Why a deep nuclear waste repository should not be sited in Cumbria: a geological review

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West Cumbria is an area in which the landscape and the working lives of local people are dominated by the underlying geology. (Peter Cook, Director, British Geological Survey, 1997)

Summary

The assertion by the Committee on Radioactive Waste Management " *that there is presently no credible scientific case to support the contention that all of West Cumbria is geologically unsuitable.*" is reviewed and refuted. The current criteria for examining potential suitability of sites for waste disposal are examined and found to be essentially devoid of geological content; the Managing Radioactive Waste Safely process is saying merely that a 'suitable host rock' will be chosen. In effect, the Nuclear Decommissioning Authority is regressing the understanding of the geology of potential repository sites by a generation.

The Potential Repository Zone at Longlands Farm was selected by a scientifically irrational process in which the political need for a site at an existing nuclear facility took precedence over rigorous assessment of the geology. The concept of basement under sedimentary cover (BUSC) was misappropriated to make sure that the site was shortlisted, despite having been introduced very late in the search process. The prior national search by the British Geological Survey (BGS) had identified no such category of site anywhere in NW England.

The coastal strip of West Cumbria is well understood but highly complex. The Longlands Farm site, although flawed, is the least unsuitable location in the region. It failed the test of the public planning inquiry of 1995-96. Northern Cumbria, between the National Park and the Solway, is geologically even more complex. The whole northern region under consideration has been the subject of hydrocarbon exploration for 40 years; applying logically the exclusion criteria defined by the BGS means that it should have been screened out.

National and international criteria for choosing a suitable waste repository are in agreement that the geology should be simple and predictable; the site should be located in a region with low hydraulic gradients. A significant change in view from the 1980s, however, is that to permit the possibility of marine discharges is now considered unlawful. Sellafield falls into such a category, since Nirex modelling of the flow paths from a leaking repository predicts such a discharge.

The regional hydrogeological regime in west and north Cumbria is dominated by the presence of the Cumbrian mountains. The extreme relief is about twenty times greater than desirable for categories of waste repository hosted in crystalline rocks. That fact alone is sufficient to characterise the region as hydrogeologically unsuitable, quite apart from the demonstrable complexity of the geology.

The well-understood geology and hydrogeology, and hence the inherent safety of any chosen potential site, is categorically against the region's suitability to host a nuclear waste repository. New searches should be undertaken elsewhere in England and Wales.

1. Introduction

The purpose of this review is to refute the assertion by the Committee on Radioactive Waste Management (CoRWM), in a letter to the Cumbrian Managing Radioactive Waste Safely group (MRWS) dated 16 February 2011, in which it stated:

> "*Our position is that there is presently no credible scientific case to support the contention that all of West Cumbria is geologically unsuitable.*"

and

> "*Our position is informed by our collective understanding of the requirements of the level of detail and quality of geological knowledge that is needed in order to move from the broader considerations of unsuitability, as used in the BGS screening study, to the more specific assessment of potential suitability in MRWS Stage 4.*"

MRWS Stage 4 above is discussed in the Nuclear Decommissioning Authority (NDA) document *Geological Disposal: Steps towards implementation* [1], which refers back to *A Proposed Framework for Stage 4 of the MRWS Site Selection Process* [2].

2. Scope of the review

I shall define West Cumbria to be the coastal plain comprising the Region defined by Nirex (Fig. 1, taken from ref. 3, fig. 1). It extends from Workington in the north to Barrow-in-Furness in the south, inland for 15-20 km from the coast, and 50-70 km out to sea to the west. Within this region there is defined a District, and within that the Site, a rectangle of 8.0 x 6.5 km^2. The Nirex definition of District corresponds approximately to the British Geological Survey (BGS) definition of the 'west Cumbria district' in its 1997 memoir [4]. Inside the Site there is defined the Potential Repository Zone (PRZ).

Following on from that I shall discuss the Solway coastal plain, extending from Workington NE towards Carlisle, an area which falls almost entirely within Allerdale District Council. Lastly I shall discuss the National Park itself.

3. Analysis of MRWS Stage 4

Let us consider the "*specific assessment of potential suitability in MRWS Stage 4"* cited by CoRWM, for which it is necessary to analyse the NDA document *Geological Disposal: Steps towards implementation* [1]. This is the document on which CoRWM's opinion rests. CoRWM has also been made aware by this same document of the "*requirements of the level of detail and quality of geological knowledge that is needed*".

One might have expected geology to comprise a large portion of this document, given the subject-matter, but this is not so: Chapter 4 deals with the geology in two and a half pages, out of a total of 65 pages of text. The approach is to:

> *"define a limited number of generic geological settings, encompassing typical, potentially suitable UK geologies"*.

The statement quoted above might further have been expected to lead the reader directly to the generic geological settings developed specifically for the UK by BGS and Nirex scientists in the 1980s by Chapman *et al*. [5], which have become a somewhat of an international benchmark. These include the well-known settings such as seaward-dipping sediments, small islands, basement under sedimentary cover (BUSC), and so on. But no; it is as if 40 years of prior research never existed. Instead, the geological settings are defined by a brand-new table categorising *host rocks* and *cover rocks*, (reproduced herein as Fig. 2). There are no supporting sketch or generic geological cross-sections.

What is the information content of this NDA table? I have ringed together the two entries in the middle Host Rocks column, because they say the same thing – sediments all the way from top to bottom. So there are only four distinct ‘Possible’ table entries. The table appears to have been devised by someone with poor logical faculties and negligible geological expertise. In particular, it does not allow for any lateral variation; that is to say, it is one-dimensional, in that rocks are either above or below. In contrast, the geology of West Cumbria is not merely two-dimensional; it is highly three-dimensional. What that means, put simply, is that any given geological cross-section – which is a two-dimensional construct – has rapidly reducing validity as it is shifted sideways (in or out of the page), because the geology changes so rapidly.

For easier comparison with earlier work I next replace in the table ‘higher strength rocks’ by *Basement*, which is a valid and familiar term in the UK context, and ‘lower strength sedimentary rocks’ by *Sediments*. This does not alter the information content of the table. The table can then be expressed more succinctly by a simple list:

- **Basement from repository depth to the surface**
- **Sediments from repository depth to the surface**
- **Sediments over basement**
- **Sediments over evaporite**

The five white boxes in the table have become four items above, because of the duplication ringed in Figure 2. We can contract this list further, and also put the host rock first:

- **<u>Any rock</u> from repository depth to the surface**
- **<u>Basement</u> under sediment(-ary cover) i.e. BUSC**
- **<u>Evaporites</u> under sediments**

provided only that the host rock (underlined above) is ‘suitable’, which of course should go without saying. Next, we omit evaporites, since they are not relevant to West Cumbria (the reason why is discussed below), and contract the list further, to obtain:

- **Any suitable host rock - whether covered or not by sediments**

The phrase above referring to the cover rocks is clearly superfluous, so we end up with:

- **Any suitable host rock**

In conclusion, once we omit the special case of evaporites acting as cover rocks, the NDA definition of ‘*generic geological settings’* is telling us nothing. The geological information content of the NDA analysis is essentially zero. The NDA is taking the geological aspects of repository search backwards by about 40 years, to the era when only the host rock was considered, and what lies ‘*Before, behind, between, above, below*’ (John Donne) was of no significance.

In my opinion this is a scientifically disgraceful state of affairs. Not only is the large corpus of prior research on generic sites discounted as if it never existed; it has been supplanted by ill thought-out waffle, signifying nothing. But such corporate amnesia appears to be a deliberate policy by the NDA, into which Nirex was subsumed in 2005. For example, the NDA website only provides online access to 36 documents dating from prior to 2004; the vast bulk of Nirex research has been removed from online availability, even though some of it was accessible a decade ago.

Returning now to CoRWM's assertion in the statement quoted above " … *our collective understanding of the requirements of the level of detail and quality of geological knowledge that is needed ...*", it is difficult to infer what exactly CoRWM means by this statement, given that the MRWS Stage 4 definition is effectively devoid of any meaningful geological content.

Given this void in NDA understanding of the geology (or, more precisely, NDA's *public admission* of what it understands), let us next examine the research that has actually been carried out.

4. Current knowledge and understanding of the geology

4.1 Introduction

The science of geology was developed largely in the UK in the late 18th century. The Lake District, or Cumbria, has been a classic study area since around 1800. David Oldroyd, an historian of science, has written a memoir on the history of geological research in the Lake District [6]. He recounts the development of Nirex work in West Cumbria, the geological arguments put forward pro- and anti-Nirex at the planning inquiry, and the subsequent events up to 2001. Even before any Nirex-sponsored research was started in West Cumbria, the region was already as well understood as any other region in the UK. Post-Nirex, the region has become exceptionally well understood.

4.2 How Longlands Farm came to be selected

The BGS was involved in early searches for suitable intermediate- and low-level nuclear waste repository sites in the 1970s, but the effort which led by a roundabout route to the choice of Longlands Farm began afresh in the 1980s. It should be noted here that the general geological advice given to government by the BGS (that is, the areas of search and the categories of potentially suitable rock formations) has not subsequently been found by any later detailed investigations to be flawed.

The national study by the BGS resulted in a map published in *The way forward. A discussion document* by Nirex in 1987 [7]. The coastal plain of West Cumbria was included under 'Areas of potentially suitable sedimentary formations', contiguous with the eastern Irish Sea, Solway Firth and onshore Solway Basin around Carlisle (Fig. 3). But no BUSC environment was identified anywhere in Cumbria. This is a factually correct finding by the BGS; there was no inadvertent omission.

The site search was conducted for Nirex by Pieda [8], relying, of course, on the BGS for the geology. The remit was to find potential sites onshore, accessed from a land base, or sub-seabed sites accessed from a coastal land base. The hydrogeological environments were:

1. Hard rocks in low relief terrain
2. Small islands
3. Seaward dipping and offshore sediments
4. Inland basins
5. Low permeability basement rocks under sedimentary cover (BUSC),

explicitly following the classification by Chapman et al. [5]. An initial list of 537 sites [9] was compiled, with the following classifications:

1. BUSC inland
2. BUSC coastal
3. Coastal

4. Hard rock coastal
5. Hard rock inland
6. Inland
7. Sedimentary coastal
8. Sedimentary inland
9. Small island
10. Ex-AOS coastal (AOS = area of search)
11. Ex-AOS inland.

In this initial list 'Sellafield' appears once, no. 433 in alphabetical order, and classified as 'Sedimentary coastal'. This site later became known as Sellafield-A. The target host rock was impermeable anhydrites of Permian age known to be present in the region. However, the Sellafield-3 borehole, drilled in early 1991 at the coast inside the Sellafield Works, confirmed, as suspected a few years previously, that the anhydrites were too deep there, at 1270 m depth and deeper, to be of use as a potential repository. They feather out inland at approximately the same line as the limit of the Carboniferous Limestone.

Nirex has recently tried to document the history of the site selection process [10], as part of its new, belated, policy of transparency. However, the account is disingenuous, because it describes the site 'sieving' from the initial 537, down to the last few, and then leading to the final choice of Longlands Farm, without ever clarifying when, exactly, this particular version of a 'Sellafield' site appeared in the lists. Thus, for example, the document lists comprehensively the sites *excluded* at each stage of the sieving process, but without declaring the initial list. To rectify this omission I have compiled a fresh initial list [11] from the Pieda documents.

The Nirex site selection review goes on to account for the apparent "*late introduction*" of the 'BUSC option' at Sellafield by explaining that:

> "*Some "sites" had two or more repository options associated with them which would potentially exploit different geological or hydrogeological settings believed to lie under the site and which would be located at correspondingly different locations on the site*." [10, section 7.5].

This is incorrect; there are four instances in the initial list of 537 sites (Colchester Barracks, Farnborough, Long Marston and Risley) where sites under both the same ownership and geological setting have been identified separately, even though they are less than 5 km apart. So Nirex is trying to argue here that the initial single 'Sellafield site' was really intended all along to include the Pelham House School option (Sellafield-B), which lies 3 km north of Sellafield-A, *and* which belongs to a different classification. Nirex's explanation is unconvincing. The reasonable conclusion is that Sellafield-B was in fact only introduced late on in the site selection exercise.

Even more curious than this omission is the assertion in the document that at the sieving exercise of December 1987, when 39 sites were whittled down to 17 onshore, Sellafield-A was not "*discussed*", whereas a new site Sellafield-B was discussed - having evidently just been introduced. Apparently the interpretation of the seismic data by then available had suggested that the anhydrites (the Sellafield-A option) would be too deep – as was later confirmed by the Sellafield-3 borehole. Clearly, the attempt to find a site within the vicinity of the Sellafield Works was distorting the whole process in 1987 – just as it is doing in 2011.

Sellafield-B, the so-called 'BUSC option', was located at Pelham House School. But even Sellafield-B was not the final choice of Potential Repository Zone (PRZ). As the Inquiry Inspector [12] states:

Nirex moved the location to Longlands Farm in 1989 to avoid the Carboniferous Limestone present under Sellafield B. The Newton Manor Estate, including Longlands Farm, had been offered for sale to BNFL in 1987, but was not purchased until March 1989 [12, para. 6B.31].

6B.34 The geological and hydrogeological requirements within the PRZ include a minimum of 100 m to 200 m of BVG cover over the DWR and a maximum depth below ground level of 1000 m. The PRZ is contained by the presence of permeable Carboniferous Limestone to the north west, the Fleming Hall Fault Zone (FHFZ) to the southwest, the Seascale Fault Zone (SFZ) to the southeast and the National Park boundary (A595T), where BVG cover is reducing, to the north east …. The 2 fault zones are presumed to be associated with enhanced hydraulic conductivity. [12].

To summarise the site search exercise; nowhere in West Cumbria is there to be found a true BUSC environment. The only environment identified by BGS in the search exercise was the (seaward-dipping) coastal sedimentary strip west of the Lake District Boundary Fault, within which it was hoped that the known anhydrite formation would prove to be a suitable candidate. Neither Sellafield-B nor Longlands Farm were in the initial search list. The Inspector was not impressed by Nirex's attempts to justify these two sites as so-called 'BUSC variants':

" … there seems to be little strength in the belated argument that Sellafield B is itself a form of BUSC site. The claim tends to confuse the description with the basic concept. The BGS has not mapped any BUSC area in West Cumbria."[12, para. 6B.99].

