DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2021/52**

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

Requirements and criteria for initial evaluation of geological properties and conditions

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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. 1. It describes the geological requirements and criteria to be used for an initial evaluation of whether the rock properties and subsurface conditions are favourable for deep geological disposal and the criteria evaluation process.

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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, 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 udført 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. 1: Krav og kriterier for indledende evaluering af geologiske egenskaber og forhold (Requirements and criteria for initial evaluation of geological properties and conditions)

Nærværende rapport beskriver krav og definerede kriterier, der skal anvendes til en kvalitativ evaluering af, i hvilken grad undergrundens geologiske egenskaber er egnede til etablering af et dybt geologisk slutdepot, samt hvordan kriterierne anvendes til evalueringen af de geologiske egenskaber.

I et dybt geologisk slutdepot er det radioaktive affald indkapslet af to konstruerede barrierer. Den omkringliggende geologiske lavpermeable formation, værtsbjergarten, hvor depotet etableres, udgør den tredje barriere. Specifikke krav til værtsbjergarten er givet i Folketingets beslutning B90 (Danish Parliament, 2018), der beskriver, at den geologiske formation skal findes i en dybde omkring 500 meter, den skal være minimum 100 meter tyk, litologisk homogen med lav permeabilitet (tæt), og den skal være horisontalt udbredt over flere kilometer.

De geologiske forhold i undergrunden skal kunne sikre stabilitet i deponeringsområdet både på kort og lang sigt. Tilstedeværelsen af effektive geologiske barrierer i form af en tæt værtsbjergart og tætte formationer (barrierebjergarter) i den overliggende barrierezone er afgørende for tilbageholdelse af radioaktivt materiale i undergrunden. Kriterierne, der defineres i nærværende rapport, har til formål at identificere områder, hvor favorable geologiske egenskaber og forhold er til stede. Egenskaber og processer, der kan kompromittere barriererne skal identificeres og undersøges, så lokaliteter, hvor ustabile forhold er forventet, kan undgås, når der skal etableres en lokalitet til deponering.

For at kunne karakterisere geologien og foretage en kvalitativ evaluering af de geologiske egenskaber, inddeles Danmark i geologisk set forskellige områder. Inddelingen, som er beskrevet i Rapport nr. 9 (jf. referencer i Kapitel 7.1), er baseret på typen af mulig værtsbjergart i dybder omkring 500 meter, den generelle horisontale kontinuitet af værtsbjergarten samt en relativt ensartet geologisk lagserie indenfor de enkelte områder. Inddelingen i geologiske områder er foretaget på baggrund af seismisk tolkning og kortlægning, og den geologiske viden, som er præsenteret i rapporterne nr. 2-8 (jf. referencer i Kapitel 7.1).

Geologiske kriterier defineres i nærværende rapport på baggrund af anbefalinger og erfaringer fra tilsvarende internationale processer og projekter vedrørende identificering af lokaliteter, der er egnede til dyb geologisk slutdeponering. De definerede kriterier relateres til barriereegenskaberne af værtsbjergarten og de overliggende formationer (barrierebjergarterne), den naturlige langtidsstabilitet i et givent område, geoteknisk gennemførlighed og mulighederne for at indsamle pålidelige, nye geologiske data. Kriteriernes relevans i forhold til de samlede geologiske barriereegenskaber på både kort og lang sigt gennemgås på grundlag af generel viden om dyb geologisk slutdeponering fra lignende projekter. De geologiske egenskaber og forhold, der er favorable for de enkelte kriterier, defineres og beskrives, og kriterierne bliver anvendt til en foreløbig kvalitativ evaluering af de karakteristiske geologiske egenskaber i hvert område, som præsenteres i Rapport nr. 9.

Til brug for evalueringen anvendes en scoring af hvert område i forhold til de konkrete kriterier. Scoringen udføres på en skala med tre trin (grøn, gul og orange), og evalueringen er baseret på de mest udbredte, generelle geologiske forhold og egenskaber i de enkelte områder. Der vil således lokalt kunne findes områder, der scorer enten bedre eller dårligere end generelt for området. En grøn scoring af et kriterium indikerer, at de relaterede geologiske egenskaber er vurderet som favorable i størstedelen af området, og at vurderingen er baseret på pålidelige data. En gul score af et kriterie betyder, at de relaterede geologiske egenskaber generelt forventes at være favorable, men at data er mangelfulde i området, eller at scoringen er baseret på analogier fra andre områder eller generel geologisk viden. En gul score indikerer således, at der er en vis usikkerhed om, hvorvidt de nødvendige geologiske egenskaber er til stede. En orange score af et kriterie indikerer, at de geologiske egenskaber generelt vurderes som mindre favorable i området, og at denne vurdering er baseret på pålidelige data. Der vil muligvis lokalt kunne findes lokaliteter, hvor egenskaberne er mere favorable (bl.a. afhængigt af depotdesign), men det vil kræve omfattende geologiske undersøgelser og studier at identificere og kortlægge disse områder. Samtidig vil der være en vis risiko for, at favorable egenskaber ikke kan påvises ved detaljerede geologiske undersøgelser. En orange score af et kriterium betyder ikke nødvendigvis, at et område er uegnet for dyb slutdeponering, da det i nogle tilfælde er muligt at mindre favorable geologiske egenskaber kan kompenseres for eller opvejes af andre favorable egenskaber eller ved design af depotet og de konstruerede barrierer.

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 km²) 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. Concepts for deep geological disposal of radioactive waste

The Danish radioactive waste currently located at Risø comprises low and medium level waste (classified according to IAEA). The medium level waste (MLW) constitutes a minor part of the total amount of radioactive waste. It includes 233 kg of special waste, which contains long lived nuclides and therefore a repository providing long term isolation towards humans and biosphere is required (https://www.dekom.dk/affaldshaandtering/#affald-1). The volume of the low-level waste (LLW) as currently stored in large containers is around 10,000 m^3. The Danish waste does not contain high-level, heat generating radioactive waste (HLW).

The most recent information available from DD with regards to waste composition and volumes is presented in the report by COWI (2011). The volume and types of radionuclides in the waste determines the length of time during which the waste must be shielded from the biosphere and protected against human interference by engineered and geological barriers.

The Danish radioactive waste has been classified and divided into five major groups with a total of 20 waste types by DD (COWI 2011). A summary is presented in the report on numerical modelling (Kazmierczak et al. 2021). The largest volumes and masses originate from construction materials from the three reactors (DR1-3) and the graphite moderator rods used in the reactors. The largest quantities of radiation are found in the group termed “special waste” specifically in 233 kg of irradiated fuel and 1.2 kg of irradiated uranium. The second largest amount of radiation is found in specific radioactive sources.

The long-lived ß- and γ-emitting isotopes as well as the long-lived α-emitting isotopes are the isotopes that can be expected to still have a substantial activity beyond 10,000 years (Kazmierczak et al. 2021). It appears that most of the radionuclides present after 10,000 years are so called actinides which is the group of elements with atomic numbers from 89-103, of which Ac, Th, U, Np and Pu (all radioactive) will be present in the waste after 10,000 years. In addition to the actinides the radionuclides ^{226}Ra, ^{210}Pb, ^{99}Tc, ^{41}Ca and ^{14}C will also be present in some of the waste types after 10,000 years.

Some of the waste contain reduced organic compounds. The organic carbon may eventually form methane CH_4 and CO_2 which to the extent that it is dissolved in the water will form carbonic acid, a relatively weak acid.

A number of factors, such as the material of the containers in which the radioactive waste is packed, backfilling material, redox conditions at 500 meters depth, the geochemical properties of the host rock, and pressure gradient, may all influence retardation of the radionuclides in the subsurface. The influence and significance of some of the variables are investigated preliminary in Report No. 7 of the current report series (Kazmierczak et al. 2021).

2.1 The engineered and geological barriers

A deep geological repository concept comprises three barriers encapsulating the waste as described below:

- First barrier (engineered): Containers or drums of steel, stainless steel, copper or other resistant materials within which the radioactive waste is encapsulated in a cement/concrete lining.
- Second barrier (engineered): An underground construction/ building/shaft (in the widest sense of the term) where the containers are stored enclosed in a sealing filling material of e.g. bentonite or cement.
- Third barrier (rocks): The surrounding low-permeable geological layers in the host rock forming a natural barrier for retainment and retardation, and additional barriers in the effective containment zone (ECZ) of overlying low permeable formations.

The engineered barriers should be designed to ensure encapsulation and retardation of radionuclides for the longest possible time. However, at some point in time the chemical interaction between the ground water and the waste containers will most likely cause corrosion and gradual degradation of the barriers. At this point in time, the host rock's barrier effectiveness to retard and delay radionuclides leaked from the containers becomes an important factor to ensure that the radioactive material does not move into the shallower layers and the biosphere.

In the next project phase, detailed geological investigations will provide new data on geochemistry of the potential host rock, the overlying formations and the groundwater will be acquired during the detailed site investigations and the subsequent analysis of drill samples. This data will be used for evaluation of the barrier effectiveness as well as for investigation of geochemical interactions between the radionuclides of the waste and the surrounding geological barriers. The results should be used to ensure an optimum design of the engineered barriers to provide long term geochemical retardation of radionuclides in the subsurface.

For the Danish disposal project, the identification and development of a feasible repository design concept is an iterative process based, among other issues, on the geological/geotechnical properties of the host rock and the overlying layers in the ECZ. The geological properties may influence the entire disposal concept and the facility design as well as the engineered barriers necessary to ensure safety during excavation, operation, and post-closure. In case it is decided to dispose only the special and MLW in a deep repository and place the LLW repository at shallower depths, separate criteria for the necessary geological properties for such a disposal concept need to be defined.

