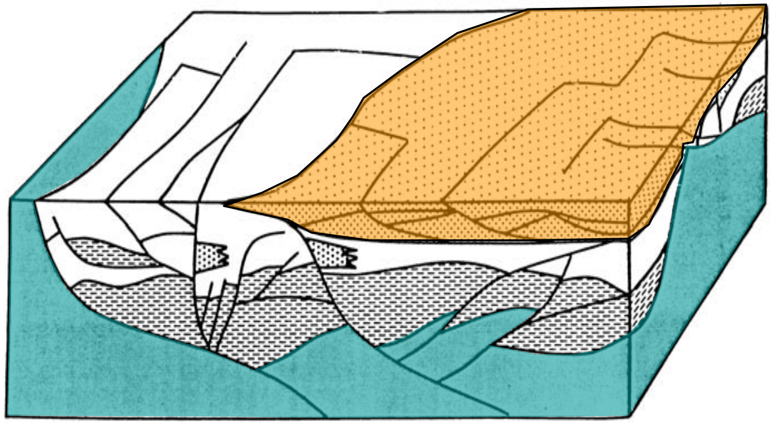
Summary comments on strike-slip basin prospectivity



Because they offer a wide variety of structural and structure-stratigraphic trap styles, because previous licensees will tend not to have mapped licences in strike-slip basins comprehensively, and because early wells may have failed whilst providing important data for more effective work, highgrade strike-slip acreage.

1. Sections which will balance in 2D cannot be shot across strike-slip faults: rock has moved out of plane.

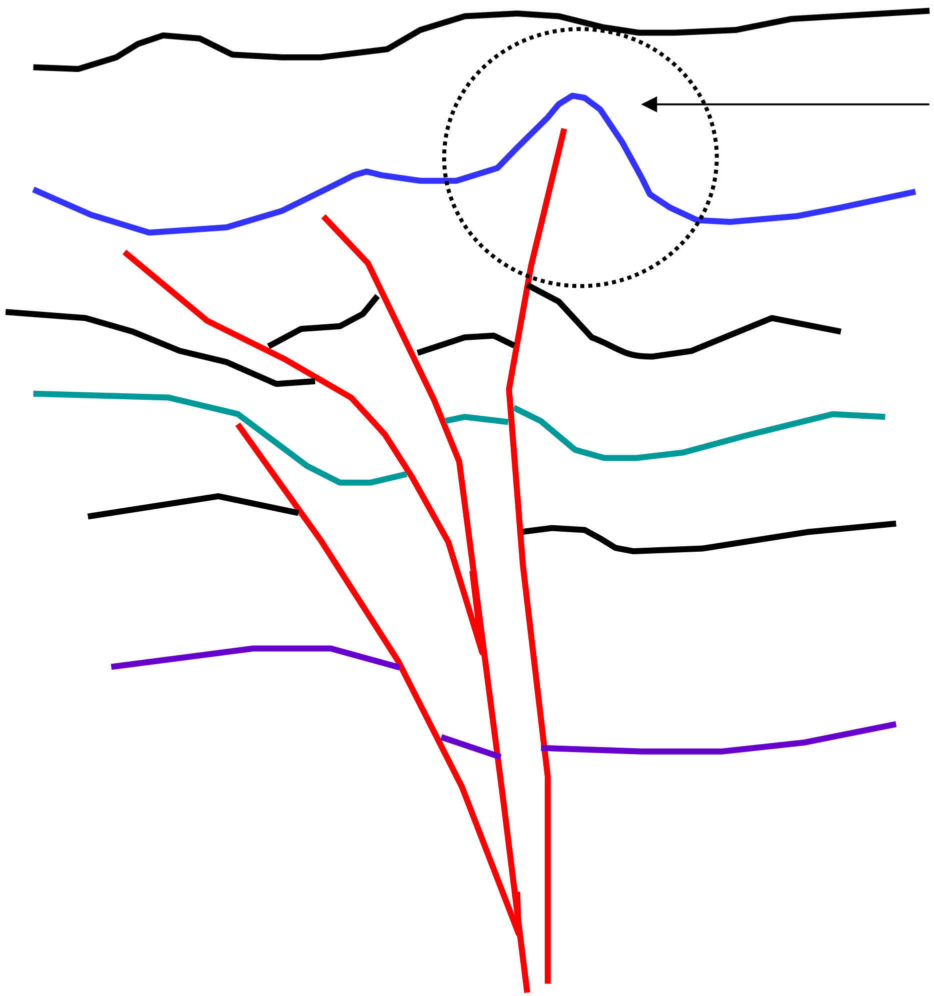
2. Diagnostic structural features are inversions and very rapid, opposing-dip changes. Displacement and direction of displacement on faults will vary abruptly.

3. Cross-fault transfers will be present between strike-slip faults, they may be bed-parallel, they may be dip-slip faults or reverse faults.

4. Stratigraphic traps, particularly fans banked against active strike-slip faults, are prime targets and may have large oil columns.

5. Its essential to have 3D seismic, to map targets reliably. Whilst 2D may give all the clues needed to take an acreage position, 3D is needed to de-risk plays: particularly if the aim is to farm-down prospects.

Strike-slip mixed-mode (extensional and compressional) structures offer a high concentration of targets for oil and gas exploration.



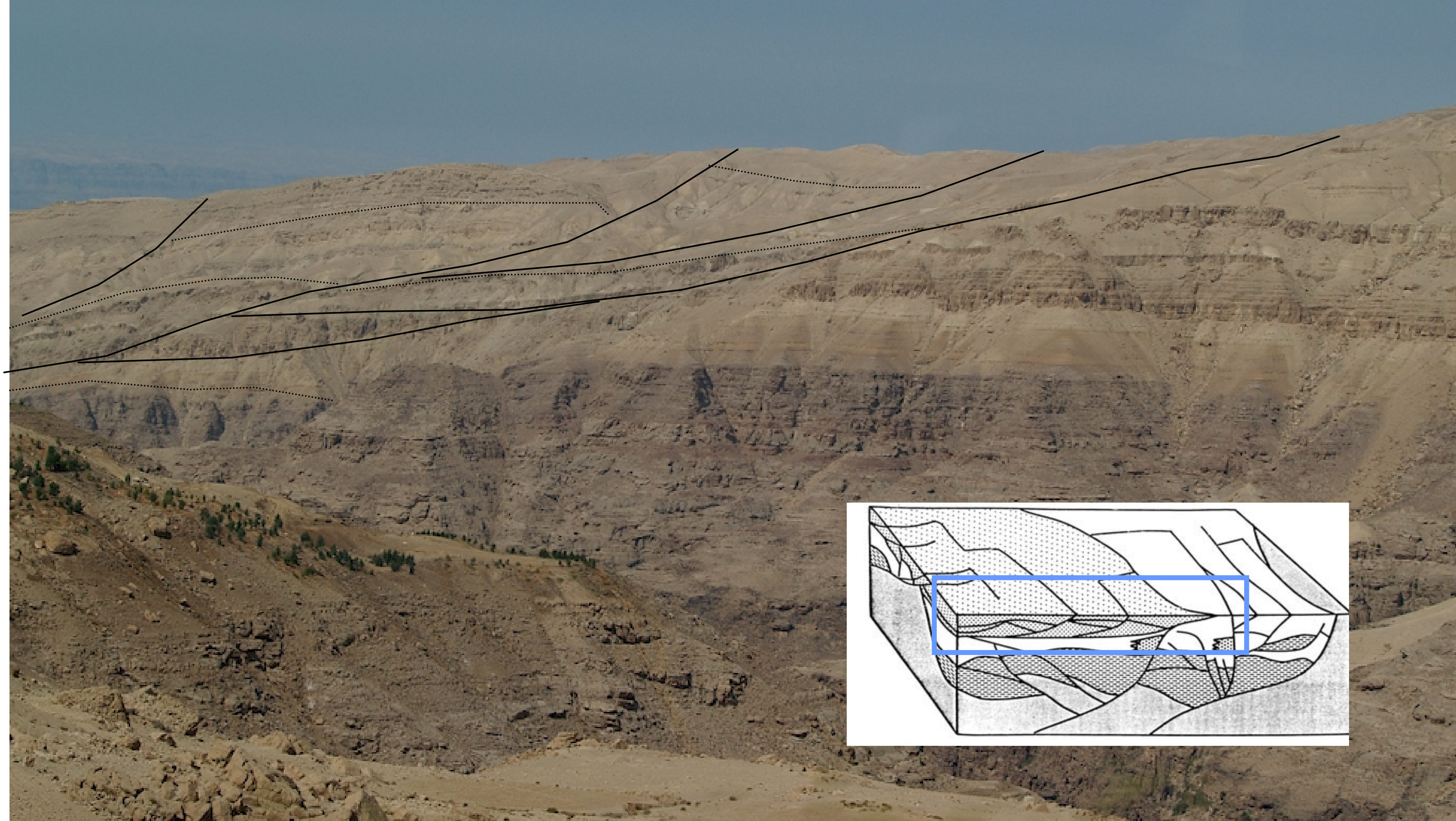
Dip closures with limited structure complexity are usually the earliest targets evaluated

Folds become tighter with depth, and develop out-of-syncline thrusts: more complex targets

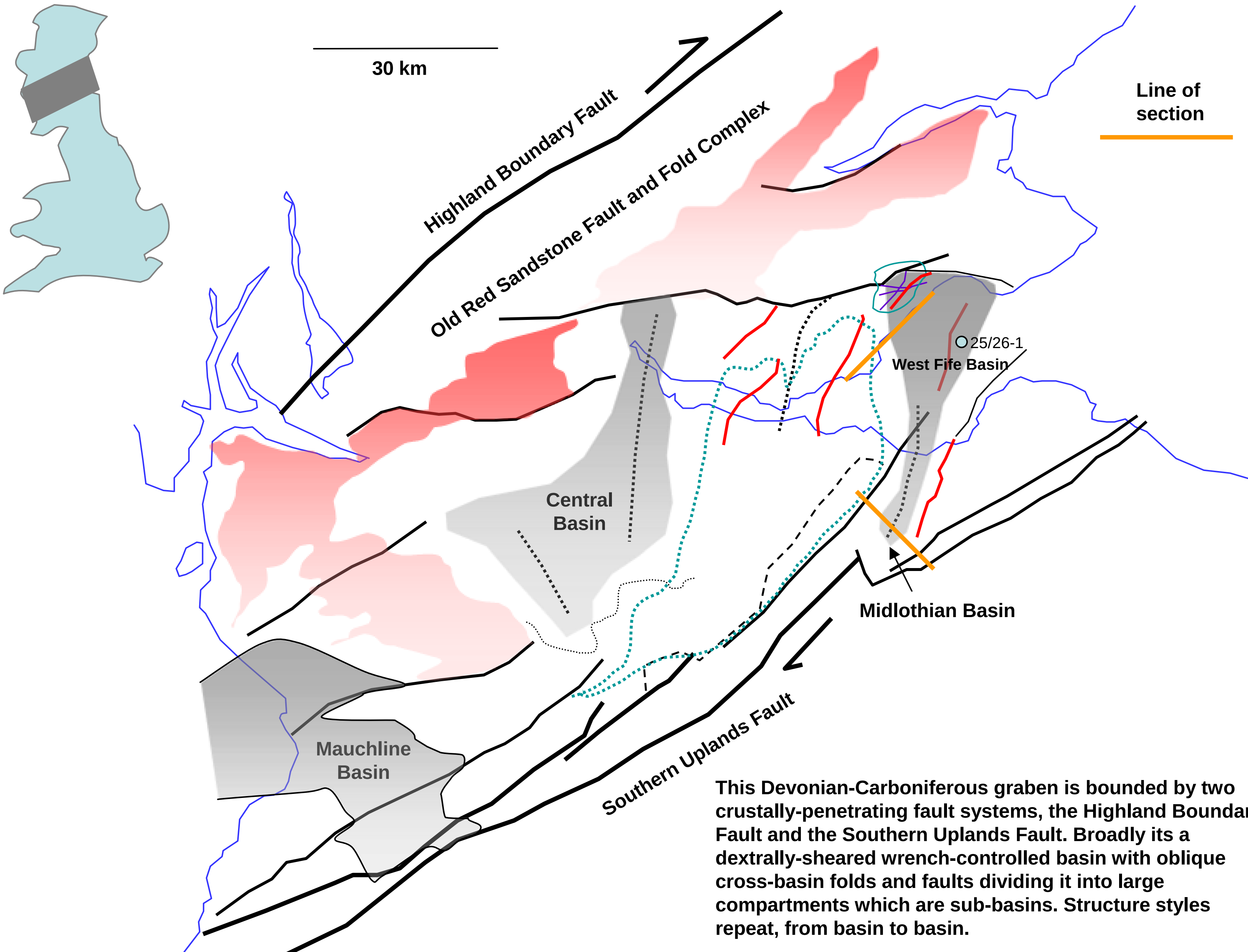
Angular rotations in 3-D, large fault blocks, often poorly imaged, deep targets may be very important but tend to be sparsely tested until proven prospective, can be the biggest structures in the basin

Faults propagate upwards during sedimentation. The lower part of the wrench zone shows transtensional geometries, the upper part becomes transpressional with thrusts and folds.

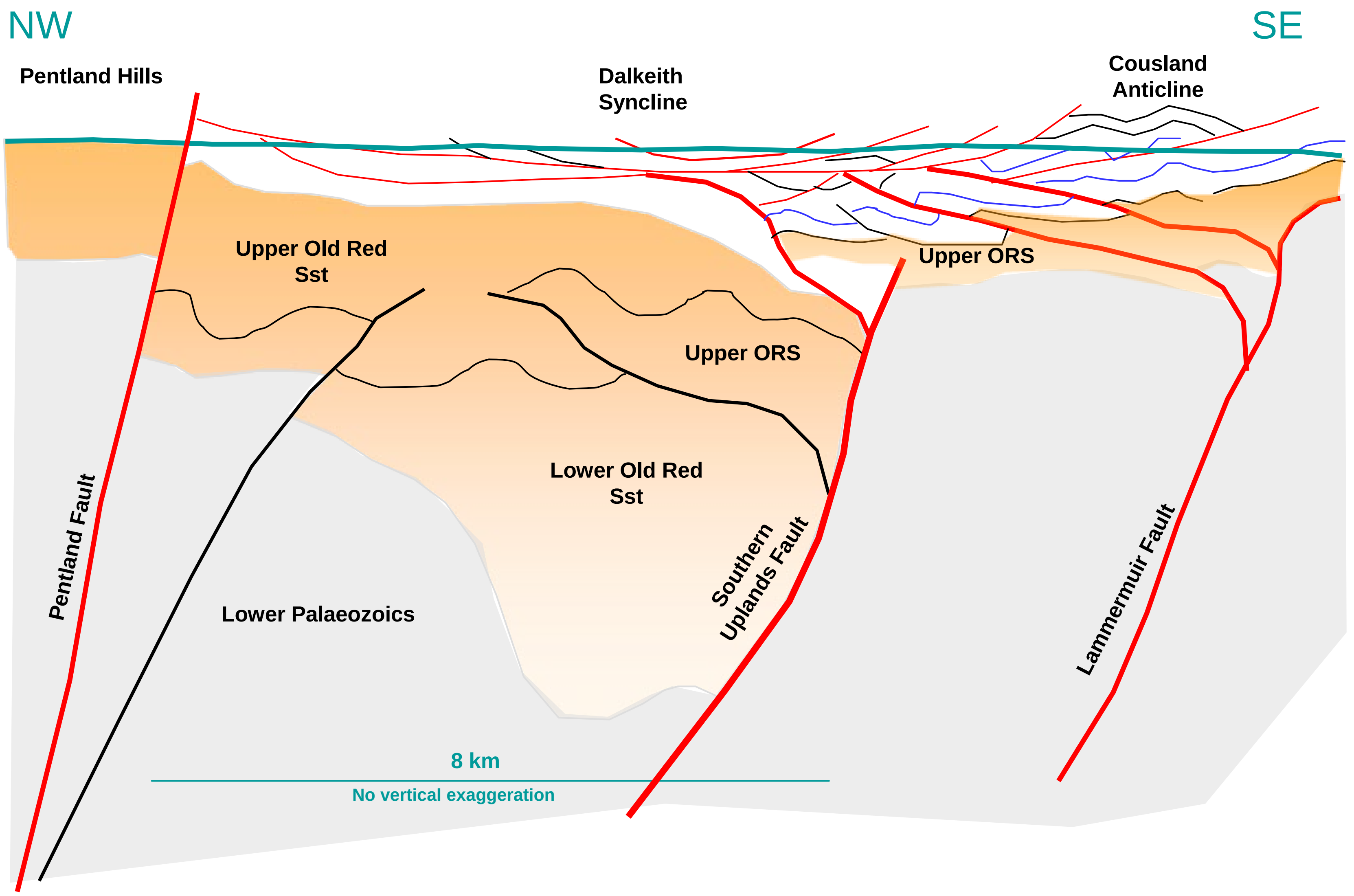
Strike-slip basins are layered, you readily see the steep faults on seismic but low-angle and bed-parallel faults are going to be important too, they play a key role in distributing the deformation, they are often growth faults with local important sequence variation.