Leaving aside the politically-driven site selection process which led to Longlands Farm, and considering that PRZ on its own merits, it can be concluded from the Inquiry evidence that the location was nevertheless the best available within the region. It had already been shifted from the earlier 'BUSC' option of Pelham House School, to avoid the Carboniferous Limestone subcrop there. It is highly constrained on all four sides. The Site area (Fig. 1) is as probably now as well understood in geological 3D as any comparable volume of rock in the world – including oil fields.

The deep geology of West Cumbria is now so well-understood that there is no realistic possibility that a new PRZ could be discovered that is geologically simpler than at the chosen Site. Since Longlands Farm failed the test of the Inquiry, it would be irrational simply to move to a new location somewhere else within West Cumbria. But in order to pre-empt a possible counter-argument along the lines of '*We have not yet studied in detail the other localities, so how do we know that other suitable locations do not exist?*' – as is implied by the first CoRWM statement quoted above - I shall next summarise the relevant geological detail in each locality to demonstrate that the other localities in West Cumbria are even less suitable than Longlands Farm.

4.3 *Coastal district of West Cumbria: geological details*

I have juxtaposed the BGS exclusion zone map from its initial screening report of 2010 [13] with a preliminary outline map showing the potential areas of interest in Figure 4. The Site rectangle is outlined in red, and the National Park boundary is denoted by red dots. These outlines will help to serve as points of reference on later maps.

Figure 5 shows the coastal geology south of the Sellafield site. There is a narrow strip of onshore Triassic outcrop, up to half a kilometre wide, from Haverigg in the south up to Sellafield, bounded by the Lake District Boundary Fault (LDBF). The fault surface dips west at about 60°. The Carboniferous Limestone seen at outcrop in the SE corner underlies the whole Triassic outcrop here [4, map 5]. To be more precise, the coastal zone lies within the Lake District Boundary Fault *Zone*, a 2-3 km wide zone of normal faulting [4, fig. 12] bounded by the LDBF *sensu stricto* on the east. The LDBF has suffered earthquake fault movement within historical time. The strip is entirely within the National Park (the boundary marked by red dots).

The geology of this district is evidently unsuitable for considering a repository site either within the sediments, or within basement below the sediments. The possibility of emplacing a ‘hard rock’ site within the Eskdale granite will be discussed below.

Moving north into the Longlands Farm Site district, Figure 6 shows the 1:250,000 geology map overlain by the sub-Permian map [4, fig. 29]. The LDBF runs NNW, then widens out into the LDBF Zone. The zone of complex faulting to the west, including part of the offshore area, comprises the Lakeland Terrace [4, fig. 16]. Both the histories and displacement senses of the faults are highly complex. For example, the High Sellafield Fault Zone in the centre of Figure 6 is interpreted as “*a continuous structure with normal displacement down to the east. However, at shallower levels …it is an echelon structure consistent with a sinistral component of strike-slip. Where the fault zone is mapped onshore it includes a significant antithetic fault and has the character of a complex flower structure with oblique and reverse components of displacement*” [4, pp. 31-32].

Both the Woodland Fault and the Seascale-Gosforth Fault Zone, each with a NE-SW trend, acted as transfer faults. Figure 6 shows how tightly constrained was the Sellafield PRZ, as the Inspector noted (quoted above). The limit of the Carboniferous Limestone subcrop is marked by the change from fawn to hatched-grey. Tracing this northwards on Figure 6 it runs into the LDBF Zone, then into the BGS exclusion zone marked by red hatching.

Lest anyone remain under the illusion that the chosen Site was simple and predictable, geologically speaking, Figure 7 should serve to remind them of the complexity of the Site. The faulting at base Brockram (Permian) is shown [3, fig. 8] with the limit of the Carboniferous Limestone subcrop again superimposed. A 3D block model view of the structure at base of the Permo-Triassic is shown in Figure 8 [3, fig. 14]. The view is to the NW, and there is no vertical exaggeration. The Permo-Triassic has been removed to leave just the Carboniferous (blue) and repository host rock, the Borrowdale Volcanic Group (BVG – green). The sticks are the boreholes. It should be borne in mind when looking at this model that a the top-basement surface of a true BUSC model should be planar and flat-lying. The faults, shown here as white surfaces, extend up into the overlying cover rocks – again, this is contrary to the BUSC concept.

This structure is extremely difficult even for a trained earth scientist to interpret, in the sense that it is not at all clear which faults moved in which order. It is very probable, given the uncertainties in building the model, that it contains errors. Furthermore, the chances of predicting accurately the fluid flow through such a model, when the fluid-mechanical properties of the faults and fractures is so ill-understood, are very poor. That is why a regime like this is too complex to be considered for a repository.

The NDA has recently claimed that the Nirex97 set of science documents, issued after the end of the 1995-96 Planning Inquiry, had solved many of the problems discovered by the Objectors at the Inquiry itself, and that the outcome of the Inquiry might have been different, had Nirex97 been available in time. This assertion is not true, and has since been withdrawn by NDA.

Moving northwestwards to the northern end of the West Cumbria district as defined by Nirex and the BGS (Fig. 1), and the northern limit of the Nirex Region, we move into the exclusion zone defined by the BGS initial screening exercise. The geology of the northern flank of the National Park and the plain bordering the southern shore of the Solway Firth is dealt with in the next section.

4.4 *Northern Cumbria: geological details*

The deep structure of the northern part of Allerdale District Council is geologically very well understood thanks mainly to oil exploration surveys (seismic reflection profiles and drilling) that has taken place over the last 40 years.

Figure 9 shows a selection of maps demonstrating the existence of hydrocarbon exploration licences in the region, some dating back to the 1970s and possibly earlier. I have put these together (Fig. 10) to show that they form one contiguous area, which runs from Carlisle and points east, round the northern and western margins of the National Park, and down into the Site quadrant defined by Nirex around Longlands Farm.

The BGS screening report [13] is inconsistent and illogical regarding the hydrocarbon exploration that has been carried out here, and the risk of possible future 'intrusion'. Firstly it states:

> "*Natural Resources exclusion criteria are based on a potential geological resource that might be the focus of exploration and/or exploitation in the distant future, leading to penetration or 'intrusion' by boreholes or mining activities into an 'unknown' engineered repository located at between 200 to 1000 m depth.*"

The logical deduction from this statement is that if there is sound geological or historical evidence that exploration boreholes have been, or might be, drilled, then the area should be excluded.

However, the interdiction is then restricted – illogically - only to *discovery* hydrocarbon wells. Defining the exclusion criteria in more detail, the screening report continues:

> "*These include ...The presence of <u>known</u> hydrocarbon (oil or gas) resources*" [my underlining].
>
> "*Exploration for oil and gas ('conventional hydrocarbons') has taken place in the north of the Partnership area, but no resources have been proved. Consequently, although a part of north Allerdale is currently licenced for oil and gas exploration, the area has not been screened out at this stage since it does not represent a known oil and gas field.*"
>
> "*A third exploration well, Fisher Gill 1 indicates that the area is still prospective for oil and gas*"

Firstly, we cannot rule out the possibility that hydrocarbons remain to be discovered, even though they have not been to date. Secondly, how can we know that a future society will not try again to find hydrocarbons here, and, whether or not they are successful, perhaps penetrate an unknown waste repository? In conclusion, the fact that hydrocarbon exploration has been going on for a generation or more should be sufficient evidence to rule out the area.

Notwithstanding this general stricture on hydrocarbon resources as an exclusion criterion, let us examine the geology summarised in the map of Figure 11. There are two geologically distinct districts left in play following the BGS screening exercise (red square hatching):

- The belt of Carboniferous Limestone outcropping approximately around the edge of the National Park, and
- The deep sedimentary basin with Triassic at outcrop.

The Carboniferous Limestone outcrops in a fringe around the crystalline basement rocks of the National Park, the latter forming the mountains. Concentrically outward from the limestones are the Coal Measures, which have been excluded by the current BGS exercise, and are therefore hidden below the hatching. The Carboniferous dips generally radially outwards away from the heart of the Lake District mountains.

Figure 12 is an extract from the 1:50,000 scale geology map used by the BGS for the screening exercise [13, fig. 8]. Being more detailed (and of more recent origin) than the 1:250,000 scale map used previously herein, it shows that the Carboniferous is sliced up by a myriad of faults, particularly with NW-SE and E-W trends. Such a density of faulting probably exists also within the Triassic as well, but has not been mapped due to poor exposure. In contrast, both the limestones and the coal measures have been mapped extensively in the past because of their economic value.

Figure 12 demonstrates the essential three-dimensionality of the geology; for example, shifting the location of a NW-SE cross-section, such as that along line AB, by as little as 1 km will yield the same generalised section, but the detail of the faulting and other structures will be very different.

The purple segment of cross-section AB located in Figures 11 and 12, extracted from the screening report [13, fig. 9], is shown in Figure 13 to illustrate the complexity of the limestone and coal measures belt. By 'complexity' in the context of a potential repository, I mean features including:

- Variety of lithologies
- Folding
- Angular unconformities
- Faults cutting through both basement and cover rocks
- Faults intersecting the ground surface
- Faults intersecting each other at shallow depth (< 1 km)
- Three-dimensionality

All these features are present in the limestone belt. They would make it effectively impossible to characterise accurately the hydrogeology by three-dimensional fluid flow models. In brief, the limestone belt is even more complex structurally and stratigraphically than the Longlands Farm Site.

This leaves the localities underlain by thick Triassic and older rocks shown in Figure 11. This corresponds generally to the area identified in the mid 1980s by the BGS near Carlisle as having potentially suitable sedimentary formations (Fig. 3). The St. Bees Evaporite Formation has potential, in principle, as a host rock. It is present offshore in West Cumbria, and was proved in the Sellafield-3 borehole at the coast, as noted above. However, it is not present onshore in northern Allerdale, where it would underlie the Sherwood Sandstone Group indicated in Figure 12. If it were present offshore beneath the Solway Firth it would be at too great a depth for a repository, as was the case in West Cumbria.

4.5 The National Park

Could a site be found within the National Park itself, assuming that such a possibility was politically acceptable? The discussion above has been confined either to sites in sediments, or else to the BUSC category. The National Park comprises hard rock at outcrop. However, it does not come into the hydrogeological category of 'Hard rocks in low relief terrain' used by Pieda in 1988, because of the extreme topography. Pieda did find a number of sites categorised as 'Hard rock coastal'or 'Hard rock inland' in its initial list of 537 sites. One site in the former category and one in the latter category (Dounreay and Altnabreac, respectively) made it into the final ten-site shortlist.

Figure 14 shows the topography of Cumbria compared with that of Sutherland, at the same scale and with the same colour relief shading. The Sutherland sites come into the category of 'Hard rocks in low relief terrain', although the relief is a lot higher than the hard rock sites being investigated in Canada, Sweden and Finland.

For illustration, consider a potential hard rock site such as within the Eskdale granite, shown in red in Figure 5. A putative site could be located in lower Eskdale, but just east of the LDBF. The hydraulic gradients here would be several times higher than at the Sutherland sites, and probably an order of magnitude higher than at the international hard rock sites. So such a site may be in hard rock, but it is certainly not in low relief terrain; evidently it does not conform to any acceptable generic category, quite apart from being close to a major UK fault zone.

The same problem of extreme relief and hence high hydraulic gradient applies to any similar site in the National park area of Copeland and Allerdale District Councils.

5. Regional and international criteria

5.1 Introduction

The aim of choosing a suitable site for a deep waste repository is the safety of future generations, typically up to 100,000 years from now. When (and not *if*) the repository leaks, the natural geological environment must be such as to minimise the rate of flow of contaminated fluid, and to try to keep it at depth.

The predictions of fluid flow to make an acceptable safety case can only be made using models which are simple. If models are built from complex geologies they will inevitably be full of multiple errors, omissions, false or dubious assumptions, and so on, and therefore unsafe. There has been recent discussion that the increase in computer processing power since the Nirex planning inquiry era will now facilitate the accurate computation of complex models. Processor speeds have increased by about 1000 times between 1995 and 2010; processor memory capacity (RAM) and disk storage capacities have increased by a similar factor. But the potential here for increase in *precision* must not be confused with *accuracy*. We may now be able to model the flow through a fault zone represented in a 3D computerised mesh (a finite-element model) by thousands of nodes, instead of a couple of dozen nodes as in 1995, but since we still have little idea whether any individual fault is a barrier or a conduit to fluid flow, and still less the magnitude of the conductivity, the fact that we can now generate and compute models thousands of times more complex than fifteen years ago is of little import.

In other words, the increase in computation power since 1995 does not permit us now to revisit failed complex potential repositories such as Longlands Farm, in the expectation that plugging in a more detailed physical model, computed far more quickly than hitherto, will circumvent the fundamental problem of incomplete knowledge of a volume of rock which is just too complex.

5.2 The BUSC concept

The geology of the BUSC concept is locally one-dimensional, in that the geology is effectively 'layer-cake' – plane flat-lying layers one above the other; there are no faults or folds within a few kilometres of the site, and lateral facies variation takes place only on a regional scale. Groundwater flow (which will, however, be two-dimensional) is hardly driven at all because there is a negligible hydraulic head due to low topographic relief. There is no need to consider three-dimensional flow, because of the simplicity of the geology. The cover rocks act as a barrier to any possible upward flow; any flow in shallow layers (the top one hundred or two hundred meters) is insulated from deeper flow by an alternating sandwich of hydraulically more and less conductive beds. In brief, such a concept leads to predictable groundwater flows.

The diagram originally used to illustrate the BUSC concept [14] is shown in Figure 15. Note the huge (x56) vertical scale exaggeration. The re-drawing by Chapman *et al.* [5] of the BUSC concept for the UK environment is flawed in several respects; the onlap of the sediments over basement is too rapid in horizontal scale; the structure of the top-basement surface is exaggerated; and the folding within the sedimentary cover is unrealistic.

