Bowland Basin geothermal potential: Clitheroe-Gisburn, Fylde, Formby and Rossendale possible geothermal plays

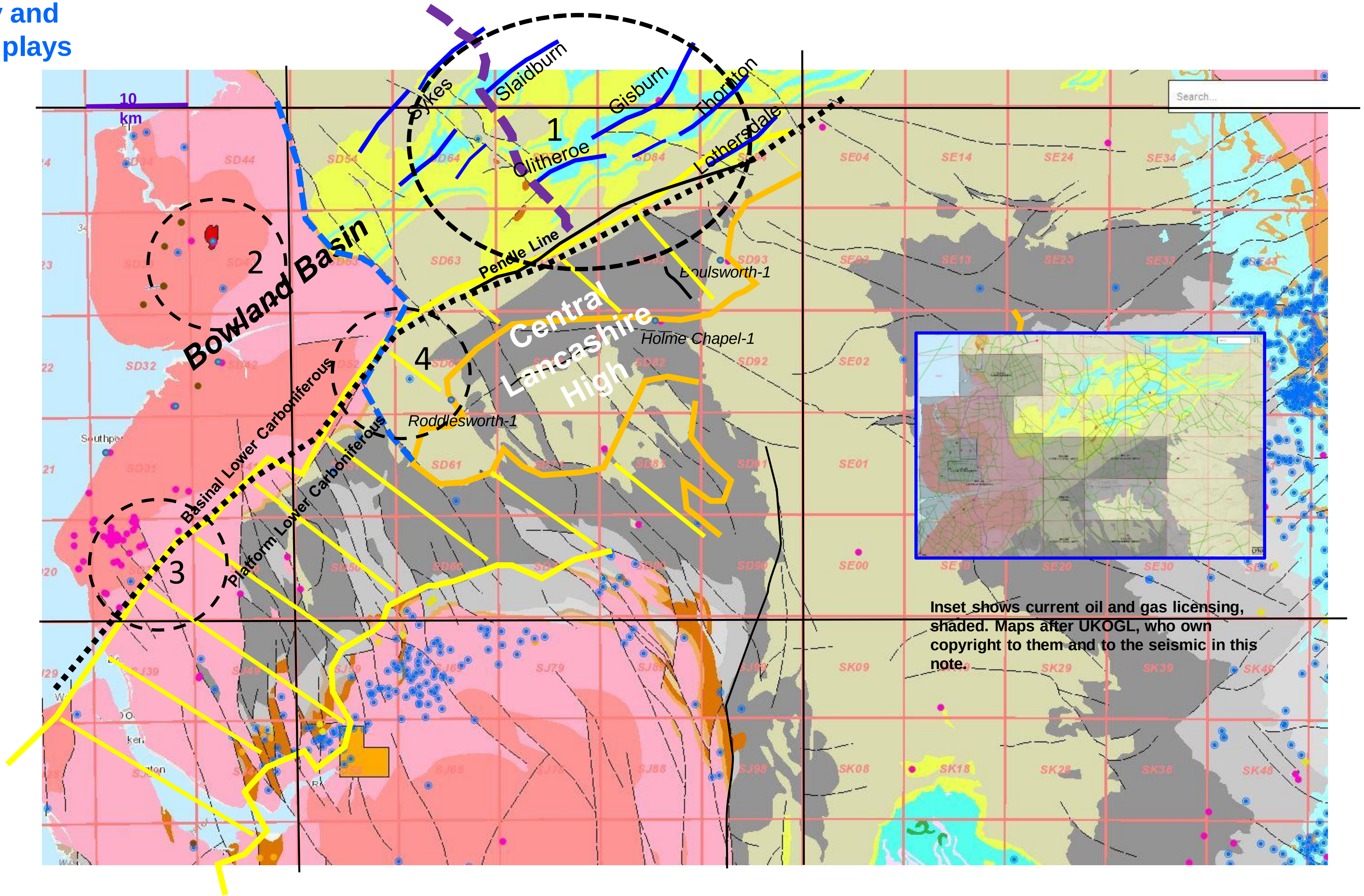
Is the Bowland-Craven Basin able to support a significant geothermal programme? Yes. We show plausible example plays in four areas of Lancashire, here.

1. East of the blue dashed line the Permo-Trias cover has gone, but the Lower Carboniferous along the Pendle Line marking the southeast-dipping Pendle Ramp is certainly deep enough to generate hot water, and the Ramp is a proven migration route to the Clitheroe-Lothersdale trend. The southern Ribblesdale Fold Belt along the Bowland south margin, is viable: Clitheroe-Gisburn offers two passive-roof duplex objectives. The purple dashed seismic profile across RFB is shown next.

2. The western part has substantial Permo-Trias cover remaining: that's the acreage west of the dashed blue line. In that area we have burial depth to basal Carboniferous, which is the prime sedimentary sequence expelling hot fluids, comfortably exceeding the threshold 1.4 seconds TWT, say 3250-3500 metres, which marks onset of 100 degrees Centigrade and more. That's high enough to be commercial.

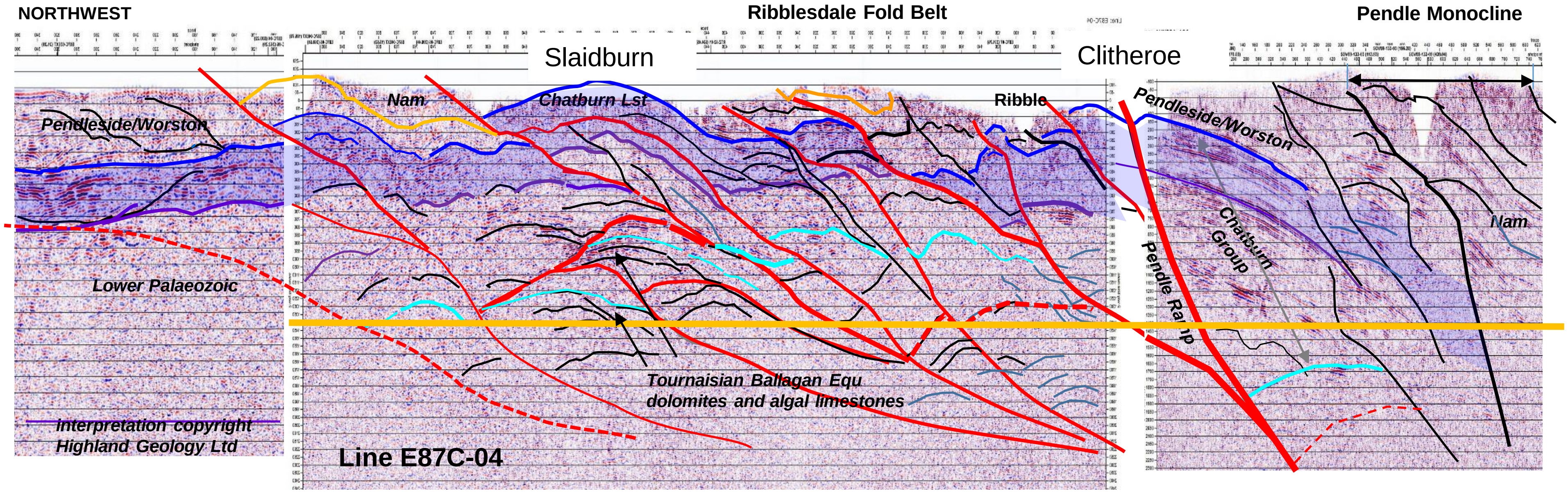
3. Formby has similar structure to Gisburn, a big stack of thrust slices which is highly fractured and offers large potential storage space for hot water.

4. On the central Lancashire High and farther to southwest, the yellow hachured area has top of Lower Carboniferous limestones at between 1000-2000 metres present depth (estimate after BGS). Limestone and dolomite units are prime targets for fracture development. Roddlesworth area is interesting.



Inset shows current oil and gas licensing, shaded. Maps after UKOGL, who own copyright to them and to the seismic in this note.

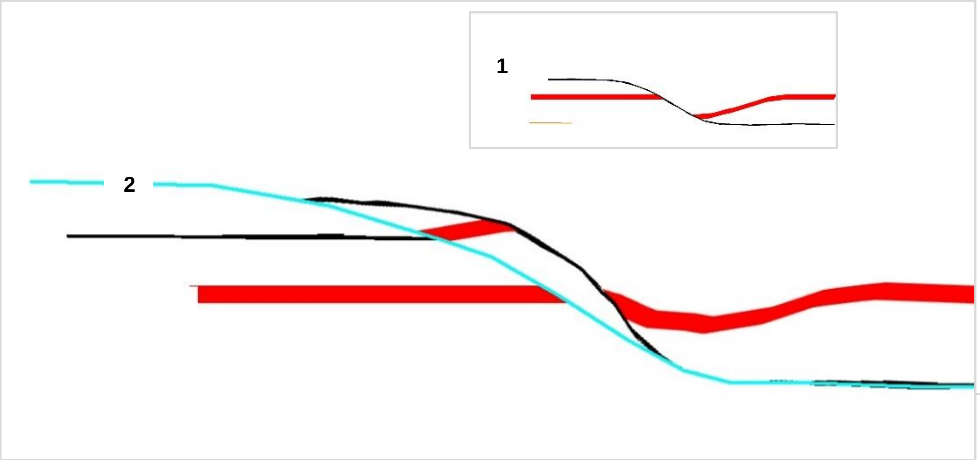
Bowland Basin geothermal potential



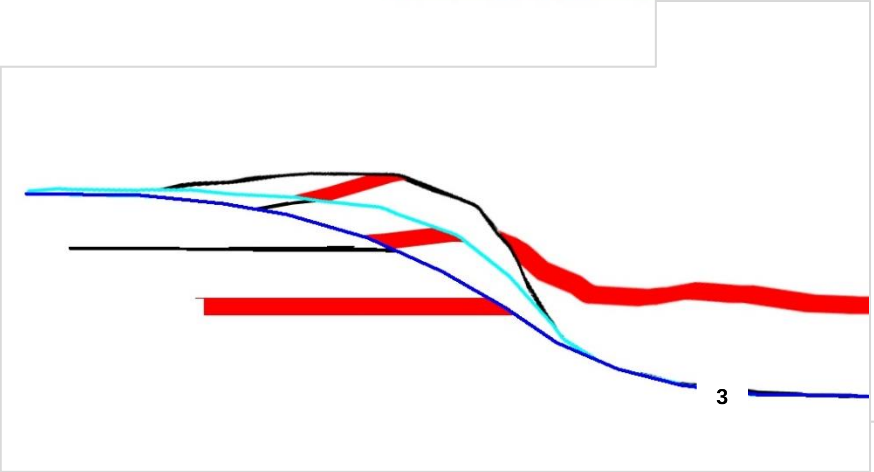
Area 1. A large market exists in places like/near Preston for thermal-sourced electricity and space heating. Structurally and provided with naturally-fractured sequences, the geology of Ribblesdale Fold Belt looks favourable for geothermal developments in fractured Lower Carboniferous limestones: permeability is good throughout those sequences. This seismic profile shows the broad structure style: E87C-04 crosses the Slaidburn and Clitheroe Anticlines, Pendle Monocline and Pendle Hill are at right.

