R-10-05

Oskarshamn site investigation

Bedrock geology – overview and excursion guide

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September 2010

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ISSN 1402-3091
SKB R-10-05

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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 author. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

A pdf version of this document can be downloaded from www.skb.se.

Contents

1 Introduction

1.1 Background

Between 2002 and 2008, the Swedish Nuclear Fuel and Waste Management Company (SKB) carried out detailed site investigations at two locations in Sweden, Forsmark and Laxemar-Simpevarp, in order to identify suitable bedrock for the construction of a repository at approximately –500 m elevation for the disposal of highly radioactive, spent nuclear fuel. During 2009, SKB decided to apply to the governmental authorities for a permit to construct a repository at the Forsmark site.

Geological mapping of the bedrock exposed at the ground surface was carried out during an early stage of each site investigation. These field data, together with airborne (helicopter) magnetic data, provided the basis for the construction of bedrock geological maps of the ground surface at each site, i.e. 2D geological models for the distribution of rock units on this surface.

The bedrock geological maps, together with data obtained from drilling activities down to approximately –1,000 m elevation, subsequently provided the basis for the construction of 3D geological models for rock domains at Forsmark /Stephens et al. 2007/ and Laxemar-Simpevarp /Wahlgren et al. 2008/. The field data also provided a foundation for the choice of sample localities for mineralogical, geochemical and petrophysical analytical work, as well as for the choice of sites for drilling activities and for the detailed mapping of fractures at both Forsmark (see overview in /Stephens et al. 2007/) and Laxemar-Simpevarp (see overview in /Wahlgren et al. 2008/). Furthermore, the field data provided a basis for the choice of sample localities for geochronological studies at both sites /Söderbäck (ed) 2008/. In summary, the field observations at the ground surface at each site have been of major importance for our understanding of the bedrock geology at depth.

Bedrock mapping of the ground surface in the Simpevarp subarea was carried out during 2003 /Wahlgren et al. 2004/ and in the Laxemar subarea during 2004 /Persson Nilsson et al. 2004/. A bedrock geological map for the Simpevarp subarea /Wahlgren et al. 2004/ and a combined map for the Laxemar-Simpevarp area and surroundings /Wahlgren et al. 2005/ were subsequently developed and described. Based on an evaluation of analytical data and data from drilling activities, an updated bedrock geological map for the Laxemar-Simpevarp area was presented in /Wahlgren et al. 2006/.

1.2 Aim and scope

Bearing in mind the significance of the bedrock data from the ground surface for the geological 3D modelling work, SKB decided to present excursion guides that serve in the demonstration of the bedrock geology at the ground surface in both the Forsmark /Stephens 2010/ and Laxemar-Simpevarp (this guide) areas. An excursion guide is also available for the Olkiluoto area in south-western Finland, which has been selected for the construction of a repository for the disposal of highly radioactive, spent nuclear fuel /Paulamäki 2009/. The current excursion guide presents the bedrock geology and describes in detail the character of the bedrock at eight representative outcrops or outcrop areas at the ground surface in the site investigation area at Laxemar-Simpevarp and at one locality north of this area, i.e. at a total of nine localities.

2 Regional geological setting

Laxemar-Simpevarp is situated in eastern Småland in the south-eastern part of Sweden, approximately 230 km south of Stockholm (Figure 2-1a). A relatively gentle relief and a landscape situated below the highest shoreline, which developed after the latest Weichselian glaciation, characterize Laxemar-Simpevarp and the area of eastern Småland (/Lidmar-Bergström 1994, Lundqvist 1994/ and Figure 2-1a). However, on a more detailed scale, the landscape is variable, with recurrent transitions between hilly areas, which are mostly barren exposed bedrock or covered by a very thin soil cover, and valleys that are filled with Quaternary sediment.

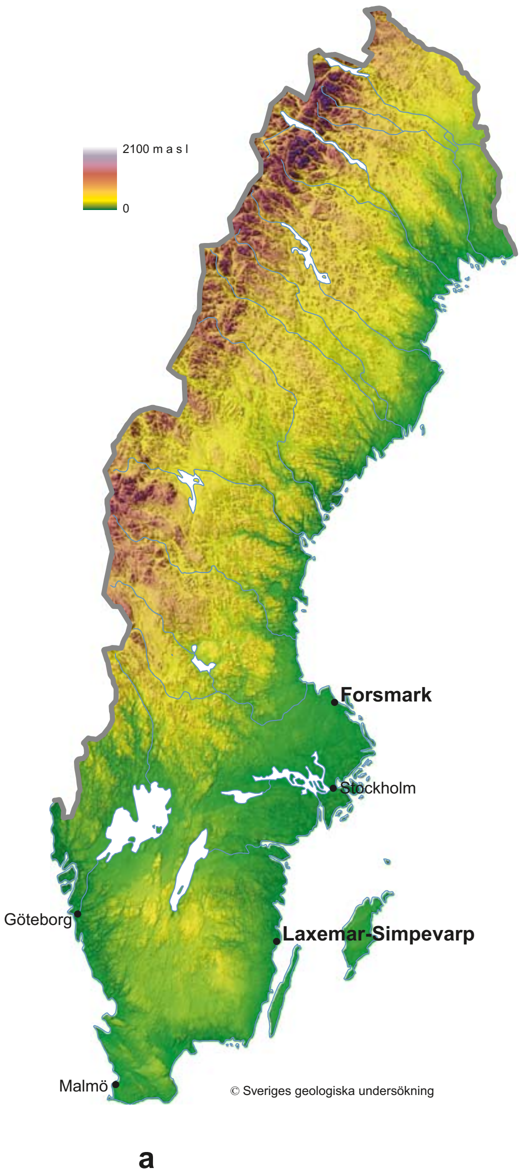
The bedrock surface beneath the unconsolidated, Quaternary glacial and post-glacial cover deposits, which is well exposed along the ground surface at Laxemar-Simpevarp, corresponds to the morphological structure referred to as the sub-Cambrian peneplain /Lidmar-Bergström 1994/. This ancient denudation surface formed more than 540 million years ago. It corresponds geologically to a sub-Cambrian unconformity and marks a long period of uplift and erosion with loss of the geological record between the formation of the crystalline bedrock and the deposition of the unconsolidated Quaternary cover deposits.

The bedrock in the Laxemar-Simpevarp area is situated inside the 1.9−1.8 Ga Svecokarelian orogen in the south-western part of the Fennoscandian Shield (Figure 2-2a), which forms one of the ancient continental nuclei on the planet Earth. Laxemar-Simpevarp lies south of and at a long distance from Sweden's important provinces for the exploitation of mineral deposits inside the Svecokarelian orogen (Figure 2-1b). This orogen is bordered by an Archaean continental nucleus to the north-east, by the Sveconorwegian orogen to the south-west and by Neoproterozoic and Phanerozoic sedimentary cover rocks of the East European Platform to the south-east (Figure 2-2a). In the north-west, the rocks in the Svecokarelian orogen are overthrust by rocks that belong to the Caledonian orogen (Figure 2-2a). The thickness of the continental crust in the Laxemar-Simpevarp area is around 50 km. However, directly south of Laxemar-Simpevarp, the crustal thickness decreases rapidly to a more normal crustal thickness of approximately 35 km /Kinck et al. 1993/.

The Svecokarelian orogen in south-eastern Sweden has been divided into six tectonic domains (tectonic domains 1 to 6 in Figure 2-2b). These domains have been separated on the basis of differences in either the timing of ductile deformation, metamorphism and igneous activity, or in the character and intensity of the ductile strain /Hermansson et al. 2007, 2008, Söderbäck (ed) 2008/. The Laxemar-Simpevarp area is situated in tectonic domain 5 (Figure 2-2b) that is dominated by igneous rocks belonging to the 1.8 Ga generation of the Transscandinavian Igneous Belt (TIB; Figure 2-2c), a major belt of 1.87−1.66 Ga intrusive and volcanic rocks. These rocks formed as a result of an intense period of igneous activity in connection with oblique subduction along an active continental margin during the waning stages of the Svecokarelian orogenic cycle.

In sharp contrast to the tectonic domains farther north (Figure 2-2b), tectonic domain 5 is dominated by rocks that are, in general, hardly affected by ductile deformation and metamorphism. However, areas that show more penetrative ductile deformation as well as low-temperature ductile high-strain zones in otherwise well preserved bedrock are present (Figure 2-2c). Consequently, the overall ductile structural character of the bedrock in tectonic domain 5, in general, and in the Laxemar-Simpevarp area, in particular, is more or less isotropic to only slightly anisotropic.

After 1.8 Ga, the focus of tectonic activity shifted away from the south-eastern part of Sweden, and the Svecokarelian orogen, towards the south and west. However, igneous activity locally continued to affect the bedrock in the south-eastern part of the country during the Proterozoic, around and after 1.7 Ga, and deformation in the brittle regime prevailed. Furthermore, sedimentary cover rocks were deposited on the Palaeoproterozoic bedrock in this area and subsequently largely removed, during both the Proterozoic and during the Palaeozoic. These post-1.8 Ga geological events can be correlated with tectonic events that were far-field with respect to Laxemar-Simpevarp (see overview in /Söderbäck (ed) 2008/ and Figure 2-3).



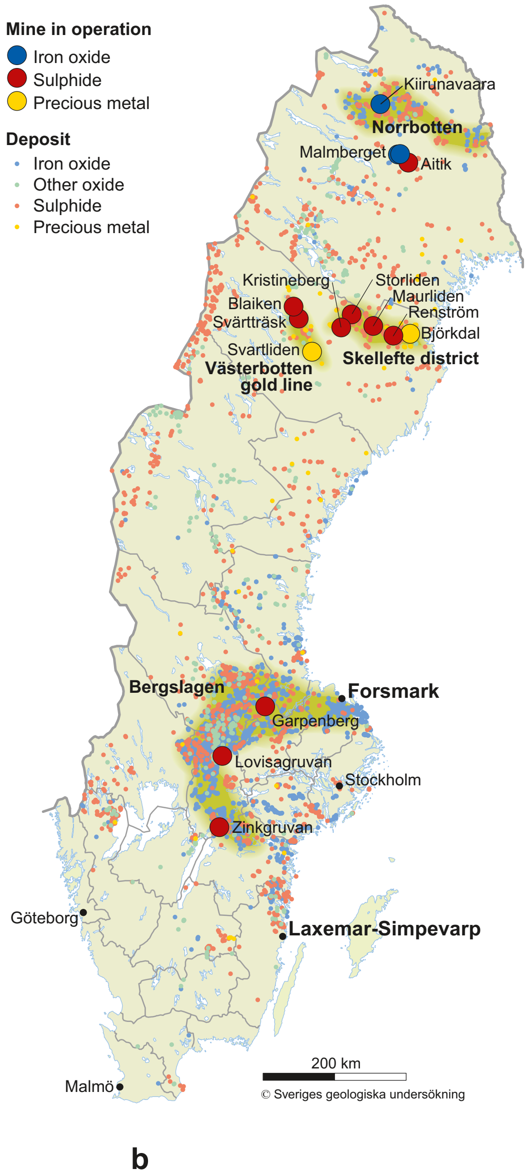


Figure 2-1. *Laxemar-Simpevarp in a regional topographic and mineral resource perspective. a) Digital relief map of Sweden based on the digital 50 m elevation database from Lantmäteriverket. Note the gentle relief along the coast in the Laxemar-Simpevarp area. b) Major mineral resource provinces in Sweden.*

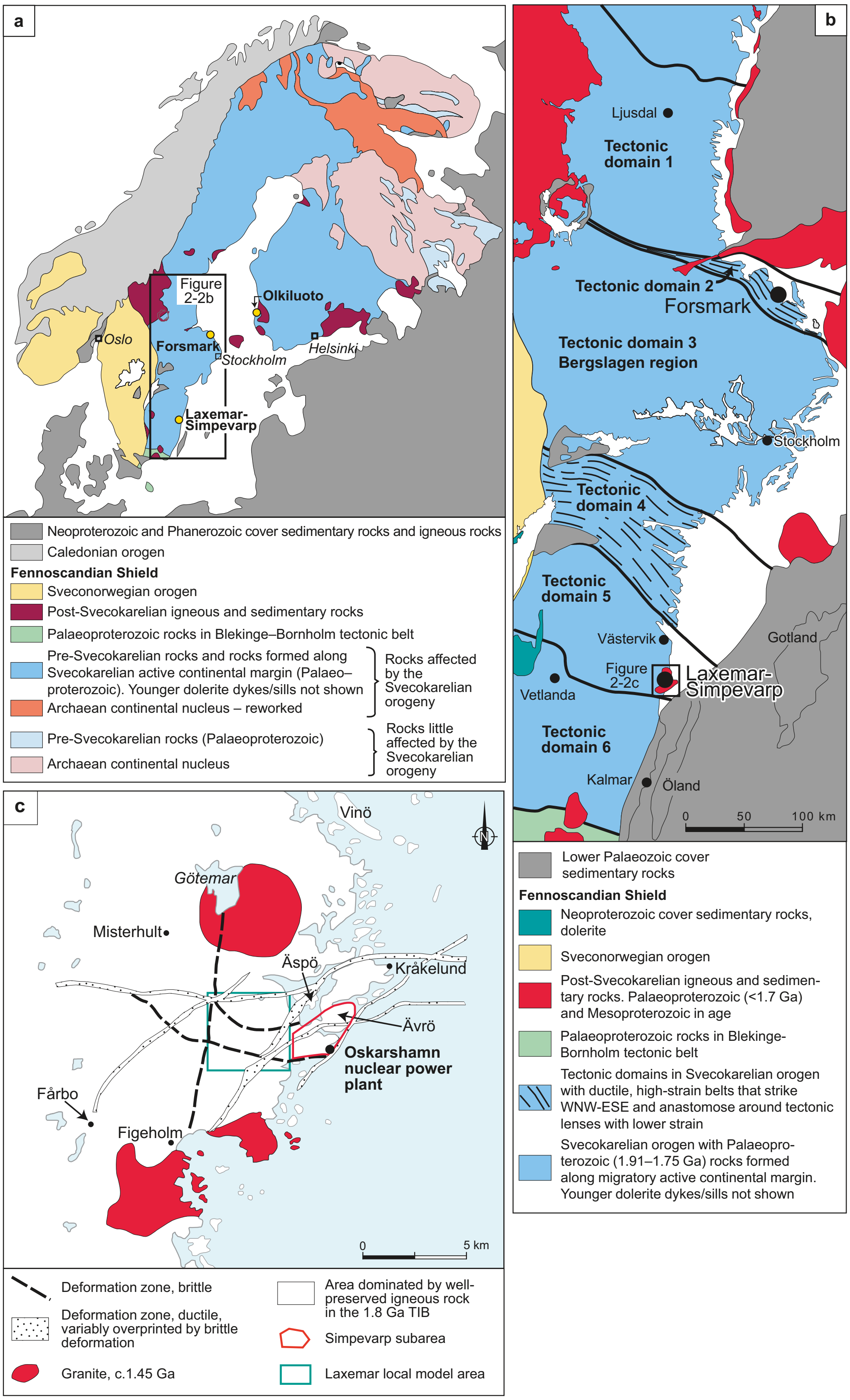


__Figure 2-2.__ Regional geological setting of the Oskarshamn site. a) Major tectonic units in the northern part of Europe at the current level of erosion (modified after /Koistinen et al. 2001/). The locations of Forsmark and Laxemar-Simpevarp as well as the proposed repository site at Olkiluoto in Finland are also shown on the map. b) Svecokarelian tectonic domains and post-Svecokarelian rock units in the south-western part of the Fennoscandian Shield, south-eastern Sweden (modified after /Koistinen et al. 2001/). c) Simplified view of the bedrock geology in the Laxemar-Simpevarp area and surroundings in tectonic domain 5. TIB = Transscandinavian Igneous Belt. The Laxemar subarea occurs inside and corresponds more or less to the Laxemar local model area.

