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Äspö Hard Rock Laboratory

The magnetic anisotropy of rocks across the deformation zone NE-1 at the Äspö HRL

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August 2006

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Abstract

This report presents the compilation and interpretation of AMS (Anisotropy of Magnetic Susceptibility) data from oriented rock samples collected in the tunnel of the Äspö Hard Rock Laboratory (HRL), along a profile across the deformation zone NE-1.

Deformation zones and their properties are important during the planning and construction of a deep repository for high level radioactive waste. One reason for this is that deformation zones constitute possible zones of weakness in the rock volume, and it is therefore important to find a tool for estimating how far from the deformation zone the rock has been affected by the deformation.

The major aim of this study was to test how far from the zone boundaries it is possible to identify variations in the magnetic properties related to the deformation processes.

The NE-1 is a highly water bearing deformation zone (brittle and ductile) with the orientation of strike = 230-240º and dip = 70-75º (right hand rule). The zone is subdivided into three branches, which roughly coincide with the occurrences of fine-grained granite rock. The host rock is mainly quartz monzodiorite ("Äspö diorite").

There is a consistent variation in the orientation of the magnetic foliation planes and the magnetic lineations in the quartz monzodiorite rocks across the NE-1. The AMS data across the southern most located branch of the NE-1 deformation zone fit very well with the fabric expected from a ductile deformation zone with a sinistral sense of movement. The data also clearly indicate that the northern side has moved upward relative to the southern side. The orientation of the zone centre estimated from the AMS data is c. N240ºE/76º, which coincides well with earlier investigations.

The transition zone southward of the NE-1, defined as the perpendicular distance from the zone boundary to the first anomalous fabric orientation relative to the regional fabric, has an estimated width of 40-50 m. The total estimated width of all three branches of intense deformation of the NE-1 is approximately 50-70 m, so the indicated transition zone is slightly narrower. However, since some parts of the rock in between the branches seem to be unaffected by the deformation, the relationship between the entire zone centre and the transition zone is difficult to interpret without more detailed studies of the core of the NE-1 deformation zone.

Sammanfattning

Föreliggande rapport presenterar en sammanställning och tolkning av AMS-data (magnetisk susceptibilitetsanisotropi) på orienterade bergartsprover insamlade i Äspötunneln (Äspölaboratoriet) längs en profil över deformationszonen NE-1.

Inför planering och byggande av ett lager för högaktivt använt kärnbränsle är det viktigt att få ökad kunskap om deformationszoner och deras egenskaper. En orsak är att deformationszoner utgör potentiella svaghetsplan i berggrunden, och därför är det viktigt kunna uppskatta hur långt utanför en deformationszon som berget är påverkat av deformationen.

Huvudmålet med denna studie var att undersöka hur långt utanför en större deformationszon det är möjligt att identifiera variationer i bergets magnetiska egenskaper kopplade till deformationen.

NE-1 är en kraftigt vattenförande deformationszon (både spröd och plastisk) med orienteringen N230-240ºE/70-75º (högerhandsregeln). Zonen delas in i tre grenar vilka i stort sammanfaller med gångar (kroppar?) av finkornig granit. Omgivande bergarter utgörs i huvudsak av kvartsmonzodiorit (”Äspö diorit”).

Det finns ett tydligt sammanhängande mönster över hur de magnetiska foliationsplanen och den magnetiska lineationen varierar i kvartsmonzodioriten över NE-1. AMS-data från en profil över den längst i söder belägna grenen av NE-1 överensstämmer väl med det mönster man kan förvänta sig från en plastisk deformationszon med sinistral rörelse. Data indikerar även en rörelseriktning som visar att den norra sidan om zonen rört sig uppåt i förhållande till den södra sidan. Orienteringen på zonens centrala delar kan uppskattas till N240ºE/76º, vilket stämmer väl överens med tidigare geologiska undersökningar.

En övergångszon söder om NE-1, definierad som det vinkelräta avståndet från den södra zongränsen till den längst bort liggande lokalen med avvikande AMS-orientering, uppskattas till 40-50 meter. Den totala bredden på alla tre grenar av NE-1 är ca 50-70 meter, vilket således är något bredare än övergångszonen. Eftersom delar av bergmassan mellan de tre grenarna dock verkar vara relativt opåverkad av deformationen, är relationen mellan bredden på zonens (zonernas) centrum och övergångszonen osäker, och skulle nog kräva mer detaljerade studier av själva zonkärnan.

Contents

1 Introduction

SKB performs site investigations for localization of a deep repository for high level radioactive waste. In the Äspö Hard Rock Laboratory (HRL), located north of Oskarshamn, SKB performs research on the processes that occur in a final repository and SKB also makes full scale tests of technical solutions. This document reports the results gained from the interpretation of measurements of the anisotropy of magnetic susceptibility (AMS) of rocks along a profile across the deformation zone NE-1. The samples were collected at c. 200 m depth in the tunnel of the Äspö Hard Rock Laboratory (HRL).

The anisotropy of magnetic susceptibility (AMS) is related to mineral grain shape and crystallographic properties of rocks. The measurements will thus mainly indicate variations in the ductile deformation properties of rocks across the deformation zone. Core samples were collected along a profile across the deformation zone NE-1. All individual samples were oriented with reference to the geographical co-ordinate system by use of magnetic compass. The field work was performed in the autumn 2005 and in the early spring 2006 by Håkan Mattsson, GeoVista AB, with support from Björn Magnor (SKB) and Carljohan Hardenby (Vattenfall Power Consultant AB). The AMS measurements were performed at the petrophysical laboratory, Luleå University of Technology, and the interpretations were performed by Håkan Mattsson, GeoVista AB.

Figure 1-1 shows the location in an airborne photography of the sampling site projected onto the ground surface. The AMS data and interpreted results are stored in the primary data base SICADA.

Figure 1-1. *Airborne photo (© Lantmäteriet) showing the location of the sampling profile (c. 200 m below ground surface) projected on to the ground surface.*

2 Objective and scope

Deformation zones and their properties are important during the planning and construction of a deep repository for high level radioactive waste. One reason for this is that deformation zones constitute possible zones of weakness in the rock volume. SKB defines a deformation zone (ductile as well as brittle) by a central core of heavily altered rock, and an outer transition zone with a lower degree of deformation /1/ (Figure 2-1). The degree of deformation decreases perpendicularly away from the core boundary. Beyond the transition zone there is fresh rock. The width of the transition zone is important for the design of the deep repository, since this width is one of the parameters that, determines how close to the deformation zone it is possible to put the canisters containing the radioactive waste. Thus, it is important to be able to estimate how far from the core of the deformation zone the rock has been affected by the deformation processes.

