Response to letter submitted to West Cumbria MRWS by Dr J. Dearlove dated 26 October 2011

David Smythe
7 December 2011

1 Introduction

This comment is a further response to my paper of 16 September 2011 [1], which elicited a reply by Dr J Dearlove of FWS Consultants, dated 26 October 2011 [2]. Dr Dearlove has also commented upon my paper dated 6 October 2011 [3] on the unsuitability of the Eskdale granite. I am grateful for these comments sponsored by West Cumbria MRWS, because they provide me with the opportunity to enlarge on some aspects of the geology and hydrogeology; his letter also demonstrates that the counter-arguments to my original case remain weak to non-existent.

2 Lack of sources

I witheld detailed citations in [1], because MRWS consultants such as Dr Dearlove should already be familiar with all the relevant literature, and I see no reason to do their homework for them. However, I note that in his latest response the only work that Dr Dearlove cites is a 33-year old summary review paper, 12 pages in length, by C.K. Patrick, from a general text on the geology of the Lake District. This is not the kind of secondary (and obsolete) citation that should be used in a serious scientific debate. In contrast, I drew on the following papers and reports in my study of the Solway Basin, with particular reference to the structural, petrological and hydrogeological characteristics of the Mercia Mudstone Group (MMG):

Authors	**Year**	**Pages**	**BGS**
Allen et al.	1985	11	Y
Maddox et al.	1995	20	
Forster et al.	1995	76	Y
Ivimey-Cook et al.	1995	13	Y
Duncan et al.	1998	15	
Jones et al.	2000	251	Y
Leicester City Council	2001	122	
Cooper	2002	16	Y
Hobbs et al.	2002	117	Y
Taylor et al.	2003	22	
Hughes	2003	21	Y
Holliday et al	2004	20	Y
Holliday et al	2008	14	Y
Howard et al.	2008	41	Y
Evans and Hough	2009	37	Y
BGS Georeport	2011	6	Y
Total number of pages		**802**	

The BGS column above indicates with a Y work emanating from the British Geological Survey (BGS). The list excludes the more general papers that I have studied, dealing with West Cumbrian or national geology. It also omits the additional dozen or more papers I have reviewed with the aim of expanding on the faulting in the MMG, discussed further below.

I also received from NERC under an FOI request the details of the Environment Agency groundwater abstraction licence information, quoted in the BGS screening report, in relation to the Solway Basin area. I have paper copies of all the relevant 1:50,000 scale BGS solid geology maps, as well as online access to the same in digital form. Similarly, I have online access to the 10 m Ordnance Survey digital elevation model (DEM), useful (*inter alia*) for a study of whether, for example, spring lines, or fine detail in the topography, could yield any new relevant clues about the underlying Triassic rocks of the Solway Basin.

So it would appear that Dr Dearlove is relying on very out-of-date sources, unless, of course, he is familiar with the body of work and reference sources referred to in the above table; if the latter is the case, then it would appear that the Patrick (1978) reference was the only one in which he could find a quotation to suit his purposes. This is discussed further below.

3 Comments restricted

Dr Dearlove is within his rights to restrict comments to what he considers his areas of professional expertise. In that case MRWS should have employed additional consultants to cover aspects of my arguments which Dr Dearlove feels he cannot address. I have amended and added to the list of unanswered issues and concerns in ref [1] not addressed the previous time by Dr Dearlove, and append the complete new list in the Appendix below.

4 The 'wider geological community'

Dr Dearlove concludes:

> "*I would re-iterate my earlier statement that I feel it is more Professor Smythe's personal opinion, and not the <u>opinion of the wider geological community</u>, that the entire MR WS Partnership area is geologically unsuitable, and should not progress to the next stage of the <u>current evaluation process to identify a potentially suitable radioactive waste repository site in the UK</u>.*" [my underlining].

Firstly, he is misrepresenting my views about finding a suitable nuclear waste repository, by conflating the current MRWS process, which involves only West Cumbria, with a hypothetical "*current evaluation process*" involving the UK. But there is no wider process involving the rest of England and Wales (Scotland is not involved). There is only West Cumbria. If there were, I would welcome such a development.

Secondly, he tries to represent me as a lone maverick earth scientist pitting his solo opinions against a supposed "*wider geological community*". Dr Dearlove has failed to produce evidence of this alleged "*wider*" community. A handful of consultants paid by MRWS Cumbria certainly does not constitute a wider community, and it most certainly is not independent. I, on the other hand, am merely collating the publicly available information from the *actual wider community of UK earth scientists*, as expressed by them in many published, and mostly peer-reviewed, research papers.

Thirdly, the scientific process is not democratic in the sense of being a vote by experts for or against a particular concept or theory, as he implies by the use of the comparative (and pejorative, in relation to myself) adjective "*wider*"; rather, it is the force, logic and predictive power of scientific arguments that should prevail.

