
Finding Prospects: Our Advice
Highland Geology Limited,
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Extension and inversion
Narhvalsund © Highland Geology Limited 2021

How can we recognise quality exploration opportunity, in acreage offered for licensing and farm-in?

How do we identify the blocks which will prove to be prime assets, in licence rounds and farm-in offers? Different observers will come up with different responses to that question, depending on what their own experience has been, opinions vary greatly!

Let's say you mainly develop your own plays, of which you want a variety, with varying risk levels. You do want to look at farm-in opportunities, though, because they improve your database and you might see something irresistible. Farming-in means being promoted, its expensive, nevertheless many people think its acceptable to buy into prospects because it accelerates the finding process and gives a wide spread of opportunity.

•Relatively unexplored basins with proven source rocks are certain to offer new plays: therefore, target basins like this. New plays will appear when you make comparisons with other basins, pull the incomplete strands of information together, talk to other explorationists. It takes time to do this. Look at the margins, outside the main producing trends. Look at blocks which risk-intolerant companies find reasons not to apply for.

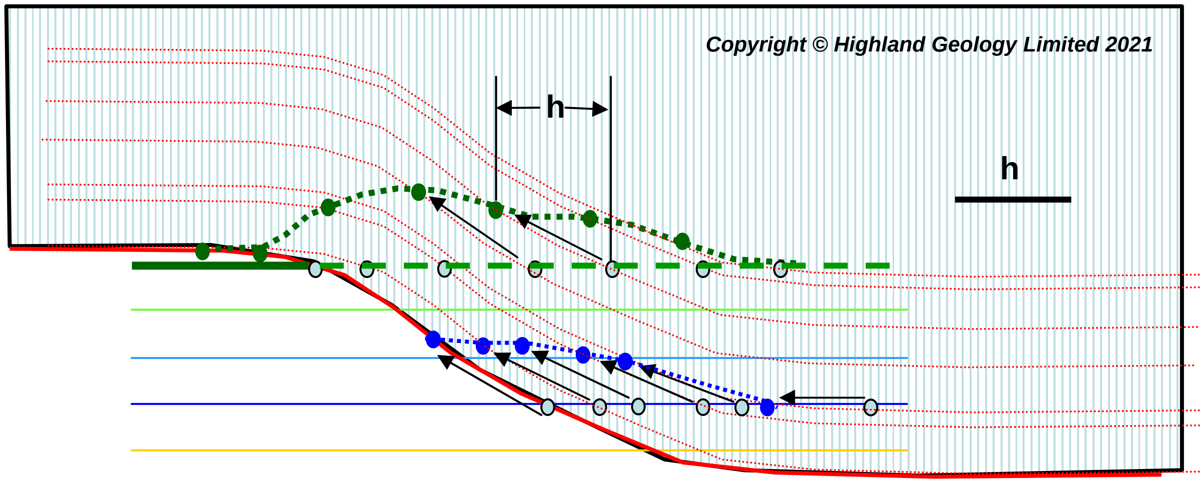
•Understand structure style by making kinematic models which show how the key structures form. <u>The structures you don't understand, are likely to become prospects when you DO understand them</u>. If you can make a close analogue for a structure by modelling it, you may reasonably argue that all of its essential features are understood and represented in your mapping.

About simple shear: area-balance

Simple shear is a reasonably good model-construction method, retaining the area of rock units as they move across fault surfaces and deform accordingly: the results are “area-balanced”. Its exceptionally useful in prospect analysis. Users can forward-model, and test given interpretations for good sense, by rejoining offsets. To do this in-house we wrote a Visual Basic program called DepthCon, which is an image processor, and its used throughout these advice notes to illustrate concepts.

(We no longer distribute it, because we don’t support it to current standards for meeting software security tests: and it doesn’t run on workstations, most IT departments don’t want stand-alone applications).

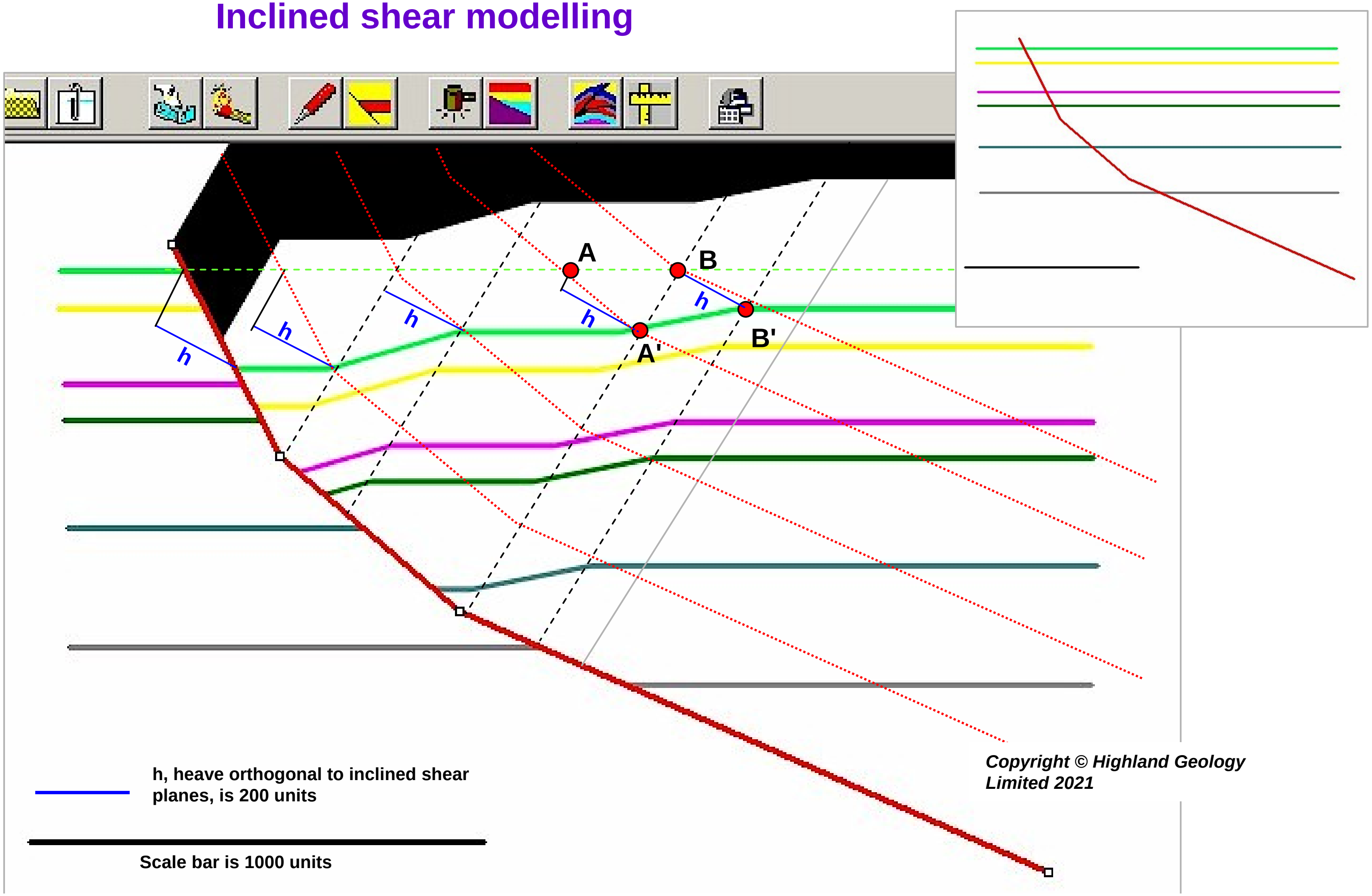
There are several commercial packages which are dedicated section balance programs, having this capability is very strongly recommended !



Suppose we want to move the hangingwall above this red fault surface, slipping the initially horizontal beds leftwards by an amount "h", using vertical shear. The construction is very simple, the same for left or right moves. Imagine an array of vertical shear planes and every particle above red fault is moved parallel to that fault surface, by an equal amount h. Here we have an inversion, leftward move, with the construction shown just for two of the beds, blue and green. The construction is constant-heave.

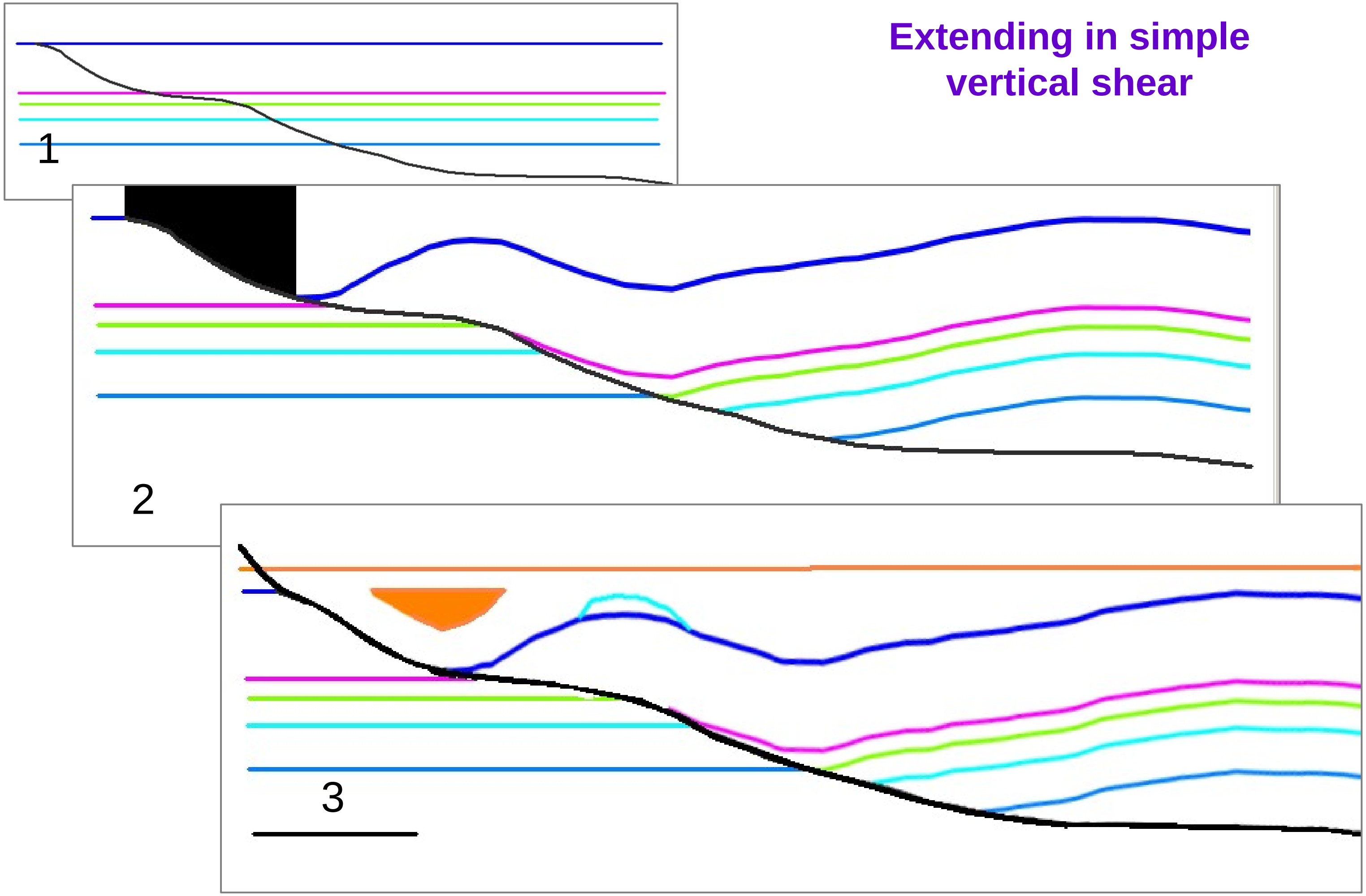
The important feature of DepthCon, is that it corrects for overlaps generated between pixels as they rotate on bends, which otherwise blur the image after a move. In its move-on-a-fault mode DepthCon shifts all pixels lying above that surface, parallel to a sketched fault, by any amount of specified horizontal heave. It does this using vertical shear planes or an inclined shear angle can be specified, antithetic or synthetic. The shape of the fault surface can be interactively altered and slips repeated, until a useful result is achieved and saved. The presumption underlying the method is that the deformation is confined to the plane of section: it is plane-strain. So its strictly intended to operate on dip sections, if the aim is restoration.

Inclined shear modelling



Here's an inclined shear model, rightward move on the red fault using inclined shear planes. It looks more complex than the vertical shear case but its the same process: each particle in the hangingwall moves parallel to the fault, the distance it moves is "h" measured orthogonally to the shear planes and now they are inclined by the amount specified. In this case its 60 degrees dipping left, the shear planes are antithetic to the red fault. Each hangingwall point has travelled rightwards by "h", here 200 units in the chosen scale, parallel to the red fault trajectory, by orthogonal amount 200. Preserving area in the plane of section requires stretching, we see the dipping segments thin accordingly. Where two points A, B move to A', B' the extensional strain is the difference between lengths AB and A'B' divided by AB. Its small in this case, so the thinning is minor.

