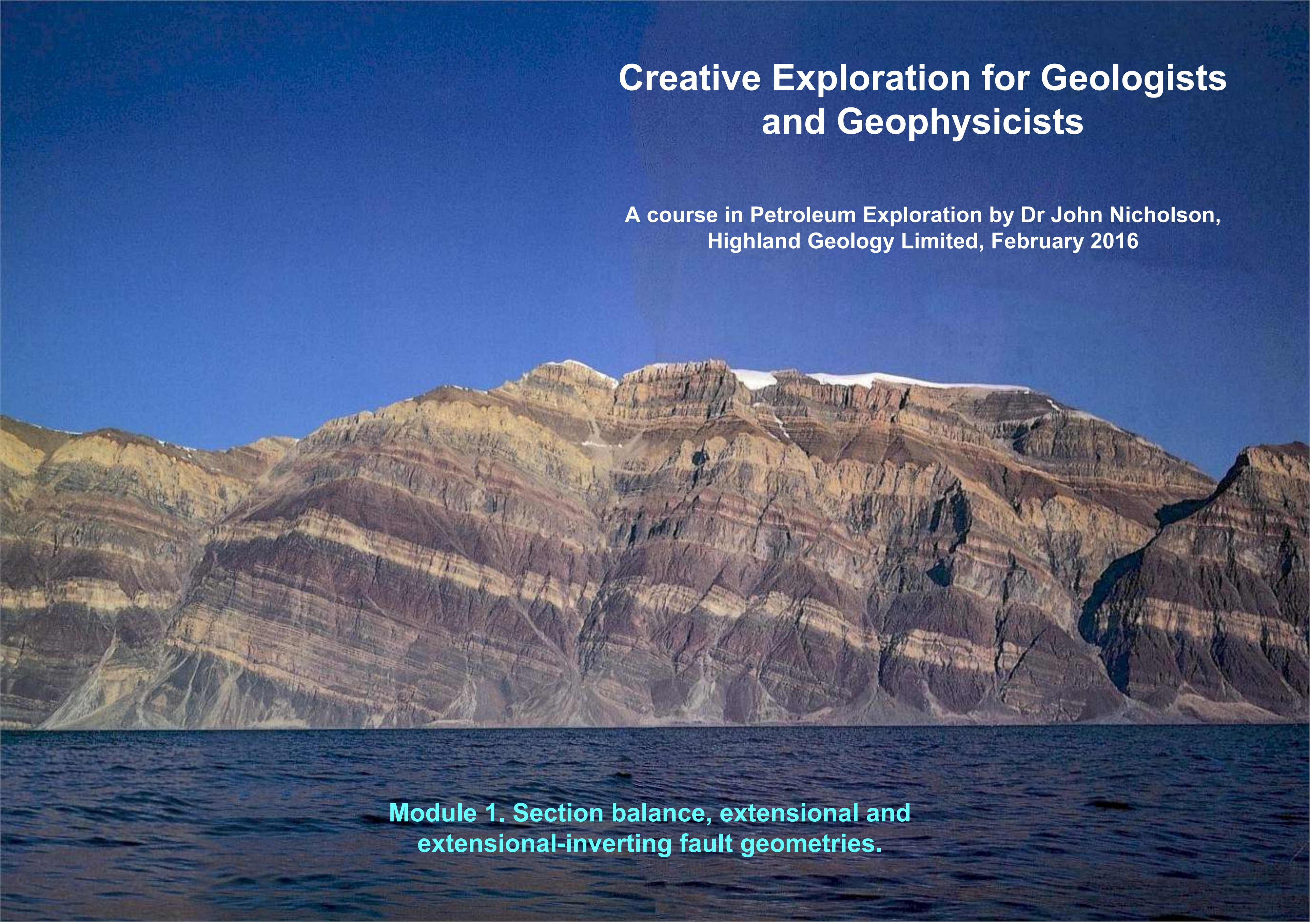
Creative Exploration for Geologists and Geophysicists

A course in Petroleum Exploration by Dr John Nicholson,
Highland Geology Limited, February 2016



Module 1. Section balance, extensional and extensional-inverting fault geometries.

Creative Exploration for Geologists and Geophysicists

A pdf set of modules with structure modelling software “DepthCon”

2nd Edition, February 2016

•How are we going to identify new plays and targets for wells, in licence round and farm-in blocks?

•How do we decide which are the top blocks to bid for?

•And how will we show management and partners, that our recommendations are worth backing?

Explorationists address these fundamental issues in many different ways, but a big step is to understand that new exploration plays very rarely come from data: they come from new ideas.

This course encourages geologists and geophysicists to make creative reviews of licence round acreage releases and farm-in opportunities, it aims to provide a quantum jump in capability and confidence to undertake such work. Its focus is on developing new play concepts, identifying and confirming high-potential oil and gas exploration and development blocks.

We hope it will boost the confidence of exploration geologists and geophysicists with limited experience to attend data rooms unsupported, and to carry out asset and farmin evaluations creatively, presenting and arguing credible technical recommendations to management on acreage acquisitions. It will also benefit geologists who are beginning to work in basin review; and assist explorationists evaluating producing assets which are up for sale.

The course scope

The approach is based on building structure interpretation skills, and the course is supported by software for forward-modeling and restoration of trap geometries. This is DepthCon, written by the author, its supplied as a multi-user licence with each course copy purchased. Its an area balance program working with seismic images, its used throughout the presentation to demonstrate concepts. DepthCon provides the option to critically-test given interpretations and to recognise new plays by experimenting with area-balance models.

This introductory module describes principles of extensional-faulting trap development and modification by inversion, and outlines the basics of simple shear modelling with DepthCon.

The modules which then follow include exploration-area case histories, which show how new ideas can radically change the way we assess prospectivity. We review structure style and trap variety in strike-slip and compressional deformation, and discuss the important role of gravity surveys in exploration work, including gravity gradiometry. We review risk assessment in exploration and the course recommends a practical approach to making sensible in-place oil and gas volume estimates for “conventional” traps, which realistically represent the probability of significant upside potential. A spreadsheet running under Excel is provided for target description and first-pass volumetrics work.

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 have a small, technically-capable team which is funded and is tasked by management to do regional work. It isn't bogged down in operating poorly-prospective "legacy" blocks which still have drilling obligations. Ideally you've got some production. 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 but can be very successful, 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. The structures you don't understand, are likely to become prospects when you DO understand them. 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.

•Re-process a lot of seismic with particular attention to getting rid of noise. Be ready to invest in gravity data. We'll discuss new technology developments, in the course.

This Module introduces the Course and its accompanying modeling software, DepthCon. The whole course is presently structured like this:

1. Extensional fault geometries, and how extensional faults invert. DepthCon, and introductory comments on extension and inversion (this module).

2. Extensional-inverted geometries illustrated by examples from Dorset/Isle of Wight, Wessex Basin, East Midlands UK; and Fitzroy Graben in Canning Basin, Western Australia.

3. Thrust-fold belts as exploration targets. Concentric folds, fault-prop folds, detachment folds, flexural slip; thin-skin versus thick-skin tectonics.

4. The thrust-fold belt of NE India, thin-skin or thick-skin?

5. Strike-slip styles, with examples from Scottish basins and Central East Greenland.

6. Gravity Gradiometry and conventional gravity surveys, their key role in exploration programmes.

7. Estimation of oil and gas in-place, and risk factor. An expectation curve spreadsheet program is introduced here, for quicklook calculations to show sensitivities and upside.

