# CCS Onshore UK

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September 2024

# Carbon Capture and Storage Onshore UK

There is general consensus that the best way to dispose of carbon dioxide produced by UK industrial activity is to pipeline it offshore to former gas field platforms via proposed hubs. Here we argue that the fastest and by far the simplest plan for UK is to convert the threatening CO2 at source into calcium carbonate slurry, which can be pumped safely into the natural rock-fracture systems which cross the onshore Carboniferous basins, for permanent storage at a very small fraction of the cost of going offshore.

Using available seismic profiles its easy to confirm candidate locations and shortlist the best of them for detail work, and design a first trial-drilling to demonstrate viable, interconnected fracturing and effective top sealing. Key technical requirements for this first well are to prove significant storage volume, reliable top-sealing, and to pump enough drilling mud downhole to show that the fractures will accept slurry in large amounts.

Natural-fractured system slurry storage is highly promising, it will work, its been done. What we are describing here is not new technology. The main issue of concern is that the clarity needed from licensing, permitting and planning authorities to attract and support capital investment in CCS onshore, is not presently in place. Until it is clear how the drilling of injectors will be legalised, authorised and monitored, even modest spend will not be available onshore UK. If the necessary legislation could appear in the next year or so, there would then be major incentive to develop this alternative option to funding expensive offshore projects. CCS could perhaps be bracketed with geothermal, with drilling and site operations subject to the same permitting and enforcement regulations as are applied to hydrocarbon exploration.

Given that framework, a prime aim is to get an R&D consortium together for a well to be drilled, collect cores and logs to maximise knowledge of the fracture networks which are the target, and inject slurry to confirm injectivity. Onshore site identification for slurry injection is straightforward. Sites don't require high-quality reservoir rocks: the store space for slurry is the fractures, not the rock. Top seal confirmation above the fracturing zone is critical. Test wells can be instrumented for pump tests to watch reservoir pressure behaviour in flow tests. If expected performance criteria are met, the site can move to extended-period injection testing with installation of compressors. Around £10 million capital would see the first site prove the method works, buy support plant and the well can go commercial.

Drilling wells of this type should not attract sustained public objection in the way that hydrocarbon projects do. Cost-effective reduction of carbon dioxide output benefits Industry and reduces government subsidy outlays, reflecting on tax burden and product costs, creating expertise and jobs in UK and internationally.

# Handling Carbon Dioxide

Separating $CO_2$ is a problem already solved, its done in many places world-wide, the technology has been advancing steadily and has been effectively trialled in UK. Drax in partnership with Mitsubishi have confirmed that MHI's market-leading amine solvent system provides large-scale producers with a commercial means of separating $CO_2$ from flue gases, and getting it ready for transport as a purified gas. There are similar, alternative solvent processes. Given that $CO_2$-sourcing sites can do that, don't put the gas into a pipeline: convert it to calcium carbonate slurry, which is safe.

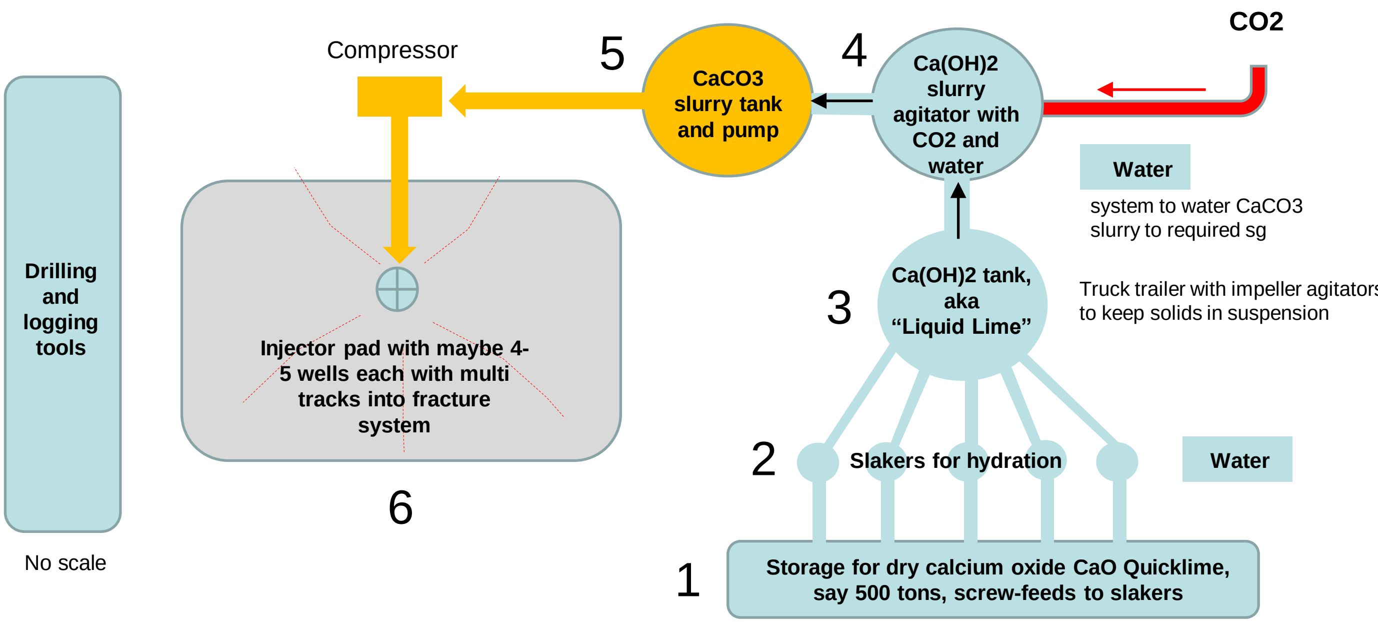
Buy-in quicklime (calcium oxide) from a cement works kiln, hydrate it in slakers, store the calcium hydroxide in a liquid-lime tank; transfer it to a mixer tank along with the producer's carbon dioxide gas. Separate the calcium carbonate precipitate slurry, pump to a holding tank, make up the slurry to equivalent density of drilling mud, pass it to a compressor and pump it downhole into the fractured rock system. All the equipment for this process can be bought, mounted on road trailers.