Comparing now the prototype BUSC diagram shown in Figure 15 with the alleged 'BUSC' geology of West Cumbria (Fig. 16), we see that there is effectively no similarity between the two. The shortening by a factor of 20 of the UK model relative to the coastal plain of Maryland, USA, together with a concomitant increase in vertical scale by a similar factor means that the essence of true BUSC has been lost. This was all pointed out by Objectors at the Planning Inquiry and accepted by the Inspector.

To call any area in western or northern Cumbria 'BUSC' is reminiscent of the architectural vogue for calling high-rise residential tower blocks 'vertical streets', as if one can imbue the block with the neighbourhood-friendly characteristics of a terraced street simply by renaming it.

5.3 International guidelines on regional hydrogeological flow

The geological disposal of nuclear waste is governed by national regulations, by EU treaties (e.g. Euratom), legislation and guidance, and by international indicative guidelines from the International Atomic Energy Authority (IAEA). The international guidelines are a general framework for individual countries to use in developing their own disposal strategies. So in the UK case, the generic geological environments developed by the BGS in the 1980s [5], and discussed above, still apply. Concerning the desirable regional hydrogeological regime, ref. 5 states:

> "*the 'site selection' exercise needs to be primarily based on defining what are considered to be suitable large scale hydrogeological environments. In some senses this reduces the emphasis on the host rock itself, and places it much more on the larger scale geological environment. … In the simplest terms these features will be characterized by:*
> *- Predictable groundwater flow paths, preferably long and resulting in progressive mixing with older, deeper waters or leading to discharge at sea;*
> *- Very slow local and regional groundwater movements in an area with low regional hydraulic gradients …*"

In 1994 the IAEA published its own guidelines [15]. This paper is due to be superseded by an update labelled DS 334. The Inquiry Inspector made frequent reference to the 1994 IAEA paper, which was cited in the Inquiry documents as GOV/507. He summarised the locational principles set out in the guidelines; I quote here from the Inspector the parts of the IAEA guidelines bearing directly on the geology and hydrogeology discussed above:

> "*6A. l l … The guidelines are not meant to be complete, neither should they be applied in isolation but used in an integrated fashion for an overall optimisation of site selection…. In summary, the DWR* [deep waste repository] *locational criteria are:*
> *…a geological setting to inhibit the movement of radionuclides from the (DWR) to the environment during the time periods of concern …;*
> *…sufficient distance from geological discontinuities that could provide a rapid pathway for radionuclide transport: uniform rock formations in comparatively simple geological settings and formations with few major structural features or potential transport pathways are preferred;*
> *… restricted groundwater flow but sufficient dilution capacity …*"

The Inquiry Inspector concluded:

> "*8.42 Although the general international and national criteria for the location of a deep waste repository are merely indicative guidance, 2 overriding principles can be derived from them. One is that the location should be in a region of low hydraulic gradients, so that there should be slow-moving and long groundwater pathways: and the other is that the geology and hydrogeology of the site and its district should be readily characterisable and predictable.*"

In 2009 the Joint Research Centre of the European Commission published *Geological Disposal of radioactive waste: moving towards implementation* [16]. This re-states the essential requirements of the geology and hydrogeology:

> "*Fundamental criteria include, for instance, long geological stability, low hydraulic gradients and permeabilities, low geochemical and other potentials, etc. In other words, a geological system is sought out that exhibits in its natural state a low potential for change and very slow rates of change.*"

All these guidelines on the desired large-scale hydrogeological environment are remarkably similar. However, there has been a change in international law regarding marine discharges. The possible flow path "*leading to discharge at sea*" considered in the 1980s [quoted from ref. 5 above] was considered unacceptable a decade later. The Inspector pointed out that the UK site selection process had *"some predisposition towards maritime settings"* which seemed to be *"contrary to international law"*, and, of course, that Sellafield was one such site. He concluded that there would have to be *"exceptional justification for locating a repository near the sea"*. Pathlines such as those predicted in Nirex97 for the Sellafield PRZ (Fig. 17, taken from ref. 17) would appear to contravene international law, since the mere acquiesence of a current local population under the voluntarist approach can hardly constitute "*exceptional justification*".

The IAEA guidance document from 1994 does not mention marine discharges explicitly. Presumably this is one instance where the forthcoming revised guidelines will be more precise. The OSPAR Commission for the protection of the North-East Atlantic (www.ospar.org) has guidelines on radioactive discharges.

5.4 *Regional hydrogeology of western and northern Cumbria*

So far I have established that the complexity of the geology around the western and northern fringes of the Lake District should rule out any future search for a waste repository in the region. One site, the Sellafield PRZ, has already been studied in extreme detail, and found wanting. In addition, the general hydogeological flow from mountains to the sea will rule out any future site in international law if the behaviour of such a site is such that a leaking repository is predicted to result in marine discharge.

The regional hydrogeology is fundamentally straightforward at the present day (i.e. in the current climatic conditions). Figure 18 shows the conceptual picture for the Sellafield PRZ [18]; a similar picture will apply anywhere in the region. The overall flow from right to left in this picture is simply controlled by the hydraulic head of the Cumbrian mountains. The division into 'Hills and Basement' and 'Coastal Plain' regimes is a second-order effect. The first-order effect is due to the topography, together with the rainfall, of course.

The topographic relief is extreme. This has already been pointed out in respect of the BUSC concept. In order to demonstrate how extreme the topographic relief of Cumbria is, Figures 19 and 20 compare, at the same horizontal and vertical scale, Cumbria with the Wash area, respectively. Eastern England, within which The Wash lies, is an area with a lot of potential for finding a true BUSC environment for a waste repository. In fact, as the Inquiry Inspector pointed out, Site no. 6

of the 1998 site selection exercise should have been scored highest, were it not for the undue weighting given to Sellafield-B in the 'multi-attribute decision analysis'(MADA) exercise. Site 6 is at Stanford, Norfolk, just to the south of the perspective view shown in Figure 20.

In conclusion, the extreme topographic relief of Cumbria, driving the regional underground water flow, is sufficient to rule out, *a priori*, consideration of any locality around the margins of the Lake District for a waste repository. It is evident that the only reason that Cumbria remains in consideration once again as a region where a repository is being sought is socio-political. The fundamental nature of the geology and hydrogeology, and hence the inherent safety of any site, is categorically against the region.

6. Conclusions

In my view, the evidence is unequivocal that the geology and hydrogeology of West Cumbria are both sufficiently well known and well understood that it is possible to say that no alternative site to the previously chosen 'least unsuitable' option of Longlands Farm can be found in the region.

CoRWM is therefore mistaken in its view that suitable localities remain to be found within West Cumbria. It is irrational to assert that more research needs to be done in the region when public money can be more effectively spent in searches elsewhere.

The voluntarist approach evidently needs to be fundamentally re-thought, or else scrapped, so that geologically more suitable localities elsewhere within England and Wales can be investigated – they are known to exist.

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[17] *Nirex 97: an assessment of the post-closure performance of a deep waste repository at Sellafield. Summary report.* (Nirex science report S/98/015, December 1998).

[18] *Nirex deep waste repository project. Scientific update 1993.* (Nirex report no. 525, December 1993).

List of figures following text

The figures are also available separately as a Powerpoint file.

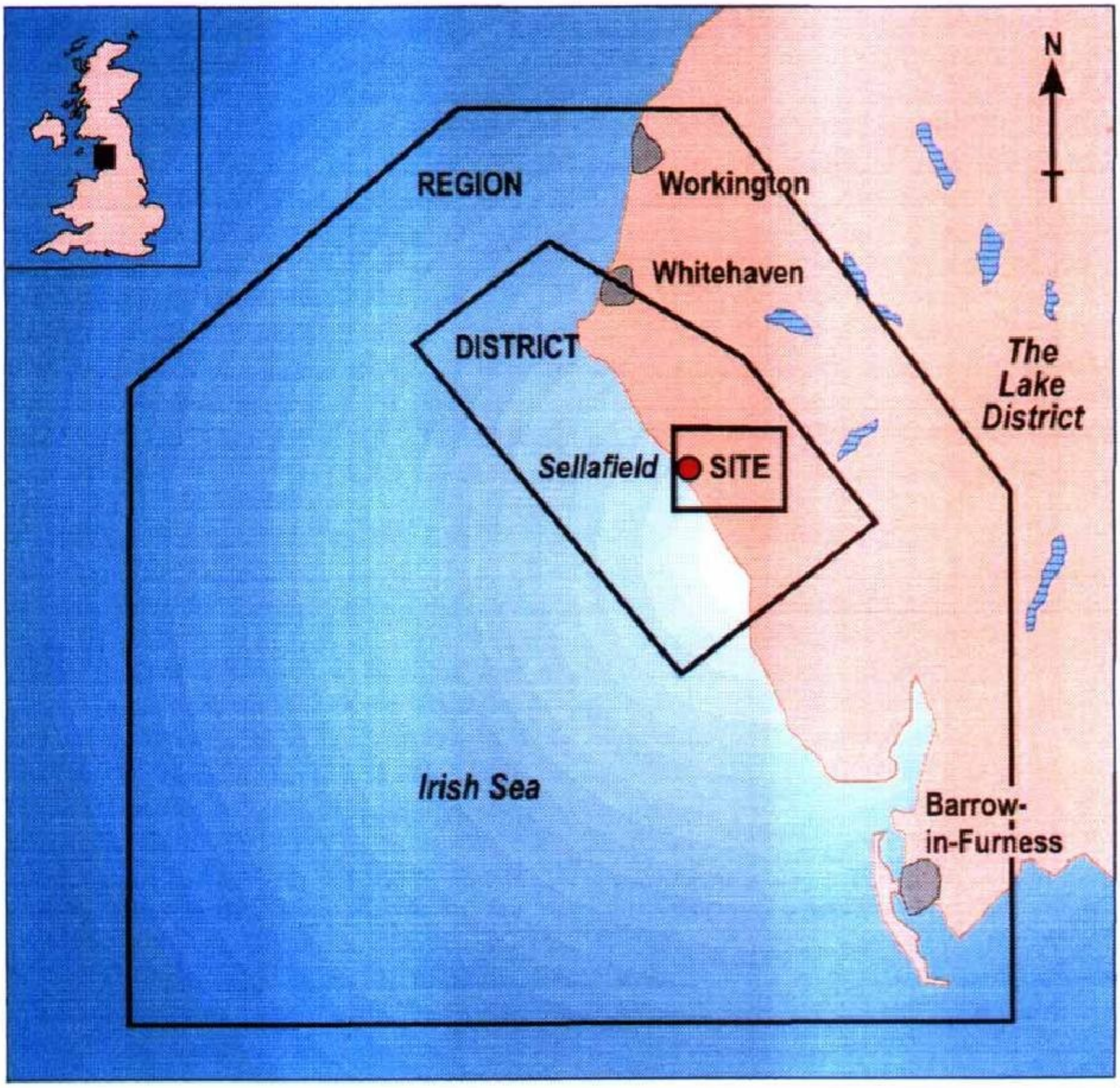

Fig. 1. Region, District and Site, as defined by Nirex in West Cumbria, from ref. 1.

		Host Rocks		
		Higher strength rocks	Lower strength Sedimentary rocks	Evaporites
Cover rocks	Host rocks to surface	Possible	Possible	Not possible
	Sedimentary cover rocks	Possible	Possible	Possible

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Fig. 2. NDA table 4.1. Host rocks and cover rocks [ref. 2].

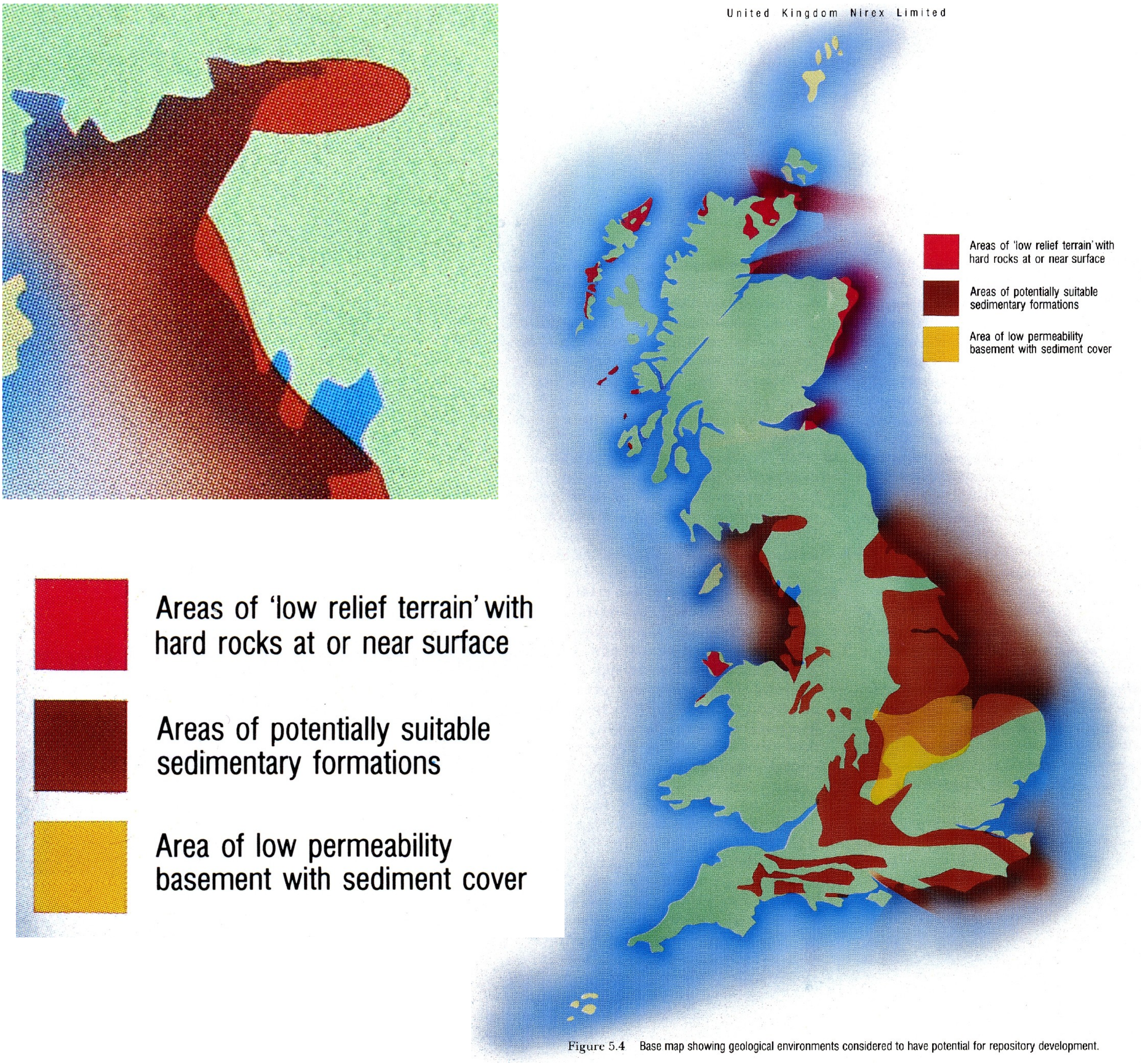


Fig. 3. Main map: areas of potentially suitable geology identified by the BGS in the 1980s [ref. 7]. Inset above shows Cumbria and the NE Irish Sea at an enlarged scale.