A preferred design concept for the repository facility is not yet available from DD and may be governed by the local geological conditions. The identified potential concepts span from disposal of parts of the waste in a deep borehole combined with a shallower repository, to an underground storage facility for the total waste volume (Danish Decommissioning, 2021). For this siting project, it is assumed that all the radioactive waste will be placed in a deep disposal facility (to be conservative) as this requires the largest rock volume to be identified. It is, however, an option that the different waste categories are disposed in repositories at different depths where only the special waste and the waste containing long-lived isotopes are disposed at depths around 500 meters (Danish Parliament, 2018). At this project stage the geological characterisation and evaluation of different areas is made to cover the range of disposal concepts and will be useful for the identification and selection of sites for detailed geological investigations.

A post-closure safety assessment should be carried out to obtain a reasonable assurance that the disposal system will provide a sufficient level of safety, rather than to predict its future specific performance (IAEA, 2011).

From other siting processes (e.g. SKB, 2007; SFOE, 2008), the importance that the waste producer/owner, in this case DD, provides information on waste inventory and properties is emphasized. Based on the waste inventory, including radionuclides and half-lives, waste volumes and categories, content of gas-producing materials (metals and organic matter), material properties and their possible impact on the host rock, the waste owner, describes the safety concept for the repository type, or types, if more than one.

3. Geological site identification

The process for identification and selection of a Danish disposal site is based on recommendations from IAEA and experiences from similar processes in other European countries including Sweden, Norway, Finland, France, Switzerland, and UK, who have worked continuously with issues related to geological disposal of radioactive material for several decades. The overall Danish plan for final disposal of the radioactive waste is described in detail in the National Programme for the Responsible and Safe Management of Radioactive waste (Danish Health Authority, 2020).

IAEA (2011) recommends the following four major phases of siting projects, with the purpose to identify suitable sites through a structured process (Figure 3.1):

1. A conceptional planning stage (feasibility phase)
2. An area survey stage (desk studies), leading to the identification of suitable areas for selection of investigation sites
3. A site investigation stage with detailed site-specific studies
4. Detailed site characterisation as basis for decision on construction of disposal facility

Subsequent phases are related to repository design, decision, and construction of the facility, operation, closure, and post-closure monitoring.

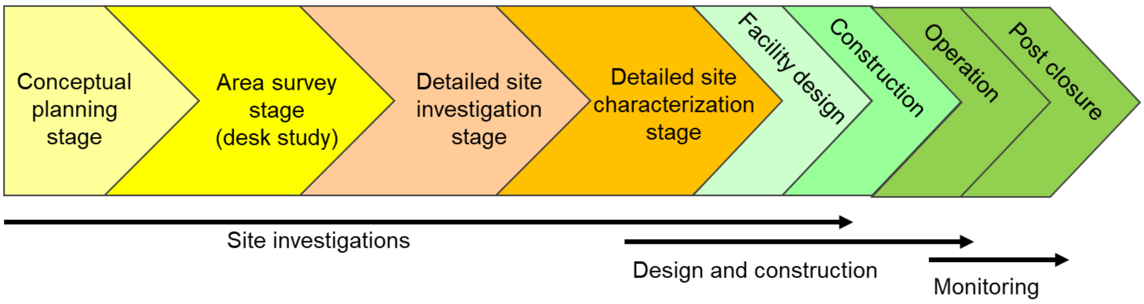

Figure 3.1. *A model for the process of establishing a deep waste repository: Four siting stages and subsequent stages of construction, operation, and post closure (modified from IAEA, 2018b).*

Figur 3.1. *En procesmodel for etablering af et geologisk slutdepot for radioaktivt affald der omfatter fire faser med område lokalisering og derefter design, konstruktion, operation og lukning (Fra IAEA, 2018b).*

3.1 Geological requirements and definition of criteria

The requirements for the present geological project, as given by the Danish Parliaments decision B90 (Danish Parliament, 2018), are that the geology must enable the establishment of a deep repository at a depth around 500 meters in a low permeable and laterally continuous formation with a thickness of 100 or more. The repository should comprise two passive engineered barriers in addition to meters the geological barriers provided by host rock and overlying low permeable formations referred to as the effective containment zone (ECZ). The geological requirements are based on the experience gathered during several decades of international research and siting processes aimed at localizing suitable sites for deep disposal of mainly HLW comprising long lived isotopes and heat generating material. Disposal in tight formations at depths around 500 meters and geological settings with long-term stability may ensure that radioactive material is held back in the geological formations. The depth will ensure that erosion during future glaciations is highly unlikely to cause exposure of the radioactive waste in the repository.

To assess whether the geological setting and the rock properties are suitable for providing effective barriers and the necessary long-term safety, criteria relating to the geological and geotechnical properties and conditions have been defined (see Chapter 4). The criteria are largely based on recommendations from IAEA and experiences from similar international projects (e.g. SFOE, 2008; SKB, 2007; IAEA, 2011). The definition of criteria and the area evaluation process benefitted from comments and recommendations provided through a review carried out by a team of international experts (Blechschmidt et al., 2021).

The criteria presented in this report are defined with the aim to ensure that the geological properties are favourable for providing efficient geological barriers for disposal of the total volume of Danish radioactive waste in a deep repository. Sites fulfilling these criteria will also be suitable for a repository concept where parts of the waste are disposed in a deep borehole in case such a solution is decided.

Since the repository concept and design will to some extent depend on properties of the host rock and the overlying layers in the ECZ, areas dominated by specific geological rock types and structural framework in the interval 0 to 500 meters are defined to enable a general characterisation of properties and conditions in each area.

When evaluating the geological barrier effectiveness based on site specific data, the type of radioactive waste (nuclide inventory, waste volumes, chemical-physical properties, etc.) must be considered, as well as the material design of the engineered barriers. This information is to be provided by the radioactive waste manager (DD). For final evaluation of safety prior to a decision whether to establish a repository, it is important to define a safety case with an integrated assessment of the retention capacity and the behaviour of the repository system including the host rock and barrier rocks forming the ECZ, and the engineered barriers (SFOE, 2008; IAEA, 2011).

3.2 Geological project phases

The current geological project comprises two major phases as illustrated in Figure 3.2, where the current phase is project phase 1. The results of Phase 1 provide the geological basis for selection of two sites for the detailed geological investigations and characterisations to be carried out in Phase 2.

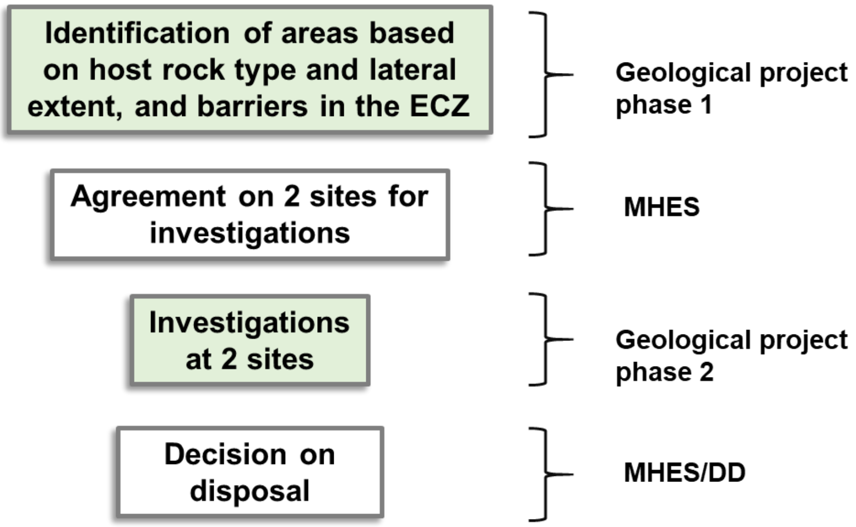

***Figure 3.2**. Overview of the overall site selection process (left side) and the geological project phases which will be carried out by GEUS.*

***Figur 3.2.** Diagrammet viser faserne for det geologiske projekt, der udføres af GEUS*

3.2.1 Project phase 1: Desk studies and area evaluation

A comprehensive desk study of the subsurface geological conditions and properties forms a major part of phase 1 and is presented in the reports no. 2-8 (references in Chapter 7.1). Based on the findings presented in these reports a stepwise approach is taken to identify, map and initially characterize different area's suitability for deep geological disposal (Figure 3.3). To enable a geological characterization of the Danish subsurface a subdivision into areas where similar rock types occur at depths to 500 meters is made in Step 1 (Figure 3.3). The area subdivision is based on seismic interpretation and mapping combined with the geological properties and conditions as presented in the desk studies.

It should be kept in mind that the area subdivision is made to enable a general description and characterisation of the subsurface geology knowing that variations and differences will occur locally in each area. Thus, boundaries between adjacent areas will in most cases be somewhat gradational and areas near the boundaries may share some characteristics of the neighbouring area.

In each area one predominant type of potential host rock occurs at the depth around 500 meters, a specific rock type constituting an additional barrier in the ECZ and a characteristic large-scale structural framework in the area. Of major importance is the absence or presence of closely spaced faults offsetting the host rock section. If many faults occur with small spacing (few kilometers) this will have a significant impact on the horizontal continuity of the host rocks, and possibly also lateral changes of thickness, lithology, and structural dip of layers.