Deformation zones are generally divided into brittle and ductile zones, and also a combination of these, such as brittle-ductile (mainly brittle) and ductile-brittle (mainly ductile). The scope of this investigation is to use the magnetic susceptibility and its anisotropy as a tool for estimating variations in the deformation properties of the rocks along a profile across the brittle-ductile deformation NE-1 in the Äspö Island.

The major aim is to test how far from the zone boundaries (defined from geological mapping) it is possible to identify variations in the magnetic properties related to the deformation processes. AMS is very sensitive even to weak ductile deformation and may detect rock deformation not visible by the eye.

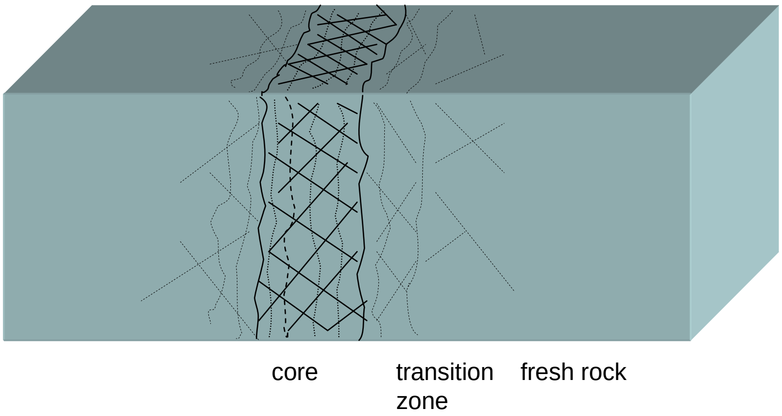

Figure 2-1. *Principle sketch of the SKB definition of a deformation zone (modified after Munier et al /1/).*

3 Equipment

3.1 Description of equipment for analyses of AMS data

The software used for the interpretation are Anisoft (AGICO Inc.) used for analyses of anisotropy data, Grapher v5 (Golden Software), Surfer v8 (Golden Software) and MapInfo v.7.0 (MapInfo Corporation), mainly used for plotting and some statistical analyses.

3.2 Description of sampling equipment

The standard petrol driven drill machine normally used for this kind of work was impossible to use because of the safety restrictions for underground work. The collection of samples was therefore performed with a water cooled electrical drill machine (HILTI DD 130), which was supplied with a specially constructed adapter to allow the use of the standard drill bits tested for the rock types in this area (Figure 3-1a).

The orientation of the drill cores was performed using the technique from traditional paleomagnetic sampling (Figure 3-1b).


a)

b)

Figure 3-1. *a) Drill machine used for the collection of samples. b) Sun compass that measures strike and dip of the drill cores (supplemented by magnetic compass if no sun).*

4 Geology

The geological, hydrological and rock mechanical properties of the NE-1 deformation zone are described in several reports published by SKB, and a summary of geological properties is given in appendix 1 of the SKB report R-05-25 /2/.

The bedrock in this part of the Äspö tunnel is dominated by quartz monzodiorite (Äspö diorite), fine-grained granite and fine-grained diorite to gabbro (greenstone), Figure 4-1. The NE-1 is a highly water bearing deformation zone with the orientation, according to the literature, of strike = 230-240º and dip = 70-75º (right hand rule). The zone is subdivided into three branches, which roughly coincide with the occurrences of fine-grained granite rock, crosscutting the tunnel along the section lengths c 1,240-1,330 m. (the start/end coordinates of the three parts were given by Björn Magnor, SKB). Based on the geological mapping in Figure 4-1 it appears as if the fine-grained granite rocks (dykes?) of parts 1 and 2 dip in the opposite direction as compared to part 3. The most intensely deformed part (part 3) intersects the tunnel at c. 1,300 m. It is 5-8 m wide and is characterized by high frequency of fractures and partly clay altered rocks. A one meter wide central core is completely clay altered.

The Äspö diorite in the vicinity of NE-1 is reported being partly altered, also carrying fracture fillings of chlorite and calcite. Small mylonite zones occur, and parts of the NE-1 are believed to indicate brittle reactivation of an older deformation zone, which was developed under ductile or semi-ductile conditions /2/.