The orange line at 1.4 seconds is roughly the 3000 metres burial indicator for this basin, much of the Carboniferous is above it. But, in mid and south end of the line we see sediments below that depth, in the RFB and on the Pendle Ramp we know hot water can transfer into the fold belt structures like Clitheroe and Gisburn Anticlines, and reach ground surface via lateral, sidewall ramps. It is the case that 40-50 warm water springs are active east of Clitheroe, and they contain H_2S which can only have come from basal Carboniferous. Slaidburn and Clitheroe/Gisburn folds will support proppant-injected acidised wells in fractured limestones of the Ballagan-equivalent formations. In the case of Slaidburn, at around 1.2-1.25 seconds (say 2750-3000 metres), brittle fractured dolomites are fractured targets for geothermal producer wells. Injectors can be much shallower.

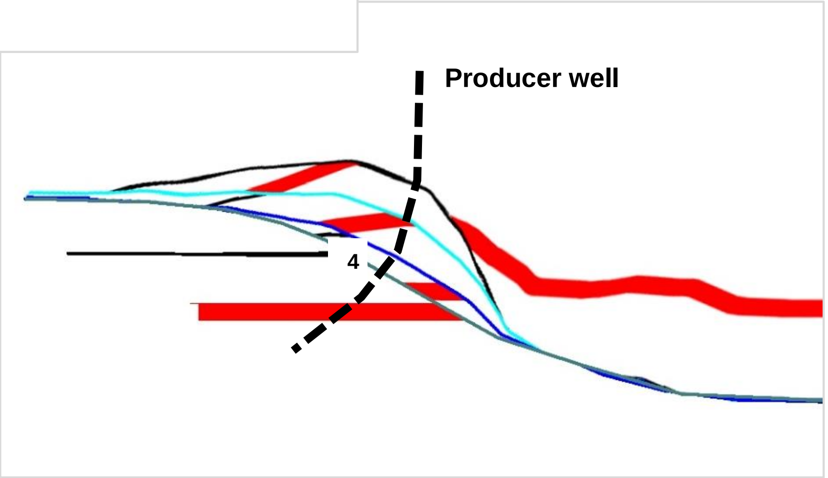
Passive Roof Duplexing creates structural highs which are excellent targets for geothermal producer wells



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.

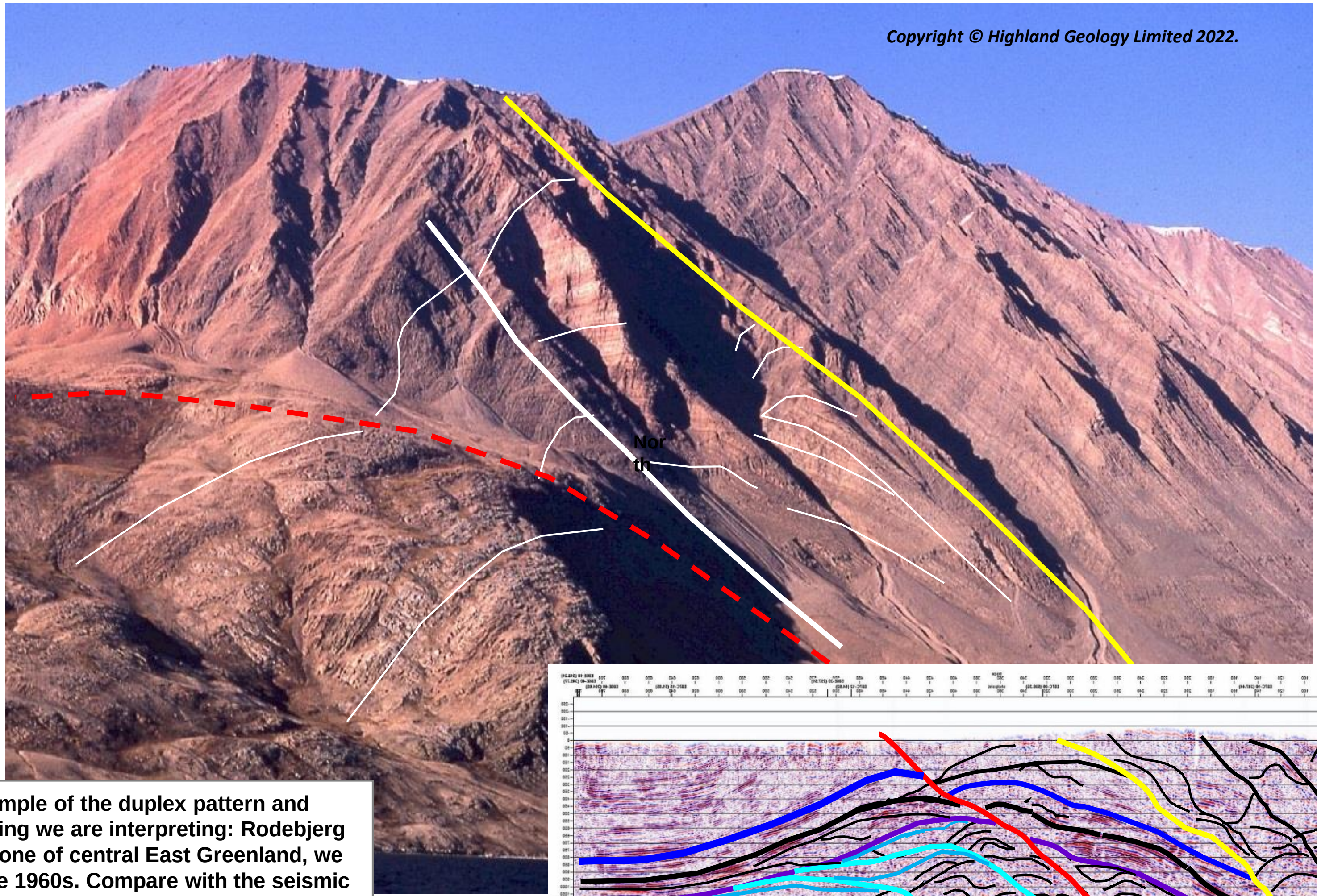


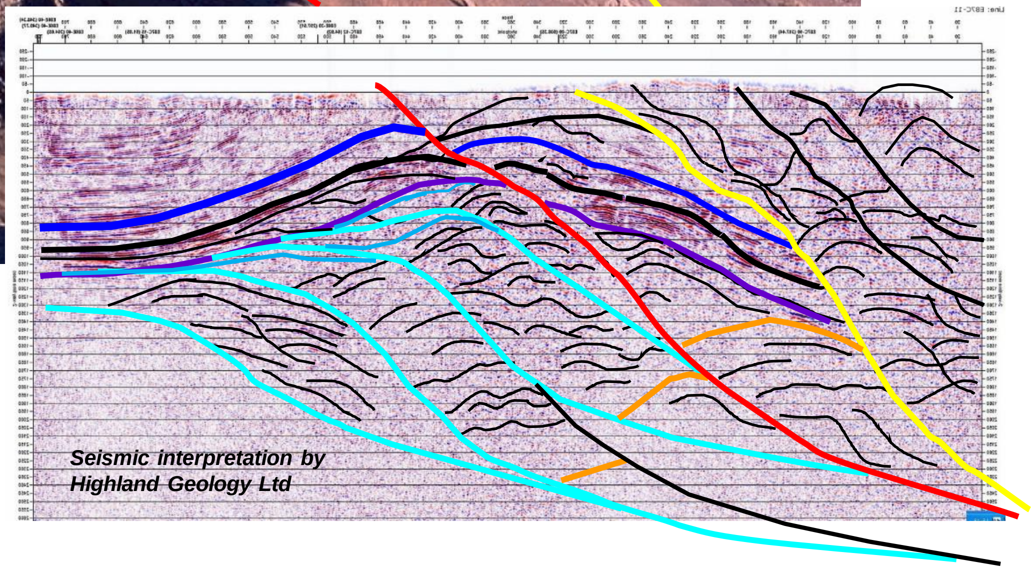
Fault 4 in dark green propagates off the floor fault of the stack next, it has less heave. There are lots of examples of small steep faults like this in places like Clitheroe fold belt.

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.