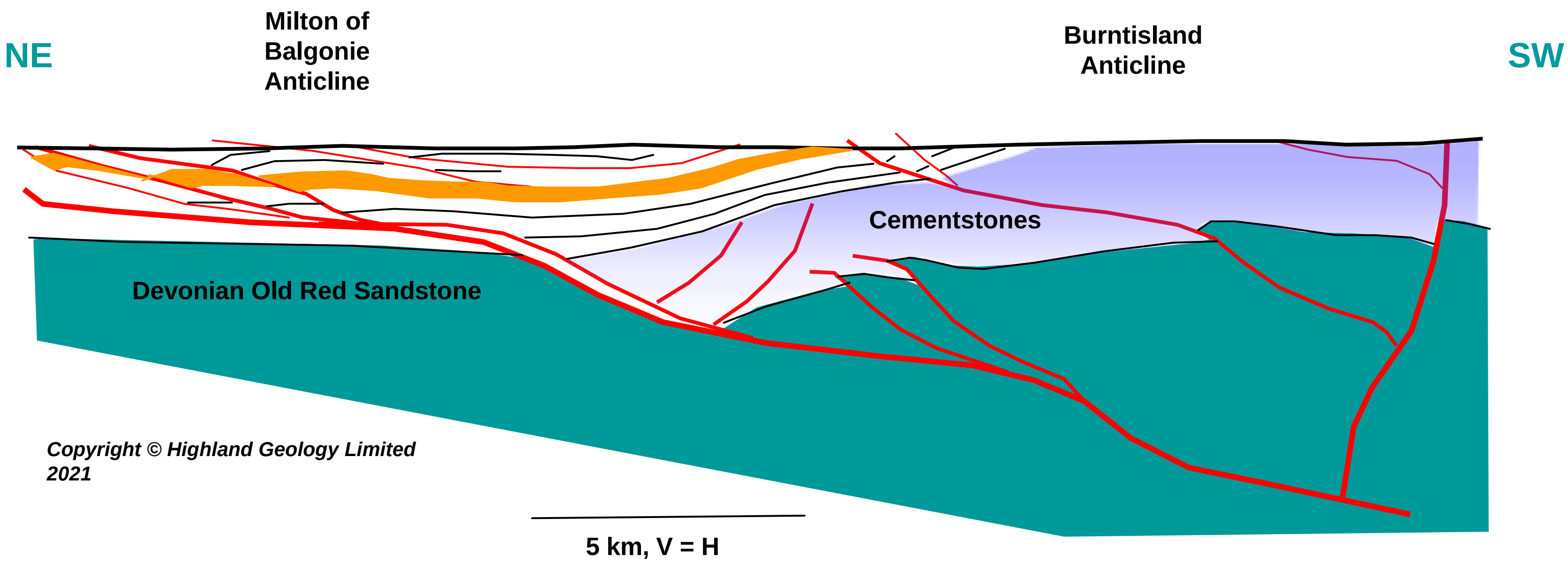
Midland Valley of Scotland strike-slip basin



This Devonian-Carboniferous graben is bounded by two crustally-penetrating fault systems, the Highland Boundary Fault and the Southern Uplands Fault. Broadly its a dextrally-sheared wrench-controlled basin with oblique cross-basin folds and faults dividing it into large compartments which are sub-basins. Structure styles repeat, from basin to basin.



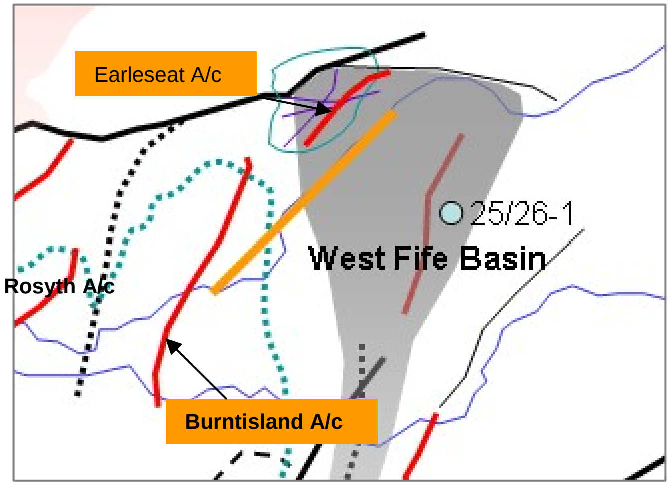
Structural style of the Dalkeith Syncline near Edinburgh, section located on the regional map, its a down-plunge projection made from the geological map. This Devonian sub-basin plunges north offshore and links with the West Fife basin, which is infilled with Carboniferous beds including thick thermally mature oil shales buried 2-3 km. The flank faults look just like Pentland and Southern Uplands Faults, they are transtensional major growth faults with transpressional closures, a large range of play types is evident. The one well drilled to date offshore reported significant shows.



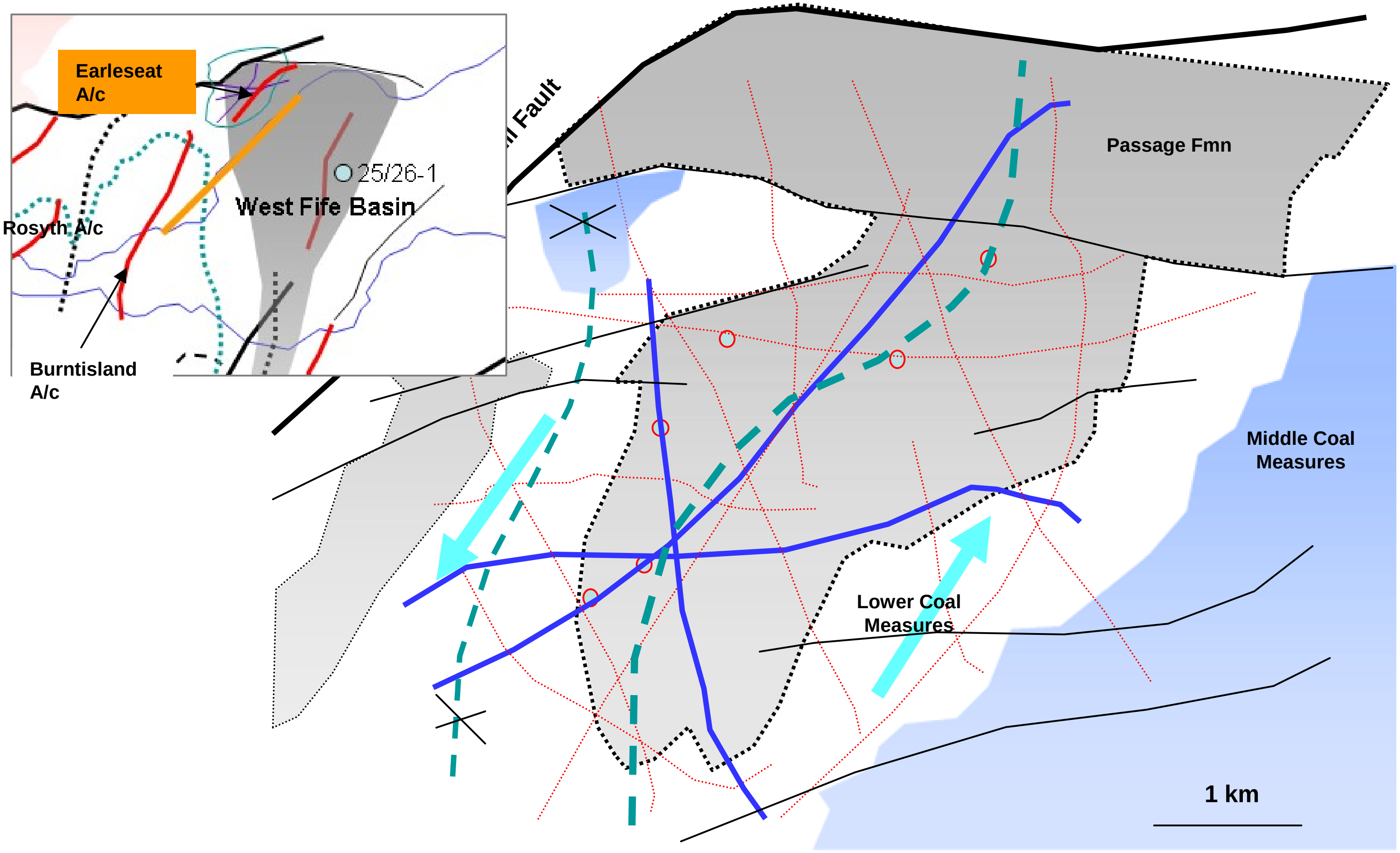
Another downplunge projection using the BGS geological mapping, this is a strike section (orange line, on location map) looking SE from the north side of the basin. The anticline at left was undrilled in the early 1980s when this section was published in a report for Industry, we recommended it for acquisition and it was indeed proved to be a trap, but the oil is heavy and waxy and it wasn't developed. Following slides show seismic from the crestal area of the rollover, which is called the Earleseat Anticline.

25/26-1 was drilled in 1990, it reported waxy oil shows in the Sandy Craig Fmn, non-commercial. It did confirm a working petroleum system. Rosyth Anticline was drilled in 1940, reporting oil shows.

Burntisland A/c is evidently untested although its on the flank of the oil-generating kitchen to east. Whilst it lacks the Carboniferous section of down-plunge Earleseat, the Cementstones and Devonian sequence is prospective. The source rocks are in basal Carboniferous and a flank fault might be large enough to juxtapose this source with sandstones of the Cementstones or top of Old Red. It would be a gas play, as the reservoirs have been deeply buried, this basin lost a lot of cover in Tertiary uplift and erosion.

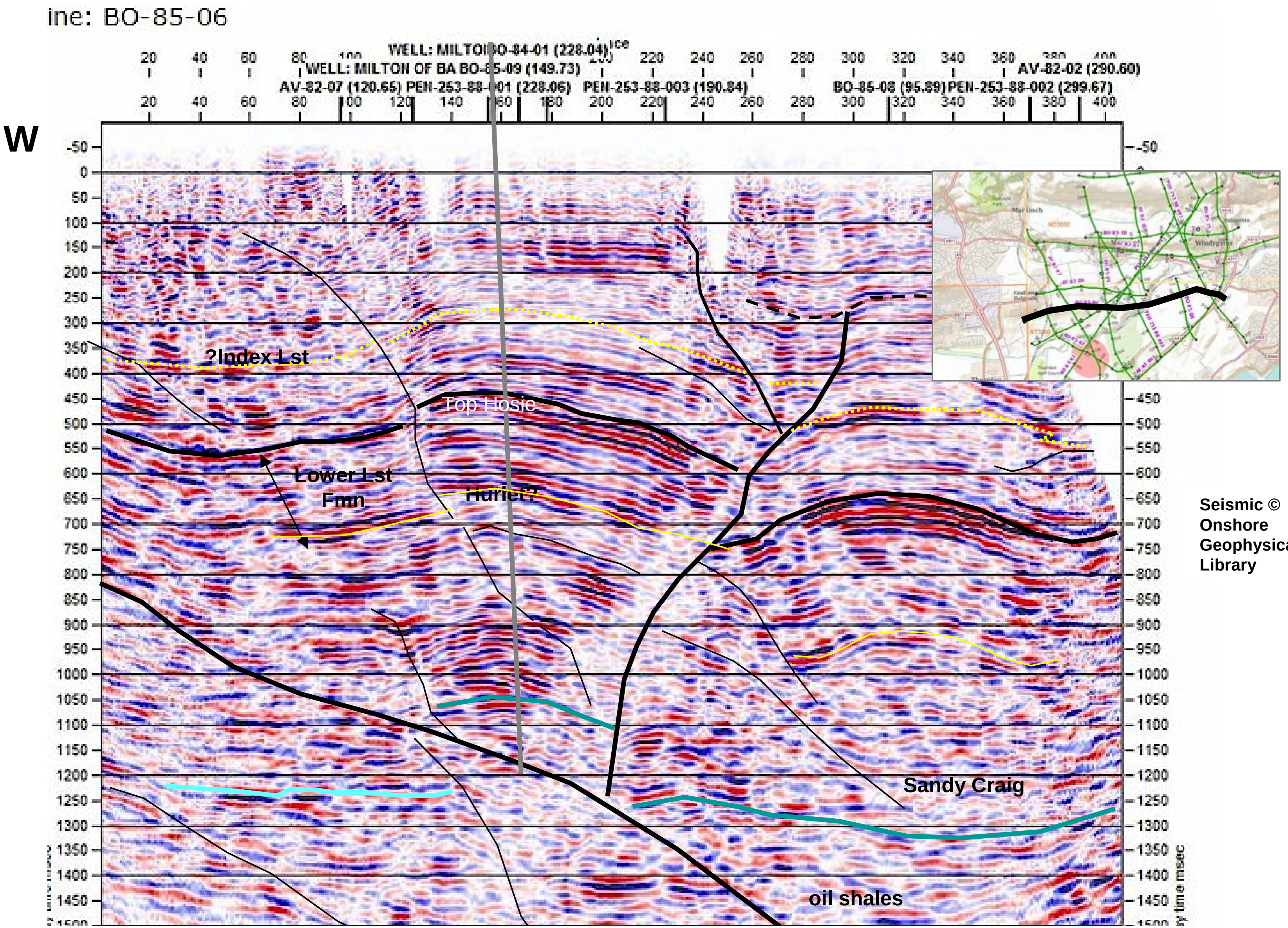


Earleseat Anticline and its seismic cover



Dealing with transpressional tectonics, you know that there are going to be detached carapace faults in the highest part of the fold. That's what we have at Earleseat, the geological map based on many local coal workings and quarries shows extensional geometries, low-angle detaching faults and gentle rollovers, it doesn't demonstrate strong compressional features.

The three sections marked in blue are shown in following slides, all show reverse faults, the structure is a compressional pop-up. Its symmetry suggests its a left-handed shear couple forming the fold, and probably there is a pair of deep faults cross-connected by a transfer, giving the jog in the axial surface.

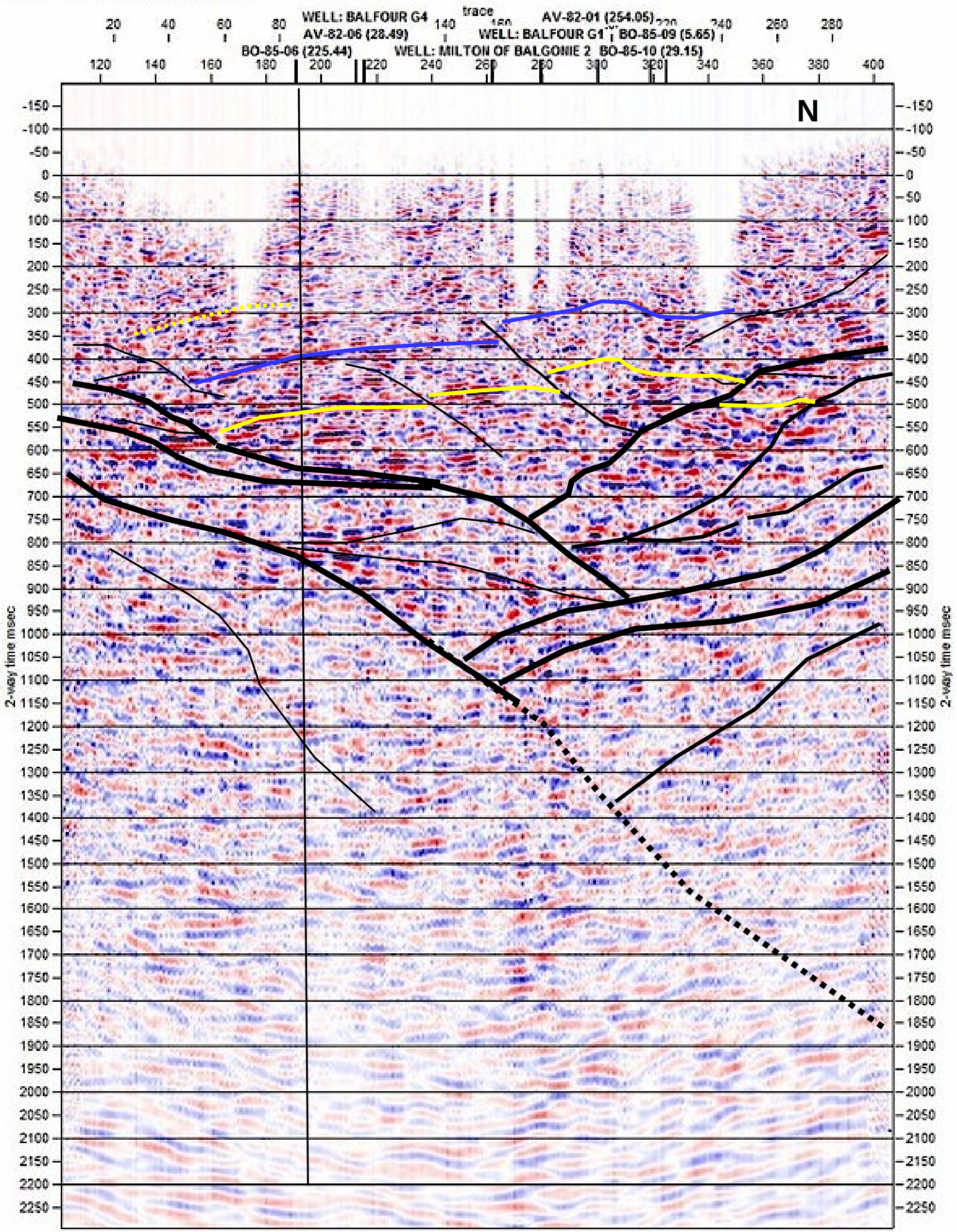


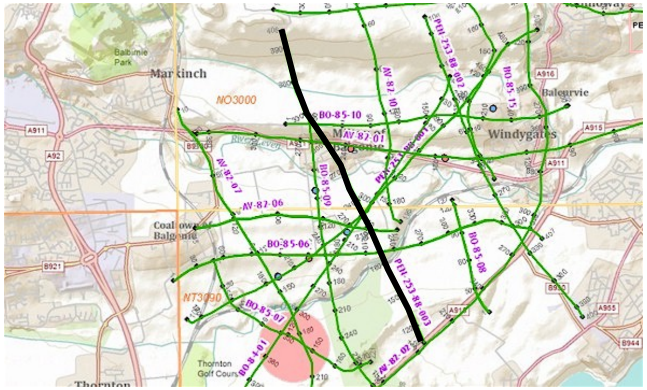
Seismic © Onshore Geophysical Library

With rapid changes in fault shape and displacement being transferred abruptly to other faults, 3D seismic is needed to map wrench zones reliably. It will take a series of wells to establish which play works and which doesn't, in strike-slip petroleum systems.