5 Solway Basin: state of knowledge and hydrocarbon prospectivity

For this area Dr Dearlove states:

> *"Professor Smythe suggests the most recent BGS review of the geology of the Solway Basin, based on numerous and recent lines of evidence (including more than 40 years worth* [of] *oil industry data) already provides "a proper evaluation" of the Solway Basin. This opinion is not shared by BGS."*

Dr Dearlove does not provide any evidence or documentation to support his statement that the BGS does not believe that a "*proper evaluation*" of the Solway Basin exists. Does his information come from his "*brief discussions with the BGS*" to which I alluded in my critique [1] of his letter of 13 May 2011 [2]? If so, it is evidently unsatisfactory that alleged opinions of the BGS (including the apparent consideration of the Mercia Mudstone Group in the Solway Basin as a potential repository host rock, discussed in section 6 below) are reaching the MRWS process, filtered *via* informal discussions with a third party. What we need for the supposedly 'transparent' process are papers, statements, reviews, etc. directly from the BGS itself; anything else is hearsay.

Dr Dearlove goes on:

> *"It is also worth mentioning that following 40 years of exploration there are no oil/gas production fields identified in this area and thus it was not excluded by the BGS on the grounds of intrusion risk."*

The area was not excluded by the BGS screening exercise [4] on grounds of intrusion risk, but it should have been. The BGS did, however, exclude most of the Solway Basin in its national search of the late 1980s. Dr Dearlove has not commented on the fact that three sites in the Solway Basin were considered and rejected on geological grounds [1]. Although it is correct that after 40 years of continuous hydrocarbon licensing and exploration in the basin, hydrocarbons have yet to be found, exploration is currently proceeding. The BGS screening report [4] stated:

> "*Identification of suitable trap structures in the Partnership area has not been carried out as part of this exercise. However, two wells: Silloth 1 and West Newton 1 (Figure 11) have been drilled to test for hydrocarbons in potential trap structures and were abandoned as dry holes (Young et al., 2001). A third exploration well, Fisher Gill 1 indicates that the area is still prospective for oil and gas (DECC, 2010)*."

The Figure 11 referred to in the BGS screening report [4] shows the three wells and the three licence blocks. For a relatively simple basin such as the Solway Basin, it has been well-explored; it is well understood in overall geological terms, even though hydrocarbon reserves remain to be discovered. There is an active oil exploration licence and an active coalbed methane licence.

6 Mercia Mudstone Group (MMG)

6.1 MMG as an aquifer

Dr Dearlove accepts that the MMG is classed as a Secondary B aquifer, and goes on to quote the detailed description of such an aquifer, whilst also pointing out, superfluously, that it was formerly classified as a non-aquifer. He contrasts the MMG with the Borrowdale Volcanic Group (BVG), even though both are classed as Secondary B aquifers.

Dr Dearlove cites the following as a summary of the hydrogeology of the MMG:

> *"Patrick (Ref. 7) states the Stanwix Shales are similar to the St Bees and Eden Shales and form* [the] *confining aquiclude over the Kirklington Sandstone. Limited water movement will probably occur within them, as in the St Bees Shales, but faulting is never sufficiently intense to provide a breach. ... 7 Patrick, 1978. Hydrogeology in The Geology of the Lake District Edited by F. Moseley. Yorks. Geol. Soc. Occasional Publication No.3."*

This out-of-date reference (discussed above) is erroneous because faults with throws of the order of 100 m are known to cut the MMG. Therefore the combination of the "*limited water movement"* combined with the faulting, which breaches otherwise possibly isolated water bodies, in fact corroborates my conclusion that the MMG is inherently unsatisfactory as a host rock.

In my previous paper I referred to the fact that the MMG is used today for water abstraction. I said that:

> "*There are a dozen or more water abstraction wells within the outcrop area of the MMG. Some of these penetrate to more than 100 m*."

Dr Dearlove has not commented on this. I have now studied the well database in more detail. Some of the wells over MMG outcrop in fact abstract water from the overlying Quaternary, which can be up to 50 m thick, and not from the MMG itself. However, there are seven wells either abstracting, or have been tested for potable water abstraction, from the MMG, in the area north of NG northing 540000 and west of NG easting 336000. Tests of their flow rate yielded flows from 1.5 to 5.8 m^3/h (mean 3.7 m^3/h), and the boreholes depths were from 41-105 m (a mean of 77 m). Thus there is good evidence that the MMG in northern Allerdale is an aquifer, capable of supplying local needs such as farms. Incidentally, the greater concentration of water abstraction wells (of all types) towards Carlisle, as opposed to the western area around Moricambe Bay (NB not to be confused with Morecambe Bay south of Cumbria), presumably reflects the greater population density in the east, rather than a decrease of MMG aquifer potential to the west.

