DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2021/56**

Studies of geological properties and conditions for deep disposal of radioactive waste, Denmark. Phase 1, report no. 5

Precambrian crystalline basement distribution and properties

Peter Gravesen, Peter R. Jakobsen, Bertel Nilsson, Stig A. S. Pedersen & Helle H. Midtgaard

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DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

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Preface

The present report is a contribution to a major geological project with the purpose to investigate whether suitable geological sites for a deep repository for the Danish radioactive waste can be identified. The Geological Survey of Denmark and Greenland (GEUS) has been given the task to identify, map, and characterize formations of low permeable rocks occurring with continuous lateral extension at 500 meters depth with thicknesses of 100 meters or more. This report is part of a series of ten reports presenting the results of the first phase of the project, which is carried out mainly as a desk study.

The geological characterisation and evaluation will provide the geological basis for the selection of two sites where, during the second phase of the geological project, detailed geological site investigations will be carried out. These two sites will be selected through a process of information sharing and dialogue between the Ministry of Higher Education and Science (MHES) and the local municipalities. The new geological data generated in the project's second phase will be used as input to a safety case when a disposal solution has been developed by the Danish Decommissioning (DD). The safety case must demonstrate that the geological properties in combination with the engineered barriers of the repository can provide the required safety for disposal on both short and long term.

In a preceding feasibility study, it was concluded that at 500 meters depth potential host rocks occur in claystones in the Jurassic and Lower Cretaceous sections, in Upper Cretaceous chalk and marl, and in Precambrian crystalline basement rocks. In this phase of the geological project, the geological properties and subsurface conditions related to these stratigraphic intervals and rock types are reviewed, and the potential host rocks' capability to retard radionuclides is investigated by conceptual 1D numerical modelling. In addition, natural processes potentially influencing short and long-term stability are identified and described.

Information gathered in the geological reports no. 2-8 forms the basis for a subdivision of Denmark into 11 areas where each area is characterized by the potential host rock type occurring at 500 meters depth, the barrier rocks in overlying sections, and the structural framework. The areas are defined to enable characterization and evaluation of the Danish subsurface at depths to 500 meters. The evaluation is based on requirements and criteria for deep geological disposal, which are defined based on international experience and recommendations. Each area is characterized and evaluated with regards to whether the geological properties and conditions are favourable for deep disposal of the Danish radioactive waste. The results of the project's first phase are presented in the following ten geological reports:

1. Requirements and criteria for initial evaluation of geological properties and conditions
2. Geological setting and structural framework of Danish onshore areas
3. Upper Cretaceous – Paleocene chalk, limestone and marl distribution and properties
4. Jurassic and Lower Cretaceous claystone distribution, sedimentology, and properties
5. Precambrian crystalline basement distribution and properties
6. Subsurface distribution of Jurassic and Cretaceous fine-grained formations based on seismic mapping
7. Evaluation of long-term stability related to glaciations, climate and sea level, groundwater, and earthquakes
8. Conceptual 1D modelling of nuclide transport in low permeable formations
9. Karakterisering og evaluering af geologiske egenskaber og forhold i 500 meters dybde (In Danish)
10. Characterisation and evaluation of geological properties and conditions at 500 meters depth (This report is an English translation of report no. 9, to be published late 2022)

This report is Report no. 5. It presents the existing knowledge about the crystalline basement as exposed on Bornholm including the distribution of granite and gneiss rock types, mineralogy and weathering, and mapping and characterisation of faults and fractures.

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0. Dansk sammendrag (In Danish)

I 2018 vedtog Folketinget, at en langsigtet løsning for håndtering af Danmarks radioaktive affald skal indeholde lokalisering for et muligt dybt geologisk slutdepot, som kan tages i brug senest i 2073 (Folketingets beslutning B90; Danish Parliament, 2018). Det radioaktive affald består af cirka 10.000 m^3 lavradioaktivt affald og mindre mængder af mellemradioaktivt affald, inklusiv 233 kg særligt affald, men intet højradioaktivt varmegenererende affald. De Nationale Geologiske Undersøgelser for Danmark og Grønland (GEUS) har af Folketinget fået tildelt opgaven med at undersøge, om der eksisterer områder i en dybde omkring 500 meter i den danske undergrund, der har de nødvendige geologiske egenskaber for etablering af et sikkert slutdepot for det radioaktive affald.

Det geologiske slutdepotprojekt omhandler de geologiske forhold, der skal tages i betragtning inden en eventuel beslutning om etablering af et dybt geologisk slutdepot for det danske radioaktive affald. De geologiske undersøgelser udføres sideløbende med aktiviteter hos Uddannelses- og Forskningsministeriet (UFM), der er overordnet ejer af slutdepotprojektet, og Dansk Dekommissionering (DD), som har ansvaret for at opbevare affaldet, indtil det skal slutdeponeres (MHES, 2021). Socio-økonomiske forhold, endeligt depotkoncept og -design, sikkerhedsforhold m.v. er ikke en del af det geologiske projekt, men varetages af UFM.

Retningslinjer for identificering af områder egnede til dyb geologisk slutdeponering
Internationale anbefalinger til de geologiske undersøgelser, der skal lede til identificering af en egnet lokalitet for dyb geologisk deponering af radioaktivt affald, er præsenteret af bl.a. det Internationale Atom Energi Agentur (IAEA, 2011) og Norris (2012) – her oversat til dansk:

"At identificere og kortlægge lav-permeable bjergarter, der udgør tilstrækkeligt tykke formationer (mere end 100 meter), og som har en kontinuert lateral udbredelse (flere kilometer i hver retning) indenfor studieområdet. Formationen skal være homogen og må ikke indeholde betydelige diskontinuiteter så som store forkastninger og sprækker. Formationen skal være så mineralogisk homogen og ensartet som muligt. De geologiske forhold skal være stabile på både kort sigt og indenfor en længere tidshorisont afhængigt af affaldets karakter."

Projektet vil følge retningslinjer fra IAEA (IAEA, 2011; IAEA, 2018a; IAEA, 2018b), Det Nukleare Agentur under OECD (NEA, 2005; NEA, 2008; NEA, 2012) og EU-direktiver indenfor området (EU, 2011).

Som bemærket af IAEA (IAEA, 2018a; IAEA, 2018b), er det ikke muligt at udpege ét enkelt område som det bedst egnede baseret på de geologiske egenskaber, idet det er umuligt at undersøge og karakterisere alle naturlige variationer af de geologiske egenskaber ned til 500 meters dybde indenfor et givent område. Opgaven er derimod at identificere et egnet område, der samlet set kan opfylde de definerede krav til sikkerhed og funktionalitet af depotet, samtidig med at etableringen af et geologisk slutdepot i området er teknisk mulig og accepteret af beslutningstagere og interessenter.

Omfanget af de geologiske undersøgelser, der er nødvendige at udføre, er defineret på basis af erfaringer fra lignende projekter i bl.a. Frankrig (ANDRA, 2005), Sverige (SKB, 2007), Schweiz (SFOE, 2008; Nagra, 2017), Holland (COVRA 2017), og Finland (POSIVA, 2017a og b). Kontakter er i løbet af projektet etableret til flere af disse organisationer med henblik på udveksling af erfaringer samt rådgivning og kvalitetssikring for det geologiske slutdepotprojekt. Som et resultat af dette internationale samarbejde, blev der i første fase af slutdepotprojektet gennemført et review af de definerede geologiske kriterier (præsenteret i Rapport nr. 1), hvor kommentarer og anbefalinger er afrapporteret i Blechschmidt et al. (2021).

På baggrund af flere årtiers undersøgelser af de lokale geologiske forhold har nogle lande besluttet at etablere et dybt slutdepot i marine lersten (ANDRA-Frankrig, COVRA-Holland, Nagra-Schweiz). I Sverige (SKB) og Finland (POSIVA) er det besluttet at etablere dybe geologiske slutdepoter i krystallinsk grundfjeld. Mange andre lande arbejder stadig med lokaliseringsprojekter, og udover krystallinsk grundfjeld og lersten er også kalksten, mergel og salt vurderet som mulige bjergarter for deponering afhængigt af de lokale geologiske forhold.

Det geologiske projekt vedrørende et muligt slutdepot i 500 meters dybde

Forud for det igangværende geologiske projekt blev en screening af den danske undergrund foretaget med henblik på at undersøge, om lavpermeable bjergarter findes i 500 meters dybde i den danske undergrund. Denne screening viste, at i 500 meters dybde findes jurassiske og kretassiske lagserier, der indeholder tætte formationer af lersten og kalksten samt prækambrisk grundfjeld bestående af granit og gnejs. Alle disse bjergartstyper kan under de rette omstændigheder have geologiske egenskaber, der gør dem egnede som værtsbjergart for et dybt geologisk slutdepot (Gravesen, 2016). Baseret på dette arbejde blev undersøgelserne i nærværende projekts første fase igangsat.

Det geologiske slutdepotprojekt blev påbegyndt i januar 2019 og forventes at forløbe over en 7-årig periode. Projektet udgør den geofaglige del af det samlede projekt om et muligt dybt geologisk slutdepot, som er defineret i Folketingets beslutning B90 (Danish Parliament, 2018). Det geologiske projekt varetages af GEUS' personale med bidrag fra eksterne forskningsinstitutioner, konsulentfirmaer og internationale eksperter, hvor det er nødvendigt. På grundlag af en karakterisering og evaluering af undergrundens geologiske egenskaber i projektets første fase, skal to lokaliteter udvælges til detaljerede geologiske undersøgelser i projektets anden fase. Uddannelses- og Forskningsstyrelsen (UFS) har ansvaret for at tilrettelægge og gennemføre en dialogproces, der inden udgangen af 2022 kan føre til afklaring af muligheden for at etablere et partnerskab mellem UFM og én eller flere kommuner om gennemførelsen af detaljerede geologiske undersøgelser.

I projektets første fase er de forskellige bjergarter kortlagt og deres egenskaber er beskrevet i det omfang, der findes data. Det skal i den sammenhæng bemærkes, at den tilgængelige information er ujævnt fordelt både geografisk og geologisk. De eksisterende data fra 500 meters dybde er hovedsageligt indsamlet fra tidligere olie- og gasefterforskningsboringer og relaterede seismiske undersøgelser og i mindre grad fra geotermiske, geotekniske og videnskabelige undersøgelser. De fleste dybe boringer i Danmark har haft som hovedformål at påvise tilstedeværelsen af sandsten og karakterisere deres reservoiregenskaber, hvorfor det er meget sparsomt med data fra de lavpermeable bjergarter som lersten og kalksten, der kan anvendes som værtsbjergarter, og som nærværende slutdepotprojekt har fokus på. Den nuværende kortlægning af undergrundens geologi er derfor behæftet med varierende grad af nøjagtighed og pålidelighed for de forskellige parametre, særligt for de lavpermeable bjergarter, som er vigtige for et geologisk sludepot. Gennemgangen af de eksisterende data har bidraget til at identificere områder med manglende geologiske data og informationer, hvor det er vigtigt at sikre indsamling af nye data i den næste fase af projektet.

I projektets anden fase skal detaljerede geologiske undersøgelser, som nævnt, foretages på to valgte lokaliteter. Undersøgelserne vil omfatte indsamling af seismiske profiler med geofysiske metoder og boring af dybe borehuller. I borehullerne udtages bl.a. borekerner og vandprøver, og der indsamles petrofysiske målinger for efterfølgende analyser med henblik på karakterisering af forseglingsegenskaberne og geotekniske egenskaber. Disse data vil indgå bl.a. i modellering af stoftransport, bestemmelse af geokemisk retardation, seismisk kortlægning og vurdering af geoteknisk stabilitet. De geologiske og geotekniske egenskaber vil også have indflydelse på hvilket depotdesign, der er teknisk muligt og sikkerhedsmæssigt forsvarligt i undergrunden. De indsamlede data og analyser vil efterfølgende indgå i en sikkerhedsvurdering, der skal afklare, om det samlede depotkoncept med de geologiske barrierer i kombination med de konstruerede barrierer kan levere den nødvendige sikkerhed for deponering på både kort og lang sigt.

Opsummering af Rapport nr. 5: Det krystallinske grundfjelds udbredelse og geologiske egenskaber (Precambrian crystalline basement distribution and properties)

Denne rapport præsenterer en gennemgang af det krystallinske grundfjeld, som i Danmark kendes hovedsageligt på Bornholm, hvor det findes nær terrænoverfladen på store dele af øen. I de øvrige områder af Danmark findes grundfjeldet i undergrunden i dybder på 800 meter eller mere og er derfor ikke relevant for et dybt geologisk slutdepot i 500 meters dybde.

Øen Bornholm i den østligste del af Danmark befinder sig geologisk set i Sorgenfrei–Tornquist Zonen med det Fenno–Skandiske Skjold mod nord og det Danske Bassin mod vest. Sorgenfrei-Tornquist Zonen har været tektonisk aktiv fra sen Karbon til tidlig Tertiær tid. De tektoniske forskydninger førte til dannelsen af en horstblok, der er et relativt højtliggende område, som er afgrænset af en række større, gamle forkastninger, der nu udgør øen Bornholm. Topografien på Bornholm er i områder med grundfjeld karakteriseret af talrige lineære dale og sprækkesystemer, der er dannet som et resultat af gentagne perioder med tektonisk aktivitet i Sorgenfrei-Tornquist Zonen og af senere glacialt betingede deformationer. Kvartære glaciale aflejringer af ler og sand dækker store områder af Bornholm med tykkelser på op til 25 meter og lokalt i større sprækker findes aflejringer med tykkelser på mere end 80 meter.

Nærværende rapport om grundfjeldets udbredelse og geologiske karakteristika er baseret på eksisterende data, der er kombineret med nogle få nye observationer fra feltarbejde herunder indsamling af en 2D seismisk linje. Den eksisterende viden om grundfjeldet er hovedsageligt baseret på observationer i blotninger og stenbrud i dybder ned til 50-60 meter under terrænoverfladen, samt kortlægning af sprækker i terrænoverfladen. Data er derfor ujævnt fordelt geografisk og med en stærkt varierende detaljegrad, der er bestemt af blotningsgraden.

Nogle få drikkevandsboringer når dybder på omkring 100 meter, mens der fra større dybder pt. ikke eksisterer data fra, og viden om, de krystallinske bjergarter og deres egenskaber. Drikkevandsboringerne viser, at der findes både horisontale og vertikale sprækker på dybder ned til 100 meter, og at afstanden mellem de horisontale sprækker øges med dybden, hvilket også er observeret i lodrette vægge i stenbrud.

Det krystallinske grundfjeld blev dannet dybt i undergrunden i prækambrisk tid for ca. 1450 millioner år siden. Det krystallinske grundfjeld er blottet i store dele af den centrale og nordlige del af Bornholm langs kysterne, i dybe dale og sprækker, samt i åbne granitbrud. Detaljeret kortlægning og karakterisering af bjergarterne har vist, at syv forskellige typer af granit og gnejs udgør størstedelen af grundfjeldet. Udbredelsen, den mineralogiske sammensætning og øvrige karakteristika er beskrevet for hver af de syv bjergarter som omfatter: Bornholms Gnejs, Paradisbakke Migmatit, Rønne Granit, Vang Granit, almindingen Granit, Hammer Granit og Svaneke Granit. Geokemiske studier viser, at alle bjergarterne oprinder fra den samme magma, der er dannet ved delvis opsmeltning og efterfølgende gradvis nedkøling og krystallisering dybt i undergrunden (mere end 10 kilometer). Afkøling og efterfølgende tektonisk opløft og erosion igennem millioner af år har resulteret i, at granit og gnejs, der er dannet på store dybder, findes i terrænoverfladen i dag.

Krystallinske bjergarter som granit og gnejs består hovedsageligt af kvarts, feldspat og glimmermineraler i varierende forhold samt mindre mængder af accessoriske mineraler. Da bjergarterne er dannet ved udkrystallisering på stor dybde under højt tryk og temperatur, er der ingen porøsitet eller permeabilitet i uforstyrrede formationer. Når der alligevel kan være vand i grundfjeldet, skyldes det tilstedeværelsen af sprækker, der kan variere i størrelse fra mikroskopiske sprækker til store sprækkedale. For at vurdere grundfjeldets egenskaber for mulig etablering af et slutdepot i 500 meters dybde er det derfor vigtigt, at have detaljeret viden om tætheden, størrelsen og orientering af sprækker både i overfladen og i 500 meters dybde. I sprækker ved terrænoverfladen ses det, at overfladen af bjergarterne er forvitrede, og mineralerne er i varierende grad omdannet til forskellige typer af ler og jernoxider. Denne forvitring er et resultat af nedsivende regnvand, og langs kysterne også havvand, der over tid nedbryder og omdanner mineralerne i grundfjeldet. Graden af forvitring af grundfjeldet og dannelsen af lermineraler kan have indflydelse både på sprækkernes hydrauliske egenskaber og de geokemiske egenskaber for tilbageholdelse af radioaktive nuklider i undergrunden.

Et vigtigt redskab til at forudsige tilstedeværelsen af sprækker på stor dybde i krystallinsk grundfjeld er kortlægning og karakterising af sprækker og forkastninger i de øverste dele af grundfjeldet sammenholdt med en god forståelse af hvilke mekanismer, der har dannet sprækkerne. Vertikale sprækker af tektonisk oprindelse fortsætter normalt til stor dybe på grund af granits stivhed og geomekaniske egenskaber.

I de øverste 10-30 meter af grundfjeldet findes ofte udbredte sprækkesystemer af tætliggende vertikale sprækker, der er orienteret overvejende i retningerne NNV-SSØ, NNØ-SSW og ØSØ-WNW. Lokalt ses der typisk vertikale sprækkesystemer med to forskellige dominerende retninger, men i nogle områder ses flere forskellige retninger. De dominerende sprækkesystemer ses at være orienteret parallelt med de nord-syd og nordvest-sydøst orienterede forkastninger, der afgrænser Bornholm. Sprækkerne menes derfor at være af tektonisk oprindelse med en sen palæozoisk alder eller yngre. Dybe horisontale sprækker menes at være dannet som et resultat af trykaflastning, efterhånden som området er opløftet, og store mægtigheder (flere kilometer) af de overliggende formationer er eroderet og fjernet.

De fleste vertikale sprækker formodes således at være af tektonisk oprindelse, men i intervallet 0-50 meter ses hyppige vertikale, hældende og horisontale sprækker, der sandsynligvis er dannet som et resultat af gentagne glaciationer i området. Perioder med overskridning af tykke iskapper og efterfølgende afsmeltning har resulteret i dannelsen af både horisontale trykaflastningssprækker samt knusning, opsprækning og erosion af de øverste dele af grundfjeldet. Disse glacialt dannede sprækkesystemer er observeret ned til dybder på omkring 60 meter i vandboringer.

Feltstudier viser, at der ikke altid er skarpe grænser mellem de forskellige krystallinske bjergartslegemer og at granitterne og gnejsen lokalt er trængt ind i hinanden inden størkning. Det må derfor forventes, at fordelingen af de forskellige bjergartslegemer i undergrunden er forskellig fra fordelingen i overfladen. De strukturelle elementer i form af horisontale og vertikale sprækker ses at være styret af senere tektoniske hændelser, da de er orienteret uafhængig af kontakterne mellem bjergarterne og også skærer strukturer i gnejsen. Det forventes derfor, at en anderledes fordeling af bjergarterne i undergrunden ikke har været styrende for forekomsten af sprækker i dybder ned til 500 meter.

En seismisk linje blev indsamlet i det nordlige Bornholm med en orientering vinkelret på en række større topografiske spring i overfladen, der antages at være tektonisk betinget, som en test af hvorvidt seismiske data kan anvendes til at kortlægge større sprækker i grundfjeldet. Konklusionen var dog, at seismiske data kun kan anvendes til kortlægning i den tynde sekvens af sedimentære bjergarter, som overlejrer grundfjeldet, mens der ingen refleksioner var internt i grundfjeldet. Dette viser, at mindre vertikale og horisontale sprækker ikke kan identificeres ved hjælp af seismiske data, da de ikke skaber seismiske refleksioner. Samtidig viste de seismiske data også, at større forkastningszoner ikke findes i dybere dele af grundfjeldet i dette område.

I Sverige er større frakturer og forkastninger i grundfjeldet kortlagt baseret på luftbårne magnetiske, elektromagnetiske og topografiske data. Overfladekortlægning er i Sverige kombineret med, og kalibreret til, boredata fra dybere dele af grundfjeldet som et led i forberedelserne til et dybt geologisk slutdepot. Det forventes, at nogle af de svenske erfaringer kan anvendes ved en eventuel fremtidig indsamling af geofysiske data til kortlægning af sprækker og deres udbredelse i undergrunden på Bornholm.

I den østlige del af Bornholm Gnejs området er der, baseret på de eksisterende studier, observeret færrest lodrette sprækker i overfladen, og det forventes, at der vil være endnu færre med stigende dybde i undergrunden. Hvad angår forekomsten af horisontale sprækker i dybder på mere end 100 meter må det, på grund af deres overvejende tektoniske oprindelse forventes, at de findes udbredt i alle dele af grundfjeldet, som har været igennem den samme strukturelle-tektoniske udvikling med associeret opløft og trykaflastning.

I relation til mulig deponering af radioaktivt affald i krystallinske bjergarter vil det være vigtigt at undersøge, hvorvidt sprækker er til stede i 500 meters dybde, og om der er strømning i sprækkerne. I vandboringer ned til omkring 100 meter er der observeret meget begrænset vandstrømning og hovedsageligt fra horisontale sprækker. Forvitring langs sprækkerne har ført til dannelse af lermineraler og oxider. Disse mineraler kan bidrage til at mindske permeabiliteten forårsaget af åbne sprækker og muligvis ved at tilbageholde radioaktive nuklider.

1. Introduction

In 2018, the Danish Parliament agreed that the long-term solution for Denmark´s radioactive waste should include a deep geological repository operating no later than 2073 (Danish Parliament, 2018). The waste is temporarily stored by the Danish Decommissioning (DD) on the Risø peninsula. It amounts to more than 10,000 m^3 and comprises mostly low-level radioactive waste (LLW), and a minor volume of medium-level waste MLW), including 233 kg special waste – but no high-level radioactive material (HLW).

The Geological Survey of Denmark and Greenland (GEUS) has been given the task by the Danish Parliament to investigate whether areas can be identified where potential host rock with suitable properties for geological disposal is present at 500 meters depth. The task is carried out in parallel with activities by the Danish Ministry of Higher Education and Science (MHES), being the project owner, and DD, being responsible for management of the radioactive waste including storage of the waste and final disposal.