The challenge, how do we get rid of very large tonnages of calcium carbonate? $CaCO_3$ water-based slurry at a specific gravity of around 1.3 is around 40 percent solids and will pump downhole just like drilling mud, it has no requirement for $CO_2$-resistant high-grade steel components in an injection system. It remains liquid and is thermally stable to temperatures far higher than injection wells reach. By the pressure-pulse method of drilling 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, the well re-opens them and creates its own local nest of slices around the bore. If the target rock type is limestone, it will be brittle and fractures mostly early-cemented: acid wash will re-establish fracture continuity. The risk of drilling capital being wasted is small. Costs will fall as experience is gained.

The optimum situation is where we have alternating limestones and shales, the carbonates reasonably thick and extending laterally for a substantial distance: the injection is into the higher permeability layers at the base of the sequence, the upper layers act as containment caps and rapid leak-off zones which stop upward fracture propagation. Suitable successions are readily available in the UK Lower Carboniferous. With depths of 1500-2000 metres slurry fluid is not going to reach drinking water aquifers.

We do not need to be located inside structural trap closure areas: the injection points can be located anywhere along the fracture trends, larger individual faults can cover tens of km. So we have enormous extent available for the sequestration, not a limited area like the offshore fields. Occupy a site for maybe 5 years, with 5-10 wells, and then replace it with a new location, restoring the old one.

# Carbon dioxide disposal as slurry onshore UK in deep boreholes: drilling pad design




**Schematically this is an outline for dealing with carbon dioxide onshore. Our concept is to construct drilling pads for injection wells more or less at CO2 source, injector wells would take calcium carbonate slurry made by passing the gas into calcium hydroxide fluid, separating the precipitated calcium carbonate and pumping it downhole.**

# Choosing natural fracture systems for storage

**How do we reliably select drilling locations and prove commercial storage capacity for injecting calcium carbonate slurry?**

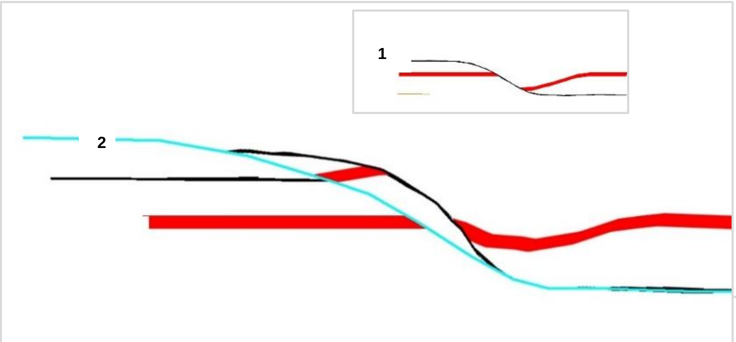
**One of the most readable guides on the subject of Slurry Injection (SI) was published in 2003 by John Veil and Marcel Dusseault, for the US Dept of Energy, National Petroleum Technology Office: "Evaluation of Slurry Injection Technology for Management of Drilling Wastes". Another good presentation is "Deep Underground Injection of Waste from Drilling Activities—an Overview", Gaurina-Međimurec et al, in *Minerals* 2020, *10*, 303.**

