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Forsmark site investigation

Boremap mapping of telescopic drilled borehole KFM05A

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December 2004

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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

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Abstract

This report presents the results from the Boremap mapping of telescopic drilled borehole KFM05A. The borehole is located northwest of the lake Bolundsfjärden, centrally in the northern part of Forsmark candidate area and plunges 60° towards east, with the main purpose to investigate the existence of N-S trending, brittle deformation zones below the lake. The full length of the borehole is ca 1,002.7 m, and the BIPS-image covers more or less the entire cored part, between 102.0 and 999.7 m. The upper, percussion-drilled part of KFM05A, was not included in the mapping engagement. All structures and lithologies intersected by the BIPS-logged interval have been documented in detail by integrating information from the drill core and the BIPS-image.

Lithologically, KFM05A is dominated by a metagranite with a tendency to be slightly granodioritic. In addition to the typical medium-grained variety, found elsewhere in the area, KFM05A includes a second variety of a fine- to finely medium-grained rock. The two facies are separated by a sharp, intrusive contact at a borehole length of 285.8 m, with the fine- to finely medium-grained rock type in the upper part of the borehole. Additional rock units within the borehole include fine- to finely medium-grained metagranitoides, various amphibolites, felsic to intermediate rocks of inferred volcanic origin and minor dykes of pegmatite, aplitic granite and fine- to finely medium-grained leucogranite. Except a major occurrence of fine- to finely medium-grained metagranitoid and a heterogeneous mixture of amphibolite and fine-grained rocks with a quartz-dioritic composition, none of these occurrences exceed a few metres in length along the borehole. Virtually all rocks have experienced Svecofennian metamorphism under amphibolite facies conditions.

Structurally, KFM05A is characterised by composite L-S fabrics, with a general predominance of planar mineral fabrics in the fine- to finely medium-grained metagranite, whereas the more medium-grained metagranite often shows linear mineral fabrics. Zones of more intense ductile deformation are few, and all less than 4 dm along the borehole. Varying degrees of oxidation has affected about 10% of the mapped interval.

The total number of fractures registered is 2,835. Most of these fractures are sealed and the frequency of open fractures is only 0.7 fractures/metre. Three rather distinct fracture sets can be distinguished in the borehole. The most conspicuous set consists of NE-SW striking, steeply dipping fractures, typically filled by an assemblage of laumontite + calcite + sub-microscopic hematite ± chlorite. Most of them are inferred to be sealed, and their frequency increases dramatically below 580 m. Fractures less than 0.5 mm in width, some of them only revealed by their oxidised walls, are common in this group. Another well-defined group, preferentially found in the upper 230 m of the borehole, consists of near horizontal to gently dipping fractures. A majority of these fractures are inferred to be open; a few with apertures that exceed 1 cm. Three minor crush zones belong to this group. Infillings of clay minerals, asphalt, Fe-hydroxide and a quartz-rich material, mapped as incohesive breccia, are broadly limited to this set. A third, less well-defined set, consists of steeply dipping fractures with roughly N-S strike. These are often intimately associated with the more conspicuous NE-SW set. Thus, KFM05A gives no unambiguous support for the existence of N-S trending, brittle deformation zones below Bolundsfjärden.

Sammanfattning

Föreliggande rapport redovisar resultaten från Boremapkarteringen av teleskopborrhål KFM05A. Borrhålet är placerat strax nordväst om sjön Bolundsfjärden, centralt i norra delen av Forsmarksområdet. Vidare stupar det 60° mot öster i syfte att undersöka förekomsten av N-S orienterade, spröda deformationszoner under sjön. Hålets fulla längd är ca 1 002,7 m och BIPS-bilden täcker mer eller mindre hela den kärnborrade delen mellan 102,0 och 999,7 m. Den övre, hammarborrade delen av KFM05A är inte inkluderad i karteringsuppdraget. Alla strukturer och litologier som förekommer i det BIPS-loggade intervallet har dokumenterats i detalj genom att integrera information från borrkärnan och BIPS-bilden.

Litologiskt domineras KFM05A av en metagranit som tenderar att vara något granodioritisk. Utöver den typiska, medelkorniga varianten som dominerar området i övrigt, innehåller borrhålet en andra fin- till fint medelkornig variant. De två typerna skiljs åt av en skarp intrusiv kontakt vid en borrhålslängd av 285,8 m, med den fin- till fint medelkorniga graniten i borrhålets övre del. Ytterligare bergartsenheter i borrhålet inkluderar fin- till fint medelkorniga metagranitoider, olika amfiboliter, felsiska till intermediära bergarter av möjligt vulkaniskt ursprung och mindre gångar av pegmatit, aplitisk granit och fin- till fint medelkornig leucogranit. Frånsett en större förekomst av fin- till fint medelkornig metagranitoid och en heterogen blandbergart av amfibolit och finkornigt material med kvartsdioritisk sammansättning, överskrider ingen av dessa förekomster ett fåtal meter i längd. I det närmaste alla bergarter har genomgått Svekofennisk amfibolitfacies-metamorfos.

Strukturellt karaktäriseras KFM05A av en sammansatt L-S-struktur, med en förhärskande foliationskomponent i den fin- till fint medelkorniga metagraniten, medan den mer medelkorniga varianten ofta uppvisar mineralstänglighet. Zoner av mer kraftig deformation är ovanliga och alla är mindre än 4 dm breda. Olika grader av oxidation har påverkat ungefär 10 % av det karterade intervallet.

Det totala antalet registrerade sprickor är 2 835. De flesta sprickor är läkta och antalet öppna sprickor är endast 0.7 sprickor/meter. Tre relativt distinkta sprickgrupper kan urskiljas i borrhålet. Den mest tydliga gruppen består av NO-SV strykande sprickor med brant stupning, ofta fyllda av laumontit + kalcit + submikroskopisk hematit ± klorit. De flesta av dessa sprickor är registrerade som läkta, och dess antal ökar drastiskt under 580 m. Viktigt att poängtera är att sprickor tunnare än 0,5 mm, somliga endast urskiljbara på grund av en oxidation av sidoberget, är vanliga i denna grupp. En annan väldefinierad grupp, som huvudsakligen uppträder i de övre 230 m av borrhålet, består av sub-horisontella och flackt stupande sprickor. Flertalet av dessa sprickor är registrerade som öppna; några med aperturer över 1 cm. Tre mindre krosszoner ingår i denna grupp. Sprickfyllnader av lermineral, bergbeck, Fe-hydroxid och ett kvartsrikt material, karterat som icke kohesiv breccia, är i stort sett begränsade till denna grupp. En tredje, mindre väldefinierad grupp, består av branta sprickor med ungefär N-S strykning. Dessa är normalt intimt associerade med den mer väldefinierade NO-SV gruppen. KFM05A ger därför egentligen inget entydigt stöd för förekomsten av spröda deformationszoner med N-S orientering under sjön Bolundsfjärden.

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1 Introduction

Since 2002, SKB investigates two potential sites at Forsmark and Oskarshamn, for a deep repository in the Swedish Precambrian basement. In order to characterise the bedrock down to a depth of about 1 km in the central part of the test site area at Forsmark, three deep telescopic boreholes were drilled. Each borehole starts with 100 m of percussion drilling, followed by core drilling down to about 1,000 m depth. To obtain drill cores for the upper 100 m, additional boreholes were drilled adjacent to telescopic boreholes at drilling site (DS) 1 and 3. After completion of these initial drillings, SKB launched a more extensive, complementary drilling program, aiming to solve more specific geological questions. An important aspect when localizing the second of these boreholes, KFM05A, was to investigate the existence of N-S trending, brittle deformation zones below Bolundsfjärden, centrally in the northern part of the test site area (Figure 1-1), as suggested by topographic and magnetic data /cf SKB, 2002/. Consequently, the borehole was set just northwest of Bolundsfjärden and plunges 60° towards east, beneath the northern part of the lake. The borehole is a telescopic borehole (cf SKB MD 620.004), identical with the four previous deep boreholes in the area, with a total length of about 1,000 m. The drilling activities in KFM05A were finished during May 2004, after which the geological logging continued to the end of June 2004.

A detailed mapping of the material obtained through the drilling programs is essential for subsequent sampling and borehole investigations, and consequently, for the three-dimensional modelling of the site geology. For this purpose, the so-called Boremap system has been developed. The system integrates results from drill core mapping, or alternatively, the drill cuttings when a core is not available, with information from BIPS-logging (Borehole Image Processing System) and calculates the absolute position and orientation of fractures and various lithological features (SKB MD 146.005).

This report presents the results from the mapping of KFM05A in the Boremap system. It also gives a brief discussion of the results in a larger context, relative to the data from the previous cored boreholes in the area, as well as the surface geology. The work was carried out in accordance with activity plan AP PF 400-04-33. In Table 1-1 controlling documents for performing this activity are listed. Both activity plan and method descriptions are part of SKB's internal controlling documents.

Figure 1-1. *General overview over Forsmark site investigation area showing the location of the cored boreholes KFM01A+B, KFM02A, KFM03A+B, KFM04A and KFM05A.*

Table 1-1. Controlling documents for the performance of the activity.

Activity plan	Number	Version
Boremapkartering av teleskop-borrhålet KFM05A	AP PF 400-04-295	1.0
Method descriptions	**Number**	**Version**
Nomenklatur vid Boremap-kartering	SKB MD 143.006	2.0
Mätsystembeskrivning för Boremap-kartering, Boremap v. 3.0	SKB MD 146.005	1.0

2 Objective and scope

Borehole KFM05A starts with percussion drilling (Ø = 165 mm) to a length of about 100 m, followed by core drilling at Ø = 86 mm to a length of 101.90 m, and at Ø = 77 mm down to full borehole length of 1,002.71 m. The diameters of the two drill cores are 70 mm and 51 mm, respectively. The soil cover at DS5 is about 7 m. In contrast to the previous four telescopic boreholes in the area, there is no BIPS-image available for the upper, percussion-drilled part of KFM05A. Drill cuttings were, however, collected at 1 m intervals between 7.5 and 100.2 m depth, though the engagement does not include mapping of this material. The usable BIPS-image of the cored part of the borehole covers the interval between 102.0 and 999.7 m.

The aim of the mapping activities is to obtain a detailed documentation of all structures and lithologies intersected by the BIPS-logged intervals of borehole KFM05A. These data will serve as a platform for forthcoming analyses of the drill core, aimed at investigating geological, petrophysical and mechanical aspects of the rock volume, as well as site descriptive modelling.

3 Equipment

3.1 Description of equipment and interpretation tools

All BIPS-based mapping was performed in Boremap v. 3.4.2. This software contains the bedrock and mineral standard used by the Geological Survey of Sweden (SGU) for geological mapping of the surface at the Forsmark investigation site, to enable correlation with the surface geology. Additional software used during the course of the mapping was BIPS Viewer v. 1.10 and Microsoft Access. The final data presentation was made by Geoplot and WellCAD v. 3.2.

The following equipment was used to facilitate the core mapping: folding rule, concentrated hydrochloric acid diluted with three parts of water, unglazed porcelain plate, knife, hand lens, paintbrush and tap water.

4 Execution

4.1 General

During the mapping, the 1,000 m drill core obtained from the interval 100.35–1,002.71 m of KFM05A was available in its full length on roller tables in the core-mapping accommodation at Forsmark (the Llentab hall, near the SKB/SFR-office). The BIPS-based mapping was preceded by an overview mapping made by Kenneth Åkerström. No thin-sections were available from the drill cores, and all lithological descriptions are based on ocular inspection. Four geologists from SwedPower AB, Johan Berglund, Peter Danielsson, Jesper Petersson and Anders Wängnerud, were involved in the BIPS-based mapping. Most of the mapping was done by two geologists at a time, forming a mapping team. However, to speed up the mapping at the prospect of a single-hole interpretation meeting at the end of June, an additional geologist was working parallel with the team part of the time.

The mapping of KFM05A was performed in Boremap v. 3.4.2 according to activity plan AP PF 400-03-100 (SKB internal document) following the SKB method description for Boremap mapping, SKB MD 143.006 (v. 2.0).