6.2 Regional continuity of MMG lithostratigraphy and hydraulic conductivity

The BGS describes the MMG of the Solway Basin lithology thus:

> *"The Mercia Mudstone Group comprises dominantly red-brown, locally grey-green, mudstones that are commonly silty; a few interbeds, up to 1 m thick, of very fine-grained sandstone have been noted. Two principal mudstone lithofacies have been noted, massive (structureless) and laminated. Cross-cutting fibrous gypsum veins are common throughout, and some intervals contain numerous gypsum-anhydrite nodules."*

Another BGS report states:

> "*As a basis for the rationalisation of Mercia Mudstone Group lithostratigraphy, we have identified a framework of five lithostratigraphical units (A to E, described below) that either possess, or can reasonably be inferred to have once possessed, a high degree of continuity. These units are mappable both at surface and in the subsurface on a regional rather than local basis, and thus comply with the definition of a formation*"

A 2008 sedimentological study emphasises the aridity or hyperaridity of the palaeogeography of the late Permian – Triassic sediments (including the MMG) of the Solway Basin, the lack of tectonic control, as well as their great areal extent. An analogy is drawn with the modern Chad Basin:

> "*In fact the entire assemblage of late Permian to mid-Triassic basins of Western Europe may simply be sub-basins within a larger Chadian-type intracontinental mega basin stretching from central Europe to eastern North America*"

So with such a high degree of lithostratigraphic continuity over 500 km within England (from Carlisle to the Channel coast), extrapolation and/or interpolation of physical parameters such as hydraulic conductivity, which depend primarily on lithostratigraphy (but also later diagenesis and in burial history), can certainly be made. Therefore the variety of hydraulic conductivity measurements of the MMG throughout England, particularly in the West Midlands and Cheshire, yielding values tending to the range $10^{-6} – 10^{-7}$ m s^{-1}, can be applied with confidence to the Solway Basin. Indeed, in central England, parts of this Group are known as 'Waterstones', because of their flowing groundwater characteristics, and this suite of rocks is correlated by BGS to be present in West Cumbria.

I therefore repeat my previous conclusion, that the MMG has a hydraulic conductivity ranging from ten thousand to millions of times higher than potentially suitable claystone host rocks elsewhere, and that this range of high values will be as applicable in the northern Allerdale district as elsewhere in England and Wales. Dr Dearlove's counter-claim, that "*Until we understand better ... we can only speculate on the hydraulic conductivity of the MMG*" is a classic example of the appeal to ignorance made by those who wish to muddy the waters.

So there is a vanishingly small chance that any significant volume of the MMG will turn out to have the required desirable hydraulic conductivity 10^4 to 10^6 times *lower* than what we can now infer from the existing database.

6.3 Redox environment

Dr Dearlove appeals to the reduction haloes (and bands) commonly seen in redbeds such as the MMG, arguing that this is evidence against an oxidising environment for the MMG:

> *"I assume Professor Smythe means that, as the MMG is generally red in colour due to the iron being in an oxidised state, this implies an oxidising environment. This is not true."*

He goes on to say that:

> "*interstitial groundwater at depths in excess of 500m (the proposed minimum depth for any potential repository facility) will be reducing as any oxygen from recharging groundwater will be consumed through biogeochemical reactions. It will also most likely be saline*."

In short, he is arguing that below about 500 m the hydrogeological environment will be extremely reducing; whether or not this is linked to the likely salinity of the groundwater below the same depth is not clear. Dr Dearlove links the geochemical attribute of 'oxidising' to the presence of dissolved oxygen, whereas it is well understood that geochemically oxidising (or reducing) depends on the electron flow between an assemblage of mineral ions dissolved in the groundwater. In that context, the desired oxidation state around an engineered repository is intended to be extremely reducing, with an Eh around -200 mV. That extreme Eh would geochemically change red iron III to green iron II, so that the rock colour would change. Dr Dearlove provides neither evidence nor measurement to support this assertion. However this is clearly unjustified, as drinking water extraction occurring from similar MMG mudrocks in Shropshire, Nottinghamshire and NW England shows that produced waters from the Sherwood Sandstone are very oxidising, with positive +500 Eh, which extends for 5 kilometres laterally beneath the MMG. The groundwater does, undoubtedly, become less oxidising with depth, and occasionally mildly reducing, but nothing as extreme as the values suggested by Dr Dearlove.

Additionally, the BGS reports that the Permo-Triassic formations encountered in the Silloth-1A well, in the centre of the basin, are typically red-brown, all the way down to about 1300 m. This would not be the case if the groundwater – particularly through the highly permeable Sherwood Sandstone aquifer – were severely geochemically reducing. I do not have the completion log for this well, but supply here instead two well log examples of MMG from the south of England – one onshore and one offshore. Table 1 shows the lithological descriptions of the cuttings from the MMG for these two wells, where the MMG is between about 1.4 and 2.0 km depth. Undoubtedly the porewater will be saline, but note the mention of red coloration and explicit mention of haematite – i.e. there is no sign of reduction. If Dr Dearlove's argument were valid, then all Permo-Triassic redbeds below 500 m or so would be reduced, and no longer red. This is not the case.

