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Detailed structural geological mapping on Äspö

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Abstract

This report presents structural data based on field measurements at the ground surface at Äspö. The study also includes an evaluation of the data and a compilation of a structural geological map of Äspö which highlights a complex network of deformation zones. The map was constructed by combining the new field observations and structural measurements with identified geophysical lineaments.

The result reveals that NE-SW striking, sinistral, ductile and brittle-ductile deformation zones are dominating in the central part of Äspö, whereas smaller scale WNW-ESE oriented zones predominantly accommodated dextral movements. Three steeply dipping brittle fracture sets striking N-S, WNW-ESE, and NE-SW overprint the ductile fabrics and dissect the island into smaller structural blocks. A N-S maximum compressive stress during ductile, brittle-ductile and brittle deformation can be inferred from fabric orientations and kinematic indicators.

Sammanfattning

I denna rapport presenteras strukturella data baserade på mätningar i fält på Äspö. Studien innefattar också en utvärdering av strukturmätningarna och en sammanställning av en strukturgeologisk karta över Äspö som visar på ett komplext nätverk av deformationszoner. Kartan är baserad på en kombination av de nya fältobservationerna och strukturmätningarna samt identifierade geofysiska lineament. Resultatet visar att inom centrala delen av Äspö dominerar nordöst-sydvästligt strykande deformationszoner som karaktäriseras av plastisk och spröd-plastisk sinistral rörelse, samt mindre västnordväst-östsydöstligt strykande zoner med i huvudsak dextral rörelse. Tre brant stupande sprickgrupper med nord-sydlig, västnordväst-östsydöstlig och nordöst-sydvästlig strykning överpräglar de plastiska strukturerna och delar upp Äspö i mindre block. Kinematiska indikatorer och orientering av strukturer mätta längs de flesta plastiska, spröd-plastiska, och spröda deformationszonerna indikerar att de är resultatet av en nord-sydlig kompression.

Contents

1 Introduction

1.1 Background

Structural geological work on predominantly ductile and brittle-ductile deformation zones in the Laxemar-Simpevarp area has been carried out by e.g. Lundberg and Sjöström (2006). Brittle deformation zones and fractures in the same area have been investigated by e.g. Viola and Venvik Ganerød (2007) and Viola et al. (2009). Previous structural geological studies on the island of Äspö are summarised in Munier (1995). Detailed studies on the deformation zones at the surface of Äspö, however, have not been undertaken and documented systematically and most of the collected data is only available in an analogue format. SGU was therefore commissioned by SKB to carry out detailed structural studies of deformation zones on outcrops on Äspö. The work has been carried out in accordance with activity plan AP TD TDLIP-16-022. The original data and the compiled structural geological map in ArcGis format have been delivered to SKB and are stored in the primary database SICADA and the GIS database (SDE), respectively, and can be traced by the activity plan number (AP TD TDLIP-16-022).

1.1.1 Coordinate system and definitions

All coordinates for observation points and map grids are given in the reference coordinate system RT90 2.5 gon W.

The definitions of the most important structural geological terms used in this report are given below:

Ductile deformation zones correspond to mylonite zones, defined by grain size reduction through mechanical comminution and dynamic recrystallisation of quartz and feldspar (e.g. Figure 1-1). A brittle deformation component shall not be detected in a ductile deformation zone.

Brittle-ductile deformation zones (Figure 1-2) correspond to zones, where either a ductile component such as drag folds or the development of a mylonitic foliation can be observed together with a brittle deformation component such as fractures or a fracture zone. In order to use the term "brittle-ductile" for a deformation zone, the same sense of shear must be observed for both the ductile and the brittle component in that zone.

*Brittle structures (*Figure 1-2). Most of the brittle structures observed on Äspö are categorized as fractures, which is a general term for a crack. Fractures are subdivided into fractures with no displacement, a joint or extension fracture (with dominantly openings displacement), or a shear fracture (mainly wall parallel displacement). A vein can be treated as an extensional fracture filled with minerals, and can be hard to distinguish from shear fractures with mineral coating. Typically, fractures have a very small thickness (generally <1 mm), whereas the term" fault" is reserved for composite structure with a thicker zone of strongly deformed rocks (the fault core) in which there may be one or more slip surfaces and is bounded by a lower deformed damage zone. The term "fracture zone" refers to zones of at least 10 cm in width, in which the density of fractures is high relative to the adjacent rock mass. In this study, fracture zones do not necessarily display kinematic markers, which contrasts to the definition given by Munier (1995). Fracture sets comprise multiple parallel fractures more or less constantly spaced and all with an observable length in the same order of magnitude.

Structural measurements are explained visually in Figure 1-3. Strike, trend (azimuth), dip and plunge (inclination) are measured using the right-hand rule and the 360 degree system. Strike is measured with a compass and given relative to magnetic north. Dip is measured with an inclinometer (0–90 degrees, positive from horizontal to vertical).

Kinematic indicators. Studies of kinematics aim to unravel the deformation history of the rock. Kinematic indicators observed on bedrock outcrop can be used to record the sense of movements along a deformation zone or fracture**.** Indicators can originate from structural observations on offset and deflected markers in both ductile and brittle fabrics, clast rotation and mineral growth (sigmoids, mica-fish etc.), cross-cutting structures and other relationships. Striations and slickensides observed on fracture planes can be used to constrain the direction of slip during solely brittle deformation.

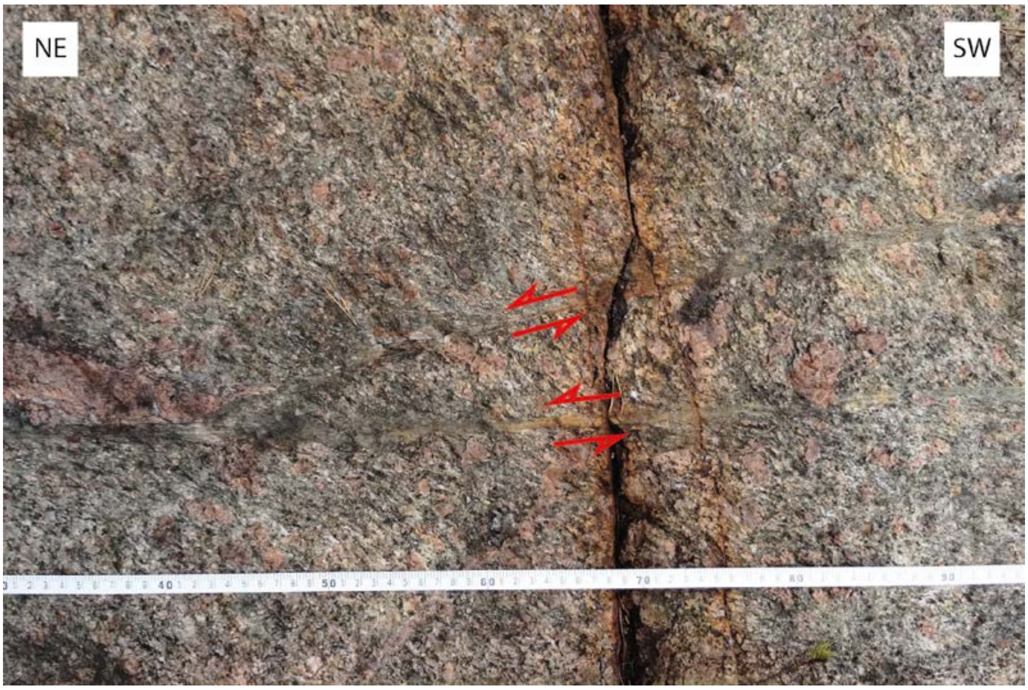

Figure 1-1. *Two merging, ductile mylonite zones with small-scale drag folds indicating sinistral kinematics. Grain size reduction towards the centre of the mylonite zones is observed. Tape unit is centimetres. Top view. Location: PAS000620 (X6367957, Y1551273).*

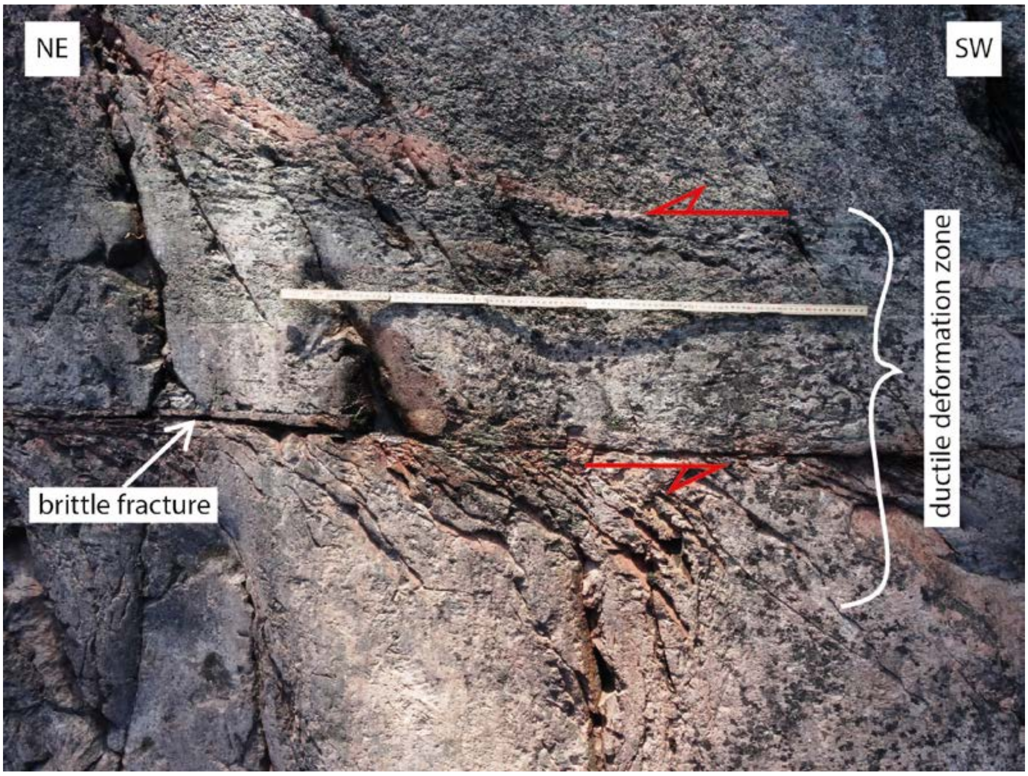

Figure 1-2. *Example of a sinistral, brittle-ductile deformation zone including a ductile and a brittle part. The shear zone developed along the boundary between a coarse-grained, porphyritic quartz monzodiorite in the southeast, and a fine-grained granite in the northwest. Brittle deformation seems to be localised exactly along that boundary. Folding ruler is 1m. Top view. Location: PAS000625 (X6367985, Y1551263).*

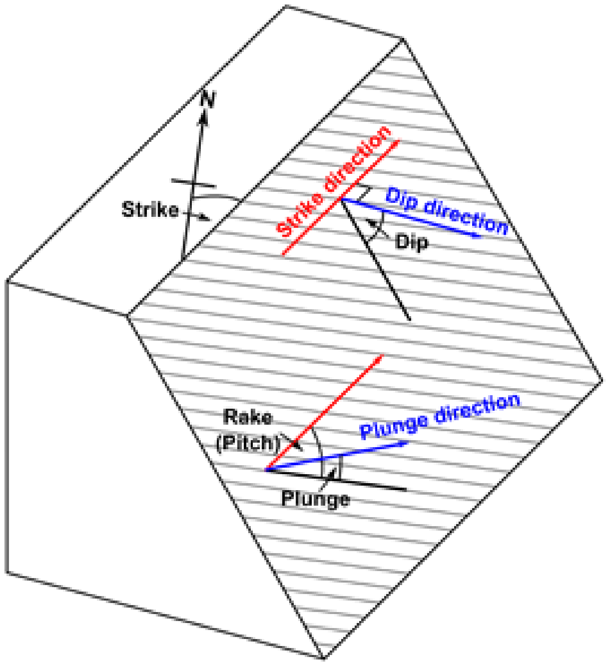

Figure 1-3. *Types of structural measurements on a dipping plane.*

1.2 Structural framework

1.2.1 Regional scale deformation zones

The structural framework including the designated names for regional scale shear zones used in this study are adapted from the site investigations carried out in the Laxemar-Simpevarp region (e.g. Wahlgren et al. 2008, Viola 2008). The island Äspö is bounded to the north by deformation zone ZSMEW002A. It is transected by a NE-SW trending deformation zone called ZSMNE005A, elsewhere known as “Äspö shear zone”. Another important deformation zone crossing the island is ZSMEW013A which is also known as “EW-1”. Deformation zone ZSMEW038A bounds the southern tip of Äspö. The deformation zones in Figure 1-4 are plotted on top of the magnetic map showing the tilt derivative of the total magnetic field. Further descriptions of the respective deformation zones can be found in Wahlgren et al. (2008).

1.2.2 Structural domains on Äspö

Äspö can be divided into three domains that trend approximately NE-SW (Figure 1-5). These domains have been defined on the basis of the different signatures of the total magnetic field. The Central Äspö domain is characterised by a low magnetic response corresponding to the Äspö shear zone and ZSMEW013A, whereas the Northern and Southern Äspö domains have a relatively high magnetic response. Contrasts between the three domains are also expressed by typical dominant fracture networks causing clear linear patterns on the map of the tilt derivative of the total magnetic field (Figure 1-6) and on the LiDAR derived digital elevation model (see Section 3.2 on brittle structures).