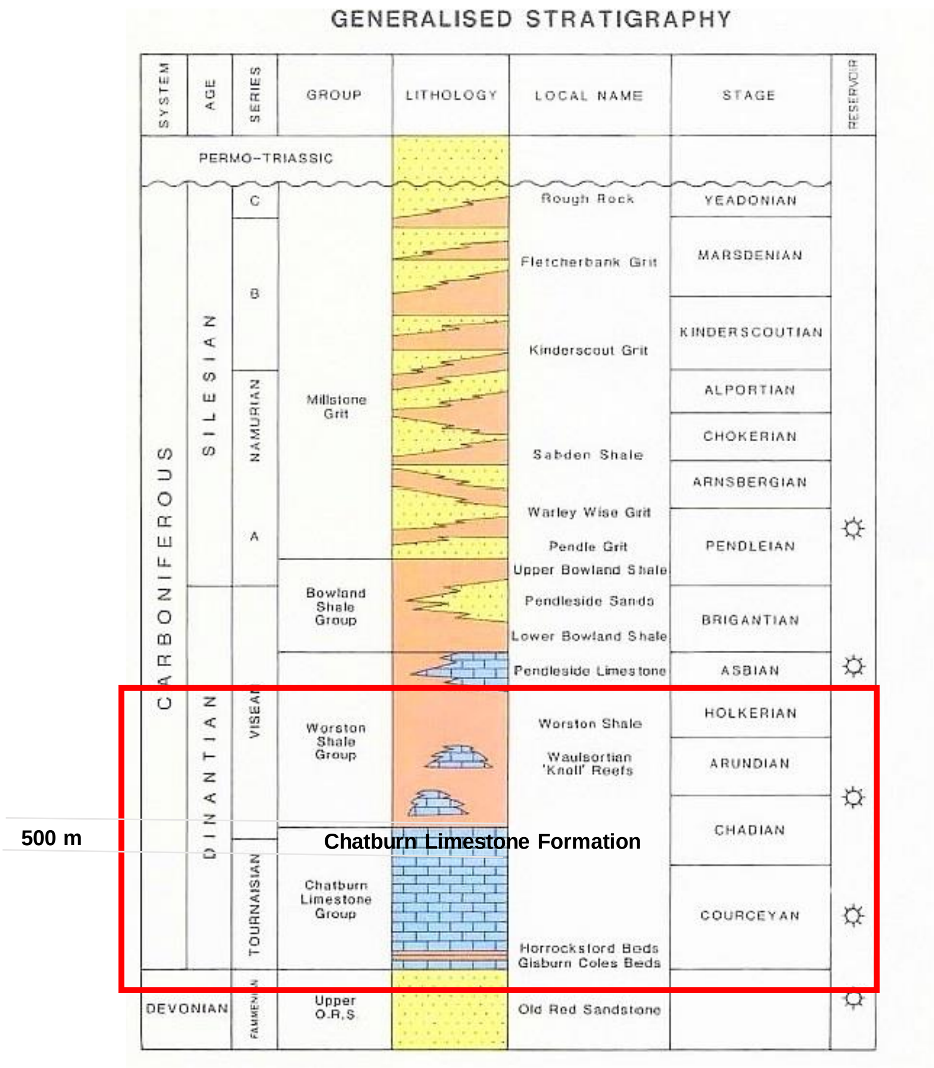




Here's a real-rock example of the duplex pattern and high degree of fracturing we are interpreting: Rodebjerg in the Old Red Sandstone of central East Greenland, we worked here in the late 1960s. Compare with the seismic profile across Gisburn Anticline, near Clitheroe.

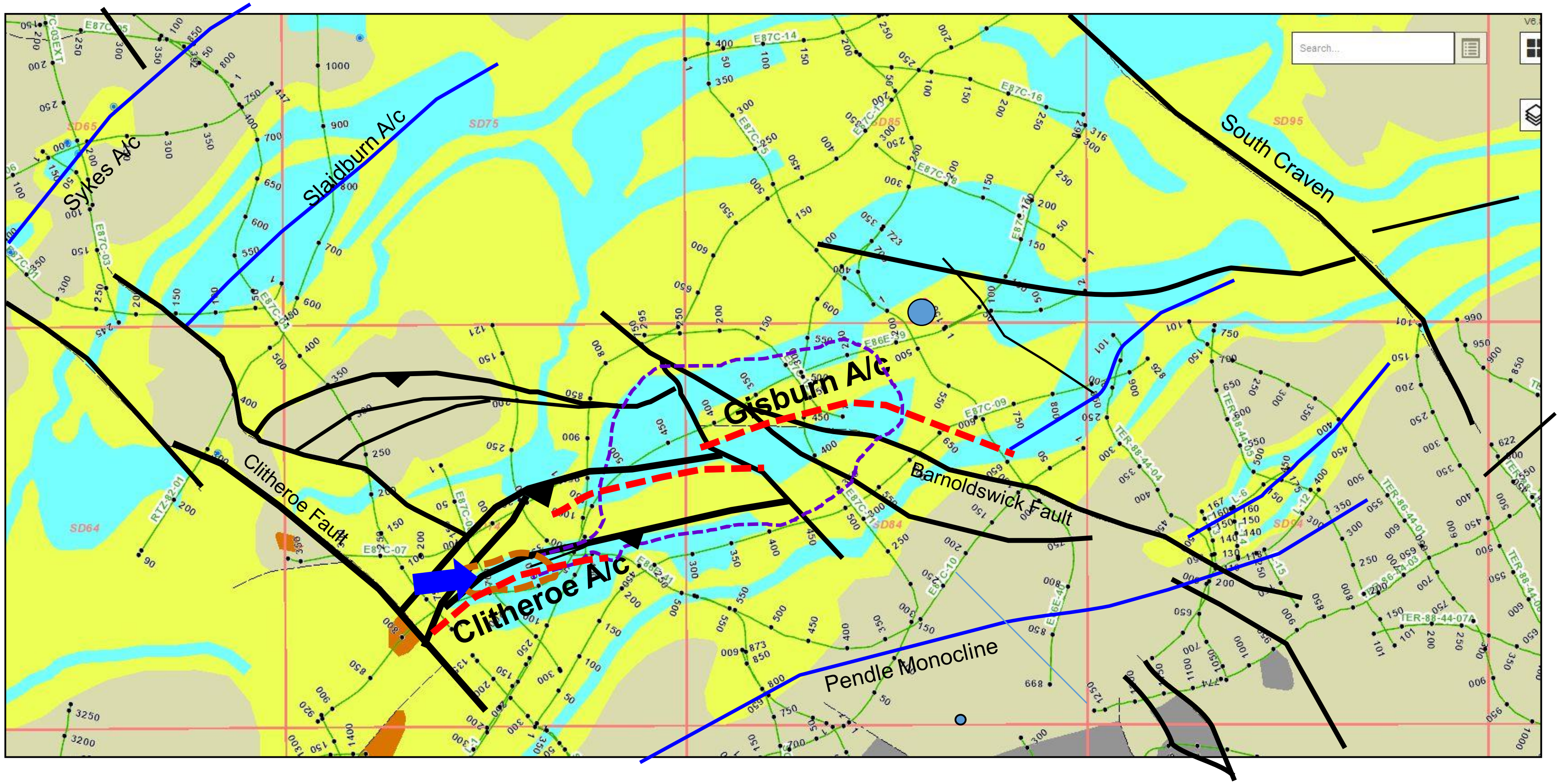
This dramatic structure trends across the basin, it was generated by cross-basin shortening. Compare red faults, its very similar to Clitheroe-Gisburn.

Bowland Basin fractured reservoirs near Clitheroe



Two sequences are interesting for geothermal wells. One is Chatburn Limestone Formation, about 500 metres thick. Below it the rest of the CL Group is a Worston-type succession of mudstone and several brittle carbonates with natural fracture systems.

Second, below the Chatburn Limestone Group base are Tournaisian dolomites and dolomitic limestones, the dolomite attributed to hypersaline lagoonal sabkha development. These are probably Ballagan-equivalents, seen in all the northern Carboniferous basins.



The geological map around Clitheroe-Gisburn displays the arcuate array of anticlines obliquely dissected by north-vergent thrusts. Quarry and stream outcrops are locally very good but glacial deposits cover much of the complex geology and there are certainly more thrust surfaces than the mapping recognises. Pale blue and yellow areas are collectively the Lower Carboniferous Bowland High Group and Craven Group, the pale blue being limestones and yellow represents mudstone, siltstone and sandstone formations.

The Gisburn to Clitheroe high is actually three arcuate folds, each fold has a thrust on its north flank, the dashed reds are the fold axial zones as mapped at around 500 milliseconds twt (about 1000 metres depth); and the purple dashed line is a closing contour, to show the dome shape.