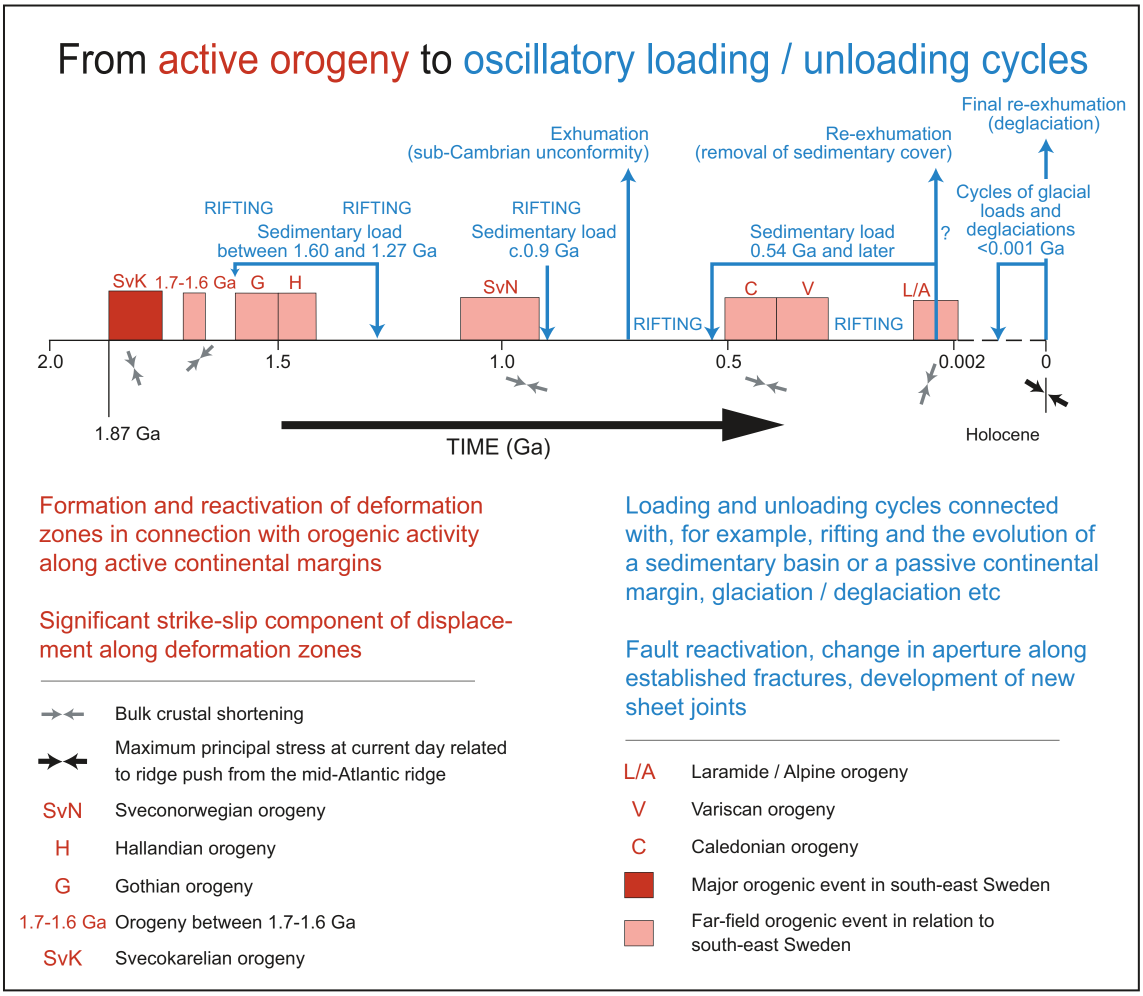


Figure 2-3. *Tectonic activity (red) and oscillatory loading and unloading cycles (blue) from 1.9 Ga to the Holocene in the Fennoscandian Shield in the south-eastern part of Sweden. Figure modified after /Stephens et al. 2007/.red.*

The far-field tectonic events after 1.8 Ga included orogenic activity related to crustal build-up and crustal reworking at 1.7–1.6 Ga, at 1.6–1.5 Ga (Gothian), at 1.5–1.4 Ga (Hallandian) and at 1.1–0.9 Ga (Sveconorwegian), rifting during the Meso- and Neoproterozoic, and rifting and the development of a passive continental margin in the northern part of Europe during the latest part of the Neoproterozoic and the Cambrian (Figure 2-3). Orogenic activity at 510–400 Ma (Caledonian), rifting during the Late Carboniferous to Permian, crustal shortening during the Late Cretaceous and Palaeogene (Laramide/Alpine), and the effects of ridge push from the mid-Atlantic ridge during the Neogene and Quaternary (Figure 2-3) have also affected Scandinavia during the Phanerozoic. Granitic magmatism at approximately 1.45 Ga in tectonic domain 5 (Figure 2-2c) is interpreted to be a far-field effect of the Mesoproterozoic orogenic activity farther to the south and west, including the Hallandian orogeny, while the approximately 900 Ma dolerite dykes in the domain represent an extensional tectonic phase during the later part of the Sveconorwegian orogeny. An overall change from active orogeny in the near-field realm to oscillatory loading and unloading cycles is apparent through time (Figure 2-3).

3 Rock types and structural geology of the Laxemar-Simpevarp area

In order to place the excursion stops in a local geological perspective, a short description of the rock types and structural geology in the Laxemar-Simpevarp area is provided below. For a more detailed description of the bedrock geology and the bedrock geological evolution of the Laxemar-Simpevarp area, the reader is referred to /Söderbäck (ed) 2008, Wahlgren et al. 2008, SKB 2009/ and references therein.

The topography and place names in the Laxemar-Simpevarp area are shown in Figure 3-1 and a regional bedrock geological map is presented in Figure 3-2. A more detailed bedrock geological map and a magnetic anomaly map of the site investigation area at Laxemar-Simpevarp area are shown in Figure 3-3 and Figure 3-4, respectively.

3.1 Rock types

The 1.8 Ga bedrock in the Laxemar-Simpevarp area is dominated by intrusive rocks with a quartz monzodioritic, granodioritic or granitic composition, i.e. with a variable content of quartz (Figure 3-5). Different rock types have also been distinguished on the basis of their variable grain size and texture. The bedrock in the area has the typical lithological characteristics of the intrusive rocks in the TIB. These characteristics include evidence for magma-mingling and magma-mixing processes, exemplified by the occurrence of enclaves, hybridization and diffuse transitional contacts between different rock types. These features demonstrate a close temporal and genetic relationship between the different rocks in the 1.8 Ga igneous suite.

The dominant rock types are medium-grained, finely porphyritic Ävrö granite and medium-grained, equigranular quartz monzodiorite (Figure 3-3 and Figure 3-5). The term Ävrö granite is a loose field term used for a variety of rocks that vary in composition from granite to granodiorite and quartz monzodiorite. The quartz monzodioritic variety of the Ävrö granite, i.e. Ävrö quartz monzodiorite (Figure 3-3 and Figure 3-5), has been distinguished at Laxemar, both at the surface and at depth in the boreholes, only with the help of modal and geochemical analyses and density logs. Furthermore, a granodioritic variety of the Ävrö granite, i.e. Ävrö granodiorite, has been distinguished in the boreholes with the help of density logs. Minor bodies of equigranular granite, diorite-gabbro and fine-grained dioritoid are also present in the Laxemar-Simpevarp area. However, the fine-grained dioritoid is a dominant rock type in the Simpevarp subarea and covers the southern part of the Simpevarp peninsula (Figure 3-3).

Important subordinate rock types are dykes, veins, patches and minor bodies of fine-grained granite, pegmatite and composite intrusions. The latter are composed of a mixture of fine-grained diorite-gabbro and fine-grained granite. Field relationships, including diffuse contacts as well as mixing and mingling relationships, strongly indicate that all these rock types formed close in time and belong to the same igneous event. However, the field relationships also indicate the relative age relationship between the different rock types (Table 3-1).

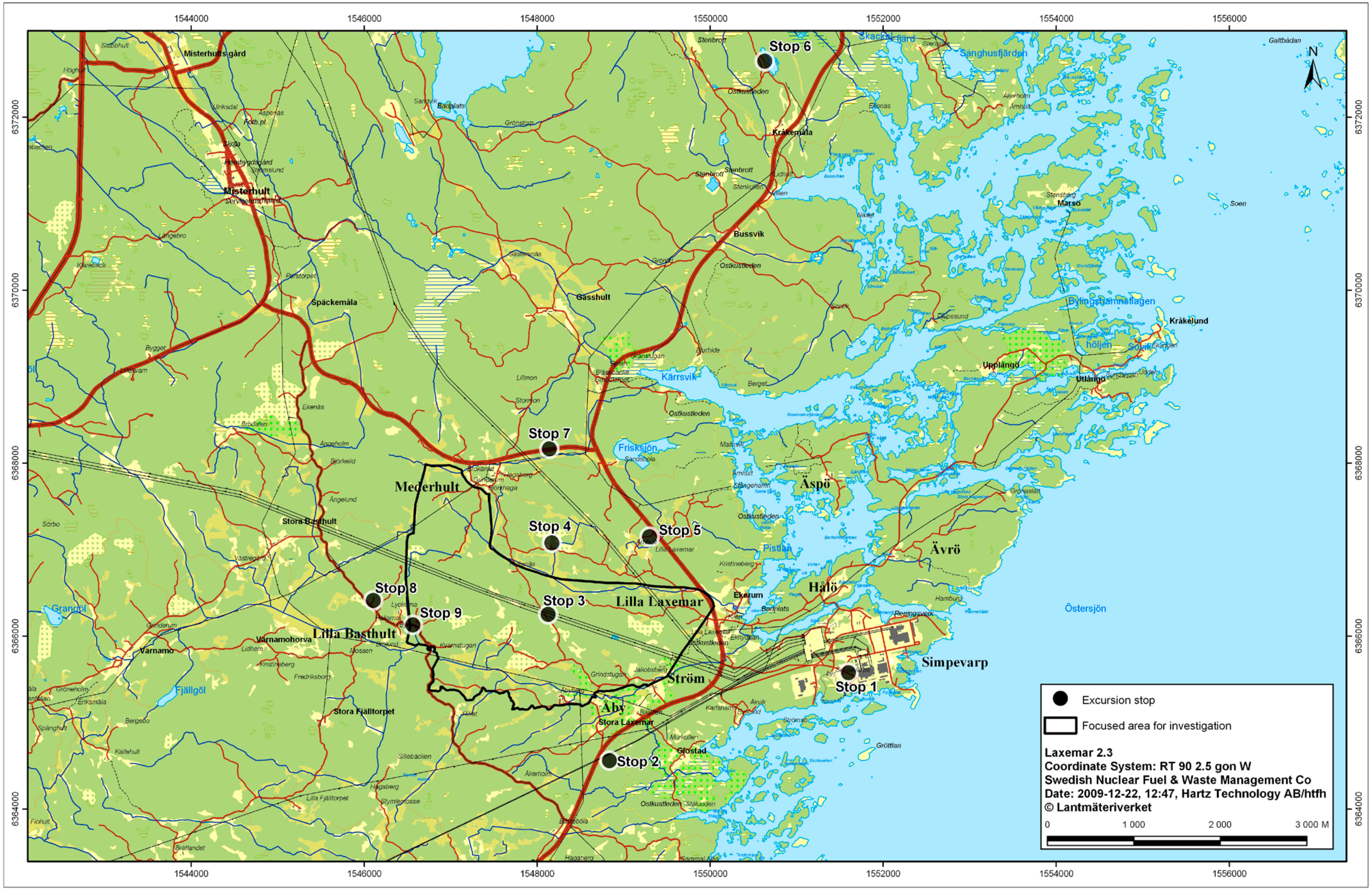


Figure 3-1. Topographic map of the site investigation area at Laxemar-Simpevarp and its surroundings.

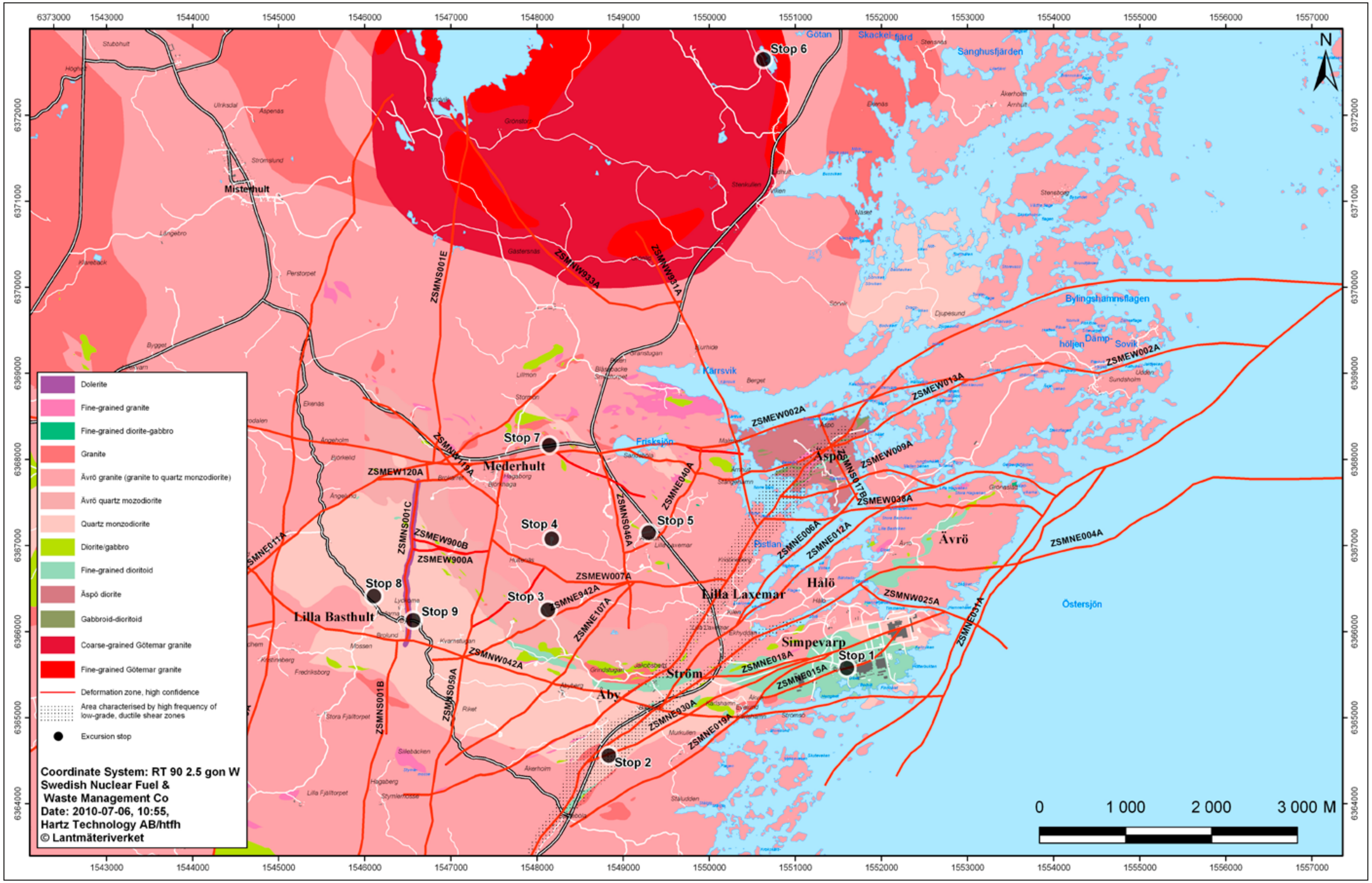


Figure 3-2. Combination of the bedrock geological map from the model version 0 /SKB 2002/ and the detailed bedrock geological map of the Laxemar-Simpevarp area.

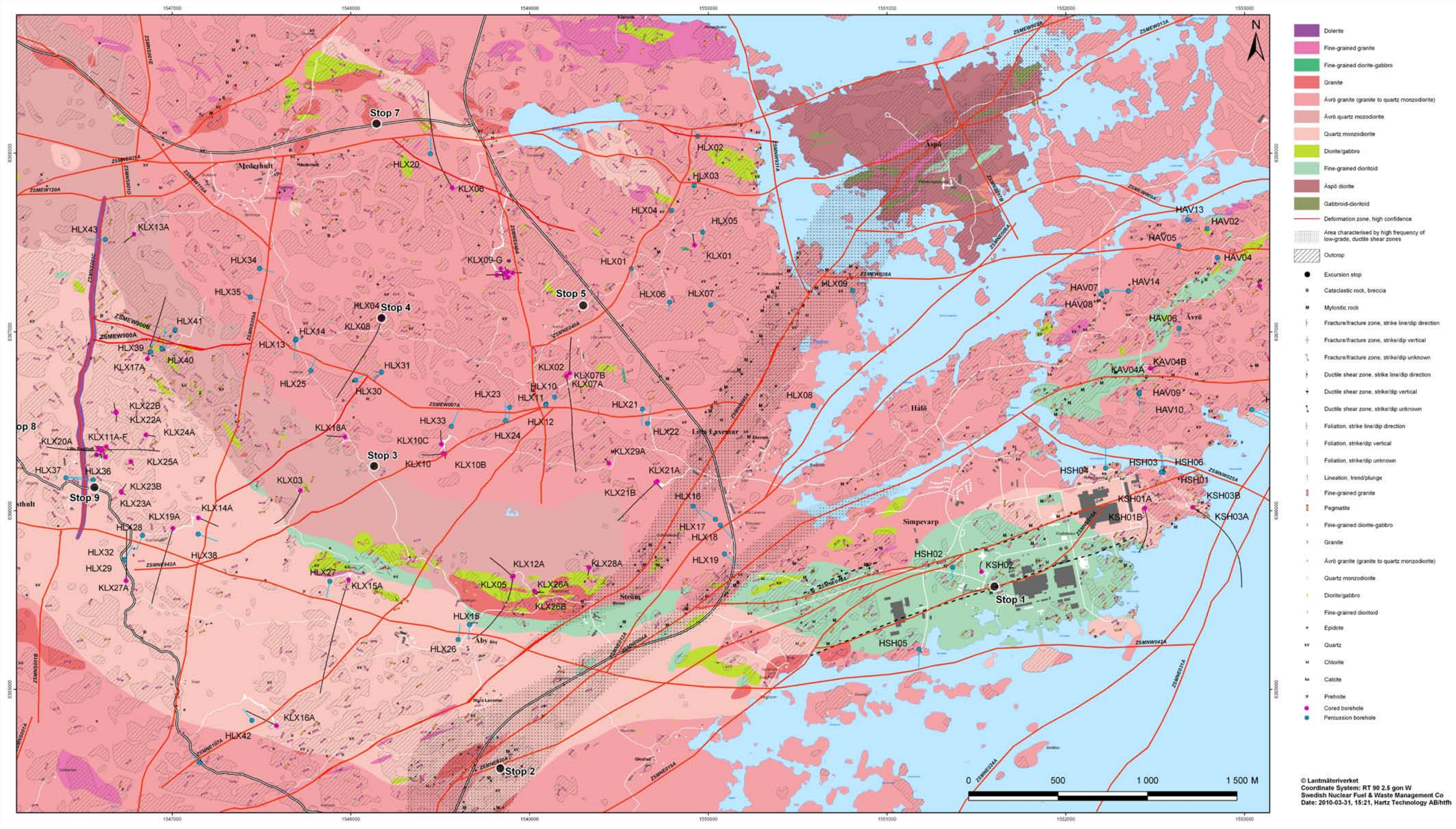


Figure 3-3. *Detailed bedrock geological map of the site investigation area at Laxemar-Simpevarp.*