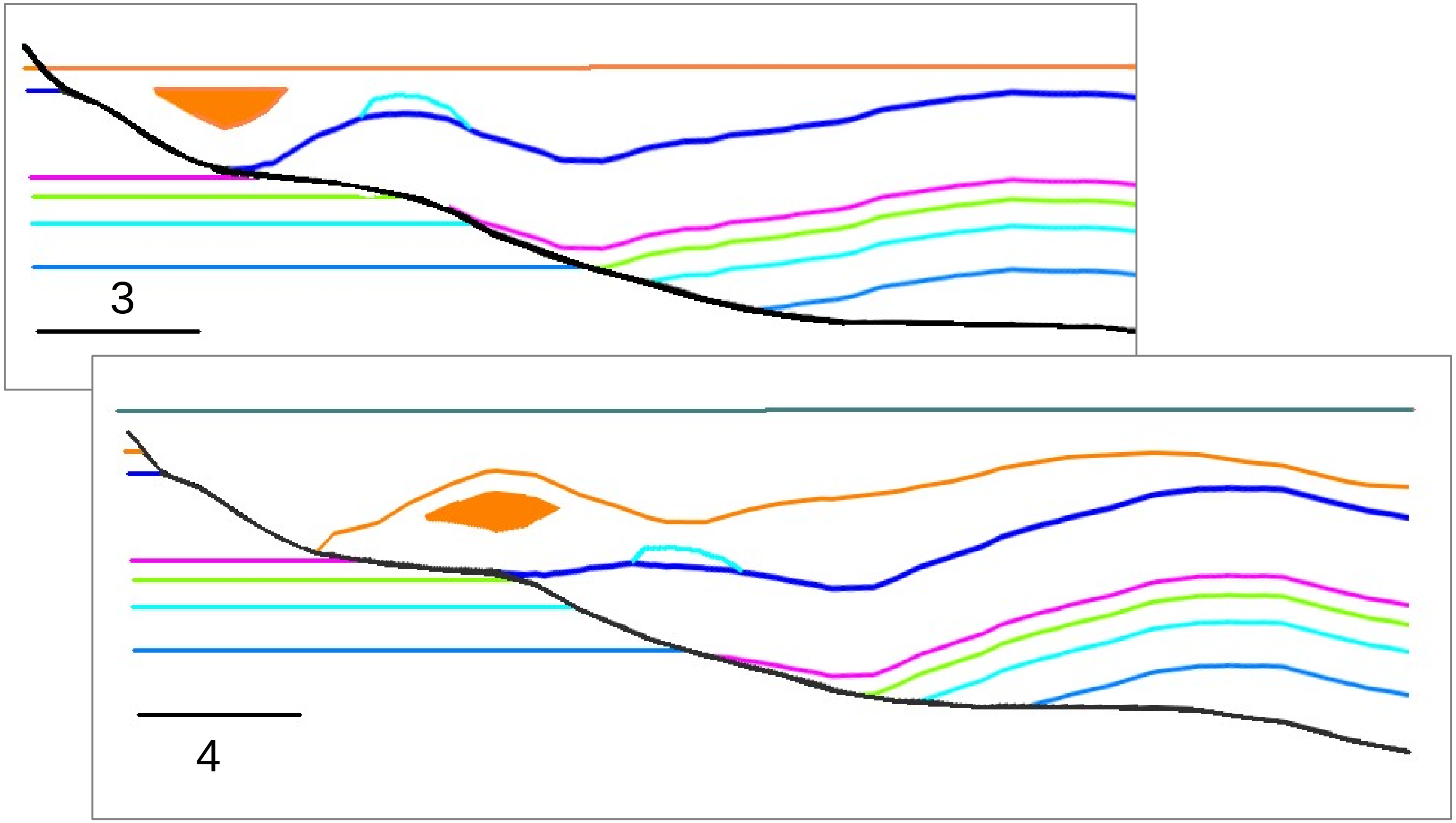
Extending in simple vertical shear



Here we take an unfaulted sequence, establish a ramp-flat-ramp fault surface (1), and in (2) move rightwards by the length of the scale bar: its a scale-independant result, in terms of geometry. A half-graben is formed over the leftward ramp, and a sag corresponds to the deeper ramp. The shape of the structures in the translated hangingwall depends entirely on the shape of the fault. The previously unfaulted sequence deforms in parallel mode, with panel areas preserved.

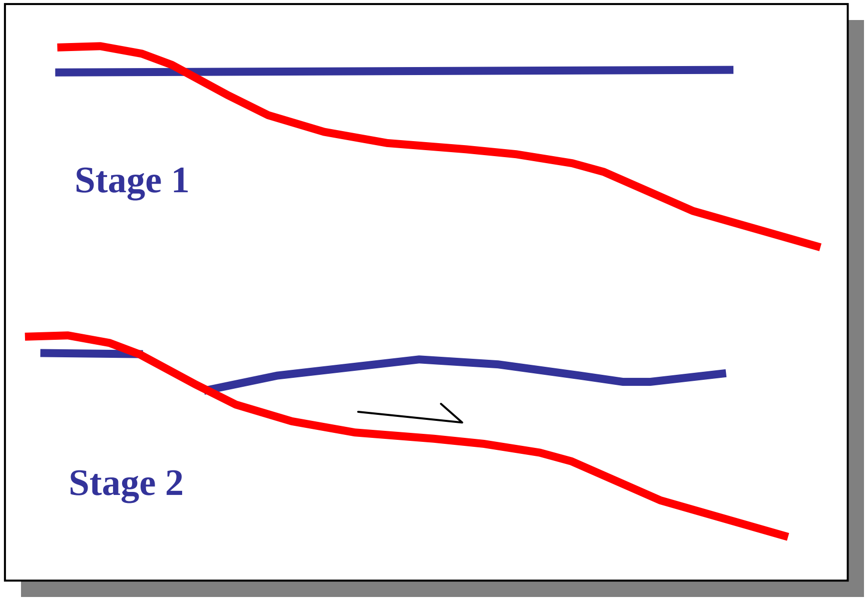
In (3), with post-blue initiation of faulting we are now making a growth fault model, and a reef and channel facies are sketched in the blue-orange growth sequence.

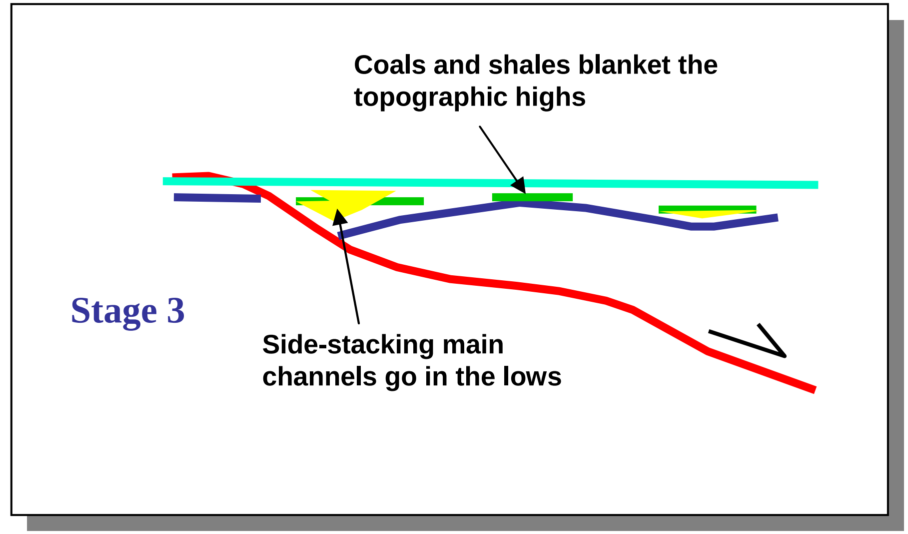
Extending in simple vertical shear (2)



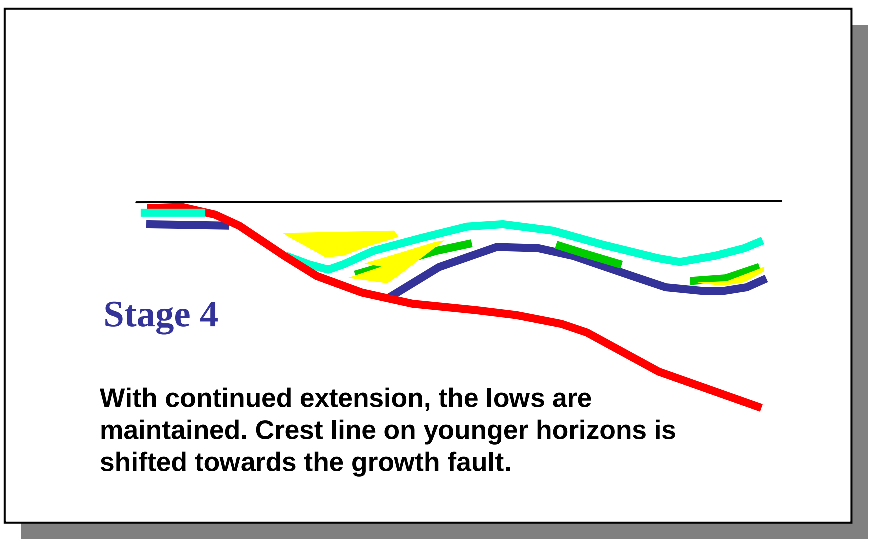
Ongoing extension from Stage 3 to Stage 4 is modifying basic, earlier geometries. The blue reef high has flattened, leaving us with a reefal buildup on a minor structure. The channel which formed in the hangingwall low at orange time is now translated to a structural high. Orange-blue sequence thins now exist downflank from the leftward orange high, over the reef, and on the right side of the major hangingwall anticline. If we were to extend again on the growth fault system we could get the reef to have no apparent relationship to positive structure.

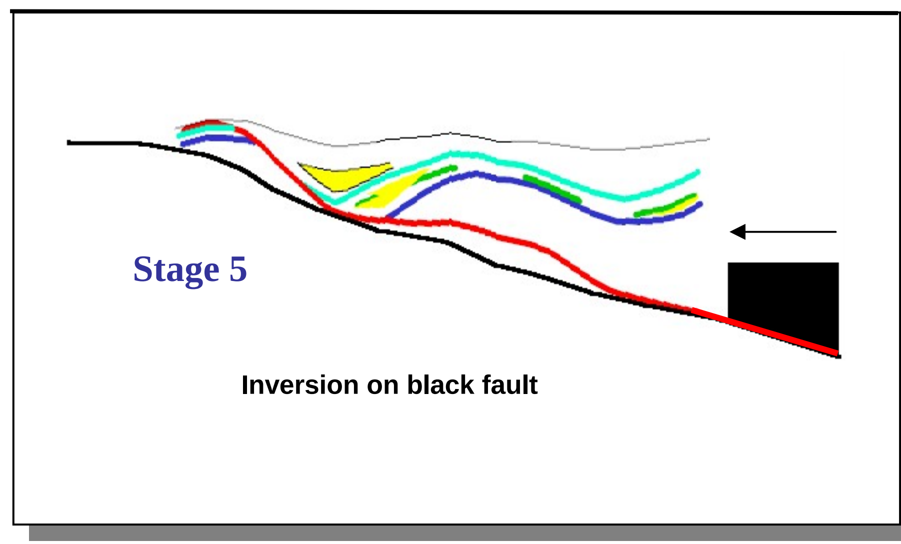
Extension and inversion during sedimentation controls bed shapes





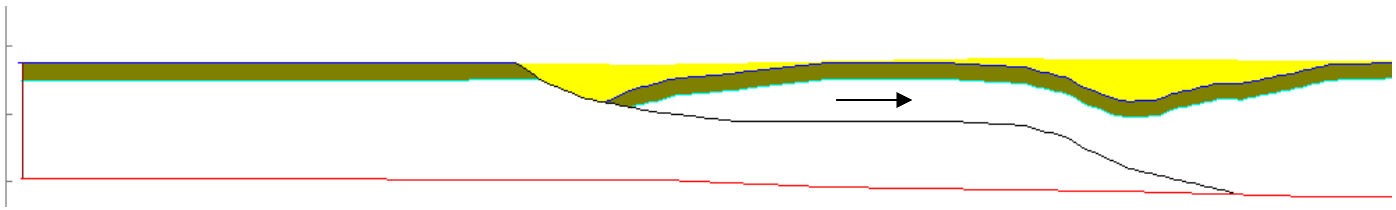
Extension creates local half-graben depocentre, and a low on blue corresponding to the deeper ramp

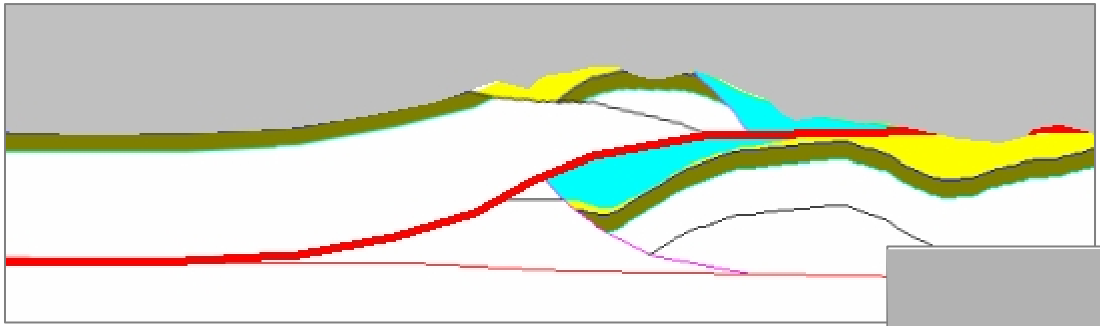


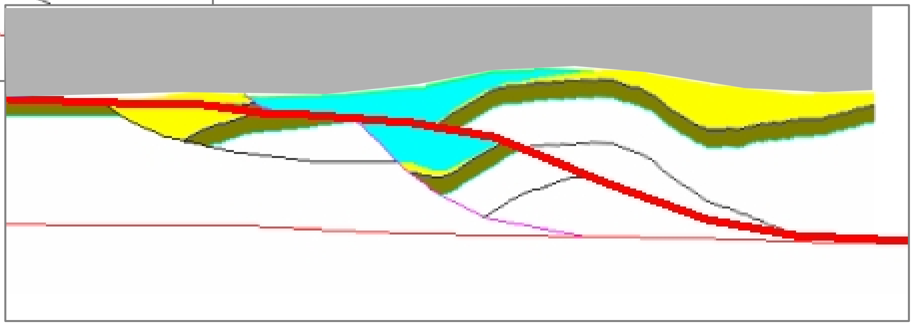


Simple shear modelling is not making any presumption of rock properties, its just a geometrical way to think about results of fault moves.

Models to assist interpretation of inversion geometries







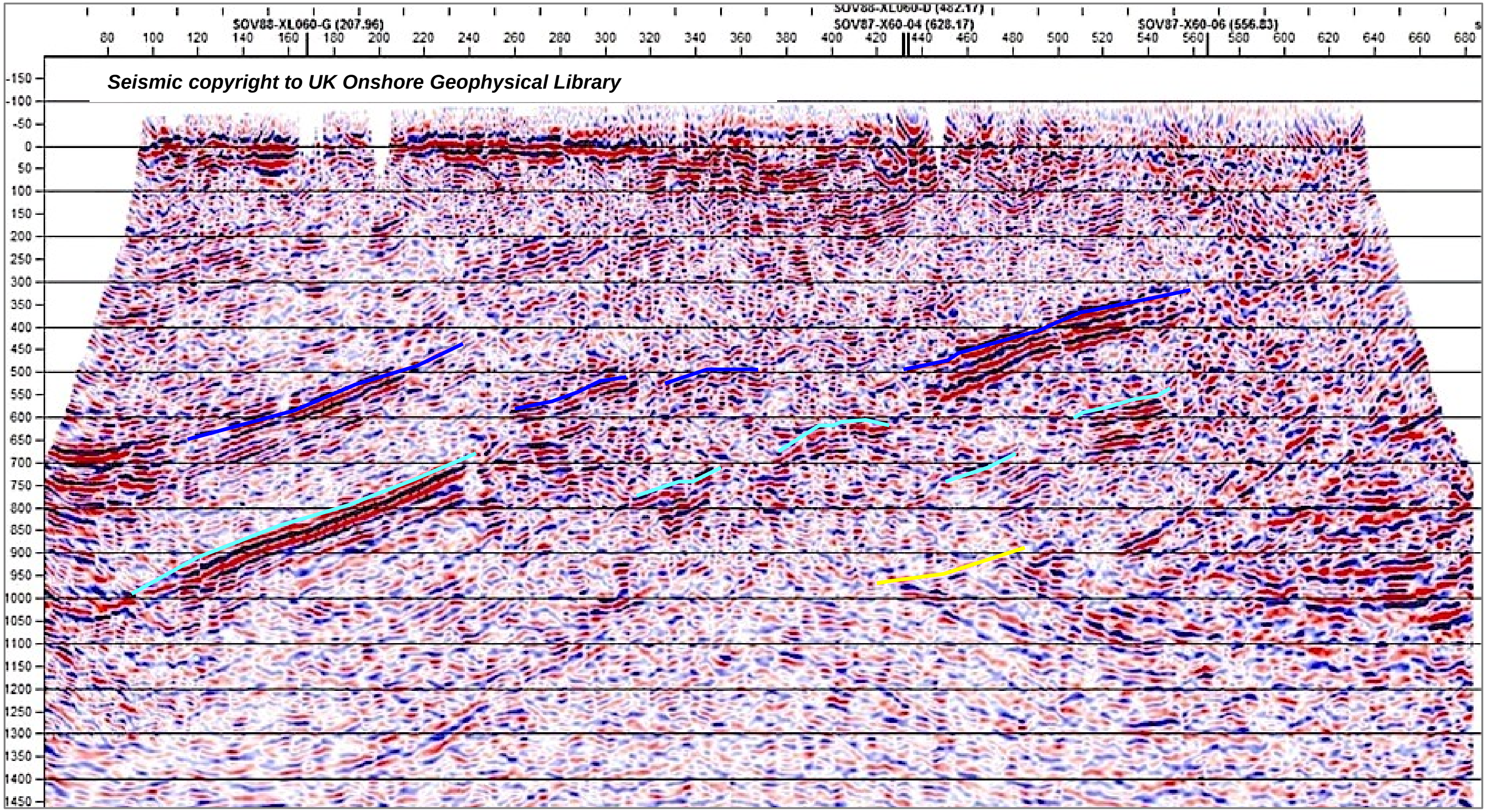
If the seismic isn't of good quality you can focus on the few lines which do provide clues and model structure development: and when you have a match, the less-clear lines become more valuable. Here, growth faults produce local basins which fill with sediment as the faults continue to move. Several generations of extensional faults are present. Two possible subsequent shortening modes are modelled, to see whether matches are possible with the data. If something plausible is found, it helps in picking the geometries where data are poor or sparse.