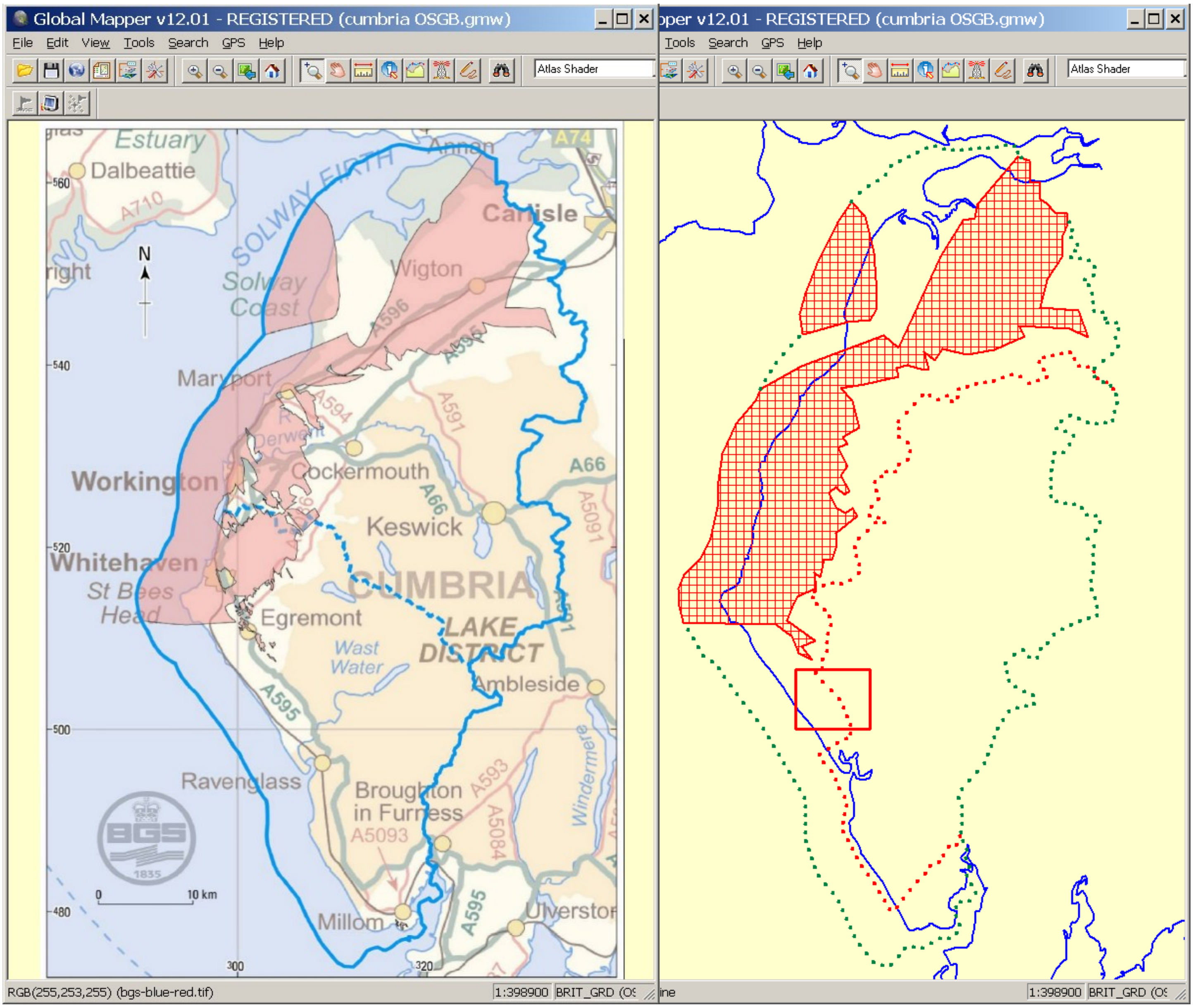


Fig. 4. Digitised outlines (right) compared with the BGS overview map (left) [ref. 13] . The green dotted outline is the area of Copeland and Allerdale District Councils; red dots show the National Park boundary within this area, and red square hatching shows the BGS exclusion areas. The Site rectangle (solid red outline) has been added from Figure 1.

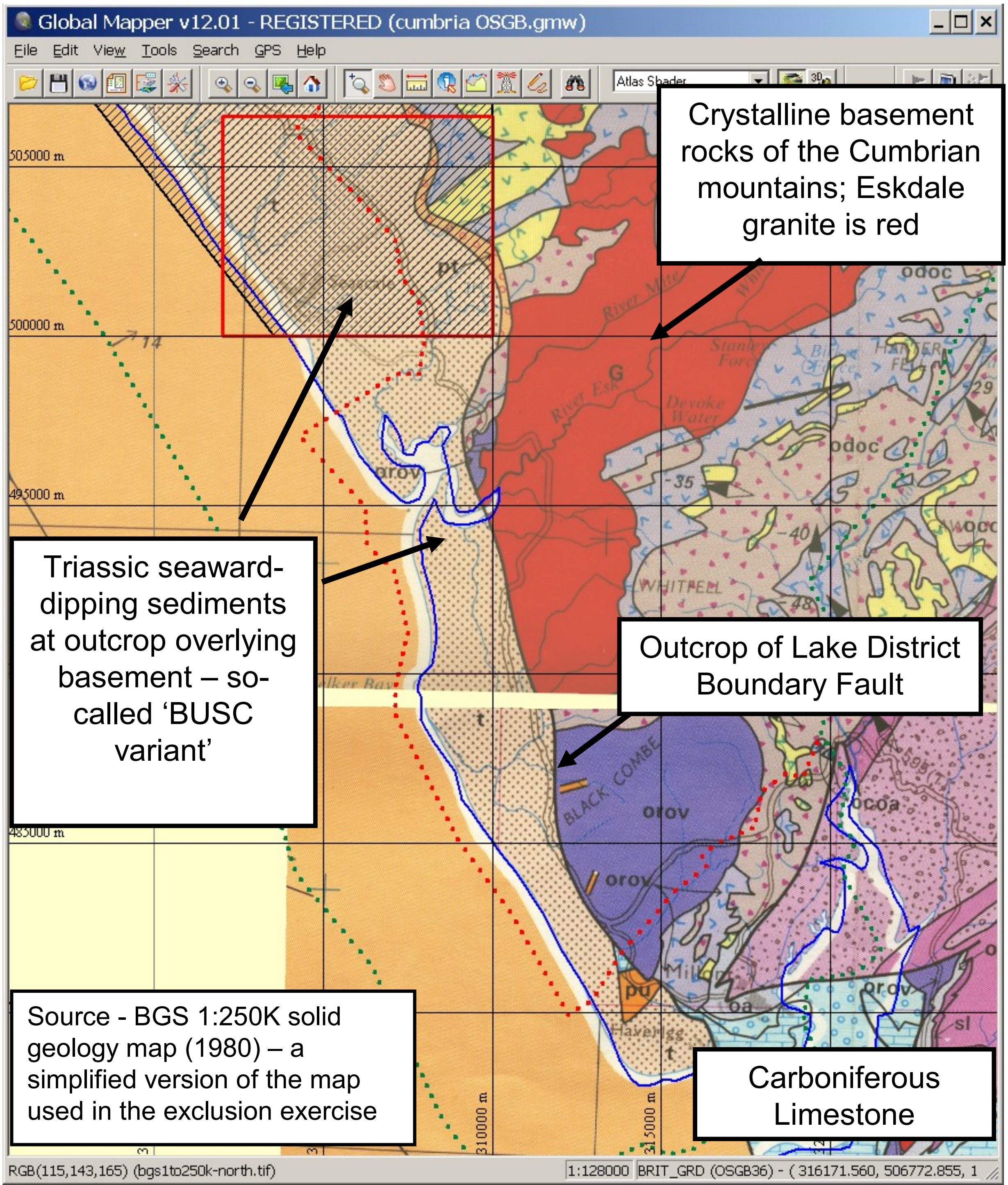


Fig. 5. Coastal geology south of the Site (red rectangle). In addition to the coastal sedimentary strip, the possibility of placing a site in the Eskdale granite is discussed.

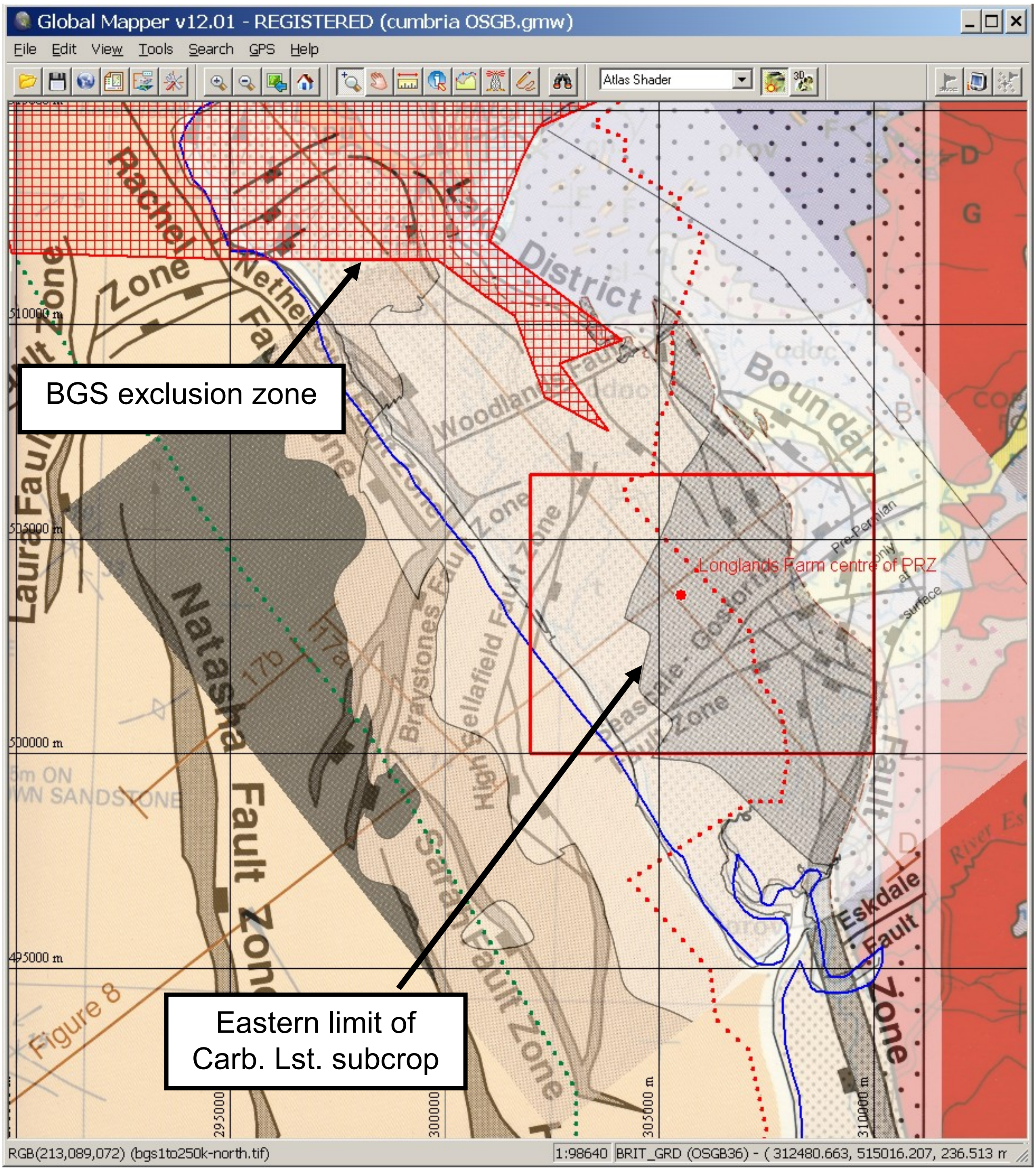


Fig. 6. Geology and faulting around the Site (red rectangle).