All the way through this Course the focus is on recognising exploration opportunity, and testing whether the picking is realistic.

Section Balance Software supplied with this Course

The literature on extension and extensional structure modelling is huge, and the value of section balancing using vertical and (especially) inclined-shear modelling has been confirmed by many authors. A paper by Hauge and Gray (1996) reviews this matter well: see "A critique of techniques for modelling normal-fault and rollover geometries", in Buchanan P.G. & Nieuwland D.A., Modern Developments in Structural Interpretation, Validation and Modelling. Spec Pub. 99, 89–97, Geological Society London.

Subject to analysed sections being orientated in the plane of extension, simple shear models produce acceptable geometrical analogues of real structure, and restoration of extensional-fault based interpretations is a proven and powerful tool for testing given picks and fault shapes.

So the ability to easily apply area-balance analysis based on simple shear is very useful indeed, and our program written to do this is distributed together with the Course as a paid, licensed piece of software. Its DepthCon2000, and its an option you may find valuable to help you visualise structure style and to interpret complex seismic. It may be applicable in a casual, occasional way, or it may fire a deep interest in section balancing and lead to your acquiring specialist packages. You can follow the course without using DepthCon, but we'll start by showing something of what it does.

DepthCon is a very powerful way to model seismic structure

DepthCon is an image-processing program, it operates with bitmaps (screendumps of seismic, usually) and was designed initially as a means of depth-converting complex seismic, hence its name. Subsequently I added the capability to deform sections in simple shear on faults drawn as overlays, where the user sketches possible fault traces on the image and slips the hangingwall sideways by any input amount, to see what kind of restorations result: are they plausible, or not.

Fault shapes can be dragged and dropped interactively with hangingwall moves. The shear algorithm is simple but constructions made with it are time-consuming if done graphically, by hand. DepthCon is an app which makes this kind of work practical in a few minutes' timescale. What it does that is particularly useful is to remove pixel overlaps which occur as the hangingwall travels on inclined surfaces, so that the result of a fault displacement exercise is a high quality, un-degraded image. With this ability in place and interfaced with depth conversion tools, I also added a simple-shear fault construction option, and various utilities such as line-length measurement which gives it value in work on compressional styles of deformation too.

The most powerful application for DepthCon is in forward modelling. You can start with a blank page, draw a sequence template of some kind, sketch faults and move on them, add more sediment, more fault displacement, and see the results of multiple moves. Creativity and understanding of complex geometries built by serial, simple moves leads to high confidence in picking structure style, especially when inversion overprints earlier extensional faulting. DepthCon is a very powerful way to model seismic structure.

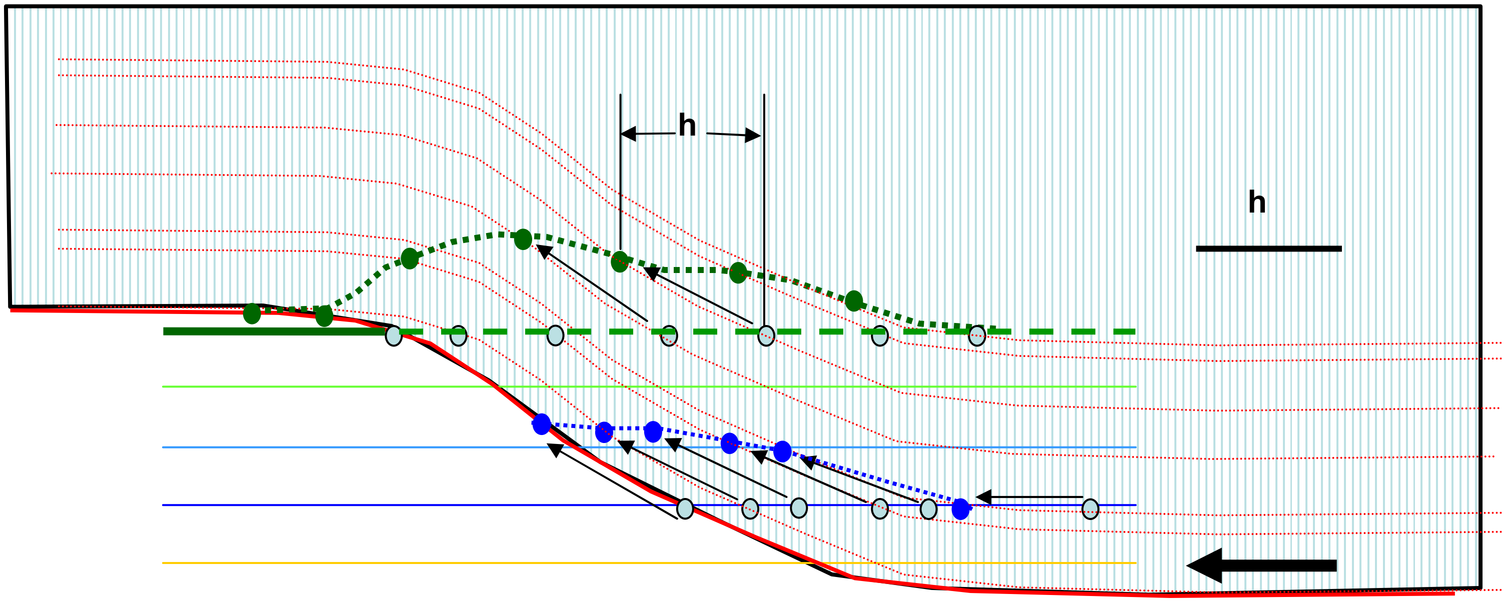
Source of the seismic in this course

Now we'll start using seismic, and nearly all of the seismic sections shown in this course 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 onshore licence rounds.