4.2 Preparations

The length registered in the BIPS-image deviates from the true borehole length with increasing depth, and the difference at the bottom of the borehole is about 5 m. It was, therefore, necessary to adjust the length with reference to groove millings cut into the borehole wall at every 50 m, with the deepest slot at a length of 900 m. The exact level of each reference mark can be found in SKB's database SICADA (Appendix 4). However, the adjusted length is still not completely identical with the one given in the drill core boxes, as the core recovery may yield erroneous lengths. The difference is typically less than about 1 dm, but may reach up to 3 dm in some intervals.

Data necessary for calculations of absolute orientation of structures in the borehole includes borehole diameter, azimuth and inclination, and these data were collected from SKB's database SICADA (Appendices 2 and 3). Corrections for the borehole deviation were done at every twelfth metre.

4.3 Data handling

To obtain the best possible data security, the mapping was performed on the SKB intranet, with regular back-ups on the local drive.

The mapping was quality checked by a routine in the Boremap software before it was archived. The data were subsequently exported to the SKB database SICADA and stored under field note no Forsmark 345.

4.4 Analyses and interpretations

The Boremap system has obviously some limitations, since all geological features must be represented by intersecting planar surfaces. Non-planar structures, such as small scale folding, linear objects (e.g. mineral lineation) and curved fractures can, therefore, not be correctly documented. The major problem is curved structures (e.g. fractures), which run almost parallel with the borehole axis. During the mapping sessions of KFM05A such features were normally approximated by fitting the plane after one of their ends in the borehole. The fact that some of these structures do not actually intersect the borehole is only noted in the attached comments.

Another problem in the system is related to geological features (mainly fractures) that can be observed only in the drill core. This problem usually arises from poor resolution in the BIPS-image, which in the present case often is caused by the presence of suspended drill cuttings and/or brownish black coating on the borehole walls. However, even in the most perfect BIPS-image, it is sometimes difficult to distinguish a thin fracture sealed by some low contrast mineral. All fractures observed in the drill core, but not in the BIPS-image, have been registered as ‘not visible in BIPS’ in Boremap to prevent them from being used in forthcoming fracture orientation analysis. Fractures suspected to be induced by the drilling activities fall within this category. Obviously drill-induced fractures are not included in the mapping.

Even though reliable measurements of fracture widths/apertures less than 1 mm would be possible to obtain in the drill core, it is often beyond the resolution of the BIPS-image. The minimum width/aperture given is, therefore, 0.5 mm. However, if the fracture width measured in the drill core is much less, it is normally noted in the attached comment.

The fracture mapping focuses on the division into broken and unbroken fractures, depending on whether they are parting the core or not. Broken fractures include both open fractures and originally sealed fractures, which were broken during the drilling. To decide if a fracture actually was open or sealed in the rock volume (i.e. in situ), SKB has developed a confidence classification expressed at three levels, ‘possible’, ‘probable’ and ‘certain’, based on the weathering and fit of the fracture planes. The criteria for this classification are given in SKB method description for Boremap mapping, SKB MD 143.006 (v. 2.0).

Up to four infilling minerals can be registered in each fracture. As far as possible, they are given in order of decreasing abundance in the fracture. Additional minerals, which occur in a few fractures, are noted in the attached comment. However, it must be emphasized that this provides no information on the volumetrical amount of individual minerals. In a fracture with two minerals, the mineral registered as ‘second’ may range from sub-microscopic staining up to amounts equal to that of the mineral registered as ‘first’. Hematite, for example, which is found in more than 15% of the registered fractures in KFM05A, occurs consistently as extremely thin coatings or impurities in other fracture minerals.

4.5 Nonconformities

A large amount of the fractures intersected by KFM05A are sealed by laumontite (Ca-zeolite). These fractures occur as both broken and unbroken, but dehydration of laumontite tends produce volumetrical changes, and the sealing will eventually crackle and break the drill core. Thus, all laumontite-bearing fractures suspected to have been sealed originally are registered as unbroken.

Some fracture filling minerals are more conspicuous than other. For example, the distinct red tinting shown by sub-microscopic hematite reveals extremely low concentrations of the mineral. Also the use of diluted hydrochloric acid for identification of calcite makes it possible to detect amounts that are macroscopically invisible. The amount of fractures filled with other less conspicuous minerals may, on the other hand, be underestimated. The most aggravating example is adularia, a low-temperature variety of K-feldspar. A recent study of fracture fillings from the previous cored boreholes in the area by /Sandström et al. 2004/ has shown that adularia, and to some extent albite, are considerably more common than expected from the Boremap data. About 1.5% of the registered fractures in KFM05A are inferred to contain K-feldspar. This number is, therefore, probably far to low. Some of the light greenish mineral mapped as prehnite is likely to be adularia. Another important fracture group that was found to contain adularia is the thin, hematite-bearing fractures, which are frequently mapped in the lower part of KFM05A.

As in previous cored boreholes, the mapping was locally hampered by suspended drill cuttings and the occurrence of brownish black coatings on the borehole walls. The gentle plunge of the borehole has even led to an accumulation of drill cuttings that obscures the borehole wall completely in the length interval 719.4–720.7 m. However, the amount of dark coating is generally less than in previous boreholes. This coating phenomenon is obviously drill induced, and the explanation proposed by /Askling and Odén, 2004/ is that the coatings originate from metal fragments abraded from the drill pipes.

Core loss has been registered at the following three length intervals: 633.26–633.46 m, 635.63–635.66 m and 636.00–636.13 m.

5 Results

5.1 Core lithology

Similar to the other deep boreholes located in the tectonic lens /rock domain RFM029; cf SKB, 2004/, KFM05A is dominated by a metagranite (rock code 101057) with a tendency to be slightly granodioritic. However, in addition to the typical, medium-grained variety, found elsewhere in the area, KFM05A includes a second, fine- to finely medium-grained variety. The two facies are separated by a sharp, intrusive contact with an orientation of 163°/56°, at a borehole length of 285.8 m. The fine- to finely medium-grained type occurs in the upper part of the borehole, west of this contact. Other rock types that form continuous occurrences of volumetric importance are a fine to finely medium-grained metagranitoid (rock code 101051) of granodioritic to tonalitic composition in the length interval 676–720 m and a heterogeneous mixture of amphibolite (rock code 102017) and fine-grained material of quartz dioritic composition (rock code 1038) in the interval 349–362 m. Additional rock units within the borehole, none exceeding a few metres in length, include various amphibolites, felsic to intermediate rocks of inferred volcanic origin and minor dykes or veins of pegmatite, aplite and leucogranite. Except for some late veins or dykes, all rocks have experienced Svecofennian metamorphism under amphibolite facies conditions.

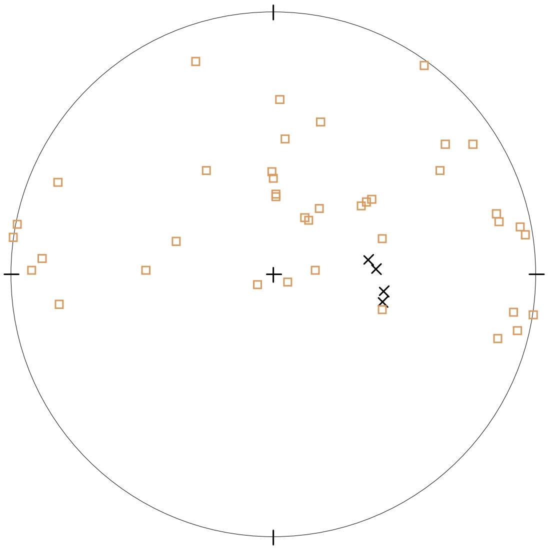
The medium-grained meta-granite (-granodiorite) (rock code 101057) below 285.8 m length of KFM05A is closely similar to the variety found in the other cored boreholes located in the tectonic lens /Petersson and Wängnerud, 2003; Berglund et al. 2004; Petersson et al. 2003a, 2003b, 2004a/. The fine- to finely medium-grained variety, on the other hand, has neither been distinguished in outcrops visited during the bedrock-mapping /Bergman et al. 2004/ nor in previous boreholes. Except for the finer grain-size, it appears to be texturally and compositionally identical to the predominant facies. Together, these two varieties comprise almost 80% of the mapped interval. The colour of the rock varieties ranges from greyish red to grey, though completely grey varieties, lacking the reddish tint, are sparse and typically restricted to contact zones with amphibolites. Minor sections variably speckled by fine-grained, whitish plagioclase occur sporadically throughout the borehole. Microscopic examination of similar rocks from KFM01A and KFM03A suggests that the feature is a result of retrograde sericitisation /Petersson et al. 2004b/.

Fine- to finely medium-grained, typically equigranular metagranitoids (rock code 101051) occupy 5.0% of the mapped interval. Except for a minor occurrence at 107.3–107.9 m, they are all found in the lower half of the borehole. More than 80% of the fine- to finely medium-grained material is restricted to the abovementioned intrusive, which extends from 676 to 720 m depth. Interestingly, this intrusive shows gradual contacts towards the surrounding, medium-grained metagranite (101057), and it is often difficult to separate the two rocks from each other. This relationship, indicating more or less coeval crystallisation, is in good agreement with existing U–Pb data /cf Page et al. 2004/. Other occurrences of fine- to finely medium-grained metagranitoids range up to a few metres in width, and show generally sharp, intrusive contacts of varying orientation (Figure 5-1) towards the wall rock. Some of them, including the major occurrence at 676–720 m, are locally somewhat porphyritic, with scattered K-feldspar megacrysts up to 2.5 cm in length. A majority of the rocks in this group are inferred to be granodioritic or tonalitic in composition /also supported by their anomalously high silica density; Thunehed and Keisu, 2004/, with about 10–20 vol.% ferromagnesian phases dominated by biotite. Significant amounts of garnet have also been identified locally in the major occurrence at 676–720 m.

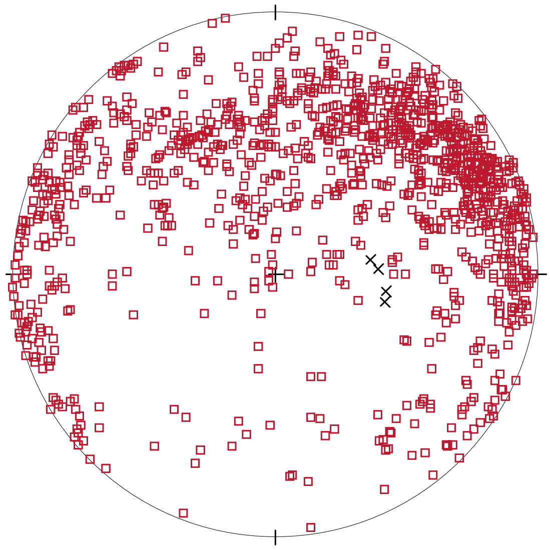
Dykes, veins and segregations of pegmatite, pegmatitic granite, aplite and leucogranitic material are frequent throughout the borehole, and the rock group occupy slightly more than 9% of the mapped interval. Most occurrences are some decimetre or less, but several pegmatites/pegmatitic granites reach up to a few metres in width. The orientations of these occurrences are highly variable, though the majority are more or less parallel with the tectonic foliation (Figure 5-1). The pegmatitic granites are generally texturally heterogeneous, often with a highly variable grain-size, and some occurrences include intervals of finely medium-grained, equigranular granite. Rather coarse magnetite, and subordinately hematite, has been identified in some pegmatites. Despite the textural variability and temporal span within this unit, most of these rocks were grouped as "pegmatite, pegmatitic granite" (rock code 101061). Rocks not included in the group are dyke-like occurrences of fine- to finely medium-grained, equigranular leucogranites (rock code 111058) and aplites. Together, these rocks constitute about one eighth of the rock group. Some of the leucogranites are highly reminiscent of the more granitic varieties of the fine- to finely medium-grained metagranitoids discussed above. A distinctive criterion apart from their late-tectonic character is, however, their anomalously high natural gamma radiation /cf Thunehed and Keisu, 2004/. The aplites, on the other hand, have been separated into two types on the basis of their tectonic character. Those that show a distinct foliation were mapped as "aplitic metagranite" (rock code 101058), whereas one, more massive occurrence at 977.18–977.27 m was registered as "aplite" (rock code 1062). Quartz-dominated segregations or veins were coded as 8021.