Dr Dearlove mentions reduction haloes in the MMG: a reducing environment is desirable in such rocks because it inhibits transport of radionuclides. This ignores the common observation that reduction haloes are small in size (centimetres to metres), and typically formed around isolated individual fragments of fossil organic debris, or reduced minerals such as isolated sulphide grains.

These haloes, in fact, clearly demonstrate that the rock formation outside the halo is geochemically oxidising compared to the formation within the halo. That rather disproves the point that Dr Dearlove is trying to make. But the presence of these haloes, or even bands, within the predominantly red, oxidising layers will have a negligible effect on inhibiting radionuclide transport; water will take the easy path around them. The haloes will be as about effective as putting isolated individual sandbags around a house to prevent it from flooding.

So his hope that "*the international requirement for a geological setting to inhibit movement of radionuclides could be achieved within the MMG*", thanks to the reduction haloes, is completely unrealistic.

Table 1. Well log descriptions of Mercia Mudstone Group (excluding Blue Anchor Formation and halites/anhydrites) Depths (tops) in m below Rotary Table

Well	Depth	Completion log comments
Bransgore-1 (BP, Dorset 1986)	*1354*	*Top Mercia Mudstone*
	1380	MUDSTONE: orange brown, red brown, firm, crumbly to angular break, silty, non-calcareous
	1430	MUDSTONE: red orange brown, firm, crumbly break, slightly silty, slightly calcareous, slightly swelling
	1460	MUDSTONE: red brown, crumbly break, firm, silty to sandy, very slightly calcareous
	1560	MUDSTONE, red brown, firm, crumbly break, silty, occasionally slightly sandy, slightly calcareous
	1570	SAND: translucent, medium to coarse quartz, sub rounded, loose
	1600	MUDSTONE: red brown, firm to moderately hard, angular break, silty, slightly sandy, slightly calcareous
	1620	SAND: transparent to red stained quartz, medium to coarse grained, rounded
	1635	*Top Sherwood Sandstone*
98/12-01 (Elf, Bournemouth Bay 1993)	*1733*	*Top Mercia Mudstone*
	1740	CLAYSTONE: medium grey to dark grey black, very calcareous to slightly calcareous, on bottom, firm to hard, subfissile grading to SHALE, micromicaceous, locally greenish, glauconitic
	1750	CLAYSTONE, purplish red brick, red, hard, iron oxyde [sic] stained, locally dolomite or anhydrite specks
	1800	CLAYSTONE: brick red, iron oxyde stained, locally grey green, generally non-calcarous, monotonous, occasional white anhydrite mottles
	1910	SAND: light grey to off white, very fine to silty, well sorted, firm to friable, slightly calcareous, abundant carbonaceous spots locally grain coating. Traces of fluorescence ...
	1950	CLAYSTONE: dark red brown, compact, uniform, Fe staining, in parts very calcareous, rare beds of ANHYDRITE …
	1975	CLAYSTONE: red, red brick, iron oxyde [sic] stained, occasionally dark grey, slightly to non calcareous, hard shaley, sandy, vey [sic] fine to fine, streaks to very thin levels of DOLOMITE …
	1990	… intercalations of SANDSTONE: pale grey, off white, very fine to fine, well sorted, spherical, subrounded to rounded, argillaceous, slightly calcareous, anhydritic …
	2040	CLAYSTONE: becoming mainly medium dark grey to reddish brown, non to slightly calcareous, anhydritic. Stringers of SANDSTONE: light dark grey, speckled black, very fine to fine …
	2090	CLAYSTONE/Shale: red purple, grey micaceous, haematitic, with very fine sand grains, opaceous, translucent, pocellanous, arenaceous, cherty
	2095	SANDSTONE: light grey, white very fine, rounded to subangular, well sorted, well cemented, calcareous, argillaceous, becoming red brown, very argillaceous, no visible porosity …
	2115	SILTSTONE: red brown, dense, haematitic, very micaceous, slightly sandy, traces of disseminated quartz grains
	2120	CLAYSTONE: red brown, uniform, silty, haematitic, basal cherts lense [sic]

6.4 Volume and depth of MMG available

Lastly, Dr Dearlove does not seem to have noticed that the maximum depth of the MMG in the one area where the MMG is deeper than 200 m (Silloth – Seaville – Pelutho, south of Moricambe Bay) is 500 m. According to him, the minimum depth for a repository is 500 m in this type of environment – presumably because he wants to place it where the groundwater will be saline. This is clearly not possible. The only possibility left is for a repository sited in the MMG between 200 and 500 m depth, in a *freshwater oxidising environment*.