The geological project was initiated in 2019 and is expected to be carried out within a period of approximately seven years. The bulk of the workload will be undertaken by staff members at GEUS, with contributions from external consultancy companies, organisations, and experts as needed. The geological siting project comprises two major phases. The current first project phase is a desk study with the purpose to map and characterize geological properties and conditions of potential host rocks in the Danish subsurface, mainly based on existing data. In the second project phase of the geological project, detailed geological investigations will be carried out at two specific sites to investigate whether the geological properties are suitable for safe disposal of radioactive waste in a deep geological repository at these specific sites. The two sites must be selected in a dialogue-based process between MHES and the local municipalities. Subjects and conditions, such as socio-economic issues, activities relating to civil participation, disposal facility design, safety cases, and other non-geological issues will be addressed and handled separately by MHES and DD with contributions from GEUS where relevant.

1.1 Guidelines for identification of deep geological repository sites

International recommendations on geological studies required to identify suitable sites for deep disposal of radioactive waste have been presented by e.g. the International Atomic Energy Agency (IAEA, 2011) and Norris (2012) as follows:

"*To identify and map layers of low-permeable rock types that are sufficiently thick (more than 100 meters) and which have a continuous lateral extension (several km^2) throughout the entire study area. The rock body should also be sufficiently homogeneous and represent no significant discontinuities like fractures and faults. Furthermore, the rocks should be as mineralogical homogeneous and uniform as possible. The geological conditions should be stable in the short term as well as in the long term.*"

These recommendations as well as experience from siting projects in other countries have been used to identify investigations that need to be performed in the Danish project. Experience from other countries include France (ANDRA, 2005), Holland (COVRA, 2018), Switzerland (SFOE, 2008; Nagra, 2017), Sweden (SKB, 2007) and Finland (POSIVA, 2017a, b).

In some countries, based on several decades of comprehensive subsurface studies, it has been concluded that marine claystones and clay rich carbonates (marl) may constitute suitable host rocks for a final geological disposal. Therefore, extensive research on clay deposits is continuously ongoing and makes available significant amounts of data and experiences that may be valuable for this project (e.g. ANDRA-Belgium, COVRA-Holland, Nagra-Switzerland). In the Czech Republic, a former limestone mine is used for disposal of institutional waste comprising radioactive material similar to the components in the Danish waste. In other countries, including Sweden, Finland, and Norway, it has been decided to establish final repositories in crystalline bedrock. When relevant, the current project in Denmark will draw on others experiences and cooperate with relevant radioactive waste disposal organisations. Furthermore, the project will follow guidelines from IAEA (IAEA 2011; IAEA 2018 a,b), the Nuclear Energy Agency (NEA (OECD), 2005; NEA 2006; NEA, 2008; NEA, 2012) and the EU directive regarding this field (EU, 2011).

As noted by the IAEA (2018 a, b), the impossibility of finding “the safest site” based on rock properties should be emphasised, because it is not possible to investigate and determine the detailed nature of every possible site. Instead, the key to find a suitable site will be to have it fulfil the required level of safety and performance, and that establishing a repository here is also acceptable to decision makers and stakeholders.

1.2 The deep geological repository project

A geological screening of the Danish subsurface layers present at 500 meters depth was carried out prior to initiation of the current geological siting project, to investigate whether low permeable rocks occur at this depth. The screening showed that the Jurassic and Cretaceous stratigraphic intervals at 500 meters depth comprise chalk, limestone, marl, and claystone, and the Precambrian basement comprises crystalline rocks in terms of gneiss and granite, which may all potentially provide a host rock for a deep geological repository (Gravesen, 2016). Based on this work, it was recommended to further analyse and characterize the geological conditions and barrier effectiveness of the geological formations at depths to 500 meters below the surface, which resulted in a decision to initiate the first phase of the present project.

The first phase of the present geological siting project comprises a geological review of all data available in the GEUS archives, the drilling-sample storage facilities, and from literature. The data have been used to map and describe relevant properties of the rock types identified at depths to around 500 meters, as well as natural processes potentially influencing the short- and long-term geological stability. The results form the basis of a subdivision into geologically different areas which are characterised and evaluated regarding the areas’ potential suitability for deep disposal as described in the project’s Report No. 9 (cf. Chapter 7.1 for reference).

The geological desk studies were carried out as separate work packages and presented in a number of reports (Reports No. 2-7; cf. Chapter 7.1 for references) addressing the following issues: overview of the onshore geological setting in Denmark; subsurface mapping based on seismic data and well data; a geological description of the three rock types chalk, claystone and crystalline basement, respectively, and issues potentially influencing long-term geological stability, such as climate conditions, possible glaciations, earthquake risks and groundwater conditions. Based on the results of the geological desk studies, conceptual 1D numerical modelling was performed to identify properties and conditions with high importance for the rocks' barrier-effectiveness for retardation of the radionuclides (Report No. 8; cf. Chapter 7.1 for reference).

Information on the subsurface geological formations onshore Denmark is quite scattered and of highly varying quality. The archives and databases comprise 2D seismic data of different vintages and quality as they are acquired for different purposes. Well data exist mainly from deep wells drilled for hydrocarbon exploration, some geothermal wells, and other technical/scientific drillings. Thus, as the data from various regions of Denmark varies in vintage, quality and level of detail, the current picture is by no means comprehensive. However, the geological desk studies combined with some new sedimentological and stratigraphic studies, and initial sensitivity studies from the conceptual 1D modelling have proven highly valuable; both in detailed mapping and identifying rock types, as well as in identifying major data gaps and critical parameters, for which it is important to obtain information during the next phase of the project.

The characterisation and evaluation carried out in this first phase of the project provide the geological basis for selection of two sites for detailed geological investigations in the second phase of the project. A dialogue-based process for the site selection is managed by MHES.

As part of the detailed investigations in the second phase of the project, new data and information will be collected at the two sites to further evaluate whether the geological properties and conditions are favourable for deep disposal. Thus, the second phase sets off with planning and preparation for the investigations, which include acquisition of seismic data and the drilling of deep boreholes (deeper than 500 meters) at each site. The extensive data sampling program will, among others, include drill-cores, well logs, and groundwater samples - thus, providing samples and measurements for laboratory analyses and various other studies. Based on the new data, a characterisation and evaluation of the geological suitability of the two sites will be made. This characterisation will also be used by DD for identification of a suitable repository design and for evaluation of the combined retention capacity of the engineered and the geological barriers as input to a safety case.

2. Geological setting of the crystalline basement exposed on Bornholm

In the Danish subsurface the crystalline basement occurs at the shallowest depths (800-1600 m) on the Ringkøbing-Fyn High (Figure 1) and significantly deeper elsewhere (Olivarius et al. 2015). The Precambrian is reached on the Ringkøbing-Fyn High at a depth of 835 m in the Glamsbjerg-1 well (gneiss) on the Glamsbjerg part of the RF-high and at 1615 meters in the Grindsted-1 well (gneiss), in the Borg-1 well at 2061 meters and Arnum-1 (breccia) well at 1805 meters and in Løgumkloster-1 at 2458 meters at the Grindsted part of the high. In the Sorgenfrei-Tornquist Zone in Bornholm the basement is rising to an altitude of up to 130 meters above sea level, whereas in Fredrikshavn-1 it occurs at 1304 meters below surface and in Terne-1 deeper than 3326 meters below surface. In the Danish and North German Basins, the top basement occurs at depths of 2500-4000 meters or more. Thus, potential areas for establishing a final disposal for radioactive waste in crystalline rocks at depths around 500 meters can be found only on Bornholm.

Bornholm is the easternmost island of Denmark, situated in the Sorgenfrei–Tornquist Zone (Fenno-Scandian Border Zone) with the Fenno–Scandian Shield towards the north and the Danish Basin towards the west (Figures 1 & 2). During the late part of the Precambrian (Neoproterozoic, 1400-900 mio. years ago) uplift of the area around Bornholm was initiated and associated with the formation of faults and fractures. The Sorgenfrei-Tornquist Zone has been tectonically active since the Late Carboniferous to early Tertiary time. The development of the Rønne Graben, on the western margin of Bornholm, was initiated in the Carboniferous–Permian Time (Michelsen & Nielsen, 1993, Vejbæk, 1985). The pre-Quaternary map of Denmark illustrates the subcrop of Bornholm and the relation to the Sorgenfrei-Tornquist Zone and southern Sweden (Figure 2). The main boundary faults are shown illustrating that the island of Bornholm is a small fault-bounded horst block.

During the Jurassic large parts of the Granites were weathered into kaolin due to a warm and humid climate. Subsequently, inversion and reactivation of older fault systems took place during the Cretaceous and Tertiary associated with a significant erosion of older sedimentary deposits (Gry, 1969; Gravesen et al., 1982; Graversen, 2009).

The Precambrian crystalline basement of Bornholm is exposed in large parts of the central and northern part of the island and a significant amount of detailed work has been carried out with regards to mapping and characterizing the various rock types. The crystalline basement includes several different rock types: the foliated and medium-grained Bornholm Gneiss and the medium-grained Paradisbakke Migmatite (Figure 3), which have been deformed by superimposed folding. Partial melting of these rocks might have been the source of the dark coloured Rønne Granite (Micheelsen, 1961a, Gravesen, 2006). Light-coloured mainly red-grey granites includes the medium-coarse-grained Vang Granite, the medium-grained Almindingen Granite and Hammer Granite and the coarse-grained Svaneke Granite (Figure 3).

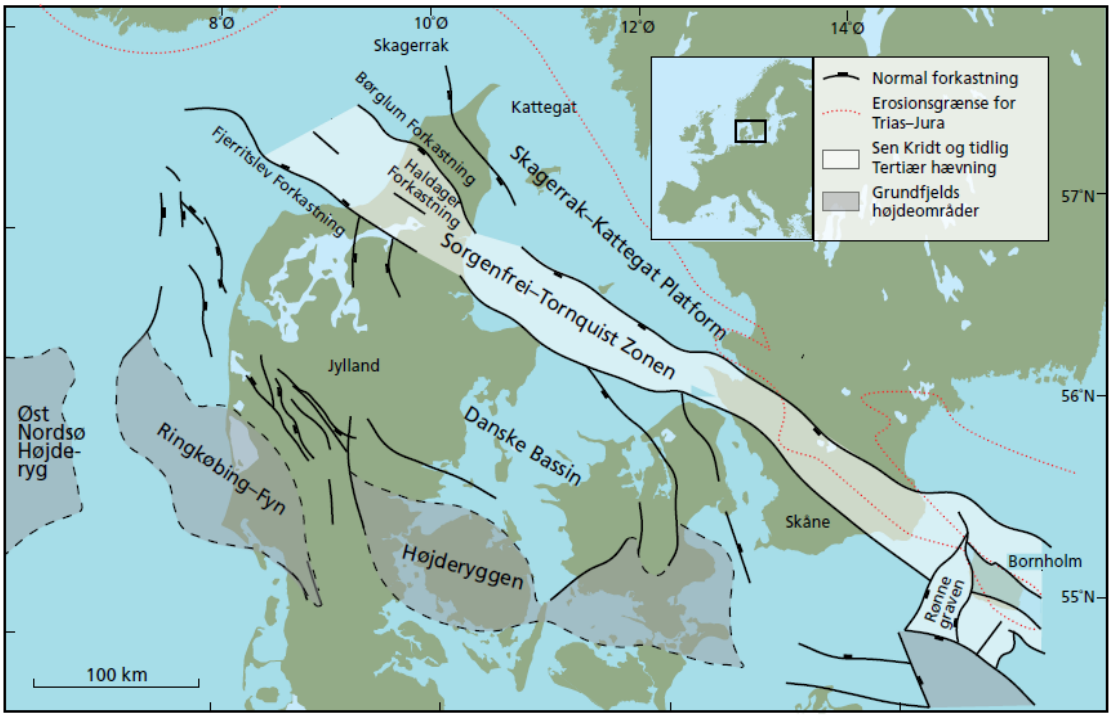


Figure 1. *The structural setting within the Danish onshore areas. The island of Bornholm is situated in the southeastern part of the Sorgenfrei-Tornquist Zone (from Gravesen, 2011).*

Figur 1. *Kort over de dybtliggende strukturelle elementer i den danske undergrund (fra Gravesen, 2011).*

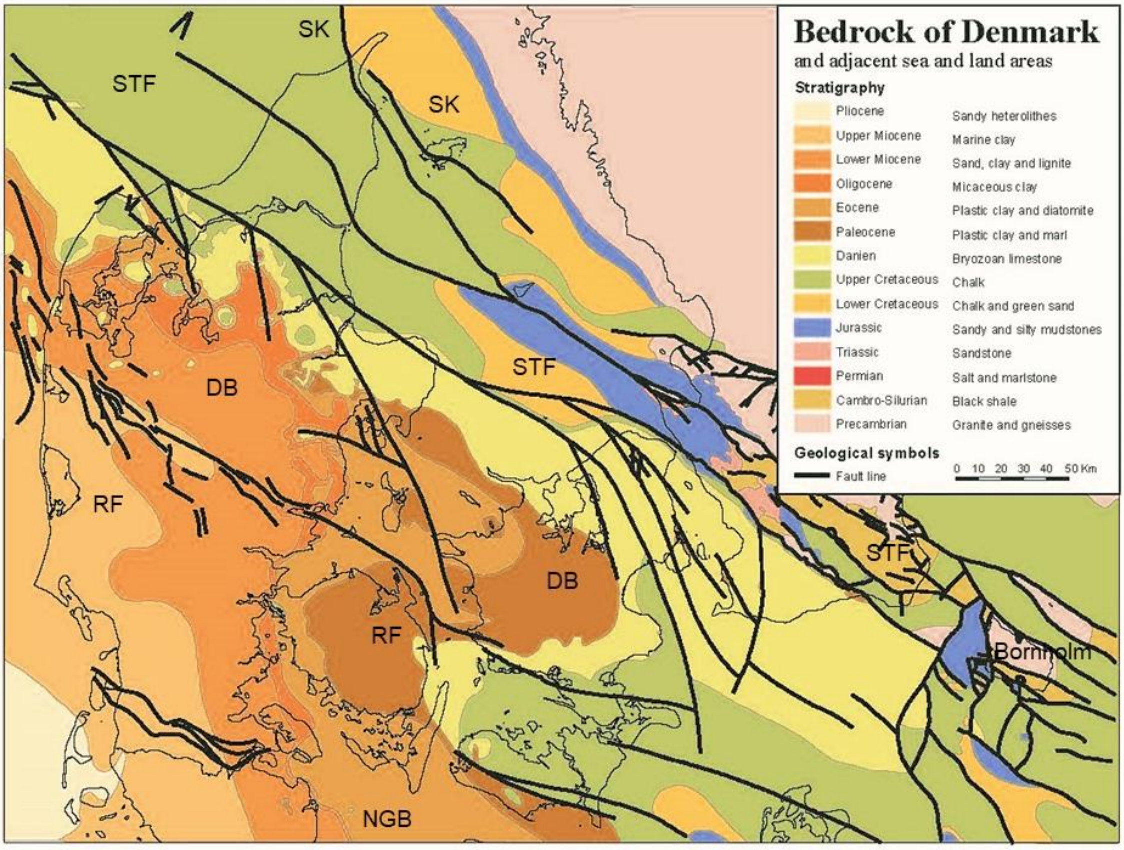


Figure 2. *Map of the Danish subsurface at the base of the Quaternary deposits (After Håkansson & Pedersen, 1992). DB: Danish Basin, NGB: North-Germany Basin, RF: Ringkøbing–Fyn High, STF: Sorgenfrei–Tornquist Fault Zone, SK: Skagerrak–Kattegat Platform.*

Figur 2. *Kort over bjergarter i den danske undergrund ved basis af Kvartæret (Efter Håkansson & Pedersen, 1992). DB: Danske Bassin, NGB: Nordtyske Bassin, RF: Ringkøbing–Fyn Højderyg, STF: Sorgenfrei–Tornquist Forkastningszone, SK: Skagerrak–Kattegat Platform.*

The topography of Bornholm is characterized by basement forming a large dome gently rising from the south to more than 100 meters above sea level on the central and northern part of the island and dipping slightly steeper towards the north coast (Figure 4a). Several straight valleys intersect the northern part of Bornholm (Figure 4b), while streams in valleys cut into sedimentary rocks to the south are more irregular.

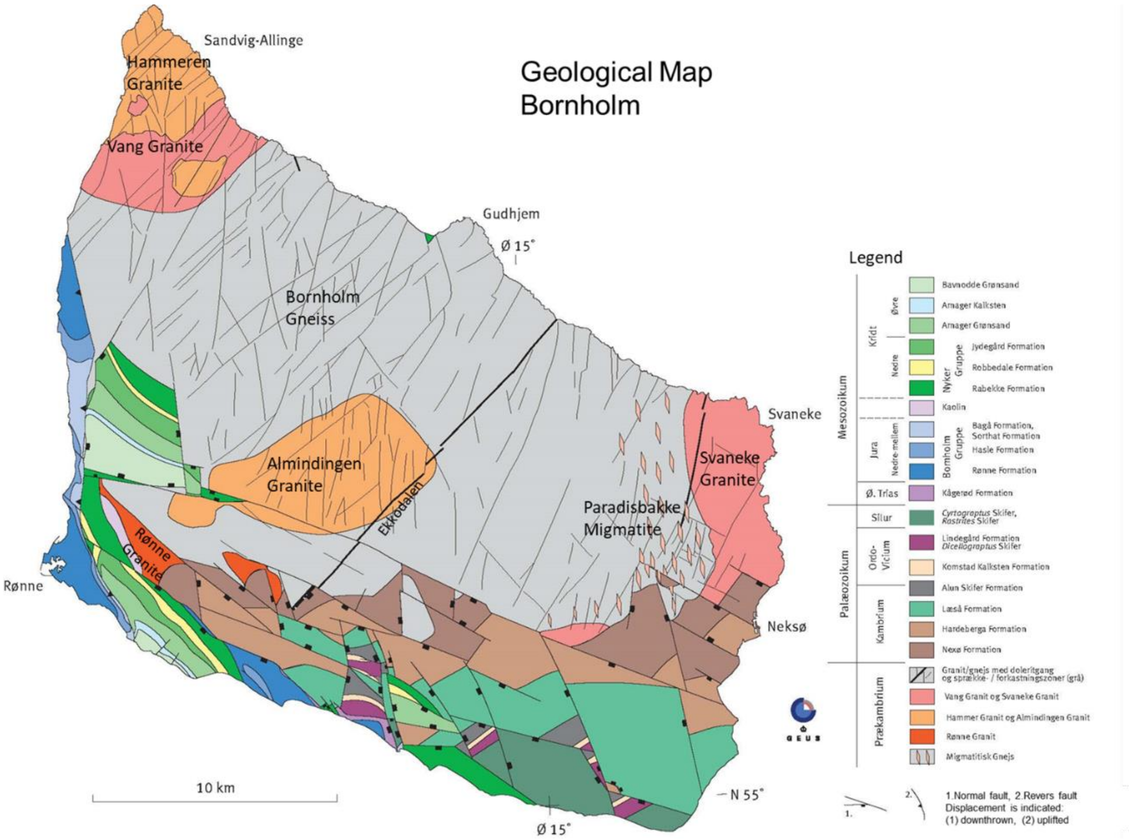
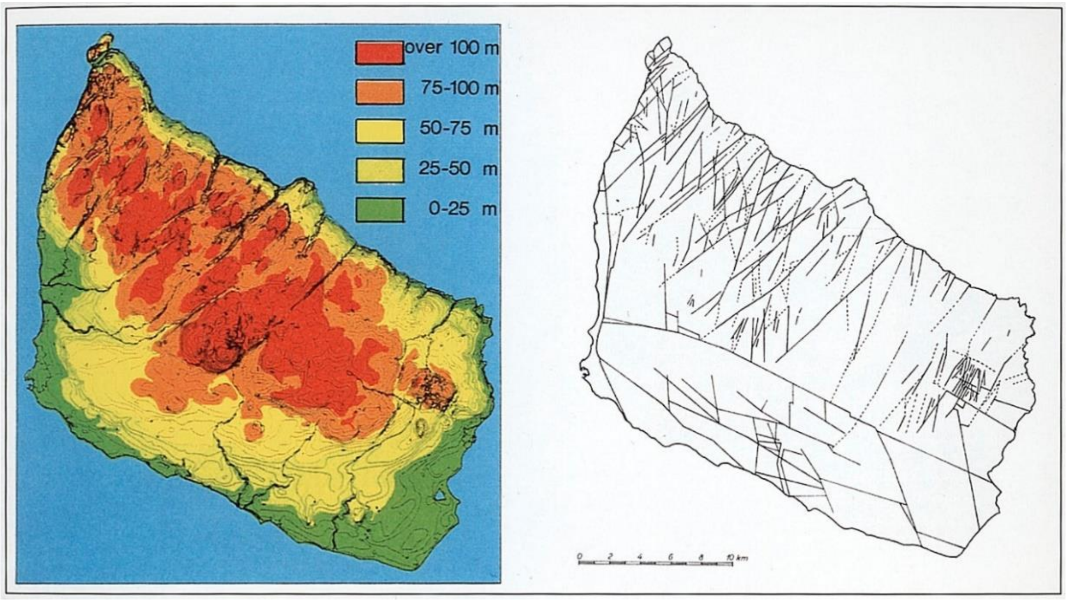


Figure 3. *Map showing base Quaternary subcrop rock types on Bornholm (modified from Varv, 1977).*

Figur 3. *Kort over Bornholms undergrund ved basis af Kvartæret (efter Varv, 1977).*

Quaternary sediments covering the shallow basement on Bornholm vary in thickness from 0 to 25 meters and consists mainly of glacial clayey and sandy tills (Figure 5) (Grönwall & Milthers 1916). Along the northern coast the cover is mostly absent and basement rocks are exposed in most areas (shown as pre-Quaternary on the map in Figure 5). Occasionally Late Glacial and Post Glacial freshwater, aeolian and marine sediments are found on the surface. The thickest Quaternary deposits occur in linear valleys where they can form up to 80 meters or thicker, successions of glacial tills and meltwater sand and gravel together with postglacial sand and clay.



a. **b.**

Figure 4. a. *The topography of Bornholm (meters above mean sea level).* ***b.*** *Map showing that major faults and valleys in the basement are oriented predominantly NNE-SSW to NE-SW and the sedimentary basins to the south-southwest are dominated by WNW-ESE trending structures (From Gravesen, 1996 after Meesenburg, 1972 and Micheelsen, 1961a).*

Figur 4. a. *Bornholms topografi (meter over havniveau),* ***b.*** *Store forkastninger og sprækkedale i grundfjeldet mod nord er hovedsagelig orienteret NØ-SW og i de yngre sedimenter mod syd og sydvest er de strukturelle elementer hovedsagelig orienteret NW-SØ til WNW-ØSØ (efter Gravesen, 1996; Meesenburg, 1972, and Micheelsen, 1961a).*

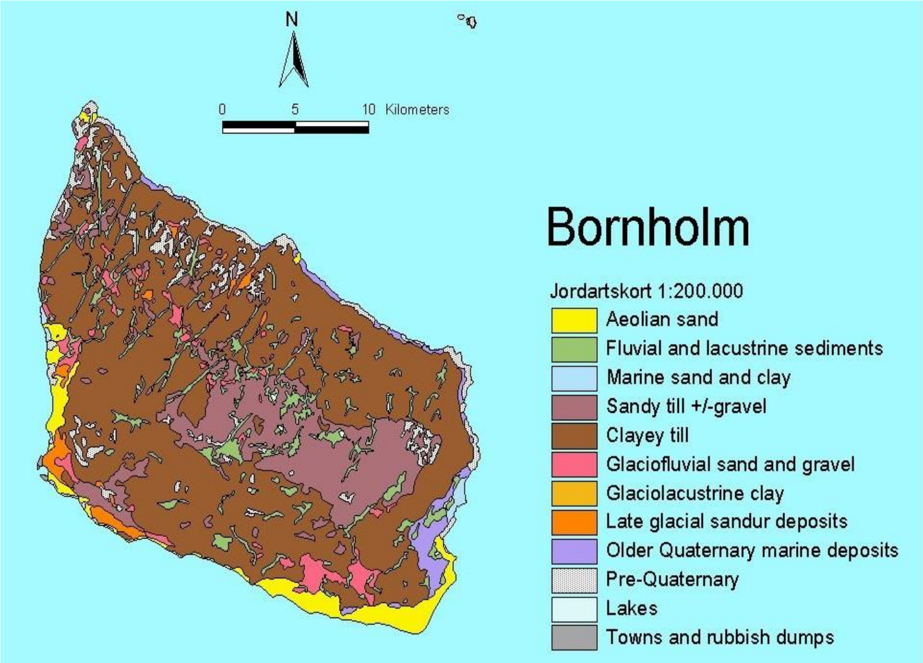


Figure 5. *Map showing the Quaternary deposits on Bornholm (after Pedersen, 1989).*

Figur 5. *Kort over de kvartære overfladeaflejringer (Efter Pedersen, 1989).*

3. Geology of the Precambrian crystalline basement

The present report is based on existing data combined with a few new observations from field work and acquisition of a 2D seismic line. The location of most of the existing detailed geological studies has been determined by the presence of natural exposures and quarrying of building material, which have resulted in the exposure of fresh, unweathered rocks enabling detailed geological and structural investigations. Thus, existing information is unevenly distributed with highly varying level of details, and in some areas on central Bornholm the basement geology is known only from few local surface exposures and a few deep-water wells.

