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Carbon dioxide and nuclear waste locked up for eternity at depth as a copy from nature

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Abstract. The subsurface provides society with many different geo-resources. In addition to the traditional raw materials of coal, oil, and natural gas or drinking water, underground geology has to be used more in future to accomplish climate and energy policy goals as part of the implementation of the energy transition. The prevailing view in the scientific community is that large amounts of carbon dioxide (CO_2) from the atmosphere and highly radioactive waste must be disposed of safely – kept away from the biosphere, the human habitat, for geological time periods. In that regard, studies on natural processes that extend over thousands of years help to assess the long-term behaviour of deep geological repositories. Experiments cannot be carried out for such a long time period. However, processes similar to those in the Earth's history can be detected at depth. With regard to the long-term safety of CO_2 storage and nuclear waste disposal, observations in nature can therefore support the evaluation of experiments and theoretical calculations via so-called analogues and hence provide a comprehensive and reliable picture of the situation and allow prognosis on the long-term. Drawing inspiration from nature and applying rigorous scientific investigation ensure that the legacy of industrial emissions and nuclear waste does not compromise the future of our environment and society. From a purely scientific point of view, CO_2 storage and final disposal of highly radioactive waste are feasible.

1 Introduction

Karl Popper (1902–1994), a philosopher who worked on the theories of knowledge and science, stated in regard to our attitude towards the future: "We are responsible now for what happens in the future." This is certainly true taking into account chances and risks of Carbon Capture and Storage (CCS), as well as the disposal of high-level radioactive waste (HLW). This statement is in the context of his conviction that we actively influence the future through our knowledge and our decisions – and therefore also bear responsibility for it.

Recently, a broad discussion is going on about the diverse utilisation of the subsurface. In addition to the traditional raw materials of coal, oil, and natural gas or drinking water, the geological formations at depth will also be increasingly used in future to realise climate and energy policy goals. For example, storage reservoirs for carbon dioxide (CO_2) are needed, and deep geological formations are also considered the safest place for the final disposal of HLW. However, the question arises: Is it possible to safely store CO_2 or dispose HLW without endangering people and the environment?

"As a copy from nature" as given in the title refers to the scientific field of bionics. This term is a combination of the words biology and technology and describes a field that is not only about new or improved devices, but also about processes such as traffic control, climate adaptation, and much more. The example of nature is inexhaustible. Below, it will be shown in the manuscript where we can learn from nature in regard to CCS and the final disposal of HLW.

"Locked up for eternity" is mentioned in the title as well. Now the question arises, what does that mean? In a nutshell: eternity means long, and that means long enough. But what is long enough for various technologies? Everyone knows how long 1 year is, how long 10 years are and how long a human life lasts. But how much is 1000 years or 10 000 years? How much is even 1 000 000 years? As will be seen in the following, the order of 10 000 years is relevant for CO_2 storage and 1 000 000 years need to be taken into account for nuclear waste disposal. When it comes to geological contexts, we often talk about unimaginably large numbers. Earth scientists have to think in unusual time dimensions. But what seems like an eternity to the individual is a brief moment for the Earth. Such numbers can only be visualised by comparison. As a rule, many processes in the subsurface take place very slowly – usually over many millions of years or even longer.

The deep subsurface is as a strategic domain for the sustainable management of environmental challenges. Two of the most prominent subsurface applications are the geological storage of CO_2 as part of CCS and the disposal of HLW. Both technologies aim to isolate potentially hazardous materials over extended timeframes. These timescales necessitate an understanding of geological processes that extend beyond direct human observation and require the use of natural analogues to validate conceptual and numerical models. Natural analogues – in this case geological systems that have retained similar substances over millions of years – offer empirical evidence of the long-term behaviour of CO_2 and radionuclides in the subsurface. These analogues provide critical insights into the mechanisms of trapping, migration, and immobilisation of substances in geological formations. By studying natural systems, scientists can assess the long-term performance of engineered storage solutions and reduce uncertainties in safety assessments.

"Natural analogues" are occurrences of materials or processes that are equivalent to expected materials or processes in a waste repository. They are used to confirm the ability of the geologic environment and engineered system to contain the waste. "It is hoped that natural analogues can provide data and insight on processes which generally occur on temporal or geometric scales which are too large to be studied in laboratory or field experiments" (Amter, 1989).