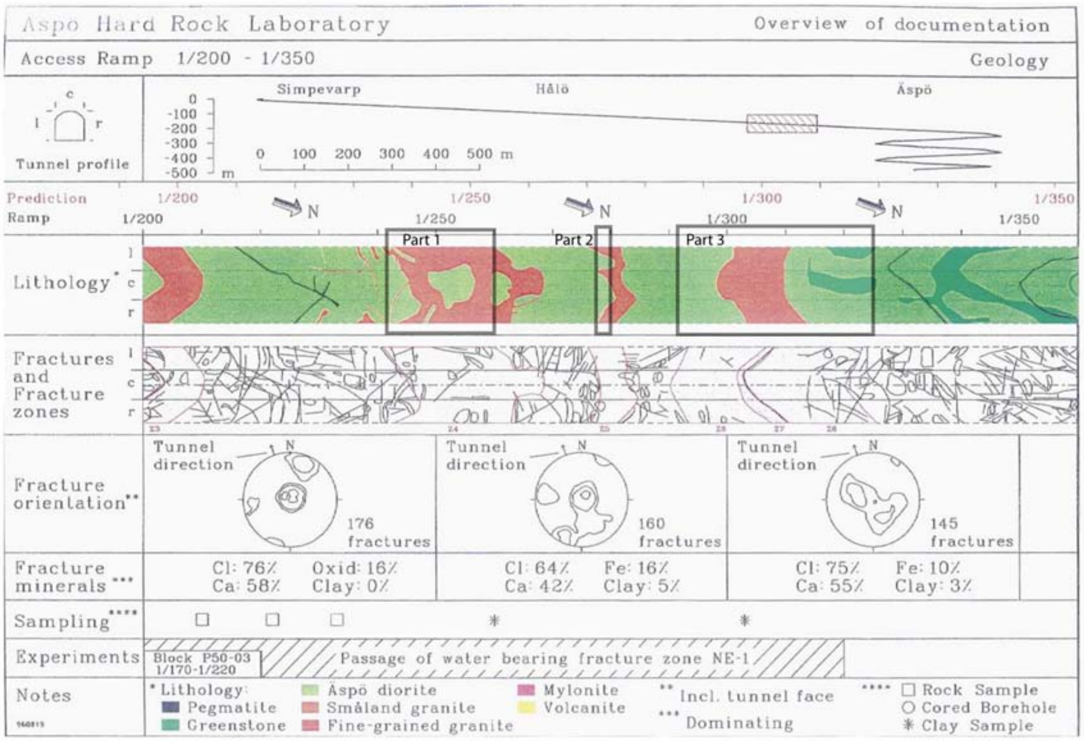

***Figure 4-1.** Geological mapping of part of the Äspö tunnel (copied from /2/). The black rectangles indicate sections of NE-1 that have suffered from intense deformation.*

5 Execution

5.1 Collection of samples

The sample collection was performed in the Äspö tunnel at c. 200 m depth below the ground surface, along a profile which is c. 220 m long, starting at tunnel section 1,185 m and ending at tunnel section 1,407 m (local system).

The collection of a first set of samples was conducted in the autumn 2005. Due to drilling technical problems the work had to be interrupted, and in order to complete the field work a second round of sample collection was performed in the early spring of 2006. All in all 64 core samples were collected at 17 site locations across the NE-1 deformation zone (Figure 5-1).

Prior to drilling the samples the shotcrete covering large parts of the tunnel wall had to be removed. This was done by use of a hand held electrically driven hammer. However, the shotcrete cover in part 3 of the NE-1 deformation zone (see Figure 4-1) was very thick (>10-20 cm), and this made it almost impossible to remove the shotcrete cover with the hammer in a reasonable amount of time. In one location we could remove most of the cover, but then the underlying rock had suffered from intense brittle deformation making it impossible to sample. Due to these difficulties, no samples were collected in part 3 of NE1.

The sample profile starts c. 60 m south of the southern boundary at X = 1,185 m (upper boundary with respect to the dip of the tunnel) of the deformation zone, cross-cuts the zone, and ends c. 80 m north of the northern boundary at X = 1,407 m (lower boundary with respect to the dip of the tunnel), Figure 5-1.

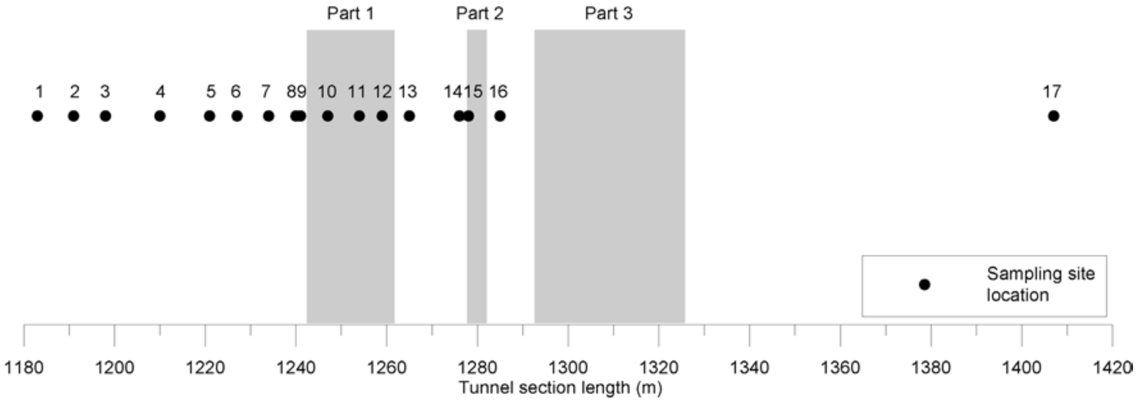

Figure 5-1. *Sample site locations (1 – 17) across the NE-1 deformation zone, plotted with reference to the tunnel section co-ordinate for each site location respectively. Observe that the profile starts in the south (No 1) and ends in the north (No 17).*

In average four drill cores were collected at each sampling location, Figure 5-2a. Each drill core is c. 4-5 cm long with a diameter of 25 mm. The strike and dip direction of each core was measured using the technique from traditional paleomagnetic sampling (only magnetic readings due to the lack of sun), Figure 5-2b. All data were stored in a field diary.

As a quality assurance the co-ordinates of the sampling sites (in the local SKB coordinate system as well as in the RT90 system) and also the orientations of the drill holes of the first set of samples (collected 2005), were measured by the professional underground surveyor Gerry Johansson (Geocon AB).

Each sampling location was given a site code (id-code) “KA” followed by “section length coordinate in the tunnel” followed by a sample number, followed by a specimen letter, e.g. KA 1183 A01a, which separates the different drill cores (samples) selected at each sample location.

Figure 5-2. *a) Petrophysical sampling by use of water cooled electrical drill machine. b) Orientation of drill core by use of magnetic compass.*

A photo of the samples is shown in Figure 5-3. The selection of sampling locations was performed in co-operation with the geologist Björn Magnor (SKB) and the sampling was performed with the support from Björn Magnor (SKB) and Carljohan Hardenby (Vattenfall Power Consultant AB).

Figure 5-3. *Photo of the samples collected across the NE-1 deformation zone (sample KA1240A03 = 8B is missing).*

5.2 Measurements and data handling

Preparations of the drill cores were performed by a technician at the laboratory of the Division of Applied Geophysics, Luleå University of Technology, according to the standard techniques used for example, in the preparation of samples for paleomagnetic analyses. All orientation information was stored in a Microsoft Excel file.

One to three 22 mm long specimens were cut off from each drill core, thus totally c. 5-10 specimens for each sampling location. AMS measurements were performed on all specimens, and the results were stored in data files sorted with reference to each sampling location.