Unfortunately for him this very limited option is even further constrained by the geology. The zone in question lies between two areas of BGS exclusion, one to the west, the other to the east. The southern part of the available area, around Edderside, is 3-4 km wide, and cut by the Crummock and other faults trending NNW-SSE. Here the MMG is around 400 m thick and deep. Further north the available area widens out to about 8 km in the Silloth – Seaville district, but is bisected by at least two important normal faults. There is further evidence (from interpretation of the logs of the Silloth-1A well by the BGS) that otherwise undetected normal faults transect this well, cutting out part of the succession. This is not surprising, as the well lies only about 1 km from one of the major N-S normal faults mapped by the BGS using seismic reflection data.

The minimum underground footprint of a repository (including Pu/U) in 'lower strength sedimentary rocks', such as the MMG, is around 20 km^2, according to the Entec environmental assessment report. Considering this as an area of dimension 4 x 5 km^2, for example, it is unlikely that a repository could be accommodated within this zone, which comprises two sub-areas on either side of the faulted horst block, each of about 30 km^2 in total area.

6.5 Hydraulic conductivity of faults cutting sediments

Dr Dearlove states:

> "*The MMG is cut by faults which can provide higher flow pathways. However, much depends on the nature of material infilling these faults/fractures/joints. Not all faults act as high hydraulic conductivity pathways. I don't believe there is a detailed hydrological* [sic] *study of these faults available to make this interpretation*."

The literature on the fluid sealing or conducting properties of faults in sediments is large and confusing. Research is driven by the need to understand sealing of hydrocarbon reservoirs at depths of 2-3 km on the one hand, and engineering properties of faults in the near-surface (down to a few hundred metres), especially in unconsolidated sediments. Nuclear waste repositories fall between these two stools. In addition, the subset of research into the effects of faulting in pelitic rocks is very limited.

My brief and necessarily incomplete review of the field leads me to the following impressions and tentative conclusions:

- There are field measurements of faults at outcrop and at shallow depth; it is realised that small-scale structures associated with faults dominate the bulk hydrogeological properties. These are characteristically fractures sub-parallel to the master fault plane, which are collectively termed the 'damage zone'. Such zones can be several metres to tens of metres in horizontal width, and are often the locus of fluid flow up or downwards, rather than across the master fault plane.

- In an unconsolidated mixed sand/clay stratigraphy, the conductivity in the damage zone can be enhanced by several orders of magnitude, but clay smearing along the core fault plane reduces the bulk conductivity.

- Iron oxide re-precipitation in the core fault, due to the enhanced flow in the damage zone, is another mechanism which can reduce the core conductivity.

- There are ample underground samples, tests and tunnel sections of the Opalinus Clay in Switzerland, which has an extremely low hydraulic conductivity (10^{-14} to 10^{-12} m s^{-1}), and in which even the fault zones show no sign of flow below 200 m depth.

- Studies of the Opalinus Clay show that it has self-sealing properties; the excavation-disturbed zone in such rock initially has hydraulic transmissivities several orders of magnitude higher than the protolith, but that it decreases by two orders of magnitude in about two years.

- The relative hydraulic conductivity of a fault cutting indurated low-conductivity clays is neutral; i.e. the conductivity of the fault zone remains within the same order of magnitude as the unfaulted clay. An example is the set of measurements across the Down Ampney fault, made by the BGS, in which Oxford Clay is juxtaposed against Oxford Clay or Forest Marble Clay.

- However, the same dataset shows that the conductivity of the fault zone as a whole is enhanced by one or two orders of magnitude, because the succession includes limestones and sandstones as well as the aforementioned clays.

- Smectite in shear zones can be dehydrated to anhydrous illite minerals as a shear fabric develops; this in turn can account for overpressure build-up. This mechanism accounts for high hydraulic conductivity observed in accretionary wedges, but contradicts laboratory experimental studies suggesting that sheared clays in fault zones represent aquitards.

Professor R. Lunn and her colleagues have recently modelled the fluid flow pathways across models derived from detailed outcrop observations. Starting with their summary that:

> "*Faults can be barriers to flow, conduits, or combinations of the two, and their hydraulic properties vary considerably over both space and time*",

they conclude from their study that the *micro* properties as opposed to the *average* hydraulic properties in a fault zone are crucial, but that these properties are *unmeasurable at depth*. A multi-variate stochastic approach is the only way forward, they say, which:

> "*implies that a very large database of fault architecture is needed to accurately characterize fault permeability distributions. This can only be achieved by pooling a large number of field datasets. This would require an international consensus on the recording of the gross parameters (e.g., lithology, offset, stress history) and the architectural detail at each site*."
> [NB authors' emphasis on *very large*].