This paper outlines the role of natural analogues in evaluating the safety of CCS and disposal of HLW and gives answers to the question if those technologies are feasible. Mechanisms of containment are discussed, key natural and experimental analogues are presented, and the importance of interdisciplinary research in ensuring long-term environmental protection highlighted (Kühn et al., 2024).

2 CO_2 storage: trapping mechanisms, field observations, and natural analogues

Carbon dioxide (CO_2) is a major greenhouse gas responsible for anthropogenic climate change. The Intergovernmental Panel on Climate Change (IPCC) identifies Carbon Capture and Storage (CCS) as a necessary technology for achieving global climate goals (IPCC, 2005, 2023). CCS involves the capture of CO_2 from industrial sources, its transportation, and subsequently injection into deep geological formations for long-term storage.

CO_2 can be stored most effectively in the pore space of rocks at a depth of at least 800 m. Due to the increasing pressure, CO_2 transforms into a denser, more compact aggregate state at this depth, which has a much smaller volume than the original gas. This saves space and the available space lasts much longer, for much more CO_2 (IPCC, 2005). The greenhouse effect redistributes the radiant energy in the atmosphere. The more greenhouse gases the atmosphere contains, the warmer it gets at the Earth's surface and the colder at altitude. Without greenhouse gases and clouds a calculated value of −18 °C would be obtained, instead of a surface temperature of 15 °C assuming today's climate conditions. CO_2 accounts for the largest share of the greenhouse gas effect with more than 60 %, followed by methane at just under 20 %. Water vapour has the strongest effect (two to three times as strong as CO_2), but is not part of the estimate due to the direct feedback with temperature. CO_2 has a very long residence time in the atmosphere, well over 1000 years (IPCC, 2023).

The primary target formations for CO_2 storage are saline aquifers due to their huge worldwide capacity (Table 1). Saline aquifers are underground geological formations, that are saturated with saltwater (brine). These aquifers are not suitable for drinking water or irrigation due to their high salinity These formations must exhibit sufficient porosity and permeability to accommodate large volumes of CO_2, while being overlain by low permeable caprocks to prevent any leakage. The effectiveness of geological storage depends on a combination of physical and geochemical trapping mechanisms. Four trapping mechanisms ensure the long-term containment of CO_2 in the subsurface (IPCC, 2005):

- structural or stratigraphic trapping, with CO_2 accumulating as buoyant plume beneath impermeable caprocks (Streit et al., 2005),
- residual trapping with CO_2 becoming immobilized in the pore space structure as the formation is swept by brine (Bachu et al., 1994),
- solubility trapping with CO_2 dissolving in the formation water, increasing its density and reducing buoyancy (Perkins et al., 2005),
- mineral trapping with CO_2 reacting with rock minerals to form stable carbonates, leading to permanent sequestration (Gunter et al., 1993).

When the CO_2 is injected, it forms a plume around the well, displacing the water laterally and vertically within the formation. Interactions between water and CO_2 allows geochemical trapping mechanisms to take effect. CO_2 forms carbonic acid and this dissolved CO_2 can eventually react with minerals in the reservoir. Breakdown of these minerals could precipitate carbonate minerals that would fix injected CO_2 in its most secure state. The trapping mechanisms progressively increase the safety of CO_2 storage over time, with mineral trapping being the most permanent, secure and therefore favourable (Bradshaw et al., 2007).

Table 1. Storage capacity for several geological storage options compared to > 37 gigatons (Gt) CO_2 emissions in 2023. The storage capacity includes as well storage options that are not economical (IPCC, 2005).

Reservoir formations	Lower estimate ($Gt\,CO_2$)	Upper estimate ($Gt\,CO_2$)
Oil and gas fields	675	900
Unmineable coal seams	3–15	200
Deep saline aquifers	1 000	10 000 (uncertain)

2.1 Natural analogues for CO_2 storage

Interestingly, the underground storage of CO_2 is not a human invention, but actually a widespread natural phenomenon: many natural CO_2 reservoirs have existed for thousands to millions of years. They provide empirical evidence of the long-term stability of geological trapping mechanisms. These reservoirs demonstrate the long-term effectiveness of CCS under natural conditions. The presence of intact caprocks and the absence of leakage in them validate the conceptual models used in engineered systems. The study of such natural analogues has significantly contributed to the development of site selection criteria and safety assessments for CO_2 storage (Jaendel et al., 2010).