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

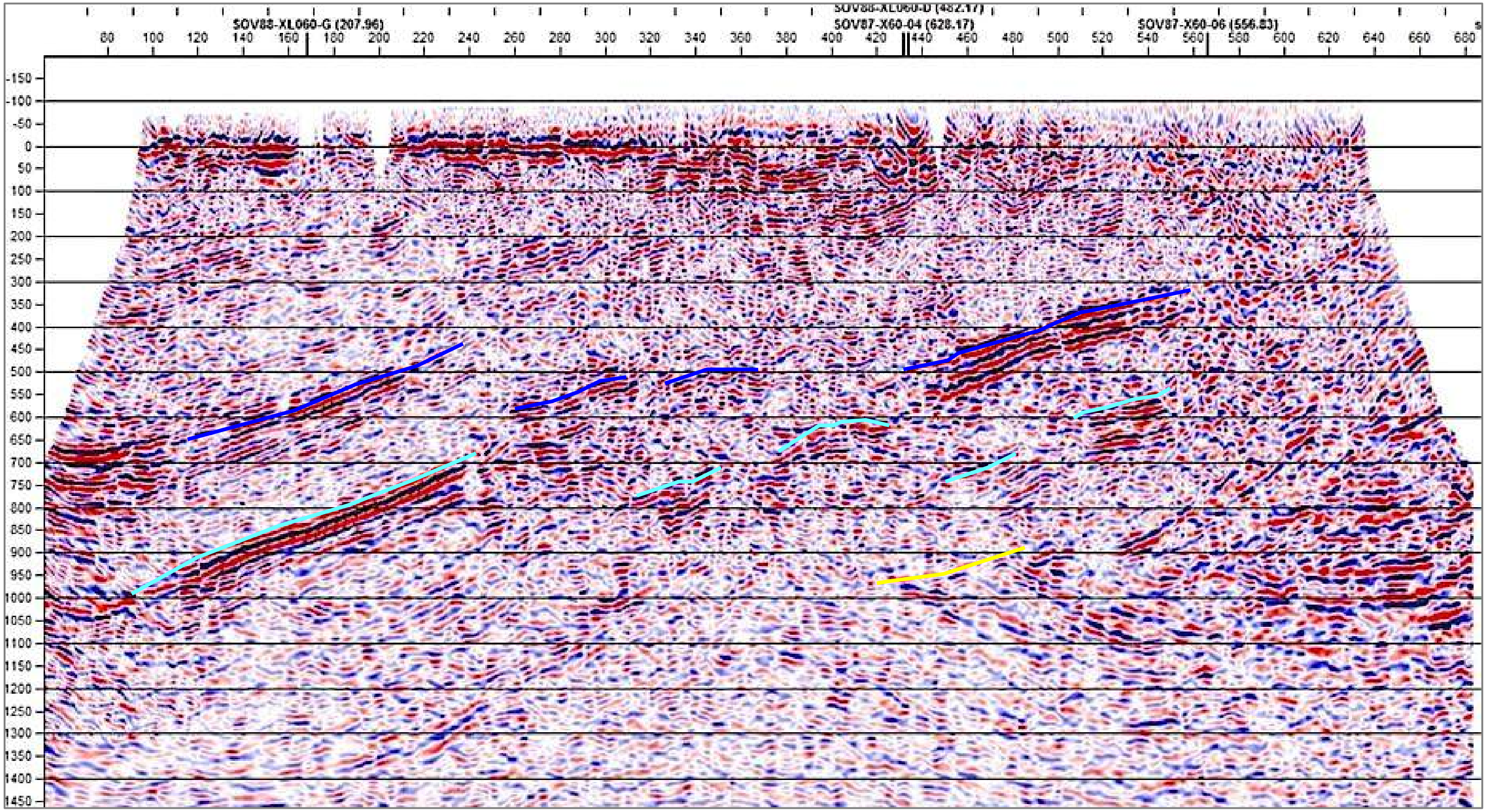
About simple shear models, and DepthCon

How does DepthCon software work? Copy your image to clipboard, import into DepthCon, clip the margins, enter scale, and you can sketch faults and slip the hangingwall laterally to rejoin beds and see whether resulting geometries look sensible. In its move-on-a-fault mode the program shifts all pixels lying above that surface, parallel to the fault by the amount of specified horizontal heave. It can do 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.



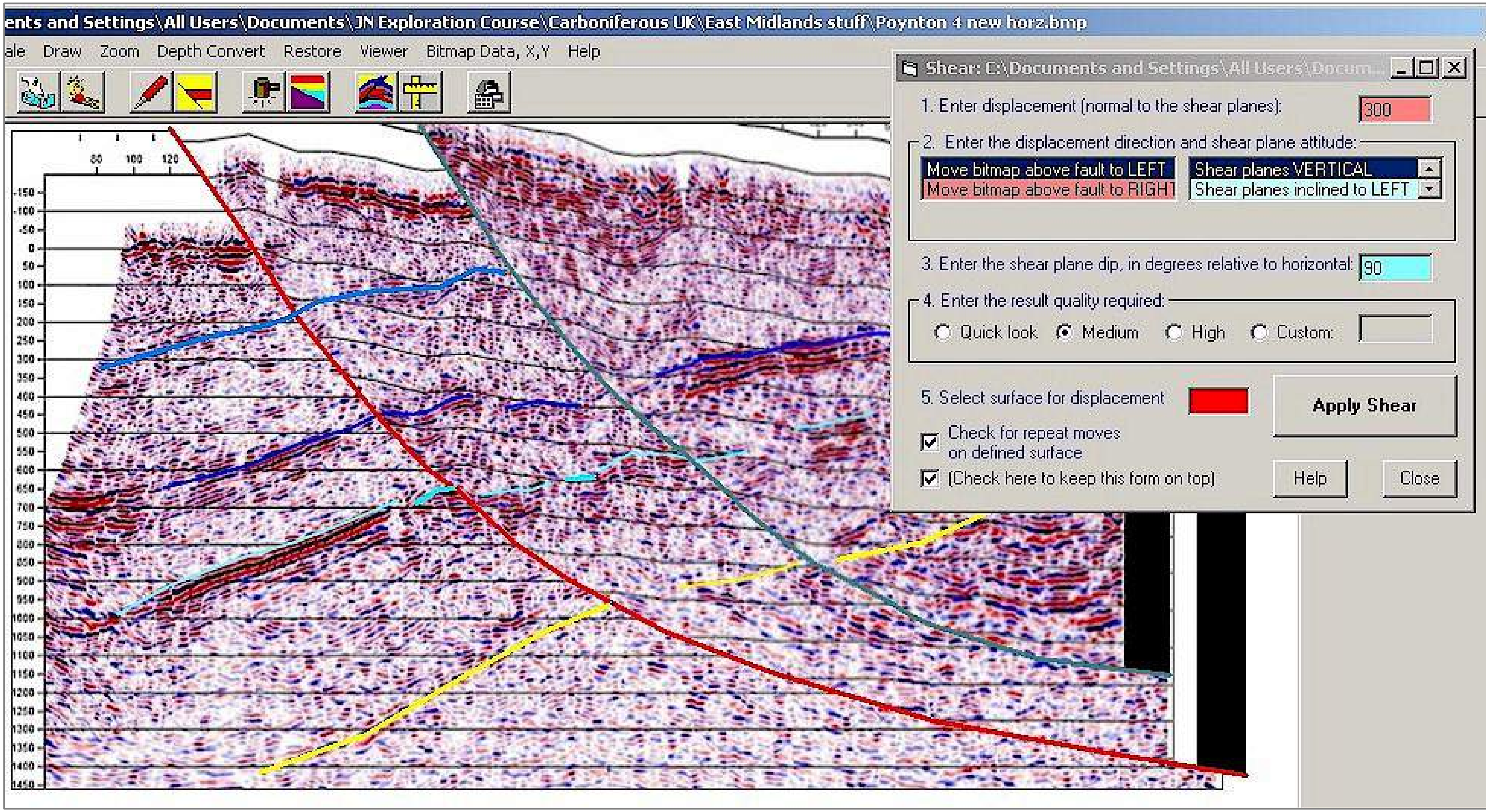
Suppose we want to move the hangingwall above the red fault surface, slipping the initially horizontal beds leftwards by an amount "h", using vertical shear. The construction is very simple, the same for left or right moves, imagine a pixel-scale array of vertical shear planes and every pixel above red 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.