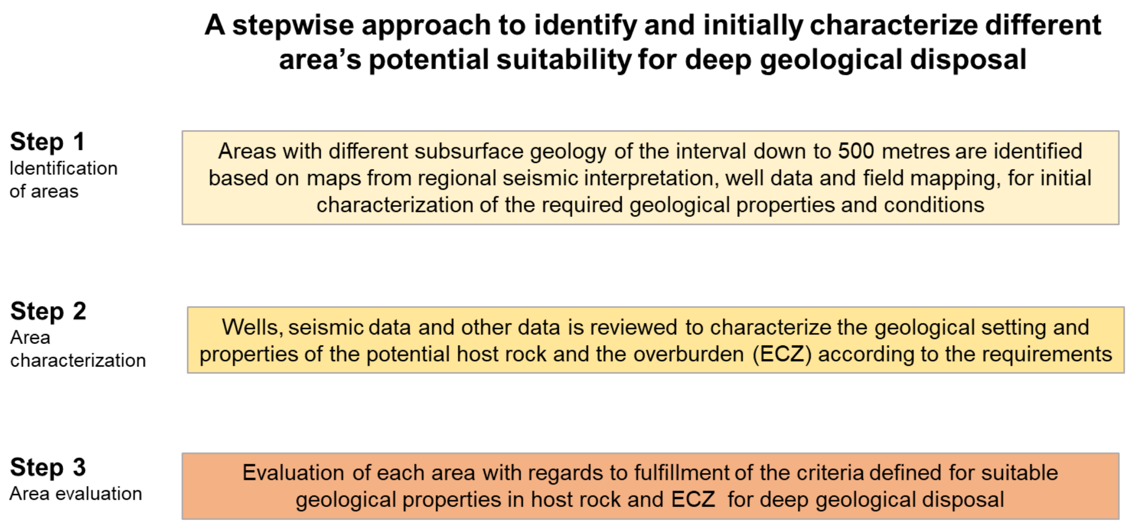

Figure 3.3. *Identification and characterisation of areas for the site selection is made through a stepwise process.*

Figur 3.3. *Identifikation og karakterisering af forskellige geologiske områder foretages ved en trinvis proces.*

In addition to the requirements defined to ensure the host rock properties can provide an effective barrier to fluid flow, geological criteria have been defined also to ensure that the rock types can provide the required safety both on short- and long-term, and technical feasibility. The criteria are defined based on experiences and recommendations from other similar disposal projects (e.g. SFOE, 2008; SKB, 2007). The criteria will at this stage be used for initial evaluation of the areas based on existing data and for identification of critical data that needs to be obtained during the geological site investigations in Phase 2.

Step 2 (Figure 3.3) is focused on investigating whether the presence of a low permeable host rock with the required thickness (≥100 meters) and lithological homogeneity is supported by well data or other data from the mapped stratigraphic interval in each area. Further, it is investigated whether the overlying ECZ is without thick, high permeability layers or zones. In most parts of Denmark, the Chalk Group will constitute a major part of the ECZ with thicknesses up to several hundred meters and therefore chalk, marl and limestone will provide the barrier rocks (Figure 3.4).

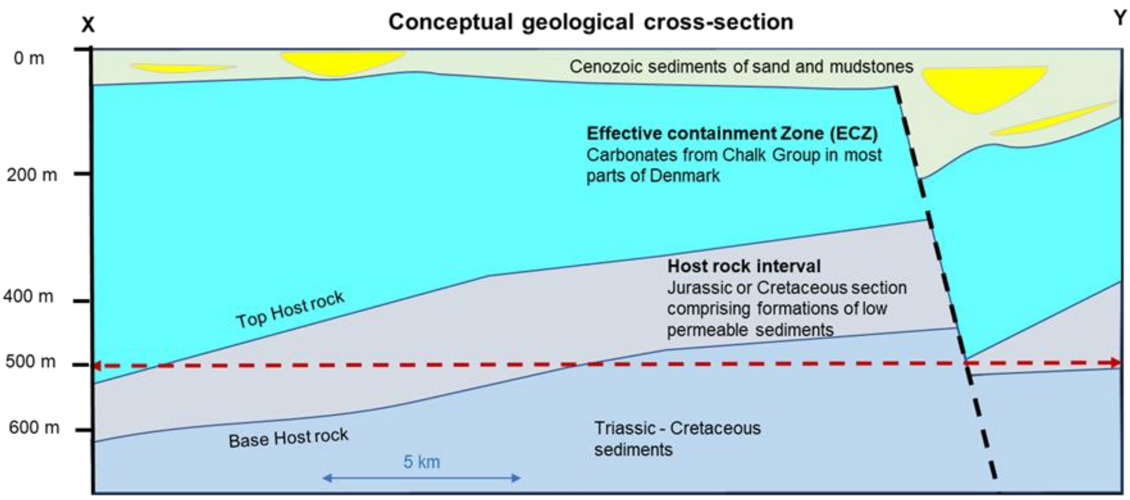

Figure 3.4. *Conceptual cross-section showing a generalized, typical geological record occurring in the Danish onshore areas with sedimentary rocks. The red dotted line indicates 500 meters depth.*

Figur 3.4. *Konceptuelt geologisk profil, der illustrerer den generelle geologiske lagserie i den danske undergrund. Den røde stiplede linje markerer dybden på 500 meter.*

The shallowest part of stratigraphic record comprises Cenozoic marine to non-marine sandstones and mudstones of varying thicknesses (Figure 3.4). The Cenozoic sediments are in general not expected to contribute to the ECZ as they comprise varying, and generally high amounts of unconsolidated sand. An average thickness of 140 meters for the uppermost part of the sedimentary record comprising ground water interests was estimated for the modelling study by Kazmierczak et al. (2021). Therefore, the thickness of barrier rocks in the ECZ overlying a host rock occurring in the 400 to 500 meters depth interval, is approximately 250 meters (Figure 3.4 and 3.5).

A qualitative evaluation of how well the defined geological criteria are fulfilled in each area is carried out as Step 3 (Figure 3.3). The evaluation is carried out as a qualitative scoring on a scale with three levels as explained in Chapter 5. It includes an assessment of the data quality and applicability (how representative the data/information is) to evaluate the reliability of existing information. Rock properties, the geological setting and long-term natural stability which in combination must provide the necessary barriers and conditions for retardation of radionuclides are evaluated. Criteria definition and their relevance for safety, and the evaluation approach is explained in detail in Chapter 5.

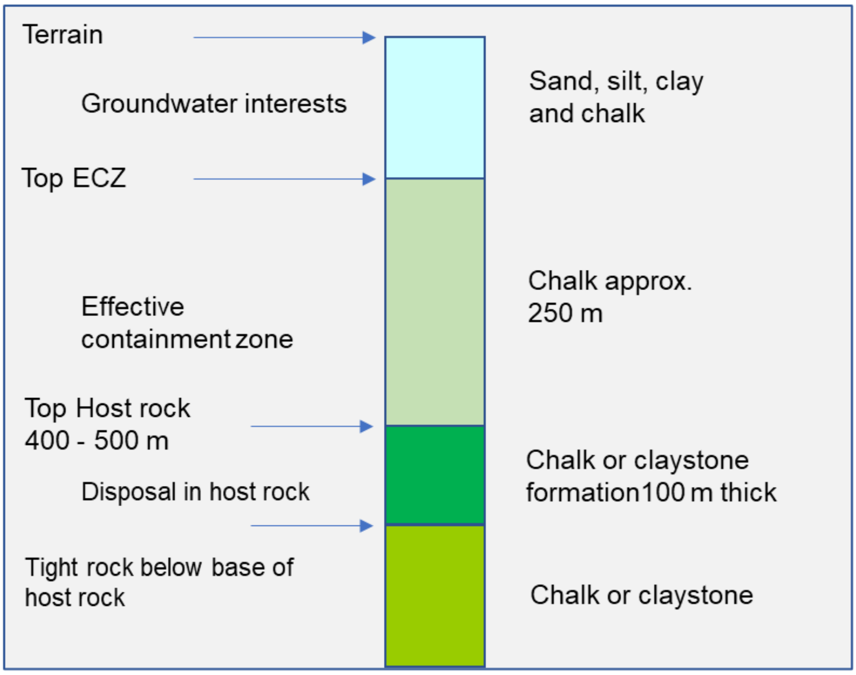

Figure 3.5. *Conceptual geological rock record of host rock for disposal and additional tight rocks in the overlying containment zone (ECZ).*

Figur 3.5 *Konceptuel geologisk lagserie med værtsbjergart til deponering og en overliggende barrierezone af tæt kalksten.*

Existing knowledge on the rock properties and the long-term natural stability will be presented for each area based on the geological reports prepared from the desk studies. In some areas specific information on rock properties is available. However, in most areas the rock properties will have to be inferred either from nearby analogs or from analogs in the literature and thus a higher degree of uncertainty exists for the rock properties in these areas.

Through this initial criteria evaluation process, it will be obvious which criteria cannot be evaluated at this project stage due to lack of data and/or experience. Highlighting the fields of knowledge where critical data must be acquired in the project's next phase of detailed site investigations is an important part of the evaluation process. As an example, the geotechnical properties necessary for engineering feasibility are addressed only very preliminarily, based on general knowledge and recommendations from similar international projects, as neither data nor experience from engineered constructions exist from 500 meters depth in the Danish subsurface.

The criteria evaluation can be regarded as a systematic approach to access the detailed geological properties and conditions, and to identify areas of major uncertainty and data gaps that need to be filled in during the detailed site investigations in Phase 2. In the project's phase 2, a further detailed evaluation of the criteria will be carried out based on new information on rock properties acquired from the detailed geological site investigations in two areas.

Geological considerations on areal extent of the sites for detailed investigations

Following the area characterisation and evaluation two investigation sites will be decided in cooperation between MHES and local municipalities. Criteria related to socio-economic conditions such as environmental issues, land use and exploitation of natural resources will be addressed during the process of site selection as managed by MHES (MHES, 2021).

When selecting the specific investigation sites and their lateral extent, it is important to revisit the geological database to check if further detailed mapping can be made, as the maps and seismic interpretations show only large, reginal faults and other major discontinuities that must be avoided within the site investigation areas. The seismic mapping and subsequent conversion into depth and thickness of the formations is made in a relatively coarse grid due to the variable data density. This is to ensure there is a high likelihood that the geological properties and the general geological setting in the specific area are favourable in terms of the requirements and criteria. A preferred repository design concept for the specific host rock at the site should be identified to estimate the areal extent and the volume of rock required for construction of the repository. This estimate includes the host rock volume required for disposal of the waste and the rock volume required in the ECZ for the construction of shafts / tunnels / boreholes giving access to placing the waste in the repository.

