Natural Analogue Studies: A strategy for bridging the spatial-temporal gap in demonstrating long-term safety

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Summary

This paper provides a synopsis of the CNSC’s developing natural analogues research program.

Introduction

One of the most challenging aspects of long-term nuclear waste management is the extrapolation of laboratory data collected over short periods of time (hours to years) to the longer periods required in safety assessment calculations. Canada’s nuclear regulator is developing a natural analogues research program that includes acquiring quantitative field data from uranium deposits, complemented by experimental and modelling studies. Data collected from the field and from experiments could be used in safety assessment models. The projects align with the status of the implementer’s site selection program, and will provide the regulator with independent experience evaluating key aspects of a potential deep geological repository’s (DGR) safety case.

Natural analogues are natural geological features or processes that are similar to those that are expected to exist in some part of a DGR system. Compared to laboratory experiments, natural analogues provide information over longer time frames and greater spatial scales required for performance assessment calculations (Figure 1), and can therefore be used to verify numerical modelling results.

Figure 1: Comparison of time and spatial scales for laboratory experiments (days to months), anthropogenic analogues (hundreds to thousands of years), and natural analogues (e.g. >1 million years.)
Uranium deposits can provide important information on the performance of radioactive waste forms and DGRs because uraninite – the most abundant uranium-bearing mineral in most uranium deposits – is similar in many ways to the UO₂ in used nuclear fuel (UNF). In this paper, we describe three components of the program focused on gathering data from natural uranium deposit analogues that possess key attributes used to evaluate long-term safety, relevant for a Canadian DGR.

**Radionuclide migration in the near surface**

Field data from a new Canadian natural analogue is being used to investigate radionuclide migration in a near surface environment. The Kiggavik deposits in northern Canada are sediment-hosted uranium deposits that formed ~1.6 Ga. The environment that hosts the Kiggavik deposits serves as a natural laboratory in which to study uraninite oxidation and migration of uranium and other radionuclides over large spatial and temporal scales. These deposits lie within a few hundred meters of the surface, in fractured metasedimentary host rocks. The setting is similar to potential future Canadian conditions, where a DGR initially constructed at a depth of at least 500m was subject to several glacial cycles over 100s of thousands of years. This represents an eroded, fractured, post-glacial geological setting analogous to an end-member assessment scenario.

Investigating uranium ore bodies as an analogue for UNF in this setting will provide information on radionuclide leaching and remobilization over a time period consistent with safety assessments (1 million years), and over a variety of spatial scales to infer migration rates for different radionuclides, including naturally occurring fission and activation products. However, fluid evolution in these deposits is complex (e.g. Shabaga et al. 2017) and there are challenges associated with constraining the timing of different phases of uranium mineral growth and dissolution, further magnified by the fine grain size of uraninite in these deposits. Uraninite is susceptible to alteration and radiation damage (e.g. Janeczek and Ewing, 1995), further magnifying these challenges.
To adequately use the Kiggavik deposits to assess actinide and fission product mobility, it is necessary to carefully characterize mineral paragenesis and constrain the timing of fluid-mineral interaction, particularly within the last 1 million years. This information will be relevant for modelling the long-term behaviour of UNF in DGRs.

Revisiting the Cigar Lake natural analogue

The Cigar Lake uranium deposit is arguably the most famous natural analogue for deep geological disposal, with characteristics representative of multiple aspects of a DGR system: the high-grade ore body is analogous to UNF, the clay halo surrounding the ore body analogous to an engineered barrier system, and the depth of the ore body (~500m) is analogous to that proposed for most DGRs. Cigar Lake can be taken to generally mimic the DGR concept with respect to isolation and containment due to limited radionuclide migration and retention in rock and in clay, while remaining impervious to disruptive geological events, including glaciation. These characteristics led to intensive study of the Cigar Lake analogue from ~1984-1992 by the Canadian and American implementing organizations of the time. Recent analytical and methodological developments, together with the progression of DGR projects globally, provide opportunities to refine earlier studies with new data. Specifically, I-129, the key isotope of concern in DGR performance assessments because of its mobility and existence as a fission product in UNF is being analysed from Cigar Lake core samples to provide information on containment and transport of fission products in a natural analogue that represents an idealized DGR system.

Natural analogue data to develop mathematical models

Using published information on the geometry, timing, geochemistry, and fluid composition as constraints, reactive flow and transport modelling of radionuclides around the Kiggavik and Cigar Lake uranium deposits will be performed. This type of modelling would need the consideration of Thermal-hydraulic-mechanical-chemical processes which are deemed to be important. The results of the modelling will help interpret and assess 1) radionuclide mobility and transport in a post-glacial DGR setting – a worst case scenario (Kiggavik) for containment provided by the geosphere and 2) in-situ radionuclide transport in the Cigar Lake analogue – an idealized scenario.

Conclusion

Ultimately, the CNSC’s natural analogues research will integrate geological, geochemical, and geomechanical data with results of planned laboratory experiments (not described here). Both the Kiggavik and Cigar Lake uranium deposits are geological systems with elements that are similar to elements of DGR safety assessments. Investigating the Kiggavik deposits as a natural analogue will further elucidate the effect of glaciation on a DGR system. Revisiting the Cigar Lake analogue will test the robustness of this analogue as an idealized scenario of the future long-term evolution of a DGR system. Both of these analogues, as well as mathematical models using data from these analogues will contribute to future regulatory reviews of DGR projects.
References