5.3 Analyses and interpretations

The magnetic anisotropy of rock forming minerals basically originates from two sources, the grain shape and the crystallographic structure /3/. Magnetite is ferrimagnetic and carries strong shape anisotropy, whereas pyrrhotite and hematite are governed by crystalline anisotropy due to their antiferromagnetic origin. Paramagnetic minerals (e.g. biotite, hornblende) and diamagnetic minerals (e.g. quartz, feldspars) are also carriers of magnetocrystalline anisotropy. The orientation of the anisotropy of magnetic susceptibility coincides with the crystallographic axes for most rock forming minerals, so it is therefore possible to directly transfer “magnetic directions” to “tectonic directions” (foliation and lineation) measured in the field. Since magnetite carries a very high magnetic susceptibility in comparison to most other rock forming minerals, only a small portion present in a rock tends to dominate the magnetic properties, including the anisotropy. However, for example for “non-magnetic” granites the magnetic anisotropy is mainly governed by biotite and other paramagnetic minerals.

The AMS measurements were performed on 3-8 specimens per site location, which produced the same number of data readings per site. Calculations were then performed of mean directions of the principal AMS axes (site mean directions) and corresponding “site mean values” of the degree of anisotropy (P), degree of lineation (L), degree of foliation (F) and ellipsoid shape (T). When calculating the site mean values of the anisotropy parameters, the orientation of the principal anisotropy directions of each specimen is taken into account. Vector addition is applied to the three susceptibility axes of the specimens from the site, which results in a “site mean ellipsoid”. The site mean values of the anisotropy parameters thus give information of the site as a whole and are not just “simple” average values. According to statistical demands at least six measurements (specimens) are required for estimating uncertainty regions (95% confidence ellipses of the mean) of the calculated mean directions. The uncertainty regions indicate how well the mean direction is determined statistically. For site locations with less than six specimens, uncertainty regions were not calculated.

6 Results

6.1 Quality controll of the orientation data

Since the first sampled 38 cores were oriented both with the traditional paleomagnetic technique and also by a professional underground surveyor a comparison between the two data sets was performed. The strike directions from the two measurements are displayed in a cross-plot in Figure 6-1. Ideally the points in the diagram should define a perfectly straight line with the slope 1.0 that crosscuts the origin. Naturally this is not the case, but as seen in Figure 6-1 the correlation between the two data sets is very good. The slope of the fitted line is 1.013 and the line crosscuts the Y-axis at -2.9°. A majority of the data points plot close to the fitted line, but there are two major outliers (5% of the total population).

Possible sources of errors in the magnetic measurements (apart from miss-readings) are magnetic objects located in the tunnel wall. Such objects are for example rock bolts or screws, fibre reinforced shotconcrete on the tunnel wall, highly magnetic rock types and the natural deviation of the magnetic north pole from the geographic north pole.

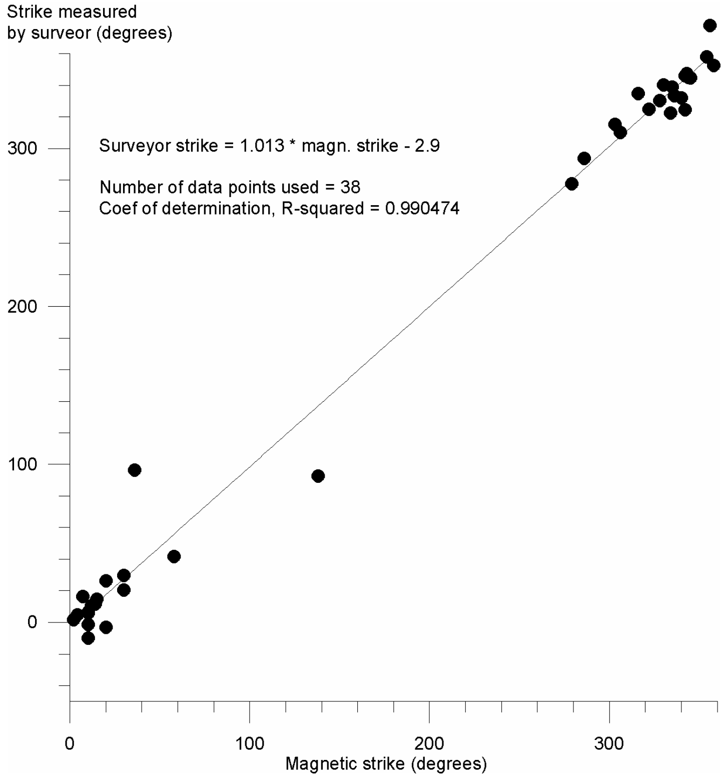

Figure 6-1. *Cross plot of strike directions for 38 drill cores measured by underground surveyor (Y-axis) and by use of magnetic compass during sampling (X-axis).*

The deviation of the magnetic north from the geographic north has been measured in previous investigations during the SKB site investigation, and these measurements indicate a deviation of <2º. During the sampling we always tried to avoid drilling close to visible bolts, screws or other metallic objects. The biggest problem is most likely caused by the iron fibres in the shotcrete on the walls. However, as seen for example in Figure 5-2b the pipe of the orientation tool is c. 30 cm long, which allows magnetic readings at some distance away from the wall. By turning the compass 180º and thus taking two opposite readings, also gives a control of possible errors during the orientation procedure (e.g. the effect of high magnetic rocks). Also, not all parts of the tunnel wall are covered with shotcrete.

The diagram in Figure 6-1 shows that the effect of the iron needles in the concrete is most likely insignificant. The two outliers may originate from metal objects hidden by the concrete or high magnetic rocks. However, there are also possible errors related to the orientation measurements performed by the surveyor. These measurements are performed by measuring strike and dip of a long stick fixed into the borehole. Some of the boreholes were only a few centimetres deep, making it difficult to fix the measurement stick parallel to the borehole wall.

The accuracy of the orientation data is estimated at c. ±10º (calculated as the standard deviation of the mean of the residual of the two data sets, disregarding the two outliers). Since several cores were sampled at each location the accuracy of the site mean directions of the AMS data is probably better than this.

6.2 Geological description of collected samples

Referring to the Figures 4-1 and 5-1 the collection of samples mainly covers quartz monzodiorite (Äspö diorite) and fine-grained granite. It is difficult to make a fully reliable rock type classification based on small core specimens (length = 22 mm, diameter = 25 mm). As noted earlier in the report large parts of the tunnel wall along the sample profile are covered with shotcrete for reinforcement, which prevented visual inspection of the sample collection sites during the field work. However, a short geological description of each sampling location, based on visual inspection of the drill cores, is given in Table 6-1 below. The geological map of this part of the tunnel was used as supportive information (Figure 4-1).