The investigation site should be selected in an area where the host rock as well as layers in the ECZ can be expected to be homogeneous and laterally continuous for several kilometers, i.e. 5x5 kilometers or more. This is to ensure that:

- There is flexibility within the area in case subsurface discontinuities are identified in the host rock or the ECZ during the site investigations
- The location of faults mapped from 2D seismic is usually unprecise, with uncertainty up to 1 kilometer and even larger uncertainty in terms of the lateral extent of the fault plane. This uncertainty must be acknowledged if faults are present at the outer boundary(es) of the area where the site is to be defined to avoid drilling into faults during the detailed site investigations.
- Deep drilling can be carried out at some distance to the specific rock volume to be used for disposal in order not to compromise the effectiveness of the geological barriers. At the same time, it is important that the drilling of deep boreholes will penetrate geological sections where the rock properties can be expected to be highly representative and very similar to the properties existing at the potential disposal location in the host rock body.

3.2.2 Project phase 2: Detailed geological site investigations

In phase 2 new data will be acquired for a comprehensive and detailed characterisation and valuation of the two sites to evaluate whether the geological properties and conditions fulfil the criteria for safe disposal of the radioactive waste on both short and long term.

The geological site investigations include acquisition of geophysical data and drilling of deep boreholes as summarized in Figure 3.2. These data will be used for detailed mapping of the subsurface to confirm the lateral continuity of the host rock and the ECZ, and for investigation of the natural long-term stability. Samples and measurements from bore holes will be used for laboratory analysis to characterize the geological, geochemical, and geotechnical properties. This information will be used for numerical modelling of nuclides transport to evaluate the geological barrier effectiveness. Subsequently the information will be used by DD as input to a safety case to investigate and demonstrate that the combined system of geological and engineered barriers of a specific repository concept, can provide the required short- and long-term safety.

4. Criteria defined for suitable disposal sites

This chapter describes how the criteria are defined and utilised with the purpose to ensure a consistent assessment of whether the geological properties of the potential host rock and the overlying ECZ may provide efficient barriers which can ensure the required short and long-term geological safety. General considerations about how the geological properties and conditions should represent favourable situations are presented for each criterium. The criteria evaluation (Step 3, Figure 3.3) is applied to each area and includes an evaluation of the requirements on host rock presence, depth, thickness, and lateral continuity (see Chapter 3.2).

The safety provided by the repository is the combined effectiveness of the engineered and the geological barriers. Some criteria may be more critical to fulfil than others, however at this stage it is not possible to distinguish as it depends on the repository concept and design. The geological criteria and sub-criteria are summarized in Table 4.1. The safety relevance for each criterium is explained followed by a description of which geological settings and properties are favourable for each criterium and, where relevant, some comments about the general knowledge database for the specific issue. It should be kept in mind that the Danish radioactive waste comprises mostly LLW and minor volumes of MLW and special waste with long-lived radioactive isotopes, but no HLW.

The evaluation of how well the criteria are fulfilled in each area is at this stage preliminary due to the limited data available. The evaluation will reflect the prevailing conditions and properties in the area, but it will by no means be representative for every part of the area. A detailed and comprehensive evaluation of the criteria will be carried out in phase 2 of the project when relevant data is available from the two geological site investigations.

Table 4.1. *Criteria related to safety and technical feasibility to be evaluated through the geological siting process.*

Tabel 4.1. *Kriterier relateret til effektiviteten af de geologiske barrierer og de geotekniske egenskaber, som anvendes for områdeevalueringen.*

Group of criteria	Criteria
1. Properties of the host rock and the containment zone	1.1 Spatial extent 1.2 Hydraulic barrier effectiveness 1.3 Geochemical conditions for retardation 1.4 Release pathways
2. Long-term natural stability	2.1 Stability of the site and rock properties 2.2 Erosion 2.3 Repository induced influences
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions 3.2 Underground access and drainage
4. Possibility to acquire reliable new geological data	4.1 Ease of characterisation of the rock 4.2 Explorability of spatial conditions 4.3 Predictability of long-term changes

The criteria are defined to ensure that the geology surrounding the repository will provide the required safety from the time of construction and into the future on a timescale of 10,000 to 100,000 years or more, during which the biosphere must be shielded from unnecessary doses of radiation. Of major importance is the presence of rocks providing effective physical and geochemical barriers, and the lack of fairways for fluid flow. In low permeable rocks nuclide movement will occur only by diffusion which is extremely slow compared to fluid flow which occurs at much shorter timescales. Safety provided by the geology depends on the host rocks ability to inhibit (or minimise) fluid flow, transport of nuclides by diffusion and additionally to retard radionuclides geochemically. In combination with the engineered barriers, the suitable rock properties will ensure that radioactive material is held back in the subsurface until the radioactive waste has decayed to a very low activity level.

Various natural processes can potentially create new weak zones and paths for fluid flow in the host rock and ECZ. The geological setting therefore must provide long term safety in the sense that it is very unlikely that neither natural processes, nor processes induced by the disposed waste, nor human activity, will compromise the barrier effectiveness (the combined engineered and geological barriers). In addition, the geotechnical properties of the host rock, and the overburden must enable feasible and safe construction and operation of the repository until the time of permanent closure and seal off.

Some of the geological properties are relevant to address with regards to different aspects of a repository. For example, the presence of faults which may compromise both the barrier effectiveness and the geotechnical feasibility. Another example is the presence of high-permeable water bearing rocks in the ECZ may compromise barrier effectiveness as well as being geomechanically less competent and may cause large inflow of water to the underground construction site. Therefore, some of the properties such as absence of major faults are, for different reasons, relevant to address for several criteria.

The criteria evaluation can be regarded as a systematic process to check all the geological properties and identify areas of major uncertainty and data gaps. This will help to ensure that the future data acquisition is aimed at filling in data gaps in the project's Phase 2 with detailed site investigations. A comprehensive evaluation of to which degree the defined criteria are fulfilled for the two sites will be made in phase 2 based on geological and technical analysis on the new site-specific data. For some of the criteria the knowledge about specific properties is very limited to non-existing due to lack of data and experience from 500 meters depth in the Danish subsurface. In these cases, relevant information from analogues, and data presented in the literature may be used for a preliminary evaluation of the likelihood that suitable conditions exist in the subsurface. The lack of data will be identified and highlighted during the criteria evaluation process. It will be considered based on general geological knowledge whether there is a high chance that new data will support the presence of favourable properties and conditions, or whether there is a risk that the properties encountered will be less favourable or unfavourable.

4.1 Properties of the host rock and the effective containment zone

An overview of the properties related to each criterium is presented in Table 4.1 and the criteria are explained in detail in this chapter. A detailed summary of the properties and their importance is presented in Table 2 at the end of this chapter.

4.1.1 Spatial extent of host rock and the effective containment zone (ECZ)

The host rock must be a laterally extensive rock body of at least 100 meters thickness with a homogeneous lithology. The mapped rock body should be without major fault zones or other discontinuities. The additional presence of a thick, homogeneous ECZ of low permeable rock is important such that the combined barrier formed by the host rock and ECZ will retain radionuclides to provide the necessary safety. An average depth to base of the groundwater reservoirs of 140 meters is used in the sensitivity studies of barrier effectiveness presented by Kazmierczak et al. (2021). To be consistent with this study tight rocks in the ECZ formation should constitute a section of approximately 260-250 meters thickness directly overlying the host rock formation.

The lateral continuity is important to enable stable underground constructions and facilities including caverns and tunnels / shafts within the host rock body in case such a disposal concept is decided. The absence of major faults is important as faults may be geotechnically less competent than undeformed rocks. In addition, the lithology and thus the rock properties of a formation may be different on either side of a major fault, especially if associated with thickness variations occurring over short distances. Lateral consistent thicknesses will allow for good predictability and higher certainty on rock properties throughout the host rock body.

Favourable conditions are those where the presence of laterally extensive, low permeable, homogeneous formation in the mapped seismic-stratigraphic units is confirmed from well data. Favourable situations are where:

- Thickness of the host rock formation is 100 meters or more
- The host rock formation occurs at depths around 500 meters below surface
- The host rock is laterally continuous for more than 5x5 kilometers
- The host rock lithology is spatially homogeneous
- The ECZ overlying Top Host rock is approximately 250 meters thick
- The ECZ is laterally continuous for more than 5x5 kilometers
- The ECZ lithologies are spatially homogeneous

Comments
Data used for evaluation of this criteria is mainly from wells and seismic data, and geological surface mapping in the basement area. As both seismic and well data is unevenly distributed, and of varying quality and vintage it is important also to consider and evaluate the data confidence used for evaluation of this criteria. The seismic mapping provides information on thickness and distribution of stratigraphic units but not with regards to lithological homoge-

neity within seismic units. The presence of a homogeneous and tight lithology must be confirmed by well data which may be combined with regional information on paleogeography and depositional environments.

The seismic interpretation and mapping are of high confidence in areas where good ties to wells with high quality data can be made. In other areas the depth uncertainty can be in the range of +/- 100 meters or more, which is significant for this project targeting a host rock at depths around 500 meters. In addition, limitations of seismic resolution are challenging, especially in sections of interbedded, relatively unconsolidated sand and shale, where the thickness of lithological units may have to be several tens of meters to be detectable and mappable. In phase 2, site specific and optimized seismic and well data acquisition should enable an improved detailed mapping of the seismic-stratigraphic interval with the host rock and lithology confirmed by well data.

