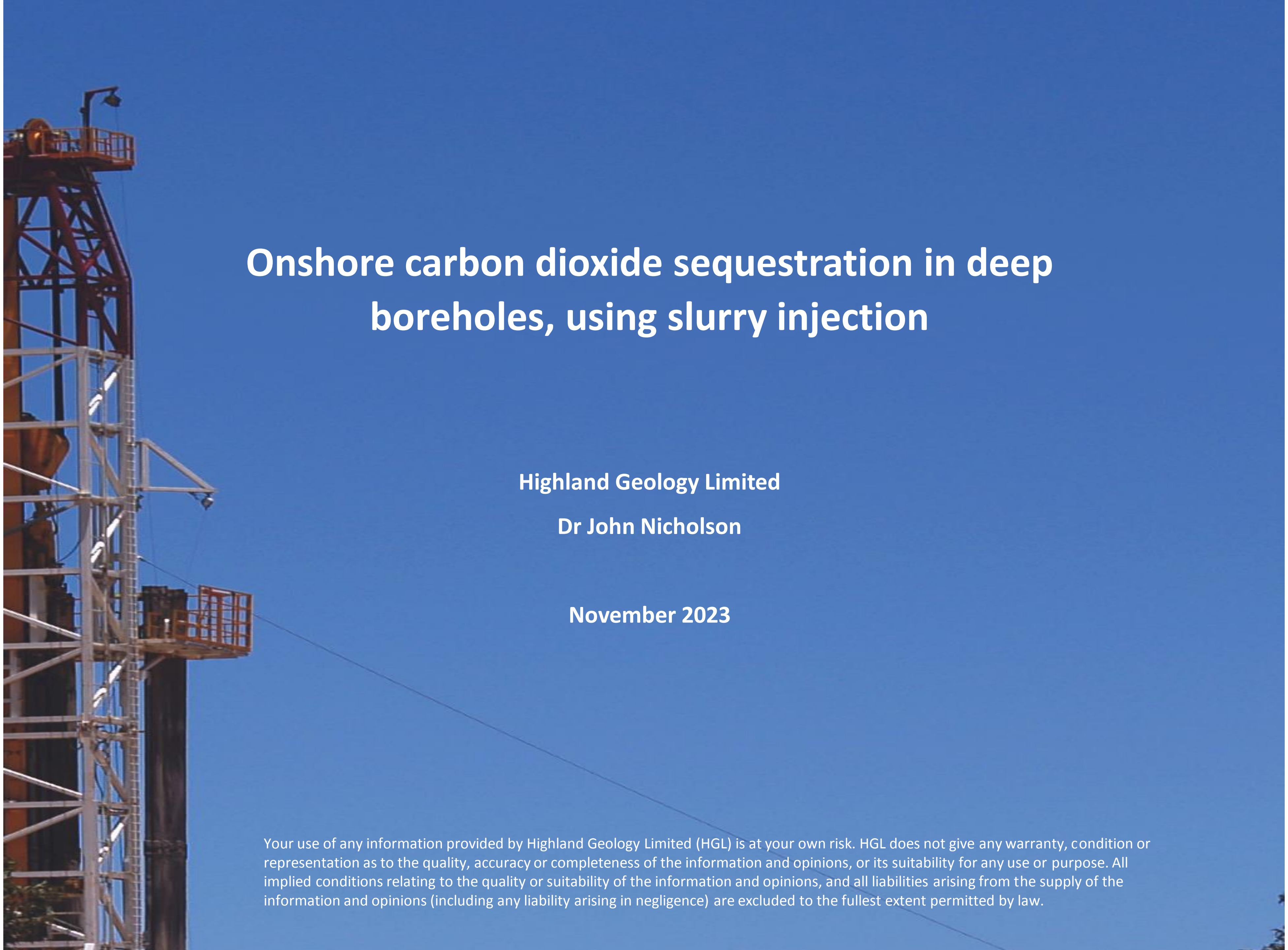


Onshore carbon dioxide sequestration in deep boreholes, using slurry injection

Highland Geology Limited

Dr John Nicholson

November 2023

Onshore carbon dioxide sequestration in deep boreholes, using slurry injection, at or close to site of production

Dr John Nicholson, 19/11/23

Looking at sequestering options for very large tonnages of carbon dioxide produced by industrial sources, we recognise a very promising onshore alternative to the UK hub and offshore burial concept: it is the conversion of CO2 to slurry, and pumping the then-harmless fluid downhole in dedicated injection wells drilled to depths of 1000-1500 metres. This process can be run at or very close to many of UK's significant CO2 production sites. There are massive cost savings to be had in disposal using this approach.

Slurry injection (SI) is a technique used world-wide over many years to improve reservoir performance and to dispose of drilling waste. One of the most valuable guides on the subject was published in 2003 by Veil and Dusseault, for the US Dept of Energy, National Petroleum Technology Office: "Evaluation of Slurry Injection Technology for Management of Drilling Wastes". That publication explains how its done. In UK it has been authorised and applied successfully recently at Humberside oil and gas wells to improve flow rates from tight reservoirs.

Water-based sodium bicarbonate or calcium carbonate slurries are innocuous and will pump like drilling mud. The drilling method to inject them enhances fracturing immediately around the borehole walls, so that small-scale fractures link into larger, pre-existing natural fractures. There is no requirement for CO2-resistant high-grade steel components in an injection system. Bicarb slurry is thermally stable to 80 degrees Celsius and won't break down until burial reaches depths around 2000 metres. Slurry is going into storage much deeper than any drinkable groundwater supply formations.

Storage in fractured rock is independent of the rock type, and it doesn't require structural closure. Given competent drilling, slurry will not migrate back to surface. We are not fracking the formation. Where it goes can be tracked using pressure measurement techniques to monitor its disposition, along with observation wells. A chain of pads for a major producer site with say half a dozen wells apiece can be set up and the storage volume available in fractures can be more than adequate to contain very large slurry tonnages dumped. The lifetime of individual wells can be made limited, to ensure fractures don't become over-pressured. Mapping of fracture systems will allow a rig to prepare new sites before they are needed.

The purpose of this note is to describe fracture systems onshore UK which can support SI. We model their geometries and describe some examples identified using seismic data, and we show some rock outcrop examples which display fractures at sub-seismic scale. Our aim is to demonstrate the importance and potential for applying this approach to one of Britain's greatest problems, and to invite support for a proving project.

Major faults and folds in the Nottingham Platform and eastern half of Widmerpool Basin

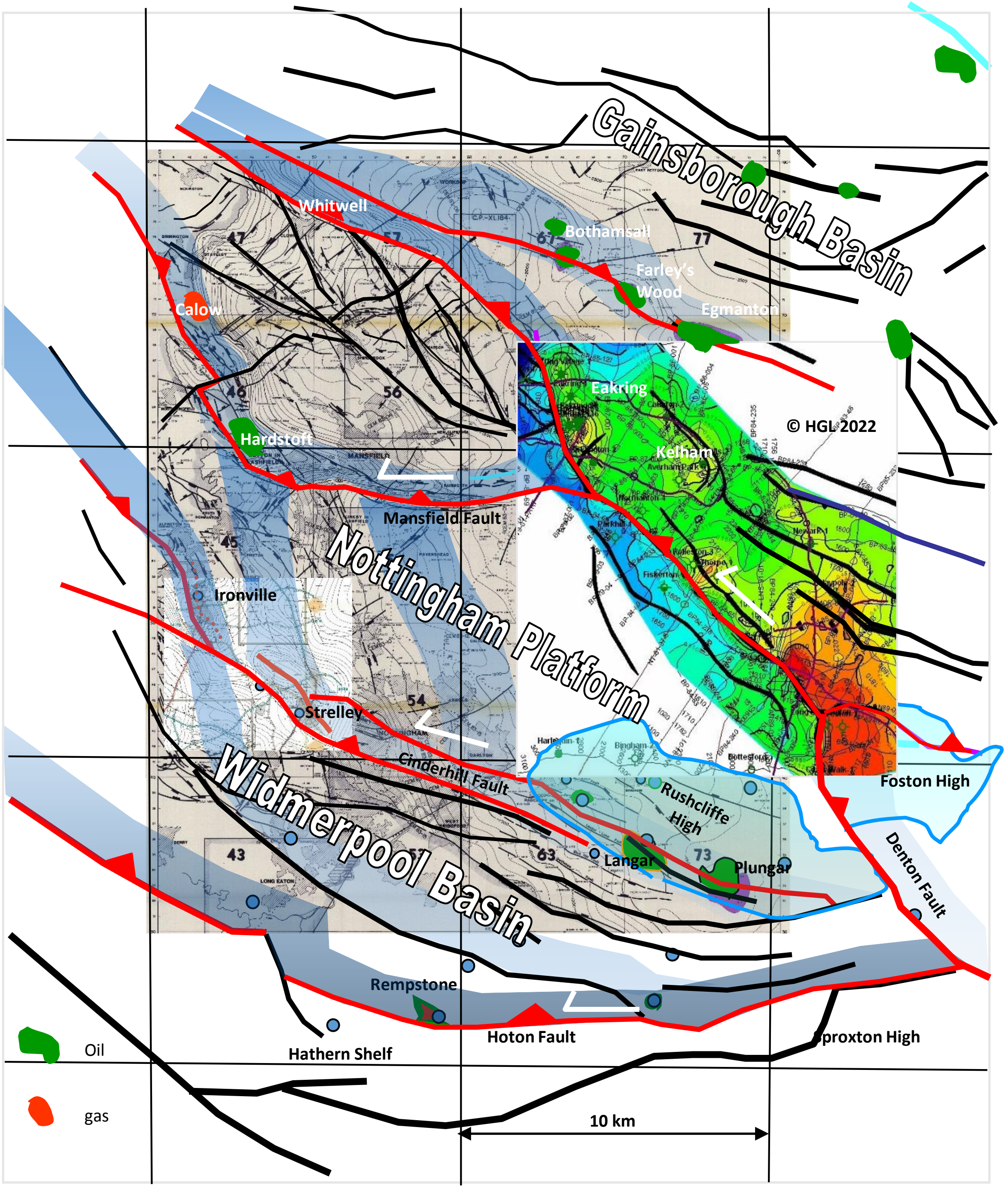
Key structural elements in the western part of East Midlands are shown here, the base map for this summary is the Coal Measures Top Hard depth compilation of Charterhouse Group, see report 40416 on UKOGL's website, made in 1984. The colour inset is our own Eakring to Foston top-Lower Carboniferous two-way time mapping.

The dominant feature is the series of northwest-trending major extensional faults (ramps) which controlled sedimentation from late Devonian to early Permian times. These were growth faults moving throughout the Carboniferous, with particular activity in and following the Caledonian breakup. These faults determined the structure and thickness variations of sediments laid down in the rifting phases of the Early Carboniferous. Their patterns are clear on seismic.

The ramps also controlled structure styles developed in cross-basin shortening, at the end of the Carboniferous, when the Variscan plate collision commenced. That compression created the various pop-up anticlines which have supported oil exploration and production commencing in the 1920s. Local anticlines were forced on the ramps, overprinting the big extensional tilted blocks. They have all been drilled and the mostly-depleted fields are now candidates for carbon capture.

But beyond the local anticlines, major footwall and hangingwall fracturing is widespread on the ramps. Oblique-slip in shortening imposed characteristic geometries. Red faults are some of the main part-inverted growth fault-zones. Variscan inversion produced left-handed shear and very large scale footwall fracturing is evident on major faults such as Mansfield, Hoton, Eakring-Foston-Denton.

Faults of this type are where the main potential lies for large-scale fracture storage. There is similar opportunity for CO2 disposal in all of the onshore northern England Carboniferous basins.