In the following sections the general geological and structural development of the crystalline basement is described, followed by a detailed description of geological properties and features of the basement rocks including the dominating structural elements. The seven most significant and mappable rock types occurring at surface and near-surface include the foliated and medium-grained Bornholm Gneiss and the medium-grained Pa-radisbakke Migmatite, which have been deformed by superimposed folding, the dark colored Rønne Granite and the light-colored mainly red-grey, medium-coarse-grained Vang Granite, the medium-grained Almindingen Granite, the medium grained Hammer Granite and the coarse-grained Svaneke Granite. Small bodies of red grey leucogranites and dark grey dolorite dykes occur locally (Micheelsen, 1961a, Gravesen, 2006). The distribution of the rock types is shown in Figure 3.

On the northern and northeastern part of Bornholm the basement is exposed at the ground surface or it is covered by just a few meters of Quaternary glacial deposits (Figure 5). Several reticular valleys occur in crushed basement rock and are usually filled by glacial meltwater sand and gravel deposits with the deepest known valley in Muredam where 80 meters Quaternary sediments have been encountered without reaching top basement (Gravesen, 1990). To the south and southwest, the crystalline basement occurs much deeper below Paleozoic or Mesozoic deposits that are presently preserved in numerous minor fault-controlled grabens (Figure 3).

The depth to the crystalline basement underlying the Paleozoic and Mesozoic sediments is known only from a few boreholes drilled in the search for groundwater. The greatest depths are observed to the south where the Svaneke Granite was encountered at 312 meters below ground level (Nielsen et al., 2006, Schousbo et al., 2015, Zhou et al., 2017) and in a well drilled in Lower Jurassic sediments east of Rønne the basement was not encountered at the total drilled depth of 400 meter (Nielsen, 2003).

The basement rocks on Bornholm have been investigated by many authors from the early 1900 to present day (e.g. Callisen, 1934, 1956, 1957; Micheelsen, 1961 a, b; Platou, 1970, 1971, Noe-Nygaard, 1963; Sørensen, 1967; Berthelsen, 1988, 1989). All these studies have contributed to the mapping and characterisation of the basements rocks and understanding of their development. Recent dating's have contributed with knowledge about the time of formation (Johansson et al., 2016, Waight et al., 2012, 2017, Zarins & Johansson, 2009). The structures have been mapped by von Bubnoff, (1932, 1938, 1942), Von Bubnoff & Kaufmann, 1933), Micheelsen (1961a, b) and Münther (1945, 1973) and deeper fractures have been identified by borehole logging (Gravesen et al, 2014). Also, mapping of groundwater and surveys addressing natural radioactivity have provided information about the basement (Andersen et al, 1997, Gravesen et al, 1980). A large part of the general characterisation of the basement rocks has been presented in reports by Gravesen et al. (2011, 2012) related to a previous project on potential near-surface storage of radioactive waste (not a final repository).

Geological development

The granite and gneiss basement rocks of Bornholm were formed during the short interval from 1450 to 1460 million years ago by intrusion of magma in a tectonic active environment where a penecontemporaneous deformation was ongoing. This Mesoproterozoic magmatism happened within an active continental shear zone (Johansson et al., 2016) and the magmatism was contemporaneous with magmatism within a large area in southern Scandinavia. Locallym, some of the basement rocks were significantly deformed and transformed into gneisses, while most of the granites remain undeformed (Johansson et al., 2016).

The small difference in crystallization age between the rock types with different mineral composition, texture and degree of deformation suggest a multi-phase emplacement history of the granites and gneisses within a geologically short time span. The granites cut the structures of the grey Bornholm Gneiss and all the basement rocks are cut by light red-grey colored fine-grained aplites and coarse-grained pegmatites. These intrusives are considered as formed from the same magma as the Hammer and Almindingen Granites but during a late stage in the process (Micheelsen, 1961a, b, Gravesen, 1996). An example is the Hammer Granite crosscutting the Vang granite, which points to a younger age of the former and with associated aplites and pegmatites (Zarins & Johansson, 2009).

There is at present no knowledge about the basement rocks and their properties at depths greater than 200 meters. It is expected that the rocks occurring at depths around 500 meters are comparable to those occurring at surface, as the rock bodies are all formed by intrusions of melts at large depth, but the three-dimensional distribution in the subsurface is most likely different from the surface distribution of the various crystalline rock types.

Main structural elements

The main structural elements observed from surface outcrops include faults and fractures of different origins and small-scale folds in the gneiss. The major structural elements of Bornholm are the faults, which are highlighted by the presence of linear valleys and diabases occurring associated with the extensional faults. The surface and upper part of the basement is generally intensively fractured, observed most easily along the coast and in quarries. The varying surface morphology of Bornholm is largely controlled by the presence of old faults and fractures, where Quaternary processes of erosion and deposition during several episodes of glaciations occurred preferentially in the pre-existing weak surfaces along old faults and fractures.

In the following the term fault is used only where clear evidence of displacement has been observed on, or across the fault plane. Otherwise, the descriptive term fracture has been used, however, not excluding the possibility that some or most fractures were generated due to faulting and associated with offset.

Folds

Some of the gneisses and granites show small fold structures formed in the Precambrian (1450-1460 m.y.) during intrusion of magma whereas there are only few observations of large-scale fold structures The fold axes are mainly oriented NE-SW and N-S, dipping towards NE and N. The foliation in the gneisses and some of the granites as the Svaneke Granite indicate fold structures inclined towards the north (Michelsen, 1961 a).

Faults

Most faults are mapped in the Svaneke Granite-Bornholm Gneiss/Paradisbakke Migmatite area, in the Hammer Granite/Vang Granite area and along the boundary between the basement and the Paleozoic and Mesozoic sediments to the south and southwest (Figures 3 & 4). A major fault forms the northern rim of Paradisbakkerne.

Large faults occur with orientations varying from N-S, NE-SW, NNE-SSW to WNW-ESE (Michelsen, 1961a, Münther, 1973, Graversen, 2009). The faults were generated during several post-Precambrian phases of uplift and extension and are expected to be deep seated due to their tectonic origin and brittle character.

The Palaeozoic fault system related to the development of the Sorgenfrei-Tornquist Zone was associated with two-dimensional plane strain during ENE-WSW and NNE-SSW extension. In contrast the Jurassic and Cretaceous fault systems were associated with three-dimensional strain with maximum extension striking NE-SW and secondary extension striking NW-SE. The Palaeozoic fault systems strike NW-SE and WNW-ESE and were associated with dolerite dyke injection during the Late Carboniferous-Early Permian time. The NNE and ESE oriented shear fractures in Vang and at Hammeren are interpreted to have formed during the main dextral trans-pression in the Sorgenfrei-Tornquist Wrench-Fault Zone during the Carboniferous to Permian time periods.

The Mesozoic faulting was associated with the development of horst and graben structures in the Bornholm-Skåne segment of the Sorgenfrei-Tornquist Zone and Mesozoic fault-controlled subsidence began in the Rønne Graben in the Triassic. During the Cretaceous and early Tertiary inversion took place, older faults were re-activated and significant erosion occurred. The latest phase of tectonic movements occurred due to wrench faulting in the Sorgenfrei-Tornquist Zone in the early Paleocene.

Fractures

The basement rocks are intersected by numerous vertical fractures oriented predominantly NNW–SSE, NNØ–SSW or ESE–WNW. Usually, two fracture orientations dominate locally but sometimes 3-5 different orientations of vertical fractures occur as well as oblique fractures. The frequency and predominant orientation of fractures vary locally and is described in more detail together with the characterization of the various crystalline rock types. A summary of the various tectonically generated deformation structures identified in the uppermost 100 meters of the basement is presented in Figure 6. Most of vertical fractures are probably of tectonic origin. In the interval 0 meters to ca. 50 meters abundant fractures, both vertical, oblique, and horizontal occur and they are interpreted to have formed mainly during glaciations.

Fracture zones in the Vang Granite are interpreted as formed in association to large Precambrian fault zones oriented parallel to the predominating N-S and NW-SE fault orientation on Bornholm (Figures 4 & 5). The ESE-WNW vertical fracture system is oriented parallel to the Paleozoic faults and was probably formed during the main phase of wrench faulting in the Sorgenfrei-Tornquest zone in the Late Paleozoic or later (Graversen 2009).

One system of horizontal fractures (sheet jointing) observed at depths to around 100 meters was probably formed due to unloading and associated pressure release as a significant thickness of overburden (> 10 km) was eroded and removed during the Cambrian to Quaternary time. It is expected that the distance between these horizontal fractures is increasing downwards but very limited data is available.

Another set of horizontal fractures also occur with spacing of 1-2 meters near the ground surface associated with blocky fractures and crushed rocks and with increasing distance downwards. This fracture system is supposed to have formed from loading and unloading of glaciers during the Quaternary. The maximum depth to which these fractures have been generated is unknown, but some horizontal fractures occur at 90 meters depth below the ground surface.

The final phase of deformation is represented by a framework of anastomosing sub-horizontal fractures (Figure 6). This fracturing was created due to glacial shearing during the advance of the Baltic Ice sheet in the final phase of the Weichselian glaciation 25–15.000 years BP, and it created the glacio-morphological features known as rock moutonnée in the basement surface.

Dykes

More than 250 diabase dykes from four generations of basic olivine dolerite composition (diabases) were intruded into sheared and brecciated fault zones, mainly in N–S or NE–SW directions. In addition, around 20 fractures filled with Palaeozoic sandstone have been identified. The cutting relations of the dykes document the successive intrusive episodes (Noe-Nyegaard, 1963). The dykes are often assumed of Late Precambrian age, but palaeomagnetic studies indicate that some of the dykes may be of Early-Middle Palaeozoic age (Abrahamsen, 1977). Some of the dykes are seen to penetrate the Palaeozoic sediment cover thus being of younger age (Münther 1973) and Holm et al., (2010) and Jensen (1989) demonstrated dykes of Permian age equivalent to Permian dykes occurring in Scania.

The largest dyke is present at Kelså in the Ekkodalen valley extending for more than 10 km (Figure 3), and another major dike occurs at Listed extending for more than 5 km from the Svaneke Granite to Tamperdal in the Paradisbakkerne where it cuts the Paradisbakke Migmatite.

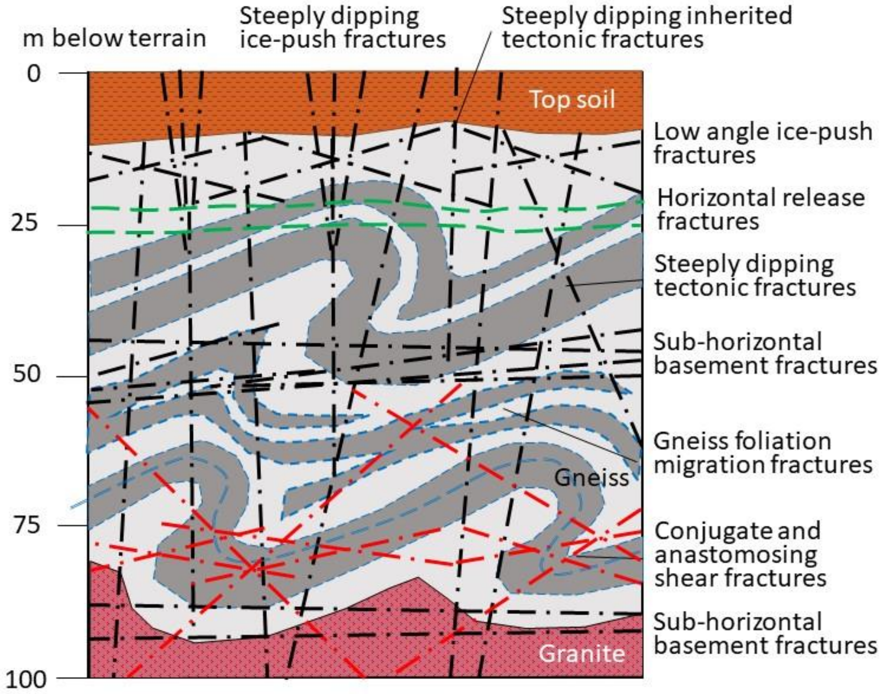


Figure 6. *Diagram summarising the various types of fractures identified in the crystalline basement on Bornholm.*

Figur 6. *Diagram der illustrerer de forskellige typer af sprækker, som optræder i det krystallinske grundfjeld.*

Present day tectonics

Bornholm is considered as tectonically stable although it is situated in the Fenno-Scandian Border Zone (Sandersen et al., 2021). Present day tectonic movements are rare and only one small earthquake has been registered on Bornholm during the latest 90 years.

4. Crystalline Rock Types

The seven most significant crystalline rock types occurring on Bornholm are described in the following. The rocks include the dark colored Rønne Granite and the light-colored mainly red-grey, medium-coarse-grained Vang Granite, the foliated and medium-grained Bornholm Gneiss and the medium-grained Paradisbakke Migmatite, the medium-grained Almindingen Granite, the medium grained Hammer Granite and the coarse-grained Svaneke Granite. Small bodies of red grey leucogranites and dark grey dolorite dykes occur locally (Micheelsen, 1961a, Gravesen, 2006). The surface distribution of the rock types is shown in Figure 3. The chemical composition of all the granite and gneiss rock types can be found in Callisen, (1934), Micheelsen (1961 a) and Johansson et al., (2016).

4.1 Rønne Granite

The Rønne Granite occurs locally in two irregular areas east of Rønne covering 1km x 3 km and 1-2 km x 5 km respectively (Figure 3). The Rønne Granite is bounded by the Bornholm Gneiss towards northeast and the Nyker fault block to the north. To the east and south it is bounded by the Cambrian Nexø Sandstone. To the west is an elongated area where intensive weathering of the granite has resulted in formation of kaolinite (Figure 3).

Large outcrops are found in quarries at Klippeløkken and Stubbeløkken northwest and southeast of the road to Rønne (Bornholms Regionskommune, 2012). Southwest of Klippeløkken a former kaolinite quarry is located at Nygård and southwest of Stubbeløkken two older kaolinite quarries are located (Bondam,1967; Gravesen, 1984, 1996, 2006).

4.1.1 Rock characteristics

The Rønne Granite is a medium grained, homogeneous, dark grey to black crystalline rock often with a reddish tint (Figure 7). The granite is often cut by several pegmatites and black dolerites (with the local name diabas). The pegmatites occur usually in series of 3-5 inclined bodies and can be up to 1 meter thick (Figures 8, 9, & 10). Thin diabase intrusions are oriented N-S and are often slightly kaolinized. A thick diabas occurs in the Klippeløkken quarry (Gravesen, 2006).

Figure 7. *Rønne Granite with reddish pegmatite veins, Stubbeløkken Quarry.*

Figur 7. *Rønne Granit med rødlige pegmatitårer, Stubbeløkken Stenbrud.*

Mineralogy

K-feldspar: 29%, plagioclase 30%, quartz 21%, hornblende 10%, biotite 5%, magnetite 3%, titanite 1%, apatite 1%, and accessory hypersthen, diopside, flourite, muscovite, zircon, epidote, chlorite, allanite (Callisen, 1934, 1957, Micheelsen, 1961a).

The grey and red feldspar grains are occasionally up to 10-15 cm.

Natural radioactivity

Minerals with radioactive components are zircon, titanite, apatite, allanite and gadolinite. Gadolinite is often found in coarse grained pegmatites (Gravesen et al, 1996) (Figure 11. The following values have been reported:

- Radium (Ra): 6.2-10.2 ppm (SIS, 1996)
- Uranium (U): 4.22 - 6.43 ppm, Thorium (Th) 13.8 -15.2 ppm (Johansson, et al., 2016).

Weathering

The granite has been weathered to kaolinite which is found locally eg. at Nygård and two other localities southeast of the main Rønne Granite rock body (Bondam, 1967, Bondam & Störr, 1988, Callisen, 1934). The weathering happened during time periods of warm and humid climate in the Jurassic where the granite altered due to downwards percolation of water through fractures in the granite. The feldspars dissolved and reprecipitated as kaolin while the more resistant quartz grains remained in-situ. The excavation of kaolin has now terminated. Recent weathering is less intense and occur locally as seen by red-brown colors due to the presence of iron oxides occurring on exposed surfaces and in fracture zones (Figure 12 and 13).

4.1.2 Structural elements

Near-surface structural features are observed in the two large quarries Klippenløkken (20-30 meters deep) and Stubbeløkken (50-60 meters deep) where the granite is intersected by vertical or subvertical fractures extending to the bottom of the quarries (Figures 8, 9, 10, 12, 13 & 14). Most fractures have a spacing of few cm to 10-20 cm but larger spacing of 1-2 meters occur as well (Figure 12). The fractures strike nearly N-S and NE-SW or NW-SE (von Bubnoff, 1942). The thick diabase (Figure 9) and abundant pegmatites are oriented parallel to the fractures. Sub-horizontal fractures dipping slightly towards the southeast are found in the uppermost parts of the exposed basement and associated with pegmatites up to 1m thick (Figure 10).

Figure 8. *Rønne Granite with abundant fractures, Klippeløkken quarry north east of Rønne.*

Figur 8. *Rønne Granit med mange sprækker, Klippeløkken Stenbrud nordøst for Rønne.*

Figure 9. *Rønne Granite cut by a several meters thick black vertical diabase seen in the central part of the picture, Klippeløkken quarry.*

Figur 9. *Rønne Granit skåret af en flere meter tyk, vertikal, sort diabas, der ses i midten af billedet, Klippeløkken Stenbrud.*

Figure 10. *Rønne Granite with several inclined, red pegmatite veins in the upper left part of the picture, exposed in Klippeløkken Quarry.*

Figur 10. *Rønne Granit med adskillige røde hældende pegmatitårer blottet i Klippeløkken Stenbrud.*

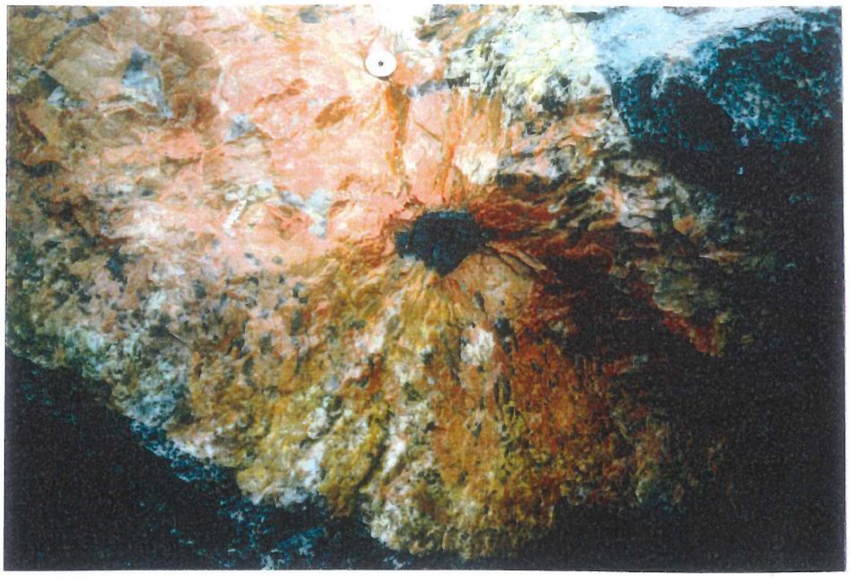


Figure 11. *Black radioactive gadolinite mineral in pegmatite in the Rønne Granite. Note the radiating fractures caused by the radioactivity.*

Figur 11. *Sort radioactivt gadolinit-mineral i pegmatit i Rønne Graniten. Bemærk de radierende sprækker i graniten, som skyldes radioaktiv stråling.*

Figure 12. *Vertical, subvertical and inclined fractures in Rønne Granite exposed in Stubbeløkken Quarry.*

Figur 12. *Vertikale, subvertikale og hældende sprækker i Rønne granit blottet i Stubbeløkken Stenbrud.*

Figure 13. *Rønne Granite with weathered reddish areas and grey diabase in the central part of the picture. Stubbeløkken Quarry.*

Figur 13. *Rønne Granit med forvitrede områder af rødlig granit og grå diabas. Stubbeløkken stenbrud.*

Figur 14. *Rønne Granite with abundant vertical fractures and few subvertical, Stubbeløkken Quarry.*

Figur 14. *Rønne Granit med talrige vertikale og enkelte subvertikale sprækker. Stubbeløkken stenbrud.*

4.2 Bornholm Gneiss

Gneiss is the most widespread basement rock and it occurs in the central part of Bornholm covering an area of approximately 10-15 km x 30 km (Figure 3). The gneiss is in general covered by Quaternary deposits, but it is exposed along the northern coast of Bornholm, in some small quarries, and in road cuts. It has been investigated in quarries at Knarregård, Hadeborg, and at Listed. At Katteslet Bakke the sharp boundary between the Bornholm Gneiss and the locally occurring Hallegård granite is exposed (Jørgart, 1977). In the Knarregård quarry at Østerlars the characteristic features of the gneiss can be observed. The gneiss is bounded by the Paradisbakke Migmatite towards the east, the Svaneke Granite towards the northeast, the Vang Granite towards the north and the Rønne granite towards southwest. It is surrounding the Almindingen Granite towards the south and it is bounded by faults towards the Paleozoic deposits to the south and Mesozoic deposits to the west.