Restoration of seismic images using DepthCon



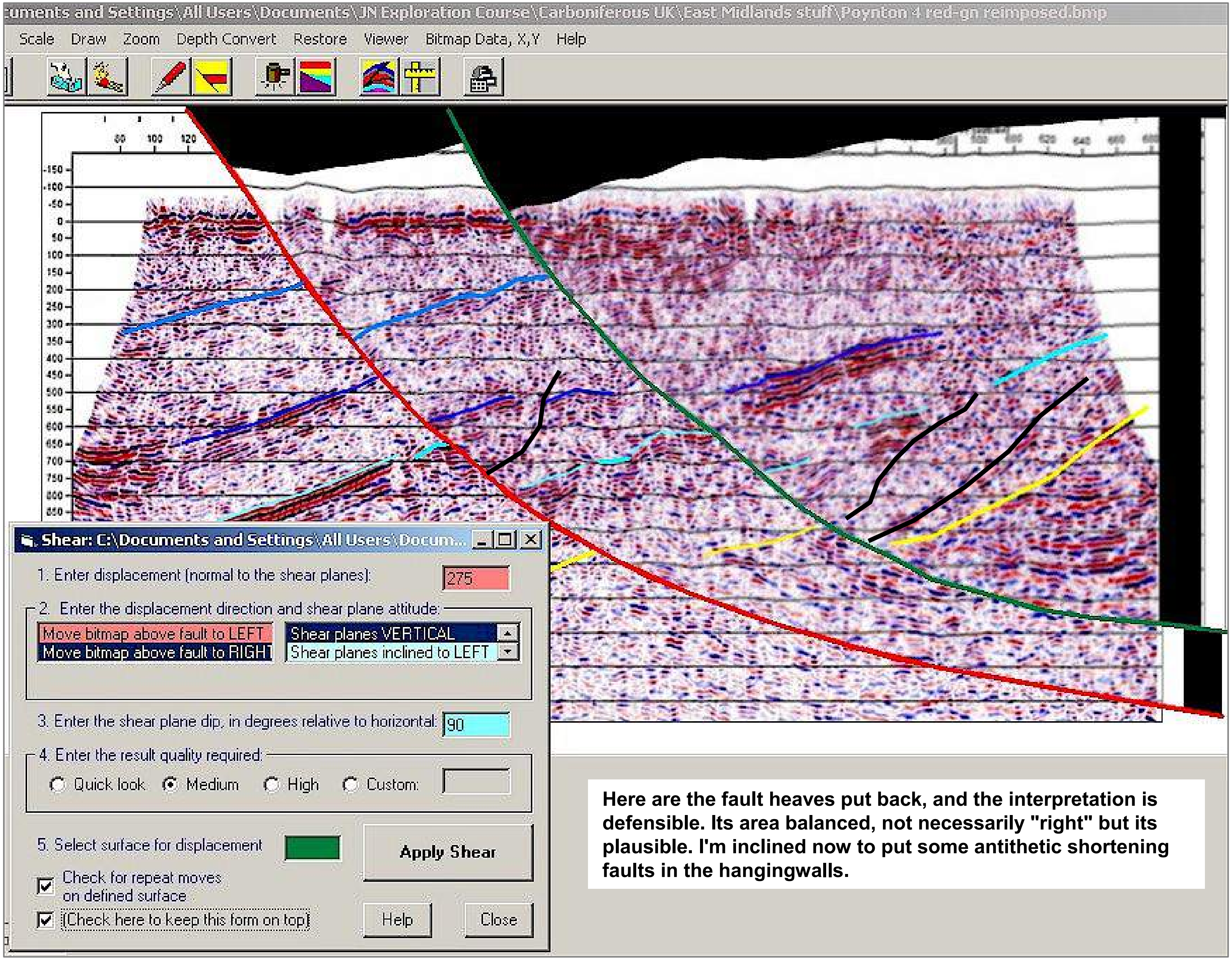
Here's a seismic line from Cheshire basin (Manchester Airport, actually). Dark blue is the Bunter Pebble Beds event, pale blue is the Manchester Marls, there's an unconformity (yellow) occasionally imaged which is base of Permian Collyhurst Sandstone deposited across tilted Westphalian. Its not easy 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 using DepthCon (2)



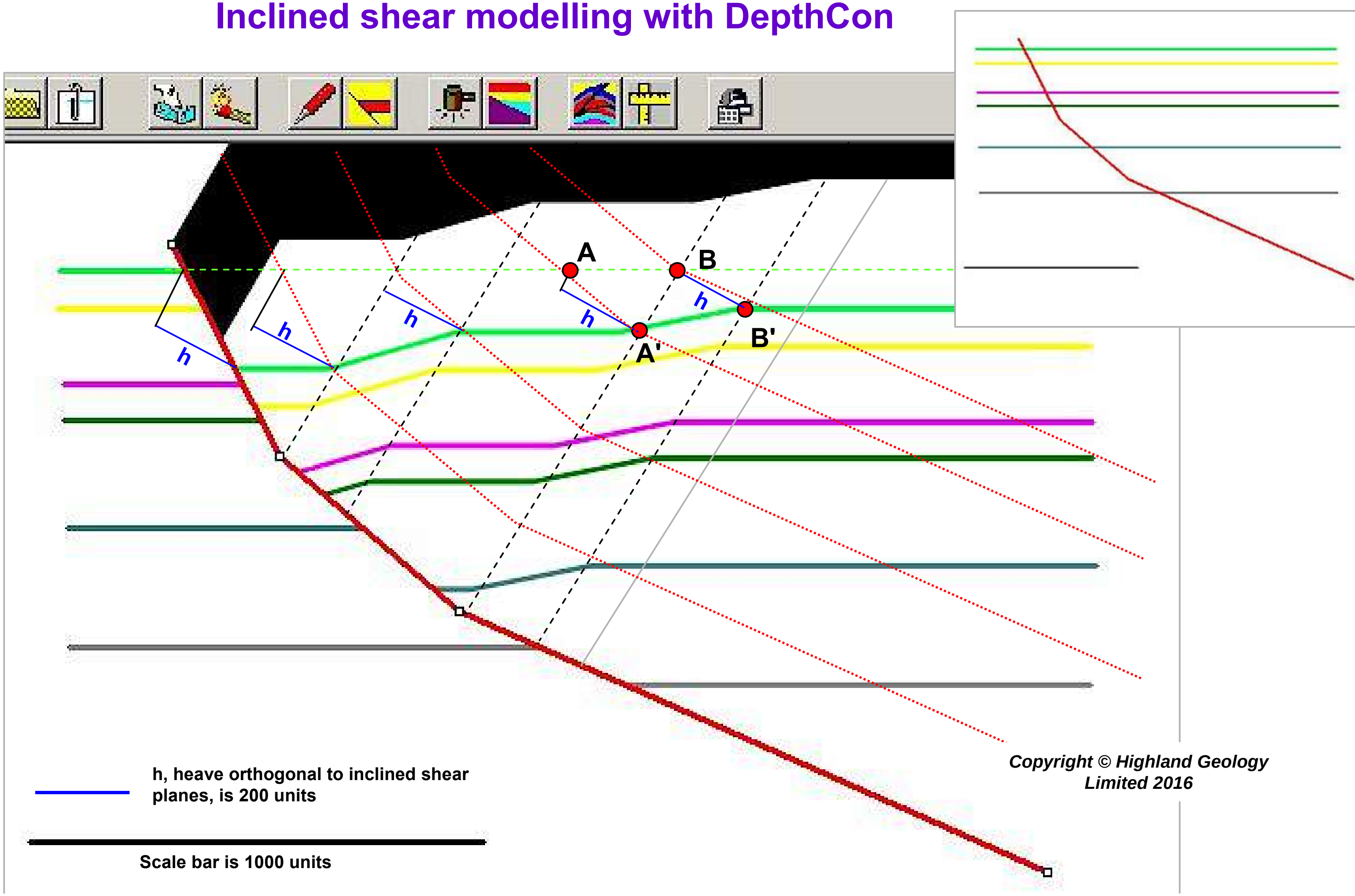
These are two vertical shear restorations using the red and grey-green faults, 275 metres and 300 metres respectively for the heaves, and the restorations look reasonable: so we can say yes, they seem OK and we can project the probable unconformity in yellow, and another marker is added above the dark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