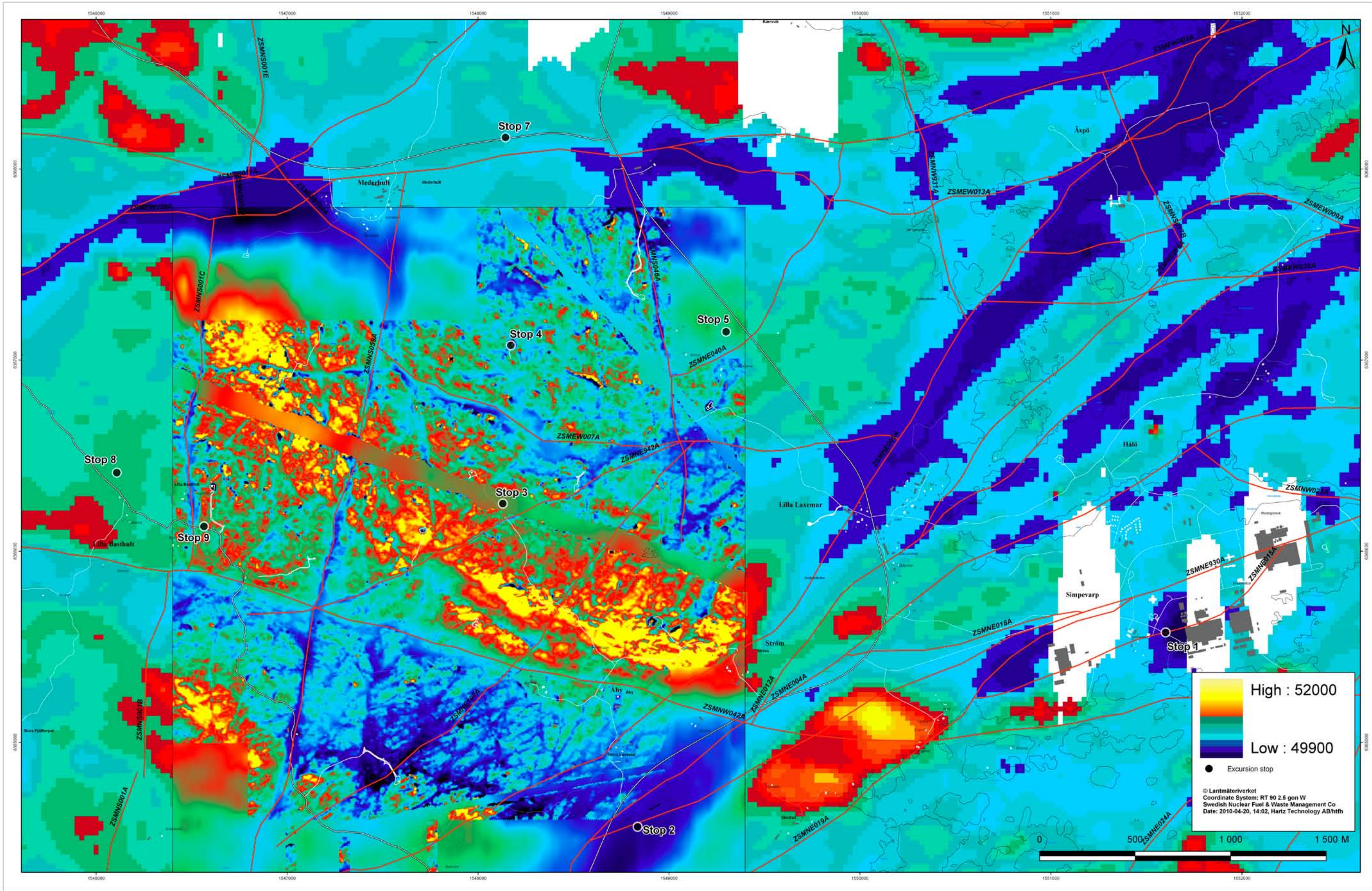


Figure 3-4. *Magnetic anomaly map of the Laxemar-Simpevarp area.*

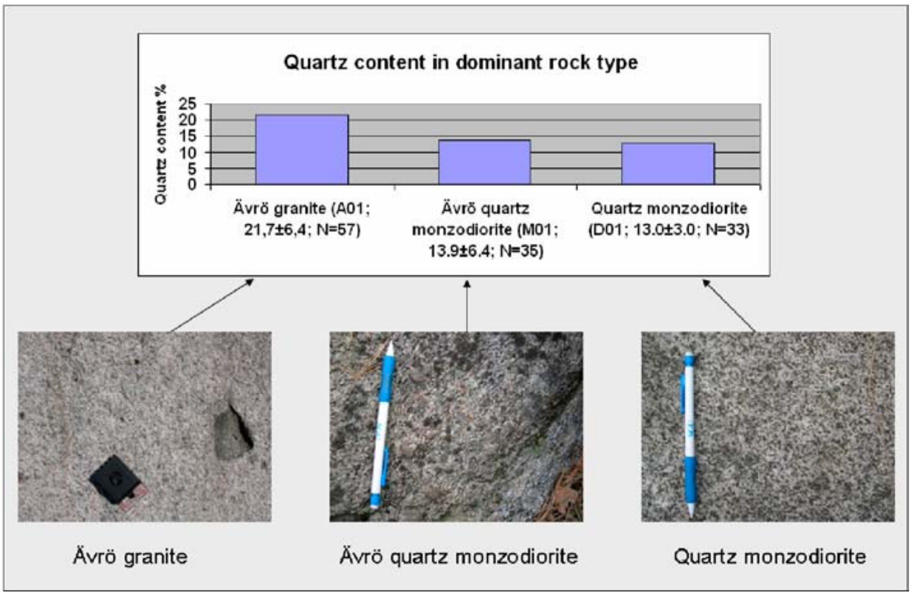


Figure 3-5. *Quartz content in the dominant rock types at Laxemar. Note the darker colour in the Ävrö quartz monzodiorite and the quartz monzodiorite compared to the quartz-rich Ävrö granite. The dark inclusion to the right in the Ävrö granite is a mafic enclave.*

Table 3-1. Relative age relationships between igneous rock types in the Laxemar-Simpevarp area, based on field relationships. SKB rock codes for each rock type are shown in brackets.

Rock type	Relative age
Dolerite (501027)	Youngest
Götemar and Uthammar granites (521058)	↓
Fine-grained granite (511058) and pegmatite (501061)	
Fine-grained diorite-gabbro (505102)	
Granite, equigranular (501058)	
Ävrö granite (501044)/Ävrö quartz monzodiorite (501046)	
Quartz monzodiorite (501036)	
Diorite-gabbro (501033)	
Fine-grained dioritoid (501030)	Oldest

U-Pb zircon (and titanite) dating of the porphyritic Ävrö granite and equigranular quartz monzodiorite, which was carried out in connection with the site investigation work, has yielded crystallization ages of 1.80 Ga (Table 3-2 and Figure 3-8). However, observed field relationships indicate that the Ävrö granite/Ävrö quartz monzodiorite is slightly younger than the equigranular quartz monzodiorite. The obtained ages are also in agreement with earlier U-Pb zircon age determinations for the so-called Äspö diorite, Gersebo granite (Ävrö granite type sampled immediately east of the Götemar granite), Virbo granite (Ävrö granite type sampled approximately15 km south-west of Simpevarp) and fine-grained granites (Table 3-2).

The subsequent rock-forming event in the Laxemar-Simpevarp area and its surroundings occurred at approximately 1.45 Ga (Table 3-2 and Figure 3-8). This event gave rise to the Götemar and Uthammar granites, north and south of Laxemar, respectively, as well as the Jungfrun granite, which is exposed on a small island in the Baltic Sea between Öland and the main land. Finally, at approximately 900 Ma, mafic magma intruded the Laxemar-Simpevarp area and crystallized in the form of dolerite dykes (Table 3-2 and Figure 3-8). These dolerites form the youngest igneous rocks in the region and belong to the regional system of dolerites with N–S strike dated to 980 to 960 Ma that can be followed from Blekinge in the south-easternmost part of Sweden to Dalarna in the central part of the country /Johansson and Johansson 1990, Söderlund et al. 2005b/.

Apart from the above-mentioned igneous rocks, Cambrian sandstone locally occurs as fracture filling (so-called sandstone dykes) in the Laxemar-Simpevarp area.

Table 3-2. Age of crystallization of igneous rocks in the Laxemar-Simpevarp area and surroundings. TIMS = Thermal Ionisation Mass Spectrometry technique. Table extracted from /Söderbäck (ed) 2008/.

Dated rock type	Method	Age	Comment	Reference
Dolerite	$^{40}Ar/^{39}Ar$ whole rock	c. 900 Ma	Drill core sample (KLX20A)	/Wahlgren et al. 2007/, /Söderlund et al. 2008a/
Götemar granite	U-Pb zircon (TIMS)	1,452+11/–9 Ma	Surface sample	/Åhäll 2001/
Uthammar granite	U-Pb zircon (TIMS)	1,441+5/–3 Ma	Surface sample	/Åhäll 2001/
Jungfrun granite	U-Pb zircon (TIMS)	1,441±2 Ma	Surface sample	/Åhäll 2001/
Fine-grained granite	U-Pb zircon (TIMS)	1,794+16/–12 Ma	Sample from Äspö tunnel	/Wikman and Kornfält 1995, Kornfält et al. 1997/
Fine-grained granite	U-Pb zircon (TIMS)	1,808+33/–30 Ma	Sample from Äspö tunnel	/Wikman and Kornfält 1995, Kornfält et al. 1997/
Äspö diorite	U-Pb zircon (TIMS)	1,804±3 Ma	Sample from Äspö tunnel	/Wikman and Kornfält 1995, Kornfält et al. 1997/
Gersebo granite	U-Pb zircon (TIMS)	1,803±7 Ma	Surface sample	/Åhäll 2001/
Virbo granite	U-Pb zircon (TIMS)	c. 1,790 Ma	Surface sample	/Bergman et al. 2000/
Ävrö granite	U-Pb zircon+titanite (TIMS)	1,800±4 Ma	Surface sample	/Wahlgren et al. 2004/
Quartz monzodiorite	U-Pb zircon (TIMS)	1,802±4 Ma	Surface sample	/Wahlgren et al. 2004/

3.2 Ductile structures

From a structural point of view, the bedrock in the Laxemar-Simpevarp area is dominated by well-preserved intrusive rocks. However, a faint to weak foliation, which is commonly gently dipping but not uniformly distributed over the area, is present. In many cases, it is difficult to decide whether this foliation represents a flow foliation formed during the igneous evolution, or whether it is an over-printing solid-state structure. On the basis of the field relationships, it is inferred that the foliation initially developed during a late stage in the igneous evolution, but continued to develop in the solid state after crystallization and solidification of the magmas. All rock types are affected by the foliation, most notably the dyke-like bodies of fine-grained granite and fine-grained diorite-gabbro. The foliation in these rocks formed in the solid state and is more or less strongly developed. Particularly in the southern part of Laxemar, these dyke-like bodies locally correspond to ductile shear zones.

Although the majority of the deformation zones in the Laxemar-Simpevarp area are characterized by polyphase brittle deformation, the majority of these zones contain ductile precursors. This indicates that the gross structural framework was formed when the bedrock still responded to deformation in the ductile regime and discrete, low-temperature, brittle-ductile to ductile shear zones form the most prominent ductile structures in the area (Figure 2-2c).

The brittle-ductile to ductile shear zones vary in size and occur all over the Laxemar-Simpevarp area. However, the Simpevarp subarea is more strongly affected by such deformation compared with Laxemar. The most conspicuous concentrations of ductile shear zones occur along two shear belts that strike NE−SW and mark the boundary between the Simpevarp and Laxemar subareas (Figure 2-2c). These belts constitute two branches of what has traditionally been called the Äspö shear zone. The shear deformation along these belts is not homogeneous, but they are characterized by a considerably higher frequency of ductile shear zones relative to that in the surrounding country rock.

The regional scale, most prominent ductile shear zones are subvertical and strike N−S, NE−SW and E−W. A study of their kinematics /Lundberg and Sjöström 2006/ has revealed that the N−S and NE−SW oriented zones are characterized by sinistral strike-slip movement (Figure 3-6), whereas the E−W shear zones on the Simpevarp peninsula show complex kinematics. This includes both reverse and normal dip-slip as well as sinistral and dextral strike-slip displacements. It has been inferred that the ductile deformation along the various sets of zones formed in response to an approximately northward-directed shortening /Lundberg and Sjöström 2006/.

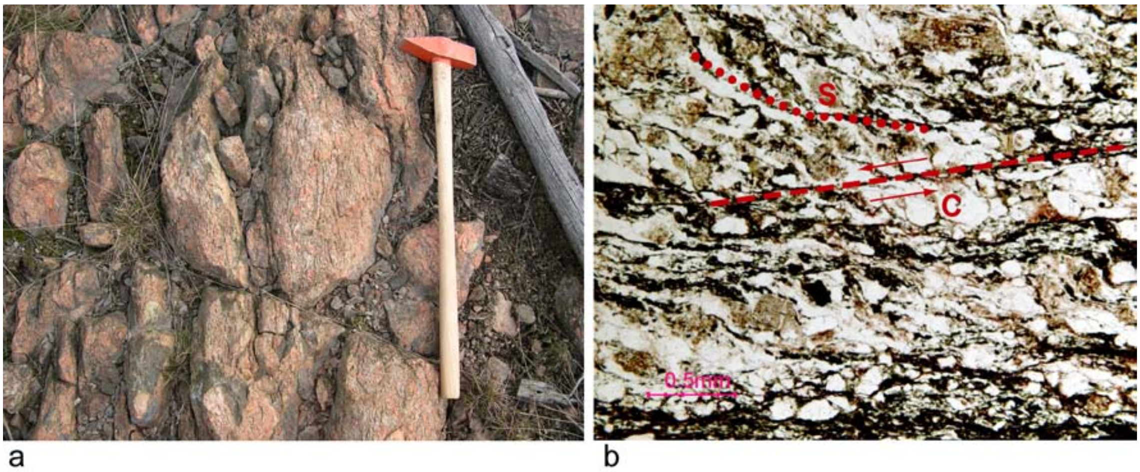


Figure 3-6. a) Strongly deformed Ävrö granite in the Äspö shear zone system (PSM003792, deformation zone ZSMNE004A /Wahlgren et al. 2008/). b) Example of structure used to decipher the sense of shear. Composite C/S fabric indicating a sinistral sense of shear.

The ductile shear zones are interpreted to have developed under upper greenschist facies metamorphic conditions /Lundberg and Sjöström 2006/, i.e. at a temperature of approximately 450 to 500°C. Assuming that the blocking temperature in the $^{40}Ar/^{39}Ar$ amphibole isotope system is approximately 500°C, an $^{40}Ar/^{39}Ar$ amphibole age of 1,773±13 Ma /Page et al. 2007, Söderlund et al. 2008a/ constrains the minimum age for the development of the ductile deformation to 1.76 Ga, while the crystallization age of the rocks (Table 3-2) sets the maximum age for this deformation at 1.81 Ga.

A close temporal relationship between the formation of the rocks and the ductile shear deformation is supported by the variable field relationships between the emplacement of fine-grained granite dykes and the shear deformation. Some of these dykes are affected and cut by ductile shear zones, whereas others are unfoliated and truncate the shear zones /Lundberg and Sjöström 2006/. However, a muscovite that defines the mylonitic foliation in the Äspö shear zone (ZSMNE005) has yielded a $^{40}Ar/^{39}Ar$ age of 1.4 Ga (/Drake et al. 2007, 2009/, Table 3-3 and Figure 3-8). This age represents either a resetting of the $^{40}Ar/^{39}Ar$ muscovite system, due to heating by circulating hydrothermal hot fluids that are related to the 1.45 Ga granites, or ductile reactivation of the Palaeoproterozoic mylonite and new growth of muscovite at 1.4 Ga.