Such a probabilistic approach to characterising the hydraulic properties of faults was tried by Nirex in its Longlands Farm site hydrogeological models, and found to be wanting. So the "*detailed hydrological study*" that Dr Dearlove requires for the MMG faulting will never be achieved except in a generalised probabilistic manner, and after the internationally agreed database has been built up. Such a database will presumably take many years to assemble. Incidentally, Professor Lunn is a current member of CoRWM.

In view of the confusing and complex nature of the current research into hydraulic conductivity in faulted clay rocks, together with the pessimistic (but realistic) view that the microscopic properties of faults can never be predicted at depth, the only rational decision in the search for a suitable clay repository is to avoid all such areas of faulting, and to find a suitable unfaulted clay formation. I have already alluded to the Opalinus Clay and the Oxford Clay as examples of potentially suitable formations. The MMG is not such a formation. It is also worth mentioning that a 3D seismic survey of one of the prospective Opalinus Clay repository sites in Switzerland shows that there exists no fault with a throw of greater than 4 m within the proposed clay volume; 4 m is the resolution limit of the 3D seismic imaging.

6.6 MMG: summary

To recap and summarise why the MMG remains unsatisfactory for consideration as a repository host rock in northern Allerdale:

- The MMG was (rightly) not previously considered as a host rock by the BGS during its national search in the late 1980s.
- This region is the subject of current hydrocarbon exploration licenses and should be excluded.
- The regional hydraulic gradient is high, contrary to international guidelines.
- A repository would have to be sited at an undesirably shallow depth of between 200 and 500 m.
- The one candidate area with these depths available is bisected by normal faults with throws of up to 100 m.
- The geology is well understood, thanks to oil industry seismic and the Silloth-1A well.
- The geochemical environment of these haematite-bearing red beds is oxidising.
- The groundwater is fresh, and exploited within this zone as an aquifer.
- The hydraulic conductivity is 10^4 to 10^6 times higher than that considered desirable by reference both to international guidelines and to current international practice.
- It is an ineffective seal for hydrocarbons if less than at least 600 m thick; this is *a priori* hydrogeological evidence that if used as a repository host rock it will be ineffective as a barrier.
- It is cut by large faults which may act as water conduits.

It is therefore irrational for Dr Dearlove to have proposed the MMG as a possible repository host rock. I therefore re-affirm my previous conclusion that the MMG is an unsuitable host repository formation.

7 Regional hydraulic gradient

Dr Dearlove selectively comments on my statement that the Solway Basin area will have a hydraulic gradient of about half that of the Sellafield (Longlands Farm) area, but he does not appear to accept that it is still an unacceptably high gradient. He then goes on to make the inference that, because I have admitted that this one aspect of the geology and hydrogeology is <u>less unfavourable</u> than at Longlands Farm (my 'least unsuitable'site), I cannot then conclude that the whole of West Cumbria is unsuitable. But the Solway Basin remains an unsuitable area because of a combination of unfavourable geology, *plus* the high hydraulic gradient. So his inference is invalid.

8 Eskdale granite

8.1 Faulting

Dr Dearlove disputes my conclusion that "*it is clear that the granite is haevily* [sic] *faulted, unlike most other granites in the UK*". He contrives to finesse this simple observation, demonstrated by reference to the BGS maps of the Eskdale and other granites, with my further (and perfectly reasonable) inference that, due to the poor exposure, the observed degree of faulting as shown on the BGS maps of Eskdale is an underestimate. Table 2 shows the degree of faulting of the three granites for which I showed maps [3]. The fault lengths quoted above include the faulted margins. My further analysis of the underestimate of faulting in the Eskdale granite, due to poor exposure and lack of lithological variety, suggests that the faulting is underestimated by a factor of 2 to 5, depending on the locality.

Table 2. Fault density in granite bodies

Granite	Area (km^2)	Fault length (km)	Fault density (km per km^2)	Exposure of solid geology (%)
Eskdale	77.2	86.7	1.1	20
Arran	107	0	0	70
Red Hills, Skye	41	1.2	0.03	95

I presume Dr Dearlove is not trying to denigrate the mapping expertise of the BGS. On the other hand, he produces no evidence to suggest that the Eskdale granite is in fact unexceptional in its degree of faulting. Whether one accepts my inference that the true degree of fault density is up to about 5 km^{-1}, or agrees only that the minimum observed mean density of 1.1 km^{-1}, from Table 2 above, my conclusion remains that the *Eskdale granite is heavily faulted*.

Lastly, if we go by the rule of thumb that the throw of a normal fault at any point is of the order of one-tenth of the distance to the end of the fault, then within the observed (mapped) faults within the Eskdale granite, there are 15 fault segments with throws of more than 100 m at the centre of the mapped fault, within the total set of 53 fault segments which all have throws of more than about 17 m.

