Comments, mainly on aspects of Technical Delivery – in particular Geology (para. 3.6 onwards)

My comments on your document concentrate on the Section on Geology – para 3.6 onwards. I also have comments on the potential problems associated with the size of the site investigation area necessary to adequately investigate a particular geological environment, and whilst it is not discussed in the DECC document, I think it needs to be and I have included it here. The size of the investigation area will vary considerably, depending on the type of geological/hydrogeological environment under investigation, but could have to extend for considerable distances beyond the boundaries of the representative authority in which a GDF might be located – and this could cause considerable problems. NUMO recognised this problem several years ago and I prepared a very extensive report for them in 2006 entitled *Preliminary Investigation Planning Manual (PIPM) - The Supporting Manual* which covers such matters in considerable detail and provides examples from different types of geological/hydrogeological environment.

Figures 1 and 2 illustrate the difference between site investigation areas: the first at Olkiluoto, where crystalline basement rocks are at the surface, and where the dimensions of the investigation area are a few square kilometres; and the second at Bure, which lies towards the margin of the Paris Basin and where the investigation area is thirty to forty times greater. A better measure of the size of the investigation area necessary is its maximum dimension. In a sedimentary environment, where the sedimentary sequence has a strong hydraulic anisotropy, the size of the groundwater flow cells is increased and the recharge and discharge points, which might well have to be investigated, can be separated by considerable distances of perhaps several tens of km. In contrast, Figure 3 shows the BFZs (Brittle Fault Zones) defined as Layout Determining Features (LDFs), these being the main features, but not the only ones, that control the groundwater flow system and thus the radionuclide transport paths at Olkiluoto. There are very few areas in England and Wales where crystalline basement is at the surface in areas of subdued topography (and thus potentially suitable for the disposal of radioactive waste) and so the situation at Olkiluoto is effectively an extreme example. In contrast, the cross section of Bure (Figure 4) shows the very simple geological structure and the paucity of potentially high permeability structural features. Radionuclide transport from a repository in the Callovo-Oxfordian Clay is dominated by the diffusional transport properties of the host rock, but release of radionuclides to the overlying and even underlying higher permeability formations means that the potential release paths can have considerable dimensions. As this subject was aired at the meeting in Warrington, I will not discuss it further.

Another matter which was not discussed in Warrington and does not appear to play any part in the proposed development of a GDF in the UK is that extensive underground research is required before construction of the actual GDF takes place. Such work can take place in a URL and/or as what could be considered the first phase of the development underground, at the proposed disposal depth. Such work is of vital importance in developing sufficient knowledge of conditions underground and in obtaining experience in situ on the practicalities of, for example, methods of detailed site investigation underground and waste emplacement techniques, before any construction of the actual GDF can commence.

Figure 1. Investigation area at Olkiluoto, Finland. The only activities outside the Island of Olkiluoto, which has an approximate area of 15 km^2, are non-intrusive in nature and relate to activities such as geological field mapping and microseismic monitoring.

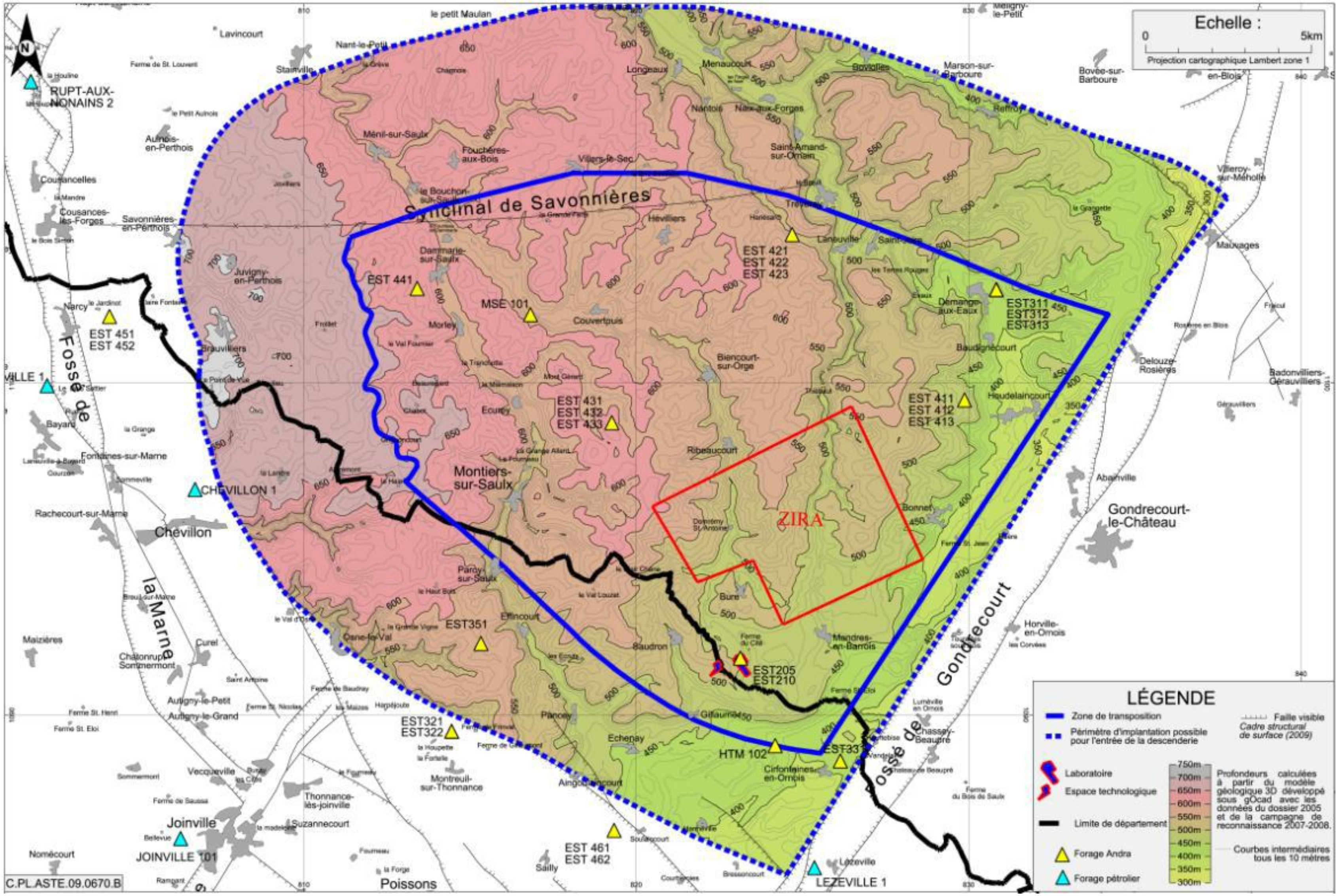

Figure 2. Map showing ZIRA (*Zone d'Intérêt pour la Reconnaissance Approfondie*) – the area in which repository will be located near Bure. The *Zone de Transposition* (solid blue line) is the maximum area in which the repository could have been located and was determined by structural features (such as La Fossé de Gondrecourt), by lithological variations and by elements of the groundwater flow system. Andra's boreholes are spread over an area of approximately 400 km^2 and they also made use of previously drilled oil exploration boreholes (forage pétrolier), at greater distances from Bure, to carry out hydraulic testing and groundwater sampling, over an area exceeding 700 km^2.