Natural accumulations of CO_2 have been studied in the United States, Australia and Europe (Pearce et al., 1996; Allis et al., 2001; Stevens et al., 2003; Watson et al., 2004) as analogues for storage of CO_2. They are found all over the world in a range of geological settings, particularly in sedimentary basins. Natural accumulations occur in a number of different types of sedimentary rocks, principally limestones, dolomites and sandstones and with a variety of seals (mudstone, shale, salt, and anhydrite).

CO_2 fields in the Colorado Plateau and Rocky Mountains, USA, are comparable to conventional natural gas reservoirs (Allis et al., 2001). Studies of the Pisgah Anticline, northeast of the Jackson Dome, is thought to have been generated more than 65 million years ago (Studlick et al., 1990), with no evidence of leakage, providing proof of long-term trapping of CO_2. Extensive studies have been undertaken on small-scale CO_2 accumulations in the Otway Basin in Australia (Watson et al., 2004) and in France, Germany, Hungary and Greece (Pearce et al., 2003). Conversely, some systems, typically spas and volcanic areas, are leaky and not useful analogues for geological storage (Pearce et al., 2003).

2.2 Field-scale experiments and monitoring at the Ketzin pilot site as an example

CO_2 is pumped into porous rocks, which absorb it like a "sponge". Enlarged in thought, this is what a sandstone looks like What cannot be seen is the structure on the very small scale. This can only be done with a microscope to put it into perspective. Sandstones usually contain 10 %–20 % porosity, air or, in the geological subsurface, water. What is needed for a repository, however, is always a combination of rocks with different properties. Any example of a sponge (the sandstone) requires a water-impermeable clay (stone) layer above it. In principle, it can be noted that the storage rocks readily absorb fluids or primarily repel them, as a barrier rock does.

"You don't find out whether something works by thinking about it, but by trying it out." Field-scale pilot projects have demonstrated the feasibility of safe CO_2 injection and storage (Michael et al., 2010). One of the most notable examples is the Ketzin pilot site in Germany. Between 2008 and 2013, approximately 67 000 metric tons of CO_2 were injected into a saline aquifer at a depth of around 650 m. The site was extensively monitored using geophysical, geochemical, and hydrological methods (Liebscher et al., 2012). The conclusion: it was a successful experiment.

Ketzin was equipped with one of the most comprehensive monitoring systems in the world (Fig. 1). The "intelligent" deep boreholes at the pilot site have provided scientific and operational monitoring data. With the help of the permanently installed sensors and measurement systems, it was possible to map the spread and behaviour of CO_2 in the subsurface with high temporal and spatial resolution. A combination of different permanent and periodic monitoring methods was used in Ketzin. These types of boreholes are the window to the reservoirs and enable timely and data-based operational decisions (Möller et al., 2014). The Ketzin project confirmed the absence of leakage and validated the expected migration behaviour of CO_2 in the subsurface. Advanced monitoring technologies, including e.g., seismic imaging, geochemical sensors, and groundwater sampling, were instrumental in verifying the performance of the storage system and improving predictive models (Martens et al., 2012). The project also demonstrated the importance of adaptive management and public engagement in building trust and ensuring the safe deployment of CCS technologies (Szizybalski et al., 2014). After completion, the site was decommissioned and returned to the landowner (Schmidt-Hattenberger et al., 2017).

The technology is ready for industrial application. If we want to do CCS for climate policy reasons, then we just have to do it and we can start immediately. It worked in Ketzin seen from all perspectives. As well with the residents, with the public. We had a lot of dialogue and regular open days, which were always well attended. "Anyone who wants to do CCS can learn how to do it from the GFZ" (https://www.co2ketzin.de/en/home, last access: 11 September 2025).