Restoration of seismic images using DepthCon (3)



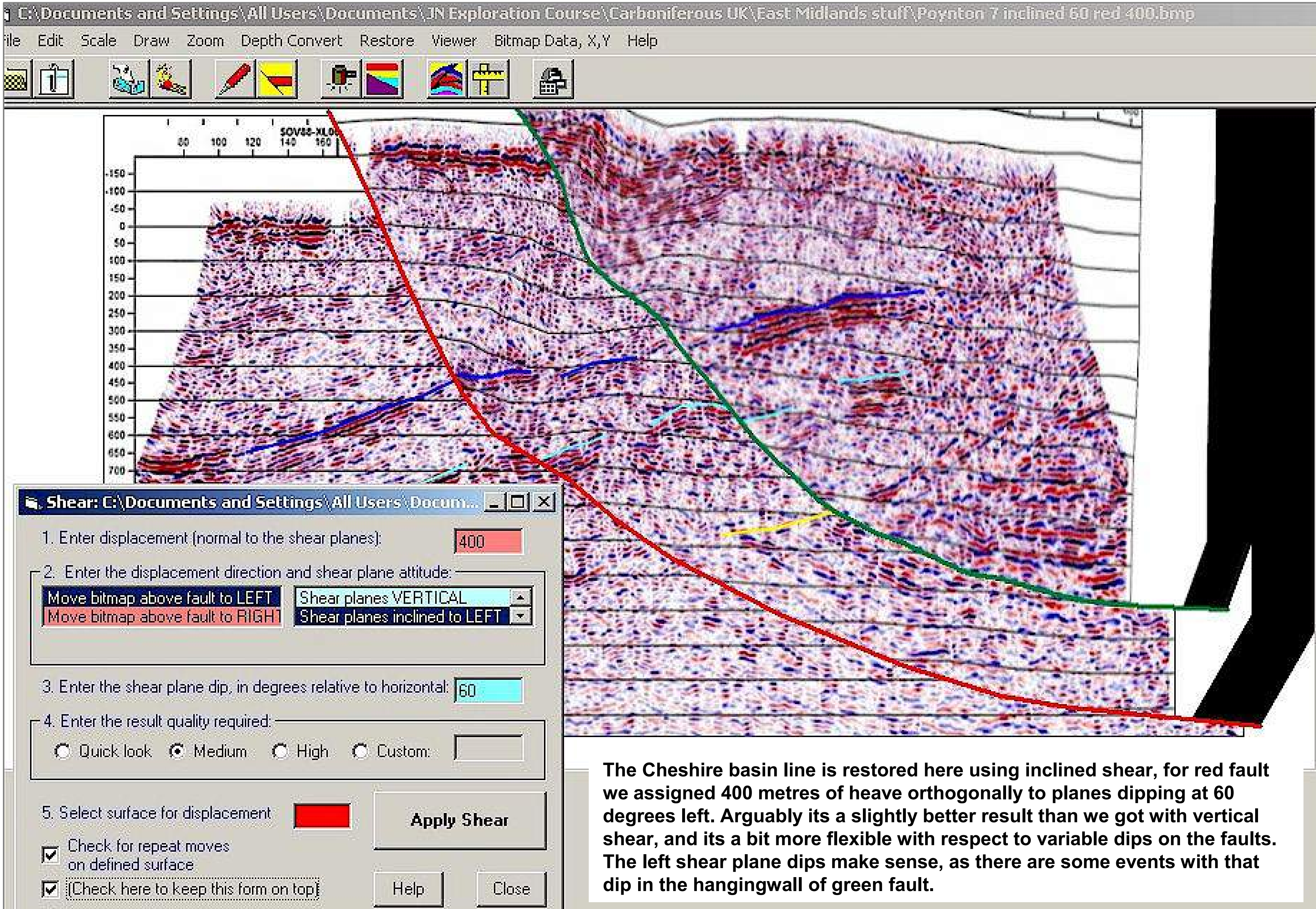
Here are the fault heaves put back, and the interpretation is defensible. Its area balanced, not necessarily "right" but its plausible. I'm inclined now to put some antithetic shortening faults in the hangingwalls.

Inclined shear modelling with DepthCon



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, i.e. parallel to the red fault trajectory by orthogonal amount 200 units. Preserving area in the plane of section requires stretching, we see the hangingwall bed thicknesses 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.

Restoration of seismic images using DepthCon: 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.

Geometrical tricks?

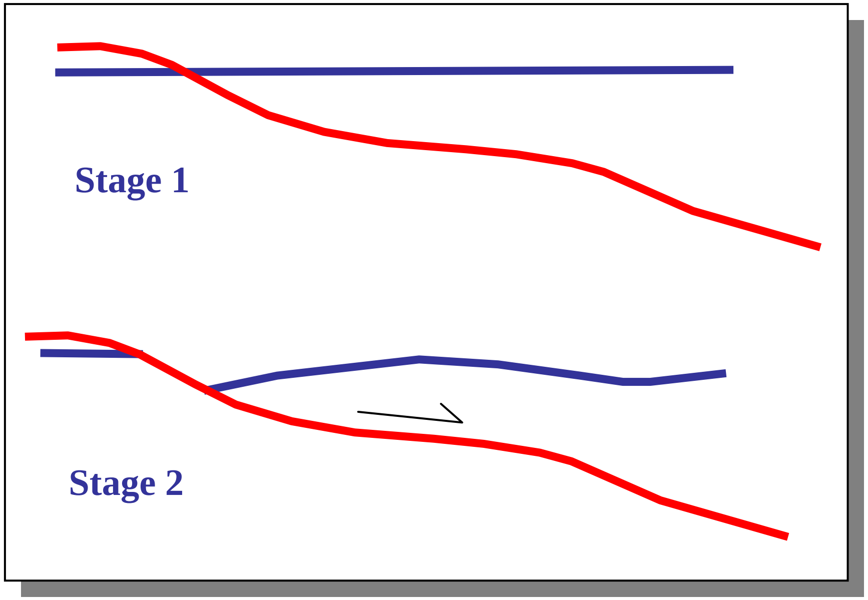
Somebody said to me once, section balancing is just a trick: and that's right, it is.

Vertical and inclined shear models and restorations preserve area but not line length. The real deformation of rocks is only roughly approximated, let's say "reasonably" so.