4.2.1 Rock characteristics

The Bornholm Gneiss is mainly fine-grained or medium-grained, grey or red-grey with locally varying gneiss types due to varying mineral content and varying textures (Figures 15, 16 & 17). The gneiss is foliated or banded, and small-scale folds are common. The gneiss often contains smaller inclusions of dark rocks and other rock types as for example the large granite body near Østerlars (Figure 18), and minor aplites and pegmatites up to 10 cm wide. Diabase’s are abundant, the largest are the 60 meters thick Kelså diabas and the Bølshavn diabas.

Mineralogy

Grey biotite gneisses are weakly foliated or foliated and occasionally banded of light and dark bands: Quartz 29 %, plagioclase 31 %, perthite 28 %, biotite 8 %, hornblende 1 %, sphene 1 % and traces of epidote, chlorite, allanite, zircon and ore.
Granitic grey foliated biotite gneiss: Quartz 25 %, plagioclase 27 %, perthite 38 %, biotite 5 %, sphene 1 %, chlorite 1 % and traces of hornblende, epidote, allanite, zircon and ore.
Quartz rich gneisses: Quartz 53-72 %, plagioclase 22-12 %, perthite 19-11 %, biotite 2-1 %, hornblende 1 %, muscovite 2-1 % and traces of sphene and epidote.
Skarn bearing biotite gneisses are grey biotite gneisses containing ellipses of garnet-epidote.
Quarzites are almost pure quartz rocks and occur often as layers in grey biotite gneisses.
The colours of the gneisses vary from grey to pale grey and sometimes reddish (Callisen, 1934, 1956; Micheelsen 1961a, b; Waight et al. 2017, Platou, 1970).

Natural radioactivity

Natural radioactive components are found in zircon, allanite and apatite (Gravesen et al, 1996). Values reported are:

- Uranium (U) 3.5 - 6.75 ppm, Thorium (Th) 14.1 - 25.6 ppm (Johansson et al. 2016).

Weathering

Weathering of the Bornholm gneiss as observed at Hadeborg near the Bornholm Museum (Figure 19) has resulted in the generation of loose mineral grains, or grain aggregates lying on top of the gneiss surface due to preferential dissolution of framework grains in massive parts of the gneiss. Where banding of the gneiss is pronounced the weathered surfaces often have a schistose appearance due to preferential dissolution of less resistant dark minerals (Figures 16 & 19). Weathering of the gneiss is generally more pronounced along the north coast of Bornholm due to the influence of sea water.

Figure 15. *Folded Bornholm biotite gneiss west of Listed, north Bornholm.*

Figur 15. *Foldet Bornholmsk biotit-gnejs vest for Listed, Nordbornholm*

Figure 16. *Bornholm gneiss with weathered schistose surface, west of Listed, North Bornholm.*

Figur 16. *Skifret overflade af forvitret Bornholm Gnejs vest for Listed, Nordbornholm.*

Figure 17. *Folded Bornholm Gneiss with dark minerals and red feldspar in the folded bands.*

Figur 17. *Foldet Bornholm Gnejs med mørke mineraler og rød feldspat i foldede bånd.*

Figure 18. *Medium-grained red-grey granite occurring in the Bornholm gneiss at Østerlars.*

Figur 18. *Mellemkornet rødgrå granit indesluttet i gnejsområdet ved Østerlars.*

Figure 19. *Weathered surface of Bornholm Gneiss at Hadeborg Hill, Åkirkeby.*

Figur 19. *Forvitret overflade af Bornholm gnejs ved Hadeborg Bakke, Åkirkeby.*

4.2.2 Structural elements

The Bornholm Gneiss is intersected by several large valleys (e.g. Ekkodalen, Kobbeådalen, Søndre Borgedal) defined by WNW-ESE and approximately N-S trending linear fault planes (Figure 3). The gneiss is cut by numerous fractures oriented mainly NE-SW and NW-SE (von Bubnoff, 1942) and large diabases in Bølshavn and Kelså (beneath Ekkodalen) show the same NE-SW orientation.

A few large faults are oriented WNW-ESE thus being parallel to the main fault zone across Bornholm separating the Paleozoic and Mesozoic sediments in the south from the basement to the north (Figure 3 & 4). Small scale folding is observed in the Bornholm Gneiss in several places (Figure 15). Foliation in the gneiss is inclined towards the north. Mylonit zones are found at Jernkås south of Gudhjem, Olskirke and in an old quarry at Bobbeå (von Bubnoff, 1942). The mylonites occur within NE-SW and W-E striking fault planes, they are from 3 cm to 30 cm wide and comprise laminated fine-grained epidote, iron-oxides and crushed rock fragments. The presence of mylonite shows that small scale movements have taken place within the faults, thus not just representing fractures.

4.3 Paradisbakke Migmatite

The Paradisbakke Migmatite occurs in an elongated area 3-4 km wide and 8-10 km long located in the north-eastern part of Bornholm (Figure 3). It is exposed in the Præstebo and Bethelegård quarries. There is a sharp boundary towards the Svaneke Granite to the east whereas he western boundary to the Bornholm Gneiss seems to be gradational. The southern boundary to the Cambrian sandstones is formed by several faults (Figure 3).

4.3.1 Rock characteristics

The rock is fine- to medium-grained, foliated, it has dark grey and white stripes and locally it is grey or reddish resulting in a characteristic flame structure (Figure 20).

Mineralogy
The Paradisbakke Migmatite consists of quartz 23 %, alkali feldspar 35 %, plagioclase 25 %, hornblende 8 %, biotite 7 %, sphene, 1 %, ore 1 %, and traces of titanite, apatite and flourite including 2–3 cm, black radioactive allanite/gadolinite minerals in pegmatites.

The migmatite is composed mainly of dark grey fine-grained, greenish rock with plagioclase (ca. 80%) and the remaining lighter parts dominated by discontinuous veins of white and red minerals. These discontinuous veins consist mainly of quartz, alkali feldspar and plagioclase and result in a characteristic foliated flame structure (Callisen, 1934, Micheelsen, 1961 a,b). In addition, coarse-grained pegmatitic and fine-grained aplitic veins occur as smaller isolated bodies (Figure 21) or as larger pegmatite veins (Figure 22). The pegmatites and aplites contain 30–40 % quartz, 45–60 % perthite, 10–20 % plagioclase and low content or traces of dark minerals as ore, sphene, apatite, epidote and fluorite including gadonilite. Thin sandfilled fractures have also been observed locally.

Figure 20. *Foliated, grey and red Paradisbakke Migmatite with the characteristic flame structure, from Præstebo Quarry at the northern rim of the Paradisbakkerne area.*

Figur 20. *Folieret grå og rød Paradisbakke Migmatit med den karakteristiske flammestruktur, fra Præstebo stenbrud ved den nordlig rand af Paradisbakke-området.*

Figure 21. *Red and grey coarse-grained pegmatite vein in the Paradisbakke Migmatite, Bertelegaard quarry, northern rim of Paradisbakkerne.*

Figur 21. *Rødgrå, grovkornet pegmatit åre i Paradisbakke Migmatiten, Bertelegaard stenbrud, nordlig rand af Paradisbakkerne.*

Figure 22. *A reddish pegmatite vein in the Paradisbakke Migmatite is dipping to the left of the photo, cross cutting the sub-horizontal fractures. Vertical fractures are less common. Outcrop in Bertelegaard Quarry, northern part of Paradisbakkerne.*

Figure 22. *Rødlig pegmatit åre i Paradisbakke Migmatiten, Bertelegaad stenbrud. Nordlig del af Paradisbakkerne.*

Weathering
The migmatite is in most areas covered by thin Quaternary sedimentary deposits. Weathering of the migmatite is only observed in fracture zones where iron minerals are oxidised.

Natural radioactivity
The minerals zircon, flourite, allanite and gadolinit (often found in pegmatites) may contain radioactive elements (Gravesen et al, 1996). Following values have been reported:

- Radium (Ra) 6.7 ppm (SIS, 1996).
- Uranium (U) 6.1 - 9.8 ppm, and Thorium (Th) 14.0 - 19.2 ppm (Johansson et al., 2016).

4.3.2 Structural elements

Linear valleys and large fracture zones in the Paradisbakkerne area are mainly oriented NE-SW and NNE-SSW. These directions are parallel to the directions of other large valleys in the basement and some of the major faults in the Svaneke granite and gneisses. Some minor valleys are oriented WNW-ESE nearly perpendicular to the large valleys and parallel to major bounding faults between the basement and Palaeozoic sediments (Figure 3). The valleys are formed by erosion of Quaternary glaciers crushing and eroding basement material in the weak fault zones. In the area north of Paradisbakkerne the density of fractures is less compared to the basement elsewhere (Figure 4).

The diabase dykes are oriented parallel to the valleys and faults (Figure 3) and dykes are observed at the bottom of some of the valleys. The Listed dyke strikes 16^o E and the Bølshavn dyke strikes 12^o E, both are near-vertical. A few fractures filled with Cambrian shallow marine sandstones have been observed. The dykes with NE-SW orientation are of Precambrian age while the more E-W and ENE-WSW oriented dykes are probably of Permian age.

Based on observations from Præstebo and Bertelegård quarries and the north coast of the area as well as lineaments mapped at surface, it seems like the migmatite is less densely fractured, i.e. comprise fewer fractures with larger distances between compared to the other basement rocks on Bornholm (Figures 22, 23 & 24). It can be speculated whether this is structurally controlled or whether glacial erosion has removed a thicker section of crushed rock in this area.

***Figure 23.** Paradisbakke Migmatite exposed in the Præstebo quarry (exposure height is approx. 12 meters). The distance between horizontal fractures is increasing downwards. Vertical fractures seem to be absent.*

***Figur 23.** Paradisbakke Migmatiten blottet i Præstebo stenbrud (Ca. 12 meter højt). Afstanden mellem de horisontale sprækker øges med dybden under terræn.*

The largest exposure showing 12–15 meters of rock below the surface occur in the Præstebo Quarry (Figure 23) showing the presence of subhorizontal fractures only. Some information about the deeper parts is provided from well logs in Østermarie Water Work boreholes, adjacent to the quarry (Rasmussen et al., 2007, Gravesen et al., 2014). Information from gamma logs, resistivity logs and flow logs indicate the presence of water bearing fracture zones at 19-22 m, 25 meters and 37 meters. The presence of clay layers has also been identified from well logs at depths of 25 m, 30 m, 31 meters and 37 meters indicating the presence of weathered fractures, and some of these are water bearing as observed from the flow logs. Based on observations from outcrops and the water wells it seems like the spacing between horizontal fractures increases downwards, and that below 40 meters water bearing fractures are scarce.

Figure 24. *Section from Præstebo quarry with vertical and horizontal fractures. The spacing of the vertical fractures is decreasing downwards from very small just at surface (cm size) to a spacing of several metres. Only one horizontal fracture is seen in the middle part of the approx. 3 meters high outcrop.*

Figur 24. *Profil fra Præstebo stenbrud med vertikale og horisontale sprækker. Afstanden mellem de vertikale sprækker varierer fra meget lille (cm størrelse) til en afstand på adskillige meter. Kun en horisontal sprække ses i det ca. 3 meter høje profil.*

The spacing between vertical fractures varies from a few cm (observed mostly in the surface), to several meters and sometimes numerous fractures occur closely spaced forming fracture zones (Figure 25). The spacing of very tiny fractures (vertical joints) is seen to vary from a few cm to five meters or more. In general, based on existing studies, vertical fractures are less frequent in the Paradisbakke Migmatite compared to the other crystalline basement rocks on Bornholm.

Figure 25. *Vertical fracture zone in Paradisbakke Migmatite, Præstebo Quarry.*

Figur 25. *Vertikal sprækkezone i Paradisbakke Migmatit, Præstebo stenbrud.*

4.4 Vang Granite

The Vang Granite occurs within an area of approximately 3 km x 6 km in the Vang area (Figure 3) and is exposed in three quarries. One quarry is located south of Vang Harbour and two quarries exist in the Ringebakker area. To the north it is bounded by Hammer Granite, but an inlier of Hammer Granite occurs within the Vang Granite as well as a Vang Granite inlier occurs in the Hammer Granite (Jørgart, 1977, Platou, 1970). North of Vang Harbour, the contact to the Hammer Granite is observed to be dipping beneath the Vang Granite. Most of the granite surface is covered by a relatively thin layer of clayey and sandy tills but it is exposed in numerous places (Figure 26) in quarries and locally along streams.

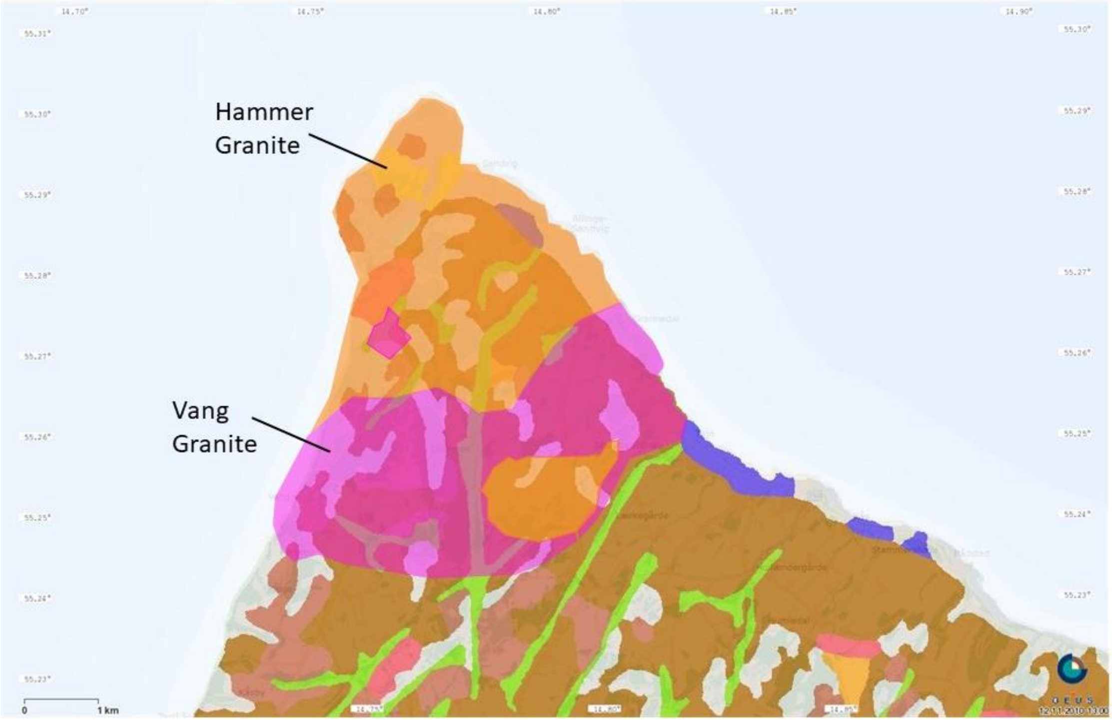


Figure 26. *Map of the Quaternary deposits of northern Bornholm (From GEUS Homepage after Pedersen, 1989). Legend: Brown: Clayey till, Red Brown: Sandy till, Red: Meltwater sand and gravel, Blue: Late Weichselian marine deposits, Green: Holocene Freshwater deposits. The outcrops of Vang and Hammer Granites are indicated with transparent magenta and orange colours. Light grey show Bornholm Gneiss outcrops.*

Figur 26. *Kvartærgeologisk kort over Nordbornholm (Fra GEUS Hjemmeside efter Pedersen, 1989). De transparente magenta og orange farver viser, hvor Vang og Hammer Granitterne er blottet, de lysegrå områder viser hvor den Bornholmske Gnejs er blottet.*

4.4.1 Rock characteristics

The Vang Granite is medium- to coarse grained grey and red with many 0.5-1 cm spots of dark minerals (Figure 27). It is often weakly foliated with c. 45º dip towards the north. The foliation increases towards the south. The granite contains many inclusions of older rocks. Veins and dykes of 10-15 cm thick pegmatites and aplites are common, and occasionally up to 1m thick. A few diabases cut the granite locally with thickness up to 1m.

Figure 27. *The red and grey, medium to coarse-grained Vang Granite from an unweathered surface in the Vang Quarry.*

Figur 27. *Rød og grå, mellem-grovkornet Vang Granit i en uforvitret overflade i Vang Stenbrud.*

Mineralogy and chemistry

The granite consists of: Quartz 27 %, perthite 33 %, plagioclase 22 %, hornblende 5 %, biotite 6 %, titanite 1 %, ore 3 %, allanite and with traces of fluorite.

The light minerals have grown to form a myrmekiltic texture in the granite. Associated pegmatites and aplites composed of quartz and perthite are common, while diabases are rarely observed in the quarries (Callisen, 1934, Micheelsen, 1961a,b).

Natural radioactivity

Radioactive isotopes occur in allanite and fluorite (Gravesen et al, 1996). Following values have been reported:

- Radium (Ra): 21 ppm (SIS,1996)
- Uranium (U): 3.8 ppm, and Radium (Ra): 5.3 ppm (Gravesen & Jakobsen, 2016; Gravesen et al., 1996).
- Uranium (U): 4.58 - 7.6 ppm, and Thorium (Th): 12.8 - 18.2 ppm (Johansson et al. 2016).

Weathering

The granite is seen to be strongly weathered in fracture zones and in the uppermost meter of the surface (Figure 28). The yellow-brown colour indicates weathering of iron-bearing minerals (Figures 29 & 30) and plagioclase weathering to sericite and chlorite is also observed in the fractures.

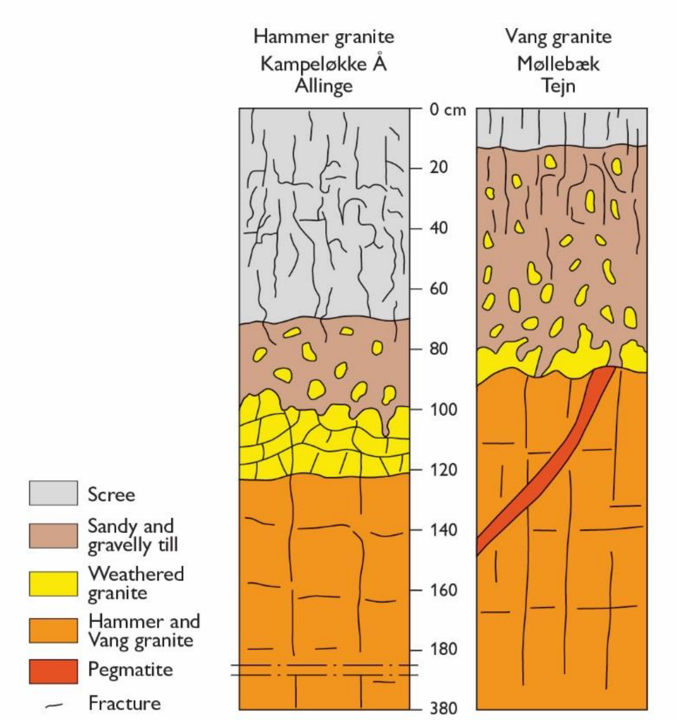


Figure 28. *Section trough the Hammer Granite surface at Kampeløkke Å, Allinge and the Vang Granite at Møllebæk, Tejn showing weathering is restricted to the uppermost meter of the rocks (From Gravesen & Jakobsen, 2016).*

Figur 28. *Profiler gennem Hammer Graniten ved Kampeløkke Å, Allinge og Vang Granit ved Møllbæk, Tejn (Fra Gravesen & Jakobsen, 2016) som viser, at intens forvitring foregår i den øverste meter af de krystallinske bjergarter.*

Figure 29. *Vertical fracture zones in the Vang Granite with the yellow-brown colours resulting from weathering of iron-bearing minerals. The outcrop in Vang Quarry is 10-15 meters high.*

Figur 29. *Vertikale sprækkezoner i Vang Granit med gulbrunt farvede stærkt forvitrede partier. Stenbruddet i Vang er ca. 10-15 meter dybt.*

4.4.2 Structural elements

The Vang Granite is to the southeast bounded by large fault-controlled zones/valleys oriented mainly NE-SW. The granite is cut by fractures with NW-SE directions often forming zones of closely spaced fractures but fractures also occurring with spacings of 2-15 meters between fracture zones. Diabase dykes and sand filled fractures cut the Vang Granite (Katzung, 1996, Katzung & Obst, 1997).

In the quarry at Vang the granite is heavily fractured by conjugate, shear fractures orientated perpendicular to each other in the directions trending NNE and ESE (Figure 29). The ESE fracture system has a fracture density of 3 vertical joints per running meter in a cross-section perpendicular to strike. Vertical and horizontal fractures are recognised down to 60 meters below top of the granite (Knudsen, 1994) (Figure 31). Core samples from three boreholes demonstrate that fractures and shear zones with weathered granite occur down to at least 60 meters below the surface (Figure 31).

Figure 30. *Vang Granite, Almeløkke Quarry. The granite is cut by northeast dipping fractures.*

Figur 30. *Vang Granit med sprækker hældende mod nordøst, Almeløkke stenbrud.*

Fractures observed in the Almeløkke Quarry are oriented predominantly ESE-WNW but varying from NNE-SSW, NE-SW and NNW-SSE. Some of the fractures dip 45^o towards NE (Figure 30). Some of the fractures are associated with breccias indicating formation due to extensional tectonic movements. The breccias have been altered to kaolinite.

Some WNW-ESE oriented fractures in the Vang Granite are filled with sandstone of Cambrian age. The sand filled fractures have widths varying from a few cm to a few tens of cm.