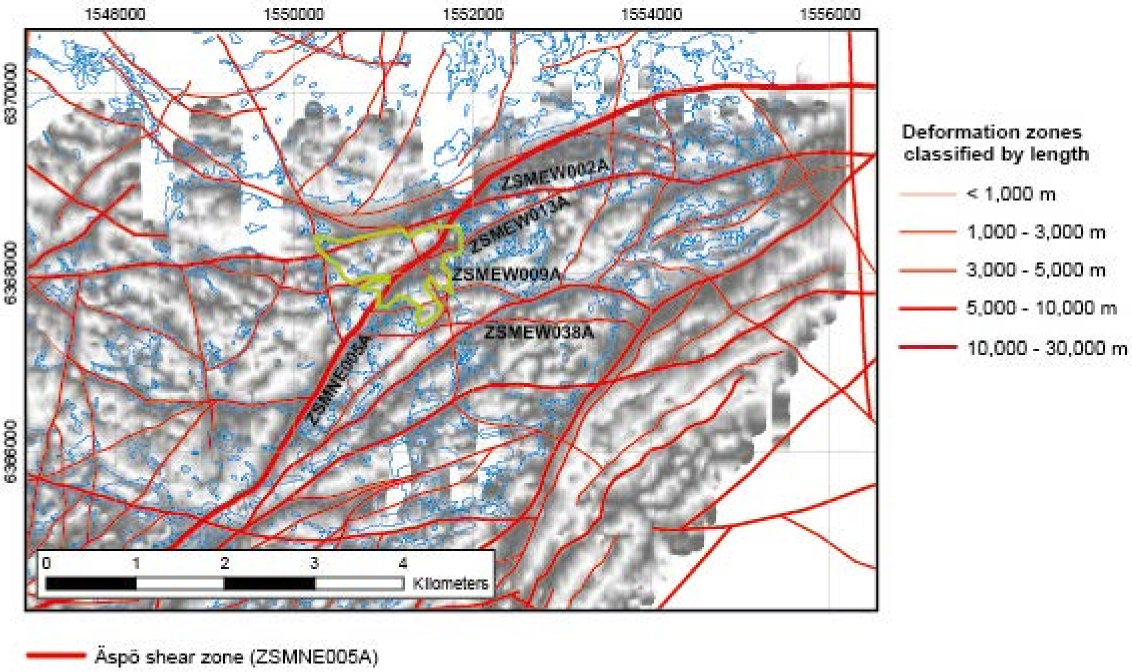

Figure 1-4. *Regional deformation zones plotted on a map of the tilt derivative of the total magnetic field. Deformation zones are classed by their length. The designated names of deformation zones are marked on the map (e.g. ZSMNEnnn or ZSMEWnnn where `nnn` is a sequential number. The contour of Äspö island is marked in green. The shore line is marked in blue colour. Reference layer files: SDEADM. SKB_SM_GEO_1489, SDEADM.GOL_LX_GEO_6081.*

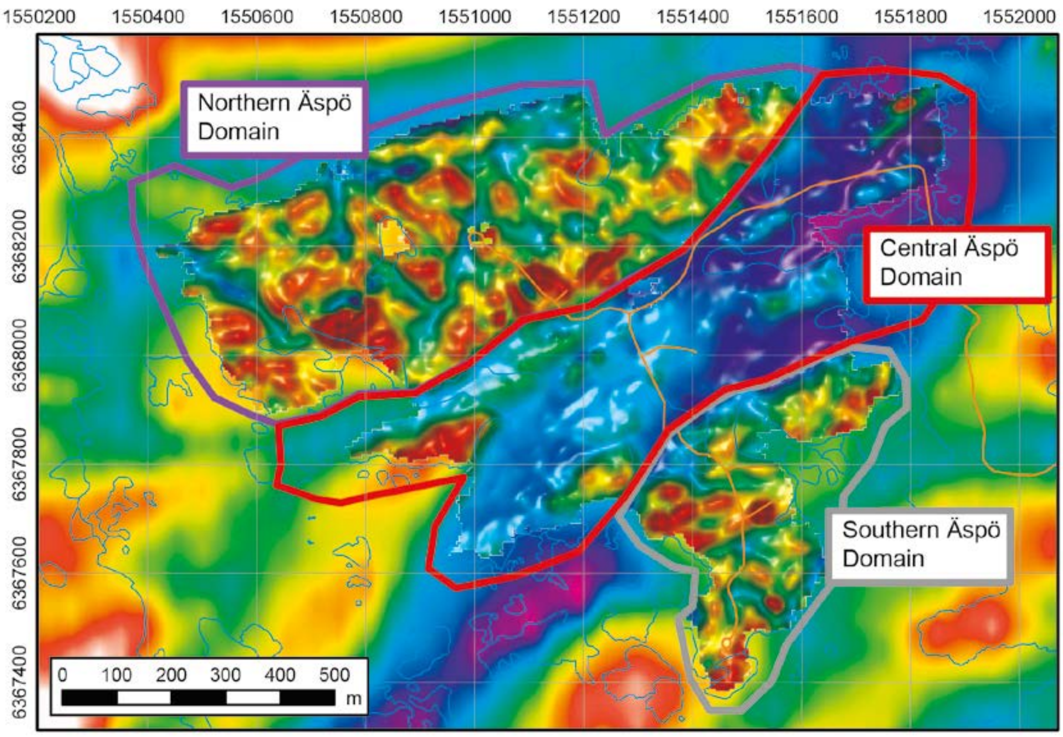

Figure 1-5. *Map of the total magnetic field compiled from magnetic data that was collected on the ground on Äspö and helicopter airborne measurements that were collected for the Laxemar-Simpevarp region. The low magnetic area cutting through Äspö is the magnetic response of the Äspö shear zone and ZSMEW013A. Reference layer file: SDEADM.GV_AS_GEO_8445.*

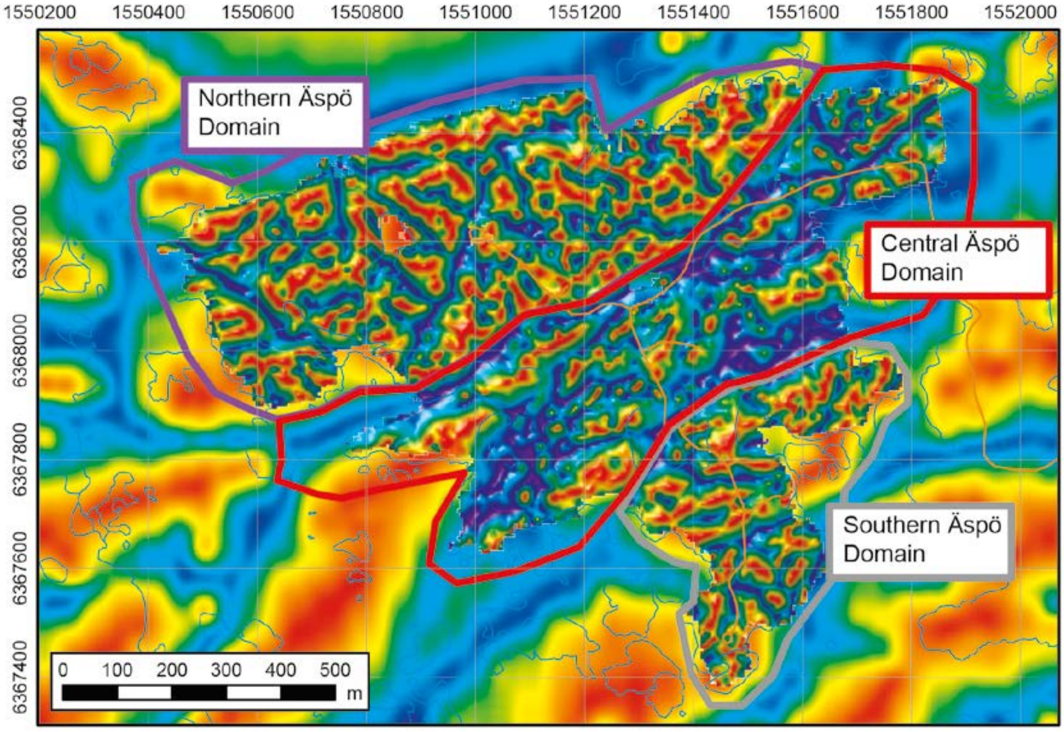

Figure 1-6. *Map of the tilt derivative of the total magnetic field compiled from magnetic data that was collected on the ground on Äspö and helicopter airborne measurements that were collected for the Laxemar-Simpevarp region. Reference layer file: SDEADM.GV_AS_GEO_8444.*

2 Methods and deliverables

Field work focus was on following up lineaments (e.g. Mattsson and Wahlgren 2010) interpreted from geomagnetic, geoelectric and topographic data in the field and attributing them to potential deformation zones or fracture sets. Wherever possible, attributes such as type of deformation zone, strike, dip, width and length were recorded in the form of geo-referenced point data. Kinematic indicators such as subsidiary structures, rotated blasts, dragged foliations, and SC or SC'-fabrics were recorded in order to determine the slip history of the deformation zones. Field work was undertaken between 07–12 June and 22–28 September 2016. The geological data were delivered to SICADA in RT90 coordinate format. The type of geological data that was collected and delivered to SICADA is presented in Table 2-1. A structural geological map including extrapolated and interpreted deformation zones is delivered as an ESRI shape file in RT90 format.

Table 2-1. Geological data collected on outcrops.

Column	Datatype	Unit	Description
site	CHAR		Investigation site name.
activity_type	CHAR		Activity type code.
project	VARCHAR		Project.
idcode	CHAR		Object or borehole identification code.
error_flag	CHAR		If error_flag = ”*” data is missing or incorrect.
sign	CHAR		If name (of manager) is set – data released for further use.
fracture_no	INTEGER	number	Fracture number.
sample_name	CHAR		Sample name e.g. PFM007085A.
structtype	CHAR		Structure type (NULL, axial plane, composite dyke, composite dyke contact, deformation zone, deformation zone set, felsic dyke contact, foliation, fracture, fracture set, fracture zone, fracture zone set, magmatic flow banding, mylonite, mylonite zone, mylonitic foliation, Observation, pristine, protomylonitic foliation, shear band, subsidiary structure, unknown plane, vein).
deftype	CHAR		Deformation type (brittle, brittle-ductile, ductile, NULL).
kinematic_indicators	CHAR		Kinematic indicators.
frac_strike	FLOAT	degrees	Angle of horizontal line of a plane clockwise from north.
frac_dip	FLOAT	degrees	Tilt angle for a plane from horizontal to vertical (0–90 deg).
strikeslip	CHAR		Strike slip (dextral, dextral and sinistral, dextral?, dilational, sinistral, sinistral?, unclear, NULL).
dipslip	CHAR		Dipslip (NULL, normal, reverse, extensional, normal?).
pitch	FLOAT	degrees	Pitch (angle on fracture plane between strike & striae).
trend	FLOAT	degrees	Trend of striae on a fracture plane.
plunge	FLOAT	degrees	Plunge of striae on a fracture plane.
lin_type	CHAR		Lineation type (slickensides, slickenline, stretching, striation).
lin_trend	FLOAT	degrees	Trend of lineation (0–360).
lin_plunge	FLOAT	degrees	Plunge of lineation (0–90).
hw	CHAR		Hanging wall (u=up, d=down).
comment	VARCHAR	no_unit	Comment.

3 Results

Figure 3-1 shows the location of point observations made during field work. A hand-held GPS device was used to record the coordinates for each field observation and the accuracy of the determination of the coordinates is estimated to be between 1 and 3 metres.

3.1 Ductile and brittle-ductile deformation

3.1.1 Ductile foliation

Foliation planes created by ductile deformation could be observed in many outcrops. These foliations are predominantly protomylonitic or mylonitic. Axial planar foliations due to folding also occur. The vast majority of (proto-) mylonitic foliations have a moderately to steep dip towards WNW or ESE and strike ENE-WSW regardless of their kinematic character. At some locations, foliations strike NE-SW (Figure 3-2). A stereographic projection (lower hemisphere) of (proto-) mylonitic foliations from Äspö is shown in Figure 3-3.

The trend of formlines of the mylonitic foliation across Äspö changes gradually over a short distance from E-W/ENE-WSW in the northwestern and southeastern part of the island to NE-SW in the central part (Figure 3-4). This change of orientations can be interpreted as drag folds being created during sinistral shearing along a NE-SW striking ductile shear belt. In the map of the total magnetic field the shear belt corresponds to a NE-SW striking zone with a low magnetic signal (Figure 3-4). This zone is commonly referred to as the "Äspö shear zone", and in the site descriptive model for the Laxemar-Simpevarp area it is called ZSMNE005A (Wahlgren et al. 2008).