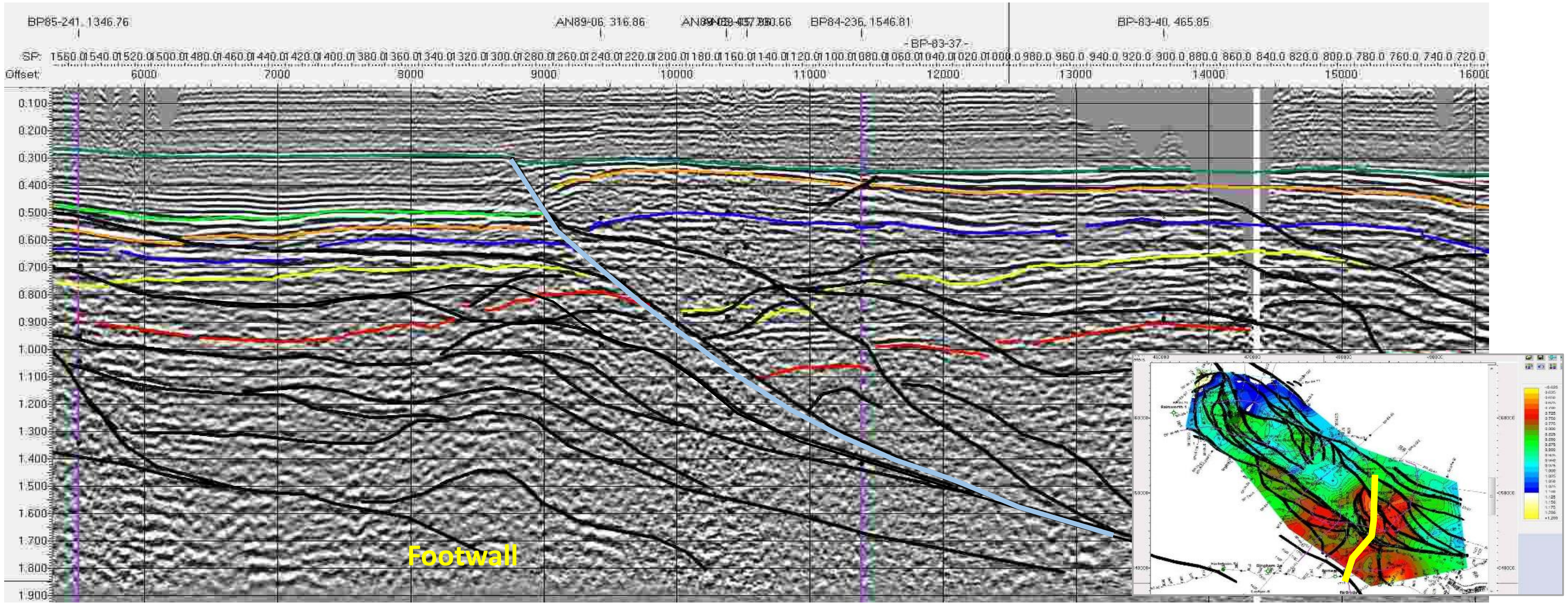
Using naturally fractured reservoirs for CCS onshore

Fractured rock trends are widespread in the Carboniferous rocks of northern England, Wales and Scotland, with highly-fractured footwalls of major fault zones present in all of the onshore basins. In oil and gas exploration HGL have long experience of onshore Carboniferous basin geology, and we have identified numerous locations where injection potential looks plausible and could be confirmed by drilling and flow testing.

The advantage of fractured systems as store space for slurry is that they are independent of porosity and permeability properties of their matrix, and they need not be in structural closure in the manner of oil and gas reservoirs. Host rocks can be tightly-cemented limestones, volcanics, hard shales, it doesn't matter what they are, fractures comprise all of the store space and they are interconnected. The important question is, what effective fracture volume is available? It is evident that strongly-uplifted anticlinal structures in those trends are typically highly fractured. Some of the structures we have identified have potential store space for hundreds of millions of barrels. Prime locations for fracturing occur where large fault systems join. There are some spectacular examples (next slide), close to or at major CO2-producing locations.

Deformation process models we have made with our in-house software replicate the origin and style of fracture patterns seen in the Carboniferous basins, with particular reference to footwall-shortening, compressive "duplex" structure, and guide seismic interpretation. These are fundamental features of cross-basin uplift in the end-of-Carboniferous deformation. Examples of highly-faulted folding from locations in the Nottingham Platform, Gainsborough Basin and in the Clitheroe fold belt of Bowland (Craven) Basin, are shown on our website and are completely convincing as injection locations for slurry. South Wales fits the pattern too: in fact South Wales coalfield is the most highly fractured area of all those we have looked at.

Let's look at how fracture systems form.



Here is an instance of very large scale natural fracturing developed in a major fault footwall. This line BP83-37 from the Nottingham Platform near Newark shows colossal footwall deformation. Nearly a mile-high stack of thrust-repeated slices of Lower Carboniferous sediments lies under the Eakring Fault (grey line) where it meets the south-trending Denton Fault. The footwall compressional shortening can only be guessed at, but it must be substantial with both faults driving the deformation. Geometries like this are encouraging examples of strongly-fractured high-potential locations to bury carbon.

Is this real structure, and is the interpretation reasonable? Yes it is. We'll review the processes that develop overlapping fault slices like these, present more examples and comment on what degree of reservoir storage this could generate for carbon retention.

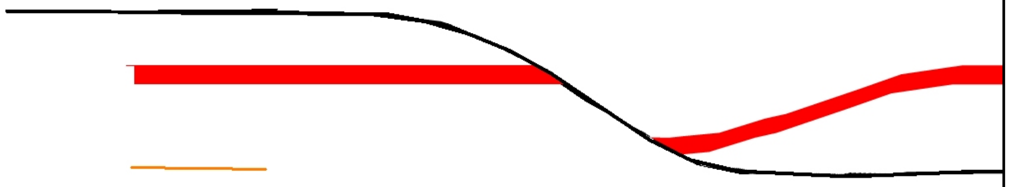
Generation of a Passive Roof Duplex

The following structure sequence has critical elements of the Eakring footwall. Its created by successive moves on faults which are closely-spaced. The result is progressive uplift passively deforming earlier structures: repetition of the same process builds the end-model which helps us interpret the seismic profiles.

Cases like this are common in East Midlands and Craven Basin.

1

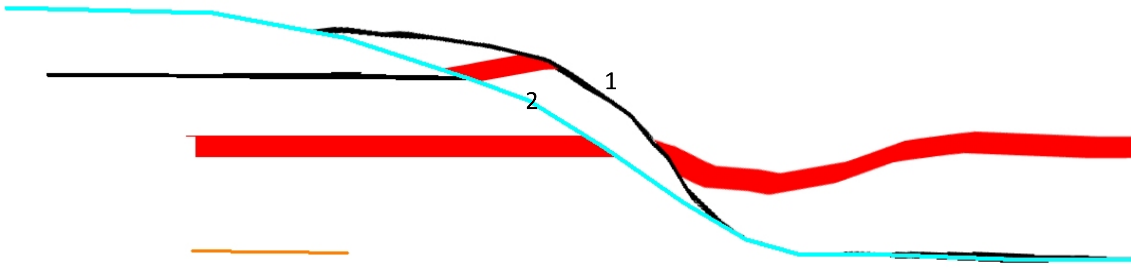
An extensional growth fault detaches on some deeper horizon and the ongoing movement on this curved surface during sedimentation forced rollover in the hangingwall. We arrive at end-Carboniferous Variscan inversion time, and the ramp is going to see footwall progressive breakdown in compression, because fault reversal from right to left is more easily done on new, shallower-dipping faults.



Models here are made with section balance software “DepthCon”, written by John Nicholson.

2

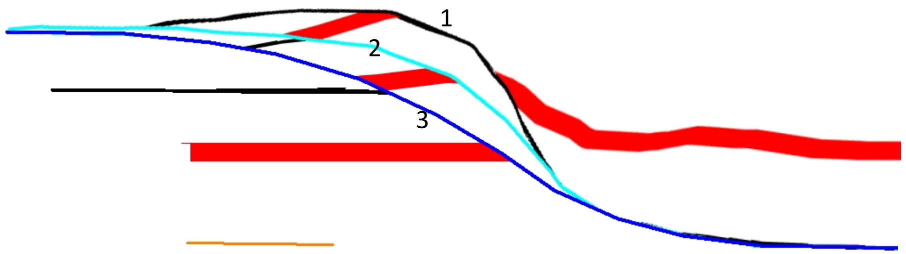
Inversion fault 2, pale blue, now breaks into the footwall of fault 1 and the only part of fault 1 which is still hydraulically pressured and moving is the shared flat at lower right, in some shale-dominant unit. The spacing between successive ramps will be kept small relative to the displacement on new footwall faults, so we will see the thrust “duplexes” overlap and the stack will climb, older slices get passively deformed according to the shape of new, active ramps.



Generation of a Passive Roof Duplex (ii)

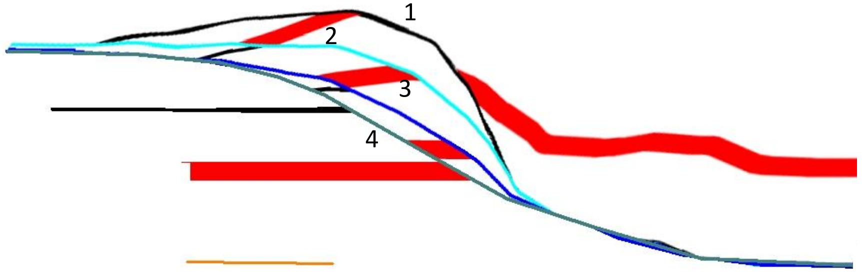
3

Pale blue 2 now stops moving and is replaced by new dark blue fault 3, and with movement on this fault whilst 1 and 2 are inactive we have some typical footwall features appearing. Fault 1 is net-extensional, the other faults are wholly reverse.



4

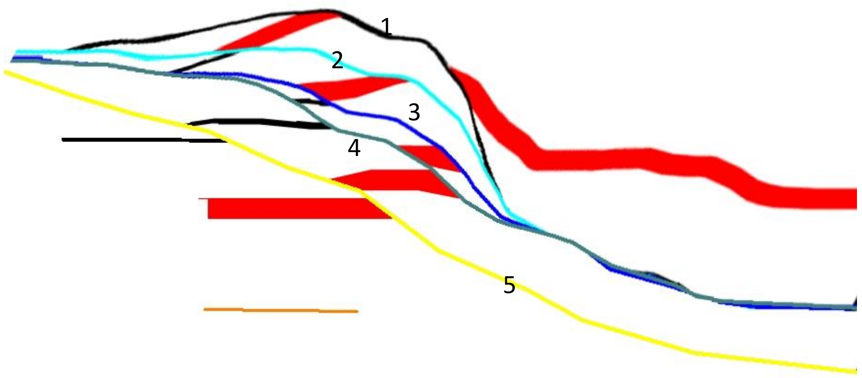
Next, fault 4 in dark green propagates off the floor fault of the stack, it has less displacement. There are lots of examples of small steep faults like this in places like Clitheroe fold belt, as we'll see.



Yellow fault 5 breaks the pattern of common sole fault 4, to replicate major faulting lateral to and below the stack.

Fault 5 could look like a reversed extensional fault, but it isn't one: its an inversion which doesn't root on the 1-4 detachment.

Fault 1 had 100 units of extension (the scale bar length). By fault 4 we have imposed a shortening of 300 units in the stack plus another 50 units on fault 5.



Generation of a Passive Roof Duplex (iii)

With this model we have a basic tool to help us identify key locations for carbon storage.

Many interpreters of seismic would think these structures are data-processing artefacts, and ignore them. An acid test is, can we deconstruct this type of structure, take it back to undeformed state without there being anomalous lumps remaining, or large unexplained imbalances in bed lengths from one horizon to another? If we can do this, and/or we have seen real rock structure like this in the field, then regardless of seismic processing issues they have a place in the interpretation.