3.3 Brittle structures

Deformation zones that are predominantly brittle in character in the Laxemar-Simpevarp area can be divided in the following orientation sets (cf. Figure 3-3):

- Northeast-southwest striking, moderately to steeply dipping.
- North-south striking, moderately to steeply dipping.
- East-west to northwest-southeast striking, steep to moderate dip to the south.
- East-west to northwest-southeast striking, moderate dip to the north.
- Gently dipping.

The absolute majority of the regional and local major deformation zones that have been deterministically modelled, although dominated by brittle deformation, show signs of having been originally formed during ductile conditions. In general, the patterns of fracture orientations and relative fracture intensities inside the defined fracture domains in Laxemar /Wahlgren et al. 2008/ are consistent with the orientations of the regional deformation zones.

As mentioned above, the bedrock at the current level of erosion in the Laxemar-Simpevarp area had cooled below 500°C at 1.76 Ga. However, there remains a greater uncertainty concerning the cooling history of the bedrock after 1.76 Ga. In particular, it concerns the time when the bedrock passed through the brittle-ductile transition in the crust and entered the brittle realm with development of fractures, brittle deformation zones (faults) and brittle overprinting of the earlier formed ductile deformation zones.

An $^{40}Ar/^{39}Ar$ biotite age of approximately 1.62 Ga (/Page et al. 2007, Söderlund et al. 2008a/, Table 3-3 and Figure 3-8) is not interpreted to indicate slow cooling below 300°C after the crystallization of the rocks at 1.8 Ga, but rather that the $^{40}Ar/^{39}Ar$ biotite system closed earlier and was re-opened and subsequently closed again at approximately 1.62 Ga /Söderlund et al. 2008a/.

The re-opening of the $^{40}Ar/^{39}Ar$ biotite isotope system may be related to /Page et al. 2007, Söderlund et al. 2008a/:

- Reheating in connection with the intrusion of 1.71 to 1.66 Ga TIB rocks farther to the west during a post-Svecokarelian orogenic event.
- Loading due to transport of erosional products eastwards from a Cordilleran type TIB mountain range.
- Reheating in connection with the intrusion of 1.65 to 1.47 Ma rapakivi granites and associated igneous rocks during and after the Gothian orogeny. This phase of reheating has also been proposed to explain $^{40}Ar/^{39}Ar$ biotite ages in the range 1.51 to 1.47 Ga.

The $^{40}Ar/^{39}Ar$ biotite ages in the range 1.51 to 1.47 Ga (/Page et al. 2007, Söderlund et al. 2008a/, Table 3-3 and Figure 3-8) mark a minimum age for the transition from ductile to brittle deformation, i.e. from approximately 1.5 Ga and onwards the bedrock responded to deformation in the brittle regime (cf. Figure 3-7a). The corollary follows that the 1.45 Ga Götemar and Uthammar granites were emplaced into a brittle crust. Brittle reactivation or at least circulating hydrothermal activity along fractures has been documented that are related to the intrusion of the 1.45 Ga Götemar and Uthammar granites /e.g. Drake et al. 2007, 2009, Söderbäck (ed) 2008/.

Effects of the Sveconorwegian tectonic activity are indicated by $^{40}Ar/^{39}Ar$ ages of approximately 989 Ma and 928 Ma for adularia fracture filling and biotite, respectively (/Page et al. 2007, Söderlund et al. 2008a, Drake et al. 2007, 2009/, Table 3-3, Table 3-4 and Figure 3-8). Furthermore, the intrusion of the approximately 900 Ma dolerite dykes is additional indication of Sveconorwegian brittle tectonic activity /Wahlgren et al. 2007, Söderlund et al. 2008a/.

Caledonian tectonic activity in the Laxemar-Simpevarp area is indicated by $^{40}Ar/^{39}Ar$ ages of adularia in the range 448 to 401 Ma (/Drake et al. 2007, 2009/, Table 3-4 and Figure 3-8). Furthermore, evidence for Palaeozoic (Caledonian?) faulting in the Laxemar-Simpevarp area is the documentation of fractures filled with Cambrian sandstone that are overprinted by brittle deformation (Figure 3-7b). In addition, a fragment of Cambrian sandstone is present in the cored borehole KSH03A close to the hanging-wall of the NW-dipping deformation zone ZSMNE024A in the sea area outside the Simpevarp peninsula and Ävrö island (Figure 3-3).

On the basis of (U-Th)/He apatite data from boreholes, some constraints on when different segments of the bedrock at different crustal levels were uplifted through the approximately 70°C geotherm have been obtained (/Söderlund et al. 2005a, Söderlund et al. 2008b/, Table 3-3 and Figure 3-8). These data indicate that a sedimentary cover was situated on top of the crystalline basement rocks throughout much of the Phanerozoic. At Laxemar-Simpevarp, a change to slower exhumation rate occurred during the Early Jurassic or the Late Jurassic to Cretaceous. It is assumed that renewed exhumation of the sub-Cambrian unconformity, with complete denudation of the sedimentary overburden, did not take place until some time during the Cenozoic.

Table 3-3. Cooling ages of the bedrock in the Laxemar-Simpevarp area based on /Söderlund et al. 2005a, 2008a, b, Page et al. 2007/. TIMS = Thermal Ionisation Mass Spectrometry technique. Table extracted from /Söderbäck (ed) 2008/.

Geological feature	Dated rock type	Method	Age	Comment
Cooling below c 70°C	Ävrö granite, fine-grained granite, fine-grained dioritoid, fine-grained diorite-gabbro, quartz monzodiorite.	(U-Th)/He apatite	Surface samples: F_{T-} corrected ages range between c 313 and 227 Ma. Uncorrected ages range between c 211 and 133 Ma. Drill core samples: F_{T-} corrected ages range between c 289 and 120 Ma. Uncorrected ages range between c 215 and 85 Ma.	Surface or near-surface samples. Drill core samples from KLX01, KLX02, KSH03A/B, and samples from the access tunnel to the Äspö Hard Rock Laboratory. In general, the ages decrease with increasing depth in each borehole.
Cooling below c 300°C	Ävrö granite	$^{40}Ar/^{39}Ar$ biotite	928±6 Ma	Sample from KSH03A (c 300 m borehole length)
	Götemar granite	$^{40}Ar/^{39}Ar$ biotite	1,421±4 Ma	Surface sample
	Ävrö granite	$^{40}Ar/^{39}Ar$ biotite	1,431±6 Ma	Drill core sample from the lowermost part (c 1,605 m) of KLX02
	Ävrö granite	$^{40}Ar/^{39}Ar$ biotite	1,434±6 Ma	Surface sample close to the Uthammar granite near Fårbo
	Ävrö granite	$^{40}Ar/^{39}Ar$ biotite	1,479±3 Ma 1,484±3 Ma	Samples from the lower part of KSH03A
	Ävrö granite	$^{40}Ar/^{39}Ar$ biotite	1,481±3 Ma	Drill core sample from the lowermost part (c 1,000 m) of KLX01
	Ävrö granite	$^{40}Ar/^{39}Ar$ biotite	1,468±2 Ma, 1,486±3 Ma, 1,491±6 Ma, 1,508±7 Ma	Surface samples or from upper part of KLX01 and KLX02
	Quartz monzodiorite	$^{40}Ar/^{39}Ar$ biotite	1,618±7 Ma, 1,621±3 Ma	Samples from uppermost part of KSH03A/B
Cooling below c 350°C	Mylonite	$^{40}Ar/^{39}Ar$ muscovite	1,406±3 Ma	Drill core sample from KA1755A (Äspö shear zone)
Cooling below c 500°C	Ävrö granite	$^{40}Ar/^{39}Ar$ amphibole	1,445±14 Ma	Drill core sample from the lowermost part (c 1,605 m) of KLX02
	Ävrö granite	$^{40}Ar/^{39}Ar$ amphibole	1,773±13 Ma	Surface sample close to KLX02
	Quartz monzodiorite	$^{40}Ar/^{39}Ar$ amphibole	1,799±4 Ma	Drill core sample from upper part of KSH03A
Cooling below 700 to 500°C	Quartz monzodiorite	U-Pb titanite (TIMS)	1,793±4 Ma (upper intercept age)	Surface sample
	Ävrö granite	U-Pb titanite (TIMS)	1,800±4 Ma (upper intercept age)	Surface sample

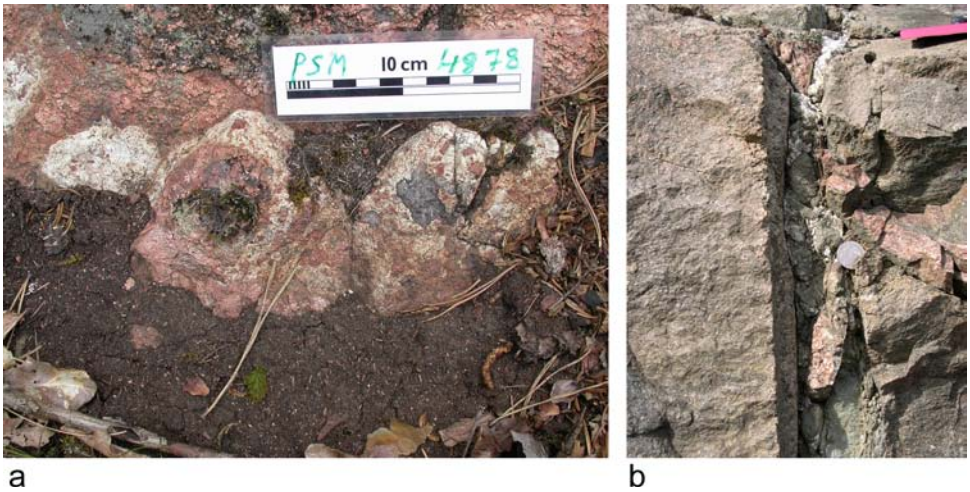


Figure 3-7. Examples of brittle deformation. a) Brecciated and red stained Ävrö granite (PSM004878). b) Brecciated and calcite-healed Cambrian sandstone in a narrow N–S trending fracture zone in a road cut immediately north of reactor 3 at the Oskarshamn nuclear plant (PSM005901). East-side-down displacement after formation of the Cambrian sandstone is indicated by the off-set of the fine-grained granitic dyke. Vertical section, view looking north.

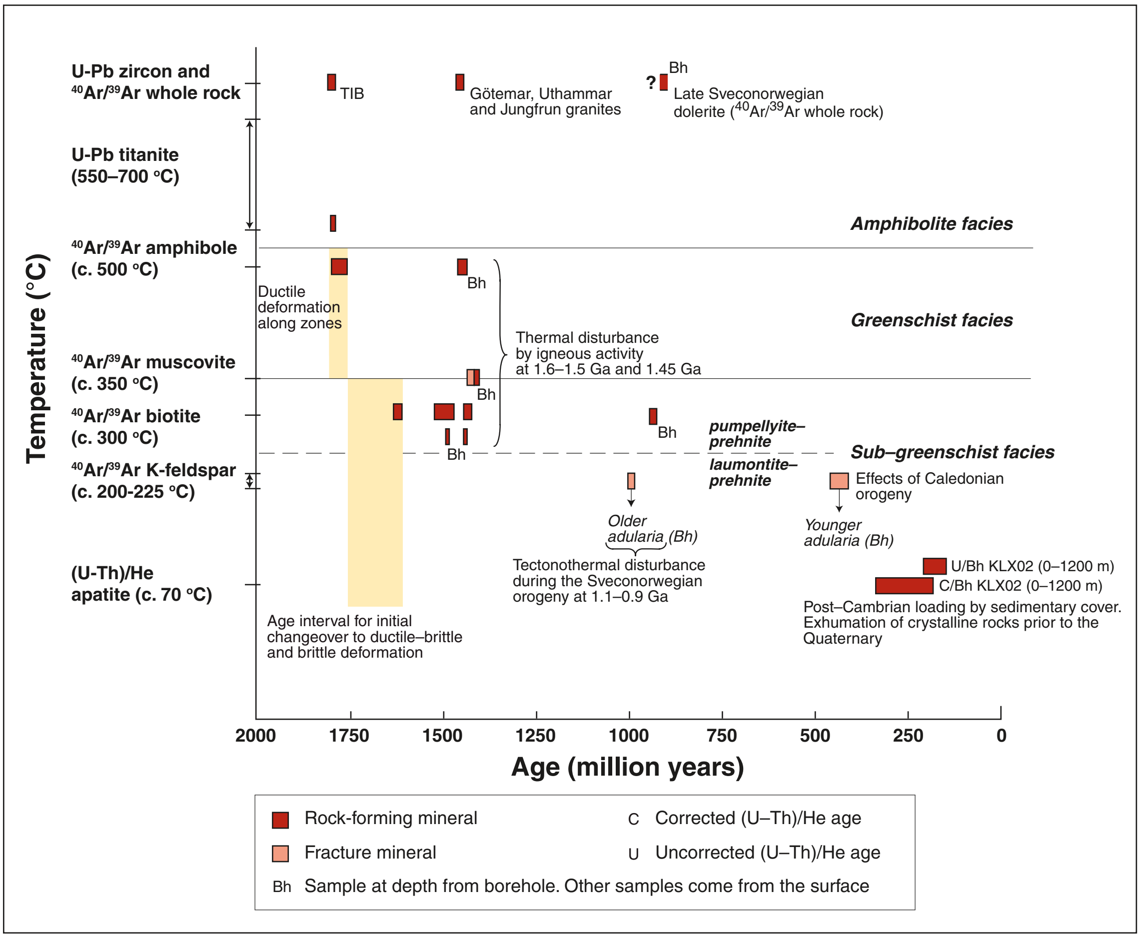


Figure 3-8. Summary of the geochronological data that constrain the bedrock geological evolution in the Laxemar-Simpevarp area. Data sources are presented in Table 3-2, Table 3-3 and Table 3-4.

Table 3-4. $^{40}Ar/^{39}Ar$ ages for fracture minerals in the Laxemar-Simpevarp area, based on /Drake et al. 2007/. Table extracted from /Söderbäck (ed) 2008/.

Borehole	Borehole length	Mineral	Fracture orientation	Method	Age
KLX02	676.82–677.00 m	Generation 5 apophyllite.	Open fracture.	$^{40}Ar/^{39}Ar$	No interpretable age defined.
KLX03	970.04–970.07 m	Generation 5 apophyllite.	Open fracture in DZ8 in the extended single hole interpretation.	$^{40}Ar/^{39}Ar$	No plateau defined in the step-heating spectrum.
KSH03A	181.93–181.98 m	Generation 5 adularia.	Sealed fracture in zone NE024.	$^{40}Ar/^{39}Ar$	400.9±1.1 Ma
KSH01A	256.90–257.10 m	Generation 5 adularia.	Sealed fractures in DZ3 in the extended single hole interpretation.	$^{40}Ar/^{39}Ar$	425.8±1.7 Ma
KSH03B	14.97–15.32 m	Generation 5 adularia.	Sealed fracture.	$^{40}Ar/^{39}Ar$	443.3±1.2 Ma 448.0±1.2 Ma
KSH03A	186.52–186.62 m	Generation 4 or 5 illite.	Sealed fracture in zone NE024.	$^{40}Ar/^{39}Ar$	No plateau defined in the step-heating spectrum. An integrated age of 488.5±1.1 Ma is inferred.
KSH03A	863.66–863.84 m	Generation 3 or younger adularia.	Sealed fracture cutting mylonite/cataclasite.	$^{40}Ar/^{39}Ar$	989±2 Ma
KLX08	933.15–933.30 m	Generation 3 hornblende.	Sealed fractures filled with hornblende.	$^{40}Ar/^{39}Ar$	No plateau defined in the step-heating spectrum.
KLX03	722.72–722.96 m	Muscovite in altered wall rock to fractures filled with generation 3 minerals.	Wall rock alteration along sealed fractures oriented 100°/6° and 92°/25° in zone EW946.	$^{40}Ar/^{39}Ar$	1,417±3 Ma
KLX06	565.22–565.38 m	Generation 3 muscovite .	Sealed greisen fracture oriented 328°/34°.	$^{40}Ar/^{39}Ar$	1,423±3 Ma
KLX06	595.08–595.18 m	Generation 3 muscovite.	Sealed fracture oriented 277°/9°.	$^{40}Ar/^{39}Ar$	1,424±2 Ma
KLX06	535.10–535.26 m	Generation 3 muscovite .	Sealed greisen fracture oriented 212°/7°.	$^{40}Ar/^{39}Ar$	1,424±2 Ma

A kinematic study of brittle deformation in the Laxemar-Simpevarp area has been carried out during the site investigation work /Viola and Venvik Ganerød 2007a, 2007b, 2008/ and, on the basis of these data, an evaluation of the brittle structural evolution has been presented by /Viola 2008, Viola et al. 2009/. The brittle structures in the Laxemar-Simpevarp area are inferred to have formed in connection with multiple reactivation of fracture and fault sets related to the effects of different orogenic episodes. These episodes affected the region during more than 1.5 Ga of geological evolution in the brittle deformational regime.

