SITE-94

Mineralogy of the Äspö Site

Karin Andersson

December 1996

30 - 01

SKi

STATENS KÄRNKRAFTINSPEKTION
Swedish Nuclear Power Inspectorate

SKI Report 96:33

SITE-94

Mineralogy of the Äspö Site

Karin Andersson

Technical Environmental Planning,
Chalmers University of Technology, Göteborg, Sweden

December 1996

PREFACE

This report concerns a study which is part of the SKI performance assessment project SITE-94. SITE-94 is a performance assessment of a hypothetical repository at a real site. The main objective of the project is to determine how site specific data should be assimilated into the performance assessment process and to evaluate how uncertainties inherent in site characterization will influence performance assessment results. Other important elements of SITE-94 are the development of a practical and defensible methodology for defining, constructing and analyzing scenarios, the development of approaches for treatment of uncertainties and evaluation of canister integrity. Further, crucial components of an Quality Assurance program for Performance Assessments were developed and applied, including a technique for clear documentation of the Process System, the data and the models employed in the analyses, and of the flow of information between different analyses and models.

Björn Dverstorp
Project Manager

SUMMARY

When performing a safety analysis of a deep rock high level waste repository, a knowledge of the chemical conditions in the groundwater surrounding the repository is of fundamental importance. The water composition has several different types of impact on the repository. It will influence the behaviour of the engineered materials (e. g. corrosion). It may also determine the possible solubility and speciation of released radionuclides, parameters of importance to the potential transport of radioactive elements out of the vicinity of the repository. It also acts as a transport medium for the released elements. The groundwater composition and the potential development of the composition due to the presence of the repository as well as due to external variations is thus an important issue in a safety analysis.

The development of the groundwater composition is strongly dependent on reactions with the minerals present in water bearing fractures. Here equilibrium chemistry may be of importance, but also reaction kinetics is important to the long-term behaviour.

Within the SITE-94 project, a safety analysis is performed for the conditions at the Äspö site, SE Sweden. The mineralogy of the area has been evaluated from drill cores at various places at the site. In this report a recommendation for selection of mineralogy to be used in geochemical modelling of the repository is given.

Calcite and iron containing minerals like in most sites in Sweden, dominate the fracture filling mineralogy at the Äspö site. Some typical fracture filling mineralogies may be identified in the fractures:

- Epidote, chlorite, calcite, some illite/smectite + quartz, fluorite, pyrite and goethite.
- Epidote, chlorite, calcite, hematite and other minor minerals

In addition to these a number of minor minerals are found in the fractures.

Uncertainties in the fracture filling data may be due to problems when taking out the drill cores. Drilling water may remove important clay minerals and sealed fractures may be reopened mechanically and treated as water conducting fractures. The problem of determining the variability of the mineralogy along the flow paths also remains. This problem will never be solved when the investigation is performed by drilling investigation holes.

SAMMANFATTNING

För att utföra en säkerhetsanalys av ett djupförvar för högaktivt avfall är kunskap om de kemiska förhållandena i grundvattnet i förvarets omgivning av största betydelse. Vattensammansättningen har flera olika typer av inverkan på förvaret. Den påverkar beteendet hos konstruktionsmaterial, t. ex. korrosion. Den kan också vara av betydelse för löslighet och kemisk speciering hos frigjorda radionuklider, något som är av stor betydelse för transport av radionukliderna ut från förvarets närhet. Vattnet utgör också transportmedium för de frigjorda ämnena.
Grundvattensammansättningen och den potentiella utvecklingen av denna på grund av att förvaret finns till och på grund av yttre variationer är således en betydelsefull fråga i säkerhetsanalysen.

Utvecklingen av grundvattensammansättningen är starkt beroende av reaktioner med mineralen i vattenförande sprickor. Här kan jämviktskemi vara av betydelse, men även reaktionskinetiken är viktig för beteendet på lång sikt.

Inom SITE-94 projektet utförs en säkerhetsanalys för ett hypotetiskt förvar på Äspö, Småland. Sprickmineralogin i området har utvärderats från borrkärnor tagan på olika platser inom området. I denna rapport ges rekommendationer för val av sprickmineralogi att användas i geokemisk modellering av förvaret.