8.2 Permeability

In reply to my discussion of high permeability zones within the Weardale granite, Dr Dearlove states:

> "*High permeability zones were reported on in* [sic] *the Weardale Granite, and commented on by my colleague Dr F W Smith. The high permeability zones he attributes to a lack of infilling of hydrothermal fractures during mineralisation in a known vein fissure, and* ***NOT*** *to the present day stress field as claimed by Professor Smythe*." [my underlining].

I did not mean to imply that Dr Smith himself attributes the high permeability zones to the present-day stress field, but my statement was not clear enough. I used the phrase "*A recent discussion by Dr F.W. Smith*" when I should also have included the other authors Younger and Manning in the Discussion and Reply; it was they who made the suggestion in their Reply, not Dr Smith. However, what they propose is based upon one of two explanations offered by Dr Smith for the unusually high permeability:

> "*The approximate north–south strike of the fractures is almost orthogonal to the trend of the Slitt Vein itself, which perhaps favours the second of the two structural explanations offered by Dr Smith (i.e. Tertiary reactivation). This is because the present principal stress direction for this region of England is currently considered to be approximately north–south … , and it may well have maintained a similar orientation back into the Tertiary period. It may be that uplift and exhumation within a stress field with a principal axis oriented north–south led to orthogonal faulting along the margins of the vein-filled Slitt Vein wrench fault, and that these fractures provide hydraulic connectivity into the Slitt Vein structure as a whole, which despite lying subparallel to the minimum stress axis for this region still appears to be highly permeable*."

Note, however, that Dr Dearlove does not comment on the main issue, which is the likely existence of extremely high permeability zones within other '*granitic terrains*', as postulated last year by Younger and Manning in a separate paper. This is surprising, given that his colleague Dr Smith is clearly an expert on the subject.

8.3 Groundwater

Dr Dearlove is himself an expert on geochemistry of groundwater. He states:

> "*The "strong" evidence presented to support the argument that groundwater in the Eskdale Granite is oxidising, namely the speculative statement by the BGS that elevated uranium in stream sediments over the outcrop of the Eskdale Granite is from scavanging (although it should be noted not necessarily from the Eskdale Granite itself which is low in uranium), is **NOT** "strong" evidence. The presence of haematite mineralisation does not indicate the presence of modern day oxidising groundwaters at depths of up to 1 km within the Eskdale Granite. At a depth in excess of 500m it is highly unlikely that potable, oxidising ground waters will be present in the Eskdale Granite.*"

There are three points here:

1. The explanation for the elevated uranium in stream sediments.
2. Haematitite mineralisation and modern-day oxidising groundwaters.
3. Depth limit of 500 m to potable oxidising waters.

Under point (1), he dismisses the BGS explanation as "*speculative*" while offering no alternative explanation.

Under point (2) he denies that there is a link between "*modern day*" groundwaters and the long-term oxidising environment implied by haematite; But the presence of haematite is just the sort of geological evidence we need to be able to infer with confidence the *long-term* groundwater state. Unless Dr Dearlove can come up with evidence that the groundwater, both today and in the geological past, is severely reducing, not around zero to oxidising, then he needs to re-enter discussions with the BGS geologists, this time about Eskdale, and ask them to revise and publish their explanation.

Under point (3) he introduces the 'magic' figure of 500 m as the depth below which the groundwater (he asserts) would be saline *and* reducing. Let us accept for the moment that he is correct, and that a repository could therefore be sited at (say) 600 m depth within the granite:

- Is he therefore relying on a purely fluid boundary between the reducing waters surrounding the repository and the oxidising waters above, all within a supposedly homogeneous rock, as the final barrier for the safety case?
- Will this barrier not migrate up and down over different climatic periods in the future, due to changes of sea level, and variations in groundwater flow beneath glaciers?
- Will it not be breached by convective flow, caused by the heat (and hence upward flow of groundwater) due to the storage of heat-generating HLW?
- How will this groundwater boundary resist gas escape from the repository?

In conclusion, his arguments against the postulated oxidising groundwater history are weak to non-existent, whether or not one accepts my qualifying adjective 'strong' for the arguments in favour of this oxidising history. As an expert in this field he should have been able to come up with some more convincing alternative scenarios.

8.4 No comment offered

Dr Dearlove offers no comment on the BGS interpretation of the western margin of the Eskdale granite, as seen on profile, as a complex 'cedar tree' structure, and with the interior of the granite holding large rafts of country rock.

9 Conclusion

Dr Dearlove's attempt to refute my arguments concerning the unsuitability of the Solway Basin area and the Eskdale granite are unconvincing. He has not addressed all the issues, but his arguments concerning what he has selected for discussion are a mish-mash of:

- Surprisingly weak evidence at best (e.g. the reducing spots within the MMG).
- An almost *ad hominem attack* on myself, suggesting that I am a lone voice.
- Hearsay evidence relayed by him from the BGS.
- One woefully outdated citation of the literature.
- Continued appeal to the alleged lack of sufficient knowledge.
- The optimistic hope that contentious geological issues will be addressed in MRWS stage 4.

