 400 m: quartz-rich schists with conspicuous chalcopyrite.

400 – 407 m: black shales with a high content of graphite.

407 – 450 m: graphite- and quartz-rich unit with talc and clay-rich crushed zones/ fault gouge silty to sandy grain size breccias (Figure 14).

Figure 14. Fault gouge/clay-rich silty to sandy grain size crushed zone/breccias with angular quartz fragments of the 416 – 425.3 m core interval (with, here, 424 m at the top left of the picture).

5.2 Geological logging of Hesteholmen Bh02.11B drill core

399 – 453 m: graphite- and quartz-rich unit with talc and clay-rich crushed zones/ gouge-bearing silty to sandy grain size breccias (Figure 15). Fold hinges and sheared intervals are conspicuous.

453 – 487.8 m: foliated and folded greenstones without massive layers, resembling those observed along Sauholmen drill core with numerous calcite and quartz veins (see section 3). Sheared and cemented brecciated layers are conspicuous along the intervals. This rock interval is highly fractured in general and some intervals are crushed rocks/ non-cohesive breccias.

487.8 – 517.5 m: interval of abundant silty to sandy grain size breccias in black shales, characterized by fragmented quartz. Aside from the crushed zones, the rocks are severely fractured. These breccias are several meters thick and contain fault gouges/clays.

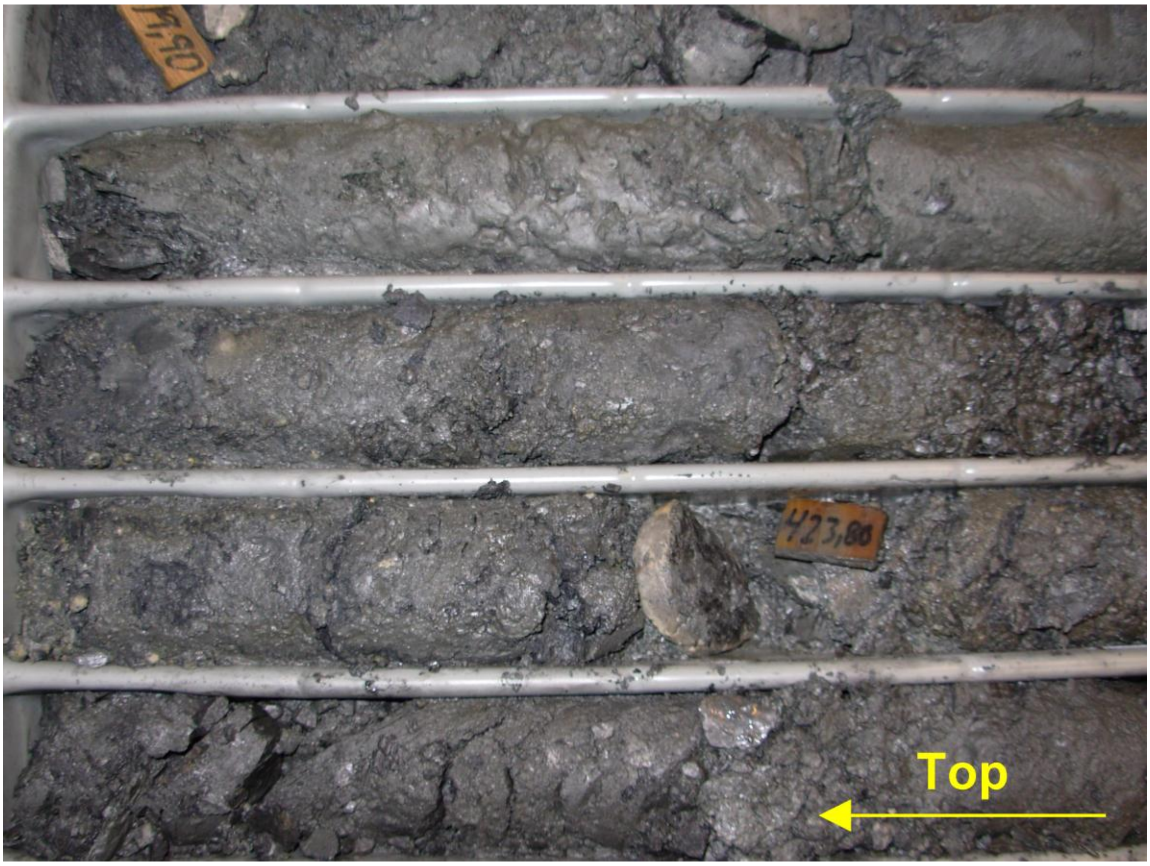

Figure 15. A picture to illustrate the severely crushed clay-rich zone, i.e. fault gouges and breccias of the 417.5 – 426 m core interval.

5.3 General remarks on Hesteholmen Bh02.11A and Bh02.11B drill cores

The drill cores from Hesteholmen, like from Krågøy and from Sauholmen, contain the typical greenstones of the rock suite of the Torvastad Group but also graphite-rich shales (or black shales). The greenstones display very massive layers that probably represent metamorphosed lava flows in contrast with the banded, foliated greenstones, likely volcano-clastic in origin. Quartz-rich intervals to nearly pure quartz/cherty intervals are very frequent. Breccias with fragmented angular quartz and gouge layers characterize the bottom part of Bh02.11A drill core and the entire Bh02.11B drill core (see Figure 14 and Figure 15).

5.4 Geological profile along Hesteholmen drill holes

The geological logs along the Hesteholmen drill holes highlight the presence of quartz-rich units in the graphite-rich black shales and the greenstones (Figure 16). The bottoms of the drill holes approach the mapped regional meridian faults (see Figure 1) which is likely reflected by the large amount of gouge-bearing crushed zones/breccias (Figure 16).

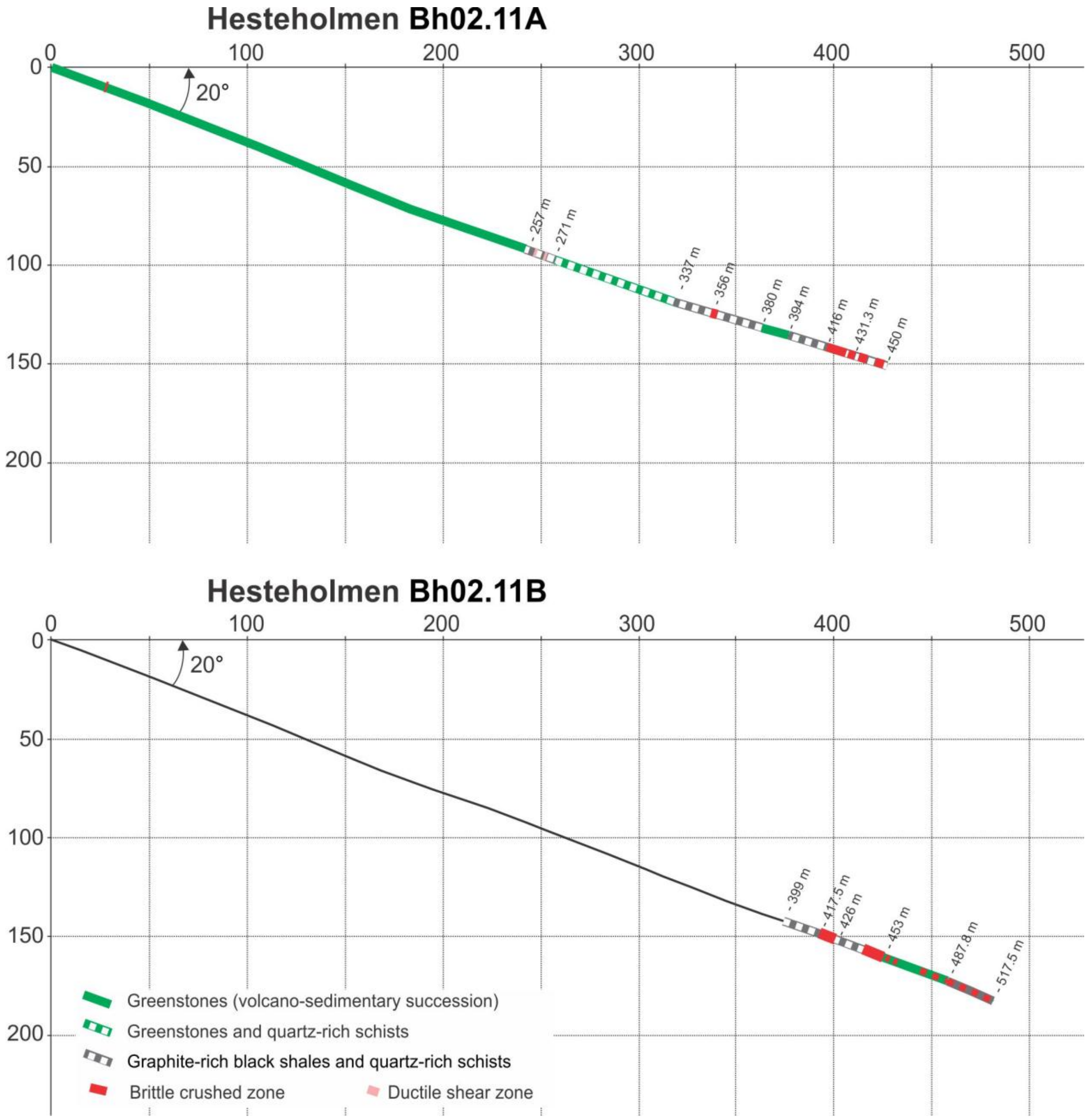

Figure 16. Geological logs along the profiles of the drill holes of Hesteholmen: Bh02.11A (top) and Bh02.11B (bottom).

6. DISCUSSION AND REVISED GEOLOGICAL MODELS

Table 1 summarizes the position of the 5 tectono-stratigraphic major units expected to be encountered in the close vicinity of the Rogfast tunnel and will guide the reader to assess the various proposed geological models. It should however, be stressed that all the proposed models are based on rather few observations along the actual trace of the tunnel, and to get more reliable models more information is needed, especially in the area between Kvitsøy and Bokn.

Table 1. Tectono-stratigraphic units encountered in the vicinity of the Rogfast tunnel (Jorde et al. 1995, Ragnhildstveit et al. 1998) and displayed in the different geological models proposed in the report (from bottom to top: oldest to youngest).

<table>
<tr><td rowspan="2">Hardangerfjord Nappe</td><td>Torvastad and Visnes groups</td><td>Middle to Upper Ordovician supracrustal cover of the Karmøy Ophiolite built of greenstones, pillow- and breccia-lavas, tuffs, quartz-rich black shales, diabase dykes, etc.</td></tr>
<tr><td>Karmøy Ophiolite</td><td>Lower Ordovician intrusive mafic and ultra-mafic rocks</td></tr>
<tr><td colspan="2">Storheia and Boknafjorden nappes</td><td>Proterozoic granitic gneisses, amphibolites and mica schists with some lenses of marble</td></tr>
<tr><td colspan="2">Viste Thrust Sheet</td><td>mainly composed by the Cambrian – Ordovician quartz-rich Ryfylke Schists</td></tr>
<tr><td colspan="2">Precambrian autochthonous basement</td><td>Granitic to dioritic gneissic basement, with some bodies of gabbro and covered by thin Cambro-Silurian phyllites.</td></tr>
</table>

6.1 Geological model between Randaberg and Kvitsøy

The sheared granitic layer at the bottom of the core from Alstein has many similarities to the gneisses in the Storheia Nappe. If that is the case, this sheared zone indicates the proximity to the sole detachment of the Hardangerfjord Nappe, and the nappe would be rather thin (Figure 17; upper part).

However, available geological sections drawn farther to the north by Ragnhildstveit et al. (1998) and across the faulted contact between the autochthonous basement and the Hardangerfjord Nappe indicate a 3 to 4 km thick Hardangerfjord Nappe. This is not necessarily a contradiction because we know from other areas in the region that the nappes can pinch and swell from thin to thick over rather short distances. If the model of Ragnhildstveit et al. (1998) is used, the shear zone at the bottom of the core would therefore be a secondary structure associated to the internal deformation of the nappe, and the situation will be like indicated in the lower part of Figure 17.

Rønning et al. (2006) in agreement with Ragnhildstveit et al. (1998) indicate a major fault between Randaberg and Alstein (Figure 1 and Figure 17). The first part of the tunnel would most likely be in the Ryfylke Schists. It seems to have a considerable thickness on Randaberg, but there is a possibility that the tunnel could reach down to the Precambrian basement, or cut through the lower part of the Storheia-Boknafjorden nappes, close to the fault.

If the offset along the steep fault north-east of Randaberg is large enough, the sole detachment of the Hardangerfjord Nappe should be deeper than the tunnel level, west of the fault.

From Randaberg to Kvitsøy, the tunnel will intersect: the steep fault between the Storheia-Boknafjorden nappes and the Hardangerfjord Nappe, the contact between the two units of the Hardangerfjord Nappe and likely steep fault zones within the Hardangerfjord Nappe (Figure 17).

If the offset along the steep fault between the Storheia-Boknafjorden nappes and the Hardangerfjord Nappe is not important, the tunnel may cross the sole detachment between these nappes (Figure 17; upper part).

The Lower Ordovician plutonic rocks of the Karmøy Ophiolite are supposed to be directly capped by the volcanic and volcano-clastic cover of the Visnes and Torvastad groups of Kvitsøy, but the contact is of unknown geometry (Figure 17). Whereas the Ryfylke Schists and the rocks of the Storheia and Boknafjorden nappes display a flat-lying to gently-dipping metamorphic foliation which looks rather constant at the regional scale, close to tight upright NNE-SSW directed folds are commonly observed within the rocks of the Hardangerfjord Nappe. The shallow-dipping eastward-directed drill cores from the two islands of Krågøy and Hesteholmen located east of Kvitsøy and across the Torvastad Group transect frequent fold hinges. This observation integrated in the proposed sections results in a truncation of the folds by the sole detachment of the Hardangerfjord Nappe (Figure 17). This truncation of the folds of the Hardangerfjord Nappe by the basal detachment is also proposed in the regional sections drawn farther to the north by Ragnhildstveit et al. (1998).

Black shales were not previously reported in the suite of greenstones of the Torvastad and Visnes groups that crop out on Kvitsøy and cap the Karmøy Ophiolite. However, the rocks drilled from the two islands of Krågøy and Hesteholmen located east of Kvitsøy comprise a high proportion of graphite-rich black shales. In terms of depositional environment, they indicate an anoxic media. The interlayered greenstones are probably volcano-clastic sediments which derived from proximal volcanic centres and sporadically deposited in the same basin. The presence of some massive greenstones may indicate lava flows which were intercalated in the volcano-clastic sediments. Quartz-rich to cherty schists are also very abundant interlayered in both the greenstones and the black shales. Finally, the breccias and associated gouges observed toward the bottom of the cores from Krågøy and Hesteholmen testify to the proximity of the regional meridian faults mapped offshore east of Kvitsøy (Figure 1 and Figure 17).

It could also be mentioned that a similar black shale and greenstone sequence belonging to the Hardangerfjord Nappe is observed on the island Stord farther north. There, Færseth (1982) has documented that the whole sequence is inverted with the greenstones on top and the black shales below. Although there is no evidence on such geometry on Kvitsøy area, the situation looks rather similar with all the inspected drill cores, also those from Sauholmen (see next section), displaying black shales at the deepest levels. Therefore the black shales may also be vertically located under the greenstones on Kvitsøy, and they may have a wide regional distribution on the sea floor both east and north of Kvitsøy.