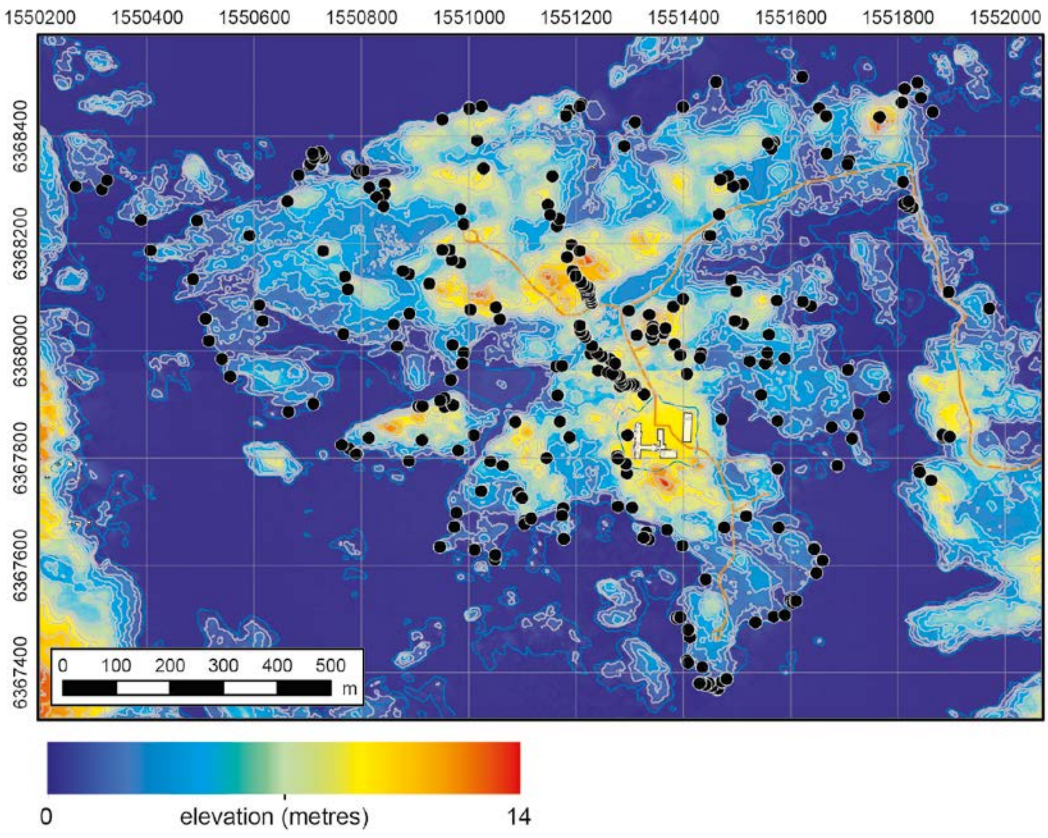

Figure 3-1. Distribution of visited outcrop observations (black points) on Äspö. The shore line is marked in blue colour. Elevation contour lines are marked in grey and the elevation is coloured with high elevation in red and low elevation in blue. Background map based on LiDAR data © Lantmäteriet.

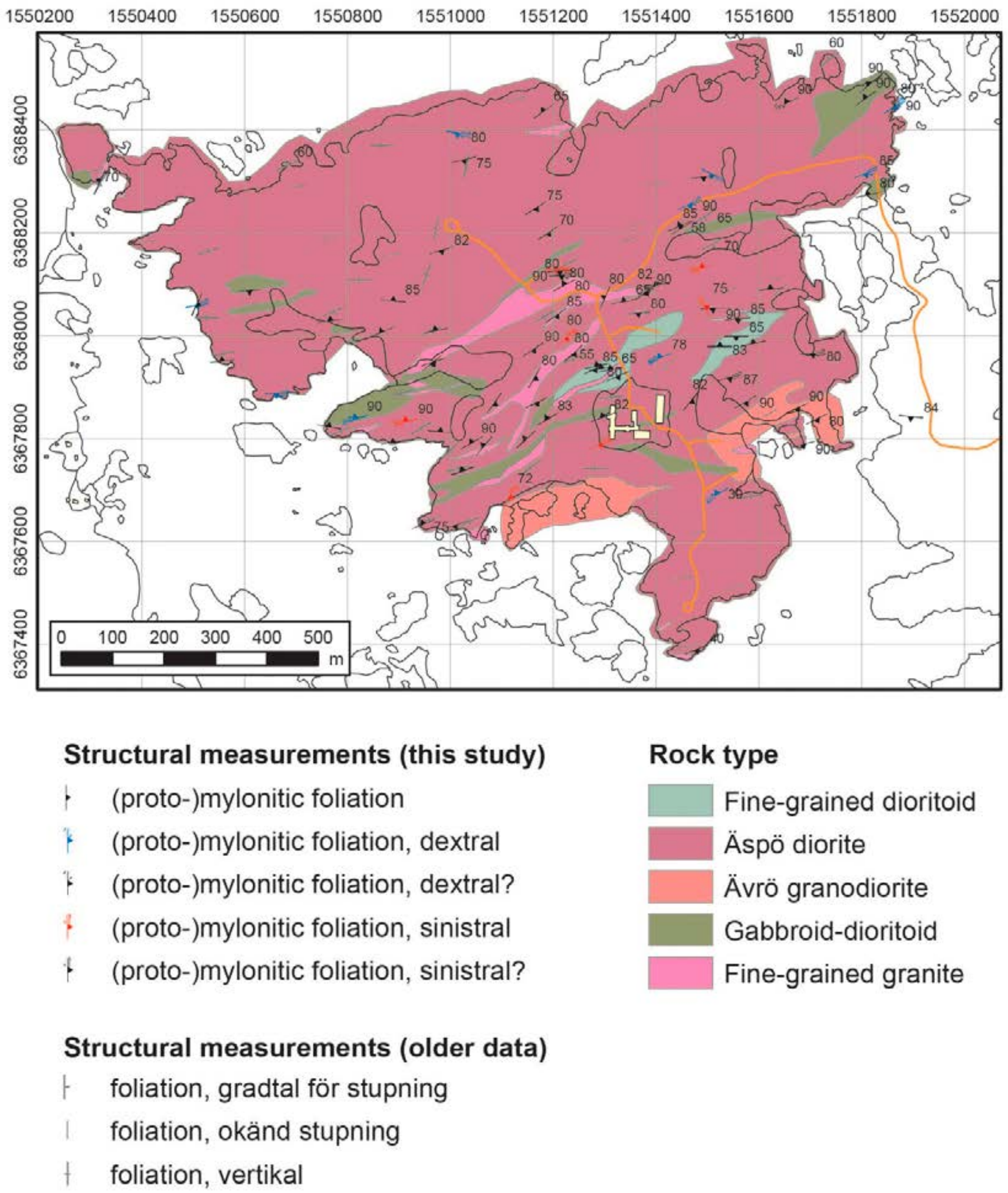

Figure 3-2. *Foliation measurements on Äspö. Kinematic indicators are shown. Numbers refer to dip angle. Symbols without dip angle represent measurements where it was not possible to measure the dip angle. Lithological background map modified after Kornfält and Wikman (1988) and its digitised version published in SKB (2006). Structural data from Kornfält and Wikman (1988) are also included and symbolised in grey. Rock type nomenclature after appendix 2 in SKB (2006). Reference layer file: SDEADM.HTC_AS_GEO_7645.*

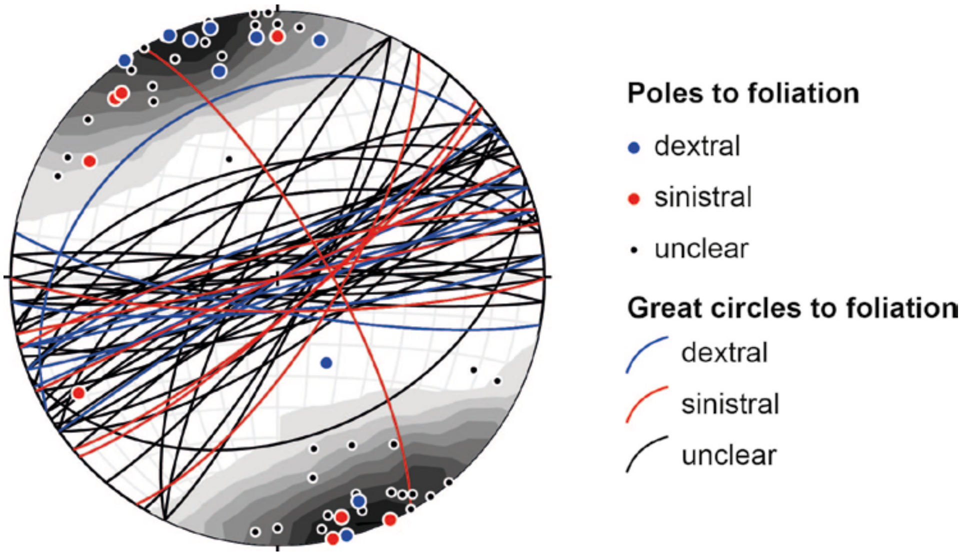

Figure 3-3. *Stereographic projection (lower hemisphere) of (proto-) mylonitic foliations from Äspö. Contours are Kamb for all foliations.*

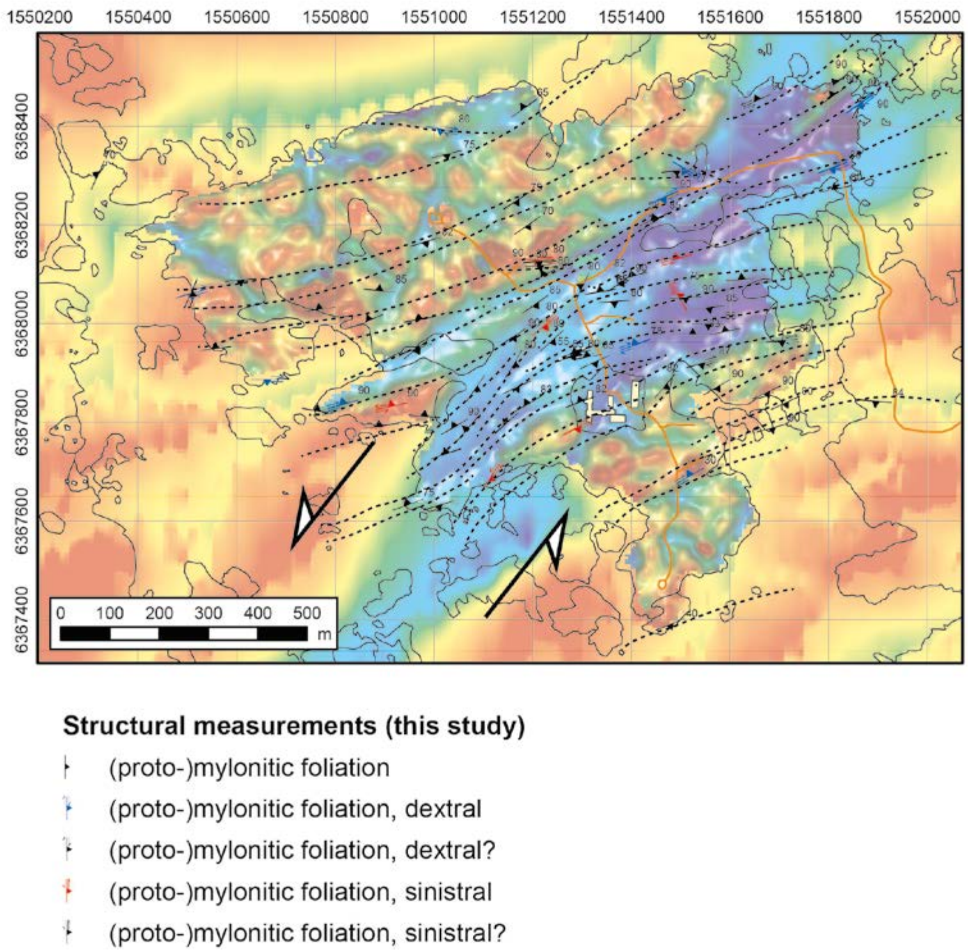

Figure 3-4. *Foliation formlines drawn based on outcrop measurements. The formlines deflect into a sinistral shear belt cutting through Äspö. The map in the background was compiled from ground and helicopter airborne data (reference layer file: SDEADM.GV_AS_GEO_8445). It shows the total magnetic field. Blue colours are magnetic minima, which often coincide with brittle or brittle-ductile deformation zones. Red colours are rocks with higher magnetisation. The shear belt corresponds to a low magnetic area cutting through Äspö.*

3.1.2 Ductile and brittle-ductile deformation zones

Due to the overall low temperature during ductile deformation on Äspö, it is often difficult to determine if deformation was originally ductile, brittle, or brittle-ductile or whether a deformation zone was brittlely reactivated. It is, however, quite common that the somewhat wider brittle-ductile deformation zones have got a core which exhibits clear signs of ductile deformation and mylonitisation, and towards the edges of these zones, deformation becomes more brittle. It is therefore suggested that, on Äspö, these deformation zones were active over a prolonged time and during the transition of the rocks from the ductile into the brittle regime.

Orientation and kinematics

Ductile and brittle-ductile deformation zones (mainly corresponding to the "mylonites" described by e.g. Kornfält and Wikman (1988) and Munier (1995) occur wide-spread across the island and are concentrated in the central part of Äspö (Figure 3-5). When plotted in a stereographic projection, a correlation becomes clear between the recorded kinematics of the deformation zones and their orientation (Figure 3-6). Deformation zones with sinistral displacement dip steeply towards NW or SE and strike NE-SW. The orientation of deformation zones with dextral displacement is somewhat more spread out, but their dominant strike is around WNW-ESE with a dip steeply towards NW or SE. This is in agreement with observations reported by Munier (1995).