Milton of Balgonie drilling tested the transpressional fold but didn't evaluate deep tilted fault blocks at top of Devonian: these are in fault contact with the oil shale facies of East Fife Basin and may prove to be significant targets. We think the structure sits on an extensional fault dipping east, subsequently shortened in left-handed oblique slip.

Line: PEN-253-88-003

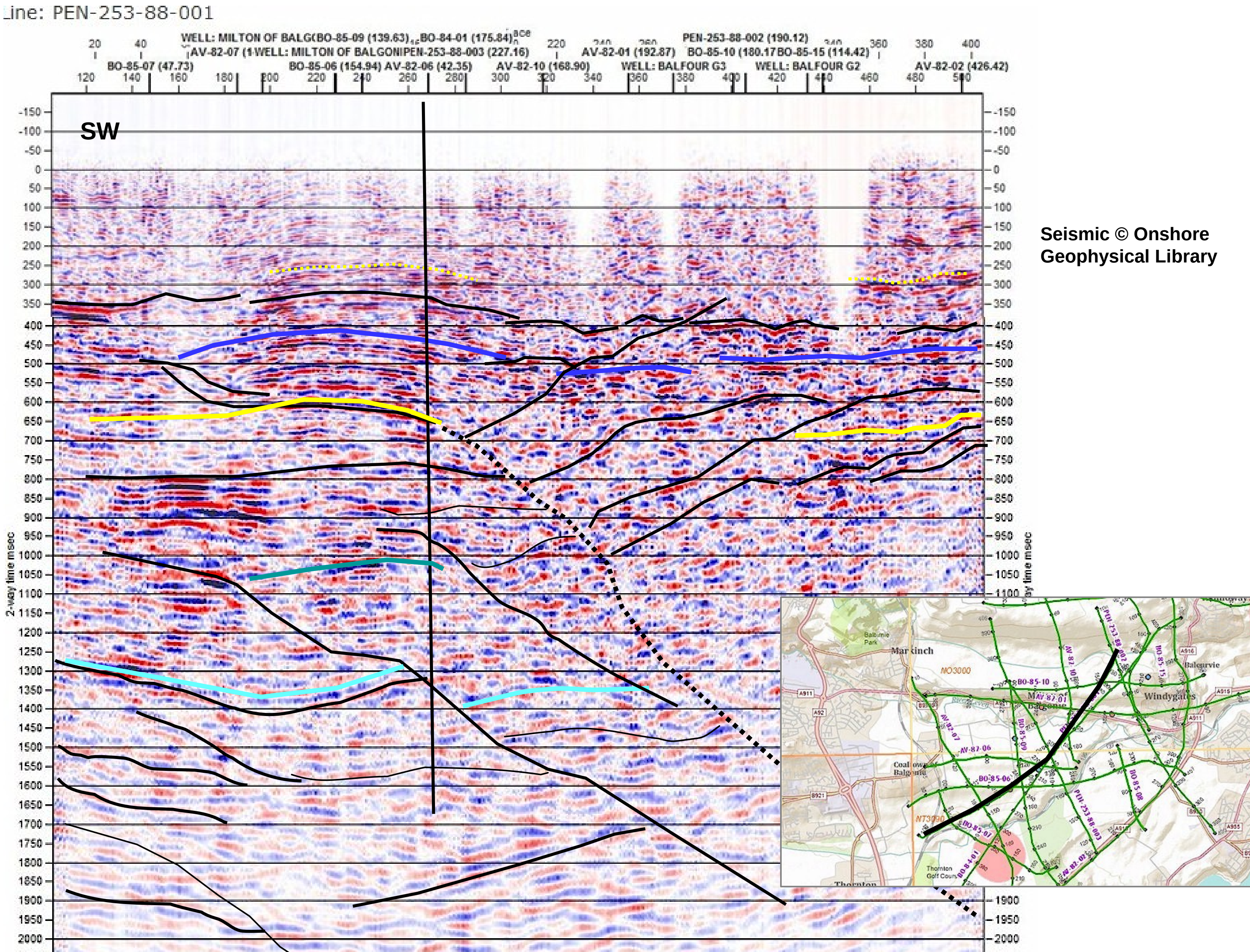




Strong compression is evident on this line across the axis of the anticline, with reverse faults on both limbs. It closely resembles sandbox models described by McClay and Bonora (2001) in Bull. AAPG 85(2), 233-260, with the proviso that those authors made models detaching on base of shear box whereas many strike-slip faults cut deeply into basement.

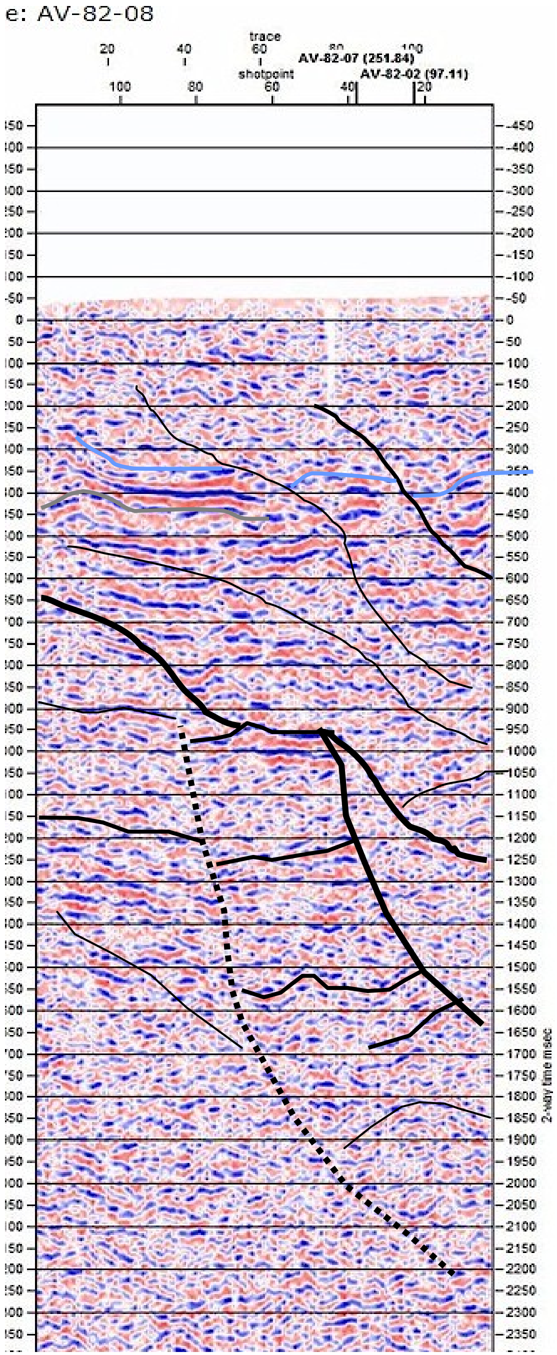
Deep structure is hard to see, part of the problem being that the data are losing fold due to topography issues, and that the area is an old coalfield. Reprocessing with special attention to noise-reducing algorithms, is best done by specialists and will always pay off.

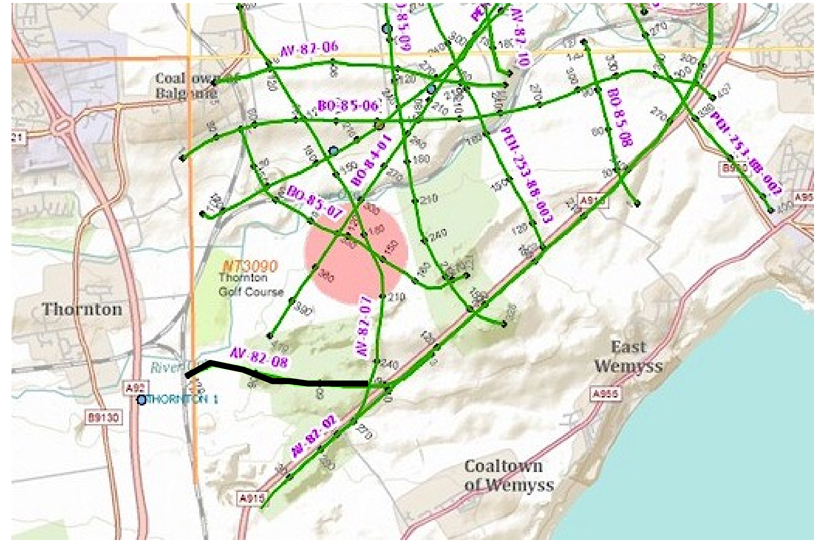
Seismic © Onshore Geophysical Library



Seismic © Onshore Geophysical Library

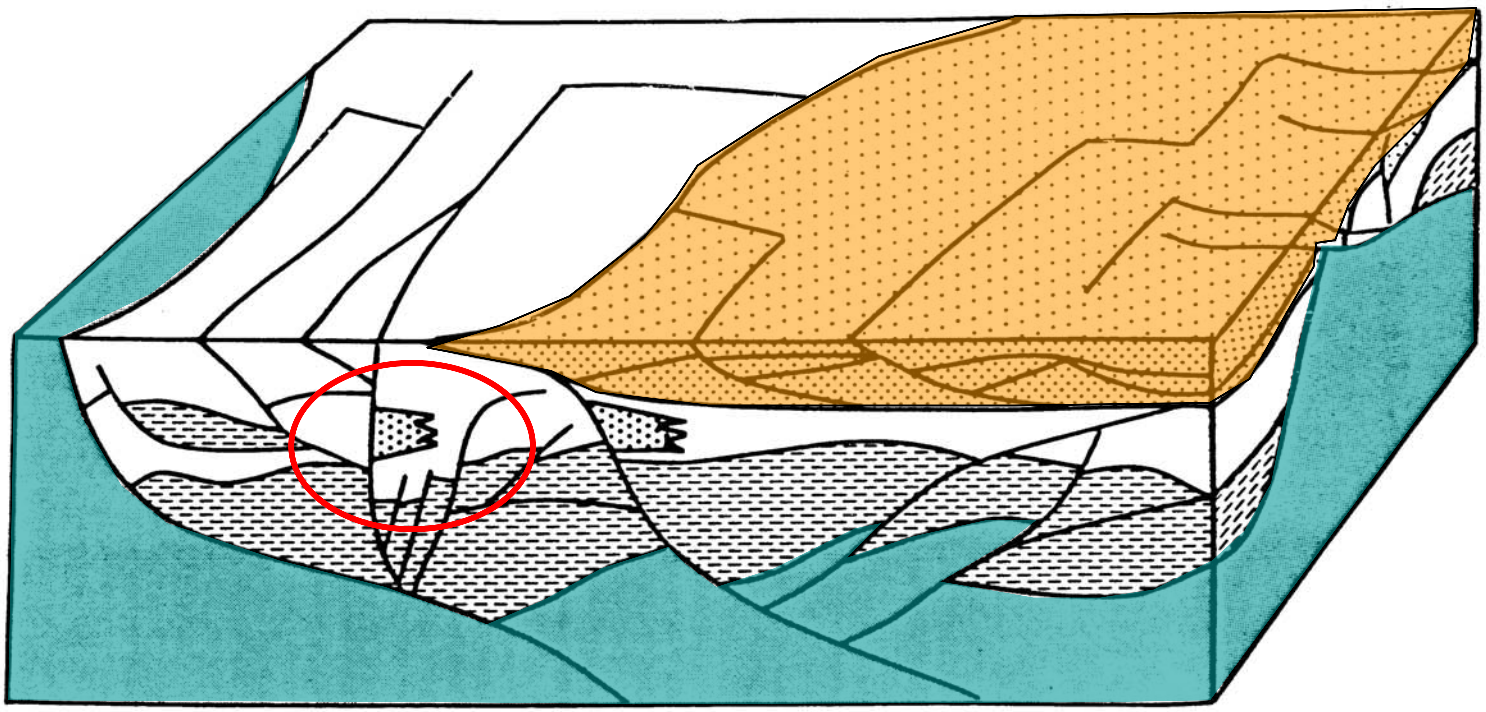
A strike line along the axis of the Earleseat Anticline shows the rollover with the Balgonie wells; the deep fault blocks which haven't been drilled yet; and on the north flank there's a complex fault zone (dotted) where the structure flexes and jogs rightwards. So the jog in the fold axis is indeed a cross-fault.





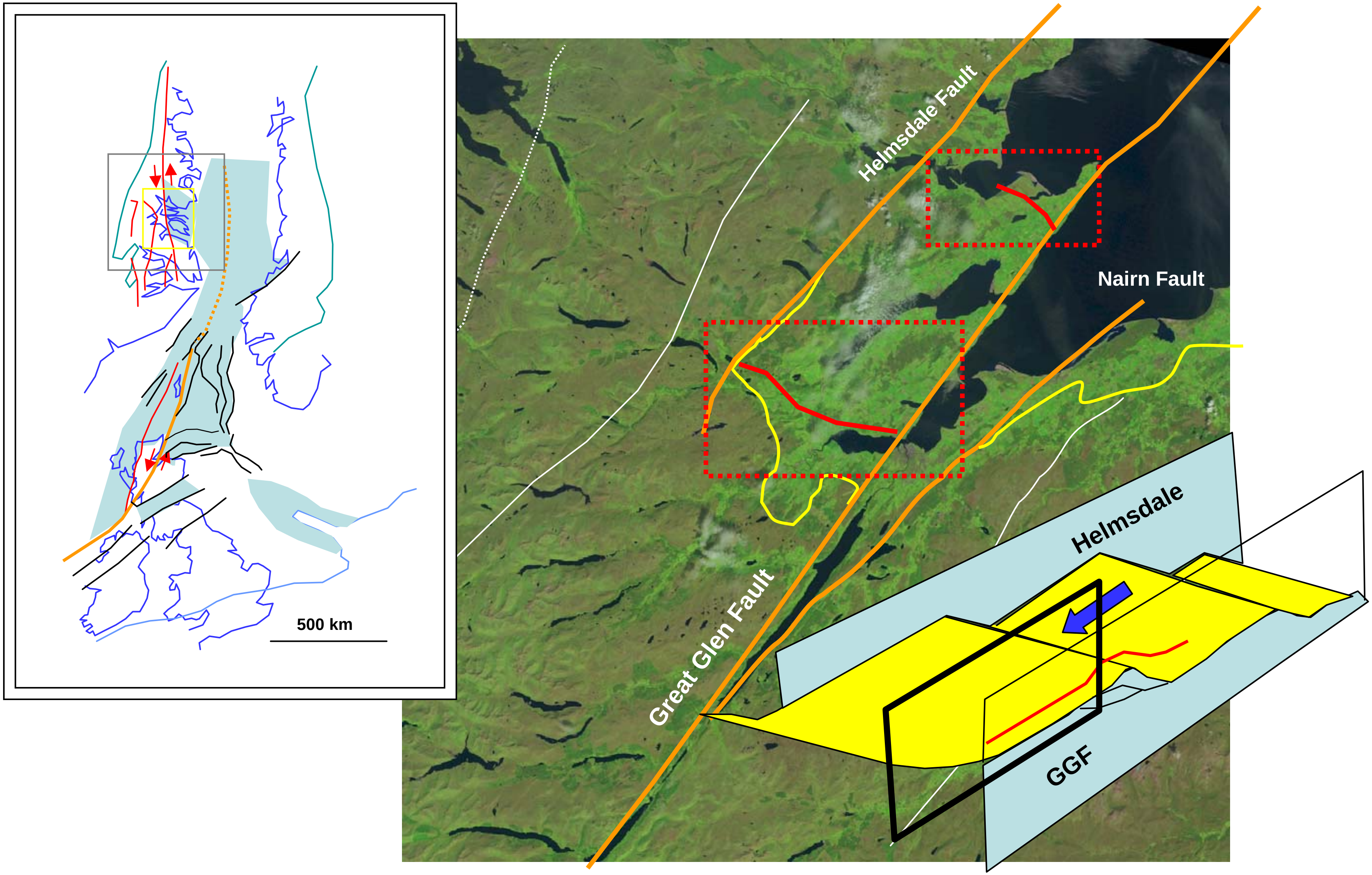
Sometimes one line gives us more confidence to pick the others in some particular respect. This line over the narrowing south end of the fold shows deep fault block structure better than the more northerly profiles.

If we have a structure model convincingly supported by some key lines, its defensible to make concept-driven picks on poorer profiles. This approach is called "over-interpreting" by people who feel uncomfortable with it.



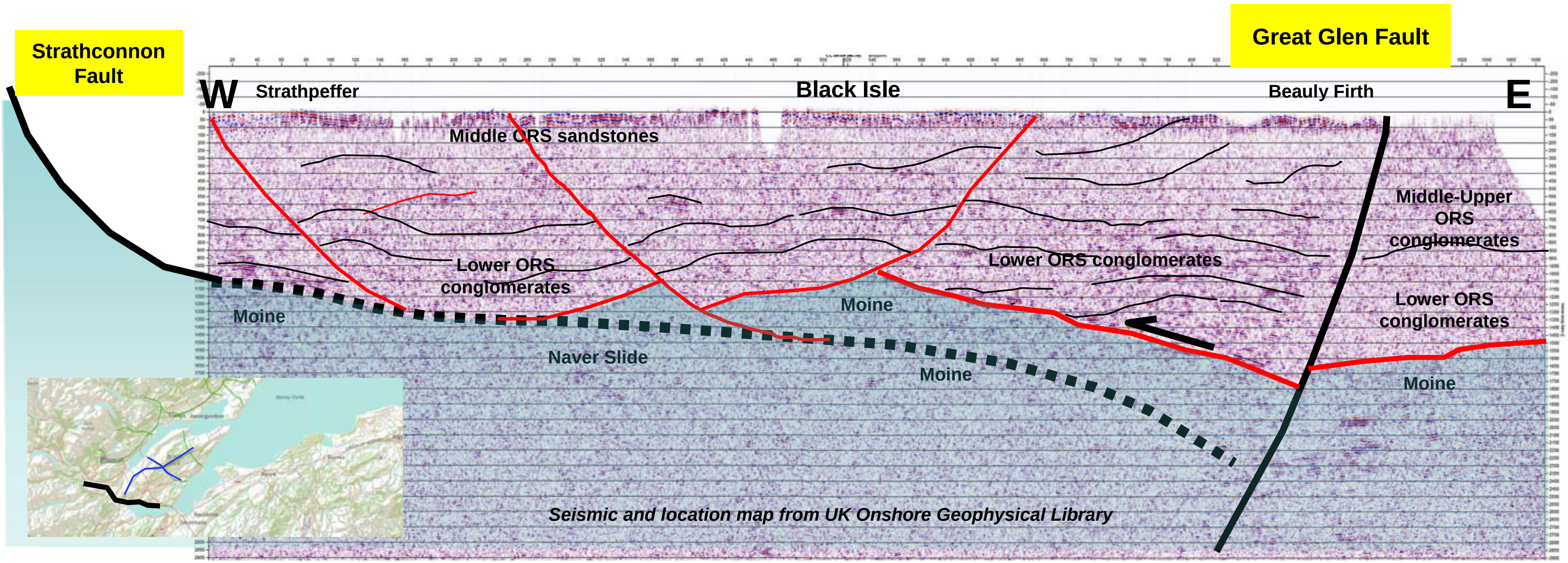
These local sediment wedges may be excellent stratigraphic traps whereas structural closures may have unfavourable timing, or reactivation of faults causes them to leak. Wedges are typically late to be explored, because a certain amount of well data is needed to de-risk them. They can be weak links in structure plays, acting as failing sideseals if they are channel-sand locators.

