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A critically reviewed catalogue of NA studies to support the NWS programme of geological disposal

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Introduction & Background

To successfully implement a geological disposal facility (GDF) for radioactive waste in the UK, NWS will produce an environmental safety case (ESC) containing a collection of claims, arguments and evidence (CAE) for which both quantitative and qualitative evidence will be presented which collectively demonstrate that long-term safety can be achieved and maintained.

Natural analogues (NA) can be helpful in demonstrating understanding of aspects of GDF performance by, for example, providing evidence that certain materials can survive for long periods.

As part of NWS' overall knowledge base, ESC-relevant NA information has been collected together in a NA Catalogue (representing an update of the original NA catalogue of Milodowski et al., 2015).

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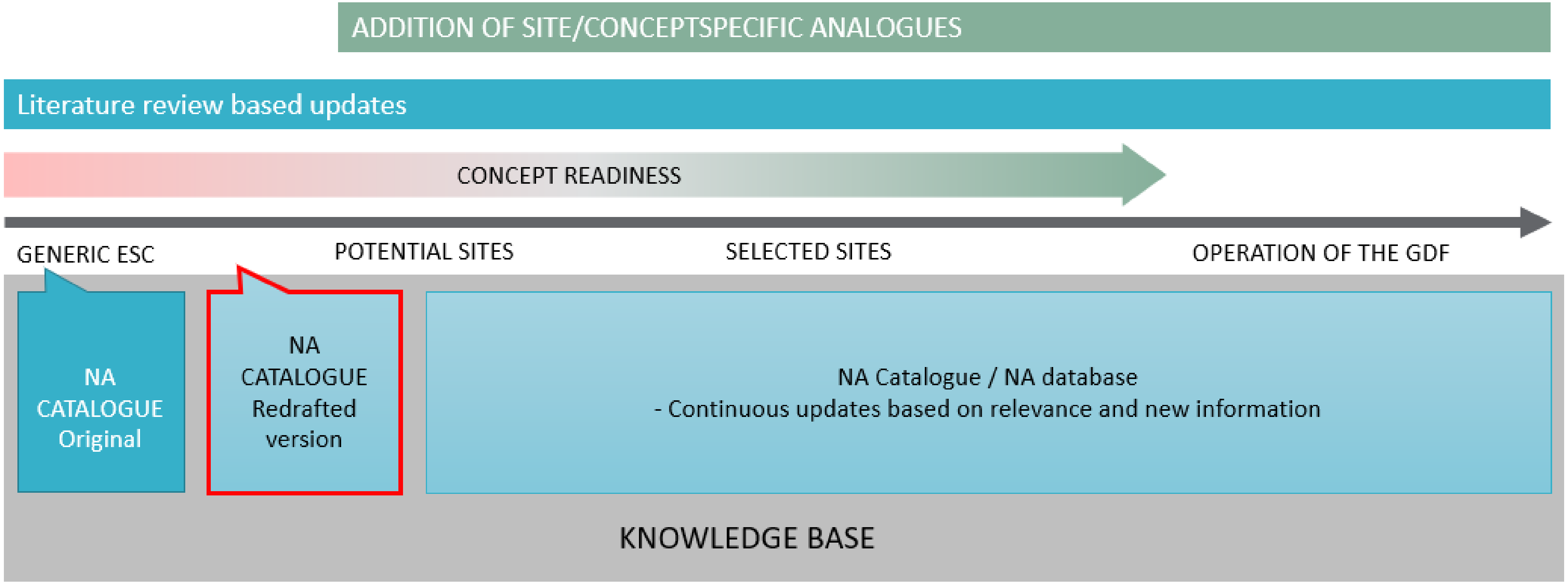
NAs form a part of the knowledge base that will go through iterations throughout the evolving GDF programme from the generic stage to actual operation of the GDF



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Why develop a NA Catalogue?

- **primarily it was to make a clear and direct connection between NA data and the ESC and other repository activities (such as site selection). To date, most NA information has tended to be from the geological, archaeological and industrial literature, so few specialists in the radioactive waste disposal community outside these fields have been aware of the material, never mind the overall approach. So, bringing together the relevant work in one place (the NA Catalogue) was considered as the most efficient way of making the information easily accessible within NWS and to improve use in future ESC**

- **this catalogue (Alexander & Reijonen, 2023) updates the previous iteration (Milodowski et al., 2015) by making a clear shift towards connecting the NA Catalogue directly to the ESC and other repository activities**

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Why develop a NA Catalogue?