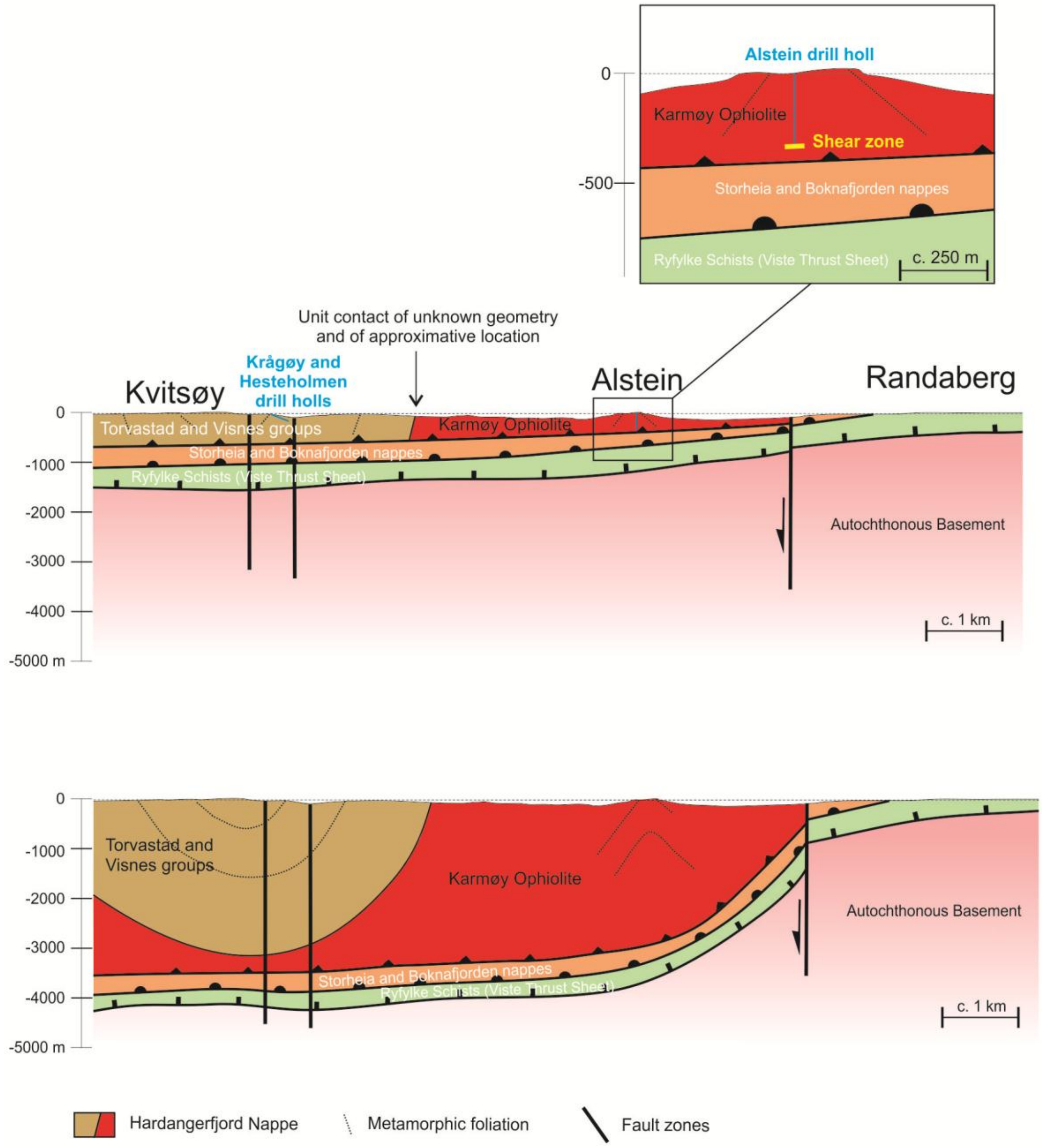

Figure 17. Possible geological sections Randaberg – Kvitsøy (modified from Rønning et al. 2006) with a zoom in on the Alstein area. Both proposed profiles show the truncation of the folds in the Hardangerfjord Nappe by its sole detachment. The faults east of Kvitsøy have unknown sense of shear and amount of offset.

6.2 Geological model between Kvitsøy and Vestre Bokn

The drill holes from Sauholmen also confirm the presence of black shales in the typical suite of greenstones of the Torvastad Group with cores even displaying a predominance of black shales. Both the black shales and the greenstones display highly fractured intervals with, in addition, the occurrence of severely crushed intervals and gouge-bearing breccias in the black shales.

North of Kvitsøy several lineaments coincide with drops in seismic velocities and magnetic linear dislocations. They were interpreted to represent a large fault or/and fracture zone with a NE-SW trend (Rønning et al. 2006; Figure 18), in the prolongation with a regional-scale steep NW-dipping normal fault mapped toward the north-east by Sigmond (1975). The Sauholmen drill hole was expected to cross this zone. Indeed, it intersects several meter wide brecciated zones that may correspond to parallel discrete zones (Figure 18) but does not support the occurrence of a large fault characterized by several meter wide fault rock cortege. The crushed zones might have developed on previously highly jointed zones, tectonic in origin. However the southernmost brittle zone along the Sauholmen Bh01.10 core is a minor tectonic fault zone characterized by a 1,4m thick gouge in the prolongation of the NE-SW trending mapped regional fault (Figure 18), it can correspond to its south-westward termination toward Kvitsøy. So far, no available data gives any support to the existence of a large fault zone further north and along Boknafjord between Kvitsøy and Vestre Bokn but it should not be considered to be unrealistic along a fjord like Boknafjord. Furthermore, crushed zones and non-cohesive breccias observed along the Sauholmen cores correspond to mapped linear features (Rønning et al. 2006) and may be a source of water leakage along the tunnel. The occurrence of similar zones farther north in Boknafjord cannot be ruled out.

As mentioned earlier, no direct observation of rocks from Kvitsøy to Vestre Bokn, a distance of nearly 10 km, is available and the interpretations herein are mainly based on geophysical evidence. Rønning et al. (2006) interpret a magnetic anomaly at shallow depth south of Vestre Bokn along Boknafjord, to correspond to the autochthonous basement (Figure 19, upper part). In another view, the anomaly could just as well reflect a rock of the Karmøy Ophiolite (as at Alstein). The exact location of the contact between the Torvastad and Visnes groups and the Karmøy Ophiolite remains unknown but, it is likely at the southern edge of the anomaly (Figure 19).

Ragnhildstveit et al. (1998) interpreted the entire area between Kvitsøy and Vestre Bokn to be occupied by the Hardangerfjord Nappe. This interpretation is based on the observation of greenstones close to the Ryfylke Schists on the small island of Solholmen, south of Vestre Bokn (Ragnhildstveit, pers. com. 2011).

In other words, we infer the presence at shallow depth of plutonic rocks, whatever their nature, i.e., granitic or basic and respectively, of the autochthonous basement or of the Karmøy Ophiolite, to be responsible of the magnetic anomaly south of Vestre Bokn.

Between Kvitsøy and Vestre Bokn, the thickness of the Hardangerfjord Nappe is unknown; it could be thick as shown in the cross section by Ragnhildstveit et al. (1998), or thin as it appears from the drill core from Alstein between Kvitsøy and Randaberg (see discussion above; Figure 19). South of Vestre Bokn, tectonic contacts between the Hardangerfjord Nappe and the Ryfylke Schists, and between the latter and the autochthonous basement may crop out. According to Ragnhildstveit et al. (1998), the Storheia and Boknafjorden nappes would be truncated by the Hardangerfjord Nappe (Figure 19), but it cannot be ruled out that, indeed, they crop out between the Ryfylke Schists and the autochthonous basement.

Figure 19 summarizes the three preferred scenarios of rocks occurring along the tunnel trace between Kvitsøy and Vestre Bokn:

First scenario (Figure 19, upper part): The situation is as indicated in Rønning et al. (2006) where the magnetic anomaly is caused by the Precambrian basement. In this case, the tunnel will intersect rocks of the Storheia-Boknafjorden nappes and probably also the Ryfylke Schists. By just an inspection of the map from Ragnhildstveit et al. (1998), this seems to be a reasonable scenario.

Second scenario (Figure 19, middle part): The presence of a thin Hardangerfjord Nappe as maybe indicated in the drill core from Alstein between Randaberg and Kvitsøy.

Third scenario (Figure 19, lower part): The presence of a thick Hardangerfjord Nappe as indicated and interpreted by Ragnhildstveit et al. (1998).

In the second and third scenarios (Figure 19, middle and lower parts), the magnetic anomaly is caused by plutonic rocks in the Hardangerfjord Nappe.

Which of these three models (if any of them) is correct is impossible to say from the data presently available.

It should also be mentioned that whatever model is preferred, it will imply a situation where the tunnel has to pass a set of nappes when starting from the Precambrian basement on Vestre Bokn and southwards, the Viste Thrust sheet (i.e. the Ryfylke Schists), the Storheia and Boknafjorden nappes and the Hardangerfjord Nappe. The contacts between these nappes are generally flat-lying, and even if brittle structures rarely occur, the contrast in lithology between some of the nappes are probably large enough to cause problems for the tunnel construction.

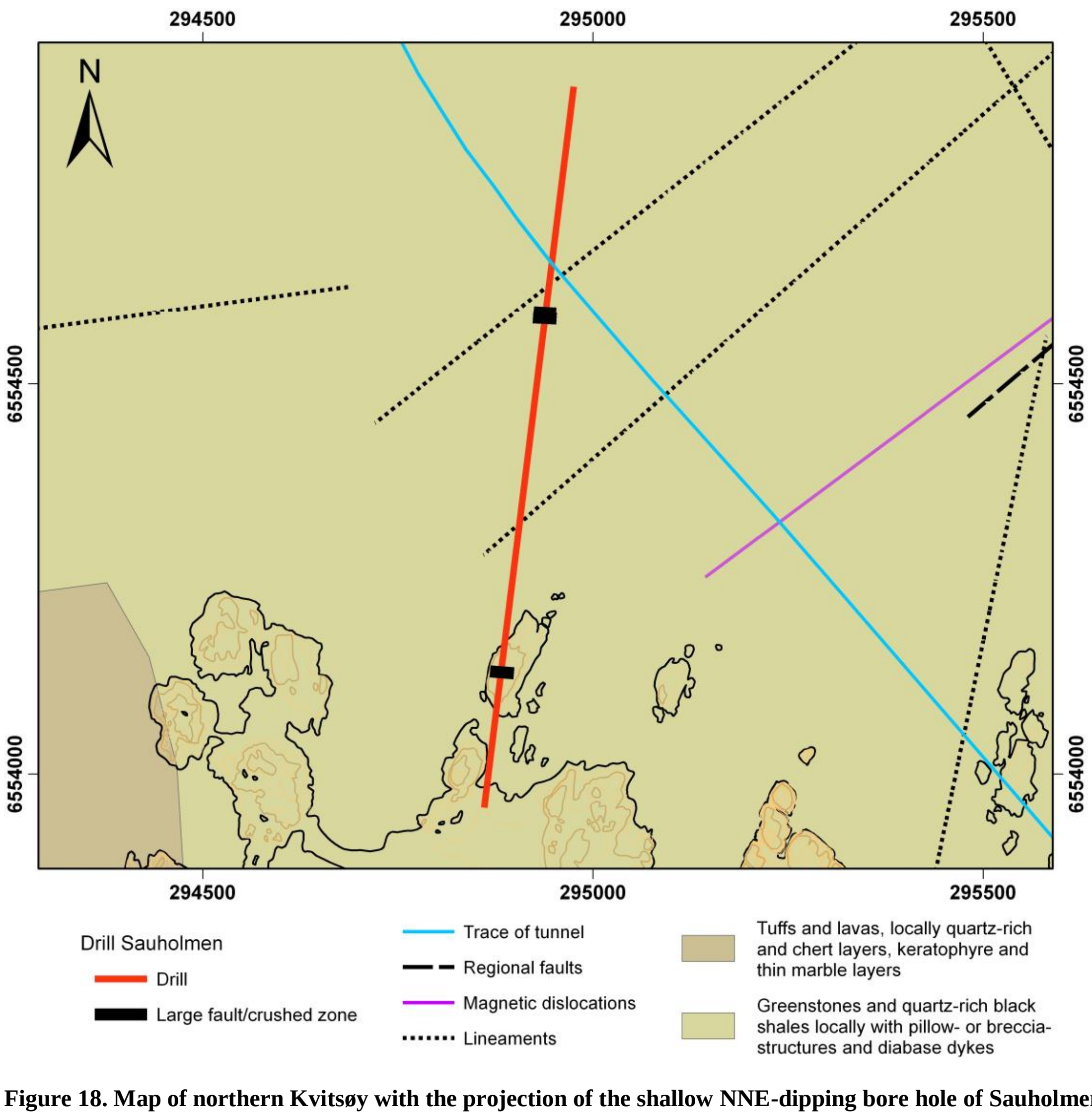

Figure 18. Map of northern Kvitsøy with the projection of the shallow NNE-dipping bore hole of Sauholmen. The fault and crushed zones may correspond to the reported lineaments and magnetic linear dislocations in Rønning et al. (2006). The geology is from Ragnhildstveit et al. (1998).

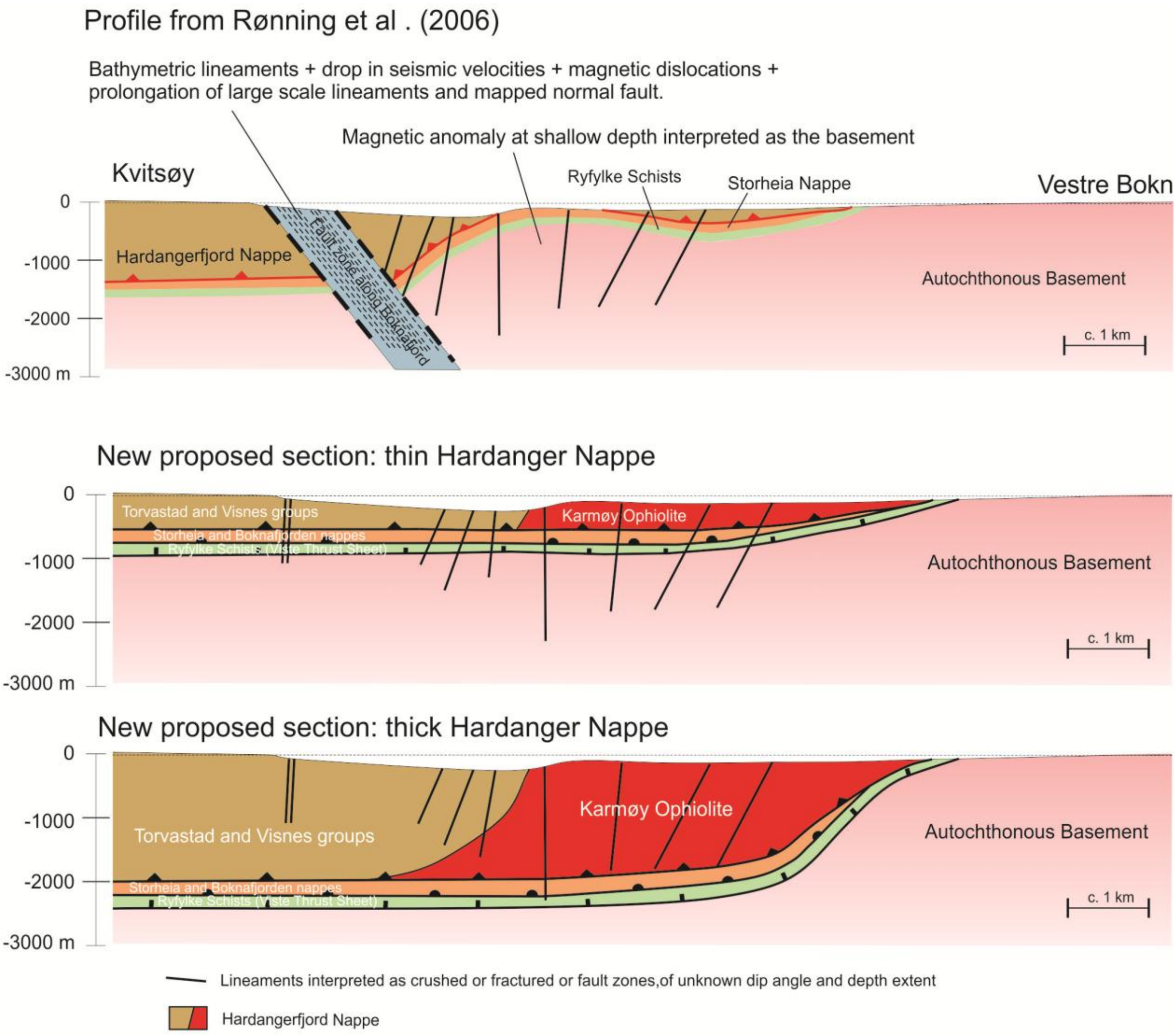

Figure 19. Possible geological sections Kvitsøy-Vestre Bokn involving plutonic rocks (the autochthonous basement or the Karmøy Ophiolite) at shallow depth south of Vestre Bokn. The proposed new sections are based on Ragnhildstveit et al. (1998). The Storheia and Boknafjorden nappes may be truncated (as proposed by Ragnhildstveit et al., 1998) or not. No large fault zone is drawn on the new profiles north of Kvitsøy as so far, no available data support its occurrence. In any case, the lineaments drilled from Sauholmen just north of Kvitsøy correspond to severely crushed zones/ gouge-bearing breccias. See text for further explanation.