2.3 Safety and risk considerations

CO_2 is a molecule consisting of the chemical elements carbon and oxygen. In nature, CO_2 occurs as a colourless and odourless gas. It is not explosive and, as a natural component of the air we breathe, is completely harmless. CO_2 is

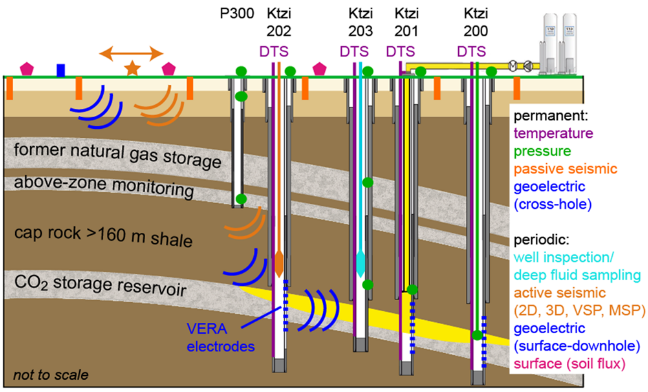

Figure 1. One of the most comprehensive monitoring systems worldwide to prove the feasibility of CO_2 storage at the Ketzin pilot site (Germany). The "intelligent" deep boreholes (P300, Ktzi201, Ktzi202, Ktzi203) provided central scientific and operational monitoring data from permanent and periodic systems including a Distributed Temperature Sensing (DTS), a Vertical Electrical Resistivity Array (VERA) and further geophysical and geochemical measures (Liebscher et al. 2012; © GFZ).

one of the so-called greenhouse gases and used for various purposes in everyday life. As CO_2 it makes drinks fizzy and as dry ice fog it creates show effects. It is also irreplaceable in firefighting: CO_2 is in many extinguishers. Without CO_2 there would be no photosynthesis, so there would be no plant growth, which means that without carbon dioxide there would be no living creatures on Earth.

The safety of CO_2 storage is a primary concern, particularly regarding the potential for leakage into overlying aquifers or the atmosphere (Fig. 2). The risk of leakage is minimized through careful site selection, monitoring, and the application of natural multiple barriers of recurring low permeable caprock formations alternating with permeable reservoir rocks. Natural analogues and field experiments have shown that geological systems can effectively trap CO_2 over long timescales. However, uncertainties remain regarding the long-term behaviour of CO_2 in different geological settings. Risk assessments must account for these uncertainties, using probabilistic modelling and scenario analysis to evaluate the potential consequences of different failure modes (Norden and Frykman, 2013; Kempka et al., 2010, 2014; Class et al., 2015; Lueth et al., 2015).

3 Disposal of highly radioactive waste: geological barriers and natural systems

The geological disposal of HLW is internationally agreed on to be the safest and most sustainable long-term solution (Ewing, 2015; IAEA, 2003; Metz et al., 2012). The concept involves isolating the waste in deep, stable geological formations, where it is enclosed within multiple engineered and natural barriers.

This includes the disposal of solid or solidified and packaged waste of all kinds in a suitable host rock in storage chambers hundreds of metres below the surface. Natural and technical safety barriers shall enclose the waste for the required period of time. The concept is passively safe, as the long-term protection of the environment is ensured without human intervention. In a deep geological repository, the radioactive materials are permanently enclosed by the containers, the tunnel backfill, the repository installations and the adjacent rock (IAEA, 2003).

Spent fuel and vitrified HLW contains highly radioactive isotopes as well as those with long half-lives. The waste is encapsulated in corrosion-resistant containers and placed in tunnels excavated within host rocks such as clay, crystalline rock, or salt. The safety of such repositories is achieved through a multi-barrier system that includes:

- engineered barriers like waste containers, buffer materials (e.g., bentonite clay), and tunnel seals (Bennett and Gens, 2008; Fayek and Brown, 2021),
- natural barriers, the host rock with specific hydrogeological and geochemical properties (Altmann, 2008; Alexander et al., 2015).

3.1 Natural analogues for nuclear waste disposal

The HLW must be kept away from the biosphere, the human habitat and thus the Earth's surface for one million years. Scientists around the world agree that the safest option is to store the waste in rock units in deep geological repositories, where it can decay over thousands of years until it is "harmless". History shows that society is not stable over long periods of time. In contrast, rock layers are stable over millions of years. In the subsurface, time stands still, so to speak.