Two compressional, approximately NW/NNW−SE/SSE and NNE−SSW oriented shortening events have generated two sets of conjugate, steep strike-slip fractures. These sets are interpreted to have formed during the late stages of the Svecokarelian and possibly also during the orogenic event around 1.7 Ga, soon after the region initially entered the brittle deformational regime. The Mesoproterozoic to Neoproterozoic Sveconorwegian orogeny generated fractures and faults that are assigned to a third set of conjugate strike-slip faults, which constrain an approximately E−W shortening. The Caledonian shortening, oriented approximately NW−SE to E−W, reactivated the latter but also formed a new, similarly oriented set of subvertical strike-slip fractures. Permian transtension was oriented NE−SW and is inferred to have caused a prominent set of moderately dipping NW−SE trending normal faults in the Precambrian basement of the study area. Two other approximately NE−SW and NW−SE oriented shortening events are recorded in Ordovician limestones on Öland and can be tentatively linked to far-field effects of the Mesozoic to Cenozoic Laramide/Alpine orogeny.

4 Excursion stops

Nine excursion stops have been selected and are described below. The sources used to describe these stops as well as information bearing on the location of each stop are also presented below. All the excursion stops are shown on the topographic map of the site investigation area at Laxemar-Simpevarp and its surroundings (Figure 3-1) and on the bedrock geological map of this area (Figure 3-2). All stops except the excursion stop in the Götemar granite are also shown on the more detailed bedrock geological map of the site investigation area (Figure 3-3) and on the magnetic anomaly map (Figure 3-4). Coordinates at the ground surface (northing/easting) and elevation are provided using the RT 90 and RHB 70 coordinate systems, respectively. The orientations of planar and linear structures are presented as strike and dip using the right-hand-rule method and as trend and plunge, respectively.

4.1 Sources of information

The descriptions of the nine excursion stops at Laxemar-Simpevarp in this report are based on the following sources of published information:

- Observational and numerical data that were acquired in connection with the standard bedrock mapping programme at the ground surface /Wahlgren et al. 2004, Persson Nilsson et al. 2004/.
- Boremap mapping and geological single-hole interpretation of the core drilled borehole KLX20A /Rauséus and Ehrenborg 2007, Carlsten et al. 2007/.
- Data acquired at two of the excursion stops in connection with the detailed mapping of fractures and rock types /Cronquist et al. 2004, Forssberg et al. 2007/and complementary analytical work /La Pointe et al. 2008/.
- The results of complementary modal and geochemical analytical work at three excursion stops /Wahlgren et al. 2005/.
- Data from a complementary geochronological study at one excursion stop /Wahlgren et al. 2007, Söderlund et al. 2008a/.
- The description of two of the excursion stops completed during the acquisition of kinematic data at the ground surface /Viola and Venvik Ganerød 2007b/.

In addition, a field check of the selected outcrops was carried out in direct connection with the preparation of the excursion guide.

4.2 Description of excursion stops

Stop 1. Road cut on the Simpevarp peninsula in fine-grained dioritoid with a low-grade, ductile to brittle-ductile shear zone (PSM005812 at 1551601/6365575)

Excursion stop 1 is situated immediately west of reactor 1 (Figure 3-1).

Road cut in grey, equigranular to unequigranular, massive, fine-grained dioritoid immediately west of reactor 1 (Figure 3-3). This rock type dominates the southern part of the Simpevarp peninsula. The fine-grained dioritoid is locally inhomogeneously coarsened and also contains a variable frequency of megacrysts of hornblende and plagioclase. Locally, megacrysts of pyroxene and biotite are also present. However, thin-section studies show that the pyroxene is generally more or less altered to hornblende, and most of the hornblende megacrysts are inferred to be secondary after pyroxene. Results of modal analyses of the dioritoid in the area (no analysis from this outcrop) show that it principally varies between quartz monzodiorite and monzodiorite in composition /Wahlgren et al. 2004/. Red, cm–m thick dykes and veins of fine- to medium-grained granite, as well as cm–dm thick pegmatites are also present. Red staining along sealed fractures or fracture networks is characteristic.

A low-grade, ductile to brittle-ductile, dm–m thick, ENE–WSW striking, vertical shear zone occurs in the western part of the road cut (Figure 4-1). Extrapolation between different outcrops indicates that the shear zone can be traced more or less continuously for at least 2 km in an ENE–WSW direction, from the area west of CLAB in the west to the area south of reactor 3 in the east.

Figure 4-1. Ductile to brittle-ductile shear zone in fine-grained dioritoid.

The fine-grained dioritoid has traditionally been classified as a volcanic rock of dacitic to andesitic composition (/SKB 2002/ and references therein). However, except for being fine-grained, no characteristic criteria exist that demonstrate a volcanic origin for this rock. Instead, it is interpreted as a high-level intrusion that subsequently was intruded by the neighbouring quartz monzodiorite (see Figure 3-3) in the country rock. The fine-grained dioritoid and the quartz monzodiorite are interpreted to be co-magmatic, i.e. they originated from the same magma source. The characteristic, inhomogeneous coarsening in the fine-grained dioritoid is inferred to be a late-magmatic phenomenon, presumably due to a thermal input during the emplacement of the quartz monzodiorite and possibly also the Ävrö granite.

Stop 2. Ductile deformation zone along the "Äspö shear zone system" (PSM004073 and PSM004085 at 1548836/6364558)

Park the car along the small road to Åby and St. Laxemar, c. 100 m north of the junction to the main road (Figure 3-1). Walk back to the main road and turn left (north). Turn right (east) after c. 30 m at the traffic sign and follow the small track up to the power line. After passing the power line, you can see the outcrop area c. 50 m away to the right (south) on a small elevation (Figure 3-1).

The most spectacular and prominent, ductile structural features in the Laxemar-Simpevarp area are low-grade, ductile to brittle-ductile shear zones. The ductile shear zones at stop 2 affect the equigranular, medium-grained quartz monzodiorite, the dominant rock type in the southern part of Laxemar (Figure 3-3). Note the strong reduction in grain size in the strongly deformed varieties of the quartz monzodiorite. The shear foliation is steeply to vertically dipping and the degree of deformation in the outcrop area varies from slightly foliated to mylonitic (Figure 4-2). Kinematic indicators indicate the dominance of a sinistral strike-slip sense of displacement /Lundberg and Sjöström 2006/, i.e. the western block has moved horizontally to the south in relation to the eastern block. Gently plunging stretching lineation and steeply plunging intersection lineation indicate that mainly horizontal movements have occurred, i.e. the component of vertical displacement is subordinate. Fine-grained granite dykes in the outcrop are affected by the shear zones and the sense of displacement can be determined (Figure 4-3). The dominance for sinistral strike-slip sense of displacement is consistent along NE–SW oriented ductile shear zones in the area.

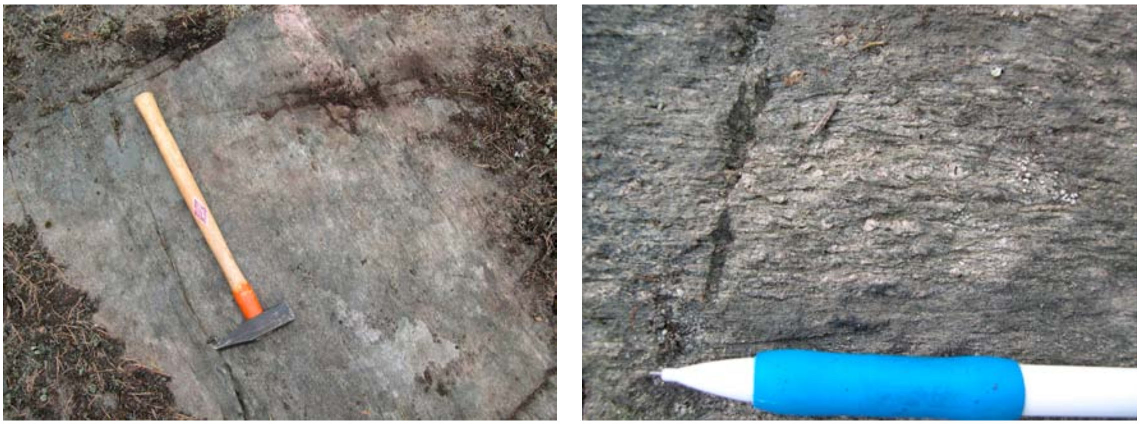


Figure 4-2. Different degree of ductile deformation in the quartz monzodiorite. Note the much stronger deformation in the quartz monzodiorite in the photograph to the left compared to the quartz monzodiorite to the right. Horizontal surfaces.

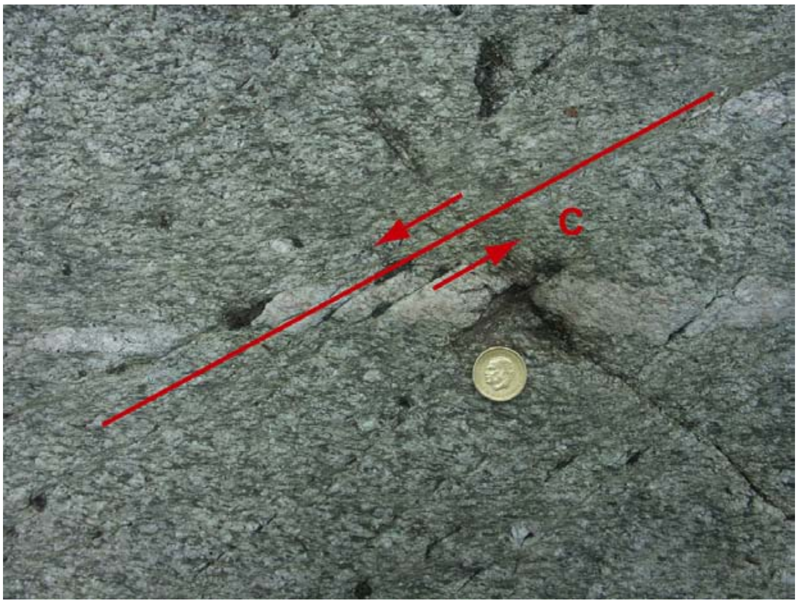


Figure 4-3. *Sinistral displacement of fine-grained granite dykes/veins in the quartz monzodiorite. Horizontal surface.*

The shear zones belong to a NE–SW striking, approximately 100–500 m thick, ductile deformation belt which can be followed for several kilometres (Figure 3-3) and is characterized by a high frequency of low-grade, ductile shear zones compared with the otherwise relatively well-preserved country rock in the area.

Stop 3. Ävrö quartz monzodiorite along an excavated trench (PSM004010, PSM007661 and ASM000116 at 1548130/6366249)

The excavated trench at excursion stop 3 is situated under a power line east of and very close to a small road (Figure 3-1).

Reddish grey, medium-grained, porphyritic, massive to faintly foliated Ävrö quartz monzodiorite in the central part of Laxemar (Figure 3-3). The excavated trench is situated close to the boundary to the more quartz-rich Ävrö granite that dominates the bedrock in northern Laxemar (Figure 3-3). The phenocrysts are generally 1-2 cm in size. Dykes and veins of fine-grained granite and pegmatite occur. The locally frequent occurrence of dark grey, fine-grained, elongate mafic enclaves is a characteristic feature of the Ävrö quartz monzodiorite. The mafic enclaves are generally 5–10 cm in size and mainly elongate in an E–W to WNW–ESE direction. The Ävrö quartz monzodiorite has been analysed for its mineralogical and chemical composition at this locality (PSM004010 in /Wahlgren et al. 2005/).

Detailed mapping of fractures and rock types has been carried out along the excavated trench at this excursion stop (ASM000116 in /Forssberg et al. 2007/). All fractures with a trace length longer than one metre, which occurred within a one metre wide strip measured from the centre line of the trench, were mapped. In contrast to the fracture mapping, the remaining bedrock properties, e.g. distribution of rock types, different types of alteration, ductile structures etc., were mapped within the entire excavated area. The result of the detailed fracture mapping is displayed in Figure 4-4. The detailed fracture data were subsequently evaluated and analysed in the statistic modelling of the discrete fracture network at Laxemar (GeoDFN in /La Pointe et al. 2008/).

***Figure 4-4.** Mapped fractures at ASM000116 /Forssberg et al. 2007/.*

The trench has also been investigated for the characterization and kinematics of the brittle structures in the Laxemar-Simpevarp area (PSM007661 in /Viola and Venvik Ganerød 2007b/). According to /Viola and Venvik Ganerød 2007b/, the outcrop is affected by systematic sets of fractures, showing variable amounts of shear. Neither fault rocks nor stretching lineations/striations were found along the fractures. However, consistent kinematic observations at the outcrop indicate predominantly strike-slip displacements. Both sinistral and dextral displacements have been documented along fractures with an approximately N–S strike (Figure 4-5). The sinistral fractures are mainly found in the western part of the trench, whereas the fractures are predominantly dextral in the eastern part, deduced, for example, on the basis of the dextral offsets of fine-grained granite dykes (Figure 4-5a). Both sinistral and dextral strike-slip displacement were observed along a single fracture surface (Figure 4-5b).

Epidote is a common fracture filling in the outcrop. Notable is the small "ridges" along certain fractures, which are caused by alteration of the side walls along the fractures which have resulted in a more weathering resistant composition (cf. Figure 4-5c).

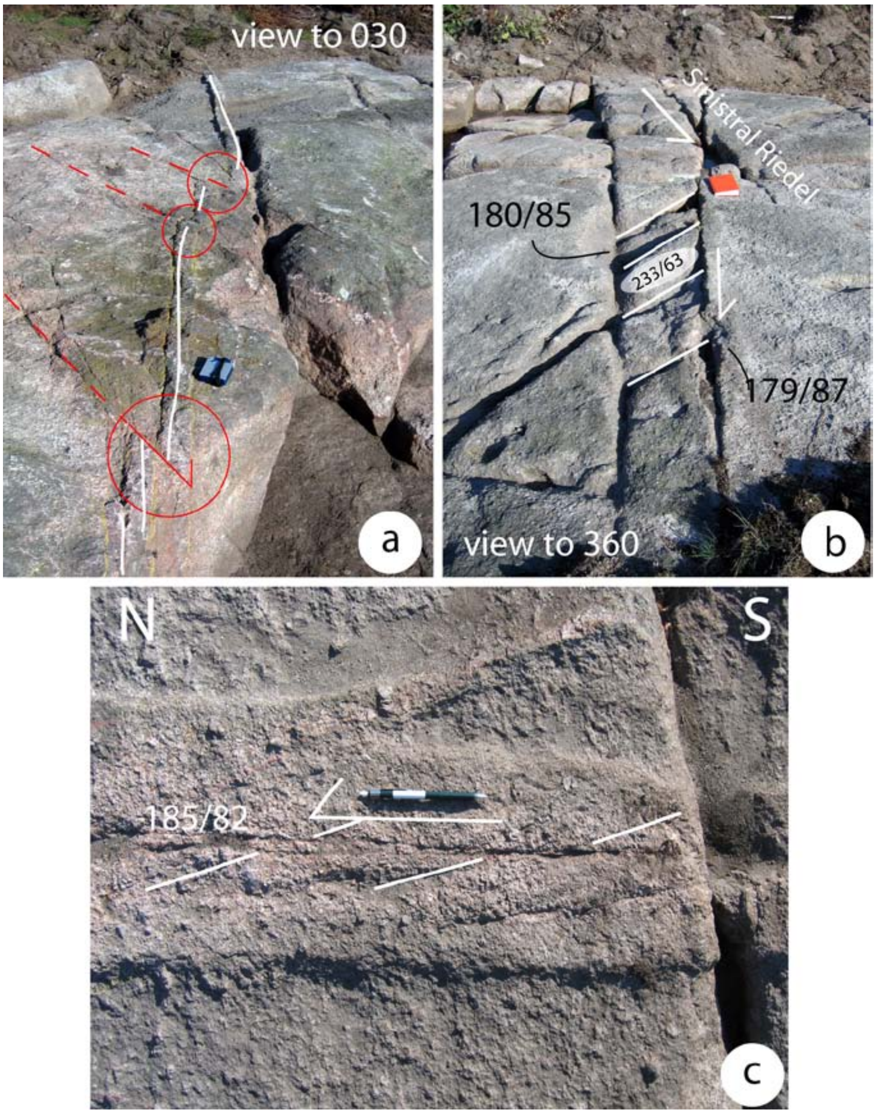


Figure 4-5. *Examples of kinematic indicators along the approximately N–S striking fractures. a) The dashed red lines (oriented 354/83) mark several c.10 cm dextral offsets of a thin granitic to pegmatitic dyke (white lines). b) Example of contrasting kinematic evidence along the one and same fracture surface. The fracture oriented 179/87 has an inferred sinistral Riedel shear in the upper part of the photograph, whereas in the lower part a systematic set of dextral tension gashes oriented 233/63 occurs. c) Sinistral kinematics along a fracture oriented 185/82 established from systematic sinistral Riedel shears. Figure caption slightly modified after /Viola and Venvik Ganerød 2007b/.*

Stop 4. Ävrö granodiorite in the area around the drill site for KLX04/KLX08 (1548172/6367077)

Park the car at the drill site (Figure 3-1). The best outcrops are found approximately 100 m north of the drill site.