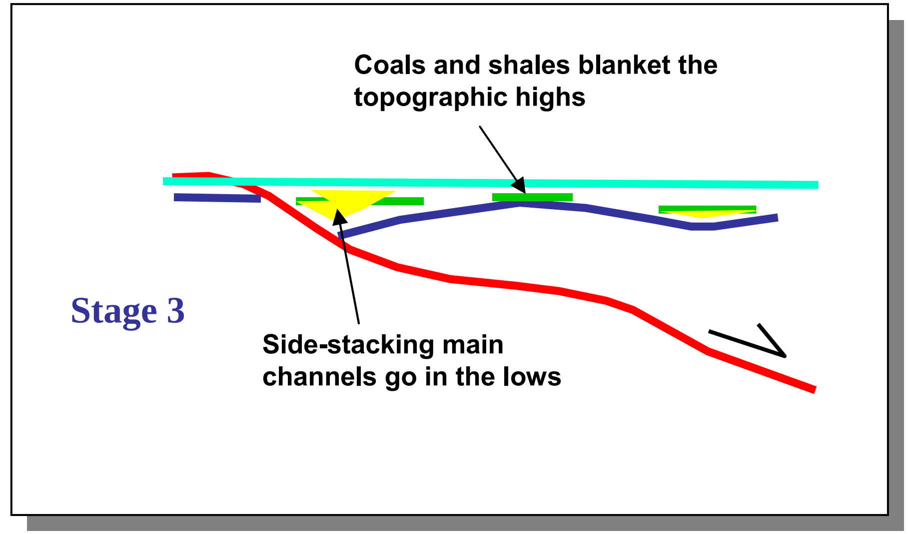
Flexural slip we'll talk about in the module on shortening styles. It preserves line lengths and areas constrained between pins. Its moderately close to real rock behaviour, though other processes are significant too. DepthCon doesn't include flexural slip as an option but it does measure line lengths, so you can restore complex thrust sheets to the pre-deformation template and see if there is a line-length mismatch: and if so, where it is.

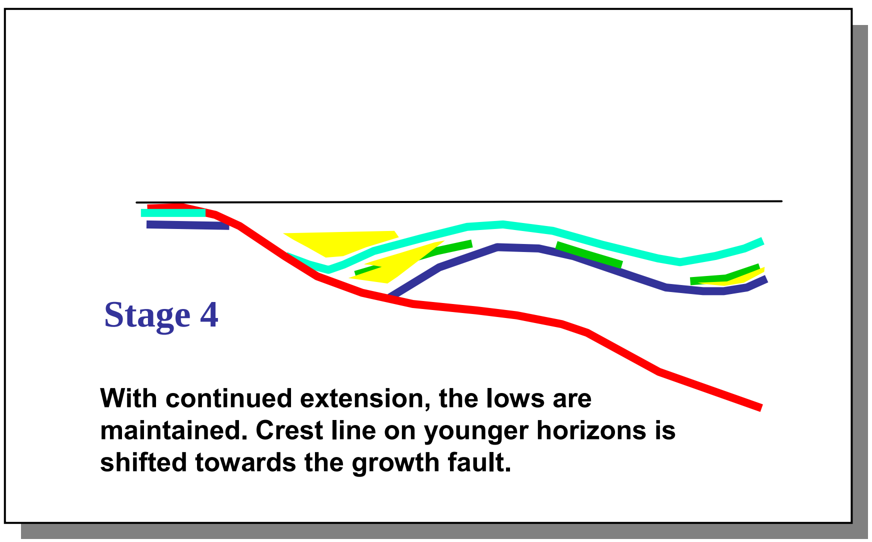
Trishear is a concept devised to model fault-propagation folds, allowing thickness variations in the triangular tip zone of the propagating fault. DepthCon doesn't do trishear, either, but we'll see how it works and the key references are given.

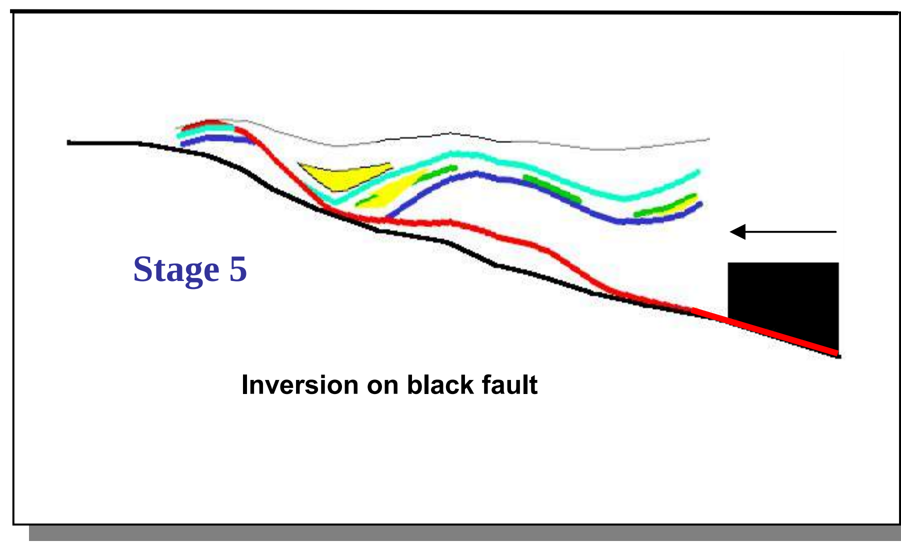
Extension and inversion during sedimentation controls bed shapes