In the West Fife Basin we could look for Sandy Craig facies change, rapid thickening into the kitchen, local back-tilted fans interfingering with the oil source rocks at base Carboniferous. Not tested yet! Scotland prefers to build hundreds of wind turbines.



Moving north: Great Glen Fault is a crustal-penetrating transform which has operated from Devonian to present day. Its a classic strike-slip fault. With Helmsdale Fault its a primary control on the Inner Moray Firth Basin geometries, and the onshore seismic from the Devonian outcrop areas tells us much about how the two major faults relate to each other. We look next at the two areas outlined in red, and evaluate the linkage concept.

Major detachments in strike-slip basins



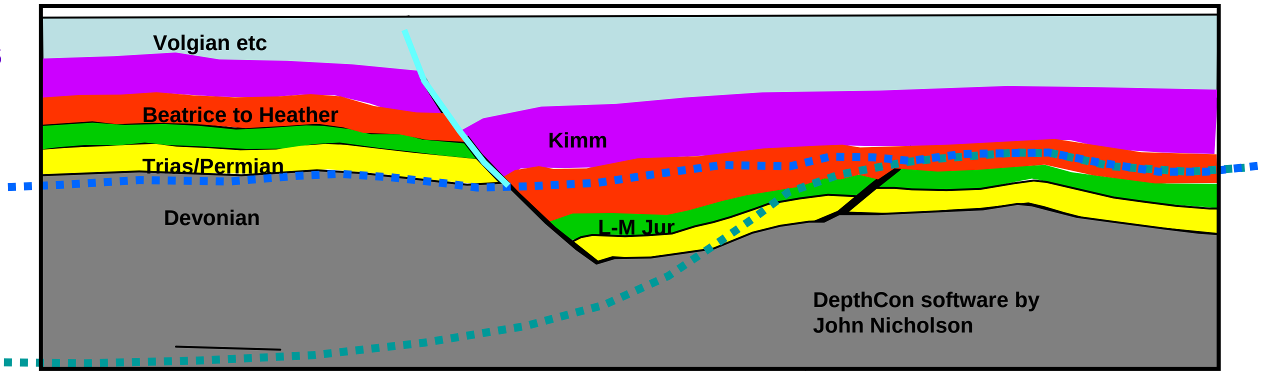
More or less flat detachments are important in strike-slip basin development. They are like the bases of sandboxes used to model basin growth, they link steep faults which detach on them, and feed displacement from the really big, crustal-penetrating faults, across the depocentres. They should be in the interpretation!

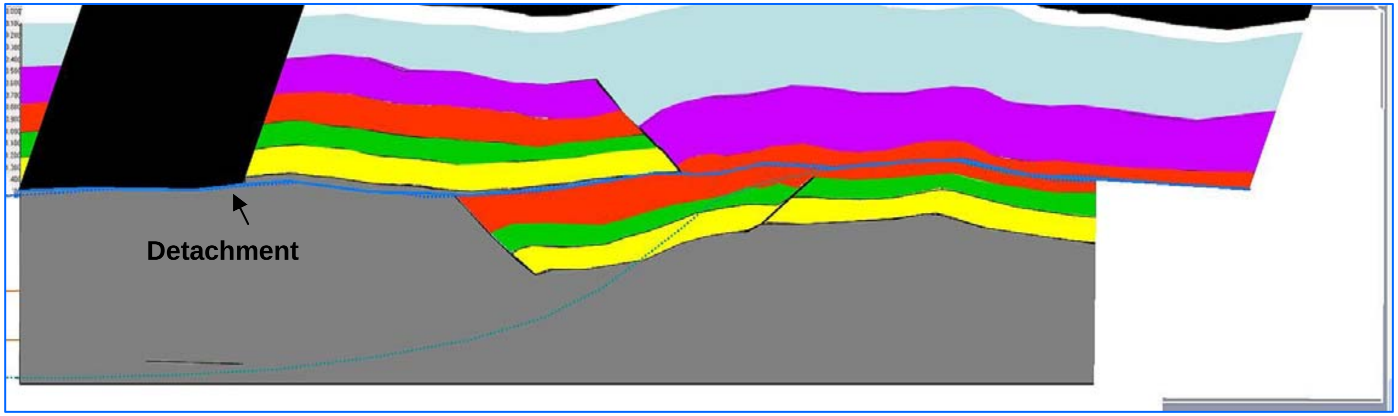
In the Moray Firth, at the south end of the Black Isle, line CC-84-01 which is about 22 km long is interpreted here to show the Naver Slide (dotted) connecting the Strathconnon (the south component of Helmsdale) and the Great Glen Faults. Slides were mapped by the British Geological Survey teams in the late 1800s, they are hard to see nowadays because the roads are tarmacced and the quarries all filled in. Naver Slide is at or near top of the Moine metamorphics, it is the detachment for growth faults cutting the thick conglomerates laid down in early Devonian.

Faults like the Naver are not picked by interpreters, but they are really important to prospectivity.

Inversion structures at convergent strike-slip faults

From Inner Moray Firth, here is an instance showing development of structure highs at transpressional convergence of strike-slip faults. We model it, starting with a late Jurassic-early Cretaceous extensional growth fault sequence.

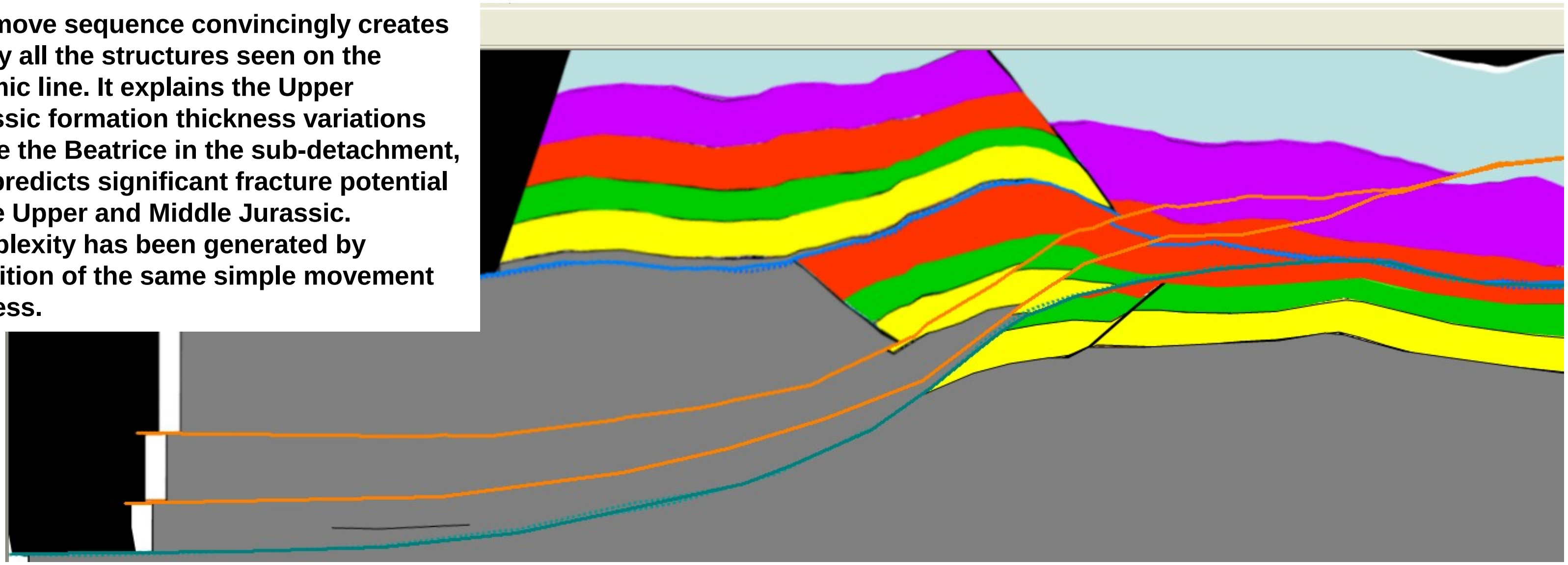




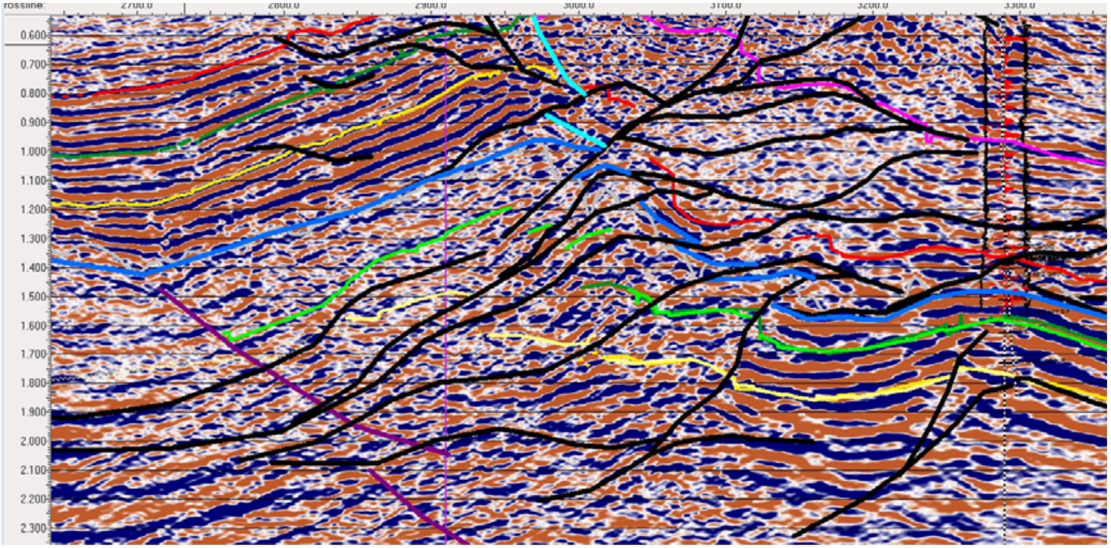
<u>Move 1</u>. Starting with this template we first generate a lateral displacement on the blue-dotted flat overthrust which links two major wrench faults, the Great Glen and the Helmsdale. As these meet, there's a space problem. The slip is obliquely towards us on the blue surface, its about 2 km of lateral movement. The detachment roots on the Helmsdale Fault just off the left end of the profile, tracks along the base of yellow Permo-Trias/top Devonian or thereabouts, and propagates farther into the basin in the shales (red) between Oxfordian Heather and the Callovian Beatrice sequence. These two units are preferred detachment horizons.

Because the blue translation surface is more or less flat there is no inversion yet: we have simply established overlap of Middle-Upper Jurassic sequence.

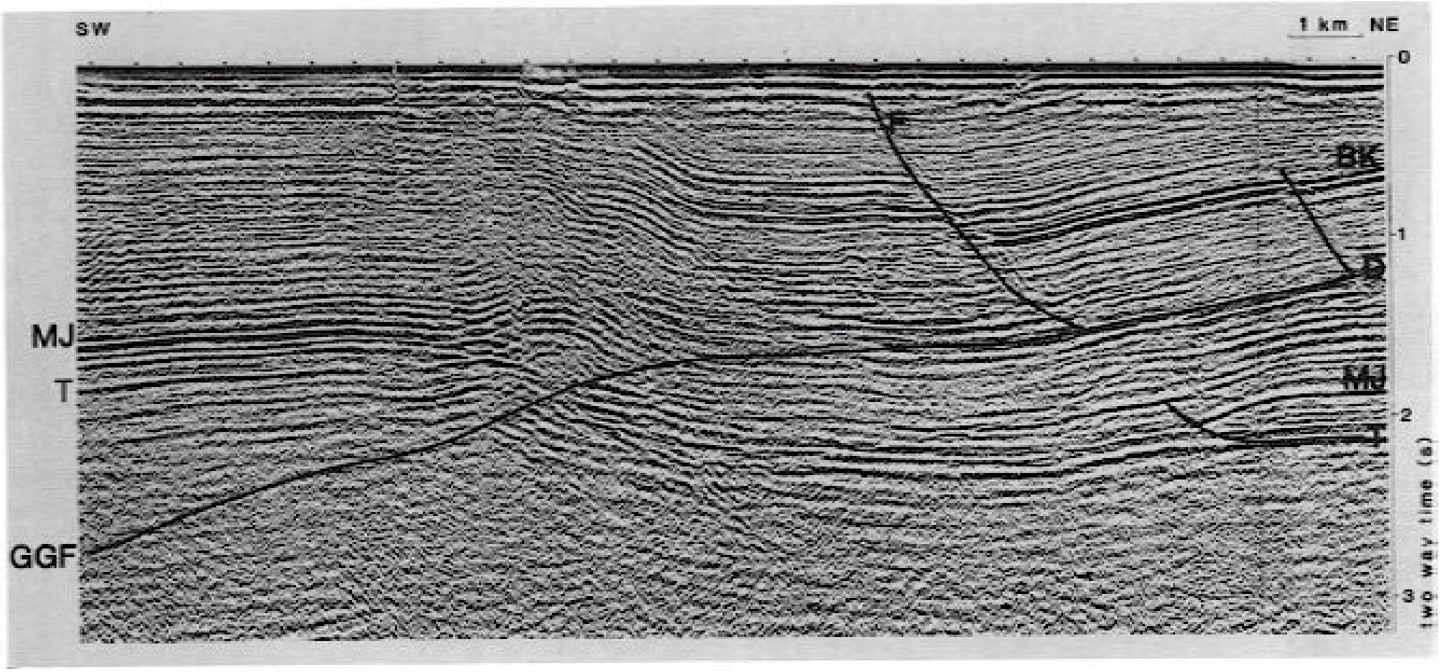
The move sequence convincingly creates nearly all the structures seen on the seismic line. It explains the Upper Jurassic formation thickness variations above the Beatrice in the sub-detachment, and predicts significant fracture potential in the Upper and Middle Jurassic. Complexity has been generated by repetition of the same simple movement process.



Step 2. A sequence of translations is now imposed, obliquely along southeast-climbing ramps linked onto the Helmsdale Fault. This profile is oblique to shortening, the displacement direction is around 45 degrees out of plane towards us. The faults young from top downwards in progressive footwall collapse, everything moving above currently-active surface gets passively deformed and has the same heave, i.e. each point in the hangingwall travels by the same amount along a trajectory parallel to the fault surface. Now a prospective high is created, its shape is a consequence of the number, position and geometry of the ramp surfaces.



All key features of the seismic are replicated in the model.