Kalcit och järnmineral dominerar sprickfyllnadsmineralogin på Äspö liksom på de flesta platser i Sverige. Några typiska kombinationer av sprickfyllnadsmineral som observerats är:
- Epidot, klorit, kalcit, lite illit/smektit + kvarts, fluorit, pyrit och götit.
- Epidot, klorit, kalcit, hematit och andra mineral i mindre mängd

Osäkerheter i sprickfyllnadsdata kan bero på problem vid uttagande av borrkärnor. Spolvatten kan ta bort viktiga lermineral och slutna sprickor kan bli öppnade igen mekaniskt och därför bli betraktade som vattenförande sprickor. Problemet att bestämma variationen i sprickmineralogi utmed strömningsvägen återstår också. Detta problem kan inte lösas med undersökning av borrkärnor från provhål.

CONTENTS

1. INTRODUCTION

When performing a safety analysis of a deep rock high level waste repository, a knowledge of the chemical conditions in the groundwater surrounding the repository is of fundamental importance. The water composition has several different types of impact on the repository. It will influence the behaviour of the engineered materials (e. g. corrosion). It may also determine the possible solubility and speciation of released radionuclides, parameters of importance to the potential transport of radioactive elements out of the vicinity of the repository. It also acts as a transport medium for the released elements.

When constructing and using the repository chemical changes occur due to the presence of air as well as to changes in materials present and to exposure of fresh mineral surfaces to the water. Changes in groundwater composition may also occur due to naturally occurring external effects like large-scale changes in the hydrogeological conditions, e. g. intrusion of saline waters or temperature changes. The groundwater composition and the potential development of the composition due to the presence of the repository as well as due to external variations is thus an important issue in a safety analysis.

The development of the groundwater composition is strongly dependent on reactions with the minerals present in the ground. Here equilibrium chemistry may be of importance, but also reaction kinetics is important to the long-term behaviour.

Within the SITE-94 project, a safety analysis is performed for the conditions at the Äspö site, SE Sweden. For this study compilations of relevant groundwater chemical data and mineralogy data have been performed. The present groundwater chemistry has been evaluated by Glynn et al [GLY 94] using a large data material consisting of analysis data of bore hole waters at the site. The mineralogy of the area has been evaluated from drill cores at various places at the site and is described in a number of reports from the SKB. Here a summary and recommendation for selection of mineralogy to be used in data selection in the mathematical modelling of the repository as well as in geochemical calculations is given.

2. MODELLING OF THE CHEMICAL COMPOSITION OF THE GROUNDWATER

2.1 Use of geochemical models

Geochemical calculations may be used for several purposes in connection with the safety assessment, e. g.:

- a mathematical modelling of chemical equilibria with different pure fracture filling minerals coupled to the flow of water.
- modelling of the mixing of some "end-member waters" waters, followed by an equilibration of fracture filling minerals and flow through a fracture in order to evaluate the origin of the waters found at large depth
- modelling of chemical equilibria between water and complex fracture filling minerals, treating these as solid solutions between pure "end-member minerals".
- modelling of the dissolution of minerals and groundwater composition evolution using dissolution kinetics of relevant minerals

A mathematical modelling of the groundwater composition may be performed as a "backcasting", i.e. explaining the present conditions as a result of what has happened earlier, or as a forecasting

1

i.e. predicting the future effect of changes in the geochemical environment. Examples of backcasting calculations are explaining the present composition of the water as a result of mixing of other waters found in the area or evaluating the effect on groundwater composition of the mineralogy of the site, taking equilibrium reactions into account. Forecasting may be used to predict the influence of human activities as well as of natural large-scale hydrogeological changes.

The groundwater/mineral system is complex and a large number of elements, dissolved species and solid phases are present. Several types of reactions occur in the system. Important reactions are:
- speciation of dissolved elements
- equilibrium between water and pure minerals, crystalline as well as amorphous
- equilibrium of water with minerals that are solid solutions
- dissolution of minerals far from saturation (weathering) - kinetically governed reactions
- precipitation of secondary phases during weathering

2.2 Speciation/equilibrium modelling
The most common type of geochemical modelling treats the speciation of macro components and testing of equilibrium conditions, e.g. in terms of deviation from equilibrium as a saturation index. In some cases also selected minerals are simulated to be equilibrated with the water phase. Many speciation/equilibrium models treating pure minerals are available and are widely used. In the Äspö calculations the PHREEQE model [PAR 90] has been used. As is the case for all mathematical modelling, not only the mathematical model and the solution to is important - the database is an equally important component. The available thermodynamic data for speciation of macro components in groundwater seem to be of good quality and applicable, while mineral data are fewer and more uncertain, although quite large databases are available.

