R-06-110

Preliminary site description Laxemar stage 2.1

Feedback for completion of the site investigation including input from safety assessment and repository engineering

Svensk Kärnbränslehantering AB

September 2006

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Preface

The Swedish Nuclear Fuel and Waste Management Company (SKB) is undertaking site characterisation at two different locations, the Forsmark and Simpevarp/Laxemar areas, with the objective of siting a geological repository for spent nuclear fuel. An integrated component in the characterisation work is the development of a Site Descriptive Model that constitutes a description of the site and its regional setting. The model addresses the current state of the geosphere and the biosphere as well as the ongoing natural processes that affect their long-term evolution.

Since the start of site characterisation in 2002, one complete site description (version 1.2) has been produced for the Laxemar subarea based on data from the Initial Site Investigation stage. During 2005 and 2006, a slightly modified working mode for site modelling has been undertaken. The primary objective of the work has been to provide feedback to the investigations at Laxemar to ensure that adequate and timely data and information are obtained during the remaining investigation stage. The present report documents the site modelling activities for the Laxemar subarea during modelling stage 2.1.

As before, the work has been conducted by a multi-disciplinary project group and associated-discipline-specific working groups. The work has been conducted in cooperation with the site investigation team at Laxemar and representatives from safety assessment and repository engineering. Data available in data freeze 2.1 have been analysed with the purpose to assess the implications of the new data for the understanding of the site and the validity of previous model versions. However, no complete integrated site description based on data compiled in data freeze 2.1 is provided within the framework of modelling stage 2.1. It should be recognised that this report represents a step in the development of the version 2.3 site model with one of its main objectives to provide feedback to investigations.

The following individuals and expert groups contributed to the project and/or to the report:

- Anders Winberg – project leader and editor.
- Carl-Henric Wahlgren, Jan Hermanson, Philip Curtis and co-workers – geology.
- Eva Hakami, Flavio Lanaro, Ann Bäckström – rock mechanics.
- Jan Sundberg and co-workers – thermal properties.
- Ingvar Rhén and co-workers – hydrogeology.
- Marcus Laaksoharju and the members of the ChemNet group – hydrogeochemistry.
- James Crawford – transport properties.
- Tobias Lindborg – ecosystems.
- Johan Andersson – remaining site specific uncertainties and their handling.
- Karl Erik Almén and members of the site investigation team at Laxemar – implications of remaining uncertainties for the site investigation programme.
- Raymund Munier, Jan-Olof Selroos, Eva Widing and Rolf Christiansson – feedback from safety analysis and repository engineering.
- Fredrik Hartz – production of maps and figures.

Anders Ström
Site Investigations – Analysis

Summary

The Laxemar subarea is the focus for the complete site investigations in the Simpevarp area. The south and southwestern parts of the subarea (the so-called “focused area”) have been designated for focused studies during the remainder of the site investigations. This area, some 5.3 square kilometres in size, is characterised on the surface by an arc shaped body of quartz monzodiorite gently dipping to the north, flanked in the north and south by Ävrö granite.

The current report documents work conducted during stage 2.1 of the site-descriptive modelling of the Laxemar subarea. The primary objective of the work performed is to provide feedback to the site investigations at Laxemar to ensure that adequate and timely data and information are obtained during the remaining investigation stage. The work has been conducted in cooperation with the site investigation team at Laxemar and representatives from safety assessment and repository engineering. The principal aim of this joint effort has been to safeguard that adequate data are collected that resolve the remaining issues/uncertainties which are of importance for repository layout and long-term safety. The proposed additional works presented in this report should be regarded as recommended additions and/or modifications in relation to the CSI programme published early 2006.

The overall conclusion of the discipline-wise review of critical issues is that the CSI programme overall satisfies the demands to resolve the remaining uncertainties. This is interpreted to be partly a result of the close interaction between the site modelling team, site investigation team and the repository engineering teams, which has been in operation since early 2005.

Compared with the CSI programme, two new telescoped cored boreholes (KLX16A and KLX21B, notations per early autumn 2006) are proposed. The purpose of the former borehole is to verify the existence of, and characterise a dolerite as previously observed in conjunction with zone NS001A in borehole KLX20A. The purpose of borehole KLX21B is to characterise the southeastern part of potential deposition areas in the focused area.

In order to meet the primary objective of the Laxemar 2.1 work, data available in data freeze Laxemar 2.1 have been analysed. However, in some cases data made available after the formal data freeze for Laxemar 2.1 have been utilised to enable more effective feedback and review of the CSI programme, e.g. use of new stress data from KLX12A. It is also noted that no (official) updated versions of the geological models for rock domains and deterministic deformation zones are presented, although working models have been produced based on which various aspects of the geological models are discussed. No work on the geological DFN model has been performed.

In the rock domain modelling the existence of the RSMBA domains (mixture of Ävrö granite and fine-grained dioritoid) in KLX05 has been redefined to RSMB (fine-grained dioritoid) and consequently, the only RSMBA domain now remains in KLX02 (outside the focused area). Furthermore, in order to improve correlation between compositional varieties of the Ävrö granite and the division in rock domains, an evaluation of available analytical data (modal, geochemical and petrophysical data) has been initiated based on both surface and borehole data. In the south and western parts of the Laxemar subarea, a preliminary division into a quartz rich (granitic to granodioritic) and a quartz poor (quartz monzodioritic) variety of the Ävrö granite has been made on the bedrock map. A possible division in 3D will be attempted as part of the L2.2 work.

In the assessment of deformation zones an independent alternative interpretation of lineaments has been reviewed, resulting in some 10 lineaments being retained in the current Laxemar 2.1 modelling. However, the majority of the lineaments proposed in the alternative study were rejected on the basis of topography and/or geophysical background data. In addition, a regional review was made of key structures intersecting the local scale model area, with special emphasis

on extent and termination modes. This assessment was complemented by a local scale review (made partly in collaboration with the site investigation team) of select key deformation zones. One new entity in the current assessment is a *potential* deformation zone manifested by the subhorizontal seismic reflector M1 at repository depth. The current position is that the reflector cannot be correlated with borehole deformation zone indicators throughout Laxemar. In order to further assess reflector M1 as a potential deformation zone, available geological, seismic and borehole radar data will be jointly assessed. If support for reflector M1 as a deformation zone is obtained, additional is situ investigations could include cross-hole interference tests and vertical seismic profiling (VSP). Furthermore, digging of trenches with alternate orientations is proposed in the focused area. The fracture data collected from such trenches would e.g. serve to corroborate linked lineament interpretations, the general fracturing pattern and would also serve as an important tool for generalising results of the assessment of minor local deformation zones (MDZ).

The rock mechanics analysis has involved consolidation work in a number of areas based on the Laxemar 2.1 data. With regards to intact rock mechanical properties it was found that high density of the Ävrö granite (caused by low quartz content) is associated with reduced mechanical strength. This provides additional support for subdividing RSMA01 (Ävrö granite) according to quartz content. A valuable verification exercise was conducted by comparing the outcome of an empirical assessment of the rock mass properties along the Äspö access tunnel (based on the subparallel KBH02 borehole) with the outcome of the tunnel mapping of the corresponding tunnel section. The study suggest use of $Q < 1$ and/or $RMR < 40$ (5 m sections) for identification of major deformation zones and $Q < 4$ and/or $RMR < 60$ (1 m sections) for identifying minor long, potentially waterbearing fractures. Stress levels in KLX12A (overcoring) indicate medium high values compared to previous observations within the local model volume.

The mineralogical variability within the Ävrö granite, as discussed above, is manifested in a bimodal distribution of thermal conductivity with in RSMA01. The area in the south, reflected by conditions seen in KLX03 and KLX05, have significantly lower thermal conductivity compared to other boreholes in the subarea. In addition, a tendency of reduced conductivity between 450–650 m is seen in all boreholes in Ävrö granite. The domain-based mean conductivity of the RSMA01 domain (Ävrö granite) is 2.75 W/mK with the mean value of the RSMD01 (quartz monzodiorite) being slightly higher. Remaining uncertainties are overall captured by the planned CSI programme. One component added to the investigation programme is the performance of in situ cross-hole thermal measurements on metre scale which are expected to yield a more representative view of the variability of thermal conductivity.

One important aspect of the hydrogeological modelling and understanding of the Laxemar subarea is the hydraulic material property distribution in potential deposition areas. A compilation of 100 m measurements of hydraulic conductivity in boreholes grouped essentially south and north of zone EW007A, shows a tendency of lower hydraulic conductivity at repository depth for the south grouping. No formal update of the hydrogeological model has been made as part of model stage L2.1.

The data base underlying the Laxemar 2.1 hydrogeochemical modelling includes significantly more representative data from the Laxemar subarea compared with Laxemar 1.2. Consequently, a full modelling step has been undertaken to elevate the hydrogeochemical model. The modelling includes reaction modelling for dilute waters (representing shallow bedrock groundwaters) and deeper waters. Calcite and/or dolomite dissolution govern the evolution of the surfical system whereas silicate weathering governs the evolution of the deeper bedrock system. Coupled modelling, performed to provide a quantitative framework for testing alternative hydrogeochemical processes and concepts, showed that a calibrated coupled hydrogeological-hydrogeochemical model could predict well the distribution of most dissolved species. The resulting conceptual model includes the four water types A–D, similarly to model version Laxemar 1.2. New hydrogeochemical data from KLX08, showing deep penetration of meteoric waters, confirm the pronounced recharge environment generally attributed to the Laxemar subarea. In the assessment relative to the CSI programme it was identified that simplified groundwater sampling in planned boreholes should be considered to obtain as much data as possible from HRD(D,E,M) in the south and west of the subarea. Furthermore, additional assessments of matrix pore water composition will be attempted in an additional borehole (KLX17A) to make up for failed measurements in KLX13A.

In the case of transport properties of the bedrock, no update of the retention model or of the model of flow related transport properties has been made compared to Laxemar 1.2. The same applies to the description of the surface system.

In summary, the performed interpretations and modelling have overall confirmed the version 1.2 results. The exception being Hydrogeology where the new Laxemar 2.1 borehole data suggest more favourable conditions in the south and west parts of the focused area compared with the assessment possible on the basis of Laxemar 1.2 data. The list of site-specific critical issues is largely considered being covered by the complete site investigation programme. The added discipline-wise activities are expected to answer up to these issues/uncertainties. Many of the findings, some being of tentative nature, will be followed up more closely in the ensuing modelling steps.

Sammanfattning

Delområde Laxemar är fokus för de kompletta platsundersökningarna i Simpevarpsområdet. De södra och sydvästra delarna av delområdet (benämnt ”det fokuserade området”) har valts ut för fokuserade undersökningar under återstoden av platsundersökningarna. Detta område, med en areal på c. 5,3 kvadratkilometer, karakteriseras på ytan av en bågformad kropp av kvartsmonzodiorit som stupar flackt mot norr, omgiven i norr och söder av Ävrögranit.

Denna rapport redovisar arbete genomfört inom ramen för steg 2.1 av den platsbeskrivande modelleringen av delområde Laxemar. Det huvudsakliga målet med det utförda arbetet är att ge återkoppling till de pågående platsundersökningarna för att säkerställa att rätt data och information kommer fram vid rätt tidpunkt under de återstående undersökningarna. Arbetet har utförts i nära samarbete med platsundersökningsgruppen i Laxemar och representanter från säkerhetsanalys och förvarsutformning. Det viktigaste målet i detta samarbete har varit att se till att rätt data samlas in för att lösa de återstående frågeställningarna och osäkerheterna som är av vikt för långsiktig säkerhet och förvarsutformning. De föreslagna tillkommande undersökningarna som redovisas i detta dokument skall betraktas som tillägg och/eller modifieringar i förhållande till programmet för kompletta platsundersökningar i Laxemar som publicerades tidigt 2006.

Den övergripande slutsatsen från den ämnesvisa granskningen av kritiska frågeställningar är att det redan redovisade programmet för kompletta platsundersökningar tillfredställer de krav som ställs för att lösa upp återstående osäkerheter. Detta utfall tolkas delvis bero på det nära samarbete mellan främst modellgruppen, undersökningsgruppen och förvarsdesign som har varit i kraft sedan tidigt 2005.

I förhållande till det publicerade programmet för kompletta platsundersökningar föreslås två nya kärnborrhål (KLX16A och KLX21B, beteckningar per tidig höst 2006). Målet med KLX16A är att verifiera existensen av, och karakterisera egenskaperna hos, en diabas som tidigare observerats i anslutning till zon NS001A i samband med borrning av KLX20A. Målet med borrhål KLX21B är att karakterisera egenskaperna hos deponeringsvolymen i den sydöstra delen av det fokuserade området.

För att nå målet med arbetet under Laxemar 2.1 så har primärdata tillgängliga i datafrys Laxemar 2.1 analyserats. I vissa fall har även data som samlats in efter datafrys Laxemar 2.1 utnyttjats för att ge en effektivare återkoppling och granskning, ex. användande av spänningsdata från KLX12A. Inga (officiella) uppdateringar av de geologiska modellerna för bergdomäner eller deformationszoner har tagits fram, men arbetsmodeller används för att diskutera olika aspekter av de geologiska modellerna. Inget arbete har genomförts kopplat till geologiska diskreta spricknätverksmodeller (DFN).

I bergdomänmodellen har existensen av RSMBA domäner (blandning av Ävrö granit och finkorning dioritoid) i borrhål KLX05 omtolkats till RSMB (finkorning dioritoid) och följaktligen återstår nu endast RSMBA domäner i KLX02 (norr om det fokuserade området). Vidare, för att förbättra korrelationen mellan varieteter av Ävrögranit med olika sammansättning med uppdelningen i bergdomäner har en utvärdering av tillgängliga analytiska data (modalanalyser, geokemiska och pertrofysiska data) initierats baserat på både yt- och borrhålsinformation. I de södra och västra delarna av delområde Laxemar har en preliminär uppdelning i en kvartsrik (granit till granodiorit) och enkvartsfattig (kvartsmonzodiorit) varietet av Ävrögranit gjorts med bergrundskartan som underlag. En möjlig uppdelning i tre dimensioner kommer att undersökas som en del av arbetet under modellsteg Laxemar 2.2.

I den genomföra utvärderingen av deformationszoner har en oberoende alternativ tolkning av lineament utvärderats. Detta resulterade i att 10 av dessa alternativt tolkade lineament har inlemmats i den aktuella Laxemar 2.1 modelleringen. Huvuddelen av de alternativt tolkade

lineamenten har dock avförts på grundval av topografiska och/eller geofysiska bakgrundsdata. Därutöver har en utvärdering i regional skala gjorts av nyckelzoner som skär den lokala modellvolymen, med fokus på utsträckning och hur zonerna slutar (mot andra zoner). Denna genomgång kompletterades av en utvärdering i lokal skala (i samarbete med undersöknings-gruppen) av utvalda nyckelzoner. Ett nytt inslag som resultat av denna genomgång är en möjlig deformationszon som återspeglas i den subhorisontella seismiska reflektorn M1 på förvarsdjup. Det aktuella ställningstagandet är att denna reflektor inte kan korreleras med deformations-indikatorer i borrhål sammanhängade över hela Laxemar. I den fortsatta utvärderingen av reflektor M1 som en möjlig deformationszon kommer tillgängliga geologiska, seismiska och radardata att samanalyseras. I det fall det finns stöd för reflektor M1 som deformationszon påvisas kan kompletterande undersökningar i form av hydrauliska mellanhålsförsök och vertikal seismisk profilering (VSP) övervägas. Därutöver föreslås grävning av undersökningsdiken i det fokuserade området med varierande riktningar. Sprickdata som samlas in från sådana diken kan användas bl a till att ge oberoende stöd för lineamentstolkningen, en förbättrad bild av uppsprickningen av berget och kan också användas som ett viktigt verktyg för att generalisera resultatet av undersökningar av mindre lokala sprickzoner (MDZ).

Den bergmekaniska analysen kar inkluderat olika sorters konsoliderande analyser och model-lering baserat på Laxemar 2.1 data. För de mekaniska egenskaperna hos intakt berg noteras att hög densitet i Ävrögranit (orsakad av låg kvartshalt) är kopplad till minskad hållfasthet. Detta förhållande ger ökat stöd för uppdelningen av domän RSMA01 (Ävrögranit) baserat på kvartshalt. Därutöver genomfördes en värdefull verifieringsövning där den empiriskt baserade klassningen av bergmassan egenskaper längs tillfartstunneln till Äspö HRL (baserat på data från det subparallella hålet KBH02) jämfördes med utfallet av tunnelkarteringen av motsvarande sträcka. Studien stöder användning av Q < 1 och/eller RMR < 40 (5 m sektioner) för identifie-ring av större deformationszoner och Q < 4 och/eller RMR < 60 (1 m sektioner) för identifiering av mindre, potentiellt vattenförande, långa sprickor. Bergspänningsmätningar i borrhål KLX12A (överborrningsmetoden) indikerar spänningsnivåer som är medium till höga i förhållande till tidigare observationer i den lokala modellvolymen.

Den mineralogiska variabiliteten inom Ävrögraniten, som diskuteras ovan, återspeglas i en bimodal fördelning av termisk ledningsförmåga i RSMA01 (Ävrögranit). Området i söder, givet av förhållanden i KLX03 och KLX05, uppvisar en signifikant lägre termisk ledningsförmåga jämfört med resultat från övriga borrhål i delområdet. Därutöver visar samtliga borrhål i Ävrö-granit en reducerad konduktivitet i intervallet 450–650 m. Den domän-baserade medelkonduk-tiviteten för RSMA01 domänen (Ävrögranit) är 2,75 W/mK, med ett motsvarande medelvärde för RSMD01 (kvartsmonzodiorit) som är något högre. Återstående osäkerheter bedöms vara intäckta av de planerade kommande undersökningarna. Ett tillägg utgör dock genomförande av termiska mellanhålsmätningar in situ i meterskala. Dessa bedöms ge mer representativa värden på variabiliteten i termisk ledningsförmåga.

En viktig aspekt på den hydrogeologiska modelleringen och förståelsen av delområde Laxemar är fördelningen av hydrauliska materialegenskaper i möjliga deponeringsområden. En sam-manställning av 100 m mätningar av hydraulisk konduktivitet i borrhål, grupperade norr och söder om zone EW007A, uppvisar en tendens till lägre hydraulisk konduktivitet på förvarsdjup i den södra grupperingen. Ingen formell uppdatering av den hydrogeologiska modellen har genomförts som en del av modellsteg L2.1.

Den hydrogeokemiska databasen för modellsteg Laxemar 2.1 innehåller väsentligt mer representativa data från delområde Laxemar jämfört med Laxemar 1.2. Därför har en full uppdatering av den hydrogeokemiska modellen utförts för att höja nivån på beskrivningen. Den utförda modelleringen innefattar modellering av reaktioner i utspädda vatten (represen-terande ytligt berg) och djupa grundvatten. Upplösning av kalcit och/eller dolomit bestämmer utvecklingen av det ytliga systemet medan silikatvittring bestämmer utvecklingen av de djupa systemen. Kopplad modellering, utförd för att ge ett kvantitativt ramverk för testning av olika hydrogeokemiska koncept och processer, visade att en kalibrerad kopplad hydrogeologisk-hydrogeokemisk modell kan ge en god förutsägelse av fördelningen av lösta ämnen. Den resulterande hydrogeokemiska konceptuella modellen innehåller fyra typvatten, på samma sätt som i beskrivning Laxemar 1.2. Nya kemiska data från borrhål KLX08, som visar en signatur av djupt penetrerande meteoriskt vatten, konfirmerar den framträdande inströmningskaraktär som tillskrivs delområde Laxemar. I bedömningen av undersökningsprogrammet har förenklad provtagning i planerade borrhål framförts som en möjlighet att snabbt och effektivt samla in så mycket data som möjligt från HRD(D,E,M) i den södra och västra delen av delområdet. Vidare förslås kompletterande undersökningar av sammansättningen av matrisporvatten i ytterligare ett borrhål (KLX17A) för att kompensera för misslyckade mätningar i KLX13A.

I fallet med bergets transportegenskaper har ingen uppdatering gjorts av retentionsmodell eller modell av flödesrelaterade transportegenskaper. Det samma gäller för beskrivningen av ytsystemet.

Sammanfattningsvis har den utförda analysen och modelleringen i huvudsak konfirmerat resultaten redovisade i SDM Laxemar 1.2. Ett undantag utgör hydrogeologi där nya borrhålsdata analyserade under Laxemar 2.1 indikerar lägre hydraulisk konduktivitet på förvarsnivå i den södra och västra delen av det fokuserade området jämfört med data analyserade i Laxemar 1.2. De sammanställda platsspecifika kritiska frågorna bedöms i stort vara beaktade av det publicerade programmet för undersökningar under den kompletta platsundersökningen. De föreslagna kompletterande ämnesvisa aktiviteterna förväntas ge nödvändiga svar på dessa frågor och kvarvarande osäkerheter. Många av de nya resultaten, vissa av översiktlig natur, kommer att följas upp närmare under de kommande modelleringsstegen.

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1 Introduction

1.1 Background

Site investigations are in progress in the Simpevarp area, cf. Figure 1-1, to investigate the potential for siting a deep repository for spent fuel. Investigations have been in progress since 2002 at the Simpevarp subarea (including the Simpevarp peninsula and the Ävrö and Hålö islands). Investigations in the Laxemar subarea commenced early 2004. The collected investigation data have been subject to site descriptive modelling. A site descriptive model of the Simpevarp subarea /SKB 2005a/ have formed the basis for a detailed repository layout /SKB 2006d/ and a preliminary safety assessment /SKB 2005c/. A first site descriptive model of the Laxemar subarea was completed mid 2006 /SKB 2006a/. Similarly, a repository design has been completed for Laxemar using this model description /SKB 2006h, in prep./ and a preliminary safety assessment /SKB 2006g/.

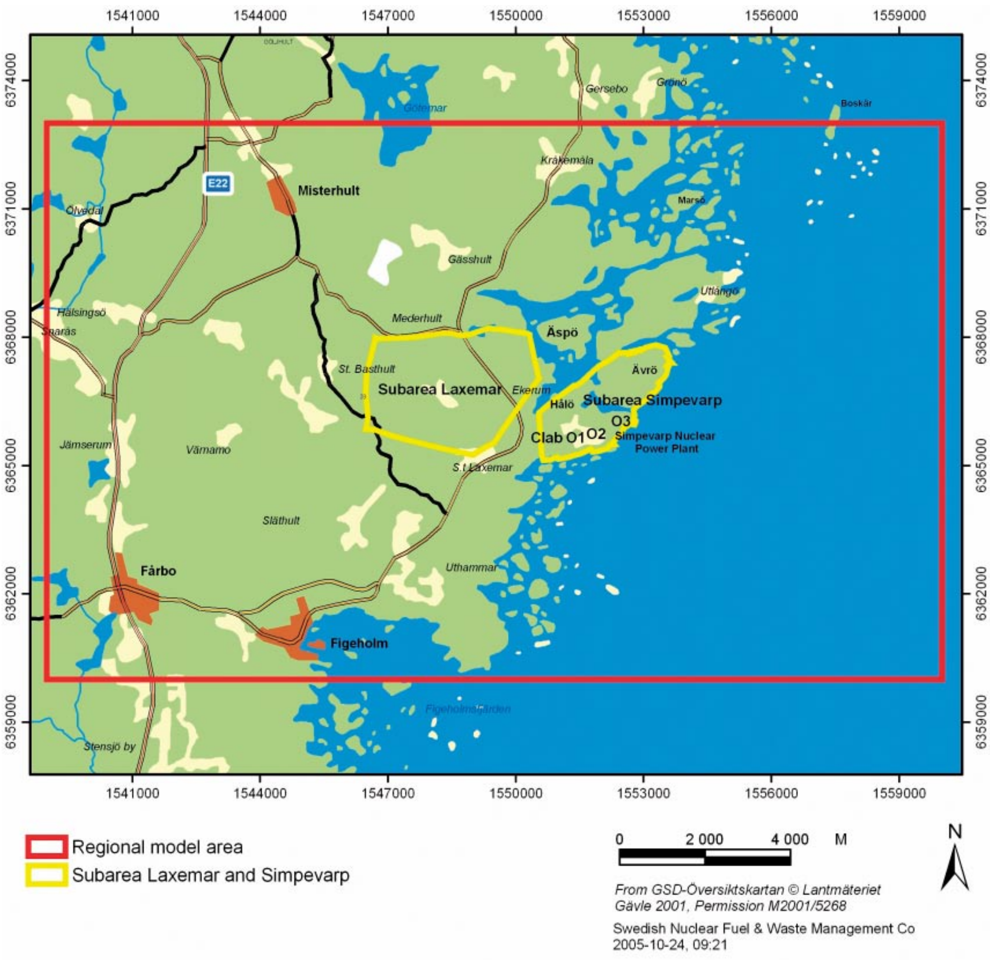


***Figure 1-1**. Overview of the Simpevarp regional model area and identification of the Simpevarp and Laxemar subareas, respectively.*

During the course of the site descriptive modelling, steps have been taken to provide effective feedback to the site and the ongoing site investigations.

As part of the Laxemar 2.1 modelling effort and parallel to the work on the Laxemar 1.2 modelling, the Oskarshamn site modelling project also contributed to the focussing (reduction) of the investigation area in Laxemar (within the so-called FIL project) /SKB 2005d/ and to the finalisation of a site characterisation programme for the complete site investigations /SKB 2005b, 2006c/. On the basis of the collective efforts, an early decision in principle to select Laxemar for continued investigations has been formalised /SKB 2006i/.

The continued site modelling within the scope of Laxemar 2.1 should be regarded as an interim middle station *en route* to the important step 2.2 deliveries, which will be used for detailed repository design (Layout D2) forming the basis for SR-Site.

The current report constitutes the formal feedback to the site investigations beyond the already existing contributions to focusing of site investigations at Laxemar and the site investigation programme for the continued site investigation programme, respectively. In the process, a review of site-specific critical issues has been performed and an assessment has been made as to whether the critical issues are covered and properly addressed by ongoing and planned modelling and characterisation. Furthermore, compact accounts of the current state of knowledge are provided for the individual geoscientific disciplines.

To be noted, and according to plan, only two disciplines produce formal updates of their site-descriptive models as part of model step 2.1, including associated supporting documents. These are Hydrogeochemistry /SKB 2006f/ and Thermal properties /Wrafter et al. 2006/. Rock mechanics accounts for selected results of its consolidation modelling /Lanaro and Bäckström 2006/. Other disciplines, e.g. geology, only provide accounts of their work as part of this document as an account current understanding. Furthermore, no formal deliveries of rock domain models and deformation zones in RVS are provided as part of model step Laxemar 2.1.

1.2 Specific objectives

The specific objectives of model step Laxemar 2.1 are to:

- Provide effective feedback to the ongoing site investigations based current model descriptions and available primary data. This in order to safeguard a sufficient collection of information for the remainder of the complete site investigations (done in close collaboration with repository engineering and Safety analysis).
- Provide time for reconsideration and evaluation of performed modelling, including resolution of remaining problems in the modelling process, to be applied in the remainder of the complete site investigations.

2 Overview of databases and primary data interpretation

2.1 Overview of site investigation

2.1.1 Investigations and primary data acquired up to data freeze 1.2

A summary of the investigations and primary data forming the base for the Laxemar 1.2 site descriptive modelling are accounted for in /SKB 2006a/, cf. Chapter 2, and is not accounted for in detail here.

2.1.2 Data freeze Laxemar 2.1 – investigations performed and data acquired

The new surface investigations provide ground geophysical data of high resolution (magnetics, resistivity (CVES method). These measurements were originally confined to a 2 km^2 area in central Laxemar but were subsequently enlarged to include a 3.8 km^2 large area in the south-western part of Laxemar, to also cover the selected "focused area" (5.3 km^2) for site investigations at Laxemar, cf. Figure 2-12. In addition, high resolution airborne laser measurements (Lidar) and high-resolution air photography were conducted over the complete Laxemar subarea. The latter information serves to construct a more refined digital elevation model (DEM). The above new surface data in combination serves to provide an improved database for lineament interpretation, and subsequently, for interpretation of deformation zones. In particular, the new data set, in combination with field control, facilitates improved interpretation and description of local minor deformation zones (MDZ), the latter partly included in interpreted deformation zones of low confidence, and in part in the stochastic description of fractures (geological DFN model).

The new borehole data have primarily been collected from cored boreholes KLX05, KLX06, KLX07 and partly from KLX08 and KLX09A, cf. Figure 2-12. The new data set thereby provide full borehole data sets from KLX05 and KLX06, where only incomplete and early data were available for Laxemar 1.2. Of particular importance are the new representative hydrogeochemical data, which provide additional representative hydrogeochemical data for the hydrogeochemical description of the Laxemar subarea (cf. Section 3.5 and /SKB 2006f/). Similarly, additional direct measurements of thermal conductivity on Ävrö granite have provided verification of the assumed bias in this relationship

It is noted that in some cases, e.g. stress measurements in KLX12A and hydraulic test results from KLX08, KLX10, KLX11A, KLX12A, data made available after the formal Laxemar 2.1 data freeze have been used. This is fully intentional with the purpose of maximizing the gain of the review process and provision of feedback to site investigations. This is done at the expense of having a "jagged" edge in the discipline-wise usage, primarily of borehole data, which potentially can make follow-up and audit difficult. Great care has taken to account for the data usage as candid as possible. It is emphasised that the overruling intention has been that of maximizing feedback to site investigations.

2.2 Databases

The bases for the work performed during model step Laxemar 2.1 are quality-assured databases containing primary data from the Simpevarp area (including the Laxemar subarea) available in the SKB database Sicada and the SKB Geographic Information System (GIS) at the time of the data freeze for model step Laxemar 2.1. Primary data used in the analysis and modelling work are described in more detail in the discipline-specific sections of Chapter 3.

2.3 Model volumes

2.3.1 Regional model volume

The model volume defined for the Laxemar 1.2 site descriptive model /SKB, 2006a/ has been retained for the Laxemar 2.1 model. The size of the model area is 21×13 km (273 km^2), cf. Figure 2-1. The model extends to a depth of 2,100 m below sea level.

2.3.2 Local model volume

Given the decision by SKB to select subarea Laxemar for further investigation /SKB, 2006d/, it was decided that there was a need to reduce the Local Scale model area for the Laxemar 2.1 modelling. This primarily in order to avoid difficulties in handling variable data density and resolution between subareas Laxemar and Simpevarp, but also to enable increased resolution in models of the Laxemar subarea. The area of the Laxemar 2.1 local scale model area is 4.25×3.2 km (13.6 km^2).

The coordinates (X,Y) outlining the Laxemar 2.1 Local Scale model area, cf. Figure 2-1, area in metres):

(1546150.0, 6368200.0), (1550390.0, 6368200.0), (1546150.0, 6365000.0)

(1550390.0, 6365000.0)

The model volume extends to a depth of 1,100 m below sea level.

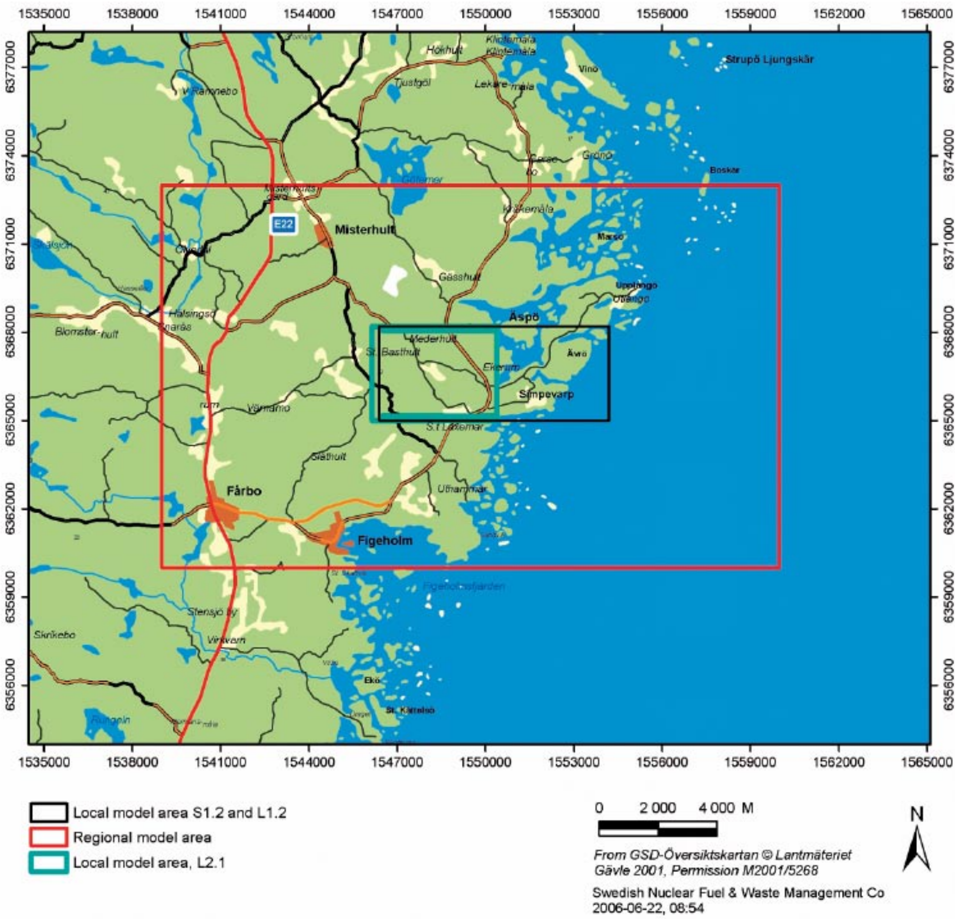


Figure 2-1*. Laxemar 2.1 Regional and Local scale modelling areas. The area of Laxemar 2.1 Local Scale model area is distinctly smaller than the one employed for SDM Laxemar 1.2, focused on the Laxemar subarea.*

2.4 Interpretation of primary geological data

2.4.1 Bedrock geology

The modelling work comprises an evaluation and analyses of primary data that were available not only at the time for the official data freeze for Laxemar 2.1 at June 30, 2005, but also a successive evaluation and analyses of data that were generated in the timed period between June 30, 2005 and the end of March 2006. This in order to maximise the gain of the current analysis.

The current reporting mainly comprises an evaluation and analyses of data that are of importance for the updating of the rock domain and deterministic deformation zone model in the new and reduced local scale model domain in the Laxemar subarea (Figure 1-1).

The ongoing work is principally a preparatory evaluation and compilation of data at depth for the 3D modelling in RVS that will be carried out in connection with the Laxemar 2.2 modelling stage.

Modelling of rock domains

No investigations that have any influence on the rock domain model have been performed in the Simpevarp subarea and the regional model area since the data freeze for model version Laxemar 1.2. Furthermore, no investigations are planned to be carried out outside the boundaries of the Laxemar subarea during the complete site investigation. Accordingly, no data are expected that would require an updating and re-evaluation of the rock domain model presented in the SDM Laxemar 1.2 for the model volume outside the new and reduced local model domain, cf. Section 2.3.2.

The rock domain modelling work during the complete site investigation phase mainly comprises evaluation of primary data from new cored boreholes, principally of the distribution and characterisation of rock types at depth. New surface information concerning the distribution of rock types is restricted to the mapping of specific outcrops that are carried out in conjunction with other activities, e.g. detailed or scan-line mapping of fractures and documentation of minor deformation zones. However, this new information is too detailed to affect on the rock domain model at the surface.

The new data at depth that has been obtained and evaluated in connection with the Laxemar 2.1 modelling step are presented in Table 2-1.

Table 2-1. New data that has been evaluated in connection with the rock domain modelling work in the modelling step Laxemar 2.1, cf. Figure 2-12.

Borehole	Boremap mapping	Geological single hole interpretation	Modal and geochemical analyses of rock samples	Geophysical logging
KLX05	X	X		X
KLX06	X	X	X	X
KLX07A/B	X	X	X	X
KLX08	X	X	X	X
KLX09	X	X		X
KLX10	X	X	X	X

Evaluation of modal and geochemical analyses from cored boreholes

Modal and geochemical analyses have been carried out in order to characterize rock samples from KLX06, KLX07A/B, KLX08 and KLX10 /Wahlgren et al. 2006/, cf. Figure 2-12. Apart from the analyses reported from KLX08 and KLX10 in /Wahlgren et al. 2006/, additional analyses have been performed. In Figure 2-2, Figure 2-3 and Figure 2-4, the modal classifications of samples from KLX07A, KLX08 and KLX10 are displayed, respectively.

It is obvious from Figure 2-2, Figure 2-3 and Figure 2-4, that the majority of the Ävrö granite samples are relatively rich in quartz, with the exception of the samples from KLX10. However, since the results of the modal and geochemical analyses may be considered as point observations along the drill core, a comparison with the recorded density in the geophysical logs along the boreholes will be rigorously evaluated in the forthcoming modelling work. Furthermore it shall be noted that the sections mapped as diorite to gabbro have, in most cases, a quartz dioritic composition (Figure 2-3 and Figure 2-4), i.e. a slightly higher quartz content than for a typical diorite to gabbro. Otherwise, the new data are in good agreement and confirm the assignment of properties in the Laxemar 1.2 rock domain model.

Modelling of deformation zones

No investigations that have any influence on the deformation zone model have been performed in the Simpevarp subarea and the larger regional model area since the data freeze for the model version Laxemar 1.2, except the Lidar investigation. Furthermore, no investigations are planned to be carried out outside the Laxemar subarea during the complete site investigation. The wealth of new data originates from within the local model volume. However, smaller adjustments in surface location of regional and major deformation zones may occur outside the local model volume.

Table 2-2 describes the used borehole data for evaluating deformation zones in model version 2.1.

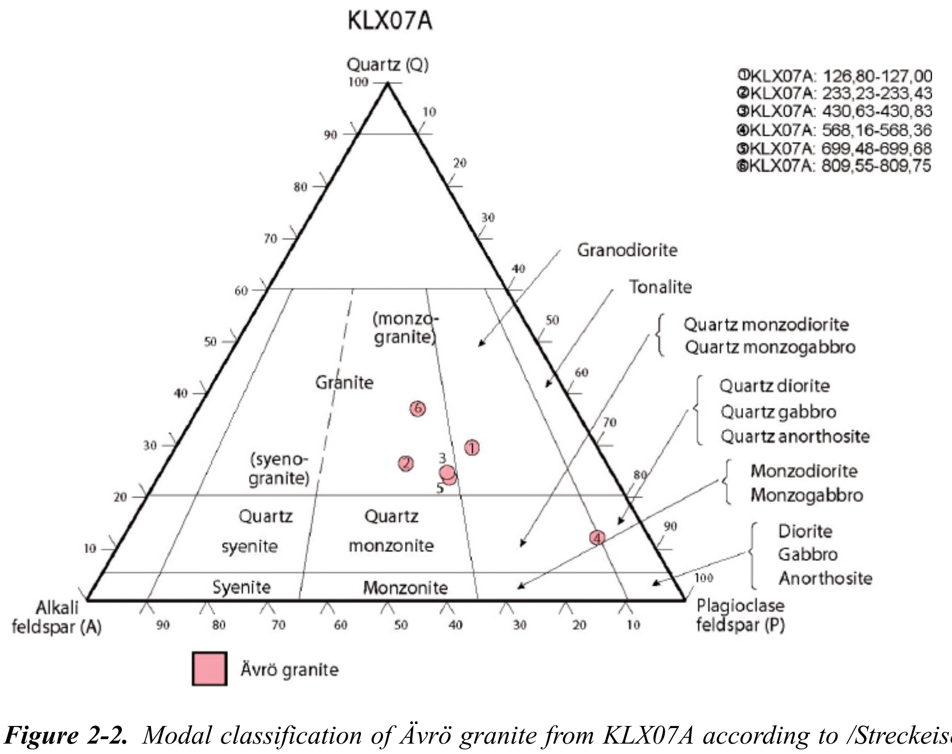


__Figure 2-2.__ Modal classification of Ävrö granite from KLX07A according to /Streckeisen 1976/. The numbers given upper right are the sampled sections in borehole length.

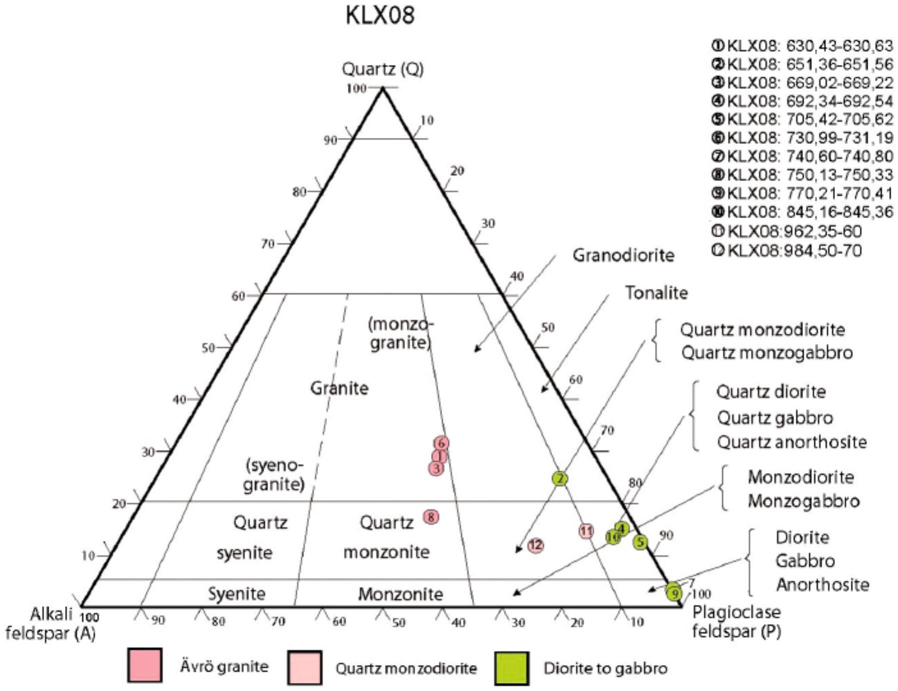


Figure 2-3. *Modal classification of Ävrö granite from KLX08 according to /Streckeisen 1976/. The numbers given in upper right are the sampled sections in borehole length.*

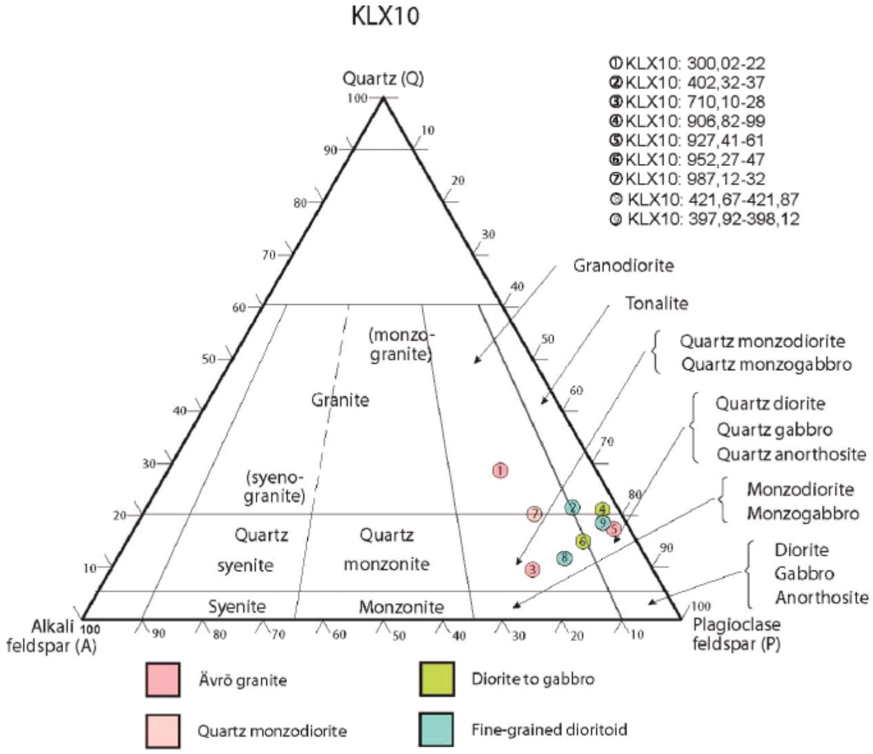


Figure 2-4. *Modal classification of Ävrö granite from KLX10 according to /Streckeisen 1976/. The numbers given in upper right are the sampled sections in borehole length.*

Table 2-2. New data that has been evaluated in connection with the deformation zone modelling work in the modelling stage Laxemar 2.1.

Borehole	Boremap mapping	Geological single hole interpretation	Preliminary Hydraulic Assessment	Geophysical logging
KLX05	X	X	X	X
KLX06	X	X	X	X
KLX07A	X	X	X	X
KLX07B	X		X	X
KLX08	X	X	X	X
HLX10	X		X	X
HLX11	X		X	X
HLX12	X		X	X
HLX13	X	X	X	X
HLX14	X		X	X
HLX21	X	X	X	X
HLX22	X		X	X
HLX23	X		X	X
HLX24	X		X	X
HLX25	X		X	X
HLX26	X	X		X
HLX27	X	X		X
HLX28	X			X
HLX30	X		X	X
HLX31	X		X	X
HLX32	X			X
HLX34	X		X	X
HLX35	X		X	X
HLX36	X			X
HLX37	X			X

In addition to the borehole data, the following major data sources have been utilised:

- Detailed ground magnetic map /Thunehed et al. 2005/.
- Detailed topographic survey, Lidar /Nyborg 2005/.
- Detailed orthophoto coverage /Nyborg 2005/.
- Coordinated presentation of topographic and geophysical lineaments in selected areas /Berglund et al. 2006/.
- Correlation of Posiva Flow Log anomalies to core mapped features /Forssman et al. 2005/.
- Seismic refraction survey /Lindqvist 2005/.