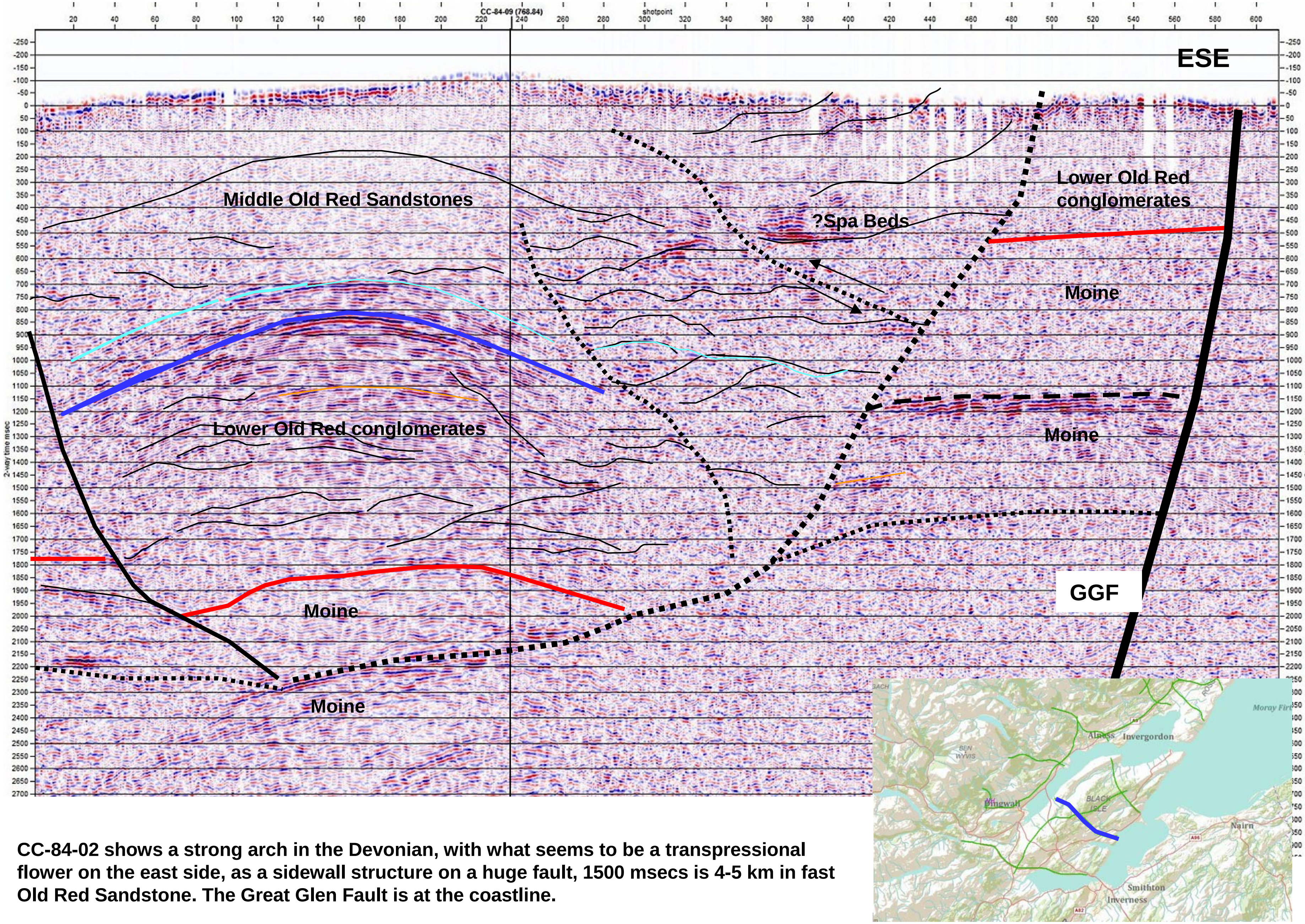
b

Fig. 9. Part of GECO line GMF 28 (1977, migrated) across thrust portion of Great Glen Fault (see Fig. 10 for approximate line location). (a) Un-interpreted. (b) Interpreted Section. Fault flattens to bedding-parallel detachment (D) ahead of the thrust ramp portion. Upper fault (F) affecting Base Cretaceous (BK) decouples on this decollement horizon. This faulting is completely unrelated (detached) to the lower levels of faulting below the detachment; for example the fault which rotates Middle Jurassic beds (MJ) at right of section, which detaches on top Triassic (T).

Do big flat thrusts and thrust ramps climbing out of Devonian exist in the Inner Moray Firth? Yes they do! A third of a century ago this writer co-authored a paper on Moray Firth describing them, using outcrop and 2D GECO seismic. Fig 9 reproduced from that paper here is actually close to and parallel to the section we've been looking at. These structures move fluids around the basin, oil and gas migrate through them from Devonian source to the Mesozoic reservoirs. Its happening now, which is probably why we see thrusts imaged on seismic deep in Devonian. The thrust zones contain hydrocarbons.

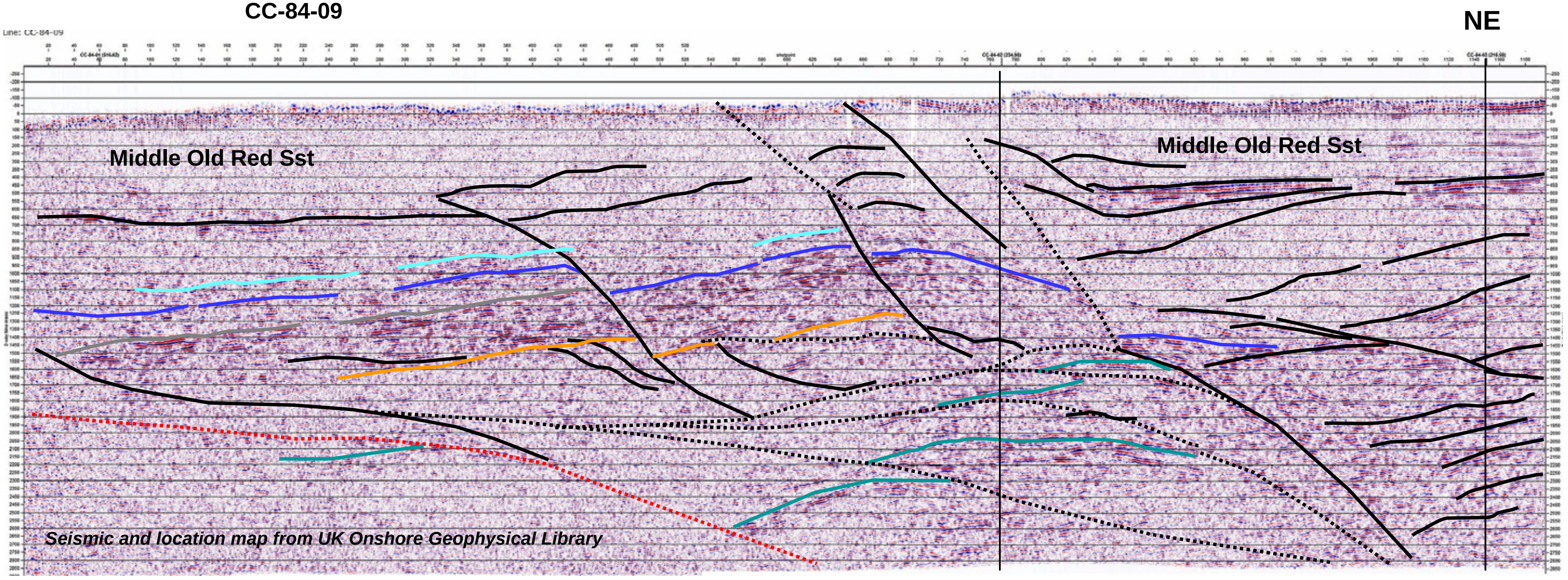
CC-84-02 12 km

Seismic from UK Onshore Geophysical Library



CC-84-02 shows a strong arch in the Devonian, with what seems to be a transpressional flower on the east side, as a sidewall structure on a huge fault, 1500 msecs is 4-5 km in fast Old Red Sandstone. The Great Glen Fault is at the coastline.

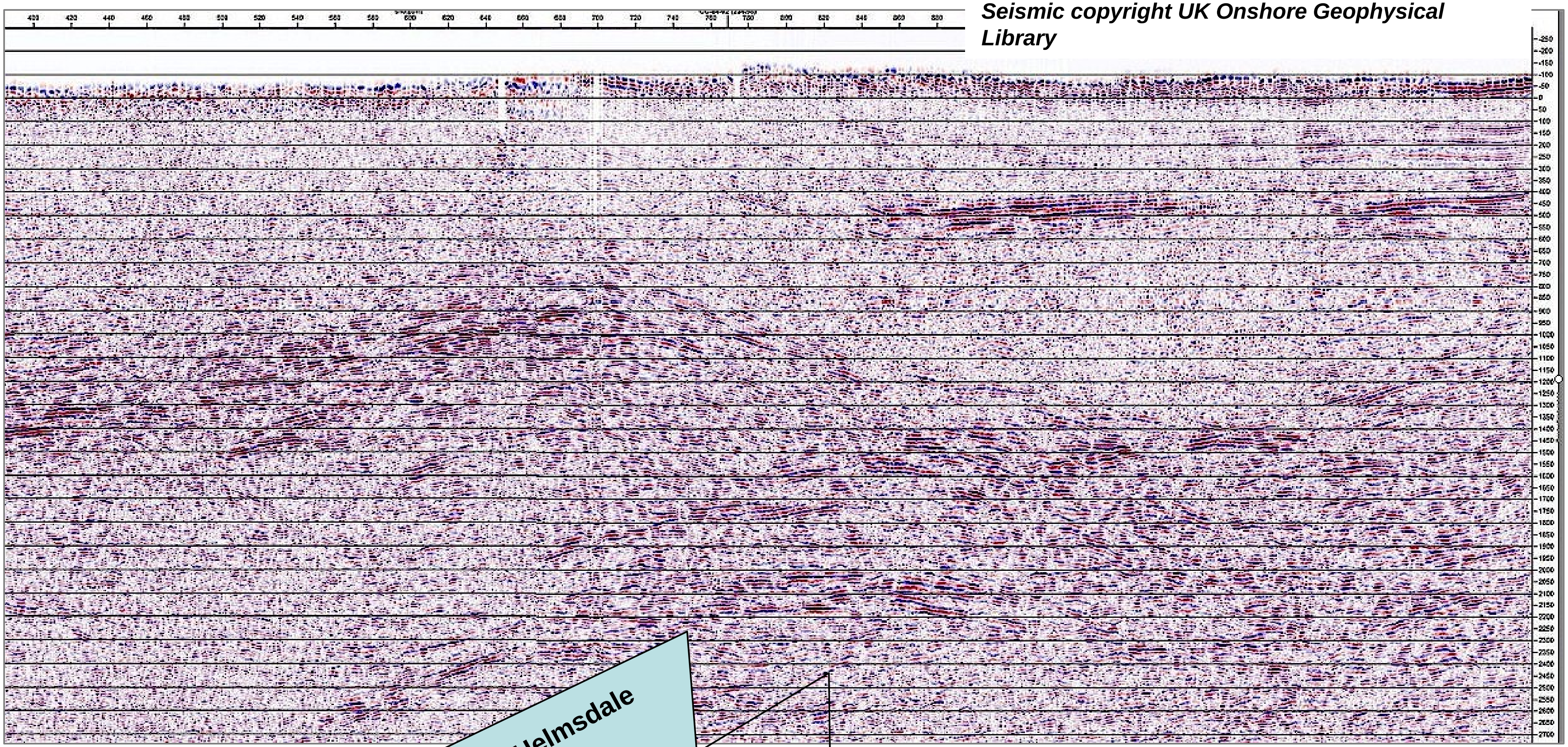
CC-84-09

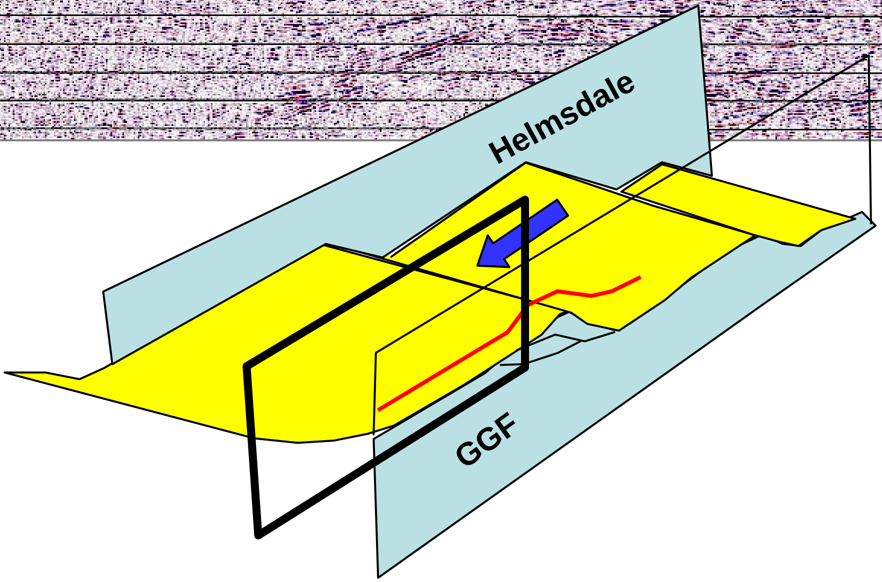


With an understanding of how wrench systems work, we are in a much better position to interpret basins like this one.

So we are aware that strong shortening is likely on sections parallel to the wrench zones.

This dip line CC-84-09 is about 25 km long, we think its showing a collapsed ramp with sequence repetition (dark green) in Lower Devonian and maybe Moine basement. We'll give the unpicked central part of the seismic line next, then demonstrate why we see this model as plausible.

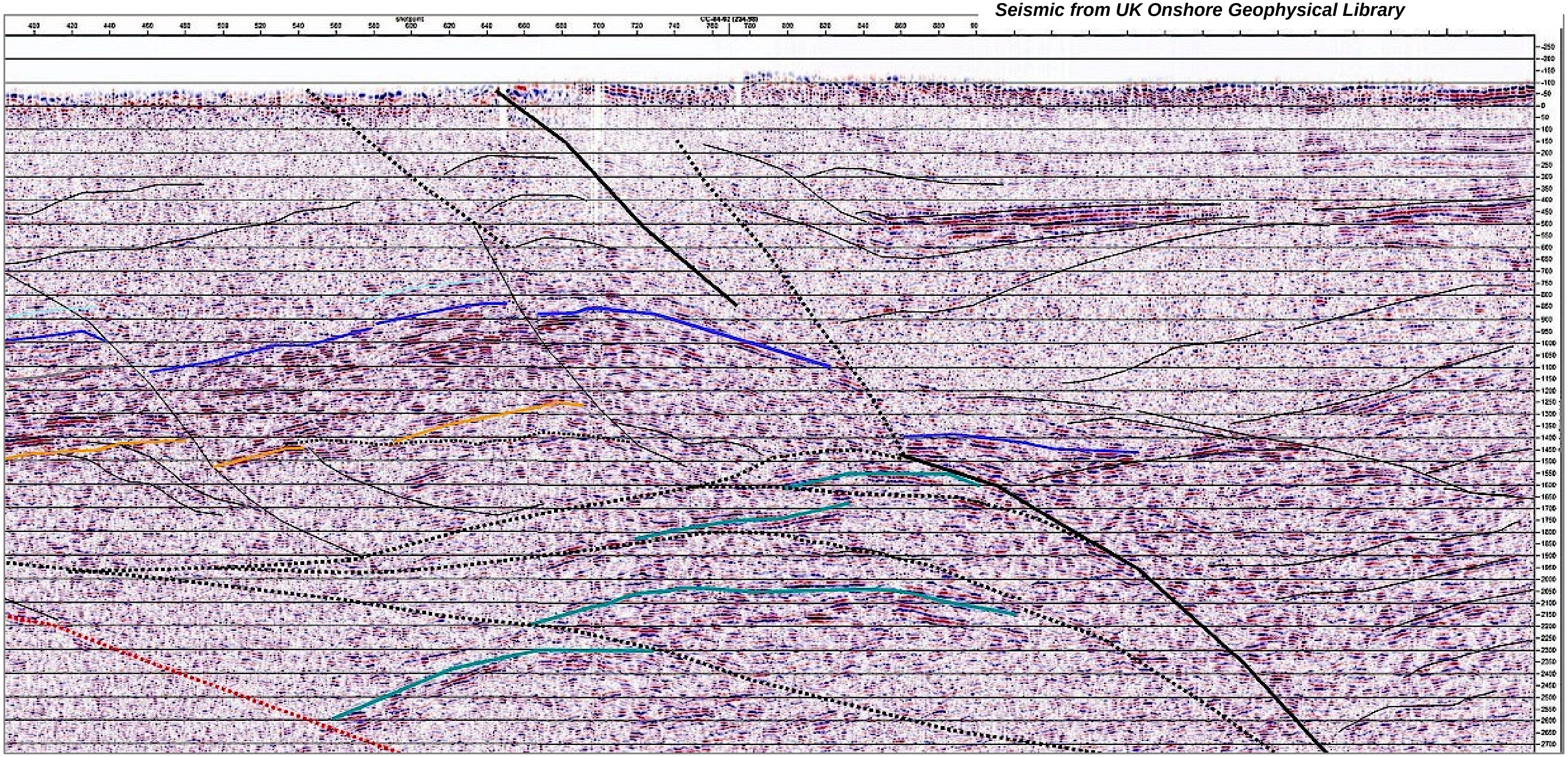




This is the unpicked main area of interest on CC-84-09, for comparison with the following model. Its a bit of a challenge!

And the setting is as shown in the sketch, we are on a ramp between two major strike-slip faults, and the concept to test is a shortening fold modifying older extensional structure.