Source of the seismic in these notes

Now we'll start using seismic, and nearly all of the seismic sections shown here are reproduced with kind permission of UK Onshore Geophysical Library, which is the repository of released seismic for the onshore basins of UK. Its run by Lynx Information Systems, and is the primary source of data for UK licence rounds.

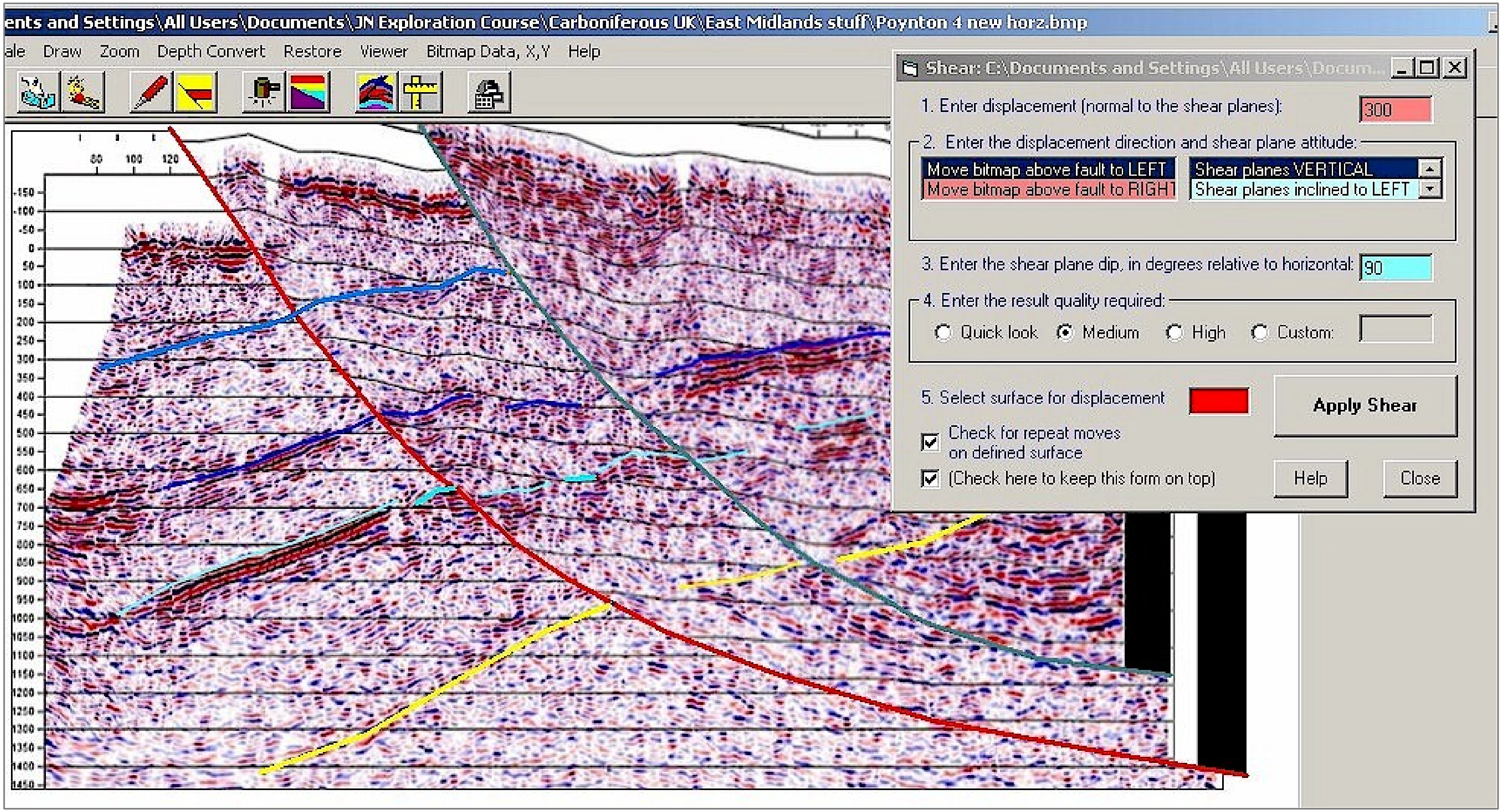
The seismic is copyright protected, it can be viewed freely on the excellent Lynx site which uses interactive line location maps.

Restoration of seismic images



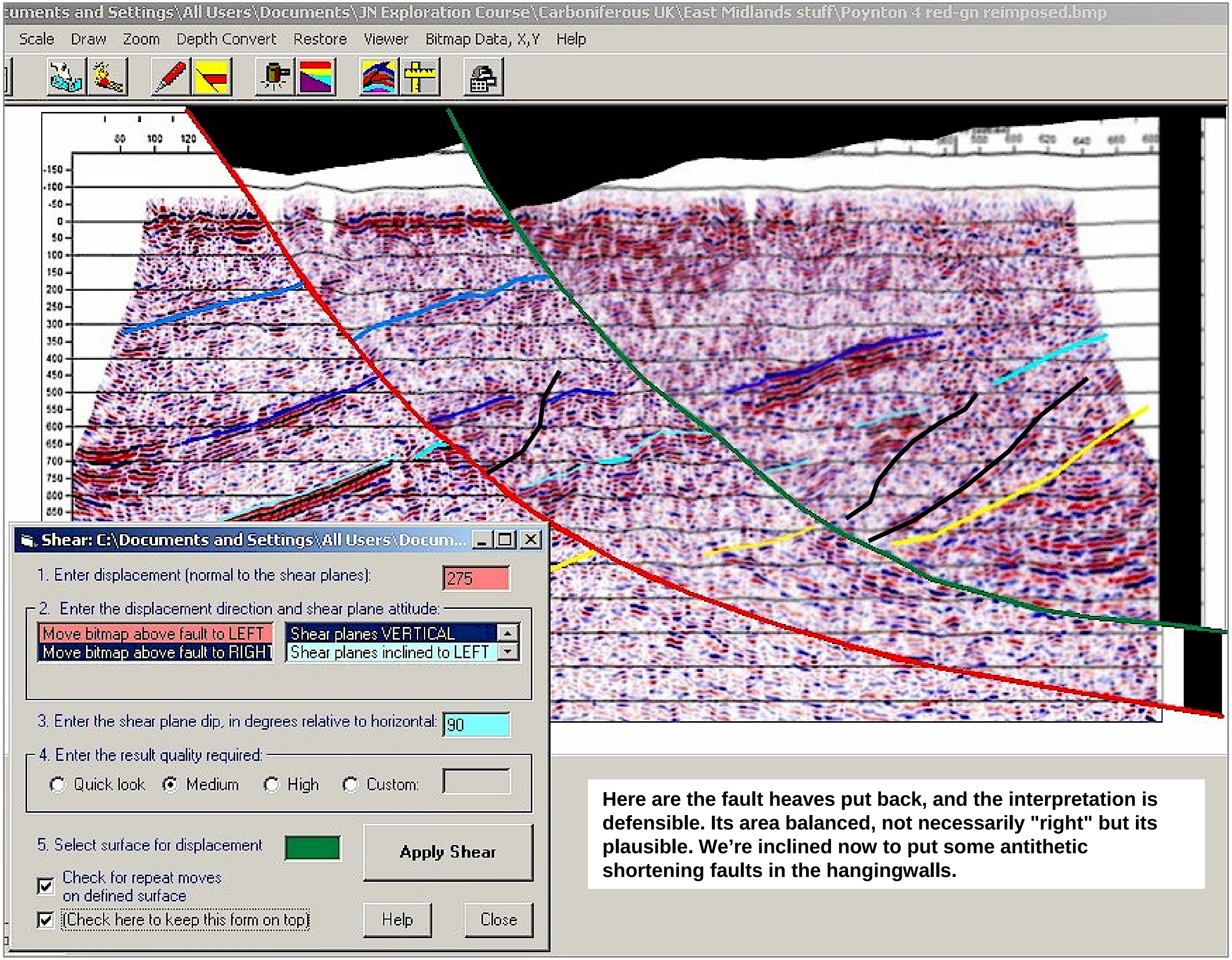
Here's a seismic line from Cheshire basin (Manchester Airport, actually). Dark blue is the Bunter Pebble Beds event, pale blue is the Manchester Marls, there's an unconformity (yellow) occasionally imaged which is base of Permian Collyhurst Sandstone deposited across tilted Westphalian. Its not easy to pick the locally stronger events consistently across the rightward (east) dipping faults, we can suspect some facies changes too, are these correlations correct? We'll draw some faults and try rejoins.

Restoration of seismic images (2)



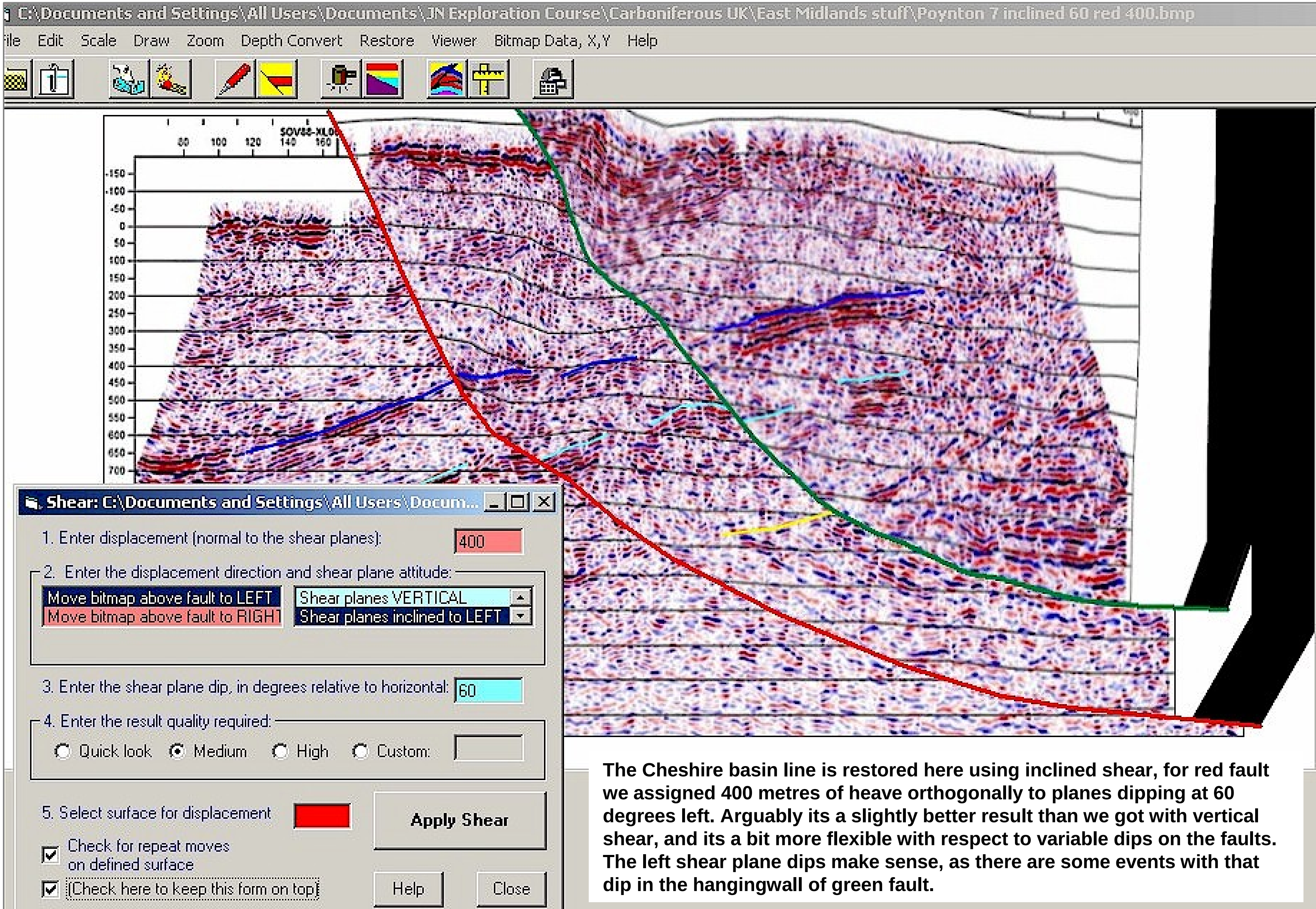
These are two vertical shear restorations using the red and grey-green faults, 275 metres and 300 metres respectively for the heaves, and the restorations look reasonable: so we can say yes, they seem OK and we can project the probable unconformity in yellow, and another marker is added above dark blue. We could now reimpose the fault heaves.

Restoration of seismic images (3)

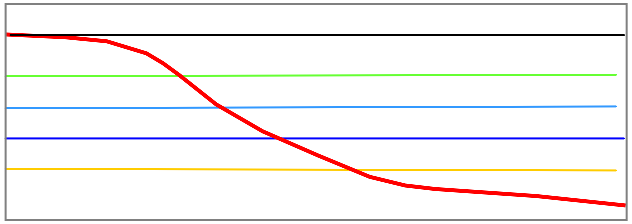


Here are the fault heaves put back, and the interpretation is defensible. Its area balanced, not necessarily "right" but its plausible. We're inclined now to put some antithetic shortening faults in the hangingwalls.