Table 6-1. Geological description of the rocks along the sample profile across NE-1.

Site number	No. of samples	Idcode Sicada	Geological description
1	5	KA1183	Quartz monzodiorite (Äspö diorite). Mainly fresh looking without macroscopic signs of deformation. One sample carries white to light orange coloured feldspars that may indicate low degree of alteration
2	4	KA1191	Quartz monzodiorite (Äspö diorite). Fresh looking without macroscopic signs of deformation. One sample contains minor mafic inclusion.
3	4	KA1198	Quartz monzodiorite (Äspö diorite). Mainly fresh looking without macroscopic signs of deformation. All samples partly carry white to light orange coloured feldspars that may indicate low degree of alteration.
4	4	KA1210	Quartz monzodiorite (Äspö diorite). Mainly fresh looking without macroscopic signs of deformation. All samples partly carry light orange coloured feldspars that may indicate low degree of alteration.
5	4	KA1221	Quartz monzodiorite (Äspö diorite). Fresh looking without macroscopic signs of deformation or alteration.
6	5	KA1227	Quartz monzodiorite (Äspö diorite). Lower amount of dark minerals as compared to surrounding sites. Mainly fresh looking without macroscopic signs of deformation. One sample has clearly suffered from alteration.
7	4	KA1234	Quartz monzodiorite (Äspö diorite). Fresh looking without macroscopic signs of deformation or alteration.
8	4	KA1240	Quartz monzodiorite (Äspö diorite). Low degree of alteration indicated by orange coloured feldspars. Sealed fractures and biotite foliation in one sample indicate brittle and low grade ductile formation.
9	4	KA1241	Quartz monzodiorite (Äspö diorite). Low degree of alteration indicated by orange coloured feldspars. Sealed and open fractures and distinct foliation in one sample indicate brittle and ductile formation.
10	4	KA1247	Fine-grained granite. Occurrences of sealed and open fractures indicate brittle deformation.
11	4	KA1254	Fine-grained granite. Fairly high frequency of sealed and open fractures indicates brittle deformation.
12	4	KA1259	Quartz monzodiorite (Äspö diorite). Low degree of alteration indicated by orange coloured feldspars. Low frequency of sealed and open fractures.
13	3	KA1265	Quartz monzodiorite (Äspö diorite). Fresh looking without macroscopic signs of deformation. One sample has suffered from low grade alteration and also crosscuts a mafic inclusion.
14	3	KA1276	Quartz monzodiorite (Äspö diorite). Fresh looking without macroscopic signs of deformation. Few samples have suffered from low grade alteration.
15	2	KA1278	Pegmatite (possibly fine-grained granite). All samples have suffered from brittle-ductile deformation and are most likely altered.
16	3	KA1285	Quartz monzodiorite (Äspö diorite). Fresh looking without macroscopic signs of deformation.
17	3	KA1407	Fine-grained granite. All samples have suffered from brittle-ductile deformation indicated by high frequency of sealed fractures and foliation.

6.3 Results of the AMS measurements

6.3.1 AMS parameters

In Figure 6-2 some AMS parameters (magnetic mean susceptibility, degree of lineation, degree of foliation, ellipsoid shape and degree of anisotropy) are plotted with reference to the tunnel section co-ordinate of each site location respectively.

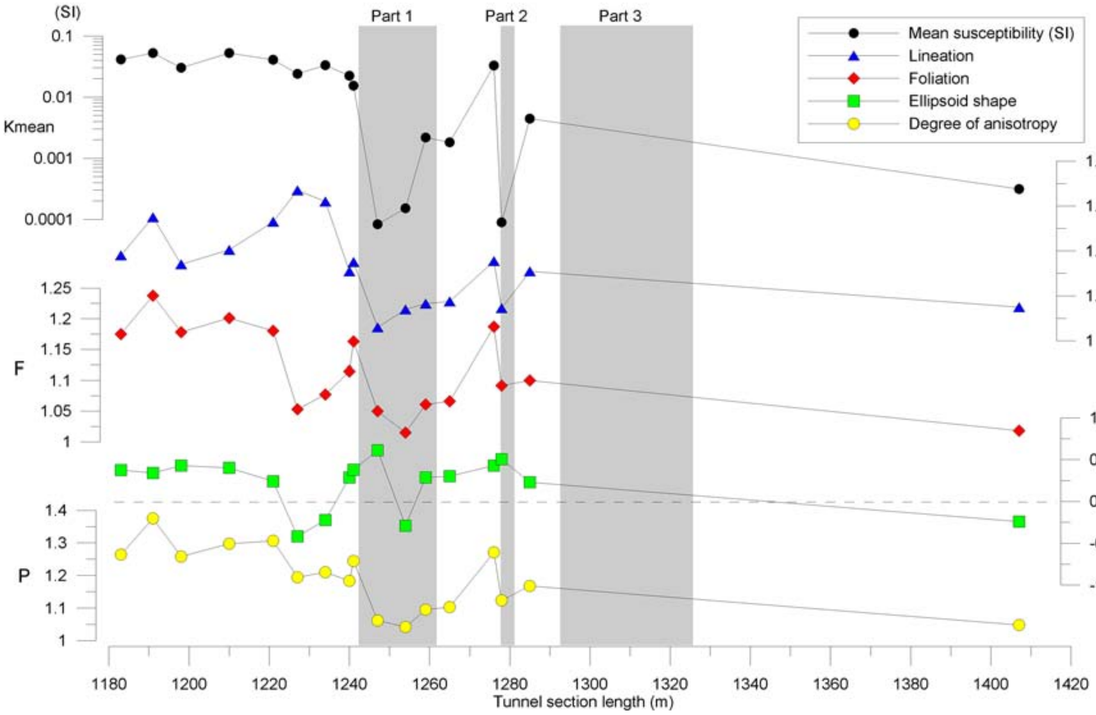

Figure 6-2. *Site mean values of the magnetic susceptibility, lineation, foliation, ellipsoid shape and the degree of anisotropy along the profile. Shaded areas indicate parts of NE-1 where the rock has suffered from intense deformation. The data are plotted with reference to the tunnel section co-ordinate of each sample location respectively. Kmean = mean susceptibility, F = degree of foliation, P = degree of anisotropy, L = degree of lineation, T = ellipsoid shape (+1 = flattened, -1 = elongated, 0 = spherical)*

Outside of part 1 of NE-1 (site numbers 1-8) the mean susceptibility shows only minor variations within the range c. 0.030-0.050 SI. The fairly high susceptibility suggests that magnetite governs the rock magnetic properties. The small variations in volume susceptibility indicate that the deformation has had no significant effect on the magnetic mineralogy in the rock outside of the deformation zone. At site 9 (very close to the boundary of part 1) there is a slight decrease in the mean susceptibility (Kmean = 0.015 SI) and this may indicate a partial destruction or alteration of magnetite.