The speciation - equilibrium models are used also in connection with the kinetic model to describe the conditions in the water phase.

2.3 Solid solution modelling
Most minerals in nature are not pure crystalline compounds, but solid solutions between two pure end-members, an example of a simple system is calcite - magnetite ($CaCO_3$ - $MgCO_3$). The presence of solid solutions affects the chemical equilibrium and various attempts have been made to model these reactions. The easiest approach is to model the solid solution as a linear mixing of the end-members, assuming that the activity coefficients in the solid solution are unity. Comparisons to experimental data show that in most cases this is far from the true situation. This means that a method to assess the activity coefficients of the solid solution is needed but an easily applicable general form does not seem to be available at present. Attempts to use equations e.g. of Margules type have been performed, but this approach introduces difficulties in finding relevant constants for the studied systems. Most modellers have used experimental data to obtain solubilities of the solid solution. This gives good results for the system in question, but is rather a fitting of experimental data than a mathematical modelling and does not allow modelling of situations with other chemical conditions than those experimentally studied [BÖR 97]. The modelling of solid solutions influence in the groundwater is thus still under development, and has not been used in the Äspö groundwater calculations.

2.4 Kinetics.
For the dissolution and precipitation of minerals like calcite and other "simple" minerals the reaction is fast and kinetics may be neglected, i.e. equilibrium conditions may be considered to

prevail. On the other hand the dissolution of silicate minerals may be considered as more or less irreversible when the reaction products are solid phases. The weathering products from the primary silicate minerals are clays. The precipitates, constituting intermediate phases in the weathering process, are amorphous secondary phases or metastable alumino silicate oxides. The net composition of the metastable phase is determined by the solution composition. The precipitate exists for some time before it begins to recrystallise into a thermodynamically more stable form. The result from the alteration of the metastable form may be e.g. a chlorite, an illite or a smectite, depending on the solution composition.

When modelling dissolution kinetics not only the dissolution and precipitation of secondary phases has to be taken into account, but also other rate determining steps like the transport of reactants and products to and from the surfaces. Additionally, a database with kinetic constants of the minerals is needed. A model taking dissolution and precipitation of secondary phase has been developed and tested on feldspar dissolution [NYS 95], [NYS 96]. The model has not been tested on a groundwater - bedrock system.

A simpler approach to the problem is to use a geochemical knowledge of the weathering sequences of minerals and decide which minerals are easily weathered i.e. will be in equilibrium with the groundwater within the time of contact between a groundwater "element" and a mineral on the surface. These minerals are treated in equilibrium calculations while other minerals on the surface are not considered to react at all.

3. GEOLOGY AND HYDROLOGY OF THE ÄSPÖ AREA

The description of the geology given below is essentially taken from Stanfors 1989 [STA 89] and Wikberg et al 1991 [WIK 91].

The dominant rocks on Äspö belong to the 1700 - 1800 Ma old Småland granite suite, with mafic enclaves and dikes probably formed in a continuous magma-mingling and magma-mixing process [KOR 88].

The rock is very inhomogeneous with mineralogy from true granite to dioritic or gabbroid rocks. Large irregular bodies of diorite or gabbro have been located in boreholes at great depth in the site area.

The rock mass in Äspö is intruded by fine-grained granites of at least two or three generations, related to the Småland granites and the 1300 to 1400 Ma old anorogenic Götemar granite. The fine grained granites form dikes of different widths but also very irregular masses and veins which have been found by coring at different depths [KOR 87].

Across the island of Äspö, from SW to NE, there are a number of outcrops with greyish black, fine-grained basic rocks with a basaltic composition. They are often strongly altered and called greenstone. Grey to dark-grey fine-grained rocks with a dacitic composition only constitute minor parts of the Äspö island. Along the border between the medium-grained granitoid and greenstone, there are sometimes accumulations of fine-grained greyish-red granite.

Aplite and pegmatite as well as diabase have only been observed in the drillcores as very narrow dikes seldom more than a few decimetres wide.

The fine-grained granite is the most fractured rock in southern Äspö and is estimated to be the most hydrologically conductive rock. The fine-grained greenstones are mostly tight but the contact zones or narrow dikes of this rock may be conductive due to increased fracturing. The more acid varieties of the Småland granitoids are normally more fractured than the basic ones

3

(Äspö diorite) and for that reason considered to be more conductive. Mylonites are very often found to be almost tight.