The area around the drill site for KLX04 and KLX08 is dominated by a reddish grey, medium-grained, porphyritic to sparsely porphyritic Ävrö granite (Figure 4-6) that dominates the bedrock in the northern part of Laxemar (Figure 3-3). Based on modal and chemical analyses of samples in the neighbouring area /Wahlgren et al. 2005/, the composition is interpreted to be granodioritic and, for this reason, this variety of the Ävrö granite can be included in the so-called Ävrö granodiorite. This rock type shows a higher content of quartz than the Ävrö quartz monzodiorite (compare excursion stops 3 and 5). The higher quartz content, at least in the upper c. 400 m of the bedrock, is also supported by density logs along the cored boreholes KLX04 and KLX08 (Figure 4-7, Figure 4-8). The frequency and size of the phenocrysts vary within the outcrop area. Red, fine-grained granite dykes to veins and mafic enclaves occur, and locally also a faint foliation. Epidote occurs as fracture filling and red staining is common immediately adjacent to fractures. Some minor ductile shear zones can also be observed within the outcrop area.

Stop 5. Ävrö quartz monzodiorite, diorite to gabbro and composite intrusion (PSM003804, PSM007664 and ASM000208 at 1549300/6367148)

The outcrop is situated very close to a small road (Figure 3-1). Park the car adjacent to the northern part of the outcrop.

The outcrop is dominated by a grey to reddish grey, medium-grained, finely to coarsely porphyritic Ävrö quartz monzodiorite. It has not been sampled for modal or chemical analyses, but is interpreted to have a quartz monzodioritic composition. A weak foliation with the orientation 285/80 is displayed in the northern part of the outcrop. In the southern part of the outcrop, inclusions of medium-grained diorite to gabbro constitute a dominant rock type together with red, fine-grained granite (Figure 4-9 and Figure 4-10). The fine-grained granite occurs both as dykes and net-veining in the diorite to gabbro (Figure 4-9b). Some of the granite dykes are coarser and pegmatitic. At least two generations of fine-grained granite occur, but they presumably formed close in time to each other.

The fine-grained granite in the southern part of the outcrop contains inclusions of fine-grained diorite to gabbro (Figure 4-9b, dark green in Figure 4-10). The latter contains 0.5–2 mm large megacrysts of hornblende. Note that the fine-grained diorite to gabbro is spatially related to and only occurs in the fine-grained granite, not in the medium-grained diorite to gabbro. The spatial relationship between the fine-grained granite and fine-grained diorite to gabbro indicates that they form a composite intrusion. Apart from the fine-grained diorite to gabbro in the composite intrusion, fine-grained mafic enclaves occur in the Ävrö quartz monzodiorite. The main orientation of the enclaves is 285/80 in the northern and central part of the outcrop, while the orientation 248/70 predominates in the southern part.

Figure 4-6. *Ävrö granodiorite with an inclusion of a mafic enclave.*

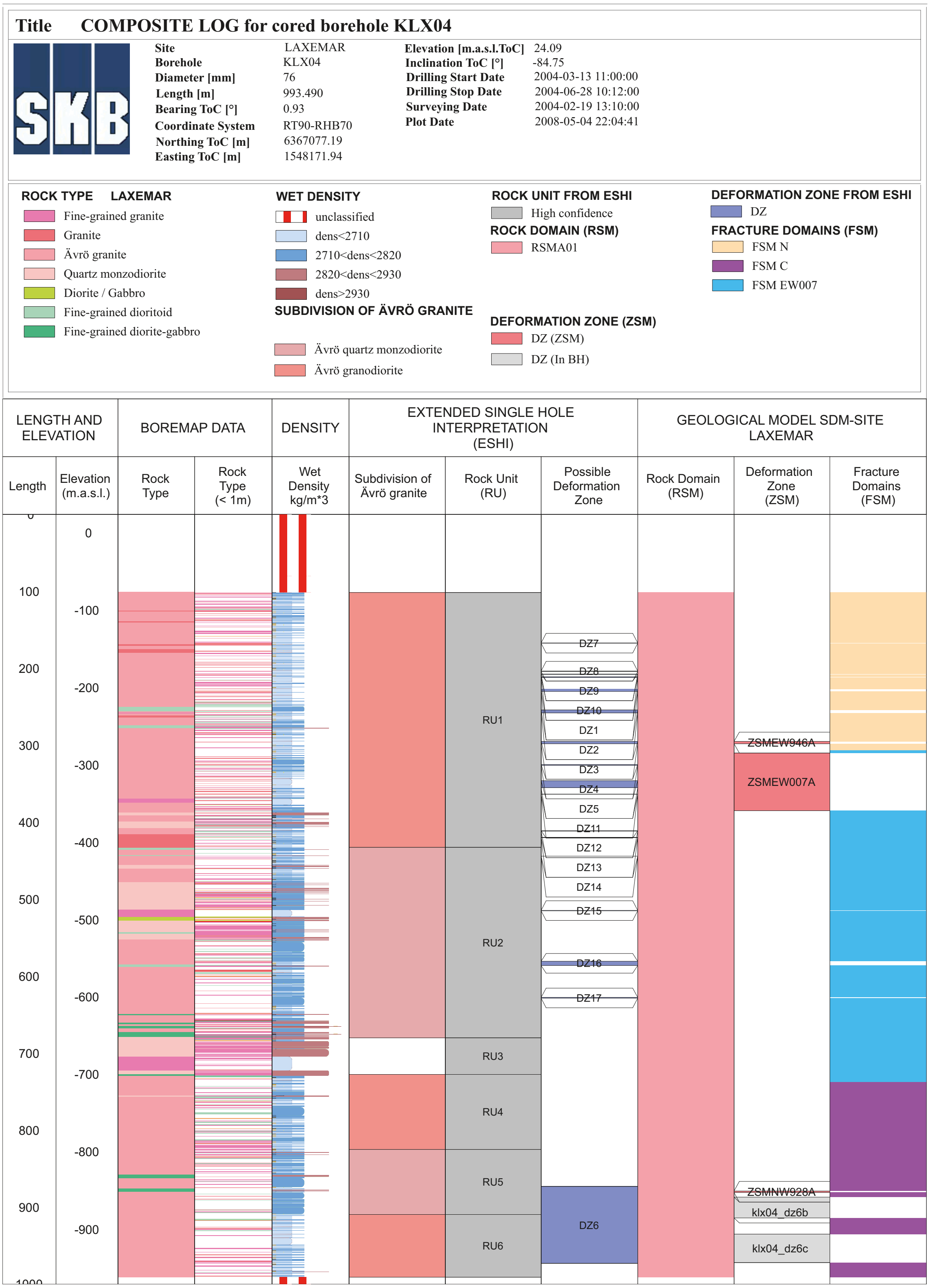


Figure 4-7. Composite log for KLX04.

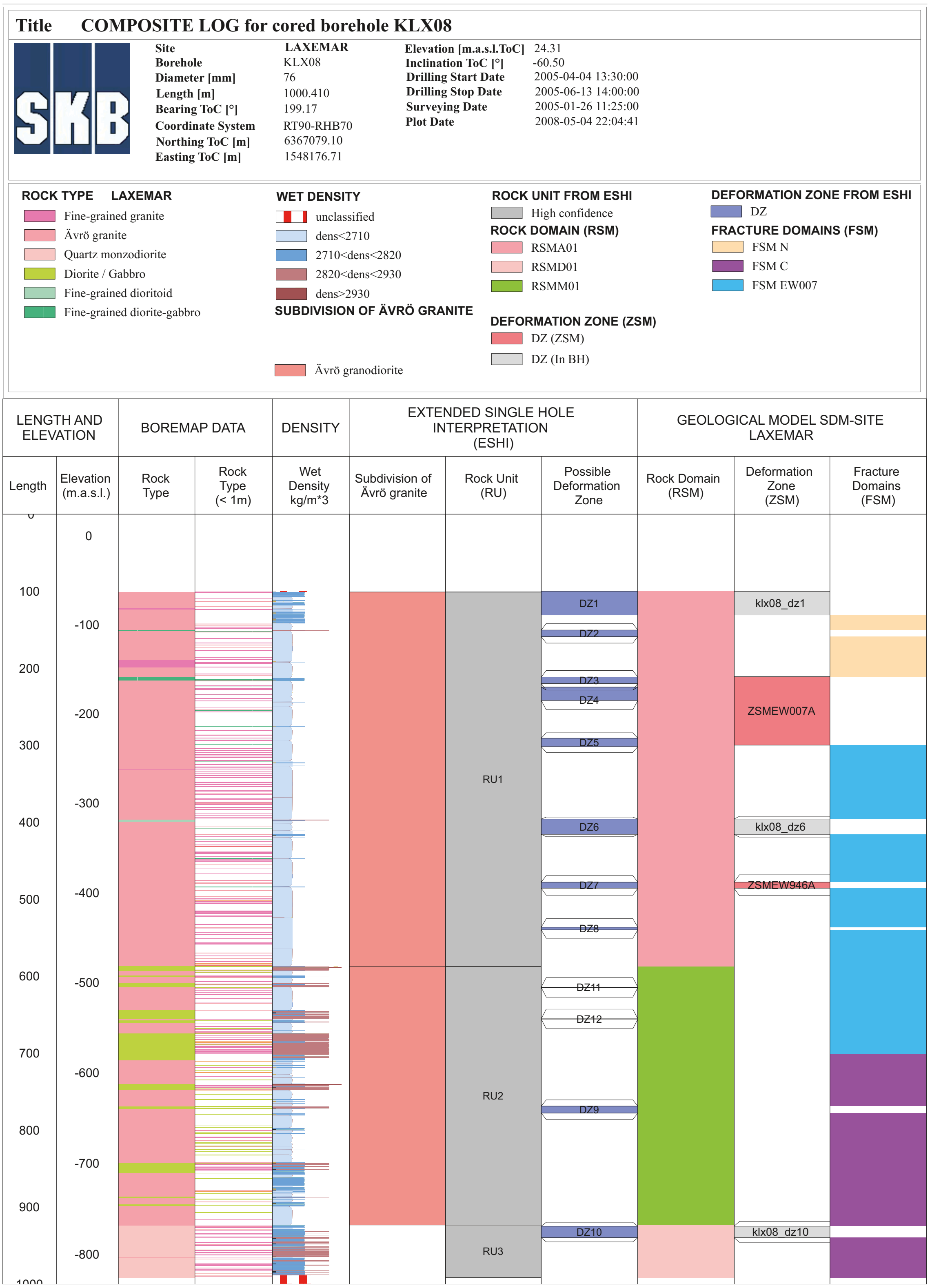


Figure 4-8. Composite log for KLX08.

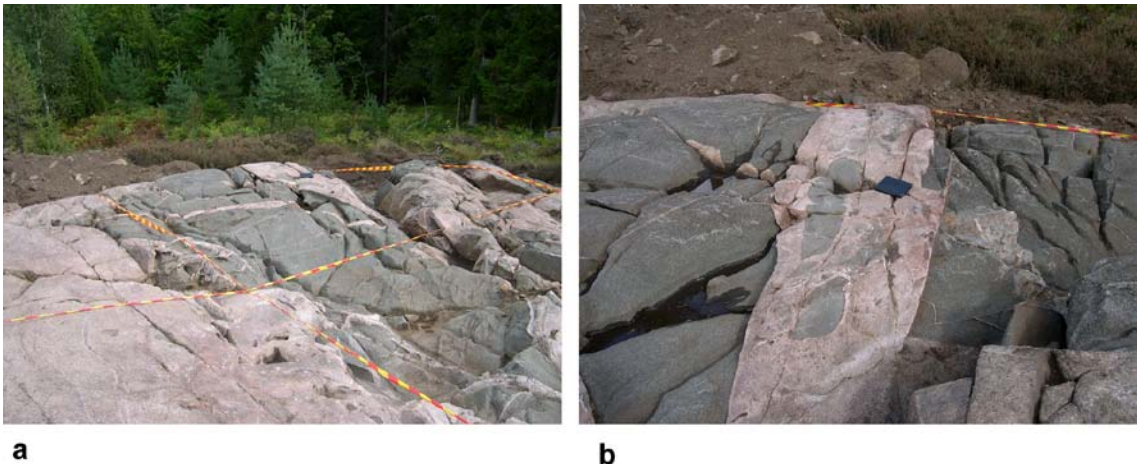


Figure 4-9. *a) Inclusions of diorite to gabbro in the southern part of the outcrop. b) Composite dyke of fine-grained granite and fine-grained diorite to gabbro cross-cuts the diorite to gabbro.*

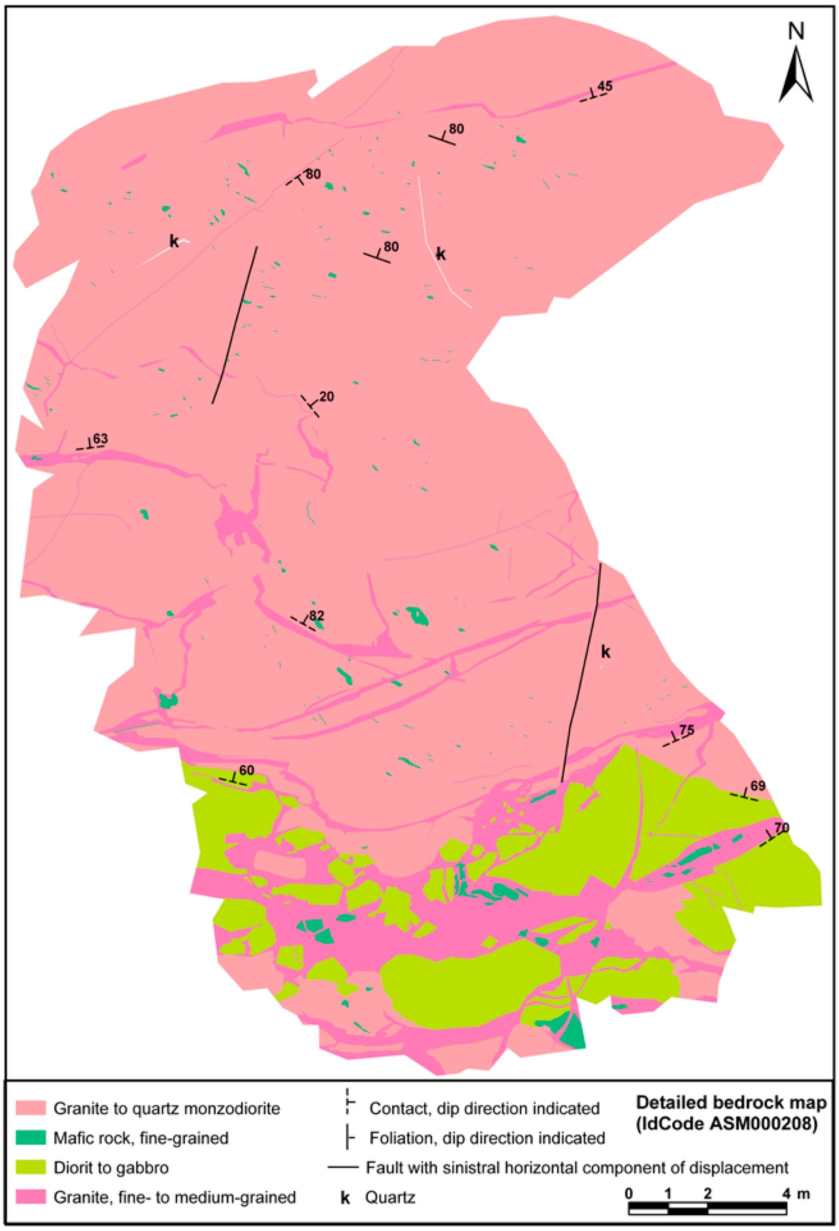


Figure 4-10. *Detailed bedrock geological map of the outcrop /Cronquist et al. 2004/.*

Detailed bedrock and fracture mapping have been carried out on this outcrop in connection with the site investigation (ASM000208 in /Cronquist et al. 2004/). All fractures with a trace length interval between 0.5 m and 10 m were mapped. Furthermore, scan line mapping was performed along two 10 m long orthogonal lines oriented N–S and E–W (LSM000293 and LSM000294, respectively). The truncation length for fracture traces in the scan line survey was 0.2 m. The fracture data were subsequently evaluated and analysed in the statistical modelling of the discrete fracture network at Laxemar (GeoDFN in /La Pointe et al. 2008/).

In addition, the fractures mapped by /Cronquist et al. 2004/ have been evaluated in a characterization of the brittle structures in the Laxemar-Simpevarp area (PSM007664 in /Viola and Venvik Ganerød 2007b/ and Figure 4-11). According to /Viola and Venvik Ganerød 2007b/, the P fractures (cf. Figure 4-11) display complex kinematics, the Y fractures display consistent sinistral sense of displacement while no kinematic constraints could be established for the S, X and low-angle fractures. The mutual angular relationship between the Y and S fractures (cf. stereonet in Figure 4-11) tentatively suggest that they are part of a conjugate system. Thus, on the basis of the sinistral character of the Y fractures, the S fractures should be dextral structures.

Stop 6. Götemar granite in old quarry (1550632/6372646)

Turn left (to the west) on the main road at the sign Kråkemåla and drive northwards to the old, water-filled quarry (Figure 3-1). Park the car and walk down to the quarry.