- **although numerous other collections of NA information exist, there have been few attempts to make a critical review of the technical relevance of NA information to the ESC**

- **in addition, this catalogue serves as a starting point for the strategic use of NA information in NWS' digital safety case (*see Simon's talk*)**

- **to broaden the reach of the information, there has been a significant effort invested in making the language used in the updated catalogue less 'geoscientific', making it open to a much wider scientific and technical audience (both within NWS and externally)**

Objectives and scope of the updated NA Catalogue

The report notes that "The main objective of the NA Catalogue is to produce examples of analogue systems that can be used to support the ESC for a GDF. Its scope includes all aspects of disposal relevant to the UK programme; a range of waste types and potential repository host rocks are considered."

For each NA example, the following information is provided:

- **An introduction to the topical matter**
- **Component of relevance (e.g. native copper for a copper canister for spent nuclear fuel) for the GDF**
- **Key IFEPs (NEA, 2019) of relevance to act as a starting point for connecting the contents to the standard FEP mapping process in national ESC (see Posiva, 2023, for details of this process)**
- **A summary description of the NA information (including sources of data etc.)**

Objectives and scope of the updated NA Catalogue

- **A summary of limitations on the use of the NA data (e.g. natural uranium does not have the same structure as spent nuclear fuel, so may not dissolve in exactly the same way)**

- **Statements of relevance of the NA study to the GDF ESC, what have we learnt from the system studied?**

- **A comprehensive and structured generic list of features, events and processes relevant to the assessment of the long-term performance safety of a GDF**

NA Catalogue organisation and structure

- a range of NAs has been selected to illustrate different components of a repository system that could be used to support an ESC

- as such, the NA Catalogue should not be seen as an exhaustive list of all known NAs (apart from anything else, the critical review of available data noted above led to the rejection of much material available in other NA data compilations)

- the updated catalogue has been compiled for the current generic stage of NWS' programme and, as such, considers several geological and EBS options

The report chapters provide a review and update of existing NA studies related to:

- radioactive waste forms (e.g. vitrified high-level waste)
- waste containers (e.g. copper, steel, iron, mixed materials)
- cementitious materials (used to immobilise the waste or as tunnel supports etc.)
- clays (e.g. bentonite)
- repository geological barrier (e.g. information assessing the likely very long-term stability of the wider geological barrier around the repository along with the actual repository host rock)

The report chapters provide a review and update of existing NA studies related to:

- post-closure processes affecting the GDF and/or geological barrier (e.g. what impact will climate change have on a GDF?)
- radionuclide retardation in the GDF geological barrier (e.g. which hydrogeochemical properties should the geological barrier display to maximise entrapment of any radionuclides released from the repository?)
- other EBS materials (such as tunnel closure, shaft and borehole sealing materials)
- GDF operational phase (e.g. information that can help to support GDF design and construction as well as guiding the GDF operations in such a way that disturbances to the system are minimised)

The report chapters provide a review and update of existing NA studies related to:

- **whole system performance (a NA of an entire repository could provide extremely valuable long-term information for understanding its behaviour and performance into the far future)**

- **biosphere (e.g. how does natural uranium leached from a sub-surface ore body interact with plants and animals when it reaches the surface?)**

Here, a couple of relevant examples will be examined briefly (details in Alexander et al., 2023) to illustrate the link between NA information and the ESC