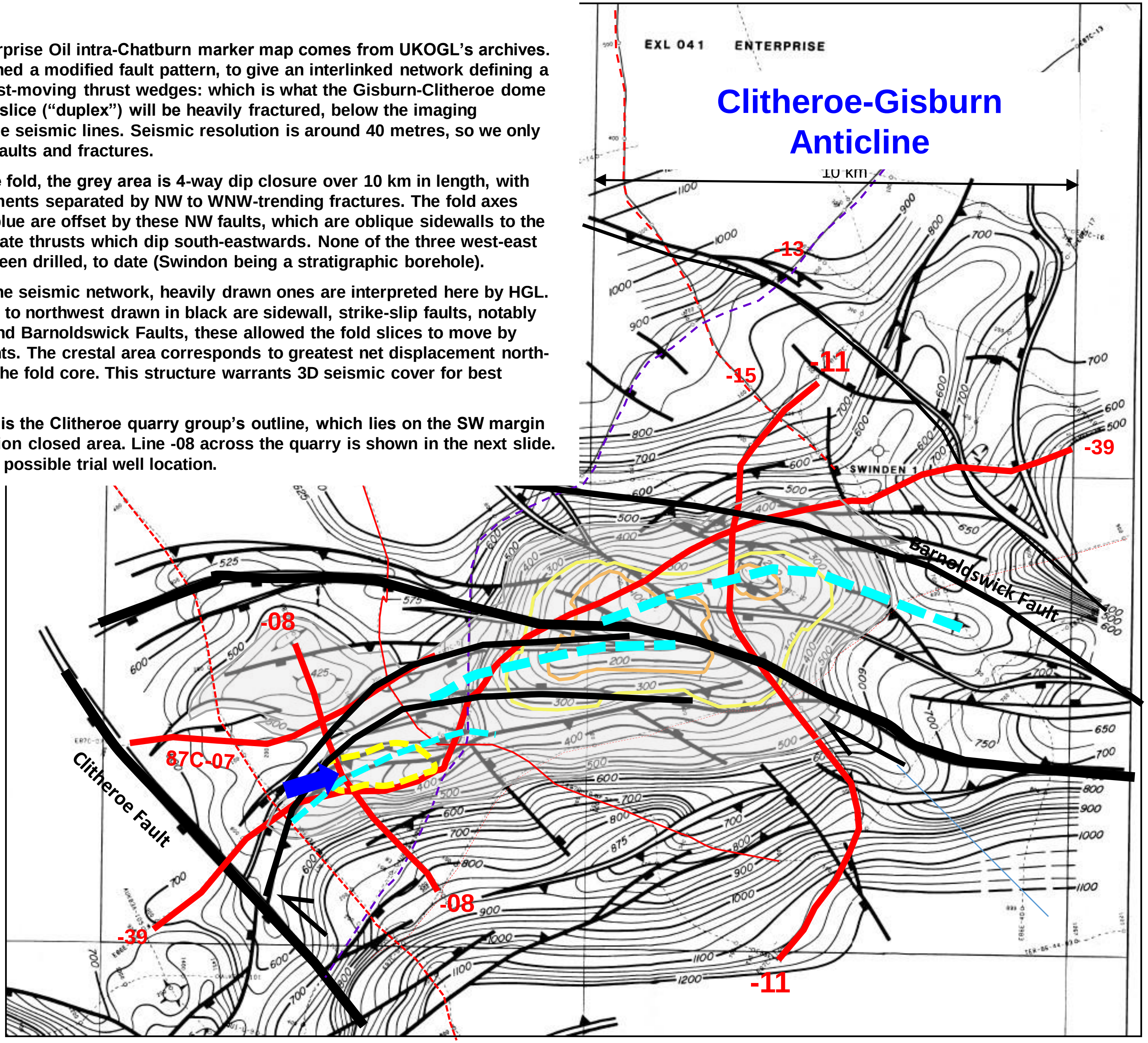
The Clitheroe quarry complex is the orange heavy dashed line. The blue arrow is a possible drilling location there for a Clitheroe geothermal, subject to confirmation from re-mapping.

This 1988 Enterprise Oil intra-Chatburn marker map comes from UKOGL's archives. We have sketched a modified fault pattern, to give an interlinked network defining a pile of northwest-moving thrust wedges: which is what the Gisburn-Clitheroe dome is. Each thrust slice ("duplex") will be heavily fractured, below the imaging resolution of the seismic lines. Seismic resolution is around 40 metres, so we only see the larger faults and fractures.

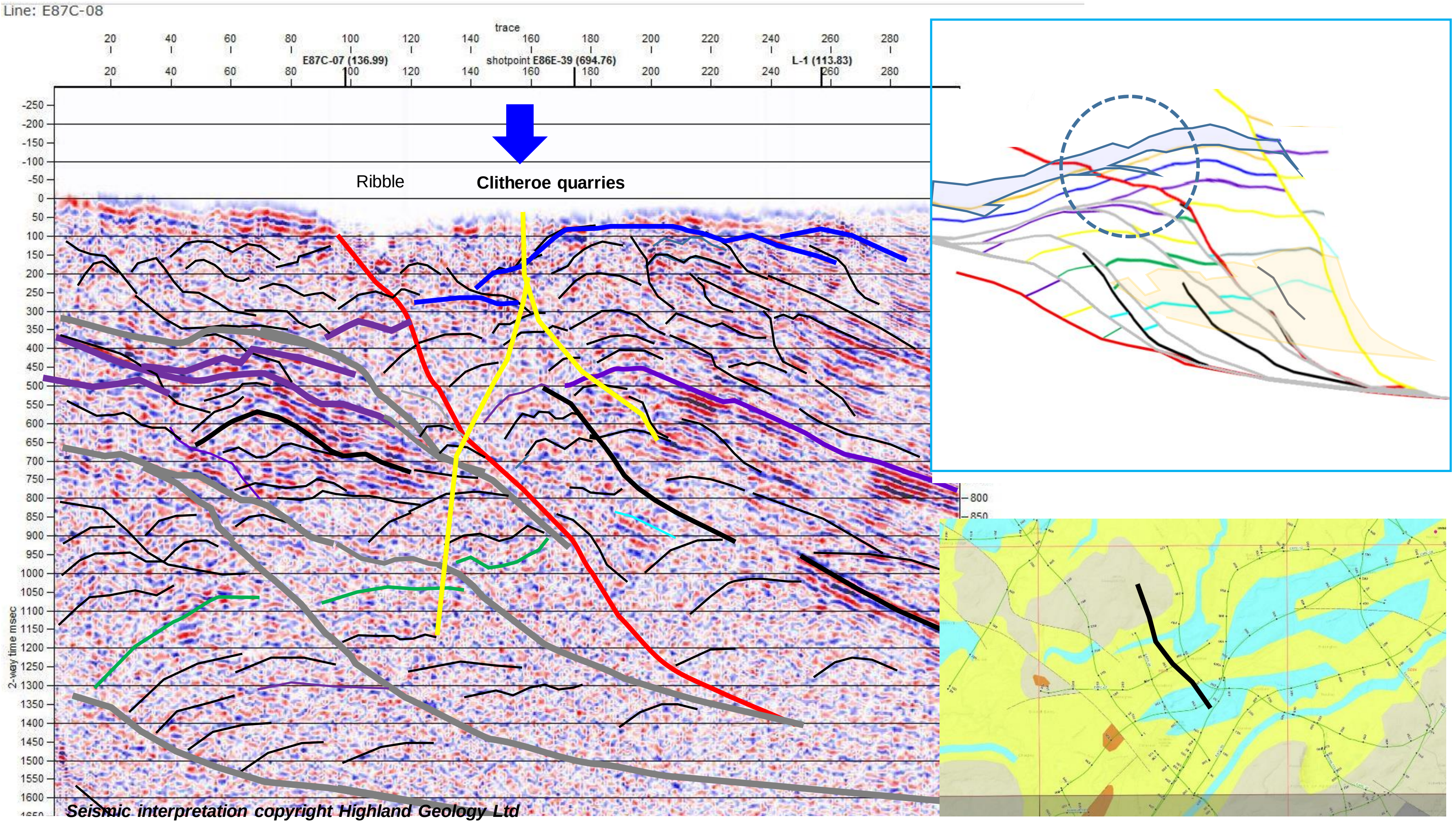
It's a very large fold, the grey area is 4-way dip closure over 10 km in length, with three compartments separated by NW to WNW-trending fractures. The fold axes drawn in pale blue are offset by these NW faults, which are oblique sidewalls to the numerous arcuate thrusts which dip south-eastwards. None of the three west-east rollovers has been drilled, to date (Swindon being a stratigraphic borehole).

Red lines are the seismic network, heavily drawn ones are interpreted here by HGL. Faults trending to northwest drawn in black are sidewall, strike-slip faults, notably the Clitheroe and Barnoldswick Faults, these allowed the fold slices to move by variable amounts. The crestal area corresponds to greatest net displacement north-westwards, in the fold core. This structure warrants 3D seismic cover for best definition.

Dashed yellow is the Clitheroe quarry group's outline, which lies on the SW margin of the culmination closed area. Line -08 across the quarry is shown in the next slide. Blue arrow is a possible trial well location.

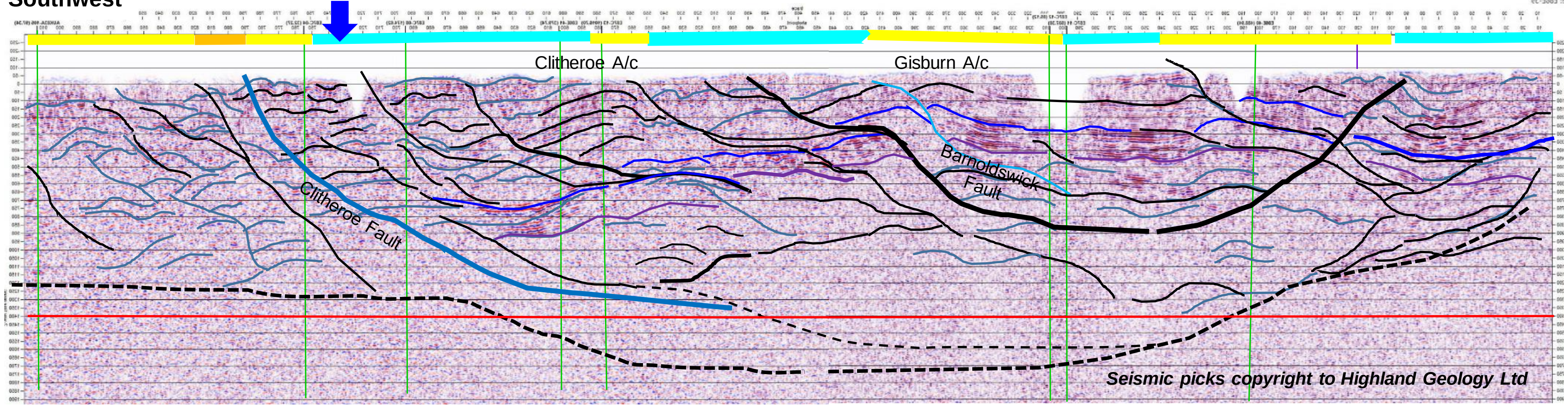


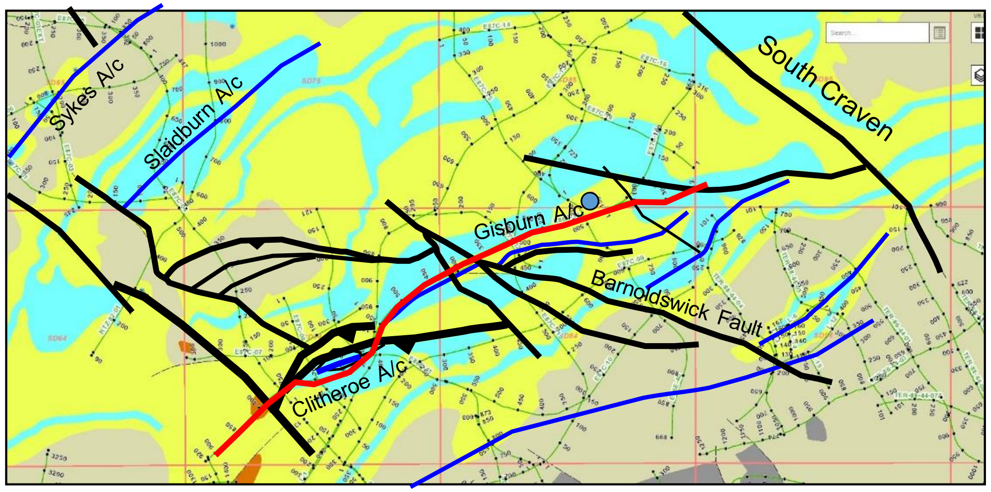
Clitheroe Anticline north limb and underlying duplex