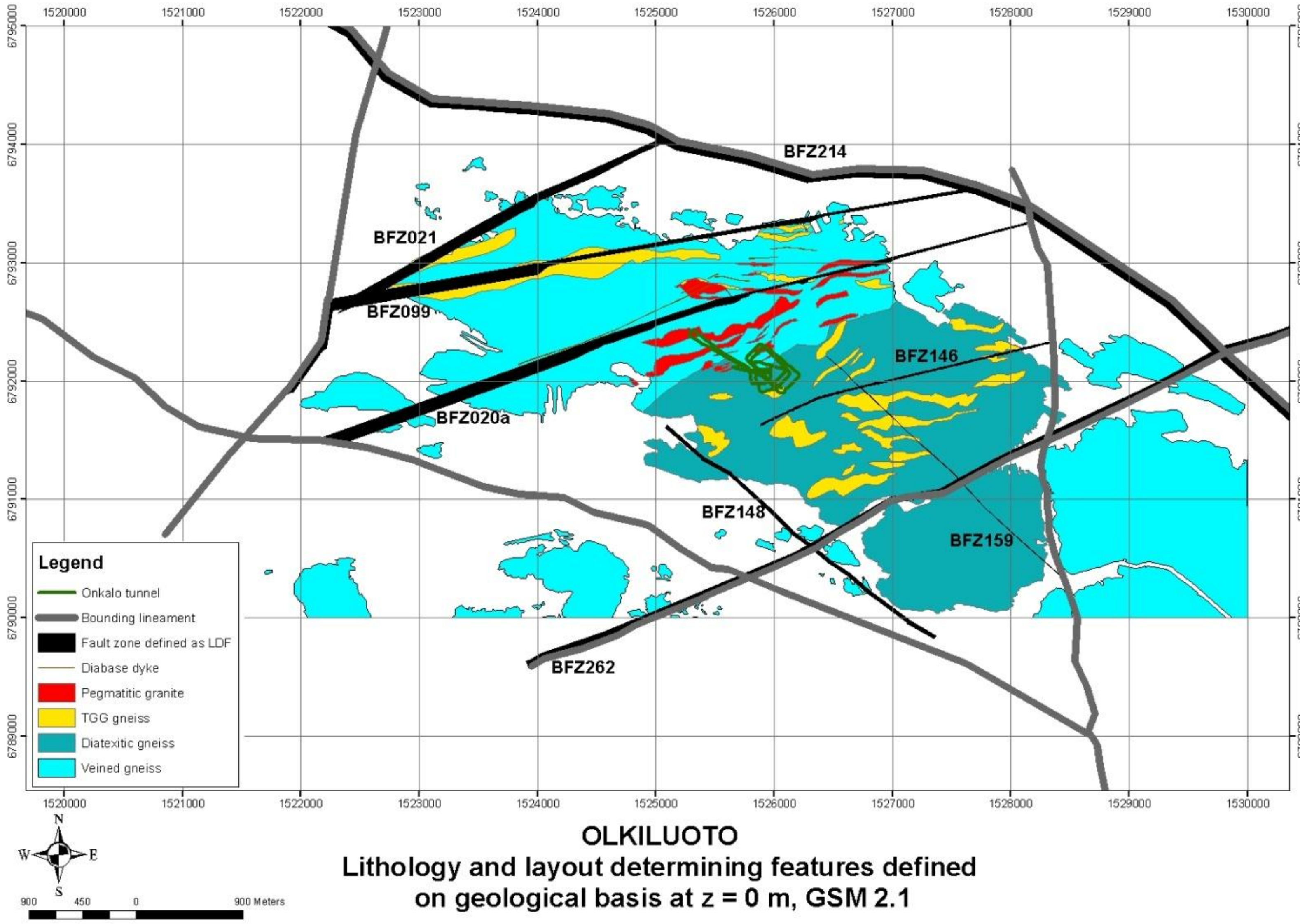

Figure 3. A geological map of Olkiluoto Island showing the lithology and the brittle fault zones (BFZ) defined as layout determining features (LDFs), i.e. features that impose restrictions on the repository layout.

BFZ = brittle fault zone

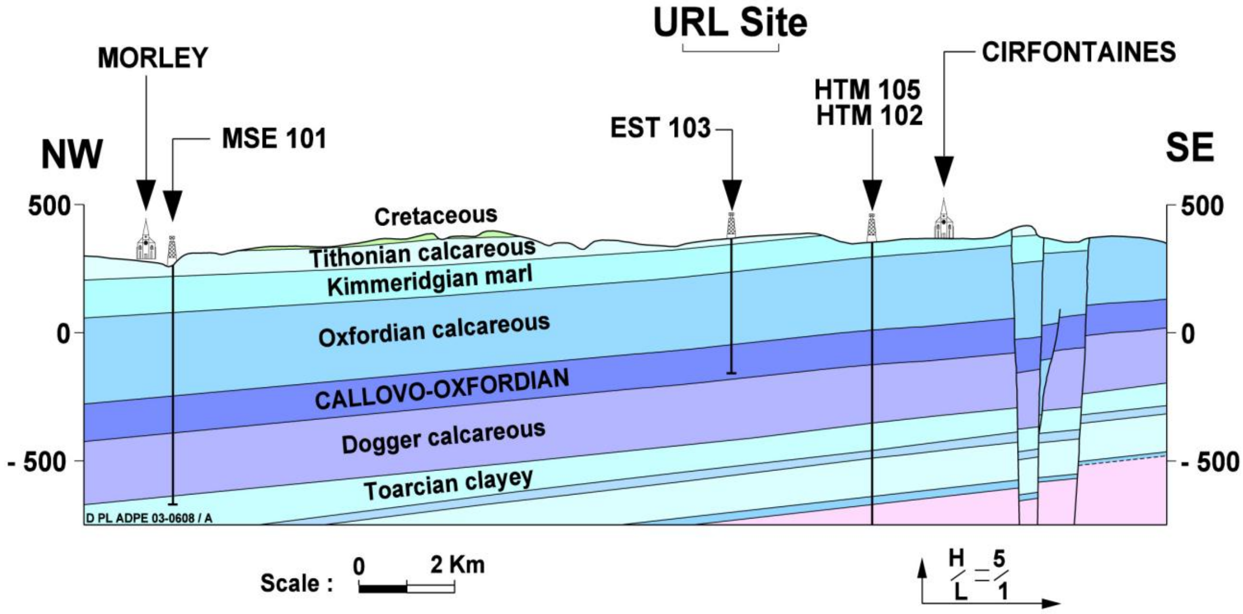

Figure 4. Cross section through URL at Bure, France, the site of the proposed Cigéo geological repository for LL-ILW and HLW, illustrating the simple geological structure (and lack of faults and fracture zones) and the proposed repository host formation, the Callovo-Oxfordian clay, which has an extremely low permeability, so that fluid movement within the system is diffusion-dominated.

Every successful radioactive waste disposal programme – SKB, Posiva, Andra, etc. – has and is followed this route. A review of Posiva's programme over the last few years and what they are currently doing underground in the ONKALO would emphasise the importance that needs to be attached to this matter. It is necessary for RWMD to have such a phase in their programme and it needs to be discussed in any document from DECC that is published on the development programme for a GDF.

I agree with your statement: "*The application of the previously defined 'unsuitability' screening criteria on a national basis is not considered to be feasible based upon discussions with the British Geological Survey (BGS).*" but these are not the types of 'criteria' that need to be applied in defining environments and areas that have the greatest potential for hosting a GDF. They are exclusionary in their nature, as was their purpose, whereas what is required is effectively the opposite. The nature of these 'criteria', although as is explained below the term 'criteria' is not appropriate in this context, is set out below, firstly by examining and commenting on what is stated in the DECC document and then by suggesting what could be done. This alternative approach is effectively what has been carried out in other countries' site selection programmes, although the way the process has been applied has varied considerably. Such a process has been applied in a very vigorous and logical manner over the last few years by Nagra in the selection of their preferred areas for investigation (Nagra, 2008, 2010, 2011).

In para 3.9 on the subject of Suitability Screening you state that: "*There is no 'best' or 'most suitable' generic type of geology*". Whilst there is no one 'best' geological environment there are definitely certain environments that are more suitable and some environments that are definitely unsuitable, although as is explained below, such environments must not be viewed only from a geological perspective but also with reference to their hydrogeological and hydrogeochemical characteristics (what is often referred to as their THMC (Thermal-Hydrogeological-Mechanical–Chemical) conditions).

You also refer to the report by Metcalfe and Watson prepared for the Environment Agency (EA). You refer to what you term "*nine potentially suitable generic settings*" described in this report and also state, in relation to these 'generic settings' that: "*Due to this wide range, it is difficult to define simple high level criteria which could be applied effectively at a national level*". I am afraid that you have misunderstood what these environments are designed to represent; they are not purely geological in nature and nor are they, in fact, purely generic in nature, as is explained in the report, although not perhaps very clearly. I defined these environments, in collaboration with the other people working on this project, and they are very similar to the smaller number of potential disposal environments (six in total) that Uisdean Michie (who was chief geologist at Nirex/RWMD for many years) and I had already defined in 2006-7 for Nirex/RWMD (e.g. Watson et al., 2007). They represent the range of potential disposal environments in the UK and are rather similar to the environments that Neil Chapman and I defined in 1986 at the start of Nirex's site selection programme for a deep geological disposal site (Chapman et al., 1986). It is thus perfectly possible to define what you refer as '*high level criteria*', as it was by the application of such criteria (although we did not refer to them as such) that these environments were selected, as is discussed in more detail below. Unfortunately, in the introduction to the EA report the nine environments have been referred to as being 'geological' when this term, without further description, is somewhat misleading (see Appendices of EA report for discussion, e.g. page 187).