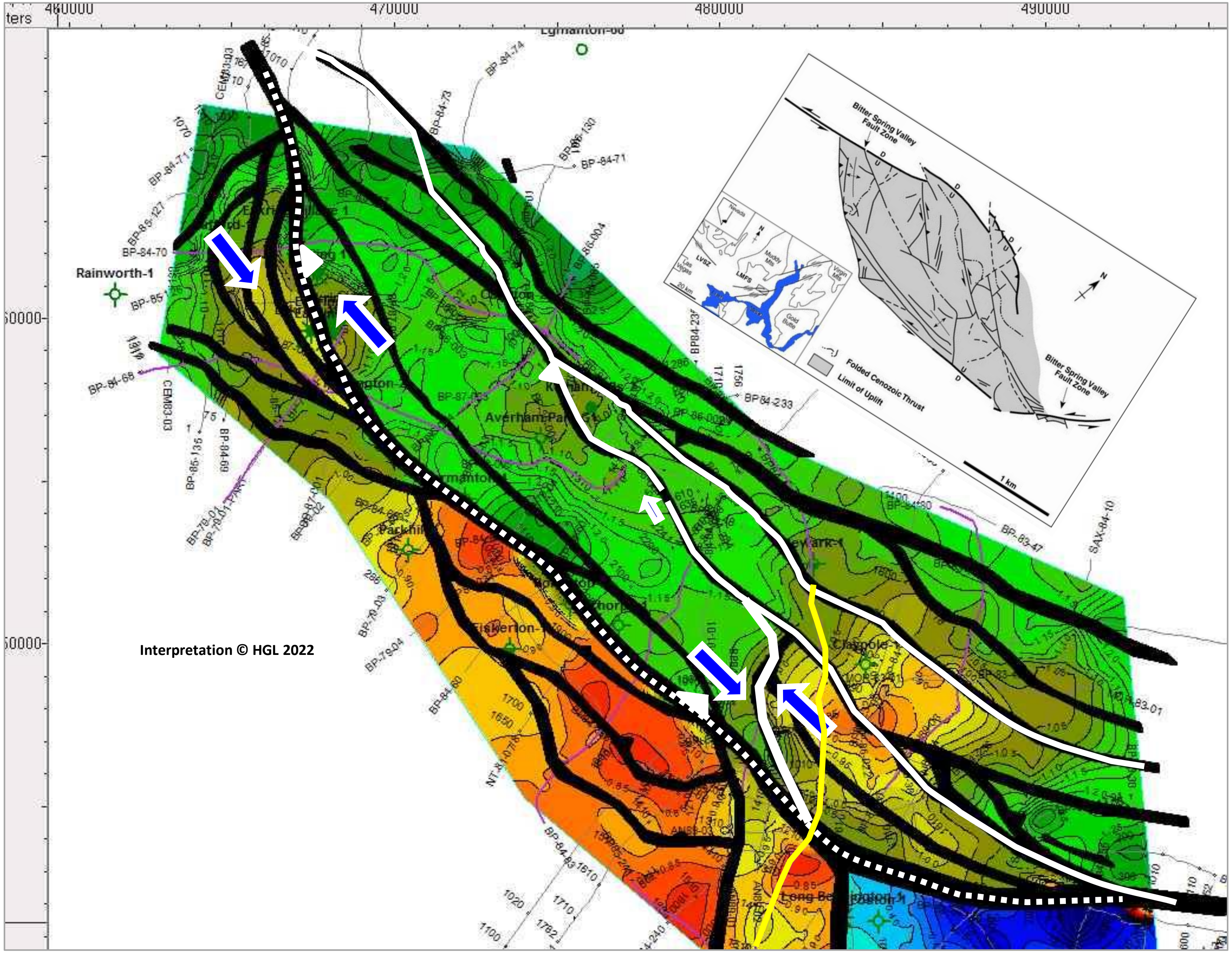
Albeit a two-dimensional model assuming the deformation is entirely in the plane of section, this model is reversible and whilst we can't say it is "correct", it certainly is geometrically sensible. It doesn't create or destroy rock in each stage and it suggests best horizon correlations for the interpreted profile.

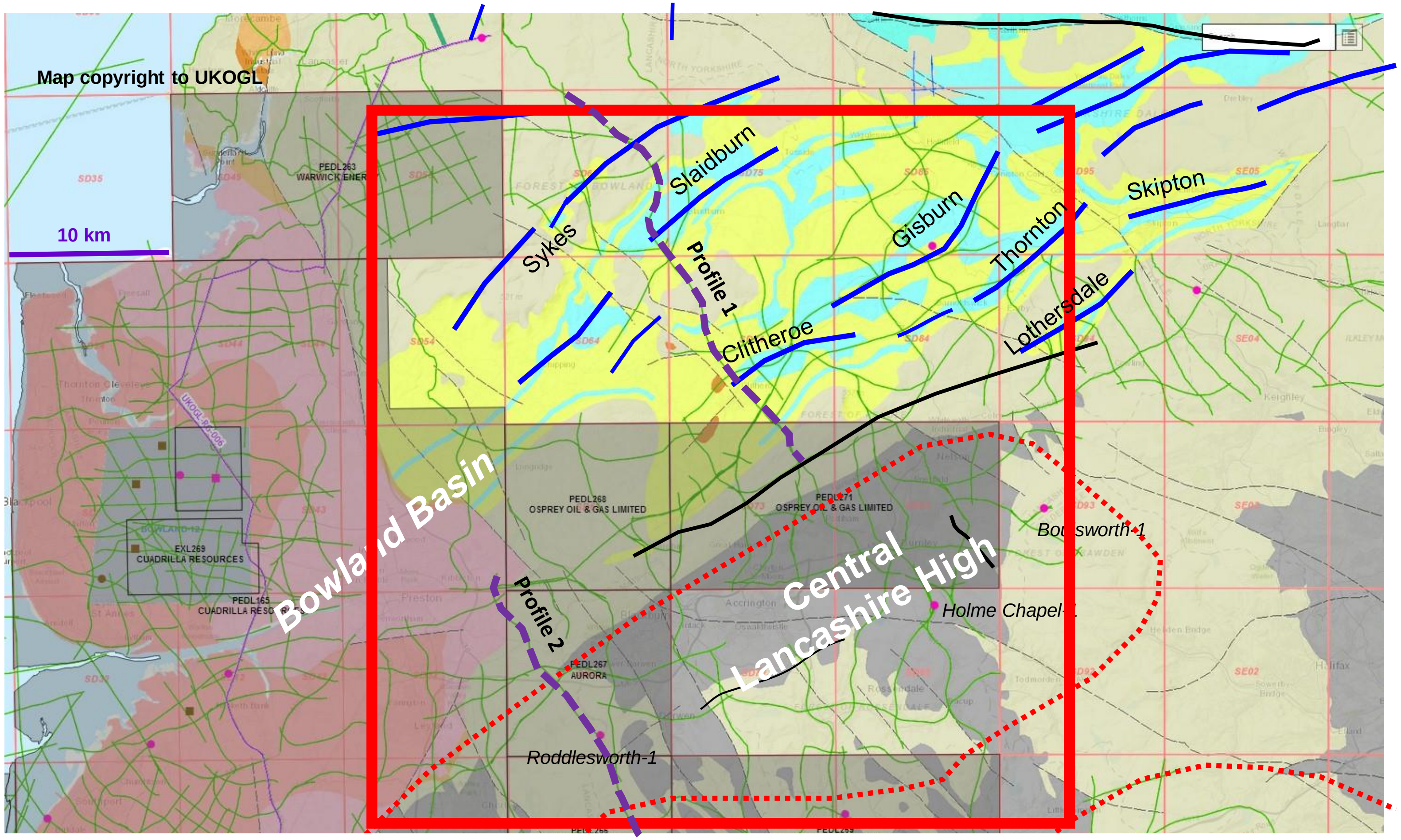
This is HGL mapping of a deep-form seismic marker in the Lower Carboniferous at Eakring-Newark. We think the Eakring Fault (dotted here) is a strike-slip fault which steps rightwards, northwards, at intervals. Where it does so the footwall at each bend is compressed and rock has to fracture to make it possible for movement to progress. The result is an arcuate shear pattern, left-lateral shear progressively faults the footwalls and forces development of the Eakring and Kelham domes.

In the Lower Carboniferous, this linked fault model tolerably well matches what we see on seismic. Inset is a similar left-handed shear system, Owl Creek in Nevada.

The footwall high at the junction with south-trending Denton Fault is strongly inverted with local culminations, seismic is sparse here and the workstation software creates spurious local contours in projecting the data: but the overall picture and causal process of uplift is clear.

When we look at lines like BP83-37 (yellow), this process explains why the footwall trend is strongly uplifted: it’s a massive stack of duplexes.

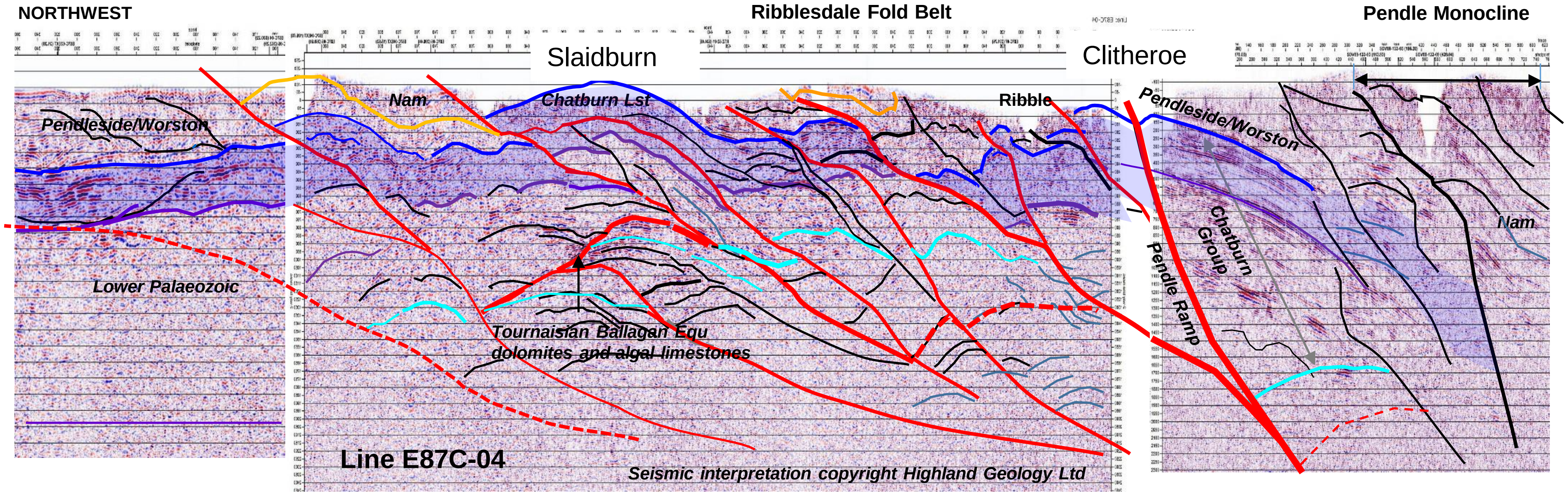




As an alternative, or backup to, the ongoing Hynet CCS hub based on Irish Sea fields disposal, seismic lines across the Clitheroe, Gisburn and Slaidburn major anticlines show the potential of these and adjoining onshore Bowland Basin structures for CCS.

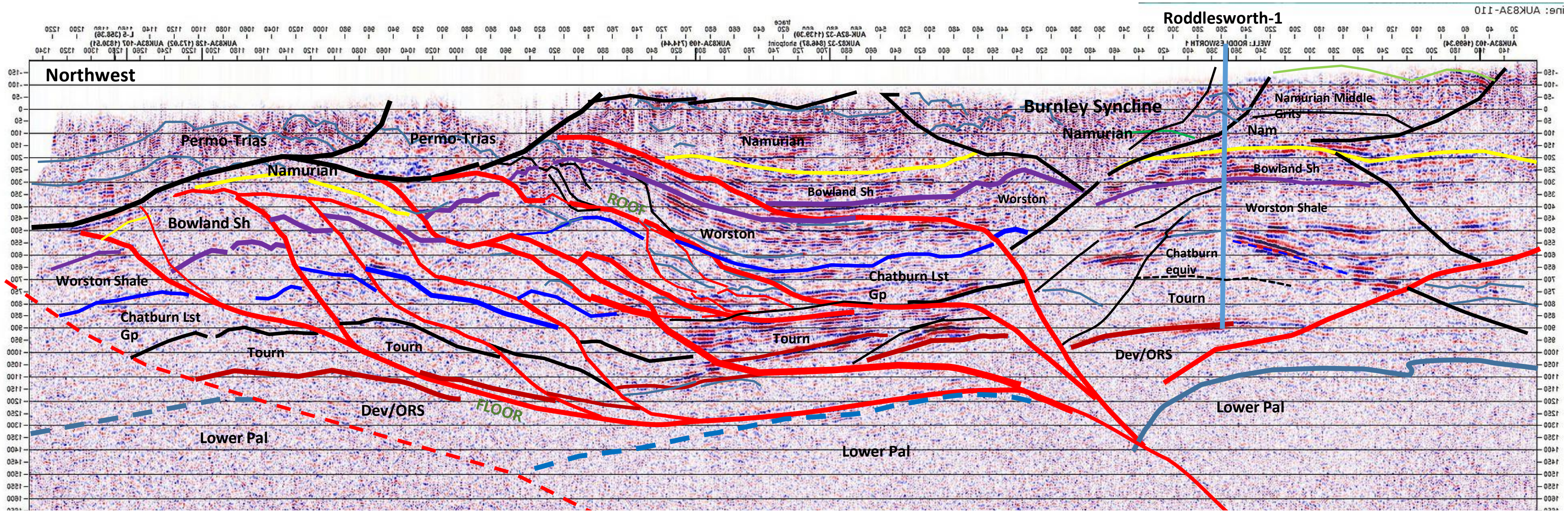
Dashed purple lines are two regional seismic sections, next slides. Blue lines are anticline axes of Ribblesdale Fold Belt. Green lines are seismic profiles available in UKOGL library. Light green and pale blue are Lower Carboniferous formations, pale brown is Namurian outcrop area, darker grey is Westphalian. Shaded areas are blocks licensed for hydrocarbon exploration.