Fracture zones are considered to be dominating the hydraulic conductivity, but also single fractures may have high conductivity.

Since it may be difficult to decide if there really is a correlation between the high conductive fractures and the identified large fracture zones, and the dominating transport paths also will be dependent on the scale of the calculations, the properties of single fractures as well as those of fracture zones will have to be considered what concerns fracture filling mineralogy.

4. FRACTURES AND FRACTURE FILLING MINERAL

The mineralogy that the flowing groundwater meets is that of the surfaces of fractures. This is often different from the bulk rock due to weathering of minerals and precipitation processes. Identification of fractures and fracture filling minerals has been performed by various methods.

4.1 Identification methods
Apart from TV-logging of the boreholes, fractures have been identified by drill core mapping, where the fractures have been opened to allow a description of the surfaces [SEH 89]. In this study the following questions were answered:

1. natural or sealed
2. fracture or infilling
3. large scale roughness
4. small scale roughness
5. fracture alteration
6. alpha angle
7. beta angle
8. width

A problem discussed by the authors is the breaking of closed fractures during the drilling and handling. These are mapped as natural fractures, since they are very hard to distinguish from real natural fractures. This gives a too high frequency of natural fractures and a too low frequency of sealed fractures.

In a later phase a computer based core mapping system was used [SEH 89], [SEH 90]. Compared to earlier studies the following changes were introduced:

- no relative orientation of fractures were made.
- the shortest recorded rock type section is increased from 10 to 100 cm, meaning that rock type sections shorter than 100 cm will be recorded as veins.
- the former lithological unit Småland granite was separated into Småland granite and Äspö diorite.

Microscopic studies have been performed for some fracture minerals (five zones from KAS02, 200 - 900 m depth, two zones from KAS06) [TUL 91]. Also isotopic and trace element analyses have been performed for the groundwater, and fracture fillings. However, the total amount of analysed samples is small.

The fracture filling mineralogy of drill cores KAS02, KAS03, KAS04 and KLX01 has been studied, using X-ray diffractometry, and microscopy [WIK 88]. Data from KAS05 - 08 are given in another report [TUL 89].

4.2 Minerals identified in fractures

There are zones of hematite observed in the granite. According to Tullborg [TUL 91], [TUL 93] this is probably formed under hydrothermal conditions long ago and not by oxidation of magnetite in contact with water. The question of what source of oxygen that has caused this remains.

There are crushed zones, measuring up to 1 m in width, containing clay minerals and crushed rock. Ingrowth of pyrite in these has been observed. This has probably occurred during the latest 300 Ma. The age dating of the crushed zone seems to be in accordance with data obtained by a British group using isotope analysis. The age correlates with the latest hydrothermal episode. [TUL 93]. An important question is if the crushed zone is high conductive or if the illite/smectite has closed the fracture. Both cases are theoretically possible.

Goethite is probably better correlated to water than is hematite, while siderite is not found in the rock at all, although it is indicated as supersaturated in equilibrium calculations [TUL 93].

The calcite has low contents of iron. Microsond analysis is not used for calcite.

Fluorite is common, explaining the fluoride content of the groundwater.

Epidote, hematite, and quartz, are most likely of later hydrothermal origin. Also iron rich chlorite is found among these minerals. These minerals are probably of the same age as the Götemar granite (1400 Ma).

Zeolites (laumontite, prehnite) are later hydrothermal.

Chlorite, illite, calcite, smectite, gypsum, fluorite, possibly pyrite and iron hydroxides formed after the hydrothermal events are also found.

Kaolinite is sparsely occurring.

Epidote is present in large amounts close to the fracture surface, a fact that indicates that it has been formed very early in the fracture history, and does probably not contribute to the present water composition.

In a study of water conductive fractures in a rock mass (no fracture zones) where the fractures were located in fine grained granite, Äspö diorite and Småland granite, the fracture filling mineralogy was found to be dominated by calcite, chlorite, and epidote [SEH 91]. Very few observations of iron minerals (hematite, hydroxides, etc.) were recorded.

In deep groundwater fractures kaolinite has been observed in very small amounts [WIK 88]. It is therefore likely that the silica- and alumino- rich precipitates, including the base cations (i. e. Na, Ca, K, Mg) of the solution, recrystallise to the clay minerals mentioned above. Chlorite may also be formed from weathering of biotite [SJÖ 92].