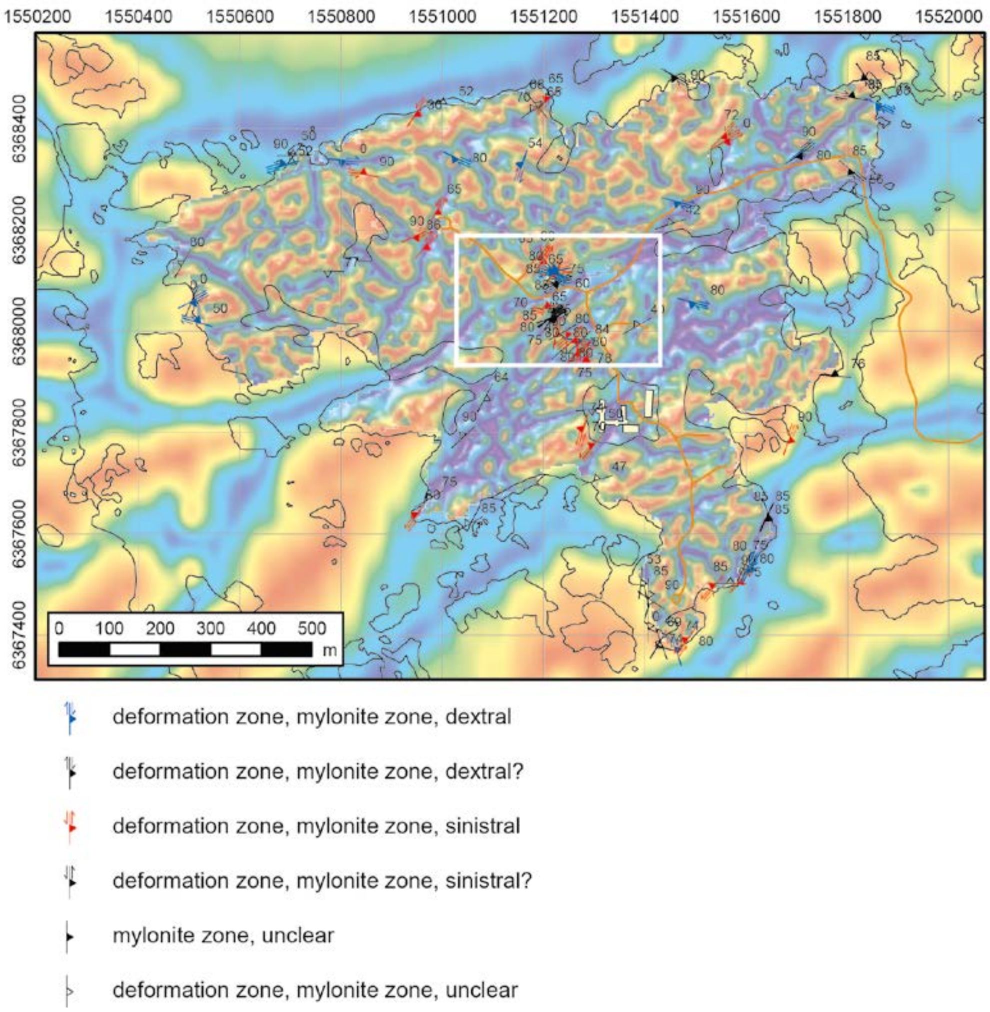

Figure 3-5. *Observed ductile and brittle-ductile shear zones and their labels. The map in the background shows the tilt derivative of the magnetic field. Magnetic data is from both ground and helicopter airborne measurements (reference layer files: SDEAM.GV_AS_GEO_8444, SDEAM.SKB_SM_GEO_1489). Blue colours are magnetic minima, which often coincide with brittle or brittle-ductile deformation zones. Red colours are rocks with higher magnetisation. The white box shows the approximate location of Figure 3-7.*

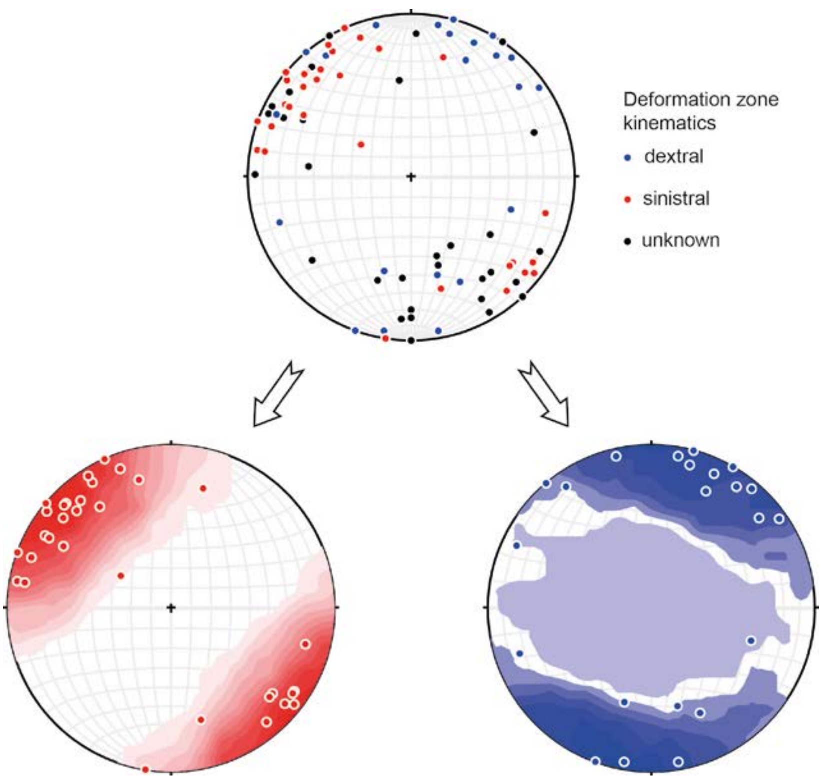

Figure 3-6. Stereographic projection (lower hemisphere) of poles to ductile and brittle-ductile deformation zones ("mylonites"). Contours are Kamb.

3.1.3 Central domain: ZSMNE005A and ZSMEW013A

In September 2016, a ca. 390 m long and ca. 10 m wide corridor of bedrock outcrops was stripped off of all soil and plant cover on behalf of SKB. This made it possible to study some of the deformation zones in detail. The corridor starts approximately at the SKB parking lot and extends north-westwards, crossing the entire low magnetic anomaly that corresponds to deformation zone ZSMNE005A (Wahlgren et al. 2008). It also crosses ZSMEW013A. This zone is, however, not well exposed and assumed to extend under the gravel road. The cleaned corridor corresponds approximately to the southern part of Trench 2 mapped in detail by Kornfält and Wikman (1988).

The central part of the Äspö shear zone consists of a belt of NE-SW striking, sub-parallel, ductile to brittle-ductile, predominantly sinistral shear zones (Figure 3-7). Shear zone widths are between decimetres and several metres. The shear zones are spaced by metres to tens of metres and become more frequent towards the core of the Äspö shear zone. Strong alteration, bleaching and red staining is common within these zones. Ductile precursors are sometimes preserved (Figure 3-8). The deformation zones occur often along lithological boundaries, and specifically along boundaries between fine-grained granitic rocks and coarser grained porphyritic quartz monzodiorite (Figure 1-2).

The core of the Äspö shear zone (Figure 3-9a) has undergone localised brittle deformation and is exposed as a strongly altered cataclasite which is dipping 70 degrees to the northwest at PAS000633 (Figure 3-9a, b). No primary structures could be observed in the cataclasite. It is therefore unclear whether the cataclastic zone is the result of reactivation of a mylonite zone or whether the deformation style was brittle from the beginning. Alteration continues for c. 21 m toward the NW (Figure 3-9a) where a c. 5 m wide belt consisting of several sinistral, brittle-ductile shear zones seems to mark the northwestern boundary of the Äspö shear zone (PAS000635-641, Figure 3-9c). These shear zones dip steeply to the southeast. Deformations zones located northwest and southeast of this high strain zone appear less altered and are more discrete and localized. The rocks located between the deformation zones are relatively unaffected by deformation.

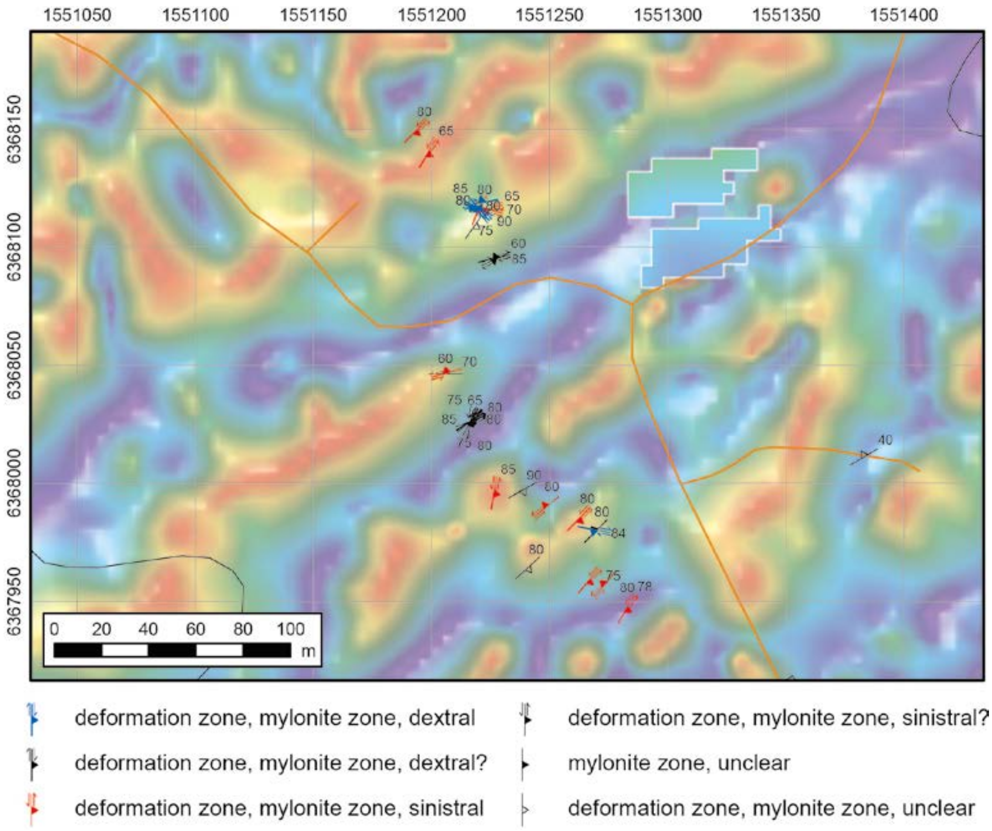

Figure 3-7. *Detailed map with plotted structural measurements within the Äspö shear zone and ZSMEW013A. Tilt derivative of magnetic field in background (reference layer file: SDEAM.GV_AS_GEO_8444). Note the high number of NE-SW striking ductile to brittle-ductile deformation zones with sinistral shear sense. For location of the detailed map, see Figure 3-5.*

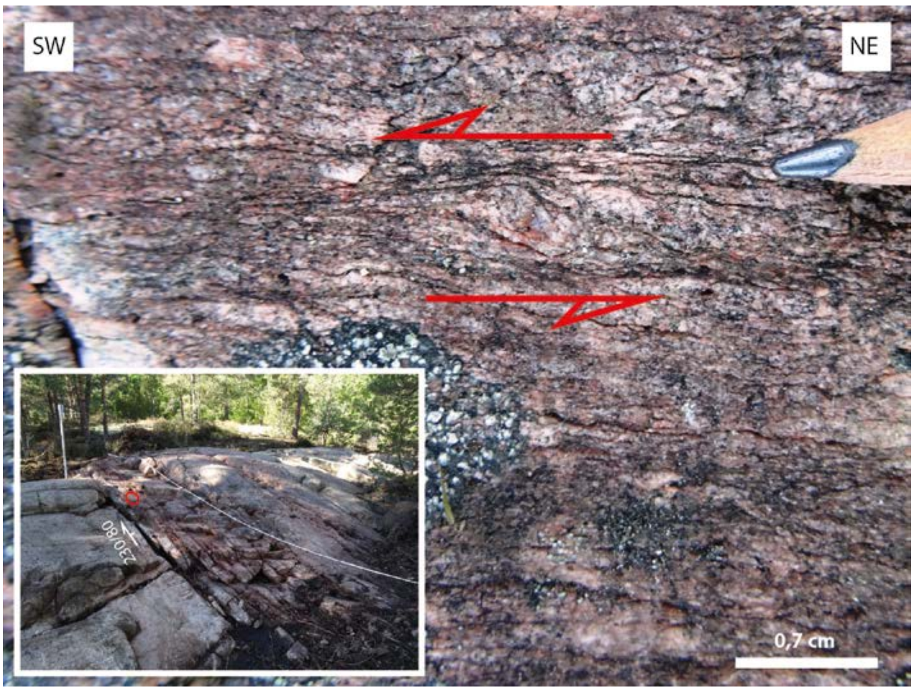

Figure 3-8. *Sigmoidal porphyroblast in porphyritic quartz monzodiorite indicates sinistral, ductile shearing. The red ellipse in the photograph in the lower left corner shows where in the brittle-ductile shear zone the porphyroblast was observed. Location PAS000628 (X6367990, Y1551248).*

Figure 3-9. *a) Cleaned trench across the central part of the Äspö shear zone. Chemical alteration can be observed across a c. 20 m wide zone (across the entire photography) and gives the rock a light grey to pink appearance.*

Figure 3-9. *b) Cataclasite in the core of the Äspö shear zone. The cataclasite consists of a c. 30 cm wide brittle shear zone that has undergone extreme alteration. Location: PAS000633 (X6368009, Y1551230).*