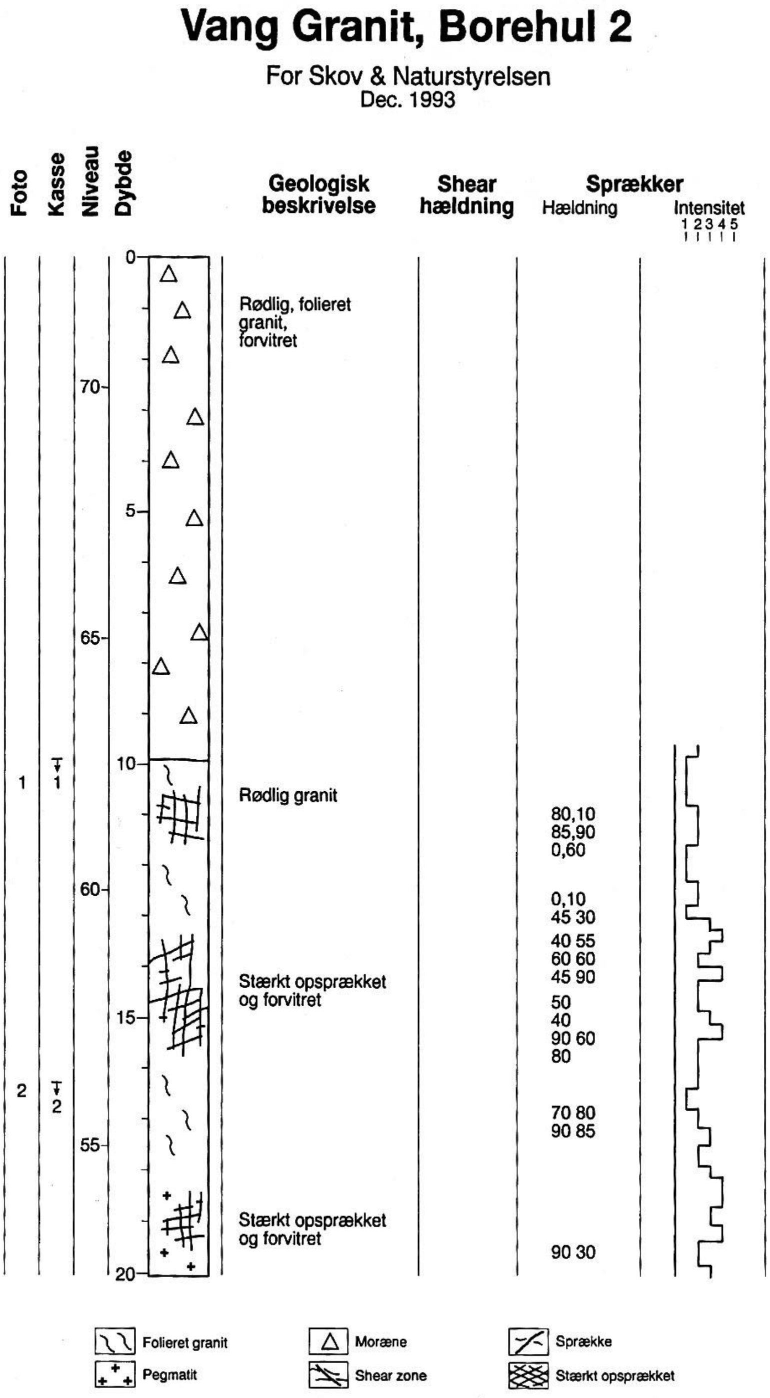


Figure 31. *Geological log from borehole DGU no. 244.555 drilled into the Vang Granite. The drill cores indicate fractures (sprækker) and shearing occur down to 60 meters below ground surface (From Knudsen, 1994).*

Figur 31. *Geologisk log fra råstofboringen DGU nr. 244.555, som er boret i Vang Granit. Borekerner demonstrerer sprækker og tektoniske bevægelser ned til 60 meters under terrænoverfladen (Fra Knudsen, 1994).*

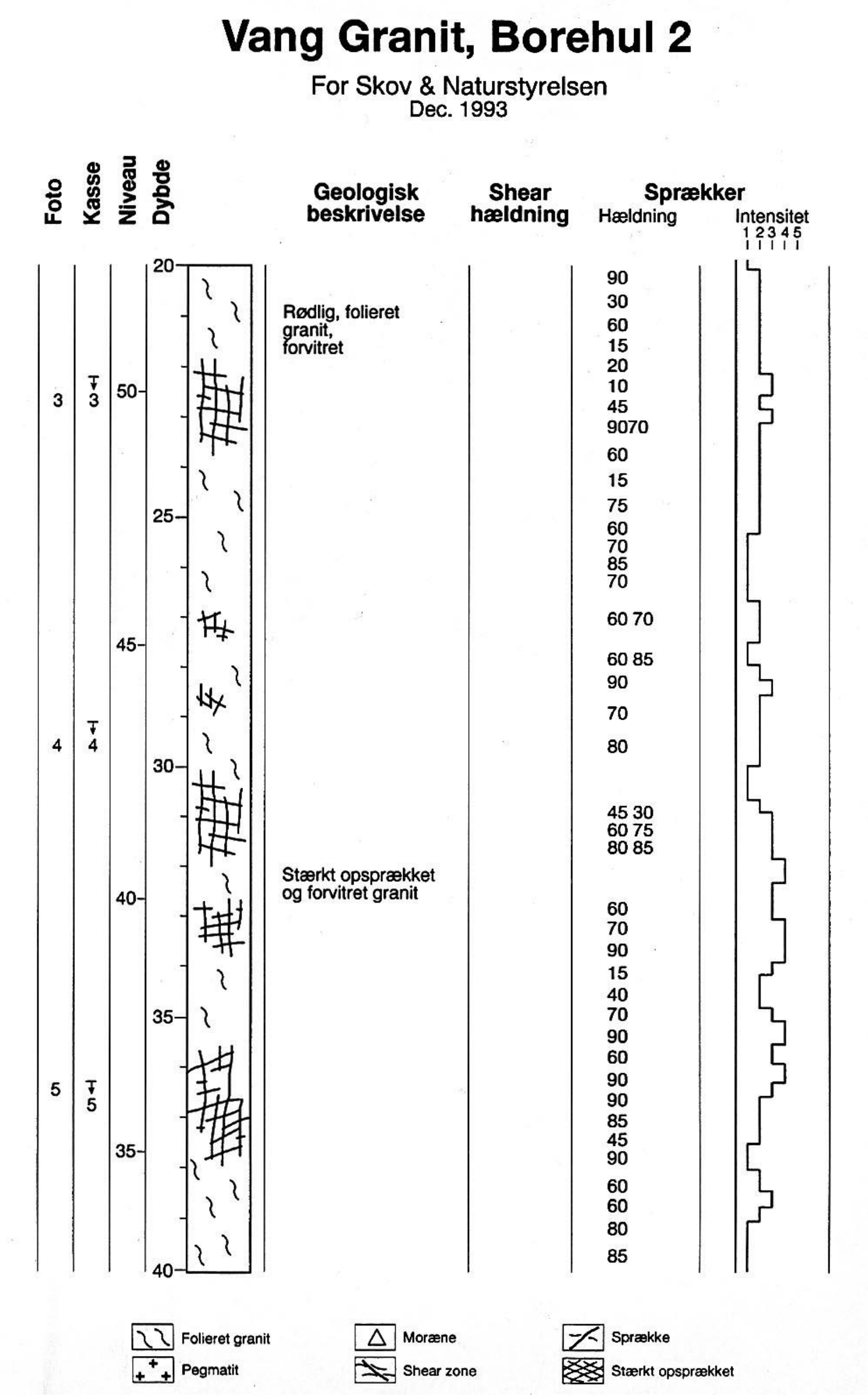


Figure 31. *Continued.*

Figur 31. *Fortsat.*

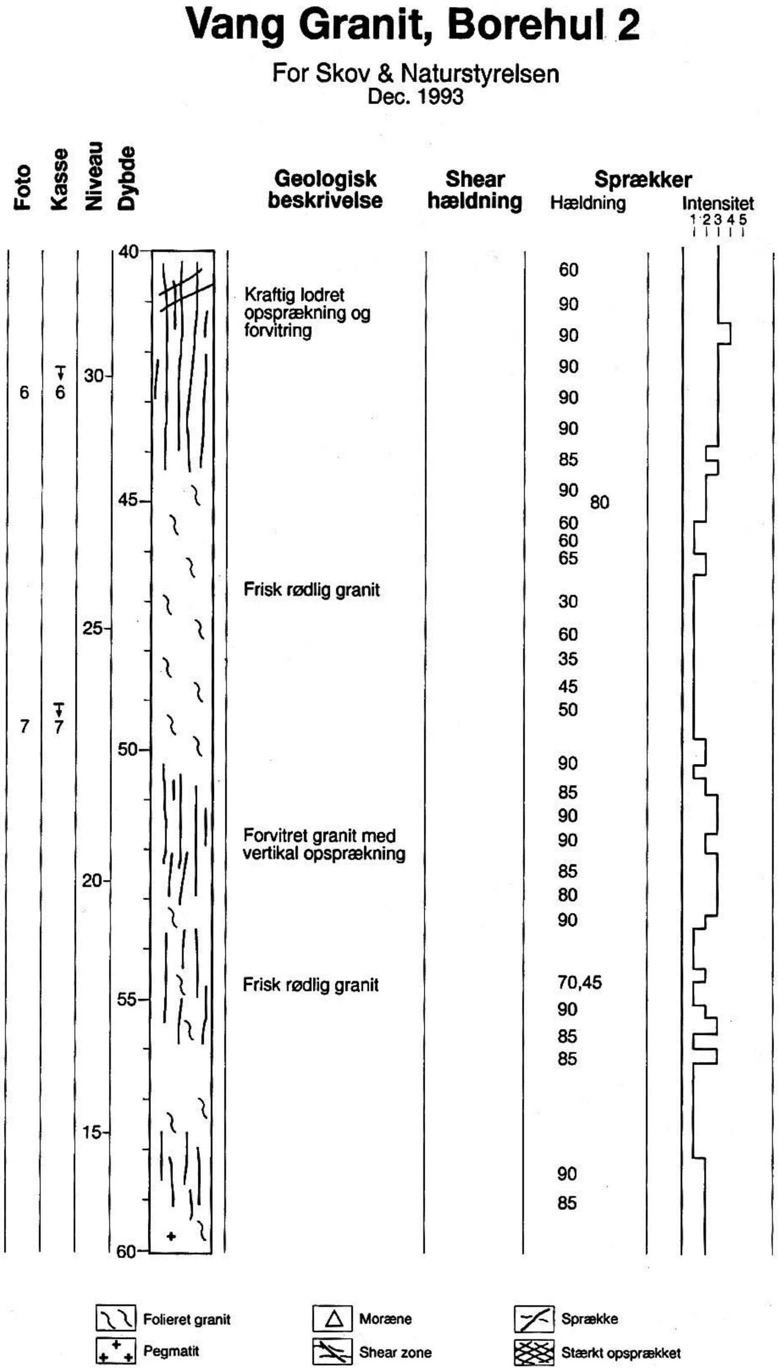


Figure 31. *Continued.*

Figur 31. *Fortsat*

The granites and gneisses have no primary porosity in the “matrix” and the porosity is only related to the presence of fractures (macro pores). These characteristics are very important for the water transport and the water supply.

4.5 Svaneke Granite

The Svaneke Granite constitutes the easternmost part of the basement occurring in a north-south elongated area 3-4 km wide and 6-8 km long (Figure 3). The western boundary is gradational towards the Paradisbakke Migmatite and Bornholm Gneiss whereas a major fault forms the southern boundary towards Cambrian sediments. The boundary between the Svaneke Granite and the Bornholm Gneiss is exposed at the coast west of Listed (Gravesen, 1996). The granite is well exposed and weathered along the north coast and the northern east coast (Figure 32). Svaneke Granite is also exposed in the Hellesgård quarry (referred to as Helletsgård Granite) and in numerous small natural exposures (Platou, 1970).

Figure 32*. Svaneke Granite exposed in a 2 meters high road cut south of Listed.*

Figur 32. *Svaneke Granit blotlagt i en vejgennemskæring syd for Listed.*

4.5.1 Rock characteristics

The Svaneke Granite is red and grey, coarse-grained with large red feldspar crystals (Figure 33). The texture in the granite is either structureless or foliated (Platou, 1970, 1971). Pegmatites, aplites and dykes cut the granite and at Gule Hald, Listed, black diabases and fractures filled with dark greenish-grey Cambrian sandstone occur (Bruun-Petersen, 1975, Gravesen 2006) (Figure 34).

Figure 33. *The red - gray coarse-grained Svaneke Granite, Svaneke area.*

Figur 33. *Rødgrå grovkornet Svaneke Granit, Svaneke.*

Mineralogy

Perthite 36%, plagioclas 26%, quartz 25%, hornblende 2%, biotite 7%, magnetite 1%, titanite 2%, and apatite, epidote, fluorite (Callisen, 1934, Micheelsen 1961a, b, Waight et al., 2017, Platou, 1970).

Natural radioactivity

Radioactive isotopes occur in titanite, apatite and fluorite minerals (Gravesen et al., 1996). The following values have been reported:

- Radium (Ra): 2.5-8.0 ppm (SIS,1996).
- Radium-226 in borehole no. 247.121 is 3.0 - 7.3 ppm (38-93 Bq/kg) (Sundhedsstyrelsen, 1984, 1987).
- Uranium (U): 6.99 - 10.70 ppm and Thorium (Th): 22.4 - 36.6 ppm (Johansson et al. 2016).

Figure 34. *Svaneke Granite at Gule Hald, Listed.*

Figur 34. *Svaneke Granit ved Gule Hald, Listed.*

Weathering

The granite surface is usually strongly weathered along the coast. A good example is at Årsdale where percolating rainwater in fractures result in rock disintegration due to physical and chemical weathering (Figure 35) forming rounded blocks of granite (Figures 34 & 36) (Gravesen, 2006).

Figure 35. *Strongly weathered Svaneke Granite at Årsdale.*

Figur 35. *Stærkt forvitret Svaneke Granit ved Årsdale.*

Figure 36. *Svaneke Granite exposed west of Gule Hald with the characteristic rounded blocks forming the surface, east of Listed.*

Figur 36. *Svaneke Granit som blotlagt vest for Gule Hald med karakteristisk rundede overflader, øst for Listed.*

4.5.2 Structural elements

Fractures in the Svaneke Granite have been mapped by von Bubnoff (1942). More recently a fracture analysis has been performed on vertical fractures exposed at Frenne Odde south-east of Svaneke based on ortho-photos. In this area the jagged coastline morphology is largely controlled by fractures, which are easily recognized on the orthophotos. This area was chosen for the analysis because the Svaneke Granite has an isotropic texture meaning where the orientation of fractures is controlled by the tectonic stress regime and the resulting structural-tectonic development (Table 1).

The resolution of the photos is 10 cm and the mapped fractures are subdivided into 5 sets of orientations as listed in Table 1. The fracture intensity and the presence of the individual fracture set varies in the investigated area and five subareas characterized by different orientations have been defined (Figure 37). The characteristics and fracture intensity of each area is summarized in Table 1.

Table 1. Fracture orientation and density observed at Frenne Odde, Svaneke (areas A-E are indicated in Figure 44).

Tabel 1. Sprækkeorientering og -tæthed målt på Frenne Odde, Svaneke (arealerne A-E er angivet på Figur 44).

Fracture set	Area A	Area B	Area C	Area D	Area E
A: 115-135	Few;	Dominating	Many	Many 2. order	Dominating
B: 140-160	Few	2. order to A	Few	Few	Many 2. Order to A
C: 0-40	Scattered	Few	Dominating	Dominating	Few 2. Order to A
D: 160-180	Dominating	Many 2. order	Few	Dominating	Many
E: 80-100	Few	few	few	Not present	few
Fracture Intensity (fractures/m)					
A: 115 - 135	0,16	0,2	0,16	0,28	0,1
B: 140-160	0,1	0,03	0,04	0,06	0,07
C: 0-40	0,08	0,2	0,23	0,08	0,04
D: 160-180	0,1	0,14	0,03	0,18	0,29
E: 80-100	0,03	0,01	0,04	0,07	0,04
Fracture bulk intensity (fractures/m^2)	0,47	0,58	0,5	0,67	0,54

Examples on detailed investigations of fractures in the surface of basement rock in Sweden are described in Stephens et al., (2003) and the methods presented in this report may be used if further detailed investigations are to be carried out in the deeper parts of the basement rocks on Bornholm.

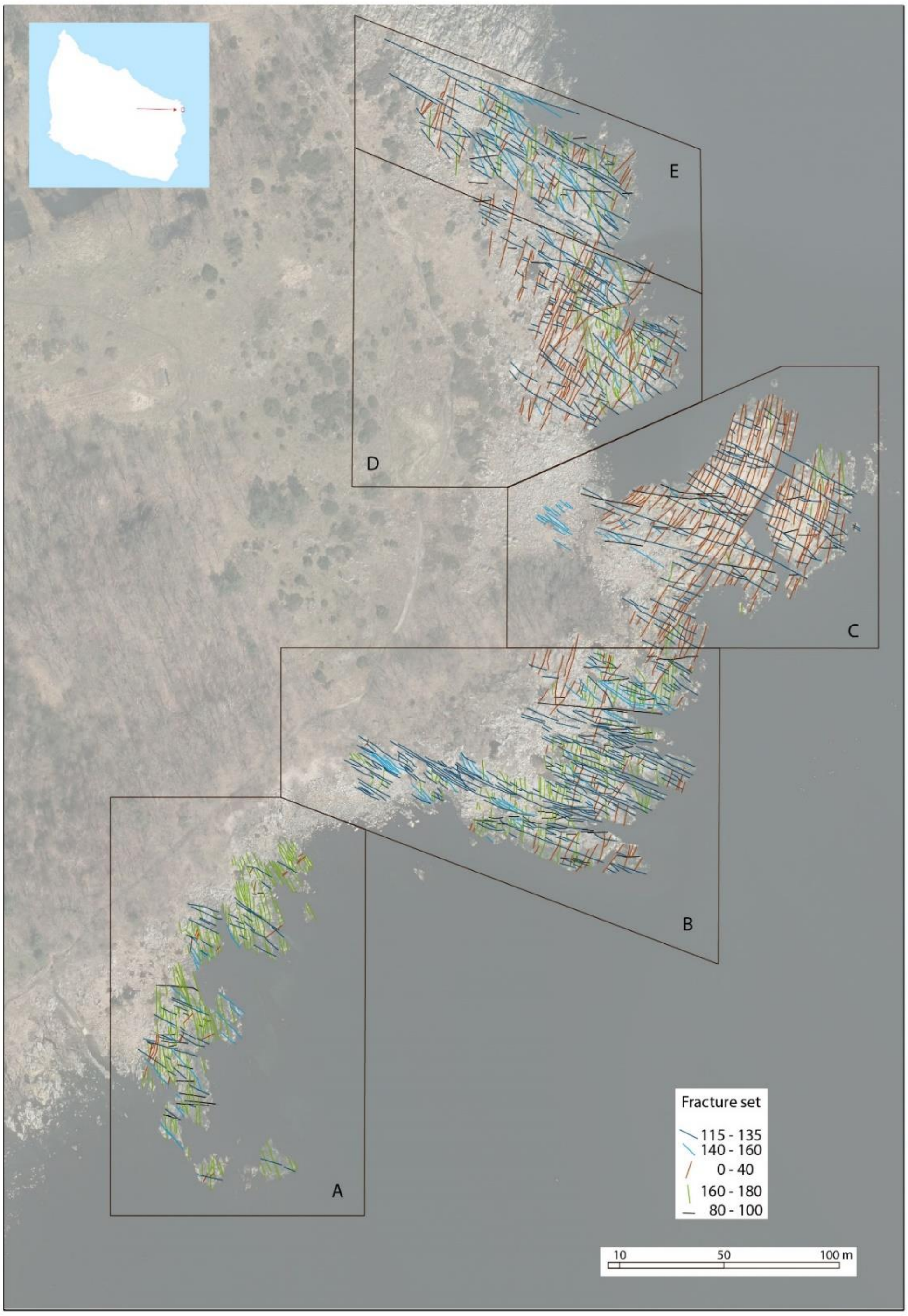


Figure 37. *Surface traces of vertical fractures along the coast southeast of Svaneke, mapped from ortho-photo. Five different orientations of fractures are identified, the orientation is indicated for each fracture set.*

Figur 37. *Overfladespor af vertikale sprækker ved kysten sydvest for Svaneke som er kortlagt ved hjælp af ortho-foto. Orienteringen af sprækker synes at være karakteriseret a fem dominerende retninger.*

4.6 Hammer Granite

Hammer Granite forms the northwesternmost tip of Bornholm in the Hammeren area covering approximately 4 x 5 km (Figure 3). Towards the south the Hammer Granite is bounded by large conjugated faults against the Vang Granite as observed in exposures in the deep Moselykken Quarry. An inlier of Vang Granite occurs north of Vang and an inlier of Hammmer Granite is found the Vang Granite at Olsker. Quarrying of Hammer Granite is currently taking place only in the Moseløkken quarry. Some abandoned quarries are presently filled with water forming the lakes Opalsøen and Krystalsøen. These lakes have different water levels, indicating that there is no, or very limited connection of the water bodies through fractures.

In most of the Hammeren area the granite is exposed at the ground surface of the Hammeren High and to the south in large natural exposures occurring along the northeast-southwest trending valley forming the southern boundary of Hammeren High. Further south the granite is exposed locally, but often covered by glacial clayey tills (Figure 26).

4.6.1 Rock characteristics

Mineralogy

The Hammer Granite is a light grey-red, fine to medium-grained rock with characteristic small red dots of hematite coatings on individual grains (Figure 38). The granite contains veins of coarse-grained pegmatites and fine-grained aplites. The mineralogy is: quartz 33 %, perhite 41 %, plagioclase 18 %, hornblende 1 %, biotite 4 %, titanite 1 %, ore 2 %, and traces of allanite, gadolinite, apatite, epidote and fluorite. The radioactive mineral gadolite occurs in feldspar and quartz rich pegmatites as observed in the Dalegård Quarry (Callisen, 1934, Micheelsen, 1961a,b) (Figure 39) and at Hammeren (Figure 40).

Natural radioactivity

Radioactive isotopes may occur in the minerals titanite, allanite, gadolinite, apatite and fluorite (Gravesen et al., 1996). Following values have been reported:

- Radium (Ra): 6.5 – 9.6 ppm (SIS, 1996).
- Uranium (U): 3.0-4.2 ppm and Radium (Ra): 5.1 – 7.0 ppm (Gravesen & Jakobsen, 2016; Gravesen et al., 1996).
- Uranium (U): 6.1 - 7.44 (12.5) ppm and Thorium (Th): 21.9 - 32.8 (99.6) ppm (Johansson et al., 2016).