7. CONCLUSION

Table 2 summarizes the characteristics of the significant zones of deformation encountered along the cores during the geological logging. It includes ductile shear and brittle fault rock bearing zones of m-scale thicknesses. The largest tectonic fault zone along the core of Sauholmen Bh01.10 is a 1.4 m thick interval of fragmented quartz- and gouge-bearing breccias. They are very numerous and up to 20 m thick along the cores of Krågøy Bh01.11 and Hesteholmen Bh02.11B. They reflect the vicinity of the mapped regional fault systems that the tunnel would intersect.

Table 2. Characteristics of the significant zones of deformation encountered along the cores during the geological logging.

Drill core	Core length interval (m)	Zone description	Host rock	Figure №
Alstein	205.5 – 208	4 cm-scale ductile shear zones; the thickest one is 20 cm	transition zone between a medium-grained gabbro and a very fine-grained gabbro	Figure A- 7
Alstein	236.3 – 236.8	lens of sheared K-feldspar with epidote	fine-grained gabbro	Figure A- 10
Alstein	c. 240	20 cm ductile shear zone	foliated fine-grained plagioclase-rich gabbro	
Alstein	243.6 and 243.8	cm-scale epidote-rich ductile shear bands	fine-grained gabbro	
Alstein	256.6	10 cm ductile shear zone	porphyritic plagioclase-rich gabbro–diorite	
Alstein	274.3 – 283	sheared granitic layer, mylonitic texture, and porphyroblasts of K-feldspars	fine grained massive garnet-rich gabbro	Figure 3
Sauholmen Bh01.10	179 – 183	Very poor rock quality with numerous crushed zones/ breccias and the presence of a soapy mineral (talc?)	greenstones	Figure B- 3
Sauholmen Bh01.10	183.3 – 184.7	fault core filled with gouge	boundary between greenstones and black shales	Figure B- 4
Sauholmen Bh01.10	492 – 494	alternating sheared layers of both greenstones and black shales	gradual transition between greenstones and black shales	Figure B- 8
Sauholmen Bh01.10	595 – 599	Crushed zone/breccia	black shales	
Sauholmen Bh01.10	678.5 – 679.5	silty to sandy grain size crushed graphite with fragmented quartz, i.e. breccias	black shales	Figure 5

Sauholmen Bh01.10B	493 – 496.3	inter-layered sheared greenstones and black shales	gradual transition between greenstones and black shales	Figure B- 10
Sauholmen Bh01.10B	525 – 542	severely fractured and crushed rocks, i.e. breccias	black shales	
Sauholmen Bh01.10B	573 – 579	damaged and crushed rocks with a 60 cm large hydrothermal calcite-rich breccia at 575.8 m	black shales	Figure B- 13
Sauholmen Bh01.10B	665.8 – 668	crushed graphite/silty to sandy grain size breccias	black shales	Figure 6
Krågøy Bh01.11	249.4 – 253.4	Abundant crushed /silty to sandy grain size brecciated zones	black shales	
Krågøy Bh01.11	253.4 – 256	cemented breccias with several cm-scale clay-bearing crushed zones (silty to sandy grain size non-cohesive breccias)	greenstones	
Krågøy Bh01.11	256 – 313.3	abundant thick (meter to several meter scale) crushed zones characterized by fragmented quartz (silty to sandy grain size breccias) and by clays/gouges. Continuous gouge-bearing breccias in the 297 – 308 m core interval.	severely fractured quartz-rich and graphite-rich schists/black shales	Figure 11
Krågøy Bh01.11C	227 – 315.5	numerous crushed zones and gouges-bearing breccias, i.e., fine-grained crushed zones with clays. Quasi-continuous fault rocks in the 245.4 – 262 m and 275– 295 m core intervals	severely damaged/fractured black shales	Figure 12, Figure C- 6, Figure C- 7, Figure C- 8
Hesteholmen Bh02.11A	28.2 – 28.7	clay-rich crushed zone/gouge-bearing fine-grained breccias	greenstones	
Hesteholmen Bh02.11A	356 – 359	crushed zone/ silty to sandy grain size breccia	Mixed black shales and quartz-rich schists	
Hesteholmen Bh02.11A	416 – 425.3	severely crushed zone/ silty to sandy grain size breccias with quartz fragments and clay-bearing/fault gouge intervals	graphite- and quartz-rich unit	Figure 14
Hesteholmen Bh02.11A	427.5 – 431.3	severely crushed zone/ silty to sandy grain size breccias with clay-bearing intervals as fault gouges	graphite- and quartz-rich unit	
Hesteholmen Bh02.11A	435 – 450	abundant intervals of crushed rocks/ silty to sandy grain size breccias	graphite- and quartz-rich unit	
Hesteholmen Bh02.11B	417.5 – 426	severely crushed zone/ silty to sandy grain size breccias with clays/fault gouges	graphite- and quartz-rich unit	Figure 15

Hesteholmen Bh02.11B	442 – 453	clay-rich crushed rocks, i.e. gouge-bearing silty to sandy grain size breccias	graphite- and quartz-rich unit	
Hesteholmen Bh02.11B	453 – 455.7	crushed rocks with clays, i.e. silty to sandy grain size breccias and fault gouges	greenstones	Figure D- 9
Hesteholmen Bh02.11B	455.7 – 458	cemented breccias in a shear zone	greenstones	Figure D- 9
Hesteholmen Bh02.11B	475 – 487.8	frequent intervals of 10-20 cm silty to sandy grain size non-cohesive and cemented breccias	greenstones	Figure D- 10
Hesteholmen Bh02.11B	487.8 – 517.5	abundant several meters thick gouge-bearing silty to sandy grain size breccias with angular quartz fragments	severely fractured black shales	

The intrusive rocks of the Karmøy Ophiolite and its cap cover, the volcano-clastic and volcanic rocks of the Torvastad and Visnes groups, both units of the Hardangerfjord Nappe, are likely prominent along the tunnel trace. The thickness of the nappe remains unknown but in the region it is often estimated to be more than 3 km thick. However, south of Vestre Bokn along the Boknafjord, the shallow plutonic rocks, instead of being of the Karmøy Ophiolite may be of the autochthonous basement, as previously and proposed by Rønning et al. (2006).

From Randaberg to Kvitsøy, the tunnel trace may intersect: (1) the Ryfylke Schist, (2) the steep faulted contact between the Hardangerfjord Nappe and the Storheia-Boknafjorden nappes, (3) the contact between the Karmøy Ophiolite and the Torvastad Group, two units of the Hardangerfjord Nappe, and (4) steep fault zones. The steep meridian regional fault zones, east of Kvitsøy, are confirmed by the drilling from Krågøy and Hesteholmen with several meters thick gouge-bearing breccias and severely damaged host rocks observed along the cores (Table 2). These non-cohesive fault rocks may be prone to water leakage during the tunnel construction. Otherwise the tunnel is expected to be at a higher level than the sole detachment of the Hardangerfjord Nappe. This is inherent to a large offset along the steep fault between the Hardangerfjord Nappe and the Storheia and Boknafjorden nappes. If this offset is not large enough, the sole detachment between the two nappes will be intersected by the tunnel.

The sole detachments of the Hardangerfjord Nappe over the Ryfylke Schists and of the latter over the autochthonous basement are expected to be intersect by the tunnel trace offshore south of Vestre Bokn. The occurrence of the units of the Storheia and Boknafjorden nappes between the Ryfylke Schists and the autochthonous basement cannot be ruled out. No available data gives so far, support to the existence of a large fault zone along Boknafjord between Kvitsøy and Vestre Bokn. Nevertheless, it cannot be excluded that a large regional fault zone may exist along such prominent fjord. In any case, the lineament identified in Rønning et al. (2006) was drilled from Sauholmen and correspond to a 1.4 m thick gouge-bearing severely brecciated zone (Table 2). These non-cohesive fault rocks may be the sources of water leakage during the tunnel construction. Also, it cannot be excluded that, farther north, similar parallel fault zones exist.

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Appendix A. Geological logging of Alstein drill core

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The main intervals are defined on distinct geological characteristics identified during the logging. They are indicated by core lengths written in bold and sub-intervals of interest are written in normal font.

0 – 21 m: mixed unit (Figure A- 1): inter-layered fine-grained mafic rocks, plagioclase-rich gabbro, feldspar-rich granitic unit (migmatitic texture) and amphibolite, slightly foliated. It looks all as a result of differentiation during magmatic processes (inter-fingered rocks).

Figure A- 1. Mixed inter-fingered felsic and mafic magmatic rocks in the core interval 0 – 21 m.

21 – 42 m: fine-grained gabbro.

42 – 47 m: more visible plagioclase in gabbro.

47.5 – 50 m: fine-grained gabbro with veining (epidote, calcite, zeolites?).

50 – 69 m: fine-grained gabbro, quite homogeneous, biotite-rich.

69 – 79 m: medium to coarse grained gabbro with few fine-grained inter-layered gabbros.

79 – 87 m: foliated medium to coarse grained gabbro (Figure A- 2), 10 cm thick very coarse gabbro with pink garnet rims around biotites (?) (Figure A- 3).

General remarks from this first depth interval: assumption of sulphides less than 1 mm size (Figure A- 2), chloritization, alteration (sericitization and/or saussuritization?) of plagioclase.

Figure A- 2. Medium-grained foliated gabbro in the 79 – 87 m core interval.

Figure A- 3. A 10 cm thick very coarse-grained gabbro with pink garnet rims around biotites (?) in the 79 – 87 m core interval.

87 – 90 m: transition to fine-grained foliated gabbro.

90 – 98 m: fine-grained foliated gabbro, sulphides.

98 – 103.5 m: plagioclase-rich coarse gabbro (Figure A- 4), not foliated, alteration (sericitization and/or saussuritization?) of plagioclases which results in a typical vermiculate texture of the plagioclases (Figure A- 4), still (very pink) garnet-rich, sulphides, blue feldspar (labrador? inclusion?).

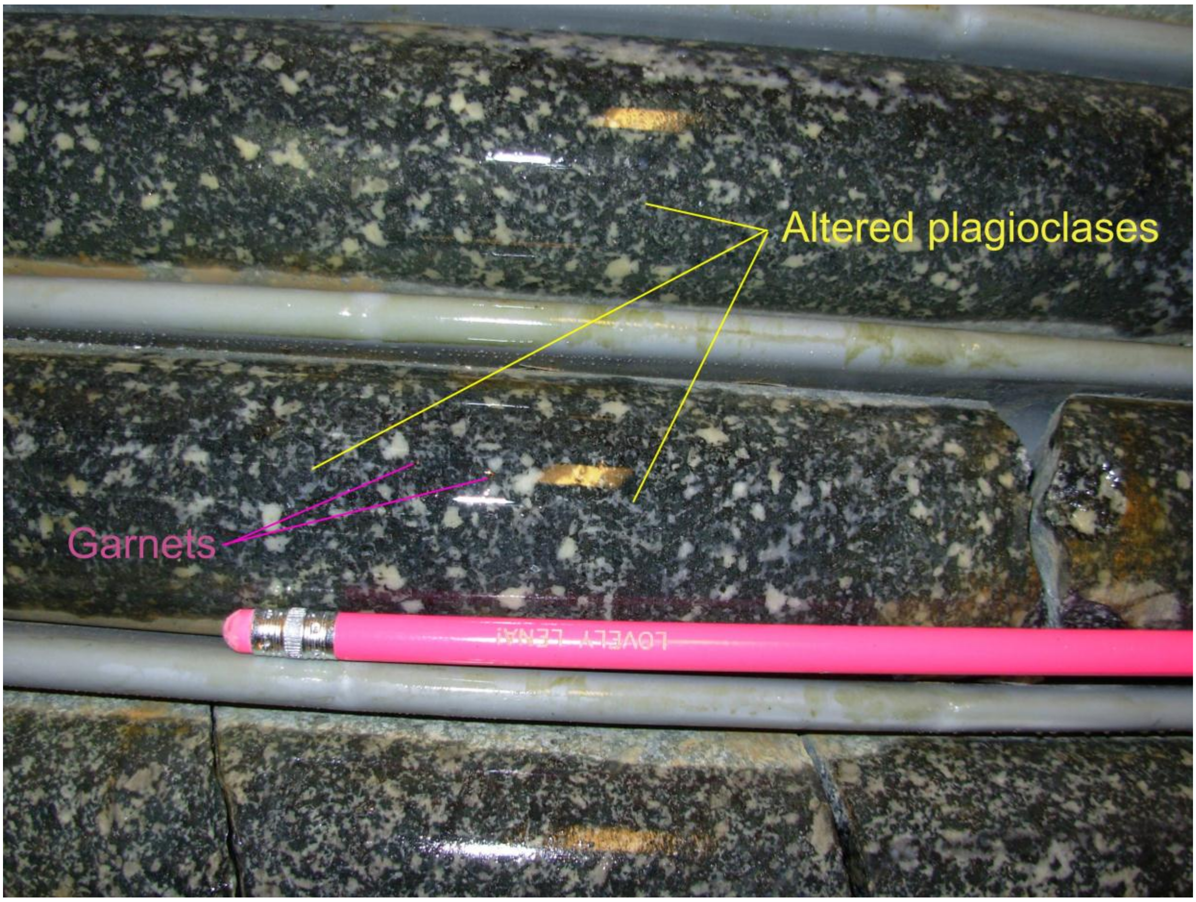

Figure A- 4. Plagioclase-rich garnet-bearing coarse-grained gabbro with alteration (sericitization and/or saussuritization?) of plagioclases and resulting in their vermiculated texture in the 98 – 103.5 m core interval.

103.5 – 118 m: mixed unit (Figure A- 5), granitic, fine- to coarse-grained gabbro, plagioclase-rich, 1 cm thick muscovite interval, blue feldspar, pegmatitic granite, no real foliation in this interval. The alternation of rocks in this mixed unit occurs every 0.5 to 1.5 m. The felsic intervals give a strong signal on the gamma log (Elvebakk, 2011).