Amphibolites (rock code 102017) and related rocks occupy 5.5% of the cored interval in KFM04A. All extensions and contacts are more or less parallel with the tectonic foliation (Figure 5-1). Included in this group is the abovementioned heterogeneous mixture of amphibolite and fine-grained material of quartz dioritic composition (rock code 1038) in the interval 349–362 m. It appears that this fine-grained facies intrudes the amphibolite. Other occurrences of dioritic to quartz dioritic composition are restricted to three minor length intervals. The more typical amphibolites are fine grained, equigranular with a large proportion of biotite. A second, hornblende glomeroporphyric variety is also rather common throughout the borehole. None of these two amphibolite varieties form occurrences that exceed a few metres in core-length, and some are surrounded by up to 1 dm wide rims of leucogranitic material. One decimetre-wide amphibolite at 487.48–487.56 m was found to contain garnet.

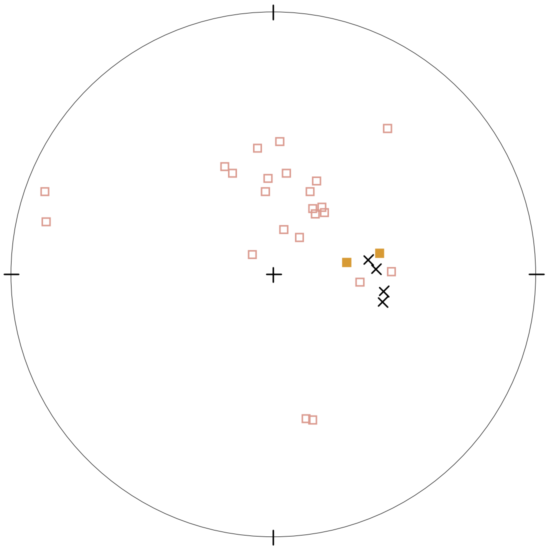
Some minor occurrences of a fine-grained, felsic to intermediate rock of inferred volcanic origin (rock code 103076) occur in the length interval 506–583 m. None of the occurrences exceed a few metres in core-length, though the majority are less than two decimetres. The rock is equigranular, dark grey in colour and all contacts are parallel with the tectonic foliation (Figure 5-1). Occurrences in the uppermost part of the length interval exhibit generally compositional banding. Apart from this banding and the grain-size, there are no textural or structural macroscopic features that unambiguously point towards a volcanic origin of the rock.



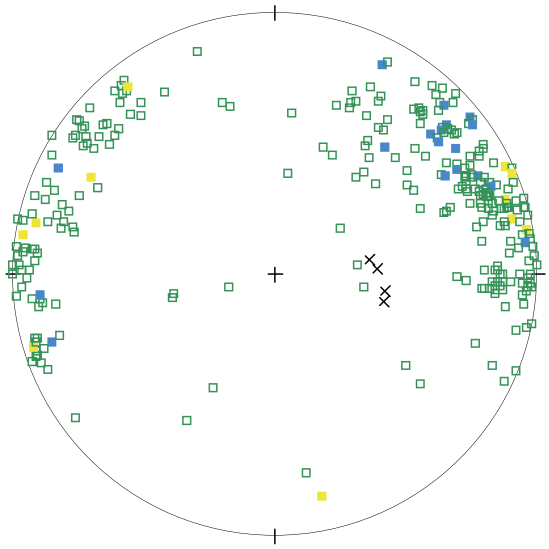
Fine- to finely medium-grained metagranitoids (101051).



Pegmatite and pegmatitic granite (101061).



Aplite (1062) **orange**, fine- to medium-grained granite (111058) **pink.**



Amphibolite (102017) **green**, quartz diorite (1038) **blue**, felsic to intermediate metavolcanic rock (103076) **yellow.**

Figure 5-1. *Lower hemisphere, equal-area stereographic projections showing the poles to the upper and lower contacts of various 'rock occurrences' and 'rock types' mapped in borehole KFM05A. The orientation of the borehole at 250, 500, 750 and 1,000 m depth is marked by ×.*

5.2 Ductile structures

The rocks in KFM05A is characterised by composite L-S fabrics, with a general predominance of planar mineral fabrics (i.e. foliation) in the fine- to finely medium-grained metagranite variety, and a predominance of linear mineral fabrics in the more medium-grained metagranite variety found below 285.8 m length. However, the relative intensity of the two components is locally highly variable. The planar fabric in the fine- to finely medium-grained metagranite variety is generally distinct, and hence, mapped as "medium" in intensity, whereas the medium-grained variety, along with the other rock units in KFM05A (e.g. 101051, 101061, 111058, 102017 and 103076), normally exhibit a weak to faint mineral fabric. It must, however, be emphasized that it often is difficult to distinguish tectonic fabric visually in the pegmatites and some of the fine-grained mafic rocks, but the fact that these appear massive does not necessarily mean that they actually are post-kinematic. Similar to the structures at the surface /cf Figure 5-11g in Stephens et al. 2003/, the foliation tends to fall along a π-circle, the pole to which plunges moderately towards SE (Figure 5-2). None of the linear fabrics have been possible to register, though the general impression is that they are gently to moderately dipping.

Fifteen zones of more intense ductile deformation, none exceeding 4 dm in width, occur down to 540 m in the borehole. The rock in these zones seems to consist of a highly deformed and grain-sized reduced variety of the metagranite (101057). Some of the zones are intimately associated with occurrences of amphibolite. Also three minor zones of brittle-ductile deformation have been registered in the length interval 139–149 m. All ductile and brittle-ductile shear zones in the borehole are more or less parallel with the local tectonic foliation (Figure 5-2).

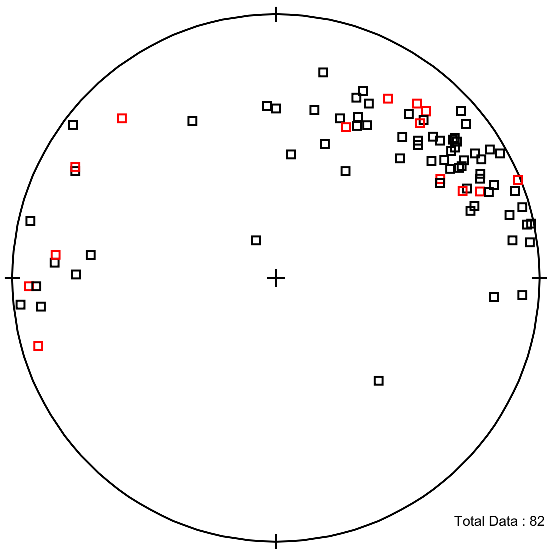


Figure 5-2. *Lower hemisphere, equal-area stereographic projection showing poles to ductile foliation planes (black squares) and all ductile and brittle-ductile shear zones (red squares) mapped as "structural features" in borehole KFM05A.*

5.3 Alteration

The most common alteration encountered in KFM05A is varying degrees of oxidation or red discolouration of feldspars by sub-microscopic hematite, which has affected about 10% of the cored interval. It is almost always associated with more intensely fractured intervals. A continuous interval of weak oxidation occurs in the uppermost 14 m of the mapped interval, down to about 116 m. Elsewhere, individual occurrences are typically less than a few metres in width.

Other types of alterations within KFM05A include chloritization of amphibolites and two minor intervals of epidotization and sericitization at 171.68–171.73 and 627.96–628.02, respectively.

5.4 Fractures

5.4.1 Fracture frequencies and orientations

Excluding crush zones and sealed networks, the total number of broken (parting the core) and unbroken (not parting the core) fractures registered within the mapped interval of borehole KFM05A amounts to 2835, i.e. about 3.2 fractures/m. This value is rather high as compared to the fracture frequencies yielded in the previous deep cored boreholes within the tectonic lens, which range from 1.7 to 2.4 fractures per metre /Petersson and Wängnerud, 2003; Petersson et al. 2003a and 2003b/. The obvious reason for this value is a conspicuous concentration of unbroken, often thin (<< 0.5 mm in width) fractures in the length intervals 588–796 and 878–1,000 m (Appendix 1). The frequencies of fractures mapped as open (aperture > 0) in these intervals are, on the other hand, merely 0.9 and 0.7 per metre, respectively, i.e. identical to that of the entire mapped interval, which amounts to about 0.7 fractures per metre. Similar to borehole KFM01A and KFM02A, there is also a generally increased fracture frequency in the upper 250 m of the borehole. An additional interval with markedly increased fracture frequency occurs at 416–436 m. Throughout all these intervals, the frequency of open and sealed fractures varies rather coherently, with an increased number of open fractures in intervals with concentrations of sealed fractures (Appendix 1). However, only about one forth of all fractures registered in KFM05A are inferred to be open (fracture aperture > 0). An interval that differs from the general pattern by a drastic increase in the frequency of open fractures, but no concomitant increase in the concentration of sealed fractures, occurs at 102–114 m.

It is reasonable to expect that mechanical discontinuities, such as lithological contacts, should be the locus of fracture formation. For this reason we have noted the proportion of fractured amphibolite contacts. About 25% of the contacts in the mapped interval of KFM05A are fractured, and about 10% of these fractures are sealed. This can be compared with KFM02A, KFM03A and KFM04A, in which 30–35% of the contacts are fractured /Petersson et al. 2003a, 2003b and 2004b/.

The fracture orientations vary considerably throughout KFM05A, though the stereographic projections in Figure 5-3 reveal at least two, possibly three distinct fracture sets. The most distinct set, also found in the other four deep boreholes in the area /cf Petersson and Wängnerud, 2003; Petersson et al. 2003a, 2003b and 2004a/, consists of vertical to sub-vertical fractures with NE-SW strike. Fractures that belong to this set are found throughout the borehole, though their amount increases dramatically below 580 m (Figure 5-4). Most of these fractures are inferred to be sealed, and a considerable proportion of the fracture orientations registered in the sealed networks fall in this group. Another well-defined group, most conspicuous in the upper 230 m of the borehole, consists of near horizontal to gently dipping fractures (Figure 5-4). A majority of these fractures are inferred to be open and a few, especially in the interval between 102 and 114 m, have apertures that exceed 1 cm in width. Three minor crush zones found at 106.88–106.95 m, 109.10–109.35 m (see Figure 5-5) and 248.93–248.99 m in the borehole belong to this group. A third, less well-defined set, consist of vertical to sub-vertical fractures with NNW-SSE strike; i.e. roughly parallel with the tectonic foliation in some intervals (cf Figure 5-2). The set is mainly found in the interval between about 300 and 800 m, and includes fractures inferred to be both sealed and open.

Twelve breccia zones and 105 sealed network have been registered in KFM05A. However, the distinction between breccia and sealed network is not straight forward, but normally zones with only minor rotation of individual rock fragments has been mapped as sealed network. Breccias dominated by matrix have been mapped as "breccia" (rock code 6005), whereas the coding of fragment-dominated zones is defined by the fragment lithology. In the latter case, brecciation is indicated by the rock structure. Most breccias and sealed networks belong to the NE-SW striking fracture group (Figure 5-6). Two short and highly fractured intervals with 8 and 14 registered sealed networks occur at about 610.8–613.3 and 713.6–720.4 m, respectively. Except for the breccia zones, fractures with measurable displacements, indicating that they have been initiated or reactivated as shear fractures, are few.

Inferred core discing occurs sporadically in a few intervals along the drill core (147.43–147.46 m, 152,10–152.11 m, 201.13–201.19 m, 348.72–348.74 m, 545.02–545.04 m, 593.72–593.79 m, 611.99–613.51 m, 635.48–635.50 m, 857.76–857.84 m, 894.97–895.05 m and 978.46–979.00 m). Some intervals include also initial core discing that not actually breaks the core. None of the intervals exceed 5 dm in width, and the typical dimension of individual discs range between 1 and 3 cm. The fractures are all planar to slightly saddle-shaped.