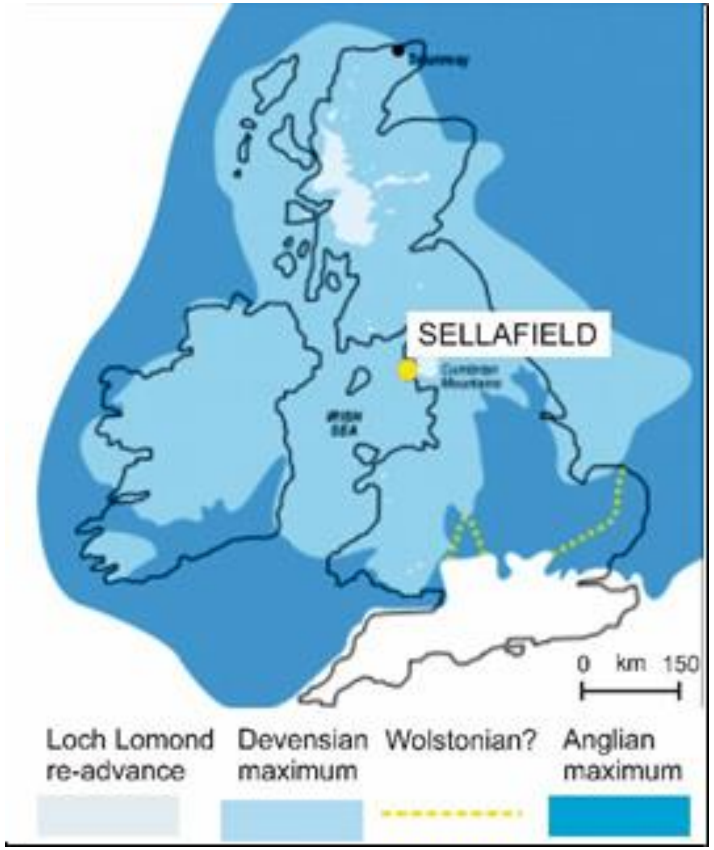
A couple of examples

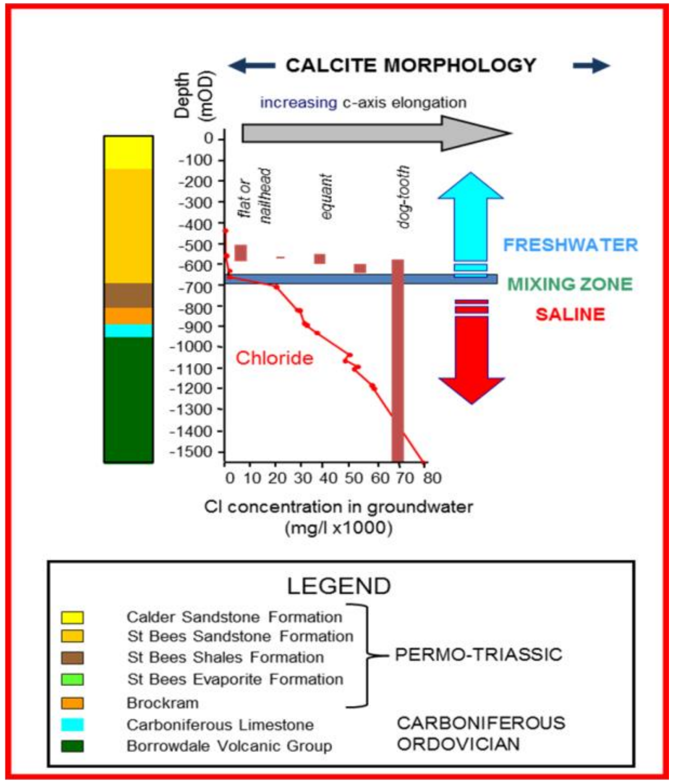
The format is:

- ***Repository components*****:** e.g. HSR (higher strength rocks
- ***Introduction:*** background to NA etc.
- ***IFEPS*****:** e.g. 4.1.2 - Large-scale discontinuities, 4.1.6 - Hydraulic characteristics and properties
- ***NA Type*****:** e.g. Regional analogue
- ***NA description****: e.g.* The Sellafield area
- ***Uncertainties and limitations:*** listed in detail, particularly ESC relevance/irrelevance
- ***Relevance – what have we learnt?:*** Again, listed in detail, particularly ESC relevance/irrelevance

Then a few summary remarks

1. Regional analogue: the Sellafield area





From Milodowski et al. (2005, 2015)

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Regional analogue: the Sellafield area

- **Studies in the Sellafield area have shown that glacially-recharged groundwater can penetrate to repository depths, but that groundwater remained anaerobic because the rock mass itself is capable of removing the oxygen from the young, fresh water very efficiently at shallow depths**