The mineral assemblage found at Äspö [TUL 91] in fractures contains phyllosilicates, iron minerals and carbonates and are dominated by calcites and chlorite. Most of these minerals are weathering products from either primary silicates or pyrite.

The iron minerals, other than pyrite, seem to be formed from weathering of pyrite or through hydrothermal alteration [TUL 91]. Pyrite weathering at low temperatures is performed through oxidation of the mineral and yields gypsum ($CaSO_4 \cdot 2 H_2O$) as a weathering product and at pH > 3 the dissolved iron forms iron oxides [STU 81]:

Pyrite + Calcite + H^+ + H_2O + ne$^-$ → Gypsum + Iron oxides + CO_3^{2-}.
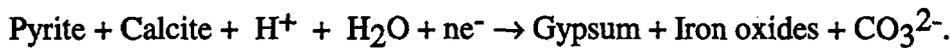
A brief look in the literature the oxidation of pyrite seemed to be performed mainly by bacteria. The rate of the oxidation process of pyrite is greatly enhanced by bacteria [BYE 92].

Calcite ($CaCO_3$), the dominating carbonate, is frequently found in fractures from drilling holes at Äspö below 20 m depth [WIK 88].

4.3 Chemical composition of fracture filling materials.

Clay minerals are often dominating when secondary minerals are produced due to alterations of primary minerals caused by water-rock interactions [FRI 85]. Since clay minerals can not be described by one characteristic formula they may instead be treated as solid solutions having a number of end-members. An example is montmorillonite, a smectite, which is listed in the literature with 24 end-members with their stability constant [FRI 75].

Other fracture filling minerals may also be described as solid solutions since they often contain impurities of other cations caused by substitution. An example is calcite, $CaCO_3$, where e. g. Fe(II) and Mn(II) may substitute for Ca(II).

Four fractures filling minerals: epidote, $Ca_2(Al,Fe(III))Al_2(SiO)_4(OH)$, chlorite, $(Mg,Fe(II,III))_5Al_2Si_3O_{10}(OH)_8$, calcite and smectite, represented by montmorillonite, may be treated as solid solutions in the calculations.

For epidote, chlorite and calcite analysis data for the chemical compositions are available [TUL 91]. For epidote a correlation between increasing content of Fe(III) and a decrease in aluminium content can be seen. The chlorite at Äspö is iron rich. The MgO/FeO ratio varies from 0.25 to 1 for the analysed chlorite samples. No data for Fe(III), Fe_2O_3, which may substitute for Al(III) in the chlorite is given. The analyse of calcite showed high content of manganese (up to 2.5 weight %) and low contents of iron and magnesium.

These results were taken into consideration when the end-members for epidote, chlorite and calcite were selected (see below). No analysis data for montmorillonite were found.

The following solid solutions were identified in the data:

EPIDOTE
The occurrence of epidote at Äspö is principally to be found in crushed zones where mylonitisised rocks are found [TUL 93]. The formula for epidote can be written $Ca_2(Al,Fe(III))Al_2(SiO)_4(OH)$. A complete solid solution extends from clinozoisite (Al:Fe=3:0) to epidote (Al:Fe=2:1). Hence, the formula for the two end-members can be written $Ca_2Al_3(SiO)_4(OH)$ and $Ca_2FeAl_2(SiO)_4(OH)$, respectively.

CHLORITE
The clay mineral chlorite found at Äspö is, as already mentioned, Fe-rich. The formula $(Mg,Fe(II,III))_5Al_2Si_3O_{10}(OH)_8$ shows that Fe(II) can substitute for Mg and Fe(III) may substitute for Al. Since no analyses on Fe(III) are available, only Fe(II) is considered here. The selected end-members are the pure Mg-chlorite $Mg_5Al_2Si_3O_{10}(OH)_8$, clinoclore, and the pure Fe(II)-chlorite $Fe_5Al_2Si_3O_{10}(OH)_8$, daphnite.

CALCITE
The fracture filling calcite at Äspö has many origins due to the complicated water situation at this site [TUL 93]. Here the two end-members calcite, $CaCO_3$, and rhodocroisite, $MnCO_3$, were selected. In the literature [HUR 71] contradictory information is found on whether calcite and rhodocroisite form a complete solid solution series or not. Since the dominating carbonate

mineral found at Äspö is calcite, that contains small amounts of manganese, any immiscible gap will probably be avoided [TUL 93].