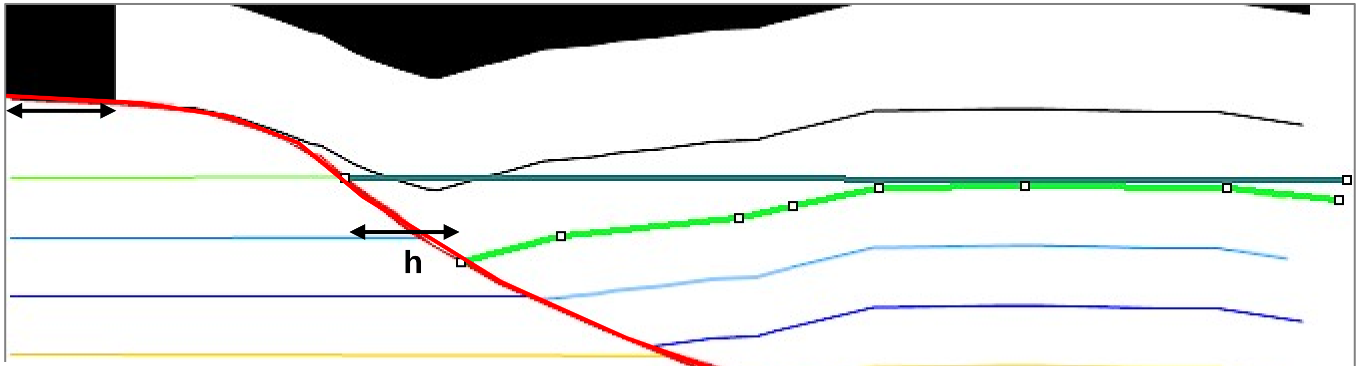
Restoration of seismic images using inclined shear



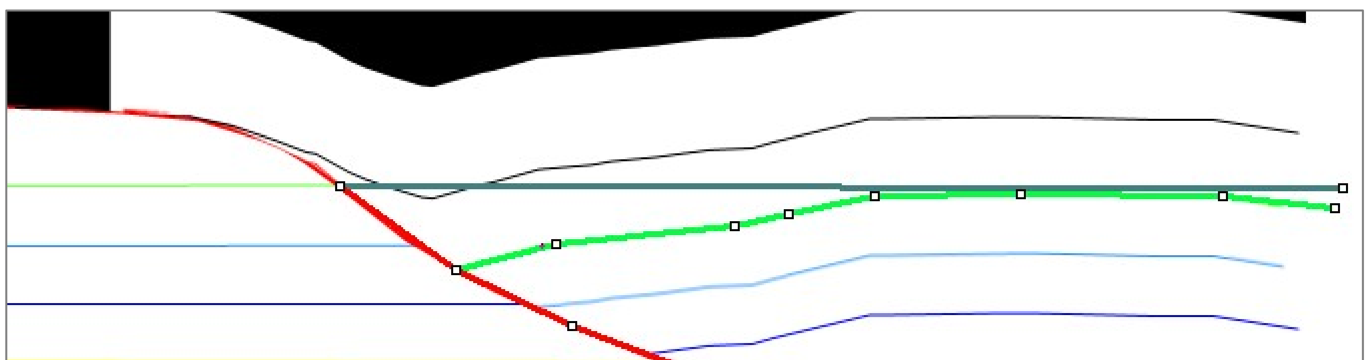
The Cheshire basin line is restored here using inclined shear, for red fault we assigned 400 metres of heave orthogonally to planes dipping at 60 degrees left. Arguably its a slightly better result than we got with vertical shear, and its a bit more flexible with respect to variable dips on the faults. The left shear plane dips make sense, as there are some events with that dip in the hangingwall of green fault.



Fault shape construction, using rollover and regional (1)

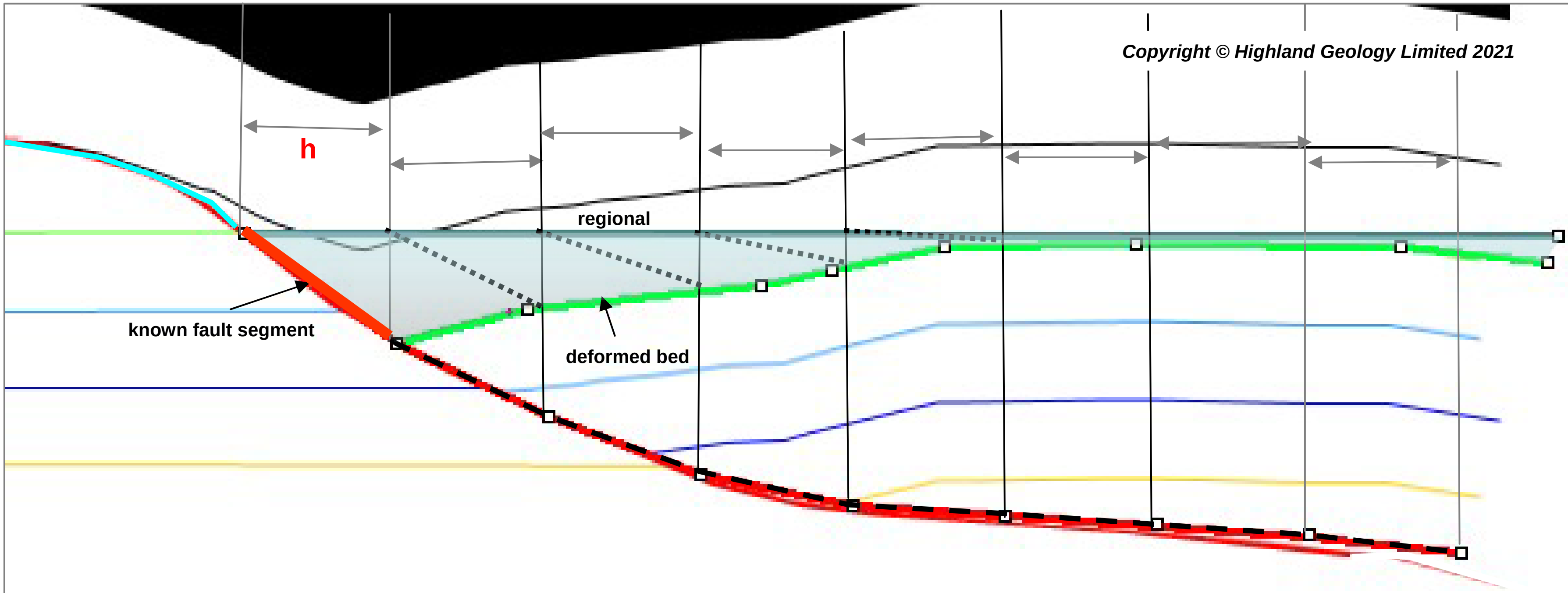


We've moved on the red fault, rightwards by 7 percent of section length, its straightforward to back-calculate the shape of the fault if we select one of the beds, like green, and assume its pre-faulting position (regional) which is drawn in dark green. We know the heave, "h".



Assuming vertical shear our software reproduces the fault used. Given just the coordinates of the points along regional and deformed bed and their intersection with the fault, it knows the heave and draws the computed fault. The construction is shown in the next slide.

Fault shape construction, using rollover and regional (2)

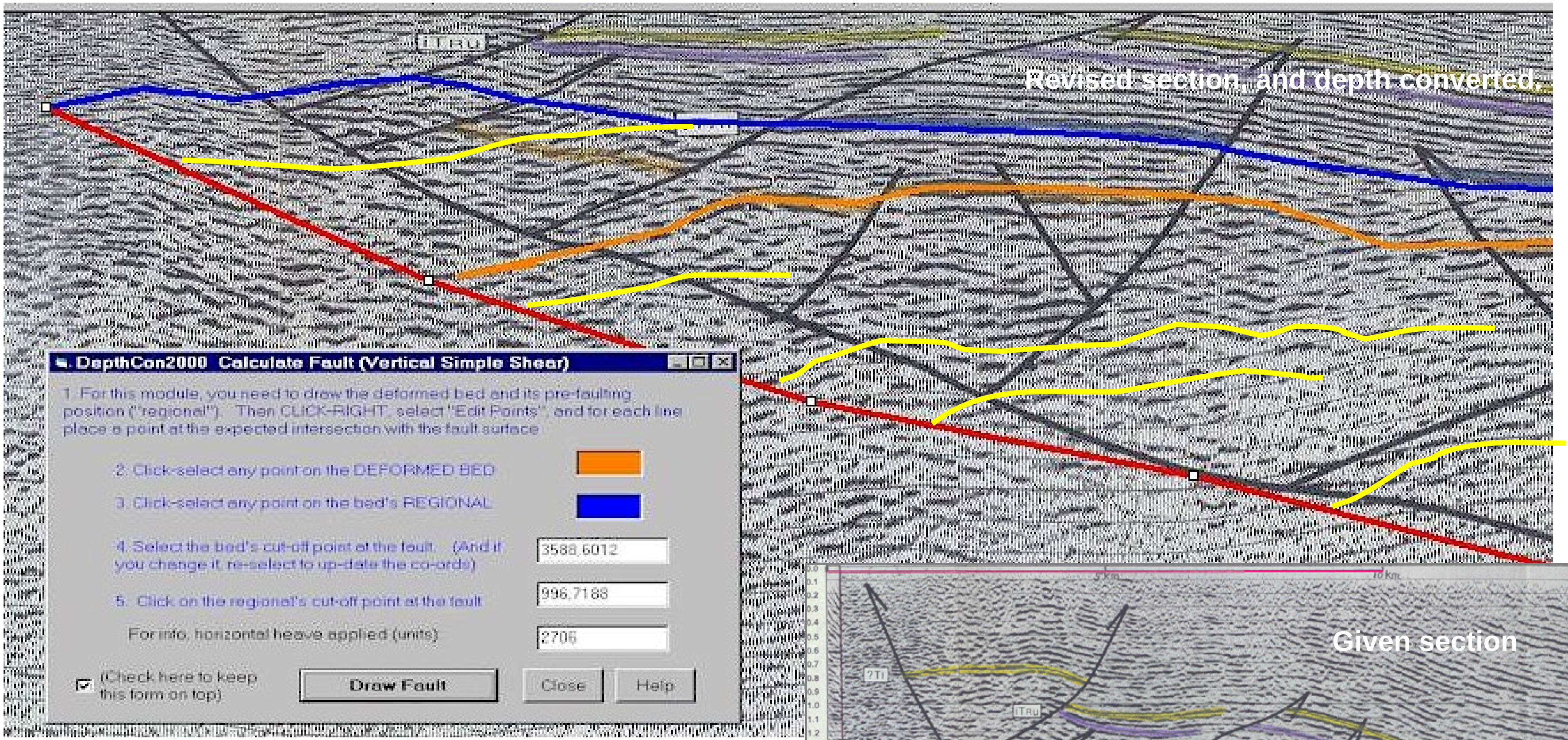


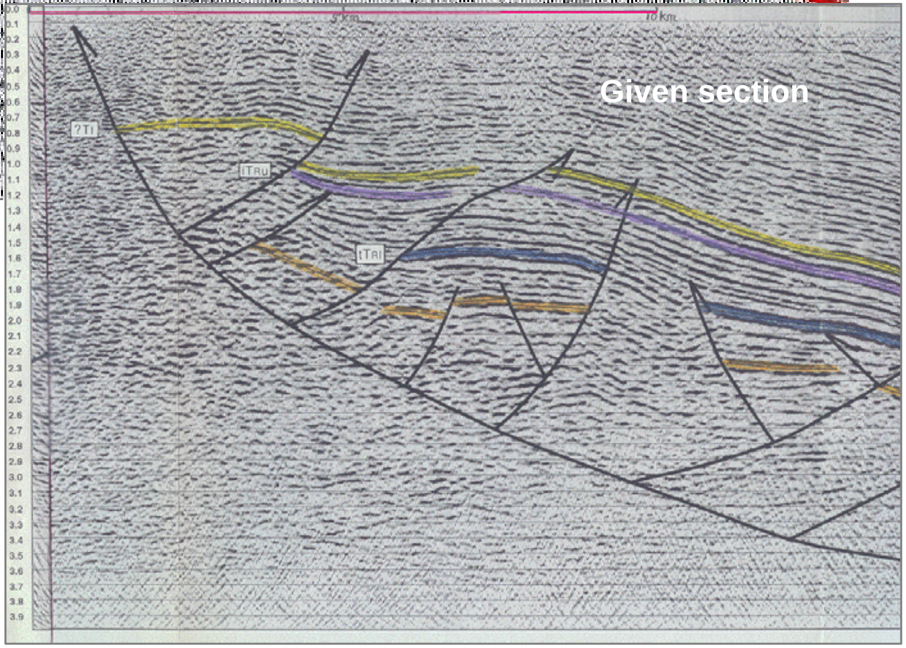
Draw one of the deformed beds, in this case green, in the hangingwall, and sketch its pre-faulting position. If looking at a growth fault, this is easy, what you want is any pair of beds in the hanging wall sequence: the younger one is the regional to the other bed, it was at the sediment-water interface on deposition. If you haven't got a growth fault, you can project a line off the footwall cut-off of the deformed bed.

Scan along the regional by an amount h equal to the heave, then drop a perpendicular to the deformed bed. This gives the dotted line, which is a segment of "h" length, parallel to the fault which we want to calculate. Project that segment from the end of the known piece of fault, and repeat the exercise for the next segment, again looking along the regional by the amount of heave. Do this until reaching the end of either of the given two lines.

The procedure draws a straight line between each calculated point, which means that if the heave is very large, any local shape on the fault between successive points is not recognised: but for most purposes the result is good enough.

Fault construction





Even this really simple approach may add new perspective to given interpretations. Here's some 1980s interpreted seismic from one of the old oilfields in onshore Cuyo basin in western Argentina, by permission of Count Geophysics Ltd to whom it is copyright. (The upper panel was depth-converted in DepthCon, the inset is the TWT version).

The interpreter drew the black fault. Bits of dip data consistent with a growth fault model can be seen below his pick. His orange horizon on the given time section looks distinctly implausible. The red fault calculated using modified orange and dark blue marker seems rather better and suggests the hangingwall reservoirs are more extensive than the given black fault would imply.

Three main types of "normal" faults

- **basement penetrative**, essentially uniformly-dipping surfaces or slightly arcuate and therefore mapping as gently arcuate planes. Dips are generally about 60-70 degrees.

- **listric**, meaning arcuate in profile and plan, detaching in lower-strength units. Listric faults map with arcuate traces. If movement continues during sedimentation we have growth faults, with hangingwall units thickening into the fault.

- **gravity slides**, synsedimentary and showing compressional toe structures.

Note that normal faulting doesn't necessarily show we have regional extension: they might be a consequence of compaction, or salt tectonics.

Fault linkage and variation in slip

An important point: don't force fault picks between mapped horizons, linking faults to make simple surfaces. Look at the seismic carefully, if there seem to be offsets between fault cuts on successively deeper markers they may well be real.

Kattenhorn and Pollard (2001) in Bull AAPG, 85 (7), 1183-1210, give this model for Wytch Farm Field in Wessex, based on 3D seismic. They consider the faults in the Triassic sequence as initiating on basement fractures, forming during the Triassic as parallel, non-connecting surfaces terminating upwards in the Upper Triassic Mercia Mudstone. Some early Jurassic faults nucleated in mid Jurassic sequence and terminated downwards in these Triassic claystones.