Ribblesdale Fold Belt: is it a candidate for onshore CO2 disposal?



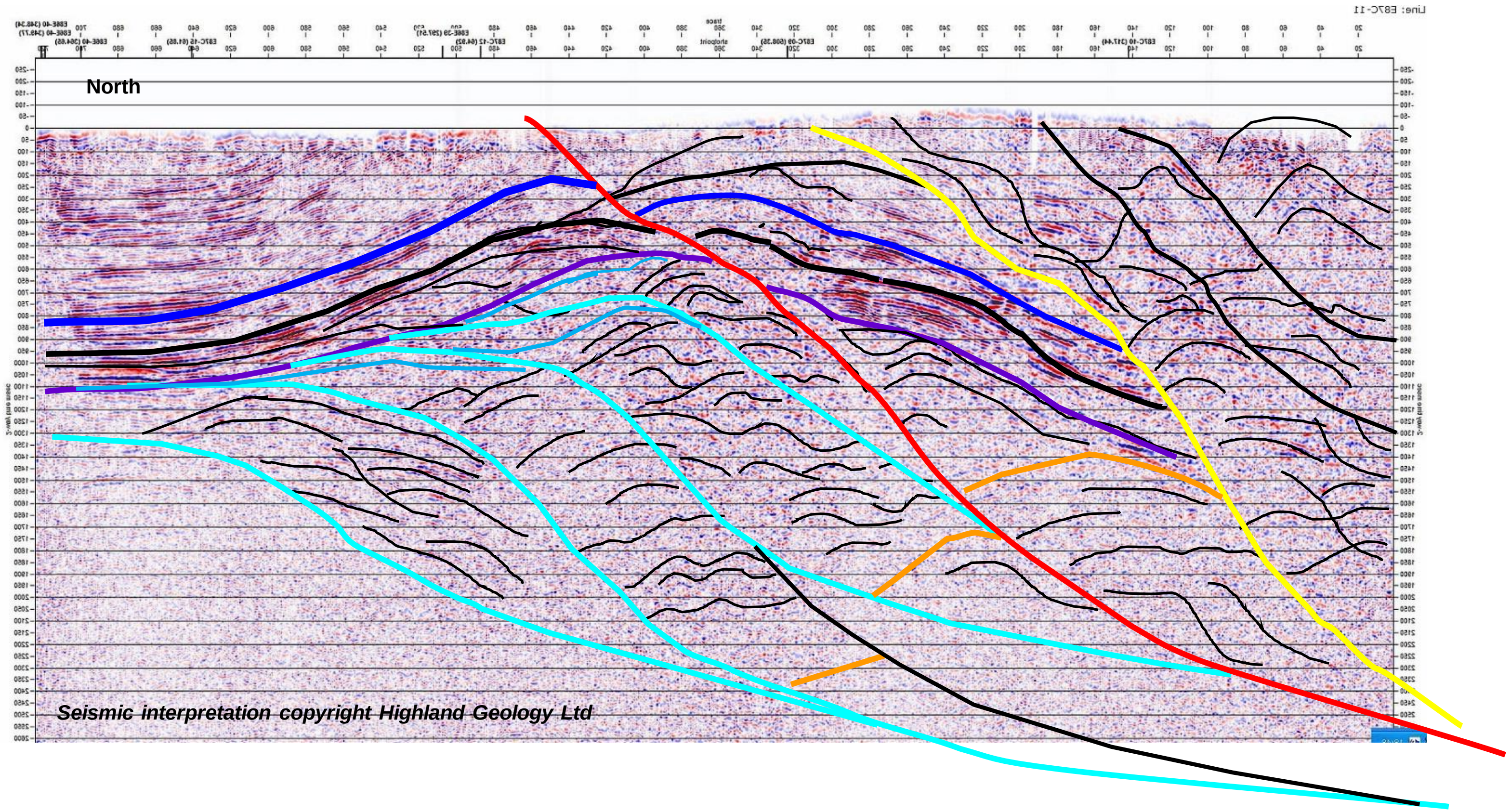
Profile 1 shows the broad structure style: E87C-04 crosses the Slaidburn and Clitheroe Anticlines, Pendle Monocline and Pendle Hill are at right. The RFB folds originated as extensional rollovers and some of the detachments under them are still net-extensional. Inversion at the end of the Carboniferous tightened the folds, generating passive-roof duplex complexes with reverse-faulted northern limbs.

The Clitheroe, Slaidburn and Gisburn structures are large domes, fracture system potential is particularly clear in the Chatburn Limestone Group, the upper limestone is the top half of the shaded blue to purple sequence.



NW-SE line AUK83-110 near Preston, across the Burnley Syncline and Anglezarke Moor, shows two large anticlines belonging to the Ribblesdale fold belt. The ramp under the syncline is not imaged but adjoining lines show it dips south-eastwards.

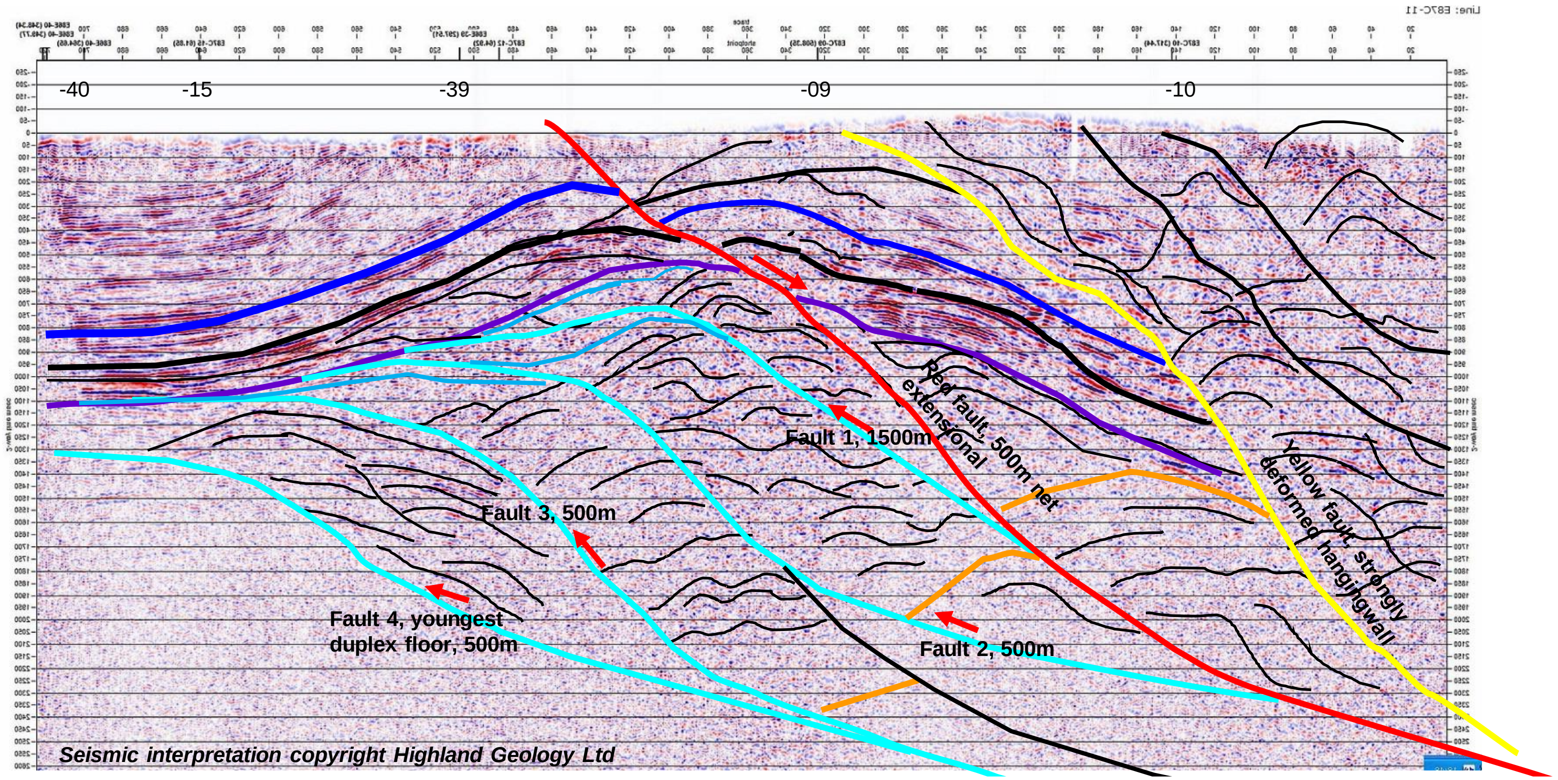
The implication of this structure style, a broad belt with footwall collapse north of the syncline, means that using footwall duplex fracture systems for injecting sodium bicarbonate slurries is likely to be possible all the way from Formby to Harrogate, with Bowland Shale and Worston wrapped over the Chatburn as top seal insurance.



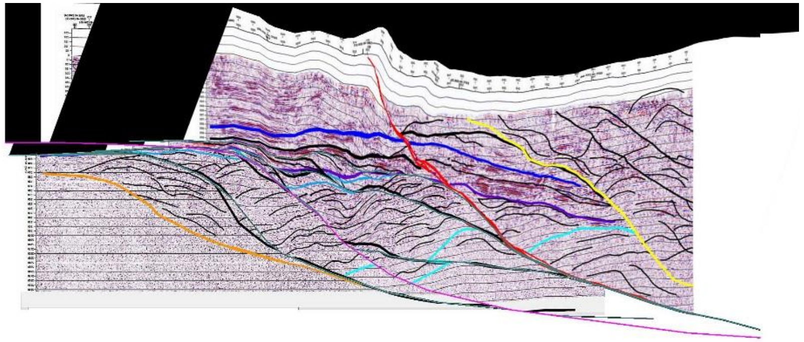
North-south line E87C-11 (14.4 km length) across the Gisburn Anticline confirms it is a pile of reverse-fault slices (duplexes) drawn pale blue, created by progressive footwall collapse in Variscan compression and inversion. Dark blue is the near-top Chatburn Limestone reflector. The northward-reverse faults climb off an early Carboniferous extensional ramp/flat system and tighten the core of the fold. These faults cut down through thick Chatburn and then Old Red Sandstone into the Lower Palaeozoic (orange, approx. position). Upwards they link into a roof thrust at around purple horizon, which is 200-300 msecs below Chatburn top. That's a very important style, from the standpoint of potential topseal for injected slurry. Purple is possibly an anhydritic horizon.

Below the roof fault group the Chatburn has several more tightly-cemented dolomitic limestone and calcareous shale sequences with good fractured-reservoir potential, repeated by the thrusting. Red fault is reversed too, but has post-Permian extensional history.

At outcrop in the Clitheroe quarry there are several thrust faults in the Chatburn, notably the Horrocksford Hall Thrust. So thrusting at top Chatburn can be significant. That thrust is heavily cemented by calcite.