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

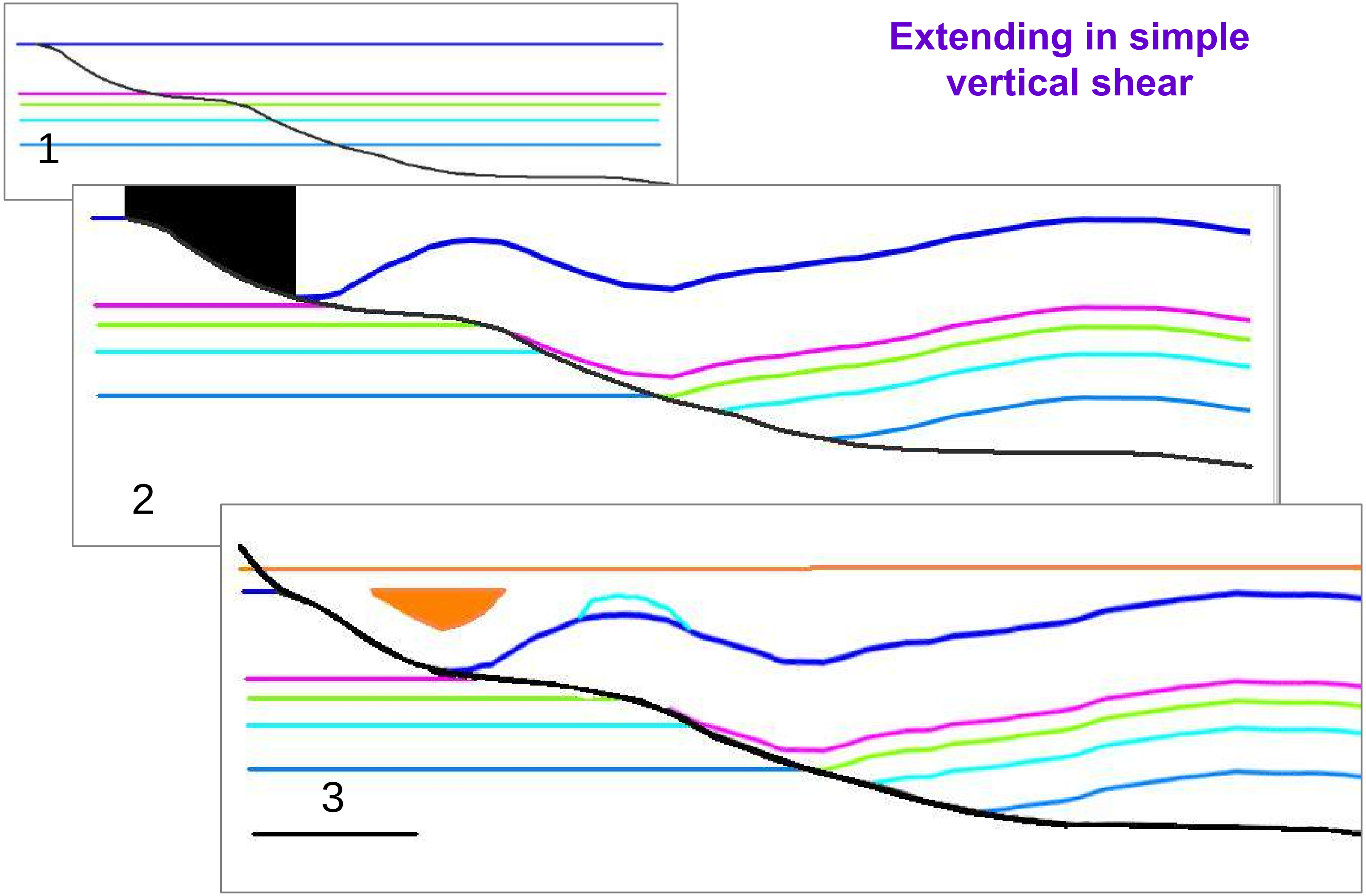






Simple shear modelling is not making any presumption of rock properties, its just a geometrical way to think about results of fault moves.

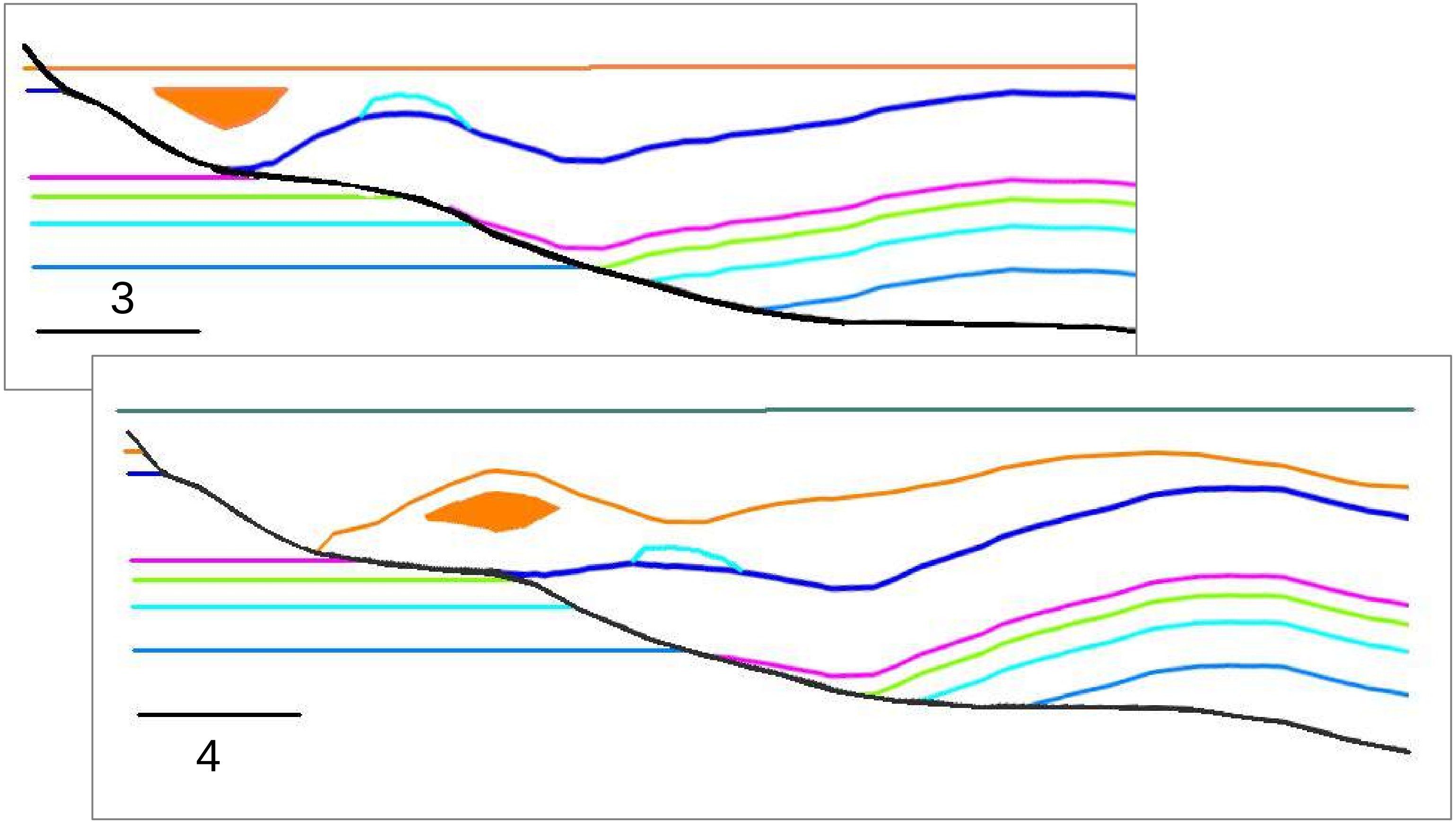
Extending in simple vertical shear



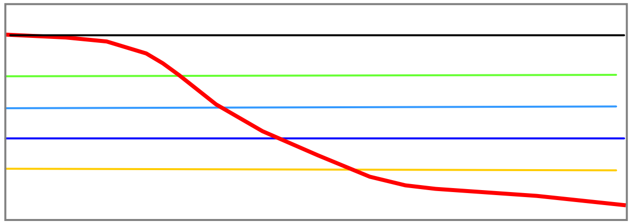
In more detail, here we take an unfaulted sequence, establish a ramp-flat-ramp fault surface (1, shown at different scale), and in (2) move rightwards by the length of the scale bar. Its a scale-independant result, in terms of geometry. A half-graben is formed over the leftward ramp, and a sag corresponds to the deeper ramp. The shape of the structures in the translated hangingwall depends entirely on the shape of the fault.

In (3), with post-dark 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, older beds are not showing thickness changes.