The excursion stop displays a red, coarse-grained granite, the so-called Götemar granite, on the western side of an old, approximately 300 m long and 80 m wide water-filled quarry (Kråkemåla 2), which was in operation until the end of the 1980´s. The granite is locally pegmatitic with dm-large crystals of K-feldspar and cm-thick packages of muscovite (Figure 4-12a). Fine-grained varieties of the granite are also present. Fluorite and calcite occur as fracture fillings (Figure 4-12b), and can, for instance, be seen on the steep fractures close to the water. Galena and pyrite, which give rise to a rusty staining, also occur as fracture fillings in the Götemar granite, but are rare at this locality. Furthermore, NE–SW oriented steep fractures filled with sandstone of supposed Cambrian age, so-called sandstone dykes, are spectacular at this locality (Figure 4-12c). Since fluorite-bearing fractures also affect the sandstone-filled fractures, it is apparent that the deposition of the fluorite, calcite and galena mineralizations occurred during the late- or post-Cambrian. Well-developed horizontal to sub-horizontal stress release joints, so-called sheet joints, in the granite can be seen on the opposite (eastern) side of the water-filled quarry (Figure 4-12d).

The Götemar granite forms part of a suite of approximately 1.45 Ga granite plutons that occur in the south-western part of the Fennoscandian Shield. The Uthammar granite in the Figeholm area and the Jungfru granite on the island of Blå Jungfrun in the Baltic Sea between Oskarshamn and Öland belong to the same suite.

Available data indicate that the Götemar granite is discordant and has not imposed any ductile deformation on its wall-rocks. These features do not support the concept that the Götemar granite has the geometrical shape of a diapir. Instead, a modelling of the residual gravity anomaly caused by the granite indicates that the Götemar granite has the 3D shape of a laccolith /Cruden 2008/. Furthermore, a $^{40}Ar/^{39}Ar$ geochronological study carried out in connection with the site investigation /Page et al. 2007, Söderlund et al. 2008a/ has demonstrated that the heat from the intrusion of the Götemar granite has had a thermal influence on and caused a resetting of the $^{40}Ar/^{39}Ar$ isotope system in amphibole and biotite in the neighbouring country rocks.

For further reading, see /Kresten and Chyssler 1976, Alm and Sundblad 2002, Page et al. 2007, Söderlund et al. 2008a, Cruden 2008/.

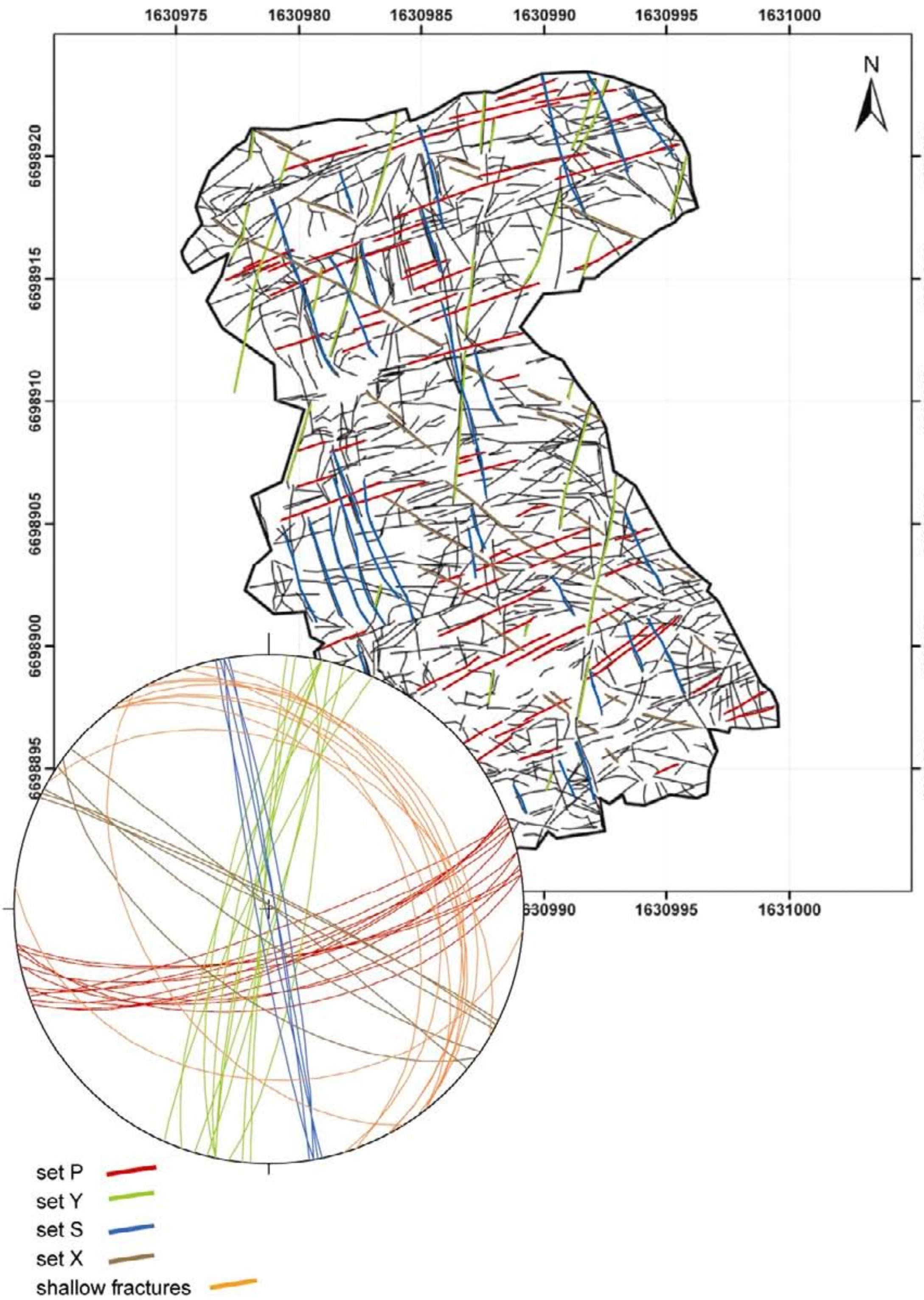


Figure 4-11. Detailed fracture map of the outcrop. Colours have been added to highlight systematic fracture sets, the orientations of which are shown by the identically coloured great circles in the stereonet. Five systematic sets are highlighted. From /Viola and Venvik Ganerød 2007b/, redrawn from /Cronquist et al. 2004/.

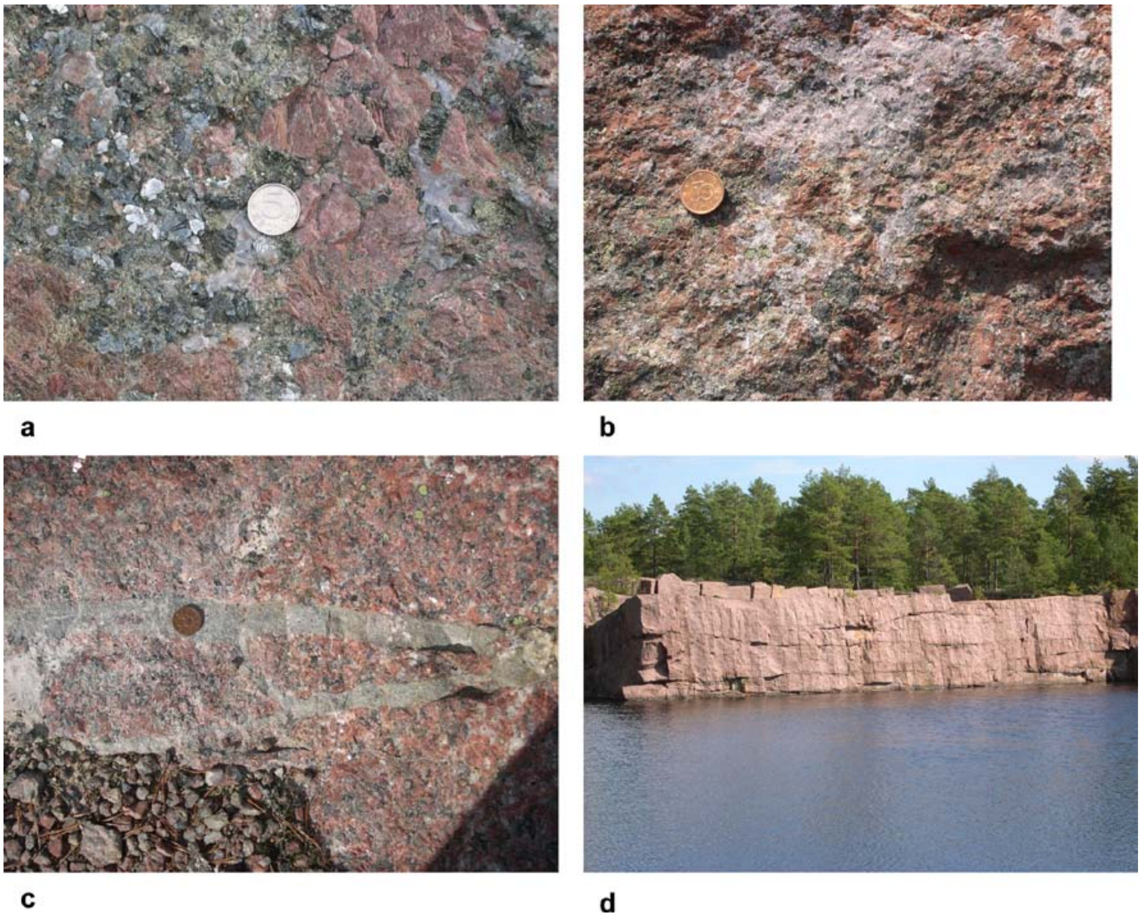


Figure 4-12. Characteristics of the Götemar granite. a) Pegmatitic variety with dm-large crystals of K-feldspar and cm-thick packages of muscovite. b) Fluorite on a fracture surface. c) Fractures filled with Cambrian sandstone ("sandstone dyke"). d) Sub-horizontal sheet joints in the Götemar granite.

Stop 7. Equigranular granite and porphyritic Ävrö granite (PSM003766 at 1548144/6368165)

Road cut along the road between Mederhult and Lake Frisksjön (Figure 3-1). Park the car east of the road cut.

Two rock types can be seen in the road cut, a red to greyish red, medium-grained, equigranular to slightly porphyritic granite, and a reddish grey, medium-grained, finely to coarsely porphyritic rock which is classified as Ävrö granite. Both rock types have been analysed for the mineralogical and chemical composition (red granite = PSM003766B, Ävrö granite = PSM003766A in /Wahlgren et al. 2005/). According to the modal analysis, the Ävrö granite has a tonalitic composition. However, the Ävrö granite is maintained as rock nomenclature since the modal analysis is not judged to be representative of the general mineralogical composition. The occurrence of scattered large microcline megacrysts has apparently not been accounted for in the modal analysis. Dykes and veins of fine-grained granite as well as pegmatitic varieties are both present. Epidote occurs as a filling in the fractures.

The reddish, equigranular granite and the porphyritic Ävrö granite show a diffuse contact relationship (Figure 4-13). This is a typical phenomenon for most contacts between the dominant rock types in the Laxemar-Simpevarp area and indicates that they belong to the same magmatic suite and were formed very close in time. This has been confirmed by the U-Pb zircon geochronological studies (see section 3.1).

***Figure 4-13.** Diffuse transition between the red to greyish red, equigranular granite (beneath finger) and the reddish grey, porphyritic Ävrö granite (above finger).*

The red to greyish red, medium- to coarse-grained, equigranular granite constitute a relatively minor lithological component in central Laxemar. However, scattered minor bodies are characteristic in the northern part of Laxemar, i.e. in the area north of the E-W trending deformation zone ZSMEW002A ("Mederhult zone"), as well as in the southern part (Figure 3-3). The "Mederhult zone" occurs along the topographic depression south of the road.

Stop 8. Quartz monzodiorite exposed along the sub-Cambrian peneplain (PSM004507 at 1546109/6366411)

The car can be parked on the excursion stop which is an extensively well-exposed area close to Lilla Basthult (Figure 3-1).

The bedrock is composed of reddish grey, medium-grained, equigranular, massive to faintly foliated quartz monzodiorite, i.e. a well-preserved variety of the rock type at excursion stop 2. A sample from this outcrop has been analysed both for mineralogical (modal analysis) and chemical composition (PSM004507A in /Wahlgren et al. 2005/). An evaluation of the modal analysis reveals that this particular rock type has a composition that corresponds to the transition between quartz monzodiorite and granodiorite. The faint foliation that locally can be observed strikes WNW–ESE and is steeply to vertically dipping. Thin (<0.1 m) dykes and veins of red, fine-grained granite with an ENE–WSW strike occur. Sparsely distributed 0.5–1 cm large phenocrysts of K-feldspar locally occur within the outcrop area.

Long, continuous fractures that strike NNE–SSW and locally displace dykes of fine-grained granite sinistrally, as well as shorter fractures that strike ENE–WSW to E–W are common at the outcrop. Red staining occurs, preferably along the fractures with NNE–SSW strike (Figure 4-14a).

The outcrop forms part of a large, flat, well-exposed area (Figure 4-14b) that is a typical example of the so-called sub-Cambrian peneplain. The latter was formed by extensive denudation of the Proterozoic crystalline rocks in late Precambrian time, i.e. sometime before 540 Ma ago. The peneplain corresponds to a major unconformity in south-eastern Sweden, between the Proterozoic rocks in the Fennoscandian Shield and the Palaeozoic sedimentary overburden. The Palaeozoic sedimentary rocks are currently only locally preserved as isolated outliers.

a **b**

Figure 4-14. *Characteristic fractures with NNE–SSW and ENE–WSW strike. View to the north in both pictures. a) Note the red staining preferably along the fractures with NNE–SSW strike. b) Overview of the outcrop area which constitutes a characteristic example of the sub-Cambrian peneplain.*

Stop 9. Topographic depression and dolerite dyke along deformation zone ZSMNS001C (1546565/6366130)

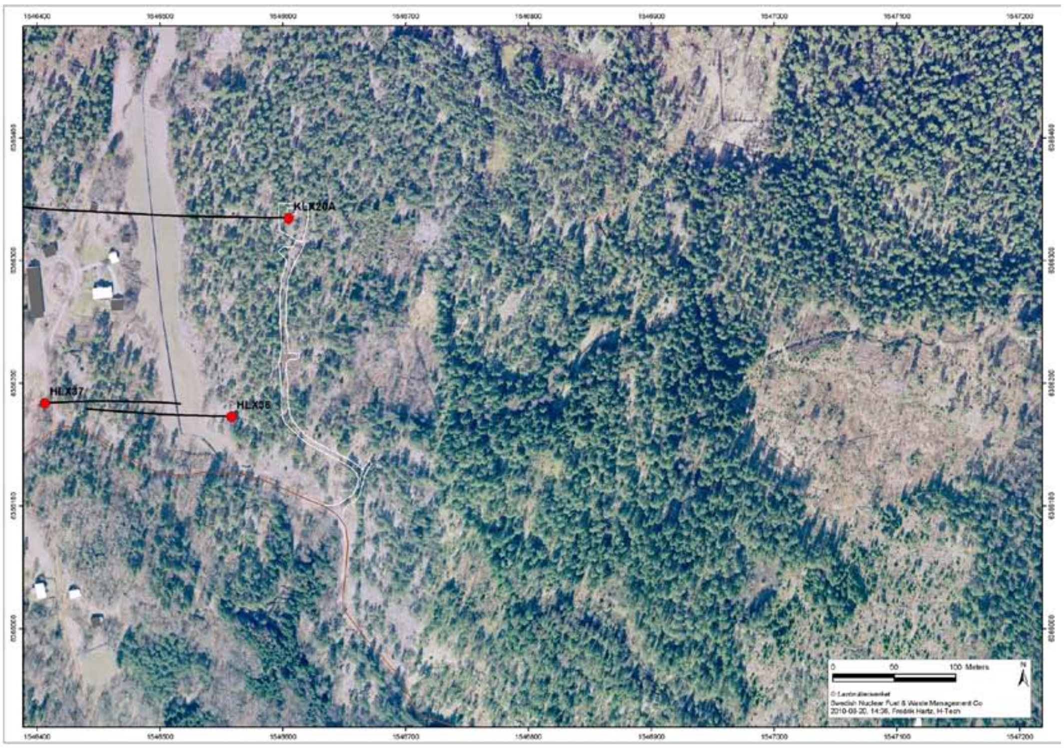
Park the car close to the road and walk approximately 50–75 m in a north-west direction. The coordinates mark the place where the car can be parked (Figure 3-1).

Excursion stop 9 shows a pronounced topographic depression oriented in a N–S direction along the deformation zone ZSMNS001C (Figure 4-15a, b, /Wahlgren et al. 2008/). During the drilling of the cored borehole KLX20A (Figure 4-15a), which was situated to the east of the zone and inclined 50 degrees to the west, a dolerite was documented between 182 and 231 m borehole length (Figure 4-16). The dolerite was interpreted to dip steeply to the west and the true thickness is estimated to approximately 20 m. The dolerite has also been documented in the percussion boreholes HLX36, HLX37 (Figure 4-15a) and HLX43 that are also inclined towards the valley. This strongly indicates that the dolerite is reasonably continuous along the topographic depression. Although the dolerite is not exposed, due to thick glacial cover in the topographical depression along ZSMNS001C, it is anticipated that it forms the bedrock surface and, for this reason, has been marked on the bedrock geological map (Figure 3-3). The dolerite is strongly fractured along its entire length in both the cored borehole KLX20A (Figure 4-17) as well as in the percussion boreholes, while the surrounding quartz monzodiorite does not display the same strong fracturing. Consequently, the deformation zone is concentrated to the dolerite (see Figure 4-16), which is interpreted to have intruded along an already existing deformation zone that was reactivated at a later stage during the geological evolution.