118 – 127 m: plagioclase-rich gabbro, with cm-scale feldspar-rich veining, not foliated, chloritization, still sulphides and blue feldspars.

127 – 151 m: medium-grained gabbro, still veining, not foliated, small pink garnet (accessory), chloritization, zeolites and calcite on fractures.

> 134 – 137 m: more feldspars and coarse veining.
>
> At 143.8 m: 10 cm thick K-feldspar pegmatite (clearly posterior to the host mafic rocks; Figure A- 6).

Figure A- 5. Alternation of mafic (dark) and felsic (light) rocks in the 103.5 – 118 m core interval.

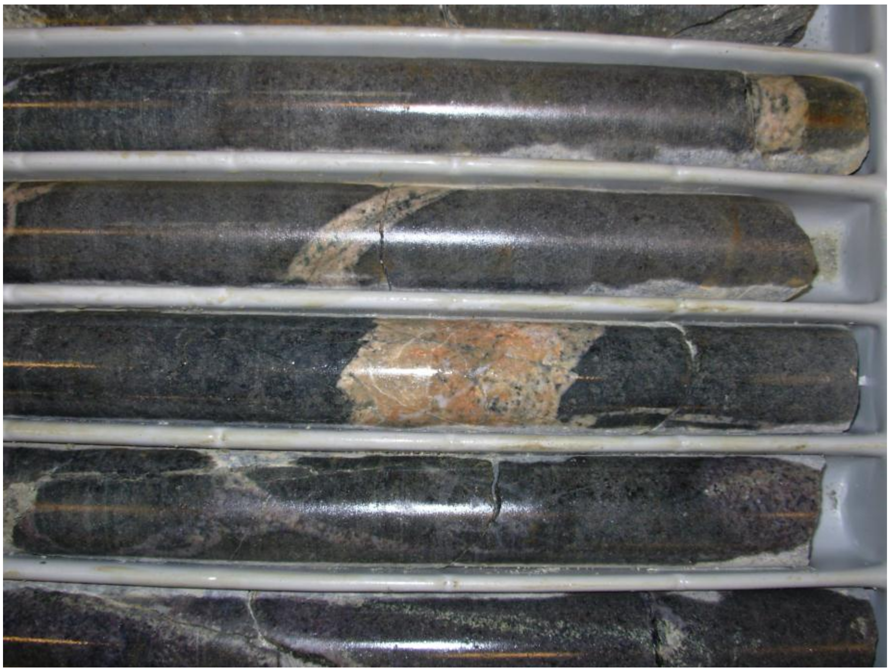

Figure A- 6. A 10 cm large K-feldspar pegmatitic vein (clearly post-dating the host mafic rocks) at 143.8 m along the core.

151 – 156 m: plagioclase-rich medium-grained gabbro, still feldspar-rich veining and calcite veins, not foliated.

156 – 168 m: medium-grained gabbro, not foliated, still felsic magmatic pockets, heterogeneous magmatic intervals, 10 cm large foliated plagioclase and mica-rich interval.

168 – 186 m: medium-grained gabbro, homogeneous, not foliated, not so chloritized.

At 178.8 m, 50 cm thick granitic pocket.

186 – 187 m: granitic interval, well detected by a strong amplitude signal on the gamma log (Elvebakk, 2011).

187 – 200 m: plagioclase-rich gabbro, no foliation, more plagioclase-rich (white) parts or more dark (amphibole, biotite) parts, blue feldspar, alteration (sericitization and/or saussuritization?) of plagioclase, sulphides, garnet.

At 197.5 m, epidote vein.

196 – 200 m: chloritization.

200 – 201 m: 'typical' medium-grained gabbro.

201 – 208 m: plagioclase-rich medium-grained gabbro (Figure A- 7).

205.5 – 208 m: 4 cm-scale ductile sheared zones, shallow to gentle dip from the axis of the drill core with the 207.8 – 208 m sheared interval at the boundary between the medium-grained gabbro and a fine-grained one (Figure A- 7).

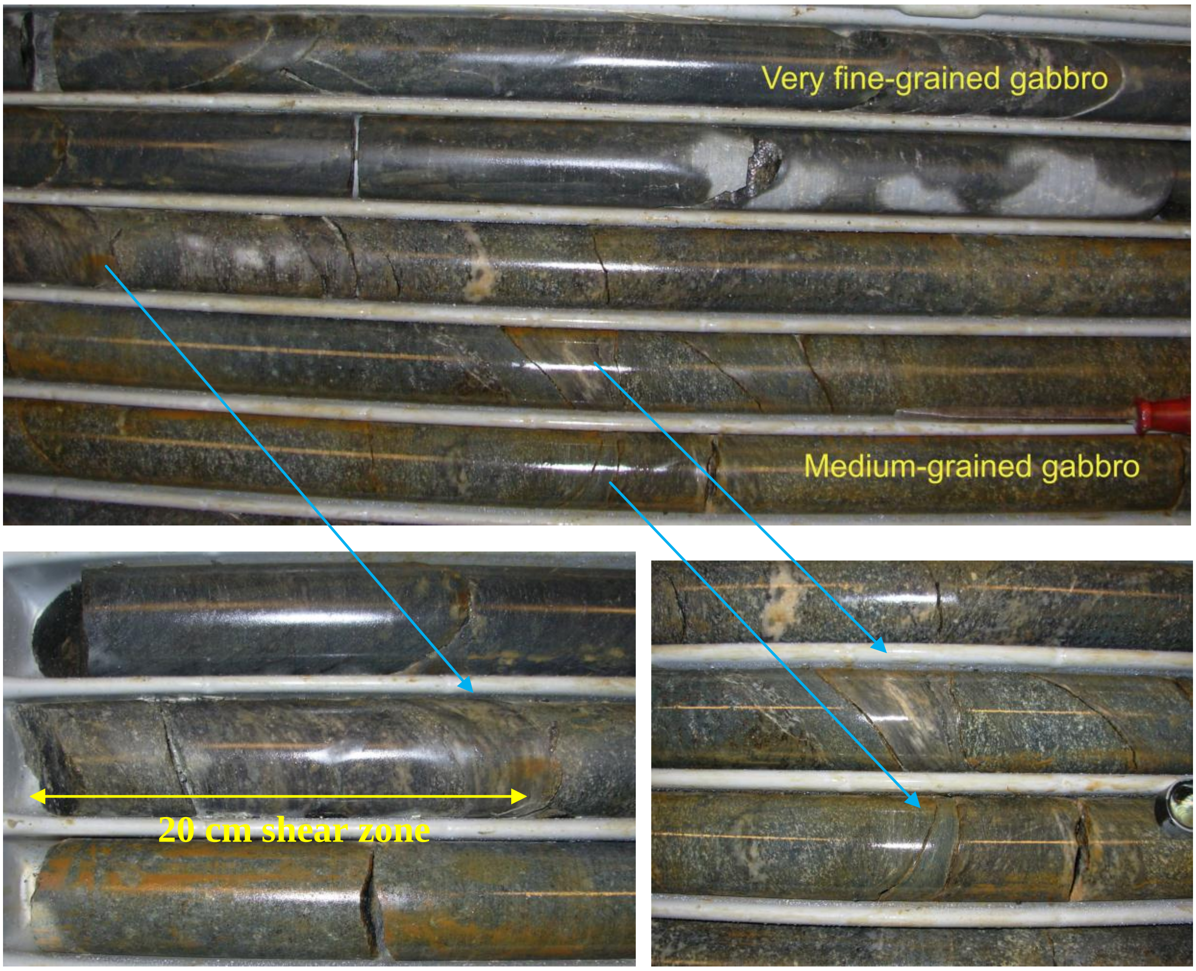

Figure A- 7. Top: transition zone between a medium-grained gabbro and a very fine-grained gabbro with 4 shear zones within the medium-grained gabbro in the 205.5 – 208 m core interval. Bottom left: 20 cm large shear band in the 207.8 – 208 m interval and at the boundary between the two gabbros. Bottom right: two cm-scale shear bands within the medium-grained gabbro.

208 – 214 m: gabbro, very dark, very fine-grained (Figure A- 7), foliated, calcite vein network.

At 211 – 214 m: very thin plagioclase but still visible.

214 – 217 m: interval with more feldspar-rich coarse bodies.

217 – 225 m: fine-grained massive plagioclase-rich gabbro.

219 – 220 m: a slight foliation, shallow dipping relatively to the axis of the drill core.

225 – 225.8 m: very thin foliation in the gabbro, folded vein (recumbent fold relatively to the axis of the core; Figure A- 8).

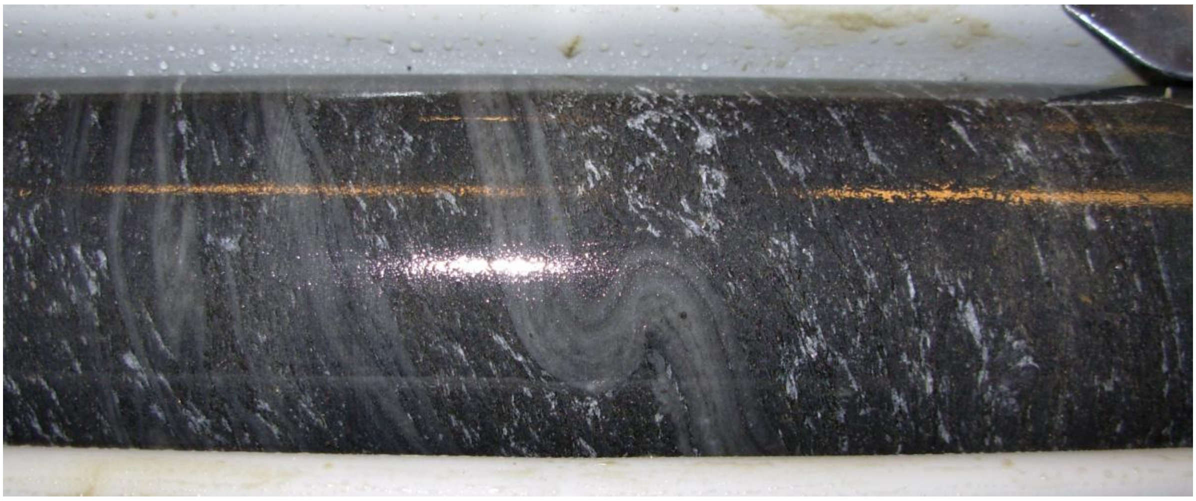

Figure A- 8. Folded vein in the 225 – 225.8 m core interval. The fold is recumbent relatively to the axis of the core.

225.8 – 231.5 m: massive, medium- and fine-grained gabbro.

228.3 – 228.7 m: coarse-grained felsic granitic interval.

231.5 – 232.8 m: medium- to coarse-grained gabbro, epidote- and quartz-rich interval and feldspar vein (Figure A- 9).

232.6 – 232.8 m: foliated.

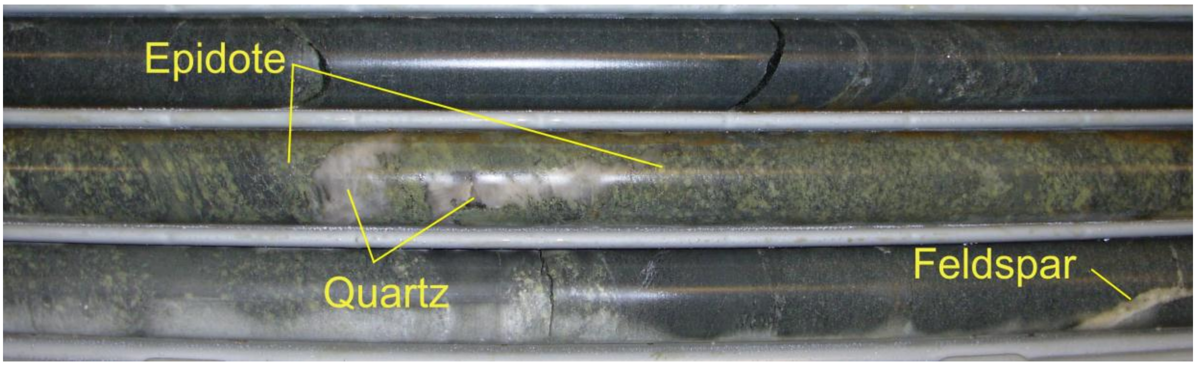

Figure A- 9. Epidote- and quartz-rich interval and feldspar vein between 231.5 and 232.8 m along the core.

232.8 – 237.8 m: fine-grained gabbroic, more plagioclase-rich at bottom of the interval.

236.3 – 236.8 m: lens of sheared K-feldspar with epidote (Figure A- 10).The fine-grained gabbro is foliated above and below the K-feldspar shear zone until the end of the interval at 237.8 m (Figure A- 10).

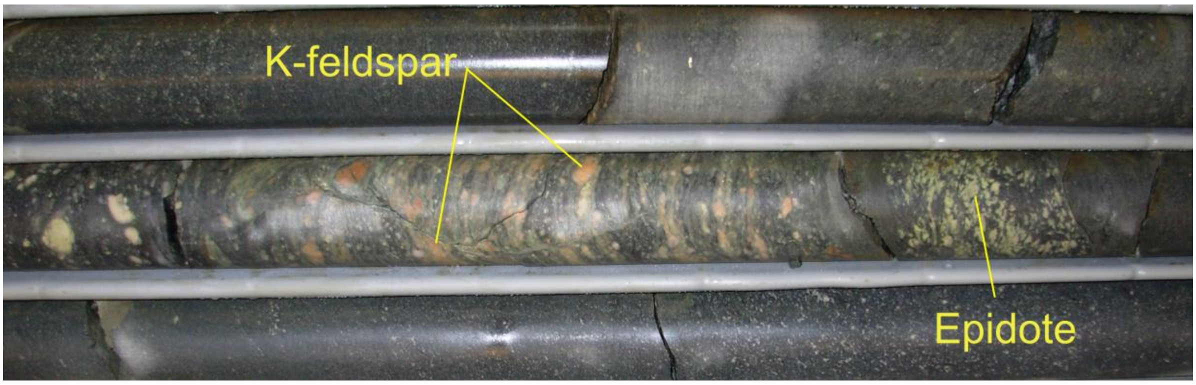

Figure A- 10. Sheared K-feldspar- and epidote-rich interval within a foliated fine-grained gabbro between 236.3 and 236.8 m along the core.

237.8 – 239.5 m: fine-grained gabbro.

239.5 – 244 m: plagioclase-rich interval, including a 20 cm sheared interval, very foliated fine-grained unit until 242.5 m; from c. 242.5 m, the rock becomes gradually so fine-grained that the minerals cannot be distinguished with naked eye until 243.6m.

At 243.6 and 243.8 m: two cm-scale epidote-rich sheared bands.

244 – 246.8 m: thin foliated, fine-grained gabbro.

246.8 – 264.7 m: porphyritic plagioclase-rich mafic rock (gabbro to diorite; Figure A- 11), some foliated intervals, pyrite-rich.

At 256.6 m: 10 cm shear zone.

At 262.8 m: white cm thick patch.

264.7 – 268.8 m: alternating plagioclase-rich –dark mineral-rich, fine-grained and medium grained gabbro/diorite.

268.8 – 273 m: fine-grained gabbro.

273 – 273.4 m: plagioclase-rich gabbro interval.

273.4 – 274.3 m: very fine-grained massive garnet-rich (very small garnets) mafic rock.

274.3 – 283 m: sheared granitic layer, mylonitic texture, and porphyroblasts of K-feldspars (see Figure 3 in section 2.1).