Natural analogues play a crucial role in validating the safety of HLW repositories by demonstrating how radionuclides behave in geological systems over extended periods. One of the most significant natural analogues are the Oklo natural reactors in Gabon (Bracke et al., 2001; Bros et al., 2003; Bruno et al., 2002). Approximately two billion years ago, natural nuclear fission reactions occurred in uranium-rich deposits in Oklo. These reactions generated significant quantities of fission products that have remained largely immobile within the host uranium ore. Geochemical analyses have shown that less than 10 % of the uranium and fission products have migrated into the surrounding rock, highlighting the natural capacity of geological systems to retain radioactive materials over geological timescales (Gauthier-Lafaye et al., 2004).

Clay rocks surround the natural nuclear reactors. Some of Oklo's 16 reactors are fully utilised, others are largely exhausted. The size of the reactors varies. The largest known reactor is 12 m long, 18 m deep and 20 to 50 cm thick. The smallest reactor is 5 m long, 1 m wide and a few centimetres thick. This smallest reactor is located very close to the

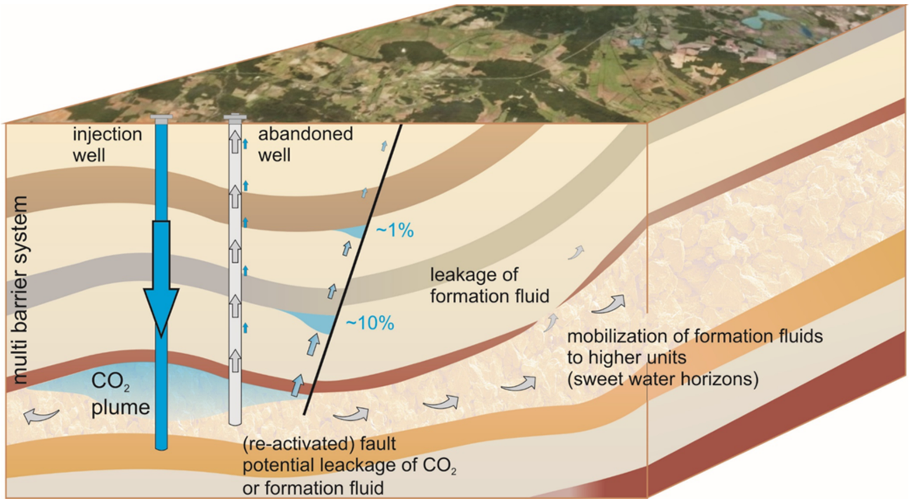

Figure 2. CO_2 storage with potential anthropogenic and natural leakage pathways. These are active wells as well as old wells that have already been shut down. It must be taken into account that the boreholes in the figure are shown in a highly simplified form and only symbolize possible flow paths in general. Leakage paths of natural origin may exist along fractures in the rock. In addition, the process of saltwater displacement that may occur is shown (© GFZ).

earth's surface and is therefore exposed to severe weathering. The actual reactor core consists of 5 to 20 cm thick layers of uraninite embedded in clay (Bracke et al., 2001; Bros et al., 2003; Bruno et al., 2002). The chemical conditions induced by the clay inhibit the radionuclides from moving.

Another important natural analogue is the Cigar Lake uranium deposit in Canada (Fig. 3). Despite the presence of groundwater flow, the uranium ore remains largely confined within a clay-rich host formation, indicating the effectiveness of natural barrier systems in limiting radionuclide migration (Cramer, 1986). The 1.3-billion-year-old uranium ore deposit at Cigar Lake has one of the highest uranium concentrations in the world (on average 12 % uranium oxide, occasionally up to over 60 %). The ore deposit cannot be detected radiologically on the Earth's surface. The radionuclides present are effectively held back by a 10–50 m thick layer of clay so that no increased radioactivity can be measured in boreholes just a few tens of metres away from the ore body. The deposit was discovered by chance based on geophysical measurements and knowledge of other deposits. The uranium ore from Cigar Lake is surrounded by a natural clay halo of varying alteration that retains the radionuclides. This envelope system is comparable to the safety barriers provided in a deep geological repository. It is important to determine the parameters that control the long-term stability of the uranium minerals in these deposits, which are open, water-saturated systems, as opposed to the "closed" system of the repository concept (Smellie et al., 1997).