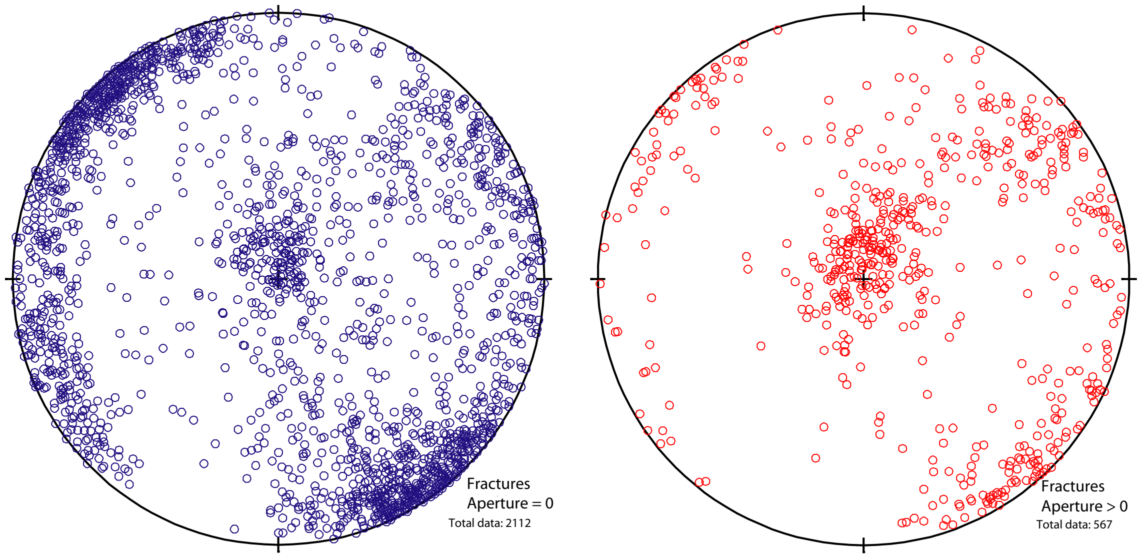


Figure 5-3. *Lower hemisphere, equal-area stereographic projections showing the poles to all sealed (blue circles) and open (red circles) fractures registered in borehole KFM05A (i.e. those fractures found in the length interval 102–1,000 m).*

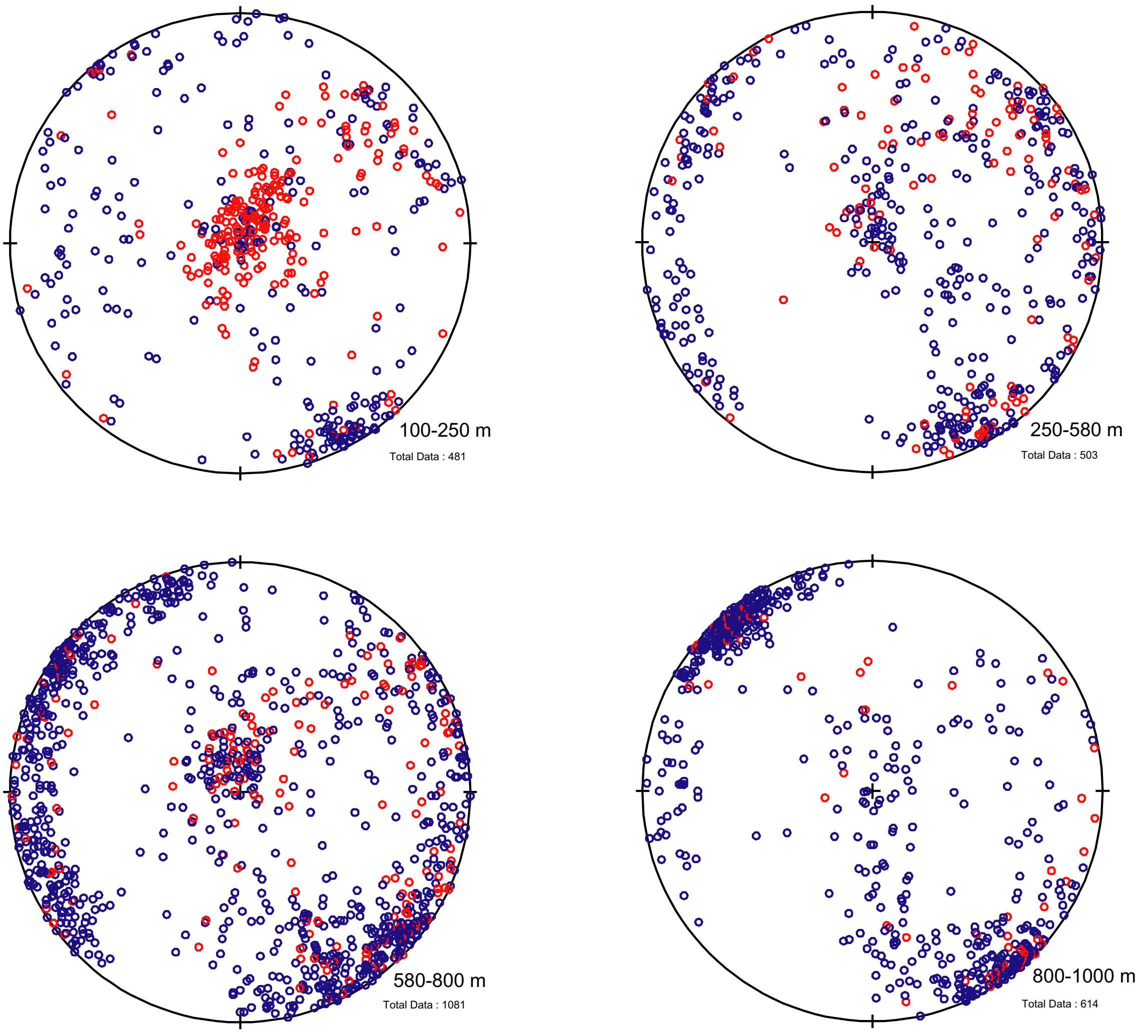


Figure 5-4. *Lower hemisphere, equal-area stereographic projections showing the poles to sealed (blue circles) and open (red circles) fractures in four length intervals of borehole KFM05A: 102–250 m, 250–580 m, 580–800 m and 800–1,000 m.*

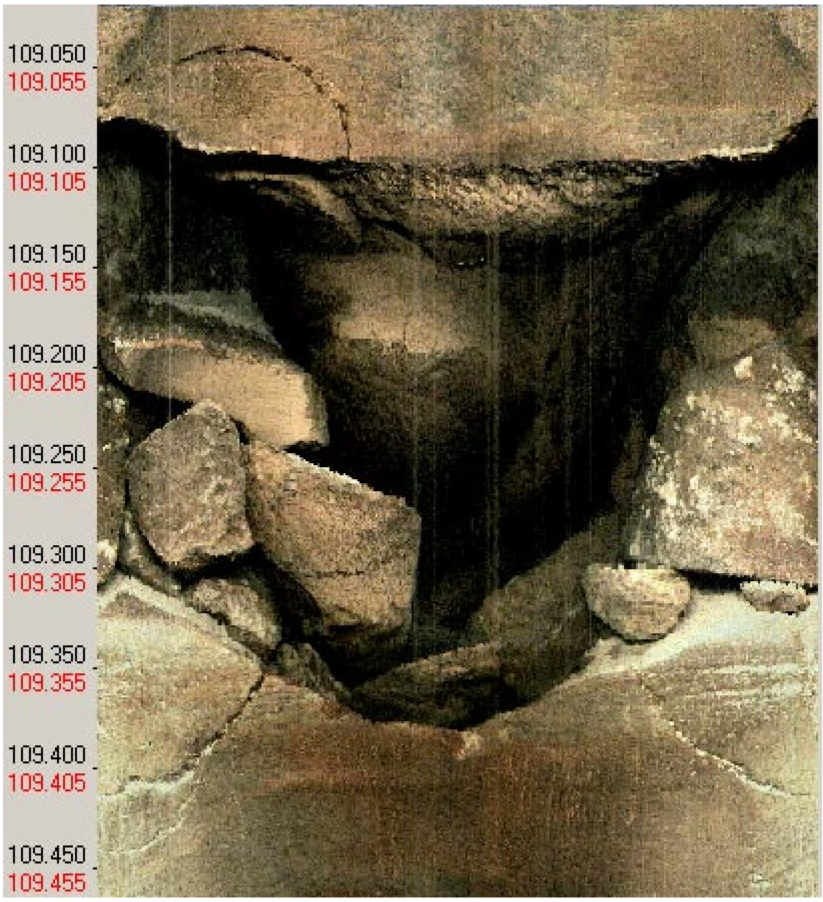


Figure 5-5. *BIPS-image from the length interval 109.00–109.47 m of borehole KFM05A, showing the widest mapped crush zone.*

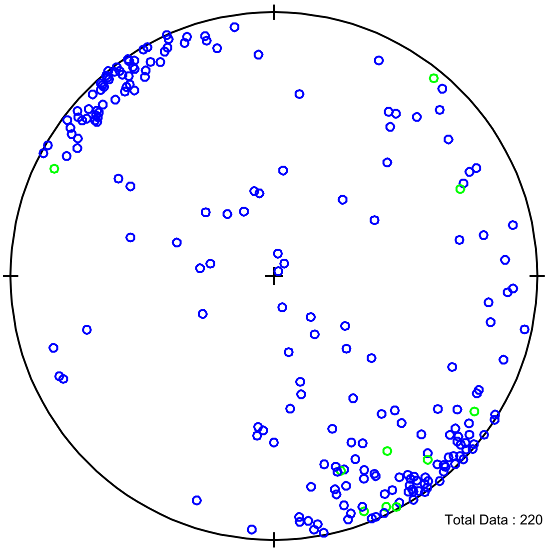


Figure 5-6. *Lower hemisphere, equal-area stereographic projections showing the poles to prevailing fracture orientations in all sealed networks (blue circles) and the mean orientation of upper and lower contacts of each breccia zone (green circles) registered in KFM05A.*