As investigations have been ongoing during work with model version 2.1 a few preliminary key data has been used in the modelling work:

- Preliminary mapping of KLX09.
- Early coordinated lineaments /Triumf and Thunehed, in prep/.
- Detailed ground magnetic map (extended coverage compared to P-05-188) /Thunehed and Triumf 2006/.
- Type profile trench excavations focused on EW007 and NS059 /Sohlenius et al. in press 2006/.

2.5 Interpretation of primary data on thermal properties

2.5.1 Review of database

The evaluation of primary data includes analyses of measurements of thermal conductivity, thermal diffusivity, heat capacity, coefficient of thermal expansion and in situ temperatures. It also includes calculations of thermal conductivity from mineral composition and establishment of rock type distributions (PDF) of thermal conductivity. The spatial variation in thermal conductivity is also investigated by using density loggings.

Data from six different boreholes within the Laxemar subarea have been used for the purpose of describing and modelling thermal properties. Much of this data were described and evaluated in model version 1.2 /Sundberg et al. 2006/. New data produced for data freeze 2.1 derive primarily from boreholes KLX03, KLX05 and KLX06, see Table 2-3. The complete database used in the evaluation of thermal properties is presented in /Wrafter et al. 2006/

Table 2-3. Available data on thermal properties and their usage in Laxemar 2.1, cf. Figure 2-12.

Available data Data specification	Ref		Usage in L2.1 Analysis/Modelling
Data from core-drilled boreholes			
Temperature logging	Results	Interpret.	Temperature and temperature gradient distribution.
KLX05	P-05-31	P-05-44	
KLX06	P-05-144	P-05-189	
Difference flow-logging (temperature)			Temperature distribution.
KLX05	P-05-74		
KLX06	P-05-160		
Density logging	Results	Interpret.	Density distribution to indicate the distribution of thermal properties.
KLX05	P-05-31	P-05-44	
KLX06	P-05-144	P-05-189	
Boremap logging			Dominant and subordinate rock type distribution.
KLX05	P-05-185		
KLX06	P-05-82		
Laboratory test of thermal properties			Thermal conductivity and specific heat capacity.
KLX03	P-05-93		
KLX05	P-05-126		
KLX06	P-05-129		
surface	P-05-169		
Modal analysis			Estimation of thermal conductivity.
KLX03	Sicada		
KLX04	Sicada		
KLX06	Sicada		
Laboratory test of thermal expansion			Thermal expansion coefficient.
KLX03	P-05-95		
Surface-based data			
Laboratory test of thermal properties			Thermal conductivity and specific heat capacity.
surface	P-05-169		
Modal analyses			
Surface samples	Sicada		Estimation of thermal conductivity

2.5.2 Thermal conductivity from measurements

Summary statistics of laboratory measurements of thermal conductivity (Transient Plane Source method (TPS) /Gustafsson 1991/) for each rock type are described in detail in /Wrafter et al. 2006/. The new measurements (56 samples) provide data for two rock types not previously analysed, namely diorite-gabbro and granite. The additional data for Ävrö granite results in a lower mean and a higher standard deviation than in model version Laxemar 1.2.

Recently acquired data, presented in Figure 2-5, display many of the key features of the important rock types, namely the large spread in thermal conductivity values for Ävrö granite and diorite-gabbro, the extremely low values for some Ävrö granite samples (down to 2.01 W/(m·K)), and the restricted range of values for quartz monzodiorite. Moreover, surface samples of the latter rock type appear to have a lower mean thermal conductivity than sample from boreholes. A closer analysis of the surface data reveals a tendency towards lower thermal conductivity for samples taken close to the contact with Ävrö granite.

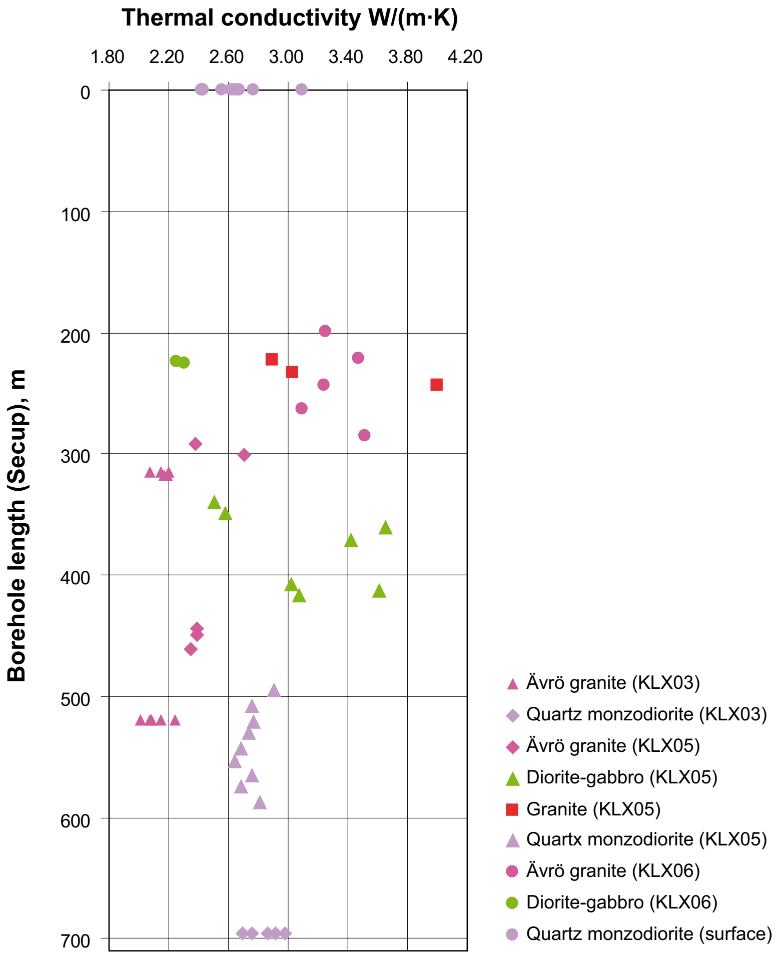


Figure 2-5*. Thermal conductivity versus borehole length for samples measured using the TPS method, divided according to rock type and borehole.*[1]

[1] Two TPS measurements of fine-grained diorite-gabbro (505102) from KLX06 were incorrectly assigned to diorite-gabbro (501033) in this figure and in the thermal modelling work. This error, discovered shortly before going to press, is judged to have little impact on the thermal modelling results presented in this report.

Since several samples of Ävrö granite and quartz monzodiorite have been taken in groups from short, c. 1 m, sections of borehole core, the data distributions are not necessarily representative for the rock types. This spatial clustering of sample data may produce bias both in the mean and the standard deviation. The effect of non-representative sampling can be analysed by using different declustering methods /Wrafter et al. 2006/. Results indicate that the mean and standard deviation most representative for Ävrö granite (Äspö data excluded) are 2.90 W/(m·K) and 0.46 W/(m·K), slightly different to values obtained using the complete data set. Given the high degree of spatial variation present within this rock type, this result seems somewhat coincidental. For quartz monzodiorite, a representative mean and standard deviation are estimated as 2.70 W/(m·K) and 0.17 W/(m·K), slightly different to statistics based on the complete data set.

Figure 2-6 shows the distribution of thermal conductivity values (TPS) for Ävrö granite based on a) all data, and b) cell-declustered data. A similar picture emerges from both histograms, i.e. at least two modes are present.

2.5.3 Thermal conductivity from mineral composition

Thermal conductivity of 28 new rock samples has been calculated from mineral composition by the SCA method (Self Consistent Approximation). Reference values of thermal conductivity for some minerals, namely amphibole, K-feldspar, clinopyroxene and orthopyroxene, have been revised compared to model version Laxemar 1.2 /Sundberg et al. 2006/. Data and results are further described in /Wrafter et al. 2006/. The newly acquired data for Ävrö granite and quartz monzodiorite have little effect on the summary statistics as presented in model version Laxemar 1.2.

Thermal conductivity values calculated using the SCA method have been compared with measured (TPS method) values of proximal samples, in order to evaluate the accuracy of the SCA calculations. New results for five data pairs for Ävrö granite indicate that for high conductivity samples (> 3.0 W/(m·K)), there is poor agreement between the two data sets (SCA underestimates the "true" thermal conductivity by about 7%) whereas for low conductivity samples (< 2.7 W/(m·K)) no obvious bias is apparent (Figure 2-7). A more detailed presentation is given in /Wrafter et al. 2006/.

Possible explanations for the bias observed in the SCA calculations are the effect of alteration minerals which have not been point-counted, variable anorthite contents of plagioclase, uncertainties regarding the reference values assigned to minerals, and errors associated with point-counting method.

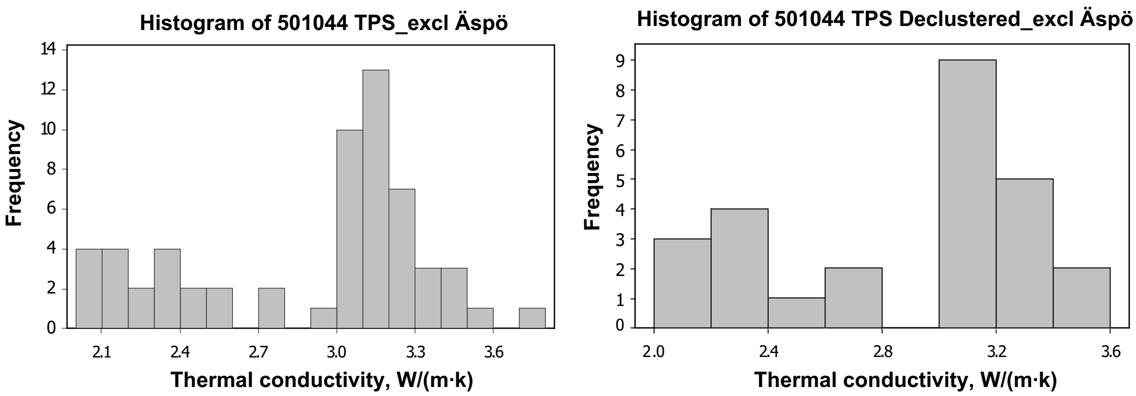


Figure 2-6. *Histograms of thermal conductivity from TPS data (all data and cell-declustered data) for Ävrö granite (Äspö data excluded).*

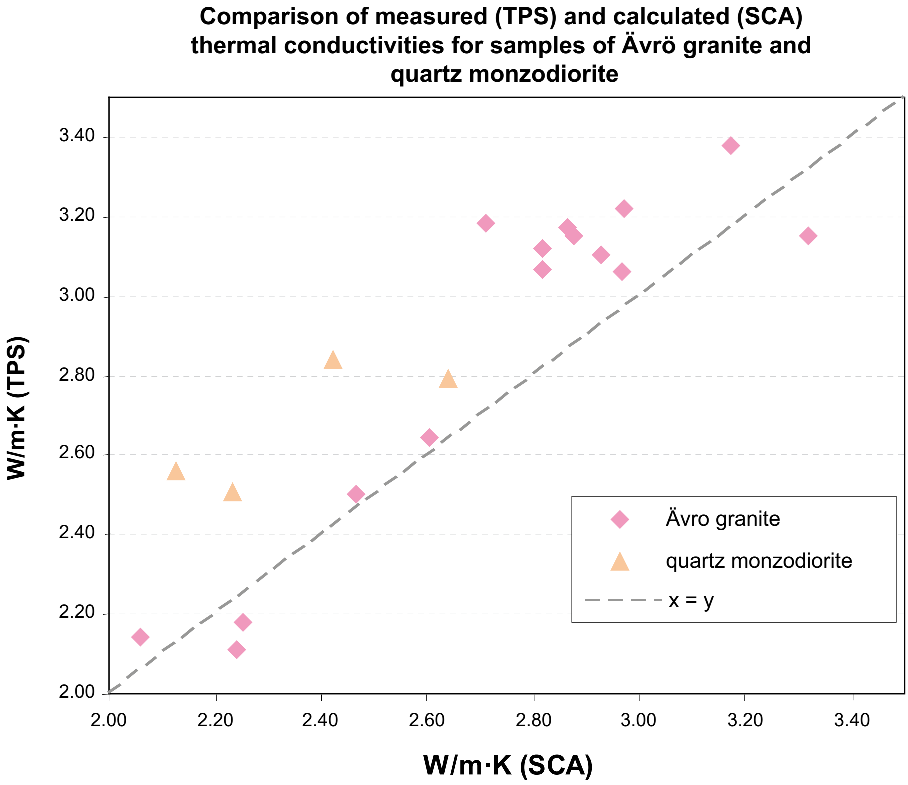


Figure 2-7. TPS versus SCA data for the "same" samples.

2.5.4 Thermal conductivity from density

A new relationship between density and measured (TPS) thermal conductivity for Ävrö granite, based on data from the Laxemar subarea only, and using both previously reported data /Sundberg et al. 2006/ together with the results from 20 new measurements has been developed, see Figure 2-8. By omitting the Äspö data, which is clearly distinguishable from the Laxemar data, a relationship that is more likely to accurately reflect the properties of the Ävrö granite within the Laxemar subarea can be produced.

An unambiguous relationship between thermal conductivity and density is also apparent for diorite-gabbro, see Figure 2-8. This has not been previously recognised due to lack of data. An interesting point to note here is that, in contrast to Ävrö granite, thermal conductivity of diorite-gabbro increases with increasing density, consistent with the results of theoretical calculations presented in /Sundberg et al. 2005a/. The other investigated rock types do not reveal any readily apparent relationships.

Based on the relationship between density and thermal conductivity derived for Ävrö granite, density values given by the density loggings of boreholes KLX01, KLX02, KLX03, KLX04, KLX05 and KLX06 were used to deterministically assign a thermal conductivity value to each logged decimetre section of Ävrö granite.

The frequency histogram in Figure 2-9 display the distribution of thermal conductivity values for Ävrö granite calculated from density loggings for all boreholes at 1 m scale. At this scale, the distribution of thermal conductivity values contains two modes, one at 2.5 W/(m·K) and one at 3.05 W/(m·K). This seemingly bimodal distribution is also evident in both the TPS and SCA data sets for Ävrö granite.

A comparison of the data distributions in the individual boreholes reveals large differences in the proportions of the low (< 2.85 W/(m·K)) and high (> 2.85 W/(m·K)) modes, cf. Table 2-4. The overall proportion of the different modes is highly dependent on the location of the boreholes used, and may not accurately represent the rock mass within the Laxemar subarea.

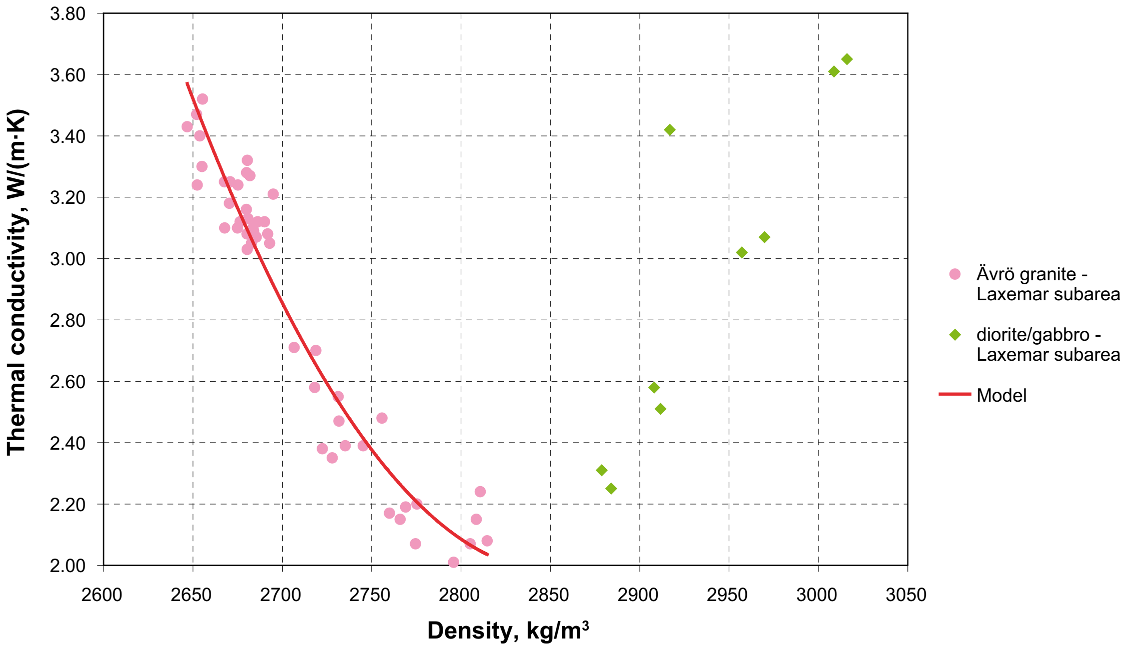


Figure 2-8. *Relationships between density and thermal conductivity (TPS measurements) for Ävrö granite.*

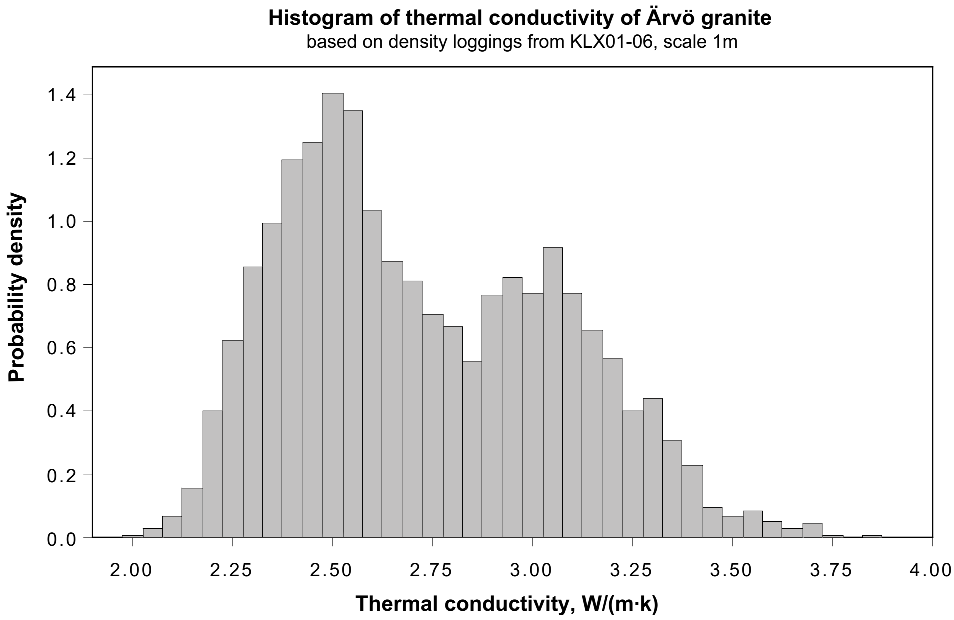


Figure 2-9. *Histograms of thermal conductivity for Ävrö granite calculated from density loggings for boreholes KLX01 – 06.*

Table 2-4. Summary of density logging of Ävrö granite per borehole.

Borehole	% Ävrö granite in borehole	Logged borehole interval, m	Thermal conductivity, W/(m·K) – Mean (St.dev.) 1 m scale	% below/above 2.85 W/(m·K) 1 m scale
KLX01	80.03	1.0 – 701.6 m	2.58 (0.23)	91/9
KLX02	70.88	201.5 – 1,004.9 m	2.90 (0.28)	40/60
KLX03	54.18	101.8 – 999.9 m	2.38 (0.16)	98/2
KLX04	72.23	101.6 – 990.2 m	2.92 (0.31)	32/68
KLX05	15.95	108.4 – 994.3 m	2.76 (0.36)	59/41
KLX06	55.6	101.90 – 989.80	2.80 (0.33)	65/35
All boreholes			2.73 (0.35)	63/37

In order to evaluate how well the model in Figure 2-9 reflects the actual thermal conductivity in the borehole, measured samples (TPS) were compared with values estimated from density logging. For highly conductive Ävrö granite, the density loggings underestimate the thermal conductivity by on average 5%, which is equivalent to 0.13 W/(m·K). For low conductivity varieties of Ävrö granite, there is a close correspondence between measured and calculated values.

2.5.5 Relationship between thermal conductivity and igneous rock type

Two distinct populations of Ävrö granite have been distinguished, one richer in quartz (granite to granodiorite), the other with a lower quartz content (quartz monzodioritic) /SKB 2006a/. A broadly bimodal distribution is displayed by thermal conductivity values determined by the TPS (Figure 2-5) and SCA methods /Wrafter et al. 2006/.

There is a clear relationship between thermal conductivity (determined from TPS and from mineral composition) and plutonic rock type as defined by the Streckeisen classification system, cf. Figure 2-10. Ävrö granite with granite to granodiorite compositions typically have thermal conductivities greater than 2.9 W/(m·K). Varieties with quartz monzodioritic and quartz diorite composition have thermal conductivities lower than 2.7 W/(m·K). Quartz diorites have particularly low values (< 2.3 W/(m·K)).

2.5.6 Alteration

Alteration observed in the Laxemar borehole cores includes oxidation, saussuritization epidotization, chloritization, sericitization and silicification. Rocks affected by alteration comprise up to 25% of boreholes KLX01 to KLX06 (/SKB 2006a/, Boremap, Sicada database). Alteration is not limited to particular rock types.

The samples from the Laxemar and Simpevarp subareas on which TPS measurements were performed were generally taken from borehole cores showing little ("faint") or no alteration. Therefore, a relatively large part of the rock mass is not represented by the available TPS or SCA data. One sample of Ävrö granite, described in Boremap mapping as having "weak" oxidation, yielded a thermal conductivity of 3.47 W/(m·K) measured using the TPS method, which is at the higher end of the range of thermal conductivity values for this rock type /Wrafter et al. 2006/. This is consistent with findings at Äspö HRL where investigations of thermal properties for a number of samples indicate that the mean thermal conductivity of altered "Äspö diorite" (Ävrö granite of quartz monzodioritic composition) is higher than that of fresh "Äspö diorite" /Sundberg 2003/.

Many of the minerals associated with alteration, such as K-feldspar, albite, sericite, epidote, prehnite, chlorite, etc, have thermal conductivities that are similar to or higher than their parent minerals, for example, plagioclase, biotite, etc. Theoretically, these mineralogical changes should then produce higher rock thermal conductivities.

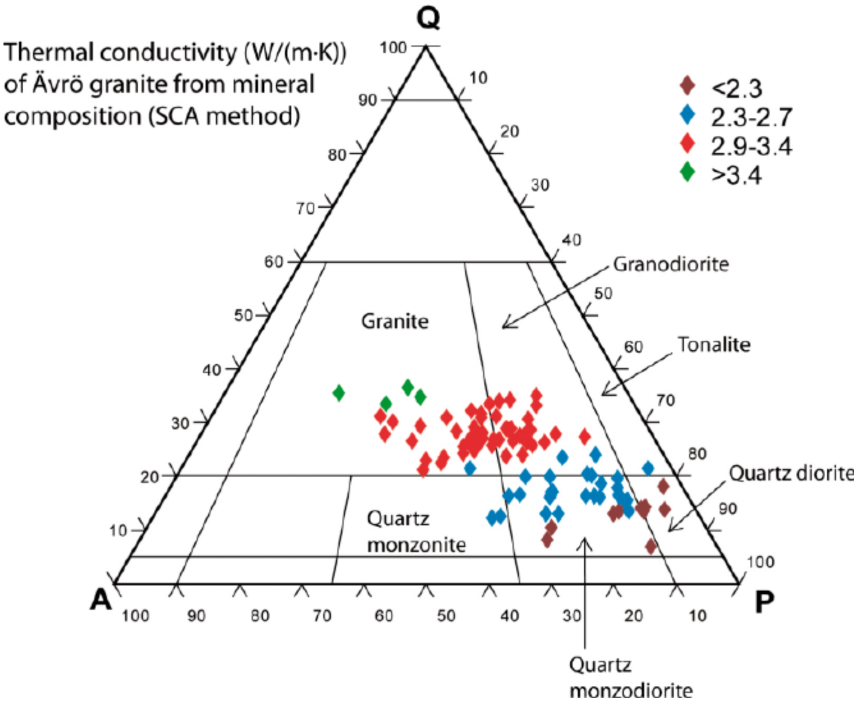


Figure 2-10. *QAP modal classification according to /Streckeisen 1976/ of Ävrö granite, colour coded according to thermal conductivity (SCA method) from samples from Laxemar subarea. It should be noted that samples with conductivities higher than 2.7 W/(m·K) have been corrected to account for the observed bias in the SCA data.*

2.5.7 In situ temperature

Large differences in logged temperature for the same depth in different boreholes has been noted previously /Sundberg et al. 2006/. Uncertainties associated with the fluid temperature loggings were judged to be high. For this reason, the temperature loggings from KLX01 to KLX06 have been evaluated with regard to their reliability /Wrafter et al. 2006/. Because of errors associated with one type of logging probe (Century 8044) used, and inadequate time delay between drilling and logging to allow stabilisation of the natural temperature conditions, measurements from four boreholes were considered to be unreliable. It is concluded that temperature loggings from KLX02 and KLX05 are the most reliable since both were logged more than 2 months after the termination of drilling using probe Century 9042, which is considered to be accurate to within ± 0.25°C.

In Table 2-5, the temperatures at different depths are presented for boreholes KLX02 and KLX05. The means at specific depths differ significantly from those reported in model version Laxemar 1.2 /Sundberg et al. 2006/ and for a given depth, KLX02 and KLX05 show almost identical temperatures.

Table 2-5. Temperature (°C) at different depths below ground surface in boreholes KLX02 and KLX05. For KLX02, results are from measurements made in 2003.

Borehole	Temperature at 400 m below ground level	Temperature at 500 m below ground level	Temperature at 600 m below ground level
KLX02 (2003)	13.1	14.5	16.1
KLX05	13.1 (12.8)	14.7 (14.4)	16.1 (16.1)
Mean of KLX02 (2003) and KLX05	13.1	14.6	16.1
Means reported in L1.2	12.3	13.9	15.6

Results from difference flow logging in italics. KLX02 has been logged three times, but only data from the most recent logging in 2003 have been evaluated.

2.6 Interpretation of primary hydrogeological data

A number of new boreholes were drilled and investigated during the initial investigation phase (core holes: KSH01A, KSH02, KSH03A, KLX03, KLX04, KLX05, KLX06 and KAV04A,B) some old core holes were tested with new methods (KAV01, KLX02), and a number of new percussion holes were drilled and investigated (HSH01-03, HAV09-10 and 9 HLXxx boreholes), see Figure 2-11.

In some boreholes (KLX05, KLX06), only preliminary tests during drilling were available for analysis, and in KLX03 not all data planned for the borehole were available for the analysis for the Laxemar version 1.2 model. Different types of investigations have been performed in the boreholes and all intended investigations for a particular borehole were not reported or performed in time to be included in SDM Laxemar 1.2 report /SKB 2006a/.

A description of the available data for the Site Descriptive Modelling (SDM) of Laxemar model version 1.2 (L1.2) is described in /Rhén et al. 2006ab/, and analysis of these data is found in /Rhén et al. 2006c/ and /SKB 2006a/.

After model version Laxemar 1.2 a few results, mainly WLP-tests but also some PSS-tests, from core holes KLX07, KLX08, KLX09, KLX10, KLX11 and KLX12 have become available and are used for the discussion in this report (cf. Section 3.4), see Figure 2-12.

The new data from PSS in KLX05 and KLX06 were used instead of the WLP data that were used from those holes in SDM Laxemar 1.2. Note that hydraulic data from KLX08, KLX10, KLX11A and KLX12A are strictly speaking not part of the Laxemar Laxemar 2.1 data freeze. However, the data have been included since they provide additional insight in the distribution of hydraulic properties important for the appraisal of the Laxemar subarea.

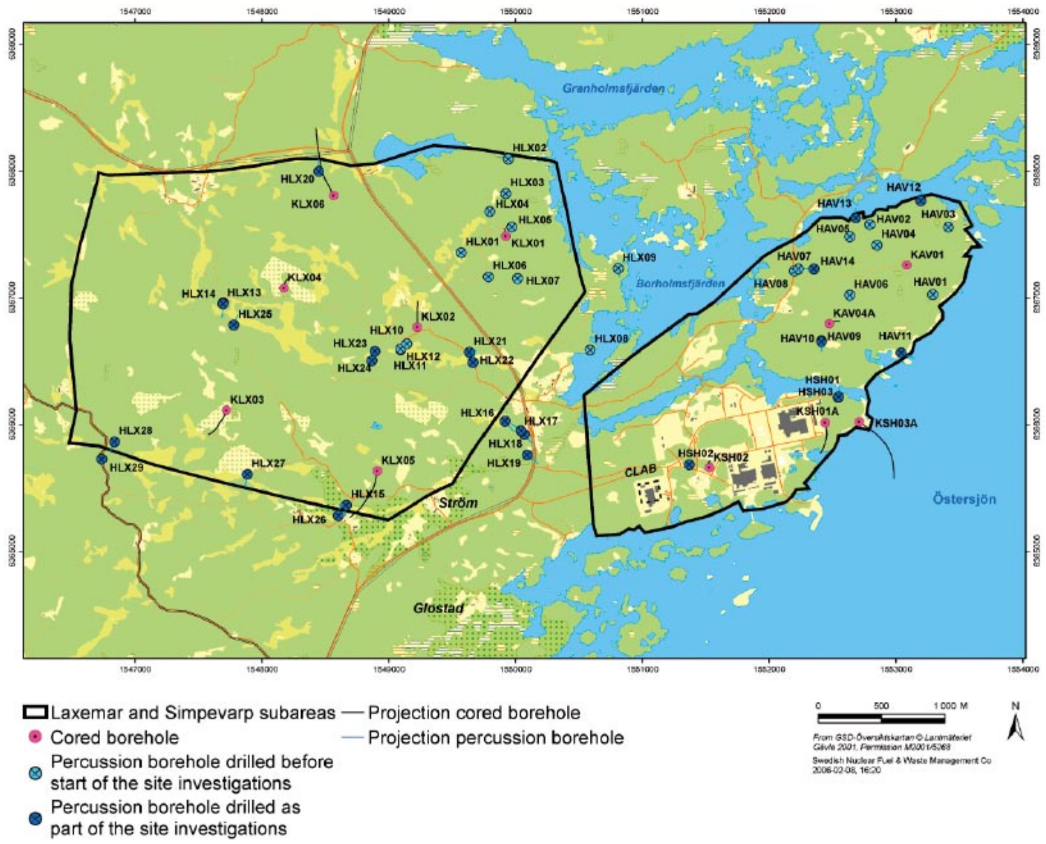


Figure 2-11. Overview map of core-drilled and percussion-drilled boreholes in the Laxemar and Simpevarp subareas at stage model version Laxemar 1.2. Location of the core-drilled boreholes with new site investigation data available for model version Laxemar 1.2: KSH01A, KSH02, KSH03A, KAV01, KLX02, KLX03, KLX04 and KAV04A,B.

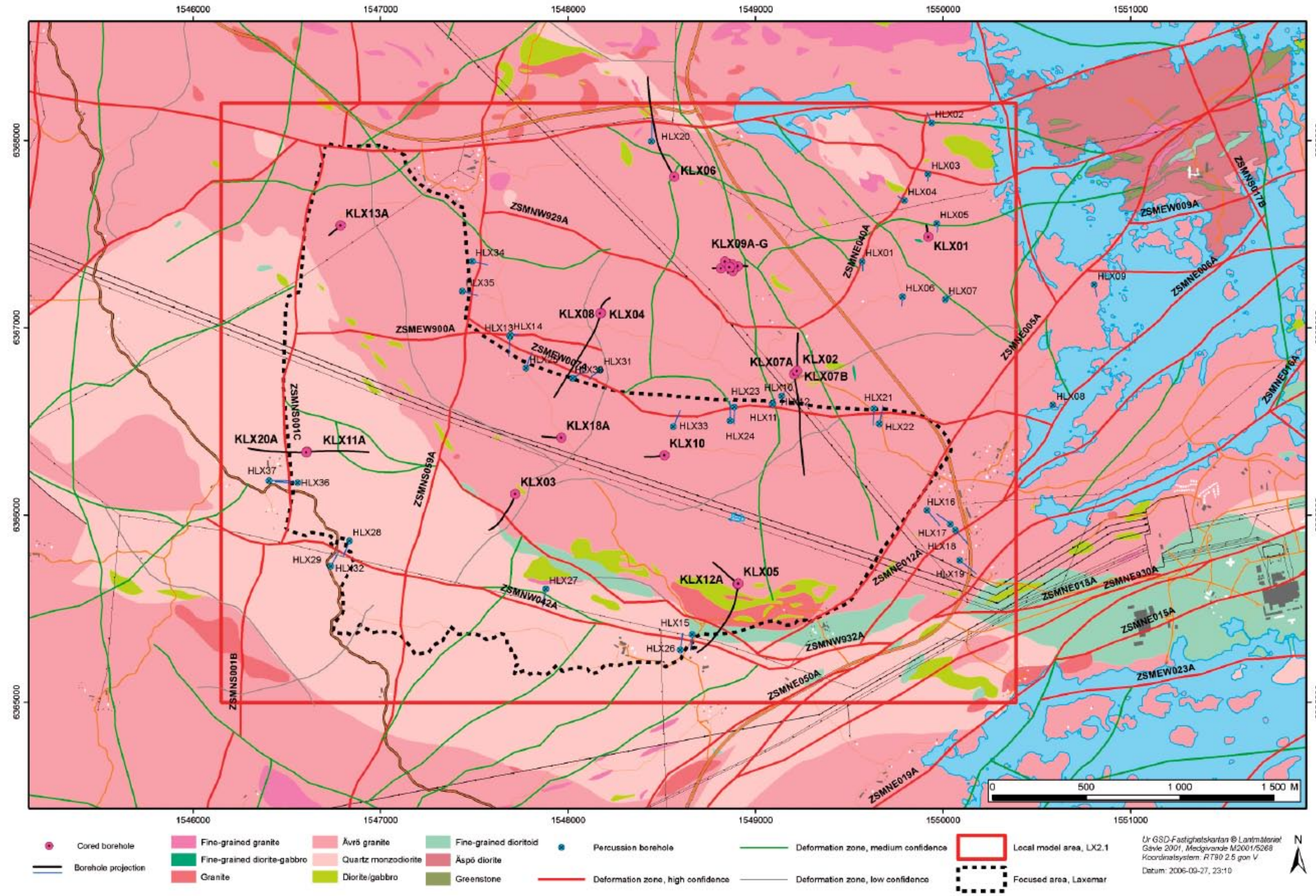


Figure 2-12. *Overview map of core-drilled and percussion-drilled boreholes in the Laxemar and Simpevarp subareas, Late spring 2006. The core-drilled boreholes with new site investigation data available after model version Laxemar 1.2 are KLX07, KLX08, KLX09, KLX10, KLX11A and KLX12A.*

2.7 Interpretation of primary hydrogeochemical data

Site characterisation at the Laxemar subarea has included the drilling of up to 34 percussion drillholes (HLX01-34) to vertical depths varying from approx. 70–200 m, and eight cored boreholes (KLX01-08) of which KLX01 extends to 1,078 m, KLX02 to 1,705 m, KLX03, KLX04, KLX05 and KLX08 to around 1,000 m, KLX06 to 850 m, and KLX07 to 830 m. Boreholes KLX01 and KLX02 are subvertical whereas KLX03 is inclined at 75°, KLX05, KLX06, KLX07A at 65° and KLX08 at 60°. Of all these boreholes, percussion boreholes HLX01-08, 10, 14, 18, 20, 22, 24, 28 and 34, and cored boreholes KLX01, 02, 03, 04, 05, 06, 07A and 08, are included in the database for the Laxemar 2.1 data freeze. The borehole sampling locations are shown in Figure 2-13. The analytical programme included: major cations and anions (Na, K, Ca, Mg, Si, Cl, HCO_3^- SO_4^{2-}, S^{2-}), trace elements (Br, F, Fe, Mn, Li, Sr, DOC, N, PO_4^{3-}, U, Th, Sc, Rb, In, Cs, Ba, Tl, Y and REEs) and stable (^{18}O, ^{2}H, ^{13}C, ^{37}Cl, ^{10}B, ^{34}S) and radioactive–radiogenic (^{3}H, ^{226}Ra, ^{228}Ra, ^{222}Rn, ^{238}U, ^{235}U, ^{234}U, ^{232}Th, ^{230}Th and ^{228}Th) isotopes, microbes, gases and colloids (cf. Appendix 8 in /SKB, 2006f/). The selected pH and Eh values correspond to available downhole data (cf. Appendix 3 and 8 in /SKB, 2006f/).

Figure 2-13. *Groundwater sampling locations in the Simpevarp area. Location of hydrogeochemically prioritised boreholes KLX01, KLX02, KLX03, KLX04, KLX05, KLX06, KLX07 and KLX08 in the Laxemar subarea. Also indicated are the percussion boreholes (HLX01-33), many of which are included in the Laxemar v.2.1 evaluation.*

The new samples evaluated in the version 2.1 "data freeze" for the Laxemar subarea include (for details see, /SKB 2006f/):

- 152 groundwater samples (GW) from the Äspö island, 25 representative samples.
- 123 groundwater samples (GW) from the Ävrö island, 6 representative samples. Four new samples were included in the Laxemar 2.1 data freeze.
- 592 GW from the Laxemar subarea (37 representative), and 51 Near-surface groundwaters (NSGW; 45 representative). 53 samples from percussion boreholes. 285 samples including tube samples, samples taken during drilling, and samples for the pore water experiments. 118 of them were delivered in the Laxemar 2.1 data freeze. 254 samples from cored boreholes and taken between packers. 68 of them were delivered in the Laxemar 2.1 data freeze. 51 shallow groundwater samples from soil pipes.
- 282 GW and NSGW, 1,271 surface waters and 56 precipitation samples from Simpevarp. 171 groundwater samples (5 representative) and 111 NSGW (32 representative); 22 samples from percussion boreholes. 99 samples including tube samples, samples taken during drilling, and samples for the pore water experiments. 51 samples from cored boreholes and taken between packers. 111 shallow groundwater samples from soil pipes. 53 of them were delivered in Laxemar 2.1 data freeze.

1,271 surface water samples: 363 sea water samples (161 samples considered representative). 46 of them were delivered in Laxemar 2.1 data freeze. 249 lake water samples (167 selected as representative samples). 24 of them were delivered in Laxemar 2.1 data freeze. 659 stream water samples (297 selected as representative samples). 75 of them were delivered in Laxemar 2.1 data freeze.

56 samples of precipitation (13 selected as representative samples). 17 of them were delivered in Laxemar 2.1 data freeze.

Altogether, there are 1,200 groundwater samples (deep and near-surface groundwaters), 243 of them included in the Laxemar 2.1 data freeze, and 1,271 surface water samples, 145 of them were included in this data freeze.

A commonly used approach in groundwater modelling is to commence evaluation by explorative analysis of different groundwater variables and properties. The water type, degree of mixing, the type of reactions and the origin and evolution of the groundwater can be indicated by applying such analyses. Also of major importance is to relate, as far as possible, the groundwaters sampled to the near-vicinity geology and hydrogeology.

2.7.1 Visualisation of sampled boreholes

An important tool for site understanding (i.e. in constructing a conceptual model and for integration of the results with hydrogeology) is the spatial representation and visualisation of available data. A specific visualisation application has been developed with the aim of representing "objectively" (i.e. without interpolation) the available hydrogeochemical information. The visualisation tool has been programmed using the IBM Open Visualisation environment, known as OpenDX (cf. Appendix 5 in /SKB 2006f/).

As examples, Figure 2-14 shows a view for the location of the main cored boreholes (from the point of view of the number of representative samples) available in the Laxemar and Simpevarp subareas, and Figure 2-15 shows all the available representative chloride data in the bedrock samples.

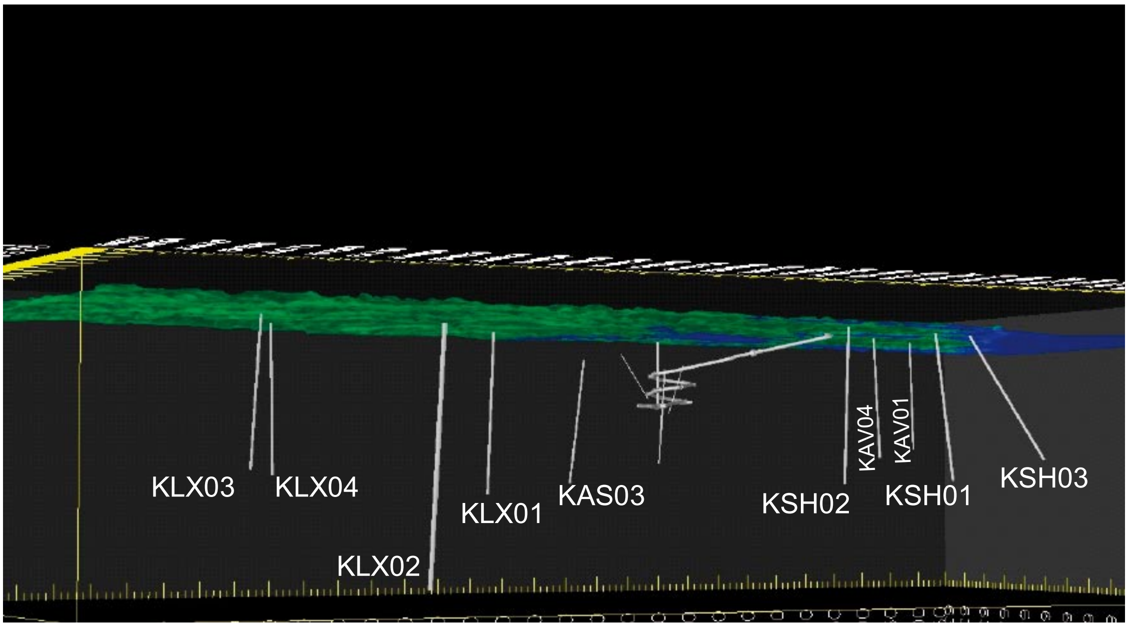


Figure 2-14. 3D-view (from the southwest) of the Laxemar and Simpevarp subareas. Some of the main cored boreholes in the Laxemar 2.1 data freeze, as well as the Äspö tunnel, have been included as geographical references in the visualisation.

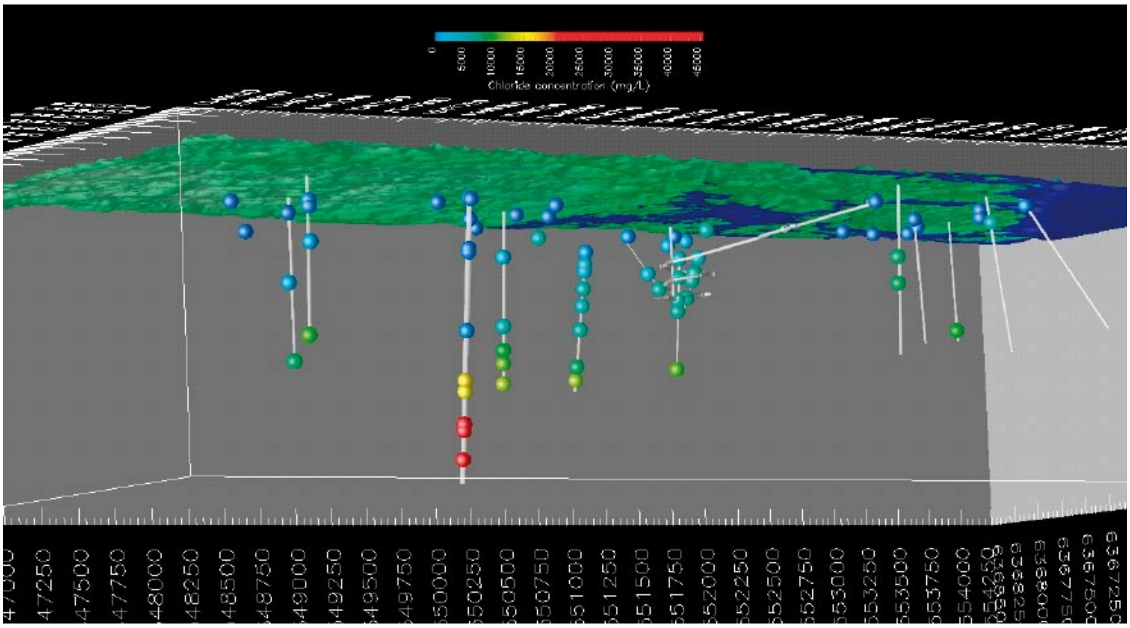


Figure 2-15. Distribution of chloride concentrations in the bedrock under the Laxemar and Simpevarp subareas. Blue indices low, green medium and yellow and red high chloride concentration value.