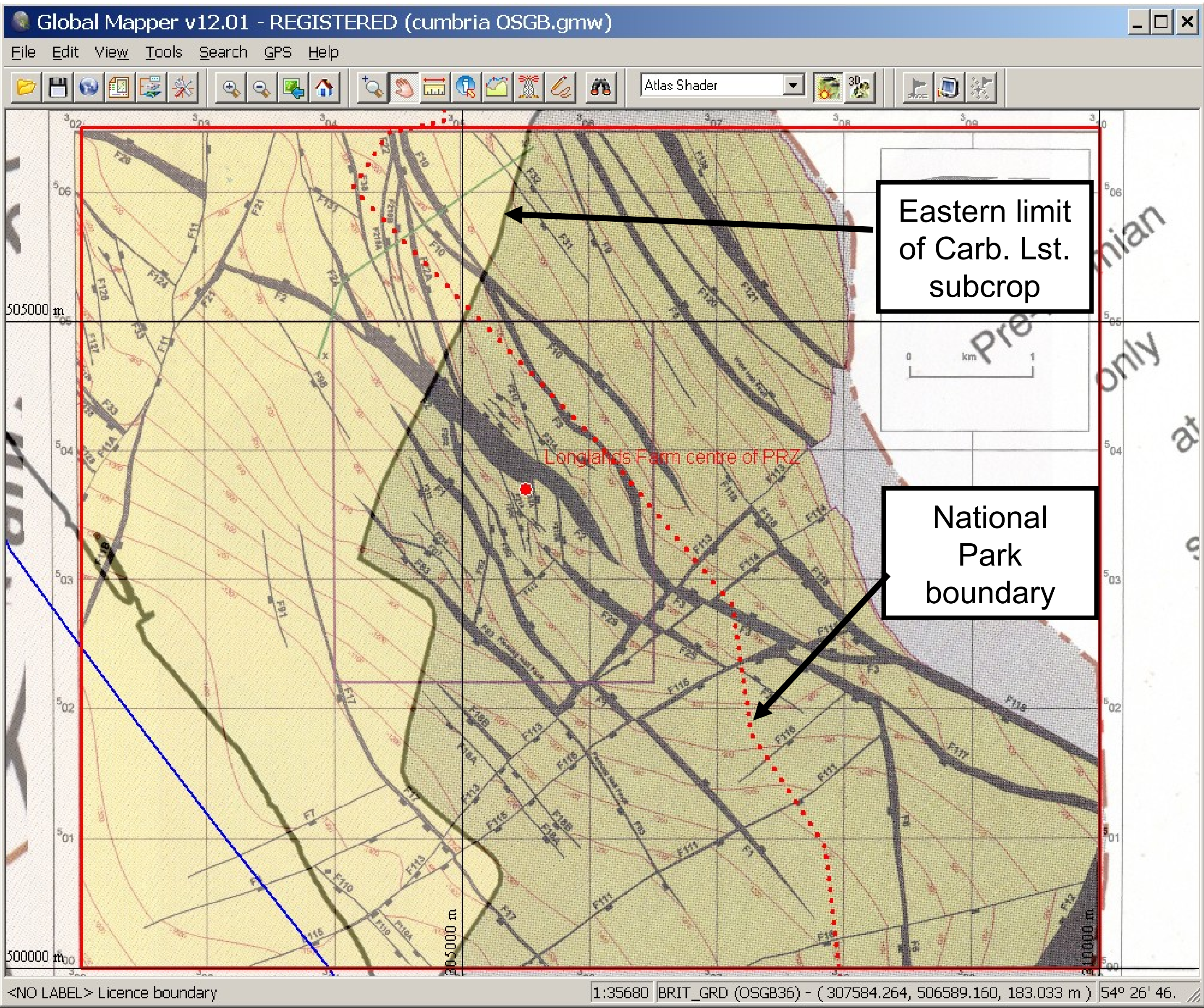


Fig. 7. Fault map of the Site at base Brockram (Permian) level, with Carboniferous subcrop map superimposed.

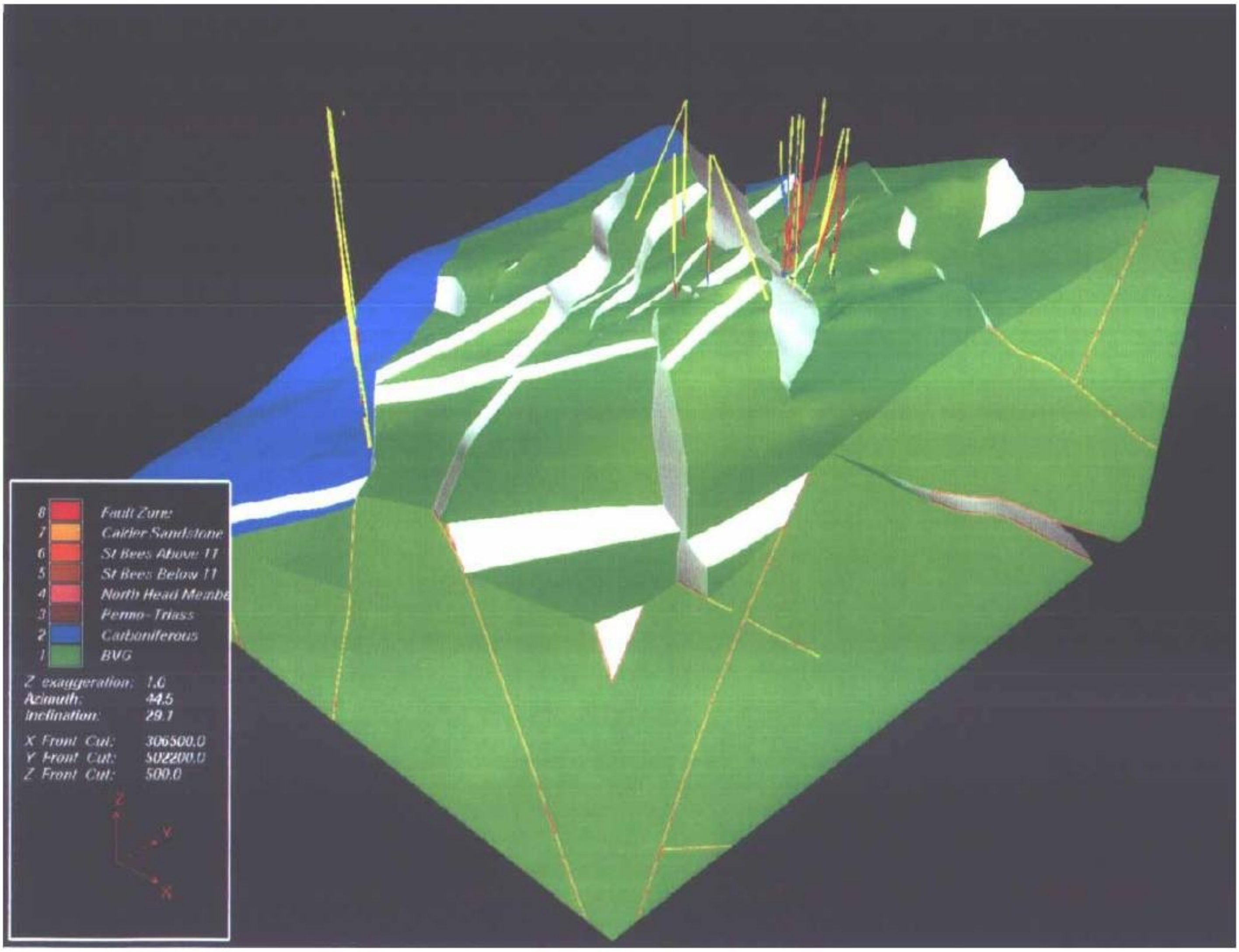


Fig. 8. Three-dimensional model of the structure at base Permo-Triassic of the PRZ [ref. 3]. The view is looking to the NW, and there is no vertical exaggeration. The Permo-Triassic has been removed to leave just the Carboniferous (blue) and repository host rock, the Borrowdale Volcanic Group (BVG – green). The sticks are the boreholes.

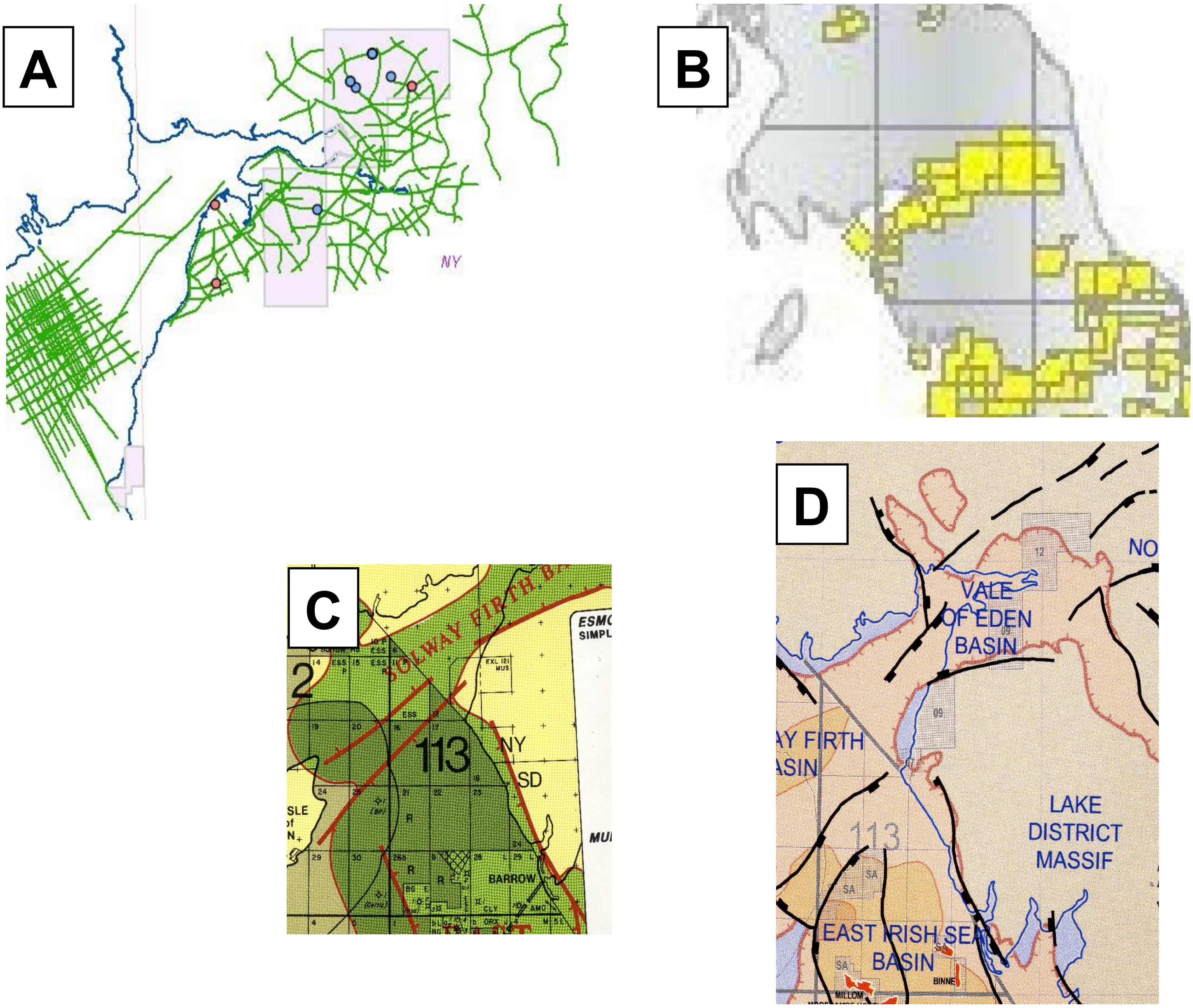


Fig. 9. Medley of maps showing exploration activity at different epochs in northern Allerdale DC.

A. DECC map (2011) showing available seismic profiles (green), exploration wells (red and blue dots) and current licensed areas (grey).
B. Historically licensed areas in the north of England (yellow).
C. PESGB map (1994) showing Mustang Resources exploration licence. extending south from Workington into the Sellafield Site quadrant.
D. PESGB map (2007) showing licences (grey).

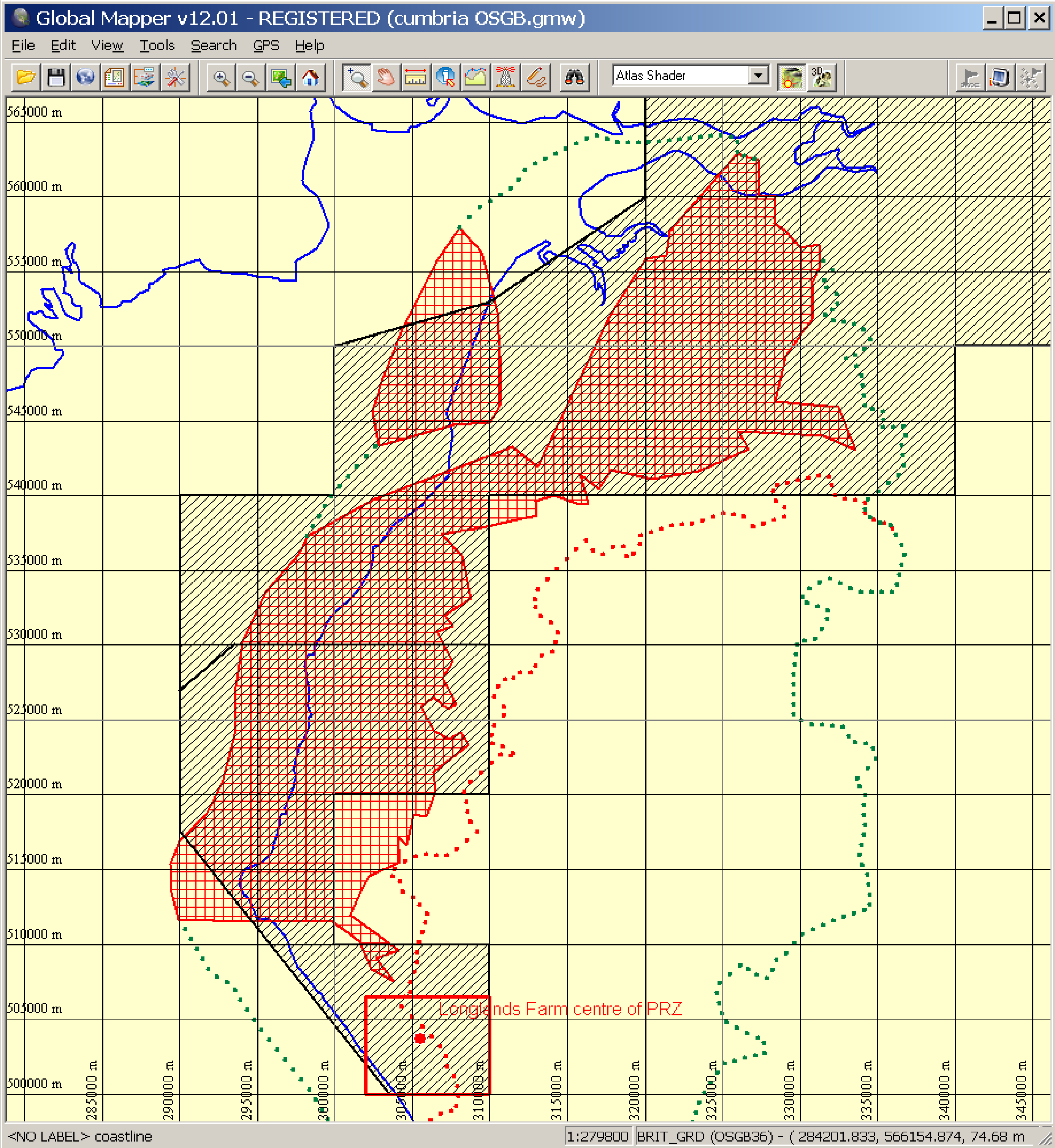


Fig. 10. BGS exclusion area (red hatching) with the total area of former or current hydrocarbon exploration licences superimposed (diagonal ruling).