In the mid-late Jurassic renewed extension creates new faults in the Jurassic sequence, and only at this time do the older, deeper faults link, by a combination of new vertical and lateral fault extensions. The end effect is to connect the Triassic faults more effectively than the Jurassic faulting network. Where faults join, there are abrupt changes in the slip pattern.

To force a simple link between successive faulted horizons, risks error!

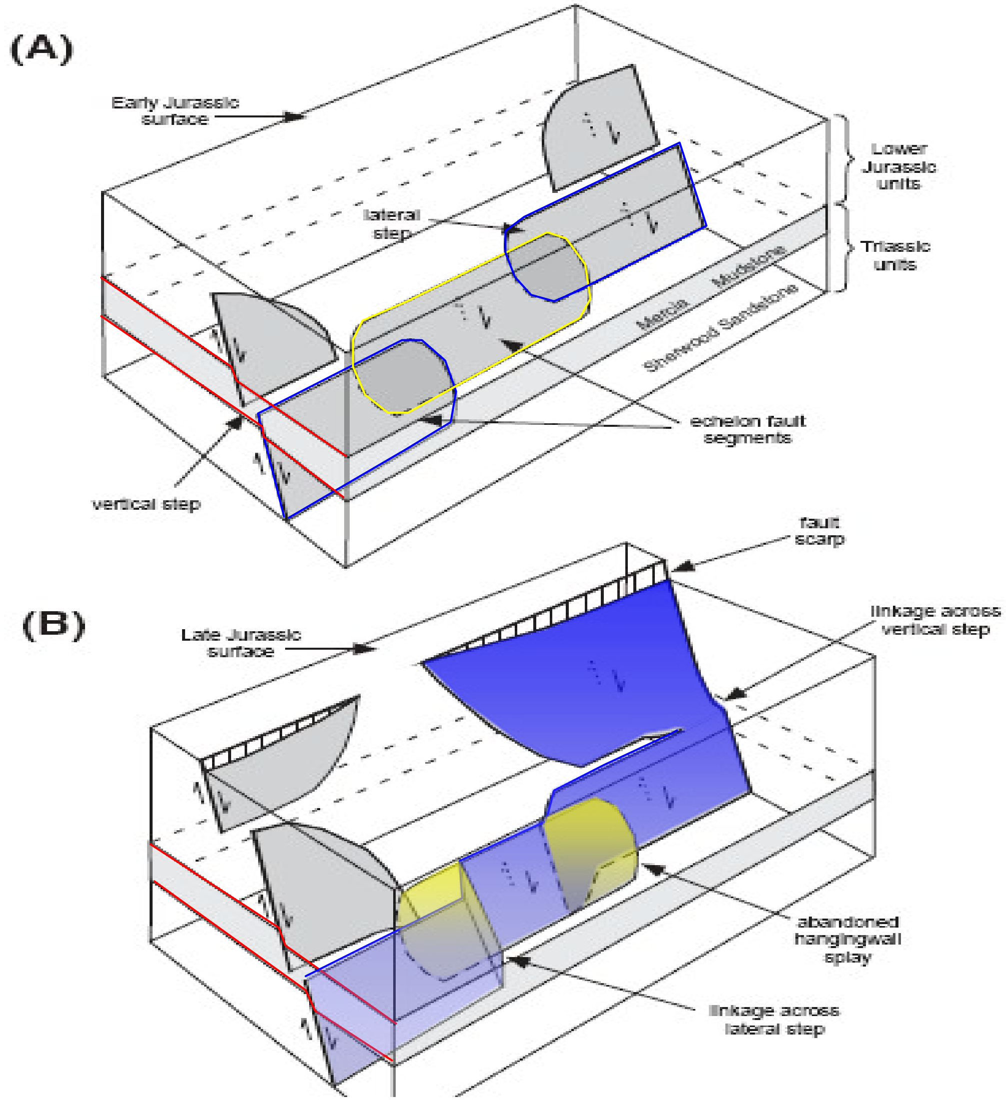
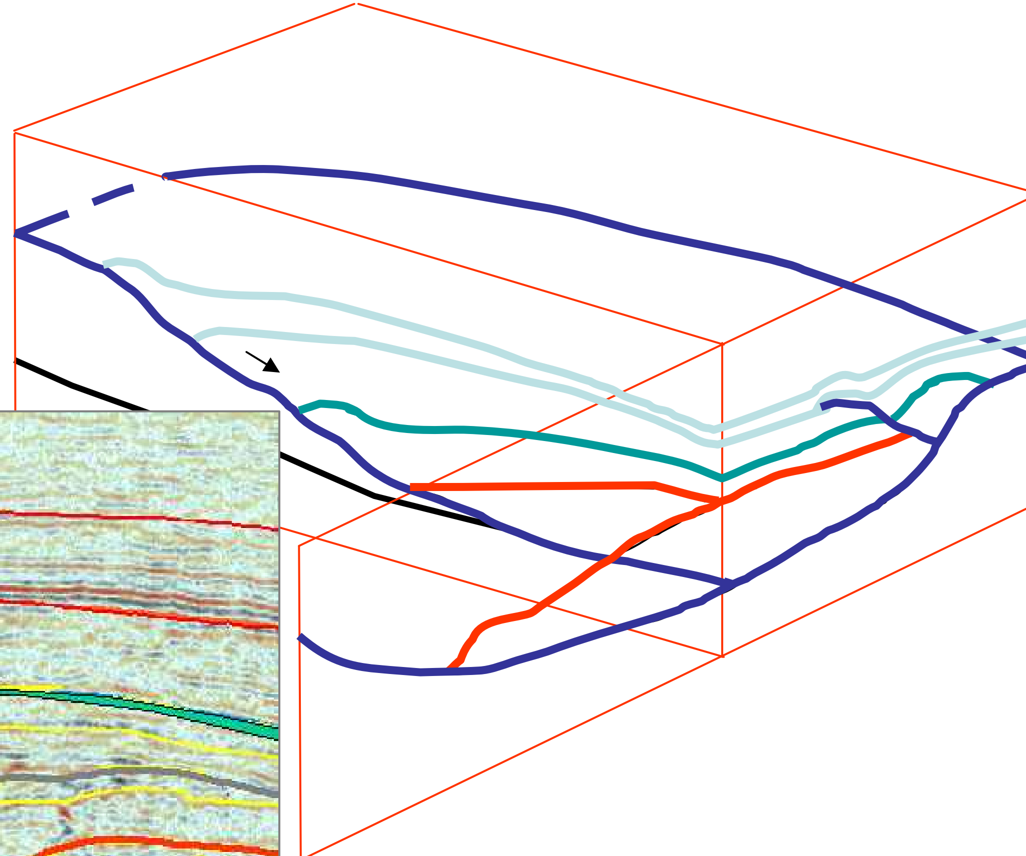
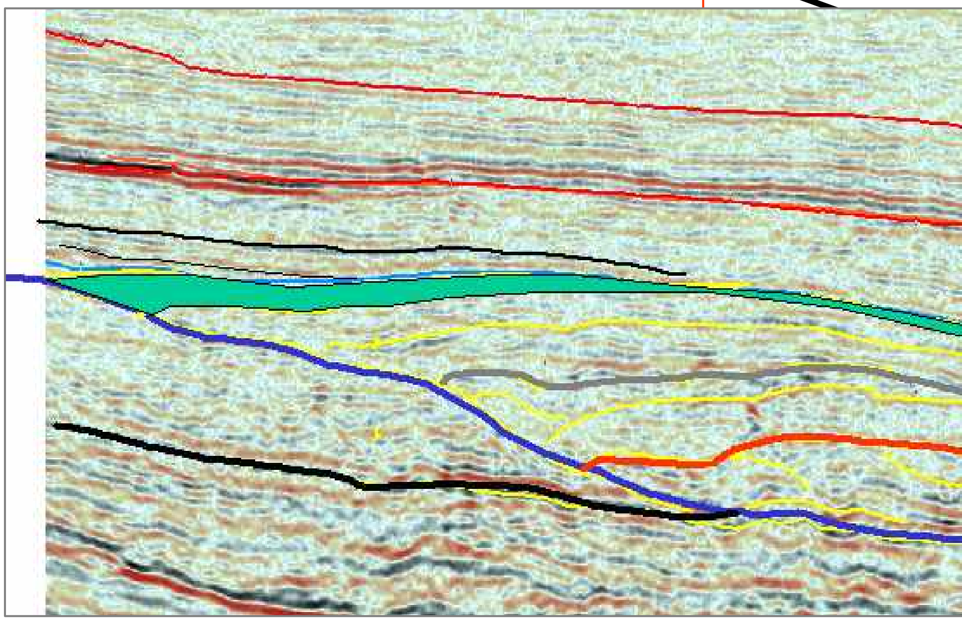


Figure 20 (page 1207), Kattenhorn, S.A. and D.D. Pollard, 2001, *Integrating 3-D Seismic Data, Field Analogs, and Mechanical Models in the Analysis of Segmented Normal Faults in the Wytch Farm Oil Field, Southern England, UK,* AAPG Bulletin v. 85/7, 1183-1210. AAPG © 2001, this figure is reprinted by permission of the AAPG.

Listric Faults

This is the pattern we may expect to see, mapping a complete listric fault structure.

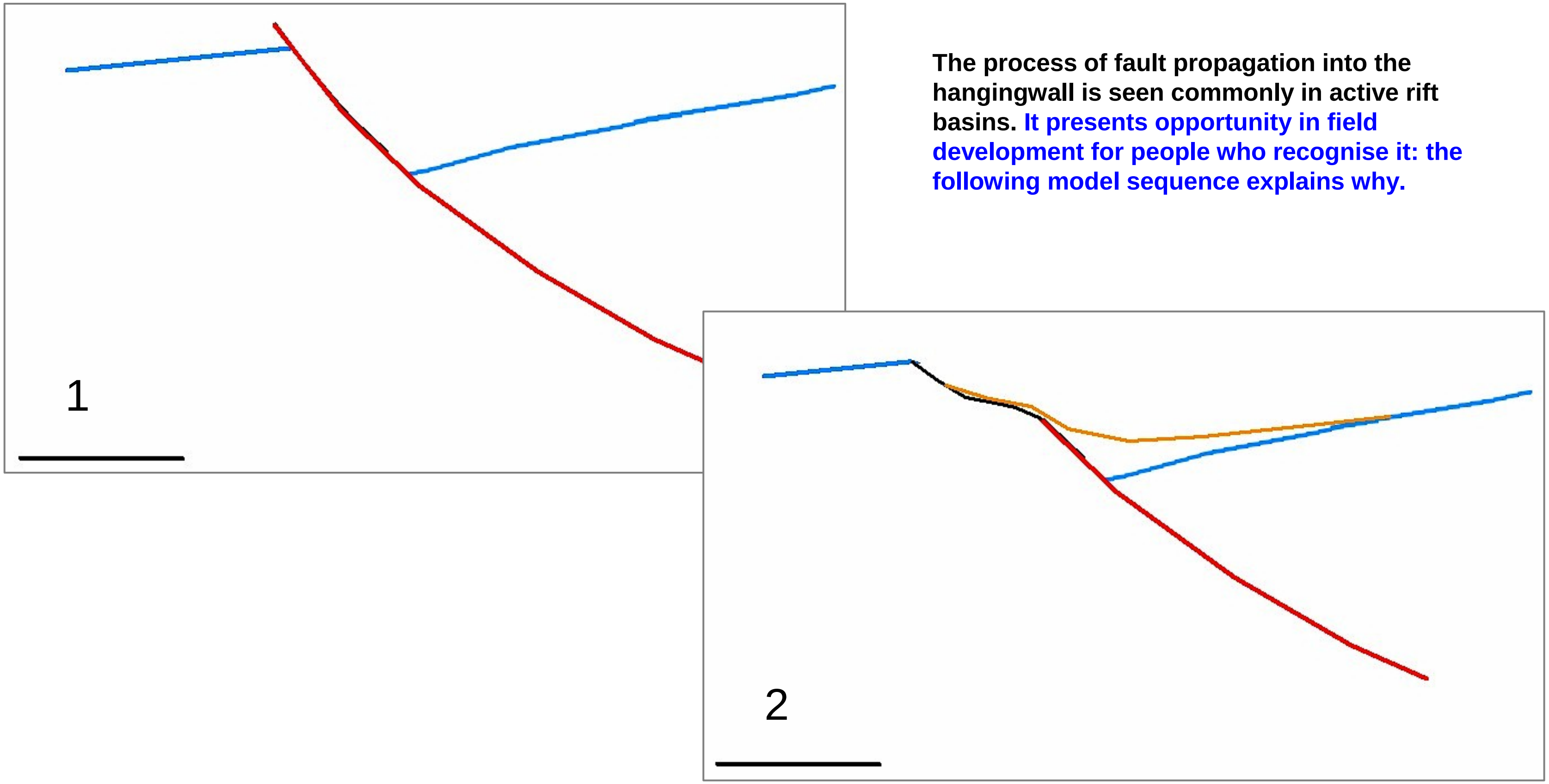




An arcuate growth fault will have a rollover in its hangingwall, which is early-formed. Compared to footwall stratigraphy this closure will have an expanded sequence, with thicker beds (or even new ones, which haven't been seen in the footwall).

Blue syn-sedimentary fault controls the thickness variations of the green-fill units, which are target sequences. If we map the blue fault, the thickness variations in green make sense and are predictable. Blue fault in this seismic example is not a reflector, its defined by terminations. It detaches and runs flat under the crest of the rollover, then may steepen and cut down to deeper levels. Be prepared to map faults which are not reflectors.

Fault propagation into the hangingwall: common, an important process!