Figure 2-15 shows the occurrence of brine-type (red symbol) groundwater at depth in the Laxemar subarea detected in borehole KLX02 at a depth greater than 1,100 m. The difference in salinity between the groundwater of the Laxemar and Simpevarp subareas is immediately noticeable. The Laxemar subarea represents a continental (inland) hydrogeological environment with a thick fresh water body reaching depths of nearly 1,000 m. In contrast the Simpevarp subarea represents a coastal hydrogeological environment were fresh water bodies are confined to the upper 100–200 m of the bedrock.

2.7.2 Major groundwater features

The major results from the hydrogeochemical explorative analysis is described in detail in Appendix 1 in /SKB 2006f/ and are summarised in this chapter.

The new Laxemar 2.1 data freeze information has served to further support the Laxemar 1.2 evaluation /SKB 2006ab/. Major ion trends and their interpretation based on quality assured data have been strengthened and similarly for the major environmental isotopes of tritium, oxygen-18, deuterium and carbon-13/14. There is now a good understanding of the origin and evolution (e.g. mixing processes) of the different groundwater groups characterising the Simpevarp area. Additional isotope data of sulphur and strontium isotopes have added further knowledge of water/rock interactions and, specifically from sulphur, the local influence of microbial activity on groundwater redox conditions and chemistry.

A marine component can be distinguished based on slightly higher Mg values, lower Br/Cl ratios and marine $\delta^{34}S$ values in the groundwaters with Cl values < 6,500 mg/L from the Simpevarp subarea and from KLX01 in the Laxemar subarea. In the rest of the Laxemar subarea, in contrast, no marine signatures can be identified. The marine component at the Simpevarp subarea is, however, much less prominent than at Forsmark.

The Cl versus depth trend for Laxemar indicated in model version Laxemar 1.2 is further supported Figure 2-16 and underlines that the very sharp transition between fresh and very saline waters in borehole KLX02 is probably not representative for the Laxemar subarea. However, fresh to brackish groundwaters (Cl < 5,000 mg/L) seem to dominate down to 600 to 700 m depth. A detectable glacial component in terms of $\delta^{18}O$ below –12‰ SMOW is found even deeper, at least down to 900–950 m.

Significant bicarbonate production is recorded in the near-surface groundwaters (upper 200 m) in the Laxemar subarea, and both the carbon and sulphur isotope ratios support microbial activity, although some contribution from calcite dissolution has probably also taken place at shallow depth.

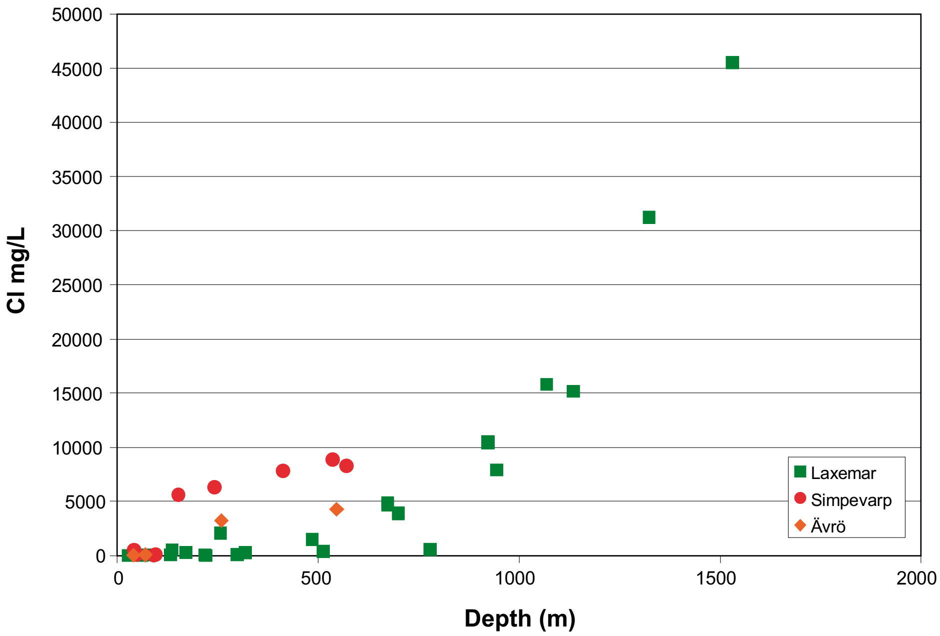


Figure 2-16. *Depth variation of chloride in the Simpevarp and Laxemar subareas.*

However one area of caution concerns the interpretation of the tritium (and carbon-14) values. Detailed examination of data at, and close to the overburden/geosphere interface, shows that some emissions from the nearby nuclear power plant have contributed to the amounts of tritium and carbon-14 analysed in the surface and near-surface groundwaters. Figure 2-17 illustrates well this hydrochemical sequence from the overburden to deep bedrock environments. A rapid decrease of tritium can be observed in the groundwaters from recharge values close to the surface (10–18 TU) to values levelling out close to zero (less than ±2 TU) around 200 m depth and remaining constant down to around 1,000 m. This indicates that despite the possible contamination from drilling water, it is clear that large portions of modern meteoric water is not affecting groundwaters below 200 m depth.

The new hydrochemical data support the 2-D integrated Laxemar 1.2 conceptual model of the Simpevarp area (see Section 3.5.4), and no significant change of the various groundwater types are necessary (cf. Chapter 3.5.4).

2.7.3 Microbes

Microorganisms are abundant in Fennoscandian Shield groundwater from surface down to at least 1,500 m /Pedersen 1993, Haveman et al.1999/. To understand the present undisturbed hydrobiogeochemical conditions at a site the following parameters are of interest: pH, E_h, S^{2-}, S^0, SO_4^{2-}, HCO_3^-, HPO_4^{2-}, Fe^{2+}, nitrogen species and TDS together with colloids, fulvic and humic acids, dissolved organic compounds and microorganisms. In addition, the concentrations of dissolved gases are of importance to explore for a complete model since many micro-organisms consume and/or produce different gases. Furthermore, for a full understanding it is necessary to be able to predict how changing conditions, during the construction of a repository and during the following repository development will influence microbes in the groundwater and vice versa.

In energy harvesting reactions, microbes use available energy-rich compounds as electron donors and various electron acceptors from groundwater and fracture minerals. Thus microbes are intimately coupled to the redox conditions in the groundwater system.

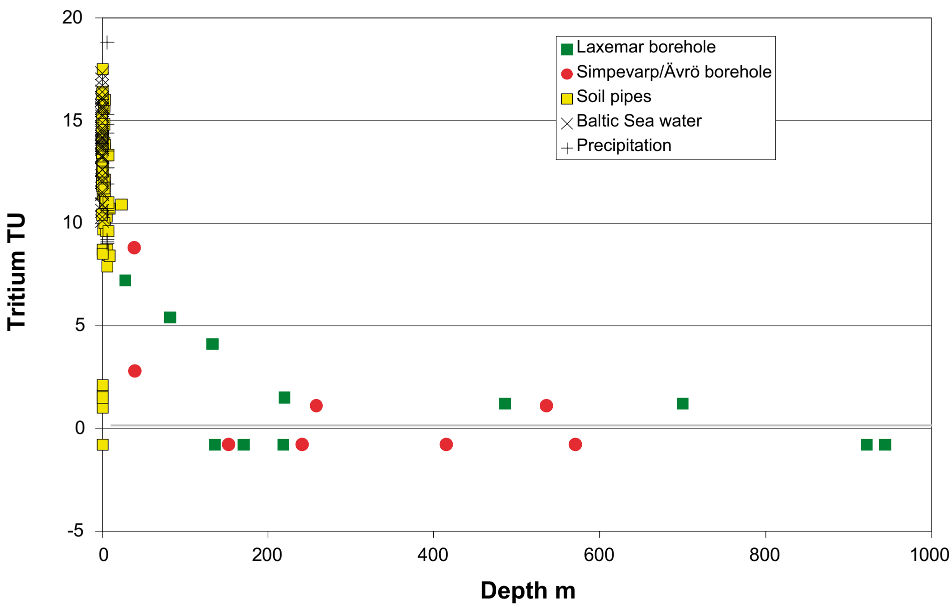
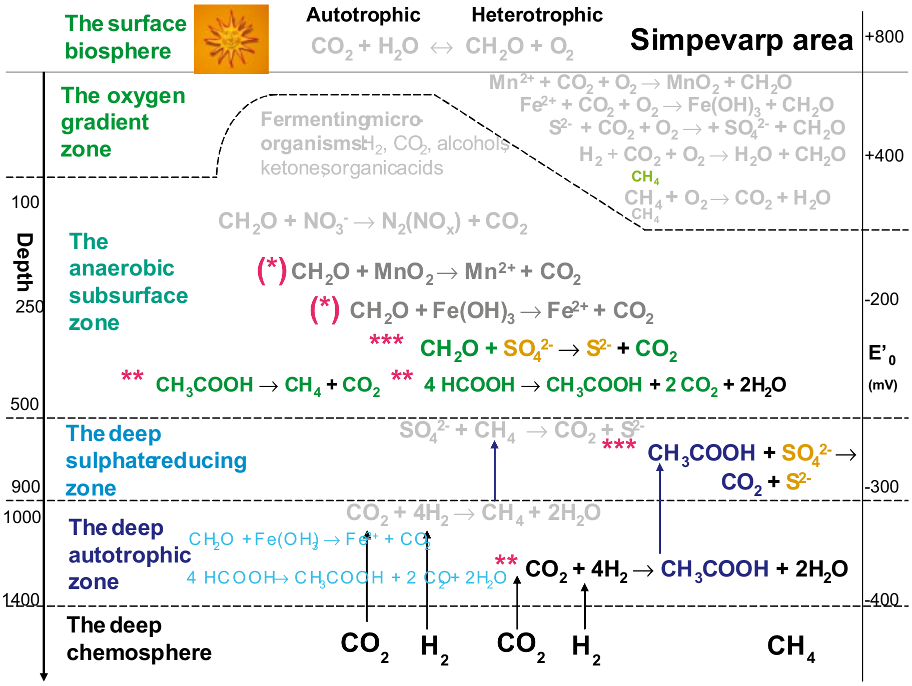


Figure 2-17. *Tritium vs. depth for the Simpevarp and Laxemar subareas.*

Microbial parameters of interest are the total number of cells and the presence of different metabolic groups of microorganisms /Pedersen 2001/. These data will indicate activity of specific microbial populations at a certain site and how they interact with the geochemistry. The groups cultured for the microbial part of the site investigation were iron-reducing bacteria (IRB), manganese-reducing bacteria (MRB), sulphate-reducing bacteria (SRB), auto- and heterotrophic methanogens (AM and HM) and auto- and heterotrophic acetogens (AA and HA).

Microbes have been evaluated from the Simpevarp area (Appendix 2 in /SKB 2006f/). There are still rather few data from the Laxemar subarea and therefore the model reflects only the regional scale of the Simpevarp area. The model predicts (Figure 2-18) that the dominating microbial process in 'The anaerobic subsurface zone' is heterotrophic sulphate reduction; this zone is found at depths from 100 to 500 m. 'The deep sulphate reducing zone' is found at about 600 to 900 m and 'The deep autotrophic zone' is found from 1,000–1,400 m. Here there are indications of ongoing iron- and manganese reduction and heterotrophic acetogenesis. The origin of carbon dioxide and hydrogen gas in this zone from 'The deep chemosphere' also requires to be verified with stable isotope studies of dissolved gas in the groundwater.



The colours in the model are used as listed below:

■, light grey:	The process is not yet studied
■, dark grey:	The process is present but without influence
■, green:	The carbon compounds originate from the surface biosphere
■, blue:	The carbon compounds originate from the deep autotrophic zone
■, black:	Compounds from the deep chemosphere
■, turquoise:	Processes found but not anticipated and not yet confirmed

The star symbols in the figure illustrate the MPN values and influence by the microbial groups on the geochemistry

(*)	1–10 ml^{-1}	Present without influence[1]
*	11–50 ml^{-1}	Present with putative influence if growth promoting changes occur
**	51–1000 ml^{-1}	Present with influence
***	>1000 ml^{-1}	Dominating with high influence

[1] influence here means that the organism group has an effect on the geochemistry of the ground water

Figure 2-18. The microbial model of the Simpevarp area based on data available at the time of the Laxemar 2.1 data freeze. The star symbols before the reactions depict the significance of the reaction.

2.7.4 Colloids

Colloid compositional data have been evaluated from the Simpevarp area (Appendix 2 in /SKB 2006f/). Particles in the size range 10^{-3} to 10^{-6} mm are regarded as colloids; their small size prohibits settling and renders them as a potential radionuclide transport mechanism in groundwater. The aim of the colloid study was to quantify and determine the composition of colloids in groundwater from boreholes, and to include the results in the hydrochemical modelling of the site.

Generally, the average amount of colloids in this study was 23.1±7.14 µg L^{-1} if the value from KLX01: 458.5 m is omitted. These values agree very well with data reported from other colloid studies in Sweden (20–45 ug L^{-1}) and Switzerland (30±10 and 10±5 µg L^{-1}) /Laaksoharju et al. 1995b, Degueldre 1994/ but about ten times lower than reported from Canada (300±300 µg L^{-1}) /Vilks et al. 1991/. The possibility that some of the iron and sulphur colloids might occur as iron sulphides has to be further investigated. Particle counting could increase the value of colloid analyses by making it possible to calculate the amount of binding sites for radionuclides in the different colloid fractions.

2.7.5 Gases

The amounts of gas data are limited and therefore exclude any considerable analysis of the impact of gases on geochemistry and microbiology; there is, however, a clear trend with increasing volumes of gas towards depth.

The available gas data for the Laxemar subarea show that the gas content is of the same order of magnitude as in most of the Nordic sites studied. The site-specific features are:

- Nitrogen is the dominating gas at all depths.
- Helium increases with depth.
- Highest amounts of methane were found above 400 m in KLX03, suggesting that it is biologically produced.
- The amounts of hydrocarbons increase with depth.
- The gases are probably mostly mantle-generated.
- Gases are probably oversaturated in relation to atmospheric pressure but this is not the case at depth.

2.7.6 Hydrochemical suitability criteria

There are new representative samples at repository depths from the Laxemar subarea. The representative samples from KLX03: 408–415.3 m and KLX04: 510–514 m were used to check if they meet the SKB chemical suitability criteria for Eh, pH, TDS, DOC, Colloids and Ca+Mg /Andersson et al. 2000/. Table 2-6 shows that these samples can meet the SKB suitability criteria for the analysed parameters.

Table 2-6. The hydrochemical suitability criteria defined by SKB are satisfied by the analysed values of samples KLX03: 408–415.3 m (sample no: 10091) and KLX04: 510–514 m (sample no: 7776).

	Eh (mV)	pH (units)	TDS (g/L)	DOC (mg/L)	Colloids (mg/L)	Ca+Mg (mg/L)
Criterion	**< 0**	**6–10**	**< 100**	**< 20**	**< 0.5**	**> 40**
KLX03: 408–415.3 m	–275	7.9	2.9	2.2	~ 0.02	245
KLX04: 510–515 m	n.a.	7.8	2.8	2.2	n.a.	241

n.a. = not analysed.

2.7.7 Pore water composition in the rock matrix

Determination of pore water composition

In crystalline rocks the pore water resides in the low-permeability zones (rock matrix) between principal water-conducting zones related to regional or local fracture networks. Depending on the residence time of water in these hydraulically active zones, interaction with water present in the pore space of the low-permeability zones might become significant. In addition, the pore water present in the low-permeability zones will be the first to interact with any artificial construction made in such zones (i.e. repository). For safety assessment considerations it is therefore important to know the composition of such pore water. The pore water studies so far carried out for the Laxemar subarea are described in detail in Appendix 1 of /SKB 2006f/.

In borehole KLX08 (Figure 2-19), concentrations of less than 1 g/kgH_2O pore water are obtained for the shallower depths down to about 500–600 m were there is a high frequency of hydraulically conductive fractures and a corresponding increase in transmissivity (up to 10^{-5} m^2s^{-1}). Furthermore, the pore water chloride increases significantly towards the transition between the Ävrö granite and quartz-monzodiorite coinciding with decreased transmissivities down to $10^{-8.5}$ m^2s^{-1} and less. From here there is a steady increase to values of 10.5 g/kgH_2O at a vertical depth of 851 m below surface (983 m borehole length).

In comparison with borehole KLX03 /Waber and Smellie 2006b/ the pore water chloride profile in KLX08 shows exactly the same general pattern, i.e. dilute water in the Avrö granite until the boundary with quartz-monzodiorite, followed by a strong increase to the top of the quartz-monzodiorite and then a decrease, and finally a strong increase at maximum depth. In contrast, the chloride pore water concentrations below about 750 m are significantly higher than the highest chloride concentrations observed in borehole KLX03.

In general, pore waters characterised by direct and indirect methods from low-permeable crystalline rocks from the Laxemar (and Forsmark) subareas have a distinct chemical and isotopic composition. Pore water compositions differ from those of fracture groundwaters

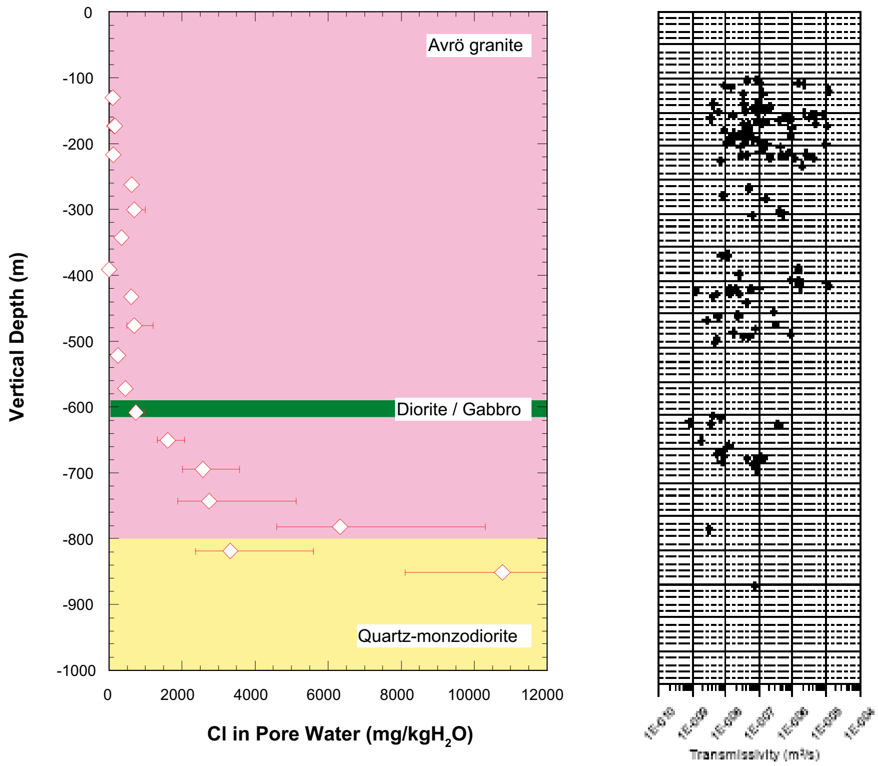


__Figure 2-19.__ Borehole KLX08: Chloride concentration in pore water as a function of vertical depth compared to fracture transmissivity.

depending on the distance between the location of the pore water sample in the rock matrix and the nearest water-conducting fracture, and the time period of constant composition of the fracture groundwater. Combined with measured and experimentally-derived hydraulic properties, these compositional differences support diffusion-dominated solute transport in the low-permeable rock masses. From the present investigations it can be concluded that in such a rock mass the diffusion-accessible porosity extends over significant distances (at least metres to tens of metres).

Pore water compositions derived by indirect methods from drill core samples from the Laxemar (and Forsmark) sites can be interpreted within a larger palaeohydrogeological framework. The methods applied minimise experimental disturbances and effects induced by drilling activities and/or stress release effects, and the obtained pore water compositions have well definable uncertainties. Further methodological improvements are, however, required to reduce these uncertainties. The pore water chemical and isotope compositions show distinct trends correlating with rock types and with depth, becoming more saline with increasing depth at both sites. Concentration gradients established between pore water and fracture groundwaters coincide with higher fracture frequency and increased transmissivity in the host rocks, where the location of the pore water sample is closer to water-conducting fractures. Differences developed in the attainment of steady-state conditions between pore water and fracture water between the Laxemar and Forsmark sites support a different hydrogeological, and therefore hydrogeochemical evolution, at least during Holocene times.

Modelling of interaction between fracture water and pore water in the matrix

The interaction between the ions dissolved in the pore water in the rock matrix and those ions dissolved in the flowing water in the fractures is studied in Appendix 7, /SKB 2006f/. The ions may migrate from the water flowing in the fracture into the pore in the rock matrix but also in the opposite direction. Migration of the ions takes place by diffusion in the matrix pores and its direction is determined by the concentration gradient. To simulate the effect of fresh water intrusion into a zone with saline water, several calculations were performed with increasing level of complexity.

In the first set of calculations the evolution of the concentration in the matrix is studied for the case where the concentration in the adjacent fractures is negligible. The results may be directly applied to the case of salinity depletion from the rock matrix into a fracture with negligible salinity. Three different geometries were modelled: a) fracture matrix interaction with diffusion perpendicular to the fracture plane, b) a narrow channel embedded in a large rock mass (Figure 2-20), and c) a rock block surrounded by conductive fractures. The results show that the time for salinity depletion is of the order of hundreds to thousands of years for distance of one metre in the rock matrix.

In a second set of calculations the evolution of the concentration in the water in the fracture was taken into account. The time to deplete the salinity in the matrix may then be strongly increased. The time to deplete the salinity in the fracture depends on the surface contacted by the fresh water along its path and the water-flow rates. Actually, it depends on the $\Sigma(FWS/Q)$ where FWS = Flow Wetted Surface and Q = Flow rate in the channel. For small values of this term (e.g. large water-flow rate) the concentration in the fracture decreases very fast. However, for large values of the term $\Sigma(FWS/Q)$, the salinity depletion in the fracture may be very long, i.e. thousands of years.

Finally, simulations were carried out to determine the paths followed by the water from the point of intrusion to the zone under study. These simulations were made using the Channel Network Model /Gylling et al. 1999/. Particle tracking was used to determine ($\Sigma FWS/Q$) for the several water parcels travelling through the channel network. The results show that fractures with large transmissivity collect water that has travelled through paths with $\Sigma FWS/Q$ varying in a wide interval. Moreover, most of water parcels were collected by the fractures with large transmissivity. Therefore, the evolution of concentration in the fracture with time is weakly related to the transmissivity of the fracture.

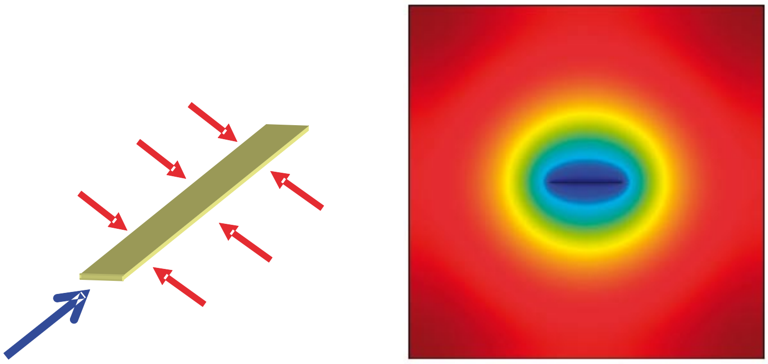


Figure 2-20. *A schematic view of diffusion into a channel/fracture surrounded by an infinite rock mass (left) and concentration profiles at the rock mass (right).*

2.7.8 Studies of fracture fillings

General characteristics

Fracture minerals are determined macroscopically (Appendix 1, /SKB 2006f/) and are mapped within the Boremap system. However, since many of the minerals are difficult to identify and small crystals are easily overlooked, fracture mineral analyses have been carried out on additional samples for quantitative identification. This information is crucial, for example for hydrogeochemical mass-balance calculations. Fracture samples have also been selected because they can provide information on the sequence of events that have resulted in fracturing and fracture mineralisation in the area. A number of samples have been taken from boreholes KLX02, KLX03, KLX04 and KLX06 for microscopy, in most cases including SEM/EDS, chemical analyses and stable isotope analyses of calcites. Results from these studies are reported in /Drake and Tullborg 2005/. The abundance of different fracture minerals in open fractures is listed in Appendix 1 of /SKB 2006f/.

Hydrochemical indicators

In the perspective of groundwater chemistry the presence of the four minerals, calcite ($CaCO_3$), gypsum ($CaSO_4$), barite ($BaSO_4$) and fluorite (CaF_2), is worth attention as their solubility has an impact on or controls the behaviour of some major ions, see Appendix 1 in /SKB 2006f/.

Calcite is the most common of these minerals. It occurs frequently at all depths except in the upper tens of metres and below approx. 1,000 to 1,100 m where it is less common. A number of calcite generations have also been identified ranging from hydrothermal to possible recent /Bath et al. 2000, Drake and Tullborg 2004/. Stable isotope ratios represented as $\delta^{18}O$ and $\delta^{13}C$ plotted versus depth are shown in Figure 2-21 and Figure 2-22. $\delta^{18}O$ versus depth shows that the highest values representing possible Baltic Sea water precipitates are found in the upper 500 m at the Simpevarp and Äspö subareas. The Laxemar subarea in contrast has generally lower $\delta^{18}O$ values. Calcites with low $\delta^{18}O$ (< –15‰ PDB) are found at all depths except for the near-surface 50 m. Such values are expected in calcite precipitated from a groundwater with a large glacial component. Mineral parageneses, trace element compositions and Sr isotope studies reveal, however, that the low $\delta^{18}O$ calcites are older and have been precipitated during increased temperatures. The carbon isotopes show large variation and extremely low values ($\delta^{13}C$ < –25‰ PDB) have been observed down to 800 m depth. Such low values are produced by in situ microbial activity causing extreme local disequilibria. On average the $\delta^{13}C$-values are lower in the upper 500 m indicating a larger input of organic carbon. The few samples below 1,000 m are all higher than –10‰ PDB supporting more stagnant conditions at depth with no sign of exchange with organic material contributed from the surface.

Barite occurs as very small grains but is relatively frequently observed (microscopically; not during the core logging) together with calcite, pyrite and the Ba-zeolite harmotome. In saline groundwater samples with very low SO_4 contents anomalously high Ba contents have been identified. For example, this was the case for the deepest saline groundwater from the KOV01 borehole at Oskarshamn, pointing towards a possible barite solubility control on the Ba and SO_4 content in the groundwater. Solubility has an impact or controls the behaviour of some major ions.

Fluorite occurs in several hydrothermal mineral associations; together with epidote and the later prehnite, but also together with the lower temperature (150°C) generation comprising calcite, barite and pyrite. Fluorite can be assumed to partly control the F content of the groundwater.

Gypsum is relatively rare but has been identified in several boreholes in the Laxemar subarea. The gypsum-containing fractures are usually located in borehole sections showing a low degree of fracturing and low (or not measurable) transmissivity. Groundwater modelling /Laaksoharju 2004a/ suggests dissolution of gypsum as an explanation for the relatively high SO_4 contents in the saline Laxemar subarea groundwaters. Although gypsum has not been iden0tified during the extensive work in the Äspö HRL, it can not be ruled out that it has been overlooked, but probably is only present in some of the low transmissive, relatively unfractured parts of the rock.

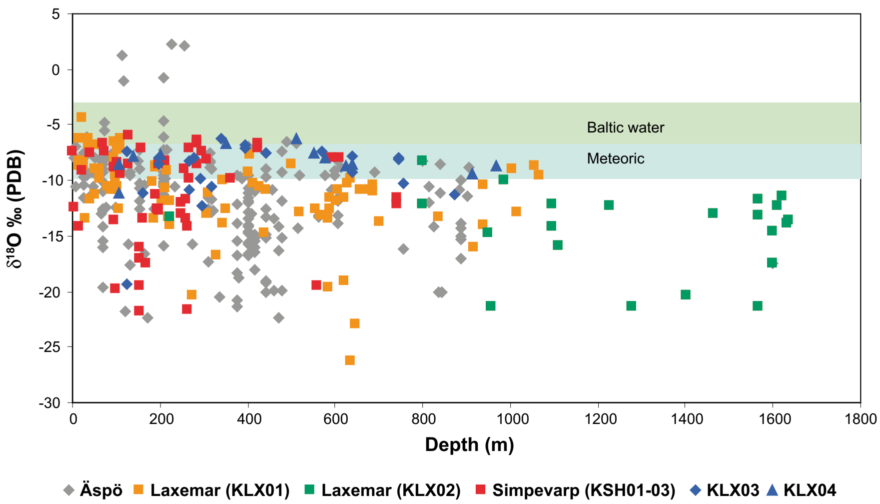


Figure 2-21. *Plot of $\delta^{18}O$ (PDB) vs. depth (calcite) with samples from KLX03 and KLX04 along with calcite from Äspö, Simpevarp and Laxemar (KLX01 and KLX02) /from Drake and Tullborg 2004, Milodowski 2005/. The range of calcite precipitates from Baltic Sea water and meteoric water at ambient temperatures is indicated.*

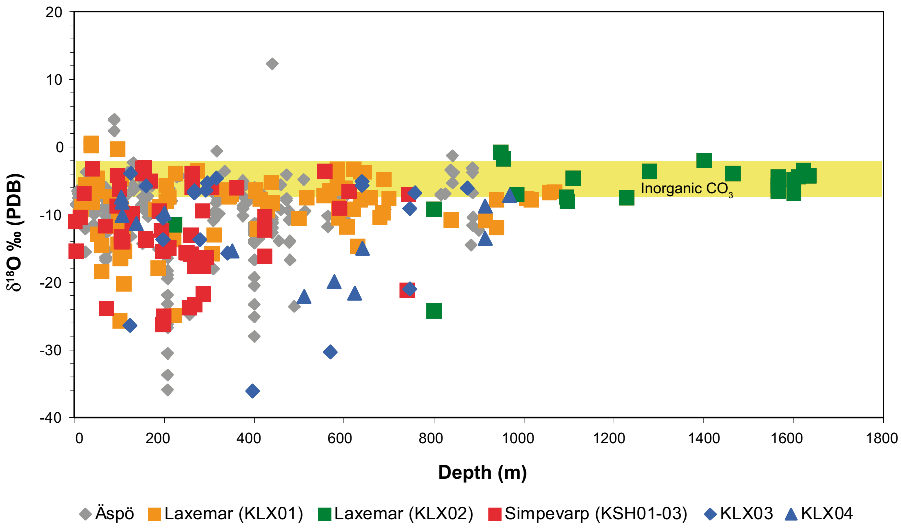


Figure 2-22. *Plot of $\delta^{13}C$ (PDB) vs. depth (calcite) with samples from KLX03 and KLX04 along with calcite from Äspö, Simpevarp and Laxemar (KLX01 and KLX02) /from Drake and Tullborg 2004, 2006, Milodowski 2005/. The range of inorganic CO_3 is indicated.*

3 Summary of current knowledge and modifications since version Laxemar 1.2

In this chapter summaries are provided of current knowledge and statements on remaining uncertainties as of the "Feedback workshop" in Mariefred, late April 2006. The latter workshop facilitated effective feedback to the developed site investigation programme for the complete site investigations. The process involved members of the site modelling and site investigation teams, and representatives from repository engineering and safety analysis.

3.1 Bedrock geology

This section comprises and describes the rock domain and deterministic deformation zone modelling work carried out during the modelling stage Laxemar 2.1 until the end of March 2006. Note that no 3D RVS models have been constructed and delivered to the SIMONE database as part of the current modelling step.

3.1.1 Rock domain model

Definition of rock domains in cored boreholes

Based on the Boremap mapping and the geological single hole interpretation, rock domains have been preliminary defined in the cored boreholes KLX05, KLX06, KLX07A, KLX08, KLX09 and KLX10 (Table 3-1). Although no 3D modelling have so far been performed in RVS, it is obvious that the new information and rock domain division in the new cored boreholes roughly confirm the geometry of the rock domain model as presented in SDM Laxemar 1.2 /Wahlgren et al. 2005/.

Table 3-1. Definition of rock domains in KLX05, KLX06, KLX07A, KLX08, KLX09 and KLX10 in the Laxemar subarea.

Borehole	Secup – Seclow (m)	Rock domain
KLX05	108–473	RSMM01
KLX05	473–995	RSMD01
KLX06	101–995	RSMA01
KLX07A	102–842	RSMA01
KLX08	101–587	RSMA01
KLX08	587–924	RSMM01
KLX08	924–992	RSMD01
KLX09	102–874	RSMA01
KLX10	102–857	RSMA01
KLX10	857–981	RSMM01
KLX10	981–996	RSMD01

In the rock domain modelling work in connection with version Laxemar 1.2 only preliminary mapping of KLX05 was available. The definition of rock domain RSMBA01 was based on a mixture of Ävrö granite and fine-grained dioritoid similar to the interval (borehole length) between 540 and 960 m in KLX02 (RSMBA03). Similarly, although no cored borehole data existed, the RSMBA02 was based on the assumption of a similar mixture. However, based on the Boremap mapping of KLX05, there is no basis for the existence of rock domain RSMBA01 in the local model volume. Instead this rock domain has been redefined to a RSMB domain, i.e. dominated by fine-grained dioritoid. In conformity, the RSMBA02 domain has also been redefined to a RSMB domain. Consequently, the only remaining RSMBA domain is RSMBA03 at depth in borehole KLX02.

Rock type proportions in rock domains

Based on Boremap mapping of additional cored boreholes in the Laxemar subarea which were not available in conjunction with the Laxemar 1.2 modelling work, the proportions of rock types in the RSMA01, RSMD01 and RSMM01 domains have been calculated (Figure 3-1). The relatively high proportion of fine-grained diorite to gabbro in the Ävrö granite in RSMA01 (Figure 3-1) mainly reflects the high proportion of this rock type in KLX06 and KLX09, and does not reflect the general proportion of fine-grained diorite to gabbro in the RSMA01 domain in southern Laxemar. The same holds for the high proportion of fine- to medium-grained granite in RSMD01 (Figure 3-1), which mainly reflects the high proportion of quartz monzodiorite which dominate in KLX05.

Subdivision of the Ävrö granite in compositional varieties

The composition of rock types is critical for the thermal properties and the division of thermal domains in the bedrock. Furthermore, variations in composition may also explain differences in uniaxial compressive strength (UCS) and crack initiation strength. These thermal and mechanical properties are critical for the design of a repository.

The Ävrö granite has been shown to have a large compositional variation, and thereby also a large variation in thermal properties /SKB 2006a/. Available analytical data in connection with the Laxemar 1.2 modelling work did not allow a subdivision of the Ävrö granite in quartz rich (granitic to granodioritic) and quartz poor (quartz monzodioritic) rock domains that in a better way would constrain the property assignment. However, in order to improve the correlation between the compositional varieties of the Ävrö granite and the division in rock domains, an evaluation of available analytical data, i.e. modal, geochemical and petrophysical data have been initiated both at the surface and at depth. In the southern and western Laxemar subarea, a preliminary subdivision has been carried out at the surface, i.e. the Ävrö granite has been subdivided in a quartz rich (granitic to granodioritic) and quartz poor (quartz monzodioritic) variety on the bedrock map. A similar evaluation at depth by use of existing modal, geochemical and petrophysical data, particularly density data from the geophysical logging of the cored boreholes, has been initiated. Relevant data from new boreholes are evaluated as soon as they are available.

Whether a subdivision of the Ävrö granite is possible to model in 3D has to await the Laxemar version 2.2 modelling work when data from all additional boreholes are available and evaluated.

In the Laxemar version 1.2 rock domain model /Wahlgren et al. 2005, SKB 2006a/, it was anticipated that the Ävrö granite in the RSMM01 domain was represented by the quartz poor (quartz monzodioritic) variety. This was based on surface samples and samples from KLX03. However, new analyses and density loggings of the Ävrö granite from the RSMM01 domain in the cored boreholes KLX08 and KLX11A indicate that this is not the case.

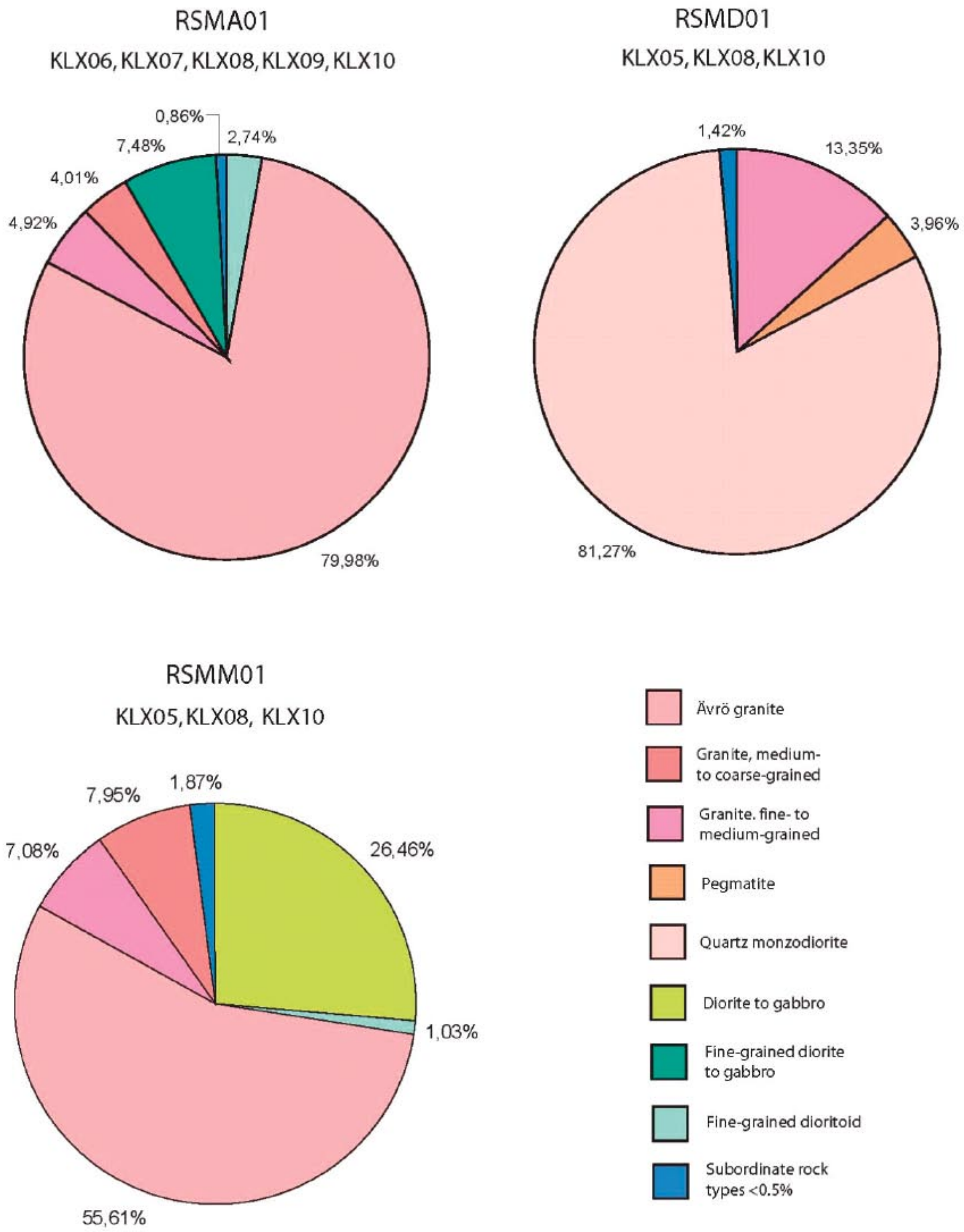


Figure 3-1. *The proportion of rock types in RSMA01, RSMD01 and RSMM01 in the Laxemar subarea based on the cored boreholes that are marked for each diagram.*

3.1.2 Deterministic deformation zone model

It is noted that overall, no major changes are inflicted on the Laxemar 1.2 deformation zone model presented in /SKB 2006a/ as a consequence of analysis of the new Laxemar 2.1 data. A review of the changes is presented in the following sections. However, no formal update of the deformation zone model is given.

Assessment of an alternative lineament interpretation and integration of the results with the current deformation zone model

A selective attempt on integration have been performed by using the existing deformation zone surface trace map from the Laxemar 1.2 deformation zone model and the new lineament interpretation at the regional scale performed by the Geological Survey of Finland (GTK) /Korhonen et al. 2005/. Only deformation zone traces and GTK lineaments with a trace length of at least 1,600 m have been considered in this attempt to investigate whether the alternative lineament interpretation made by an independent team would significantly change the resulting co-interpretation of deformation zones in the working-model RVS model.

The methodology involved comparison of both data sets over the entire regional scale domain, with special focus on the local scale model domain. Lineaments where the differences were judged to suggest significant differences for the deformation zone model were identified. This process resulted in a selected 'short list' of lineaments that were considered to justify a more detailed study of the background geophysical and topographical data.

The selection was made by taking GTKs linked lineaments; making a sub-selection of all traces > 1,600 m, corresponding to the earlier regional model scale, and selectively extracting geometries that constituted significant changes relative to the Laxemar 1.2 model. In practice this meant that traces were selected on the following basis:

- a very similar geometry to an existing trace but with a greater lateral extent resulting in a higher connectivity and possibly isolating a block that was only partially defined in the Laxemar 1.2 model,
- a similar alignment to an existing trace but with different linkages, resulting in a much more significant extent,
- a completely new geometry that simply was not identified previously, but fit in well with the current understanding of prevailing tectonic patterns.

The continued study also involved re-examination of the background data of the selected lineaments. This final review resulted in the majority of the GTK lineament alternatives being rejected based on either topographical or geophysical background data. However, a number of alternative interpretations, shown in blue colour in Figure 3-2, were retained for integration in the current modelling. The remaining GTK lineaments shown in thin black were not considered to justify any further action for the regional model outside the local model boundary, i.e. they coincide with those of the SKB interpretation.

Regional scale review of key structures

At an early stage of the Laxemar 2.1 deformation zone modelling resulting from the integration of the alternative lineament study, a review was made of a number of key interpreted deformation zones intersecting the local scale model area. The aim was to review the Laxemar model version 1.2 deformation zone model, identifying key zones, sections of zones or structural relationships of significance for the regional model framework. From examination of surface data the aim was to confirm existing interpretations or identify significant alternatives for further consideration.

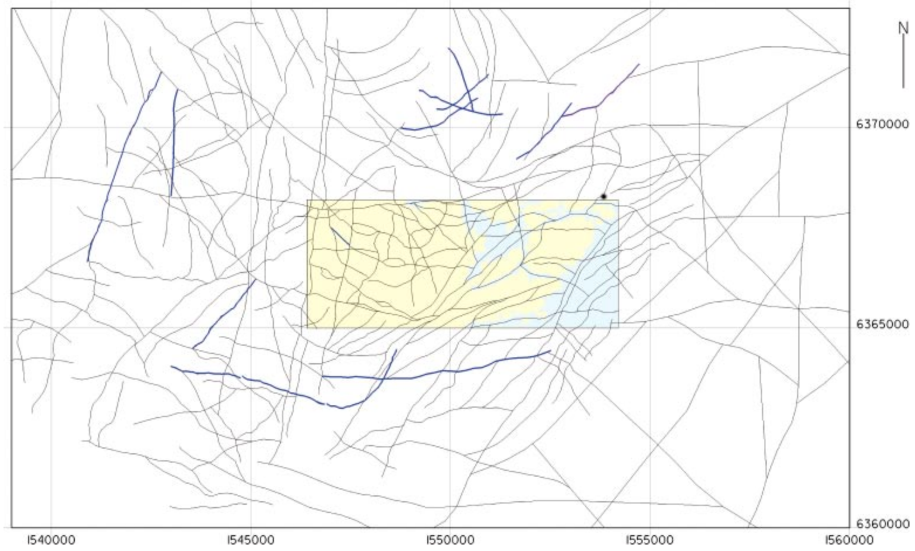


Figure 3-2. *Overview of modified lineament map based on a review of GTK lineament interpretation. Blue lineaments represent alternative interpretations made by the GTK team that have been incorporated into the Laxemar 2.1 deformation zone modelling. Thin black lineaments were considered not to require further action, i.e. they coincide with the SKB interpretation.*

The working method consisted of review of existing lineament extensions, positions and linkages in relation with their underlying geophysical and topographical background data with due consideration of possibly associated geological structures. Consideration was also given as to how changes to such lineament linkages etc, would affect the structural model. It is important to note that this review was performed at a regional scale in the regional deformation zone model.

Key deformation zones reviewed, questions posed and key conclusions

In the current Laxemar 2.1 work focus has been on enhancing the understanding of key deformation zones in the central part of the local model area. These key deformation zones are identified in Figure 3-3.

Below follows discussion sections regarding the interpretation of specific deformation zones based on new surface and sub-surface information acquired during model version 2.1 and taking the comparison with the GTK lineament interpretation in to account.

Southern termination of ZSMNE005A (Äspö shear zone)

The southern termination of the Äspö shear zone is against ZSMNW042A in the Laxemar 1.2 deformation zone model. However, the background geophysical and topographical data, together with available lithological information, show an area with multiple contacts between several rock types and intense magnetic anomalies which do not provide a conclusive interpretation.

Is there a justification for an alternative interpretation that this zone continues to the SW, with or without an offset across ZSMNW932A or ZSMNW042A? The complex local rock geometries make this assessment difficult and maybe the magnetic map is not the best guide.