Apart from the above mentioned boreholes, dolerite has also been documented in the cored boreholes KLX14A and KLX19A, and the percussion boreholes HLX13 and HLX38. However, dolerites have not been observed in any outcrops in the Laxemar area despite the detailed mapping of the bedrock. The reason for this is presumably that the dolerites are more easily eroded than the surrounding bedrock due to the strong fracturing and, therefore, occur in topographic depressions in the area. However, it is inferred that any additional dolerites are thin and that dolerite constitutes a very subordinate rock type at Laxemar.

The magnetic susceptibility of the dolerites is generally lower than the average susceptibility of the country rock. This implies that the dolerites show low magnetic signatures similar to deformation zones. The lower magnetic susceptibility is partly due to the strong fracturing, but also that the dolerites lack the magnetic mineral magnetite and are dominated by the less magnetic Fe-Ti oxide ilmenite.

A $^{40}Ar/^{39}Ar$ age determination of the dolerite has yielded a whole rock age of approximately 900 Ma /Wahlgren et al. 2007, Söderlund et al. 2008a/. This implies that the dolerites form the youngest igneous rocks in the region and belong to a regional system of dolerites with N–S strike, dated to 980 to 960 Ma, which can be followed from Blekinge in the south-easternmost part of Sweden to Dalarna in the central part of the country.



a

b

Figure 4-15. *a) Aerial view to the north of the topographic depression (upper left part of the picture) along a part of deformation zone ZSMNS001C. The drill sites (red spots) and the horizontal projections for the cored borehole KLX20A and the percussion boreholes HLX36 and HLX37 are marked. b)View to the north along the topographic depression in which the dolerite occurs.*

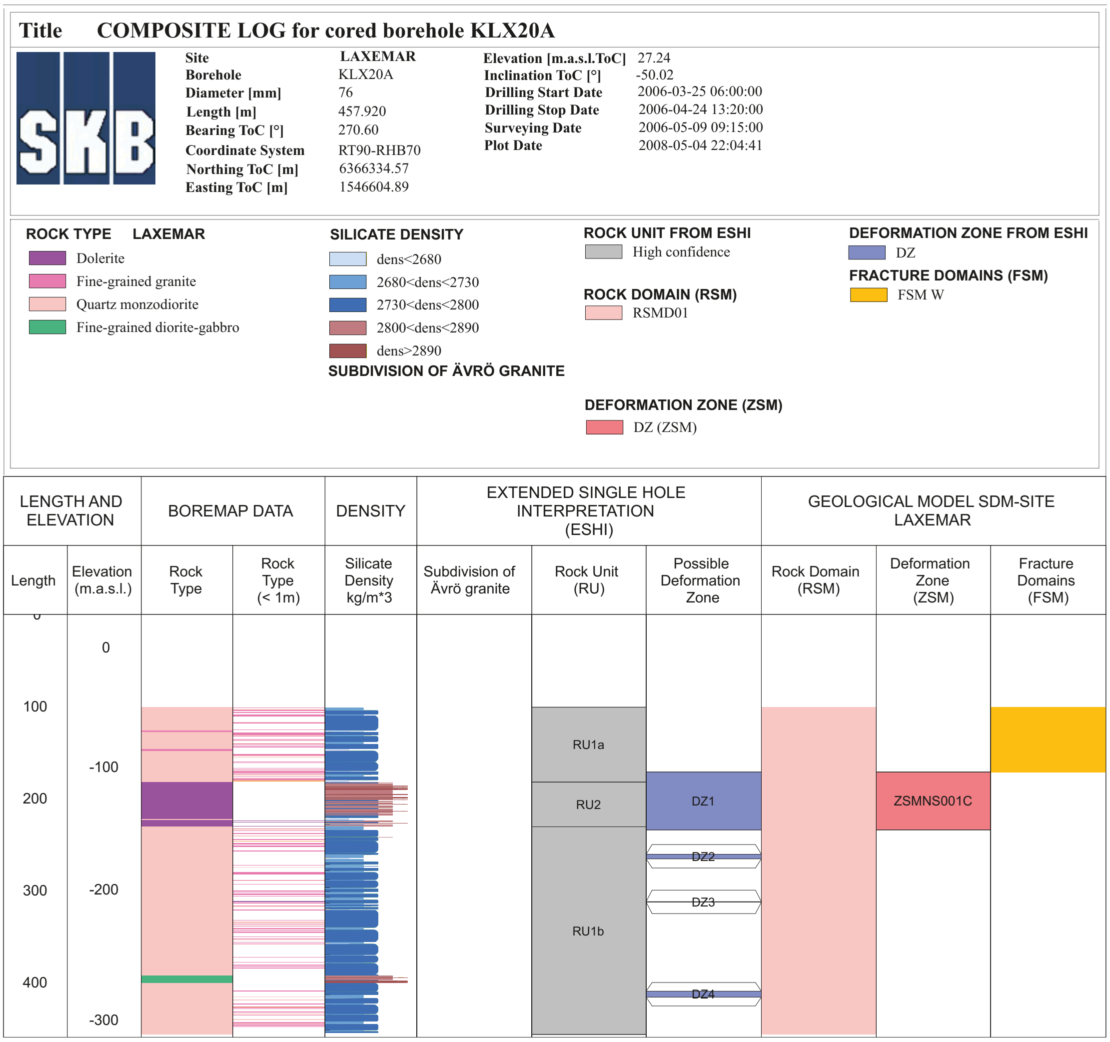


***Figure 4-16.** Composite log for KLX20A. The lilac colour in the rock type column marks the position of the dolerite. Note that the position of the modelled deformation zone ZSMNS001C corresponds to the position of the dolerite.*

***Figure 4-17.** Characteristic strong fracturing in the dolerite dykes. Drill core from borehole KLX20A.*

5 References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

Åhäll K-I, 2001. Åldersbestämning av svårdaterade bergarter i sydöstra Sverige. SKB R-01-60. Svensk Kärnbränslehantering AB.

Alm E, Sundblad K, 2002. Fluorite-calcite-galena-bearing fractures in the counties of Kalmar and Blekinge, Sweden. SKB R-02-42, Svensk Kärnbränslehantering AB.

Bergman T, Rudmark L, Wahlgren C-H, Johansson R, Isaksson H, 2000. Förstudie Oskarshamn. Kompletterande geologiska studier. SKB R-00-45, Svensk Kärnbränslehantering AB.

Carlsten S, Stråhle A, Hultgren P, Mattsson H, Wahlgren, C-H, 2007. Oskarshamn site investigation. Geological single-hole interpretation of KLX18A and KLX20A. SKB P-07-70, Svensk Kärnbränslehantering AB.

Cronquist T, Forssberg O, Hansen L, Jonsson A, Koyi S, Leiner P, Sävås J, Vestgård J, 2004. Oskarshamn site investigation. Detailed fracture mapping of two outcrops at Laxemar. SKB P-04-274, Svensk Kärnbränslehantering AB.

Cruden A, 2008. Emplacement mechanisms and structural influences of a younger granite intrusion into older wall rocks – a principal study with application to the Götemar and Uthammar granites. Site-descriptive modelling SDM-Site Laxemar. SKB R-08-138, Svensk Kärnbränslehantering AB.

Drake H, Page L, Tullborg E-L, 2007. Oskarshamn site investigation. $^{40}Ar/^{39}Ar$ dating of fracture minerals. SKB P-07-27, Svensk Kärnbränslehantering AB.

Drake H, Tullborg E-L, Page L, 2009. Distinguished multiple events of fracture mineralisation related to far-field orogenic effects in Paleoproterozoic crystalline rocks, Simpevarp area, SE Sweden. Lithos 110, 37–49.

Forssberg O, Cronquist T, Vestgård J, Bergkvist L, Hermanson J, Öhman J, Pettersson A, Koyi S, Bergman T, 2007. Oskarshamn site investigation. Detailed outcrop mapping in trenches. SKB P-07-29, Svensk Kärnbränslehantering AB.

Hermansson T, Stephens M B, Corfu F, Andersson J, Page L, 2007. Penetrative ductile deformation and amphibolite-facies metamorphism prior to 1,851 Ma in the western part of the Svecofennian orogen, Fennoscandian Shield. Precambrian Research 153, 29–45.

Hermansson T, Stephens M B, Corfu F, Page L, Andersson J, 2008. Migratory tectonic switching, western Svecofennian orogen, central Sweden: Constraints from U/Pb zircon and titanite geochronology. Precambrian Research 161, 250–278.

Johansson L, Johansson Å, 1990. Isotope geochemistry and age relationships of mafic intrusions along the Protogine Zone, southern Sweden. Precambrian Research 48, 395–414.

Kinck J J, Husebye E S, Larsson F R, 1993. The Moho depth distribution in Fennoscandia and the regional tectonic evolution from Archean to Permian times. Precambrian Research 64, 23–51.

Koistinen T, Stephens M B, Bogatchev V, Nordgulen O, Wennerström M, Korhonen J, 2001. Geological map of the Fennoscandian Shield, scale 1:2 000 000. Geological Surveys of Finland, Norway and Sweden and the North-West Department of Natural Resources of Russia.

Kornfält K-A, Persson P-O, Wikman H, 1997. Granitoids from the Äspö area, southeastern Sweden – geochemical and geochronological data. GFF 119, 109–114.

Kresten P, Chyssler J, 1976. The Götemar Massif in south-eastern Sweden; a reconnaissance survey. Geologiska Föreningen i Stockholm Förhandlingar 98, 155–161.

La Pointe P, Fox A, Hermanson J, Öhman J, 2008. Site Descriptive Modelling. SDM-Site Laxemar. Geological discrete fracture network model for the Laxemar site. SKB R-08-55, Svensk Kärnbränslehantering AB.

Lidmar-Bergström K, 1994. Morphology of the bedrock surface. In C Fredén (edit.), Geology. National Atlas of Sweden, 1st edition, 44–54.

Lundberg E, Sjöström H, 2006. Oskarshamn site investigation. Kinematic analysis of ductile and brittle/ductile shear zones in Simpevarp and Laxemar subarea. SKB P-06-118, Svensk Kärnbränlehantering AB.

Lundqvist J, 1994. The deglaciation. In C. Fredén (edit.), Geology. National Atlas of Sweden, 1st edition, 124–135.

Page L, Söderlund P, Wahlgren C-H, 2007. Oskarshamn site investigation. ^{40}Ar/^{39}Ar and (U-Th)/He Geochronology of samples from the cored boreholes KSH03A, KSH03B, KLX01, KLX02 and the access tunnel to the Äspö Hard Rock Laboratory. SKB P-07-160, Svensk Kärnbränlehantering AB.

Paulamäki S, 2009. Geological Setting of the Olkiluoto Investigation Site, Eurajoki, SW Finland. Excursion Guidebook. Working Report 2009-53. Posiva Oy, Eurajoki, Eurajoki.

Persson Nilsson K, Bergman T, Eliasson T, 2004. Oskarshamn site investigation. Bedrock mapping 2004 – Laxemar subarea and regional model area. Outcrop data and description of rock types. SKB P-04-221, Svensk Kärnbränslehantering AB.

Rauséus G, Ehrenborg J, 2007. Oskarshamn site investigation. Boremap mapping of the core drilled borehole KLX20A. SKB P-06-241, Svensk Kärnbränslehantering AB.

SKB, 2002. Simpevarp – site descriptive model version 0. SKB R-02-35, Svensk Kärnbränslehantering AB.

SKB, 2009. Site description of Laxemar at completion of the site investigation phase. SDM-Site Laxemar. SKB TR-09-01, Svensk Kärnbränslehantering AB.

Stephens M B, 2010. Forsmark site investigation. Bedrock geology – overview and excursion guide. SKB R-10-04, Svensk Kärnbränslehantering AB.

Stephens M B, Fox A, La Pointe P, Simeonov A, Isaksson H, Hermanson J, Öhman J, 2007. Geology Forsmark. Site descriptive modelling. Forsmark stage 2.2. SKB R-07-45, Svensk Kärnbränslehantering AB.

Söderbäck B (ed.), 2008. Geological evolution, palaeoclimate and historic development of the Forsmark and Laxemar-Simpevarp areas. Site descriptive modelling SDM-Site. SKB R-08-19, Svensk Kärnbränslehantering AB.

Söderlund P, Juez-Larré J, Page L, Dunai T, 2005a. Extending the time range of apatite (U-Th/He) thermochronometry in slowly cooled terranes: Palaeozoic to Cenozoic exhumation history of southeast Sweden. Earth and Planetary Science Letters 239, 266–275.

Söderlund U, Isachsen C, Bylund G, Heaman L, Patchett P J, Vervoort J D, Andersson U B, 2005b. U-Pb baddeleyite ages and Hf, Nd isotope chemistry constraining repeated mafic magmatism in the Fennoscandian Shield from 1.6 to 0.9 Ga. Contributions to Mineralogy and Petrology 150, 174–194.

Söderlund P, Page L, Söderlund U, 2008a. ^{40}Ar/^{39}Ar biotite and hornblende geochronology from the Oskarshamn area, SE Sweden: Discerning multiple Proterozoic tectonothermal events. Geological Magazine 145, 790–799.

Söderlund P, Juez-Larré J, Page L M, Stuart F M, Andriessen P M, 2008b. Assessment of discrepant (U-Th)/He and apatite fission-track ages in slowly cooled Precambrian terrains: a case study from SE Sweden. In Söderlund P, ^{40}Ar-^{39}Ar, AFT and (U-Th)/He thermochronologic implications for the low-temperature geological evolution in SE Sweden. PhD thesis, University of Lund, Sweden.

Viola G, 2008. Ductile and brittle structural evolution of the Laxemar-Simpevarp areas: an independent analysis based on local and regional constraints. SKB R-08-124, Svensk Kärnbränslehantering AB.

Viola G, Venvik Ganerød G, 2007a. Oskarshamn site investigation. Structural analysis of brittle deformation zones in the Simpevarp-Laxemar area, Oskarshamn, southeast Sweden. SKB P-07-41, Svensk Kärnbränslehantering AB.

Viola G, Venvik Ganerød G, 2007b. Oskarshamn site investigation. Structural characterization of deformation zones (faults and ductile shear zones) from selected drill cores and outcrops from the Laxemar area – results from Phase 2. SKB P-07-227, Svensk Kärnbränslehantering AB.

Viola G, Venvik Ganerød G, 2008. Oskarshamn site investigation. Structural characterization of deformation zones (faults and ductile shear zones) from selected drill cores from the Laxemar area. SKB P-08-07, Svensk Kärnbränslehantering AB.

Viola G, Venvik Ganerød G, Wahlgren C-H, 2009. Unraveling 1.5 Ga of brittle deformation history in the Laxemar-Simpevarp area, southeast Sweden: A contribution to the Swedish site investigation study for the disposal of highly radioactive nuclear waste. Tectonics 28, TC5007, doi:10.1029/2009TC002461.

Wahlgren C-H, Ahl M, Sandahl K-A, Berglund J, Petersson J, Ekström M, Persson P-O, 2004. Oskarshamn site investigation. Bedrock mapping 2003 – Simpevarp subarea. Outcrop data, fracture data, modal and geochemical classification of rock types, bedrock map, radiometric dating. SKB P-04-102, Svensk Kärnbränlehantering AB.

Wahlgren C-H, Bergman T, Persson Nilsson K, Eliasson T, Ahl M, Ekström M, 2005. Oskarshamn site investigation. Bedrock map of the Laxemar subarea and surroundings. Description of rock types, modal and geochemical analyses, including the cored boreholes KLX03, KSH03 and KAV01. SKB P-05-180, Svensk Kärnbränslehantering AB.

Wahlgren C-H, Bergman T, Ahl M, Ekström M, 2006. Oskarshamn site investigation. Modal and geochemical analyses of drill core samples 2006 and updated bedrock map of the Laxemar subarea. Classification of rock types in KLX08, KLX10, KLX11A, KLX12A, KLX18A and KLX20A. SKB P-06-279, Svensk Kärnbränslehantering AB.

Wahlgren C-H, Bergman T, Ahl M, Ekström M, Page L, Söderlund U, 2007. Oskarshamn site investigation. Modal and geochemical analyses of drill core samples 2007 and $^{40}Ar/^{39}Ar$ dating of a dolerite. Classification of rock types in KLX15A, KLX16A, KLX19A, KLX20A and KLX21B. SKB P-07-191, Svensk Kärnbränslehantering AB.

Wahlgren C-H, Curtis P, Hermanson J, Forssberg O, Öhman J, Fox A, La Pointe P, Drake H, Triumf C-A, Mattsson H, Thunehed H, Juhlin C, 2008. Geology Laxemar. Site descriptive modelling. SDM-Site Laxemar. SKB-R-08-54, Svensk Kärnbränslehantering AB.

Wikman H, Kornfält K-A, 1995. Updating of a lithological model of the bedrock of the Äspö area, SKB PR 25-95-04, Svensk Kärnbränslehantering AB.