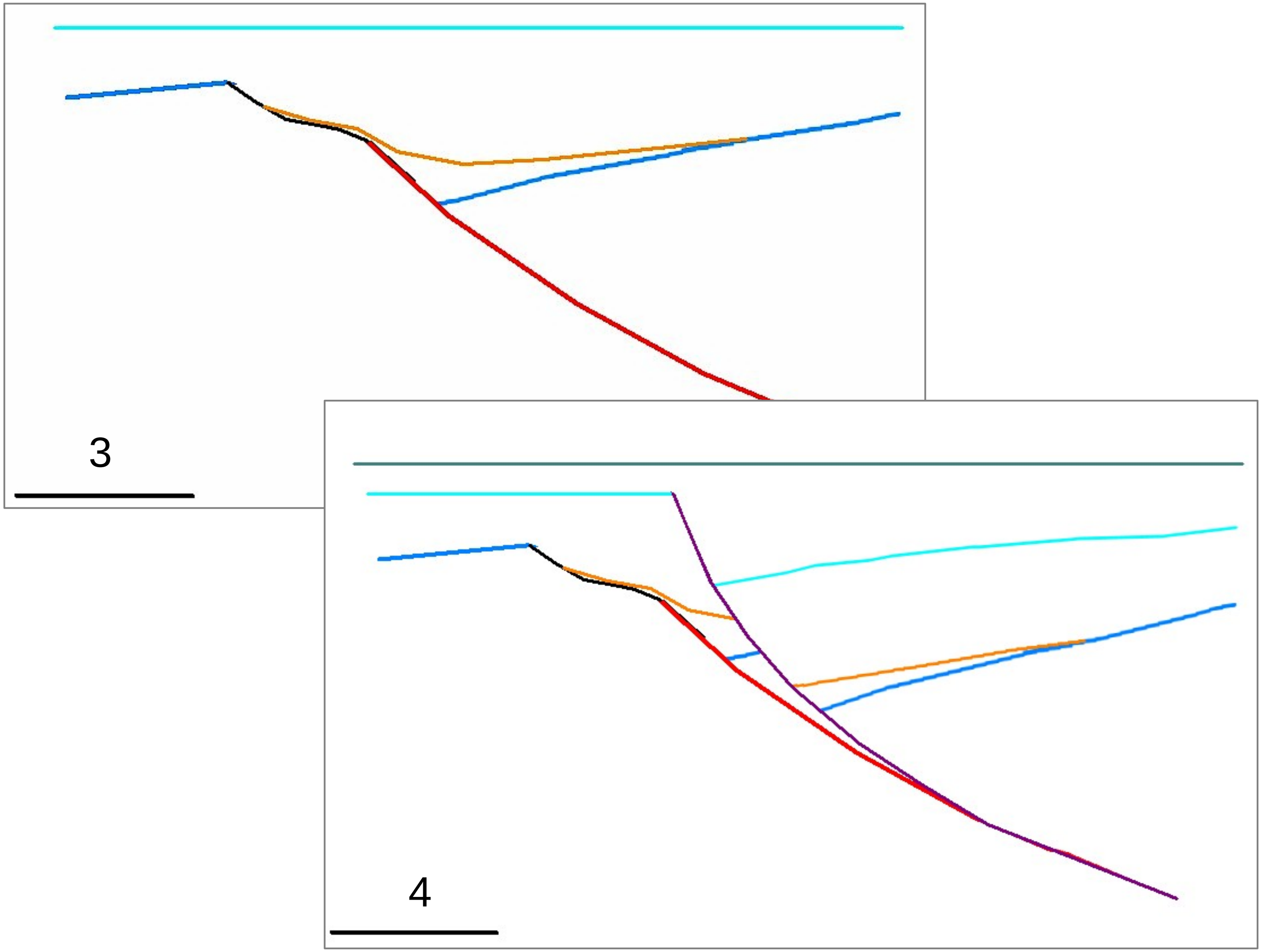
The process of fault propagation into the hangingwall is seen commonly in active rift basins. It presents opportunity in field development for people who recognise it: the following model sequence explains why.

Let's follow the evolution of a tilted fault block where the flank fault system is active.

The process is syn-depositional and involves a “jump” in the flank fault position, followed by renewed subsidence on the fault line. Erosion and re-deposition of footwall sediment goes on at the same time because there is topography in the footwall, due to a variety of factors: sideways slip on the fault may be one, elevating parts of the footwall system; and another is “bounce” due to flexural isostatic movements.

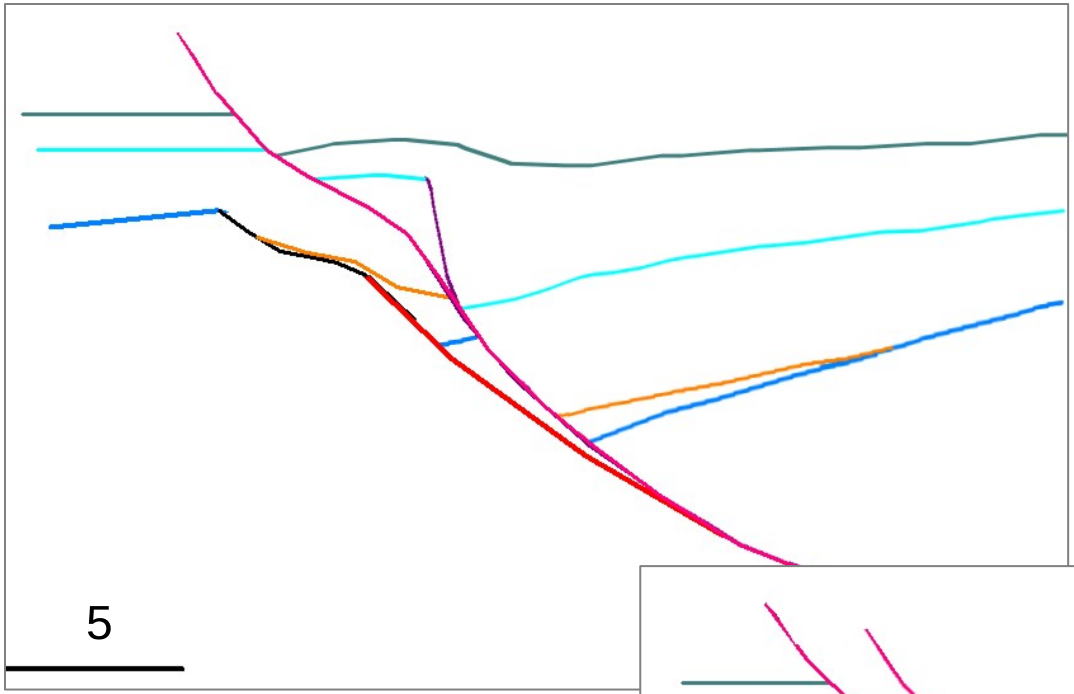
Stage 1 is the establishing of tilted fault block topography, and in Stage 2 there is erosion of the upstanding footwall and deposition of sediment on the hangingwall, this could be alluvial sediments or we might be in a marine environment with slumping off the footwall.

Fault propagation into the hangingwall (2)



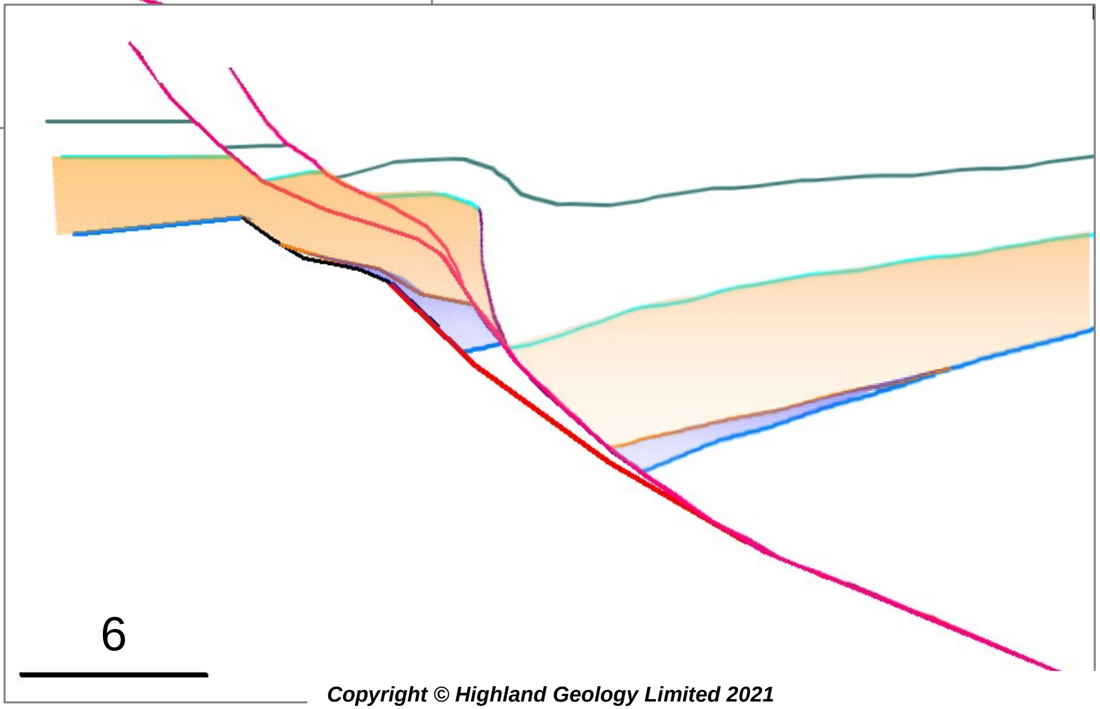
Stage 3 sees sediments blanket the high, as the red fault has gone quiescent. In Stage 4 it reactivates but the upper segment of the fault surface is new, shifted towards the hangingwall, its the purple surface. Upper red segment will not move again.

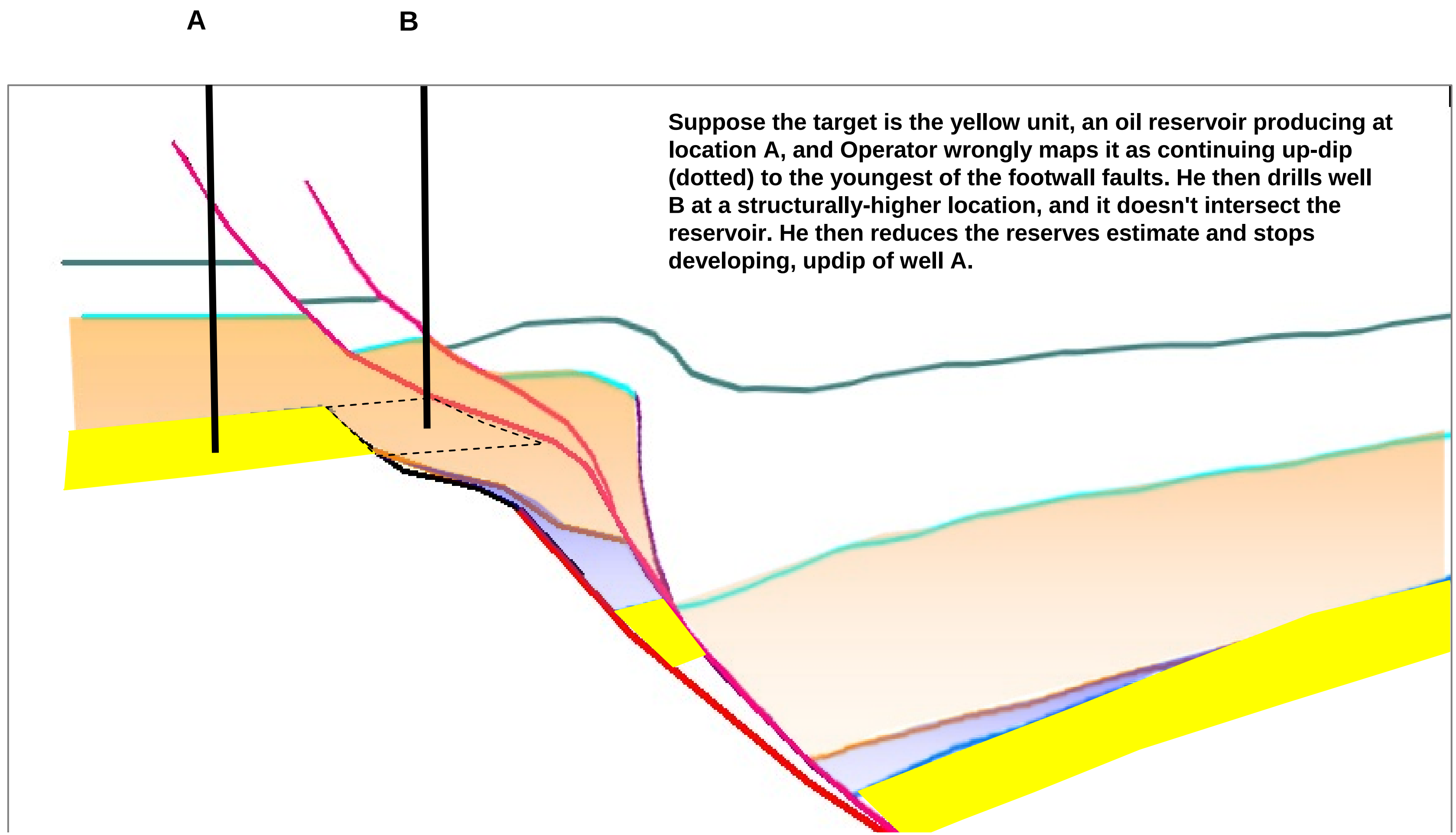
Fault propagation into the hangingwall (3)



Stage 5 sees more displacement on the purple fault, and it propagates upwards into the youngest beds, creating a synthetic extensional fault and local rollover.

Stage 6, another branch forms off the purple fault, in small-scale footwall collapse. These lowish-angle superstructure faults passing above the reservoir zone make it harder to map reliably.





Geometries like this are common, but many interpreters continue to think in terms of very simple fault patterns. There is an excellent paper on this topic by Morley et al (2007) in Bull. AAPG 91 (11), 1637-1661 focussed on Sirikit Field, Thailand, re-mapping faults there has led to significant reserves addition. North Sea Viking Graben has similar degradation of late Jurassic Brent Group scarps in major fields, examples being Ninian, Brent, Statfjord, where significant additional oil has been developed in submarine slide reservoir zones up to 25 km in length by 1-2 km wide.

If you see large fault-bounded structures with one unsuccessful well drilled crestally, where there are known to be prolific source rocks adjoining, and the location was picked using 2D data there's a good chance the operator mapped it simplistically and drilled too close to the flank fault. North Perth Basin in Western Australia has examples, a number of wells have been drilled too close to the crest of fault blocks, finding the Permian sandstone target structurally low or missing. You need 3D to map complex footwalls: and 3D will commonly clarify that remaining potential is more interesting than disappointed operators suppose.

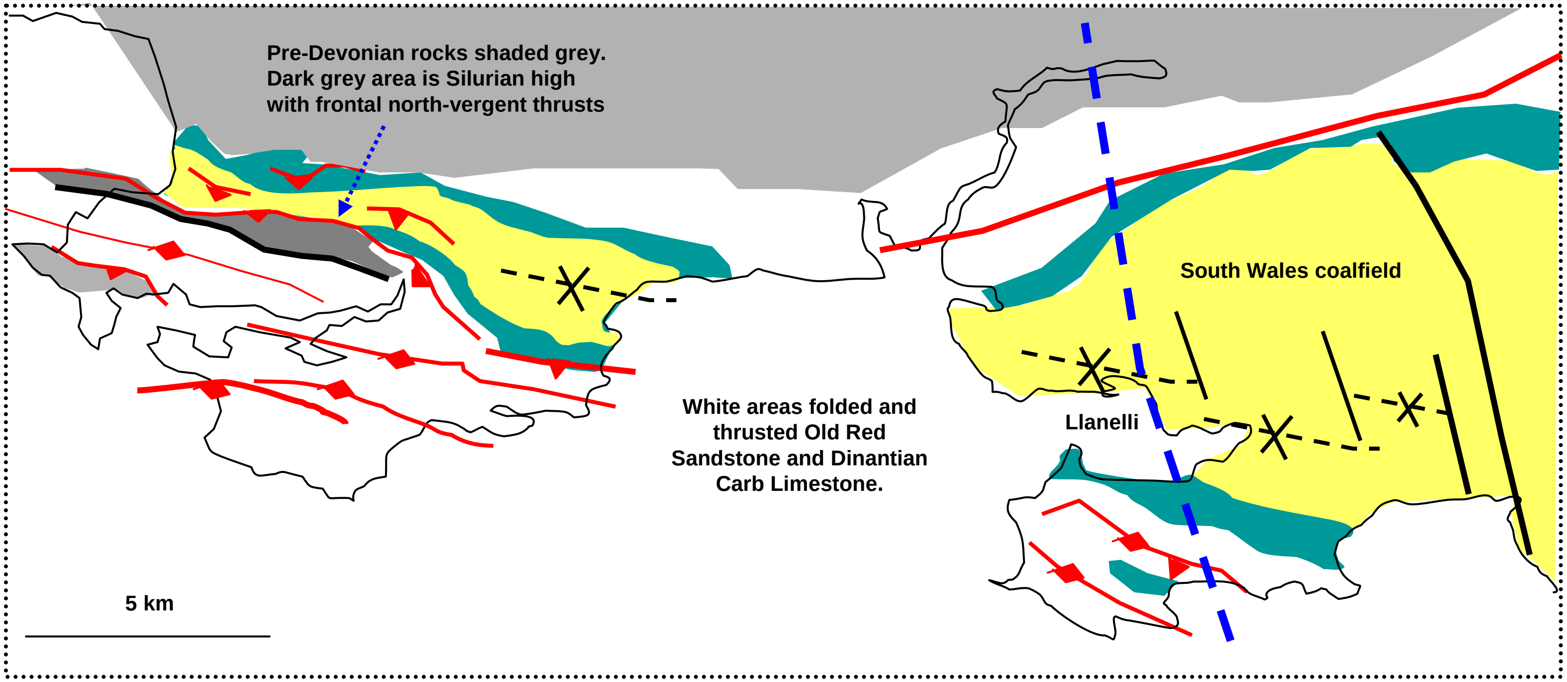
Ultimate Inversion: extensional detachment surface at summit of Everest

Perhaps the most spectacular inversion example of all, the south face of Mt Everest and Lhotse photographed here in December 2010, from a Drukair Delhi-Bhutan flight.