Figure A- 11. Typical porphyritic plagioclase-rich mafic rock (gabbro to diorite) of the 246.8 – 264.7 m core interval with some foliated parts.

283 – 284 m: chlorite-rich altered-biotite gabbro (see Figure 3).

284.20 – 301 m: fine grained foliated mafic rocks banded with quartz-rich layers, 20 cm feldspar-rich at 287.2 m.

Appendix B. Geological logging of Sauholmen drill cores: Bh01.10 and Bh01.10B

Figure B- 1. Typical greenstones of the 1 – 183.3 m core interval. 44

Figure B- 2. Pictures illustrating the pattern of the 84 – 98 m core interval. Top picture: alternating calcite-rich layers and greenstones; the parallel-to-foliation calcite veining is associated to quartz fabrics. Bottom picture: first generation of parallel-to-foliation calcite veins cuts by second generation of calcite veins. 45

Figure B- 3. The quality of the rocks is very poor between c. 179 m and 183 m with numerous crushed zones, i.e. breccias, and the presence of a soapy mineral (talc?). Note the presence of fragmented/brecciated angular quartz grains that testifies to fault rock formation. 46

Figure B- 4. Fault core filled with gouge between 183.3 – 184.7 m at the boundary between greenstones and black (i.e., graphite-rich) shales. 46

Figure B- 5. Typical facies of the black shales with sheared/eye-shaped quartz patches. 47

Figure B- 6. Typical structures within the black shales with sheared quartz patches and ptygmatitic folds of quartz bands. 47

Figure B- 7. Thirty cm of quartz at the boundary between black shales and greenstones at 383 m along the core. 48

Figure B- 8. Gradual transition between greenstones and black shales with alternating sheared layers of both types of rocks in the 492 – 494 m core interval. 48

Figure B- 9. Forty cm interval of greenstones in the black shales at c. 557 m along the core. 49

Figure B- 10. Top picture: gradual transition from the greenstones to the underlying black shales with inter-layered sheared greenstones and black shales in the 493 – 496.3 m core interval (see on Figure B- 8 the same pattern of transition between the two types of rocks at 492 m along the core of Sauholmen Bh01.10). Bottom pictures: zoom in on the sheared layers. 50

Figure B- 11. Green (chloritization?) alteration of the black shales in the 555.5 – 557 m core interval and clays/ fault gouge of the 557.6 – 558 m core interval. 51

Figure B- 12. Quartz-rich schist inter-layered within the graphite-rich black shales at c. 571.5 m along the core. 52

Figure B- 13. A 60 cm large calcite-rich hydrothermal breccia surrounded by severely damaged and crushed zones (non-cohesive breccias) in the 573 – 579 m core interval. 52

Figure B- 14. A typical pyrite and green Cu-rich coating of fracture surface in the black shales at 595 m along the core. 52

Figure B- 15. A typical ptygmatitic fold of quartz layer in the black shale at 608.7 m along the core. 53

Figure B- 16. Green altered intervals within the black shales in the 635 – 639 m core interval. 53

Figure B- 17. Very quartz-rich layers of the black shales between 678.6 and 679 m. 54

Figure B- 18. Graphite-rich layer at 749.5 m along the core in a quartz- and muscovite-rich black shale interval. 54

Figure B- 19. Sharp boundary between two compositions of black shales at 794 m along the core, i.e. between the graphite-rich (dark) layers of the 496.3 – 794 m core interval and the graphite-poor (pale gray) layers of the 794 – 850 m core interval. 55

Figure B- 20. Folded chlorite-rich layer at 878 m and other typical folds of the surrounding black shales. 55

Figure B- 21. Left picture: chalcopyrite at 922.8 m (note the typical folds of the host black shales). Right picture: pyrite and green Ccuu-oxidized coating at 949 m. 55

The main core intervals defined during the geological logging are indicated by core lengths written in bold and sub-intervals of interest are written in normal font.

Geological logging of Sauholmen Bh01.10 drill core

1 – 183.3 m: chlorite-rich, epidote-bearing schists - greenstones (metamorphosed volcanic and volcano-clastic succession) - quartz veins but mainly calcite veins, folded, some parts are less schistosic (Figure B- 1).

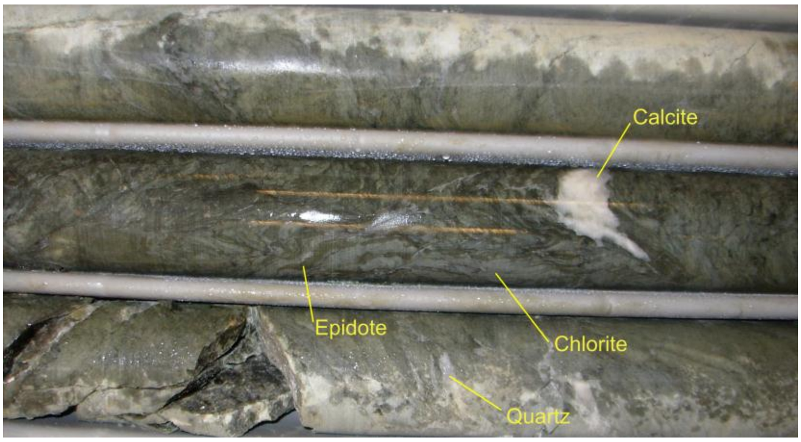

Figure B- 1. Typical greenstones of the 1 – 183.3 m core interval.

84 – 98 m: large patches of calcite and along several meters of core: alternating calcite-rich layers and greenstones (Figure B- 2). Two generations of calcite veins with quartz veins and patches associated with a first calcite generation, along the foliation and a second calcite generation cutting the foliation (Figure B- 2).

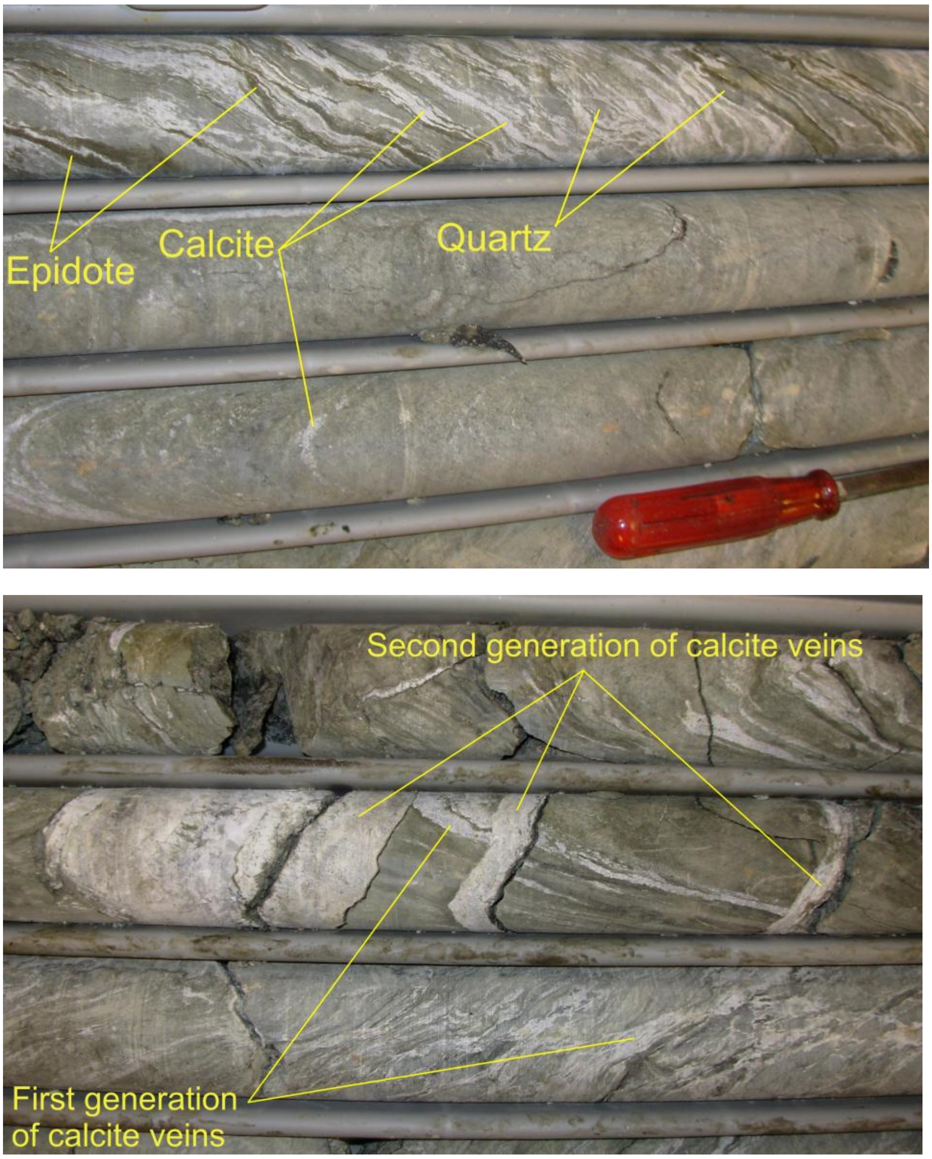

Figure B- 2. Pictures illustrating the pattern of the 84 – 98 m core interval. Top picture: alternating calcite-rich layers and greenstones; the parallel-to-foliation calcite veining is associated to quartz fabrics. Bottom picture: first generation of parallel-to-foliation calcite veins cuts by second generation of calcite veins.

At 132 m onward, more crushed and fractured zones, meter-scale thick.

179 – 183 m: abundant crushed zones containing clays, soapy talc and fragmented angular quartz grains (Figure B- 3). The fragmented/brecciated quartz grains are the products of friction along shear planes/faults. The crushed zones are tectonic in origin. They are breccias, i.e. non-cohesive fault rocks with fragmented/brecciated quartz grains surrounded by fine-grained material that correspond to fault gouge. Deep weathering may have occurred along the faults with the formation of clays and talc.

183.3 – 184.7 m: clay-rich layer that corresponds to a fault core filled with gouge (Figure B- 4) at the boundary between greenstones and black (i.e. graphite-rich) shales.

Figure B- 3. The quality of the rocks is very poor between c. 179 m and 183 m with numerous crushed zones, i.e. breccias, and the presence of a soapy mineral (talc?). Note the presence of fragmented/brecciated angular quartz grains that testifies to fault rock formation.

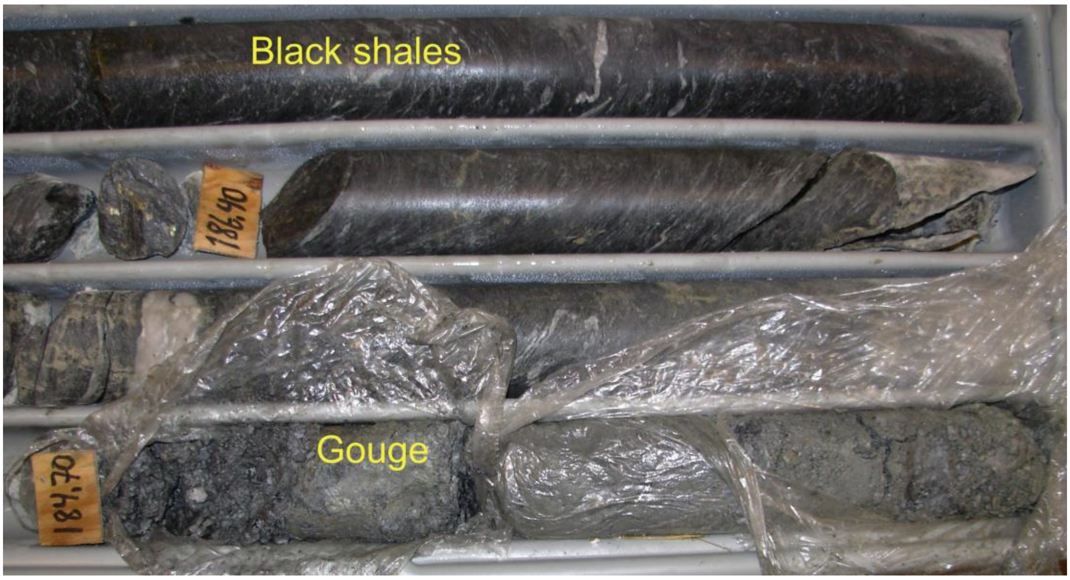

Figure B- 4. Fault core filled with gouge between 183.3 – 184.7 m at the boundary between greenstones and black (i.e., graphite-rich) shales.

184.7 – 383 m: Black shales with a lot of quartz and pyrite (Figure B- 5), still calcite associated with quartz but less than in the previously described greenstones. The structural pattern of the black shale significantly differs from the structural pattern of the greenstones (compare for example, Figure B- 1 and Figure B- 5): (1) the quartz layers of the black shales are more sheared than in the greenstones (Figure B- 5and Figure B- 6), (2) the overlying greenstones are more continuously layered/foliated, (3) the black shales shows a lot of ptygmatitic folds of quartz layers (Figure B- 6; N. B. ptygmatitic folds are disharmonic folds that develop in individual layers, typically veins in metamorphic rocks).

The black shales have a very high content of graphite in the interval 360 – 383 m.

The black shales contain very small garnets (note that there are many holes in this interval that we suspect were filled with now dissolved garnets).

Figure B- 5. Typical facies of the black shales with sheared/eye-shaped quartz patches.

Figure B- 6. Typical structures within the black shales with sheared quartz patches and ptygmatitic folds of quartz bands.

At 383 m: 30 cm of quartz at the boundary between black shales and greenstones (Figure B-7).

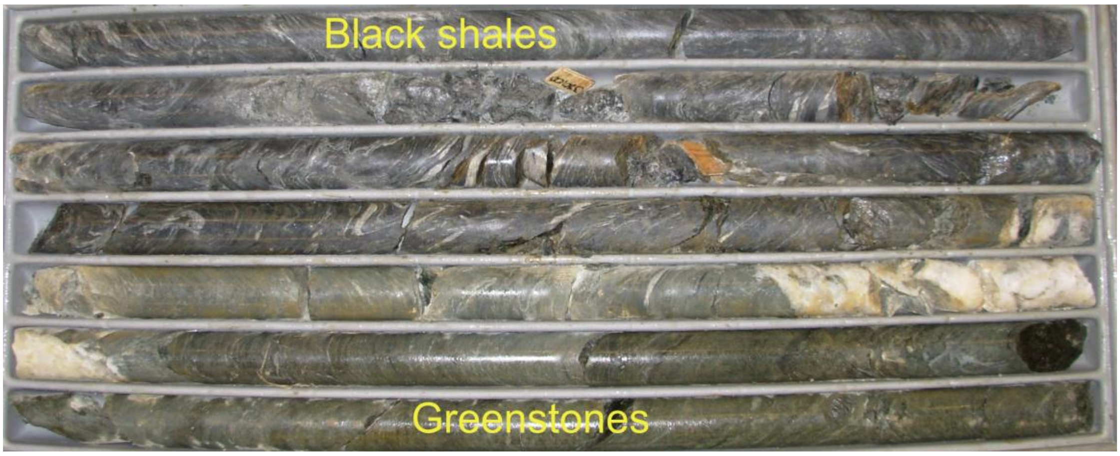

Figure B- 7. Thirty cm of quartz at the boundary between black shales and greenstones at 383 m along the core.

383 – 492 m: greenstones with characteristics as in the 1 – 183.3 m interval.

492 – 494 m: alternating sheared layers of both greenstones and black shales, gradual transition between the two types of rocks (Figure B- 8).