For the detailed site investigations, the host rock formation should be laterally continuous for approximately 5x5 kilometers or more to enable deep drilling at the margins of the area thus leaving a large area with undisturbed host rock and ECZ at the potential repository location in the area centre. Future rock characterisation and modelling will be made in the next project phase to investigate whether the rock thickness in combination with the properties of the host rock and ECZ may provide the necessary barrier.

4.1.2 Hydraulic barrier effectiveness

The barrier effect depends on the hydraulic conductivity and hydraulic gradient which will determine the dominant transport processes. A low rate of water flow in the formation is favourable for the functioning and protection of the engineered barriers (1. and 2. barriers) and will delay time of radionuclide leakage into the host rock (3. barrier). At a later stage, when nuclides begin to leak through the engineered barriers, a low hydraulic conductivity will contribute to an effective geological barrier retarding the radionuclides for the needed time-period by ensuring that radionuclide transport in the host rock and the ECZ is sufficiently slow.

The properties of the host rock and the ECZ are evaluated in terms of water flow and transport of dissolved substances by diffusion, which are determined partly by the hydrogeological setting and gradients, and regional ground water characteristics.

Low hydraulic conductivity in the host rock body is promoted by a low-permeable, homogeneous lithology in the entire host rock body and isotropic stress conditions. The amount of clay and the clay mineralogy in sedimentary rocks (limestone, marl, and mudstone) provide important data for the preliminary permeability assessments, as the presence of clay minerals, especially smectite and montmorillonite, promotes a high degree of compaction resulting in lower permeability, compared to for instance kaolinite. Also, diagenetic cementation promotes low permeability by clogging up pore throats. In un-fractured crystalline rocks such as granite and gneiss the matrix permeability is extremely small close to nil.

Potential flow paths in terms of laterally widespread high porosity and high permeability sand layers, and faults extending from the host rock to shallow near-surface layers should be absent. Such flow paths may compromise the barrier effectiveness however, the local geological setting has a large impact on the flow directions and rates and specific models are needed to evaluate the potential flow and the impact.

The required hydraulic conductivity values needed to provide an effective barrier depends on the combined effect of rock properties and total thickness of the host rock and the overlying formations (ECZ). Favourable conditions are:

- Very low permeability (low hydraulic conductivity) to promote transport by diffusion

Comments
When no direct data is available on permeability it can be assumed that the presence of clay with smectite will promote the occurrence of low permeability in the rock due to high compressibility. The combined effect of rock properties and formation thickness is investigated by numerical modelling. As very little data on hydraulic conductivity (permeability) is available from low permeable rocks occurring in the interval 100-500 meters below surface in Denmark (and only from sections of limestone and marl), preliminary numerical modelling based on representative data is carried out in the current project phase. In a siting project, where significant amounts of data and studies were available, Nagra used a K-value of 10-9 or less as a criterium, or alternatively, when no measurements were available, a clay content of more than 25% (Nagra, 2008). Phase 2 of the present project will include site specific well data acquisition allowing for systematic permeability analysis and numerical 3D modelling. Also, clay content and clay mineralogy will be investigated in detail.

4.1.3 Geochemical conditions for retardation

The geochemical conditions in the host rock and ECZ (mineralogy, water chemistry, pH, redox conditions, salinity, water-rock interaction, microbial processes) influence both the long-term behaviour of the engineered barriers and the host rock’s capability for retention and retardation of leaked radionuclides (solubility, sorption capacity).

A favourable situation is when the geochemical conditions and rock composition result in a high degree of radionuclide retention in the host rock and the ECZ which, amongst other parameters, is promoted by the presence of clay minerals, calcite and Fe- and Mn-oxides, and reduced groundwater conditions. Geochemical conditions that lead to radionuclide retention in the engineered barriers and to long-term stability of the engineered barrier properties are also important, but the required favourable conditions are poorly known at this stage. At present, limited information is available on the geochemistry of the waste inventory and the design of the engineered barriers is unknown wherefore this issue should be addressed at a later stage when designing the repository facility.

Clay minerals in general have the capability to absorb high percentage of cations, thus their presence in high volumes in the host rock matrix and in the overburden (ECZ) is favourable for retention of radionuclides. Saline groundwater may for some nuclides cause formation of phases with low solubility. Saline groundwater is in general expected at 500 meters depth in all areas and is therefore not considered further. Favourable conditions are where:

- Host rock matrix has a high percentage of clay minerals
- Host rock clay include smectite and/or montmorillonite
- ECZ rock matrix has a high percentage of clay
- ECZ clay include smectite and/or montmorillonite

Comments

Detailed information on the subsurface geochemical conditions is sparse and new data will be obtained from the future detailed geological site investigations. This includes the capability of the different types of clay minerals for retarding specific long-lived nuclides occurring in the waste. This investigation should be made as an integrated analysis of the minerals capability and capacity to retard the long-lived nuclides potentially released from the Danish waste based on an updated, detailed waste characterisation and the retardation capacity of the engineered barriers.

4.1.4 Release Pathways

Slow transport of nuclides in the rock will ensure that a large proportion of the radionuclides decay in the deeply buried rocks and thereby not enter the shallow layers and the biosphere. Local variations of the host rock properties may form release pathways potentially influencing and focussing radionuclide migration. Variations in rock properties may occur due to the presence of high porosity layers, subsurface structures such as faults and fractures, the nature of the pore space and connectivity, or the transmissivity. In addition, migration may occur along excavation induced fractures in the rock, and therefore the self-healing capacity which depends largely on the clay content in the rock (amounts and types of clay minerals) is addressed.

In favourable settings, transport pathways are absent or inefficient which will ensure a significant retardation of radionuclides released into the host rock and the ECZ. The host rock should be homogeneous to promote dissolved matter to move by diffusion only, and pathways in the host rock such as high permeable layers, open faults, and fractures, or other inhomogeneities should be absent. Favourable conditions are where:

- Laterally widespread, high permeable layers are absent in, and beneath the host rock
- Laterally widespread, high permeable layers are absent in the ECZ
- Absence of connected large open fractures extending from the host rock through the ECZ
- Smectite and calcite is present in host rock and ECZ to enable self-healing (is evaluated in chapter 4.2.3 as criteria 2.3, see Table 4.3)

Comments

Faults are mapped from seismic and other geophysical data including petrophysical data from well logs, and from descriptions of core material. A detailed, high-resolution, site-specific dataset is needed to enable identification of high permeable layers which might form release pathways, which could be only a few meters thick. In crystalline basement rocks mapping is made from surface outcrops, orthophotos, and data from drill holes (mostly water wells < 100 meters deep). The potential for self-healing should be investigated through clay mineral analyses and petrographic studies combined with studies of potential excavation damage of the rocks.

Homogeneity and presence of clay in the host rock and ECZ will be investigated from drill cores and petrophysical well logs where available, otherwise information from literature analogues will be used. Potential for self-healing will be inferred from data and information on the presence of smectite in the rocks.

***Table 4.2**. Summary of the criteria for host rock and ECZ properties.*

***Tabel 4.2.** Oversigt over kriterier for værtsbjergart og overliggende formationers (CZ) egenskaber.*

1. Properties of the host rock and the effective containment zone (ECZ)		
	Criteria	Comments
1.1 Spatial extent	Thickness of the host rock should be 100 m and the formation should occur laterally continuous at depths around 500 m below surface. Formations in the ECZ directly overlie the host rock are laterally extensive and lithological homogeneous.	For detailed site investigations, the host rock and ECZ formations should extend laterally for 5x5 km or more. Future rock characterisation and modelling may show whether smaller thicknesses for some rock types/lithologies may be sufficient or if greater thicknesses are required.
1.2 Hydraulic barrier effectiveness	Very low hydraulic conductivity / low permeability is needed to ensure transport occur as diffusion and not fluid flow. Fine grained rocks such as claystone, chalk, marl and crystalline basement may provide the necessary hydraulic barrier at depths around 500 m in combination with tight formations in the ECZ.	The hydraulic conductivity and permeability values that may provide an effective barrier depends on total thickness of host rock and overburden rocks (ECZ), and bedding geometry which will be investigated by numerical modelling. Presence of high amounts of clay size grains and clay minerals including smectite promote low permeability.
1.3 Geochemical conditions for retardation	High percentage of clay minerals in the host rock matrix and in the overburden (ECZ) is preferred. A favourable situation is where the clay fraction comprises smectite and/or montmorillonite minerals which are known to have a high sorption capacity. Saline groundwater conditions will cause low solubility of actinides	The capability of the clay minerals, calcite, and various oxides to retard the most critical nuclides will be investigated further in phase 2 based on site specific data. An integrated analysis of which minerals are favourable to retard nuclides in the Danish waste should be made based on a detailed waste characterisation and the design concept of engineered barriers (from DD).
1.4 Release pathways	Absence of connected open fractures and faults, and high permeable layers or zones in the host rock and ECZ.	Faults and fractures to be mapped from seismic and other geophysical data, petrophysical data from well logs and cores. In basement also mapping in field.

4.2 Long term stability

A summary of the properties related to each criterium is presented in Table 4.1 and explained in detail in this chapter. A table summarising the properties is presented at the end of this chapter (Table 4.3).

4.2.1 Stability of site and rock properties

Long-term geological stability of the site and the rock properties is important to ensure that the existing barriers effectiveness will not be compromised by the formation of new release pathways. The long-term stability is evaluated in terms of tectonic activity which could result in re-activation of existing fractures and faults, the formation of new fractures. In case there is a risk of generating fractures in re-activated faults it is a favourable situation if clay is present in the host rock, and the ECZ, as clay may help to seal the fault from clay smearing and swelling of smectite clay minerals. The rock's potential for self-healing is addressed in criteria 2.3.

A favourable situation is a geological setting within a tectonically stable environment, where major events capable of generating new flow-paths through the host rock and ECZ are very unlikely to occur.