In the current assessment it was concluded that the termination of ZSMNE005A cannot be dealt with in isolation. It is clearly linked to other deformation zones located in this area; the eastwards extension of ZSMNW042A, the location of the mixed rock domain M etc. Current evidence clearly suggests that alternatives should be considered. However, it was considered that this item should stay on the list and be dealt with at an early stage of version L2.2 modelling.

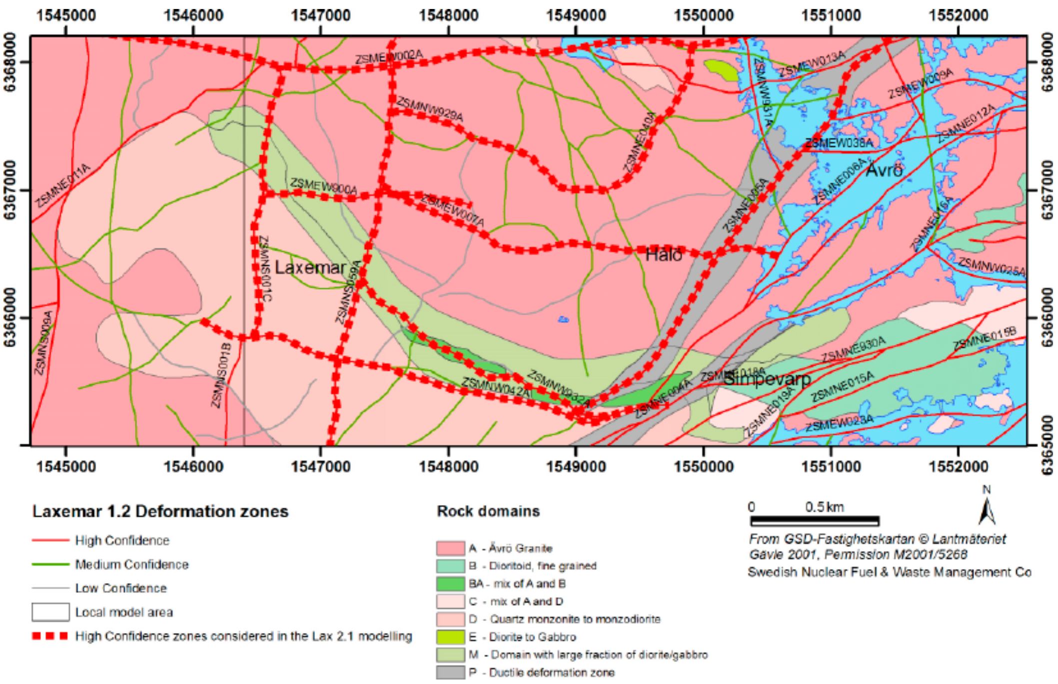


Figure 3-3. *Key deformation zones (red hatched) that have been re-assessed in model version 2.1. suprimposed on the Laxemar 1.2 deformation zone model.*

Possible eastern extension of ZSMNW042A or ZSMNW932A

An alternative interpretation of the extension ZSMNW042A and ZSMNW932A towards the east has been analysed in the current model version 2.1. Is it possible that these zones continue eastward and constitute a similar regional geological boundary as ZSMEW002A, making up the northern boundary?

A re-analysis of the background geophysical and topographical data suggests that such an extension scenario is unlikely with the current knowledge, but cannot be discounted. No new regional data will appear in the next model version that could help reduce the uncertainty of the eastern extension of ZSMNW042. However, new data will appear in model version 2.2 from boreholes intersecting both ZSMNW042A and ZSMNW932A that could help reduce uncertainty about the geological character of the latter zones.

NW extension of ZSMEW007A

The alternative interpretation that ZSMEW007A extends towards the north-west has been in focus since Laxemar model version 1.2. There are topographical indications that ZSMEW007A, or an associated zone, does not terminate against ZSMNS059A, but continues north-westwards aligned with a watercourse. Magnetic background data do not give conclusive evidence about a termination and it is therefore concluded that the lineament and possible alternative NW extents of ZSMEW007A need to be analysed in the model for further analysis during model version 2.2.

Continuity of ZSMEW900A towards the east

A revisit has been made of the ZSMEW900A interpretation as to whether it continues east of ZSMNS059A, or terminates against ZSMNS059A.

It is concluded that with the current knowledge ZSMEW900A should be divided in two legs at ZSMNS059A – this being a documented alternative included in v1.2. However, this would have resulted in trace lengths less than 1,000 m resulting in the structure being omitted from the model.

NW extension of ZSMNW932A

The bedrock map shows that the surface trace of ZSMNW932A follows the rock type boundary between RSMD01 and RSMM01, cf. Figure 3-3. A reassessment of the background data have been made to investigate the continuation of ZSMNW932A northwest of ZSMNS059A.

It is concluded that the north-western extension of the zone is not supported by the currently available information. The continuity of ZSMNW932A as a deformation zone is doubtful. However, there is sufficient new detailed lineament information available for model version 2.2 to clarify the character and existence of this proposed deformation zone.

Assessment of medium confidence zones

NE terminations of ZSMNE094A, ZSMNE108A, ZSMNE107A, ZSMNE063A

This readily identified set of NE trending deformation zones all terminate at, or near, ZSMNW042A, cf. Figure 3-4. The terminations need to be checked to assist in the assessment of structural relationships. Do any of these zones have indications of existence on the northern side of ZSMNW042A, or are all current terminations clear and without alternatives?

It was concluded that the general pattern of these lineaments/zones terminating at ZSMNW042A seems well supported. However, this area will be covered by the forthcoming detailed Lidar and ground magnetic study of lineaments of short extent. However, the observed pattern of termination seems to elevate the significance of ZSMNW042A acting as more of a regional structural control. This also has a linkage to the extent to the east of this zone, and its relationship with ZSMNE005A.

Degree of continuity of ZSMNW170A, ZSMNE138A, ZSMNE043A, ZSMNW051A and ZSMNS046A

A review of the continuity of ZSMNW170A, ZSMNE138A, ZSMNE043A, ZSMNW051A and ZSMNS046A was made as to whether or not they are continuous or whether there is a basis for breaking them up in shorter segments.

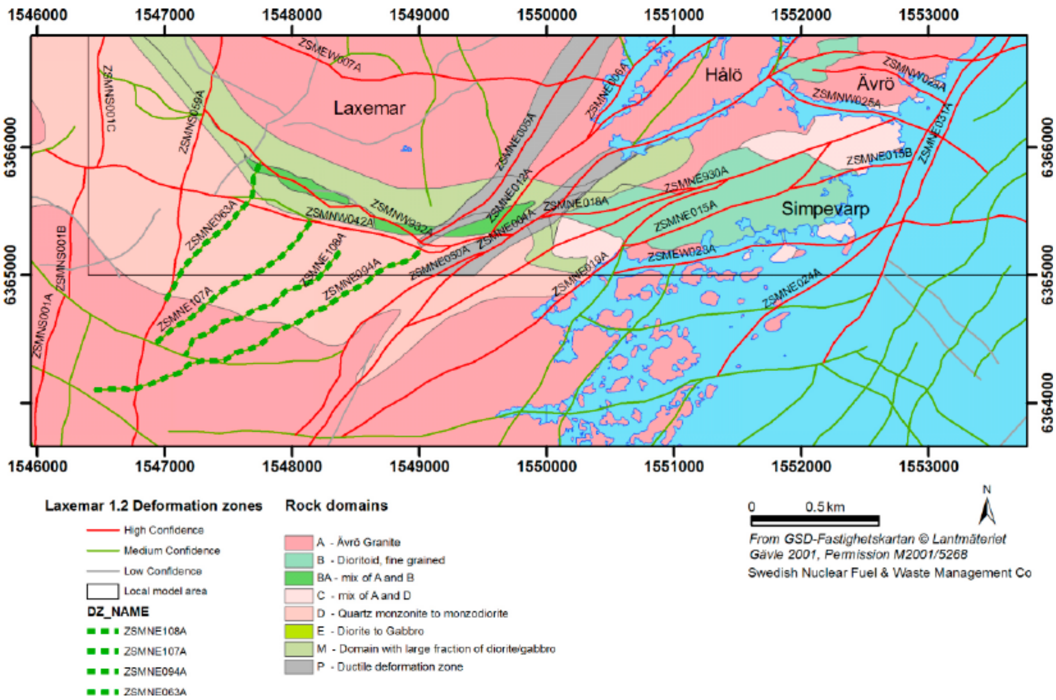


***Figure 3-4.** Plan view of medium confidence zones ZSMN094A, ZSMNE108A, ZSMNE107A, ZSMNE063A (green hatched) re-assessed in model version 2.1 superimposed on the Laxemar 1.2 deformation zone model.*

ZSMNW170A and ZSMNE138A: based on Lidar data and the detailed ground magnetic map it is concluded that the lineament/zone should be broken up into shorter segments. The current total length is not justified even at a regional scale. This has not yet been incorporated in model version 2.1.

ZSMNE043A: it is concluded that there is a lack of confidence in the degree of continuity in this zone based on how it is currently modelled. However, a reassessment will be made once the detailed coordinated lineaments are available for model version L2.2.

ZSMNW051A: it is concluded that the lineament is weakly supported and should be further reviewed once the detailed coordinated lineaments are available for model version L2.2.

ZSMNS046A: it is concluded justified to divide the current lineament into two, sectioned along the Mederhult zone ZSMEW002A, once the detailed coordinated lineaments are available in model version 2.2.

Review of the apparent "tectonic eyes" based on ZSMNW042B, ZSMNW932B and ZSMNW932C.

After a review of the Lidar data and the detailed ground magnetic map it was decided that the "tectonic eye" features, as they are drawn today, can be abandoned and be replaced by a more rationale pattern of less continuous lineament traces. This will be implemented as part of the model version L2.2 work.

Local scale review of key structures

A detailed review of key structures has been made based on both approved and early data from all sources, considering all available data from both the surface and borehole investigations. A part of this process included a workshop involving members of both the Laxemar Modelling and Site investigation teams.

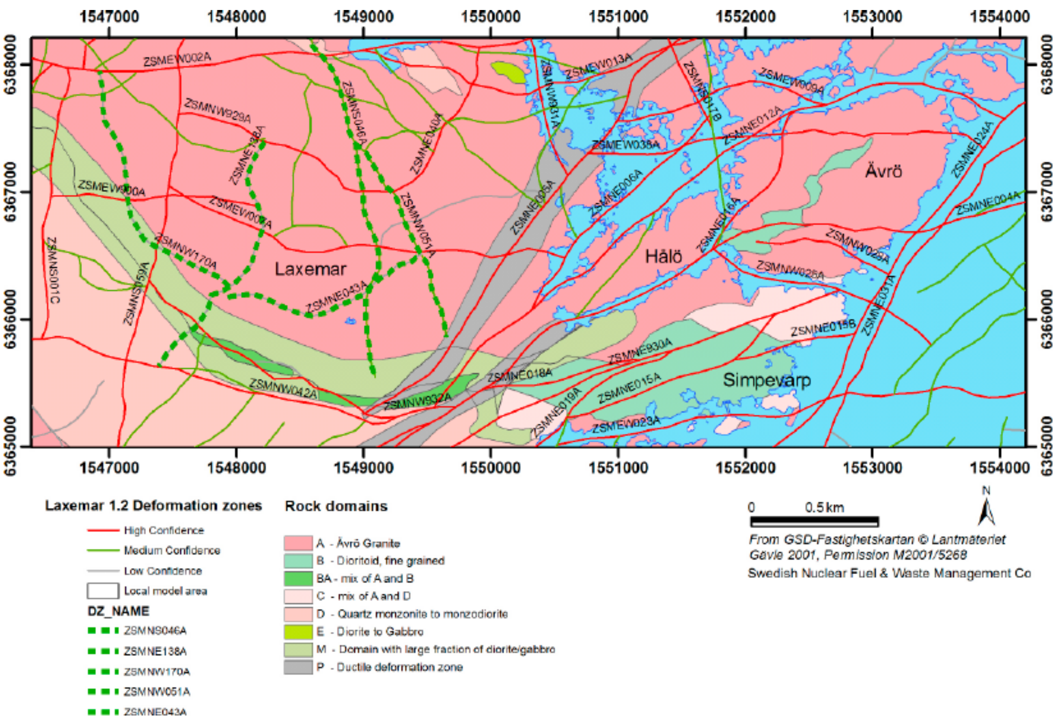


Figure 3-5. *Plan view of medium confidence zones ZSMNW170A, ZSMNE138A, ZSMNE043A, ZSMNW051A and ZSMNS046A (green hatched) re-assessed in model version 2.1 superimposed on the Laxemar 1.2 deformation zone model.*

ZSMEW002A

The existing background data and version Laxemar 1.2 zone interpretation has been reviewed. Apart from Lidar data no other new information was available. The existing interpretation remains unchanged from that presented in the Laxemar 1.2 model. No further major modifications to the zone's geometry are expected at the regional scale. Future work is likely to focus on the degree of continuity of the zone and its character and properties within the local model volume.

ZSMEW007A

In the model version Laxemar 1.2 the zone was modelled with a thickness of 50 m, dipping north at an angle of 43°. This dip was based mainly on the seismic reflector A, /Juhlin et al. 2004/. After a reassessment making use of the lineament trace geometry based on the Lidar and detailed ground magnetic information, it was considered likely that the zone would have to be remodelled in two or three shorter segments. The trench excavation /Sohlenius et al. in press/ in the centre part of ZSMEW007A revealed an orientation of the mapped deformation zone (300/40) that deviates from the other known intersection points further to the east. This suggests that a segment break point is located to the east, between HLX33 and HLX23. A break point at this location is supported by the currently available hydrological pumping test data which suggests the western and eastern segments of ZSMEW007A are not hydraulically connected. A comparison of the trench excavation and the magnetic and resistivity profiles available at the same position as the trench, reinforces the validity of the interpretation of a northerly dip to the zone. A re-evaluation of the lineament map and background data has lead to a significant extension of the zone geometry to the NW, extending beyond ZSMNS059A. This extension has been modelled with the same northerly dip. Whether the zone should be broken up in additional segments at ZSMNS059A is an open question. The geometry of the easternmost portion of the zone has also been modified to more closely conform to the new Lidar and detailed ground magnetic lineament map. It seems that the alternative eastern termination interpretation is most plausible from a hydrogeological viewpoint.

The zone has also been modelled at a more local scale tying in the new, shorter, lineaments to the mapping, geophysical profiles and deformation indicators in boreholes. These surfaces are also compatible with the 35–45° northerly dip to the zone.

A third group of surfaces have been generated in the model: a number of subparallel lineament traces have been used to visualise other subparallel 'splays' of the zone in an attempt to portray the assumed character of the zone. However, other than the lineament traces, there is little to support these representations. Figure 3-6 attempt to outline the current status of the interpretation of the zone in the current working model (per March 2006).

ZSMNE040A

The existing background data and model version Laxemar 1.2 zone interpretation has been reviewed. Other than the Lidar data no other new information is available. The zone is transacted by a geophysical magnetic, resistivity and seismic refraction profiles /Thunehed et al. 2004/. A seismic reflector 'I' has previously been associated with the surface lineament /Juhlin et al. 2004/. Potential intercepts in percussion boreholes HLX01, HLX02, HLX03, HLX04, KLX01 and KLX02 were all considered. However, no conclusive evidence was identified that could specify a particular dip to the zone other than being generally subvertical. The existing interpretation remains unchanged compared to that presented in Laxemar model version 1.2. The zone is modelled with a vertical dip and a thickness of 20 m.

No further major modifications to the zone's geometry are expected at the regional scale that would increase the significance of this zone. Future work is likely to focus on the degree of continuity of the zone and its character and properties within the local model volume.

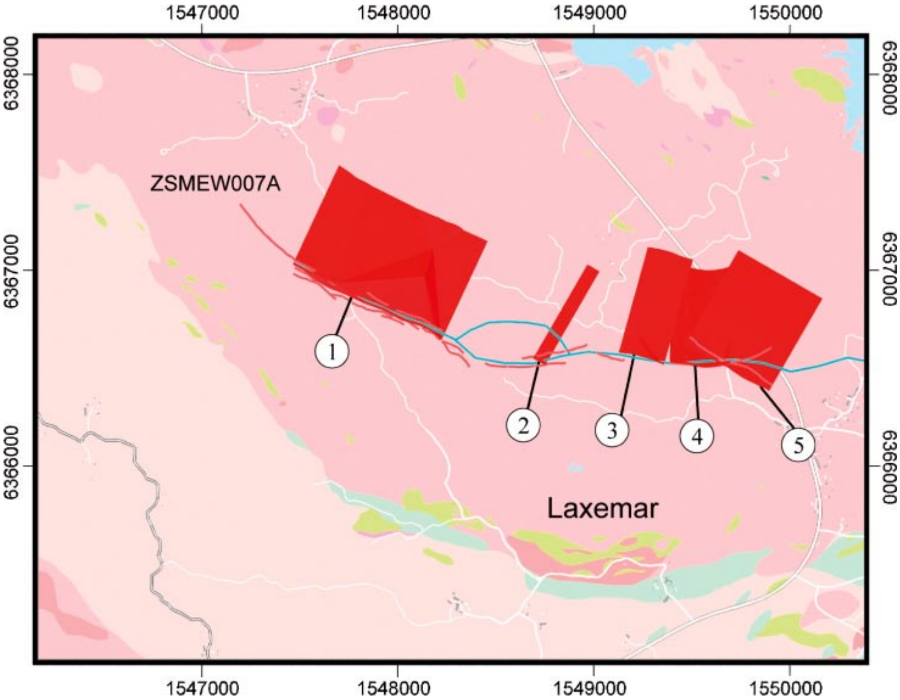


__Figure 3-6.__ An illustration of the updated geometry of identified sections of ZSMEW007A. See text below for explanations to the identified sections of ZSMEW007A (1 through 5). (1)The westernmost segment of ZSMEW007A is based on a topographical and magnetic lineament trace and tentative intercepts at KLX08 (DZ4 at 295 m) and KLX04 (DZ5 at 228 m) together with the northern dip interpretation from /Thunehed et al. 2004/ group 4 geophysical profiles. (2)This segment of ZSMEW007A is based on a mapped feature in trench excavation by /Bergman et al. in prep 2006/. (3,4,5)The eastern identified strands of ZSMEW007A which are based on topographical and magnetic lineaments /Triumf, in prep./, seismics /Lindquist 2005/ and intersection points in KLX07A, KLX07B , KLX02 and in HLX21.

ZSMNW929A

The existing background data and the model version Laxemar 1.2 zone interpretation have been reviewed including the field observations /Wahlgren et al. 2005/, topographic and airborne geophysical lineaments. The zone is modelled with the geometry 113/79, the dip being based on intercepts in KLX02 and KLX04. Early information from detailed resistivity ground surveys suggests that the zone is essentially subvertical rather than the assigned steep dip to the south west. The borehole intercepts and the shallow dipping nature of the fractures in the core may be associated with ZSMNW928 (seismic reflector N) rather than a steeply dipping ZSMNW929A. The review has resulted in the zone being assigned a vertical dip in the current model.

ZSMNW928 (seismic reflector N)

Seismic reflection profiling identified a fairly clear, extensive reflector (120/28) with an apparent termination in the north against the Mederhult zone (ZSMEW002A). This reflector has not been associated with any lineament or surface anomalies. This reflector has not been associated with any lineament or surface anomalies.

The existing background data and model version Laxemar 1.2 zone interpretation has been reviewed and the earlier interpretation remains essentially unchanged, see Figure 3-7.

In addition to seismic reflector N, a set of four subparallel, shallow dipping, reflectors (M1–M4) have been reported by /Juhlin et al. 2004/. The borehole data, from KLX03, KLX05, KLX07 and KLX08, provides a new opportunity to further investigate the origin/explanation of these

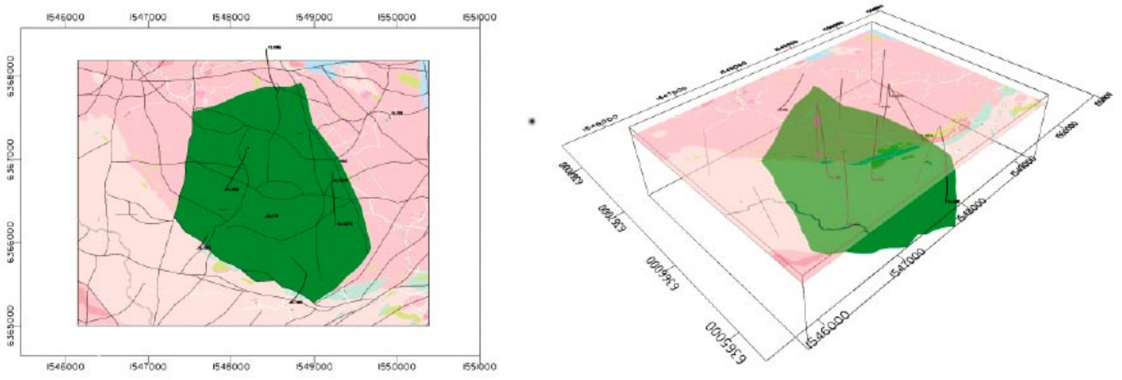


Figure 3-7. *ZSMNW928 (seismic reflector N).*

reflectors and examine possible correlations with deformation zone indicators. Results show that reflectors M2 and M3 appear to correlate with rock type boundaries and changes in density. Reflector M4 is the strongest and appears to coincide with reflector N (ZSMNW928A).

Currently, the geometry for reflector N is assumed to represent a deformation zone. However, pre,iminary analysis of the borehole data indicates that mafic intrusion(s) is (are) an alternative interpretation and that several subparallel, shallow dipping, reflectors could have similar attributes (M2–M4).

The suggested extent of the reflector geometry is shown in Figure 3-8 in combination with a series of horizontal planes set at elevation levels of –400, –500, –600 and –700 m above sea level.

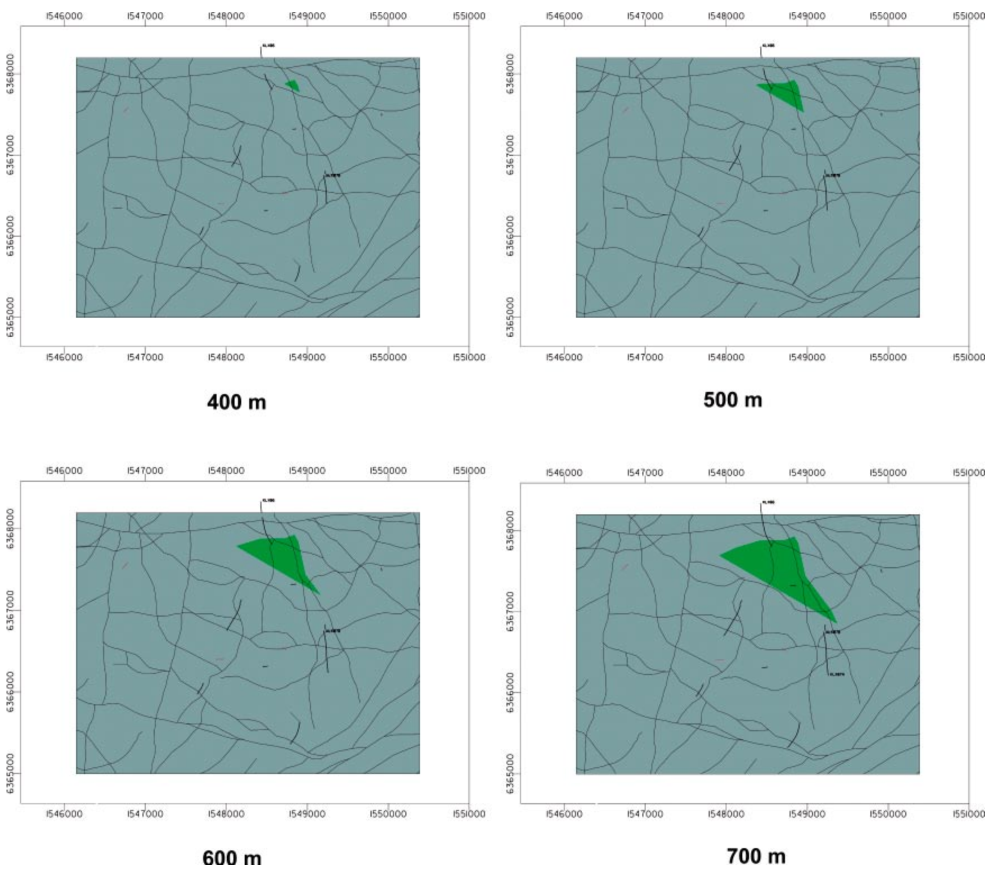


Figure 3-8. *Illustration of the extended model version 1.2 geometry in combination with a series of horizontal planes set at elevation levels of –400, –500, –600 and –700 m above sea level.*

Further direct investigations of NW928A do not appear to be a priority as the reflector geometry extends well below the proposed repository depth in the focussed area. However, continuing attempts to model this structure with existing and new direct and indirect investigation data remain highly relevant to establish the existence, extent and origin of this type of shallow dipping structure.

ZSM*** Reflector M1

The reflector has not been associated with any lineament or surface expression.

The current position is that a single planar geometry of reflector M1 (095/20) cannot be correlated with borehole deformation zone indicators across Laxemar. Therefore the reflector geometry should not be assumed to represent any continuous deformation zone. The borehole evidence also correlates with mafic intrusions, although this is far from conclusive from a preliminary analysis of the borehole data.

The next step will be to compare the signatures of the DZs interpreted from the single-hole geological interpretation (SHI) that do have interpreted coincidence with the interpreted geometry of reflector M1.

Possible further developments include additional in-depth review of the seismic reflection results with the aim of generating a series of very local reflector geometries that more closely will represent the reflection data output. Thus, it is expected that a more, complex and broke up geometry for M4 and possibly other reflectors will facilitate improved correlation with the available drill cores and borehole logs. Candidate boreholes for this analysis are KLX03, KLX05, KLX07 and KLX08 plus possible intercepts in new boreholes.

ZSMNS059A (north)

This zone has been artificially subdivided into two segments due to the current lack of confirmed data covering the southern section; ZSMNS059 'North' ,that lies to the north of ZSMEW007A/ZSMEW900A and ZSMNS059 'South' that lies to the south of ZSMEW007A/ZSMEW900A.

ZSMNS059 north: the current interpretation for the northern segment of the zone is one of a reactivated ductile-brittle zone, water conducting, with 2 m–10 m thick multiple cores of highly fractured rock and a total thickness of 50 m including transition zones.

The detailed coordinated lineament data obtained as early information indicated possible significant modifications to the associated zone concerning its continuity. The northward extension of the earlier Laxemar 1.2 lineament is now significantly reduced. Instead of continuing north, penetrating ZSMEW002A (Mederhult zone) and terminating at ZSMNE058A, the lineament now terminates immediately south of zone EW002A. The field mapping at the location immediately to the north of Mederhult also suggests that the zone may be associated

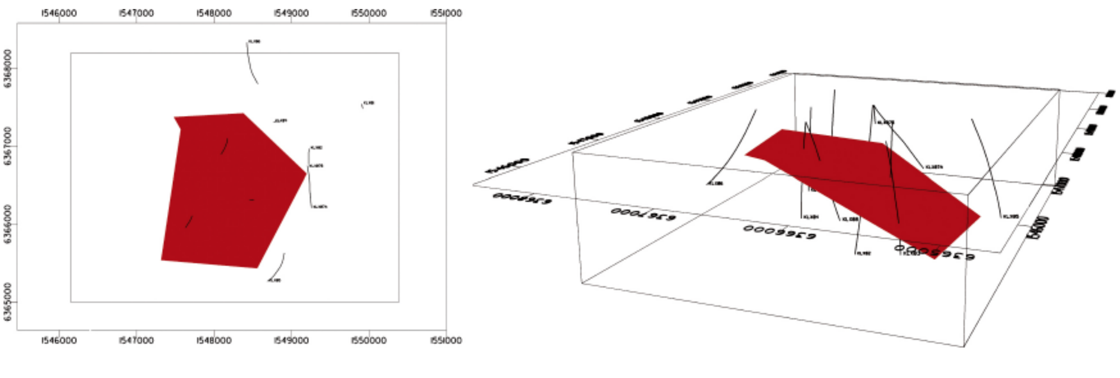


Figure 3-9. *ZSM*** Reflector M1, plan and perspective views.*

with basic dykes. The rock outcrops suggest that, at least locally to the north of Mederhult, the apparent thickness of the zone is less than 20 m. The lineament study based on Lidar and ground magnetic data now supports the earlier removal of a significant offset to the zone when crossing ZSMEW900A.

Two seismic refraction profiles cross the zone corresponding to the positions of percussion boreholes HLX34 and HLX35, at approximately 220 m and 350 m to the north of ZSMEW900A respectively. The northerly profile indicates possibly two cores of highly fractured rock with apparent thicknesses of 3 m to 10 m, although the detailed lineament map allows for alternative interpretations. The southerly profile indicates possibly three core sections of highly fractured rock with apparent thicknesses of 10 m, 7 m and 7 m. The geophysical profiling carried out across the lineament, approximately 220 m to the north of ZSMEW900A indicates a complex zone. The resistivity and chargeability profiling indicates a total apparent thickness, including transition zones, of around 50 m.

The zone has been modelled as vertical with a ±10° uncertainty attributed to the dip.

The water yields during the drilling of HLX34 and HLX35 were both high, being more than 185 litres per minute. Hydraulic responses during drilling of HLX34 could only be established in borehole HLX35. During the drilling of HLX35 responses were only observed in boreholes HLX13 and HLX14. None of the other monitored boreholes showed any response. The hydraulic responses in surrounding boreholes show that the structure is at least partly connected to the south and with other fracture zones to the east.

3.2 Rock mechanics

The rock mechanics description may be divided into four subjects: intact rock, single fractures, rock mass and in situ state of stress, respectively. This section summarises the findings related to these headings as obtained during the rock mechanics part of the consolidation modelling performed during Laxemar model step 2.1. The focus is here on the additional understanding gained during this phase, and the reader is referred to the previous analysis of SDM Laxemar version 1.2 /SKB 2006a/ for a complete description and background information on the rock mechanics modelling.

3.2.1 Intact rock mechanics properties

Uniaxial Compressive Strength – UCS

The compilation and analysis of all data available gave mean and standard deviation values that were not very different from the results presented in Laxemar model version 1.2. However, during this phase the picture of a large spatial variation in properties within the same rock type has been strengthened.

Figure 3-10 shows the uniaxial compressive strength, UCS, relative to sampling location for Ävrö granite in the three boreholes in the Laxemar subarea where tested samples were available, KLX02, KLX03 and KLX04 (see Figure 2-12). From these diagrams, it is clear that the spread in UCS from samples taken close to each other is much lower than the total spread in UCS value. The explanation to the variation is expected to be due to the mineralogical variation, which has been already described in Section 2.4.1.

Since the actual mineral compositions of samples are unknown the correlation between density and UCS was studied. Higher density is expected to be caused by low quartz content, which is in turn expected to be associated with reduced mechanical strength. The low quartz content of the samples might therefore explain the correlation between low density and higher strength shown in Figure 3-11. In particular, the samples from Äspö plotted in the same diagram show a lower density and higher strength than most samples from Laxemar. A study of the actual mineral composition of the tested rock samples is under way to further strengthen this observation.

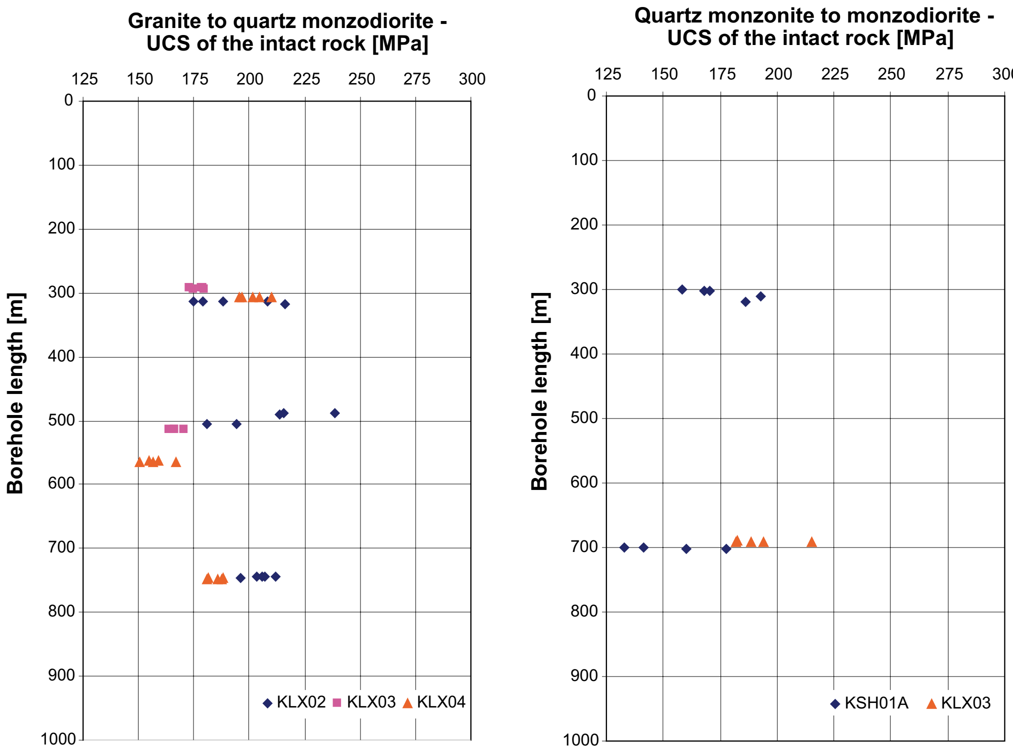


Figure 3-10. *Uniaxial compressive strength of samples from the Laxemar subarea – Ävrö granite (left) and quartz monzodiorite (right). The location of the boreholes may be seen in Figure 2-12.*

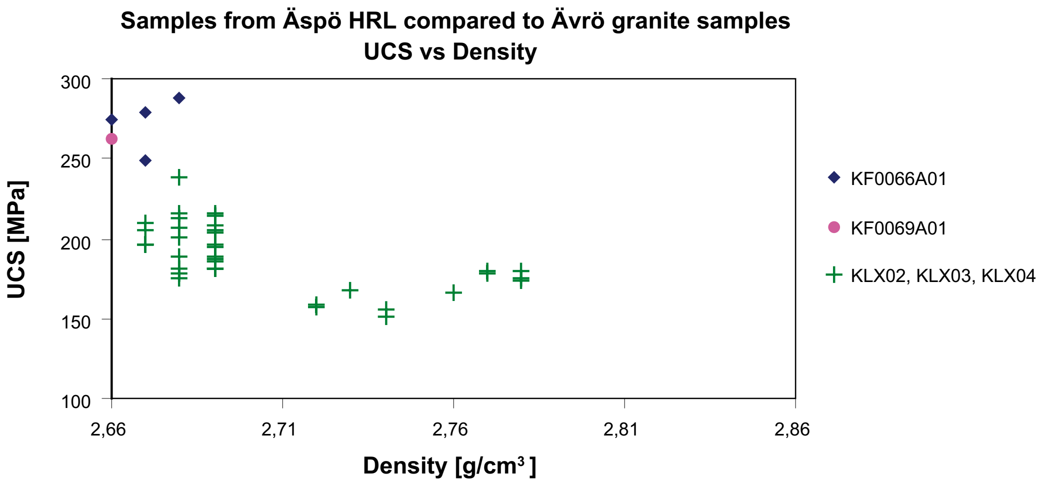


Figure 3-11. *Uniaxial compressive strength vs. density of the intact rock samples of Ävrö granite in Laxemar subarea (same as in Figure 3-10) together with samples from two boreholes (KF1006A01 and KFI0069A01) at the Äspö HRL.*

The rock mechanics results on intact rock in stage 2.1 thus further support the already planned subdivision in coming modelling of the rock domain “Ävrö granite” in the lithological model into sub-domains based on the quartz content (see also Section 3.1.1).

Crack initiation stress

The new data support previous model, i.e. the crack initiation stress is about 50% of the uniaxial compressive strength, UCS.

Indirect tensile strength

The new results from indirect tensile tests agree well with the model in version 1.2.

The compilation of borehole mapping data showed that a fairly large portion of the rock is expected to be altered to some degree (Figure 3-12) /Hakami and Johansson 2006/. A finding within this phase, although based on few data, is that the quartz monzonite to monzodiorite samples that were mapped as slightly altered show lower tensile strength (about 25%) compared to the fresh samples, cf. Figure 3-13.

A similar trend was not seen for the samples from Ävrö granite. However, an actual influence in the case of the latter rock type may possibly be concealed by the overall large variation in strength and mineralogy.

Therefore the plan for the next modelling phase is to look further into the potential need for having a specific description of the slightly altered rock. (A similar comparison was not possible for the UCS due to lack of altered samples in uniaxial compressive tests.)

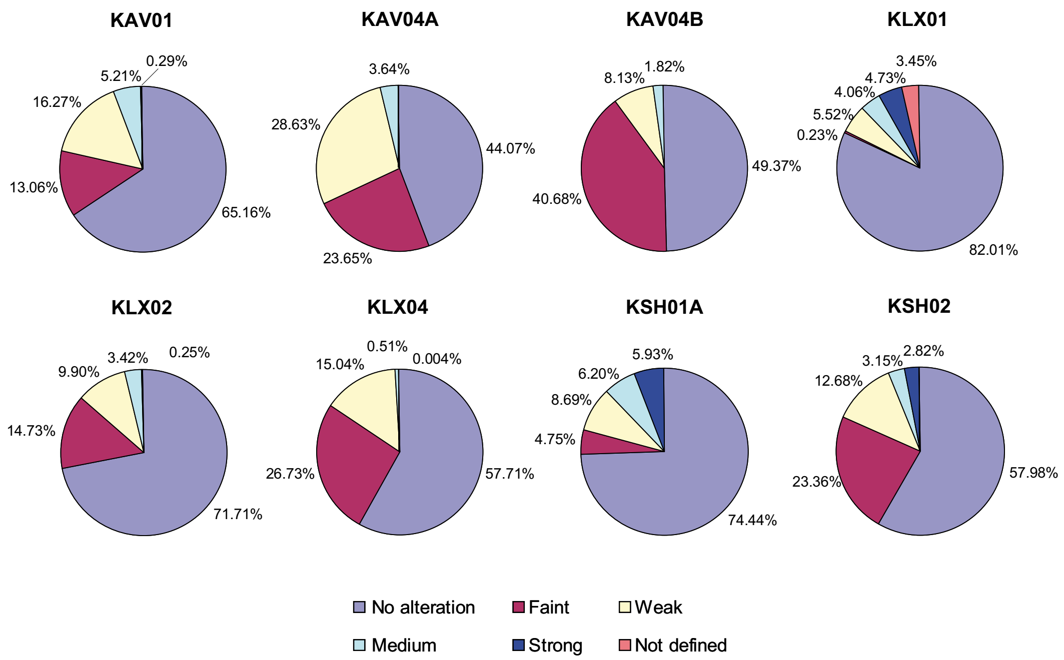


Figure 3-12. *The percentage of different degrees of alteration of the rock as they occur in the boreholes (also including deformation zones).*

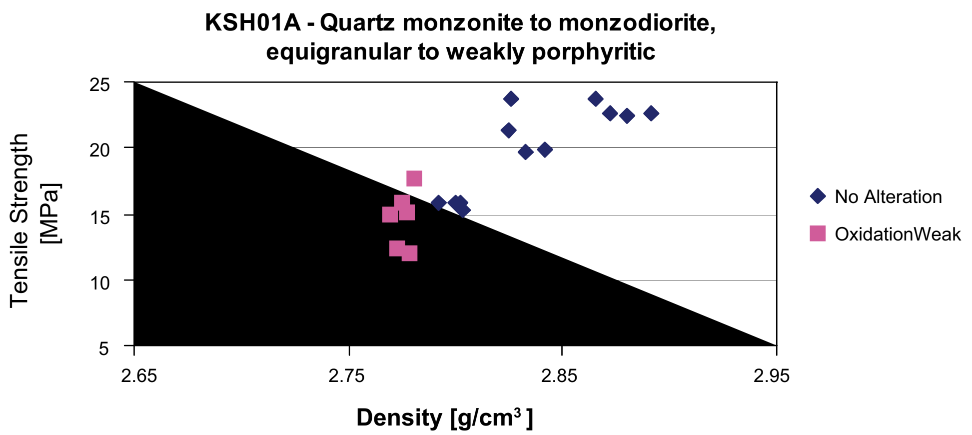


Figure 3-13. *Results from indirect tensile strength tests on samples of quartz monzodiorite. The different symbols refer to the difference in mapped degree of alteration. NB. This borehole is located in the Simpevarp area.*

3.2.2 Single fracture mechanics properties

Data on samples from two more boreholes KLX03 and KLX06 were available in version 2.1 of the modelling. These boreholes are located in the southwest and north part of the Laxemar area, respectively (see Figure 2-12).

Influence of orientation – fracture sets

In this model version no new check for possible correlation to fracture orientation was performed. However, the previous results have showed that no major difference can be seen depending on the fracture orientation. Possibly some difference exists between the subvertical fractures, lumped together, and the subhorizontal fractures.

Fracture tilt tests – Joint Roughness Coefficient

The new tilt tests (N=18) show similar values compared to previous results (N=172). The mean JRC_0 for all samples is 6.1 and mean JCS_0 is 68.4.

Fracture normal and shear stiffness

Test results from two additional boreholes (KLX03 and KLX06) gave results from a total of 14 new samples tested in direct shear tests. The results from all boreholes in Laxemar subarea are summarized in Table 3-2. It can be noted that the normal stiffness and the shear stiffness have increased significantly according to the new results. The explanation to this is that the test set-up has been modified (see next section). Considering that the new data are considered the most confident, the normal stiffness of the tested samples is much higher compared to what has been estimated in previous models, in the order of 900 MPa/mm compared to 220 MPa/mm in Laxemar 1.2. The shear stiffness, however, is now lower, about 40 MPa/mm. Thus the ratio between normal and shear stiffness is quite high according to these new results.

The comparison between laboratory results and the Boremap characterisation of the tested samples indicated that there is probably a correlation between surface character and the normal stiffness such that the fractures having “smooth” surfaces have about half the normal stiffness compared to the “rough” fractures. The vast majority of fractures, both in the boreholes and the laboratory tested samples, are mapped “rough” and “planar”. In the coming modelling work the need for specific description of the single fractures of different Boremap parameters will be considered based on the amount of occurrence of the different types.

Fracture cohesion and friction angle

In Table 3-2 the values for cohesion and friction angles are also given. The new values from Boreholes KLX03 and KLX06 are similar in value compared to the data available for model version Laxemar 1.2. It may also be noted that the absolute value of the cohesion is low, such that the relative differences may look large, whereas the importance of this difference is minor

Table 3-2. Mean fracture parameters from direct shear tests based on drill core samples from the Laxemar subarea. Note the order of boreholes in the table, KLX03 was drilled and tested after KLX04. Note also that the test procedure was modified between KLX04 and KLX03 (see text).

Borehole	Number of samples	Mean Normal Stiffness MPa/mm	Mean Shear stiffness MPa/mm	Peak cohesion MPa	Peak friction angle	Dilation at 0.5 / 20 MPa
KLX02	9	221.6	43	0.67	37.6	12.3/4.2
KLX04	10	251.4	40	0.95	35.7	19.2/3.75
KLX03	8	878.8	21	0.62	36.1	12.3/2.35
KLX06	6	902	24	0.75	36.6	16.7/3.29

at non-low stress levels. More important for actual shear strength, using a Mohr-Coulomb model, is the internal friction value. The results show fairly consistently values in the span 31–41°. The mean peak friction angle for all 33 Laxemar samples is 36.5°.

When comparing samples having different Boremap characteristics (roughness, alteration etc) we were not able to detect any correlation with variation in friction angle or cohesion. However, it should be noted that the number of fracture samples were not large enough to enable a proper statistic comparison.

Fracture shear dilation

In SDM version Laxemar 1.2 the model proposed for the dilation of single fractures was a linear function of the normal stress, σ_n , on the fracture, when stresses were below 10 MPa. The model function was $i_{mean} = 16 – 1.2\ \sigma_{n.}$ For stresses above 10 MPa the mean dilation was estimated to four degrees and the uncertainty to 25% of the mean value. This model seems to fit quite well also with the recent laboratory results (see Table 3-2).

Influence from laboratory test set-up

Again turning to Table 3-2 and the results for the stiffness parameters, it is clear that a conclusion possible to draw from the laboratory testing of single fractures is that the experimental set-up is a delicate issue. Already during previous stages of the project the set-up has been modified resulting in changes in the values obtained. The spread in values, while keeping the set-up fixed, is not too large. Also, similar values are obtained irrespective of site (i.e. irrespective of rock type). The latest results from Forsmark show the same levels of stiffness parameters as experienced in Laxemar.

The modification made in the set-up before testing on materials from KLX03 and KLX06 is that there is now a separate normal loading performed to determine the normal stiffness, using a different loading set-up before the shear test. Also, the normal deformation is now measured directly on the rock samples with COD gauges at the fracture. These changes may both have contributed to the higher values obtained. Otherwise, the sample preparation, moulding geometry and material were exactly the same as those employed for KLX02 and KLX04.