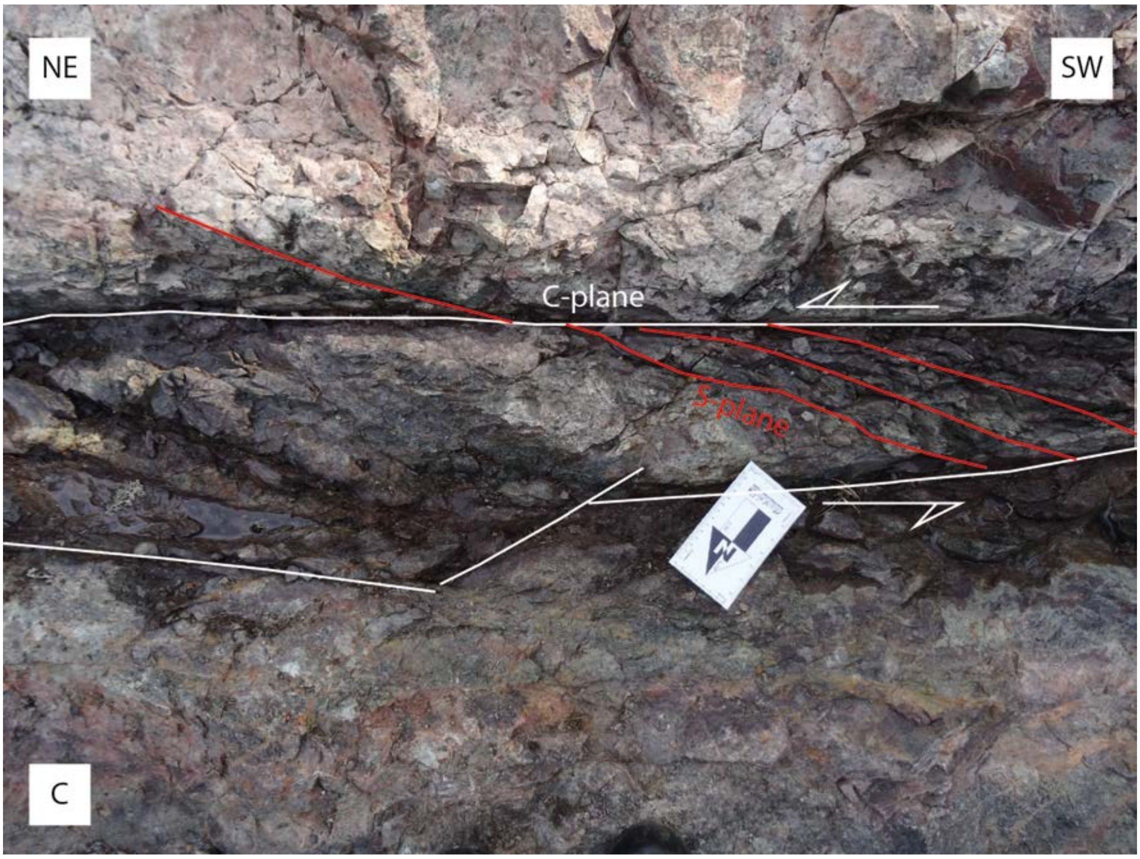

Figure 3-9. c) One of five brittle-ductile shear zones, c. 20 cm wide at the northern border of the central Äspö shear zone. CS-fabrics indicate sinistral shear. Location: PAS000641 (X6368026, Y1551217).

Deformation zone ZSMNE013A is poorly exposed and it is difficult to determine the associated sense of shear. It remains therefore difficult to determine whether ZSMNE013A cuts through ZSMNE005A, whether it terminates against it, or whether these two zones merge towards each other. However, what could be observed is that the strike of the deformation zones changes from dominantly NE-SW to ENE-WSW within the magnetic low that is caused by ZSMEW013A. A few of the measurements within or at the edge of that zone show dextral displacements whereas others record sinistral-reverse movement. More investigations are needed to determine the character of this shear zone more precisely.

3.1.4 Northern Äspö domain

The northern part of the island is marked by an approximately E-W trending deformation zone which is probably a splay of the major ZSMEW002A (Mederhult shear zone) to the north of Äspö. The western part of this zone trends c. WNW-ESE, and field observations made here seem to indicate predominantly dextral movement. The eastern part of the zone is oriented ENE-WSW, and a sinistral-reverse brittle-ductile shear zone was observed here.

Otherwise, the Northern Äspö Domain (cf. Figure 1-5) is characterised by a lack of wide shear zones compared to the Äspö shear zone. Instead, the domain seems to have undergone deformation along strongly localised zones. However, at a few locations, small-scale, cm-spaced, brittle-ductile shear zones could be found. These occur usually in conjugated pairs and are only recognisable if they offset geological markers such as granitic veins (Figure 3-10). The orientation of the conjugated pairs indicates that the maximum horizontal stress was oriented c. N-S during their formation.

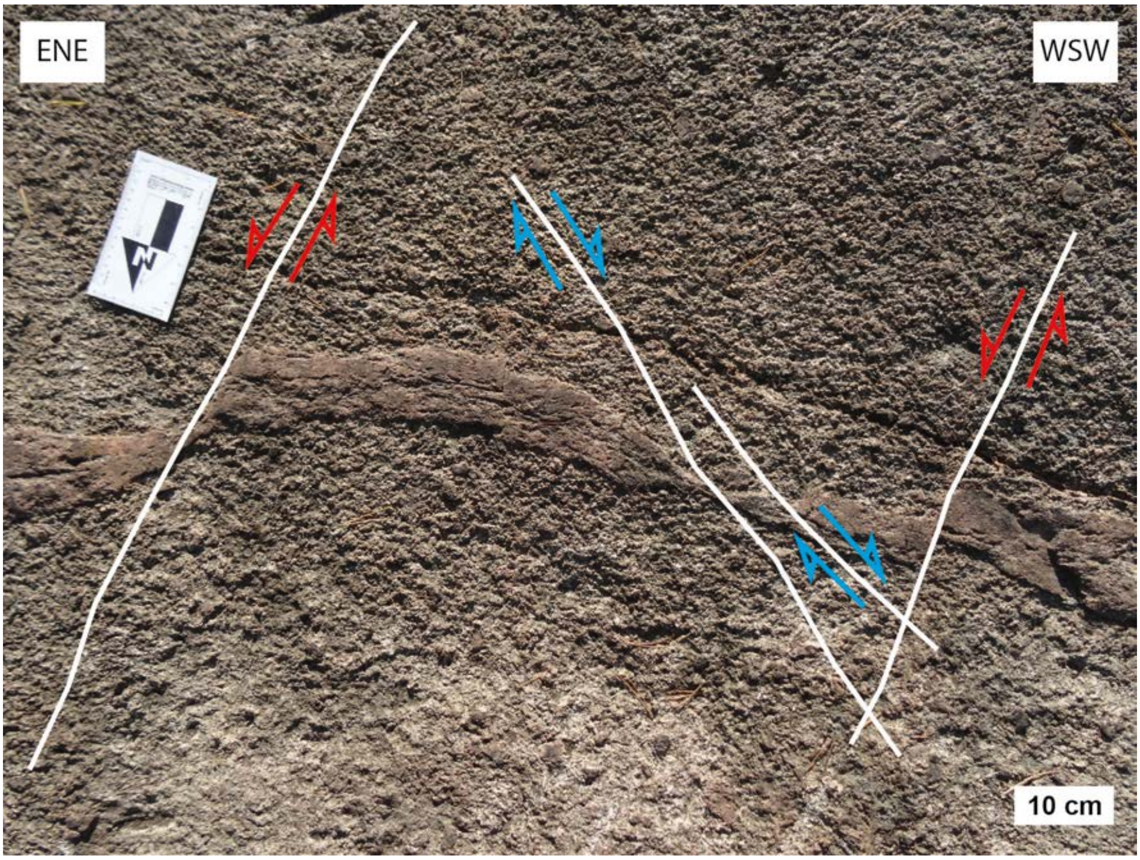

Figure 3-10. Set of conjugate, small scale brittle-ductile shear zones displacing a composite dyke (fine-grained granite). Sinistral strike-slip is marked with red arrows and dextral strike-slip is marked with blue arrows. Location: PAS000667-669 (X6368116, Y1551220).

3.1.5 Southern Äspö domain

In the southern part of Äspö (Figure 1-5), localised brittle-ductile and brittle deformation zones dominate. Especially along the coastal outcrops brittle-ductile, steeply dipping deformation zones were observed striking approximately NNE-SSW to NE-SW. Deformation zone widths are on the decimetre scale. NE-SW striking deformation zones observed along the eastern shore line are sub-parallel and both dextral and sinistral to sinistral-reverse slip has been interpreted from kinematic indicators (Figure 3-11). Based on the opposing sense of shear it is questionable whether these zones formed under the same stress conditions.

ENE-WSW to E-W oriented deformation zones also occur in the southern domain. These zones correspond to magnetic and topographic lineaments, but it remains often difficult to unravel their dip, strike and kinematics due to the lack of exposures.

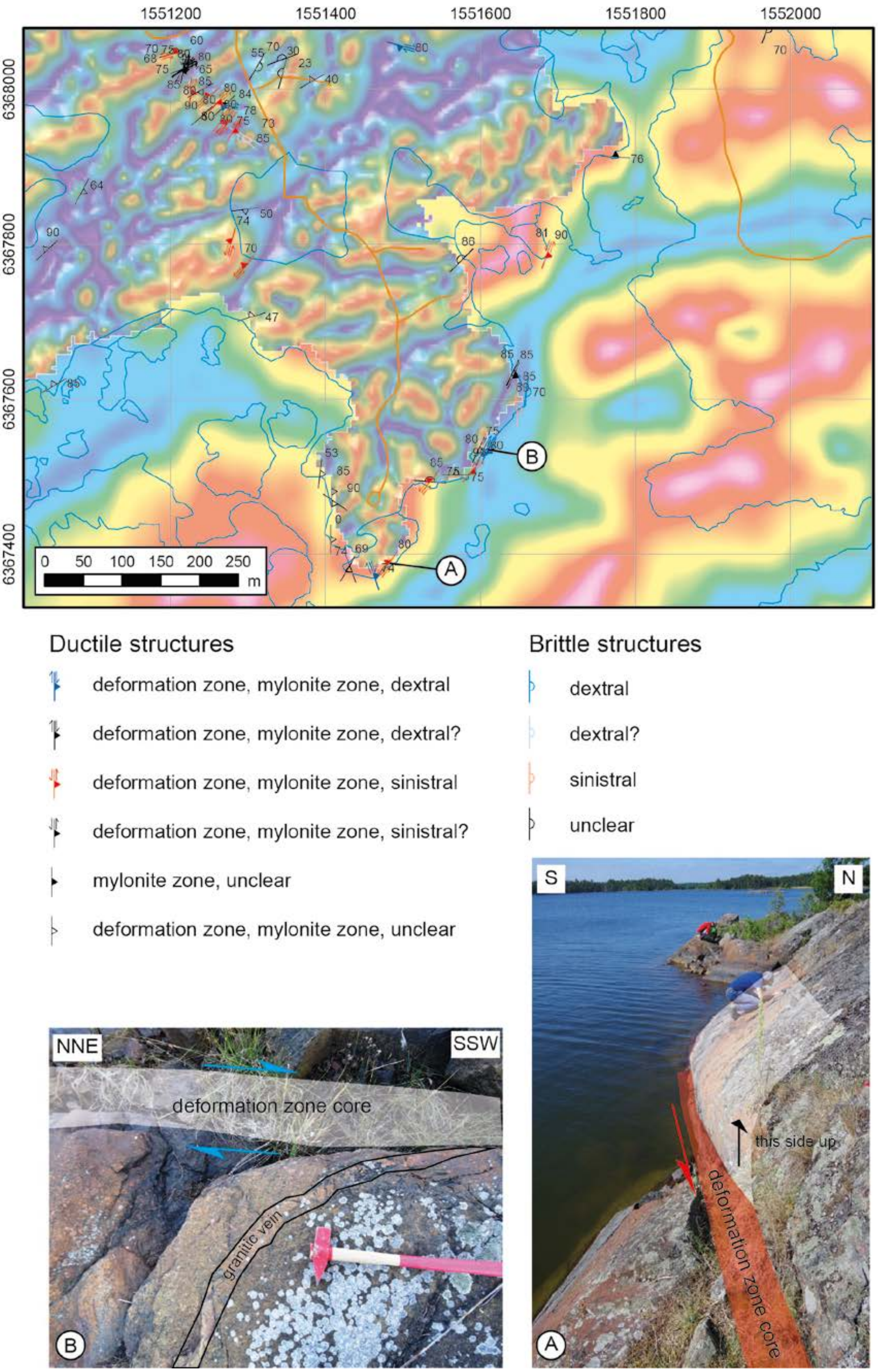

Figure 3-11. *Top: Structural measurements for brittle-ductile and ductile deformation zones observed in the Southern Äspö Domain. The map in the background shows the tilt derivative of the total magnetic field (reference layer files: SDEADM.GV_AS_GEO_8444, SDEADM.SKB_SM_GEO_1489). The photographs show that both sinistral-reverse (A) and dextral (B) deformation zones have the same NE-SW strike at the eastern shoreline of Äspö.*

3.2 Brittle deformation

3.2.1 Geophysical signature of brittle deformation

On the magnetic anomaly map (total field and tilt derivative) the Central Äspö domain is characterized by a network of magnetic lineaments. The network consists of three dominant sets (Figure 3-12) which strike on average N-S (FM1), NW-SE to WNW-ESE (FM2) and NE-SW (FM3). These sets correlate well with the three distinctive fracture sets measured in outcrop (see sections below). Consequently, the network of magnetic lineaments most likely represents the imprint of brittle deformation. However, a one to one correlation between magnetic lineaments and individual fractures observed in outcrop is difficult to determine because of the difference in resolution. The magnetic lineaments correspond to sets of brittle fractures or brittle-ductile deformation zones with a width of several metres rather than corresponding to single fractures or fracture zones. The spacing between magnetic lineaments of sets FM2 and FM3 ranges between 100 to 200 metres, and between 200 and 400 metres within set FM1. The total length of the magnetic lineaments varies between 100 to 500 metres for all sets.