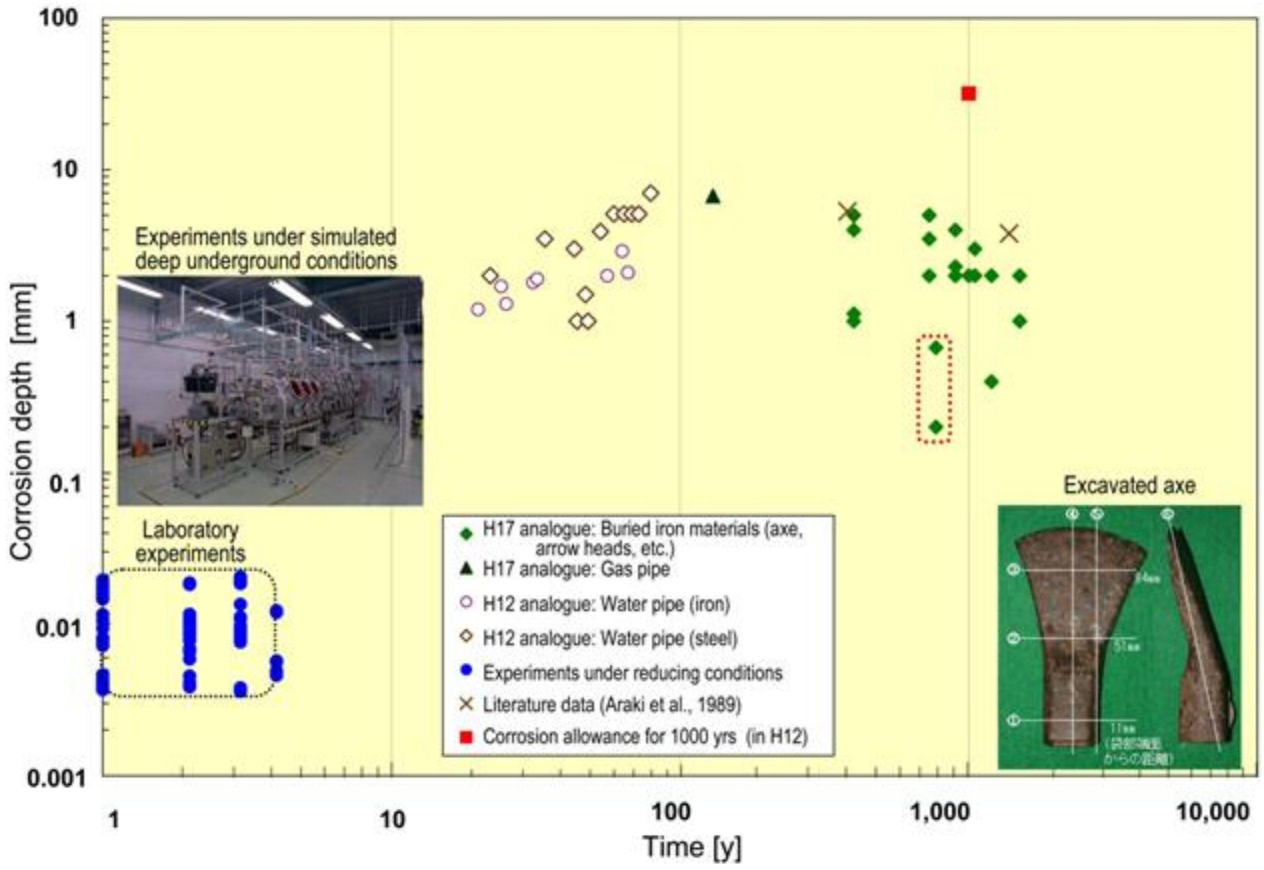
- **Similar patterns of the near-surface rock protecting the deep system has been observed at numerous coastal sites around the world, including Aspö/Laxemar and Forsmark (Sweden), Olkiluoto (Finland) and Horonobe (Japan). This builds confidence that is it at least plausible that conditions will remain similarly reducing at depth at other sites during future episodes of climate change.**

2. Longevity of iron and steel - direct comparison of archaeological/natural analogue and laboratory corrosion data

Here, we took existing information cited in the

- **H12 (JNC 2000)**
- **Kristallin-1 (Nagra 1994)**
- **H17 (JNC 2005)**

SCs and updated the conclusions with recent laboratory and URL experimental data.