Within the sections of more intense deformation there is a major decrease in the magnetic susceptibility, which clearly shows that the magnetic mineralogy differs from the surrounding rocks. The sites 10 and 11 are fine-grained granite and earlier AMS measurements of primary fine-grained granite from the Laxemar area shows that their mean susceptibility averages at 0.005 SI /4/. The sites12, 13 and 16 are located in quartz monzodiorite and these sites also shows a clear decrease in the susceptibility (0.002-0.005 SI), which indicates that the rock has suffered from alteration. The quartz monzodiorite (Äspö diorite) at site 14 has similar volume susceptibility as the rock outside of the deformation zone centre. The pegmatitic rock at site 15 has very low magnetic susceptibility, and this is often the case for primary as well as altered pegmatite dykes.

The parameters that describe ellipsoid shape characteristics (L, F, T and P) are all dependent of the magnetic mineralogy. Thus, if the magnetic mineralogy varies along the profile it might be difficult to compare and interpret ellipsoid shape variations with respect to deformational properties. For the sites 1-9 + 14 there are only minor variations in the susceptibility and it is likely to assume that magnetite governs the magnetic mineralogy.

The degree of magnetic lineation increases when going from site 1 towards site 6, approaching part 1 of the deformation zone. The peak at site 6 is followed by a successive decrease and the degree of lineation is generally low through out the rest of the profile. The degree of foliation (F) of sites 1-5 is 1.15-1.20. Between the site 5 and 6 there is a major drop followed by a successive increase up to c. 1.15 at site 9. At site 14 the foliation degree F = 1.19 (same as outside of NE-1).

The ellipsoid shape (T) is oblate (disc-shape) for a majority of the sampled rocks, indicating dominant compressive deformation. However, between the sites 5 and 8 there is dominant prolate shape (elongated ellipsoid), which suggests that stretching was the dominant deformation at these sites. The sites 11 and 17 also show dominant prolate shaped ellipsoids.

The degree of magnetic anisotropy (P) can under certain conditions be used as an indicator of the degree of rock deformation. However, one important requirement is that the magnetic mineralogy must not be altered, and this is unfortunately the case for the rocks in this investigation. Generally, the sites 1-5 show highest degree anisotropy of P = 1.25 – 1.35, followed by decreased degree of anisotropy at the sites 6-8 (P = 1.20), followed by another decrease beyond site 9 (with the exception of site 14).

6.3.2 The orientation of AMS fabrics

The orientation in 3D of the anisotropy ellipsoid axes relative to the geographical co-ordinate system was calculated for each sample location respectively. For some site locations the scatter in the orientations between individual samples is too high to allow the calculation of a reliable mean value, and these sites were consequently rejected. The mean orientation of the maximum axis of site number 8 and of the minimum axis of site number 11 were rejected.

The strike and dip of the magnetic foliation planes and the magnetic lineations along the sampled trajectory are presented in Figure 6-3. Starting from the lower section co-ordinate (left side of the figure) the magnetic foliation planes approximately strike 270º and dip 40-50º. When approaching part 1 of NE-1 (X = 1,210-1,240 m) there is a slight counter clockwise rotation of the foliation planes. At the boundary of part 1 (sites 8 and 9) the counter clockwise rotation increases and the dip of the foliation becomes steeper (foliation strike = SW, dip = 70º-80º, which is sub-parallel to the orientation of the NE-1 deformation zone reported in the literature /2/). The fine-grained granite at site 10 shows

ESE strike direction and a dip of 60º. However, the orientation data of the fine-grained granites and of the pegmatite at site 15 should not be directly compared to the quartz monzodiorite rocks, since different rock types behave differently when subjected to deformation due to variations in the mechanical properties related to mineral composition. Felsic rocks are generally more competent than mafic rocks.

The quartz monzodiorite rocks at the sites 12 and 13 show foliation planes oriented at c. N240ºE and steep dips (70º-80º). This orientation is sub-parallel to the orientation of the NE-1 deformation zone reported in the literature /2/. At the sites 14-16 the foliation planes strike c. N270º-310ºE with moderate dips, which is sub-parallel to the fine-grained granite at site 17, and deviates significantly from the orientation of NE-1.

The magnetic lineation (lower diagram in Figure 6-3) indicates the orientation of the mineral lineation and is likely to indicate the orientation of the maximum strain. The quartz monzodiorite at the sites 1-6 show dominant NNW trending lineations and moderate to shallow plunges. Disregarding the fine-grained granites at sites 10 and 11, NNE trending lineation directions are identified at the sites 7, 9, 12 and 13 (with plunges in the range 3º-65º). At the sites 14 and 16 (also quartz monzodiorite) the lineation is oriented in the same direction as for the group of sites 1-6. Moving along the sample trajectory towards the zone centre, starting at site No 1, there is a clear clockwise rotation of the lineation when approaching the part 1 of the NE-1.

The data shown in Figure 6-3 are also plotted in stereographic diagrams presented in Figure 6-4. Data of fresh Ävrö granite rock measured on samples collected all over the Laxemar area are also plotted as reference (yellow dots), indicating a regional fabric orientation /4/. A majority of the magnetic poles to the foliation (upper diagram in Figure 6-4) collected across the NE-1 overlap with the regional fabric indicated by the Ävrö granite samples from Laxemar. However, the four NE-1 sites 8, 9, 12 and 13 deviate significantly from the regional fabric orientation, which suggests that the rock at these sites is altered or deformed. Also note that the sites 5, 6 and 7 also show a slight counter clockwise rotation relative to the regional fabric.