There are also several other components of the experimental set-up, whose influence on the results have not been studied within the site investigation program. This is for example the size of the tested fracture sample surfaces, the impact of repeated shearing using the same sample (with increasing normal load) and the influence of having non-saturated dry fracture surfaces during shearing. (The latter aspect may become subject for investigation in the coming model version.)

Therefore, in absence of a (widely used) detailed international standard for shear tests, a large part of the differences in single fracture parameters, seen in our results and also in the literature, should be attributed to the variation in laboratory set-up. These circumstances also give rise to an uncertainty in the relevance of laboratory tests compared to the real in situ fracture situation, and this should be considered in the application of parameters in analyses. However, single fracture mechanical parameters are not expected to be critical for repository engineering or in safety assessment.

3.2.3 Rock mass mechanics properties

Empirical approach – the KBH02 study

To evaluate further the previously adopted empirical approach to estimate rock mass properties, a comparison was made between the rock mass characterisation along the borehole KBH02 and the tunnel mapping from the nearby access tunnel to the Äspö HRL /Lanaro and Bäckström 2006/. The outcome from the EXPECT project /SKB 2006e/ was used for the comparison (Figure 3-14).

Exactly the same procedure for determining Q and RMR in the site investigation was applied on the KBH02 borehole data (or more precisely the same procedure as for the older borehole KLX01). The length of each characterised borehole section is 5 m. The criterion used for identifying a deformation zones was in this case set to Q < 4 and/or RMR < 60 and the results are given in Figure 3-15. The length of each characterised borehole section is 5 m. As can be seen in the figure thirteen deformation zones of differerent thickness were identified using this criterion and Q and RMR give similar results.

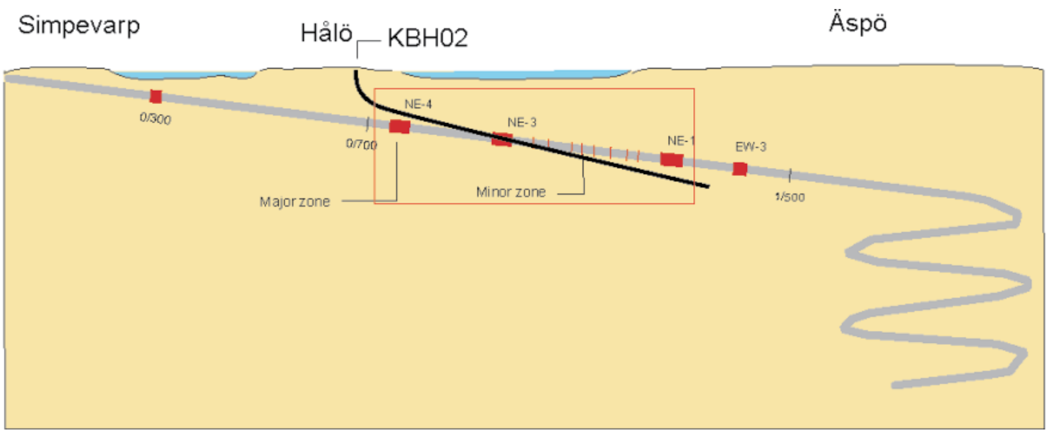


***Figure 3-14.** The borehole KBH02 is drilled prior to the excavation of the access tunnel and is sub-parallel from about 100 m borehole depth /SKB 2006e/.*

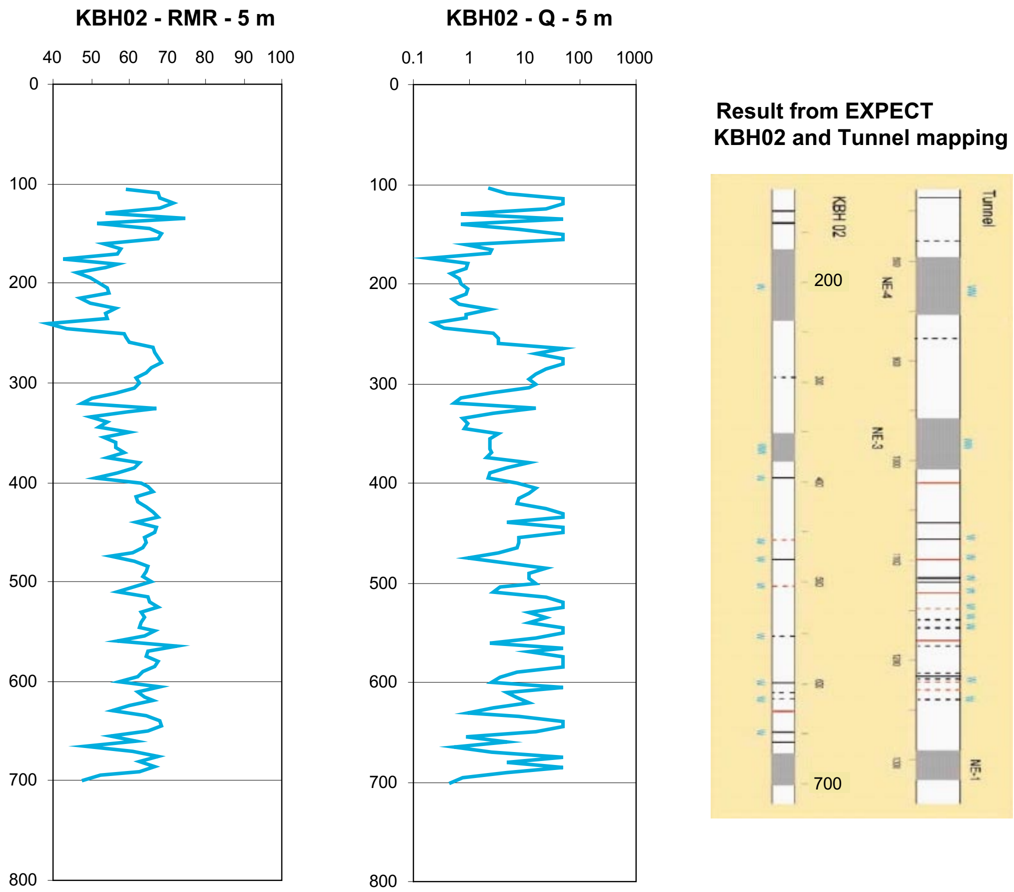


***Figure 3-15.** Tunnel mapping results reported by the EXPECT-project (right) compared to Q and RMR characterisation along borehole KBH02 using 5 m section (middle and left). The grey marked intervals show where Q < 4 and/or RMR < 60. (The EXPECT results are positioned in the figure with the length coordinates such that a direct comparison is possible.)*

The conclusion from the 5 m characterisation is that the Q and RMR indices, which are determined purely based on geological mapping data (Boremap), give a fairly good match with the tunnel mapping concerning number and location of the major zones. Furthermore, this type of characterisation with 5 m sections, previously used also in Laxemar 1.2, returns 5 of the 10 minor deformation zones and 3 of the 8 long fractures. The reason why the long fractures are not detected is probably because they are thin and do not directly affect the rock mass quality expressed by Q and RMR in the analysed 5 m scale. Also, it can be seen from Figure 3-13 that the total volume of deformation zones would be overestimated if the criterion of Q < 4 and/or RMR < 60 was used to determine the thickness of zones. However, when the threshold is lowered to Q < 1 and/or RMR < 40 the zone thickness fits much better to the tunnel mapping. (This case is not shown here.)

A characterisation was also carried out on 1 m sections, again using two different thresholds. All sections outside the major deformation zones were in this way localized. The case with of Q < 4 and/or RMR < 60 is shown in Figure 3-14, and a comparison with the tunnel mapping for this case gives a fairly good correspondence.

Out of the 18 features (10 minor deformation zones and 8 long water bearing fractures), identified by the EXPECT project, 15 features could be detected by the borehole characterisation in approximately the same position. (Note that Q and RMR characterisation do not make use of any flow information as input.)

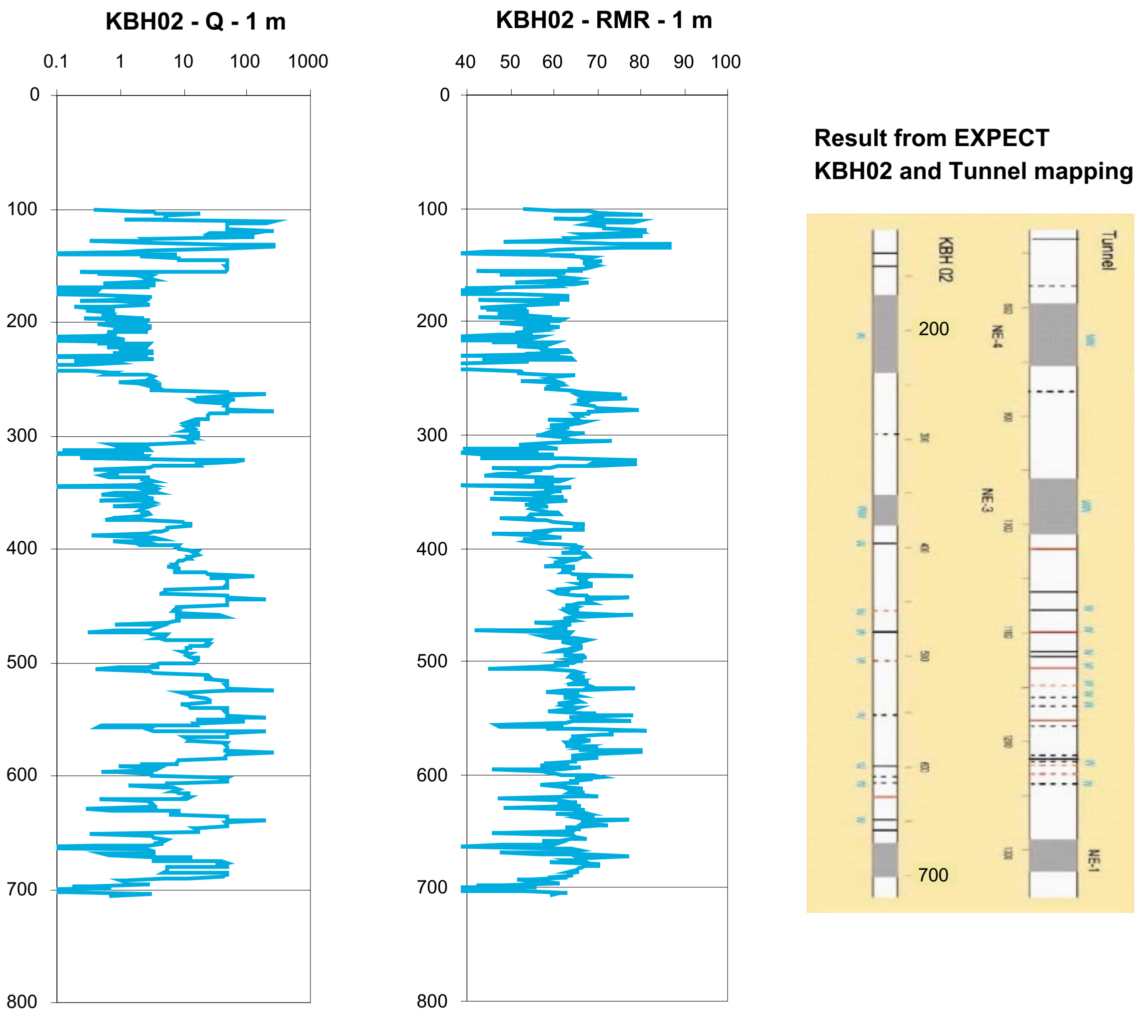


***Figure 3-16**. Tunnel mapping results reported by the EXPECT-project (right) compared to Q and RMR characterisation along Borehole KBH02 using 5 m section (middle and left). The grey marked intervals show where Q < 4 and/or RMR < 60. (The EXPECT results are positioned in the figure with the length coordinates such that a direct comparison is possible.)*

Thus, the KBH02 study indicates that the modified thresholds of Q < 1 and/or RMR < 40 applied to 5 m sections might be the most adequate for the identification of major deformation zones, and the criterion of Q < 4 and/or RMR < 60 applied to 1 m sections the most suitable for identifying the minor zones and long, potentially water bearing, fractures.

Out of the 18 features (10 minor zones and 8 long water bearing fractures) identified by the Expect-project, 15 features could be detected by the borehole characterisation in approximately the same position. (Note that Q and RMR characterization do not make use any flow information as input.)

Thus, the KBH02 study indicates that the modified thresholds of Q < 1 and/or RMR < 40 applied to 5 m sections might be the most suitable for the identification of major deformation zones, and the thresholds of Q < 4 and/or RMR < 60 applied to 1 m sections the most suitable for identifying the minor zones and long water bearing fractures.

3.2.4 State of stress

New overcoring measurements were made in one borehole, KLX12A (see Figure 2-12). It is noted that borehole KLX12A is not formally part of the Laxemar 2.1 data freeze, but stress data there from are deemed important for the feedback to the finalisation of the CSI programme at Laxemar and have consequently been included in the discussion in this section. The preliminary reported results from these measurements show stress levels that are medium high, compared to what has previously been observed within the local model area (Figure 3-17).

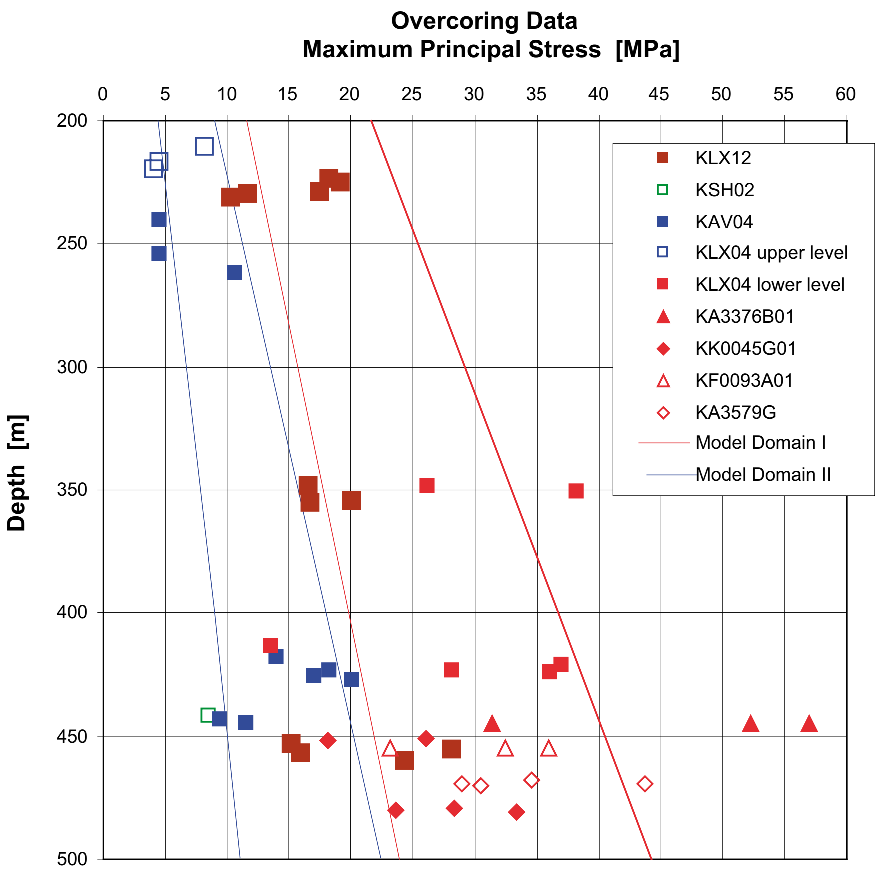


Figure 3-17. Overcoring measurement results for the maximum principal stress magnitude. The square symbols refer to measurements performed within the site investigations other boreholes are from Äspö HRL. The preliminary results from Overcoring measurements in KLX12 are added. The red and blue lines indicate the stress model for SDM Laxemar 1.2, which included two domains. (Note that for visibility the y-axis shows the depth only between 200 m and 500 m.)

Compared to model version 1.2 for stress domain I (where KLX12A is located) the new measured stresses in KLX12A are at the lower boundary. It may be noted that the variation in magnitude between the four close measurement points at about 470 m depth is large, varying from about 15 to 25 MPa twice within a 7 m distance. Currently there is no explanation for this variation in stress (also consider that these are preliminary reported results). Similarly, the orientation of the principal stress varies fairly much between the close measurements, and the maximum principal stress is in three cases dipping 13–16 degrees towards southeast.

In the numerical model (3DEC) of version 1.2 the stresses were comparatively high at the location of KLX12A. This was due to a slip mode on deformation zone NW042A terminating at the Äspö shear zone in the east. The character and extent of NW042 is however uncertain (see Section 3.1.3) This zone is now in version 2.1 model described as less continuous and with smaller thickness. No updated numerical modelling was performed within modelling step 2.1, but the decreased importance of zone NW042A in the new DZM would give an effect in accordance with the observed lower stresses at KLX12. If the eastern extent of the deformation zone is much longer, or if the continuity of the zone is less, these changes are expected to produce an effect in an updated numerical model which complies with the observed stresses in borehole KLX12A.

The inclined maximum stress indicates that there might be an influence from a wedge release southeast of Laxemar, i.e. an extension of the eastern wedge as proposed as an alternative in the stress model of Laxemar 1.2. The deformation zone model is uncertain in this part of the model area.

The uncertainty in the stress model within the local model volume is now considered highest in the westernmost part, where no measurement data are available. Very high stresses are, however, not anticipated since no extensive core disking has been observed.

Measurements using hydraulic fracturing will be performed in KLX12 in summer 2006. These results will be important because it is the first time within the site investigation in Oskarsham that two different stress measurement methods are applied in the same borehole. The very few results from Simpevarp subarea (KSH01 (hydrofracturing) and KSH02 (overcoring)) indicate that the results may not give similar results. According the strategy the hydraulic fracturing is given more confidence when it comes to estimation of the minor horizontal stress, while the overcoring is needed to estimate the anisotropy in the stress, i.e. the ratio between the minimum and maximum stress. An updated stress model based on new data and updated deformation zone model, also including numerical modelling, will be made in modelling step Laxemar 2.2.

3.3 Thermal modelling of lithological domains

3.3.1 Modelling procedure

The rock domain model from the Laxemar site descriptive model version 1.2 forms the geometrical base for the current thermal model and is described in /SKB 2006a/. The Laxemar subarea is characterised by five lithological domains, three of which dominate the modelled rock volume, namely RSMA01, RSMD01 and RSMM01, cf. Figure 3-1.

Compared with model version Laxemar 1.2, two additional boreholes, KLX05 and KLX06, are available in Laxemar 2.1 for thermal modelling of domains. For the purposes of thermal modelling, the characterisation of rock domains by borehole intervals, as described in the rock domain model, has been modified so as to better represent the variability in thermal properties within domains A01 and D01 (for details see /Wrafter et al. 2006/).

Statistical rock type models (Probability Density Functions, PDFs) of thermal conductivity used to model thermal properties for lithological domains are based on TPS and SCA data. For details of the data on which these models are based see /Wrafter et al. 2006/. The methodology for thermal conductivity domain modelling is described in /Sundberg et al. 2005b/. For model version 2.1, only the so-called base approach has been employed.

3.3.2 Modelling results

For a fuller discussion of these results, the reader is referred to the thermal modelling report for Laxemar version 1.2, /Wrafter et al. 2006/.

Borehole modelling

Modelled thermal conductivity for boreholes KLX01–KLX06 are summarised in Table 3-3 for the 0.8 scale. Results for the depth interval 400 m–600 m, which is the envisaged repository depth, are given for comparison. With the exception of borehole KLX01, the modelled thermal conductivities at depths of 400 m–600 m are 0.05 to 0.15 W/(m·K) lower than the corresponding values for the entire borehole.

Domain modelling – base approach

Modelling results for domains RSMA01, RSMD01 and RSMM01 according to the base approach /Sundberg et al. 2006/ are presented as histograms in Figure 3-18. Histograms of modelling results for the domains RSMBA and RSME are presented in /Wrafter et al. 2006/.

For domain A, the bimodal distribution and large variance of thermal conductivity reflects the characteristic bimodal frequency distribution of the dominant rock type, i.e. Ävrö granite. There is a large difference in thermal conductivity between boreholes making up domain A. KLX01 and KLX03 have significantly lower mean thermal conductivity values than the other boreholes, see Figure 3-19. A tendency towards lower thermal conductivities at depths of 450 m to 650 m is apparent in all boreholes making up domain RSMA01, see Figure 3-19.

The modelled data distribution for domain D, dominated by quartz monzodiorite, is characterised by a relatively low standard deviation and a long tail towards higher values.

Table 3-4, presents the mean thermal conductivity together with standard deviations and upper and lower tails (defined as 0.5, 2.5 and 97.5 percentiles) for the modelled domains. Percentiles are estimated directly from the modelled data sets generated by the base approach. It should be noted that this approach inadequately describes the distribution of thermal conductivity values for a given scale, which means that standard deviations and percentiles require adjustment.

3.3.3 Evaluation of domain modelling results

The base approach is believed to underestimate the spatial variability for domains A and BA, but particularly for D, since the within-rock variability is not fully accounted for. For domains in which Ävrö granite is important (domains A and BA), the use of density loggings to model Ävrö granite mean that much of the within-rock type spatial variability is accounted for. As regards domains E and M, the base approach overestimates the variability, since no scaling up has been performed.

Table 3-3. Summary of thermal conductivity (W/(m·K)) modelling results at 0.8 m scale for boreholes KLX01, KLX02, KLX03, KLX04, KLX05 and KLX06.

Borehole	Scale, m	Borehole length	Entire borehole		Depth interval 400 m–600 m below sea level	
			Mean	St dev	Mean	St dev
KLX01	0.8	0-701 m	2.60	0.28	2.61	0.31
KLX02	0.8	202-1,005 m	2.84	0.28	2.79	0.29
KLX03	0.8	100-1,000 m	2.53	0.24	2.38	0.17
KLX04	0.8	100-990 m	2.90	0.31	2.78	0.27
KLX05	0.8	108–994 m	2.84	0.31	2.77	0.22
KLX06	0.8	102-965 m	2.82	0.36	2.67	0.30

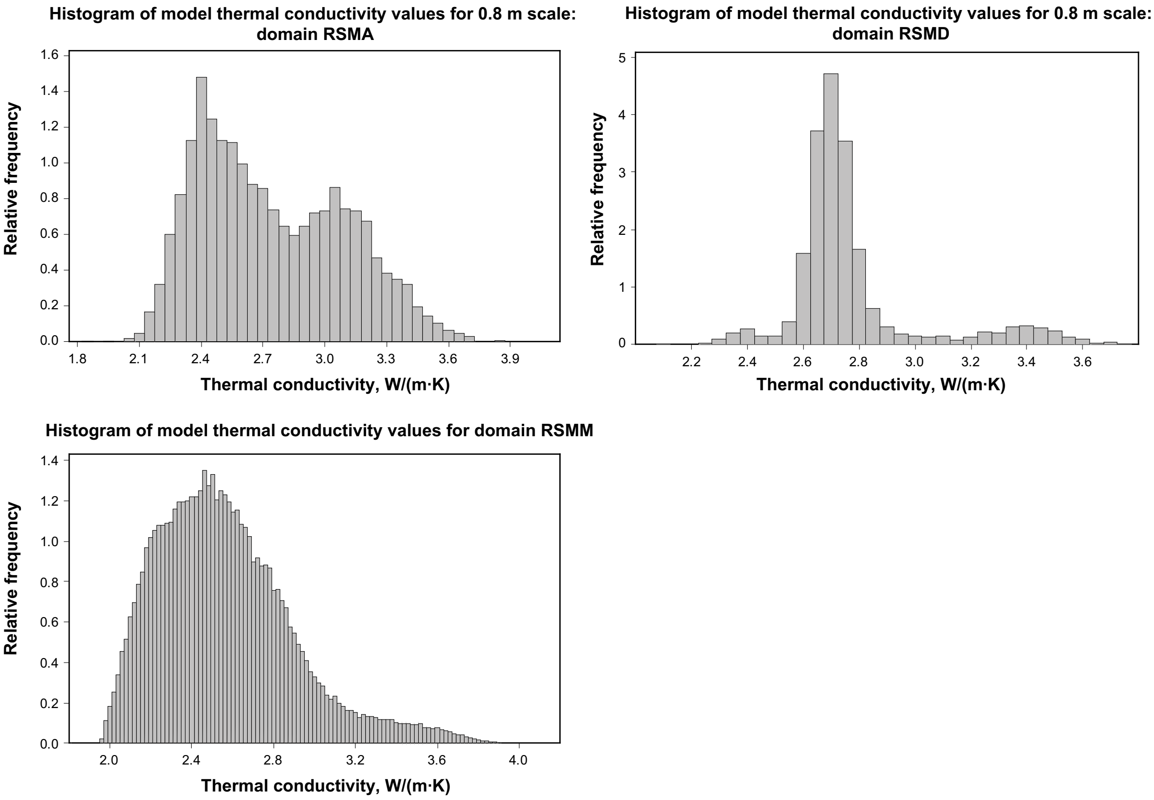


Figure 3-18. *Histogram of modelled thermal conductivities values for domain RSMA01, RSMD01 (both at the 0.8 m scale) and RSMM01 (scale < 0.1 m) according to the base approach.*

Table 3-4. Thermal conductivity (W/(m·K)) domains modelling results according to base approach. Upper and lower tails (percentiles) are calculated from the modelled data distributions. Note that the results at the 0.8 m scale apply to domains RSMA, RSMBA and RSMD only.

Scale (m)	Mean	Std dev	2.5 percentile	97.5 percentile
RSMA (0.8 m)	2.75	0.35	2.22	3.44
RSMBA (0.8 m)	2.79	0.26	2.32	3.31
RSMD (0.8 m)	2.77	0.24	2.41	3.48
RSME (< 0.1 m)	2.68	0.47	2.07	3.71
RSMM (< 0.1 m)	2.56	0.33	2.06	3.41

In the thermal modelling work in version Laxemar 1.2, four complementary approaches were used to evaluate the spatial variability at domain level /Sundberg et al. 2006/. In this model version, however, a judgement of the spatial variability is made based on results from version 1.2 /Sundberg et al. 2006/. Revised standard deviations for domains A, BA and D are summarised in Table 3-5.

A comparison of the thermal conductivity results for domain level presented in the site descriptive model Laxemar version 1.2 /SKB 2006a/, and the current Laxemar 2.1 thermal model is provided in Table 3-5. For domain A, the mean thermal conductivity is somewhat lower and the standard deviation significantly higher in the current model version compared to the previous version. The lower tail percentiles are also lower, even without making the correction discussed in the previous section. For domain D, both the mean and standard deviation are somewhat higher in Laxemar 2.1, an effect of the higher proportion of rock type fine-grained granite, which imparts a pronounced upper tail to the distribution, see Figure 3-18. Although the mean thermal conductivity for domain M shows little change from model version 1.2, variability,

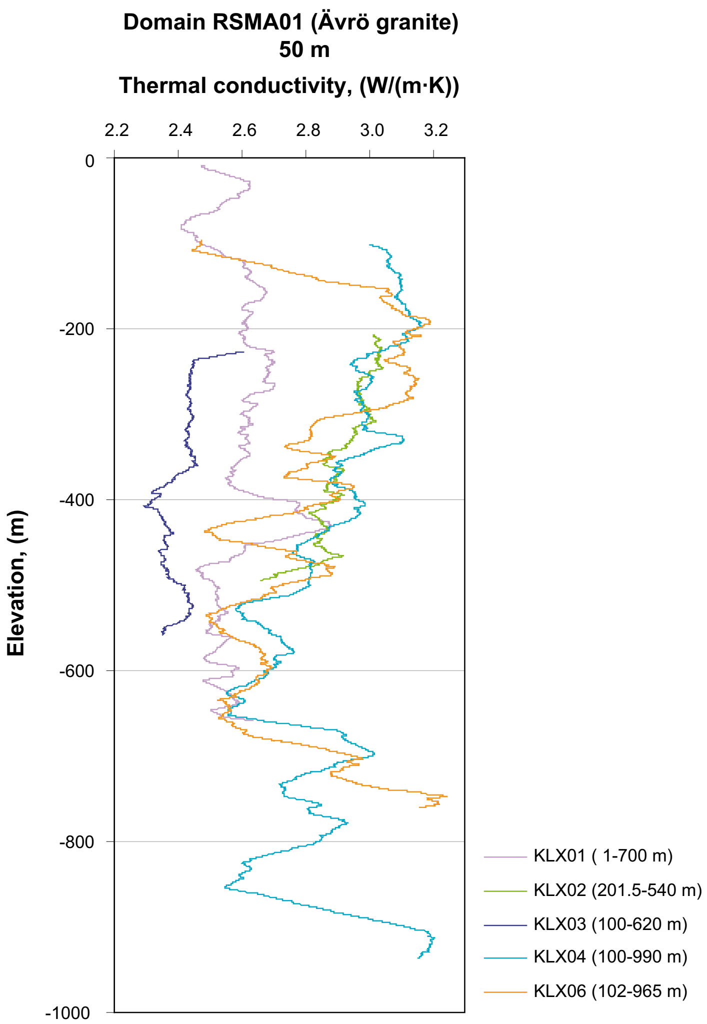


Figure 3-19. *Visualisation of large-scale changes in thermal conductivity with depth for boreholes sections belonging to domain A. Thermal conductivity is expressed as moving geometrical mean calculations over 50 m long borehole sections. The results are based on only one realisation. The diagram illustrates large-scale trends in thermal conductivity only. Spatial variability is considerably reduced because of the upscaling involved.*

as expressed by standard deviation, is significantly higher. Uncertainty remains high for this domain due to the lack of representative borehole data and a poorly constrained statistical model for diorite-gabbro.

Table 3-5. Comparison of modelling results (the mean and the standard deviation) from Laxemar 1.2 and Laxemar 2.1 model versions. Standard deviations have been revised on the basis of results from the complementary approaches in model version 1.2 /Sundberg et al. 2006/.

	Mean (W/(m·K))		St dev (W/(m·K))	
Domain	Version L1.2	Version L2.1	Version L1.2	Version L2.1
RSMA	2.82	2.75	0.29	0.36
RSMBA	2.87	2.79	0.29	0.30
RSMD	2.70	2.77	0.17	0.28
RSME	2.45	2.68	0.29	0.47
RSMM	2.58	2.56	0.22	0.33

Observe that the above table is valid at 20°C. The thermal conductivity decreases slightly at higher temperatures, 1–5% per 100°C temperature increase.

3.3.4 Discussion

Summary of current knowledge – impact of recent data on the understanding of thermal properties in the Laxemar subarea

Results of modelling for five rock domains in the Laxemar subarea indicate that the mean thermal conductivity varies between the different domains, from 2.56 W/(m·K) to 2.79 W/(m·K). The spatial variation is considered to be large, especially for domain RSMA. Upper limits for the lower 2.5 percentiles are 2.2 W/(m·K) for domain A and 2.4 W/(m·K) for domain D. Compared to model version Laxemar 1.2, the modelling results for all domains show larger variation in thermal conductivity at the 0.8 m scale.

Only two of six boreholes in Laxemar have yielded reliable in situ temperature data. The mean of temperature loggings at 500 m depth for KLX02 and KLX05 is 14.6°C.

The revised model for the relationship between density and thermal conductivity for Ävrö granite, based on more plentiful data from the Laxemar subarea, better describes the rock volume in Laxemar, and has led to a reduction in bias associated with estimation of thermal conductivity from density logging. Comparison of measured values and modelled values show a better correspondence than in previous model versions /Sundberg et al. 2006/, especially for low thermal conductivity Ävrö granite.

The lowest measured thermal conductivity is 2.01 W/(m·K), for a sample of Ävrö granite from KLX03 in south Laxemar. This compares with the previous minimum of 2.16 W/(m·K) for a sample of Ävrö granite from Äspö. In the light of this new data, the lower 0.5 percentile value of c. 2.1 W/(m·K), derived by modelling of domain A at scale 0.8 m, would appear reasonable.

The presence of considerable compositional variation within the Ävrö granite, from granite (*sensu stricto*) to quartz diorite, is well established /SKB 2006a/. Not surprisingly, this is reflected in the wide spread of thermal conductivity values (2.0 to 3.8 W/(m·K)) for this rock type, both measured on core samples and modelled from modal analyses and density loggings. A clear relationship between igneous rock type, as defined by Streckeisen, and thermal conductivity has been established, Figure 2-10. Ävrö granite in boreholes in south Laxemar, KLX03 and KLX05, display low thermal conductivities, as do surface samples from the same area. A similar pattern is obvious in the north-eastern part of the Laxemar subarea. Boreholes in the central part of the subarea (KLX02 and KLX04) show generally high thermal conductivities for Ävrö granite, although the situation is more complex at depths greater than c. 500 m, where thermal conductivities tend to be lower and more variable.

Variation in both mineralogy and thermal properties within Ävrö granite in a north to south direction have been noted previously /SKB 2006ac, Sundberg et al. 2006/. Interpretation of plots of thermal conductivity versus depth for boreholes intervals within domain A indicates that thermal conductivity may be considerably lower at depths of 450 m to 600 m (Figure 3-19). However, analysis of additional boreholes is required to test whether this trend is a random effect of the positions of the available boreholes. Data from both recently drilled and planned boreholes should resolve this issue. The observed large-scale variations in thermal properties of Ävrö granite may have implications for the geological modelling of this rock type.

Diorite-gabbro is an important rock type from a thermal properties perspective since it occurs at repository depths in several boreholes, and displays a wide spread in thermal conductivity values. Density loggings indicate the possible existence of two or more distinct compositional types of diorite-gabbro, while an apparent correlation between density and thermal conductivity (Figure 2-8) opens the possibility of modelling spatial variability in thermal conductivity with the aid of density loggings, in the same way as has been done for Ävrö granite.

Uncertainties and remaining issues – implications for future work

For a discussion of the uncertainties associated with thermal modelling in general, and model version in Laxemar 1.2 in particular, the reader is referred to /Sundberg et al. 2006/. The current model version has produced some reductions in uncertainties. More specifically, the statistical relationship between density and thermal conductivity for Ävrö granite has been improved, measurement data on rock types are considered to be more representative, statistical rock type models are in some cases more certain, and the rock volume is represented by more boreholes. In addition, errors associated with temperature logging have been defined, and poor quality logging data has been excluded from calculations of mean temperatures for various depths.

Thermal conductivity of Ävrö granite is modelled from borehole density loggings using a model based on the relationship between density and thermal conductivity. More measurements are planned with the purpose of both refining this relationship, particularly at the lower range of thermal conductivity, and of verifying the method.

The high noise in the density logging data, on which modelling of spatial variability within Ävrö granite relies, is an important source of uncertainty. Improvements in this respect have been achieved with boreholes logged since July 2005 (KLX07 and subsequent boreholes), which will reduce uncertainty in future borehole modelling.

Robust rock type models are highly dependent on representative data sets for each rock type. The representativity of data sets (both TPS and SCA) for some rock types has improved greatly compared to the previous model version, e.g. quartz monzodiorite, which has resulted in more certain models. Gaps remain, however. Laboratory measurements for some rock types, in particular for diorite-gabbro (see below) and fine-grained diorite-gabbro, are required.

The reason for bias in SCA results for several rock types remains to be resolved. An interesting feature revealed by recent data is that for Ävrö granite, bias is apparent in high conductivity samples but not in low conductivity samples. This issue may be partly resolved by determining, for a number of samples, the anorthite content of plagioclase, a factor influencing thermal conductivity.

Uncertainties associated with the thermal modelling results of domain M continue to be particularly large. Firstly, there is an incomplete understanding of the proportions of different rock types that comprise this domain. Secondly, the large variation in thermal conductivity measurements (TPS) for diorite-gabbro (2.25 to 3.65 W/(m·K)) displayed by a relatively small number of samples means that statistical distribution models used for this rock in thermal modelling are still highly uncertain.

Additional direct measurements (TPS) of diorite-gabbro to strengthen the new relationship between density and thermal conductivity are ongoing or planned. Modal analysis data for diorite-gabbro is also required so as to describe the relationship between mineralogy and thermal conductivity more precisely, especially for samples that have values that do not conform to the simple relationship of increasing thermal conductivity with increasing density.

The method used in this and earlier model versions /Sundberg et al. 2005b, Sundberg et al. 2006/ to evaluate and describe spatial variability of thermal properties at relevant scales is associated with uncertainties. More refined modelling strategies are required. An ongoing project dealing with modelling strategies aims to resolve these issues.

For dominant rock types, for which density loggings cannot be used to evaluate spatial variability, sampling at different distances is required to produce variograms of spatial variability. This applies primarily to quartz monzodiorite.

In modelling, the upscaling procedure involves uncertainties. Field measurements of thermal conductivity are planned in order to reduce these uncertainties. Investigations to detect the possible presence of anisotropy in thermal properties will be carried out at the same time.

A significant volume of rock (up to 25%) within the Laxemar subarea consists of altered rocks, although the location of boreholes in relation to fracture and deformation zones may result in alteration being over-represented. Altered rocks are extremely under-represented in the available thermal properties data, a factor which may significantly bias the results of the thermal modelling. Based on our knowledge of the mineralogical changes associated with alteration, these altered rocks are expected to have higher thermal conductivity than unaltered equivalents. This has yet to be demonstrated, however. Direct measurement (TPS) of thermal conductivity on altered rock samples, for which modal analysis is also available, are required. The effects of alteration on thermal conductivity may also be evaluated directly from mineral composition, using the SCA method on the data reported by /Drake et al. 2006/.

Evaluation of temperature loggings in Laxemar has shown deficiencies in the data for several of the boreholes. Data from KLX02 and KLX05 are considered to be the most reliable. The technical problems which were causing the inaccurate data have been discovered and corrected, so future data can be used to produce a more precise description of the in situ temperature distribution in the rock volume.

Stress dependence on thermal conductivity and thermal expansion have not been investigated, although it is thought to be small. Measurement in the laboratory of at least one sample should be performed for verification purposes.

There is a potential bias in heat capacity data determined indirectly through conductivity and diffusivity measurements (TPS method). For this reason, direct measurements by the calorimetric method have been initiated.

3.4 Hydrogeology

The Simpevarp area is dominated by a crystalline bedrock covered by a fairly thin overburden mainly consisting of till /Wahlgren et al. 2005/. The crystalline bedrock is fractured and it is interpreted that there are a number of major deformation zones within the area. The existence of these deformations zones have to some extent been confirmed by surface geophysics and drilling. Hydraulic tests have confirmed, in some cases, that the deformation zones are more conductive than the surrounding rock, as further elaborated in Section 3.4.2.

Different geological and geophysical investigations have resulted in a description of the spatial distribution of rock types, and interpreted larger geological entities (rock domains) consisting of rock types with similar geological properties, see /Wahlgren et al. 2005/. The deformation zone model developed for SDM Laxemar 1.2 is presented in /SKB 2006a/, and is further detailed by /Wahlgren et al. 2005/. Observations of the general character of the hydraulic tests, as shown in /Rhén et al. 2006abc/ indicate that the defined geological rock domains also exhibit distinct and significant hydraulic characteristics. Preliminary results from boreholes drilled after data freeze for Laxemar 1.2 confirm the results, see Section 3.4.3.

The overburden constitute mainly of till, but glaciofluvial sediments, peat and clay are also found. The hydraulic conductivity of these components is generally higher than for the crystalline bedrock.

The topography in the area is rather flat but with numerous small hills, see Section. 3.4.4. The area is covered with several small streams and a number of peat lands, indicating relatively small drainage basins. The water table is general found near the surface, generally just a few meters below topographic heights.

3.4.1 Laxemar 2.1 modelling

No new Hydrogeological descriptive modelling or numerical groundwater flow modelling have been performed Laxemar model version 2.1. The scope for hydrogeology has been to compile new data in test scale 100 m and make assessments of some major uncertainties found in SDM Laxemar 1.2 /SKB 2006a/. The suggested depth trends of the hydraulic conductivity and the division of the rock mass into different hydraulic domains were considered uncertain.

3.4.2 Geometry

The basis for the interpretation of the HCD properties is the 3D deformation zone model in the RVS (Rock Visualisation System) and the intersections between boreholes and deformation zones in the RVS model. The judgement of the geologists as to where the deformation zones intersect the boreholes has guided the search for relevant hydraulic information. The hydrogeological properties extracted from transient pumping or injection tests have been used to estimate the HCD parameters. If a single hydraulic test section covers the entire part of a deformation zone defined in a borehole, the corresponding test results have been used, instead of summing up transmissivities for shorter test sections.

The hydraulic conductivity (K) of each HCD transmisivity value was calculated dividing the transmissivity value with the estimated geological thickness for each deformation zone, the latter given as a mean value for HCD /Rhén et al. 2006c/. The depth trend for the hydraulic conductivity of the rock mass, excluding test sections intersected by deformations zones (HCDs) and the depth trend in the HCDs are shown in /Rhén et al. 2006c/. The geometric mean values of K for HCDs and HRD (representing the rock mass in between the HCDs) are plotted in Figure 3-20. As can be seen, the mean K of the HCDs is about an order of magnitude more conductive than the mean value of the HRDs. As can be seen in the geometric mean transmissivity values differ on a confidence level of 0.95 down to elevation –600 m. Below –600 m the samples in HCD are few, so the confidence band is wide for hydraulic conductivity in HCD, thus indicating that the confidence level is less than 0.95 that the geometric means differ. In combination, the results seem rather conclusive that it is meaningful to identify and model large deformation zones as separate domains as they have significantly higher hydraulic conductivity than the surrounding rock mass. However, the results also points out that some HCDs, as now interpreted in Laxemar 1.2, may have low transmissivity (and hydraulic conductivity). In the context of groundwater flow modelling, including or excluding such low-transmissive deformation zones is a matter of its location and hydraulic characteristics. If it may act as a hydraulic barrier, it should be included in the modelling. If it has the character of "normally fractured rock" (as can be the case for mainly ductile deformation zones) it may be justified to exclude those zones. It should be observed that in model version Laxemar 1.2, none of the geologically defined deformation zones have been excluded on the basis of the above discussion.

3.4.3 Distribution of material properties

Interpreted depth trends in hydraulic properties

The depth trends of the properties in the HRDs and HCDs were considered uncertain in the Laxemar 1.2 model, and particularly properties for HCDs. New data in test scale 100 m were compiled and evaluated and are shown in Figure 3-21 and Figure 3-22, including both old and new data for the Laxemar subarea. Table 3-6 shows the statistics for elevation intervals: 0 to –300, –300 to –700 metres above sea level (m.a.s.l.) and deeper than –700 m.a.s.l. based on data considered to represent the rock between the major deformation zones. As can be seen in there is at least a significantly higher hydraulic conductivity above –300 m.a.s.l. of the bedrock compared to the bedrock below –300 m.a.s.l. A tendency may also be noted of lower hydraulic conductivity at repository depth amongst the boreholes of the Laxemar south grouping.

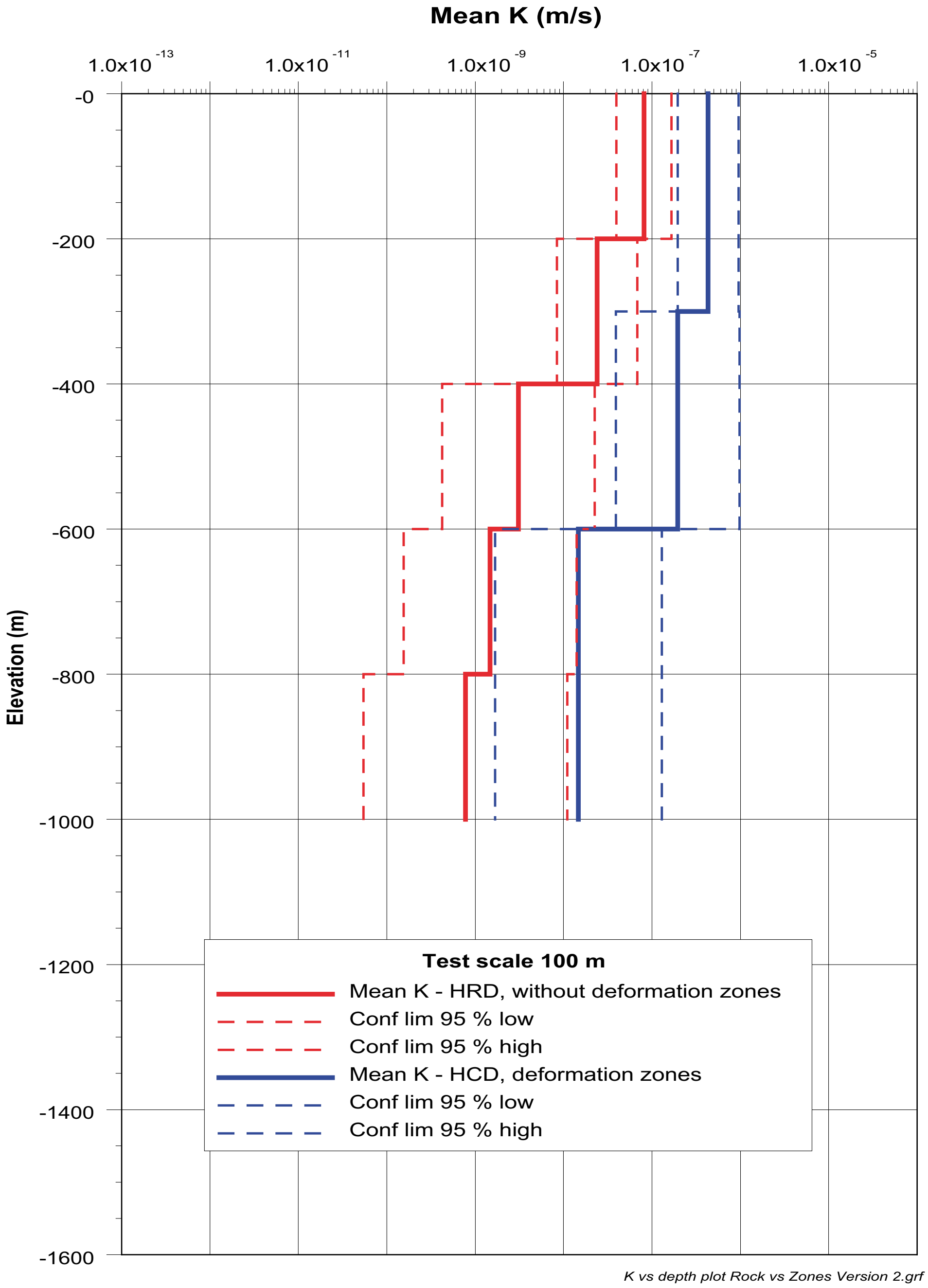


Figure 3-20. *Comparison between the depth trend of the hydraulic conductivity in HCDs (equated from on geometric mean transmissivity, geological thickness and the depth trend of the geometric hydraulic conductivity of HRDs (excluding data from HCDs)), as seen in /Rhén et al. 2006c/.*

Significance of RD for division in hydrogeological domains

In /SKB 2006a/ it is shown a correlation between hydraulic properties and rock domain, but also said that the correlation is uncertain due to the fact that for some rock domains the results are only based on one borehole. The new data in test scale 100 m shown in Figure 3-21 and Figure 3-22 were used to see if there is a relative difference between the rock domain as shown in Laxemar version 1.2 /SKB 2006a/.