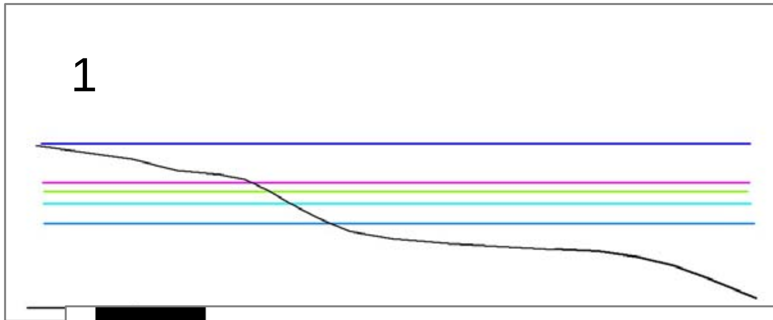
Seismic from UK Onshore Geophysical Library

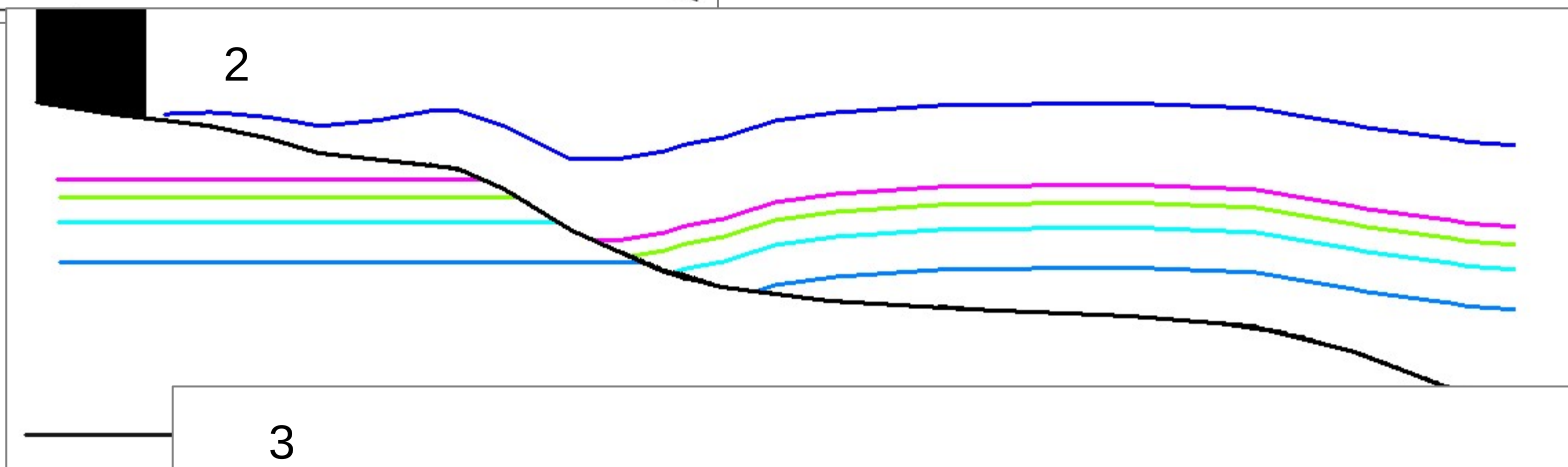


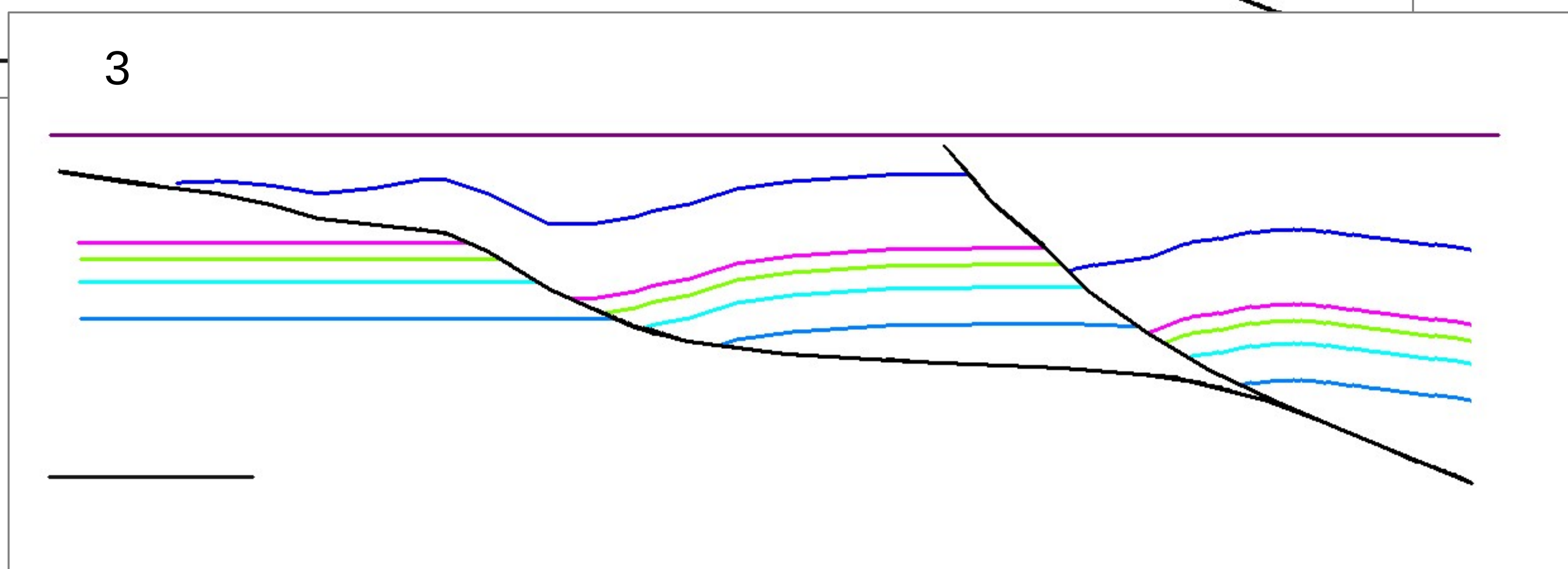
This is a difficult section to pick, and we tackle it with a combination of selecting the faults and events which we think are reasonably well founded, and a forward modelling exercise, shown in the following slides, to advise what kind of geometries will result in a ramp collapse.

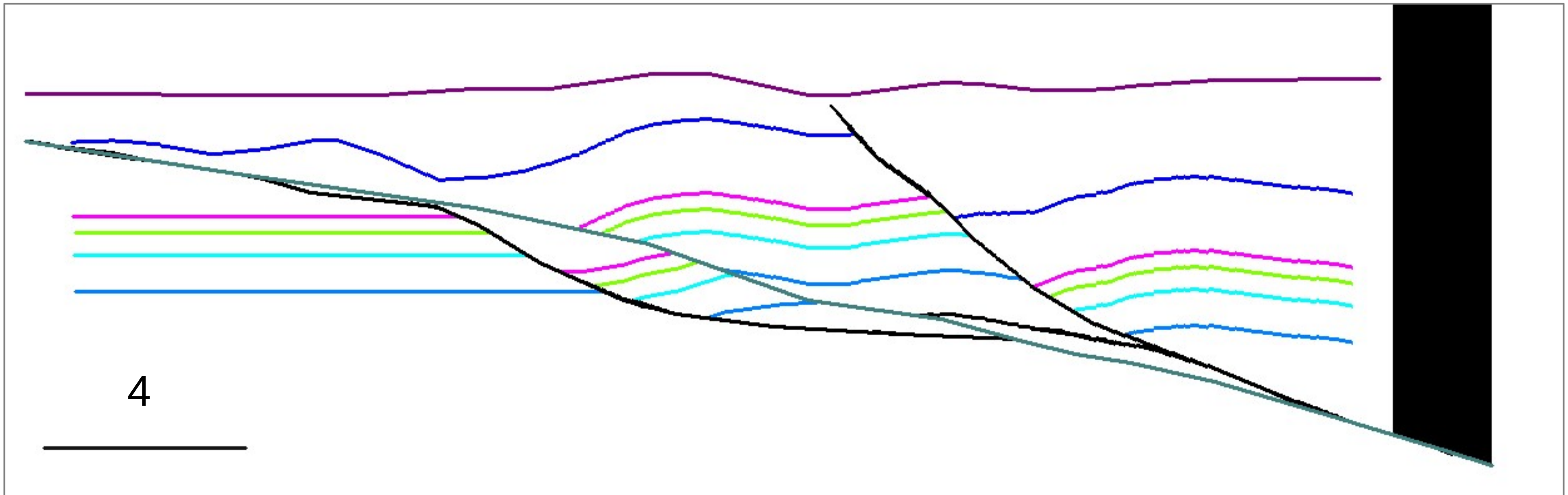
We know there's a very large shortening implicit on the ramps between the GGF and the Helmsdale Fault, so we expect to see sequence repetition at basement and lower sedimentary sequence level which isn't evident in the upper part of the profile, which is still net extensional. Therefore we experiment with the idea that the dark green is repeating, as shown.

Model for Black Isle fold. Extensional phase on the ramp, we made the left-side fault post-depositional because the Lower Devonian seems to be a uniform-thickness layer, the right fault is a growth fault, with Middle Devonian thickening, post-blue. What we want to do next is initiate a ramp collapse and see how the geometry develops.

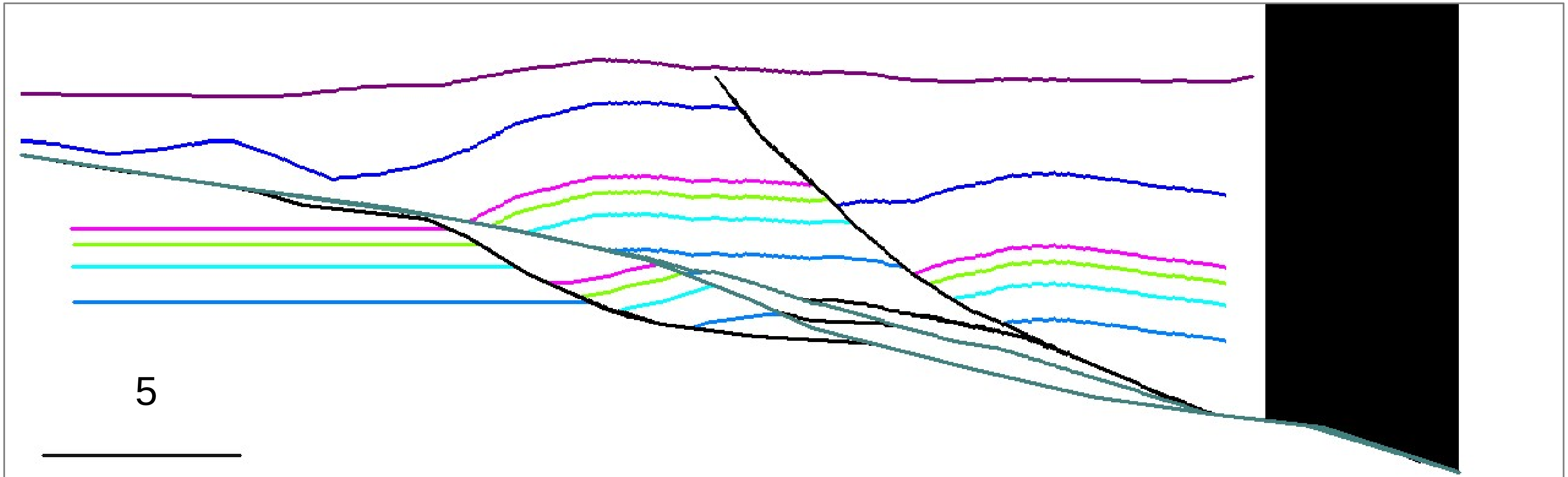




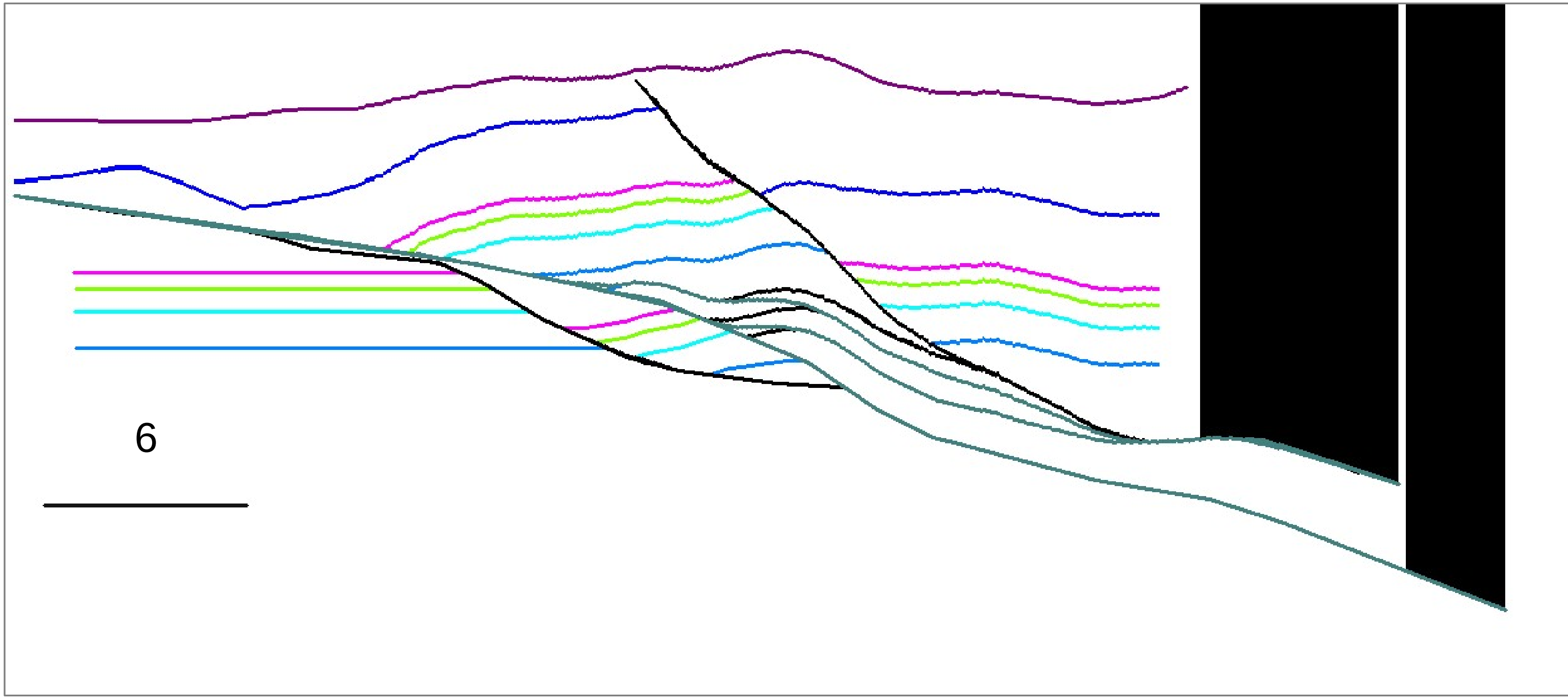




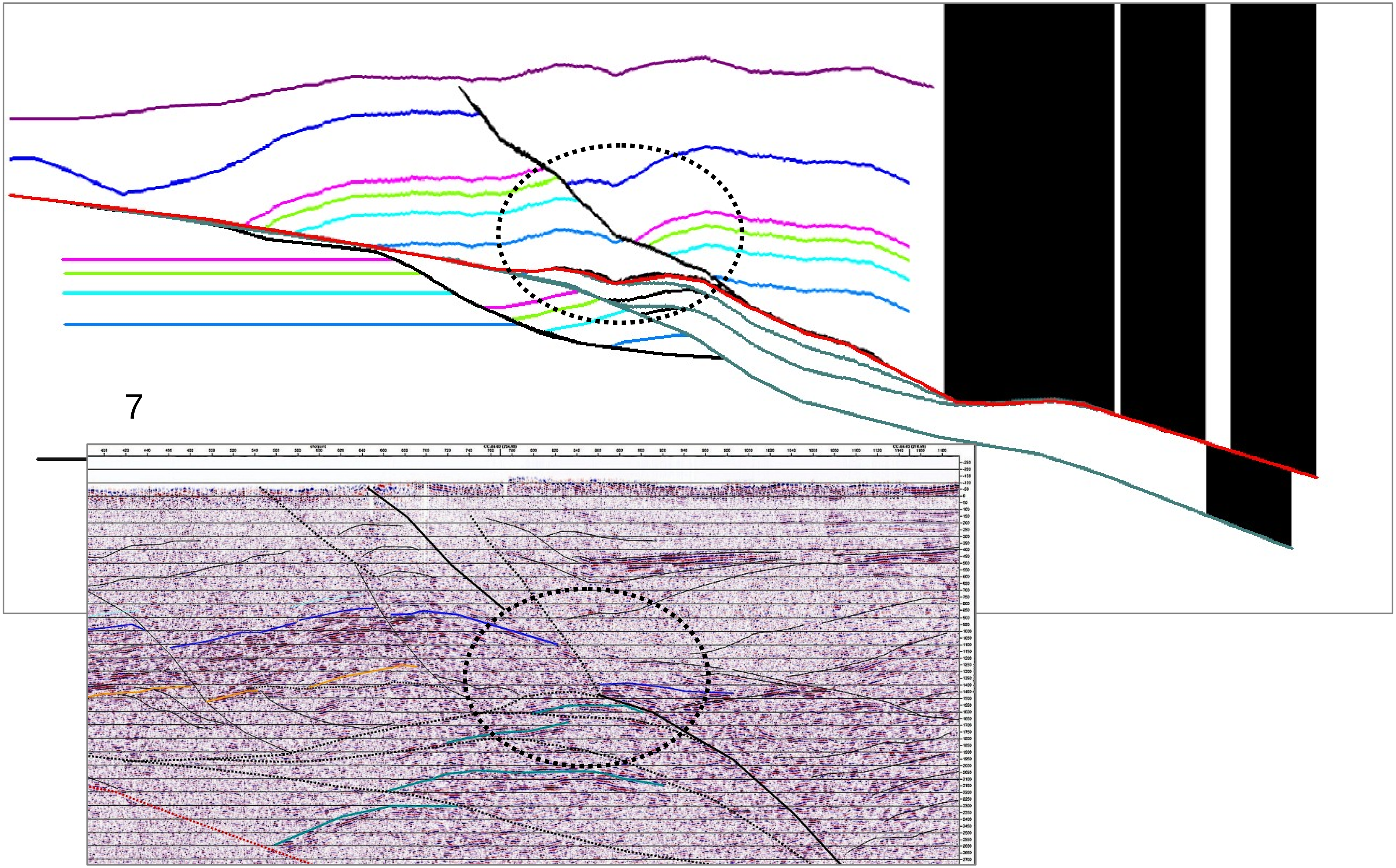
Stage 4 is a footwall collapse fault, dark green, reversing the main ramp slip sense, and we'll add more of these, from right to left.