A similar comparison made for the lineation data (lower diagram in Figure 6-4) shows that a majority of the magnetic lineations from the NE-1 profile deviate from the regional fabric orientation (light blue squares).

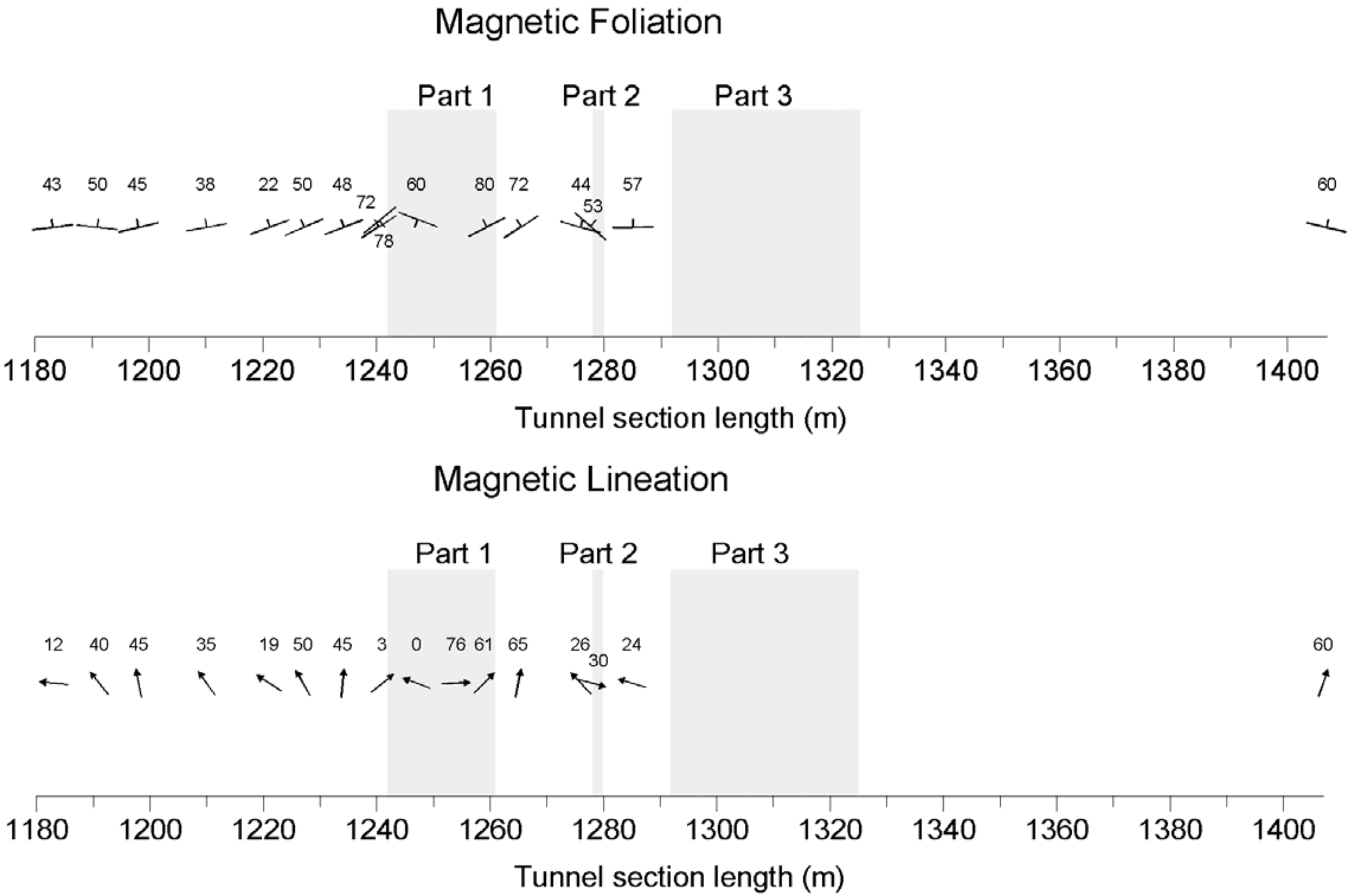

Figure 6-3. *The orientation (site mean values of strike and dip) of the magnetic foliation (upper plot) and of the magnetic lineation (lower plot). The shaded areas indicate parts of NE-1 where the rock has suffered from intense deformation. Observe that the left hand side of the figure is oriented towards the SSE and the right hand side towards the NNW.*