The Quintessa report for RWMD (Watson et al., 2007) would have been a better report to reference, as it explains more succinctly and presents the data more clearly regarding the six types of environments that are most suitable for disposal purposes. These environments are:

- Basement rock to surface;
- Basement Under Sedimentary Cover (BUSC) with permeable sedimentary rocks;
- BUSC with low permeability sedimentary rocks;
- Evaporite host rock;
- Mudrock hosted environment; and
- Strong sedimentary host rock.

Collectively, these environments represent all the environments in the UK that could be considered as having potential for the disposal of long-lived radioactive waste and encompass all the environments that have ever been considered in any country in the world for a mined repository for long-lived wastes – except for what might be termed unusual environments that do not exist in the UK for climatic reasons, e.g. Yucca Mountain, potential areas of interest for the Pangea proposals for an international repository in places such as the Australian desert, the potential Chinese repository site in a remote part of northwestern China, or rather special environments for relatively small volumes of long-lived waste, such as the situation in Belgium where plastic clay (Boom Clay) is being considered as the host rock.

They were selected based on the following basis, as set out in Watson et al. (2007):

- The geological environment is required to provide a sufficiently large volume of suitable host rock to accommodate the repository at depths greater than 300 m, but shallower than 1000 m.
- The characteristics of the host rock are required to be suitable for the construction of disposal vaults of the required dimensions.
- The geological environment should be sufficiently stable to ensure the adequate functioning of the barrier system, in spite of any likely changes in the surface environment.
- A low groundwater flow rate through the repository, which implies low host rock permeability and a low hydraulic gradient, is a requirement of all aspects of the system.
- The groundwater composition is compatible with a cementitious backfill (specific to RWMD's current concept) and does not promote corrosion of the repository infrastructure or the waste containers.
- The physical and chemical characteristics of the geosphere are required to prevent any gas that might be generated from reaching the surface in concentrations that are sufficient to cause safety to be compromised.
- It is required that there are no natural resources in the geosphere that would encourage human intrusion.

In addition, certain characteristics would tend to favour the compatibility of a particular environment with the requirements of a GDF, such as:

- It would be advantageous for the geotechnical characteristics of the host rock to be such as to minimize the maintenance of vaults that will be necessary during the period prior to backfilling and closure.
- It would be advantageous for the geosphere to be able to retard radionuclides dissolved in groundwater, thereby helping to ensure that radionuclides leaving the repository will take a long time to travel from the repository to surface, allowing much of the radioactivity to decay.
- It is desirable for the characteristics of the geosphere to favour the dilution of radionuclides that leave the repository, thereby reducing their concentrations in groundwater.
- It would be advantageous for the physical and chemical conditions underground (other than geotechnical characteristics) to be such as to minimize the measures that need to be taken to create a suitable environment for operations.
- More generally, there are many advantages in selecting a 'simple' and easily characterised environment (c.f. Nagra, 2002a,b; Andra, 2005a,d; AkEnd, 2002 and McEwen and Äikäs, 2000) that has been termed the site's *explorability* (Zuidema in NEA, 1991).

A very useful summary of which factors are important in defining a suitable disposal environment is also provided by Nagra as part of the NEA AMIGO project. These are defined under the title of: *Favourable characteristics of the geosphere that could be cited in a safety case, using the example of the Opalinus Clay in Switzerland, as presented at the AMIGO 1 workshop* (Gautschi et al. in NEA, 2004). Although these were defined in relation to the Opalinus Clay (the proposed host rock in Switzerland for the disposal of long-live wastes), the general principles apply to all potential disposal environments:

- Long-term geological stability, implying, for example, a low rate of uplift and erosion and an insensitivity of the geochemical and hydrogeological environment to geological and climatic changes;
- Favourable physical, chemical and structural properties, including thickness of the host formation, low rates of groundwater movement, a geochemical environment that is beneficial in terms of radionuclide retention and protection of the engineered barrier system, and rock mechanical properties that support the feasibility of construction (although not strictly part of the safety case, engineering feasibility is relevant in that the system described in the safety case must be one that can be realised in practice);
- Sufficient lateral extent, which gives flexibility in the location and layout of the repository;
- Absence of, low likelihood of, or insensitivity to detrimental phenomena and perturbations, including climatic and geological events and processes, perturbations caused by the repository itself (gases, chemical alterations), and future human intrusion;
- Explorability, or the ability to characterise the rock at any stage of the project to a degree that is adequate to support a decision to proceed (or not) to the next stage (e.g. site characterisation from the surface can provide sufficient evidence to support the decision to proceed with further characterisation from underground tunnels); and
- Predictability, meaning that the range of possible geological evolution scenarios is sufficiently limited over the time scale for which the geological environment plays a role in the safety case (perhaps, for example, a million years).

It can be seen that these are essentially the same as those outlined in Watson et al. (2007) and referred to in the EA report. They are universally accepted by all countries considering the disposal of long-lived radioactive waste. The essential characteristics of these environments are explained in more detail below, as the selection of potentially suitable disposal environments, from a geological-hydrogeological-hydrogeochemical standpoint is of over-riding importance.

In addition to the existence of one or more of these environments in an area of the UK, there are of course other factors that also need to be taken into account, several of which are also geological in nature, e.g. coastal erosion; however, these are of secondary importance, at least during the early stages of any site selection programme. Agreeing and defining these environments at the outset would help in developing a much more logical and defensible site selection programme, in that it would demonstrate to communities what types of the environment were being sought. Communities in areas where none of these environments existed would then know from the outset that there was no point in expressing an interest in being considered for hosting a GDF. This could save considerable time and effort and possible political ill-will. In a similar manner to the definition of areas of the UK by the BGS that have potential for shale gas, it should be possible to define areas which have potential for radioactive waste disposal, although the process is more complex. As is explained below, this was done in the 1980s for Nirex, and the approach of defining suitable environments and also potential areas of interest has also been carried out in other countries' site selection programmes.

These environments in the Watson et al. (2007) report and also the EA report are based on actual locations in the UK, but rather simplified and somewhat purposely disguised (for perhaps obvious reasons), and were selected based on the following principles (which are universally accepted by almost all waste management organisations and regulatory bodies throughout the world). Although they have actual locations, they are representative of larger areas of the country (not necessarily continuous) where these types of environments are present - some of these are quite extensive whereas others cover considerably smaller areas. The distribution of these environments was not carried out as part of the work for RWMD or the EA. If you would like to know where the examples of these environments in the Watson et al. (2007) report are located I could let you know:

- They are in areas of relatively simple structure, not just in a geological sense but also in relation to their anticipated hydrogeological and hydrogeochemical environments. This inherent relative simplicity is very important in being able to investigate and characterise the site and also in the development of a convincing safety case – this simplicity was termed *investigability* by Nagra several years ago (e.g. NEA, 1991), as referred to above, and is discussed as part of Nagra's current site selection programme in several recent reports (e.g. Nagra, 2008, 2010, 2011; DETEC, 2008) and elsewhere in NEA reports, for example, e.g. NEA, 2005, 2009, 2010.

- They are expected to be stable, not just in relation to their geology but also in relation to their hydrogeology and hydrogeochemistry (and also in relation to rock mechanics, microbiology, etc.). This intrinsic 'stability' is an extremely important attribute of such an environment, as has been discussed in considerable detail in several NEA reports, in particular, over the last ten years, e.g. NEA, 2005, 2009, 2010. What the term 'stability' means is that the system is effectively buffered against events and processes, whatever they may be, so that the environment at depth is thus very different from the rapidly changing environment at the surface. This is one of the prime reason for disposing of radioactive waste in a GDF at depth and not storing it at the surface.

- The expected groundwater-mediated return times for radionuclides from a GDF in all of these environments are likely to be long. The reasons for this desirable characteristic are outlined below.