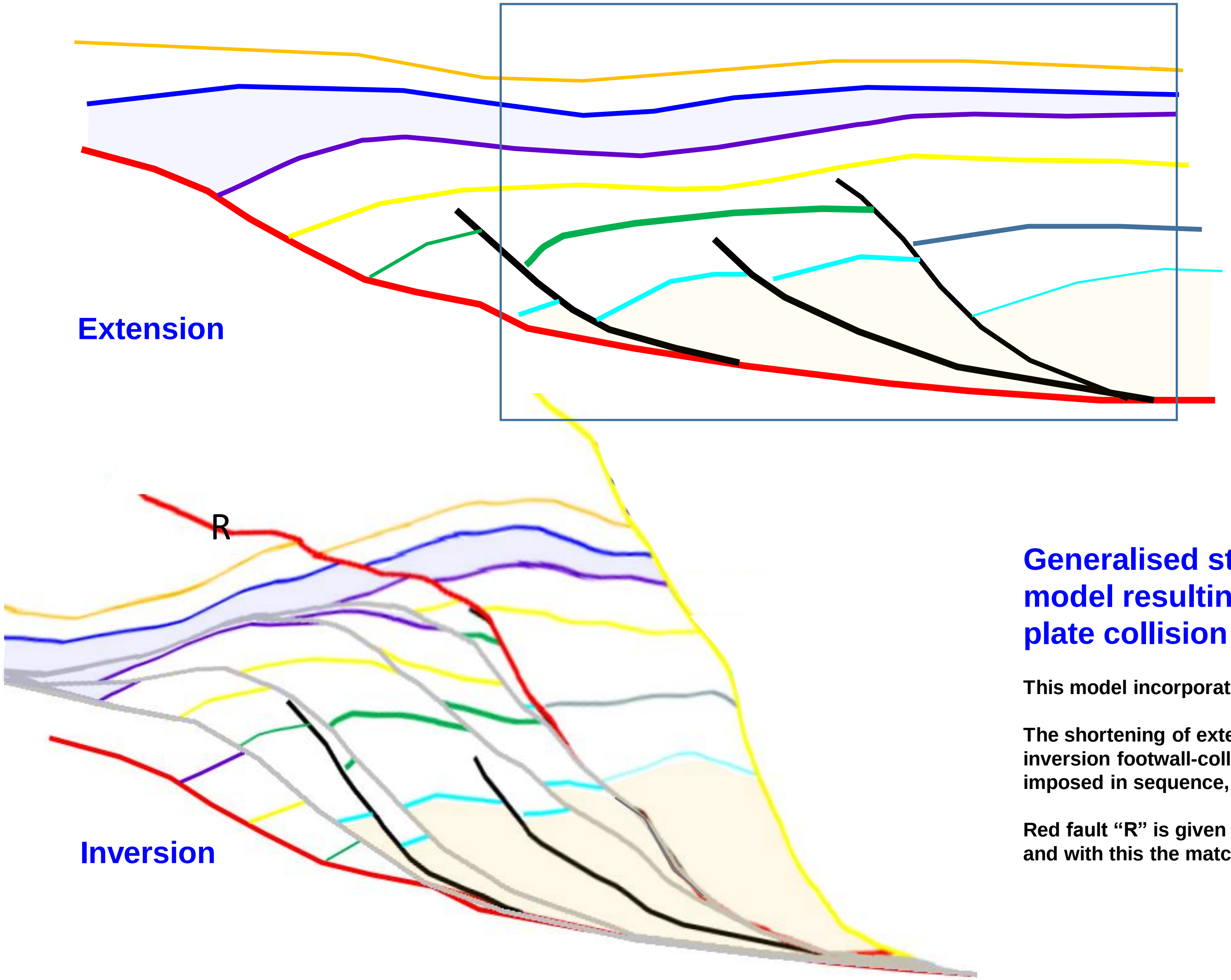
Seismic interpretation copyright Highland Geology Ltd



Shortening by footwall collapse looks to be of the order of 20-25 percent.

This interpretation restores reasonably to pre-late Carboniferous compression state, using inclined-shear (70 degrees left) area balance to reverse the reverse faults; the figures shown on the four pale blue faults were derived by experimentation and are compatible with BGS Clitheroe memoir's displacement estimates. The result portrays a series of extensional fault blocks rooting onto a common detachment, with displacement towards the Burnley Syncline ramp. It suggests only limited growth faulting in later Chatburn beds, most of the extension took place in early-mid Chatburn time. The shape of the deeper fault pattern is not correct, as there is too much south-easterly dip, but the basic pattern is clear and we can generalise it for all of the Fold Belt anticlines.

The duplex faults 1 to 4 wrapping over the top of the stack adds confidence to top seal potential for CO2. Red fault penetrates to present ground level, and for seal security we should aim for fracture systems below it.

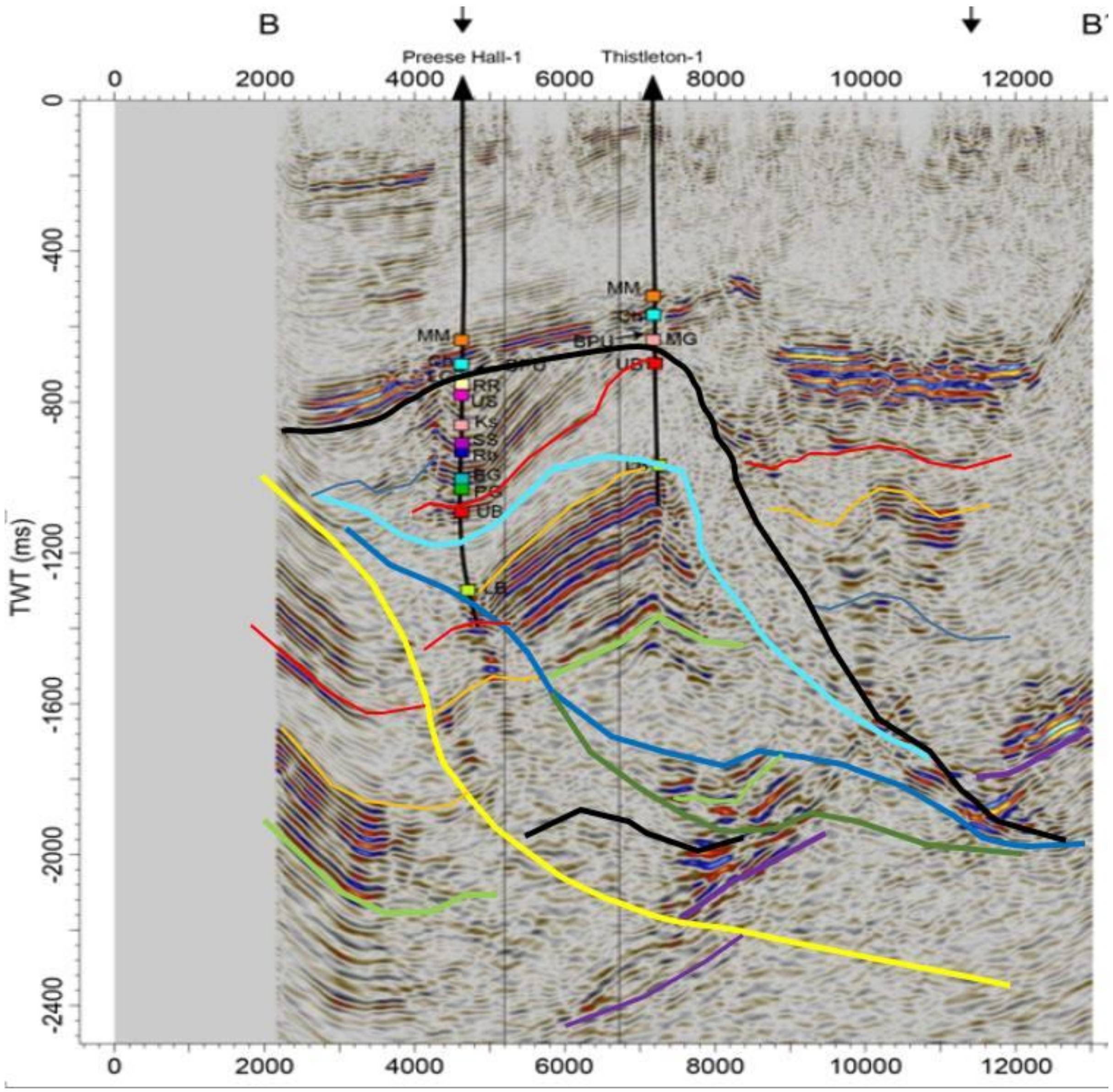


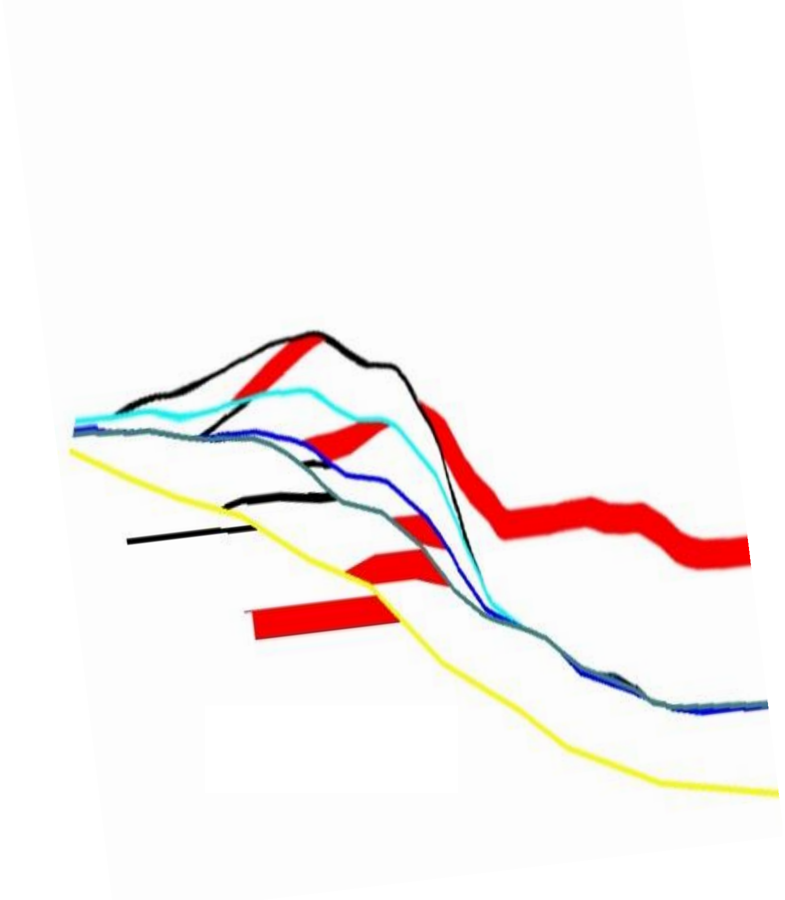
Generalised structure shortening model resulting from late Westphalian plate collision

This model incorporates styles seen at Gisburn Anticline.

The shortening of extensional structures by the four grey inversion footwall-collapse thrusts is substantial. Its imposed in sequence, top right to bottom left.

Red fault “R” is given a post-Permian extensional history, and with this the match to Gisburn is close.