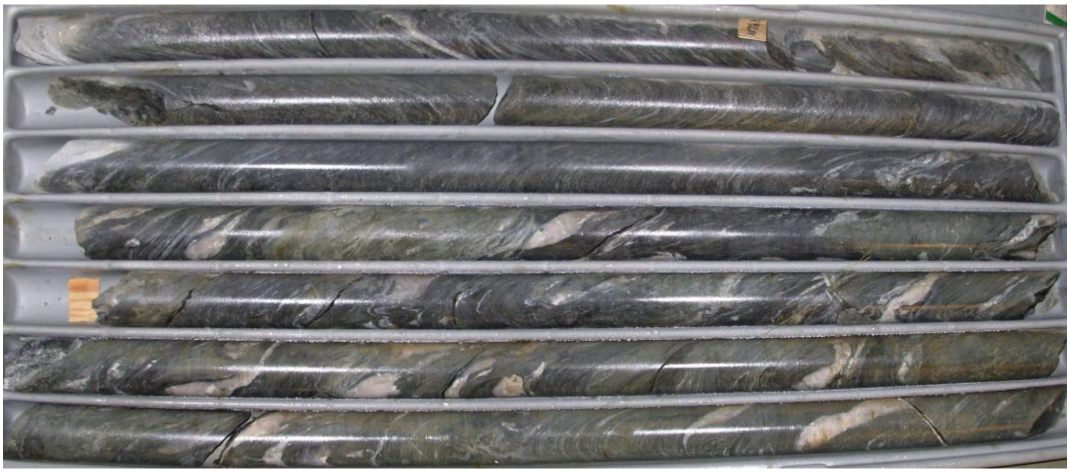

Figure B- 8. Gradual transition between greenstones and black shales with alternating sheared layers of both types of rocks in the 492 – 494 m core interval.

494 – **571 m:** black shales, with the typical structures as observed in the interval 184.7 – 383 m, i.e. ptygmatitic folds, sheared, strongly deformed, pyrite-rich unit.

At 533 m: crushed rocks/breccias with clays/gouge and muscovite.

At 557 m: 40 cm of greenstones in the black shales (Figure B- 9; assumption of volcano-clastic inputs in the anoxic basin during the sedimentation of the black shales).

571 – 588 m: a lot of thick quartz layers in the black shales with inter-layered greenstones.

588 – 679 m: black shales with the same typical structures as in the other intervals of the same units.

595 – 599 m: crushed black shales/breccias.

600 – 606 m: quartz-rich and thick veins of quartz.

620 – 625 m: chloritization.

At 625 m: schists with muscovite, but graphite, chlorite still present.

At 678.5 m: 1 m of breccias, i.e. crushed graphite (silty to sandy grain size) with brecciated quartz (see Figure 5 in section 3.1). The drill hole collapsed at this depth and the drilling was not continued, due to poor rock quality.

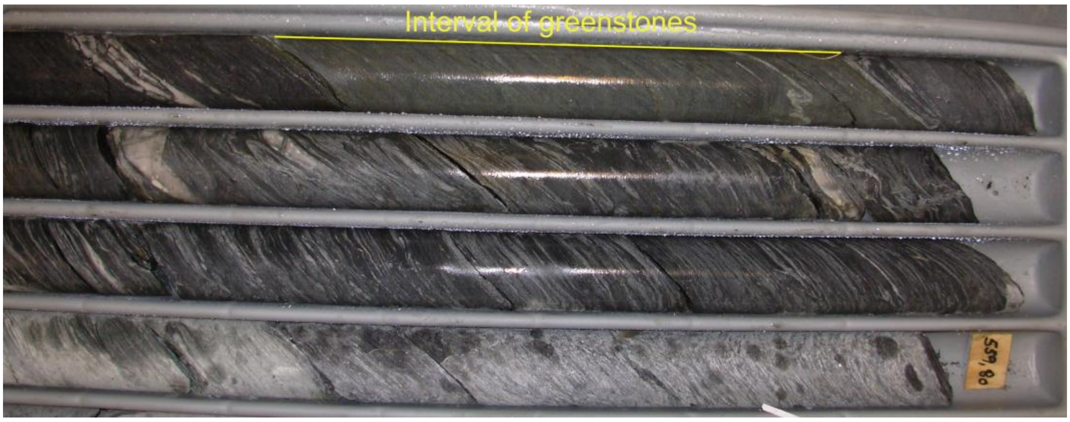

Figure B- 9. Forty cm interval of greenstones in the black shales at c. 557 m along the core.

Geological logging of Sauholmen Bh01.10B drill core

The drilling of Bh01.10B is slightly deviated from the first one, Bh01.10, and was performed from c. 469 m of the first hole length to a final length of c. 970 m. The two drill cores from Bh01.10 and Bh01.10B overlap for c. 210 m.

469.4 – 493 m: greenstones with the structural pattern as in Bh01.10, foliated.

493 – 496.3 m: gradual transition to the underlying black shales with inter-layered sheared greenstones and black shales (Figure B- 10; like at 492 m along the core of Sauholmen Bh01.10; see Figure B- 8 in Appendix B).

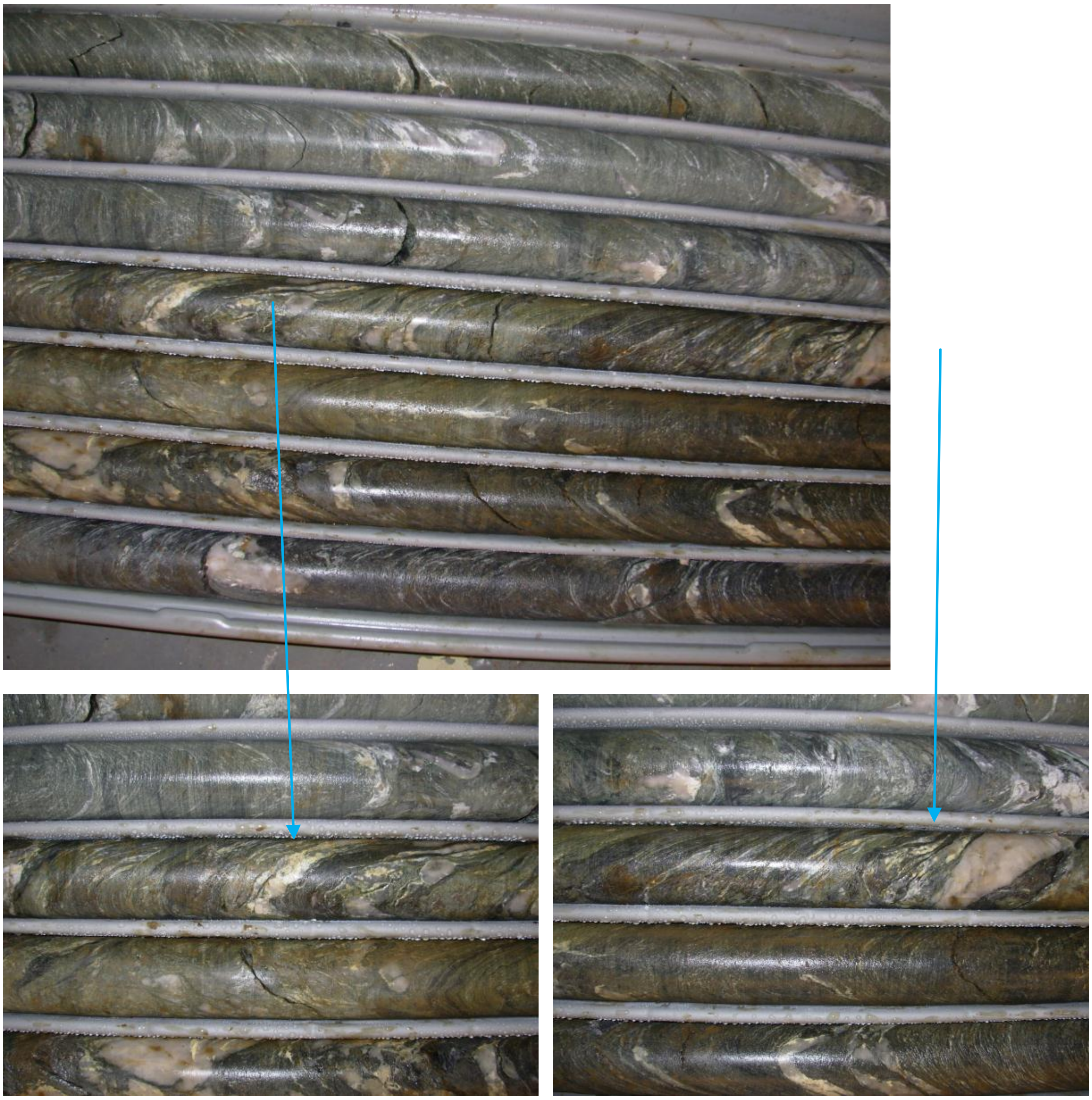

Figure B- 10. Top picture: gradual transition from the greenstones to the underlying black shales with inter-layered sheared greenstones and black shales in the 493 – 496.3 m core interval (see on Figure B- 8 the same pattern of transition between the two types of rocks at 492 m along the core of Sauholmen Bh01.10). Bottom pictures: zoom in on the sheared layers.

496.3 – 794 m: black shales with typical sheared layers and ptygmatitic folds, sulphides (pyrite and chalcopyrite) and green Cu-rich coating of fracture surfaces are common. Layers are more or less quartz-rich and/or graphite-rich. Calcite is common.

525 – 542 m: severely fractured and crushed black shales, i.e. breccias.

555.5 – 557 m: green (chloritization?) alteration of the black shales (Figure B- 11).

557.6 – 558 m: clays/ fault gouge (Figure B- 11).

Figure B- 11. Green (chloritization?) alteration of the black shales in the 555.5 – 557 m core interval and clays/ fault gouge of the 557.6 – 558 m core interval.

560 – 570 m: intervals with muscovite, some intervals are green in the black shales, all of about 10s cm scale.

At 571.50 m: very quartz-rich schist inter-layered within the graphite-rich black shales (Figure B- 12).

573 – 579 m: damaged and crushed rocks, i.e. breccias, and a 60 cm large hydrothermal calcite-rich breccia at 575.8 m (Figure B- 13).

At 595 m: a typical pyrite and Cu-rich coating observable at many location in the black shales (Figure B- 14).

At 608.7 m: a typical ptygmatitic fold of quartz layer in the black shale (Figure B- 15).

611 – 612 m: green alteration of the black shales. These intervals are most probably more siliciclastic (like the greenstones themselves).

Figure B- 12. Quartz-rich schist inter-layered within the graphite-rich black shales at c. 571.5 m along the core.

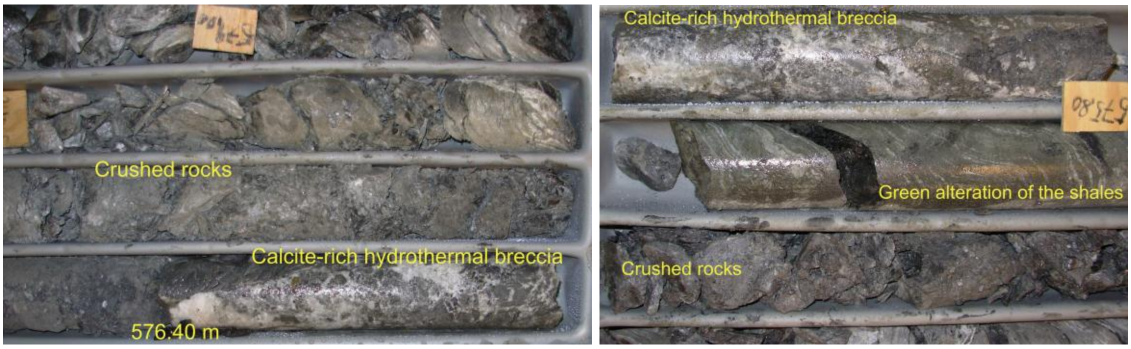

Figure B- 13. A 60 cm large calcite-rich hydrothermal breccia surrounded by severely damaged and crushed zones (non-cohesive breccias) in the 573 – 579 m core interval.

Figure B- 14. A typical pyrite and green Cu-rich coating of fracture surface in the black shales at 595 m along the core.

Figure B- 15. A typical ptygmatitic fold of quartz layer in the black shale at 608.7 m along the core.

635 – 639 m: 20 to 30 cm long intervals of green altered black shales (Figure B- 16).

665.8 – 668 m: crushed graphite (silty to sandy grain size breccia; see Figure 6 in section 3.2).

678.6 – 679 m: very quartz-rich layers (Figure B- 17). In the adjacent layers, the black shale unit is very quartz-rich with still a lot of graphite.

Drilling was stopped at 700,40 and resumed at 671 m (the direction and inclination of drilling was probably readjusted).

700 – 750 m: muscovite and quartz are very obvious but graphite-rich layers are still abundant like in the 749 – 749.5 m interval (Figure B- 18).

At 785 m: secondary minerals of low temperature like white feldspars (?).

Figure B- 16. Green altered intervals within the black shales in the 635 – 639 m core interval.

Figure B- 17. Very quartz-rich layers of the black shales between 678.6 and 679 m.

Figure B- 18. Graphite-rich layer at 749.5 m along the core in a quartz- and muscovite-rich black shale interval.

794 – 850 m: less graphite in the schists, with a max total thickness of 2 m in this interval. The boundary between the two graphite-rich and graphite-poor black shale units is sharp at 794 m (Figure B- 19).

850 – 961.4 m: graphite is not so abundant but still present, muscovite, quartz, chlorite and less pyrite. Garnets have probably been dissolved but some very small grains still remain. The structures of the unit in this interval remain the same as in the other black shale intervals (Figure B- 20 and Figure B- 21).

At 878 m: folded chlorite-rich layer (Figure B- 20).

At 914.8 m: chalcopyrite.

At 922.8 m: chalcopyrite (Figure B- 21).

At 949 m: pyrite and green Cu-oxidized coating (Figure B- 21).

Figure B- 19. Sharp boundary between two compositions of black shales at 794 m along the core, i.e. between the graphite-rich (dark) layers of the 496.3 – 794 m core interval and the graphite-poor (pale gray) layers of the 794 – 850 m core interval.

Figure B- 20. Folded chlorite-rich layer at 878 m and other typical folds of the surrounding black shales.

Figure B- 21. Left picture: chalcopyrite at 922.8 m (note the typical folds of the host black shales). Right picture: pyrite and green Ccuu-oxidized coating at 949 m.

Appendix C. Geological logging of Krågøy drill cores: Hull1, Bh01.11 and Bh01.11C

Figure C- 1. Picture of the well foliated quartz-rich greenstones that are typical of the 95 – 123 m core interval with epidote-rich bands and epidote-bearing fold hinges (one can be seen at the top of the picture). (Core interval of the box: 112 – 119 m from the top left to the bottom right). 57
Figure C- 2. Picture of the folded and foliated black shales with crushed rocks here in the 133 – 140 m core interval. They are typical of the entire 131 – 148 m core interval. 58
Figure C- 3. Picture of the core interval 179 – 186 m (from top left to bottom right in the box). At the top of the box, the rocks are typically those of the 170 – 181.8 m interval i.e. very quartz rich black shales. The remaining core of the box corresponds to the foliated and banded quartz-rich greenstones with here, specifically, the folded 183 – 185 m interval. 59
Figure C- 4. Picture of the core interval 233.8 – 240.4 m (from top left to bottom right in the box) that illustrates the foliated and folded greenstones with some graphite-rich and quartz-rich schist layers of the 203 – 249.4 m interval with, at the bottom of the picture, the foliated and sheared quartz-rich schists of the 236.7 – 249.4 m sub-interval. 60
Figure C- 5. Picture of the very quartz-rich folded and well foliated greenstones and schists of the 96 – 120 m drill core interval. Note the fold hinge at the top of the picture. The green veins are epidote-filled. 61
Figure C- 6. Sheared and brecciated layer at 245.3 m with calcite patch. The mm-scale angular fragments are brecciated quartz grains. 62
Figure C- 7. Picture of the clay-rich fine-grained fault gouge and breccia (at c. 267 m) and of the damaged severely fractured host black shales. Note the fragmented/brecciated quartz grains. 62
Figure C- 8. At c. 287 m, example of the clay-rich silty to sandy grain size breccia with fragmented quartz in the large fault rock zone of the 275– 295 m core interval. 63

The main intervals defined by distinct geological characteristics are indicated by core lengths written in bold and sub-intervals of interest are written in normal font.