- These environments achieve these characteristics by:

- Being selected so as to have a simple structure (geological, hydrogeological, hydrogeochemical), as discussed above. In the case of sedimentary environments this will be related to the thickness of potential host formation(s), their continuity, their lateral consistency, both down-dip and along strike where possible, with respect to their lithology (i.e. so that their expected properties remain similar), low and rather constant dips, a general lack of faulting or extensive folding, etc. Such features, combined with others listed below, will tend to be associated with a relatively simple and predictable hydrogeological environment which, in turn, is likely to be associated with a relatively simple and predictable hydrogeochemical environment. In fractured hard rocks it is desirable to have as simple a structure as possible, e.g. sufficiently removed from major structural features such as major shear zones (see, for example, extensive discussion on this subject by SKB and Posiva). Such desirable features are also more likely to ensure that the conditions at depth remain stable (though this does not necessary mean constant, but does mean they will only evolve relatively slowly – again see recent NEA reports on the great importance of this stability (NEA, 2005, 2009)).
- Being in areas where the groundwater velocities are minimised and the size of the groundwater flow cells maximised by having subdued topographies and not being located in areas with higher heat flows. This applies to all of the environments, whatever their geology. For some of the sedimentary environments they are located, where relevant, towards the margins of sedimentary basins, so that the groundwater flow tends not to have a dominant upward orientation (that it would tend to have as the centre of the basin is approached). A multi-layered sequence, which is normally associated with a sedimentary environment, is likely to have a high ratio of horizontal to vertical hydraulic conductivities, with the result that hydraulic heads are transmitted over greater distances, with the flow cells thus becoming larger and the transport lengths tending to increase (compare Figures 3 and 5). This has obvious advantages, however, it means that the size of the investigation area has also to increase, which is a potential problem that has been recognised by NUMO (see McEwen, 2006). This contrast in investigation areas is well illustrated by comparing the current investigations at Olkiluoto and Bure (see discussion above).
- Having potential GDF host formations which have a sufficiently thickness – this is mainly of significance in sedimentary environments and is so that the formation (which will to be suitable will have a low hydraulic conductivity) provides a sufficient barrier to radionuclide migration, bearing in mind the expected dimensions of the GDF. A thickness of perhaps 50 m minimum may suffice (see Chapman et al., 1986, for example), though a thickness of perhaps 100 m would be preferable – this should be discussed with relation to the formations in the UK (also see current discussion by Nagra vis a vis the Opalinus Clay, e.g. Nagra, 2010, 2011). Recent NEA reports, e.g. the AMIGO report (NEA, 2010), have highlighted the links that need to exist in the

development of the safety case, in the associated R&D programmes and in the site investigations.

- In basement rocks, being in an environment where the expected structural complexity is such that the separation of fracture zones (which are universally present in such rocks) are such that it is possible to locate sufficient deposition tunnels/caverns which are not intersected by these features, which are often referred to as LDFs (layout determining features, see Figure 3) because they have substantially higher hydraulic conductivities, are major controls on groundwater chemistry and can be associated with seismic events (see for example recent Posiva report on rock suitability criteria, McEwen et al. 2012).
    - In this regard, older basement rocks will be more likely to possess structures such as shear zones, which may have relatively low dips, with the result that the rock mass is effectively compartmentalised, not just in a geological sense but also with respect to its hydrogeology and hydrogeochemistry. Such compartmentalisation can, for example, be seen at Olkiluoto (see for example Posiva, 2012). Younger basement rocks are still likely to be similarly compartmentalised, but in a different manner, and more likely by what might be termed simpler fracture zones, which are likely to have higher dips – although this is not universally the case.
- In areas with no expected mineral reserves of any type, e.g. obvious ones such as oil, coal and metallic deposits, but also potentially exploitable reserves of gas, in whatever form, hydrothermal potential, etc.
- There are obvious constraints on the depth of a GDF. Its minimum depth will definitely be in excess of 200 m, so the geosphere can provide the necessary stable conditions and so that it acts as a suitable barrier for radionuclide migration. The maximum depth is likely to be approximately 1000 m, although for some host rocks, which are most likely to be sedimentary, the maximum depth may be considerably less due to the requirements for geotechnical stability at depth. There may well be other constraints on the maximum depth – these are most likely to be geochemical in nature and relate to factors such as the salinity of the groundwater, as an excess salinity has deleterious effects on any bentonite-based EBS (this is one of the main reasons for the depth of the proposed repository at Olkiluoto being less than 500 m). Such depth constraints have obvious effects on the potential location and extent of the environments presented in the report to the EA.
- The dimensions of the repository have constraints on the suitability of potential host rock environments. In sedimentary environments this places bounds on the minimum thickness of the host formation, on its lateral extent and on the separation of structures such as major fracture zones. In hard fractured rocks the constraints are mainly related to the structural features, such as major shear zones, major fracture zones, etc. In evaporitic sequences again it is the thickness of the potential host rock (most likely a halite) and on the location of

other evaporites in the sequence that could cause problems, in particular anhydrite.

Examples of potentially suitable disposal environments in the UK

Three environments taken from Watson et al. (2007) and modelled in Towler et al. (2007) (Figures 5, 6 and 7) are used to illustrate the different types of disposal environment present in the UK, which display all of the necessary requirements of a potentially suitable disposal environment described above. Together with these figures are tables that illustrate what it is possible to estimate in advance of any site investigations, based on the vast amount of data from other sites which have similarities with these three environments.

The three environments from Watson et al. (2007) used for the purpose of illustration are (numbers as used in Watson et al. 2007) :

- Environment 3 – a BUSC environment with low permeability overlying sediments
- Environment 1 – basement rocks to the surface and
- Environment 5 – a mudrock-hosted environment

They are included here to illustrate what is reasonable to assume about a potential disposal environment - at least one in an area of relatively simple geology – in advance of any site investigation. It is this type of information that could be used to carry out a far more sophisticated site selection programme than is currently proposed for the UK and one that is more in line with the current programme in Switzerland, for example. Considerably more information on such matters is presented in Watson et al. (2007).

Environment 3 – BUCS environment with low permeability sediments *3 – a BUSC environment with low permeability overlying sediments*

A cross section through such an environment is shown in Figure 5, where several mainly low permeability Jurassic sediments overlie metasedimentary basement rocks. The area is one of subdued relief, the geological structure is simple and the assumed location for the GDF used in the groundwater flow modelling exercise, which is presented in Towler et al. (2007), is also indicated.

The hydraulic properties assumed for the formations shown in Figure 5 are listed in Table 1. These are based on examples of these formations from other parts of the UK and/or on similar formations in the UK and are backed up by similar formations in other parts of the world which have been investigated, in many cases for radioactive waste disposal purposes. For depths greater than about 100 m it is possible to make quite reliable estimates of these properties.

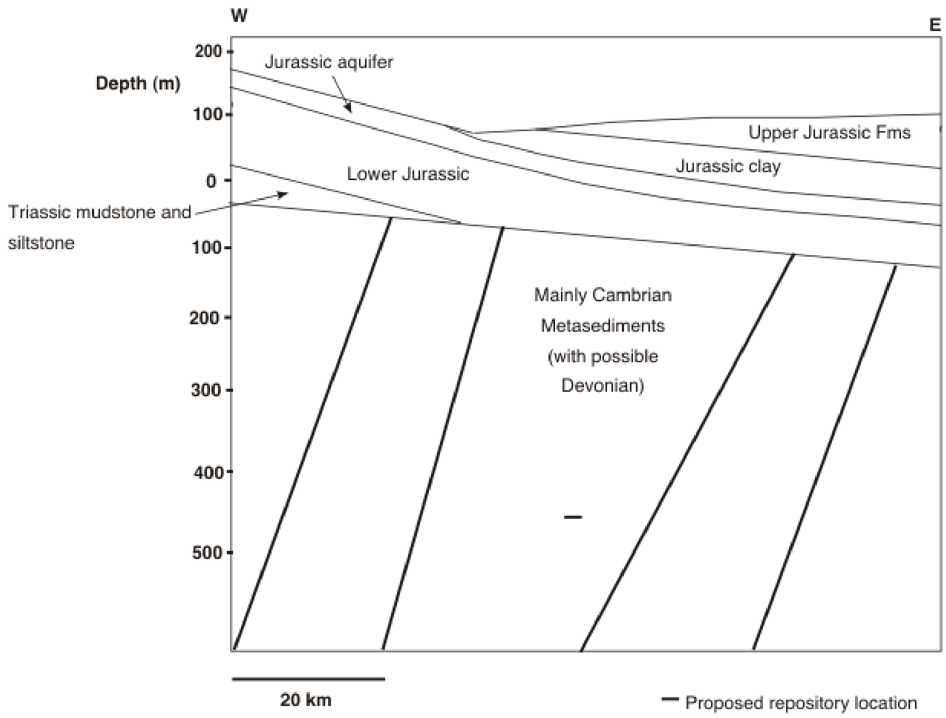

Figure 5. One cross section from Environment 3 – BUSC overlain by low permeability sediments (from Towler et al., 2007 and Watson et al., 2007). The proposed location for a GDF at a depth of approximately 600 m is also indicated. Notice the enhanced vertical to horizontal exaggeration in all the figures.