3.2.2 Northern Äspö domain

Brittle structures in stereographic projection

From the total collection of steeply dipping fractures (dipping more than 60°) three main fracture sets were identified with three dominant orientations: N-S (Fs1), NW-SE to WNW-ESE (Fs2) and NE-SW (Fs3) (Figure 3-13). Within fracture set Fs1 two clusters of NNE-SSW and NNW-SSE orientations can be recognised which most likely correspond to conjugate fracture sets. Fracture sets Fs2 and Fs3 have a wider spread in strike distribution and no clustering is observed around a specific orientation. The mean orientation of subset Fs3 (NE-SW) is sub-parallel to the southern domain boundary, the main ductile foliation as well as to the Äspö shear zone. Fractures dipping less than 60° are mainly dipping with an angle between 40° and 60° and strike typically NE-SW or N-S.

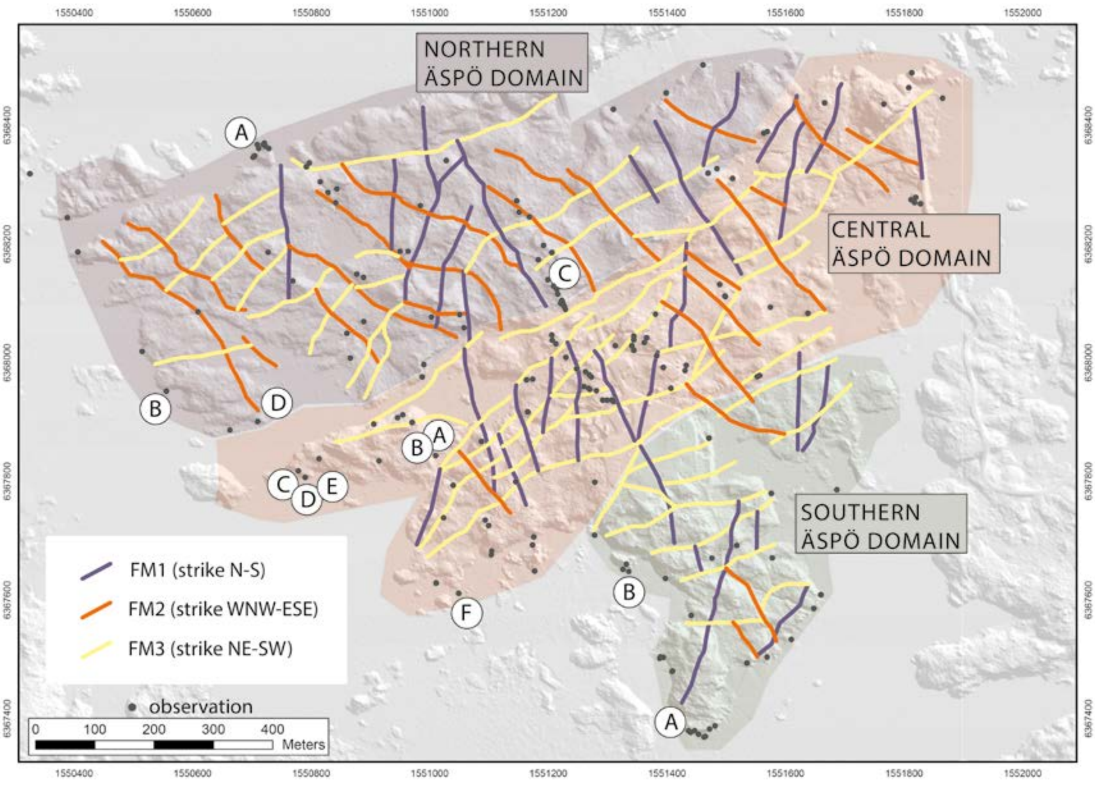

Figure 3-12. *Magnetic lineaments grouped into three main groups (FM1, FM2, FM3) based on strike. The lineaments were interpreted from the tilt derivative of the total magnetic field (Figure 1-6; reference layer: SDEADM.GV_AS_GEO_8403). Letters within circles refer to the outcrop pictures for each domain shown in Figure 3-14, 3-16 and 3-18. Small dots are locations of studied outcrops. Lidar-based shaded relief as background map and colouring refers to the three domains. Lidar data © Lantmäteriet.*

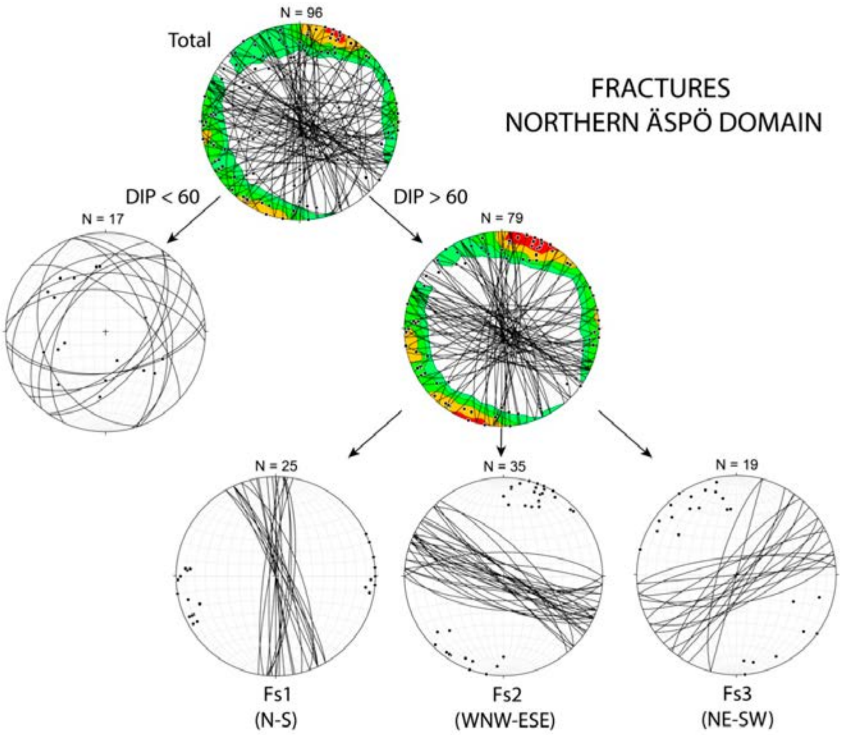

Figure 3-13. *Orientation and grouping of brittle structures from the Northern Äspö domain plotted on the lower hemisphere of a Schmidt, equal-area stereographic projection. The structures are plotted both as planes and poles to planes (dots). The colouring indicates contouring of the poles (red: high abundance). N refers to the total amount of plotted fractures. The fracture sets is divided into dip more than or less than 60° and orientation in NS (Fs1), WNW-ESE (Fs2) and NE-SW (Fs3).*

Brittle structures in outcrop

Within the northern Äspö domain, the most common brittle structures observed in outcrop are steeply dipping fractures belonging to fracture sets Fs1, Fs2 or Fs3 (Figure 3-13). No specific fracture set dominates within a certain area of the domain, and frequently all sets are present within a single outcrop (Figure 3-14a). However, the attitude of the fractures differs locally and also within the main fractures sets. For instance, fracture width, fracture spacing, fracture length and the style of fracture junctions typically vary within a few metres distance. As such, a specific fracture set can be best developed within a certain lithology (Figure 3-14b), whereas in a nearby locality fractures belonging to the same set may intersect or even displace lithological boundaries (Figure 3-14c). Fracture kinematics is another parameter that is variable within the three different fracture sets. In the northern Äspö domain, shear fractures belonging to fracture sets Fs1 or Fs2 reveal both dextral and sinistral slip movements. Within fracture set Fs1, opposing kinematics is mostly likely associated with the formation of conjugate sets, with NNW-SSE striking fractures accommodating primarily dextral slip and the N-S striking fractures sinistral slip (Figure 3-14c). In addition, some N-S striking fractures are clearly dilatational (mode 1) fractures and are often filled with quartz and epidote. Altogether these observations suggest formation of Fs1 during N-S to NNW-SSE shortening. The few observations on fault kinematics associated with fracture sets Fs2 and Fs3 are not straight forward to interpret in terms of shortening direction. Fractures belonging to fracture set Fs2 have a major imprint on the morphology of the northern Äspö domain and clearly shaped the western shore of the island (Figure 3-14d). The scarcity of kinematic indicators, however, may indicate that no significant horizontal movement has occurred along those large planes. Fracture set Fs3 also rarely exhibits kinematic indicators and is generally less well developed in the Northern Äspö domain compared to the Central Äspö domain.

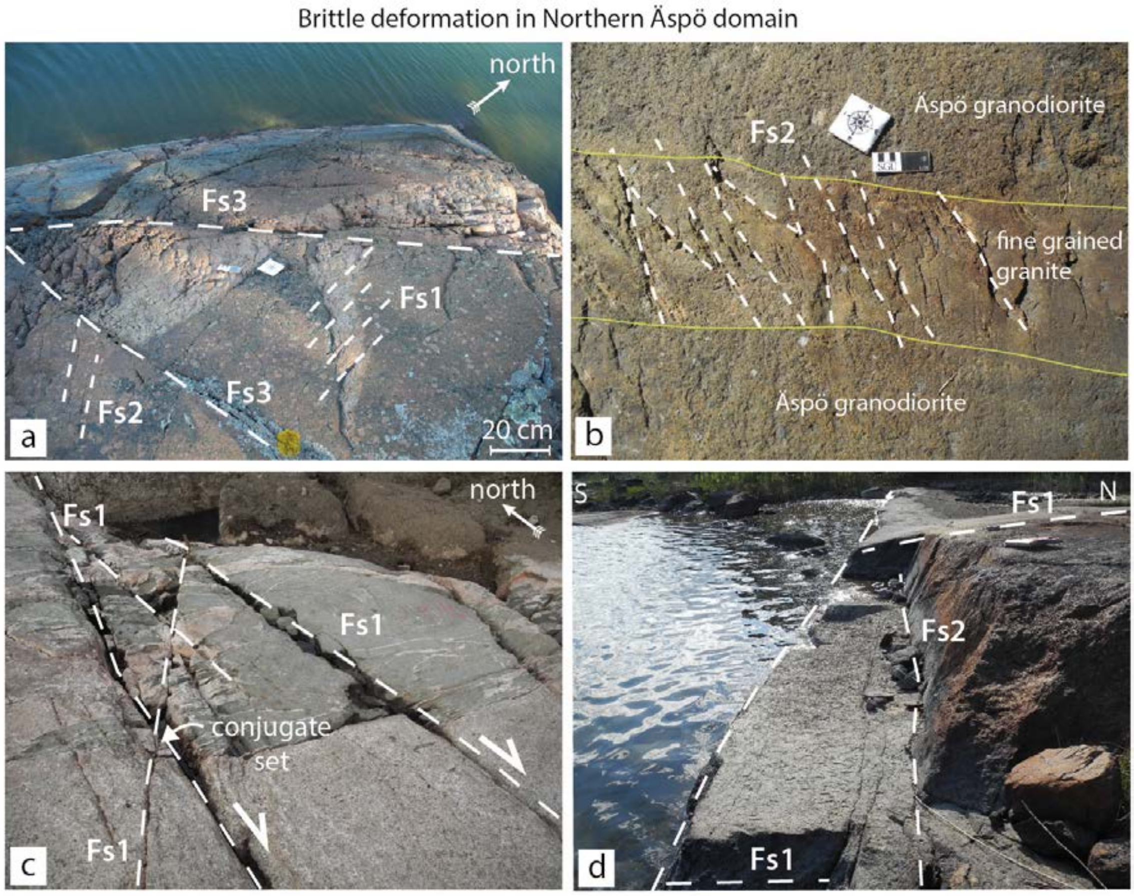

Figure 3-14. *Field observations of the rocks inside the Northern Äspö domain. a) Occurrence of all three main fracture sets within a single outcrop composed of Äspö granodiorite and pegmatite (light coloured rock). Location: PAS000412 (X6368370, Y1550721). b) Fracture set grouped as Fs2, which is developed mainly within the fine grained granite. Location: PAS000347 (X6367952, Y1550556). c) Fractures and conjugate sets included in fracture set Fs1 displacing dextrally the contact between felsic and mafic rock types. d) Fractures belonging to sets Fs1 and Fs2 within Ävrö granodiorite. The western shoreline of Äspö trends often parallel to Fs2 fractures. Location: PAS000352 (X6367900, Y1550710).*

3.2.3 Central Äspö domain

Brittle structures in stereographic projection

Similar to the Northern Äspö domain, steeply dipping fractures (dip > 60°) in the Central Äspö domain were grouped into three main fracture sets according to their mean strike: N-S (Fs1), NW-SE to WNW-ESE (Fs2) and NE-SW (Fs3) (Figure 3-15). Fracture sets Fs1 and Fs2 are fairly well clustered around their mean orientation, whereas fracture set Fs3 has a somewhat wider spread around the mean strike. The mean orientation of subset Fs3 (NE-SW) is parallel to the strike of the Central Äspö domain as well as to the main ductile foliation and the Äspö shear zone. In contrast with the Northern Äspö domain, most of the fractures within the Central Äspö domain belong to fracture set Fs3. Another difference between the two domains is that the majority of fractures dipping less than 60° are sub-horizontal or dip only very gently towards the north.