Figure 38. *Fine-grained un-weathered Hammer Granite with characteristic red dots in the background. The four smaller fragments on top of the granite represent different levels of weathering: One fragment has yellow-brown coating of iron oxides, two grey and white fragments display different degrees of kaolin weathering. The black fragment of manganese oxide was formed in a fracture. Width of the picture is approximately 50 cm.*

Figur 38. *Finkornet uforvitret Hammer Granit med fire mindre fragmenter på toppen, der repræsenterer forskellige grader af forvitringsprocessen for graniten. Et fragment har gulbrunt overtræk af jernoxider, to grå og hvide fragmenter har forskellig grad af kaolin forvitring. Det sorte fragment indeholder manganoxid, der er udfældet i en sprække (Hammer granitbrud).*

Weathering

Weathering of the Hammer Granite is most intensively developed in fracture zones. Surface processes of a rocky landscape are slowly degrading the rock and are primarily related to frost–thaw-processes. The result of four different types of chemical weathering processes is illustrated in Figure 38 and a strongly weathered vertical fracture zone is seen in Figure 41. The iron minerals are oxidised to yellow-brown ochre whereas feldspars in the rocks are altered to white kaolin. Black manganese oxide is formed locally in fractures.

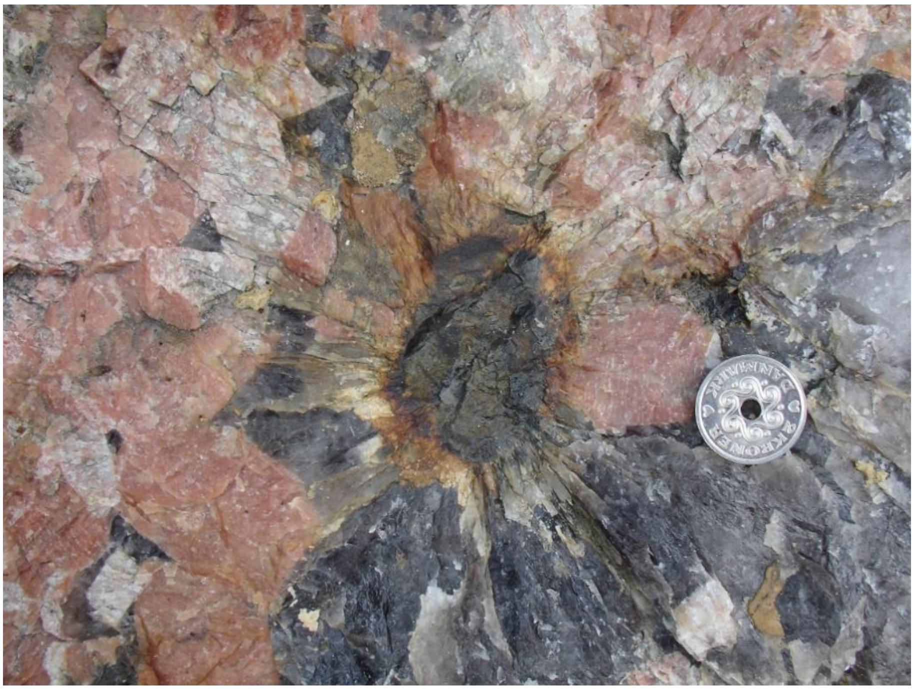


Figure 39. *Black radioactive gadolinite mineral in pegmatite in Hammer Granite (from Butzbach, 1996).*

Figur 39. *Sort radioaktiv gadolinite mineral i pegmatit i Hammer Granit (fra Butzbach, 1996).*

Figure 40. *Hammer Granite, Hammersø-Hammerknuden. The black area in the central part of the photo is where radiation from the mineral gadolinite has caused the generation of radiating fractures.*

Figur 40. *Hammer Granit, Hammersø-Hammerknuden. Det sorte område centralt i billedet er der, hvor radioaktiv stråling fra mineralet gadolinit har påvirket sidestenen og dannet radierende sprækker.*

Figure 41. *Weathering along a fracture in Hammer Granite with yellow-brown coatings of iron oxides, Hammeren Quarry.*

Figur 41*. Gulbrun forvitring ses langs en sprækkezone i Hammer Granit, Hammeren stenbrud.*

4.6.2 Structural elements

At Hammeren, forming the northwestern corner of Bornholm (Figure 3), structural features are dominated by planar, vertical fractures related to the pre-Quaternary geological development, and sub-horizontal to slightly northernly inclined fractures formed during the glaciation of Bornholm during late Weichselian (Figure 42).

The pre-Quaternary fractures include compressional shear joints trending SSE–NNW and extensional fractures trending ENE–WSW. The presence of vertical fractures forms the characteristic rugged coastal morphology and the extensional fracture orientation is parallel to the elongation of the lake Hammer Sø separating the rocky landscape at Hammeren from the mainland of Bornholm. The vertical fracture systems are oriented N-S, NE-SW and NW-SE. The spacing between the vertical fractures varies from a few cm to 2–3 meters. In the extensional fractures the brecciated granite kataclasts are altered to kaolinite. Rusty brown iron oxides (jarosite and limonite), pyrite and black manganese oxides have precipitated in voids, with a scattered distribution in the extensional fractures (Figure 41).

Horizontal fractures occur closely spaced in the uppermost few tens of meters and they are seen to occur with increasing distance downwards (Figure 42). In the Moseløkken area large NE-SW oriented conjugate faults are observed as well (Figure 43).

Figure 42. *Hammer Granite exposed section is ca. 15 meters high, Hammeren Quarry. The granite is cut by abundant vertical and horizontal fractures, especially near the terrain surface.*

Figur 42. *Hammer Granit, Hammeren. Graniten er skåret af mange vertikale og horisontale sprækker, særligt lige under terrænoverfladen. Blotningen er ca. 15 meter høj.*

Figure 43. *The Hammer Granite is cut by vertical fractures/faults and large conjugated fractures down to the base of the quarry around 50 meters below ground surface (dipping surfaces in the right side of the photo). Moseløkken Granite Quarry.*

Figur 43. *Moseløkken Granit Stenbrud. Hammer Granit er gennemskåret af vertikale sprækker og store konjugerede sprækker eller forkastninger, der fortsætter til bunden af stenbruddet 50 meter under terrænoverfladen (til højre på fotoet).*

Figure 44. *Large near-vertical fractures/faults in the Hammer Granite, Moseløkken Quarry.*

Figur 44. *Store vertikale sprækker i Hammer Granit, Moseløkken stenbrud.*

4.7 Almindingen Granite

The Almindingen Granite occurs in an area approximately 5 km x 9 km in the central part of the crystalline basement area and it is surrounded by Bornholm Gneiss with a sharp boundary (Figure 3). Towards the southwest the granite is bounded by a fault and juxtaposed against Upper Cretaceous sediments (Figure 3). A prominent NE-SW oriented straight, fault-controlled valley occurs in the western part of the Almindingen Granite in the Ekkodalen area (Figure 45). The granite is often exposed at the ground surface, at steep walls along Ekkodalen valley, in the high lying areas in Almindingen, in the Birkely quarry (Gravesen & Jakobsen, 2016) and Bjergebakke quarry (Münther, 1945, 1973).

4.7.1 Rock characteristics

The granite is red-grey, medium grained and occasionally coarse grained, with small red dots, often displaying a lineated mineral texture (Figures 45 & 46). Several diabases cut the granite, including the Kelså dyke, and a 2-3 meters thick trachytic dyke with kalifeldspar (called Kullait) found at Bjergebakke (Holm et al., 2005, 2010; Jensen, 1966, 1989; Münther, 1945) (Figures 45 & 46).

Mineralogy and chemistry
The mineralogy is:
Perthite 41%, plagioclas 18%, quartz 33%, hornblende 1%, biotite 4%, magnetite 2%, titanite 1%, with small amounts of apatite, epidote, fluorite, allanite (Callisen, 1934, Micheelsen, 1961a, b).

Natural radioactivity
The minerals that may contain radioactive isotopes include titanite, epidote, flourite, allanite and clay minerals (Gravesen et al.,1996).
Following values have been reported:

- Radium (Ra): 9.5 ppm (SIS,1996).
- Granite: Uranium (U): 3.4–4.3 ppm, Radium (Ra): 3.3-4.9 ppm.
- Diabase: Uranium (U): 4.2 ppm, Radium (Ra). 8.8 ppm.
- Weathered diabase: Uranium (U): 8.5 ppm (Gravesen & Jakobsen, 2016, Gravesen et al. 1996).
- Uranium (U): 4.6 - 6.74 (16.6) ppm and Thorium (Th): 12.1 - 35.9 ppm (Johansson et al. 2016).

Weathering
Weathering occur intensively along fractures as seen in Figures 47 and 48 and the diabases are often altered to greenish clay comprising chlorite.

4.7.2 Structural elements

The Almindingen Granite is cut by numerous horizontal (Figures 45 & 46) and vertical fractures (Figure 47). Some fractures are inclined towards the north. The main fracture orientations are NE-SW and NW-SE and more rarely E-W (von Bubnoff, 1942). A sub-horizontal fracture with an aperture of several cm can be followed laterally for at least 500 meters along the entire outcrop in the vertical cliff bounding Ekkodalen (Figure 45).

The horizontal fractures (Figures 45 & 46) were formed from unloading as the thick Weichselian glaciers melted whereas the vertical fractures are of tectonic origin (Figure 48).

Figure 45. *Almindingen Granite exposed in the north western wall of Ekkodalen. Notice the continuous prominent, undulating sub-horizontal fracture in the central part of the approximately 10 meters high cliff.*

Figur 45. *Almindingen Granit er blottet i den nordvestlige væg af Ekkodalen. Bemærk den kontinuerte, ondulerende subhorisontale sprække midt i klippevæggen.*

Figure 46. *Picture showing a close-up of the fracture seen on Figure 45. It occurs as a several cm wide, sub-horizontal fracture in the central part of the picture and is associated with several minor fractures.*

Figur 46. *Nærbillede af en bred, subhorisontal sprække (nærbillede af Figur 45) der ses midt i billedet, samt adskillige mindre sprækker Almindingen Granit, Ekkodalen.*

Figure 47. *The presence of subvertical fractures and faults in Almindingen Granite. Diabase dykes is associated with weathering of the rocks and the diabase is often altered to greenish clay.*

Figur 47. *Subvertikale sprækker og forkastninger i Almindingen Granit. Diabasgange er associeret med intens forvitring, og diabasen er ofte omdannet til grønt ler.*

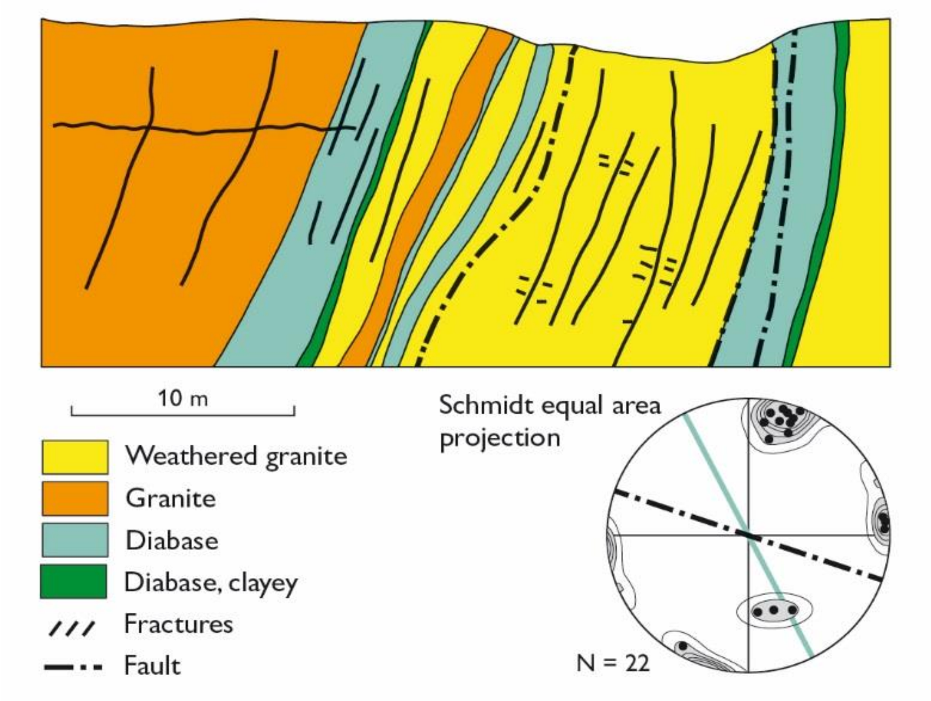


Figure 48. *Vertical section measured in the Birkely quarry south of Almindingen where the Almindingen Granite is cut by near-vertical fractures and faults striking northeast- southwest. Diabases intruded into some of the faults during a late phase of faulting. The granite is weathered along the planes of faults and fractures (From Gravesen & Jakobsen, 2016).*

Figur 48. *Vertikalt profil fra Birkely stenbrud i den sydlige del af Almindingen, hvor granitten er gennemskåret af vertikale sprækker og forkastninger med retning nordøst-sydvest. Diabas er trængt ind i forkastningerne i en sen fase af forkastningsdannelsen. Diabaserne er forvitret til grønt ler, og granitten er også stærkt forvitret i områder med tætte sprækker (Fra Gravesen & Jakobsen, 2016).*

4.8 Pegmatites, aplites, dolerites and other associated rocks

Minor bodies of different mineralogical compositions occur locally including pegmatites, aplites, dolerites and granites. The basement rocks in general have a low content of minerals with radioactive isotopes, but locally slightly higher concentrations have been measured, as described later in this section.

4.8.1 Locally occurring intrusive pegmatites and aplites

Pegmaties and aplites bodies consisting of perthite 45-60%, plagioclase 10-20%, quartz 30-40%, hornblende 0-1%, biotite 0-2%, magnetite 0-2%, titanite, apatite, epidote, fluorite and gadolinite are abundant in the basement rocks (Callisen, 1934, Micheelsen, 1961a, b).

Diabases (Dolerites)
On Bornholm more than 250 mafic dykes cut the crystalline basement rocks. The dykes are oriented mainly NNW-NNE and a few NE-SW. The dykes have intruded into the basement

during four episodes: 1326 Ma (e.g the Kelså diabas), 1220 Ma (numerous thin diabases), 950 Ma (Kaas and Listed diabases) and 300 Ma (NW oriented diabases) (Holm et al., 2010).

At least four different mineralogical compositions of dykes have been identified based on petrography. The Kelså dyke, as an example, is grey and massive with grain size from fine to medium. The main constituents are plagioclase, olivine and augite with accessory Ti-magnetite, apatite, hyperstene, amphibole, biotite, microcline and quartz (Callisen, 1934, Jensen, 1966, Holm et al., 2005, 2010).

Kullaites
In the Bjergebakke quarry a 2-3 meters thick NW-SE oriented dyke cuts the Almindingen Granite. It is composed of albite, K-feldspar, chlorite and accessory mica epidote, titanomagnetite and traces of calcite and amphibole. The dyke is strongly altered but is similar in composition to Permian kullaite dykes in Scania (Jensen, 1989).

4.8.2 Local variations of granite

Variations of the texture and mineralogical composition occur locally. The Helletsgård Granite, near Paradisbakkerne is a variety of Svaneke Granite (Platou, 1970). Maegård Granite occurs south of Kirkeby comprising pyroxene granite (hypersthene), dark grey, with high concentrations of dark minerals (Jørgart, 1977). Hallegård Granite in Katteslet Bakke is a dark reddish granite.

The chemical composition of the pegmatites, aplites, diabase and kullaites can be found in Callisen (1934), Micheelsen (1961 a), Jensen, (1966, 1989), Holm et al. (2005, 2010) and Johansson et al. (2016).

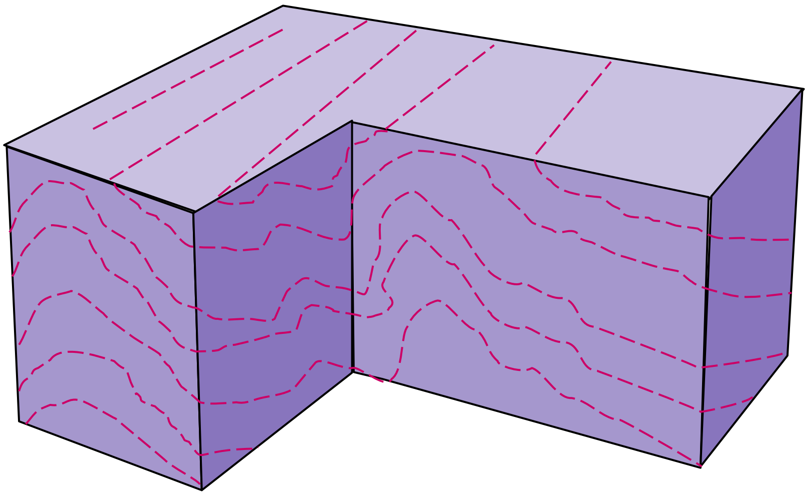
5. Structural control on crystalline basement rock properties

For the evaluation of the potential for the basement rocks to provide a safe repository rock at depths of 500 meters it is important to be able to map and characterize the properties of fractures in the subsurface including size, density and orientation. Crystalline rocks as granite and gneiss which formed from melts that intruded and cooled at large depths (>10 km) have no primary effective porosity or permeability, thus being impermeable to fluid flow. The presence and the connectivity of fractures will have significant impact on fluid flow, where horizontal fractures are generally most important for lateral flow. Weathering of rock surfaces exposed in fractures is also controlled by the origin of the fractures and this may have an impact on both porosity and permeability, as well as potential geochemical sorption of radionuclides on clay minerals. Weathering along fractures is observed from outcrops and water wells to have formed various types of clay including kaolin and chlorite as well as iron and manganese hydroxides. This means that the fractures comprise minerals that may retard the mobility of radionuclides. Therefore, understanding the mechanisms that caused the formation of faults and fractures may be important for the ability to predict the presence and the properties of fractures in the subsurface. These issues will be further investigated in case the basement is considered a possible repository rock for disposal of radioactive waste.

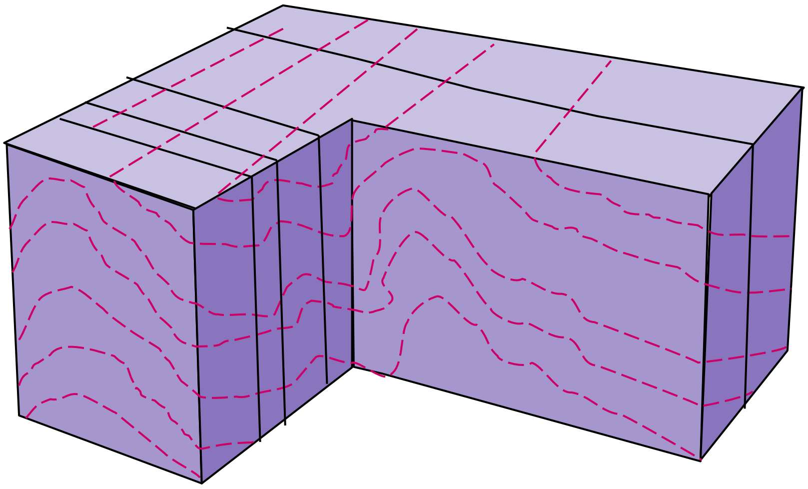
A summary of the formation of the rocks and the faults and fractures observed from ground level and down to ca. 100 meters is shown in Figure 6. In the subsurface below 100 meters the orientation of fractures is expected to be similar to the large tectonically controlled faults identified at surface. The lateral spacing is expected to increase downwards as observed in other basement rocks (Juhlin & Stephens, 2006; SKB 2004).

- The grey units (Figure 6) illustrate the formation of layers that are foliated (blue dashed lines) and folded during the formation of the basement rocks about 1450-1460 mill. years ago, when granitic magma was intruded during the Precambrian orogenic event (Figure 49).
- During the subsequent cooling process the rocks were faulted to a large depth. The tectonically vertical (black lines), horizontally anastomosing and conjugate dipping fault structures (red lines) were formed. The faults extend deeper than 100 meters below present surface.
- Cooling and differential uplift initiated in Palaeozoic time, resulted in the formation of small vertical and inclined tectonic faults and fractures (black lines at 25–50 meters depth). Slickensides are found on the fracture surfaces in the Paradisbakke Migmatite, indicating block displacements.
- During the Quaternary glaciations vertical fault and fractures were formed by advancing glaciers (black lines, down to 25 m). Moreover, shallow, gently dipping minor fractures were formed as the advancing glaciers crushed the uppermost parts of the basement rocks (anastomosing fractures).
- Horizontal fractures within the upper 25 meters (green dashed lines, Figure 6) formed due to unloading of the retreating glaciers during their melting.

The structural development for e.g. the Bornholm Gneiss area and the Paradisbakke Migmatite is illustrated in Figure 49. It is slightly different from the areas with granite as it includes a very early phase of deformation where the gneiss was generated and folded. However, as the predominant orientation of faults and fractures is similar for all parts of the crystalline basement on Bornholm, it is concluded that the structures in the Precambrian gneiss have no influence on the subsequent development and orientation of faults and fractures.



a.



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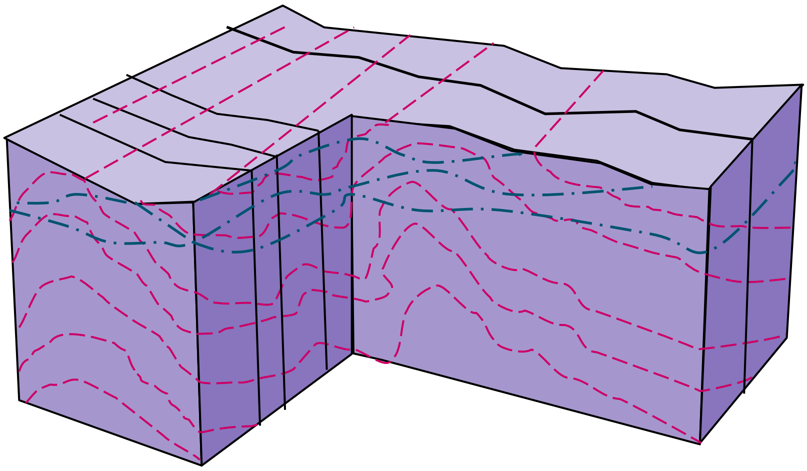

c.