The yellowish sequence near the summit is Cambrian marble overlain by low-grade metamorphosed Ordovician limestone and dolomite now at around 8600 metres. These rocks are separated from mid-crustal black schists by the low-angle extensional Chomolungma detachment. The schists pass downwards into gneiss invaded by white granites.

Severe inversion at a thrust front: South Wales, UK.

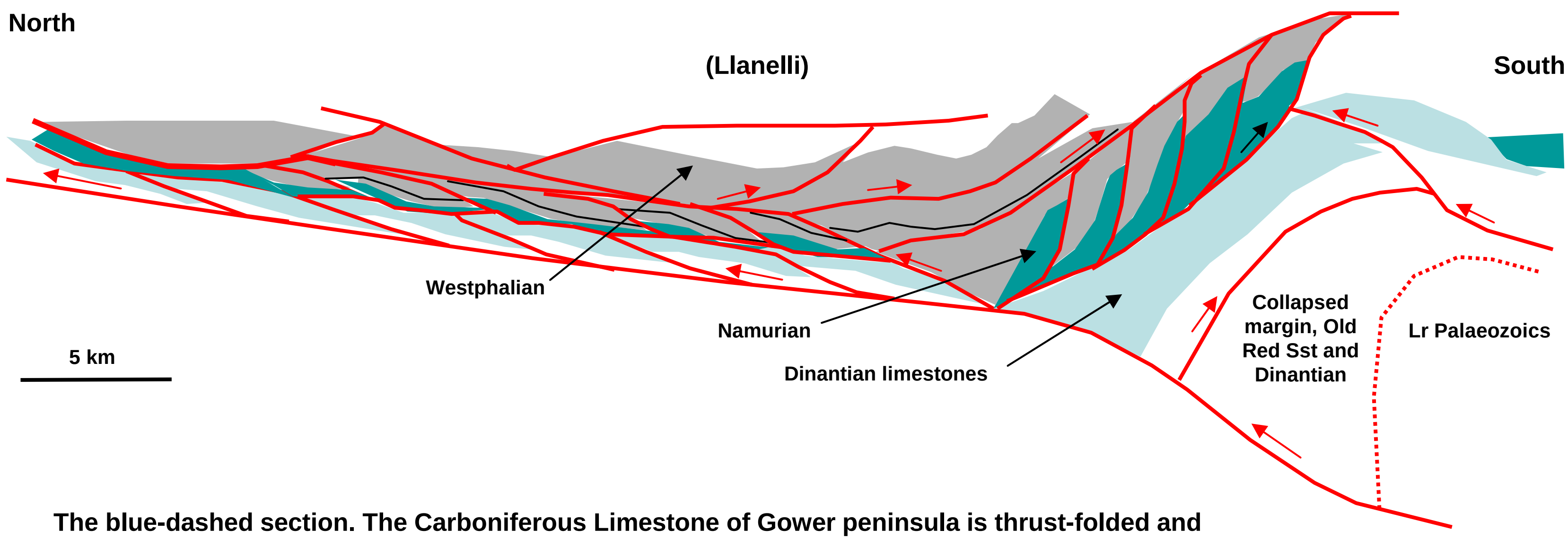
Inversion processes have various origins and effects, many petroliferous basins have been regionally or locally inverted above original regional depositional surface, some markedly so. Severe uplift of a basin has happened here: South Wales, UK, exposes late Carboniferous (Variscan) northward-vergent strongly compressional structures on the inverted north flank of the South Wales and Pembrokeshire basin. Prior to the compression this basin had developed in active rift phase on a set of south-dipping Devonian and Carboniferous growth faults, buried by Late Carboniferous coal field sequences in regional subsidence.



The western side of the map (South Pembrokeshire) shows a diagnostic feature of major shortening: strong compression across an extensional fault zone often produces new, low-angle footwall thrusting ("break-back" faults) as well as some element of reversal on the old extensional faults. Break-backs can elevate basement rocks, so that with erosion they will appear at ground surface. A number of basement inliers are seen in Pembrokeshire, with reverse faults on their northern flanks.

Next slide is the blue-dashed profile across the South Wales coalfield and the peninsula of Gower, down-plunge from Pembrokeshire.

Section across the inverted South Wales coalfield

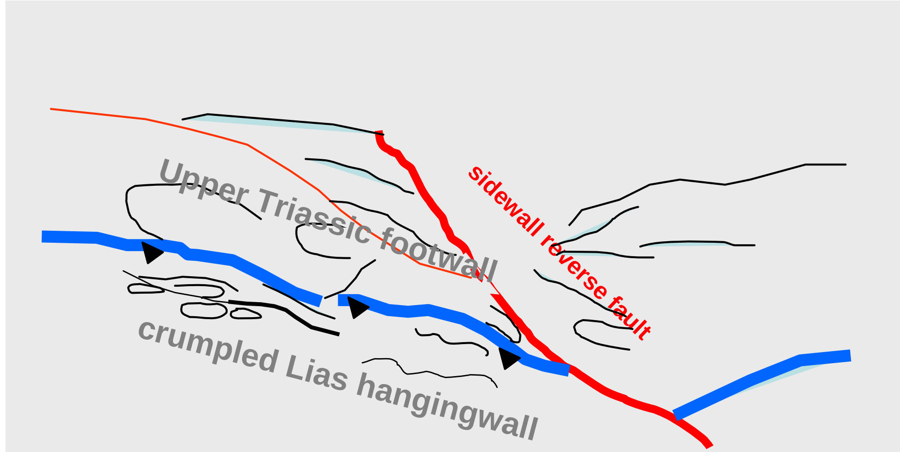


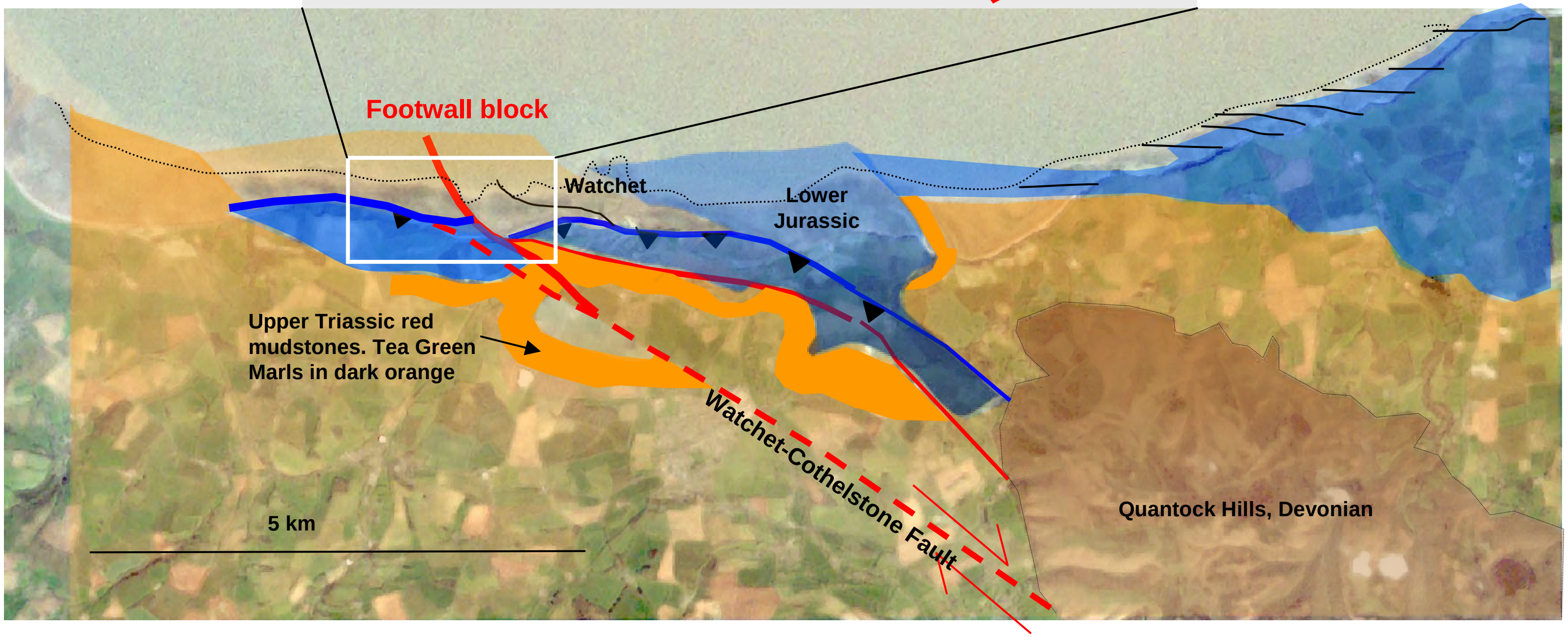
The blue-dashed section. The Carboniferous Limestone of Gower peninsula is thrust-folded and dips at around 60 degrees on the south side of the coalfield. Strong shortening is evident on what was a major extensional growth fault in the Dinantian and Namurian. Some of this propagates into the footwall, at various stratigraphic levels depending on where the shales are, and some generates out-of-syncline backthrusting. There's about 5 km of vertical inversion indicated in this profile, which was drawn using the geological map for Llanelli area.

It can be hard on seismic to confirm footwall thrusting which is more or less bedding-coincident, but the interpreter is justified in mixing model-based speculative fault picks with data-confirmed picks if the result is a geologically-sensible, integrated interpretation which can be rough balanced in 2D. A wholly seismic-driven interpretation of strongly inverted sequences with bed-parallel faulting is probably going to miss key structure elements, even with 3D data.

(Note that accurate estimates of shortening in inverted rocks are very difficult to make, the strain is distributed across many structures at sub-seismic resolution scales).

N-S Tertiary shortening inverts late Jurassic extension, Somerset

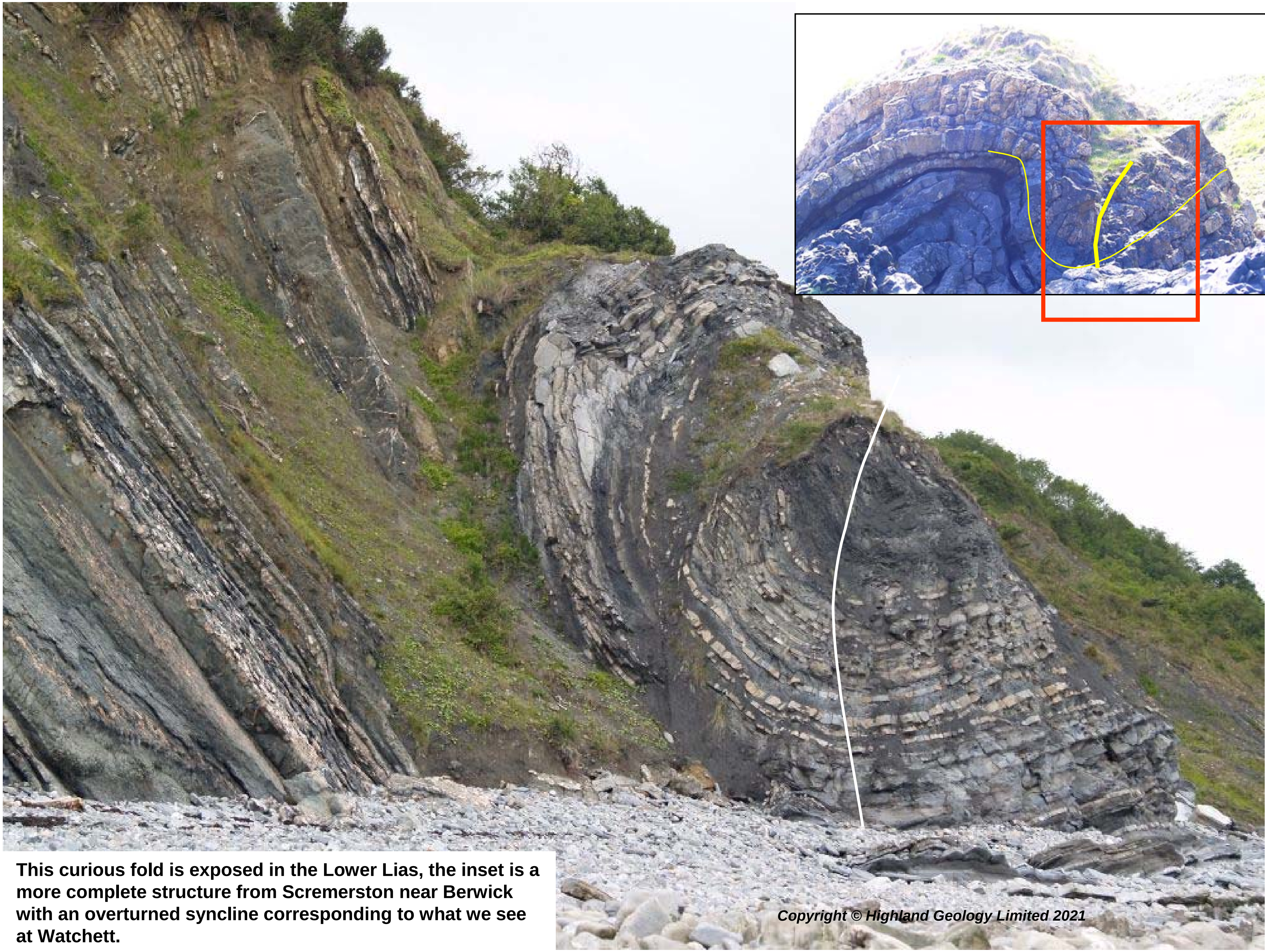




At Watchet on the north coast of Somerset, UK, an inverted fault (blue) is well exposed: Upper Triassic is bounded southwards by the blue fault which reversed some of its down-to-southward displacement in the Tertiary, when the footwall acted as a buttress to the weaker Lower Lias (blue shaded), which was compressed and crumpled against it. Six following photos show features of the compressed hangingwall between the red sidewall fault and the village of Watchet to right.