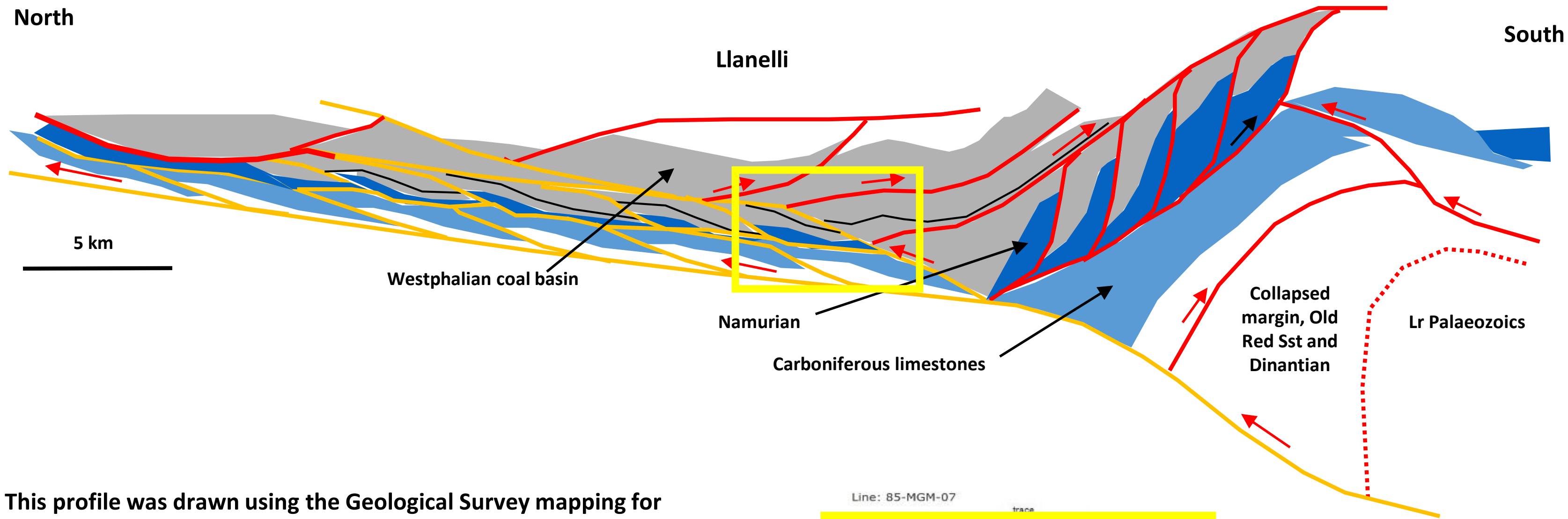


This is a seismic profile from the Fylde licence of Cuadrilla near Blackpool, its from a 3D survey shot for fracking and gives high quality imaging. It confirms the passive-roof structure process is operating in the Craven, it's a clear example. There is much more shortening of this structure, than steep straight faults can generate.

This is Highland Geology's interpretation. Recent publications see it differently.

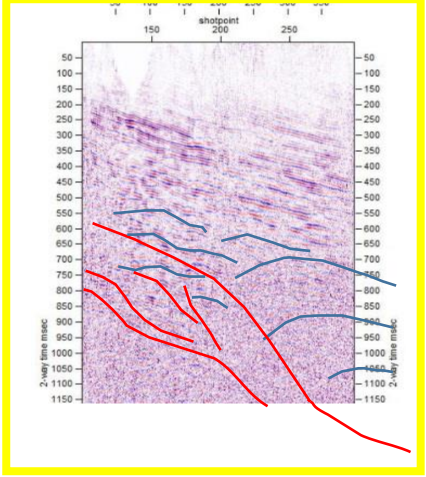
South Wales has a lot of structures suitable for storing carbon. Its also the second largest producer of carbon in UK.

Seismic and outcrop show north-thrusting faults (orange) in duplex patterns: these are full of natural-fracture store space, ideal for sodium bicarbonate slurry and they continue laterally for many tens of km.



This profile was drawn using the Geological Survey mapping for Llanelli and Swansea areas. It runs across Gower Peninsula. Project the line 25 km eastwards to Margam and the position of Port Talbot steel works is approximately where the yellow box is drawn.

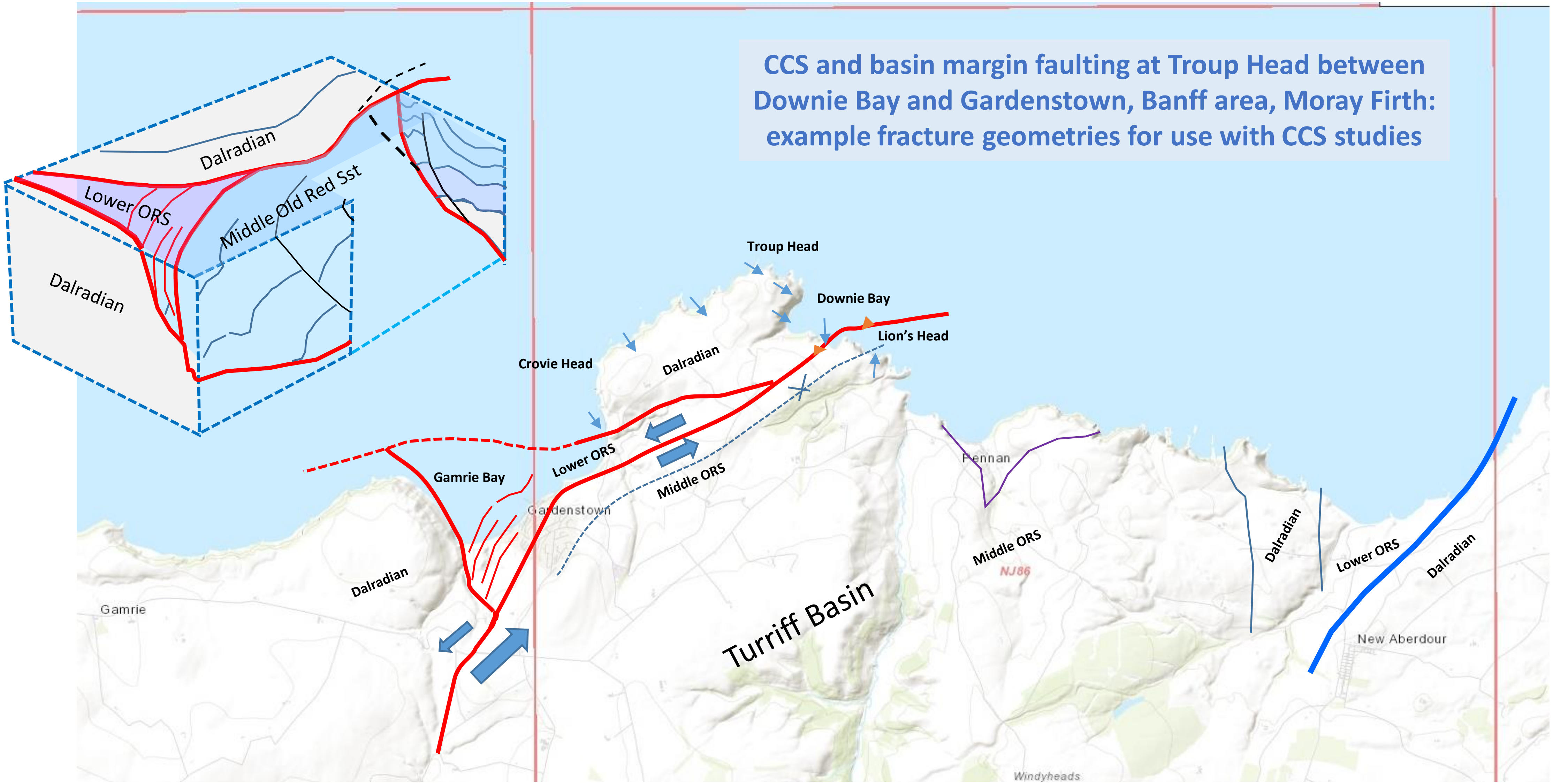
The Carboniferous Limestone (Dinantian, blue) and the Millstone Grits (dark blue) are thrust-folded and dip at around 60 degrees northwards on the south side of the coalfield (grey). Strong northward shortening with orange duplex faulting is evident on the footwall of what was a major extensional south-dipping growth fault system in the Dinantian and Namurian. Orange faults progressively propagated into the collapsing footwall, at various stratigraphic levels depending on where the shales are, and some large-scale out-of-syncline back-thrusting developed (red faults) in the hangingwall.



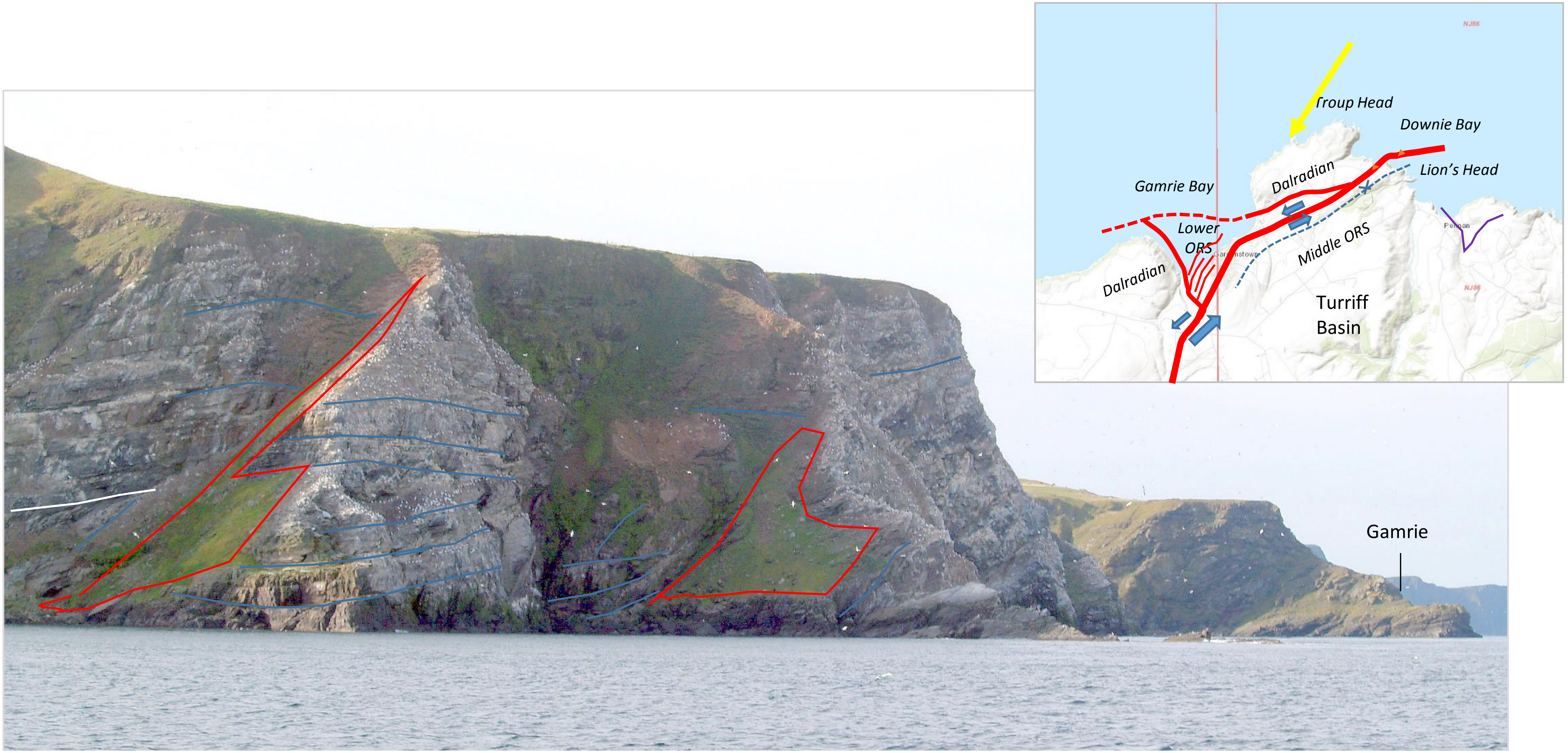
Do rocks really deform in the way we interpret the seismic? Yes.

Rodebjerg in central East Greenland is Middle Devonian, our photo here shows the footwall at left is densely fractured, slices in centre and right are pushed up and over it. Seismic lines shot over structures like this will not have resolution better than 30-40 metres: we can't expect to see the small and medium size faults and joints, but the deformation process requires the rock is progressively broken by linked fracture surfaces.

CCS and basin margin faulting at Troup Head between Downie Bay and Gardenstown, Banff area, Moray Firth: example fracture geometries for use with CCS studies



This area on the south Moray Firth coast exposes a fracture zone similar to onshore CCS candidate structure trends identified by us in the Carboniferous basins of England and Wales. Like Rodebjerg it shows what fractured rocks look like in smaller scale than seismic can image: in particular, what is their likely density. The focus is the Dalradian basement rocks of Turriff Basin's north flank, well seen along the Gardenstown to Downie Bay fault which is a strike-slip zone established in Devonian times and reactivated at intervals to present day in Moray Firth Banff Fault development.



At Collie Head in the main Troup cliff section, which is about 80-90m high, looking SSW the Dalradian dip is into the plane of the photo, away from us at about 30 degrees, which is consistent for the whole Troup block. Some very large fractures cut through the section (grass areas mark the planes of displacement), dipping around 45 degrees northeast: these are extensionals dipping in the same direction as the Devonian basin was opening.