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2. Longevity of iron and steel - direct comparison of archaeological/natural analogue and laboratory corrosion data

Finally, to strengthen the link to the UK programme, we added the conclusions of an UK review of iron corrosion data including laboratory, archaeological and natural analogue information (see Crossland, 2005, 2006, for details).

Form of data	Corrosion depth (per 1000 years)	Reference	Comments
Short-term laboratory experiments	31.8 mm	JNC (2000)	Uniform corrosion of carbon steel. ESC Base Case value
Short-term laboratory experiments	29 mm	NWGCT (1984)	Conservative corrosion rate, including an allowance for pitting. ESC Base Case value
Short-term laboratory experiment	1.21 - 3.38 mm	Smart et al. (2017)	Corrosion of carbon steel in a range of bentonites (varying mineralogy, density and form)
Short-term (accelerated) laboratory experiment	0.01 mm	Neeft (2018)	Corrosion of irradiated stainless steel under cementitious repository conditions
Short-term (5 years) FEBEX URL experiment	0.1 mm	Madina (2004)	Generalised corrosion of a carbon steel coupon in the bentonite (recovered following dismantling of Heater 1)
Medium-term (18 years) FEBEX URL experiment	6-11 mm	Wersin & Kober (2017)	Generalised corrosion of a carbon steel heater (Heater 2) and liner surfaces
Natural analogue	0.09×10^{-3} mm	Hellmuth (1991a, b)	Weathering of native iron in basalt (Disko Island)
Archaeological analogue	10 mm	Range of studies cited in Nagra (1994)	Uniform corrosion of iron and steel
Archaeological analogue	<15 mm	Range of studies cited in JNC (2000)	Uniform corrosion of iron and steel
Archaeological analogue	0.1 - 10	David (2001)	Literature review of corrosion of archaeological samples
Archaeological analogue	<10 mm	Range of studies cited in JNC (2005)	Uniform corrosion of iron and steel

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The way forward – future NA studies of relevance to the SC

The NA Catalogue contains examples of studies and related literature available for ESC use as a part of the overall knowledge base of the GDF programme in the UK . The very nature of the NA Catalogue, as with any database, is such that it needs to be updated during the GDF programme Although it should be noted that the information in the NA Catalogue is of relevance to other national programmes as well (for example, the Milodowski et al., 2015, version has been translated into Japanese).

In addition to critically reviewing the existing literature, a gap analysis regarding the processes discussed in the report has also been undertaken. In this case, the gap analysis has focussed on pointing out potential sources of new NA information.

Gap analysis: an example

Previously, an example of a regional study from a HSR was presented but, here, as an indication of the flexibility of the regional analogue approach, another potential UK geological barrier is examined. Here, examples of future studies in low strength sedimentary rocks (LSSR; RWM, 2016) are presented briefly.

Although there are limitations on the use of existing shallow geological data (see the discussion in Alexander & Reijonen, 2023), those on LSSR can be carefully extrapolated to provide initial information on what could be expected at GDF depths (taking, for example, the presence of secondary phases produced by weathering etc. into account).

Gap analysis: an example

Processes of interest	Locality	Potential for new research	References
Formation properties (including geotechnical, lithological, mineralogical, geochemical etc.)	Mercia Mudstone Group – outcrops in Cumbria and Lincolnshire	While the number of relevant sites is limited, outcrops do exist in Cumbria and Lincolnshire and these should be investigated to provide initial impressions for NWS' and contractors' staff. Clearly, the focus shall be on outcrops in the relevant Mercia Mudstone Group depositional basins, but preferably at some distance from the potential repository sites As noted in Alexander & Reijonen (2023), the use of data (and/or future samples) from quarries and shallow boreholes must be treated with caution as certain processes which occur near-surface are irrelevant to repository depths. As long as these limitations are kept in mind, examination of outcrops is always of value.	Reijonen & Alexander (2023, sections 3.3.1 and 3.3.2) Alexander & Reijonen (2023, section 3.3.3.3)
Formation properties (including geotechnical, lithological, mineralogical, geochemical etc.)	Mercia Mudstone Group – road and rail tunnels	Setting aside the increased likelihood of accidental death and injury of field staff from vehicles, such environments are more likely to provide more relevant samples/information than surface outcrops. The generally low formation strengths of the Mercia Mudstone suggest that most tunnels which intersect the host rock will be lined or shotcreted, but drilling through the concrete to obtain sample cores is not difficult once agreement with the proprietors has been reached.	Cantine (2021) Bradbury et al. (1990)