BGS 1:250,000 geology map – northern Allerdale

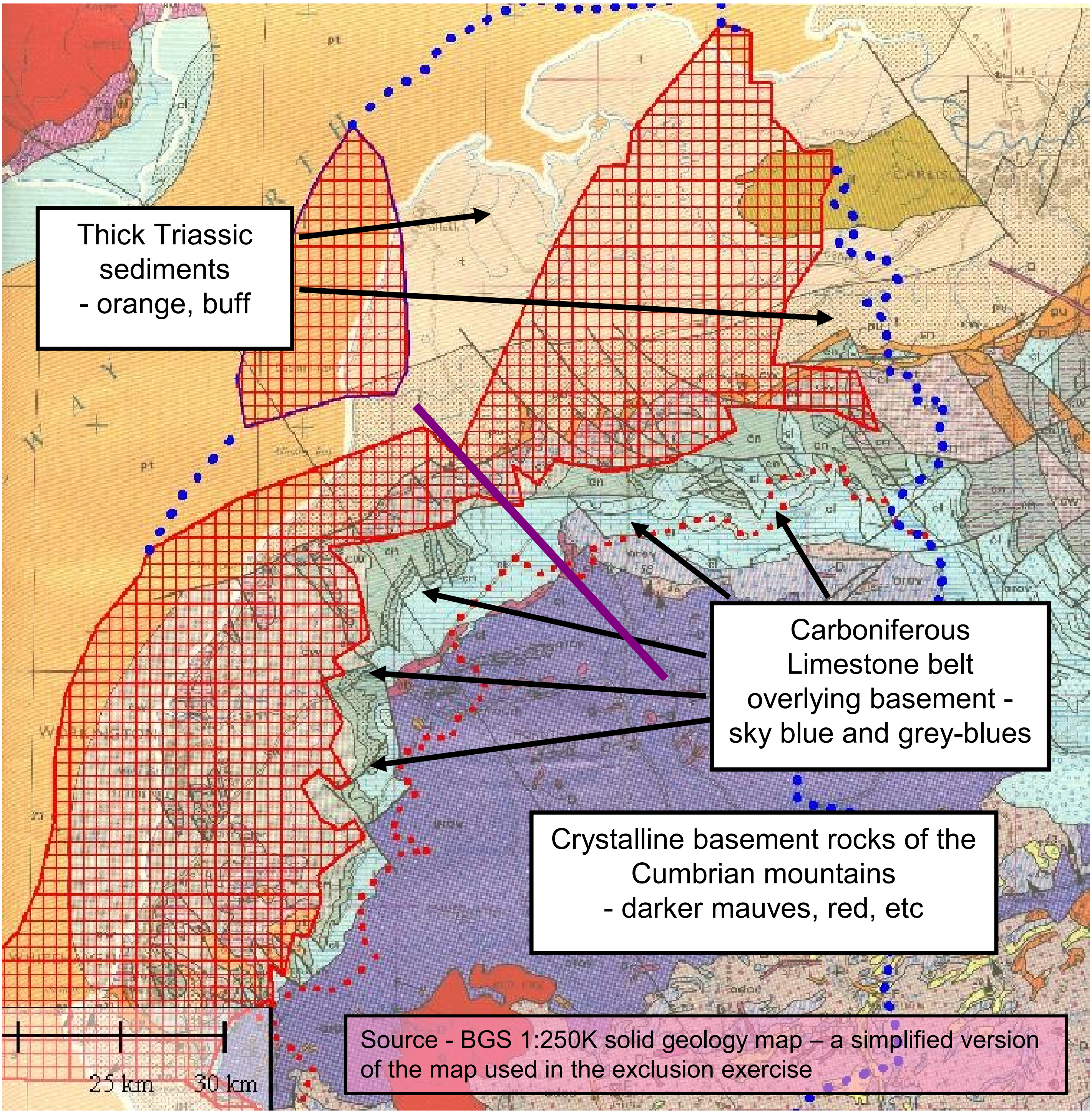


Fig. 11. Guide to the geology of northern Allerdale. Purple line is the approximate location of the cross-section shown in the next but one diagram.

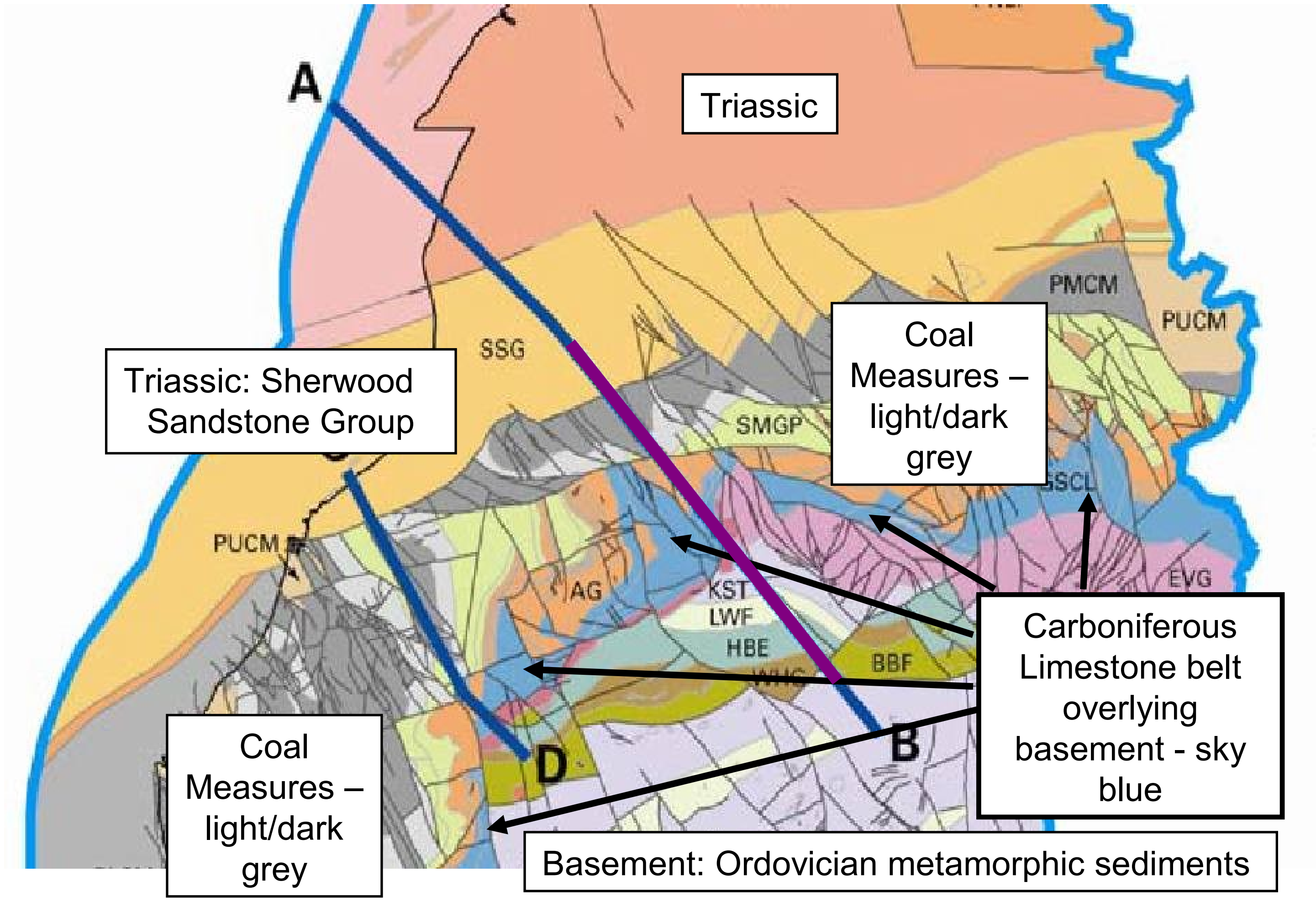


Fig. 12. Geology of northern Allerdale (extracted from the geology map of ref. 13, fig. 8). The colour coding of the formations is somewhat different from that of the BGS 1:250,000 scale map used in the previous diagrams. A cross-section along the purple segment of line AB is shown in the next diagram.

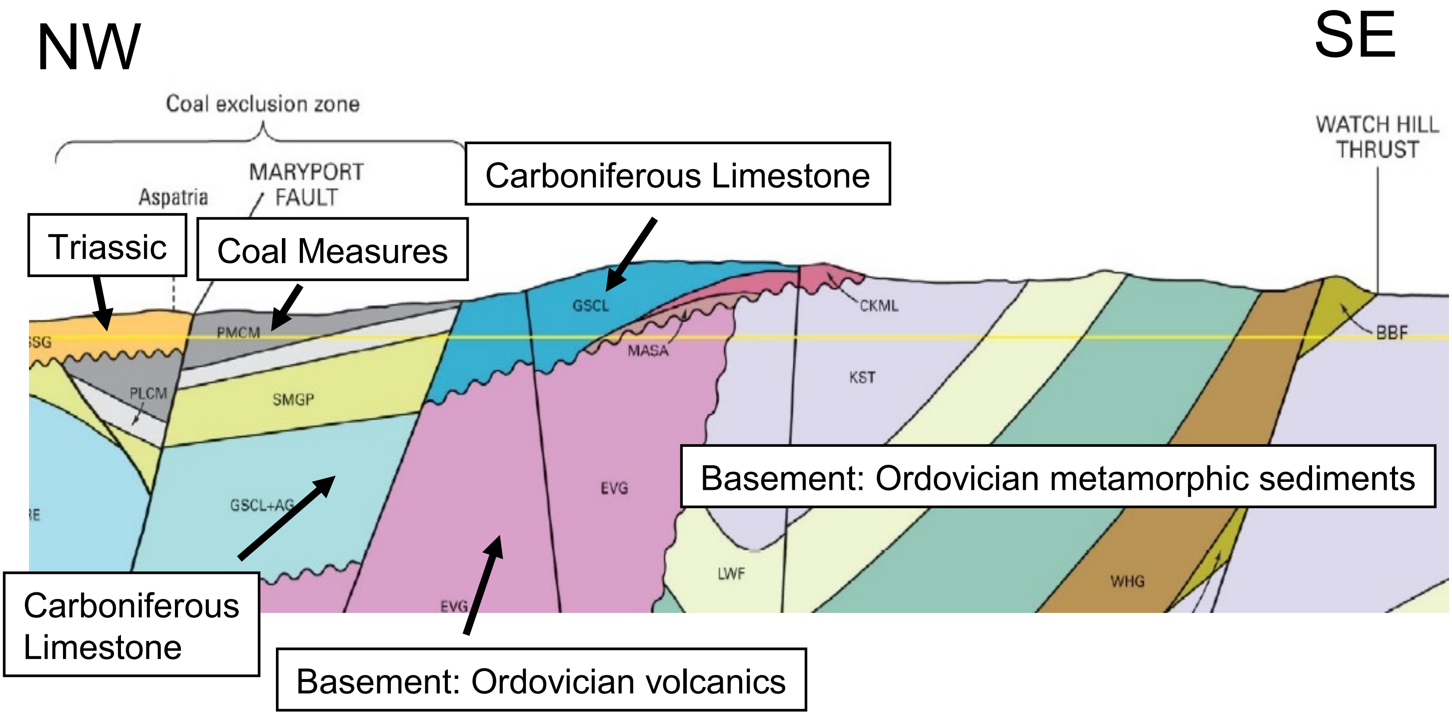


Fig. 13. Cross-section AB, extracted from BGS screening report [ref. 13, fig. 9] (located in the two previous diagrams). Vertical scale 3x horizontal. Sea level – yellow line; base of section at 1500 m. Faults are denoted by solid lines, unconformities by wavy lines.