**A key point about slurry injection is that it will invade natural fractures and the driller can add to fracture space by maintaining mud pressure high enough to continuously micro-fracture the immediately adjacent annular space around the well, behind the casing. When the injection stops, the slurry will be trapped in place and the slurry fluid bleeds off. The process is intermittent, repeated, and no injection well need be used for more than a short period.**

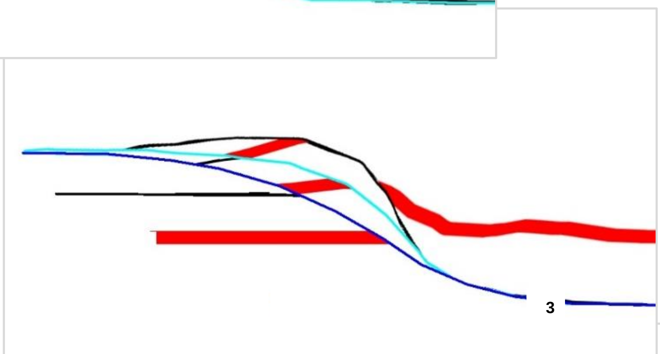
**This is *NOT* fracking: the pressure is not kept on the formation. Its standard drilling procedure accepted world-wide as environmentally positive, and routinely used for disposing of drilling waste. The well bore is lined with casing before injection, efficiently cemented in place and the casing is then perforated across the injection zones selected. 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 from the well bore, they have slightly different angles around the bore, giving slices like the pieces of chocolate in the orange. As we go on pushing 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 calcium carbonate.**

**We expect that five or so wells will be drilled off one central point, with an element of deviation from vertical (the target formation isn't deep enough to build enough angle for horizontals). With multi-well onshore pads each successive well can have its waste injected into the first well, which is finally completed as an injector. If a well lasts more than a hundred or so days, that's fine. Carbon dioxide arrives via a small diameter pipeline which might be up to 20 km long: but ideally the injection point is very local or at the source producing the gas ready for converting to calcium carbonate.**

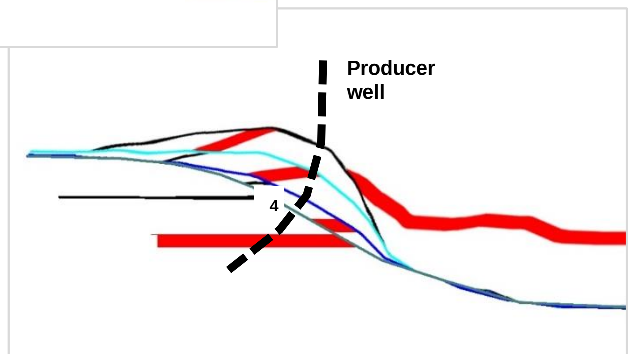
## Passive Roof Duplexing creates structural highs which are excellent targets for injector wells




Inversion fault 2, pale blue, breaks into the footwall of extensional fault 1, and now 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.




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 stacked footwall features appearing. Fault 1 is net-extensional, the other faults are wholly reverse.




Fault 4 in dark green propagates off the floor fault of the stack next, it has less heave. There are lots of examples of small steep faults like this in places like Clitheroe fold belt.