Table 1: Proposed hydraulic properties for Environment 3 (Figure 1).

Formation	**Hydraulic conductivity (range) (m/s)**	**Transport Porosity**	**Properties based on**
Upper Jurassic formations	Uppermost 50 m: 10^{-8} – 10^{-10} Greater depth: 10^{-9} – 10^{-11}	0.2-0.3	Kimmeridge Clay and Ampthill Clay
Middle/Upper Jurassic clay	Uppermost 50 m: 10^{-8} – 10^{-10} Greater depth: 10^{-9} - 10^{-11}	0.05-0.25	Oxford Clay
Jurassic aquifer	10^{-6} – 10^{-8}	0.1	Various Middle Jurassic formations
Lower Jurassic clays	10^{-11} – $10^{-12/13}$	0.1	Various Lower Jurassic (Lias) formations (mainly clays)
Triassic mudstone and siltstone	10^{-9} – 10^{-11}	0.1	Mercia Mudstone
Cambrian metasediments (with possible Devonian)	10^{-10} – 10^{-12}	0.01 – 0.05	Tremadoc (Cambrian)

Environment 1 – basement rocks to the surface*1 – basement rocks to the surface*

In contrast, Figure 6 illustrates a cross section for a an environment where the basement rocks extend to the surface, i.e. similar to Forsmark and Olkiluoto. Tables 2 and 3 list the assumed values for the hydraulic properties. Two tables are provided, as the different types of fracture zones provide the main pathways for groundwater flow and solute transport through the geosphere.

Table 2: Hydraulic properties of the superficial deposits and the rocks for Environment 1 – basement rocks to surface. The values for the crystalline basement rocks are for the rock lying between fracture/deformation zones (from Watson et al., 2007).

Formation	Hydraulic conductivity (range, m/s)	Porosity
Peat	2.10^{-8} – 5.10^{-9}	0.5 -0.7
Glacial deposits	10^{-5} – 10^{-7}	0.3
Uppermost part of crystalline basement	$10^{-6.5}$ – $10^{-8.5}$	0.01 -0.05
Deeper part of the crystalline basement	10^{-9} – 10^{-11}	0.001 – 0.01
Fracture zones	See Table 3 (from Watson et al. (2007)	0.001 – 0.05

Environment 5 – a mudrock-hosted environment

Figure 7 shows a cross section for a mudrock-hosted environment, where the sediments have very shallow dips to the east and the geological structure is very simple – rather like the situation at Bure (Andra's proposed disposal site) in the southeastern part of the Paris Basin. Table 4 lists their hydraulic properties. In this case two assumed depths are assumed for a GDF in different host rocks to examine the difference that might result.

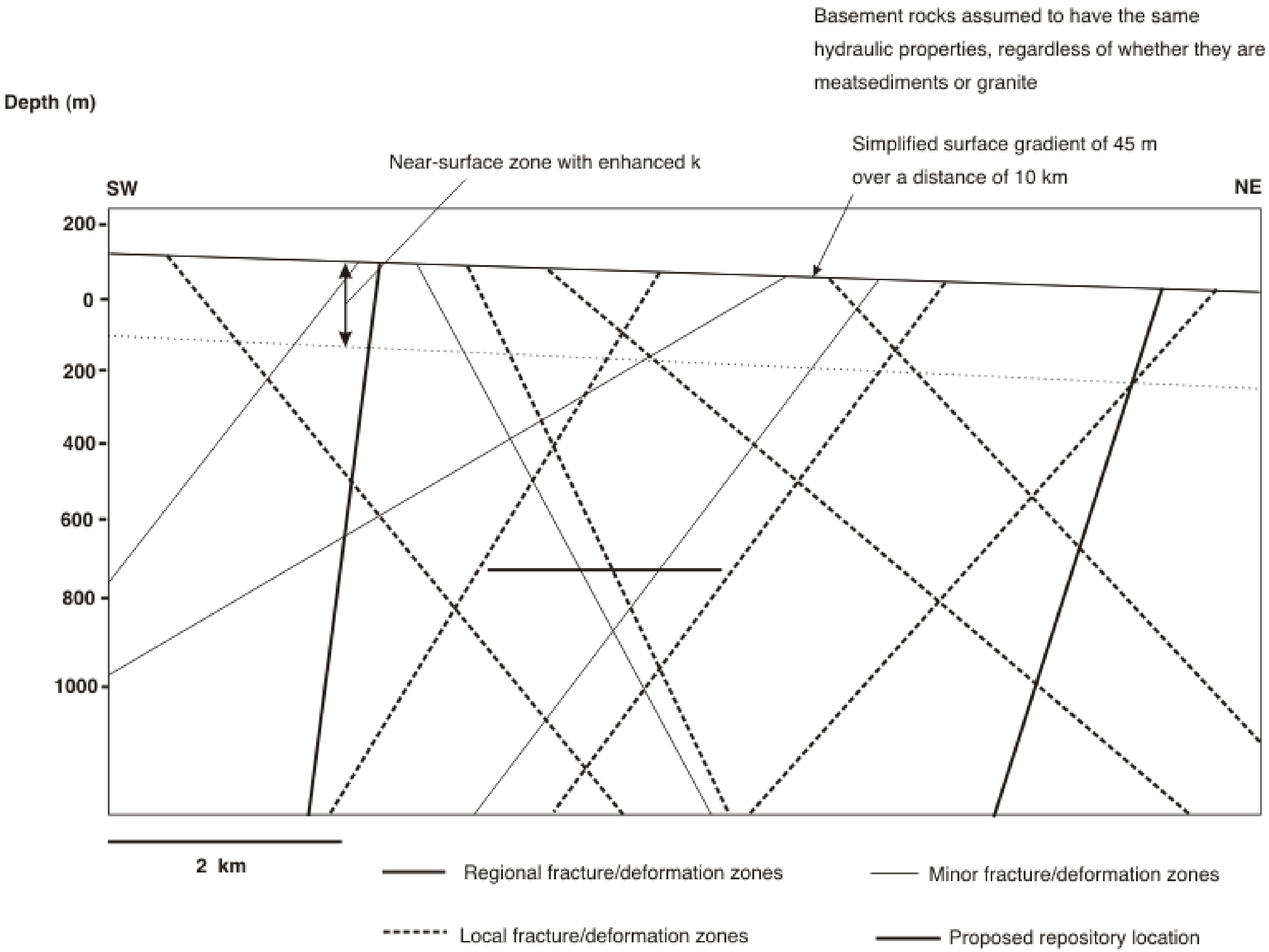

Figure 6: Cross section for Environment 1 – basement rocks to surface - showing the three scales of fracture/deformation zones and the proposed location of the GDF.

The dips of the fracture zones are based on an actual area in the UK, however there is also the possibility that even lower angle zones may be present, as is the case at Olkiluoto, and this depends on the type of basement that is being considered.

Table 3: Hierarchy of discontinuities in a crystalline rock, illustrating typical values and ranges. Although indicative hydraulic and other properties of fracture zones at all scales are shown, for Environment 1 there may not be fracture zones at the largest scale, nor may there be any horizontal or sub-horizontal fracture zones (from Watson et al., 2007).

Discontinuity type	Spacing (m)	Width (m)	Mean k (m/s) (3)	Assumed k range (m/s)
Regional fracture zones	3 - 7 10^3	50-100	10^{-7}	$10^{-5.5}$ – $10^{-8.5}$
Local fracture zones	400 - 800	15-50	10^{-8}	$10^{-6.5}$ – 10^{-10}
Minor fracture zones	50 - 200	2-10	10^{-8}	$10^{-7.5}$ – 10^{-10}
Fractured rock (1)				
(above approx. 200 m)			10^{-8}	10^{-7} – 10^{-10}
(below approx. 200 m)	0.4 – 0.8		10^{-9}	10^{-8} – 10^{-12}
(Sub)-horizontal fracture zones	500 - >2000	5-40	10^{-7}	$10^{-5.5}$ – $10^{-8.5}$
Other transmissive elements/structures (2)	100 - 250	1-25	10^{-8}	$10^{-6.5}$ – 10^{-10}

Notes

1 The rock between the fracture zones; although this represents the actual fracture spacing, in terms of hydraulically-connected fractures the ratio may be of the order of 1:10, so that the spacing of hydraulically-conductive fractures is 4-8 m for an observed total fracture spacing of 0.4 to 0.8m.