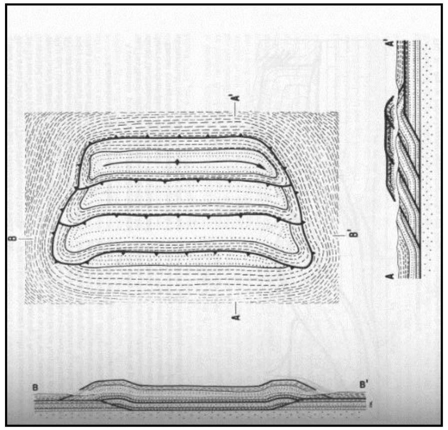


NW-SE 23 km line E87C-08 across the Clitheroe quarry complex shows a highly-fractured structure which is an excellent candidate location for a producer well. Its close by the Heidelberg Materials cement kilns and so it's favourably located for borehole planning and environment approval. Yellow tracks are potential well trajectories. Purple level duplexes are possible producer targets, with combination of structural dip and wrap-over by several shears in mainly-shale sequence, to provide high-potential caprock. With significant fracturing destroying event continuity the red fault is a possible very large fluid migration zone; it could have enormous capacity to deliver hot water. 3D seismic shooting would be justified for detail here.

Southwest







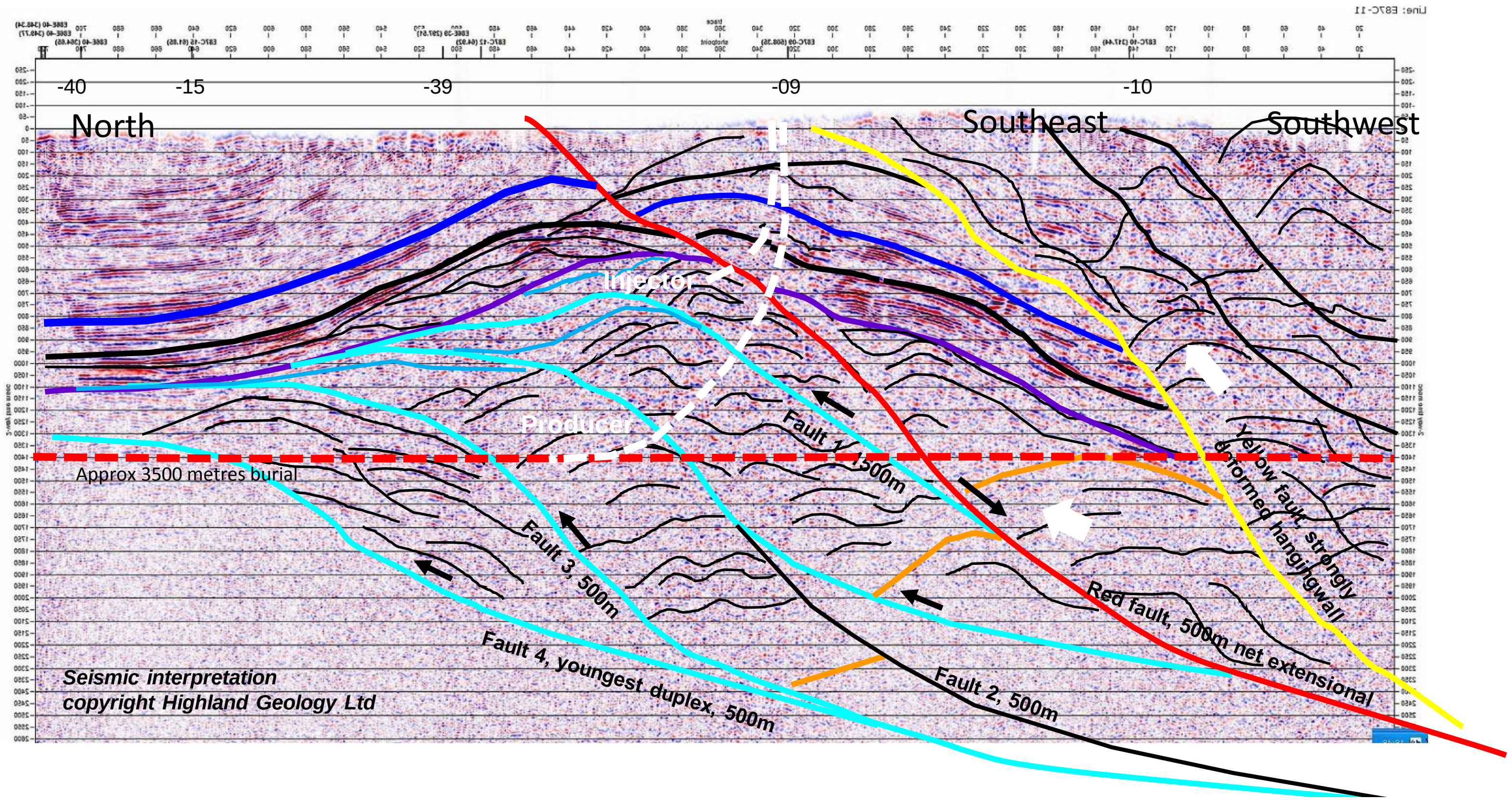
Moving to Gisburn, the strike line E86E-39 marked in red trending SW to NE along the crest of the Gisburn-Clitheroe anticlines is interpreted here, after the classic model of Boyer and Elliott (1982). The floor fault and various lateral ramps connected to it form shapes which force the observed fold geometries into the over-riding, northward-pushed cover sequence.

Even where the seismic is difficult to pick at depth, the geometry at intra-Chatburn level is a good guide to deeper structure style.

Gisburn Anticline, section E87C-11, 14.4 km

This interpretation of Gisburn anticline as a passive roof anticline dome balances, the component reverse faults are drawn in pale blue and reversal of displacement restores it to the pre-inversion extensional structure geometry. The figures shown on the faults were derived by experimentation with our section balance software, and are compatible with Geological Survey Memoir typical displacement estimates.

The structure style applies for all of the Fold Belt anticlines. Passive-roof anticlines are prime targets for geothermal wells.



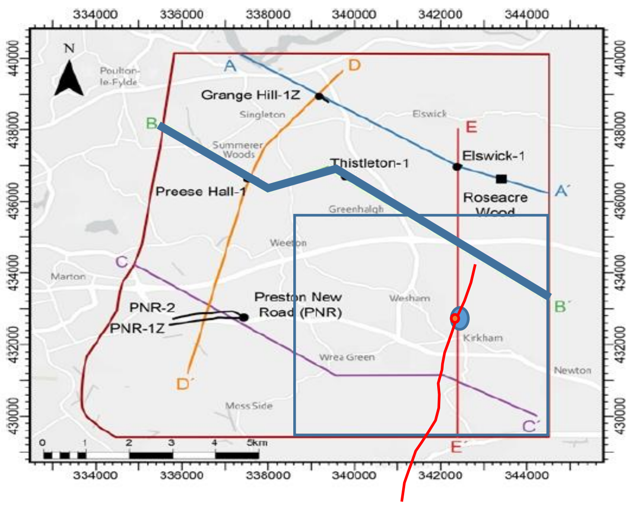
The two white dashed lines are a possible producer and injector pair, the producer has an optimum track for high-density fracturing and is arranged to be at right angles to minimum principal stress, the natural fractures would be re-opened by pulse drilling, acidized and propped. The well would penetrate brittle, fractured dolomitised limestones separated by hard shales.

Yellow fault is approximately the north flank of the Burnley Syncline, with deep sediment at over 100 degrees Centigrade southeast of that huge lineament, capable of supplying hot connate water (arrows) to Gisburn and Clitheroe folds.