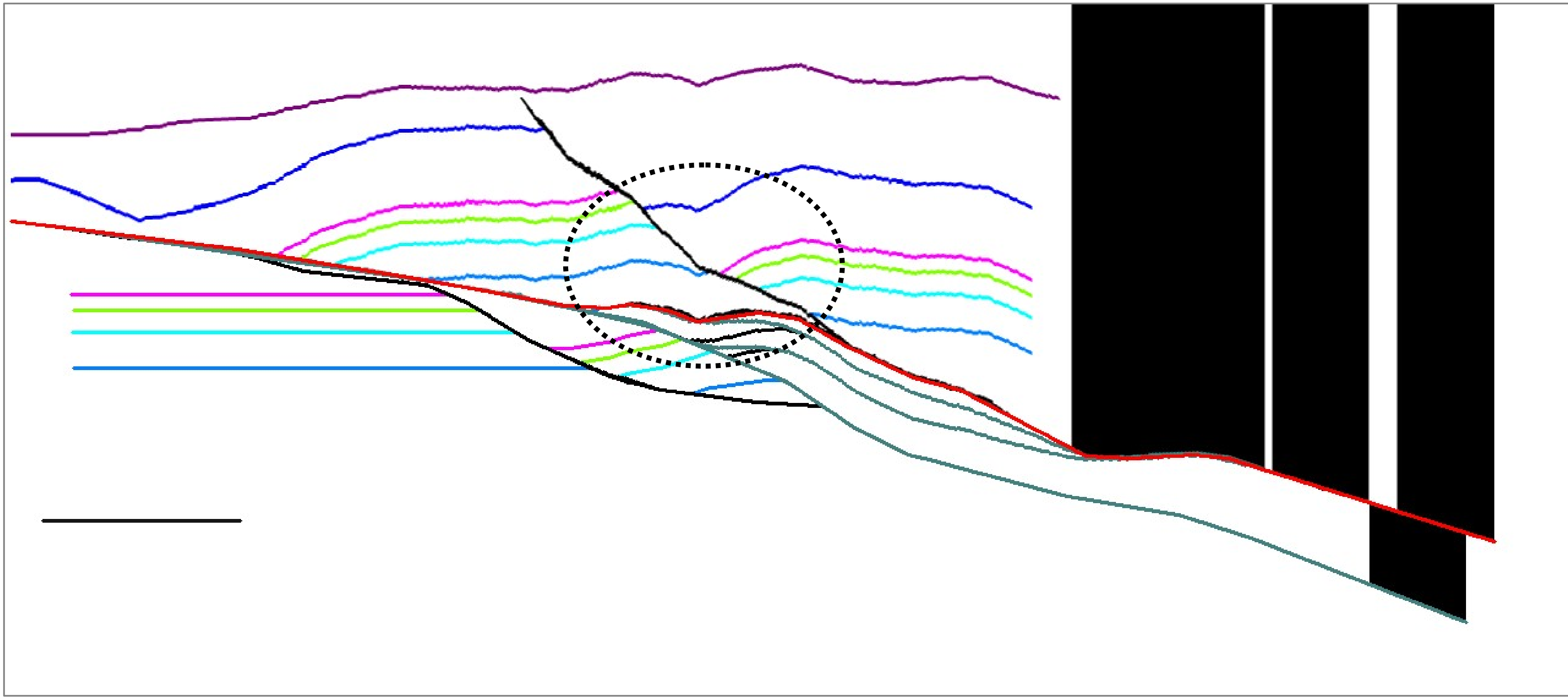
What we want to do is create an offset between the growing ramp collapse anticline and the older extensional rollover; and also understand what shape changes will develop in the main extensional fault, as the collapse fold grows under it.



Building a dome on the ramp requires a shaped fault, like the third, deepest dark green surface, and by adding it and putting in a modest compressional shortening we are now folding the extensional black ramp fault, as well as segmenting it.



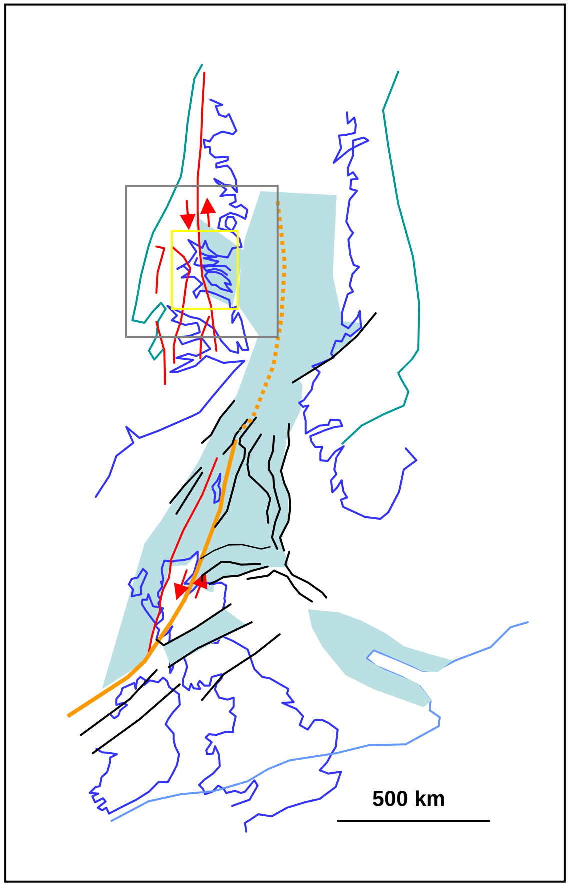
There's enough correspondence with the seismic, in this model, to make us think its more or less on the right track, and if we add some more rightward extensional displacement using the roof fault on the collapse duplex (red) we can reposition the fault blocks to give that kink we see, in the black fault.



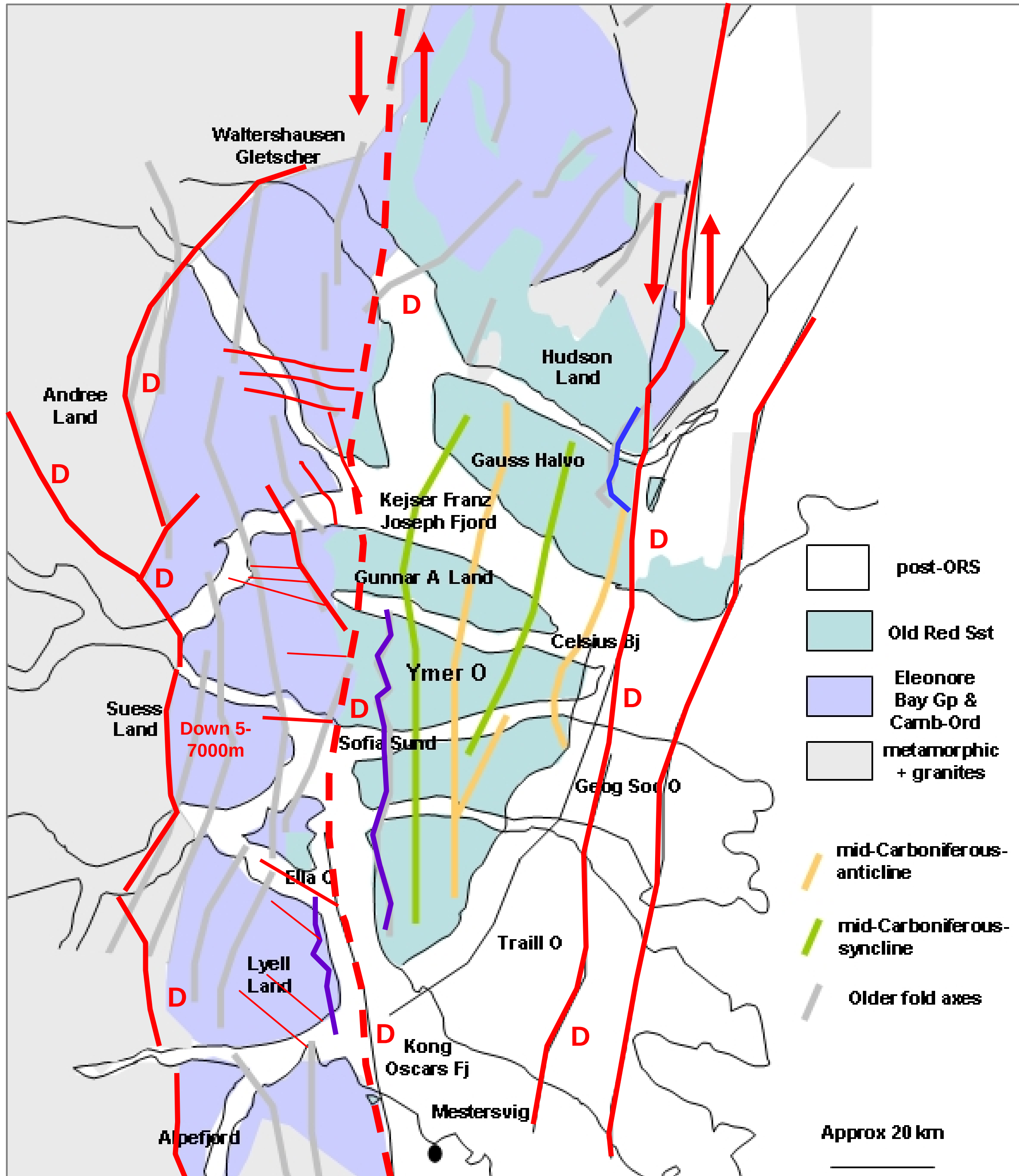
The structure model is important because it repeats on Jurassic ramp sequences farther northeast, near Wick, it tells us how to interpret undrilled plays in the Mesozoic offshore. Without concept-driven picking, interpreters are reduced to character correlation, and they miss half the important faults.

Its an interesting basin, with one large field and nothing else yet, of any importance: but good source rocks. So the problem is structure mapping.

Devonian: major extensional faults, and inversions



The Old Red Sandstone basins of East Greenland and UK show very similar structural style. Central East Greenland has excellent exposure, which this writer enjoyed in 1968-70. Let's visit East Greenland and look at some of the outcrops.



Central East Greenland Devonian-Carboniferous Basin structure

Key features, numbers refer to following slides:

- Western side Eleonore Bay Precambrian sediments were folded in Ordovician, thickened crust then collapsed and sliced by huge N-S trending wrench faults which are left-handed, down to east by 2-7000 metres, driving the growth of Old Red Basin through Devonian-Carboniferous times.

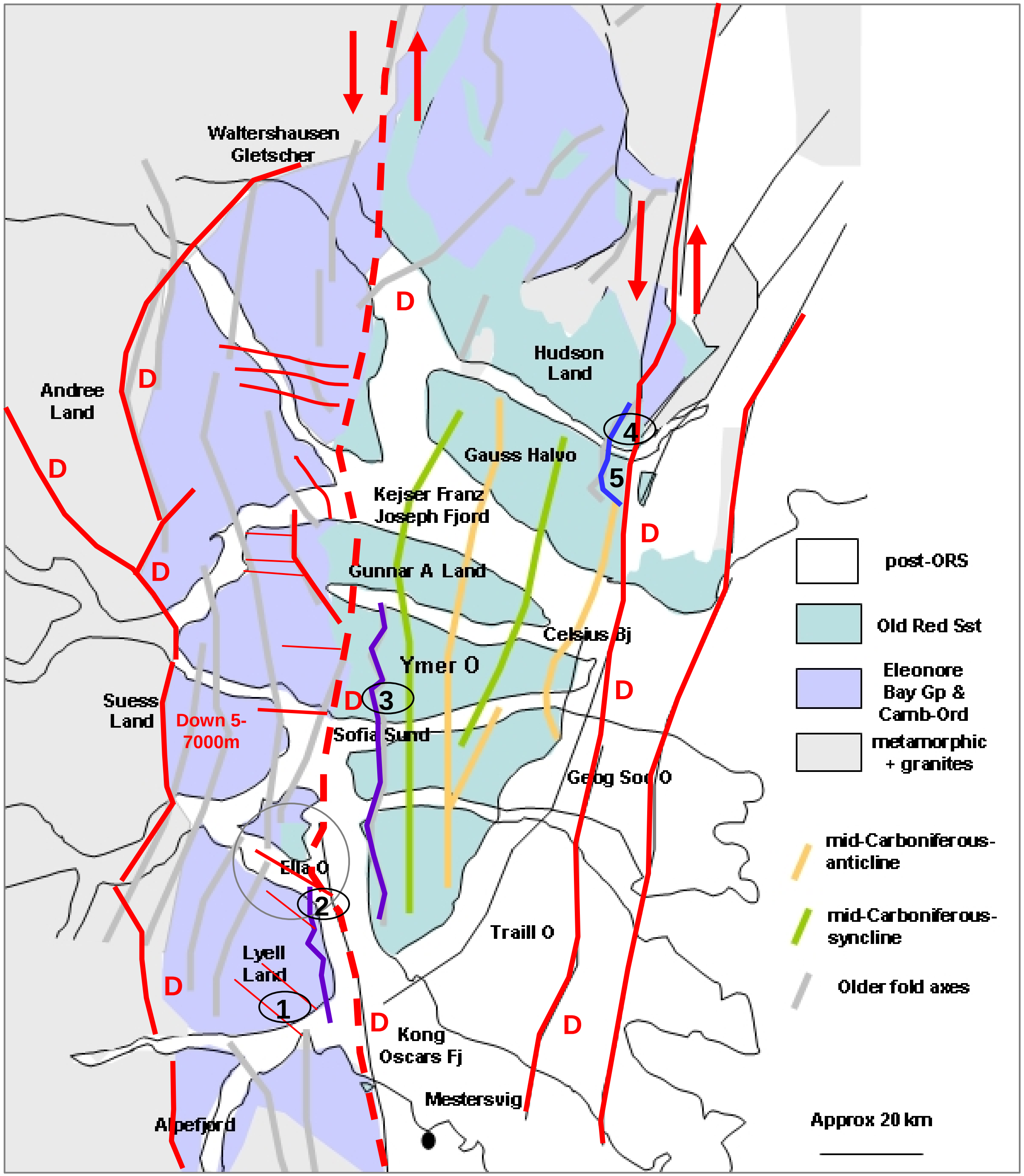
- Eleonore Bay and Lower Palaeozoics cut by extensional faults with 1-2000 metres throw, linking into these megafaults on trends W-E and NW-SE, these are probably also Devonian. Examples at Berzeleus Bjerg (1)

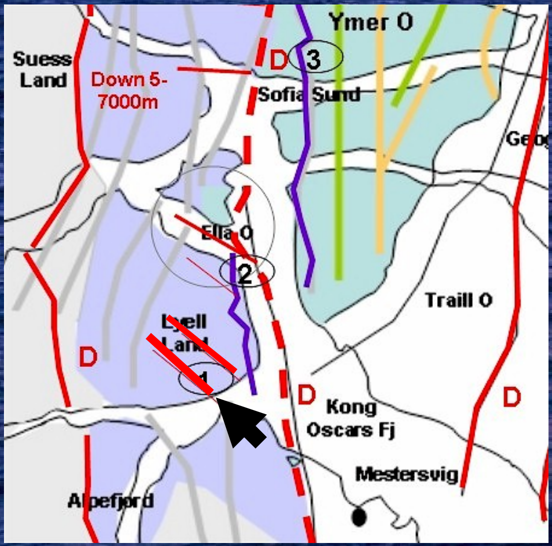
- Western margin of the Devonian is erosional, Middle Devonian shows great thicknesses of conglomerates on releasing bends at Ella O (2), Bjorn O.

- Western Old Red sequence is thrust-shortened (3).

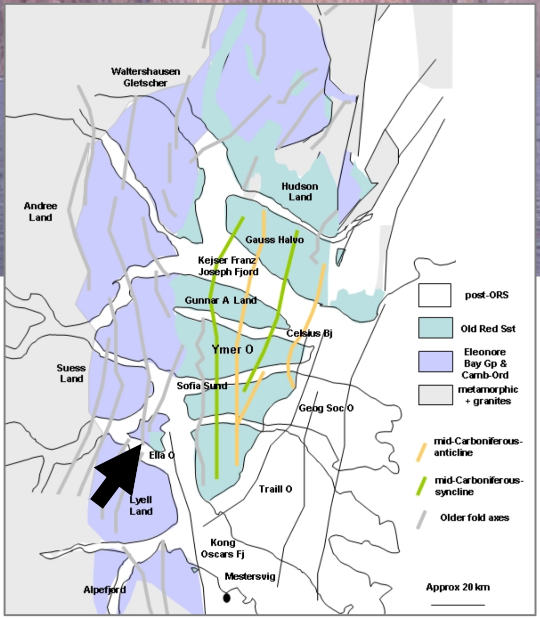
- Restraining bend thrusts e.g. well seen in Moskusoksefjord at Hogbomsbjerg (4), Sederholms Bjerg (4).

- series of unconformities in the 8 km Old Red succession, correspond to movement on the wrench faults.



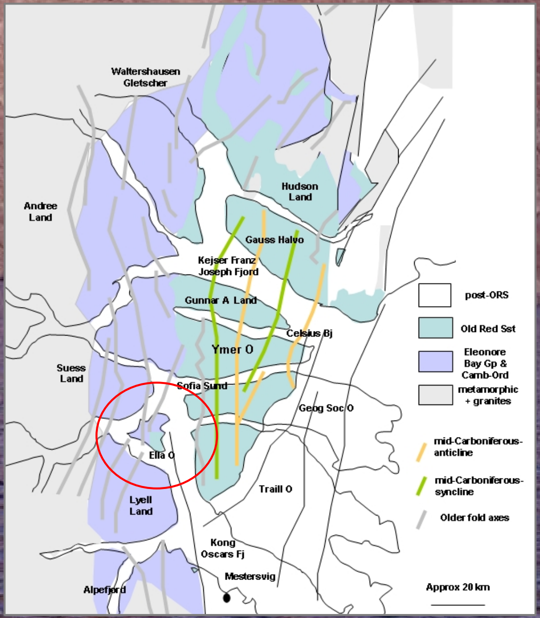


Berzelius Bjerge, Eleonore Bay Group Precambrian, cliffs about 1000 metres. These are 200-300 metre planar extensional faults antithetic to the N-S Kong Oscar Fjord wrench fault. These look like domino faults, the whole set needs to rotate by the same amount, like books on a shelf, to give sizable extension.



Devonian unconformity at Narhval Sund, Ella Ö, Central East Greenland. Approx 1000 metres of Middle Devonian sandstones and conglomerates are banked against eroded Ordovician limestones, and the top of the limestones is gullied and infilled with red beds, presumably this is a karst surface.

A very similar feature to Great Glen Old Red Sandstone depocentres, which we showed as fault-bounded: but whilst this initiated as a major fault there was evidently strong erosion before beds were deposited. Next slide shows the main cliff.