2 These could be, for example, dykes.

3 Arithmetic mean, in the case of the fracture zones at a scale of perhaps 100 m, and in the case of the fractured rock at a scale of perhaps 25 m.

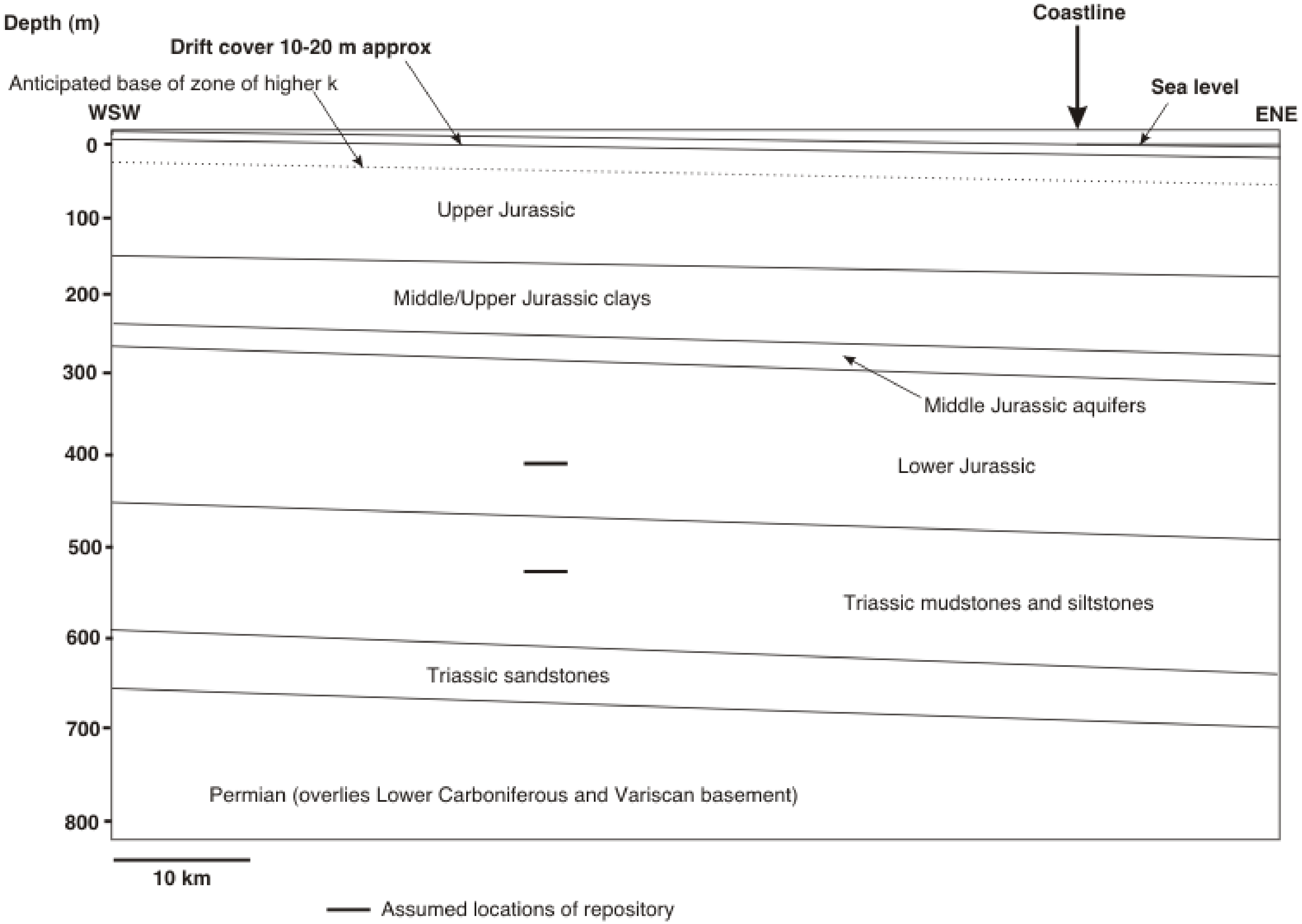

Figure 7. Cross section of Environment 5 – mudrock hosted environment - showing the two assumed locations of the GDF.

Table 4: Summary of Stratigraphy for Environment 5 – mudrock-hosted environment

Formation	Approx Depth Range (m)	Description and Notes
Upper Jurassic	0 - 150	Relatively thin siltstones and limestones interbedded with mudstones. Properties based on Kimmeridge Clay and Ampthill Clay
Middle/Upper Jurassic clays	150 - 200	Mainly clay, with subordinate higher-k units (e.g. minor limestones). Properties based on Oxford Clay and West Walton Formation
Middle Jurassic aquifers	200 -250	Massive limestone overlying ferruginous sands. Properties based on Lincolnshire Limestone/ Northampton Formation/ Rutland Formation. May also contain some lower permeability horizons e.g. Blisworth Clay.
Lower Jurassic (Lias)	250 - 450	Organic-rich shales (commonly containing pyrite), mudstones and micritic limestones; may have thicker limestones in lower parts.
Triassic Mudstones/siltstones	450 - 600	Mudstones in central part (approx 100 m thick), with evaporites and shales; sandstones near the base. Properties based on Mercia Mudstone Group
Triassic sandstones	600 - 660	Sandstone. Properties based on Sherwood Sandstone Group
Permian	660 - 800	Continental facies - breccias and conglomerates - aeolian sands towards base, overlain by Zechstein sediments (halite possibly).
Lower Carboniferous	thin	Contains some thin coals but not exploitable
Variscan basement	>800	Precambrian to Ordovician. Mostly phyllites.

You also state in para 3.9 that: "*The suitability of specific areas is dependent on more than just their geology; it also includes other factors such as the way water moves through the rocks (hydrogeology) and the chemical characteristics of the water moving through the rocks hydrogeochemistry). Even if high level criteria could be developed, the information would not be available to apply these in an effective way. It will not be possible to make reliable judgements about these factors without years of detailed study of particular sites, which means that initial screening has limited usefulness when it comes to providing evidence for definitive statements about suitability*."

This, I am afraid and as is shown above, is not true or is only partially correct. It is perfectly possible to develop such 'high level criteria' and such 'criteria' have been and are being applied in France, Switzerland, Finland, Sweden, Canada, Bulgaria, Japan, etc. Their relative use, their significance and the comprehensiveness of such criteria varies from country to country, as is also the ways they have been applied**.** I have worked on many site selection programmes in countries as diverse as the UK, Japan, Spain, Russia, Iran, Slovenia, Croatia, Bulgaria and South Korea, for example, and the majority of these programmes applied such criteria – they are, however, very infrequently referred as criteria, as this is considered to imply more precision that should exist for some of the factors involved and might also imply a greater level of knowledge of the environment at depth than actually exists – better terms are attributes, guidelines, etc. Such 'criteria' were in effect employed by Uisdean and me in our definition of environments, both for RWMD and later for the EA (as outlined above).

Your statement: "*The suitability of specific areas is dependent on more than just their geology ...*" implies, unfortunately, that you have not appreciated how these environments for RWMD and the EA have been defined, nor how other countries have either applied such 'criteria' or are effectively applying them in the assessment of sites they are currently examining. These environments for the EA and the environments selected in other countries' site selection programmes were not selected on purely geological grounds but, as has been explained above, on a combination of geological, hydrogeological and hydrogeochemical factors. For example, the process by which Nagra have recently selected their preferred disposal environments (e.g. Nagra, 2008, 2010, 2011) and the methods which were employed over many years by Andra to chose the granitic sites on their short list (e.g. see Andra, 2006 – 78 granitic areas which lacked what Andra referred to unsuitable characteristics were initially examined) and subsequently to make decisions as to which three sites to investigate in detail, employed guidelines which are very similar to those that Uisdean and I applied in defining the environments for RWMD and the EA. As explained above, these were essentially similar to the guidelines and principles that Neil Chapman and I applied in 1986 for Nirex (Chapman et al., 1986).