5.4.2 Fracture mineralogy

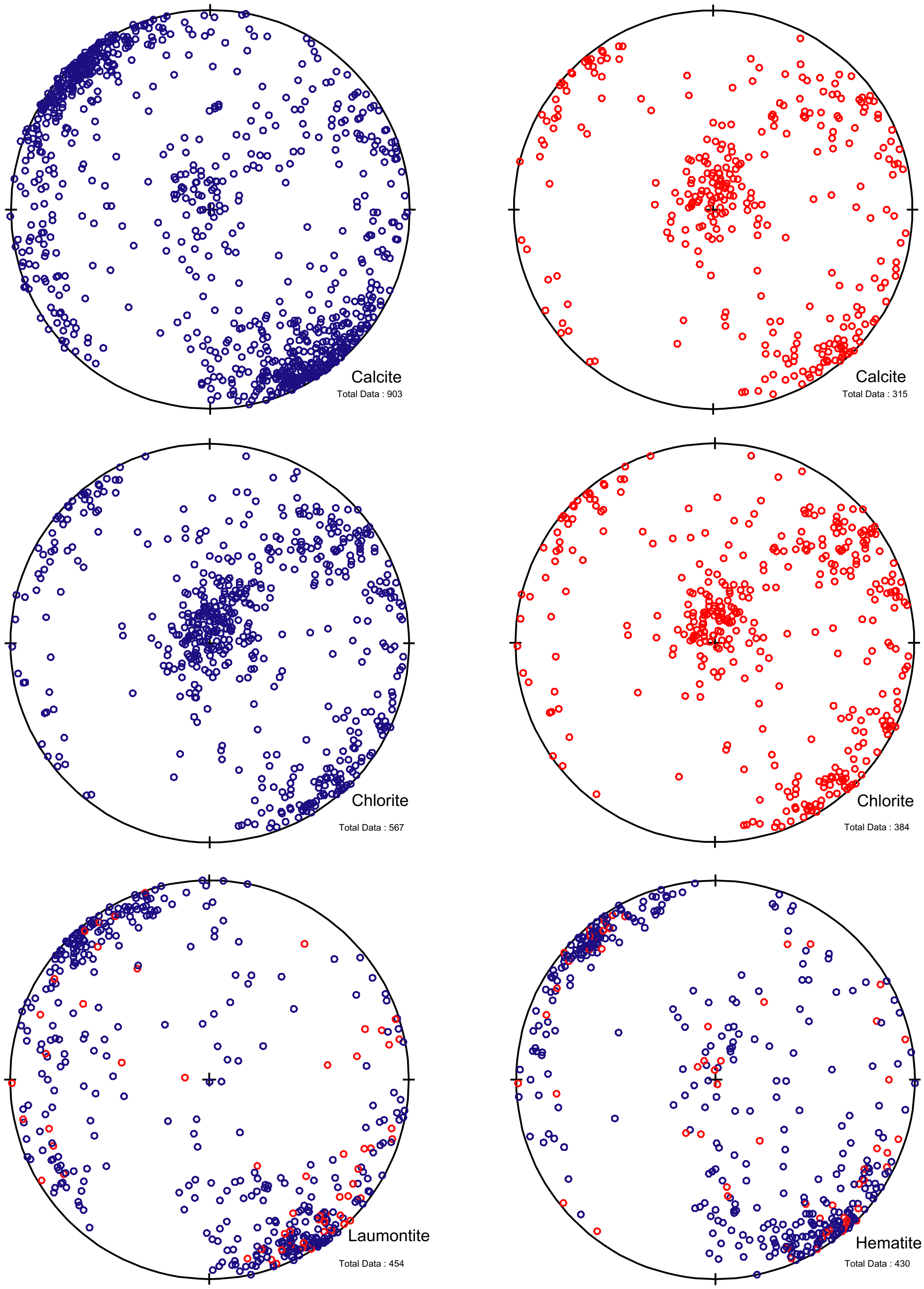
Chlorite and/or calcite are found in more than half of the total number of fractures in the mapped interval of KFM05A. These minerals are found in all abovementioned fracture groups, but with an overrepresentation of chlorite in the near horizontal fractures and calcite in the NE-SW striking set (Figure 5-7). In this context, it is worth to mention that two ca 4 cm wide, calcite-dominated veins, recorded as a "carbonate-dominated hydrothermal vein" (rock code 8022), occurs at 702.72–702.76 and 774.55–774.58 m length. Other infilling minerals, in order of decreasing abundance, include laumontite, sub-microscopic hematite, undifferentiated clay minerals, quartz, prehnite, pyrite, epidote, feldspars, Fe-hydroxide, sulphides and zeolite. In addition, there are a number of fractures with unknown mineral filling. XRD analyses of similar material from the previously mapped cored boreholes in the area have revealed that most such filling are mineral mixtures, or in some cases, feldspars, apophyllite or analcime /Sandström et al. 2004/. There are also 114 fractures that are virtually free from visible mineral coatings. These are mostly open, and the majority belong to the sub-horizontal set (Figure 5-7).

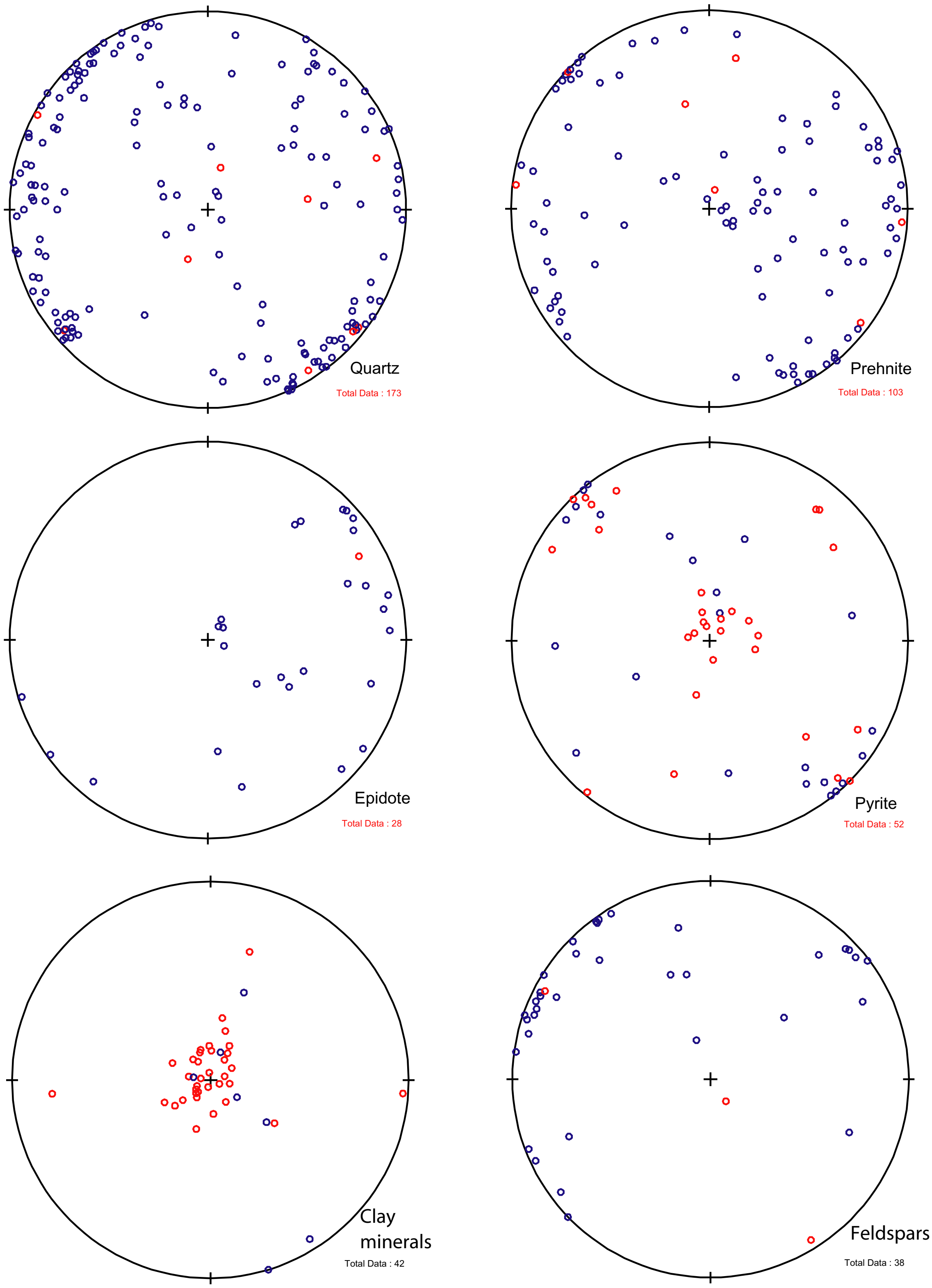
The various clay minerals are more or less restricted to open fractures of the flat lying sets in the upper half of the borehole. Also asphalt and Fe-hydroxide are limited to this set, but down to a borehole length of only 112.9 and 127.0, respectively (Figure 5-7). Another interesting filling found in these open flat lying fractures down to a maximum length of 135.9 m, is a typically millimetre-wide filling classified as incohesive breccia. Preliminary analysis by Eva-Lena Tullborg (Terralogica AB) has shown that is consists of fine-grained, angular rock and crystal fragments in a crystalline matrix dominated by quartz and clay minerals. These rocks may in part represent an inchoesive cataclastite holding more than 30% fragments /cf Passchier and Trouw, 1996, p 98–99/. Thus, the rock code used in Boremap is 'cataclastic rock' (rock code 8003).

All other minerals, as well as the presence of oxidized walls, are preferentially associated with sealed fractures (Figure 5-7). A typical mineral assemblage is laumontite + calcite ± chlorite ± hematite ± pyrite. Laumontite tends to contract, and eventually crackle in the drill core. Thus, some laumontite-bearing fractures that are broken in the drill core may in fact represent originally unbroken fractures. As in the other deep, cored boreholes in the area, the laumontite-dominated assemblage is mainly found in sealed fractures of the NE-SW trending set. This is also the assemblage most commonly found in the breccias and sealed networks. Hematite occurs exclusively as sub-microscopic staining of various silicates, mainly laumontite and adularia (mapped as K-feldspar).

The orientation of fractures filled by quartz, prehnite and epidote are more variable, though quartz shows a slight tendency to occur in the steeply dipping NE-SW trending fractures (Figure 5-7). As pointed out previously, some of the light greenish mineral mapped as prehnite is likely to be adularia.

Fractures sealed by the laumontite-dominated assemblage, hematite, prehnite and epidote typically exhibit oxidized walls. A number of very thin (<<1 mm), sealed fractures are typically revealed only by their oxidized walls. Several of these thin fractures have been sealed by a mineral inferred to be hematite, but it might well be hematite-stained laumontite or adularia.


Calcite
Total Data : 903
Calcite
Total Data : 315
Chlorite
Total Data : 567
Chlorite
Total Data : 384
Laumontite
Total Data : 454
Hematite
Total Data : 430


Quartz
Total Data : 173
Prehnite
Total Data : 103
Epidote
Total Data : 28
Pyrite
Total Data : 52
Clay minerals
Total Data : 42
Feldspars
Total Data : 38

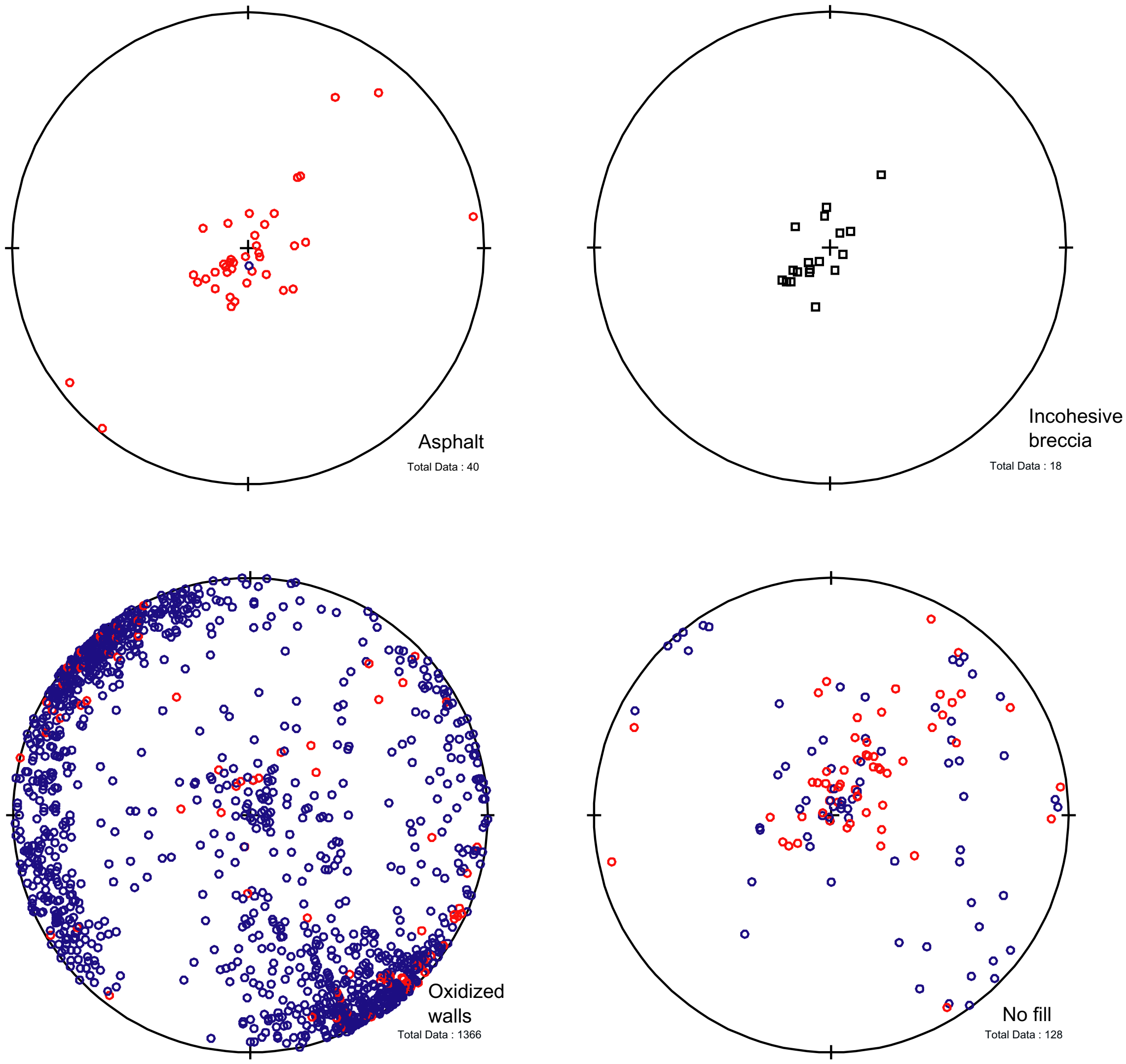


Figure 5-7. *Lower hemisphere, equal-area stereographic projections showing the poles to sealed (blue circles) and open (red circles) fractures filled with: calcite, chlorite, laumontite, hematite, quartz, prehnite, epidote, pyrite, clay minerals, feldspars, asphalt and possible clastic, and incohesive breccia. Also shown are those that are free from visible filling and those surrounded by oxidized walls.*