Looking east, blue fault runs along the base of the cliff. The grey Lower Lias beds here are downfaulted to right (south) against red mudstones of the Upper Triassic, on a major extensional fault of late Jurassic age. Subsequent compression of the Lias hangingwall in the early-mid Tertiary has buckled and faulted the Lias beds, we still have net extension but the hangingwall is strongly deformed, showing upright, almost isoclinal structures.

Detail of the Lower Lias deformation. This outcrop doesn't prove inversion, in itself, arguably the red mudstone footwall could just be acting as a buttress. But there is abundant evidence that Bristol Channel and South Wales have been regionally uplifted and this fault is highly likely to be one of the lineaments which accomodated the event.



This curious fold is exposed in the Lower Lias, the inset is a more complete structure from Scremerston near Berwick with an overturned syncline corresponding to what we see at Watchett.

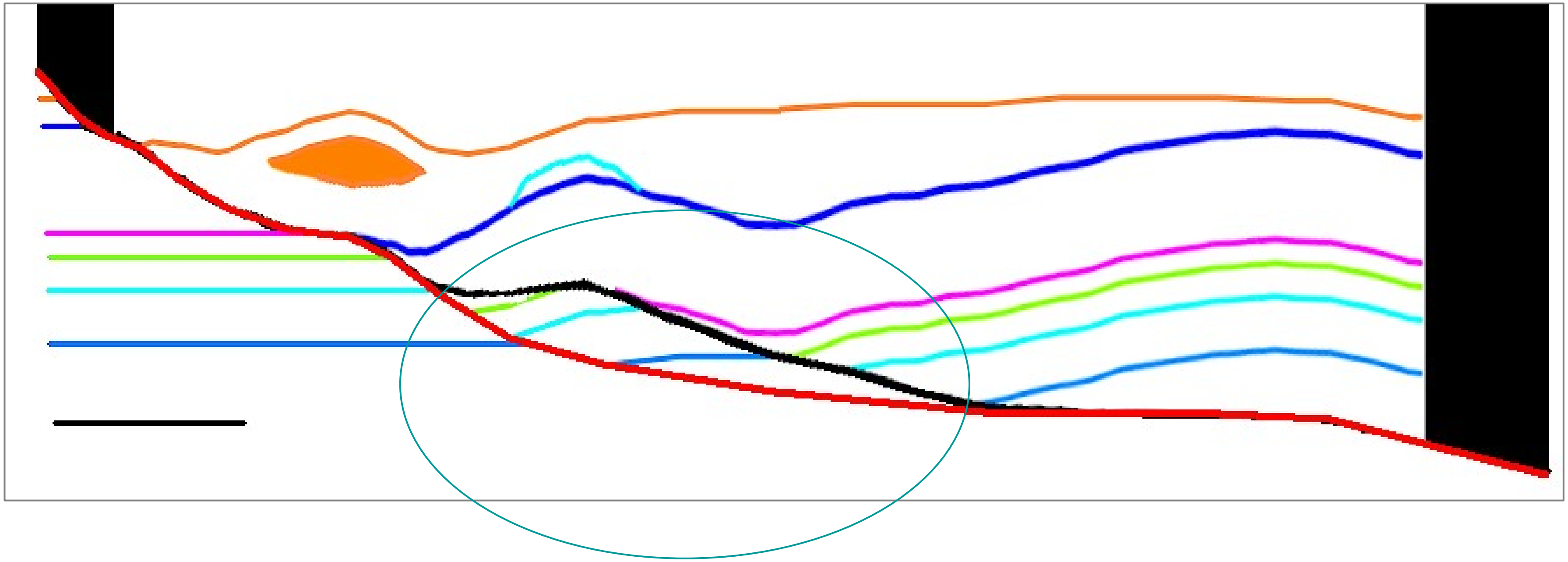
The inverted blue fault is just a few metres behind the outcrop face, dipping away from us. Subsidiary footwall faults and a maze of hydraulic fractures in the red footwall mudstones are sealed by gypsum.

Here's the mudstone which we might think is a safe side-seal for a hydrocarbon trap, its been comprehensively fracced. Hydraulic fractures close to the inverting fault were pervasively injected by gypsum-bearing hot water, very large volumes of pore fluid bearing the calcium sulphate must have escaped up the main fault zone during the inversion phases. Shale-shale juxtapositions evidently are not necessarily going to be seals at all stages in their development. This kind of fluid transmission might be critically important in pushing oil and gas up the faults, cracking traps but topping them up, too.

Extensional duplexes

Duplexes are lenticular rock masses entirely bounded by faults. The term was first used for thrust duplexes created by footwall collapse but subsequently broadened for describing wedges of fault-bounded rock in strike-slip and in extensional settings too. Anywhere a bend gets sliced off by continuing faulting, expect duplex systems made of "horses".

In the context of extensional modelling we simply slice off a piece of the ramp footwall, and if the new fault (red, below) is curved we will see a dip rotation and may generate a structural closure. The floor fault is the active one, the roof can be a composite surface of faults which never operated together as a single fault.



Can they be commercial prospects? Certainly, and if one of these plays works there may be a whole series of traps to pursue. If you can demonstrate by restoration experiments that the fault system is understood, the risk comes down.

This is a duplex on a fault surface, in North Somerset at Kilve. Its a partly-inverted extensional surface with a reverse drag fold, convex-up in the hangingwall. The blue extensional fault is corrugated and coated with calcite which is heavily slickensided, the fibres have the same dip as the blue fault surface so they probably belong to the extension phase. The reversal is partly made on a new surface, red, maybe because its locally mechanically weaker than the calcite-hardened plane.

Lenses on faults are common, they can be very large, they may develop by multiple extensional faulting.

It tends to be the case, that only some of the extensional faults in an inverting basin are reversed: which ones will they be?

-The longer the history of fault movement, the smoother the fault is and therefore the easier it is to reverse.

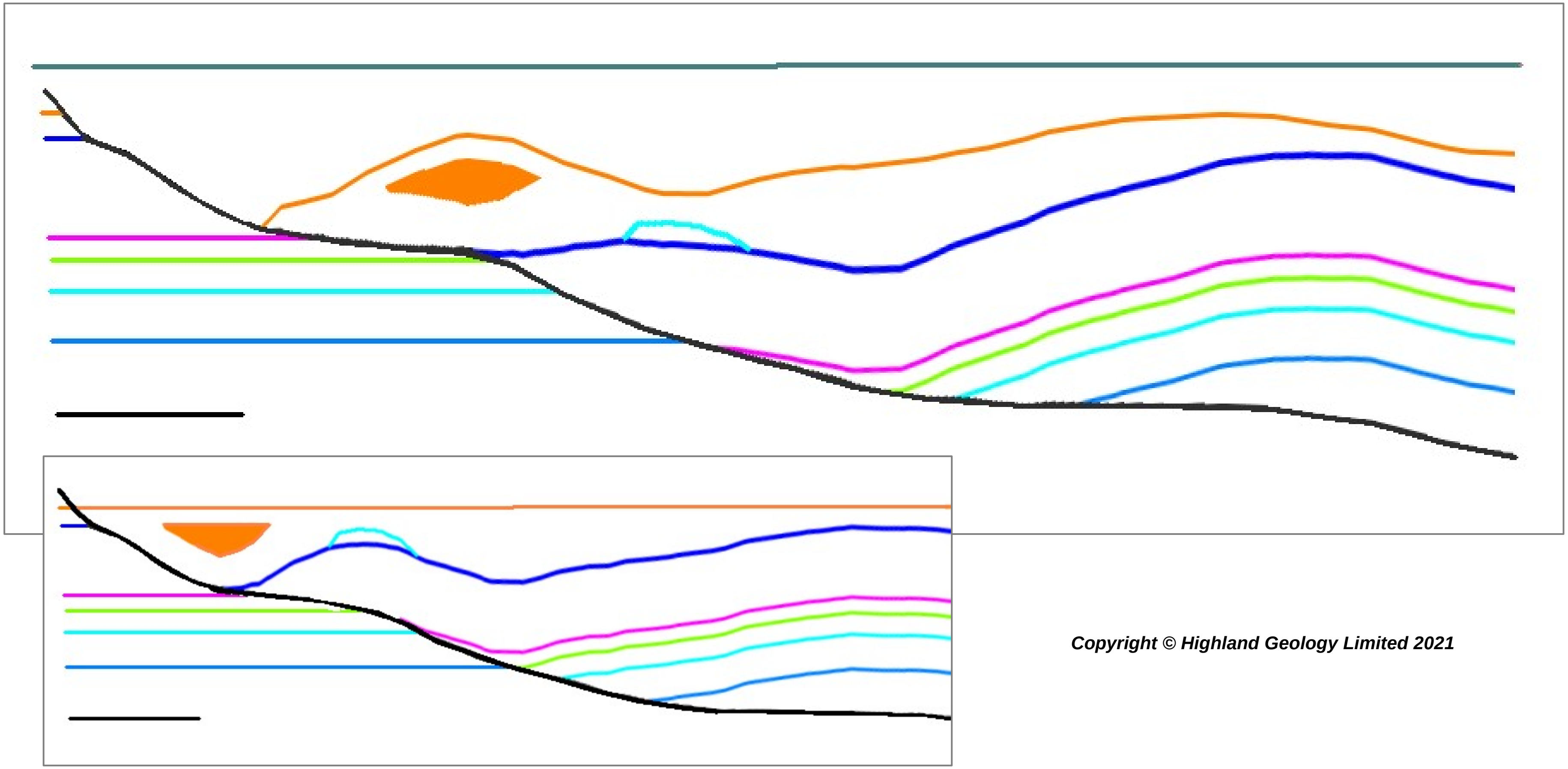
-The largest-displacement faults which have movement past a major shale unit, will reverse more readily.

- Limited fault gouge means high frictional strength. Does inversion on a fault stop at the point when gouge thickness is reduced?

- Faults which are oblique to the inversion may be easier to reverse.

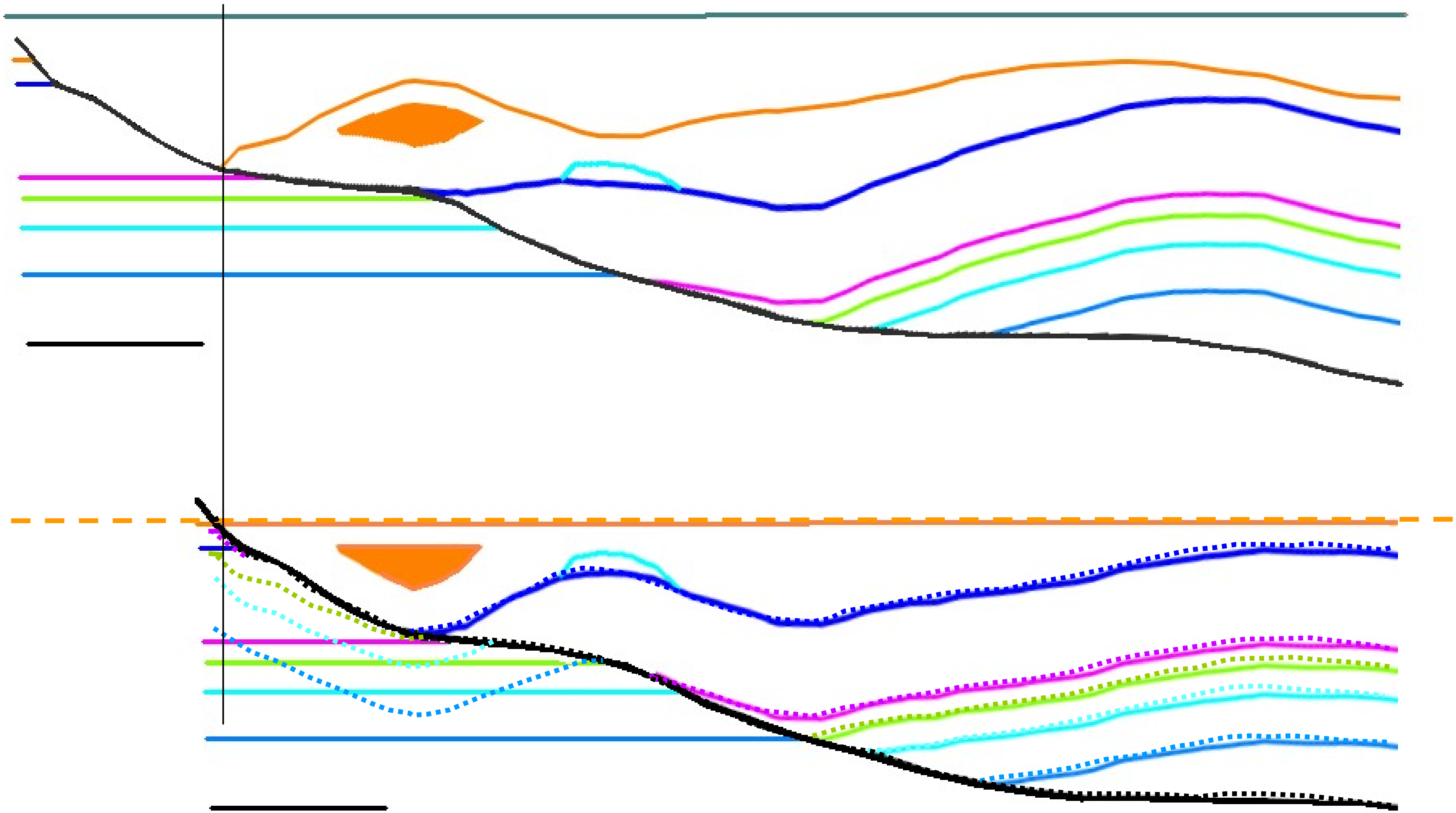
Does this all suggest, the biggest faults (particularly those which cut basement) are the most susceptible to trap cracking when the basin inverts?

Flattening on faulted horizons: what is really happening?



Many interpreters like flattening and re-datuming on seismic surfaces, workstations have automated flatteners for data cubes and 2D profiles, so its easy. These transforms shear the image vertically, all the data are pulled up or down. Some software developers recommend vector flattening to "minimise" distortion.

A little thought shows that flattening on a horizon which is faulted can produce structure which never existed. Going back to our model for growth faulting, in the next slide I flatten on the orange marker: will we see the same geometry as orange really had, at orange time?



No. Flattening on orange marker by shifting the picks vertically (dotted lines) is compared here with the real model at orange time. Above the black growth fault the results are OK, but in the footwall below it the markers take up spurious positions. Blue and older beds in the footwall were flat prior to the growth fault, now we see a pronounced footwall deformation. To flatten on faulted horizons work down horizon by horizon, remove fault offsets on each horizon, thereby place hangingwall sequences in their correct positions laterally, then flatten; then work the next horizon down, and so on.

We think flattening is a dangerous tool. Think carefully about flattening, and don't trust bulk flattening on cubes of data unless you fully understand what it means for faulted beds. There must be lots of dry holes drilled on false structures made in this way.