- Registered earthquake frequency and magnitude is low and not expected to cause reactivation of major faults or generate new, large faults
- Glacio-tectonic deformation during a future glaciation is expected to influence only the overburden and shallower parts of the ECZ (0-300 meters below terrain).

In general, the earthquakes registered in Denmark are of low to very low magnitude (Sandersen et al. 2021). Large scale faults extending to surface may be re-activated due to seismicity related to large scale tectonic events. Based on maps of registered recent earthquakes and seismic mapping of major faults, tectonically active zones can be avoided. Minor faults with limited vertical extent, i.e. terminating within deeply buried formations are unlikely to form fairways for fluid flow during reactivation and therefore not of concern.

The possibility of deep deformation such as thrust faulting related to future glaciations exist across entire Denmark. The tectonic impact of glaciations due to loading and un-loading of thick ice sheets can be crushing of rocks just beneath the ice, or formation of horizontal fractures. Faults generated from thrust-faulting due to compression during previous glaciations have been observed to extend into the ECZ. These glaciotectonic complexes are observed locally in Denmark within the upper 200-300 meters sections below terrain. The associated faults may thus extend into the ECZ but are not expected to form deep faults cutting into a host rock at 500 meters depth.

4.2.2 Erosion

The potential for deep surface erosion related to tectonic uplift or glacial valley incision which could compromise the barrier effect of the host rock and the ECZ or, in the worst case, lead to exposure of the repository is evaluated. The Danish land area is not subject to major tectonic uplift during the coming millions of years due to the current tectonic framework, and thus major surface erosion is not expected. The geological record, however, shows that glacial erosion can extend to several hundred meters below surface. Glaciers and river courses tend to occur predominantly in pre-existing lows in the landscape, often controlled by the presence of lithologic weak zones. Thus, areas with a gentle topography and without deeply incised, buried valleys are preferred to reduce the risk of future deep glacial or fluvio-glacial erosion.

A favourable situation is where the barrier functions of the host rock at depths around 500 meters is highly unlikely to be compromised, or in a situation where deep erosion might occur only at a late stage of disposal, when radiation from the waste has significantly decreased: Favourable conditions are where:

- Areas without buried, deep sand filled valleys
- The surface topography has a gentle relief, without deep valleys

In Denmark deep valleys formed from glacial erosion have locally incised as deep as 300-400 meters below terrain and are referred to as buried valleys. They have often formed along pre-existing weak zones as for example fault zones, existing valleys or buried valleys. Such valleys can be mapped from shallow seismic and SkyTEM data combined with borehole data.

4.2.3 Repository induced influences

Physical and chemical processes occurring within the repository may affect the host rock properties and thus the barrier effectiveness. The waste is expected to produce some biogenic gas over time (CH_4 and CO_2) from decomposition of organic matter as well as H_2 from anaerobic corrosion of iron and aluminum (at high pH). H_2 and CO_2 may form biogenic CH_4. Calcite may reduce the effect of generated CO_2 and is thus considered a favorable property. The influence of gas generated from the waste should be investigated in future site-specific studies addressing the potential impact on the host rock (pressure increase, pH changes of formation water, bacterial activity and other). Micro-fracturing may be generated in the host rock due to processes such as gas transport, pressure increase, compaction, and chemical interaction between the engineered barriers, the waste and the ground water.

Host rocks are considered favourable when potential repository induced processes do not lead to a significant reduction in their barrier function. Rocks having the ability to self-heal fissures and fractures are favourable. The Danish waste does not generate heat and therefore potential temperature effects on the host rock are not considered.

The host rock barrier effectiveness should not be significantly influenced by chemical interaction between the waste and the repository. Swelling clays in the host rock and ECZ may allow for self-healing in the case fractures are generated. A favourable situation is where

- Smectite and/or montmorillonite is present in the host rock
- Smectite and/or montmorillonite is present in the ECZ
- Calcite is present in the host rock

The potential impact on the host rock is addressed only conceptually at the present stage. In the next project phase with geological site investigations these issues will be investigated in further detail when information is available at present regarding the repository design. Critical issues should be identified, addressed, and mitigated by the design of engineered barriers including the material used for the waste containers and backfill material, where possible.

Table 4.3. *Summary of the criteria for long-term natural stability.*

Tabel 4.3. *Oversigt over kriterier for den naturlige stabilitet på lang sigt.*

2. Long-term natural stability		
	Criteria	Comments
2.1 Stability of the site and rock properties	Registered earthquake activity indicates low risk of re-activation of deep-seated faults extending from host rock to surface are absent.	Re-activation of deep-seated faults due to seismicity may create high-perm zones and thus flow fairways compromising barrier effectiveness. Based on detailed seismic mapping sites above deep-seated faults extending to the surface will be avoided.
2.2 Erosion	A favourable situation is where deep glacial incision such as buried valleys is absent in the area and the surface topography has a gentle relief without deep valleys.	In Denmark deep valleys formed from glacial erosion are locally incises as deep as 300-400 m below terrain and often located along pre-existing weakness zones. To reduce the risk of future deep glacial incision sites with deeply incised buried and open valleys are avoided. Due to the very gentle, low relief surface topography of the Danish area other processes capable of significant deep erosion are not expected.
2.3 Repository induced influences	A favourable situation is where swelling clays are present in the host rock and the overburden ECZ rocks which may allow self-healing of micro-fractures, if microfractures are generated. Presence of calcite will neutralize the potential effect of CO2 in the ground water.	The waste will not generate heat, but it is expected to produce some gas over time (CH_4, CO_2 and H_2). The influence of gas generated from the waste should be investigated in future site-specific studies addressing the potential impact on the host rock and the engineered barriers (pressure increase, pH changes of formation water). Any issues should be mitigated by the engineered barriers and backfill material. The presence of clays promoting self-healing in the repository and ECZ rocks may mitigate the potential formation of microfractures generated due to e.g. compaction in the repository.

4.3 Geotechnical feasibility

In the Danish subsurface engineered constructions at depths of 500 meters below the surface exist presently only as drill holes made mainly for hydrocarbon exploration, for drilling related to exploration and utilisation of geothermal energy, and for gas storage. Thus, very limited geotechnical data and experience exist from engineering in the geological formations of chalk, marl, and mudstones at 500 meters depth and in the overlying formations, and the criteria can only be addressed very preliminarily at this phase of the project. In crystalline basement experience exist from e.g. Sweden, Finland, and Switzerland and experience from sedimentary rocks exist from studies performed by Nagra (Switzerland), ANDRA (France), SUARO (Czech Republic) and NWMO (Canada) amongst others. In the Danish subsurface significant experience exist from drilling of tunnels in the shallower part of the Chalk for the Copenhagen metro, and other tunnels.

A summary of the properties related to each criterium is presented in Table 4.1 and explained in detail in this chapter. A detailed summary of the geological properties is presented in Table 4.4 at the end of this chapter. The information needed to fill in data gaps will be further detailed in cooperation with geotechnical experts to ensure this will be acquired during the project's next phase of detailed site investigations.

4.3.1 Rock mechanical properties and conditions

To ensure safe and feasible construction, operation, monitoring and closure of a geological repository, competent, homogeneous, and isotropic rock formations are required. Parameters to be evaluated include rock strength, deformation behaviour, rock stresses, stability of voids and self-healing potential. This applies to both the host rock and layers in the ECZ. Most of these parameters cannot be evaluated at the present stage due to lack of data and experience from engineered constructions in the Danish subsurface, and due to the current absence of a design concept for disposal of the radioactive waste. Some general assumptions can be made based on the geological conditions expected to influence the rock mechanical properties. The criteria are made based on the assumption that the geological properties should enable the establishment of a deep repository comprising the entre volume of the Danish radioactive waste. In case a geotechnically simpler borehole solution is chosen for the long-lived part of the waste the requirements for competent, and low permeable rocks and sediments without high permeable zones in the overburden may be less important and should be revisited. The risk significant waterflow into the repository during construction and operation is less important as it can be managed more easily in a borehole.

A favourable situation is where isotropic (geo-mechanical) stress conditions prevail which is more likely to occur in areas characterized by tectonically undisturbed bedding compared to areas with steeply dipping sections close to major structural elements. Areas with deformable formations such as salt diapirs are avoided to reduce risk of future deformation in the host rock as well as deformation and fracturing of formations in the ECZ. Formations in the host rock and the ECZ should be competent for engineering both during the construction phase and during the operation and closing phases. Such conditions may be promoted by the presence of a lithologic homogeneous host rock with a consistent thickness and without major faults and fractures off-setting the formations. Thick formations of unconsolidated sand or crushed carbonate may be a risk due to very low geotechnical competence. A potential for self-healing of formation damage induced during excavation is favourable, this can be promoted by the presence of smectite/montmorillonite and sometimes calcite. Presence of thick sections with very high amounts of swelling clays may be a challenge for drilling and underground constructions and it will be indicated if there is a risk of swelling clays that must be mitigated.

Geological properties and conditions that may influence technical feasibility and subsurface stability are assessed only very preliminarily at this point due to lack of subsurface data. Also, the repository design may influence which issues are most important and which properties are more (or less) favourable. Important parameters such as rock strength, deformation behaviour, rock stress and stability of voids are not considered further at this stage. This information is lacking from all parts of Denmark and is therefore used for comparison of the suitability of properties in different areas.
Assumed general favourable situations are where:

- Layering of the geological formations is horizontal or near horizontal
- Host rock comprises smectite and/or montmorillonite, or evidence for calcite precipitation in locally generated fractures
- The ECZ comprises smectite and/or montmorillonite, or evidence for calcite precipitation in locally generated fractures
- The ECZ is without thick sections of unconsolidated sand or fractured carbonates
- The host rock is without thick section of unconsolidated sand or fractured rock
- The ECZ is without thick units of swelling clay

4.3.2 Underground access and water drainage

The conditions for safe access to disposal shafts, tunnels and caverns are considered with regards to the engineering and hydrogeological conditions for constructing and maintaining the access tunnels/shafts to the disposal tunnels and caverns during operation until the repository is sealed off. Presence of high permeable, water bearing layers or zones in the ECZ may cause significant water flow into the construction which may compromise safety and engineering feasibility.