6 Summary and discussions

The lithology of KFM05A generally corresponds well with what might be expected from both the previous deep boreholes /Petersson and Wängnerud, 2003; Berglund et al. 2004; Petersson et al. 2003a, 2003b, 2004a/ and the surface geology in the area /Bergman et al. 2004/. However, the fine- to finely medium-grained facies of the metagranite that occupy the core-drilled interval down to 285.8 m was a surprise. It has neither been found in any of the other boreholes or in any of the investigated outcrops. Another interesting feature is the gradual contacts between the medium-grained metagranite and the fine- to finely medium-grained metagranitoid (rock code 101051) in the length interval 676–720 m. Elsewhere in the area, the fine- to finely medium-grained metagranitoid is clearly intrusive into the metagranite. Existing U–Pb data presented by /Page et al. 2004/ indicate, however, a more or less coeval crystallization; a result now also supported by the contact relationship in KFM05A. Also the ductile structures, often with a predominant linear mineral fabric and a weaker foliation (the poles to which fall along a π-circle), are in close agreement with the surface structural trend in the area /Stephens et al. 2003/.

An important aspect when localizing the second of these boreholes, KFM05A, was to investigate the presence of N-S trending brittle deformation zones below Bolundsfjärden, in the northern part of the test site area. An increased frequency of roughly N-S striking fractures does indeed exist in the length intervals 300–440 and 580–800 m. However, the majority of the fractures registered in these intervals belong to the NE-SW set.

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Appendix 1

WellCAD images

Title LEGEND FOR FORSMARK KFM05A

Site	FORSMARK
Borehole	KFM05A
Plot Date	2005-03-15 22:16:40

ROCKTYPE FORSMARK

- Granite, fine- to medium-grained
- Pegmatite, pegmatitic granite
- Granitoid, metamorphic
- Granite, granodiorite and tonalite, metamorphic, fine- to medium-grained
- Granite, metamorphic, aplitic
- Granite to granodiorite, metamorphic, medium-grained
- Granodiorite, metamorphic
- Tonalite to granodiorite, metamorphic
- Diorite, quarts diorite and gabbro, metamorphic
- Ultramafic rock, metamorphic
- Amphibolite
- Calc-silicate rock (skarn)
- Magnetite mineralization associated with calc-silicate rock (skarn)
- Sulphide mineralization
- Felsic to intermediate volcanic rock, metamorphic
- Mafic volcanic rock, metamorphic
- Sedimentary rock, metamorphic

ROCK ALTERATION

- Oxidized
- Chloritisized
- Epidotisized
- Weathered
- Tectonized
- Sericitisized
- Quartz dissolution
- Silicification
- Argillization
- Albitization
- Carbonatization
- Saussuritization
- Steatitization
- Uralitization
- Laumontitization

MINERAL

- Epidote
- Hematite
- Calcite
- Potash Feldspar
- Chlorite
- Quartz
- Unknown
- Pyrite
- Sulfides
- Clay Minerals
- Laumontite
- Prehnite
- Asphalt
- Iron Hydroxide
- Oxidized Walls

STRUCTURE

- Cataclastic
- Schistose
- Gneissic
- Mylonitic
- Ductile Shear Zone
- Brittle-Ductile Zone
- Veined
- Banded
- Massive
- Foliated
- Brecciated
- Lineated

TEXTURE

- Hornfelsed
- Porphyritic
- Ophitic
- Equigranular
- Augen-Bearing
- Unequigranular
- Metamorphic

GRAINSIZE

- Aphanitic
- Fine-grained
- Fine to medium grained
- Medium to coarse grained
- Coarse-grained
- Medium-grained

STRUCTURE ORIENTATION

- Cataclastic
- Bedded
- Gneissic
- Schistose
- Brittle-Ductile Shear Zone
- Ductile Shear Zone
- Lineated
- Banded
- Veined
- Brecciated
- Foliated
- Mylonitic

ROCK ALTERATION INTENSITY

- No intensity
- Faint
- Weak
- Medium
- Strong

ROUGHNESS

- Planar
- Undulating
- Stepped
- Irregular

SURFACE

- Rough
- Smooth
- Slickensided

CRUSH ALTERATION

- Slightly Altered
- Moderately Altered
- Highly Altered
- Completley Altered
- Gouge
- Fresh

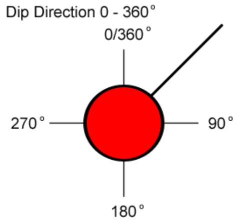
FRACTURE ALTERATION

- Fresh
- Gouge
- Completely Altered
- Highly Altered
- Moderately Altered
- Slightly Altered