These are the scale of fracture surfaces which can be visible on seismic, provided there are velocity changes associated with them to give an impedence contrast, making a seismic reflector: in very hard, formerly deeply-buried and well-cemented rocks that means the fracture has to be open with water or hydrocarbon charge. They interconnect smaller-scale fracturing in the rock between them.

White spots are gannets.

Pinch-points where faults converge, like this one at Troup, show intensive fracturing due to space problems at such locations.

Comparing Lancaster and Troup

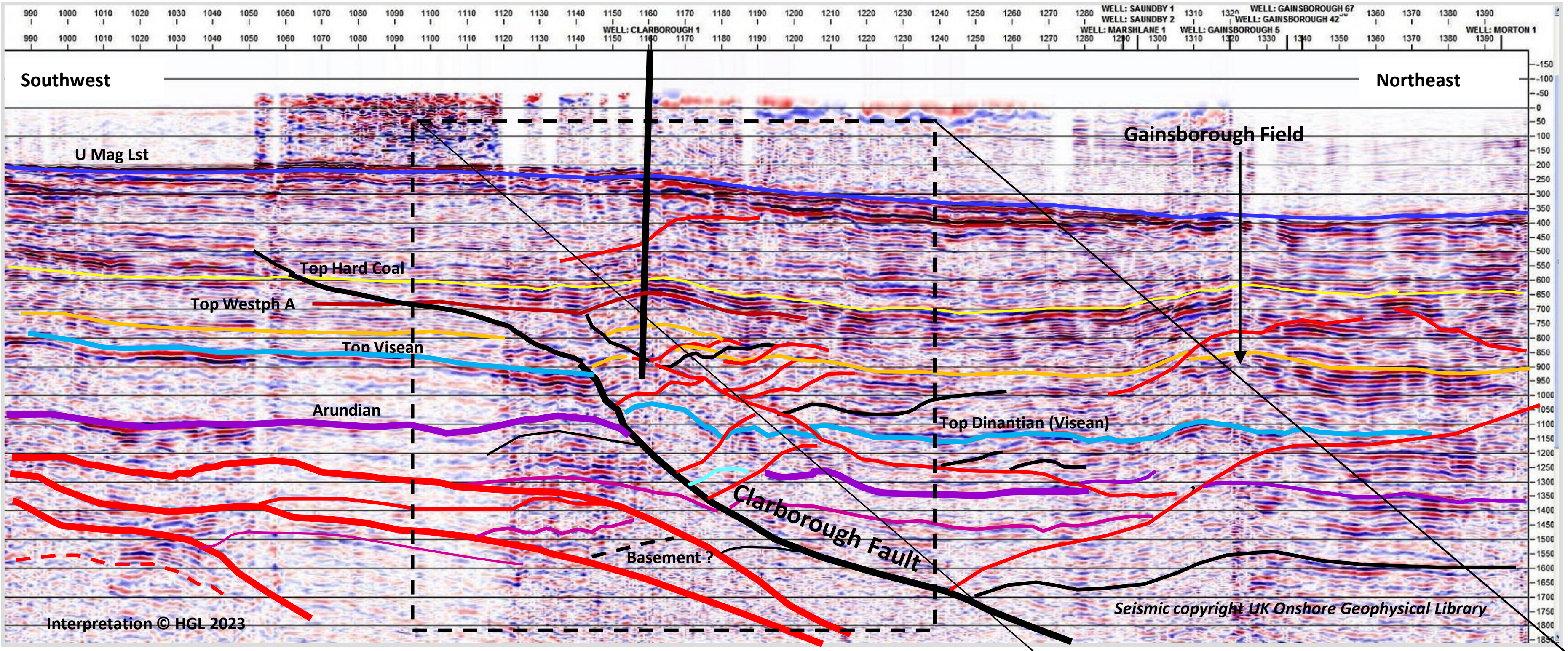
Lancaster oil field in the West of Shetlands Rona Ridge granites is an informative comparison for Troup fracturing. The original Lancaster wells were inconclusively drilled and tested. Based on subsequent development using 3-D seismic data and long deviated and horizontal well drilling with cores, the fault zones at Lancaster are now known to comprise a surprising 30-40 percent of the gross rock volume in closure. Storage space in the main fracture zones ranges 2/5/8 percent with average “porosity” 4.8 percent.

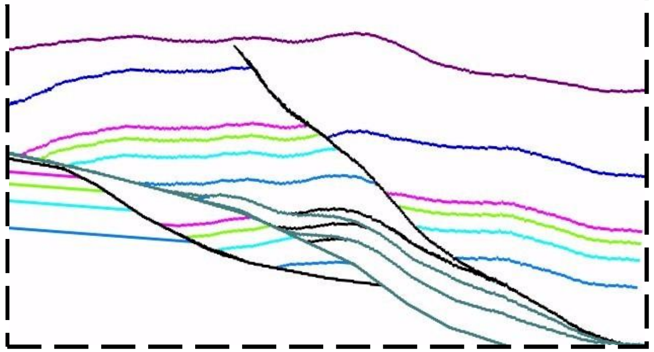
At Lancaster highly-connected matrix fracturing between the main fault zones is proved by the abundant core and by production logging, and it is critically important additional storage space for oil. The granite “pseudo-matrix” has lower fracture volume than the main fracture zones but its pervasive, just as we see at Troup, and this inter-main fracture matrix makes up about 60 percent of gross rock volume.

So Troup confirms for us, high volumes of bicarbonate slurry made with carbon dioxide could be held in this type of reservoir. Also, that a huge percentage of fractures are sub-seismic in scale and we should apply geological modelling as well as seismic interpretation in selecting potential sequestration sites.

A prime candidate for carbon sequestration : southwest margin of the Gainsborough Basin, Clarborough Fault zone

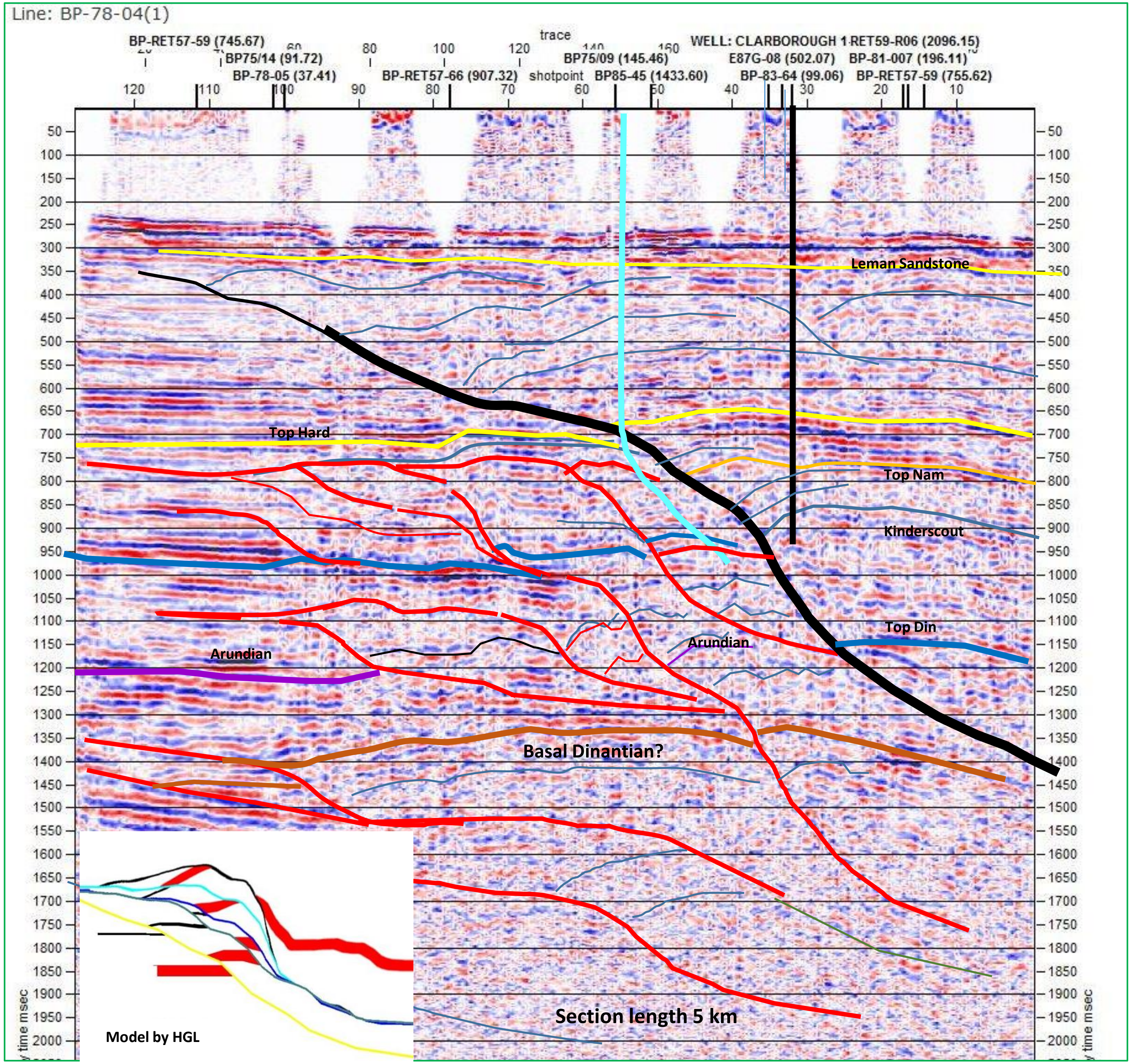
Part BPRG-85-02





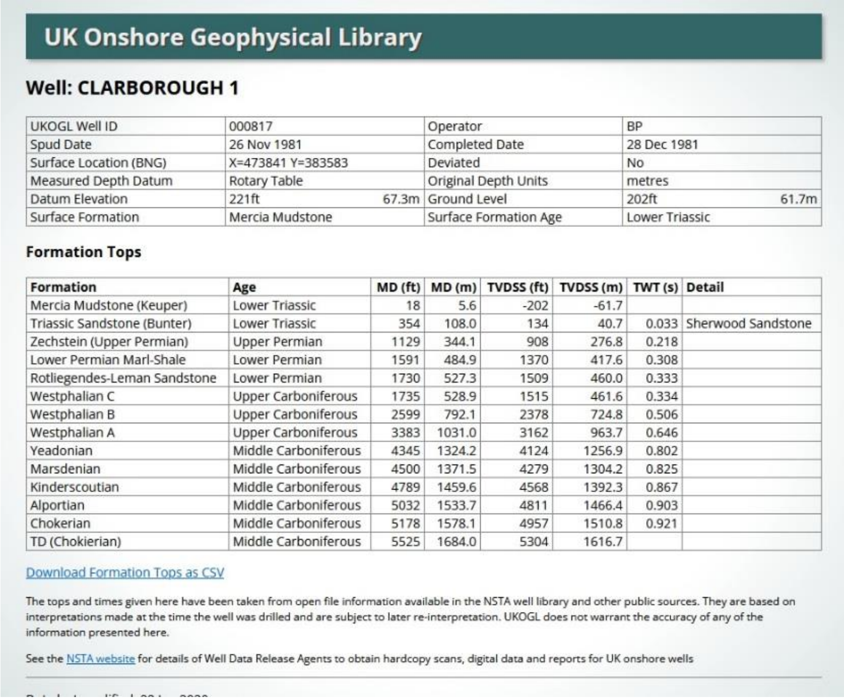
The southwest flank of Gainsborough Trough is a Lower Carboniferous rift margin comprising back-tilted, large extensional fault blocks. The Clarborough extensional fault shown here is one of the faults separating these blocks, its an interesting one for its carbon sequestration potential. The fault separates strongly different lithologies, with brittle platform carbonates at left in the footwall passing abruptly north-eastwards into more ductile deeper-water mudstones in the hangingwall. Important footwall breakdown faults are evident (red), as per the generalised model made with our software, inset.

Clarborough-1 was drilled by BP in 1981. It was a Namurian rollover test intended to penetrate all the Namurian (Millstone Grit) and reach top of Lower Carboniferous Dinantian limestones at 1830m: but it didn't get there. Whilst 100msecs or more above the Clarborough fault, still in the hangingwall, it lost circulation at 1685m which despite control efforts became enforced TD. Mud loss was total back to 9 5/8 shoe at 570m. It's a valuable result, for confirming that connected natural fractures can give potentially commercial store space in the zone adjoining the main fault, and supports the likelihood that fracture development we interpret on seismic in the footwall will be significant too. We think it's the footwall faults which are the ones which really matter for CSS.