The safe containment of HLW in a deep geological repository is achieved through a combination of engineered and natural barriers. Each individual barrier has the task of protecting the HLW from interference and preventing the ra-

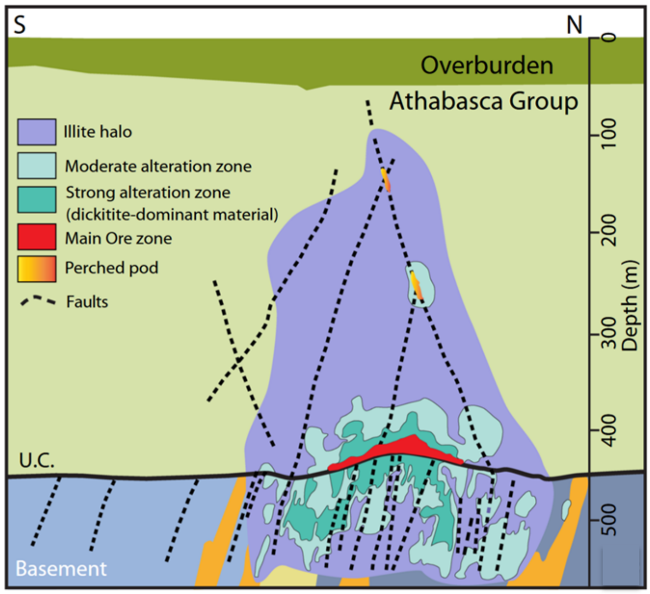

Figure 3. In the Cigar Lake area an uranium ore deposit formed in the sandstones of the Athabasca Group due to hydrothermal processes. It is located at around 400 m depth is 2000 m long, 20 to 100 m wide, and up to 15 m thick. Two types of mineralisation occur: (i) high-grade mineralisation at or proximal to the unconformity (U.C.) including almost all of the mineral resources and reserves (red) and (ii) low-grade, fracture controlled, vein-like mineralisation which are located either higher up in the sandstone ("perched" mineralisation) or in the basement rock mass (yellow). Due to the hydrothermal alteration of the host sandstone, an illite-rich clay layer (the halo) formed (after Eldursi et al., 2021; © Springer Nature).

dioactive substances from leaving the repository for as long as possible. The radionuclides decay over thousands and millions of years to the "harmlessness" of natural radiation and beyond. These analogues reinforce the scientific basis for engineered geological repositories by demonstrating the importance of mineralogy, geochemical conditions, and physical confinement in ensuring long-term containment (Smellie and Karlsson, 1999).

3.2 The Mont Terri underground rock laboratory

Safety assessments for potential nuclear waste repositories can only be carried out using numerical models. However, models are only reliable on the basis of field data. Important data is collected in the underground rock laboratory at Mont Terri (Bossart and Milnes, 2018). Knowledge of the hydrogeological system is required, as the migration of radionuclides is determined by the hydrogeochemical situation (Fig. 4; Hennig and Kühn, 2021a, b, c).

The Mont Terri underground rock laboratory in Switzerland has been a key site for studying the hydrogeological and geochemical behaviour of the Opalinus Clay formation, a potential host rock for HLW repositories. The laboratory provides a controlled environment for conducting experiments that simulate repository conditions and assess the performance of natural and engineered barriers (Bossart and Milnes, 2018).

Studies at Mont Terri have focused on understanding the diffusion and sorption of radionuclides in clay-rich formations, which are key processes in determining their migration potential (Hennig et al., 2020). These studies have provided essential data for safety assessments and the design of engineered buffer systems, such as bentonite seals, which are critical for limiting groundwater flow to and radionuclide transport from the disposal site (Bourg and Tournassat, 2015). The Mont Terri project has also demonstrated the importance of long-term monitoring and data integration in validating conceptual models and improving predictive capabilities. The laboratory continues to serve as a testbed for new technologies and methodologies in geological disposal research (Bossart and Milnes, 2018).