Geological logging of Krågøy Hull1 drill core

0 – 95 m: massive greenstones with quartz and calcite veins. Some intervals display a well-developed foliation.

82 – 83 m: abundant quartz layers.

95 – 123 m: foliated and folded quartz-rich greenstones with conspicuous epidote-rich bands (Figure C- 1).

Figure C- 1. Picture of the well foliated quartz-rich greenstones that are typical of the 95 – 123 m core interval with epidote-rich bands and epidote-bearing fold hinges (one can be seen at the top of the picture). (Core interval of the box: 112 – 119 m from the top left to the bottom right).

123 –131 m: alternating graphite-bearing black shales and greenstones.

127 – 131 m: cm-scale quartz pegmatites.

131 –148 m: Folded and foliated black shales with a high frequency of fractures and intervals of several cm-scale rock fragments (Figure C- 2). The latter are not clay or fine-grained fault rock- or gouge-bearing.

141 – 143 m: some green intervals.

Figure C- 2. Picture of the folded and foliated black shales with crushed rocks here in the 133 – 140 m core interval. They are typical of the entire 131 – 148 m core interval.

Geological logging of Krågøy Bh01.11 drill core

151.8 – 181.8 m: well foliated mixed greenstones and black shales every 3 – 4 m intercalated. The fracture frequency is high.

170 – 181.8 m: very quartz-rich black shales and greenstones (Figure C- 3).

181.8 – 188.5 m: foliated and banded greenstones with quartz bands.

183 – 185 m: several fold hinges (Figure C- 3).

Figure C- 3. Picture of the core interval 179 – 186 m (from top left to bottom right in the box). At the top of the box, the rocks are typically those of the 170 – 181.8 m interval i.e. very quartz rich black shales. The remaining core of the box corresponds to the foliated and banded quartz-rich greenstones with here, specifically, the folded 183 – 185 m interval.

188.5 – 203 m: foliated mixed greenstones and black shales.

194 – 198 m: highly fractured interval.

203 – 249.4 m: foliated and folded greenstones with some graphite-rich and quartz-rich schist layers (Figure C- 4).

203 – 205.8 m: foliated quartz-rich schists.

236.7 – 249.4 m: foliated and sheared quartz-rich schists (Figure C- 4).

249.4 – 313.3 m: abundant thick crushed zones (breccias) characterized by angular fragments of quartz and by clays/gouges in severely fractured quartz-rich and graphite-rich schists/black shales. Quartz pegmatitic intervals are common.

253.4 – 256 m: cemented brecciated greenstones with several cm-scale clay-bearing crushed zones (non-cohesive breccias).

At 259 m: 50 cm graphite-rich crushed (silty to sandy grain size) zone/breccia.

261.5 – 263.5 m: abundant graphite-rich crushed (silty to sandy grain size) zones/breccias.

Figure C- 4. Picture of the core interval 233.8 – 240.4 m (from top left to bottom right in the box) that illustrates the foliated and folded greenstones with some graphite-rich and quartz-rich schist layers of the 203 – 249.4 m interval with, at the bottom of the picture, the foliated and sheared quartz-rich schists of the 236.7 – 249.4 m sub-interval.

268 – 279 m: alternating 50 cm to 1 m thick crushed (silty to sandy grain size breccias) or heavily fractured graphite-rich shales.

284.2 – 288.1 m: clay-rich, silty to sandy grain size crushed zone (gouge-bearing breccias).

297 – 308 m: clay-rich, silty to sandy grain size crushed zone (gouge-bearing breccias; see Figure 11 in section 4.2).

Geological logging of Krågøy Bh01.11C drill core

65.3 – 96 m: foliated greenstones characterized by quite massive intervals and a high density of quartz and calcite veins. Chalcopyrite is abundant.

87.5 – 90 m: interval with quartz pegmatites.

At c. 95 m: strong schistose.

96 – 120 m: very quartz-rich folded and well foliated greenstones and schists with abundant epidote veins (Figure C- 5).

Figure C- 5. Picture of the very quartz-rich folded and well foliated greenstones and schists of the 96 – 120 m drill core interval. Note the fold hinge at the top of the picture. The green veins are epidote-filled.

120 – 129 m: greenstones.

129 – 227 m: quartz-rich schists with some graphite-rich and greenstone intervals. Fold hinges are commonly observed. Foliation is well developed.

148.5 – 154.5 m: interval with a very high content of quartz/chert-like rock.

187.5 – 187.8 m: quartz pegmatite.

192.2 – 192.7 m: quartz pegmatite.

227 – 315.5 m: severely damaged/fractured black shales and crushed zones with clays, i.e., gouge-bearing breccias.

At 245.3 m: sheared and brecciated layer (Figure C- 6).

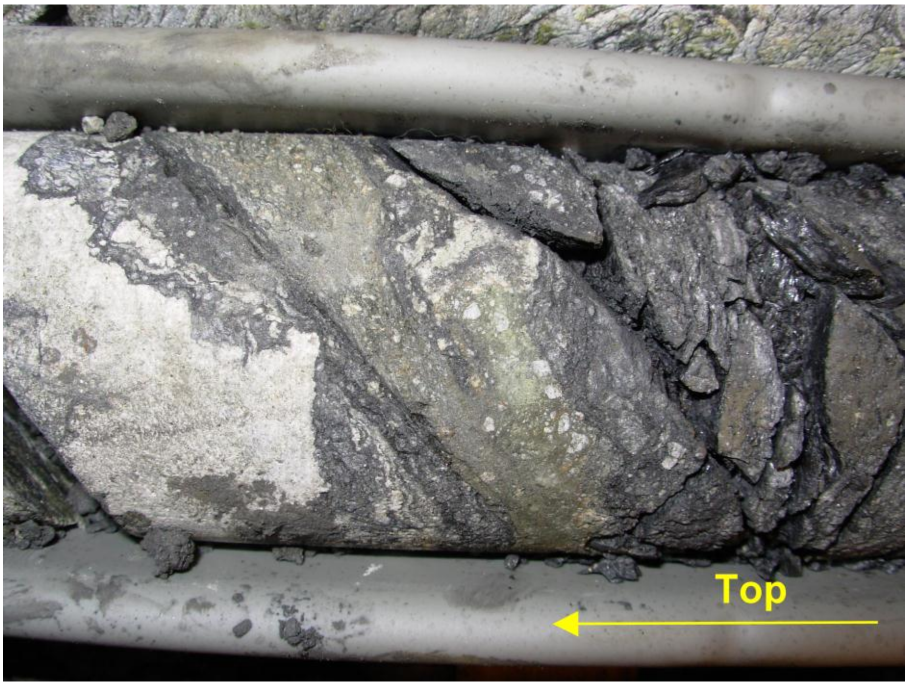

Figure C- 6. Sheared and brecciated layer at 245.3 m with calcite patch. The mm-scale angular fragments are brecciated quartz grains.

245.4 – 262 m: quasi continuous fine-grained crushed zone with clays/gouges and brecciated quartz grains.

267 – 268 m: fine-grained crushed zone with clays (gouge-bearing silty to sandy grain size breccias; Figure C- 7).

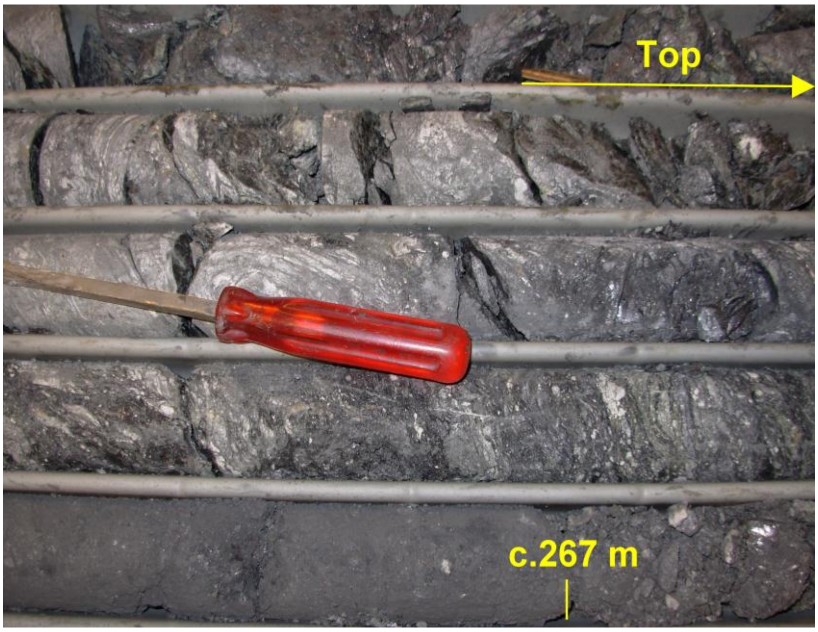

Figure C- 7. Picture of the clay-rich fine-grained fault gouge and breccia (at c. 267 m) and of the damaged severely fractured host black shales. Note the fragmented/brecciated quartz grains.

275– 295 m: quasi continuous breccias, i.e. fine-grained crushed zone (Figure 12 in section 4.3) with clays/gouges and fragmented quartz grains (Figure C- 8).

295 – 315.5 m: crushed zones/ silty to sandy grain size breccias with less clay content than above.

Figure C- 8. At c. 287 m, example of the clay-rich silty to sandy grain size breccia with fragmented quartz in the large fault rock zone of the 275– 295 m core interval.

Appendix D. Geological logging of Hesteholmen drill cores: Bh02.11A and Bh02.11B

Figure D- 1. Massive greenstones in contrast with banded and foliated greenstones. The first type of greenstones likely corresponds to metamorphosed massive lavas while the second type is metamorphosed volcano-clastic sediments. (Core interval: 54 m at the top left of the picture and 60.9 m at the bottom right). 65
Figure D- 2. Contrast between the massive greenstones and the foliated banded and deformed greenstones. The green intervals are epidote-rich. (Core interval: 67.8 m at the top left of the picture and 74.8 m at the bottom right). 66
Figure D- 3. Radial secondary minerals at c. 232 m along the core. 66
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Figure D- 5. Picture of the quartz-rich schists/chert-like rocks of the 291 – 300 m core interval. 67
Figure D- 6. Quasi pure quartz rocks/cherts at 321 m depth along the core in the alternating quartz-rich schists and greenstones (seen on the top of the picture) of the 300 – 337 m interval. 68
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Figure D- 8. Secondary dark minerals (garnets?) in the greenstones of the 380 – 394 m core interval. 69
Figure D- 9. Top: picture of the clay-rich/fault gouge silty to sandy grain size breccias of the 453 – 455.7 m core interval and of the shear zone with brecciated quartz (in the yellow rectangle which is the frame of the bottom picture). Bottom: picture of the shear zone with brecciated quartz of the 455.7 – 458 m core interval. Note at the bottom of the picture the greenstones with a network of micro-veins. 70
Figure D- 10. Cemented breccia intervals at 483 m (top picture) and at 484.8 m (bottom picture) along the core. 71

The main intervals are defined on distinct geological characteristics observed during the logging. They are indicated by core lengths written in bold and sub-intervals of interest are written in normal font.

Geological logging of Hesteholmen Bh02.11A drill core

0 – 51 m: Foliated banded greenstones with quartz-rich intervals. Calcite veins, epidote-rich layers and pyrite-coated fractures are common. Some intervals display a thin foliation.

28.2 – 28.7 m: clay-rich crushed zone/gouge-bearing silty to sandy grain size breccias.

51 – 60 m: abundance of massive layers (suspected to correspond to metamorphosed lava flows) in contrast with the banded and foliated greenstones, volcano-clastic in origin (Figure D- 1). These massive layers were not so obvious and frequent along Sauholmen and Krågøy cores (see sections 3 and 4).

Figure D- 1. Massive greenstones in contrast with banded and foliated greenstones. The first type of greenstones likely corresponds to metamorphosed massive lavas while the second type is metamorphosed volcano-clastic sediments. (Core interval: 54 m at the top left of the picture and 60.9 m at the bottom right).

60 – 130 m: foliated banded deformed greenstones with epidote-rich intervals, abundant quartz veins and some massive layers.

At 70 m: sharp limit between the massive greenstones and the foliated deformed greenstones (Figure D- 2).

At 101.50 m: 50 cm thick quartz pegmatite.

130 – 137 m: massive greenstones.

137 – 257 m: alternating massive greenstones up to some meters scale with foliated, banded and folded greenstones. Massive layers display a thin foliation. Talc is obvious in the foliated and banded intervals.

199 – 204 m: massive greenstones with a strong sericitization (and/or saussuritization?) of the plagioclases.

At c. 232 m: radial secondary minerals (zeolites? prehnite?; Figure D- 3).

250 – 257 m: strongly foliated greenstones.

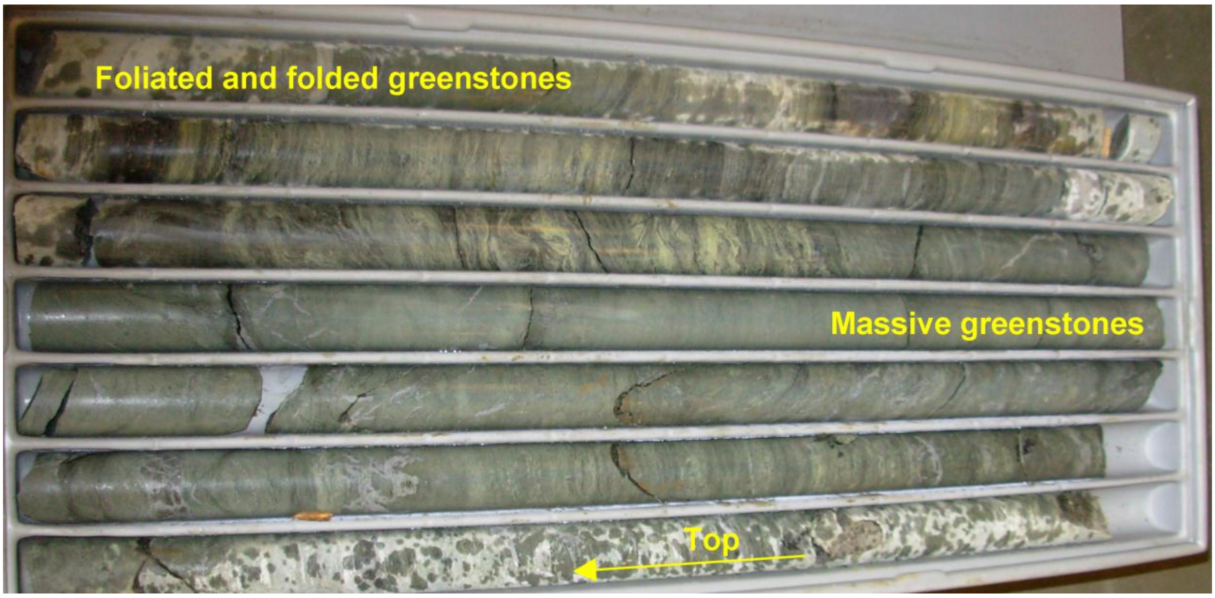

Figure D- 2. Contrast between the massive greenstones and the foliated banded and deformed greenstones. The green intervals are epidote-rich. (Core interval: 67.8 m at the top left of the picture and 74.8 m at the bottom right).