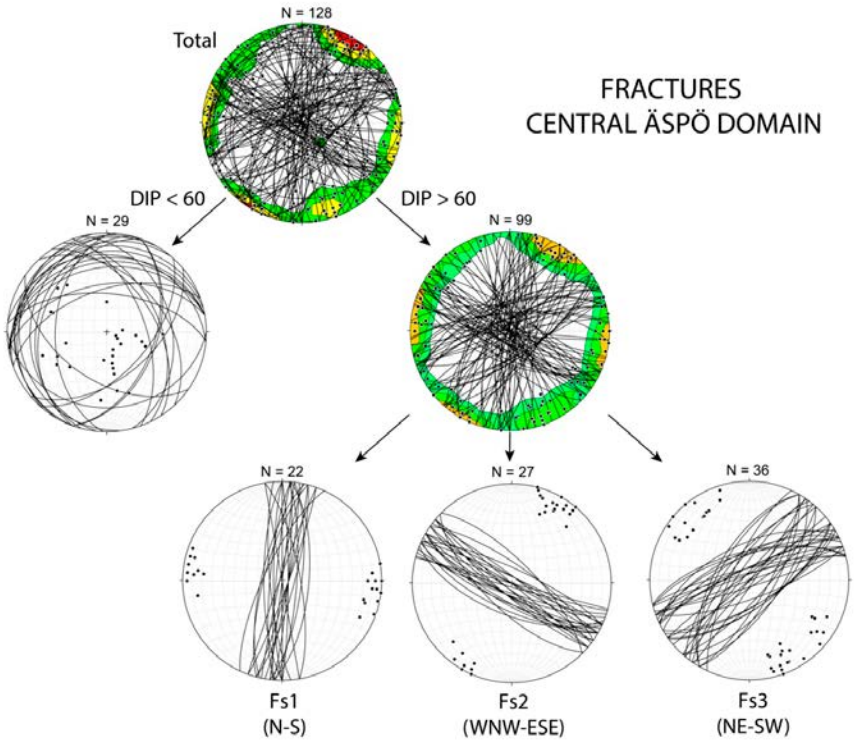

Figure 3-15. *Orientation and grouping of brittle structures from the Central Äspö domain plotted on the lower hemisphere of a Schmidt, equal-area stereographic projection. The structures are plotted both as planes and poles to planes (dots). The colouring indicates contouring of the poles (red: high abundance). N refers to the total amount of plotted fractures. The fracture sets is divided into dip more than or less than 60° and orientation in NS (Fs1), WNW-ESE (Fs2) and NE-SW (Fs3).*

Brittle structures in outcrop

The Central Äspö domain is characterised by very diverse structural features related to brittle deformation. Similar to the surrounding domains, most fractures observed in outcrop can be included into fracture sets Fs1, Fs2 or Fs3 (Figure 3-15). Many of the remaining fractures are sub-horizontal or shallowly dipping towards the north. Again, no specific fracture set dominates within a certain area of the domain, and more than one set was often identified within a single outcrop. However, fracture set Fs3 seems to be the dominant fracture set within the Central Äspö domain. Fractures included in this set form escarpments that can reach up to several tens of metres in length and are usually two to three metres in height (Figure 3-16a). The rocks along the escarpments are often fractured parallel to strike and are enriched mainly by K-feldspar, epidote, and more locally calcite and chlorite (Figure 3-16b). On the magnetic anomaly map, these escarpments often coincide with areas of low magnetic intensity. They may therefore actually reflect the margins of brittle-ductile or ductile deformation zones rather than being purely brittle deformation zones. However, some brittle reactivation along the margins of these zones seems likely to have occurred (see also previous sections on ductile deformation). Interpretations of kinematic indicators associated with fracture set Fs3 reveals that many of the fractures accommodated dextral or sinistral movements or even both. Unfortunately, no clear overprinting relationships were observed that could have revealed the relative timing of movements. The same holds for fracture sets Fs1 and Fs2 which often intersect, but without any observable horizontal displacement (Figures 3-16c–f). In several outcrops along the island's western shore conjugate sets were identified that match with the orientation of fracture set Fs1. Although the evidence on the kinematics associated with these conjugate sets is often lacking, N-S directed shortening direction is inferred from their acute angle. In addition, N-S striking fracture zones of 20 to 30 cm in width were observed and included in fracture set Fs1. Internally, these zones shows a complex network of at least two different fracture sets, Fs1 and Fs2, (Figure 3-16e,f). These fracture sets intersect without the accommodation of horizontal displacement.

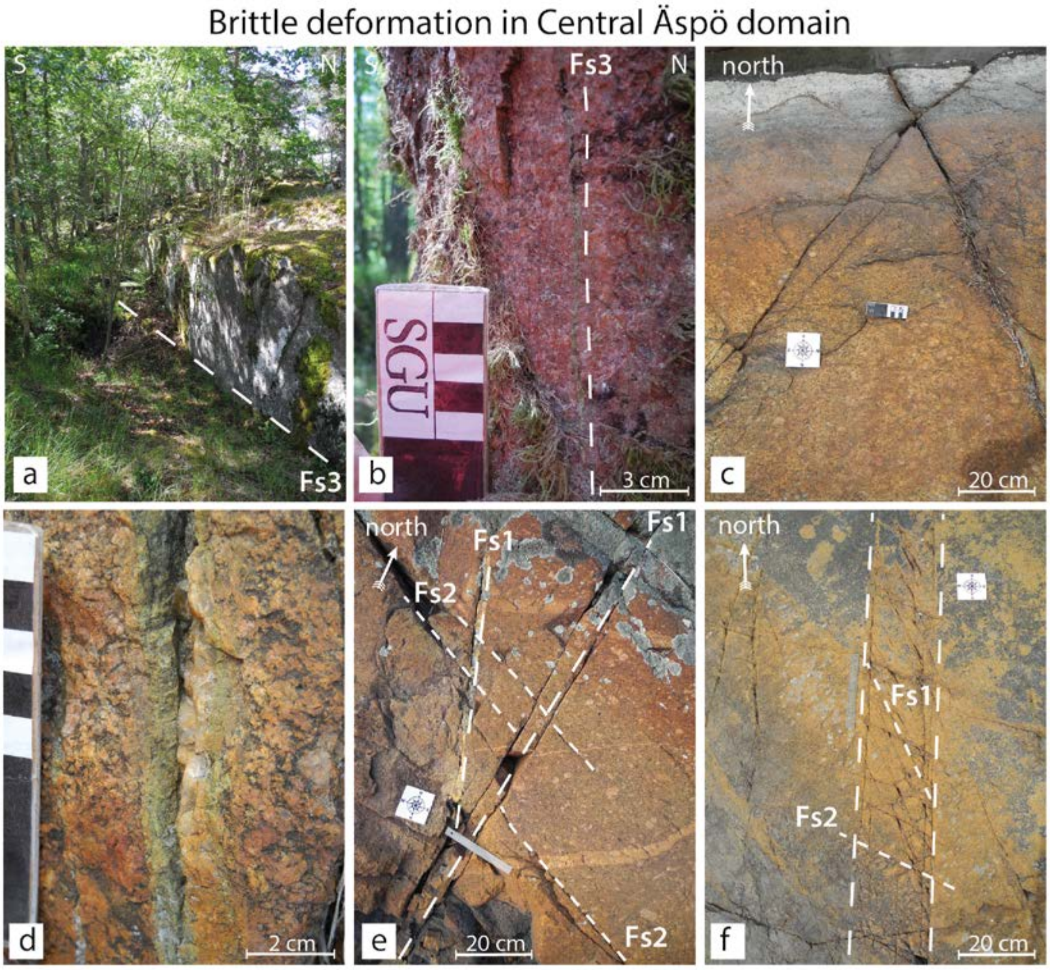

Figure 3-16. *Outcrop observations of the rocks inside the Central Äspö domain. a) Escarpment associated with the margin of a deformation zone striking parallel to fracture set Fs3. b) Rocks along the escarpment are often altered by K-feldspar and epidote occurring penetrative and in veins striking parallel to the escarpment, respectively. Location: PAS000305 (X6367844, Y1551010). c) Conjugate fracture set consistent with N-S directed shortening. Location: PAS000316 (X6367807, Y1550790). d) N-S striking fracture filled with epidote along the margins and quartz in the centre. Location: PAS000316 (X6367807, Y1550790). e) Intersection between fractures set Fs2 and fracture zones of Fs1 within porphyritic Äspö granodiorite. The ductile foliation strikes parallel to the bottom of the picture. Location: PAS000301 (X6367634, Y1550946). f) N-S striking fracture zone with associated fracture sets Fs1and Fs2. Notice that both fracture sets also occur outside the fracture zone. Location: PAS000296 (X6367611, Y1551049).*

3.2.4 Southern Äspö domain

Brittle structures in stereographic projection

The three main fracture sets identified for the Northern and Central Äspö domain can also be recognized in the fracture dataset collected throughout the Southern Äspö domain (Figure 3-17). However, the relative small amount of data did not allow for a reliable subdivision into main fracture sets (Figure 3-15). In addition, a disperse distribution or fanning pattern of the plotted fracture data make it difficult to identify clusters defining a particular fracture set. Another typical characteristic for the southern Äspö domain is the relative large amount of fractures with shallow to moderate dip angles, which dip mainly towards the north but also towards the south.

Brittle structures in outcrop

The Southern Äspö domain features relatively large outcrops (Figures 3-18a, b). In particular, along the shore of the island`s southernmost tip, the orientation of many fractures, overprinting various ductile fabrics, were measured. The fractures were grouped in the field into fractures sets, conjugate sets, fracture zones, and faults. Specific to the Southern Äspö domain are abundant moderately dipping fracture sets. At the southernmost tip for example, two fracture sets dip at an angle of 37° but in opposite directions. Both sets are closely spaced (around 10 cm) and are intersected by steeply dipping conjugate sets of which the NE-SW striking fractures are mostly associated with sinistral slip and the NW-SE striking fractures with dextral slip. The interpreted kinematic indicators were mainly slickensides composed of quartz or calcite. The bulk of the associated slickenlines plunge very shallowly revealing that slip along the fractures was primarily horizontal. Other intersecting fracture sets are dilatational fractures or veins striking mainly N-S (Figure 3-18b). This suggests that many of the fractures in the Southern Äspö domain probably formed during shortening in N-S direction, similar to the fractures included into the Fs1 fracture set in the Northern Äspö domain.

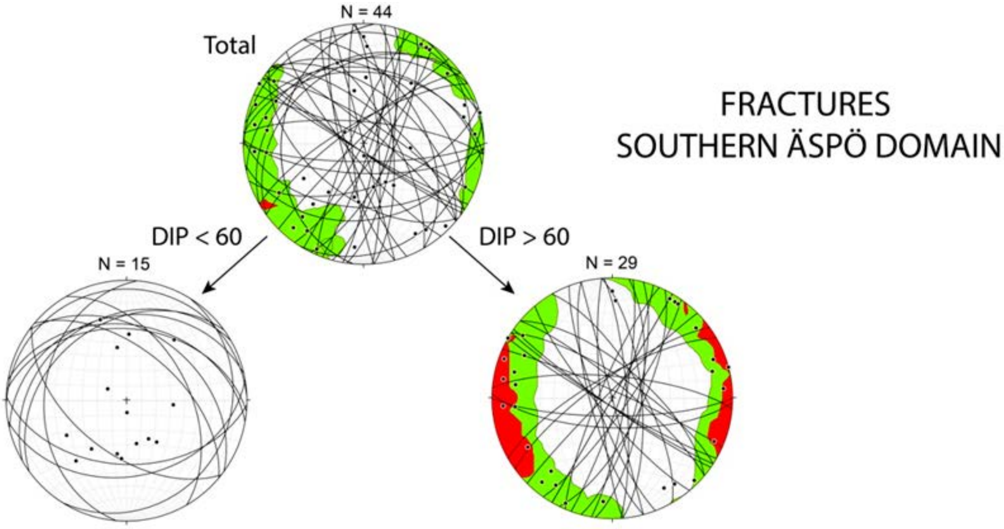

Figure 3-17. *Orientation and grouping of brittle structures from the Southern Äspö domain plotted on the lower hemisphere of a Schmidt, equal-area stereographic projection. The structures are plotted both as planes and poles to planes (dots). The colouring indicates contouring of the poles (red: high abundance). N refers to the total amount of plotted fractures. The relative small amount of data did not allow for a reliable subdivision into main fracture sets (see Figure 3-15).*

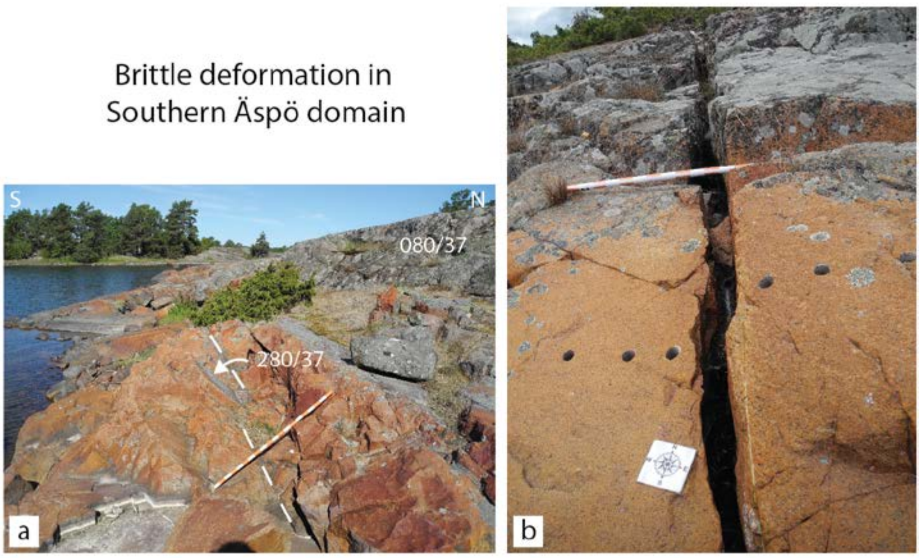

Figure 3-18. *Field impression of the rocks inside the Southern Äspö domain. a) Two different fracture sets dipping only at an angle of 37°. Measuring tool is 1 meter long. Location: PAS000253 (X6367370, Y1551453). (b) NNW-SSE striking joint that may be connected to water bearing fractures observed in the tunnel below –220 m, e.g. subvertical dipping and WNW to NW-SE to ESE striking water conductive fractures. Location: PAS000277 (X6367661, Y1551332).*

4 Data interpretation and structural geological model for Äspö

4.1 Deformation zones kinematics and domains

A geological interpretation of the deformation zones (Figure 4-1) was made mainly based on the field observations collected during this field period and on interpretation of geophysical lineaments (Mattsson and Wahlgren 2010) derived from magnetic, resistivity and topographic data. Detailed maps by Kornfält and Wikman (1988) and Munier (1995) were also used as a base, as well as the updated geological model for Äspö from Berglund et al. (2003). The interpreted deformation zones are delivered to SICADA as polyline features.