3.3 Safety and risk considerations

Radioactive waste is material that cannot be reused and is always subject to regulatory control. Radioactive waste arises from many useful applications in medicine, industry, and research and is also produced during the dismantling of nuclear facilities that are no longer required (decommissioning). This waste must be treated accordingly and disposed of safely. At the time of removal from the reactor, the radiotoxicity (radiation-induced toxicity when physically ingested) of spent nuclear fuel is 10 000 times greater than that of the uranium ore once mined for it. Three principles apply to protection from external irradiation: shield, maintain distance, and limit exposure times.

Radioactivity is a natural component of the environment. Radioactive substances emit ionising radiation. The biological effect is known as the dose. The radioactivity we are exposed to varies, depending on where we live and what job we do. It comes mainly from soils and rocks. The health effects of radioactive substances are greater when they are absorbed into the body than when their radiation affects the body from the outside. One example is potassium, a vital element that is naturally to 0.012 % radioactive. Ingested radioactive substances decompose inside the body. This can directly damage cells, tissue or organs. How long this radiation exposure lasts depends on the half-life and the biological residence time of the radionuclides in the body. The effect of the radiation depends on the dose absorbed. The body can tolerate a small amount of radioactivity because there are also repair mechanisms.

Site selection and the design of a deep geological repository ensure long-term safety. The highest safety requirements are imposed. In the safety analyses, the possible release of radionuclides occurring in the repository and their potential pathways from the geological repository to the biosphere are quantitatively determined. The calculations are based on the waste inventory and scientifically supported information on the properties of the planned engineered and natural barriers. The investigations also consider various scenarios with unfavourable situations: e.g., increased water movement through the repository area, unfavourable values of diffusion coefficients, increased solubility of radionuclides, increased dissolution rate of emplaced fuel elements, reduced life of disposal containers, reduced retention capacity (sorption) of the engineered barriers and the host rock. However, even under pessimistic, partly hypothetical assumptions regarding the behaviour of the engineered barriers and the host rock the protection criteria are met (NAGRA, 2002).

The long-term safety of HLW disposal depends on the combined performance of engineered and natural barriers. The multi-barrier concept ensures that even if one barrier fails, the others continue to provide protection. Risk assessments use probabilistic modelling and scenario analysis to evaluate the likelihood and consequences of different failure modes.

Perception, acceptance and confidence of the public in HLW disposal is closely linked to transparency, stakeholder engagement, and the use of robust scientific evidence. Natural analogues and field experiments play a crucial role in communicating the safety of geological disposal to the public and addressing concerns about long-term risks.

4 Comparative analysis and scientific implications

While CO_2 and HLW differ significantly in their chemical and physical properties, both technologies rely on sim-