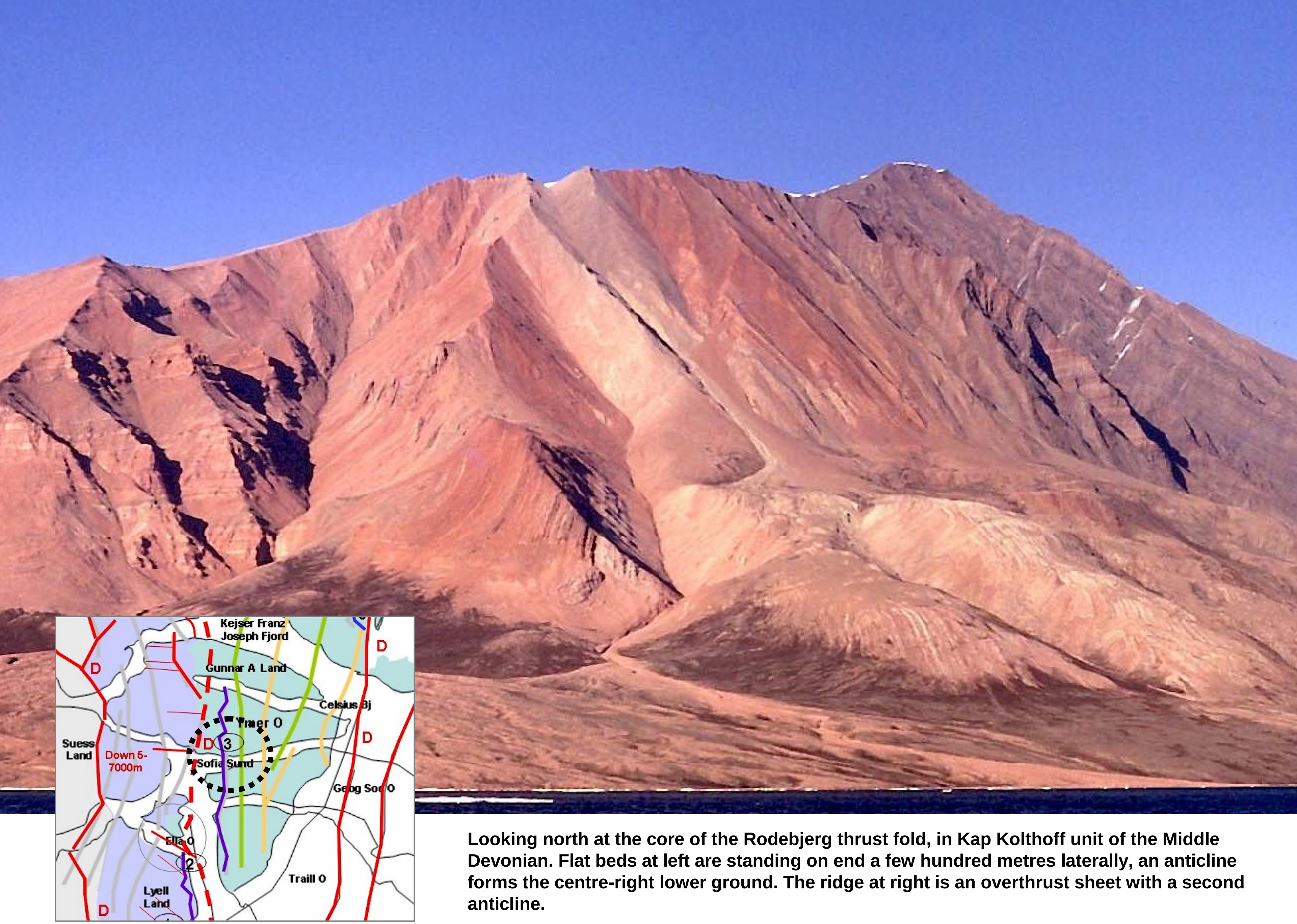


Broader view of the Narhvalsund exposure, the cliff is around 1000 metres high. It does look li fault. It must be a fault, but it was eroded before deposition started. We see the Old Red sedim simply side-stacked against it.

Can we have pull-apart on this scale without sedimentation starting immediately? Yes, there a plenty of modern cliffs in tectonically active arid areas with only small fans at present. Sinai de example. If there's no rainfall, large fans won't form.

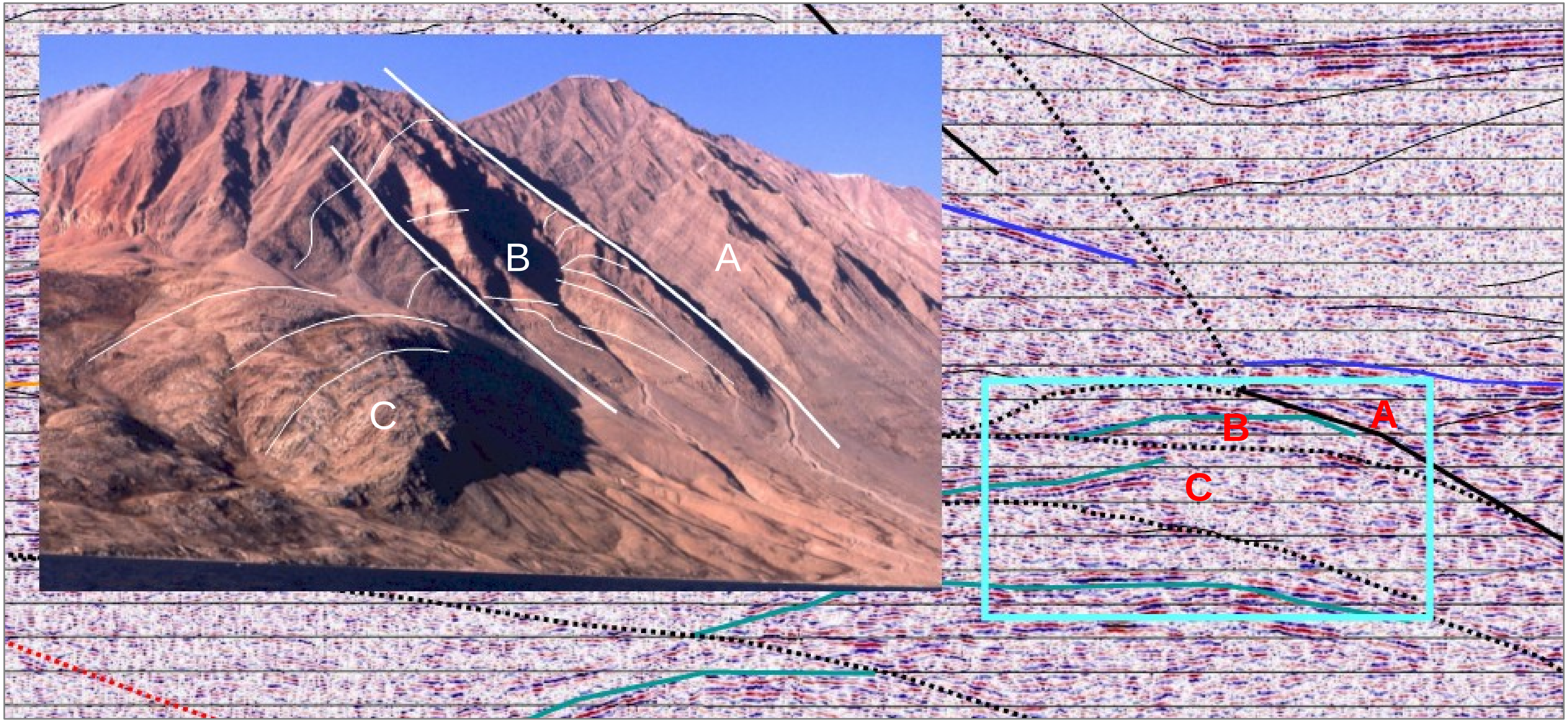
If we shot seismic over this we'd certainly conclude it was a fault.

Analogue for Ella Ö. This is Sinai Desert, very big cliffs in actively faulting area. No rivers supply sediment, which is moved around by the wind and some locations trap big side-building sequences whilst other cliffs get no sediment cover.



Looking north at the core of the Rodebjerg thrust fold, in Kap Kolthoff unit of the Middle Devonian. Flat beds at left are standing on end a few hundred metres laterally, an anticline forms the centre-right lower ground. The ridge at right is an overthrust sheet with a second anticline.

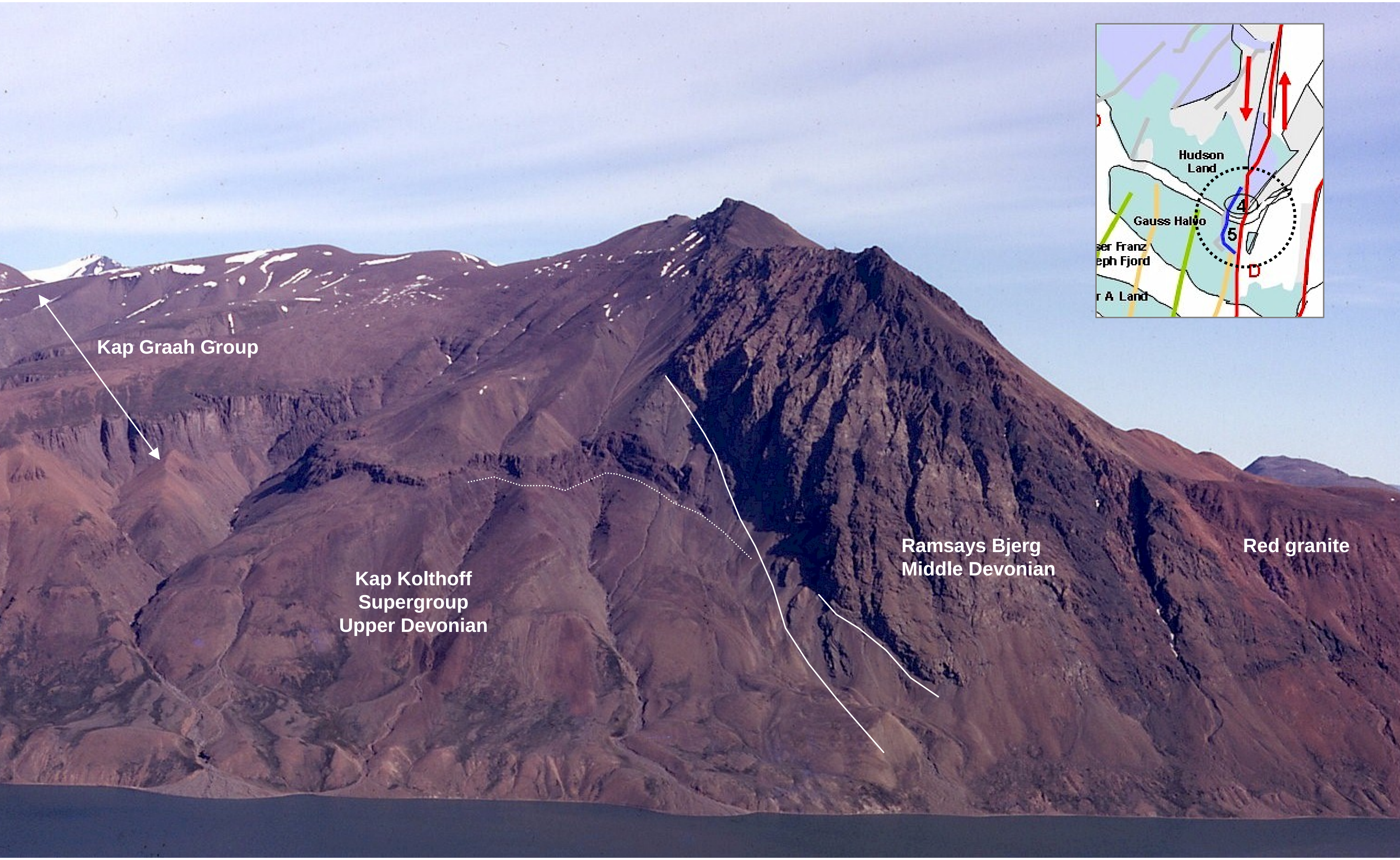
Rodebjerg from a more easterly viewpoint. Is this an inversion fold on an easterly-dipping ramp?



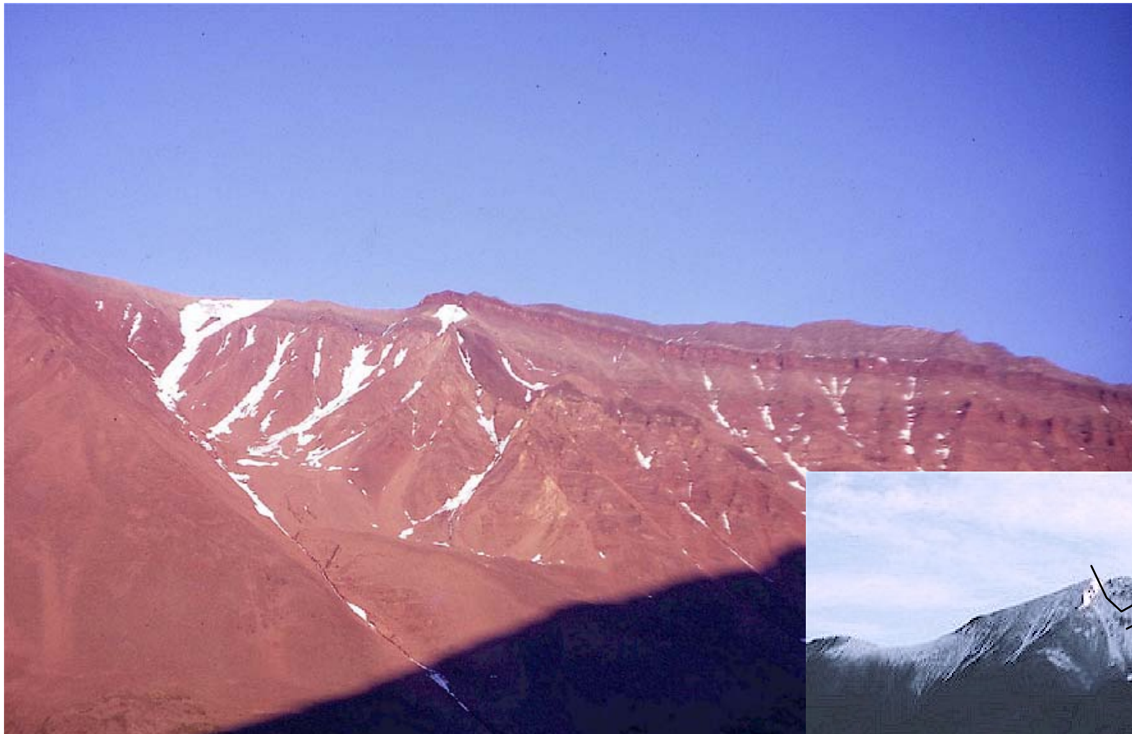
When seismic is complex and hard to interpret, its tempting to say there are problems with acquisition and processing. Consider this proposition: seismic is commonly better than we think it is?

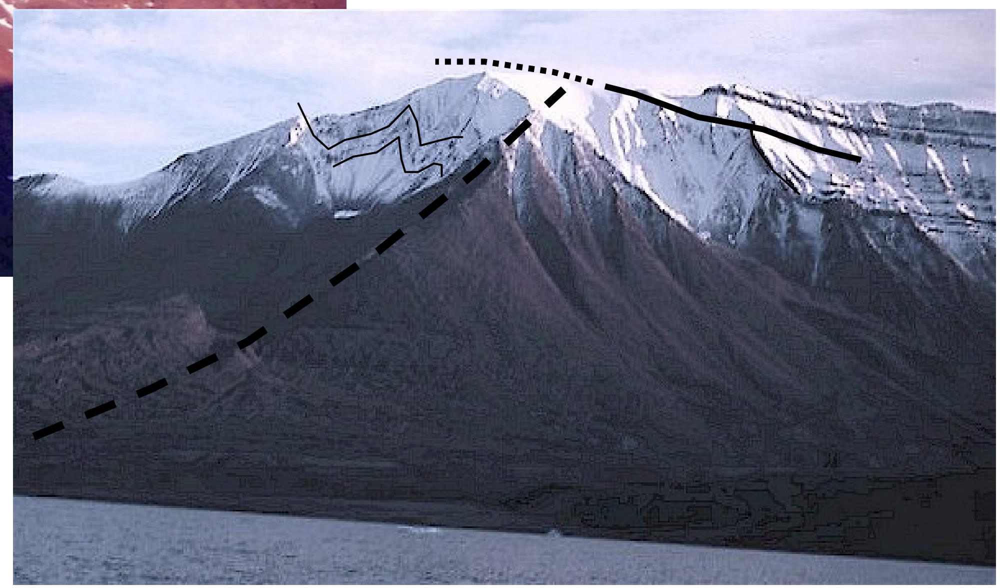
Did we see an analogue for these structures, in modelling the Black Isle ramp dome? Its certainly plausible that the Rodebjerg fault-bounded slices are put together in this way, structure complexity has arisen by repetition of a simple process.

A thought following from that analogy: is the seismic very much more informative than initial impressions might suggest? Are we over-interpreting, if we pick this seismic in detail? There will definitely be people closing their minds to plays where numerous faults are drawn on the seismic. If the plan is to farm out, should we "keep it simple" or show things as they more probably are?



Hogboms Bjerg in Moskusoksefjord, west-east profile looking north. This is a local reverse fault on a restraining bend, Middle Devonian Ramsays Bjerg beds are resting on a footwall comprising two Upper Devonian units, Kap Kolthoff below and Kap Graah Group above. These latter two are separated by an unconformity with conglomerate, corresponding to a phase of transpression in Hudsons Land, which gets jammed under the thrust surface. What would seismic resolve in all this?





Opposite side of the fjord, looking south now at the end of Sederholms Bjerg, with some new snow marking folding in the hangingwall of the inverting reverse fault. Likewise there's folding in the footwall too, obscured by scree at the fault but clear in the upturning of a basalt sill which is truncated by a latest-Devonian unconformable pale grey sandstone. This unconformity only persists laterally for a few km. In showing rapid lateral change in stratigraphy and structure that's typical of strike-slip systems, and points to the need for close-spaced seismic control in mapping prospects.