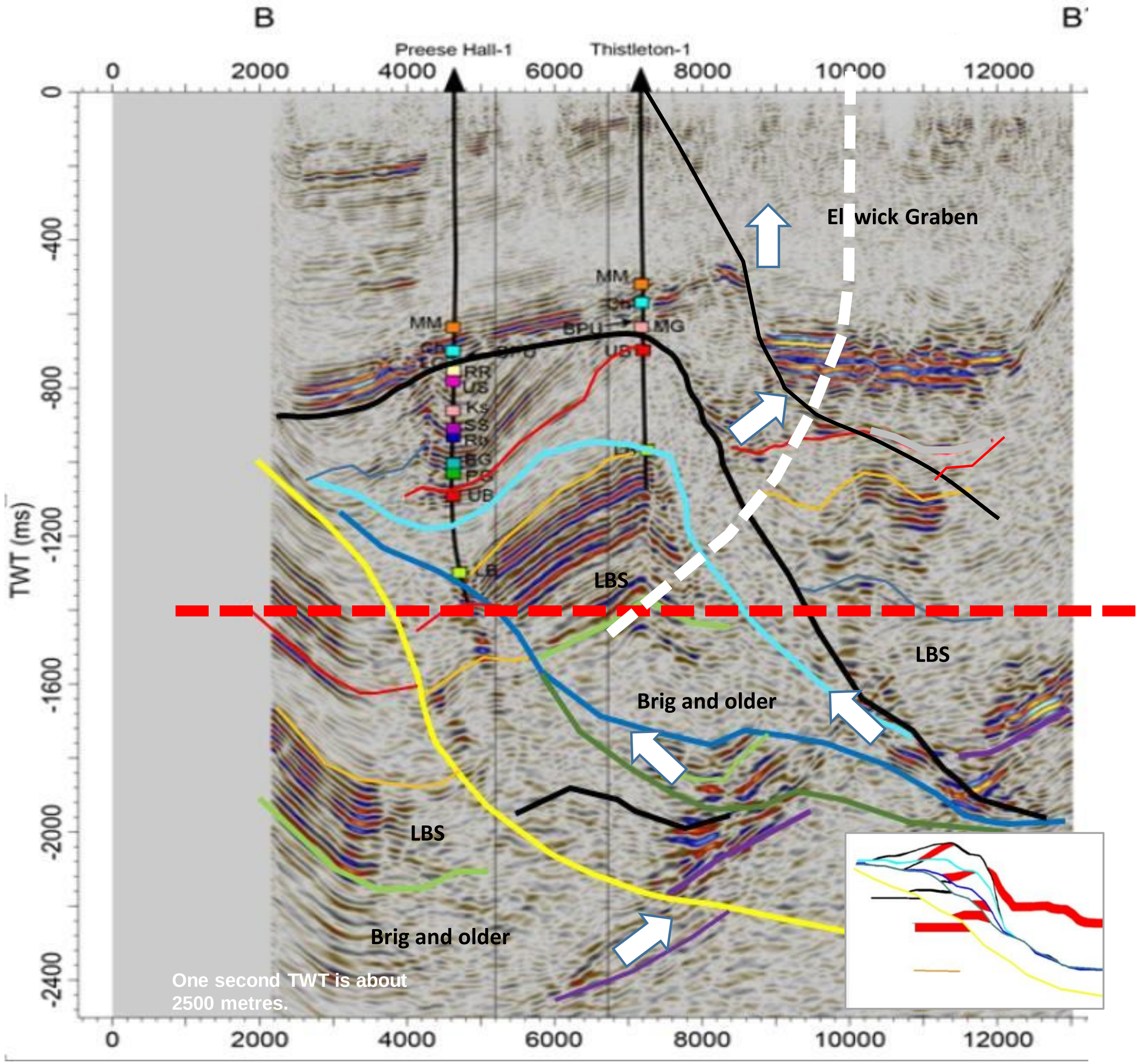
Fylde area, geothermal potential

Area 2. Round about 1.4 seconds, say 3250-3500 metres present burial, with a temperature gradient of about 30 degrees centigrade per kilometre, we could reasonably presume the rocks beneath dashed red in the interpreted section are presently heated above 100 degrees. <u>Do we have to drill to that depth</u>, to get hot connate water to surface and run the fluid through a heat exchanger and turbine to generate electricity: or could formation fluid be migrating updip to substantially shallower locations, as shown by the arrows, allowing extraction wells at much reduced cost? A possible producer track to as deep as 3500 metres is shown in dashed white. (This high-quality imaging is released 3-D seismic cover).

Let's consider the main source for hot water is the seismic bright zone in the basal Carboniferous, purple. This is Dinantian brittle limestone and dolomites, anhydrites, and basal sandstones all fractured and readily able to pass hot fluids updip to major faults (arrows), thence through leaky cap rocks to surface. Methane plus anhydrite gives hydrogen sulphide, hence 40 or so stinking springs at and east of Clitheroe. This signals there is no doubt that fluids from 2 seconds or more are reaching the present ground surface.

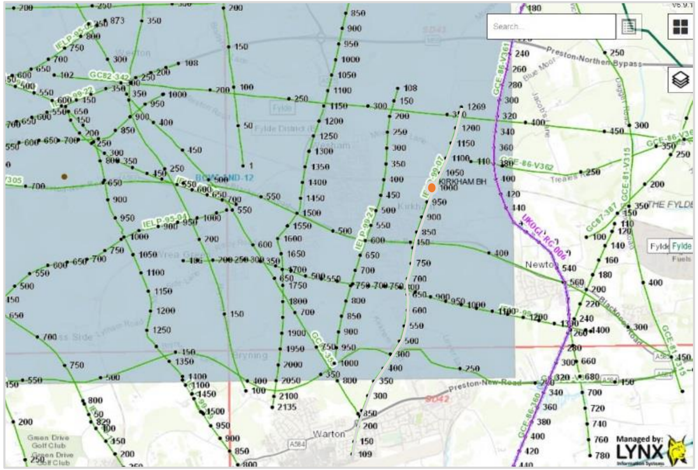


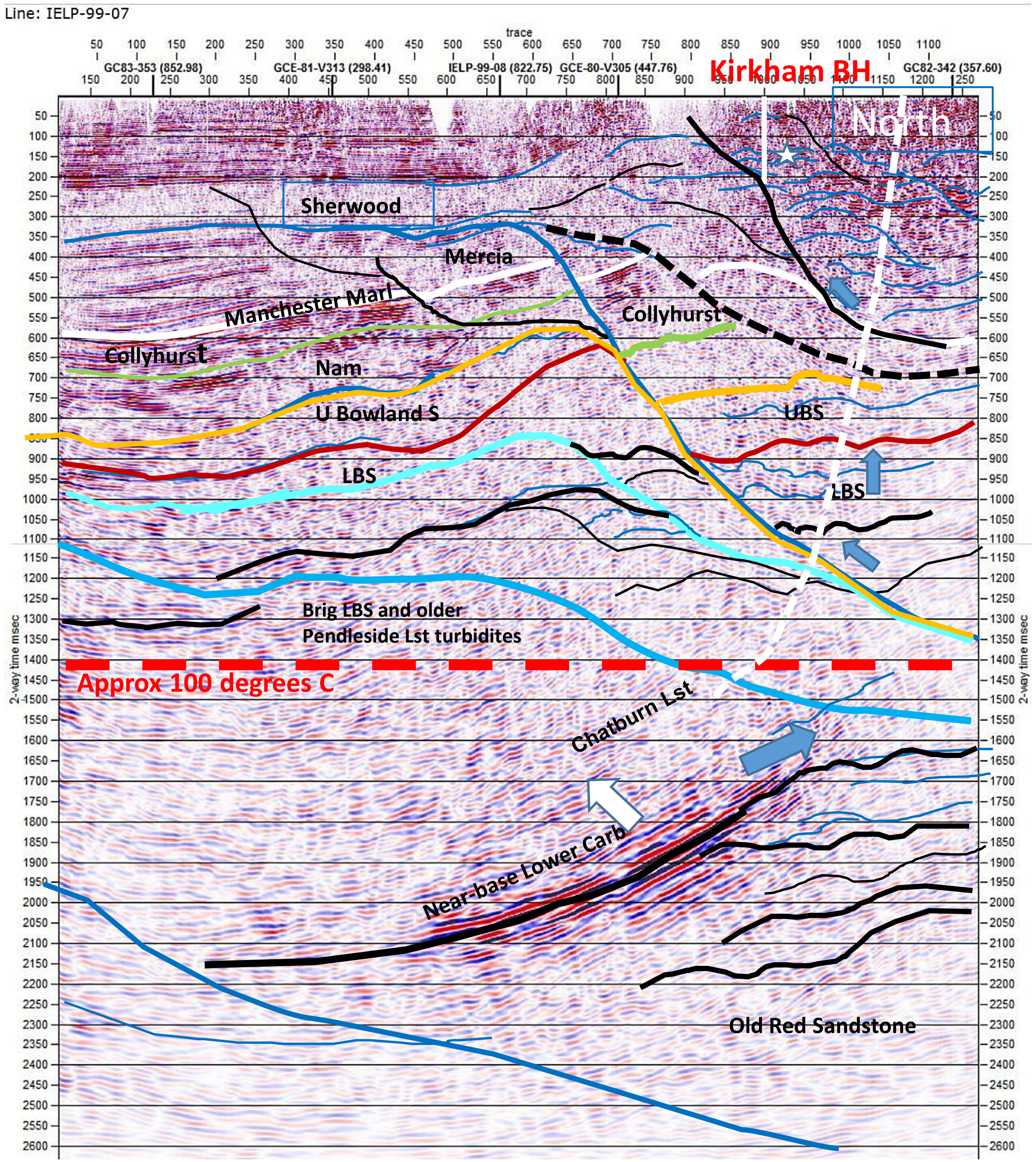
Profile B of Anderson et al 2020, re-picked with faults as per HGL inset model