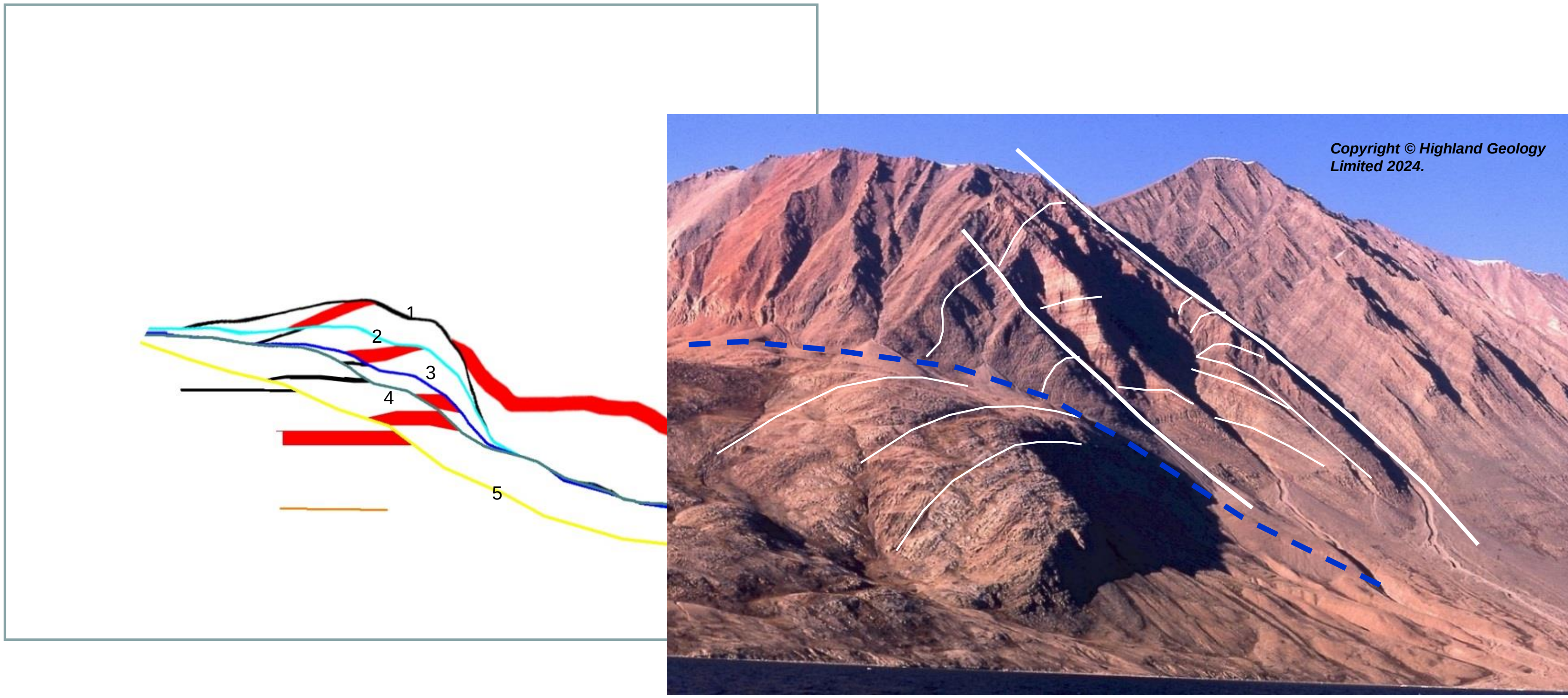
Models here are made with section balance software written by John Nicholson.

**Repeated close-spaced footwall faulting in shortening of earlier extensional structure, forces a stack of thrust slices (duplexes) to develop and progressively climb, each slice stretches as it travels over an upward-convex new fault. The evolving hangingwall will fracture continuously as all previous slices of rock are passively flexed in the inversion. The new faults propagate downwards, each new one's curvature imposes more stretching of the evolving stack above it, because the stack has to stay in contact: hence "passive". Each new footwall collapse fault inflicts its own phase of stretching, and renewed axial fracturing on all of the overlying rock travelling across it. Brittle limestones and dolomites will be particularly likely to fracture.**

**So we can expect significant opening fractures to develop and thoroughly penetrate the hangingwall. A deviated well drilled through the stack will find a high concentration of interconnected faults.**

**The drilling method for the injection well is pressure-pulse injection. A competent drilling crew can use mud pressure variation to break rock immediately around the well bore, interlinking the injection wells with natural fractures. This is standard drilling practice (not to be confused with shale gas fracking!), has been for a quarter of a century, and is accepted onshore UK by environmental agencies. The proposed R&D well will demonstrate the method in the context of carbon disposal.**

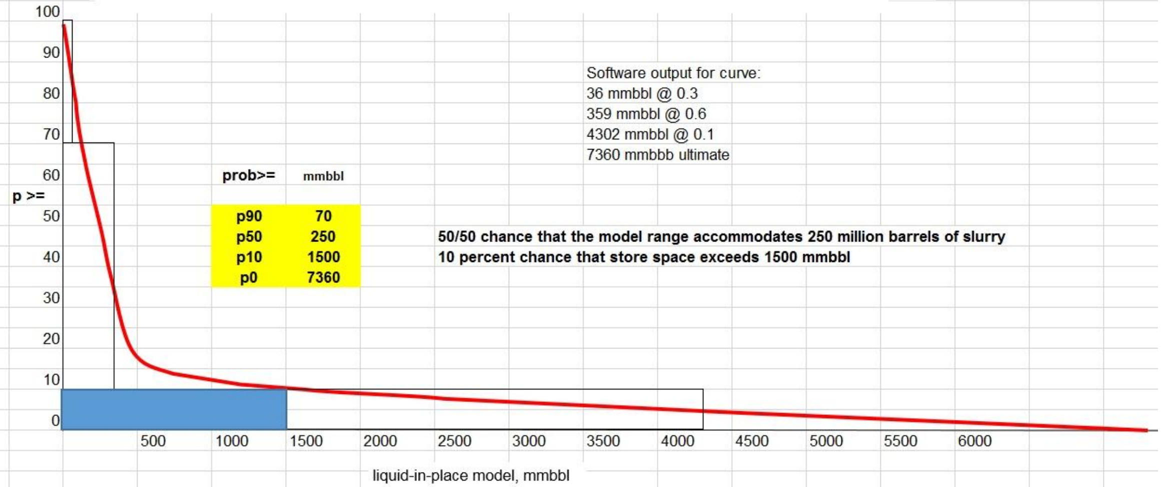
## And here’s a real duplex, from East Greenland, which we worked on in 1970