SMECTITE (MONTMORILLONITE)
Montmorillonite will here represent the clay minerals in the smectite group. Due to the number of complex stoichiometrics of the mineral only four pure compositional end-members have been considered. They are $CaAl_{14}Si_{22}O_{60}(OH)_{12}$, $MgAl_{14}Si_{22}O_{60}(OH)_{12}$, $Na_2Al_{14}Si_{22}O_{60}(OH)_{12}$ and $K_2Al_{14}Si_{22}O_{60}(OH)_{12}$ [MUL 85].

4.4 Uncertainties - possible errors due to drilling
The drilling involves the use of drilling water. This may remove fine-grained material from the fracture planes. The material thus removed comes from high conductive parts of the rock, and the surface area in contact with the water is large. A large proportion of this material may be expected to consist of alteration products, i. e. clay minerals like illite and smectite. The amount of these minerals in the fractures may thus be underestimated by the study of drill-cores.

The importance of these zones may be significant if a large part of the water transport occurs here. In that case these zones will constitute the major transport paths for the dissolved radionuclides. Also the water composition may be strongly dependent on the minerals in these zones, where a weathering obviously has occurred, causing a release of components to the groundwater. However, the formation of clay minerals may have given a low permeability of the zone due to the volume of the mineral. The fact that these zones exist and may constitute major transport paths is important and has to be taken into account in the discussion on water compositions.

An unknown mineralogy in these important zones is not a satisfactory result of a site investigation of drill cores.

The problem of determining the variability of the mineralogy along the flow paths also remains. This problem will never be solved when the investigation is performed by drilling investigation holes. The influence on groundwater composition of variations in mineralogy may be investigated in computer modelling (CRACKER) but the result has to be validated by some further site investigations, e.g. by drilling along some fractures in the Äspö laboratory and investigating the mineralogy.

5. CONCLUSIONS

The minerals that are of importance to the reactions in the groundwater and that are the ones to be used in geochemical modelling of the groundwater/mineral evolution are the ones found on fracture surfaces.

The fracture filling mineralogy at the Äspö site is, like in most sites in Sweden, dominated by calcite and iron containing minerals. As is usual in site investigations, the amount of data on fracture filling mineralogy is limited compared to hydrological data. A location of fractures and a (visual) determination of mineralogy is performed for a number of drill cores, but chemical analyses of the minerals are few. For minerals in minor amounts there are no total analyses.

Some typical fracture filling mineralogies may be identified in the fractures:

- Epidote, chlorite, calcite, some illite/smectite + quartz, fluorite, pyrite and goethite.
- Epidote, chlorite, calcite, hematite and other minor minerals

In addition to these a number of minor minerals are found in the fractures.

In the present compilation of data important minerals for equilibrium and kinetic calculations have been identified. Calculations on water compositions, using thermodynamic data for these minerals, will give further indications on the applicability of the different models to the data.

To earth surface conditions the weathering of primary silicate minerals is responsible for the cation budget in soils. In deep rock fractures the silicates present are phyllosilicates and metastable aluminosilicate minerals. The weathering rate of the phyllosilicates are of the same order or magnitude as that of primary silicates. When considering the residence time of groundwater in the deep rock, the weathering is a process that will be of large importance to the composition and properties of deep groundwaters. The rates and reactions of iron minerals weathering are not fully investigated as yet. The pyrite weathering reaction seems mainly to be performed by oxidation of bacteria.

Uncertainties in the fracture filling data may be due to problems when taking out the drill cores. Drilling water may remove important clay minerals and sealed fractures may be reopened mechanically and treated as water conducting fractures.

The problem of determining the variability of the mineralogy along the flow paths also remains. This problem will never be solved when the investigation is performed by drilling investigation holes.

REFERENCES

BÖR 97   S Börjesson, "Computer modelling of the interaction between water and complex solid phases", Ph D thesis, Department of Nuclear Chemistry, Chalmers University of Technology, Göteborg 1997

FRI 75   B Fritz , "Étude thermodynamique et simulation des réaction entre minéraux et solutions. Application a la Geochemie des altérations et des eaux continentales", Mémoire no 41, Université Louis Pasteur de Strasbourg, Strasbourg 1975

FRI 85   B Fritz, "Multicomponent solid solutions for clay minerals and computer modeling of weathering processes", J.I. Drever (ed.), The Chemistry of Weathering, 19-34, D.Reidel Publishing Company. 1985