At Clarborough-1 the major mud losses started at black fault zone or just above. Its hangingwall must be full of fractures which are probably mainly vertical and will be interconnected with the main fault surface.

What we want to know, is what sort of fracture storage volume exists in the fault-separated compartments (duplexes) under black, compared to the loss in the well: and is there a potentially commercial volume available for bicarbonate slurry, on this trend? A well such as pale blue would test black fault updip for more fracturing, and go on to explore the footwall duplex below it, with option to side-track back into the proven loss zone if lateral duplexing proved to be poorly developed.



UK Onshore Geophysical Library

Well: CLARBOROUGH 1

UKOGL Well ID	000817	Operator	BP
Spud Date	26 Nov 1981	Completed Date	28 Dec 1981
Surface Location (BNG)	X=473841 Y=383583	Deviated	No
Measured Depth Datum	Rotary Table	Original Depth Units	metres
Datum Elevation	221ft 67.3m	Ground Level	202ft 61.7m
Surface Formation	Mercia Mudstone	Surface Formation Age	Lower Triassic

Formation Tops

Formation	Age	MD (ft)	MD (m)	TVDSS (ft)	TVDSS (m)	TWT (s)	Detail
Mercia Mudstone (Keuper)	Lower Triassic	18	5.6	-202	-61.7		
Triassic Sandstone (Bunter)	Lower Triassic	354	108.0	134	40.7	0.033	Sherwood Sandstone
Zechstein (Upper Permian)	Upper Permian	1129	344.1	908	276.8	0.218	
Lower Permian Marl-Shale	Lower Permian	1591	484.9	1370	417.6	0.308	
Rotliegendes-Leman Sandstone	Lower Permian	1730	527.3	1509	460.0	0.333	
Westphalian C	Upper Carboniferous	1735	528.9	1515	461.6	0.334	
Westphalian B	Upper Carboniferous	2599	792.1	2378	724.8	0.506	
Westphalian A	Upper Carboniferous	3383	1031.0	3162	963.7	0.646	
Yeadonian	Middle Carboniferous	4345	1324.2	4124	1256.9	0.802	
Marsdenian	Middle Carboniferous	4500	1371.5	4279	1304.2	0.825	
Kinderscoutian	Middle Carboniferous	4789	1459.6	4568	1392.3	0.867	
Alportian	Middle Carboniferous	5032	1533.7	4811	1466.4	0.903	
Chokerian	Middle Carboniferous	5178	1578.1	4957	1510.8	0.921	
TD (Chokierian)	Middle Carboniferous	5525	1684.0	5304	1616.7		

Download Formation Tops as CSV

The tops and times given here have been taken from open file information available in the NSTA well library and other public sources. They are based on interpretations made at the time the well was drilled and are subject to later re-interpretation. UKOGL does not warrant the accuracy of any of the information presented here.

See the NSTA website for details of Well Data Release Agents to obtain hardcopy scans, digital data and reports for UK onshore wells

Confirming that natural fractures are commercially viable for storage

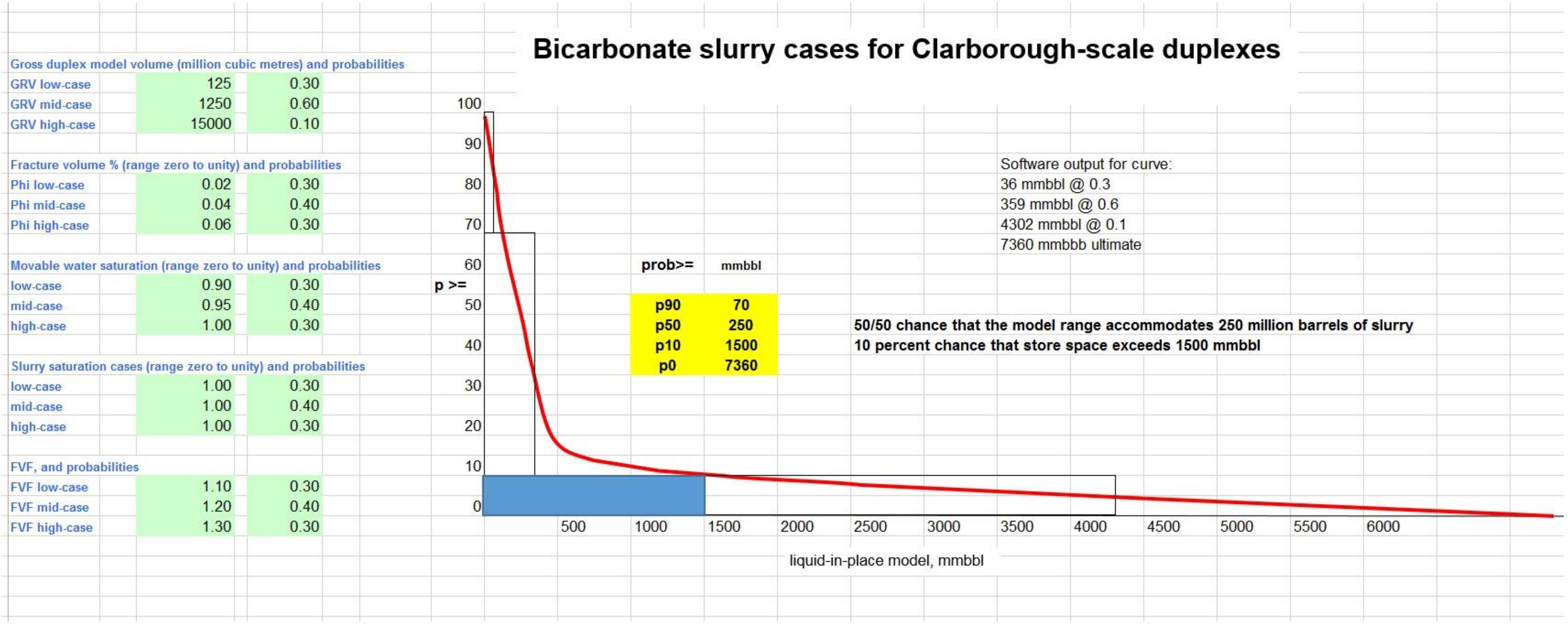
Given a general overview of the location and potential for natural-fracture storage trends, the crucial aspect of our review is how do we progress to proving commercial sustained flow rates and storage capacity for injecting slurry? Overall, it's easy to short-list suitable locations for a trial project. For competent interpreters who know how rocks deform, its standard structure mapping.

Intermittent pressuring and pumping re-opens and re-connects fractures around the well bore, allowing large volumes of slurry to be pumped downhole. Each successive well drilled can inject slurry waste into earlier wells. Think about a chocolate orange. What happens with intermittent pressuring is an annular fracture bundle forms around the well bore, it's a disposal domain with a series of vertical fractures radiating off from the well bore, they have slightly different angles around the bore, giving slices like the pieces of chocolate in the orange. As you go on pushing bicarb solids into the receiving formation, the micro-fractures grow horizontally and the space for solids increases accordingly. The volume available becomes far bigger than simple models predict. It's not a big fracture plane: it's a large number of sequential micro-fractures each taking slurry.

The whole process depends on experienced drillers running it. Monitoring fluids movement in injection is always going to be uncertain: and shooting seismic doesn't help, it won't show slurry location. One can drill observation wells laterally to an injection site, and install meters downhole in wells to detect sudden pressure changes which will be a warning of problems appearing. If slurry does reach surface that's most likely to be caused by failure of cement bond integrity between casing and rock, and calls for packers to be run, perforations made and cement injection at leak points. (A strong argument for staying clear of old oil wells, is that they could be potential escape routes if abandonment was done many years ago).

Volumetric cases for Clarborough-style duplex fracture systems

Intensive fracturing exemplified by the Clarborough Fault was created in the late Carboniferous uplift and inversion and renewed in Jurassic, again in mid Tertiary uplift, and probably yet again re-opened by serial loading and unloading in the various glacial advances of the past several million years. Potential fracture networks reservoirs for SI are divided into (i) discrete through-going fault zones, which are the ones we can see on seismic, and (ii) pseudo-matrix which is tight sediments fractured at sub-seismic scale, whose interconnected fractures are linked into the main fault zones. Let's look at potential reservoir storage in fractured Lower Carboniferous for three arbitrary volume cases which might be reasonable expectations. It serves to show that we have a very large potential SI zone on the Clarborough Fault.



Gross duplex model volume (million cubic metres) and probabilities		
GRV low-case	125	0.30
GRV mid-case	1250	0.60
GRV high-case	15000	0.10
Fracture volume % (range zero to unity) and probabilities		
Phi low-case	0.02	0.30
Phi mid-case	0.04	0.40
Phi high-case	0.06	0.30
Movable water saturation (range zero to unity) and probabilities		
low-case	0.90	0.30
mid-case	0.95	0.40
high-case	1.00	0.30
Slurry saturation cases (range zero to unity) and probabilities		
low-case	1.00	0.30
mid-case	1.00	0.40
high-case	1.00	0.30
FVF, and probabilities		
FVF low-case	1.10	0.30
FVF mid-case	1.20	0.40
FVF high-case	1.30	0.30

Bicarbonate slurry cases for Clarborough-scale duplexes

Software output for curve:
36 mmbbl @ 0.3
359 mmbbl @ 0.6
4302 mmbbl @ 0.1
7360 mmbbb ultimate

prob>=	mmbbl
p90	70
p50	250
p10	1500
p0	7360

50/50 chance that the model range accommodates 250 million barrels of slurry
10 percent chance that store space exceeds 1500 mmbbl

All three cases have the same range of 2-6 percent interconnected fracture "porosity" which is stringently low, and nearly all of that is water-filled and can be displaced by bicarbonate slurry. The low case is a 1000 metre long slab of fractured footwall duplex some 500 metres wide, adjoining the Clarborough Fault, its height between roof and floor is 250 metres measured parallel to the fault. It could be viewed as a sample abstracted from a single, sizable footwall duplex. The mid case is a 5000 metre length slab which is 500 metres wide and 500 metres high between roof and floor. This could be a composite of several duplexes, or just a bigger one. The high case is a 10 km slab x 2 km wide, which is a series of duplexes, and 750 metres high. Seismic supports this high-case geometry as a realistic model where several major inverting faults converge; and the BP mapping shows the Clarborough Fault has this length and more, along with a large, linked sidewall fault. The weighting probabilities are loaded towards the smaller cases. The answer is, we have a p50 storage case of 250 million barrels of slurry, and the top end is over 1.5 billion barrels.

Onshore UK CCS is a great opportunity !

By this slurry injection method we are insured against a well failing to find store space: if it intersects predicted natural fracture sets with some of them open, that's good: if they are cemented, SI re-opens them and creates its own local nest of slices around the bore. The risk of drilling capital being wasted is small. An optimum situation is where we have alternating sandstones and shales at target depth, with sandstones which are reasonably thick and extend laterally for a substantial distance: the injection is made into higher permeability layers at the base of the sequence, the upper shale layers act as containment caps and rapid leak-off zones which stop upward fracture propagation.

We do not need to be located inside structural trap closure areas: the injection points can be located anywhere along the fracture trends, and these cover 40-50 km in South Wales and East Midlands. So we have enormous extent available for the sequestration.

A site might be used for maybe 5 years, with 5-10 wells, and then the process moves on to a new location, restoring the old one. Individual well clusters will cost around £10 million. Probably the most expensive aspect of sequestration is the CO2 separation, which is an expense common to any sequestration method. Making up slurry at site requires tankage for high volumes of chemicals, but will be far cheaper than pumping CO2 away by new steel pipeline for removal offshore and injection downhole to much greater depths from a platform.

The next step for this very promising approach to solving the carbon problem, is to drill a trial well and demonstrate the method. The risk is small. We will welcome inquiries and dialogue on how to finance and perform such a test: we think a single injector well with logging and lots of core would cost about £3 million to drill and test. When injectivity is confirmed, trials with slurries could start. We have some locations to propose, one of which has a recent well we could probably re-enter, cutting costs substantially. Please talk to us!