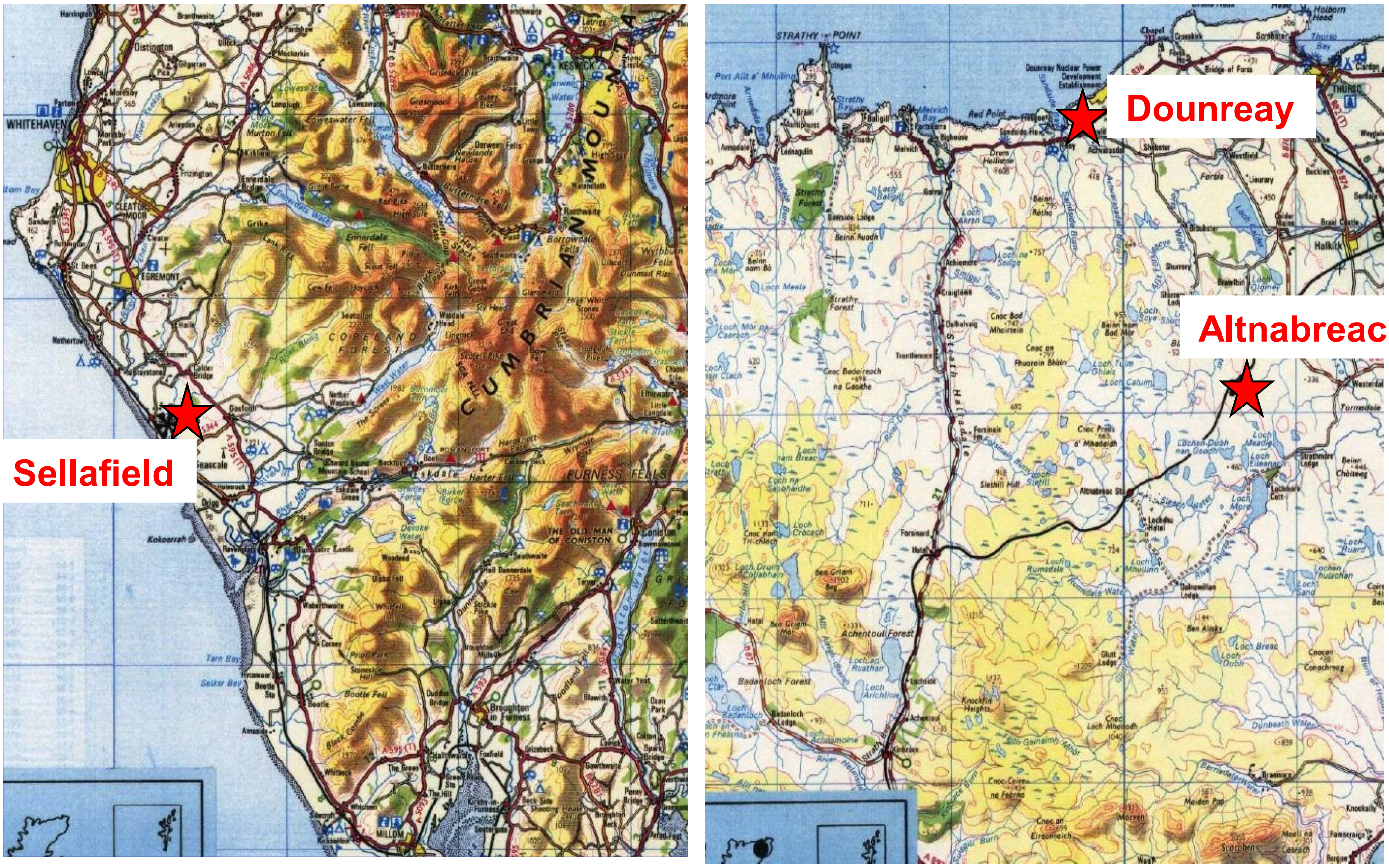


Fig. 14. Topography of Cumbria (left) and Sutherland (right) compared at the same scale. The latter is an area of low relief with two potential repository sites identified by the 1988 exercise, Altnabreac and Dounreay. Maps are taken from the Pieda site descriptions, and are shown at the same scale. The Sutherland sites are in areas of ‘Hard rock with low relief’. In contrast, no hard rock location (e.g. Eskdale) can be found within the National Park area of Cumbria that has low relief.

Geological cross-section through the coastal plain of Maryland, USA

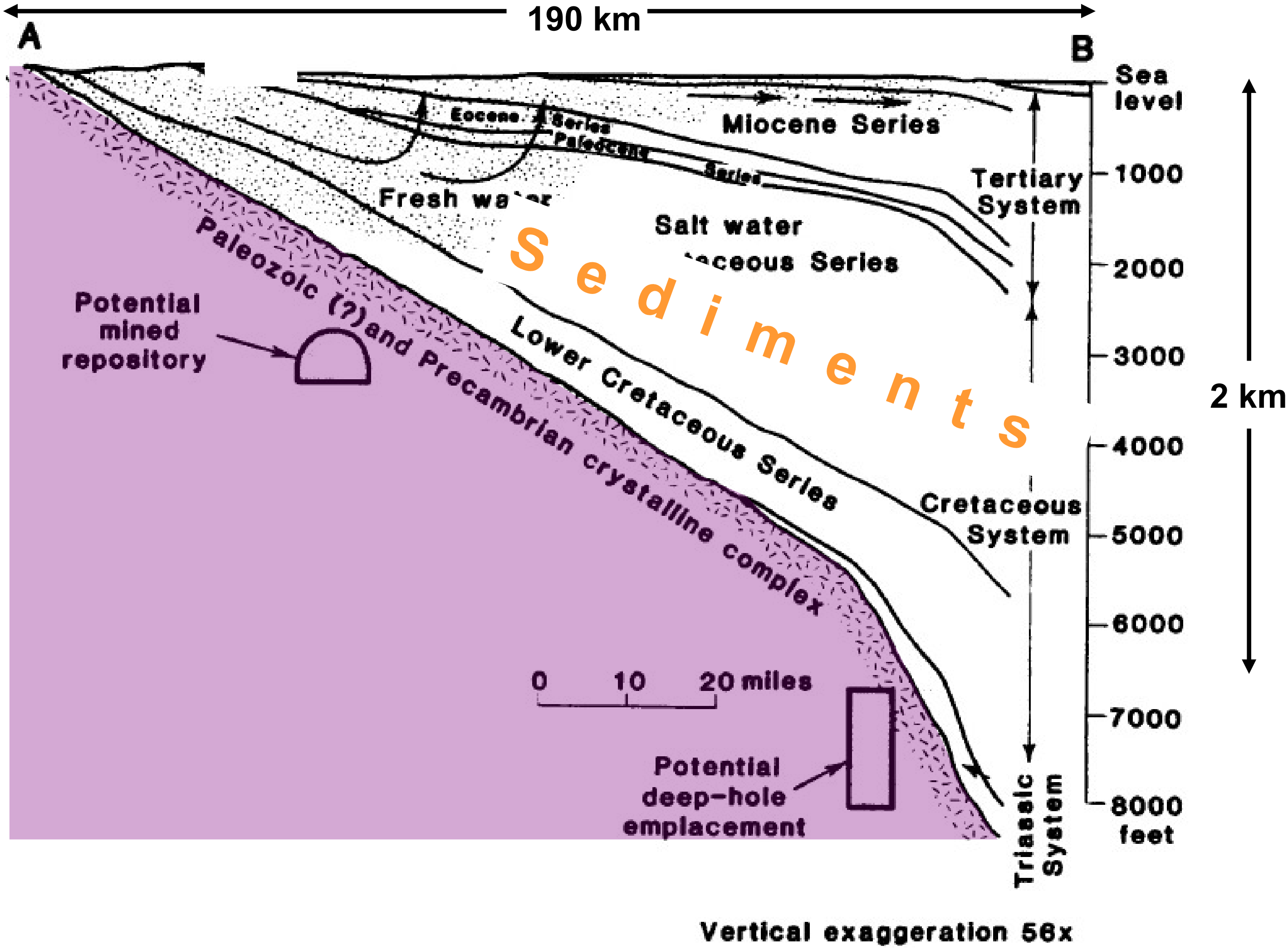
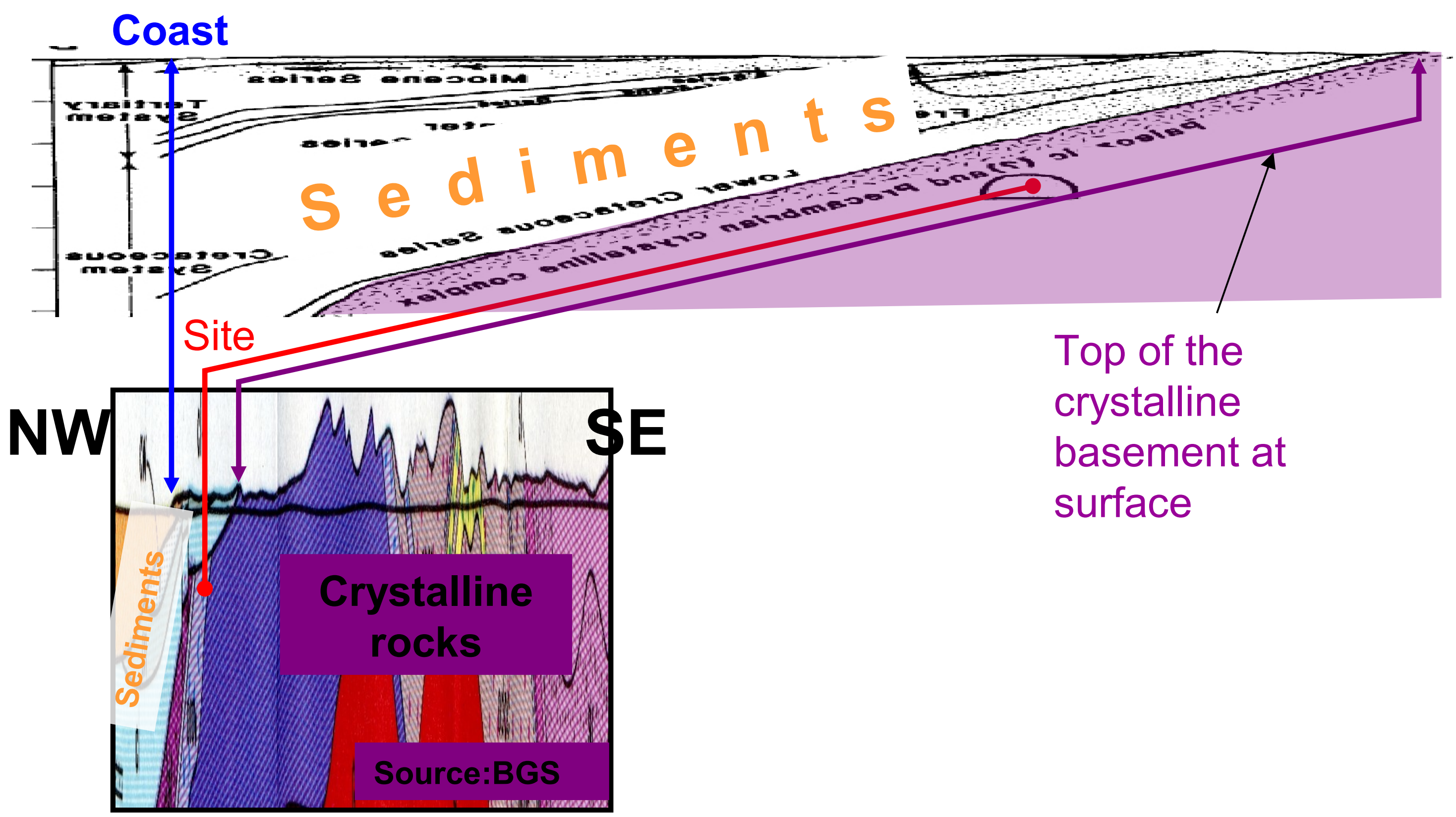


Fig. 15. Cross-section from Bredehoft & Maini 1981 [ref. 14]. This is the prototype for waste disposal in basement under sedimentary cover (BUSC). Vertical scale exaggerated x 56. The slope of the top basement surface is actually 0.6°. Because of this very low gradient, water flow within it is almost stagnant.

True BUSC cross-section mirrored (sea now on left) at V.E. x 10



Geological cross-section from Windermere to the Solway. Same scales as the BUSC cross-section above.

Fig. 16. Flaws in the Cumbrian model compared to the true BUSC type:

•Horizontal scale compressed by x 20.
•Height of terrain within zone of interest higher by x 20.
•Dip (tilt) of the sedimentary layers higher by x 40.

So the relative proportions of BUSC are distorted by 20 x 20 = 400.

Result: the water flow patterns within West Cumbria are far too vigorous and complex – it is not a BUSC environment.