Figure 49. *Diagrams showing the successive development of structurally generated features in the Bornholm Gneiss Area:* ***a.*** *Metamorphic foliation (striking 170^o) and folding of the gneiss (stippled red lines).* ***b.*** *Deformation associated with vertical fracturing (black lines).* ***c.*** *Deformation during the Weichselian glaciation resulting in sub-horizontal fractures (blue lines) in the uppermost tens of meters.*

Figur 49. *Diagrammer der viser den successive udvikling af strukturelle elementer i området med Bornholm Gnejs:* ***a.*** *Metamorf foliation og foldning af gnejsen.* ***b.*** *Sekundær deformation med vertikal opsprækning af gnejsen.* ***c.*** *Deformation skabt af Weichsel gletsjeres bevægelse resulterede i subhorisontale sprækker.*

A summary of the structural development of the granites as interpreted based on observations from two quarries in the Vang Granite is presented in Figure 50. The diagram shows three sets of vertical fractures (joints), where one set is clearly extensional and associated with breccias and kaolin alteration (vertical fractures indicated with blue lines in Figure 50). Horizontal fractures generated during glaciations are common in the uppermost part of the rocks (few tens of meters).

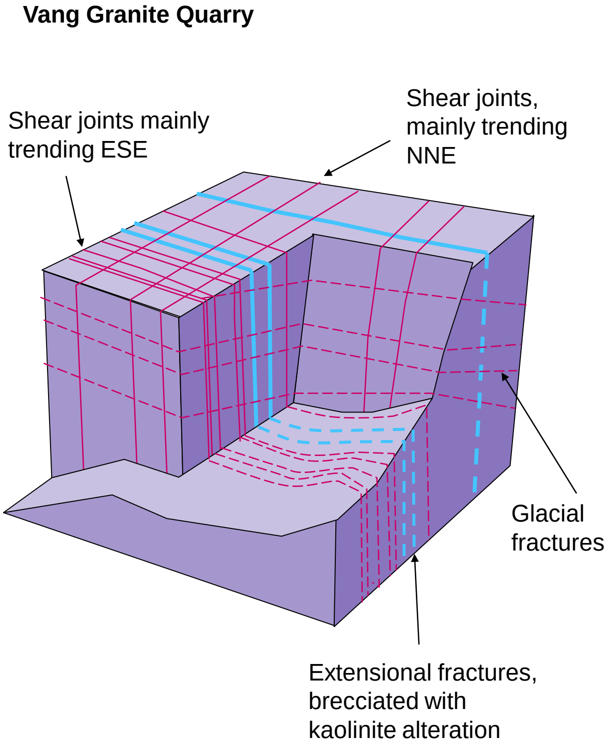

Figure 50. *Diagram summarising the structural development of the Vang Granite, Vang Granite Quarry.*

Figur 50. *Diagram der illustrerer den strukturelle udvikling, Vang Granit stenbrud.*

6. Naturally occurring radioactivity

The Precambrian rocks of Bornholm generally have a low content of radioactive minerals and isotopes, but occasionally higher concentrations are found locally. High contents of radon sourced from the basement rocks are found in air inside houses and in the groundwater. Therefore, it will be important to map the radon occurrence and sources in case it is decided to construct a deep final repository in the crystalline basement rocks, and also for post-closure monitoring.

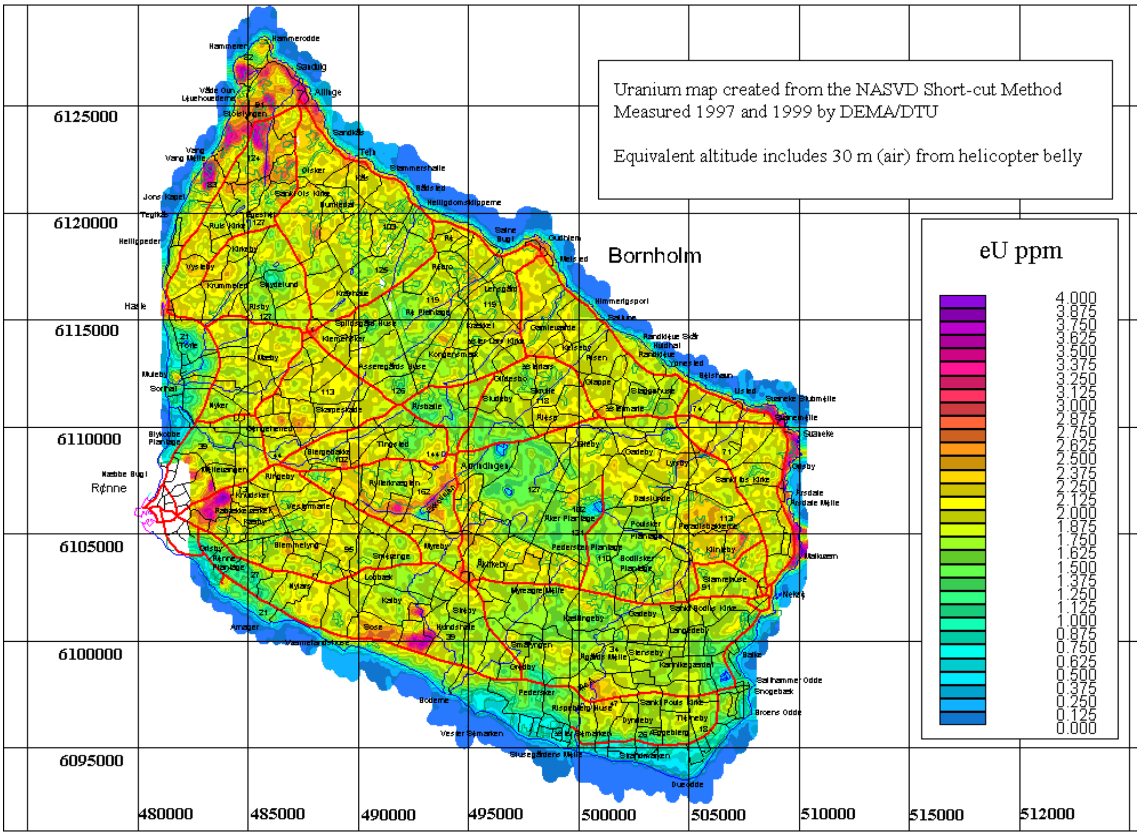

__Figure 51.__ Map of the uranium (eUran in ppm) levels on Bornholm measured airborne from helicopter (From Aage et al. 1999).

***Figur 51**. Kort over uranniveauer (eUran i ppm) på Bornholm målt fra helikopter (Fra Åge et al., 1999).*

The basement of Bornholm has uranium, thorium and radium concentrations similar to average values measured in Norway, Sweden and Finland (between 4 and 5 ppm), which is lower that common values reported from other parts of the world.

Uranium air borne measurements

The map in Figure 51 demonstrates that the highest levels of U (in eU ppm) are ca. 4.0 at Rønne (Rønne Granit) where gadolinite is found locally at Hammeren (Hammer Granite) and locally in the Vang granite and Svaneke granite areas. In addition, high levels are found in the Cambrian-Ordovician alum shale in the Læså stream.

Distribution of the radioactive components in the basement rocks
Radioactive components are mainly found in allanite, gadolinite, zirkon, titanite and apatite. All these minerals are accessory minerals in the granitic and gneissic rocks while gadolinite is very rare and mainly found in pegmatites (Figures 11, 39 & 40).

Analyses of U, Th, Ra and Rn from the rocks are sparse but give some indications of the level in the basement. The general level of U is ca. 3,5 - 5 ppm which is equal to observations from other basements areas (Gravesen et al., 1996, Gravesen & Jakobsen, 2016). Locally the values may be higher. In borehole samples from Svaneke Granite values between 40 and 90 Bq/kg Ra-226 have been measured (Sundhedsstyrelsen, 1987).

Radon measurements (Rn) have been reported from Almindingen Granite as (Rn): 8.8.-9.6 atoms/kg/sec (Gravesen & Jakobsen, 2016, Gravesen et al. 1996) and from clay in a weathered diabase in granite as (Rn): 39.6 atoms/kg/sec

Radioactive components in groundwater
The groundwater in the basement rocks contain radioactive components in larger concentrations than in most other places in Denmark. Measurements of U and Ra have been made at depths of more than 100 meters (Sundhedsstyrelsen, 1987). Results from 45 wells show radon-226 of up to 740 Bq/l and 0.25 Bq/l radium. A water work has reported values up to 1100 Bq/l radon and 0.55 Bq/l radium in Svaneke granite at Listed and values at Nydam show 434 Bq/l in groundwater in gneiss (Miljøcenter Roskilde, 2009). Both studies demonstrate that values are usually below 1100 Bq/l.

Radioactivity in indoor air
Radon levels in houses have been measured by Bornholms Amt (1999) and Andersen et al. (1997). Average year values up to 1500 Bq/ m^3 is measured and maximum values of more than 2500 Bq/m^3 are found. The map in Figure 52 shows radon values measured from the various rock types.

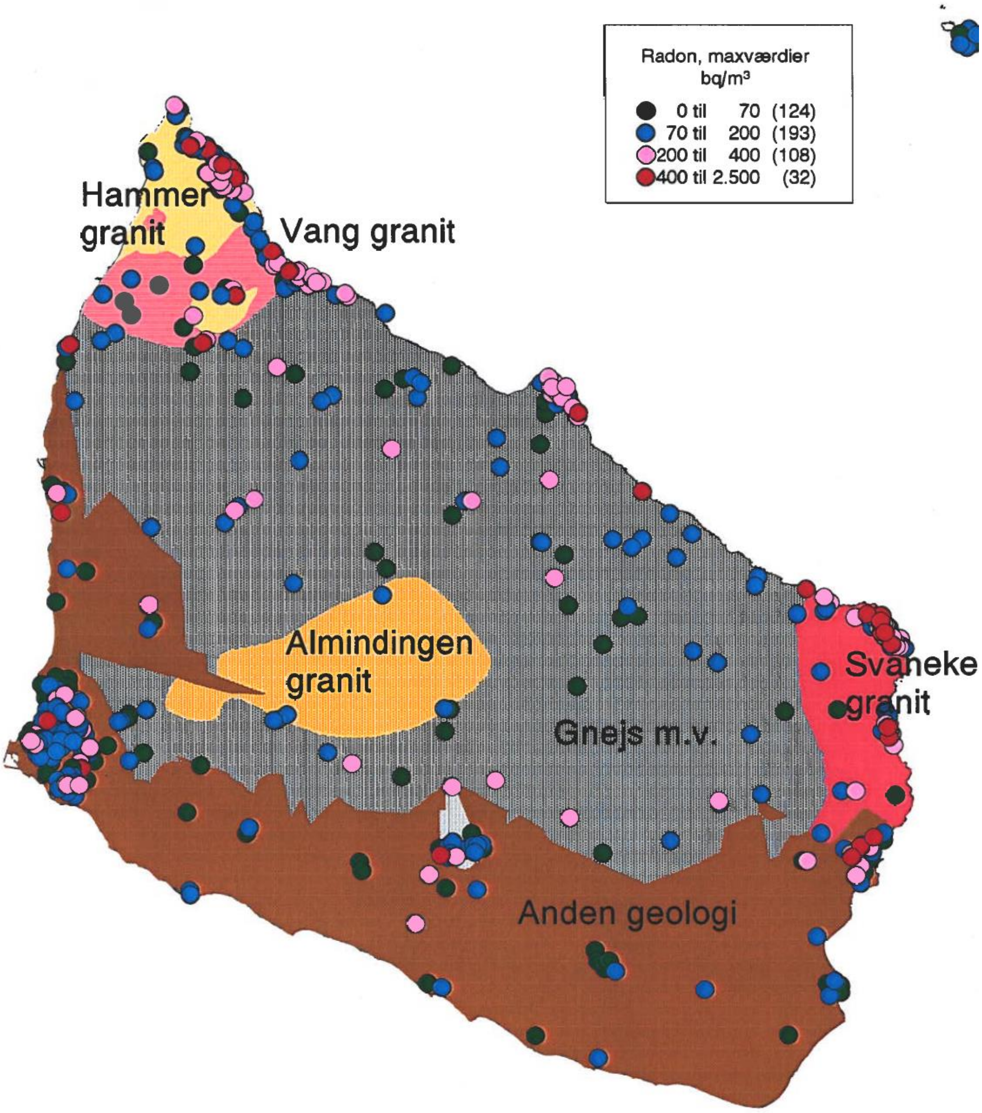

Figure 52. *Map of maximum indoor radon concentrations in houses on Bornholm in areas of different basement rocks and the sedimentary deposit to the south (Brown areas with “Anden geologi”) (from Bornholms Amt, 1999). Numbers of measured values are presented in brackets.*

Figur 52. *Kort over maximum indendørs radon værdier i relation til geologien (Fra Bornholm Amt, 1999). Antal målinger for de enkelte værdier er angivet i parentes.*

7. Geophysical investigations

Standard geophysical exploration and rock characterisation methods are generally not very useful for mapping of mineralogical variations or minor faults and fractures in basement due to the massive nature of crystalline rocks. Conventional seismic data is used to interpret and map contrasts in the acoustic impedance in the subsurface caused by variations is seismic velocities in the rock, density variations caused by lithological variations, porosity variations and fluid density variations. These rock parameters do not vary significantly in massive bodies of crystalline rocks, and contrasts occur only where major fault zones have caused deformation (crushing, myolinitisation) of the rock, or where thorough alteration or erosion in large fault and fracture zones has occurred. On Bornholm, it is expected that minor faults and fractures in the basement are below seismic detection size. However, to test this assumption seismic data was acquired along a line oriented perpendicular to structural lineaments observed on the surface as well as significant topographic changes believed to be structurally controlled. The results and conclusions are presented later in this chapter.

Conventional petrophysical and geophysical logs in boreholes are also of limited value in crystalline rocks, however, flow tests may reveal the presence of fractures, as these have porosity and therefore can be water bearing. Therefore, wells drilled for water supply may comprise quite detailed information about faults and fractures in the basement as described below, but only for the upper 0-100 of the basement, as only few wells are drilled to deeper levels around 150 meters.

7.1 Basement properties interpreted from geophysical well logs

On Bornholm many water wells have been drilled into the basement (Gravesen & Rasmussen, 1988). Most are shallower than 50 meters and only 151 boreholes are more than 150 meters deep. The deepest boreholes are drilled for groundwater extraction, shallow geothermic investigations, and natural resources (locations shown in Figure 53).

Rock samples from the borehole occur as cuttings of sand size and occasionally gravel size due to crushing of the crystalline rocks during drilling. Sometimes larger cuttings material occurs indicating the presence of fractures associated with weathered rock. The presence of fractures can also be identified from well logs.

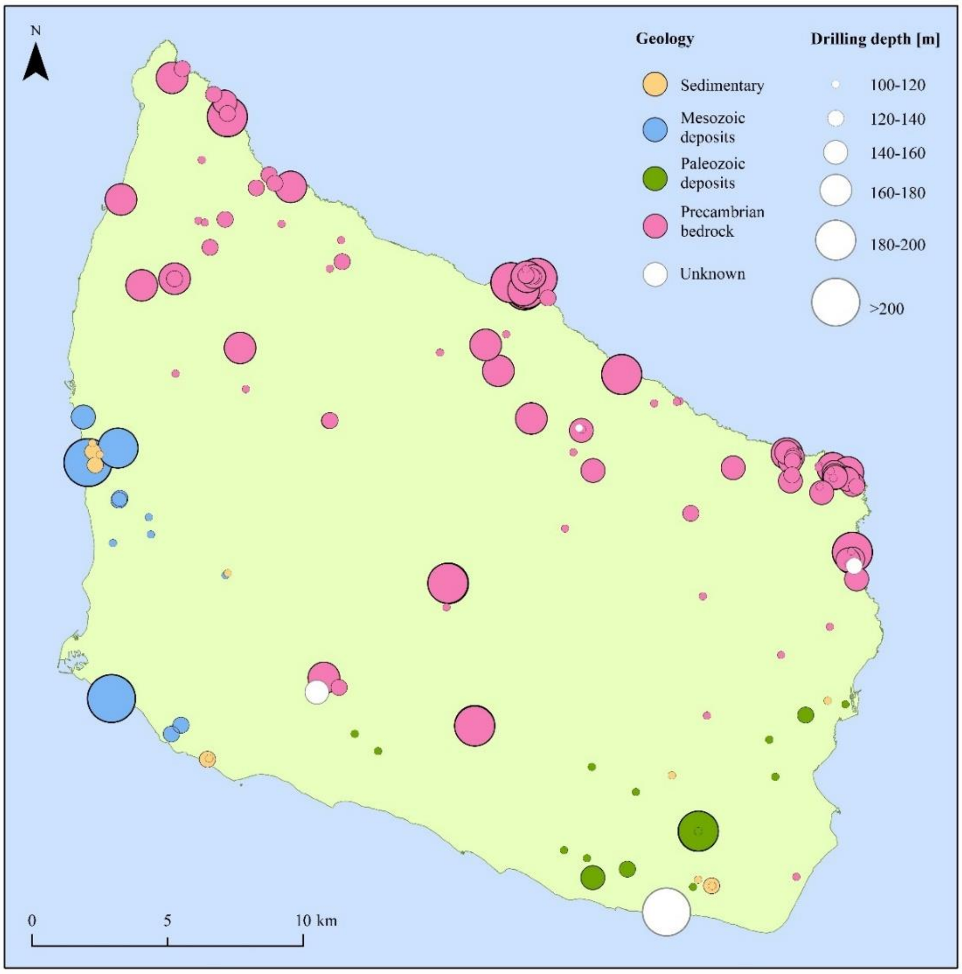

Figure 53. *Map of the distribution and depth of boreholes deeper than 100 meters showing that just a few are drilled deeper than 200 meters.*

Figur 53. *Fordeling af boringer dybere end 100 meter, det ses, at kun få er boret til 200 meter under terræn eller dybere.*

Groundwater reservoirs in basement rock occur in 3-dimensionel fracture networks of crossing vertical/subvertical and horizontal fractures. The vertical fractures act as fairways supplying surface water into the groundwater reservoirs, while the horizontal fractures may enable the groundwater to move laterally for long distances. It is difficult to map these subsurface fracture systems, but borehole logs can contribute to identify and characterize the network. Examples of geophysical methods with logging in boreholes and wells drilled for groundwater resource investigations can be found in e.g. Rasmussen et al., (2007) where flow logs demonstrated inflow of groundwater from 4-5 levels down to at least 50 meters in the basements. This has been interpreted to indicate the presence of horizontal fractures (Figure 54).

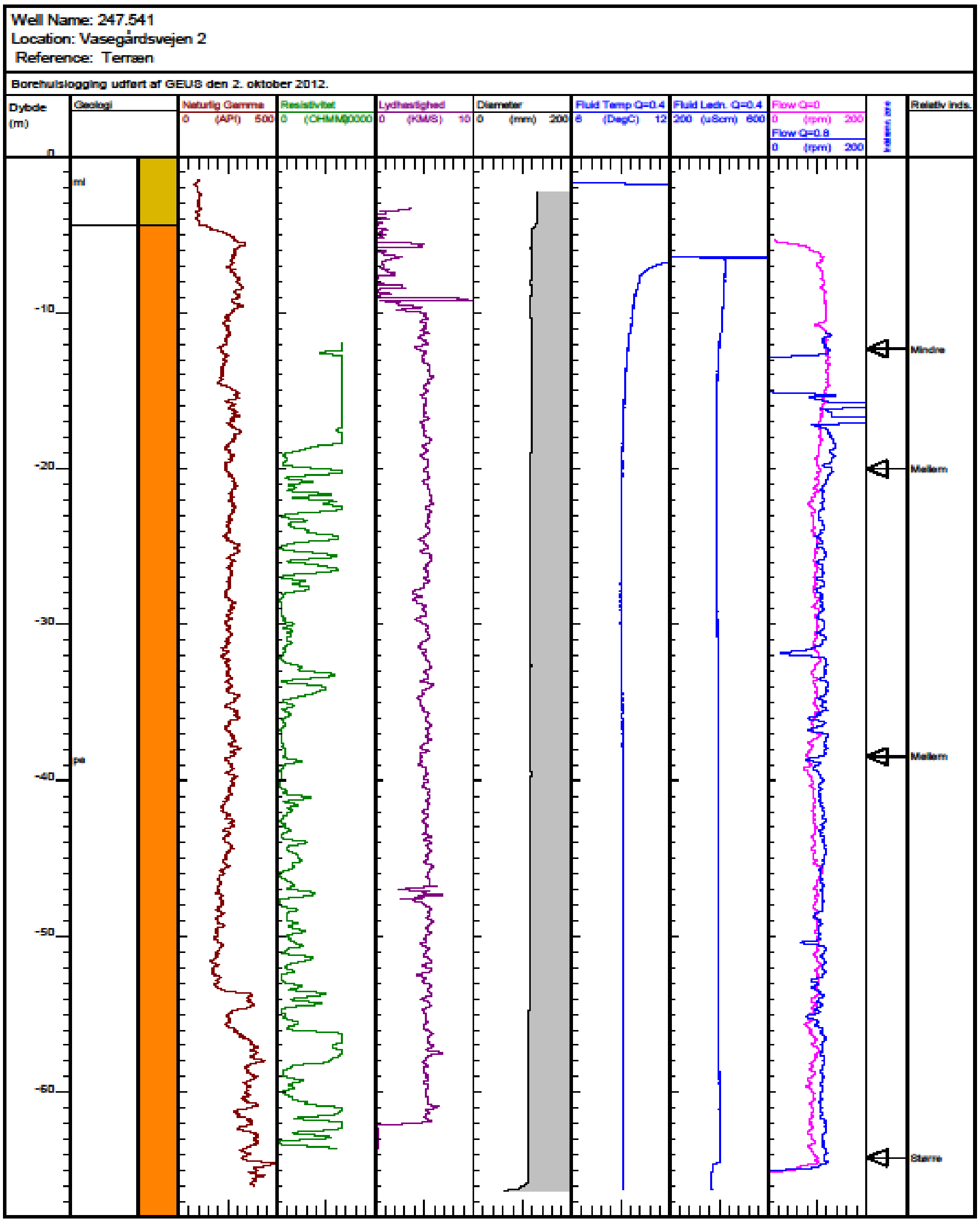

Figure 54. *Borehole log from DGU no.247.541. The flow log shows the levels where inflow of groundwater from fractures occurs (indicated with arrows).*

Figur 54. *Borehuls log for boring DGU nr. 247,541. Flow-loggen viser niveauer, hvor der sker indstrømning af grundvand fra sprækker (vist med pile).*

An example of identification of fractures in the basement is presented below. In the Paradisbakke area a logging programme was carried out in water wells drilled into migmatite and gneiss as part of a previous project related to the search for a shallow waste repository site (Gravesen et al., 2014).