FRACTURE DIRECTION

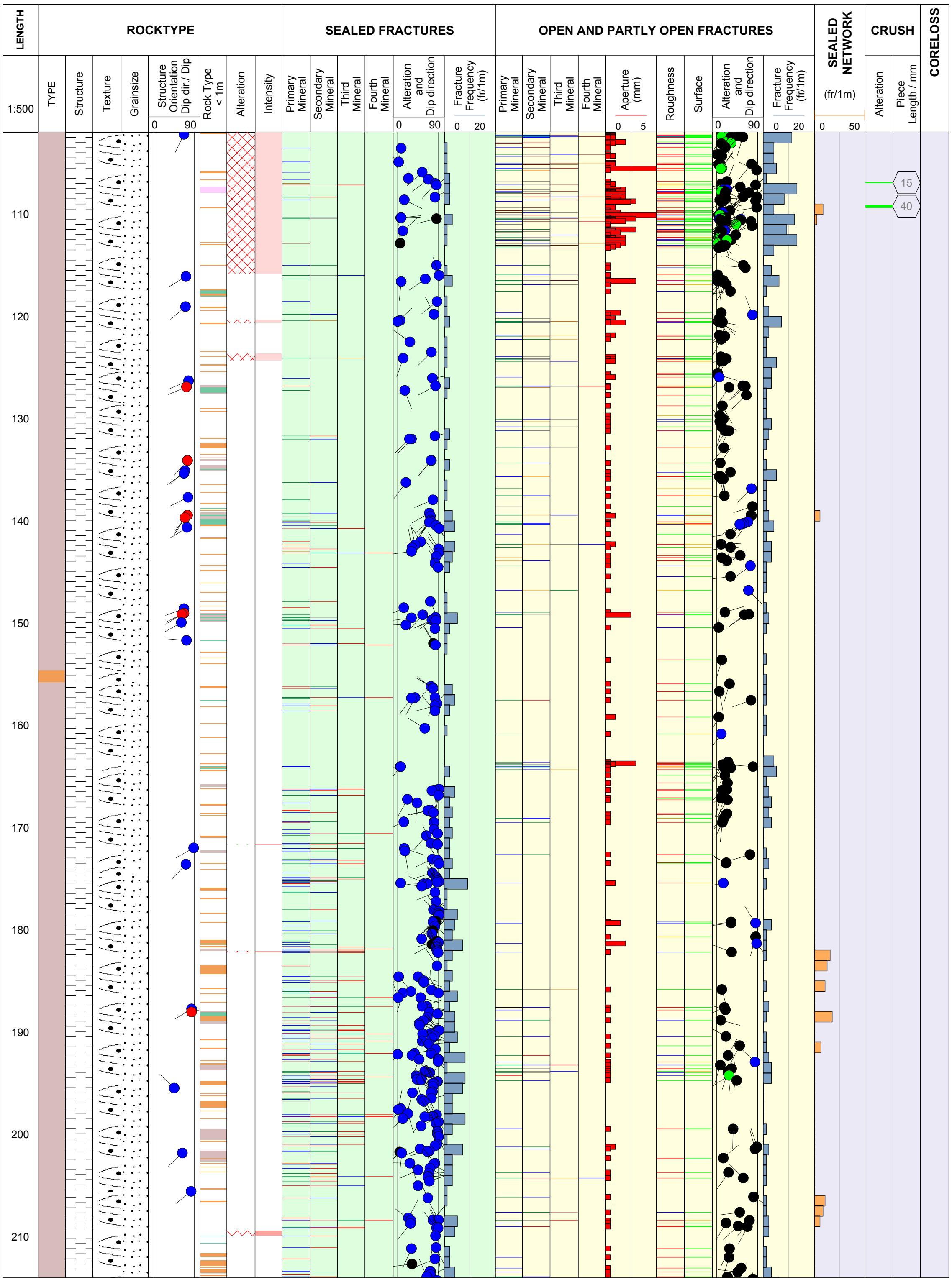
STRUKTURE ORIENTATION

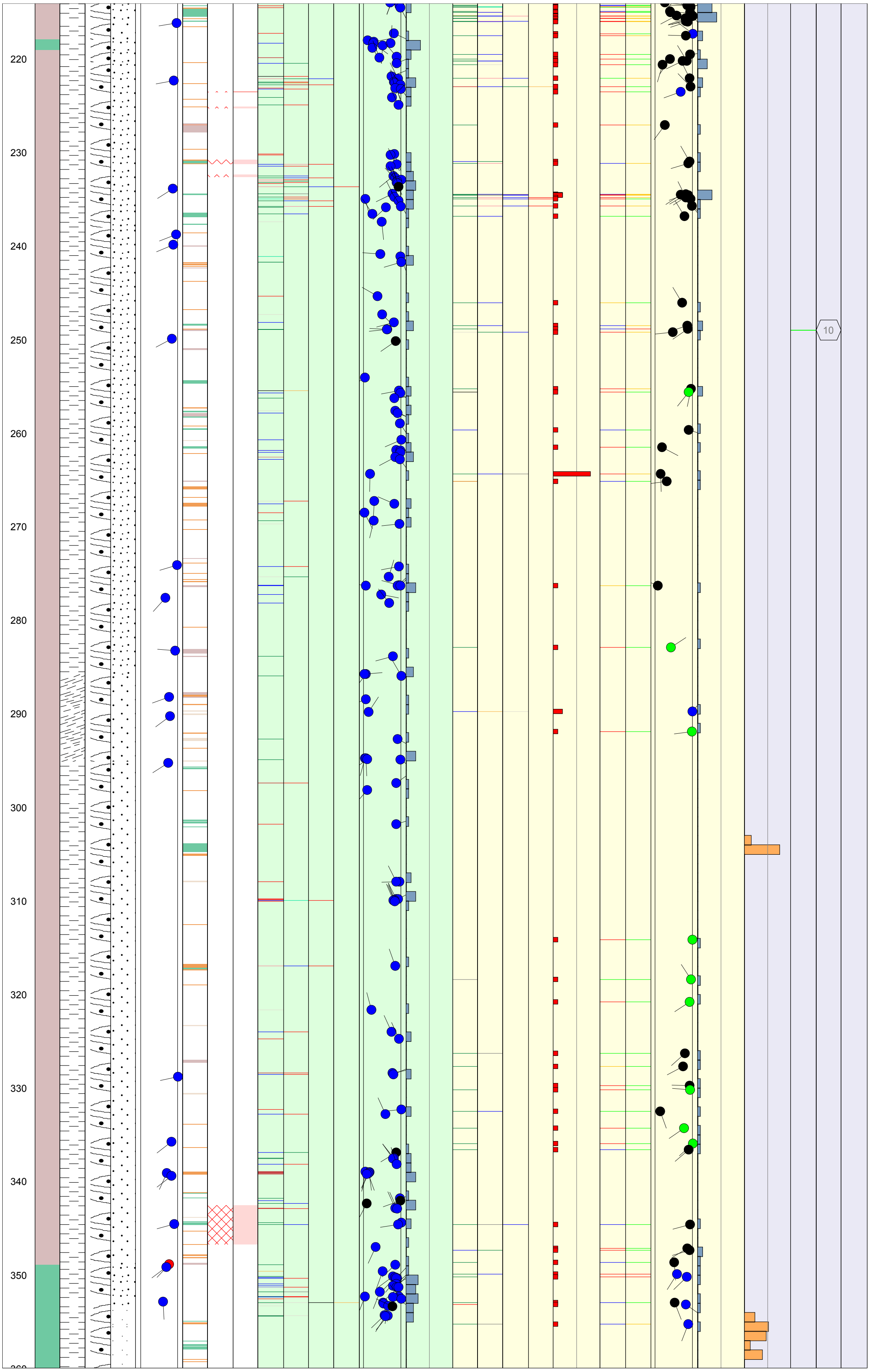
Dip Direction 0 - 360°



Dip 0 - 90°

Title	**GEOLOGY IN KFM05A**		**Appendix:**	
	Site	FORSMARK	**Coordinate System**	RT90-RHB70
	Borehole	KFM05A	**Northing [m]**	6699344.85
	Diameter [mm]	77	**Easting [m]**	1631710.80
	Length [m]	1002.710	**Elevation [m.a.s.l.]**	5.53
	Bearing [°]	80.90	**Drilling Start Date**	2003-11-23 14:30:00
	Inclination [°]	-59.79	**Drilling Stop Date**	2004-05-05 10:00:00
	Date of mapping	2004-05-24 00:00:00	**Plot Date**	2005-01-23 21:53:59
	Rocktype data from	p_rock_XXXXX	**Fracture data from**	p_fract_core

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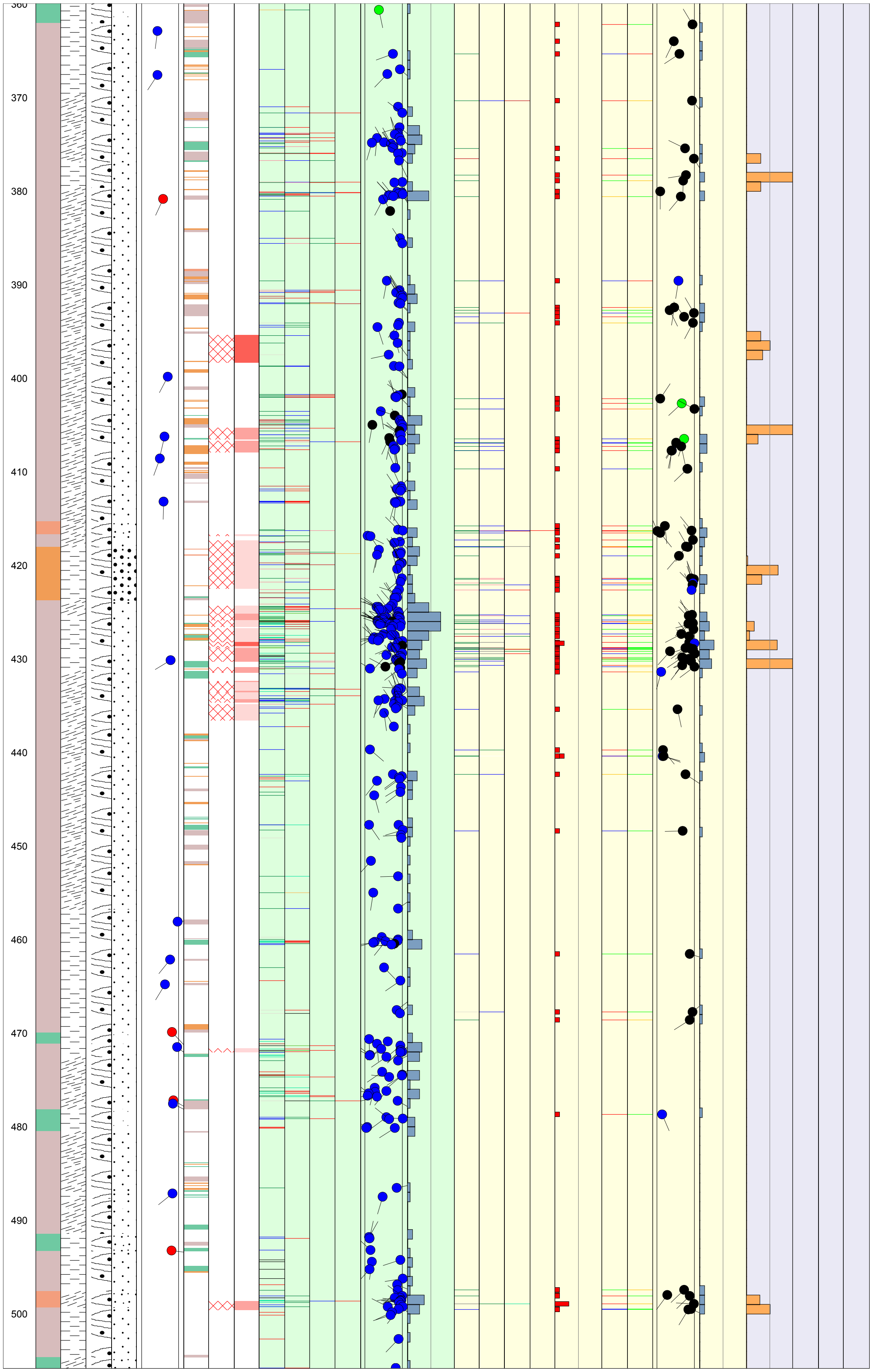
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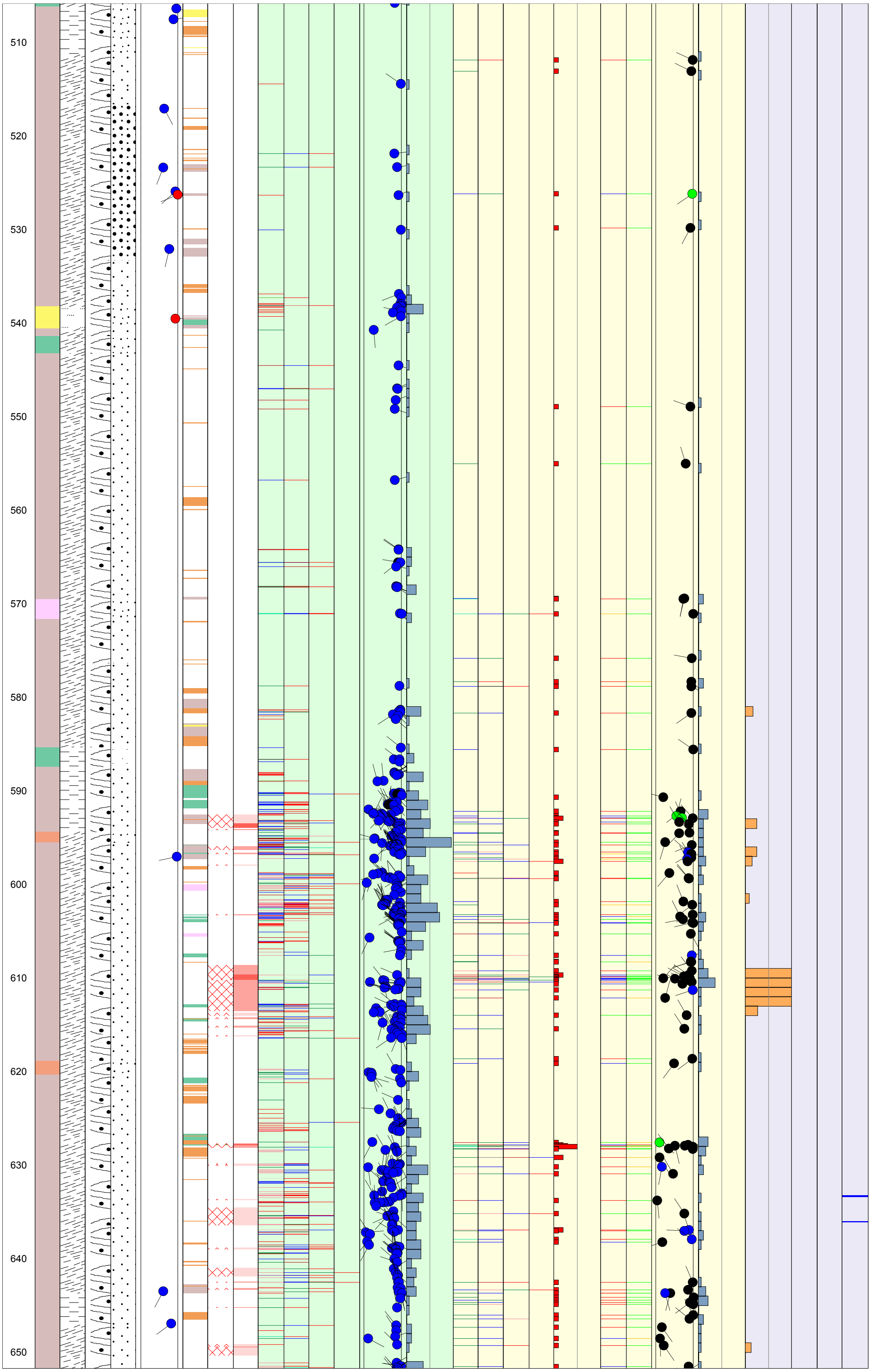
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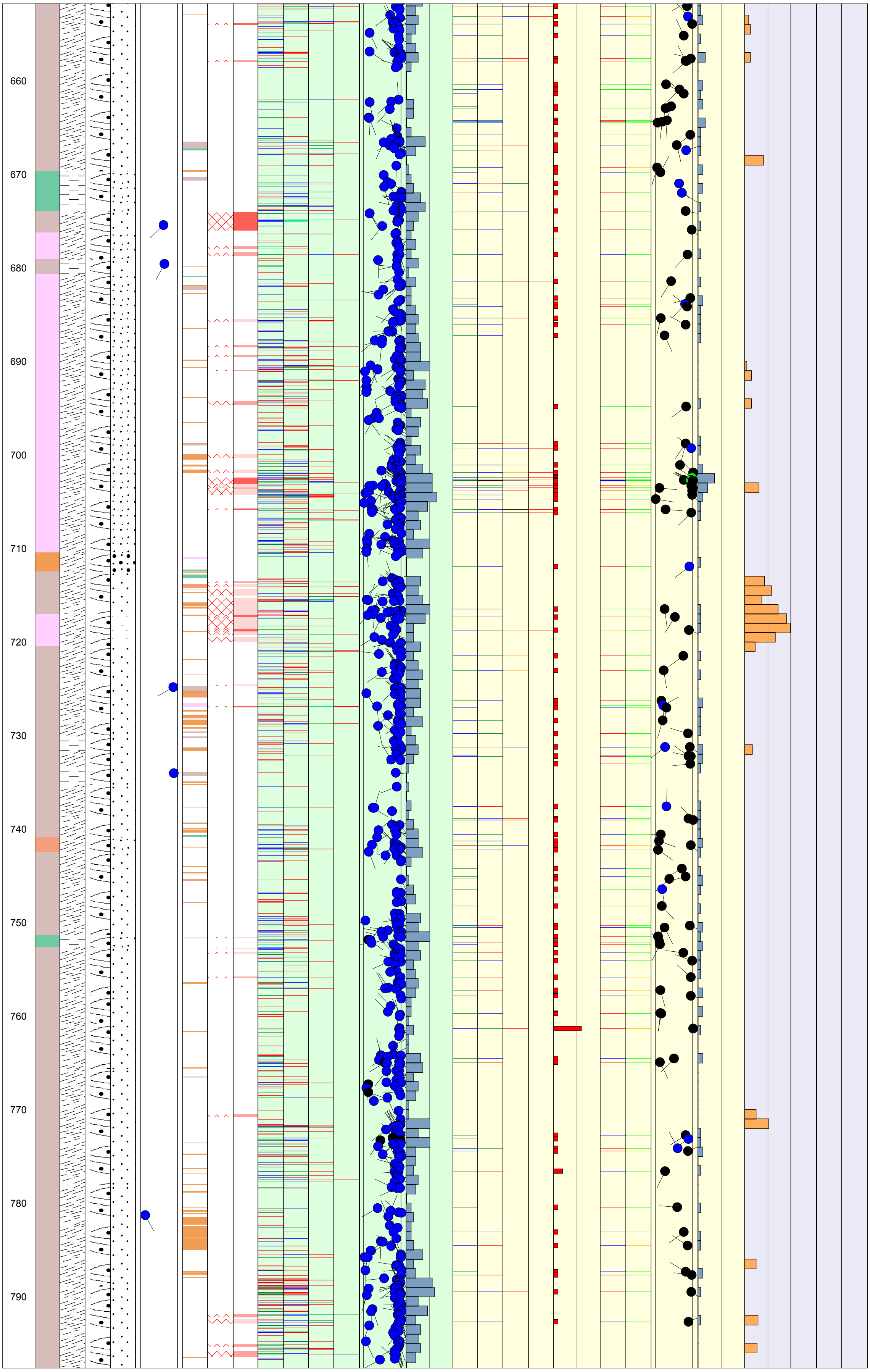
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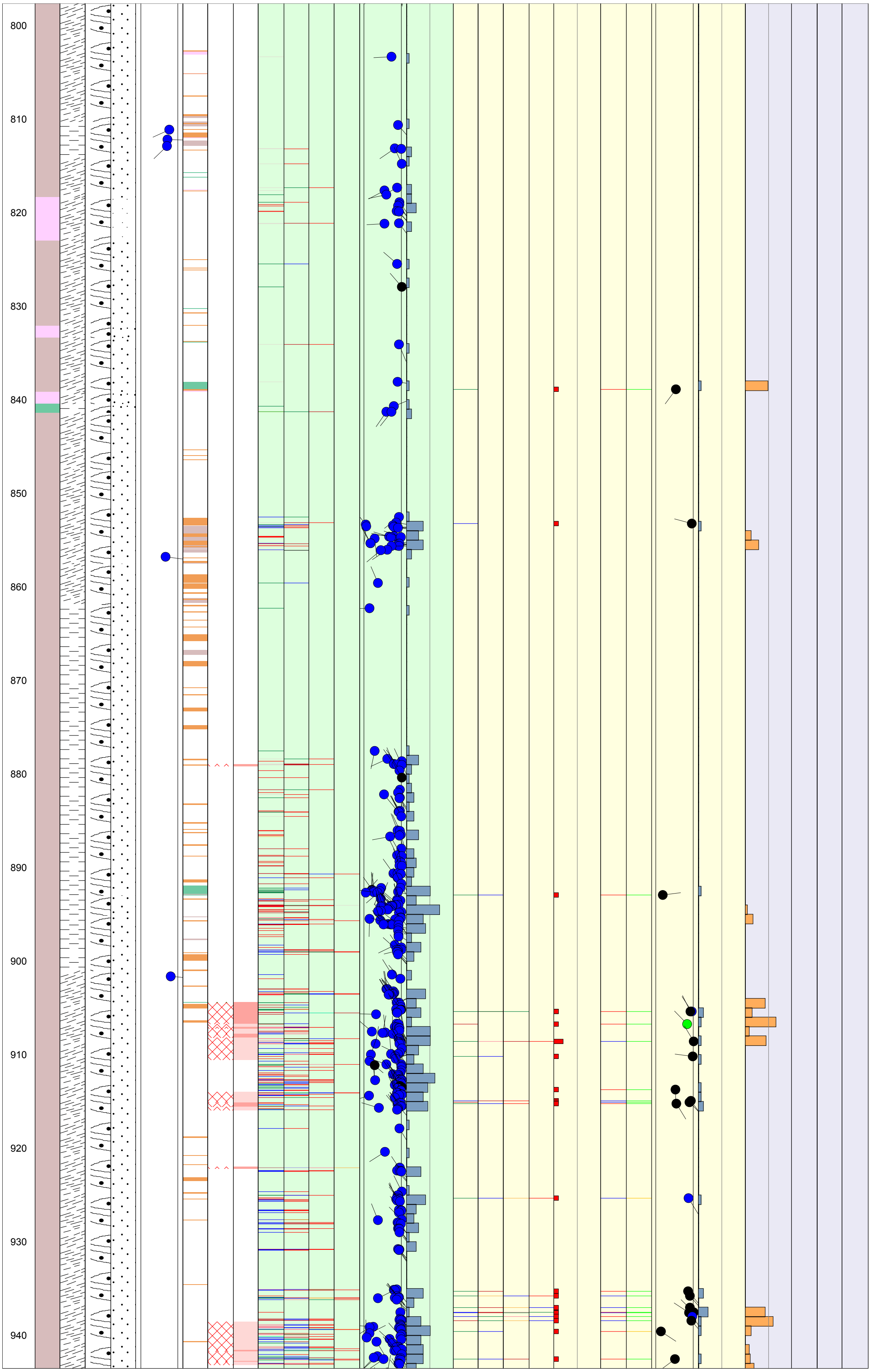
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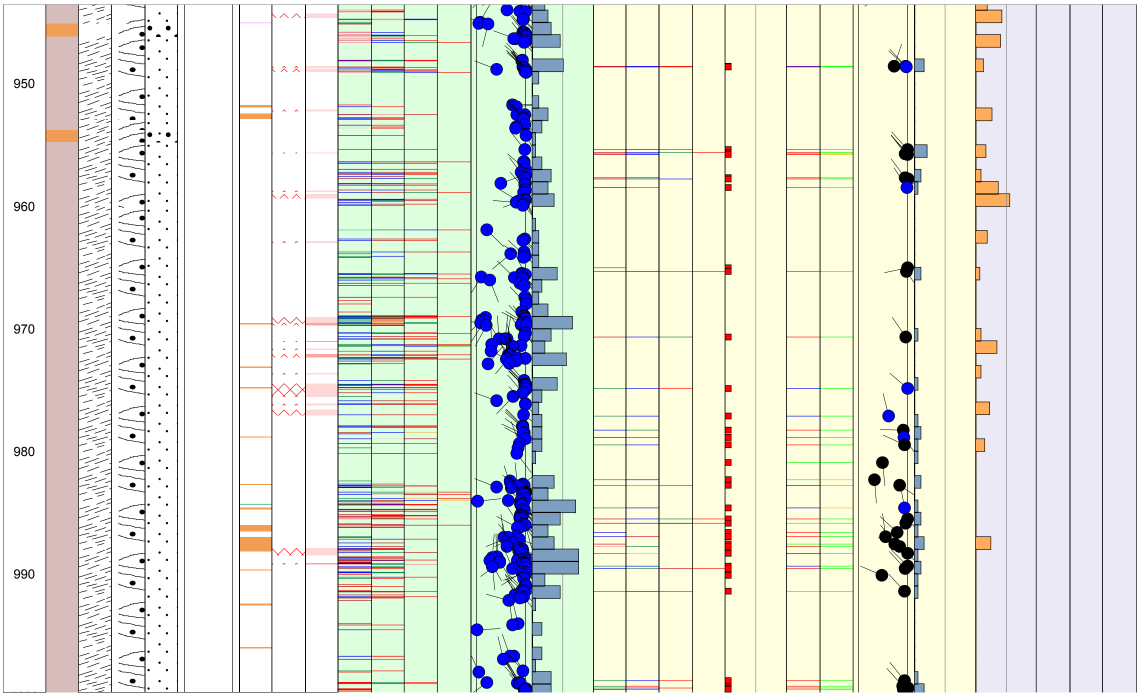
950
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970
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990