**With this model we have a geometrically sensible concept to help us identify key locations for slurry storage.**

# Potential storage volume for slurry: three model cases

| | | |
|---|---|---|
| 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 |

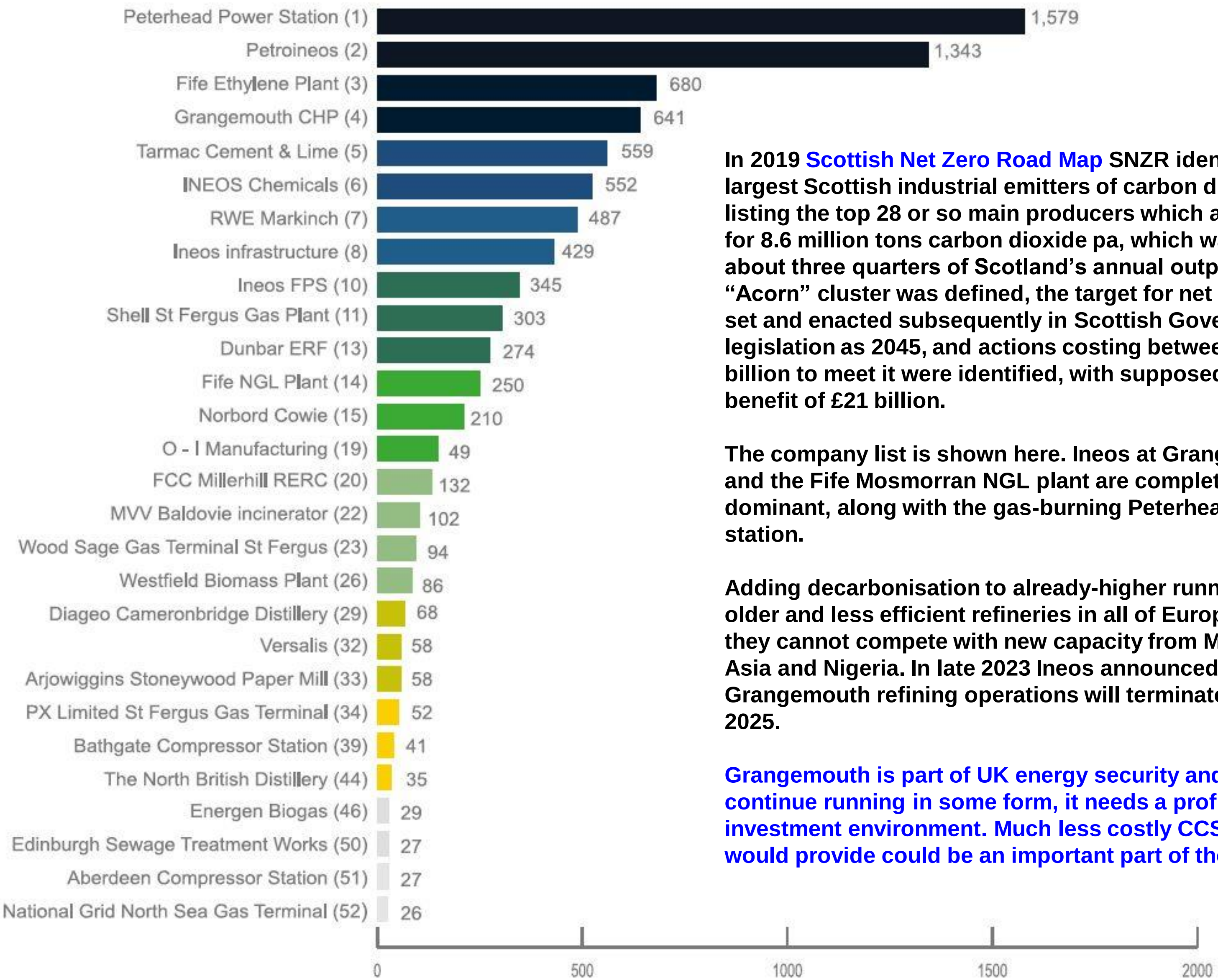



**This is an expectation curve for three general volume cases, its based on the Clarborough-1 well in Gainsborough Trough which penetrated a fracture system into which the total mud volume was lost, and the well was abandoned as circulation couldn't be restored. All cases have the same range of 2-6 percent interconnected fracture "porosity" which is stringently low. Nearly all of that is water-filled and can be displaced by calcium carbonate slurry.**

**The low case is a 1000 metre long slab of fractured footwall duplex some 500 metres wide, its height between roof and floor is 250 metres. 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 the high-case geometry as a realistic model for locations where several major inverting faults converge; mapping shows the Clarborough Fault has this length and more, along with a large, linked sidewall.**

**The weighting probabilities are loaded towards the smaller cases, and the cases certainly demonstrate the potential! A fifty-fifty chance of 250 million barrels storage volume is suggested.**

# A possible first site?



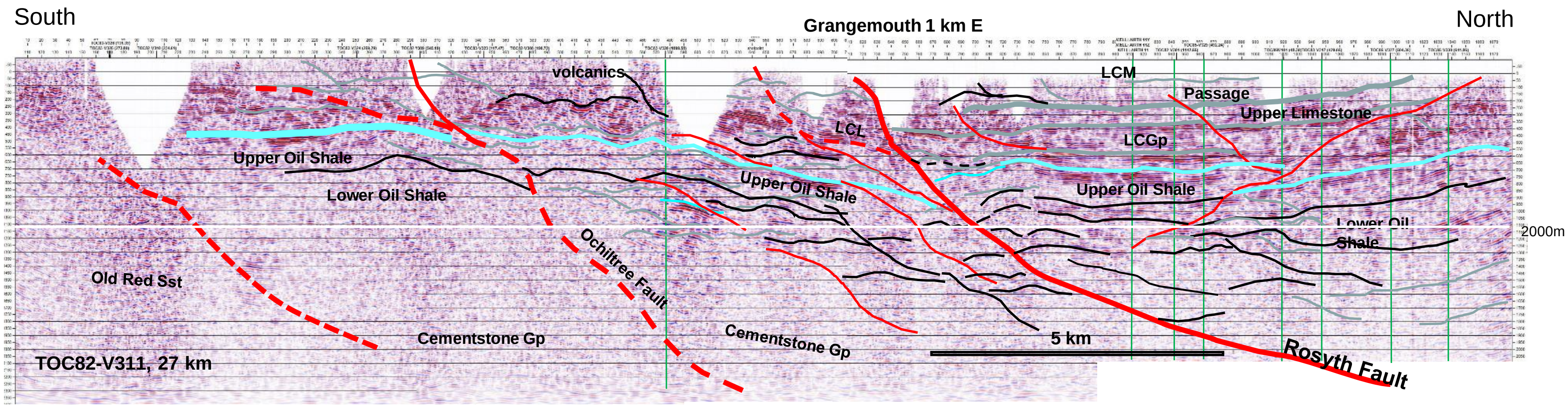

**In 2019 Scottish Net Zero Road Map SNZR identified the largest Scottish industrial emitters of carbon dioxide, listing the top 28 or so main producers which accounted for 8.6 million tons carbon dioxide pa, which was then about three quarters of Scotland's annual output. The "Acorn" cluster was defined, the target for net zero was set and enacted subsequently in Scottish Government legislation as 2045, and actions costing between £6-9 billion to meet it were identified, with supposed economic benefit of £21 billion.**

**The company list is shown here. Ineos at Grangemouth and the Fife Mosmorran NGL plant are completely dominant, along with the gas-burning Peterhead power station.**

**Adding decarbonisation to already-higher running costs of older and less efficient refineries in all of Europe means they cannot compete with new capacity from Middle East, Asia and Nigeria. In late 2023 Ineos announced that Grangemouth refining operations will terminate by end-2025.**

**Grangemouth is part of UK energy security and to continue running in some form, it needs a profitable investment environment. Much less costly CCS than Acorn would provide could be an important part of the answer!**