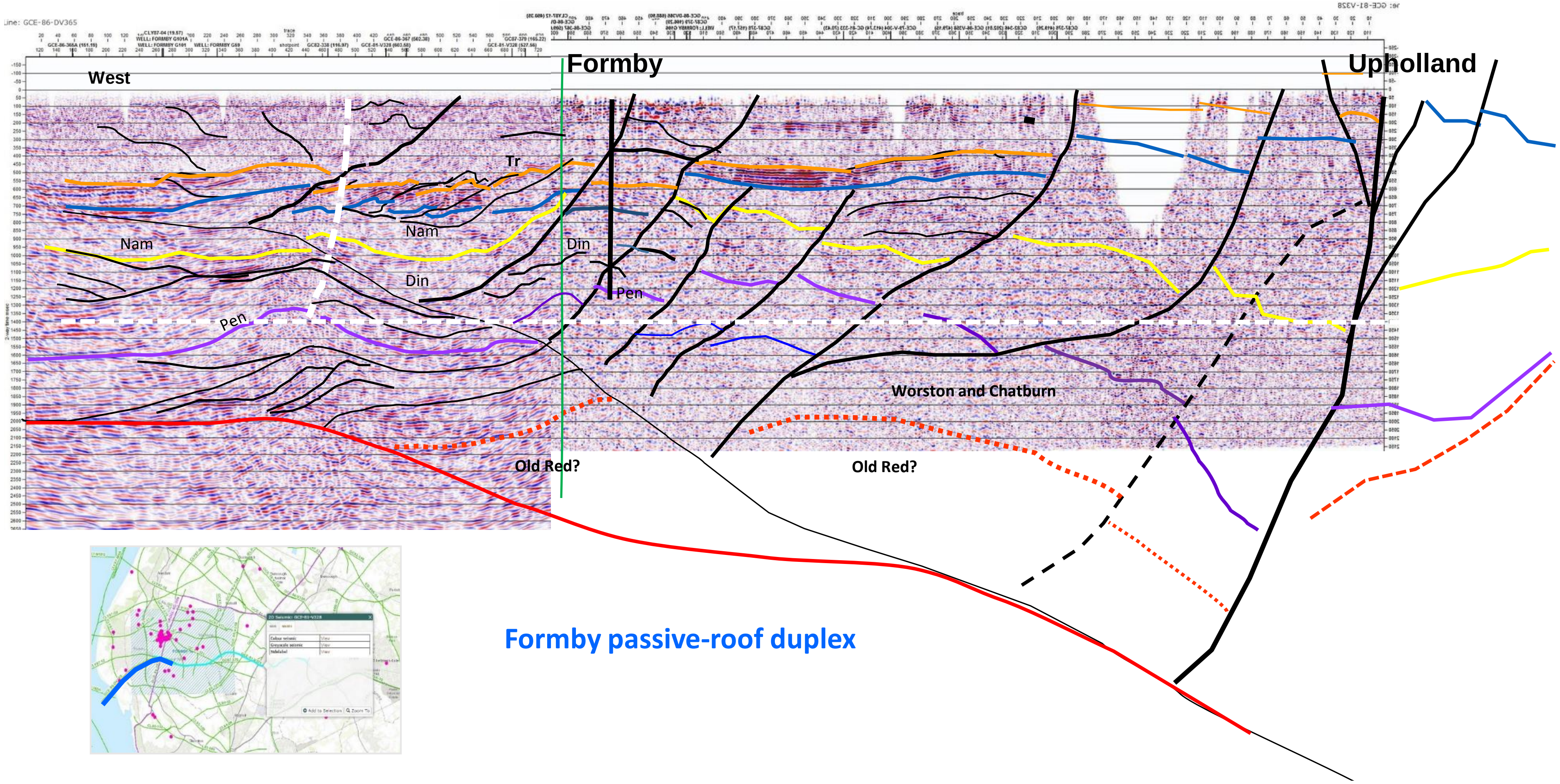


Kirkham borehole near Preston is interesting, in mid-1980s the North West Gas Board drilled it for underground gas storage studies. In Permo-Trias beds at less than 400 metres depth it proved a heat flow of 71mW per square metre. Deep fluids here can get to present ground surface: typical heat flow elsewhere in the Fylde averages 50 mW/square metre in comparable depth BGS boreholes Thornton-Cleveleys and Weeton Camp.

British Aerospace airfield at Warton is only a km or so south of the south end of this line. A pad with several producers like the white dashed line to Chatburn is capable of providing electricity for the very large manufacturing complex there.



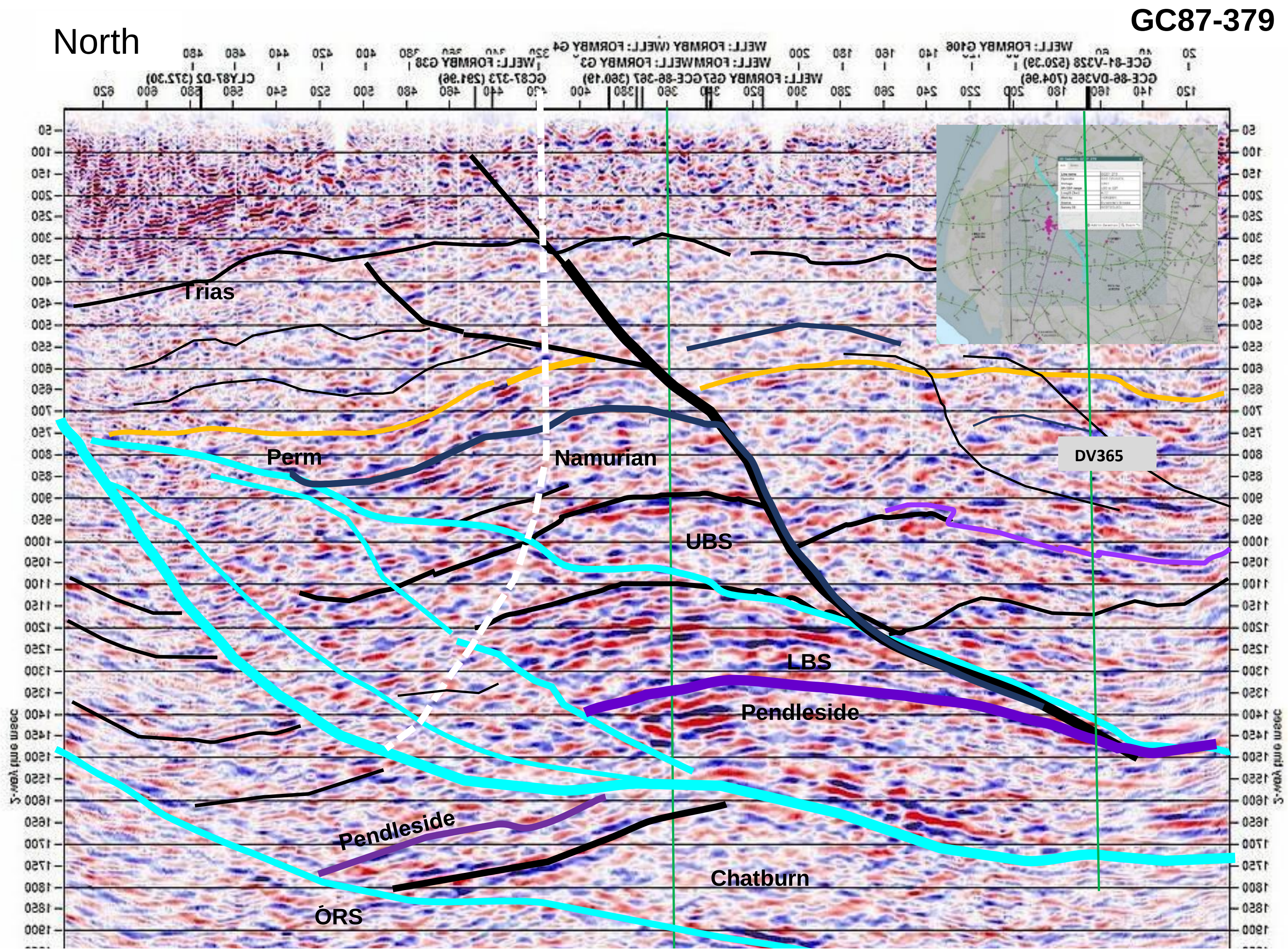




Area 3. This line-pair GCE-86-DV365 (dark blue in the location inset) and GCE-81-V328 (light blue) is on trend with the WSW-ENE Pendle Line flanking the Ribblesdale fold belt, it runs obliquely across the ramp forming the southwest margin of the Basin. Formby structure is a very large late Carboniferous-early Permian inversion of an extensional rollover developed through Dinantian-Westphalian times, Variscan uplift and erosion removed at least 3 km of Namurian and locally all Westphalian sequence from the rising high during Permo-Trias deposition. Dark green is base Permian unconformity, yellow is top Visean, i.e. base of Namurian. Purple is a guess at Pendleside Limestone, below which is Chatburn, dotted red is highly tentative top of Old Red.