Appendix 2

Borehole diameter

Hole Diam T – Drilling: Borehole diameter

KFM05A, 2003-11-25 12:00:00–2004-05-05 10:00:00 (100.350–1,002.710 m).

Sub secup (m)	Sub seclow (m)	Hole diam (m)	Comment
100.350	110.100	0.086	
110.100	1,002.710	0.077	

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Appendix 3

Downhole deviation measurements

Magnetic Acc Dev T – Magnetic accelerometer deviation measurement

KFM05A, 2004-08-25 00:00:00 (0.000–999.000 m).

Bhlen (m)	Magnetic bearing (degrees)	Dip (degrees)	Northing (m)	Easting (m)	Elevation (m)	Locala (m)	Localb (m)	Localc (m)
120.00	81.0	–60.0						
150.00	81.5	–59.5						
180.00	80.1	–59.2						
210.00	82.7	–58.6						
240.00	81.1	–58.2						
270.00	84.4	–57.7						
300.00	83.7	–57.0						
330.00	86.6	–56.4						
360.00	84.6	–56.2						
390.00	86.3	–56.0						
420.00	87.2	–55.9						
450.00	87.1	–55.6						
480.00	88.9	–55.1						
510.00	89.6	–54.8						
540.00	91.1	–54.7						
570.00	92.5	–54.6						
600.00	92.9	–54.6						
630.00	93.6	–54.8						
660.00	104.4	–54.7						
690.00	96.0	–54.6						
720.00	97.3	–54.0						
750.00	99.7	–53.9						
780.00	106.6	–53.6						
810.00	106.0	–53.7						
840.00	100.8	–53.9						
870.00	102.7	–54.1						
900.00	102.9	–54.1						
930.00	107.8	–53.7						
960.00	110.4	–53.3						
990.00	108.1	–53.3						
993.00	108.4	–53.1						
996.00	106.2	–53.1						
999.00	108.4	–53.1						

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Appendix 4

Length reference marks

Reference Mark T – Reference mark in drillhole

KFM05A, 2004-05-17 10:00:00–2004-05-17 14:30:00 (120.000–900.000 m).

Bhlen (m)	Rotation speed (rpm)	Start flow (l/min)	Stop flow (l/min)	Stop pressure (bar)	Cutter time (s)	Trace detectable	Cutter diameter (mm)	Comment
120.00	400.00	600	600	38.0	5	Ja		120.07–120.17
152.00	400.00	600	800	46.0	4	Ja		152.12–152.22
199.00	400.00	600	800	48.0	4	Ja		199.17–199.27
252.00	400.00	350	900	52.0	6	Ja		252.23–252.33
300.00	400.00	500	1,100	52.0	8	Ja		300.30–300.40
352.00	400.00	500	1,100	52.0	4	Ja		352.35–352.45
402.00	400.00	400	1,100	52.0	9	Ja		402.46–402.56
450.00	400.00	550	1,100	52.0	9	Ja		450.49–450.59
501.00	400.00	400	1,100	52.0	9	Nej		
550.00	400.00	400	1,100	52.0	9	Nej		
606.00	400.00	400	1,100	52.0	9	Ja		606.59–606.69
650.00	400.00	1,000	1,100	52.0	9	Nej		
700.00	400.00	800	1,100	52.0	15	Nej		
750.00	400.00	450	1,100	52.0	9	Ja		750.47–750.57
800.00	400.00	500	1,100	52.0	9	Ja		800.90–801.00
850.00	400.00	400	1,100	52.0	9	Ja		850.92–851.02 Fastnade på vägen ner ca: 872 m.
900.00	400.00	600	1,100	52.0	10	Nej		

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