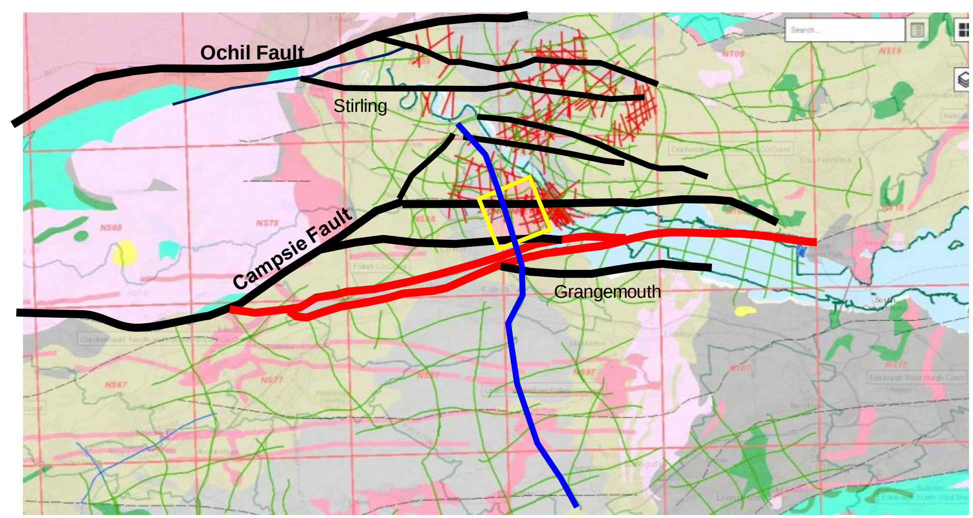
# Potential Application at Grangemouth

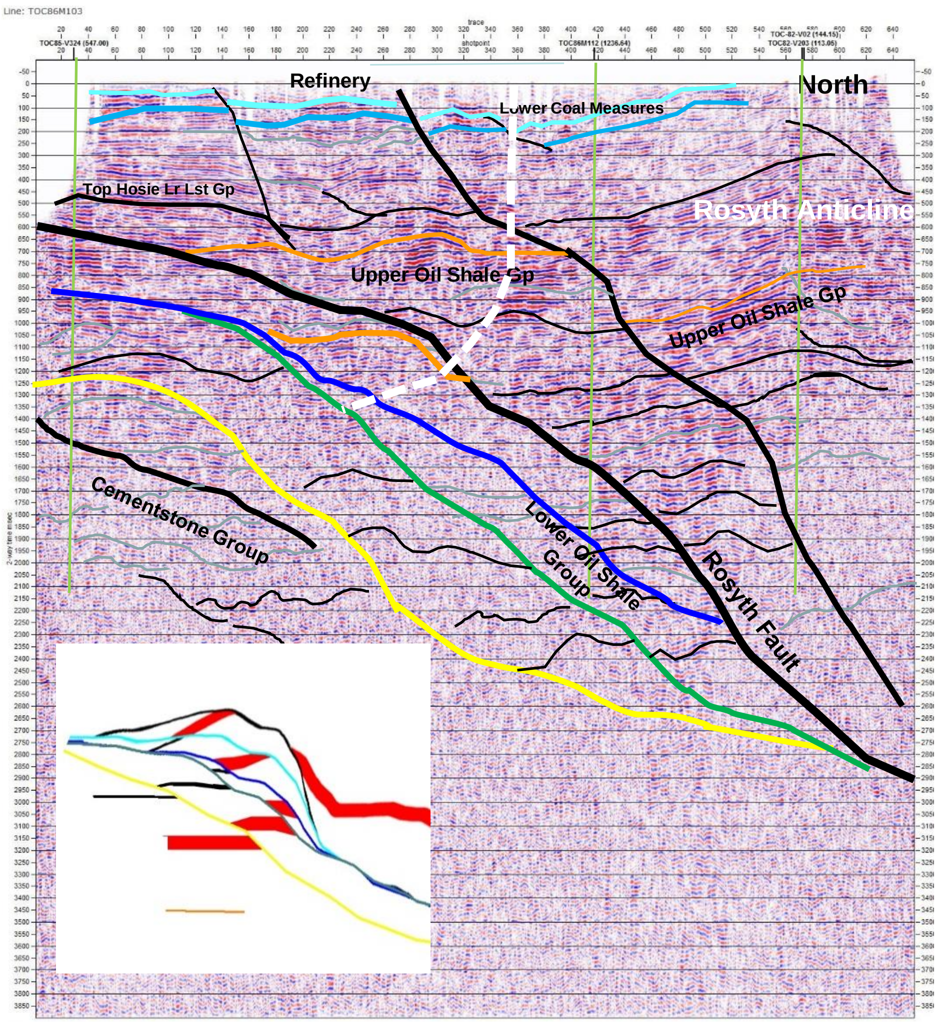



This north-south profile across the central basin of the Midland Valley is based on seismic shot by Tricentrol in 1982, the line is 27 km long and passes close to the Grangemouth site. Green lines are released 2D seismic profiles, the line illustrated is marked in blue on the index map. Note there is a local 3D seismic grid (yellow outline) which would be of value in further work to define fracture patterns near Grangemouth.