The report for RWMD also included the expected hydraulic properties and porosities of each of the formations present in the six different environments (see Tables 1-4; Watson et al. 2007). Such values could be considered as 'criteria' in the sense of the term that has been used by DECC, but they probably should be viewed in a more nuanced manner. These values are based, as is explained above, on the known or expected characteristics of each of these formations and are based, to a great extent for some of the formations, on proxy data from similar formations – often examined in other countries' radioactive waste management programmes. I supplied the majority of such data for the RWMD report. Many years ago I also supplied the majority of such data to Nirex in their modelling activities in the 1980s as part of their R&D programme linked to the their site selection programme (as outlined below).

Here are two examples:

- Figure 5 assumes a Lower Jurassic potential host formation, but this type of potential disposal environment also extends to the south where the preferred host formation is more likely to be of Middle Jurassic age. In both cases the potential host rocks will have very low hydraulic conductivities. The Middle Jurassic host rock is similar in many respects to the Opalinus Clay in Switzerland (Nagra's proposed host formation in all their selected areas) and to the Callovo-Oxfordian Clay at Andra's Bure site. It is also similar to one of the formations tested in the deep boreholes drilled at Harwell in the early 1980s as part of DoEn's R&D programme - this programme was managed and run by the BGS). The testing of such formations in Switzerland over the last twenty years, in deep boreholes, in the research facility at Mt Terri, and also from an analysis of deep road and rail tunnels in the Alps, has provided a great deal of information on the properties of such formations, and these data are in agreement with extensive in situ testing by Andra at Bure and their experiments at Mt Terri. Testing of similar formations in the deeper boreholes at Fulbeck, as part of Nirex's site investigations at the four potential LLW disposal sites in the early 1980s, are also in agreement. The intrinsic properties of such low permeability, indurated mudstones have been shown to be determined by their mineralogy, water content and hydrochemistry, which are heavily inter-related (see for example, NEA Clay Club reports – Simon Norris at RWMD has access to these). Their properties are extremely stable, in particular their hydraulic properties, which cannot rise above certain values, except locally due to excess gas pressure (a potential problem with the disposal of LLW(LL) and ILW) or when associated with a significant fault zone. Any fractures that might exist in such formations are self-sealing or self-healing (see NEA Clay Club report on this subject, Bock et al. 2010) and, in fact, their hydraulic conductivities are so low that the transport of radionuclides through them is diffusion-dominated, although gas transport is likely to be episodic on the small scale. There is very convincing evidence from Nagra and Andra as to the excellent properties of such formations as host rocks for a GDF. One of the most convincing is the distribution of pore water chemistry across them which can be fitted to a modelled diffusional process, demonstrating that they have behaved in this manner for very considerable periods of time – many millions of years (Figures 8 and 9). The distribution of hydraulic heads also can be modelled in the same manner – the heads are out of equilibrium to the extent expected assuming the system is diffusion-dominated. It is thus possible, when considering such a formation at depths at more than approximately 200 m (based on evidence, for example, from an extensive analysis of data from Alpine tunnels by Nagra), to provide a range of hydraulic conductivities and porosities which are very likely to be close to the actual values – as has been done in Watson et al. (2007). The values provided for the modelling by RWMD and the EA are precisely in line with those used by Andra and Nagra, as the formations of interest in the UK were deposited at the same time as these to the south, in an environment that was very similar and, particularly with regard to the Callovo-Oxfordian clay at Bure, have similar subsequent compaction histories.

- As part of Nirex's safety programme in the 1980s different potential disposal environments were modelled – these included, for example, two BUSC environments (based on areas in East Anglia) and two potential environments at Sellafield – one for disposal in anhydrite offshore and one onshore where the host rock was the BVG. Based on the cross sections developed and the values ascribed to the properties of the formations present (which I supplied to Nirex when I worked at the BGS), groundwater flow and transport modelling was carried out to examine the differences in the performance of the various disposal environments. This information was used as input in the site selection programme. The values of hydraulic conductivity for the BVG basement rocks at Sellafield were, for example, provided as a triangular-shaped pdf (as this assumed least knowledge of the actual distribution). The pdf I provided in advance on any deep boreholes, based on the expected properties of this formation, was almost precisely the same as the actual distribution eventually measured after the testing of many deep boreholes, with respect to the 90% probability limits and the location of the maximum. I was slightly less accurate with respect to the overlying sedimentary formations, but not by a substantial margin, which meant that the modelling carried out before any boreholes had been drilled and tested was similar to that of the eventual models. The two attributes that were perhaps not appreciated was the extent to which there was a considerable measured upward head gradient, nor the complications caused by the very high salinities derived from offshore evaporites In retrospect, these should perhaps have been expected, due to the noticeable hydraulic head inland of the site due to the elevated topography of the Lake District and the fact that the presence of these evaporites was known. Otherwise, many of the values provided in advance of the site investigations proved to be reasonable, although the complexity of the geological and hydrogeological environments of the Sellafield area made such estimates liable to considerable error. In a less complex geological/hydrogeological environment, such as in a sedimentary environment with constant shallow dips with little or no faulting (e.g. Figure 7 and at Bure, Figures 2 and 4) or one in which the basement rocks are distant from major structural boundaries and in areas of subdued relief (such as Figure 6), such problems are unlikely to exist, or at least have a considerably lower significance. All the environments presented in Watson et al. (2007) are considerably less complex than the environment at Sellafield.

- There are many other examples I could provide on the use, for example, of proxy or estimated data in determining, in advance and before any site investigation programme has taken place, the expected properties of the relevant formations. In an area of relatively simple geology the likelihood of there being unexpected formations and rock types at depth is also minimised. It is thus perfectly possible and also defensible scientifically to be able to provide reasonable estimates of such properties which can be used in carrying out assessments in advance of any site-specific data and to help define the different types of disposal environments that are present in the UK. You will notice in Watson et al. (2007) that the magnitudes of the ranges given for some of what would appear to be rather similar formations do vary – this reflects the expected natural variability of the specific formation in question (due to, for example, the sedimentary depositional environment and the formation’s subsequent geological history, etc.) and also the level of uncertainty associated with the estimate. For some of the formations, e.g. the Oxford Clay, there is both extensive deep borehole data (e.g. from Harwell) and also comparisons that have been made of this formation with the Callovo-Oxfordian clay at Bure, which has almost identical properties.

This means that your statement: "*An important factor that has been taken into account in our proposed amended approach is that, although a lot is known about the general geological structure of the UK, particularly at shallower depths, there is significant uncertainty at the depths at which a GDF would need to be constructed. In particular, the hydrogeological and hydrogeochemical conditions in the 200 m to 1000 m depth range, which will have a strong influence on the potential suitability of an area, are not well known*." is thus incorrect or only partially correct. There is a considerable amount of evidence as to what these properties are likely to be, in the absence of any deep borehole data over a large part of the UK, as indicated above. For several parts of the country where there are few deep boreholes or relevant geophysical data, the geological environment is, in any case, generally unsuitable for hosting a GDF, e.g. over the majority of central and northern Wales.

The values and ranges for hydraulic conductivity and porosity presented in Watson et al. (2007) are in line with the values measured in other countries, with many of the data having been derived as part of their respective investigation and research programmes on radioactive waste disposal. The uncertainty in the some of the ranges varies quite considerably, but for some of the formations, e.g. the indurated mudstones at depths of more than 200 m, the hard fractured rocks again at depths in excess of about 100-200 m (in particularly the crystalline basement rocks) and the evaporites, the values are likely to be very close to the actual values. This is because there are definite physical and chemical constraints on the possible ranges of such parameters. It is only in specific locations within, say, an indurated mudstone at depth, for example within a fault zone, that its hydraulic conductivity can rise above a certain value. Similarly, in crystalline rocks it is mainly only within certain types of fracture networks and shear/fault zones that open fractures can be sufficiently well connected, with the result that the hydraulic conductivity can rise above a certain value – although there can be single, long, transmissive fractures, present that need to be avoided in locating waste canisters (see, for example Posiva, 2012). There is a very extensive literature on this subject regarding crystalline rocks, mainly from SKB and Posiva (see for example recent reports on LDFs and rock suitability criteria from Posiva, e.g. McEwen et al., 2012; Pere et al. 2012). Specific evaporites at depth, e.g. halite, have very well-constrained properties, based mainly on their precise mineralogy and content of impurities, such as clays (there are many reports from organisations such as DBE and BfS on this subject). Similar constraints exist regarding the range of porosities and effective porosities, with the result that the transport characteristics of such rocks can be reasonably well estimated before any specific site investigation data are obtained, by making certain assumptions regarding the extent of, for example, matrix diffusion.