Figure D- 3. Radial secondary minerals at c. 232 m along the core.

257 – 271 m: quartz-rich black shales with ductile sheared intervals.

At c. 258 m: a 20 cm thick typical ductile sheared interval (Figure D- 4).

271 – 291 m: alternating greenstones and quartz-rich schists with foliation varying along the core from shallow to steep (for example at c. 278 m) relatively to the axis of the core. This testifies for the occurrence of folds in the units. Quartz-rich veins and pegmatites 1-2 to 10-20 cm thick are frequent.

291 – 300 m: quartz-rich schists/chert-like rocks (Figure D- 5).

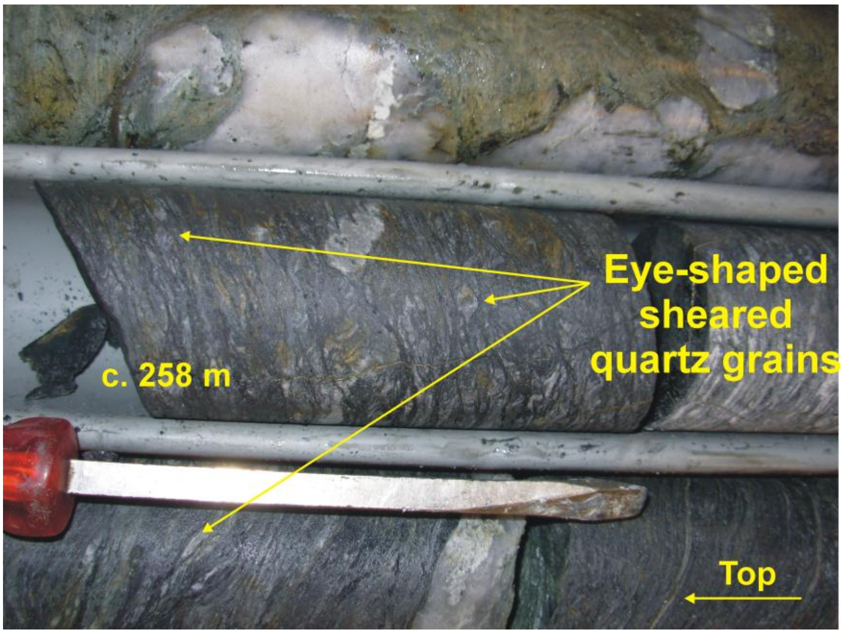

Figure D- 4. Typical sheared intervals with deformed eye-shaped quartz grains.

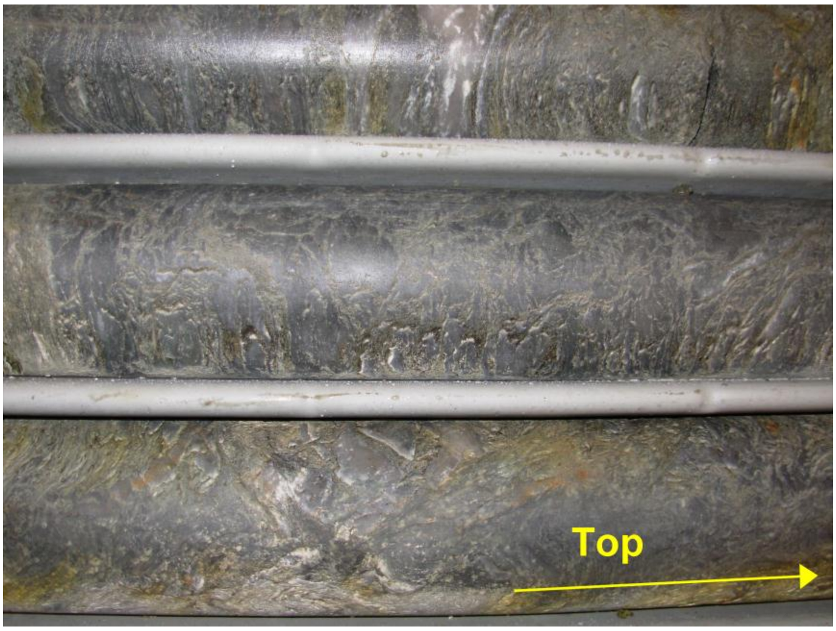

Figure D- 5. Picture of the quartz-rich schists/chert-like rocks of the 291 – 300 m core interval.

300 – 337 m: alternating greenstones and quartz-rich schists.

At 321 m: quasi pure quartz rocks/cherts (Figure D- 6).

337 – 347 m: graphite-rich black shales alternating with quartz-rich schists. Pyrite is conspicuous.

347 – 356 m: quartz-rich schists.

356 – 359 m: crushed zone/silty to sandy grain size breccias in a unit of mixed black shales and quartz-rich schists. Core lost at the bottom of the interval.

360 – 364.5 m: quartz-rich schists and black shales with a high content of graphite (Figure D- 7).

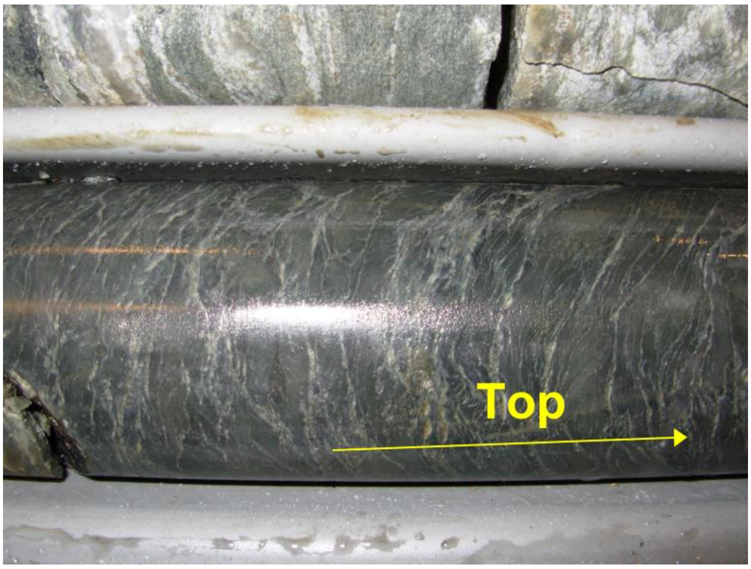

Figure D- 6. Quasi pure quartz rocks/cherts at 321 m depth along the core in the alternating quartz-rich schists and greenstones (seen on the top of the picture) of the 300 – 337 m interval.

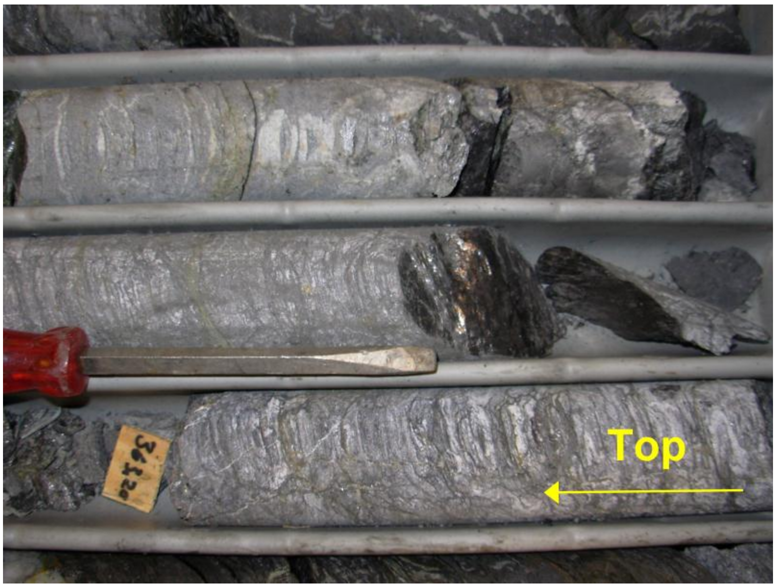

Figure D- 7. Quartz-rich schists and black shales with a high content of graphite (black surface on the picture) in the 360 – 364.5 m core interval.

364.5 – 380 m: quartz-rich schists.

380 – 394 m: greenstones with dark secondary minerals (garnets?; Figure D- 8).

394 – 400 m: quartz-rich schists with conspicuous chalcopyrite.

400 – 407 m: black shales with a high content of graphite.

407 – 450 m: graphite- and quartz-rich unit with talc and clay-rich crushed zones/ fault gouge silty to sandy grain size breccias.

> 416 – 425.3 m: severely crushed zone/silty to sandy grain size breccias with fragmented quartz and clay- bearing/fault gouge intervals (see Figure 14 in section 5.1). The contacts between the clay/gouge and the host rock are very sharp.

427.5 – 431.3 m: severely crushed zone/silty to sandy grain size breccias with clay-bearing intervals as fault gouges.

434.7 – 434.9 m: vuggy quartz layer.

435 – 450 m: abundant intervals of crushed rocks/ silty to sandy grain size breccias present until the core loss at 450 m.

Figure D- 8. Secondary dark minerals (garnets?) in the greenstones of the 380 – 394 m core interval.

Geological logging of Hesteholmen Bh02.11B drill core

399 – 453 m: graphite- and quartz-rich unit with talc and clay-rich crushed zones/ gouge-bearing silty to sandy grain size breccias. Fold hinges and sheared intervals are conspicuous.

417.5 – 426 m: severely crushed zone/ silty to sandy grain size breccias with clays/fault gouges (see Figure 15 in section 5.2).

426 – 439 m: damaged rocks

442 – 453 m: clay-rich crushed rocks, i.e. gouge-bearing breccias.

453 – 487.8 m: foliated and folded greenstones without massive layers, resembling those observed along Sauholmen drill core with numerous calcite and quartz veins (see section 3). Sheared and cemented brecciated layers are conspicuous along the intervals. This rock interval is highly fractured in general and some intervals are crushed rocks/ non-cohesive breccias.

453 – 455.7 m: silty to sandy grain size crushed rocks with clays, i.e. breccias and fault gouges (Figure D- 9).

455.7 – 458 m: cemented breccias in a shear zone (Figure D- 9).

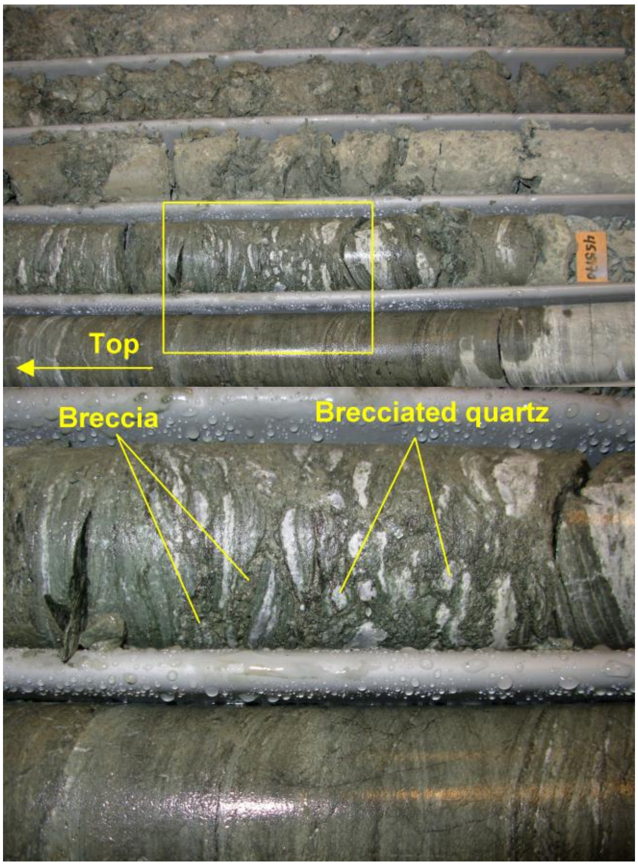

Figure D- 9. Top: picture of the clay-rich/fault gouge silty to sandy grain size breccias of the 453 – 455.7 m core interval and of the shear zone with brecciated quartz (in the yellow rectangle which is the frame of the bottom picture). Bottom: picture of the shear zone with brecciated quartz of the 455.7 – 458 m core interval. Note at the bottom of the picture the greenstones with a network of micro-veins.

475 – 487.8 m: frequent intervals of 10-20 cm silty to sandy grain size non-cohesive breccias. The remaining intervals commonly display cemented breccias (Figure D- 10).

487.8 – 517.5 m: interval of abundant silty to sandy grain size breccias in black shales, characterized by fragmented quartz. Aside from the crushed zones, the rocks are severely fractured. These breccias are several meters thick and contain fault gouges/clays.

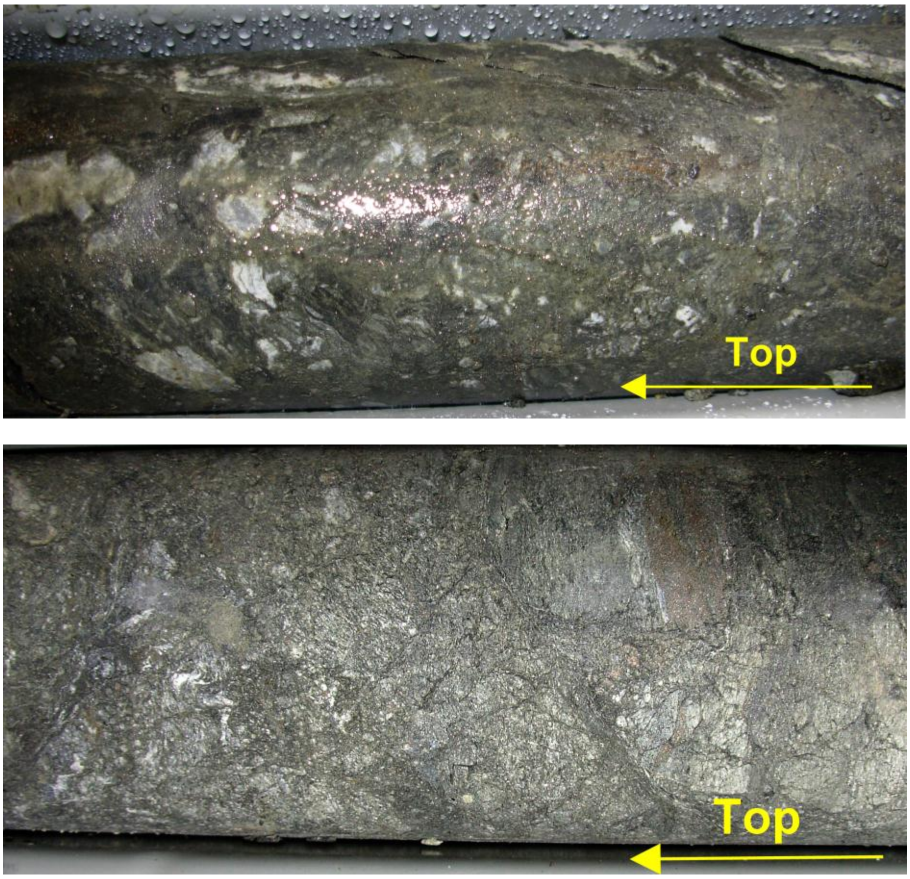

Figure D- 10. Cemented breccia intervals at 483 m (top picture) and at 484.8 m (bottom picture) along the core.