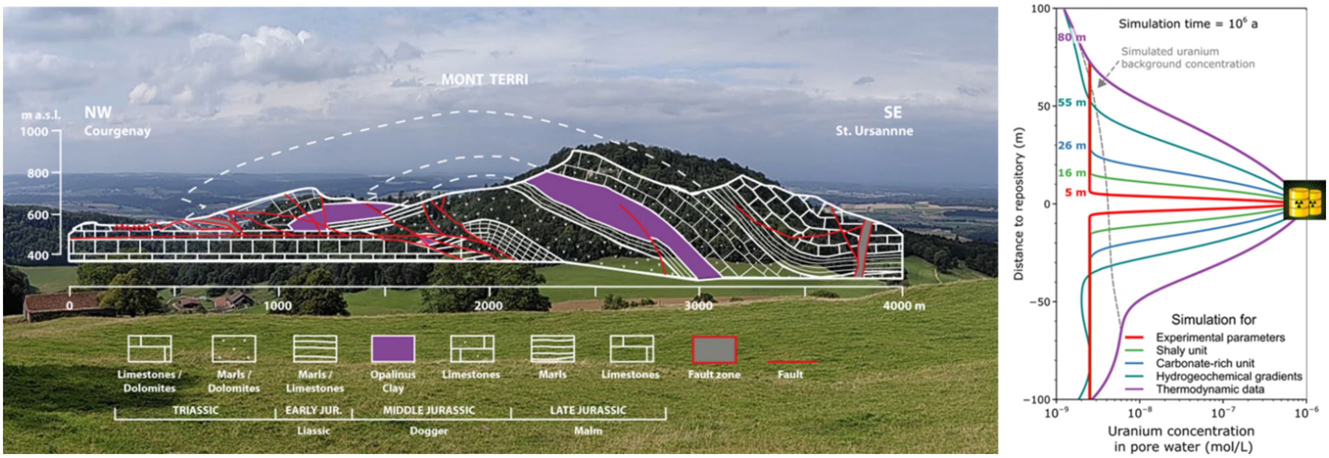

Figure 4. Mont Terri underground rock laboratory as natural analogue of a host rock for nuclear waste disposal (© Theresa Hennig). Knowledge about the hydrogeological system is required because radio nuclide migration is governed by the hydrogeochemical situation. This is prerequisite for safety assessments. The right-hand side figure outlines how in this case uranium migration through the Opalinus Clay depends on applied concepts as well as underlying data and rock types (Hennig and Kühn, 2021a, b, c).

ilar geoscientific principles to ensure long-term safety. Both require a thorough understanding of fluid-rock interactions, mineral dissolution and precipitation reactions, and the transport behaviour of dissolved species in porous and fractured media.

The use of natural analogues in both contexts serves to validate conceptual models and reduce uncertainties in long-term predictions. For example, uranium deposits provide insights into the immobilization of radionuclides, while natural CO_2 reservoirs demonstrate the effectiveness of trapping mechanisms over millions of years.

One key difference lies in the temporal scale of concern. For CO_2 storage, the primary objective is to ensure containment for at least 10 000 years, during which the risk of leakage must be minimized. In contrast, HLW repositories must remain safe for up to one million years, reflecting the long half-lives of many radionuclides. This extended timescale necessitates a more conservative approach to safety assessment, including the consideration of future climatic and tectonic changes that may affect the disposal site performance.

The integration of natural analogues into safety assessments also highlights the importance of interdisciplinary collaboration between geologists, geochemists, and engineers. Numerical modelling, supported by field observations and laboratory experiments, is essential to extrapolate short-term observations to the long-term behaviour of storage systems.

5 Risk, perception, and societal responsibility

Deep geological repositories offer possible solutions for dealing with the CO_2 that we are releasing into the atmosphere in excessive quantities and the radioactive waste that is dangerous for us humans. Every technology involves risks; no action is without risk. Accordingly, not doing things also involves a risk of avoidance. When fears are stirred up, it is not about the risks, but about their perception (Renn, 2014).

The deployment of both CO_2 and HLW storage technologies is inevitably accompanied by risk, which must be carefully managed and communicated. Risk, defined as the product of the probability of an adverse event and its potential consequences, is an inherent component of any technological solution. However, the perception of risk is often influenced by societal and psychological factors that may not align with scientific assessments: "Deep geological repositories of nuclear waste [...] and the substantive storage of carbon dioxide to relieve the world's climate from excessive system change are intricate and contentious policy fields with an impact of decades to hundreds of thousands of years" (Flüeler, 2023).

Natural analogues play a crucial role in addressing public concerns by demonstrating that geological systems have successfully retained similar substances over millions of years. This evidence supports the argument that engineered systems can achieve comparable or superior levels of safety. Nevertheless, transparency, public engagement, and continuous monitoring are essential to build trust and ensure the responsible implementation of these technologies. The ethical dimension of geological storage cannot be overlooked. As noted by philosopher Karl Popper: "[...] we are responsible for the future consequences of our actions". The scientific community has a duty to ensure that these technologies are developed and deployed with the highest standards of safety and integrity, guided by a commitment to intergenerational equity and environmental stewardship (Flüeler, 2023).

6 Conclusions

The long-term storage of CO_2 and HLW in geological formations represents an essential component of global efforts to mitigate climate change and manage nuclear waste. Natural analogues provide valuable insights into the behaviour of these substances in the subsurface, offering empirical validation of theoretical models and engineering designs. I would like to answer my initially posed question if CO_2 and nuclear waste disposal technologies are feasible clearly with "yes". While the specific challenges of each storage solution differ, both benefit from a shared geoscientific framework that emphasizes the importance of geological stability, barrier function, and long-term containment. It is our task as scientists and stewards of the planet to learn from these examples and apply them wisely in shaping a secure and sustainable future. From a purely scientific point of view, CO_2 storage and final disposal of highly radioactive waste are viable.

Data availability. Presented data are published and all given with reference.

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