On the last issue, stage 4 studies, it is worth repeating Dr Dearlove's comment from his letter of 13 May 2011 [5]:

> "*I would agree, in general, with Professor Smythe that the MRWS Stage 4 technical criteria for the selection of areas for further investigation is lacking in detail. I believe it may be this uncertainty in the Stage 4 evaluation criteria that exacerbates the current disquiet as to whether or not the MRWS Partnership should proceed to Stage 4 and the fear that, irrespective of past events, the former Longlands Farm site will emerge on the potentially suitable site list at Stage 4, possibly at or near the top in terms of priority*."

He encapsulates perfectly my own views about the inadequate and biased nature of the search process, based on the unjustified placing of 'voluntarism' ahead of geological suitability, and my suspicion that the whole exercise is indeed geared to a return to Longlands Farm. I shall expand on this last point elsewhere.

References

[1] Smythe, D. Response to letter submitted to MRWS:Cumbria by Dr J. Dearlove. 16 September 2011.

[2] Letter from Dr J. Dearlove of FWS Consultants Ltd to West Cumbria MRWS Partnership dated 26 October 2011 (document no. 237).

[3] Smythe, D. Unsuitability of the Eskdale granite as a host rock for high- and intermediate-level nuclear waste. 6 October 2011.

[4] British Geological Survey 2010. *Managing Radioactive Waste Safely: Initial Geological Unsuitability Screening of West Cumbria.* Commissioned Report CR/10/072.

[5] Letter from Dr J. Dearlove of FWS Consultants Ltd to West Cumbria MRWS Partnership dated 13 May 2011 (document no. 175).

Appendix

Dr Dearlove has completely ignored, or made no substantive comments on, various detailed issues and concerns I raised, including:

1. The removal from the NDA website of the vast bulk of Nirex documents, so that there is no record of the 1995-96 Planning Inquiry.
2. The fact that Cumbria is an exceptionally well-understood region, geologically.
3. The flawed, politically skewed, site selection process of the late 1980s.
4. The unsuitability of the coastal zone south of the Esk estuary and west of the Lake District Boundary Fault.
5. The fact that the Longlands Farm site, which I describe as the 'least unsuitable' site in West Cumbria, is highly complex, its location tightly constrained on all four sides, and with unpredictable hydrogeological flow.
6. The stillborn attempt by Nirex to argue that had the Nirex-97 set of science documents been available in time, the outcome of the Inquiry might have been different.
7. The discussion of the extensive oil exploration and wealth of resulting seismic and exploration well data in the onshore Solway Basin, much of it interpreted and published by the BGS.
8. The essential three-dimensionality of the limestone belt, illustrating what I mean by 'complexity' of geology.
9. The fact that the increase in computing power since 1995 does not imply greater accuracy in modelling.
10. My synthesis of EU and international guidelines for deep geological disposal, together with the Inquiry Inspector's observations, that all agree on the desirability of both low hydraulic gradients and simple geology.
11. Thinness of the Preesall Halite Formation in the Solway Basin.
12. Thickness of at least 600 m of MMG for it to be an effective hydrocarbon seal.
13. The BVG has a hydraulic conductivity three to four orders of magnitude less than the MMG.
14. The MMG in two areas within Allerdale DC and outwith the BGS initial screening area is at shallower than 300 m depth, and therefore should be excluded.
15. The MMG is cut by significant faults.
16. The MMG is nowhere deeper than 500 m in the Solway Basin.
17. The MMG is currently used for water abstraction (seven wells; see above).
18. The inappropriateness of his citing the Grimsel test site in Switzerland as an example of a site in a high hydraulic conductivity region.
19. The Anthorn candidate site in the Solway Basin, investigated by the BGS in the 1980s but rejected on geological grounds.
20. The previous exclusion by the BGS, both nationally and in the Solway Basin, of the MMG as a potential host rock.
21. Comparison of the hydraulic conductivities of the MMG and the Gault Clay.
22. Hyperpermeable zones within granitic terrains, based on the Weardale granite.
23. Unfavourable present-day stress regime in the Eskdale granite.
24. Inhomogeneity and complex 'cedar-tree'structure of the western margin of the Eskdale granite.
25. The fact that the Eskdale granite is pre-orogenic, thus accounting for its exceptional complexity.
26. The fact that 'normal' post-Caledonian granites in the UK are completely unfaulted.
27. Comparisons of the Eskdale granite with the low-relief gneisses currently being considered for waste repositories in Finland and Sweden.
28. The omission of the Eskdale granite from the 1980s BGS national survey of potential waste repository sites.