A favourable situation is when the ECZ comprises mainly low permeable formations without thick, high porosity intervals capable of flowing significant amounts of water. Isotropic stress conditions exist which are likely to occur in areas of flat lying formations (steeply dipping beds or major faults are absent). The rocks should be competent for engineering both during the construction phase and during the operations and closing phases. It is assumed that consolidated sediments from the Mesozoic formations are more stable than unconsolidated sediments which constitute most of the Cenozoic section.

Areas with risk of inflow of significant amounts of water during construction and operation of the repository from the ECZ should be avoided meaning that favourable situations are:

- The ECZ does not contain thick, and laterally extensive high-permeable, water-bearing layers such as sand or fractured zones

- Large open fractures and large faults/fault zones with fault planes extending from 500 meters depth to surface are absent

During the site investigations it should be investigated whether leakage of radon or other toxic gasses occur from the geological formations such that any issues can be mitigated during the eventual construction phase.

***Table 4.4**. Summary of the criteria for geotechnical feasibility.*

***Tabel 4.4.** Oversigt over kriterier relateret til geotekniske forhold.*

3. Geotechnical feasibility		
	Criteria	Comments
3.1 Rock mechanical properties and conditions	Areas of horizontal to low angle dipping beds in the host rock and in the ECZ are favourable as low stress conditions are expected. Lithologies with clay minerals promoting self-healing of microfractures potentially generated during excavation are favourable. ECZ should be without thick sections of unconsolidated sand or other rock types with low competence. Deformable formations such as salt diapirs are absent. Sections with high amounts of swelling clays are absent.	Self-healing potential and rock stress can at this stage be inferred preliminarily based on general geological considerations only. Properties such as rock strength, deformation behaviour, rock stresses, stability of voids, natural gas transport (e.g. radon) are not evaluated at this stage assessed only very preliminarily due to lack of data. Rock mechanical data from chalk, marl and claystone formations at 500 m depth, and the overlying sections is very sparse and exist only from deep boreholes. No experience exists from construction at these depths in the Danish subsurface. Sections with high amounts of swelling clays may be a challenge to underground construction.
3.2 Underground access and drainage	The EZC should be without thick water-bearing, high-permeable layers, large open fractures, and large faults/fault zones to limit the risk of significant flow of water into the repository during construction.	Sand filled, Quaternary glacial valleys occur locally as shallow features with limited width (few hundred meters), but sometimes to significant depths. Highly fractured zones often occur in the uppermost part of the chalk section. At deeper levels high porosity sand layers may occur in the U. Jurassic – L. Cretaceous sections and areas with thick sand units should be avoided to reduce significant water flow during construction and operation of the repository.

4.4 Possibility to acquire new, reliable geological data

The criteria on possibilities for acquisition of new geological data that will increase confidence and reduce uncertainties are related to the next phase of detailed geological site investigations. They address the expected ability to acquire data that will enable detailed and reliable geological characterisation of the site. This ability depends both on the nature of the surface and subsurface geology as well as available measuring tools and analysis methods. A summary of the properties related to each criterium is presented in Table 4.1 and explained in detail in this chapter. A detailed summary is presented in Table 4.5 at the end of this chapter.

4.4.1 Ability of rock characterisation

The possibilities for determining the safety-relevant properties with high reliability such as homogeneity/heterogeneity of rock composition, property variability, characterising and mapping the host rock and ECZ properties are evaluated. It is considered whether the necessary data and information of sufficient quality can be obtained to provide sufficient reliability with regards to predicting the geological barriers effectiveness at the site.

The site investigations will include data acquisition in deep drill holes (well logs and cores) combined with non-destructive geophysical surface investigations. It is important that the subsurface layer architecture and rock distribution is such that data acquired from drill holes can be regarded as representative for the entire site.

A preferred situation is when well established data acquisition methods exist to provide detailed and high confidence data from the geological site studies enabling detailed mapping and characterisation of the host rock and formations in the ECZ. Geological formations should be laterally homogeneous to ensure that the data acquired from drilling will be representative for the entire study area. Favourable situations are where:

- The host rock formation is laterally continuous with constant thickness
- The ECZ formation(s) is laterally continuous with constant thickness
- Data from coring and logging in new boreholes is expected to provide detailed and high-quality data on homogeneity and variability of properties the host rock
- Data from coring and logging in new boreholes is expected to provide detailed and high-quality data on homogeneity and variability of properties the ECZ and overlying sections

4.4.2 Explorability of subsurface layers and discontinuities

The acquisition of new data should enable detailed mapping of depth to lithological boundaries, layer thickness, location of fault zones, small scale faults and off-sets which is all important to evaluate barrier functions and geotechnical feasibility. Detailed mapping of the subsurface formations depends on the presence of high resolution seismic and/or other geophysical data and well data. The acquisition of such data depends on the presence of layers with contrasting physical properties forming well defined and mappable boundaries. Surface accessibility for the geological investigations, such as topography, paved roads, ground water level, and forests, also impact data quality and the suitability depends on the actual geophysical methods applied. The surface conditions may also influence the geophysical data quality which should be considered.

The situation is favourable when the bedding conditions and the geometry of the host rock and the ECZ are simple and easy to explore from the earth's surface (using geophysical methods as for example reflection seismic in a dense grid) and when the observations and investigation of safety-relevant properties can be interpolated and extrapolated with confidence in all directions (3D). The area should be without steep dipping topography to ensure accessibility and without deep sand filled Quaternary valleys or sand dunes to enable data of high quality.

Tie(s) to existing or planned new wells with high quality / high resolution data is a prerequisite for the interpretation of, and mapping based on new seismic data.
In crystalline rocks the relationship between fracture density at surface and subsurface depths around 500 meters should be investigated and methods for subsurface mapping and prediction of fractures should be evaluated/addressed. Favourable situations are where:

- Lithological contrasts in the subsurface layers enable confident, high-resolution mapping of layer boundaries, architecture and faults based on seismic data and/or other geophysical methods.
- Surface access, topography and depth to free water level is suitable for acquisition of high-resolution geophysical data

4.4.3 Predictability of long-term changes

The effectiveness of the barriers formed by the host rock and the ECZ should be predictable with sufficient reliability over the necessary time-period assumed to be in the order of 10,000 - >100,000 years (depending on the waste inventory, the repository design and the engineered barriers which is not yet specified). The predictability of possible long-term changes includes the occurrence of future glaciations, salt movement and seismicity, which could compromise the barriers and thus containment capacity of the host rock and the ECZ.

A large amount of data and studies provide comprehensive knowledge about previous glaciations demonstrating that several glaciations have covered the entire Danish area. Data show that future glaciations may occur in all parts of Denmark and may impact the surface as well as subsurface layers. The impact in specific areas is a combined result of the subsurface geology and the natural processes related to advance and retreat of an ice sheet. Potential glacial induced changes include fracturing due to loading and unloading of thick ice sheets, thrust faulting, fluvio-glacial erosion, and groundwater salinity and oxidation state. Based on these studies, glaciation is expected to occur in Denmark in the future, but new data will not enable prediction of the areal extent of future ice sheets. Thus, the impact of the surface and subsurface formations should be considered in all parts of Denmark, where the potential impact will be governed by the rock types and tectonic framework in the specific area.

Table 4.5. *Summary of the criteria related to the reliability of geological findings and data confidence.*

Tabel 4.5. *Oversigt over kriterier relateret til pålideligheden af nye geologiske data.*

4. Reliability of new geological data		
	Criteria	Comments
4.1 Ability of rock characterisation	Lithological units in host rock and ECZ have uniform thicknesses within the area. High quality data can be acquired from coring and logging to provide representative data on lateral and vertical homogeneity and variability of properties in host rock and the ECZ	The host rock and ECZ formations should be without major lateral facies changes over short distances, to enable representative well data to be acquired at margins of the site. A combination of well logs and cores should enable detailed characterisation of rock properties.
4.2 Explorability of subsurface layers and discontinuities	Lithological contrasts in the subsurface layers is sufficiently high to enable confident mapping of lithological boundaries and discontinuities such as faults. Surface access, topography and physical/acoustic properties of the soil is suitable for acquisition of geophysical data of high quality.	Tie(s) to wells with high quality data is required. Acquisition of high-quality seismic data depends on e.g. a gentle topography of the land surface, short distance to the (groundwater) saturated zone, absence of deep sand filled buried valleys, physical accessibility to the area, and other local issues. In crystalline rocks relationship between fracture density at surface and subsurface (500 m) are investigated from literature as well as methods for subsurface mapping and prediction of fractures.
4.3 Predictability of long-term changes	Deep-seated faults extending to surface and large salt diapirs can be mapped from seismic data. New geophysical and geological data will enable identification and mapping of buried sand filled, deep Quaternary valleys.	Faults extending to near-terrain positions may be reactivated and could thereby create a flow fairway from the repository to ground surface. Salt diapirs in the subsurface may move on short and long-term scales, if influenced by significant loading / unloading of ice sheets, or erosion and dissolution of salt. Pre-existing deep valleys may be re-used and further eroded during future glaciations, and should be avoided

Major fault-zones occurring in areas where seismicity has been registered or where data suggest that future tectonic activity or salt intrusion may occur represents a risk of compromising the barriers. Faults mapped into the Cenozoic sections and/or to near-surface positions may still be active. Host rocks with independent evidence of long-term quiescence and isolation (i.e. containment of old porewater) or the presence / distribution of natural tracers, which indicate low water circulation may indicate previous long-term stability and can be investigated in Phase 2. Favourable situations are:

- New seismic and geophysical data will allow for identification and mapping of major active faults, fault zones and large salt diapirs if present
- Long-term quiescence and isolation of ground water in host rock and ECZ can be investigated from groundwater samples

5. Area evaluation based on defined criteria

An evaluation of how well the criteria are fulfilled will be made for each area defined in Step 1 (Figure 3.3) based on existing knowledge about the geological properties and conditions. The evaluation addresses the general, predominant geological conditions in each area, and it is acknowledged that local variations occur which cannot be detailed in the current high-level regional characterisation and evaluation of Danish subsurface. If a criterium is scored suitable this means that the associated properties are expected to be favourable in most of the specific area. Likewise, if a property is scored potentially suitable or less suitable this indicates that most of the area is characterized by this suitability, but different properties may occur locally.