Each test section with hydraulic data has been classified to the dominating rock domain within each test section to explore if there is a difference in hydraulic properties between the geologically defined rock domains. As can be seen in Table 3-7 there is a difference between RDs that probably is relevant to consider when defining HRDs.

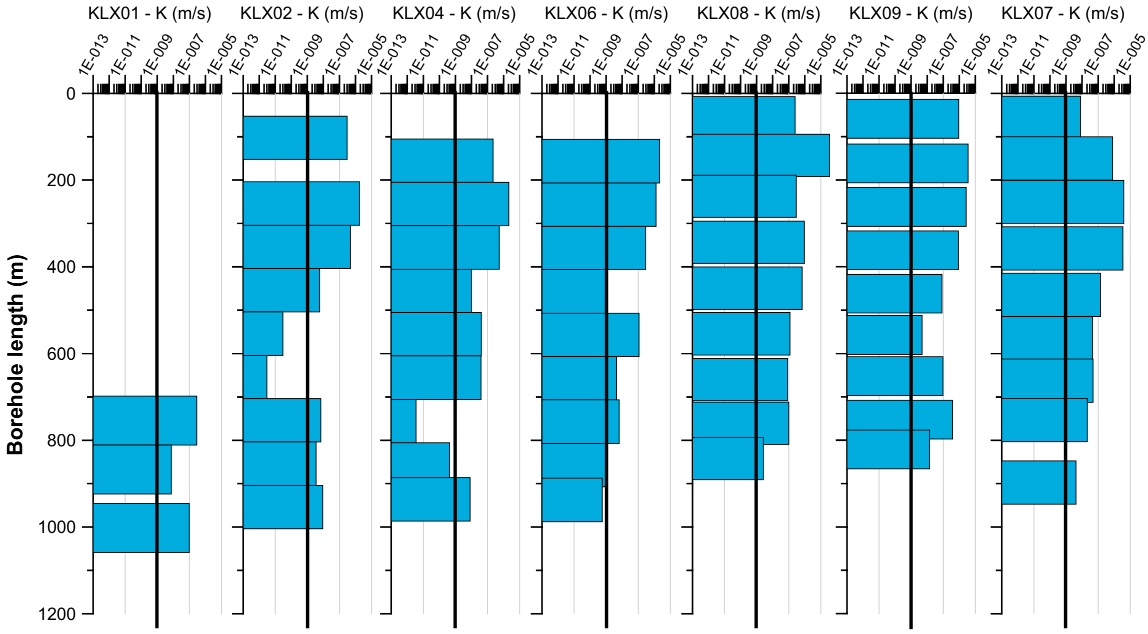


Figure 3-21. *Laxemar North – Hydraulic conductivity at a 100 m test scale. Results from injection tests (PSS) in KLX02, KLX04, KLX06 and KLX07. Preliminary results from WLP tests during drilling in KLX08 and KLX09. Old test methodology employed in KLX01. Depth is given as borehole length, cf. Figure 2-12.*

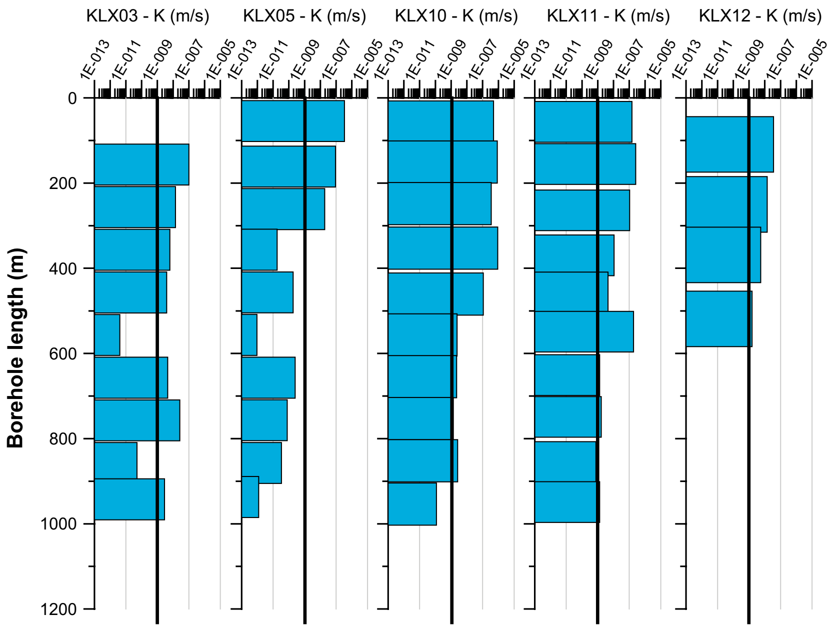


Figure 3-22. *Laxemar South – Hydraulic conductivity at a 100 m test scale. Results from injection tests (PSS) in KLX03 and KLX05. Preliminary results from WLP tests during drilling in KLX10, KLX11 and KLX12. Depth is given as borehole length, cf. Figure 2-12.*

Table 3-6. Univariate statistics of hydraulic tests performed in cored boreholes in the Laxemar subarea based on a lognormal distribution. Statistics are based on PSS and WLP data from core-drilled holes (100 m test scale). Confidence limits for mean Log10(K) is expressed as the deviation D from mean in the table. For a confidence level of 0.95 the mean will be within value "Mean Log10(K)" ±D. Data type "All" means that all data are used, implying that data associated with deformation zones interpreted from geological single hole interpretation and the deterministically defined deformation zones in the Laxemar model 1.2 deformation zone model are not excluded. Laxemar North includes data from KLX01, KLX02, KLX04 and KLX09. Laxemar South includes data from KLX03, KLX05, KLX10, KLX11 and KLX12. Preliminary results based on WLP tests during drilling from KLX09, KLX10, 11 and 12. Unit for K is m/s.

Area	Data type (m)	Test type	Upper elevation limit (m.a.s.l.)	Lower elevation limit (m.a.s.l.)	Test scale (m.a.s.l.)	Sample size, All	Sample size, Lower meas. lim.	Lower meas. limit[1] Log10 K	Mean Log10(K)	Std Log10(K)	D Conf.lim Log10(K): Mean±D, conf.level 0.95:
Lx north	All	PSS, WLP	ca–0	–300	100	7	0	(PSS≈–13) (WLP ≈–8)	–6.29	0.51	0.47
	All	PSS, WLP	–300	–700	100	12	0	(PSS≈–13) (WLP, ≈–8)	–7.80	1.89	1.20
	All	PSS, WLP	–700	ca –1,000	100	13	0	(PSS≈–13) (WLP,≈–8)	–8.33	1.22	0.74
Lx south	All	PSS, WLP	ca –0	–300	100	13	1	(PSS≈–13) (WLP ≈–8)	–7.04	0.64	0.39
	All	PSS, WLP	–300	–700	100	20	0	(PSS≈–13) (WLP, ≈–8)	–8.95	1.47	0.69
	All	PSS, WLP	–700	ca –1,000	100	11	1	(PSS≈–13) (WLP,≈–8)	–9.64	1.32	0.89

PSS: Pipe String System.

WLP: Wire Line Probe.

Table 3-7. Hydraulic conductivity of different rock domains. Method employed: PSS[1] and WLP[2] in core drilled holes and different hydraulic tests in percussion boreholes (HTHB[3], Test scale 100 m. All data included in analysis, i.e. deformation zones in the geological single-hole interpretation and the deterministic deformation zones defined in RVS for version Laxemar 1.2 are not excluded. Based on data from KLX01–12 and 18 HLXxx boreholes (Confidence limits for mean Log10(K) is expressed as the deviation D from mean in the table; for confidence level of 0.95 the mean of Log10(K) will be within value "Mean Log10(K)" ±D.) Data includes KLX01–12. K: m/s.

Rock domain	Sample size	Mean Log10(K)	Std Log10(K)	D Conf. lim Log10(T): Mean±D, conf. level 0.9	Comments
All	103	–7.86	1.58		
A	59	–7.21	1.29		
BA	4	(–10.07)	(2.49)		
D	18	–9.03	1.76		
M	22	–8.57	1.29		

[1] PSS: Pipe String System.

[2] WLP: Wire Line Probe.

[3] HTHB: Hydraulic test system percussion boreholes.

3.4.4 Boundary conditions

Upper present boundary

In a landscape of low conductive bed rock, thin overburden and high precipitation, as in large parts of Sweden, one can expect that the water table follows the topography rather well and that the topography may be used as a head boundary. The numerous small streams, small lakes and peat lands in the Simpevarp regional model confirms that the small discharge areas are well spread over the area, and also indicating a lower possible level for the water table. This level can be an alternative representation of the head boundary condition compared to the topography.

In Figure 3-23 the topography is shown and in Figure 3-24 all points representing streams, lakes, peat lands and sea level as elevation 0 as well as the interpolated surface between in all these points. The intensity of points representing streams, lakes, peat lands clearly shows that there are a large number of discharge areas and really small drainage basins.

Location of discharge areas

It is expected that several of the major deformation zones coincides with the valleys. As both peat lands and streams in the area are found in the valleys, above major deformation zones, the deformation zones are probably important major discharge features, not always but frequently. Possibly one can expect discharge from deep levels in some deformation zones, though mixed with water from more near surface rock.

Vertical boundaries useful for regional flow models

Water divides in the regional model area are fairly well defined topographically. It is assumed that these water divides can be used as no-flow boundaries.

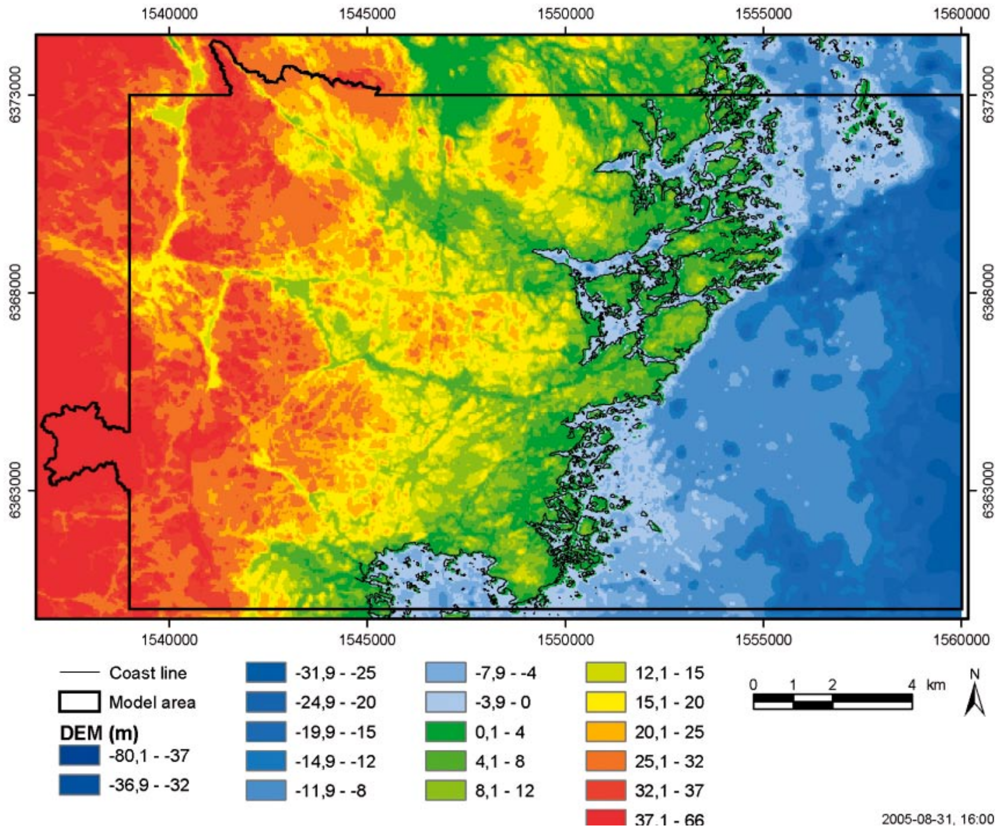


Figure 3-23. *Topography in the Simpevarp area. The black line shows the regional model area and parts of drainage areas that extends a bit outside the regional model area /Rhén et al. 2006c/.*

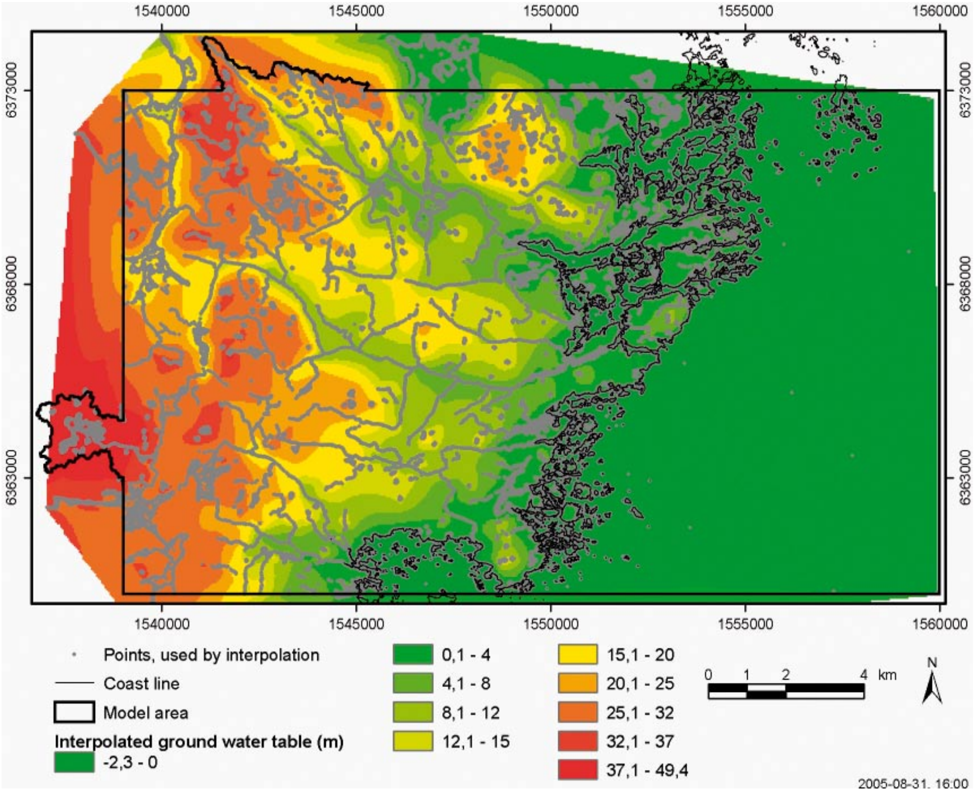


Figure 3-24. *Estimated level of the water table based on levels of discharge points Discharge points used for the interpolation shown in grey. (Water table-base.) The black line shows the regional model area and parts of drainage areas that extends a bit outside the regional model area /Rhén et al. 2006c/.*

3.4.5 Groundwater flow

No new groundwater flow simulations have been made since L1.2. /SKB, 2006/. However, a brief summary of the Laxemar 1.2 modelling results and findings is provided.

The groundwater flow in the Laxemar subarea is driven by topography with a general gradient from the high elevated areas in the west to the Baltic sea in the east. The modelled flow pattern is largely governed by the mutual connections of the deformation zones included in the model. A general feel of the flow system and an overview of the modelled area is provided by Figure 3-23, where results of performed particle tracking are presented, recharge (red) and discharge (blue) points, for particles released within the local scale area (reference case). As can be seen, discharge areas are mainly located in valleys to the south and north of Laxemar and along the shoreline, especially south of the Äspö isand. There is also a minor discharge area associated with a small stream in the centre of the Laxemar subarea.

The model size shown in Figure 3-25 is presently judged adequate for study of the recharge and discharge characteristics relevant to the Laxemar subarea. In the evaluation of the present regional scale groundwater flow model various assumptions and sensitivities regarding boundary and intitial conditions, material properties assignment and their effect on various calibration targets have been evaluated, for detailed information cf. /Hartley et al. 2006/ and /SKB 2006a/.

The hydraulic boundary conditions on the top surface of the model have been shown to have considerable impact on the results. A simulated water table, in some areas several metres below the topographic surface, gives the best calibration results relative to measured hydrogeochemistry. Using the Hydro-DFN base case, which includes a depth dependency, gives interval conductivities consistent with the PSS 100 m interval data, and when anisotropy is introduced a reasonable match with hydrogeochemistry is obtained. Model changes related to the stochastic nature of the hydraulic DFN and the associated transmissivity model have moderate effects on the simulated chemistry profiles in boreholes.

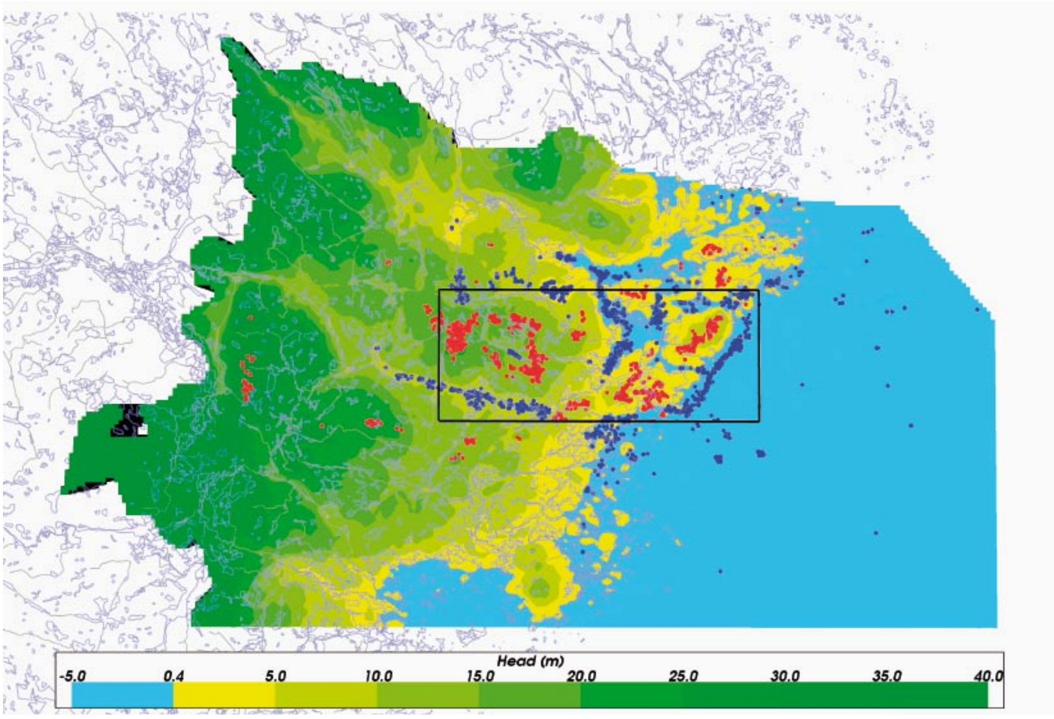


Figure 3-25. *Recharge (red) and discharge (blue) locations for particles released in the local-scale area for the reference case. The local-scale release area (black rectangle) is shown for orientation. The recharge points are the upstream start points on the model surface for flow-paths through the release area. The discharge points are the equivalent downstream exit points /Hartley et al. 2006/.*

3.5 Hydrogeochemical model

Unlike the Laxemar 1.2 hydrogeochemical modelling /SKB 2006a, SKB 2006b/, the data set available for the Laxemar 2.1 hydrogeochemical modelling is composed of more representative data from depth. This has motivated a full modelling step for hydrogeochemistry as part of the current modelling.

Evaluation of the hydrogeochemical data has been carried out by considering not only the samples from the Laxemar subarea, but also in relation to those from the Simpevarp subarea, Äspö and, in some cases, also related to the entire Fennoscandian hydrochemical dataset. Information from hydrogeochemical model versions based on previously investigated sites in Sweden and elsewhere, and information from ongoing geological and hydrogeological modelling in the Laxemar subarea, where included in the evaluation when possible.

The evaluation and modelling of the hydrogeochemical data consist of visualisation of the groundwater properties, explorative analysis which involves manual evaluation and expert judgment, and mathematical modelling, all of which must be combined when evaluating groundwater information.

The results presented herein represent the collective effort made by the ChemNet Analysis Group; details of the modelling are described in /SKB 2006f/.

3.5.1 Reactive modelling

Dilute meteoric groundwater

The geochemical modelling presented in Appendix 6 in /SKB 2006f/ considers speciation-solubility calculations, reaction path modelling and redox system analysis. The numerical calculations have been conducted using the PHREEQC code and the M3 code.

The methodology used in this analyses, though simple, aims at setting the basis for achieving a proper understanding of some of the main water-rock interaction processes acting in the upper part of the system, where the mixing process with saline water is though to be of minor importance or it has no substantial effects on the chemical composition of groundwaters (i.e. only diluted groundwaters are considered, despite their origin).

The existing hydrochemical data for dilute meteoric groundwaters (representing shallow bedrock groundwaters) indicate that there are two relatively independent hydrogeologically active systems, one corresponding to near-surface groundwaters and other represented by the granitic bedrock. For near-surface groundwaters there is a clear evolution driven by calcite and/or dolomite dissolution, increasing the concentration of both aqueous calcium (and magnesium) and carbonate and increasing the pH. In the granitic aquifer, the increase in pH can not be attributed to the dissolution of calcite but it seems that silicate weathering plays a major role on the observed pH increase. This increase in pH can be properly reproduced by a geochemical model simulating the silicate weathering process through a theoretical flow line (cf. Appendix 6 in /SKB 2006f/). The model can also reproduce the decrease in calcium and magnesium associated with the water-rock interaction processes (see Figure 3-26).

However, the detailed geochemical model fails to reproduce the aqueous carbonate behaviour, most probably due to the oxidation of organic matter, which would induce an increase on water alkalinity.

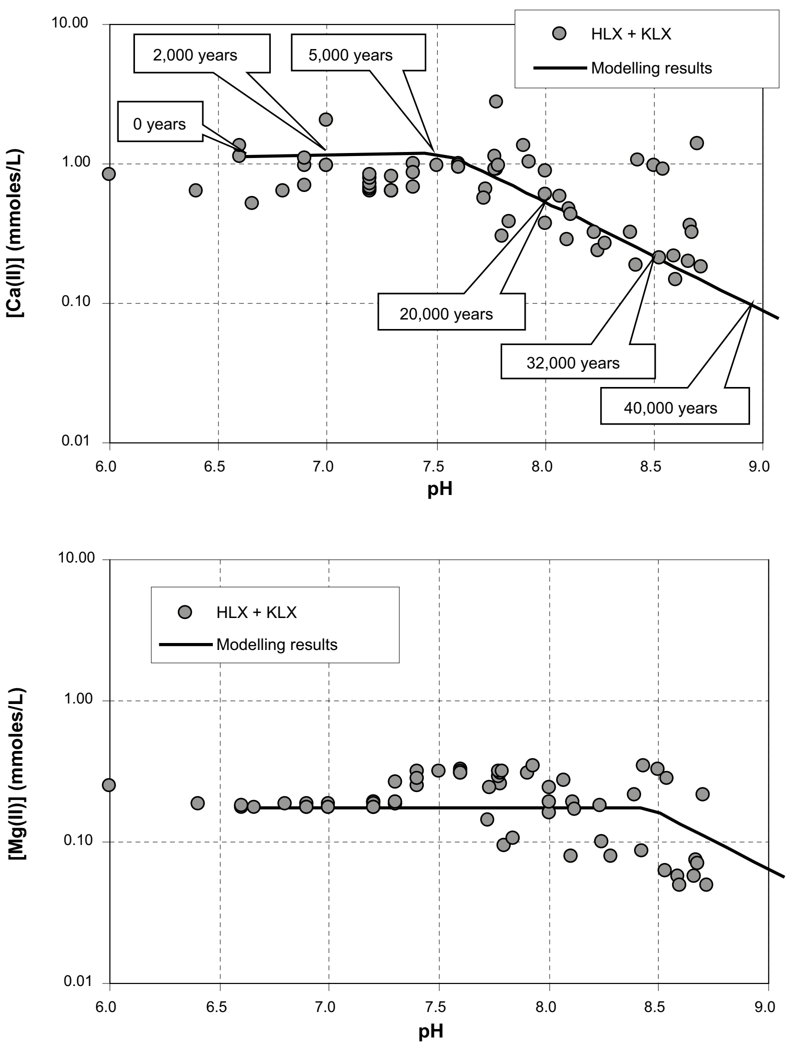


***Figure 3-26.** pH-Ca(II) and pH-Mg(II) diagrams showing the analytical data for deep boreholes together with the modelling results. In the upper plot the simulation time is also indicated for the modelling results.*

All groundwaters

In parallel, complete site-specific reactive hydrogeochemical modelling has been carried out with PHREEQC /Parkhurst and Appelo 1999/ using the WATEQ4F thermodynamic database. The main goal of the modelling was to investigate the processes that control water composition at the Simpevarp area. The main conclusions from this work (cf. Appendix 3 in /SKB 2006f/) are summarised below.

Shallow groundwaters are mainly controlled by "pure" water-rock interaction (infiltration water) with minor influence of mixing with older waters. They lack a clear thermodynamic control; if there is any, it is by fast chemical reactions (ionic exchange, surface complexation reactions, calcite dissolution-precipitation, etc) coupled to several irreversible processes (mineral dissolution, decomposition of organic matter, etc). Major ions show a constant increase as reactions proceed. The dissolution of calcite and silicates controls alkalinity and pH until equilibrium is attained, as they evolve towards the more saline and deeper groundwaters.

Chemical contents in deep groundwaters (especially for Cl concentrations higher than 10,000 mg/L) are mainly controlled by mixing with a brine end member. Most of the major ions are controlled by mixing, with minor influence from reactions (even Ca and sulphate in spite of calcite and gypsum equilibrium). Alkalinity is low because it has been consumed by calcite precipitation. Calcite reaches equilibrium or keeps slightly oversaturated. The pH is mainly controlled by calcite equilibrium and, possibly, by aluminosilicate reactions which keep pH values higher than what calcite equilibrium would impose.

The potentiometrically measured Eh ranges from –210 to –380 mV. Sulphur redox pairs and the iron pair calibrated by /Grenthe et al. 1992/, show, in general, good agreement with the measured Eh (see Figure 3-27).

Apart from this analysis and comparison, the speciation-solubility calculations have shown a clear equilibrium with amorphous iron monosulphides in most of the groundwaters from this area. This fact implies important sulphate-reducing bacterial (SRB) activity at present (in agreement with the microbiological information (cf. Appendix 2 in /SKB 2006f), and an iron source

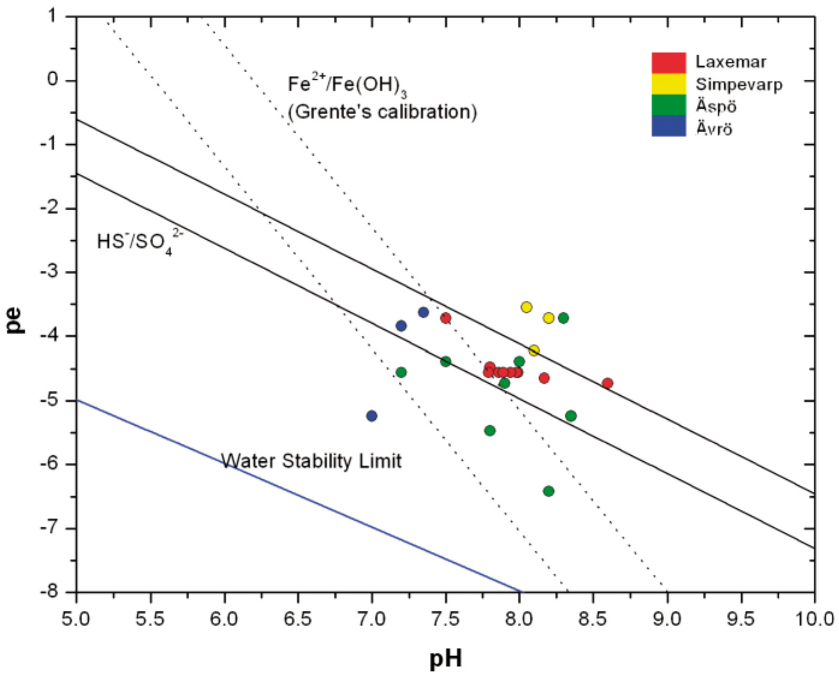


Figure 3-27. *Eh-pH diagram showing the measured Eh and pH of the selected samples in the Laxemar subarea. Boundaries for $Fe^{2+}/Fe(OH)_3$ and SO_4^{2-}/HS^- (dotted and solid black lines, respectively) are also shown for the range of pH, Fe^{2+} and S_2^- concentration in the Laxemar subarea groundwaters. Data for the $Fe^{2+}/Fe(OH)_3$ are from /Grenthe et al. 1992/ and data for the SO_4^{2-}/HS^- are from the WATEQ4F database included in PHREEQC /Parkhurst and Appelo 1999/.*

(in agreement with the mineralogical information, in Appendix 2 in /SKB 2006f/. An additional conclusion is that pyrite is presently formed at from monosulphide precursors (isotopic values from pyrite seem to support this).

In summary, the redox state of groundwaters in the Laxemar subarea appears to be well described by sulphur redox pairs in agreement with some previous studies in this area /Glynn and Voss 1999, Laaksoharju 2004a/ and in other sites from the Fennoscandian Shield /Nordstrom and Puigdomenech 1986, Laaksoharju et al. 2004b, Pitkänen et al. 2004/. The presence of sulphate-reducing bacteria widely distributed in the Äspö and Simpevarp subareas can be related to this description and supports the idea that sulphur redox pairs could be controlling the microbiologically-mediated redox state.

However, in agreement with /Grenthe et al. 1992/, the work presented in Appendix 3 in /SKB 2006f/ also supports the conclusion that the iron system contributes to the redox control in some of the groundwaters through different oxide-oxyhydroxides. The plausible explanation to this is that the sulphur system governs the redox state for most of the groundwaters, and that the iron system is controlled by the microbially mediated sulphate-sulphide ratio. Hence the concentration of ferrous iron is controlled by the kinetically fastest Fe(II)/Fe(III)-oxide and sulphide phases.

The coupling between the iron and sulphur systems occurs via sulphate-reducing bacteria and sulphide mineral precipitation. Several lines of reasoning indicate that this process is effective at different levels in the Laxemar subarea. For instance, pyrite coatings have been identified on fracture fillings, which is additional evidence of the active participation of sulphur redox pairs.

The good results obtained using the monosulphides saturation indices as tracers of SRB activity in Scandinavian groundwaters, indicate that the methodology is useful in these types of systems. It can solve the common problem related to the absence of any correlation between SRB occurrence and its effects (dissolved S^{2-}) on the geochemistry of waters /Pedersen 2000/.

Finally, in the framework of repository safety assessment, the precipitation of monosulphides can have important consequences: (1) it is a process not considered (up to now) in the geochemical evolution of these kinds of systems, (2) it can affect the canister integrity and the stability of colloids, and (3) a more reliable thermodynamic value for their equilibrium constant has been deduced and it must be included in the databases commonly used in safety evaluations.

3.5.2 Mixing modelling

The need for additional M3 uncertainty tests was identified during the Laxemar 2.1 modelling phase. Issues such as the use of tritium as a variable in PCA calculations and the use of different end members were addressed in Appendix 4 /SKB 2006f/. The PCA model, which employs all the samples including major elements (Na, K, Ca, Mg, SO_4, HCO_3, Cl), isotopes ^2H, ^3H, $\delta^{18}O$ with the end members: Littorina, Brine, Glacial and Meteoric, provide the most robust mixing calculations for the Laxemar 2.1 dataset. This model was suggested as the final model.

The M3 code has been updated to include the option to calculate the mixing proportions in multivariate space which decreases the uncertainties (Gómez et al. 2006). Tests shows that the new code works properly and reduces the uncertainties especially for the dilute groundwaters. The results were delivered to the hydogeological group (HydroNET) for comparison with independent hydrogeological mixing fraction calculations.

3.5.3 Coupled modelling

The aim of coupled modelling of flow and reactive transport is to support the hydrogeochemical interpretation of field data (cf. Appendix 5 in /SKB, 2006f/). It is expected that reactive transport modelling will provide a quantitative framework for testing alternative hydrochemical hypotheses and conceptual models of key hydrochemical processes.

The SUTRA /Voss and Provost 2003/ and CORE /Samper et al. 2003/ codes were used to integrate current hydrogeological and hydrogeochemical data and knowledge of the site. After calibration, it has been possible to reproduce the salinity fields corresponding to the current hydrogeological pseudo steady-state flow field. The numerical model has been calibrated assuming a heterogeneous equivalent porous media approach, and calibrated values of hydraulic conductivity are consistent with measurements within the range of field-derived values.

Contrary to what it was expected, the distribution of most major dissolved species (see Figure 3-28) could be predicted by using the calibrated model, showing a conservative behaviour similar to the TDS distribution. The reason for such an apparent conservative behaviour is due to the large concentration contrast existing between fresh meteoric and deep saline waters. Thus, small amounts of mixing (by hydrodynamic dispersion) induce mass transfers much larger than those produced by active geochemical process, which are eventually masked.

The reactive transport model accounts for mineral dissolution/precipitation processes under both local equilibrium and kinetic conditions. Taking into account silicate weathering processes under kinetic conditions leads to a better agreement between modelled results and field observations in terms of dissolved silica and pH. The reactive transport model fails at reproducing measured bicarbonate concentrations, most probably because of the occurrence of microbially-mediated respiration of dissolved organic matter present in the fresh groundwater of meteoric origin. These kinds of processes should be further studied in the near future by incorporating the simulation of microbially-catalysed processes.

3.5.4 Resulting description

The results of the hydrogeochemical modelling have been used to support and consolidate the hydrogeochemical site descriptive model presented in the Laxemar 1.2 evaluation /SKB 2006a/. The conceptual hydrochemical model of the site summarises most of the important findings. The approach to construct the conceptual model is described in Appendix 1 in /SKB 2006f/.

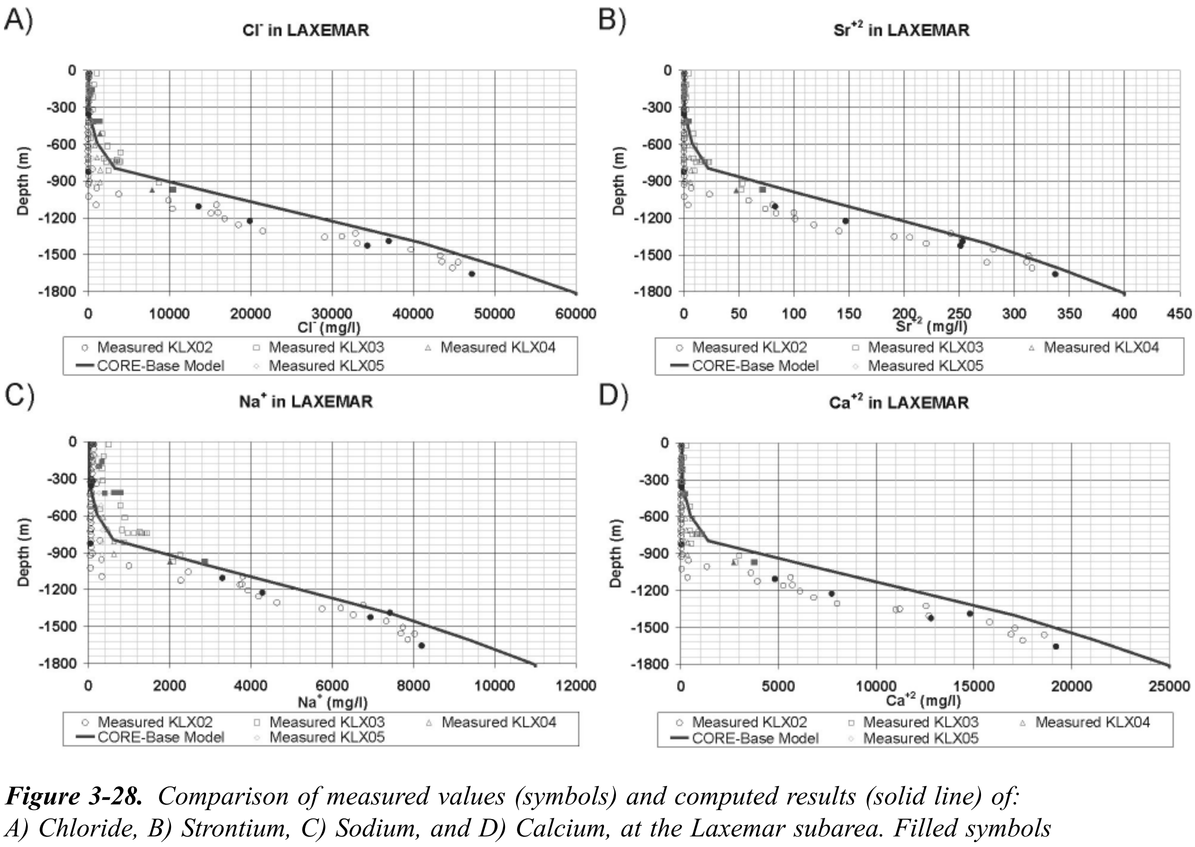


__Figure 3-28.__ Comparison of measured values (symbols) and computed results (solid line) of: A) Chloride, B) Strontium, C) Sodium, and D) Calcium, at the Laxemar subarea. Filled symbols correspond to representative samples.

Based on existing geological and hydrogeological information and in collaboration with the site hydrogeologists and geologists, schematic manual versions of these transects were produced to facilitate illustrating the most important structures/deformation zones and their potential hydraulic impact on groundwater flow. This hydraulic information was then integrated with the results of the hydrogeochemical evaluation and modelling results to show the vertical and lateral changes in the groundwater chemistry.

There is no convincing evidence of a Littorina Sea component in the hydraulic rock domains of the Laxemar subarea. The presence of such old marine waters, and additional waters with a glacial melt water component, may be preserved as lenses/pockets along dead-end fractures and/or within rock masses of low transmissivity, but as yet the drilling campaign has not revealed such sources. Since the focus has been to quantify the structural understanding of the site, most of the boreholes, and subsequently the groundwater samples, are associated with major water-conducting zones where preservation of palaeowaters would be least expected.

Borehole KLX08 has also confirmed the strong recharge environment generally represented by the Laxemar subarea, with deep penetration of meteoric waters. At depth mixing with a cold climate component is sometimes observed.

The marked differences in the groundwater flow regimes between the Laxemar and Simpevarp subareas are reflected in the groundwater chemistry. Along the main WNW-ESE transect Figure 3-29 shows the four major recognised groups of groundwaters and their interpreted spatial extent, denoted by A–D. The 'B' type groundwaters are subdivided into 'B_L' and 'B_S' types referring to Laxemar and Simpevarp respectively. The water types have the following features:

Type A: Shallow (< 200 m) at the Simpevarp subarea but deeper (down to a maximum of ~ 800 m) at the Laxemar subarea. Low saline groundwater (< 2,000 mg/L Cl; 0.5–3.5 g/L TDS); $\delta^{18}O$ = –11 to –8‰ SMOW. Mainly meteoric and $Na\text{-}HCO_3$ in type. *Redox:* Marginally oxidising close to the surface, otherwise reducing. *Main reactions:* Weathering; ion exchange (Ca, Mg); dissolution/precipitation of calcite; redox reactions (e.g. precipitation of Fe-oxyhydroxides); microbially-mediated reactions (SRB) which may lead to formation of pyrite**.** *Mixing processes:* Mainly meteoric recharge water at the Laxemar subarea; potential mixing of recharge meteoric water and a modern sea component at the Simpevarp subarea; localised mixing of meteoric water with deeper saline groundwaters at the Laxemar and Simpevarp subareas.

Type B: Shallow to intermediate (150–600 m) at the Simpevarp subarea but deeper (down to ~ 500–950 m) at the Laxemar subarea. Brackish groundwater (2,000–10,000 mg/L Cl; 3.5–18.5 g/L TDS); $\delta^{18}O$ = –14 to –11‰ SMOW. B_L – Laxemar subarea: Meteoric, mainly Na-Ca-Cl in type; Glacial/Deep saline components. B_S – Simpevarp subarea: Meteoric mainly Na-Ca-Cl in type but some Na-Ca(Mg)-Cl(Br) types (± marine, e.g. Littorina); Glacial/Deep saline components. *Redox:* Reducing. *Main reactions:* Ion exchange (Ca, Mg); precipitation of calcite; redox reactions (e.g. precipitation of pyrite). *Mixing processes:* Potential residual Littorina Sea (old marine) component at the Simpevarp subarea, more evident in some fracture zones close to or under the Baltic Sea; potential glacial component at the Simpevarp and Laxemar subareas; potential deep saline (non-marine) component at the Simpevarp and at Laxemar subareas.

Type C: Intermediate to deep (~ 600–1,200 m) at the Simpevarp subarea but deeper (900–1,200 m) at the Laxemar subarea. Saline (10,000–20,000 mg/L Cl; 18.5–30 g/L TDS); $\delta^{18}O$ = ~ –13‰ SMOW. Dominantly Ca-Na-Cl in type at the Laxemar subarea but Na-Ca-Cl changing to Ca-Na-Cl only at the highest salinity levels at the Simpevarp subarea; increasingly enhanced Br/Cl ratio and SO_4 content with depth at both the Simpevarp and Laxemar subareas; Glacial/Deep saline mixtures. *Redox:* Reducing. *Main reactions:* Ion exchange (Ca). *Mixing processes:* Potential glacial component at the Simpevarp and Laxemar subareas; potential deep saline (i.e. non-marine) and an old marine component (Littorina?) at shallower levels at the Simpevarp subarea; deep saline (non-marine) component at the Laxemar subarea.

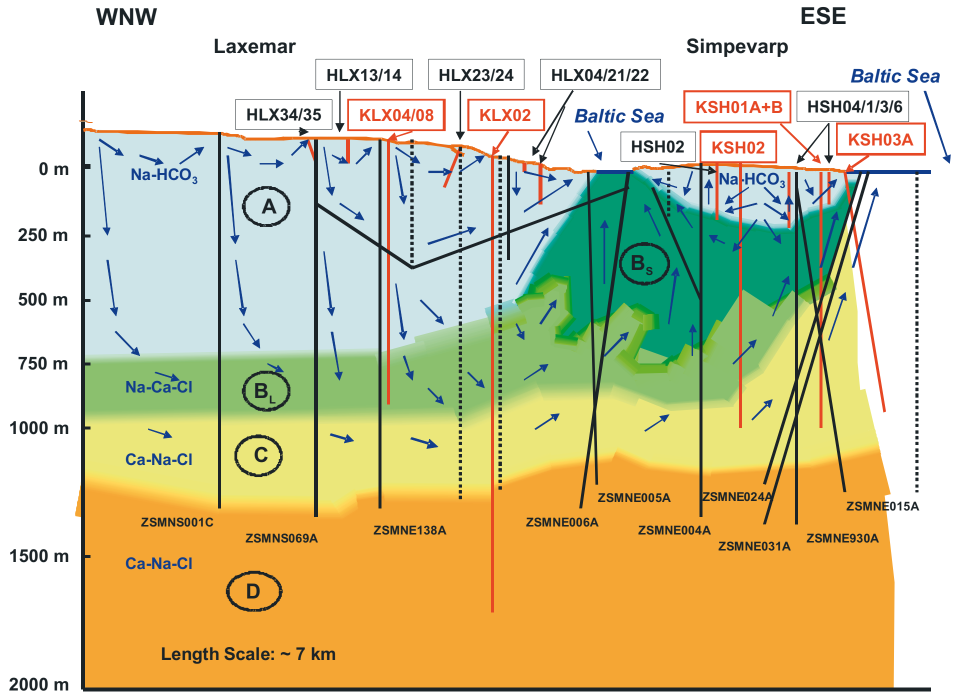


Figure 3-29. *Schematic 2-D visualisation along the WNW-ESE transect integrating the major structures, the major groundwater flow directions and the variation in groundwater chemistry from the sampled boreholes. Sampled borehole sections are indicated in red, major structures are indicated in black (full lines = confident; dashed lines = less confident), and the major groundwater types A–D are also indicated. The blue arrows are estimated groundwater flow directions.*

Type D: Deep (> 1,200 m) only identified at the Laxemar subarea. Highly saline brine-type (> 20,000 mg/L Cl; to a maximum of ~ 70 g/L TDS); $\delta^{18}O$ = > –10‰ SMOW. Dominantly Ca-Na-Cl with higher BrCl ratios and a stable isotope composition that deviates from the GMWL when compared to Type C groundwaters; Deep saline/brine mixture; Diffusion dominant transport process. *Redox:* Reducing. *Main reactions:* Water/rock reactions under long residence times. *Mixing processes:* Probably long term mixing of deeper, non-marine saline component driven by diffusion.