Figure 55. *Map showing the location of the 8 water wells included in the study, and the well from Østermarie Water Work (DGU no. 247.496). The two sections A and B indicated with white lines are shown in Figure 61 and Figure 62 (From Gravesen et al., 2014).*

Figur 55. *Oversigtskort viser placering af 8 boringer, der indgik i borehulslogging-programmet, samt en borehulslog i Østermarie vandværksboring (247.496). De to profiler A og B er indtegnet og vist i Figur 61 og 62 (fra Gravesen et al., 2014).*

Normally the undisturbed natural groundwater level occurs a few meters below the ground surface, but pumping will often lower the groundwater level very fast because of a small, connected volumes of water reservoirs in the fractured basement. The yield from the borings is often low but in borings investigated for supply to Østermarie Water Work relatively high yields were measured.

Eight private water supply boreholes in the area were investigated by geophysical wireline logging. Fluid conductivity and flow logging was performed during groundwater pumping from the borehole. Natural gamma, resistivity, and sonic velocity logs provide information about lithological variations in the borehole. The fluid conductivity log gives information about groundwater chemistry and under certain conditions also about groundwater inflow zones. The flow log measures the vertical flow velocity in the borehole. Measurements of changes in flow velocity during pumping can be used for interpretation of groundwater inflow zones at specific depths or depths intervals as well as the accessible volume in the borehole.

Two sections with wells projected onto the profile lines have been made (Figures 55, 56 & 57). In the 5 km long north-south section (Figures 55 & 56) is shown inflow from fractures in four wells. The size of the fractures is evaluated semi-quantitatively as “major” or “minor” depending on the relative inflow rates.

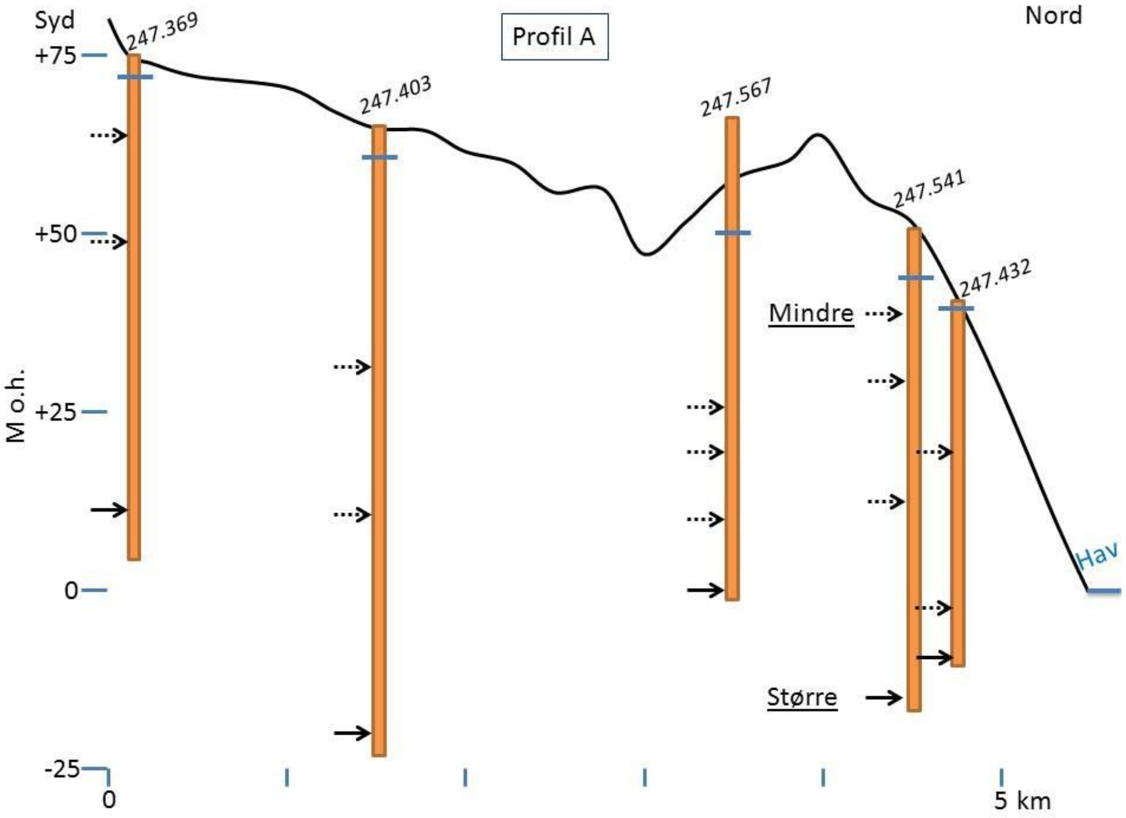

Figure 56. *North-South oriented section A with 5 logged wells. Thick arrows show relatively larger inflow from fractures while hatched arrows show levels of minor groundwater inflow from fractures. Groundwater level is indicated with a blue line in each well. The section is 5 km long.*

Figur 56. *Nord-syd-orienteret Profil A. I profilet er vist 5 boringer, der alle er blevet logget. Tykke pile angiver større indstrømning af vand fra sprækker, mens de stiplede pile angiver niveauer med en lille grundvandsindstrømning. Ro-vandspejlet er vist med tyk blå streg i den øvre del af hver boring. Profilet er ca. 5 kilometer langt.*

All the wells have the same low specific yield (0.05-0.22 m^3/t/m) with large inflow registered near the bottom of the borings and minor fracture inflow observed closer to the ground surface. It is not possible to measure the orientation of the fractures from flow logs but fractures occurring at the same level may be laterally connected across a distance of some kilometers. In the west-east section (Figure 57) fracture inflow of water was measured at several levels in the 50 to 100 meters deep wells. The largest inflow was from the bottom of the easternmost and deepest wells where it seems like the vertical distance between fractures is larger. The existing borehole logs cannot be used to map the orientation of the fractures, but the regional structural model might be used as a framework for interpretation and mapping of major fractures and fracture networks.

The water bearing fractures may be connected over long distances on a km scale, and the connectivity could be investigated by flow testing of specific levels in one well and measuring of water levels in nearby wells contemporaneously.

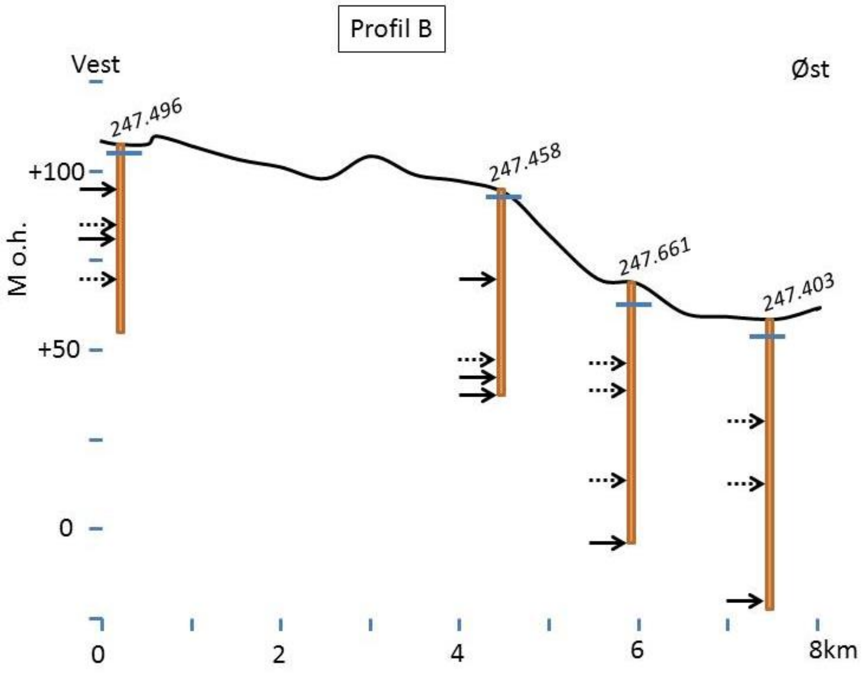

__Figure 57.__ West-East oriented section B from well no. 247.496 to well no. 247.403. The section has a length of 8 kilometres (explanation as Figure 56)

__Figur 57.__ Vest-øst-gorienteret profil B fra Østermarie boringen (247.496) i vest til boring 247.403 i øst. Profilet er ca. 8 km langt (Forklaring se Figur 56).

7.2 Hydraulic conductivity in groundwater reservoirs

There is only sparse information available from groundwater in the basement (e.g. Miljøcenter Roskilde, 2008, 2009). The groundwater aquifers located in the basement rocks are formed by horizontal and vertical fractures whereas the crystalline rock matrix is expected to have nil porosity. The basement rocks have low porosity and permeability as it restricted to areas of vertical and horizontal fractures, which have a low storage capacity and limited potential for groundwater abstraction.

Two types of confined groundwater reservoirs occur in the basement areas 1) Relatively undisturbed basement with some water-bearing fractures 0-100 meters below ground level, 2) Sand in valleys formed due to incision into the basement, usually occurring in weak fault zones (Gravesen et al., 1980).

Some examples of hydraulic conductivity from the upper part of the gneiss basement, where it is fractured, are presented by Miljøministeriet, Miljøcenter Roskilde (2009):

- Østermarie (Sortebjerg) 30-40 meters below ground., Horizontal 5.9 x10^{-5}m/s, Vertical: 5.3 x 10^{-8}m/s
- Østermarie (Nydam). 20 meters below surface Horizontal 1.73 x 10^{-4}m/s, Vertical 9.74 x 10^{-7}m/s.

Investigations in the Bornholm Gneiss and Paradisbakkerne Migmatite areas have, based on C^{14} ages, given the following values:

- Average value in borehole (DGU no. 247.369) from ground level to 68 meters below is 1.44 x10^{-9} m/s.
- In borehole DGU no. 247.403 the value is 3.5 x 10^{-10} m/s from ca. 68 meters to 88 meters below ground level.

The horizontal hydraulic conductivity is higher than the vertical, which is interpreted to indicate better connectivity, and larger lateral extent of horizontal fractures.

7.3 Groundwater chemistry

The groundwater occurring in the crystalline basement is characterized as a calcium-bicarbonate type which is reduced and without nitrate. A high content of iron results from weathered basement rocks and pyrite oxidation which has mobilized nickel and arsene. Arsene has been identified at a few waterworks. A high content of fluorite occurs, which is normal for granitic basement rocks. The content of chloride and excessive CO_2 is very low. The groundwater does not seem to comprise any aggressive components based on existing analyses (Miljøcenter Roskilde, 2009). The relationship between the rocks and the groundwater has been investigated on eastern Bornholm (Gravesen et al., 2015).

7.4 Seismic investigation

A seismic survey of one line has been acquired in the Bornholm Gneiss area southwest of Gudhjem in 2019 (Rambøll, 2019). The line is oriented northwest - southeast from Østerlars to Rø and is 6389 meters long (Figure 58).

The purpose of the acquisition was to investigate whether seismic data can be used for mapping and characterisation of geological structures in the deeper parts of the Bornholm gneiss. Therefore, the section was laid out to cross several potential fault or fracture zones as identified from surface studies (Figure 58). In Sweden in the Forsmark areas it was possible to recognize a large inclined fault and mylonite zone in the crystalline basement rocks based on seismic surveys combined with a deep borehole (Juhlin & Stephens, 2006) and these results have been important for the Swedish project on localising an area for radioactive waste disposal.

The seismic section from Bornholm is shown in Figure 59 covering the time interval from 0 (at surface) to 600 ms two-way travel-time (TWT). This corresponds to a depth of approximately 1500 m. Two to three well defined seismic reflections are present in the uppermost part of the section, however with limited lateral continuity. These reflections are generated from lithological boundaries in the overlying Quaternary sedimentary deposits, and the top of the crystalline basement. The abrupt terminations of these reflectors are interpreted to indicate the presence of faults, which in the present landscape often controls the location of valleys and streams at the surface, as well as abrupt changes of altitudes on a meter scale in the terrain, as also displayed in Figure 58.

In the deeper parts of the seismic section continuous reflections are totally absent, and the seismic signal is dim to transparent with no features indicating changes in the acoustic impedance. This is interpreted to indicate that the subsurface is composed of homogeneous crystalline rock without any major faults or significant lithological boundaries. The minor faults and fractures observed in the overburden layers cannot be identified in the underlying basement from seismic, even though some of them are generated from major tectonic events and thus are expected to extend deep down into the basement rocks. Therefore, seismic data cannot be used to map surface lineaments in basement below the sedimentary cover. Likewise changes from one type of granite rock to another cannot be identified either.

The presence of fractures in the subsurface at depths down to 100 meters is indicated from flow logs in water wells, and general water inflow in deep wells in the basement. Knowledge about the presence of fractures in the basement as well as the density, the orientation and connectivity, is important for characterizing the basement rock. This information can be obtained mainly from boreholes, which combined with geophysical methods may be used to provide such data at depths of 500 meters or more below the ground level.

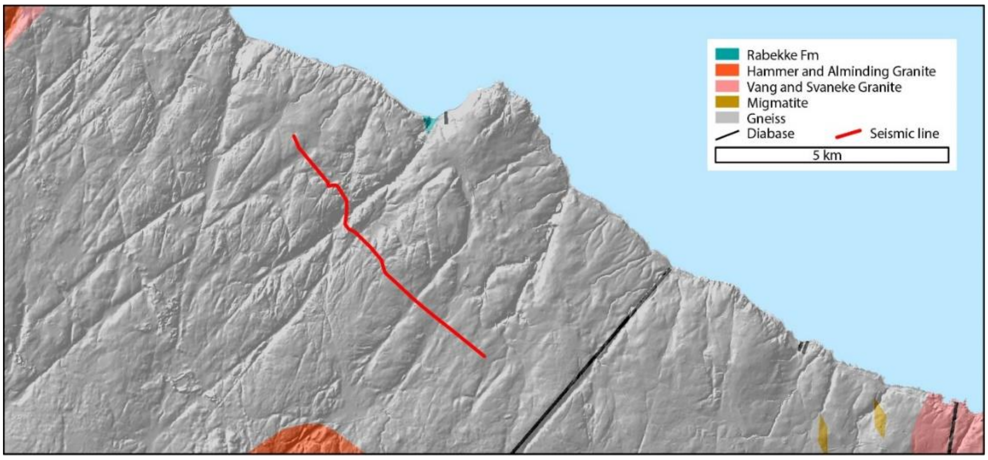

Figure 58. *Map showing the location of the seismic profile acquired south of Gudhjem.*

Figur 58. *Kort der viser orientering af den seismiske linje, der blev indsamlet syd for Gudhjem.*

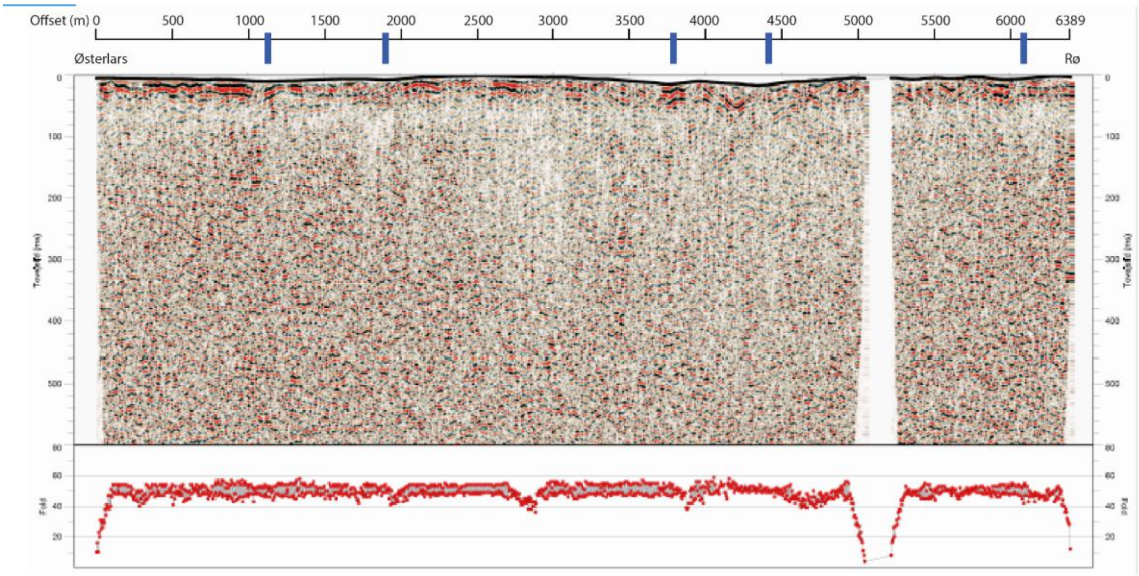

Figure 59. *Seismic section showing reflections occur from the uppermost approximately 100 meters, which to some degree enables mapping of major faults and fractures occurring in this depth interval. In the deeper parts continuous reflections are absent indicating the presence of a massive rock without any variations in lithological/density. The seismic section represents an interval from ground level to a depth of approximately 1.5 km below surface (vertical scale on the section is 0-600 ms).*

Figur 59. *Det seismiske profil viser et dybdeinterval fra 0 meter til ca. 1,5 km under terræn. I profilet ses tydelige reflektioner fra de øverste ca. 100 meter, som gør det muligt at identificere større overfladenære forkastninger. Fra de dybere dele ses ingen kontinuerte seismiske reflektioner, hvilket tyder på at den underliggende bjergart er homogen uden variation i lithologi og densitet.*

8. Summary

Rocks of crystalline basement occur in most of the Danish subsurface at depths greater than 800 meters, except for the island of Bornholm.

The basement on Bornholm is composed of various rock types developed from intrusion of magma during a period of approximately 10 million years in the Precambrian time. Cooling and subsequent uplift and erosion has caused these originally deep-seated crystalline rocks to be locally exposed at surface. Bornholm is a small tectonic horst block bounded by large faults. It was formed due to tectonic movements in the Fenno-Scandian Border Zone during the Carboniferous to Tertiary times. Presently no tectonic movements occur, and historic earthquake registration shows the activity is very low and of very low magnitude. Thus, formation of new faults and fractures due to tectonic activity is very unlikely within the near geological future (few million years).

In areas where basement occur at or near the ground surface, the repository rock and the overlying effective containment zone will both comprise crystalline rock, which in general is much more competent than sedimentary rocks at same depth. There is no knowledge about how the rock types are distributed laterally at depths around 500 meters. It is expected that the rocks are similar in composition to those observed in the surface, as the rock bodies all formed from large intrusions at significant depths. Most likely the relative amounts of the various rock types and their distribution will be different in the subsurface.

Crystalline rocks as granite and gneiss formed from melts that cooled at large depths have no primary effective porosity or permeability, thus being impermeable to fluid flow. However, porosity and permeability may exist in the rock if fractures are present. Therefore, it is important to be able to map and characterize fractures and their properties in the subsurface when evaluating the potential of basement rocks to provide a safe repository rock for radioactive waste.

The presence and the connectivity of fractures will determine the ability for fluid flow, where horizontal fractures are generally inferred to be the most important for lateral flow. The basement surface and the uppermost approximately 100 meters are generally intensively dissected by closely spaced vertical fractures and faults of glacial and glacio-tectonic origin. Horizontal fractures occur to depths of at least 100 meters, possibly with larger spacing than observed at the surface. Horizontal fractures are probably mainly of tectonic origin as the result of unloading during tectonic uplift and subsequent erosion, but also to some extent from loading and unloading of glaciers during the Quaternary glaciations.

Based on existing data, it appears that the texture of the crystalline rocks and the lateral change in rock type (mineralogical composition) apparently does not influence the presence and the orientation of fractures. Mapping of structural elements at the surface has shown the presence of both vertical, inclined, and horizontal fractures, however, limited experience exists with regards to mapping and prediction of the fractures at larger depths. Some information exists from flow tests in water wells suggesting that lateral flow depends on the presence of laterally extensive horizontal fractures. 2D seismic data does not allow for mapping of small features such as fractures and minor faults in basement, expect for the upper 100 meters.

Due to their inferred tectonic origin, the vertical and oblique faults and fractures are expected to extend quite deep into the subsurface, and the major faults/fractures are expected to extend further than the smaller fractures. The closely spaced glacially generated horizontal fractures are seen to occur mainly within the upper 10-30 meters and with decreasing frequency downwards. Based on data from water wells, it is observed that horizontal fractures are locally important for the flow of ground water at depths of 50-100 meters. Whether the fracture width, and lateral extent of fractures decrease with depth can at present only be speculated.

Mapping and characterization of fractures are subject to further investigation in case the basement is considered a potential repository rock for disposal of radioactive waste. Understanding the mechanisms that caused the formation of faults and deep and laterally widespread fractures may be important for the potential to predict and model the presence, the extent, and the properties of fractures in the subsurface.

An important tool for predicting the presence of deeper vertical and dipping fractures and faults in basement is to map tectonic structures in the shallower parts of the basement. Faults of tectonic origin are normally deep seated in brittle crystalline rocks and it is reasonable to expect that faults extend quite deep into subsurface. The identification of faults is based on the presence of lateral and/or vertical displacement across the fault plane, presence of mylonite zones of crushed rock and slickensides, all which indicate tectonic movement. Horizontal fractures in the subsurface can only be identified from drilling.

The degree of weathering of rock surfaces exposed in fractures into clay minerals may have an impact on both porosity and permeability, as well as potential geochemical sorption of radionuclides on clay minerals. Weathering of basement rock along the planes of faults and major fractures has resulted in the formation of clay comprising chlorite, kaolinite and hydroxides with iron and manganese. Different mineralogy of the basement rock may provide slightly different types of clay minerals during weathering. The clay may potentially prevent or retard flow in fractures, as well as retard the movement of radionuclides. At present, no studies exist on the mineralogy of clay formed in the fractures due to weathering of the various types of crystalline rocks, and neither on the clay mineral sorption capacities specifically for Bornholm.

From the density and size of the surface structural elements observed in the basement areas, it might look as if the eastern part of the Bornholm gneiss and the Paradisbakke Migmatite are the areas where least vertical faults and fractures occur. However, as the horizontal fractures that occur in the deeper parts of the basement are all generated as the result of large-scale tectonics, uplift and erosion (unloading), the frequency and spacing of horizontal fractures should be similar in all areas with crystalline basement.

In Sweden, mapping of fractures and faults in basement has been carried out based on field data including airborne magnetic, airborne electromagnetic and topographic orthophoto data. The surface mapping was combined with, and calibrated to, subsurface data from drilling of boreholes in the order to map structural features in the subsurface at depths of hundreds of meters. Thus, the subsurface mapping of faults and fractures of tectonic origin was used as the basis for siting wells and seismic lines for deep disposal projects in Sweden (SKB 2004, 2005, Juhlin & Stephens, 2006). The existing data from Bornholm on brittle faults and fractures at the surface can be used for planning of further geophysical and geological investigations. It is expected that surface mapping in combination with geophysical investigations at the surface and in boreholes can be used to identify and characterize faults and predict their downward extension (SKB, 2004, 2005, Stephens et al., 2003, Juhlin & Stephens 2006).

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