Figures 8 and 9 illustrate the situation in the Callovo-Oxfordian clay at Bure and the Opalinus Clay in the Benken borehole in Switzerland (Nagra, 2002a,b) – formations very similar to these, mainly of Jurassic age, are also present in the UK at suitable depths over quite large areas of the country, although, of course, such detailed, site-specific information would not be available before at least one deep borehole had been drilled and tested. I have included it here to demonstrate the type of proxy data that are available for such potential host formations in the UK – such data can be used to demonstrate the likely values of the important properties of such formations, which can then be used as input to models of different types of potential disposal environment. Lots of this type of work has been carried out in many countries' site selection and associated R&D programmes and was extensively employed in the UK as part of Nirex's site selection programme in the 1980s – before Sellafield and Dounreay were selected for investigation. Extensive groundwater flow and transport modelling was carried out for different types of disposal environment as part of Nirex's CASCADE programme – five different cross sections in different parts of the UK were used to investigate the general performance of these different environments. This work is summarised in Chapman and McEwen (1991).

Figure 8 shows the δ^2H profile through the Opalinus Clay, which lies between two more permeable formations of the Malm and the Keuper, and a similar profile exists for chloride and other elements. The measured values have been compared with the results of a pure diffusion model, and the good fit demonstrates that there is no significant vertical advective flow, which implies that the hydraulic conductivity of this clay is substantially less than 10^{-10} m/s and very probably in the range 10^{-11} – 10^{-12} m/s. The value of such data, which is equivalent to a natural experiment, is that the results are relevant for long timescales (in this case perhaps as much as many millions of years) and over significant distances (again in this case more than 100 m). A similar result for the Callovo-Oxfordian clay with regard to the hydraulic head distribution is shown in Figure 9. Here the effective heads within the clay are substantially greater than the theoretical heads, based on the heads in the adjacent higher permeability formations. This is because the hydraulic conductivity of the C-O clay is so low that its response time to changes in head, due to natural processes such as erosion and uplift, which are in this region nevertheless insubstantial, is very slow; so that it will always be out of equilibrium. This is another means of demonstrating that this clay has a hydraulic conductivity in the range 10^{-11} – 10^{-12} m/s. The properties of the Oxford Clay beneath Harwell are almost identical to those of the Callovo-Oxfordian clay at Bure. Data of this type, therefore, provide convincing evidence of the stability of this type of natural system at depth – something that is of considerable advantage in being able to demonstrate the intrinsic suitability of such an environment for disposal purposes.

The hydrochemical conditions at depth can also be reasonably well-constrained. As is explained with regard to the selection of the environments for the EA and also in Watson et al. (2007), the relatively simple geological structure and the hydrogeological environment together place constraints on the hydrogeochemical environment, with the result that it is perfectly possible to make reasonable estimates of the likely conditions at depth regarding, for example, Eh and pH conditions. This has been done on several occasions as part of this and other countries' safety assessment programmes, in advance of any site-specific data (see for example several recent reports from Nagra setting out their proposals for using the Opalinus Clay as their preferred host rock for HLW disposal, Nagra, 2010, 2011).

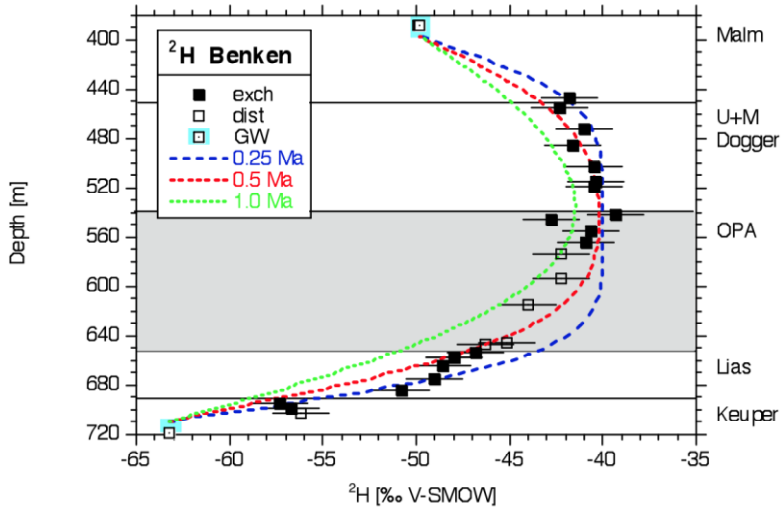

Figure 8. Natural tracer in porewaters in the Opalinus Clay (OPA) (grey) and surrounding formations. Best fit simulations of profiles of δ^2H for pure diffusion and constant concentrations in the Keuper and Malm. GW = groundwater compositions in under- and overlying formations (from Nagra, 2002a,b).

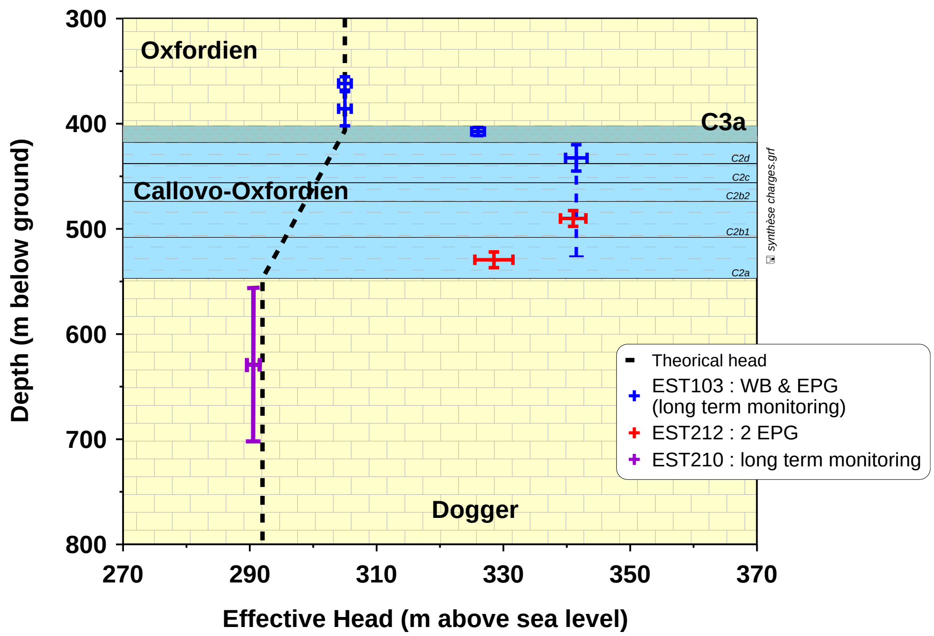

Figure 9. Pressure profile through the Callovo-Oxfordian clay and the surrounding aquifers at the Bure URL site. The theoretical head gradient in the clay (i.e. due to the heads in the adjacent aquifers) is shown for comparison (from Andra).

Concluding remarks

Whilst, therefore, you may wish not to have what you term *suitability screening*, you will need to present a far more cogent argument as to why you believe this approach is unsuitable. Asking the BGS to provide a series of regional guides, which would provide a geological model of each of the areas in plain English, would of course be useful in informing an early discussion with local authorities, etc., but such documents would not, in themselves, be sufficient. Unless there is also more information as to what types of environment at depth might be suitable for hosting a GDF, I cannot see what this would achieve, as very few local authorities, etc. have any knowledge of radioactive waste disposal not what other countries are doing to solve the problem. The recent review of site selection by the RWMD (RWMD, 2013) does not discuss such matters.

A good example of what might be necessary for the UK is the SKB report: *General Siting Study – Siting a deep repository for spent nuclear fuel*, October 1995, SKB Report 95-34. This report considers factors at a national and regional scale that would influence the siting of a repository, and was a requirement from the government in association with SKB's RD&D Programme 95. This would, of course, take a considerable time to produce, but rather than rush precipitously into yet another site selection programme that might end in failure, sufficient time needs to be taken to consider all elements of such a programme before it proceeds. I have been involved in all the UK's failed site selection programmes and abandoned R&D programmes associated with radioactive waste disposal since I started work in this field when I joined the BGS in 1978, and I do not wish to live through yet another failure.

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