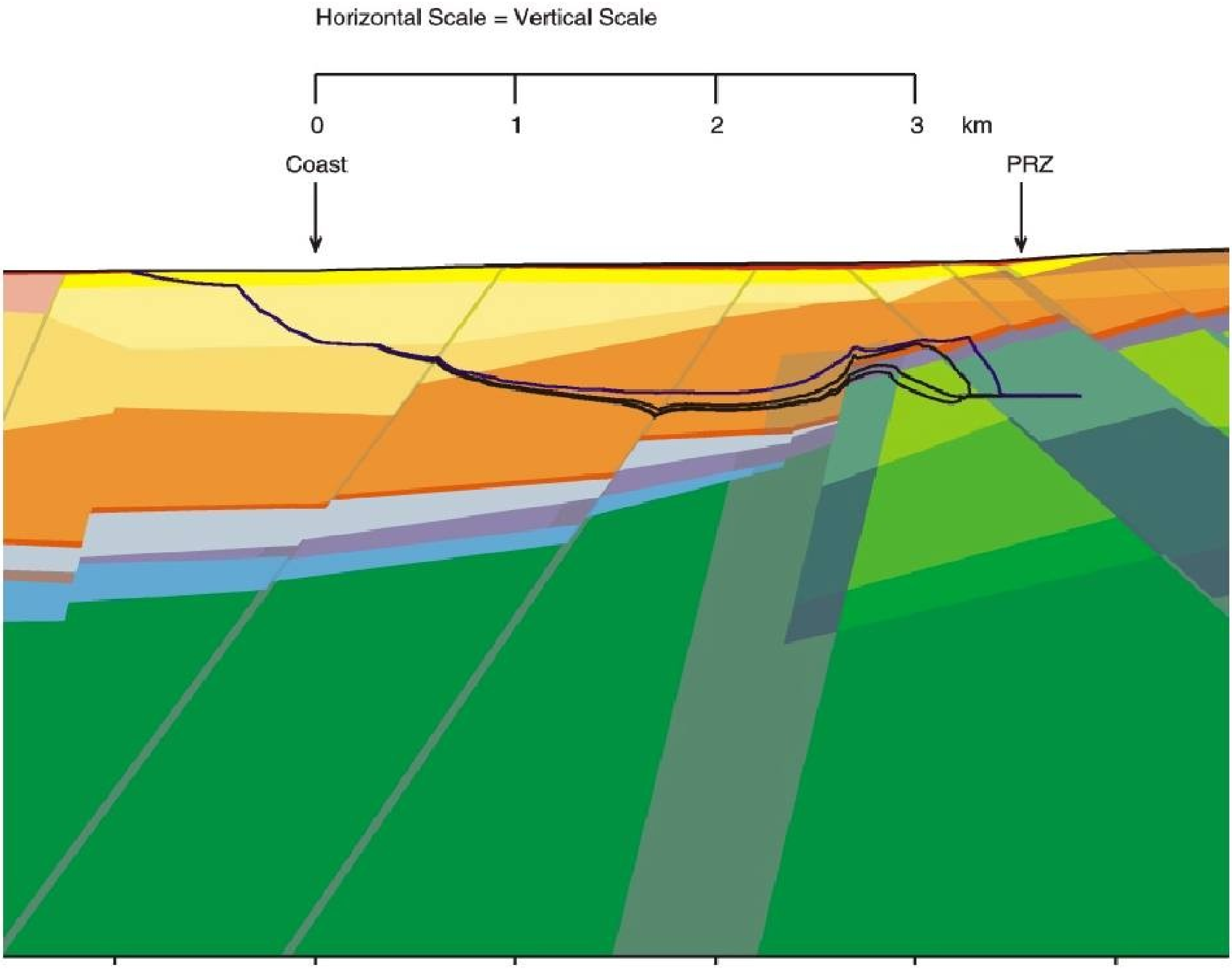


Fig. 17. Groundwater pathlines from the Sellafield PRZ, as modelled in Nirex97 [ref. 17].

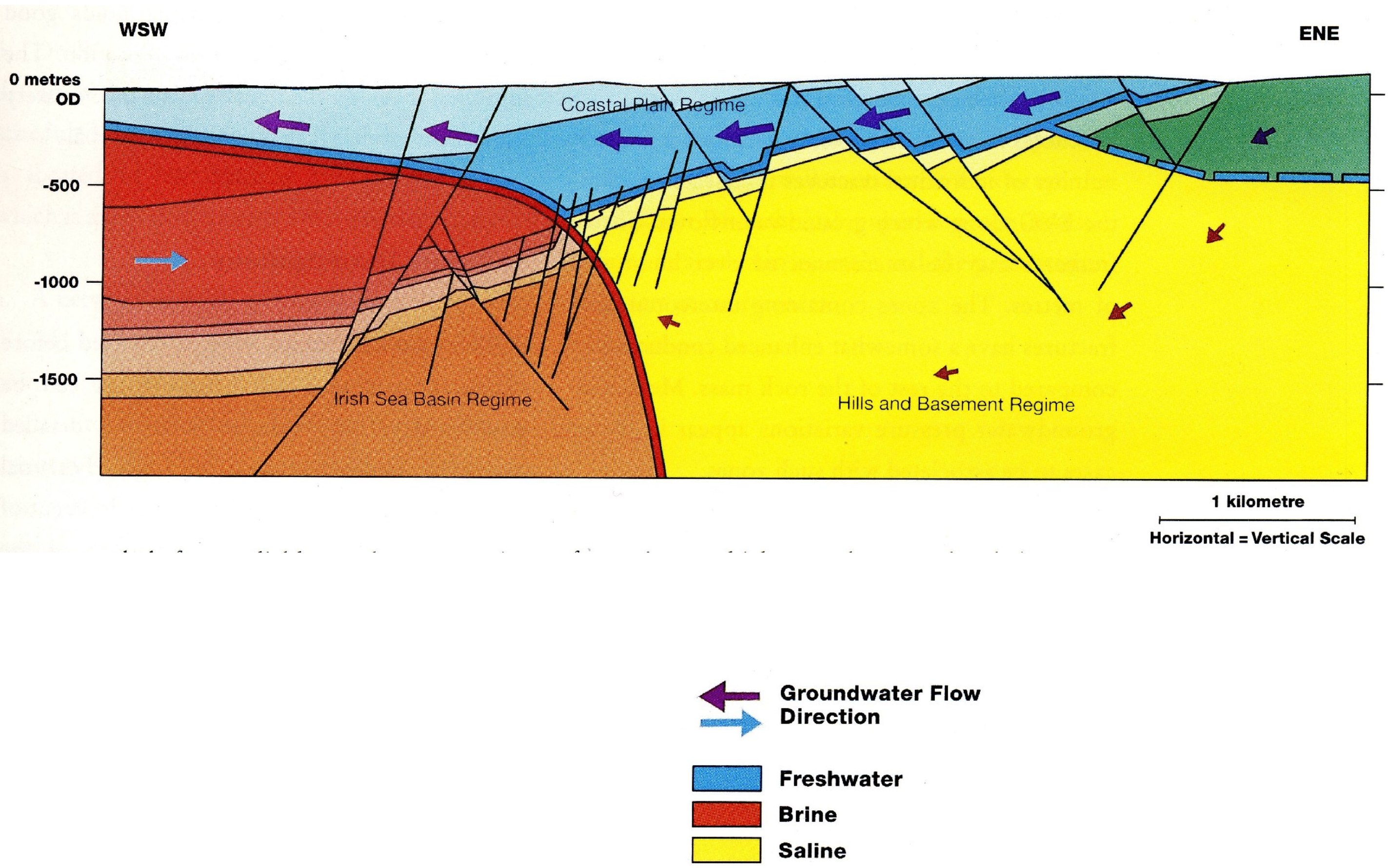


Fig. 18. Conceptual groundwater regimes through the Sellafield PRZ. Taken from ref. 18.

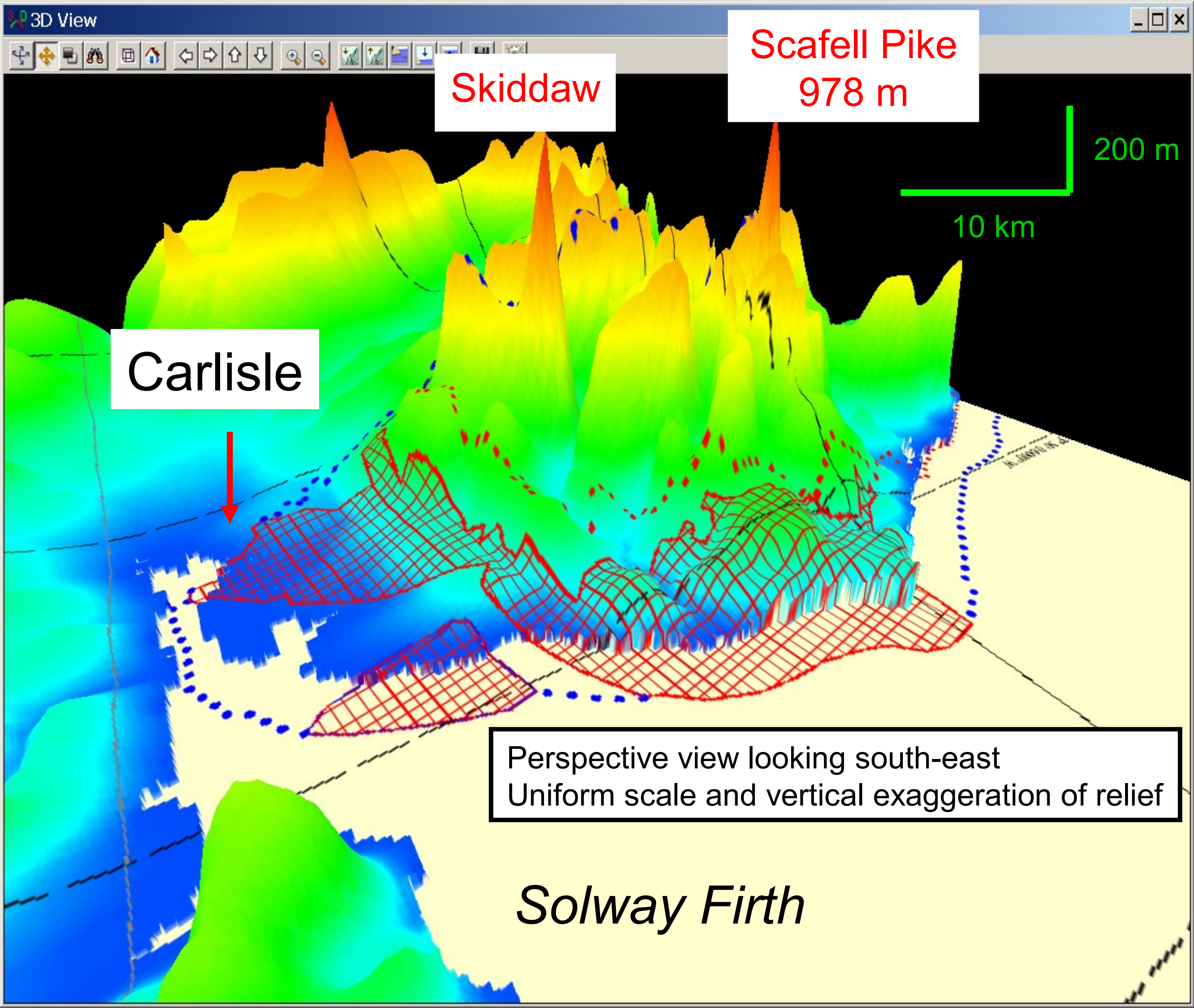


Fig. 19. Digital elevation model of northern Cumbria: the high relief crystalline rocks of the National Park (within red dotted line) are flanked by Carboniferous and younger rocks of the coastal plain. The Copeland Allerdale boundary and the BGS exclusion zone are also draped over the terrain.

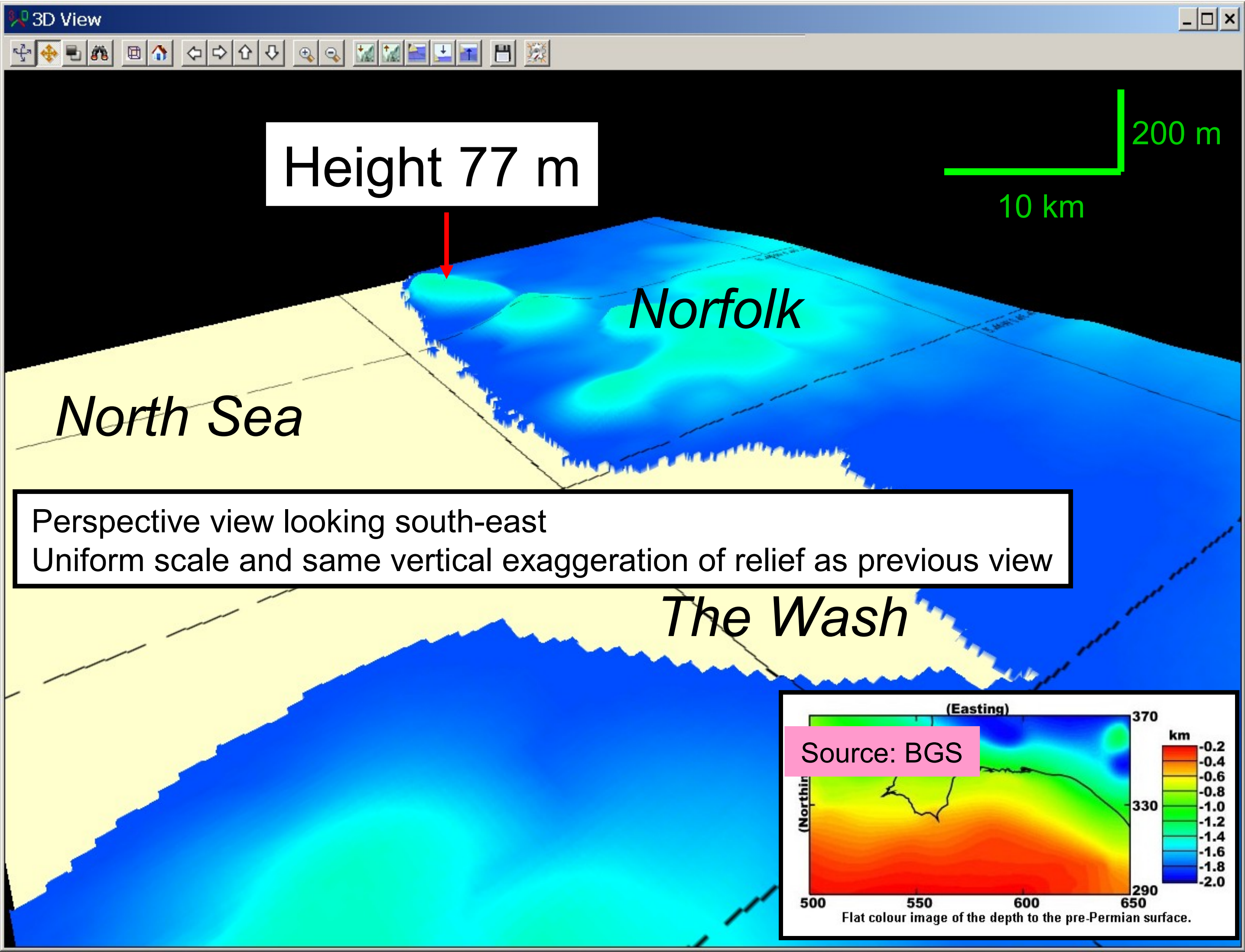


Fig. 20. Digital elevation model of the Wash and Norfolk – a good example of 'basement under sedimentary cover' (BUSC). The inset colour map shows that the top surface of the hard-rock basement along an east-west line through the southern Wash is about 700 m deep. The surface is shallower to the south and deepens to the north.