3.5.5 Comparison between hydrogeological and hydrogeochemical models

The present 2.1 modelling has further developed the comparison and integration between hydrochemistry and hydrogeology. Measured hydrogeochemical data, end-member compositions and their variability, M3 mixing calculations using the 2D and the new multispace option, and conceptual understanding, were delivered to the hydrogeological group.

As an example of the integration work, Figure 3-30 and Figure 3-31 show two examples of combining computed hydrogeological results (the hydrogeological model used is the Laxemar 1.2 /SKB 2006b) and chloride measurements. It can be seen that there is a very good qualitative agreement between modelled results and measurements in terms of a conservative tracer such as chloride. A comprehensive comparison and integration between hydrochemistry and hydrogeology will be conducted as part of the Laxemar 2.2 modelling stage.

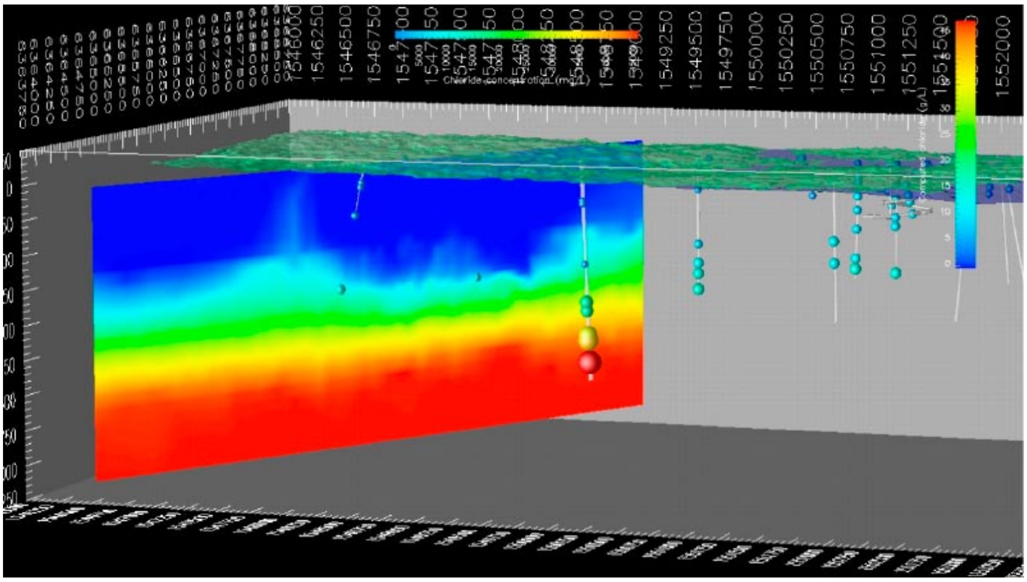


Figure 3-30. 3D view of computed and measured chloride distributions. Computed results correspond to the second NW-SE cross-section. Colour scale is the same for both computed and measured chlorides.

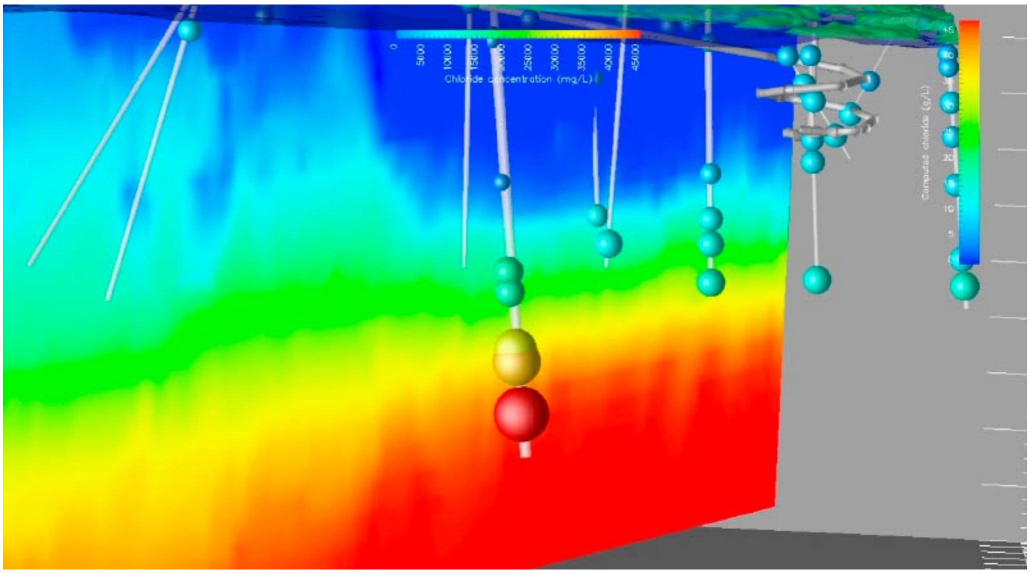


Figure 3-31. Close-up view of computed and measured chloride distributions. Computed results correspond to the first NW-SE cross-section. Colour scale is the same for both computed and measured chlorides.

3.6 Bedrock transport properties

Owing to the lack of data available at the data freeze for version 1.2, much of the data presented in the Laxemar 1.2 SDM actually belonged to the version 2.1 data freeze. For this reason, the Laxemar 2.1 model for transport properties is essentially unchanged since version 1.2. Much of this data consisted of effective diffusivities and porosities determined in the laboratory /Börjesson and Gustavsson 2005, Thunehed 2005/ as well as formation factors determined by in situ resistivity measurements /Löfgren and Neretnieks 2005/. Other data, specifically for the sorption properties of Ävrö granite and BET surface areas of rock types were not part of the data freeze. The sorption properties for Ävrö granite took the form of preliminarily reported measurements as presented in the background report by /Byegård et al. 2006/.

As described in the version 1.2 SDM, measurement data from the laboratory programme have been used to parameterise a retardation model that considers the transport properties of the major rock domains, as well as the properties of type fractures, with focus on the Laxemar area. The retardation model for rock domains considers the properties of the unaltered intact rock matrix, whereas that for type fractures additionally considers the material properties of alteration zones of various kinds and extents within the wall rock adjacent to fracture flow paths. No attempt has been made thus far to parameterise local minor and local major deformation zones owing to a lack of hard data for these structures. Local major deformation zones residing in the hydraulic conductor domain (HCD) are not currently considered to contribute substantially to the overall transport resistance. Local minor deformation zones (MDZ) residing in the hydraulic rock domain (HRD), although not previously considered to contribute significantly to the transport resistance, are now regarded as part of a broader definition of the fracture types A–D presented in the Laxemar 1.2 SDM. A retardation model describing the properties of MDZ is not presented in this model version although will be presented in model version 2.3.

3.6.1 Transport properties of rock domains

There is currently good data support for the diffusive properties and porosity of the major rock types, Ävrö granite and Quartz monzodiorite. Some data values are available for minor rock types, although they are associated with greater uncertainty owing to the smaller number of samples that have been investigated (in some cases only single measurements). It is therefore not possible at this time to make unequivocal quantitative distinctions between the diffusive properties of the different rock types in the Laxemar area. Notwithstanding this, there does not currently appear to be large differences between the diffusive properties of the various unaltered rock types.

At present, formation factor estimates based upon laboratory electrical resistivity measurements are given as recommended values for use in Safety Assessment. It is noted, however, that in the Laxemar subarea, formation factors measured in the laboratory may be greater than values obtained by resistivity measurements in situ by as much as a factor of 2–4. Although there is little statistical evidence for an increase in formation factor with depth, we note that in situ compression coupled with mechanical damage during drilling, bore core retrieval, and sample preparation may result in laboratory measurements of the formation factor being overestimated. In situ measurements of formation factors are thought to be more relevant for model parameterisation owing to that they are obtained under prevailing formation stresses and are less subject to stress release and drill bit induced damage than core samples used in laboratory measurements. Uncertainties exist relating to the actual pore water composition relative to that sampled in the borehole which could have an impact upon the interpretation of borehole resistivity measurements, although this is thought to be less than the uncertainty introduced by stress release and artefacts relating to mechanically induced damage.

Detailed in situ measurements of formation factors are, however, forthcoming and, although not used for parameterisation of the retardation model in L2.1, it is anticipated that these will be used in the version 2.3 retardation model. Currently, Ävrö granite is thought to have the highest diffusivity of the site specific rock-types with a formation factor estimated to be on the order of $F_f \geq 10^{-4}$. Other rock types have slightly lower formation factors, although with a maximum of about an order of magnitude variation relative to Ävrö granite. Although Ävrö granite appears to have the highest effective diffusivity it is noted that the minor rock types have significantly smaller sample support and the variation between rock types is typically of the same order of magnitude as the variation observed within individual rock types.

The relative retention properties of the altered and unaltered rock are gauged in terms of the material properties group, or MPG; a parameter that describes the combined effect of the sorptive and diffusive properties of the rock. In the previous S1.2 SDM for Simpevarp, data for Cs(I) and Sr(II) sorption on Äspö diorite was imported from Äspö HRL studies and pooled with site specific effective diffusivities for the major rock types /SKB 2006c, Byegård et al. 2005/. In that case, Äspö diorite was considered to be an analogue for the sorption properties of all rock types in the Simpevarp subarea. Owing to a possible lack of consistency between the procedures used to evaluate the sorption properties of altered and non-altered materials and possibly also due to the pooling of site-specific diffusivities and imported sorption data, the altered layers of rock were parameterised with weaker retention properties than the unaltered rock matrix. This is now thought to be an artefact of the previous data import.

Although not part of the Laxemar 1.2 or 2.1 data freeze, some preliminary sorption data were reported in the Laxemar 1.2 SDM /SKB 2006a, Byegård et al. 2006/. Sorption K_d values were reported for Cs(I), Sr(II), Ra(II), Ni(II), and Am(III) in contact with crushed Ävrö granite. The rock material was taken from a single location in borehole KLX03A. The K_d values were based upon sorption measurements with two different particle sizes of crushed rock and subjected to an extrapolation procedure to estimate sorption on internal surfaces of the rock matrix. The results are preliminary as they were based upon a contact time of one month with the exception of Am(III) where a contact time of three months was used. Final values will be reported after a contact time of six months. Although sorption data for other rock types was unavailable, estimates of the sorption properties of other rock types was estimated by extrapolation assuming the sorption K_d to be proportional to mineral surface area as measured by the BET method /Brunauer et al. 1938/. The same procedure was also used to derive sorption data for representative fracture filling materials, fracture coatings, and altered Ävrö granite. There is currently insufficient data to rigorously describe the properties of the alteration layers of rock relative to the unaltered rock matrix for Laxemar, although it is expected that the retention properties of the altered rock will prove to be stronger than those for the unaltered rock.

3.6.2 Transport properties of fractures and deformation zones

In the Laxemar 1.2 retention properties model, an identification and quantitative description of different fracture types was presented. This is unchanged in the current model version. Given the current state of knowledge, no identification of deformation zone types can be made owing to the limited data available. The limited availability of data also implies that some parameter values are missing in the tables for the identified fracture types. The on-going site investigation programme will improve the basis for parameterisation of fractures and deformation zones.

According to the presently available data, the presence of different fracture coatings cannot be related to specific rock types. This is important for the application of the identified fracture types in transport models. If such relations exist, they could provide a basis for assigning different fracture types to the various rock domains. For the rock hosting fractures, it is thought that a significant fraction of the fractures are situated within altered parts of the rock, although there is some uncertainty concerning the actual fracture frequency in altered zones /Byegård et al. 2006/.

Based on the information available at this stage in the site investigation, it is not possible to provide a retardation model for the local minor and local major deformation zones. This is partly due to a lack of transport data, although also related to uncertainties in the classification of deformation zones. Although no retardation model has been developed, it is implicitly assumed that deformations zones consist of one or several types of altered wall rock (i.e. layers of hydrothermal and tectonic alteration that extend from fracture surfaces to some distance within the host rock). The conductive parts of the zones are conceptualised to consist of multiple fractures and regions with crushed material that can be classified as belonging to one of the main fracture types or a broader fault gouge classification.

3.6.3 Transport properties of flow paths

In the Laxemar 1.2 SDM, flow-related transport properties were included as part of the transport properties description. These took the form of a first order analysis of the possible F-factor distribution in the first 10–100 m of rock within the hydraulic rock domain (HRD) surrounding the repository. In the SDM this was referred to as the "immediate far field" for solute transport.

The mean F-factor of the rock volume and its distribution was estimated using a number of complementary methods based upon different modelling concepts. The idea was to estimate an envelope of possible F-factors that can be reasonably expected to describe the flow-related transport properties of the HRD. The results detailed in the background report by /Crawford 2006/ suggest a mean F-factor on the order of about 10^6 y/m for a mean path length of 100 m and typical in situ conditions, although based on the extreme assumptions of channel length and flow channel interdependence investigated, up to 10% of the migration paths could have an F-factor less than 10^4 y/m.

3.6.4 Concluding remarks

Given the provisional nature of the retention properties data and the fact that a large proportion of the data are extrapolated on a tentative basis, it is not currently possible to rigorously compare the retention properties of different rock domains, nor draw specific conclusions concerning the differences between rock domains in the Laxemar subarea and those within the Simpevarp subarea and Forsmark. The rock types found in all areas appear to have broadly similar retention properties based upon the current level of understanding. Based upon the available data, the diffusive properties of the different rock types are similar with about an order of magnitude variation. The same amount of variation can also be seen for the sorptive properties of the various rock types as estimated by BET extrapolation of K_d values. It is noted that given the large uncertainties in the underlying datasets for both sorptive and diffusive properties, the differences between the average retention properties of the different rock types is typically of the same magnitude or less than the data variability for individual rock types.

3.7 The surface system

The Laxemar 1.2 site descriptive modelling of the surface system is presented in /Lindborg 2006/. The surface system description has not been updated during the Laxemar 2.1 stage. Consequently, a brief summary of selected parts of the surface system description is provided here. For information on the work not covered, and more details on those that are, the reader is referred to /Lindborg 2006/ and the associated background reports.

3.7.1 Surface hydrology and near-surface hydrogeology

The Laxemar 1.2 conceptual, descriptive and quantitative modelling of the meteorological, surface hydrological and near-surface hydrogeological conditions in the Simpevarp area is presented in /Werner et al. 2005/. The conceptual descriptive model is based on three types of "elements": type areas, flow domains, and interfaces between flow domains. The identified type areas are (1) *high altitude areas* (dominated by exposed or very shallow bedrock), (2) *valleys* (with thicker Quaternary deposits, and postglacial sediments at the surface), (3) *glaciofluvial deposits* (of which the Tuna esker in the western part of the regional model area is the largest), and (4) *hummocky moraine areas* (primarily existing in the south-western part of the regional model area and in the central part of the Laxemar subarea).

The Simpevarp area has a relatively small-scale topographical undulation and shallow overburden. This implies that the area is characterised by a large number of relatively small catchments with mostly small watercourses. Surface and near-surface run-off takes place in the high altitude areas of exposed or very shallow bedrock areas, from which water is diverted into the valleys, and further into watercourses, lakes and wetlands. Considering a time period of one year, it was assumed that the storage change $\Delta S = 0$. The average (corrected) precipitation in the Simpevarp area (P) is c. 600–700 mm·y^{-1}, and the average specific discharge (R) is estimated to be in the interval 150–180 mm·y^{-1} /Larsson-McCann et al. 2002/. Hence, the evapotranspiration (E) was estimated to be in the interval 420 to 550 mm·y^{-1}.

Numerical flow modelling presented as a part of the Laxemar 1.2 SDM resulted in an average specific discharge slightly larger than the interval for the regional, long-term discharge given above (c. 190 mm·y^{-1}), see /Werner et al. 2005/ for details. However, the Laxemar 1.2 hydrological simulations were made using (locally measured) meteorological data for a single year (2004), which means that they are not directly comparable with long-term average values. Concerning flow modelling it may also be noted that an updated model of the Laxemar subarea (relative to the Laxemar 1.2 SDM model) has been presented in connection with the "open repository" modelling undertaken in order to study the short- and long-term effects of a repository in Laxemar /Bosson 2006/.

3.7.2 Near-surface chemistry

The chemistry of near-surface groundwater and surface water at Laxemar is described in /Tröjbom and Söderbäck 2006/ and /Lindborg 2006/.

The freshwater systems in the Simpevarp area can generally be classified as mesotrophic, brown-water types. Most freshwaters are markedly coloured due to a high content of humic substances, indicating very high levels of dissolved organic carbon. Both streams and lakes are also relatively rich in nitrogen and phosphorus. These high levels of dissolved organic carbon and nutrients imply poor light penetration conditions in the lakes, and periodically also high levels of chlorophyll in the surface water and low oxygen concentrations in the bottom water of the lakes.

The chemical composition of shallow groundwater is an integrated result of both present and past processes. Shallow groundwater in the Simpevarp area is characterised by neutral or slightly acid pH values, an alkalinity ranging from high to very low, and a normal or slightly elevated content of major constituents in a national context. The groundwater in the area is influenced by marine relics, resulting in elevated content of e.g. chloride and sulphate in both shallow groundwater and fresh surface waters.

When data on the chemical composition of till from the Simpevarp area are compared with regional and national data, only minor differences are revealed, indicating that the till in the Simpevarp area is relatively normal in a Swedish context.

3.7.3 The Sea

The marine system is described in /Lindborg 2006/. The marine system in Laxemar encompasses three major habitats; semi-enclosed bays (to a varying degree affected by the fresh water effluence), coastal archipelago (with sheltered areas) and a Baltic Sea coastal habitat (exposed to sea currents and wave action). The bays have variable geometry, large shallow areas (water depth less than 1 m) are found as well at depths as large as 18 m. Area, volume and mean depth of the basins are found in Table 3-8 The bay areas have an average surface salinity of 3.5–4.5‰ whereas the bottom water (16 m) has a salinity close to that in the surrounding coastal area of 6‰. The bay areas are characterised by humic, low transparency conditions, averaging a light penetration of 2–3 m in enclosed bays, 4–7 m in the archipelago and 12 m in the open sea. The Laxemar marine ecosystem has been divided in fourteen basins. This division is based on bathymetry and coincides with projected future drainage basins. Their characteristics are described in Figure 3-32.

The inner soft bottom parts of the archipelago northeast of Laxemar (around Äspö) are dominated by *Chara* spp. West of Ävrö a large area is covered by the Xanthophyceae *Vaucheria sp.* On corresponding bottoms in the southern area the vegetation is dominated by vascular plant communities, dominated by *Potamogeton pectinatus* and *Zostera marina*. The sheltered inner coastal waters, particularly southeast of Laxemar, are dominated by *P. pectinatus*. Further out towards more exposed areas *P. pectinatus* and *Z. marina* occur together in a patchy appearance. On hard substrates, in shallow areas, the vegetation is dominated by the kelp-like algae *Fucus vesiculosus* and in deeper areas red algae cover the hard substrata /Fredriksson and Tobiasson 2003/. *Fucus sp.* in low abundance is recorded to approximately 10 m depth and red algae

Table 3-8. Area, volume and mean depth of the basins in the Laxemar area.

Number	Name	Area (m²)	Mean depth (m)	Volume (m³)
1	Basin Borholmsfjärden	$1.37 \cdot 10^6$	1.6	$2.21 \cdot 10^6$
2	Basin Granholmsfjärden	$1.29 \cdot 10^6$	5.3	$6.88 \cdot 10^6$
3	Basin Getbergsfjärden	$3.61 \cdot 10^5$	3.2	$1.17 \cdot 10^6$
6	Basin Eköfjärden	$1.63 \cdot 10^6$	2.6	$4.30 \cdot 10^6$
8	Basin Talleskärsfjärden	$4.30 \cdot 10^6$	5.6	$2.40 \cdot 10^7$
9	Basin Fläsköfjärden	$1.03 \cdot 10^6$	0.6	$6.04 \cdot 10^5$
10	Basin Mjältnatefjärden	$2.85 \cdot 10^5$	0.7	$1.94 \cdot 10^5$
11	Basin Sketuddsfjärden	$1.56 \cdot 10^5$	0.9	$1.48 \cdot 10^5$
12	Basin Kråkefjärden	$8.99 \cdot 10^5$	5.7	$5.15 \cdot 10^6$
13	Basin Långvarpsfjärden	$8.91 \cdot 10^4$	estimated: 0.5	$4.58 \cdot 10^4$
14	Basin Hamnefjärden	$1.61 \cdot 10^5$	2.2	$3.58 \cdot 10^5$
15	Basin Ävrö Coastal	$2.02 \cdot 10^7$	11.9	$2.40 \cdot 10^8$
16	Basin Kalmar sund	$4.89 \cdot 10^8$	13.2	$6.44 \cdot 10^9$
17	Basin Finngrundsfjärden	$1.89 \cdot 10^6$	6.7	$1.27 \cdot 10^7$

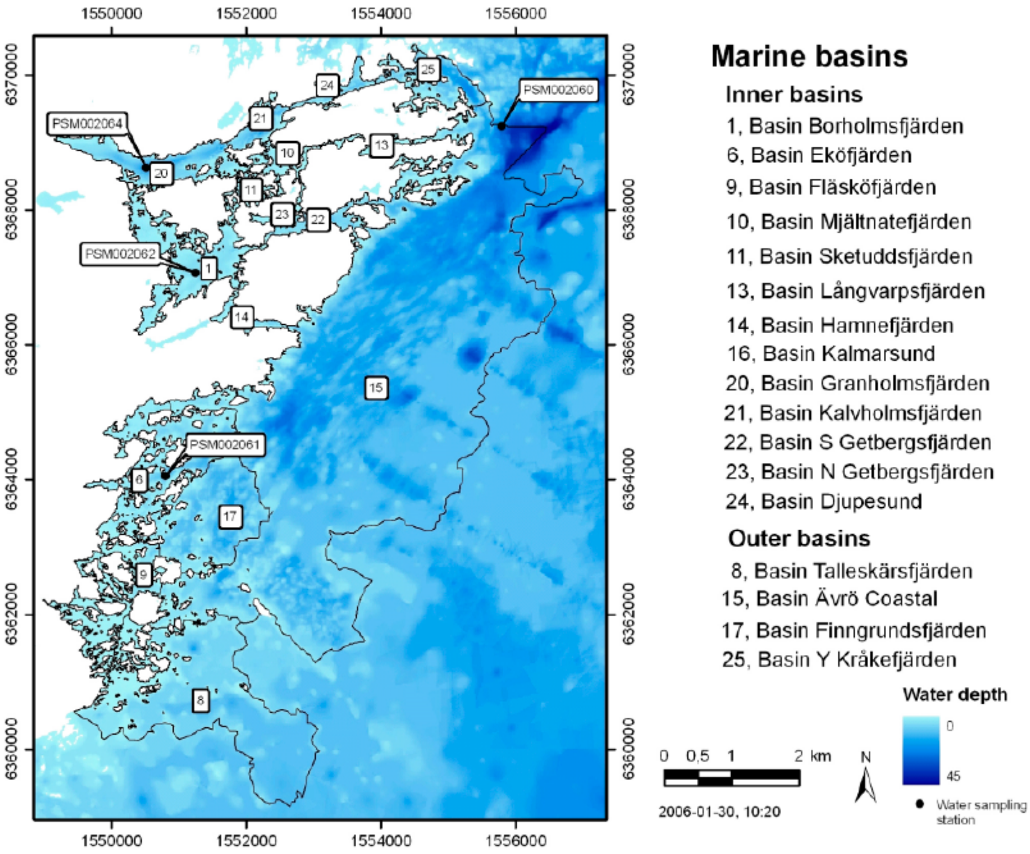


Figure 3-32. The basins in the Simpevarp area. The digital elevation model for the sea is displayed in increasing dark blue with depth /Lindborg 2006/.

down to approximately 30 m /Tobiasson 2003/. The benthic fauna is dominated by filter feeders (*Mytilus edulis*) and detritivores, often *Macoma baltica* or *Hydrobia* spp. In the coastal hard bottom areas filter feeders constitute for up to 95% of the biomass /Fredriksson 2005/ and detritivores on the other hand constitute 50–80% of the biomass in the inner areas eg. basin Borholmsfjärden. In total 45 animal species associated with the vegetation occurred in the area around Laxemar. The *Fucus sp.* communities are the most diverse concerning associated fauna and harbour some 31 species or higher taxa, while in the soft bottoms without vegetation only 14 species have been found.

Primary producers in the pelagic habitat, which account for a relatively small part of the turnover of matter of the ecosystem (see Chapter 5 in /Lindborg 2006/), seem to be dominated by the diatoms. Copepods are the dominating zooplankton, and zooplankton is more abundant in the inner bays than in the coastal areas.

3.7.4 Lakes

An overview of the lakes and lake sediments is found in /Lindborg 2006/, further information about the lakes is given in /Brunberg et al. 2004/ and the surface water chemistry is presented in /Tröjbom and Söderbäck 2006/

The regional area of Simpevarp contains relatively few lakes. In total six lakes, situated partly or entirely within the regional model area, have been investigated for habitat characterisation during the site investigations. For some of the lakes there are also other biotic data collected, e.g. plankton, macrophytes, fish, and invertebrates. In this section an account is given of data from the four lakes Jämsen, Frisksjön, Söråmagasinet and Plittorpsgöl.

Data have also been collected in streams, where a characterisation of the watercourses concerning vegetation, substrate, and encroachments has been performed. Moreover, invertebrate data have been collected in two of the streams.

The lake habitats have been characterised and the borders between different habitats within the lakes have been defined /Brunberg et al. 2004/. Furthermore, phytoplankton sampling for biomass estimation has been performed in Frisksjön during one year /Sundberg et al. 2004/. Macrophyte biomass has been investigated in Frisksjön in August 2004 /Aquilonius 2005/, and macrophyte vegetation in watercourses has also been studied /Carlsson et al. 2005/.

The lakes in Oskarshamn have been divided into five different habitats according to /Brunberg et al. 2004/.

Littoral type I: The littoral habitat with emergent and floating-leaved vegetation. This habitat is developed in wind-sheltered, shallow areas where the substrate is soft and allows emergent and floating-leaved vegetation to colonise.

Littoral type II: The littoral habitat with hard substrate. This habitat develops in wind-exposed areas of larger lakes, but also in smaller lakes, where the lake morphometry includes rocky shores. The photosynthesising organisms colonizing these areas include species that are able to attach to the hard substrate, e.g. periphytic algae.

Littoral type III: The littoral habitat with submerged vegetation. This habitat is found in areas of the lakes without emergent or floating-leaved vegetation, but where the light penetration is enough to sustain photosynthetic primary production all the way down to the sediment.

The profundal habitat: This habitat develops at the sediments of the lakes where light penetration is less than needed to sustain a permanent vegetation of primary producers. Non-photosynthesising organisms dominate this habitat. The profundal organisms are dependent on carbon supplies imported from other habitats of the lake or from allochtonous sources.

The pelagic habitat: This habitat includes the open lake water, where a pelagic food-web based on planktic organisms is developed. Depending on the light availability, these plankton are dominated by either photosynthetic production (i.e. by autotrophic phytoplankton) or, if the water is strongly coloured or turbid, by heterotrophic carbon processing (e.g. by heterotrophic/mixotrophic bacterioplankton and phytoplankton). The pelagic habitat covers the same area as the sum of littoral type II, littoral type III and profundal habitats within a lake.

Below, the habitat characterisations for one of the investigated lakes, Lake Frisksjön, are presented. All five major habitats are present in Lake Frisksjön, see Table 3-9 and Figure 3-33. Despite the relative shallowness of this lake (maximum depth 2.8 m), the brown colour of the water prevents light from penetrating down to the bottom in large parts of the lake. Thus, the profundal habitat covers a substantial part of the bottom area (41%). The dominating littoral habitat is of type III.

Macrophyte biomass in Lake Frisksjön was studied in August 2004, when the vegetation had reached its maximum biomass for the season. The calculations were often based on only one weight of each plant species and are therefore to be considered as rough estimates. In Littoral III, no vegetation was found. Littoral II hosted low vegetation biomass, whereas the biomass was higher in Littoral I. This indicates that the bottom area with light conditions below the compensation level, i.e. where it is too dark to enable primary production, is larger than the area classified as Profundal in /Brunberg et al. 2004/.

Table 3-9. Distribution of major habitats in Lake Frisksjön /Brunberg et al. 2004/.

Habitats	Area (%)	Area (m^2)
Littoral type I	18	24,200
Littoral type II	< 2	1,430
Littoral type III	38	49,130
Pelagial	82	107,270
Profundal	41	52,250
Sum		127,010

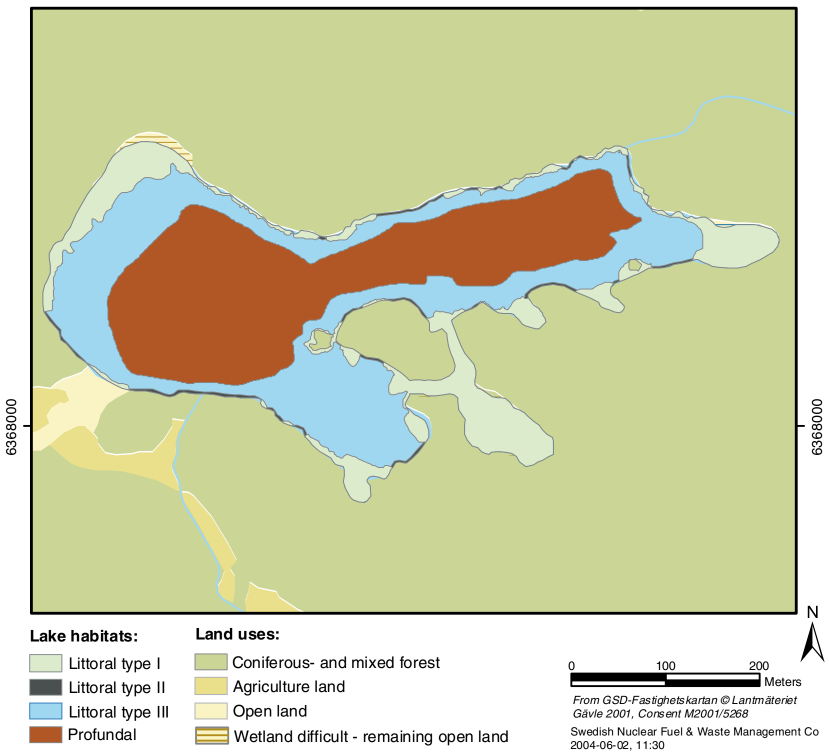


Figure 3-33. Distribution of major habitats in Lake Frisksjön /Brunberg et al. 2004/.

3.7.5 Terrestrial ecosystems

An overview of the ecosystem on land is found in /Lindborg 2006/.

The terrestrial vegetation is highly influenced by the bedrock composition, quaternary deposits and human land management. The bedrock mainly consists of granites. The Quaternary deposits are mainly wave-washed till while silt and clay have been deposited in the valleys. This is manifested in the vegetation where pine forests dominate on the till and all the arable land and pastures (abandoned arable land) are found in the valleys. Human management has been restricted to agriculture activities in the valleys, while forestry has been the dominating activity elsewhere. The spatial distribution of different vegetation types is presented in the vegetation map /Boresjö Bronge and Wester 2003/.

The forests are dominated by dry Scots pine (*Pinus sylvestris*) forests situated on bedrock or nutrient poor thin soils with shrubs, mostly *Calluna vulgaris* (Scotch Heather), and grasses, such as *Deschampsia flexuosa*, *Agrostis vinealis* and *Festuca ovina*, and with lichens and mosses dominating the ground layer. When these pine forests get moister *Vaccinium vitis-idaea* and *Vacinium myrtillus* become more common in the field layer. Norway spruce (*Picea abies*) becomes abundant where a deeper soil cover is found, while deciduous tree species are an important constituent near the coast, i.e. mainly *Quercus robur* (Pendulate Oak) but also *Corylus avelana* (Haze*l*), *Sorbus aucuparia* (Rowan), *S. intermedia* (Swedish whitebeam) and *Acer platanoides* (Norway maple), making the mixed forest the second commonest forest type. *Q. robur* is often the dominant tree species when more or less pure deciduous forests are found. The character of these forests is a function of boulder frequency, nutrient availability and earlier history of management.

Arable land, pastures and clear cuts dominate the open land. Arable land and pastures are found in the valleys close to settlements. The pastures were earlier intensively used, but are today a part of the abandoned farmland following the nation wide general regression of agriculture activities. As a consequence of the forestry activities in the area many clear-cuts of different successional stages are found. *Betula pendula* (European White Birch) is the dominating species in many of the earlier successional stages until it is replaced by young *P. abies* or *P. sylvestris* depending on soil type and/or management.

The dominating wetland type is the nutrient poor mire that is accumulating peat /Rühling 1997, SNV 1984/. A special type of semi wetland is found in the pine-dominated bedrocks, where water filled depressions, rock pools (Sw: *hällkar*), are formed /Lundin et al. 2005/. These obtain all their water from precipitation and have therefore a S*phagnum*-dominated community, much bog-like, with labrador tea *Rhododendron tomentosum* and *P. sylvestris*, and a peat layer accumulating on the bedrock. These vary a lot in size and may in some cases be large.

3.7.6 Human population

In /Miliander et al. 2004/ the human population is described further. In total, 2,709 people lived in Misterhult parish in 2002. The population is slowly decreasing, with a maximum in 1993 of 2,987 inhabitants. The density has been on average 7.1 inhabitants per square kilometre.

The dominant employment sector within Misterhult parish is electricity-, gas- and water supply, sewage and refuse disposal and it relates to 60% of the employed day-time population (working in the area). Within the employed night-time population (living in the area) on the other hand, only 11.7% is working in that sector.

The land use in Misterhult parish differs evidently from the average land use in Kalmar County. The forest area is far more dominating in Laxemar area than in Kalmar County. The proportion of arable land is considerably lower in Laxemar area, 4.4% compared to 11.6% in Kalmar County. The same holds for wetlands.

The agricultural activities are limited in Misterhult parish compared to Kalmar County. The farm density in Misterhult parish is on average only 0.2 farm·km^{-2}, which is half of the density in Kalmar County as a whole (0.4 farms·km^{-2}). The main part of the arable land (64%) is used for fodder production. Barley is the far most dominating crop in Misterhult parish according to data from 1999. The standard yield of spring barley in harvest area nr. 0814, in which the Misterhult parish is located, is slightly below the county average (90%) and clearly below the national average (79%).

The number of cattle, sheep and fowls (*Sw: hönsfåglar*) has decreased between 1990 and 1999. In 1999 the number of cattle was 1,207. For cattle the breeding of cows has increased, whereas the dairy cows and heifers, bulls and bullocks are decreasing in numbers.

The water use within Misterhult parish in the year 2000 has been roughly calculated based on the water use within the municipality of Oskarshamn, see /Miliander et al. 2004/.

4 Remaining critical issues, uncertainties and their handling

During the course of the site descriptive modelling performed in the Simpevarp area performed during the initial site investigation phase, a series of internal workshops have been held addressing the confidence in models, remaining uncertainties and identification of site investigation data required to reduce, or eliminate, the remaining uncertainties. Furthermore, these workshops have accounted for the amount and nature of interactions and feedback between disciplines. The reporting of the results of these workshops are reported in Chapter 12 of the produced site descriptive model reports, the most recent one being SDM Laxemar 1.2 /SKB 2006a/.

The programme for the complete site investigations at Laxemar /SKB 2005b, 2006c/ was presented before the completion of the site descriptive model Laxemar 1.2 and the subsequent Preliminary Safety Evaluation of the Laxemar subarea /SKB 2006g/, and Layout D1 for the Laxemar area /SKB 2006h/. Hence, there is a need to review the developed site investigation programme for the complete site investigations, not only in relation to the final results and conclusions of the Laxemar 1.2 site descriptive modelling, but also in relation to the preliminary safety evaluation and layout D1 for the Laxemar subarea.

In order to organise an effective means to provide feedback to the continued complete site investigation programme, taking new results into account (in many cases incorporationg new results and information which postdate the Laxemar 2.1 data freeze), a workshop was organised in April 2006 with participation from the site investigation team, the site modelling project, the performance assessment team and the repository engineering team.

Based on uncertainties in the preliminary site description for Laxemar, i.e. version 1.2, the results of analyses carried out in modelling stage 2.1, the experience from the work with repository layout D1 and the PSE for Laxemar, the remaining site-specific issues/uncertainties were compiled and documented in a protocol. These issues were then explored with the purpose to:

- provide a motivation for the issue to occur on the list and, if possible, prioritise the importance of the issue for the current stage of the site investigations, i.e. before conducting underground investigations,
- identify potential modelling actions to resolve the issue, and,
- propose investigations that could produce data to resolve the issue, separating between investigations already decided upon and new investigations,
- The results were documented in the protocol and are presented in the following sub-sections. Using the completed protocol, necessary modifications to the CSI programme /SKB 2005b, SKB 2006c/ were subsequently discussed. These implications are presented in Chapter 5.

4.1 Geological issues

The remaining issues are:

- Subdivision of rock domain RSMA01.
- Alteration of intact rock.
- Occurrence, geometry, character and properties of deformation zones in the focused area.
- Description of minor local deformation zones (MDZ).
- Assessment of reflector M1 a potential subhorizontal deformation zone.

- Possible existence of minor subhorizontal deformation zones in south-western Laxemar.
- Geological DFN model.
- Occurrence, geometry and properties of deformation zones in the local model area (surrounding the focused area).

4.1.1 Subdivision of rock domain RSMA01

Existing mineralogical and geochemical suggest a difference between the northern and southern parts of the rock domain RSMA01 (dominated by Ävrö granite). This difference is mainly reflected in distinctly lower quartz content in the south (10–15%) compared to the northern parts (17–30%). Given the established link between reduced quartz content (paired with increase mainly in plagioclase) and thermal conductivity, the differences mineralogical is also noted in a bimodal distribution of thermal conductivity, see e.g. /SKB 2006a/. Furthermore, reduced quartz content is also associated with reduced mechanical strength (UCS), se e.g. Section 3.2.1.

In order to enable reduction of the variance of thermal conductivity a subdivision of rock domain RSMA01 is proposed, whereby the southern parts, mainly aligned with the mixed domain RSMM01 will make out the variety with low quartz content. This division will be based on existing data and does not require any new primary data. The division is made first in 2D (plan view) and subsequently in 3D. It is expected that the 3D modelling will be uncertain. The size of volumes with similar properties can be assessed using geostatistical techniques.

4.1.2 Alteration of intact rock

Analysis performed during model step Laxemar 2.1 has indicated a correlation between (hydrothermal) alteration and the mechanical strength of the rock. Rock alteration is also strongly correlated to the proximity of deformation zones. This reduction is mainly attributed to higher porosity with and resulting lowered density. Alteration is also associated with oxidation and a resulting lowered magnetic susceptibility. This latter effect enables mapping of deformation zones and zones of intensive fracturing by means of magnetic methods.

Modelling activities required to resolve this issue include geostatistical analysis to assess sufficiently large volumes of rock with intact rock.

Data needs include complementary mineralogical and geochemical analyses to support the current, for the most part, qualitative assessment of rock alteration. New data which may shed some light on possible anisotropy are measurements on magnetic anisotropy on the Äspö shear zone (ZSMNE005A)

4.1.3 Occurrence, geometry, character and properties of deformation zones in the focused area

The understanding of the location and geometry of local minor and local major deformation zones (including possible subhorizontal zones) in the focused area has a strong impact on the repository layout and the distribution of depositional volumes. Similarly, the geometries of deformation zones within the focused area are important for groundwater flow and the distribution of groundwater chemical entities. Apart from understanding and qualifying the geometry of already interpreted deformation zones included in the current site description, special attention should be given to possibility of yet unidentified zones, and also to the possibility to discard currently interpreted zones of low confidence of existence.

For the layout planning a high degree of certainty is needed in the access/central area, but less in the area for the first 1,500 canisters, and even less certainty is required in the area needed for the remaining 4,500 canisters. What is important is the number of local zones and their length, but not their absolute positions. Detailed information on the position of the local deformation zones will be acquired during excavation of repository panel. A local adaptation to the actually found zones will be made.

Understanding of the character and material properties of deformation zones are important both for the assessment of groundwater flow as well as for the assessment of the stress situation and mechanical stability and inflow (in conjunction with excavation through deformation zones). The wish list from repository engineering for the L2.2 deliverables includes:

- Deformation zones geometries (including thicknesses).
- Quantification of geometrical uncertainties.
- Conceptual model of variability in deformation zone properties.

The modelling activities required during model step L2.2 include joint re-evaluation of existing seismic data and available directional borehole radar data. Numerical simulations can also be used to assess the role and effect of identified uncertainties in deformation zone geometries.

The ongoing and planned site investigations, although to a large extent directed on repository volumes, will also shed light on select deformation zones in and in the vicinity of repository volumes. Important surface data comprise strategically positioned and oriented refraction seismic surveys. Information at depth will be obtained form the planned cored boreholes KLX09G (NS046), KLX14A (NS059A, southern portion, short cored borehole), KLX19A(NW042), KLX17A (EW900), KLX21A (NE005A).

Although all of the above boreholes are deemed justified, final decision regarding some of these boreholes is pending the results of the refraction seismic surveys indicated above. Information on the connectivity (spatial extent) is expected from planned/on-going hydrogeological (interference) tests in existing and new boreholes. Worth mentioning is also that ongoing detailed characterisation and kinematic investigations on brittle structures (surface and boreholes) together with studies of the kinematics of ductile DZs will shed light on the evolution and deformation history of deformation zones in the Laxemar subarea.

4.1.4 Description of minor local deformation zones (MDZ)

Minor deformation zones (MDZ) will occur within the repository volume. These deformation zones are very important for assessing the long term safety, and for design, since the MDZ have a size range (radius larger than 75 m), that they must not intersect an accepted canister deposition hole. An improved understanding of minor local deformation zones will entail an improved handling and parameterisation of the geological DFN structures at the critical size range. Likewise, such improved description would also lead to an improved basis for the hydraulic DFN model, and hence for the flow pattern within repository areas. MDZ are also expected to affect migration and constitute components between the near filed and the canister. A deterministic description of MDZ is not foreseen needed, and would anyway be an unattainable goal for a surface based investigation. However, during the repository construction it will be essential to locate the MDZ in the deposition area in order to select proper deposition holes.

During the past year an effort has been made through detailed geophysics and high resolution airborne photography and airborne radar (Lidar) to produce a data set to serve as a platform for updating of the lineament map (L > 100 m), but also a training data set on which select potential minor local deformation are selected for more detailed studies, this with the intention to establish for improving the understanding of the nature and properties of local minor deformation zones (MDZ).

Modelling activities include establishment of updated lineament maps (coordinated and linked) and for the threshold lengths of > 100 m and < 100 m, followed by a stochastic address of MDZ with special focus on the repository volume and repository depth. The detailed surface data can be used for validation and verification purposes. There also exists a need to decide on a useful cut-off on the size of the deformation zones included in the deterministic model (presently 1,000 m, which may be too small). A perhaps even more important activity is to transfer the understanding of the performed characterisation to the identification of MDZ as part of single-hole interpretations (SHI), and also to generalise the findings of the MDZ project to a larger area.

The existing Lidar and high resolution geophysics (resistivity and magnetics) will be key input to the continued modelling. Following field control some 8–10 MDZ objects, covering representative orientations, are selected for further studies. At these selected sites attempts will be made to clear the surfaces of the MDZs along their surface exposure, which will enable compilation of photo mosaics, simplified sketches of the networks of fractures, and to perform geological mapping.

4.1.5 Geological DFN model

The primary role of the geological DFN is to assess (in Repository Engineering) the degree of utilisation and the probability of mechanical damage (in Safety assessment) due to shearing. However, the latter could only occur in case a canister is erroneously emplaced in deposition hole intersected by a too large fracture or MDZ The geological DFN-model is also used as input to the hydraulic DFN, since flow is only considered to take place along fractures. However, since many fractures are non-conductive, and only few fractures are needed to provide a connected fracture network, there is potentially only a relatively weak correlation between the geological DFN and the hydrogeological DFN. Confidence in the geological DFN models is required to enhance understanding. This also calls for an assessment of the coupling and possible correlation between the geological DFN and the hydraulic DFN models. The hydrogeological DFN is further discussed in Section 4.3.1.