Each criterium is evaluated and scored on a scale with three levels (green, yellow, and orange, Figure 5.1). The suitability of the properties associated with each criterium is scored qualitatively based on the available data and information. The scale distinguishes between suitable, potentially suitable, and less suitable. The scoring is a combined measure of the suitability of the properties and the current level of confidence determined by the amount and quality of available data.

Properties and conditions related to the host are given more emphasis than the ECZ in the evaluation, since the requirements for the geological siting project are all related to host rock properties. The statements are scored with respect to whether favourable conditions are supported by data and therefore with reasonable certainty can be expected to be widespread in the area. In other words, this means that many options for investigation sites can be identified where the properties are favourable.

A green score of a criterium indicates that most of the related properties are favourable. For a criterium to score in the “suitable” green area reliable data that are representative for the area is available. Thus, a green score indicates that high-quality data exist which leads to relatively high certainty in the property evaluation. Also, it indicates that acquisition of new data is expected to support the presence of favourable properties and that the risk of encountering different, unfavourable properties is small.

A yellow score of a criterium indicates that some properties are expected to be favourable based on limited, unrepresentative, or uncertain data, or from analogues and geological models. Thus, a yellow score indicates the available data is of limited confidence leading to less certainty. This implies that acquisition of new data is expected to support the presence of favourable properties and conditions, but comes with a risk of encountering different, less favourable properties. Thus, a yellow score indicates it is expected that acquisition of data from the area will demonstrate the presence of favourable properties but there is a risk that the properties are less favourable than expected.

In contrast the orange colour indicates that the properties related to the specific criterium are generally evaluated as being less suitable. For a criterium to score in the orange “less suitable” field the existing data on the properties should be representative and of sufficiently good quality to provide reasonable reliability and certainty, to allow for this score. An orange score of a certain criterium does not mean that the entire area must be disregarded for disposal as the suitability also depends on the deep disposal design concept which is unknown at present. It will for some criteria mean that the less suitable properties or conditions must be compensated either by engineered or by high suitability of other criteria. For some of the criteria an orange score means that the identification of a specific site for detailed investigations may require additional seismic or other data. Additionally, the geological site investigations required to characterize the related parameters and conditions may be very comprehensive and time consuming due to high subsurface complexity. Finally, there will be a significant risk that favourable properties and conditions cannot be identified or proved from the geological site investigations.

Score	Data support
Suitable	Reliable data show predominantly favourable properties
Potentially suitable	Data and / or analogues indicate that favourable properties are expected to be present, however with some uncertainty
Less suitable	Reliable data show that geological properties and conditions generally do not fulfil the criteria.

Figure 5.1*. The diagram shows how the scoring of criteria and the related properties is carried out qualitatively reflecting both the suitability of the properties and the reliability of existing data.*

Figur 5.1*. Diagram der viser hvordan kriterierne bliver evalueret kvalitativt afhængig af de relaterede geologiske egenskaber og pålideligheden af det eksisterende datagrundlag.*

The criteria evaluation provides a simple tool to characterize the suitability, the existing data base and certainty level of information from each area (Figure 5.2). A less suitable score of one or several criteria in an area does not indicate the area is disregarded for disposal as it is the combined effect of the geological and engineered barriers that determines whether a site is suitable. This can only be determined once the detailed geological site investigations have been made and when the repository design concept has been decided. The suitability indicated from the assessment in the current phase may change if more data become available (to increase confidence), if potential consequences can be mitigated through engineering, or if the issue can be handled in other ways.

The scoring of how well criteria are fulfilled in each area is accompanied by a summary presentation of the existing data used for the evaluation of properties related to the specific criterium. The data quality and the relevance for the specific area is addressed. For most criteria, several properties together contribute to provide a favourable situation, and the scoring is based on a preliminary qualitative assessment of the combined properties, or the most critical property. Focus of this project is the identification of a suitable host rock, thus properties related to the host rock requirements and criteria will be weighted higher than properties related to the ECZ in case their suitability are different.

The area characterisations and evaluations will contribute to DD's identification of the preferred geological disposal concept, which may depend on the local geological properties and the conditions for long term natural stability.

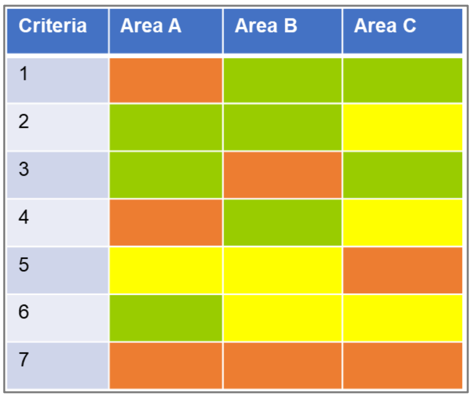

***Figure 5.2**. The diagram illustrates how the score of criteria in different areas can be compared.*

***Figur 5.2.** Diagram der viser, hvordan vurderingen af de geologiske egenskaber og pålideligheden af de eksisterende data kan sammenlignes for forskellige områder.*

Emphasis will be made to carry out a consistent evaluation of properties and the data quality for each area to enable a reasonable and transparent overview of pros and cons for the areas as well as a description of the overall level of information certainty. Thus, the evaluation will provide an initial assessment of the criteria and identification of data maturity for each area. In addition, and very importantly, the evaluation will identify data gaps and knowledge that needs to be filled in during the geological site investigations in next phase of the project.

6. Summary

The present report describes geological requirements and criteria to be used for an initial evaluation of whether rock properties and subsurface conditions are favourable for deep geological disposal of radioactive waste. It further describes the evaluation process which also serves as a systematic approach to identify data gaps that need to be filled in during the detailed geological site investigations in the project's next phase.

In a deep geological repository, the radioactive waste is surrounded by two engineered barriers, the waste containers and a backfill material filling in the space between the containers. The surrounding geological formation, referred to as the host rock, provides the third passive barrier which is capable to retain radionuclides in the subsurface formations. The requirements given in B90 (Danish Parliament, 2018) state that the host rock should be a tight, low permeable formation occurring laterally widespread at depths around 500 meters, with a thickness of 100 meters or more.

The geological setting and the subsurface formations must provide safety and stability on both a short-term and a long-term timescale. Of major importance is the presence of effective geological barriers formed by a low permeable, homogeneous host rock and additional barriers in the overlying formations in the effective containment zone (ECZ). Geological properties and natural processes that may compromise the barriers' effectiveness are identified to avoid such geological settings.

To enable a geological characterisation and evaluation of the Danish subsurface, a subdivision into areas characterized by similar rock types occurring at depths to 500 meters will be made prior to the evaluation. The area subdivision will be made based on the results of the desk studies, including seismic interpretation and mapping and presented in Report no. 9.

Geological criteria and sub-criteria have been defined based on experiences and recommendations from similar international siting projects. The defined criteria relate to host rock and ECZ properties, long-term natural stability of the area, geotechnical feasibility, and reliability of geological data. The safety relevance of each criterium is explained, and for each criterium favourable geological properties and conditions are defined based on current knowledge about deep geological disposal.

In each area an evaluation of to what extent the requirements are fulfilled will be carried out based on the defined criteria. At present, geological data from the depth interval 100-500 meters is for some criteria sparse since this depth interval has not previously been of major interest for acquisition of data and analysis of properties. Based on the geological characterisation and evaluation, two specific sites must be selected and agreed between the Ministry of Higher Education and Studies (MHES) and the local municipalities, for carrying out detailed geological investigations during the second phase of the geological project.

From the criteria evaluation process data gaps and fields of limited knowledge will be identified and the program for data acquisition and analysis in the project's second phase will be targeted to fill in the data gaps.

A qualitative scoring system with three levels (green, yellow & orange) has been defined in the present report and will be used for the initial evaluation of how well the criteria are fulfilled in each area. A green score of a certain criterium indicates that the area is characterized by having generally favourable properties, where less favourable properties may occur only locally. A yellow score of a criterium indicates that the properties are considered as potentially favourable based on uncertain data or data from analogues, but generally there is some uncertainty to the suitability of the properties. An orange score indicates that generally the properties are less favourable. In some areas where criterium 1.1 regarding the host rock and ECZ properties is scored as less favourable, investigation sites with potentially favourable properties may be identified. However, this will require comprehensive geological investigations and is associated with a considerable risk that the required favourable properties and conditions cannot be identified in the area.

In some cases, an orange score of a criterium does not indicate that the area should be disregarded for potential disposal but rather that the less suitable properties must be compensated for by suitable properties related to other criteria and/ or mitigated by the engineered barriers and the facility design, which is yet unknown.

The defined criteria and the related properties will be used for an evaluation of the suitability of the areas based on the data and knowledge presented in the geological reports generated from the present project (Reports No. 2-8, references listed in Chapter 7.2). The evaluation of the areas will be presented in Report No. 9 (in Danish) and No.10 (in English). It forms the geological basis for selection of the two sites where detailed geological investigations must be carried out in the project's next phase (Phase 2). Further, it also provides input to DD for the identification and development of feasible concepts for deep disposal.

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