GLY 94   P Glynn, C Voss, "Geochemical Characterisation of Simpevarp Groundwaters Near the Äspö Hard Rock Laboratory, (SITE-94)", SKI Report 96:29, Swedish Nuclear Powler Inspectorate, Stockholm 1996

HUR 71   C S Hurlbut Jr, "Dana's Manual of Mineralogy", 18th ed., John Wiley & Sons, Inc. New York, 1971

KOR 87   K-A Kornfält, H Wikman, "Description to the map of solid rocks around Simpevarp", PR 25-87-02 & PR 25-87-02a, Svensk Kärnbränslehantering AB, Stockholm 1987

KOR 88   K-A Kornfält, H Wikman, "The rocks of Äspö island. Description to the detailed maps of solid rocks including maps of 3 uncovered trenches" PR 25-88-12, Svensk Kärnbränslehantering AB, Stockholm 1988

MUL 85   A B Muller, "NEA compilation of chemical thermodynamic data for minerals associated with granite", RWM-5, OECD/NEA, Paris 1985

NYS 95   A Nyström-Claesson, "Kinetic modelling of aluminium silicate minerals in geochemical systems", Lic Eng thesis, Dept of Nuclear Chemistry, Chalmers University of Technology, Göteborg 1995

NYS 96   A Nyström-Claesson, K Andersson, "PHRQKIN, a program simulating dissolution and precipitation kinetics in groundwater solutions", Computers and Geosciences, 22, No 5, (1996) pp 559-567

PAR 90   D L Parkhurst, D C Thorstenson, L N Plummer, "PHREEQE, A Computer Program for Geochemical Calculations", USGS/WRI-XXX, 1990.

SEH 89   S Sehlstedt, A Stråhle, "Geological core mapping and geophysical bore hole logging in the boreholes KAS05-KAS08 on Äspö" PR 25-89-09, Svensk Kärnbränslehantering AB, Stockholm 1989

SEH 90   S Sehlstedt, A Stråhle, C-A Triumf, "Geological core mapping and geophysical bore hole logging in the boreholes KAS11 - KAS14 and HAS18 -HAS20 on Äspö" PR 25-90-06, Svensk Kärnbränslehantering AB, Stockholm, 1990

SEH 91   S Sehlstedt, A Stråhle, "Identification of water conductive oriented fractures in the boreholes KAS02 and KAS 06" PR 25-91-11, Svensk Kärnbränslehantering AB, Stockholm 1991

SJÖ 92   L Sjöberg, M Mört, et al, "Experimentella studier av silikatvittring", Department of Geology and Geochemistry, Stockholm University, 1992

STA 89   R Stanfors "Underjordiskt berglaboratorium. Översiktlig beskriving av berggrunden i Simpevarpsområdet 1989" T PM 25-89-003, Svensk Kärnbränslehantering AB, Stockholm, 1989

STU 81   W Stumm, J J Morgan, "Aquatic chemistry: An introduction emphasising chemical equilibria in natural waters" 2nd ed. John Wiley & sons inc., 1981

TUL 89   E-L Tullborg, "Fracture fillings in the drillcores KAS05-KAS08 from Äspö, south-eastern Sweden", PR 25-89-16, Svensk Kärnbränslehantering AB, Stockholm, 1989

TUL 91   E-L. Tullborg, B. Wallin, O. Landström, "Hydrogeochemical studies of fracture minerals from water conducting fractures and deep groundwaters at Äspö", Äspö Hard Rock Laboratory, SKB PR 25-90-01, Svensk Kärnbränslehantering AB, Stockholm 1991

TUL 93   E-L Tullborg, Terralogica AB, Gråbo, personal communication, January 1993

WIK 88   H Wikman, K-A. Kornfält, L. Riad, R. Munier, E-L. Tullborg, "Detailed investigation of the drillcores KAS02, KAS03 and KAS04 on Äspö island and KLX01 at Laxemar." SKB Progress Report 25-88-11, Svensk Kärnbränslehantering AB, Stockholm 1988

WIK 91   P Wikberg, G Gustafson, R Stanfors, "Äspö hard rock laboratory. Evaluation and conceptual modelling based on the pre-investigations 1986-1990", TR 91-22, Svensk Kärnbränslehantering AB, Stockholm 1991

SKi

STATENS KÄRNKRAFTINSPEKTION
Swedish Nuclear Power Inspectorate