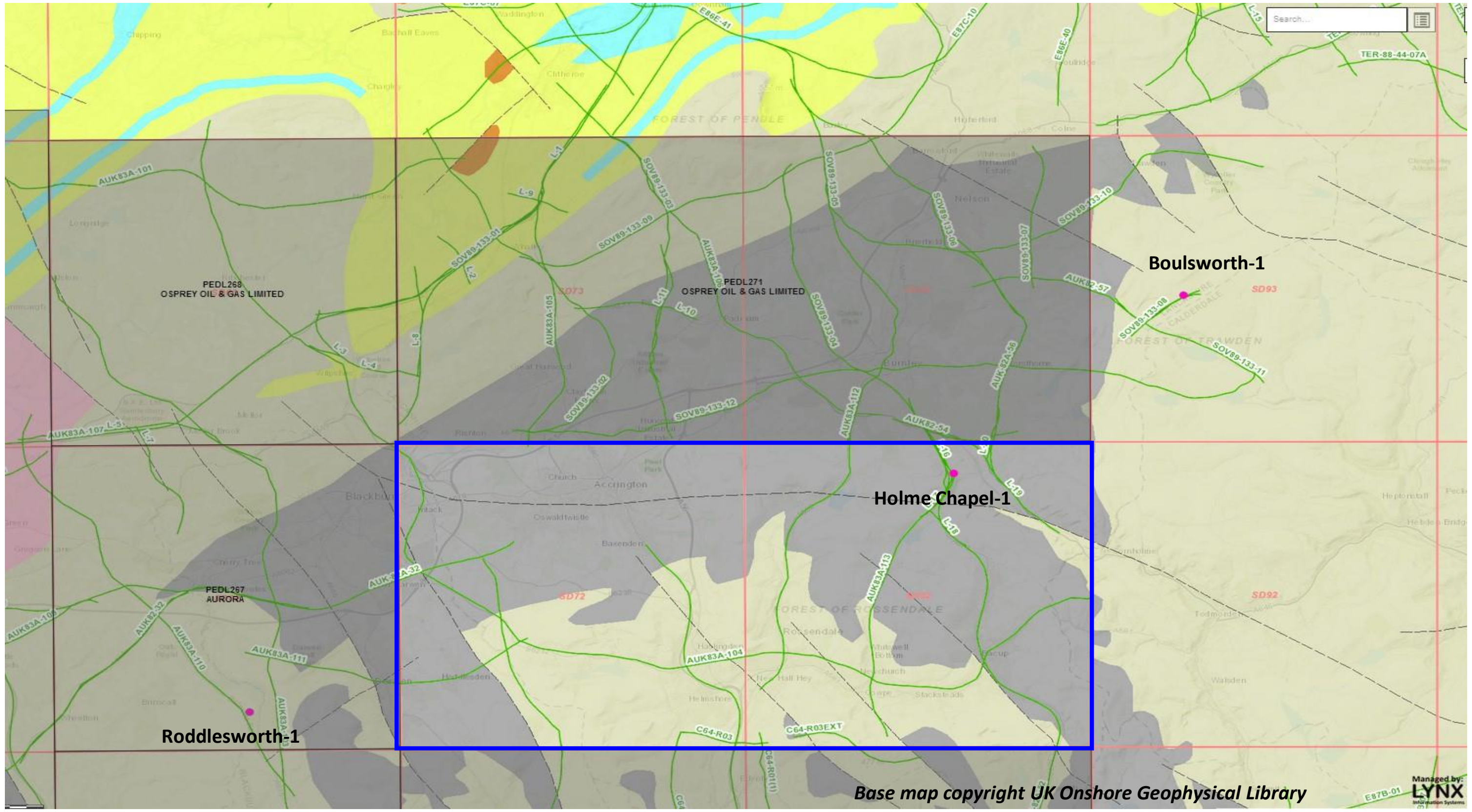
Red is near base of the downward-propagating footwall collapse sequence of faults, which rise southwards towards the eye. Upholland Fault roots onto it, there's a massive facies change between Formby and Upholland in Lower Carboniferous, in the space of 15 km the basin muds on northwest are replaced by platform limestones, the same transition seen at Clitheroe/Gisburn.

The broad rollover beneath the Formby area is a footwall collapse, a passive-roof duplex, its in basinal Lower Carboniferous muds and it's a deep drilling candidate to explore for Tournaisian fractured geothermal reservoirs. The 1.4 second pecked line (white) is the approximate 100 degree onset, it tracks through the footwall stretched folding and is a target to be pulse-drilled followed by acid wash to re-establish fracture connection.



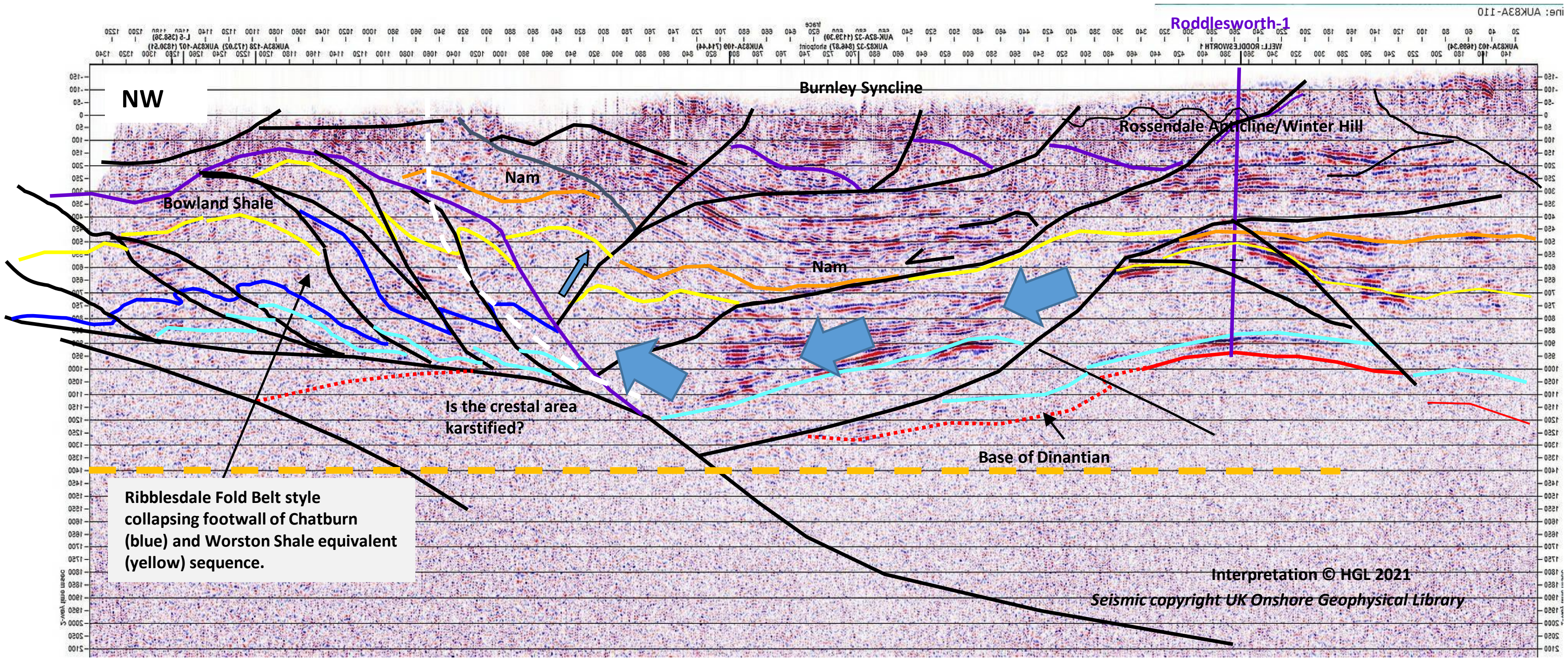
Dip section GC87-379 at Formby has strong structure-style similarities with the Gisburn anticline inversion stack, a possible producer track is shown. The bright zone under Lower Bowland Shale LBS is Pendleside Limestone, reached by Formby-1 where it was gas-bearing but didn't produce fluids on test: it was tight. Chatburn was not reached by Formby-1, its a shaly deep-water micrite section, not a shelf "limestone". The basin carbonate muds can be acidized to open the fractures, its an efficient process, there's no need for any kind of fracking.

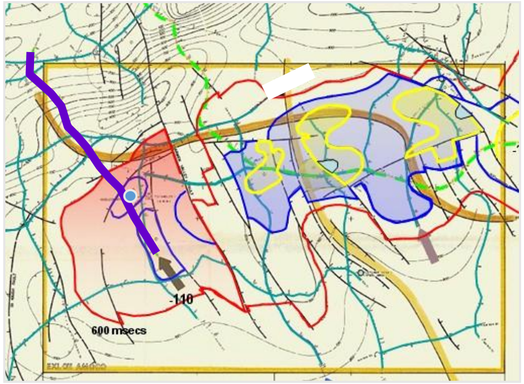
Rossendale Anticline



Area 4. Top Mississippian maps in Amoco and Sovereign relinquishment files are incomplete representations of structure style and fault geometries of Ribblesdale fold belt, Burnley Syncline and Rossendale Anticline. Nobody cared in the late 1990s, it was North Sea oil that majors wanted. Our interpretation indicates a large high due east of Roddlesworth-1 on Rossendale Anticline, separate from and several hundred metres up-structure from Roddlesworth-1, this is a significant geothermal play because it had an extended period of erosion before top Mississippian limestone was sealed by Bowland Shale and tight turbidite sandstones of Pendle Grit. Natural fracture systems opened by karst development, with ground water reflux generating a zone of brittle dolomites at the Pendle Line where platform limestones pass into the basin carbonate muds to northwest, are a significant target for fractured reservoir potential in Tournaisian platform carbonates

Rossendale Anticline





Our interpretation of 15 km vibroseis line AUK83A-110 (purple line, inset) shot by Amoco in 1983 at Anglezarke. Their Roddlesworth-1, along with Boulsworth-1 and Holme Chapel-1, are supposedly definitive tests of the huge extensional Rossendale Anticline rollover, which developed and part-inverted on the south-dipping major ramp under Burnley Syncline.

Yellow marker picked here is top Dinantian at Roddlesworth, equivalent of top Worston Shale (Asbian-Brigantian). Base Tournaisian is pale blue at 0.88 sec in the well; top Courceyan basal conglomerate was only 22 metres beneath this event. After 18 metres of this unit the well penetrated 40 metres of “Old Red” and was terminated. The main ramp has seen significant Variscan inversion with backthrusts and footwall collapse, Clitheroe structure model and down-plunge projection of BGS mapping is used in our picks for this profile’s footwall structure.

Top-sealed by Bowland Shale, which in turn is under the purple roof fault, the complex footwall is prospective for hot water producing wells. Over the last 2-3 million years the more northerly Carboniferous basins of UK have undergone around 18 glacial advances and retreats. This means that melt water has recharged fracture systems repeatedly. Further, as they have been stressed and de-stressed by ice loading and unloading so the permeability of large faults has been cyclically restored. There’s a high chance that many of those oriented parallel to the regional principal stress direction, which is north-westward as here, will currently be re-connected with lesser fractures in an effective network. Where water is stored in fracture systems at depths of around 3000-3500 km, say about 1.4 seconds two-way time on seismic (orange line), it will now be at 100 degrees Centigrade or more. In the rebounds from ice loading, that water will be mobile, as the arrows suggest.