It's a sketch, to show structure style: the positions of faults and formation boundaries are only approximations at this stage. We interpret classic strike-slip (wrench) faulting with the gigantic Ochil Fault (4 km vertical displacement) driving Devonian opening and subsequently active again as an oblique frontal ramp for late Carboniferous contraction of the basin. The faults on all scales are inter-linked, distributing cross-basin deformation and dividing the infill sequence into discrete tectonic slices.

Immediately north of Grangemouth in the hangingwall of the Rosyth Fault (red) there is a series of closely-spaced west-east faults, they root westwards onto the Campsie Fault. These present fracture targets for CCS. A zone of duplexes (fault-bounded slices) adjoining the Grangemouth plant, formed in the tightening of the Rosyth Anticline rollover, defines a location for the R&D well and possible subsequent commercial use in the general area. A first, single injector can go into the Upper Oil Shale at 2000 metres or so, located on one of the industrial estates near the refinery.

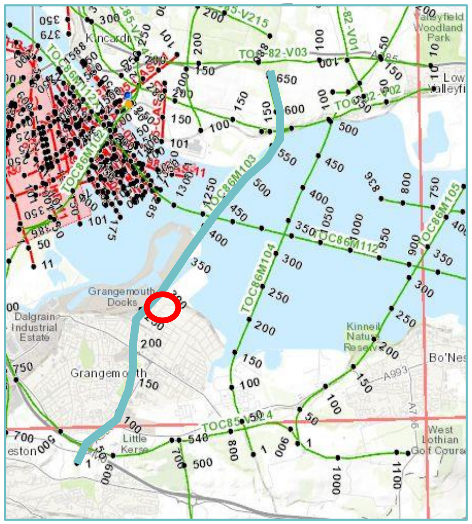





Section TOC86M103 through the refinery location (red circle) is a dip profile across the Rosyth Fault: it images a complex array of folds and discordant bedding contacts which is not easy to interpret! Which surface is the Fault? Some seismic reprocessing would help.

The inset model is a useful guide to what's a reasonable representation of likely structure style. The structure drawn is a hangingwall duplex made by moving on overlapping faults successively, so that the structure grows progressively higher: it matches Rosyth Anticline geometries reasonably closely.

We can be confident that folded fault-bounded duplexes will be strongly fractured. It would be easy to position a rig within a kilometre or so of the plant and drill to a target area at about 2000 metres. (In two-way time which is the vertical scale of the seismic, a thousand metres would be roughly 550-600 milliseconds). A well with the white-dashed trajectory could be drilled and tested for around £3-3.5 million.



# What next? FEED using AI

Our aim in this presentation is simply to outline a plausible alternative to the present, massively-expensive and overly-complicated offshore sequestration plans for carbon dioxide. An efficient and environmentally acceptable way to do this onshore, using proven technology, has been summarised here. We dispose of $CO_2$ by converting it to something safe, which is calcium carbonate slurry, and pump it downhole. Very large tonnages would be involved, but natural fracture systems are readily able to accept huge slurry volumes.

We think a multi-skilled group (adding some chemical engineering expertise too) should work together with government representation (GB Energy?) to look at this option in detail, and run a Front-End Engineering Design. Following definition of the project objectives, using artificial intelligence a good-enough FEED will take only a few weeks. Start to finish. A million pounds will easily cover that work.

With a FEED completed one has the costs and timetable for a trial well, and can put a consortium together to organise location and funding for it. To contract a rig, one has to buy things up-front that need manufacturing and storage, critical hardware like well heads and tubulars. Another million covers that outlay.

To get to spud-in day for the well, will take about 1 year because permissions are needed from dozens of interested parties, and whilst that process is happening the consortium becomes a private company, including (probably led by) the people who will provide the location and logistic support, and the carbon dioxide for extended trials. There are dozens of locations which are close to industrial centres generating carbon, the site selection probably depends mainly on facilities available: for example, if it’s in a steel works, chemical plant or a big quarry, that will greatly simplify and fast-track matters.

Speed is a key factor. Let’s remember that important industrial capability is on the verge of being lost, pointlessly, with deeply upsetting consequences for a lot of people.