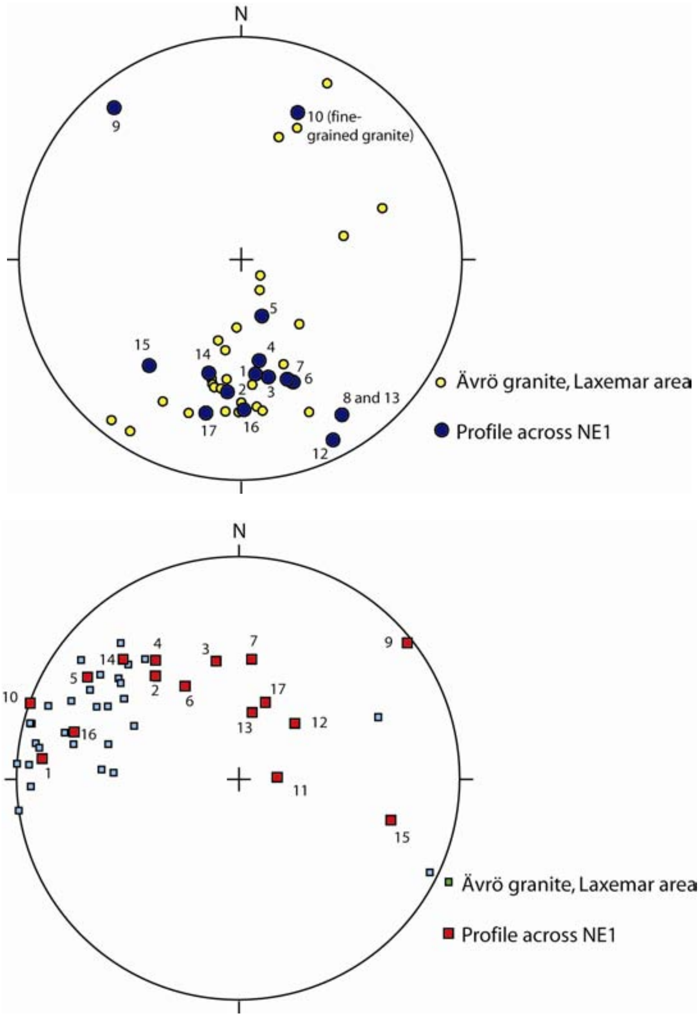

Figure 6-4. *Equal area projection plots showing site mean values of the magnetic poles to the foliation (upper plot) and the magnetic lineation (lower plot). In both diagrams AMS data of fresh Ävrö granite from samples collected all over the Laxemar area are plotted as reference to the measurements across the NE-1 deformation zone. Numbers denote site numbers with reference to Figure 5-1.*

7 Discussion and conclusions

The aim of this study is to test how far from the centre of the NE-1 deformation zone it is possible to identify variations in the magnetic properties related to the deformation processes. The AMS data presented in this report mainly covers the outer (southern) parts of the NE-1 deformation zone and not the zone centre, which is the unintentional result of the sample collection, primarily governed by practical conditions during the field work. However, geological information of the zone centre (width, orientation, type of deformation) is presented in previous investigations, and since the main objective of this investigation is to test the possibilities of detecting rock deformation in the transition zone outside of the zone center, the AMS data are believed to be sufficient for drawing reliable conclusions.

All three branches of the NE-1 coincide with occurrences of felsic rocks, mainly fine-grained granite but also pegmatite. The host rock mainly comprises quartz monzodiorite and partly fine-grained diorite to gabbro (no mafic rocks were collected in this investigation). The interpretation of the AMS data is focused on the quartz monzodiorite rock samples. The main reason for this is that all sampling locations along the tunnel section coordinates 1,180-1,240 m are classified as quartz monzodiorite. It is also in general very difficult to compare magnetic anisotropy data of different rock types from a rock deformational point of view, for example due to differences in magnetic mineralogy and in mechanical properties.

The different AMS parameters plotted in Figure 6-2 are difficult to interpret, as previously mentioned, due to the variations in rock types across the profile. However, it seems clear that the magnetic mineralogy of the quartz monzodiorite is almost unaffected by the deformation outside of part 1 of NE-1, except for a minor susceptibility decrease at the very boundary.

The parameters related to the anisotropy ellipsoid shape seem to indicate some kind of “event” around the sampling locations 5 and 6 (approximately 20 m south of the boundary of part 1 of the NE-1). The degrees of lineation, foliation and anisotropy indicate a general decrease when moving closer to the deformation zone from the sites 5 and 6, which is possibly related to the deformation activities. However, one would normally expect increased degrees of lineation, foliation and anisotropy with increased degree of deformation.

The orientation data presented in the Figures 6-3 and 6-4 show a well defined and consistent pattern. Farthest away from the zone (sites 1, 2 and 3) the foliation has an approximate east-west strike and moderate dips. Closer to part 1 (starting at the sites 3 or 4) there is a slight counter clockwise rotation of the foliation planes, and still moderate dips. Close to the boundary of part 1 (sites 8 and 9) there is a significant increase in the counter clockwise rotation and the dips become steep, strike of foliation is SW and dip of 70-80° (this orientation is sub-parallel to the orientation of the NE-1 deformation zone reported in the literature /2/).

The orientation variations of the foliation planes fit very well to a sinistral deformation zone with an indicated transition zone that is 30-40 m wide (Figure 7-1).

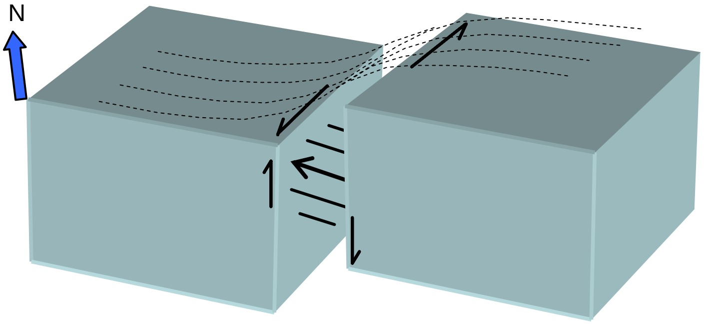

Figure 7-1. *Interpretation of the AMS data across the eastern branch (part 1) of the NE-1 deformation zone.*

An AMS study of the regional deformation zone “the Äspö shear zone” performed in 2005 /5/ shows results that remind a great deal of the results from this study, with the exception of the orientation of the lineation. The orientation of the magnetic lineation across the NE-1 shows a similarly well defined successive rotation (in this case clockwise) as the foliation planes, which however starts already at site location 2 (the lineation orientation at site 1 is sub-parallel with the regional fabric orientation indicated by the Laxemar data in Figure 6-4). At site No 9 the trend of the lineation is N51ºE and the plunge is 3º. The lineation orientations suggest a combination of pure and simple shear deformation and, in combination with the foliation data, the lineations indicate that the northern side has moved upward relative to the southern side. The lineation rotation suggests a transition zone width of c. 50 m.

In conclusion, the oriented magnetic fabric (foliation and lineation) across part 1 of the NE-1 deformation zone fit very well with the fabric expected from a ductile deformation zone with a sinistral sense of movement. The data also clearly indicate that the northern side has moved upward relative to the southern side. The orientation of the centre of part 1 of the NE-1 is estimated at N240ºE/76º, which coincides well with earlier investigations. The transition zone south of part 1 of the NE-1, defined as the perpendicular distance from the zone boundary to the first anomalous fabric orientation relative to the regional fabric, has an estimated width of 40-50 m. The total estimated width of all three branches of intense deformation of the NE-1 is approximately 50-70 m, so the indicated transition zone is slightly narrower. However, since some parts of the rock in between the branches seem to be unaffected by the deformation, the relationship between the entire zone centre and the transition zone is difficult to interpret without more detailed studies across the NE-1 deformation zone.

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