Modelling activities include use of MDZ statistics (see above) as input and for verification purposes and for testing the assumed size distribution. This also implies a reassessment of what borehole features that should be included in the DFN model and how these features are included in the single-hole interpretation, see Section 4.1.4. There is furthermore a need to analyse the spatial variability in fracture intensity, and in particular a possible correlation between fracture stats (primarily density) and rock domain and proximity to deterministic deformation zones.

The findings from the MDZ project will be important input to the revision of the geological DFN model. In addition, boremap loggings and continued Single-Hole interpretations of the new boreholes (see Section 4.1.3), and updates of the Single-Hole interpretation considering the MDZ findings in existing boreholes will be key new data for the modelling. Important new data for testing out DFN strategies and impact of potential orientation biases are the dedicated short inclined DFN boreholes centred on the two deep cored boreholes KLX09A and KLX11A, respectively. Flow logging (PFL) data are required by data freeze L2.2 in the above DFN boreholes and also from all cored boreholes drilled in the repository volume. Potential new necessary investigations include additional outcrop fracture mapping in the designated potential access area (Oxhagen).

4.1.6 Assessment of reflector M1 – a potential subhorizontal deformation zone?

During the Laxemar 2.1 geological modelling a noticeable correlation was observed between the simplified and extrapolated geometry of reflector M1 and anomalous borehole characteristics in cored boreholes in the south-central parts of the Laxemar subarea. These indications constitute a blend of indicators ranging from fractured (DZ) portions and those being characterised by mafic (gabbro/diortic) rock, cf. Figure 3-9. In the event this interpreted reflector in fact turns out to be a deformation zone it could potentially have a strong impact on location, depth and size of suitable deposition volumes.

Modelling activities to assess the reflector during the early stage of step Laxemar 2.2 include re assessment of seismic data, both reflection and refraction, jointly with an assessment of directional radar data. This is complemented by calculating theoretical reflection coefficients based on density to compare with borehole logs and seismics. Verification by hard site investigation data will be obtained through drilling of cored borehole KLX18A where projected intercepts (assuming a planar structure) can be compared with borehole data. Possibilities for cross-hole interference tests will be explored as well as the possibility to conduct vertical seismic profiling (VSP) to improve further the basis for interpretation and description of the reflector.

4.1.7 Surficial subhorizontal zones in southwestern Laxemar

Subhorizontal zones of relatively limited extent have been indicated by the detailed resistivity measurements (CVES) conducted in south-western Laxemar. These measurements have a limited depth view (c. 60 m) but could be indicative of repeated possible patterns of conditions seen at depth. Assessment of these indications will be assessed in conjunction with the revisit of seismic anomalies mentioned above. No further site investigation data are required at this time.

4.1.8 Occcurence, geometry and properties of deformation zones in the local model area outside the focused area

Deformation zones outside the focused area have little impact on the location and size of suitable deposition volumes. They may affect the regional flow pattern and location of migration end points although this is of minor importance for safety analysis. An interesting aspect is the recently noted dolerite dyke associated with deformation zone NS001A observed in borehole KLX20A. It is expected that the core of the dolerite dyke may show a significantly lower hydraulic conductivity, at least in its core parts, whereas the flanks may be more conductive.

Expected modelling actions to further resolve these aspects include the planned deformation zone modelling during model step Laxemar 2.1 and associated hydrogeological model assessments.

No new experimental data are expected north of zone EW007A, the exception being a short cored verification borehole targeted on the dolerite dyke associated with deformation zone NS001A.

4.2 Rock mechanics and thermal issues

The rock mechanics issues include:

- Rock stress magnitudes and orientations in Stress domain I.
- Consistency between stress magnitudes and hydraulic properties (addressed in Section 4.3.5).
- Intact rock mechanics.
- Measurement and modelling of thermal properties at a relevant scale.

4.2.1 Rock stress magnitudes and orientations

The rock stress magnitude and orientation is important for the design of the repository and for assessing mechanical stability. Apart from the rock engineering implications, rock stress will also affect the potential for thermally induced spalling after deposition of the spent nuclear fuel. This affects the long term performance.

Data requirements include new stress measurement data from KLX12A. The overcoring data from this borehole show a wide spread at the three depth levels measured, although data appears to be shifted toward the lower bound of Stress domain I, as given in SDM L1.2. A question in this context is whether a large uncertainty span is acceptable in the repository volume (close proximity of stress borehole KLX12A), and an even larger uncertainty span more distal to KLX12A.

4.2.2 Intact rock mechanical property dependence on mineralogy and alteration

The mechanical properties of intact rock (uniaxial compressive strength and crack initiation strength) are of importance for assessment of thermally induced spalling. A clear dependence between mineral content and strength has been observed, the lower the quartz content the lower the strength. This has implications for the focused area in Laxemar which is featured by lower quartz content and in addition is located primarily in Stress domain I, featured by medium to high rock stresses.

Modelling activities to address the issue include detailed study the relationship between UCS/CIS and the quartz content. Furthermore, the relationship between tensile strength and density (alteration) has been studied. For the latter, preliminary results suggest an increased tensile strength with density for quartz monzodiorite, but not so for Ävrö granite. Preliminary results suggest a decrease in UCS with increasing density. In addition a dedicated action will be directed to better understanding the spatial variability in mechanical properties.

The data needed to address the issue include new laboratory data on samples of quartz monzodiorite and Ävrö granite in south-western Laxemar. These data will improve the statistical basis in the focused area.

4.2.3 Representativity, spatial variability and scaling of thermal conductivity

The dioritic to gabbroic rocks in the Simpevarp Laxemar area are generally characterised by a low thermal conductivity, and also by high spatial variability in conductivity. It is envisaged that a reduction of the uncertainty in the spatial variability of thermal conductivity would entail permit a more efficient design of the repository.

The modelling activities taken include adoption of the planned subdivision of rock domain RSMA01 in two varieties, depending on the basis of quartz content, and by a geostatistical modelling approach intended to capture the spatial variability with the domains. There exists a need to further assess the spatial variability within thermal domains, the latter strongly correlated with geological rock domains. The new boreholes planned will allow for more representative rock samples within the focused area.

4.3 Hydrogeological issues

The hydrogeological issues, which are intimately coupled to geology, hydrogeochemistry and bedrock transport properties, comprise:

- Hydraulic properties of hydraulic rock domains in the repository area and their variability.
- Hydraulic properties of hydraulic conductor domains and their variability.
- Regional scale hydraulic properties.
- Systematic exploration of conditions/process that govern groundwater flow.
- Consistency check between stress situation and hydraulic conditions.

4.3.1 Hydraulic properties of hydraulic rock domains

The hydraulic properties of the rock mass (HRD) in potential deposition areas are of high importance for safety. Of general importance is assessment of the distribution of flow in the repository volumes and assessment of connectivity. Specific safety assessment motives include estimation of flow-related retention properties (radionuclide migration) and the evolution of buffer stability. In the case of repository engineering hydraulic parameterisation is required for routing needs and strategies. Hydraulic anisotropy may potentially affect optimal tunnel orientation, but is considered second order for the final layout.

Particular emphasis is in this context put on the mixed domain (M) and the quartz monzodiorite (D) in southern Laxemar, where no or very small amounts of data existed after data freeze 1.2.

As per data freeze Laxemar 1.2, hydraulic test data essentially only exist from one borehole per hydraulic rock domain which has entailed questioning of the representativeness of the data and expressed needs of more data. The new data in KLX05 suggest low hydraulic conductivity (less than $K=10^{-9}$ m/s) over the major portion of the interval 300–900 m in the borehole, corresponding to Domain (domains D,E and M). New hydraulic test data from KLX12A and KLX11A also seem to confirm this picture. New data in HRD(A) north of Zone EW007A (KLX07) appear to confirm relatively high hydraulic conductivity values in HRD(A). The old data also suggest that the hydraulic anisotropy may be significantly different from L1.2.

An updated hydrogeological modelling strategy has been developed in order to meet these demands. It includes the steps conceptual modelling, quantification and calibration of the main hydrogeological features) and quantification and calibration in repository scale. The last item is firmly related to development of the hydraulic DFN model where the focus is mainly on calibration using PFL-data. A continuous process is to consider the correlation between Hydro and geological DFN-analyses. In this context there is also a need to explore the overall correlation between PFL-signals and MDZ indications – what basis exists for assigning hydraulic significance to MDZs. The developed hydraulic DFN may also be used to assess different options for connectivity in the rock mass.

Even if the special, but relatively surficial DFN-holes at KLX09 are very interesting, there is a need to limit the scope on analysing them, since they are not located in the potential repository volume. Although the DFN holes should be used for demonstration of new DFN strategies, focus should be put on correlation between outcrop and borehole making use of the more versatile directional data involved. The surficial DFN-holes near KLX11 may in this respect be very useful as these are located in the potential repository volume.

New hydrogeological test data will emerge from the following existing and planned cored boreholes: KLX07 (Domain A), KLX08 (Domain A, M, D), KLX10 (Domain A, M, D), KLX09 (Domain A), KLX11A (Domain D), KLX12A (Domain M), KLX13A (Domain A, M, D), KLX18A (Domain M, A). Data from the above boreholes may be sufficient, although there still is some directional bias (especially in relation to the principal horizontal stress orientation (NW) direction). It would therefore be potentially useful to obtain hydraulic test data from another borehole orientation in the key area of the deposition. In doing so, it is important to incline boreholes significantly e.g. dip 70–60 degree and that the borehole data used for anisotropy evaluation (with different dip directions) can be said to be in the same structural and stress domain. Additional data on the KLX12/KLX05 drill site (targeted on the potential central area Oxhagen) may be useful, but realistically another hole cannot be completed and logged for data freeze L2.2. so such hole could only be seen as a further confirmation for L2.3. Overall, the L2.2 data are expected to provide indications on whether there is any significant anisotropy.

4.3.2 Hydraulic properties of HCDs (spatial variability, anisotropy and scaling)

A better understanding of the hydraulic properties of HCDs, especially in the focused area, would improve the site scale flow modelling. It affects the extent of grouting needed and locally affects the assessment of drawdown although these aspects are not critically important. It is furthermore important for the distribution of groundwater chemistry. In Safety Assessment it is conservatively assumed to be no transport resistance in large deformation zones. However, migration properties in MDZ (as included in the HydroDFN) may still be of importance, but are not critically important.

Modelling activities to resolve the issue include demonstration of the hydraulic significance of the HCDs (visualisation, Step#1 in new strategy). Comparison and evaluation of test data at different locations, both in terms of variable structural and stress domain, and variability along and also across HCDs. However, variability along individual HCD can only be studied in a few cases and then with very few direct observations (= borehole intersections. The latter aspect relates to the possible barrier effect that a fault gouge filled deformation zone may have on groundwater flow. The DFN aspects of MDZ are covered in Section 4.3.1.

4.3.3 Processes and conditions that govern the distribution of groundwaters

In the Laxemar 1.2 modelling it was not possible to fully match measured and modelled chemistry data. It therefore exists a need for a systematic assessment of the effects of e.g. initial and boundary conditions. Many of these aspects are expected, at least in part, to be assessed as part of the Laxemar 2.1 "consolidation modelling" and Laxemar 2.2 "Preliminary modelling". The data needs are covered by the account in Section 4.3.1.

4.3.4 Consistency between stress situation and hydraulic anisotropy

Assessing the consistency between stress magnitudes, stress orientations and observed anisotropy in hydraulic conductivity would enhance understanding. Further, assessment of hydraulic data is needed to establish the strength of anisotropy and depth dependence. However, if there is such a coupling it would most likely not be due to the direct coupling between stress and fracture aperture, since this coupling reaches a residual value already at moderate stress levels. This also means that coupled hydro-mechanic modelling is not seen as the way forward.

New data include rock stress data from KLX12A, fracture data and hydraulic test data from "DFN boreholes" at the KLX09A and KLX11A drill sites. As the principal horizontal stress orientation is NW direction, the data from nearby boreholes oriented NE (or SW) and NW (or SE) are preferred to assess anisotropy in hydraulic properties.

4.4 Hydrogeochemical issues

The Hydrogeochemical issues include:

- Presentation of overall conceptual model for groundwater evolution.
- Variability and spatial distribution in hydrogeochemistry at repository depth.
- Uncertainty in selection of end-member groundwater chemistries.
- Redox and alkalinity buffering capacity of the bedrock.
- Dilute groundwaters in conjunction with future glaciations.
- Consideration of elevated sulphide contents in old boreholes.
- Interaction between surface water and groundwater.
- Conservatism of natural tracers.

4.4.1 Presentation of overall conceptual model for groundwater evolution

There exists a strong need of a further development of the conceptual models for groundwater evolution. Enhanced understanding will improve the predictions of groundwater composition in the long term (e.g. during glaciations) of Eh, pH, divalent cations etc. This, in turn, is of vital importance for the future evolution of the Engineered Barriers (buffer and canister).

The running hypothesis is that reactions mainly takes place near the surface where infiltrating meteoric water is buffered with respect to redox, alkalinity etc, whereas after this buffering water composition is mainly altered by mixing due to advection with the groundwater flow. However, the nature of the near-surface reaction zone needs further study. It is of high importance to show existence of a non-organic (weathering) reaction zone. If the reactions are coupled to organic matter and microbiology this near-surface buffering will be much less effective over long terms (e.g. during glaciations) than if the reactions are a result of a non-organic nature.

These issues will be addressed within the ChemNET modelling activities, by assessment of DFN-hole fracture mineralogy combined with surface water samples analyses. and by enhanced integration with hydrogeology (see new hydromodelling strategy Step #2 and also Section 4.3.3). An additional challenge is to make optimal use of existing (and planned) "low quality" water samples, i.e. samples that contain too much drilling water.

Data needs include results of fracture mineralogy characterisation of the cored DFN-holes (e.g. what is the depth extent calcite dissolution, rust, etc). Some additional water samples would be useful, the location of which are to be discussed with hydrogeology. It is not clear if there are enough samples from typical recharge areas. Assessing more simplified groundwater sampling from planned boreholes could be an alternative. Still, the practical possibilities for enhancing the chemical sampling are limited.

4.4.2 Variability and spatial distribution in hydrogeochemistry at repository depth

It is suggested that there are too few representative samples in L1.2. This is partly remediated in Laxemar 2.1 but there is still a lack of information in parts of the deposition volumes. The modelling methods required include the standard procedures already employed. In addition, it would be advantageous to also consider the "semi-quality" data from the hydraulic domains HRD(D,E,M).

The data needs include data from the ongoing hydrogeochemical sampling in KLX08A complemented by a full hydrogeochemical characterisation in borehole KLX13A. As mentioned above there is a growing concern that there will not be any high-quality groundwater samples from HRD(D,E,M). A possible resolve may be to assess more simplified groundwater sampling from planned boreholes.

4.4.3 Uncertainty in selection of end-member groundwater chemistries

There exists a need to improve understanding of the effects of the uncertainties in end-member groundwater chemistries (including that of the intact rock matrix). In this context consistency is also sought with groundwater flow modelling, cf. Section 4.3.3. Modelling activities include sensitivity analyses on end-member composition (examples already given in SDM L1.2). Furthermore, understanding in the flow modelling should be enhanced that there are no fixed compositions and that the groundwater dating is associated with uncertainty. Finally, the end-members should not be used as tracers in the modelling, but rather predict the migration of some major species (e.g. Cl, O-18, ..) and then if desired) apply M3 on model results (in collaboration with Hydrogeochemistry).

4.4.4 Redox and alkalinity buffering capacity of the bedrock

The redox and alkalinity buffering capacity of the bedrock is important for the groundwater composition and possible future changes thereof, e.g. due to a potential intrusion of oxygenated water in conjunction with future glaciations. Foreseen modelling activities include employment of coupled flow and reaction modelling. Existing previous redox analyses and assessments should be compiled, included performed modelling. It should in this context be taken into consideration that Laxemar is situated in an area characterised by recharge, whereas Äspö HRL (for which assessments are available) is located in an area characterised by discharge. This issue is also directly linked to the revisit of the hydrogeochemical conceptual model, cf. Section 4.4.1.

Data needs include results from planned/on-going characterisation of fracture minerals (Fe(II) and sulphides), partly in the DFN-boreholes. These investigations will increase e.g. the understanding of the location of the redox front in the bedrock. Finally, there is a need for data for estimation of the alkalinity buffering capacity of the rock.

4.4.5 Dilute groudwaters in conjunction with future glaciations

There is a risk that too dilute groundwaters, i.e. too low concentrations of Ca and Mg, could pose a treat to the stability of the bentonite buffer. The current concern is that if the Ca concentration is less than 1 mM over a longer period of time, this could entail chemical "erosion" of the bentonite. This issue is intimately coupled to the reassessment of the hydrogeochemical conceptual model, see Section 4.4.1 for discussion of the required modelling activities and data needs.

4.4.6 Consideration of elevated sulphide contents in old boreholes

In the recently concluded SR-Can analyses concern has been raised regarding the validity of sulphide concentrations above 10^{-5} M as noted in Äspö HRL boreholes and in if correct could have potential detrimental impact on canister corrosion, if combined with bentonite buffer density losses as described in Section 4.4.5.

Modelling activities include revisit of the data as such – most likely no errors have been made in the laboratory, but errors may have been in the sampling. Furthermore the importance of intrusion of marine water should be assessed. The issue is also related to the revisit of the hydrogeochemical conceptual model, cf. Section 4.4.1. The data needs are those defined in Section 4.4.1 plus improved characterisation of microbes near the ground surface.

4.4.7 Interaction between surface water and groundwater

The interaction between surface waters and groundwaters is intimately coupled to the conceptual model, cf. Section 4.4.1, and affects the understanding of the present system and confidence in our ability to predict future changes. Modelling and data needs are the same as those listed in Section 4.4.1.

4.4.8 Conservatism of natural tracers

Concern has been raised that the natural traces ^{2}H and ^{18}O, traditionally in hydrogeological modelling contexts assumed conservative, in fact are subject to reactions. The question is whether the residence times are sufficiently long to allow reactions to occur along the flow paths. This will be assessed by scoping modelling. No need of additional data identified.

4.5 Bedrock transport issues

The remaining issues related to the bedrock transport properties concern both flow-related transport properties, especially channelling, and migration properties (i.e. material properties) of the rock matrix. These issues are described further below.

4.5.1 Flow-related transport properties – channelling

The transport resistance, or F-factor, is a measure of the potential for solute retention along flow paths in the fractured rock and is simply defined as the flow-wetted surface to flow ratio. Indeed, it is the F-factor and a materials property group, combining both diffusive and sorptive properties of the rock, which are the central parameters for the estimation of the solute residence time distribution, and thus both affect the evolution of groundwaters and the retention of radionuclides if they were to be released from the repository. The interconnectivity, complexity and channelling characteristics of fractured rock affect the F-factor. Current hydraulic DFN models do not capture all aspects of channelling, but the main ones are possibly already incorporated. For fractured rock systems where diffusive exchange with the rock matrix dominates the solute residence time distribution, the magnitude of the surface area over which matrix diffusion takes place is a key entity governing solute transport.

Further modelling activities that will be carried out to reduce uncertainties in the F-factor and its distribution involve analyses of the sensitivity to different assumptions concerning flow path geometry and transmissivity, building on the analyses carried out in the PSE for Laxemar /SKB 2006g/ and in version 1.2 of the Laxemar site descriptive model /SKB 2006a, Crawford 2006/. In addition, it is intended that a more complex analysis will be undertaken using DFN models as a complementary activity to the above. Modelling actions related to use of hydraulic DFN models are assessed in Section 4.3.1.

It has been concluded that it is difficult to carry out more experiments from the surface to characterise flow-related transport parameters, especially channelling within individual fractures. It will, however, be possible to perform more detailed investigations during the construction phase. Notwithstanding this we note that a suite of in situ tracer tests are planned including tracer dilution, long term pumping, and SWIW tests for the Laxemar site during the remaining time available in the site investigation. These are important confirmatory tests for establishing the qualitative existence of retardation. These issues will be further addressed in the position paper under preparation concerning the utility of tracer tests.

4.5.2 Migration properties of the rock matrix

The retention properties of the rock matrix (i.e. porosity, diffusivity and sorption properties), are important input to safety assessment analyses of radionuclide migration from a repository at the site. These properties are also important for understanding the water chemistry at the site and thus also for enhancing confidence in, or providing direct input to the hydrogeological model.

The diffusivity in the rock matrix is quantified through the formation factor, which is determined both by measurements in situ and in the laboratory. Although both provide results that are internally consistent, there is a considerable systematic difference between the results obtained in the in situ measurements and the corresponding laboratory measurements.

There are substantial uncertainties in the parameterisation of the sorption properties of the rock. This stems partly from the long times required for laboratory characterisation of the samples leading to a somewhat delayed delivery of material properties data for bedrock transport property parameterisation. Other uncertainties relate to the use of crushed material which can give sorption K_d values that are substantially overestimated by as much as an order of magnitude, or more depending upon the relation between sorptive surface area of the crushed rock used in laboratory measurements and that of the intact, in situ rock. Currently this is dealt with by performing measurements on multiple size fractions of crushed rock and using an extrapolating procedure to estimate data for intact rock. Problems relating to the extrapolation of data in this manner as well as the physical interpretation of time dependent effects in sorption experiments are significant factors contributing towards the uncertainty of the sorptive properties estimated for different rock types.

Analyses of new results from on-going and planned laboratory and in situ experiments in combination with further hydrogeological and hydrogeochemical modelling will contribute to reduce uncertainties in bedrock transport properties. One specific issue of importance in the context of formation factors measured in situ is related to the composition of the pore water in the rock matrix and the possibility to quantify uncertainties in the analyses of this water. This should be further explored.

Already on-going and planned in situ and laboratory experiments for measuring matrix retention properties will provide a data set that has been judged sufficient for handling uncertainties as they are presently understood. Concerning sorption it has been concluded that on-going and planned SWIW tests can demonstrate the existence of sorptive solute retention and give an indication of its magnitude, at least over the short The long-term diffusion experiment (LTDE), already underway at the Äspö Hard Rock Laboratory aims to give indications of sorptive-diffusive properties of the rock matrix under conditions that more closely resemble those that would characterise a repository environment. Measurements of K_d on larger samples from boreholes are already planned as a complement to the LTDE experiment. This should go some way towards resolving some of the issues of data representativity.

4.5.3 Validation of rock mass flow-related transport properties

The validation of flow-related transport properties through some type of integrating test over considerable distance is important for understanding. However, it will not be possible to fully validate migration modelling in relevant repository volumes. A position paper outlining the possibilities and limitations of tracer tests is currently in preparation. The main findings of this investigation are:

- Field scale tracer tests can confirm flow connectivity.
- Field scale tracer tests can confirm the existence of retention.
- Field scale tracer tests alone can only broadly substantiate our process understanding.
- Field scale tracer tests can deliver the "apparent" numerical product of the material property group (MPG) and the F-factor, valid only for the tracer test configuration, but not separate them without introducing further assumptions.
- Field scale tracer tests alone cannot deliver individual transport parameters, such as effective diffusivity, flow-wetted surface, etc.
- If lumped or individual transport parameters are abstracted in some manner from tracer tests, these are not directly transferable to safety assessments and are likely to be highly non-conservative.

4.5.4 Low Am(II) K_d values a possible experimental artefact

The Am(II) K_d values reported for Laxemar 1.2 are found to be 3–4 orders of magnitude lower than batch sorption values in the literature. This is possibly due to experimental difficultities, but needs to be resolved, since low Am sorption would also imply low sorption of other actinides. It is also possible that previous investigations have neglected surface area effects and other aspects of data evaluation that have led to overestimation of K_d values for these substances in the literature data. This is currently under investigation. Modelling activities include reassessed interpretation methods and further assessment of the effects of altered and non-altered samples (and definition of alterations).

Data needs include corroborating laboratory experiments. Completion of the tests will probably provide much less uncertain (and more reasonable) values. These data needs are covered by existing plans.

4.6 Surface properties

The remaining surface ecological issues relate mainly to the description and understanding of the mutual interface between the surface system and the bedrock system. This interface pertains mainly to geology, hydrology/hydrogeology and chemistry.

4.6.1 Shore line displacement and chemical evolution of the Baltic

There exists a need to lay firm the premises for unified description of shoreline displacement and chemical evolution of the Baltic since the latest glaciation. This in order to properly model the successive evolution of the palaeohydrogeological flow system over time and the associated evolution of groundwater chemistry. Modelling activities to resolve this issue is to hold a Baltic workshop involving, apart from the Forsmark teams also the Finnish team working at Olkilouto.

No additional data are required.

4.6.2 Hydraulic properties of near-surface rock

This issue is important for assessing inflow and grouting requirements in shafts and tunnels. Also important for understanding near-surface chemistry and for enhancing confidence in the hydrogeological model. Can possibly affect the location of migration end points (entrance points to the surface system).

Data requirements include time series of streamflow data for model calibration.

4.6.3 Impact of surface conditions on bedrock conditions

This issue involves impact of surface and near-surface hydrology and hydrochemistry on bedrock hydrogeology and hydrogeochemistry.

Needs to be specified (see also items Hydraulic properties of near-field rock above and spatial variability in groundwater composition (Section 4.4.2)).

5 Implications for site investigation programme

This chapter reviews the implications for the remainder of the site investigation programme in order to resolve the identified remaining critical issues as described and discussed in Chapter 4. Focus is here primarily put on changes and modifications in relation to the Complete Site Investigation programme (CSI) /SKB 2006c/. The modifications and additions concern all aspects of the remaining site investigation programme, including drilling, borehole investigations, surface-based investigations and laboratory analyses. The outcome discussed in this chapter is based on modelling work performed during model step 2.1 (Geology, Thermal properties, Rock mechanics, Hydrogeology, and Hydrogeochemistry). The work here ranges from full model descriptions (Thermal properties and Hydrogeochemistry), to variable amounts and degrees of consolidation modelling in preparation for model step 2.2 (Geology, Rock mechanics and Hydrogeology). For some disciplines (Bedrock transport properties and Surface system) the assessments are essentially based on the modelling and the underlying data base which formed the basis for model step 1.2.

It is noted that select data and information made available after data freeze Laxemar 2.1 have been used in the assessment of implications for the site investigation programme. This is motivated by the fact that this information has been continuously assessed by the site investigation, repository engineering and site modelling teams within the framework of so-called SUMP-meetings, aimed at providing guidance to the site in carrying out the site investigation programme.

The text provided in the forthcoming sections is intended to give an overview of the investigations proposed with reference to the critical issues raised in Chapter 4.

5.1 Cored boreholes

A general observation is that the drilling programme presented in Section 3.6 of the CSI programme /SKB 2005b, SKB 2006c/ largely stands. This drilling programme includes a blend of further investigation of potential deposition areas (KLX12A, KLX13A, KLX18A) and verification of interpreted deformation zones (KLX14A, KLX15A, KLX17A, KLX19A, KLX20A and KLX21A). To these boreholes should also be added some 15–20 boreholes making up the DFN-boreholes in conjunction with the KLX09A and KLX11A drilling sites and additional targeted drilling on interpreted minor local deformation zones (part of MDZ project). Relative to the proposed programme, two additional cored boreholes are proposed. The first (KLX16A, NB notation per August 2006) is a short borehole with the objective to further investigate and verify the nature and characteristics of the interpreted high confidence deformation zone NS001A (also investigated by borehole KLX20A). The second borehole (KLX21B) is intended to be drilled in a SW orientation in the relevant deposition area in the south east. Results from this borehole can complement geological and hydrogeological assessment of anisotropy. Furthermore, the two proposed cored boreholes on deformation zones NS059A and NS046A, respectively, are attributed questionmarks pending the outcome and joint evaluation of additional refraction seismic profiling and percussion-drillings on these zones, cf. Figure 5-1 In conclusion, the number of cored boreholes during CSI is expected to remain essentially constant, although with slight redispositions and changes to the total drilled borehole length.

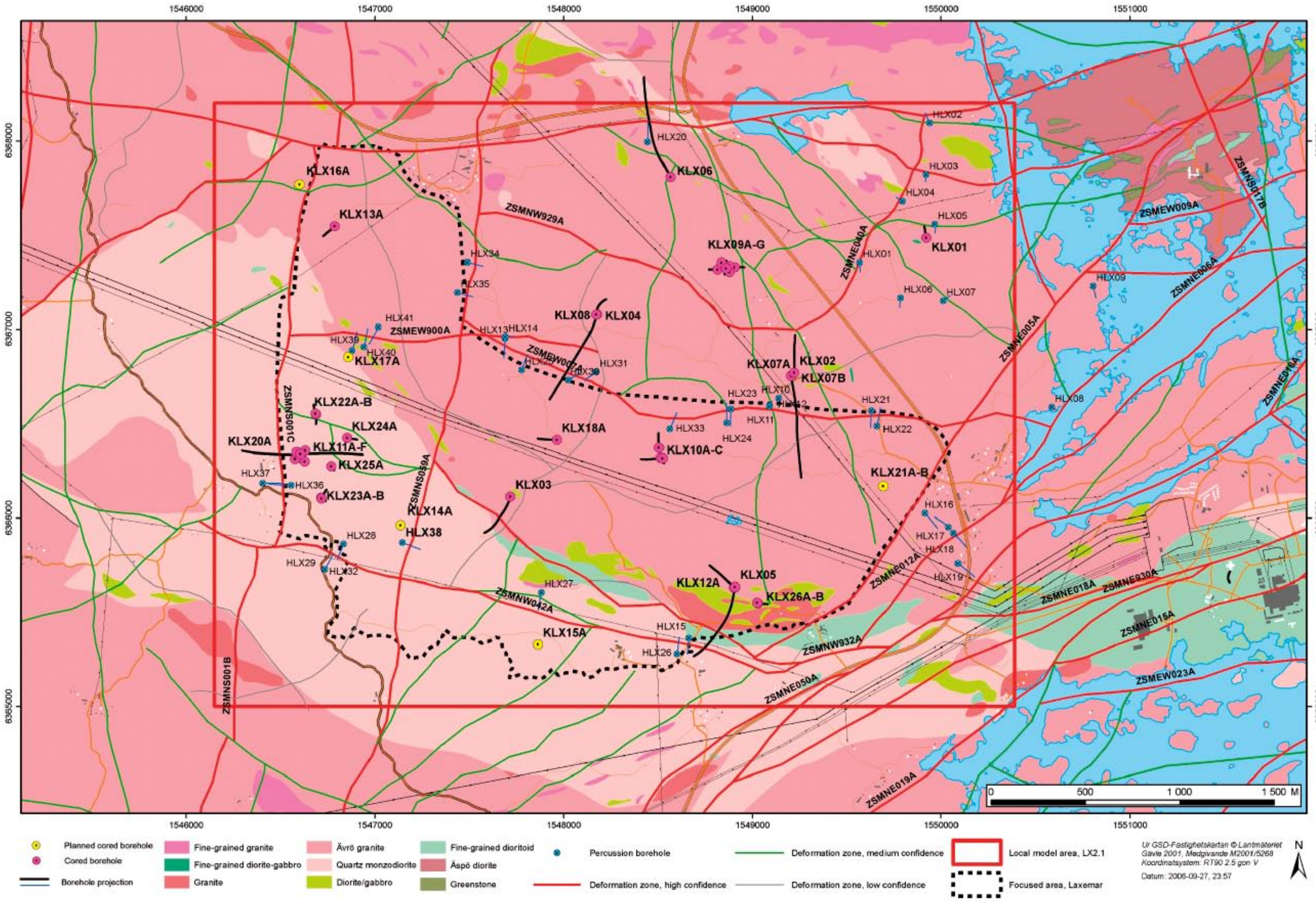


Figure 5-1. Plan view of existing and boreholes in the Laxemar subarea. NB. Positioning and targeting of KLX15A and KLX16A as of mid September.

5.1.1 Borehole KLX16A

This borehole is intended to corroborate the recent findings from borehole KLX20A, cf. Figure 5-1, which indicted that the core of the southern part of ZSMNS001A is composed up of a dolerite. The potential barrier function of the dolerite could have a strong impact on the flow conditions in the Laxemar area. The aim of the proposed additional borehole is to verify the existence and characteristics of the dolerite core also in the northern parts of Laxemar, between the NS001A's intercepts with the east-west trending zones EW002A and EW900A. The characterisation programme includes assessment of the geological characteristics of the dolerite dyke it terms of petrophysics, fracture characteristics, homogeneity and continuity along its extent. However, the most important component of the ensuing borehole investigations is the characterisation of the zone's hydraulic properties, both in terms of the transverse hydraulic properties (potential barrier function) and the hydraulic properties (magnitude and continuity) of any flanking open fractures associated with the dolerite dyke.

5.1.2 Borehole KLX21B

A need has been identified to investigate the deposition areas in the southeast part of the focused area, immediately west of zone NE005A (Äspö shear zone). Information from this borehole will complement information from boreholes KLX07A, KLX05A and KLX12A. Furthermore, by drilling this borehole in a essentially southwest direction, fracture data and fracture filling mineralogy from the borehole will be highly relevant for the ensuing geological DFN modelling and also for characterising the hydraulic characteristics of identified fracture sets. The current borehole array and associated data are slightly biased towards being collected in vertical of very steeply inclined boreholes. The data collected from the multi-hole DFN borehole arrays centred on the KLX09A and KLX11A drill sites provide important additional information covering the most relevant orientations and fracture sets. However, given the surfical nature of the latter boreholes, there is a need to collect additional information also at depth.

5.2 Other investigations

Overall the defined CSI programme of percussion drilling, surface investigations, borehole investigations in existing or planned boreholes and laboratory investigations is expected to satisfy the data needs for the data freeze Laxemar 2.2. In the following the complementary investigations required to resolve the identified remaining critical issues are reviewed.

5.2.1 Percussion-drilled boreholes

The programme for percussion drilling has multiple objectives. Foremost, the percussion drilling is used to establish the geometry of deformation zones before employing core drilling. The resulting array of boreholes can subsequently be used to assess integrated properties (hydraulic conductivity and connectivity) of deformation zones between boreholes. A similar approach is also occasionally applied in conjunction with characterisation of minor local deformation zones. No additional percussion boreholes with specified additional objectives are required.

5.2.2 Surface investigations

As indicated in Section 4.6.2, there is a need to improve the description of near surface hydraulic properties. Assessment of these properties can in part be assessed by direct measurements in surficial boreholes with no, or with casing of smaller extent (most existing cored boreholes have casings extending to 100 m). Given that the number of new data collection points is expected to be minute, one would partly have to resort to indirect assessment using modelling. For this purpose time series measurements of streamflow are proposed to serve as calibration data for supporting indirect assessment of material properties. Using the improved description of near-surface properties the description and modelling of the interplay and linking between the surface and deep bedrock systems with regards to hydraulics, hydrogeochemistry and transport can be improved, cf. Section 4.6.3.

A second recommendation is to carry out digging of extended trenches with alternate orientations in the focused area. The trenches would serve to corroborate the linked lineament interpretation, general fracture pattern and would in particular serve as an important complement and tool for generalisation of the results of the interpreted MDZs. Furthermore, fracture statistics inferred along the trenches could be used to study variation in fracture frequency in the proximity of deformation zones. The positioning and orientation of such dug trenches are restricted by the relatively deep soil cover in southwestern Laxemar. Therefore, the trenches would preferentially have to be located to connected patches of outcrop rock to minimize digging costs and to obtain data in due time. The proposed series of dug trenches are indicated in Figure 5-2

5.2.3 Integrated assessment of reflector M1

One of the outcomes of the Laxemar 2.1 geological modelling work is the reappraisal of the reflection-seismic reflector M1 in the focused area. The reflector is variably associated with mafic rock and/or fracturation as indicated in Section 4.1.6. In the event the ongoing joint reinterpretation of available geophysical and geological data provide support for M1 being associated with a deformation zone, additional experimental activities are proposed to assess the significance of the potential zone. The proposed investigations include hydraulic testing, and preferably attempting to assess the potential zones hydraulic continuity using cross-hole interference tests. An alternative investigation technique which could be used to map the potential deformation zone's extension is vertical Seismic Profiling (VSP). The two proposed investigation methods, conditioned on the ongoing joint seismic evaluation, could make use of cored borehole KLX18A.

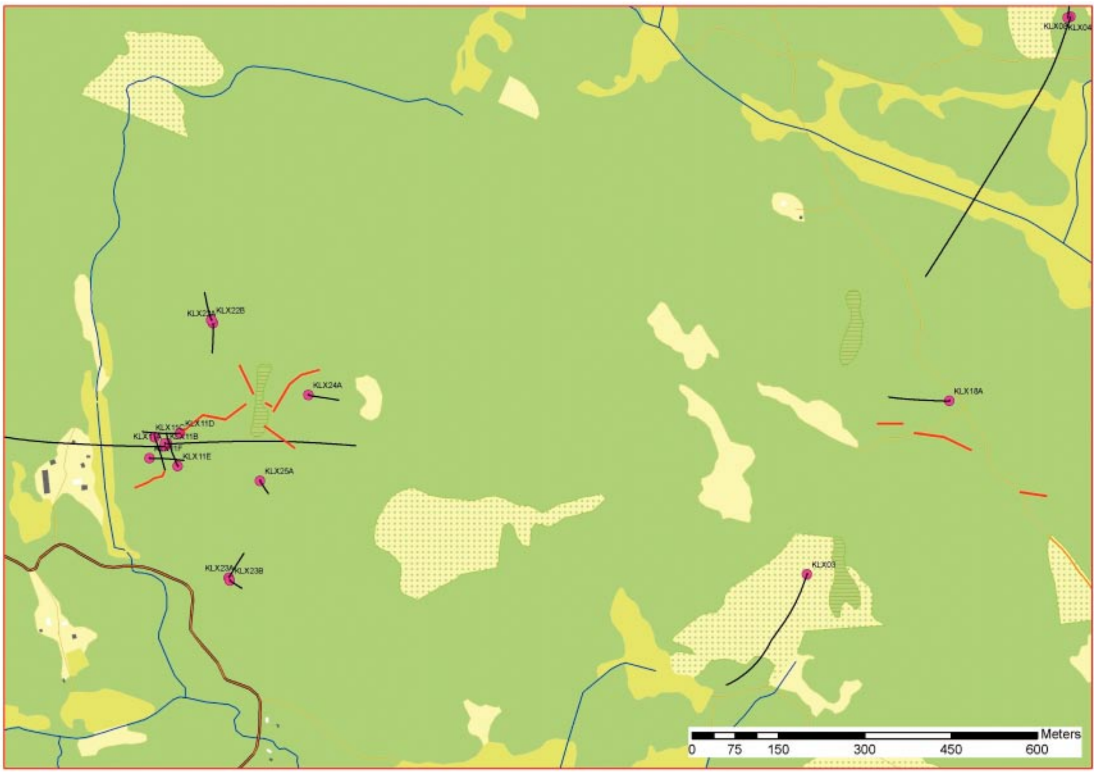


Figure 5-2. Plan view showing traces of planned dug trenches (red) in the Laxemar subarea.

5.2.4 Cross-hole measurement of thermal conductivity

Statistical parameters which describe thermal conductivity within a rock mass, in particular its variance, vary according to the scale considered. In practice, the most appropriate scale to measure variability within the rock volume is at the metre scale. At this scale, the small-scale variations in thermal properties, caused by mineral grains, have been levelled out, with a resultant reduction in variance. There is a lack of measurement data for the metre scale, which means a considerable uncertainty in the current thermal model. Upscaling of small-scale measurement data (e.g. laboratory measurements, indirect determinations from density logging) by theoretical means involves uncertainties in the estimation of variance. Therefore field measurements are preferable. A modified multi-probe method for measurement on surface outcrops at the metre scale has been chosen for field measurements. Three parallel boreholes, c. 3 m long and c. 25 mm in diameter, are drilled as illustrated in Figure 5-3. A heater is placed in the centre hole and temperature sensors are placed in the peripheral holes. From the temperature-time data it is possible to evaluate the thermal properties of the rock.

5.2.5 Simplified groundwater sampling in planned cored boreholes

There is a great need to obtain hydrogeochemical data from the repository area, and in particular from hydraulic rock domains HRD(D,E,M). A careful selection of the sampling will be considered in KLX13A with additional sampling in KLX17A. Given that only a few cored boreholes remain to be drilled, and revisiting of existing instrumented boreholes is restricted, there is a need to use more simplified groundwater sampling methodologies, both in planned and existing boreholes, to increase the database. A question to be resolved is how this alternative and simplified method can be employed without lowering stipulated ground water quality standards, e.g. with regards to drilling water content.

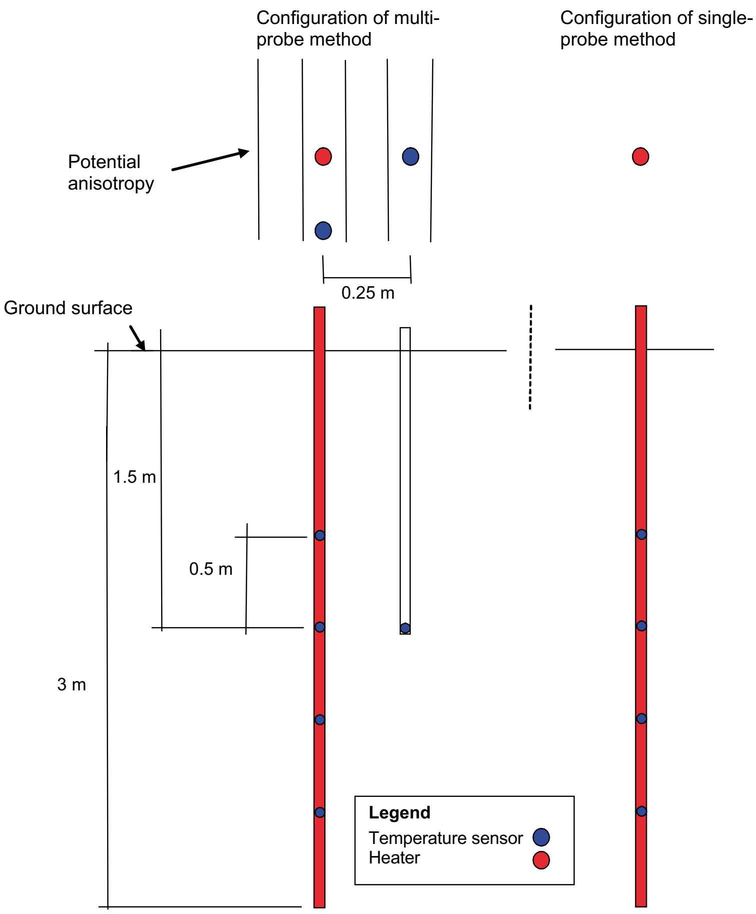


Figure 5-3. Schematic diagram of modified multi-probe method and single-probe method.

5.2.6 Additional assessment of matrix pore water composition

Matrix pore water sampling has been performed in KLX03A and KLX08A and has recently been attempted in KLX13A, although the latter which failed due to the highly fractured nature of the borehole at interesting depths. Additional sampling for matrix porewater will therefore be made in an alternative borehole (KLX17A), cf. Figure 5-1. Groundwater sampling from water-conducting zones in KLX17A is therefore recommended to provide supporting valuable data for pore water interpretation.

5.2.7 Tests demonstrating in situ retardation

Further in situ SWIW tracer tests are planned for Laxemar. These are important confirmatory tests for establishing the qualitative existence of retardation. In addition the LTDE project currently underway at the Äspö Hard Rock Laboratory intends to demonstrate coupled diffusion and sorption into the rock matrix under in situ conditions (metre scale).

6 Conclusions

The purpose of model step Laxemar 2.1 has been to provide important feedback to the site to ensure an adequate and efficient finalisation of the complete site investigations. In practice, the site modelling project has in part been involved in such process since mid 2005, i.e. even before finalising the Laxemar 1.2 modelling.

It is noted that the modelling and the site investigation teams have collaborated in a close fashion during model step 2.1, both in conjunction with identification and delineation of the focused area in Laxemar /SKB 2005c/. Subsequently, the modelling team also contributed actively to the development of the CSI programme /SKB 2005b, SKB 2006c/. In succession to these activities, the modelling team has also participated in integration meetings held at the site on a regular basis, so-called SUMP-meetings, with participation from the site investigation team, repository engineering and the site modelling team. These meetings have served as effective vehicles for implementing, adapting and specifying the CSI programme on a continuous basis. This applies both to general plans and plans for specific objects, e.g. boreholes.

The establishment of the above processes has most likely ensured that most of the critical issues already identified are properly addressed by current CSI plans. However, as outlined in Chapter 5, a number of additional investigations have been proposed as complements:

- Two additional cored boreholes with the purpose of verifying existence of dolerite and improving understanding of potential repository volumes in the southeast.
- Assessment of reflexion seismic data, borehole radar, synthetic reflexion coefficients and single hole geological interpretations with the purpose of exploring evidence of the existence, character and extent of reflector M1.
- In situ experiment of thermal conductivity on the metre scale.
- Simplified borehole sampling and analyses of hydrogeochemistry.
- Additional analysis of matrix fluid chemistry.
- Additional SWIW tracer tests at Laxemar and follow-up of the long-term diffusion experiment (LTDE) at the Äspö HRL, the latter analysing in situ coupled diffusion and sorption on a metre scale.

7 References

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