Gap analysis: an example

Formation properties (including geotechnical, lithological, mineralogical, geochemical etc.)	**Mercia Mudstone Group – hydro-power plant access and pipeline tunnels**	**As above, but with less danger from vehicles**	
Formation properties (including geotechnical, lithological, mineralogical, geochemical etc.)	Mercia Mudstone Group – resource exploration records	Although many cores and associated information are held in the UK's national core store at the British Geological Survey, some material is not. Such information is generally deemed to be commercial-in-confidence by the owners and so difficult to access, but the authors are aware of two national waste management organisations which have reached agreement with resource exploration companies to exchange data for use confidentially. Crucially, this use of information was also agreed in advance with the relevant national regulators	

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Gap analysis: an example

Formation properties (including geotechnical, lithological, mineralogical, geochemical etc.)	**Mercia Mudstone Group – abandoned mines**	**Clearly this calls for a full occupational health safety assessment beforehand, but such facilities do exist in the Mercia Mudstone Group and are worth detailed evaluation as the in situ conditions are much more likely to be GDF-relevant**	**Macmillen, (2009)**
Formation properties (including geotechnical, lithological, mineralogical, geochemical etc.)	Mercia Mudstone Group – active mines	There are currently no mines actively exploiting the Mercia Mudstone Group – it outcrops in the vicinity of the Boulby mine in NE England, but it is in the overlying strata. All mine workings are in the deeper (Permian) strata and the shaft is lined along its entire depth	Woods (1973)

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Gap analysis: an example

Formation properties (including geotechnical, lithological, mineralogical, geochemical etc.)	**Mercia Mudstone Group – future mines**	**The nearby (to Boulby) Woodsmith mine is currently driving two shafts (service and production) to a depth of 1600 m, also potentially allowing access to the Mercia Mudstone Group above the evaporite deposits. As this construction work is currently ongoing, it is crucial to contact the mining company on this immediately to initiate and develop a mutually beneficial relationship**	**https://uk.angloamerican.com/the-woodsmith-project**
Formation properties (including geotechnical, lithological, mineralogical, geochemical etc.)	Comparison with other coastal sites internationally	The Olkiluoto repository site in Finland is not unique in displaying both long-term stability at repository-relevant depths and significant hydrological and hydrogeochemical buffer capacity against potential future disturbances. A useful stakeholder confidence building exercise would be to develop the current arguments on this further	Posiva (2022) Alexander & Reijonen (2023, sections 6.2.1, 6.2.3)

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Conclusions

The examples presented here from the new NA Catalogue provide an update based on a review of the existing catalogue and additional information from the literature. The update has been based on the overall guidelines, which arose from the strategic review (*Simon's talk*) of NA requirements in the future UK national GDF programme, resulting in the following updates:

- **NA data presented are assessed based on their relevance to the present status of the UK national GDF programme (at the time of writing, generic ESC + volunteer sites)**
- **Topical additions have been made on the subjects that could benefit from NA input in the future, or that were not included in the discussion in the earlier version**
- **The catalogue is compiled in a form that can be applied to both traditional report formats and interactive content management tools (digital ESC)**
- **The information presented can be linked to other parts of the ESC in the future or other documentation related to this part of the overall GDF knowledge base**

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Conclusions

- During the update, relevance screening was carried out, meaning that some information has been substituted as it was felt to be less relevant to the current and foreseen requirements of the UK national programme
- Some of the information in Milodowski et al. (2015) has been retained, but its role in the catalogue may have changed
- Component level gap analysis was also performed, leading to additions at the topical level
- In addition to this, the IFEP database (NEA, 2019) has been mapped to the contents of the catalogue. This mapping is a first step towards full integration of the NA Catalogue in the overall GDF programme knowledge base that is linked to the other related components within it

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