One of the most difficult tasks was to estimate the length of individual deformation zones since they are generally not exposed along their entire length. In the Northern and Southern Äspö Domain the magnetic lineaments derived from the tilt derivative of the magnetic field can locally be used in order to determine the length of predominantly brittle and brittle-ductile deformation zones and major fracture sets. However, in the Central Äspö Domain it was usually not possible to assign a single magnetic lineament to a single deformation zone. This is to a higher sampling resolution in the field with respect to the resolution of the ground magnetic data.

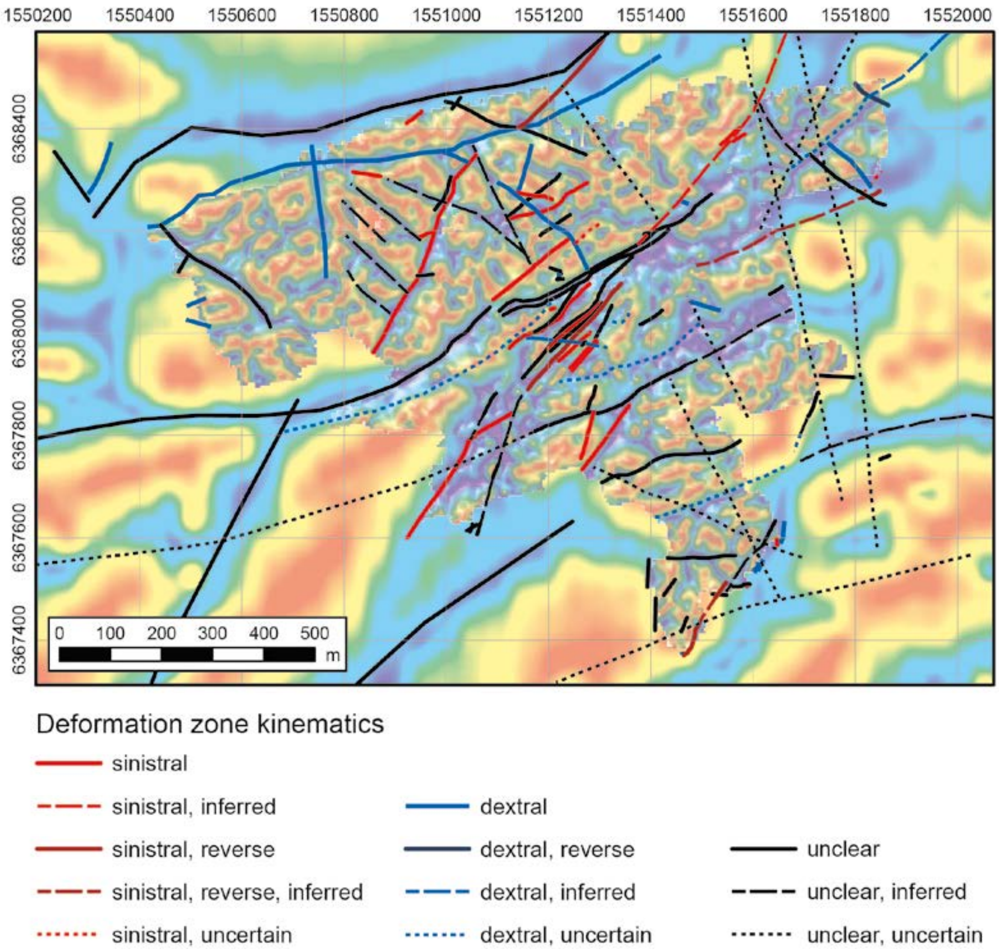

Figure 4-1. *Deformation zones grouped according to the observation of kinematic indicators. The zones are interpreted on the basis of field data collected during this study, and magnetic and topographic lineaments. In this figure no difference was made between brittle, ductile, or brittle-ductile deformation zones, however, this information is included in the shape file that was delivered to SICADA. The map in the background shows the tilt derivative of the total magnetic field (reference layers: SDEADM.GV_AS_GEO_8444, SDEADM.SKB_SM_GEO_1489).*

It´s possible that ductile deformation and chemical alteration during deformation have made the differences in magnetic susceptibility unclear leading to an overall low magnetic response in the Central Äspö domain. Magnetic susceptibility was measured on a few outcrops within the Äspö shear zone, but did not result in noticeable differences between mylonite zones and less deformed rocks. The lengths of the individual deformation zones in the structural geological map (Figure 4-1) have a high uncertainty and must be treated with caution during further modelling.

An attempt was made to group the deformation zones into domains which coincide with broad areas of low magnetic intensity in order to estimate the width of those areas that are affected by high strain deformation relative to those that accumulated less strain (Figure 4-2). In Figure 4-2 it becomes clear that the NE-SW trending Äspö shear zone consists of several spaced, predominantly sinistral deformation zones. Its thickness ranges from 130–350 metres. Major ENE-WSW trending deformation belts (like ZSMEW013A) are generally thinner (20–120 m) than the Äspö shear zone and occur at c. 100–300 m spacing. It appears that ENE-WSW oriented shear belts contain predominantly dextral deformation zones, but it is important to note that most of these zones are classified as uncertain and the dominant shear direction within these zones needs further investigation.

On the basis of the orientation and according shear sense of mylonite zones, ductile and brittle-ductile shear zones and brittle fractures, it is inferred that the largest horizontal stress was oriented c. N-S during the establishment of the shear zones and the bulk of the fractures. It is also suggested that the ductile and brittle-ductile structures observed on Äspö developed in a transpressive tectonic regime.

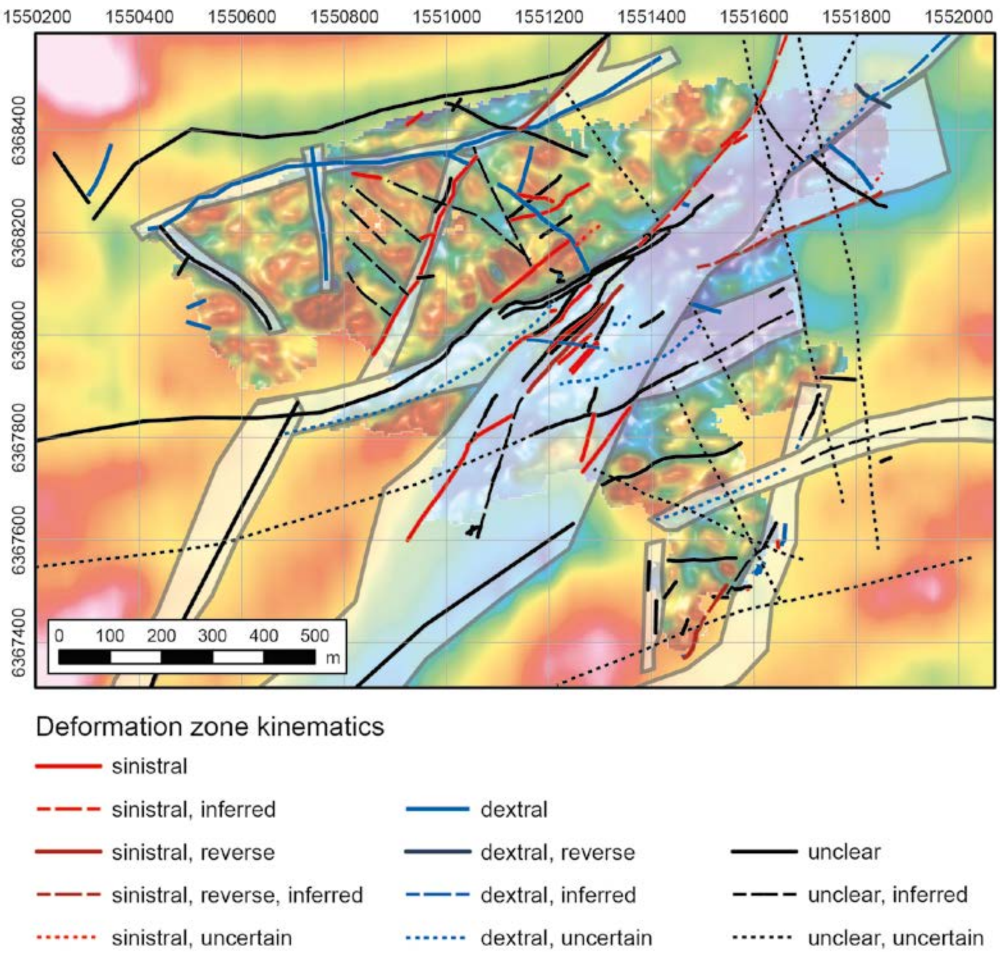

Figure 4-2. *Deformation zones from Figure 4-1 grouped into domains that are interpreted to be major shear belts (transparent polygons). The map in the background shows the total magnetic field (reference layer: SDEADM.GV_AS_GEO_8445, SDEADM.SKB_SM_GEO_1489).*

The northern domain is interpreted to be a contraction-controlled domain (CCD), accumulating most of the compressional component. The central domain is a so-called wrench-controlled domain (WCD) with the Äspö shear zone in particular taking up most of the sinistral strike slip movement. Although the southern domain is probably also contraction-controlled, there are some irregularities regarding the NE-SW striking, brittle-ductile, *dextral* shear zones which are not expected to develop under N-S directed compression.

4.2 Scenarios of development of deformation zones

The relationship between ENE-WSW trending deformation zone ZSMEW013A and the main Äspö shear zone ZSMNE005A could not be resolved due to a lack of reliable kinematic indicators for ZSMEW013A. Four scenarios could be evoked that require confirmation through further studies.

1) A first scenario, both deformation zones formed under N-S compression, but since ZSMEW013A is oriented nearly perpendicular to the compression direction, it takes up a larger amount of dip slip than ZSMNE005A.

2) A second scenario (Viola 2008) where the Äspö shear zone forms a major C'-band belonging to a several tens of kilometres wide sinistral shear belt occurring between the Oskarshamn shear zone in the south (~20 km from Äspö) and the Mederhult shear zone in the north (ZSMEW002A). This scenario would require that the E-W oriented structures such as ZSMEW013A are parallel to the main shear belt boundaries and that the major compression direction was NE-SW. Under a NE-SW directed maximum horizontal stress it would be possible to explain the dextral NE-SW oriented brittle-ductile shears mentioned above. Instead, it would require an E/ENE-W/WSW directed maximum horizontal stress to form these dextral deformation zones. Such stress conditions were suggested to have produced brittle shear fractures during the Sveconorwegian orogeny (Viola et al. 2009).

3) A third scenario could be that deformation zone ZSMEW013A has developed before or coevally to ZSMNE005A and during ongoing N-S compression and shearing along ZSMNE005A is displaced sinistrally along ZSMNE005A.

4) The last senario both the Äspö shear zone (ZSMNE005A) and ZSMNE013A develop coevally during N-S compression at first. A later stress change to NW-SE compression during the Caledonian orogeny leads to brittle reactivation of ZSMEW013A, dextrally displacing the formerly ductile Äspö shear zone.

All of these scenarios can explain parts of the deformation zone patterns observed on Äspö. However, more work is recommended in order to fully understand the development of these deformation zones. In particular, better kinematic constraints for ZSMEW013A are required.

5 Conclusion

In this report structural data based on field measurements at the ground surface at Äspö are presented. The study included also an evaluation and compilation of structural geological map of Äspö highligting a complex network of deformation zones. The map was constructed by combining the new field observations and structural measurements with identified geophysical lineaments.

The result reveals that NE-SW striking, sinistral, ductile and brittle-ductile deformation zones are dominating in the central part of Äspö, whereas smaller scale WNW-ESE oriented zones predominantly accommodated dextral movements. Three steeply dipping brittle fracture sets striking N-S, WNW-ESE, and NE-SW overprint the ductile fabrics and dissect the island into smaller structural blocks. A N-S maximum compressive stress during ductile, brittle-ductile and brittle deformation can be inferred from fabric orientations and kinematic indicators.

All four presented scenarios could explain parts of the deformation zone patterns observed on Äspö. However, more work is recommended in order to fully understand the development of these deformation zones. In particular, better kinematic constraints for ZSMEW013A are required.

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