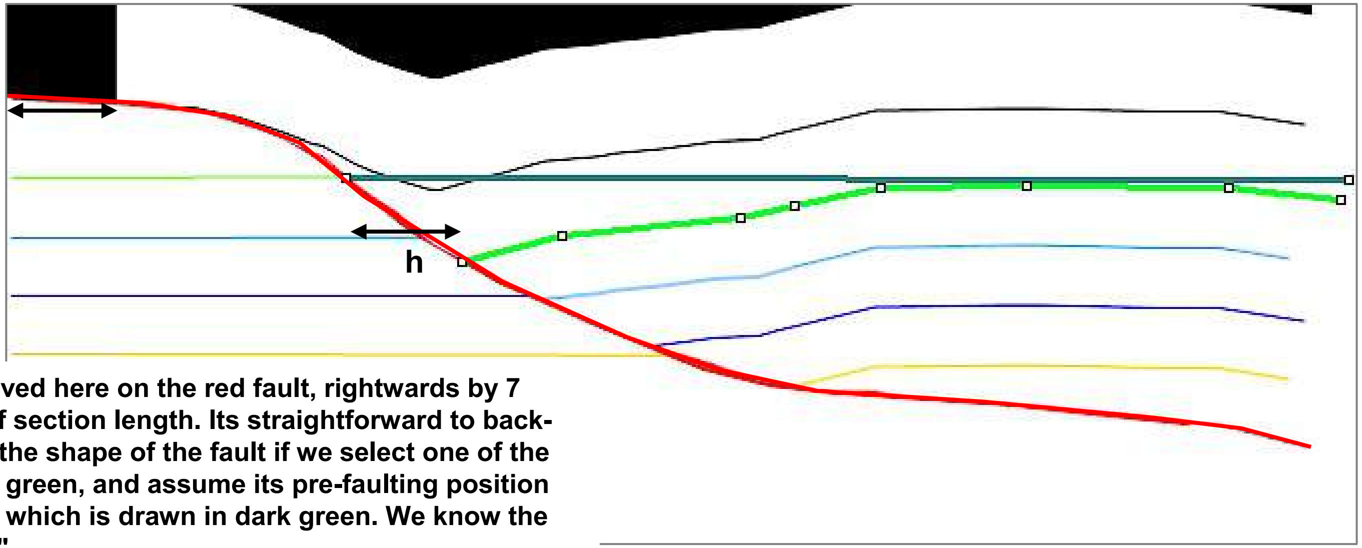
Extending in simple vertical shear (2)



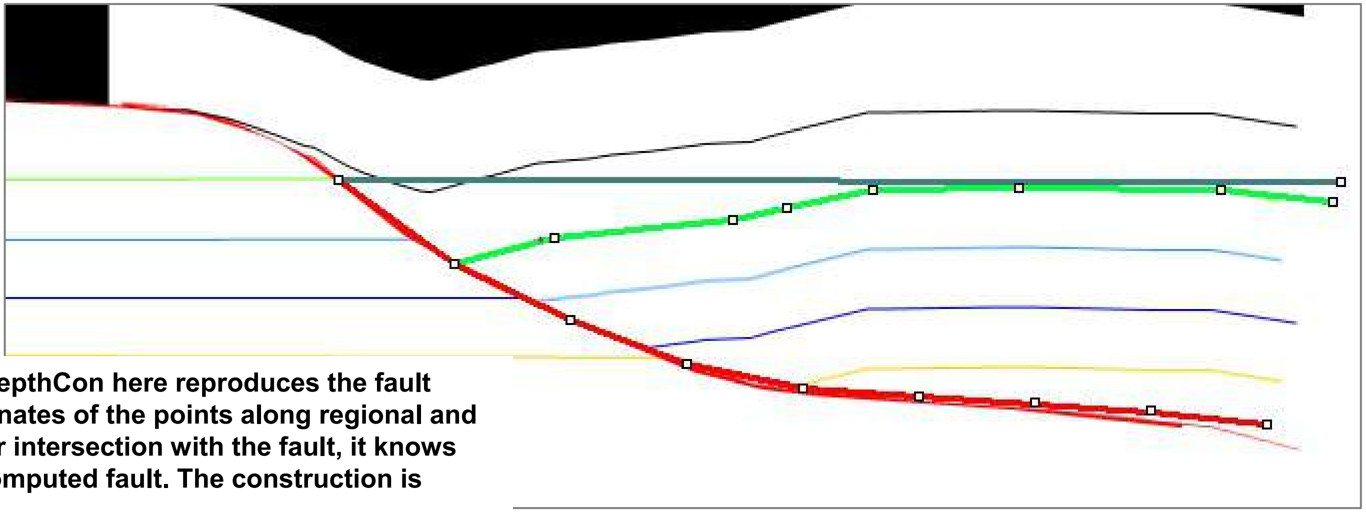
Ongoing extension from Stage 3 to Stage 4 is modifying basic, earlier geometries. The pale blue reef high has flattened in 4, leaving us with a puzzling large reefal buildup on a minor structure. The channel which formed in the hangingwall low at orange time is now translated to a structural high. Orange-blue 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 force the reef to have no apparent relationship to positive structure.



Fault shape construction, using rollover and regional (1)

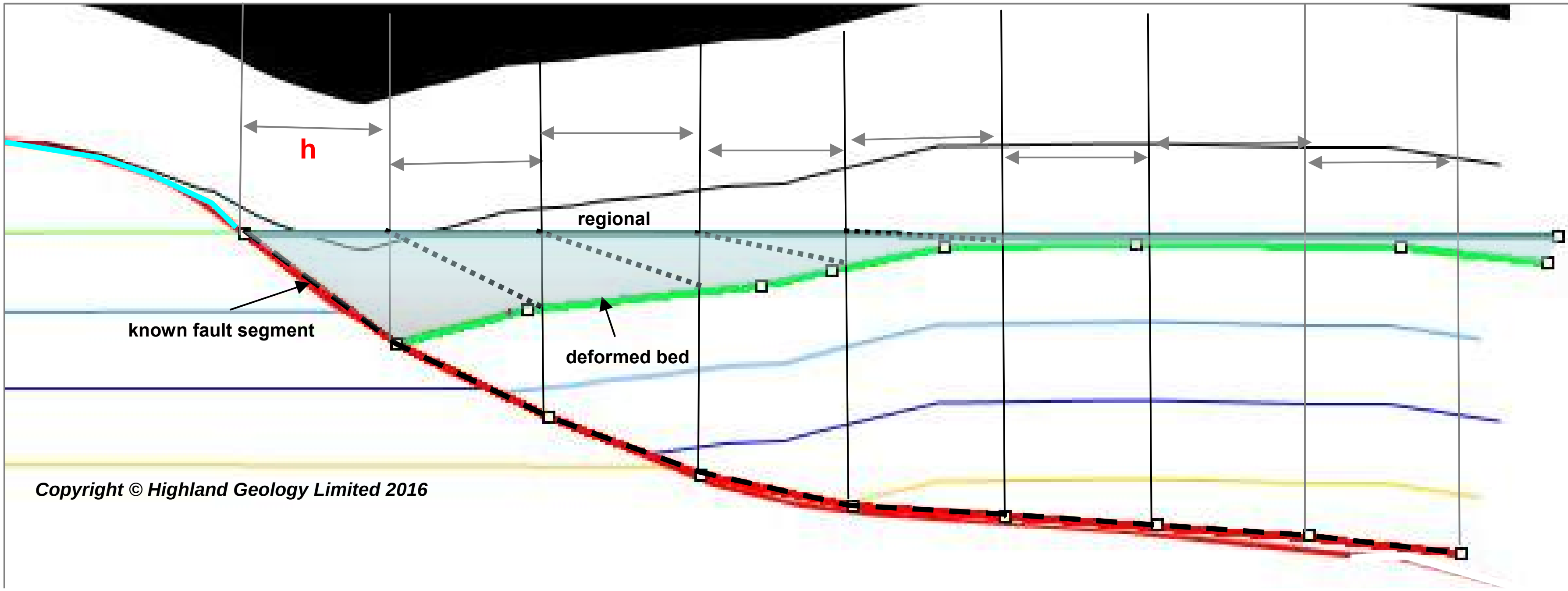


We've moved here on the red fault, rightwards by 7 percent of section length. Its straightforward to back-calculate the shape of the fault if we select one of the beds, like green, and assume its pre-faulting position (regional) which is drawn in dark green. We know the heave, "h".



Assuming vertical shear, DepthCon here reproduces the fault used. Given just the coordinates of the points along regional and the 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)



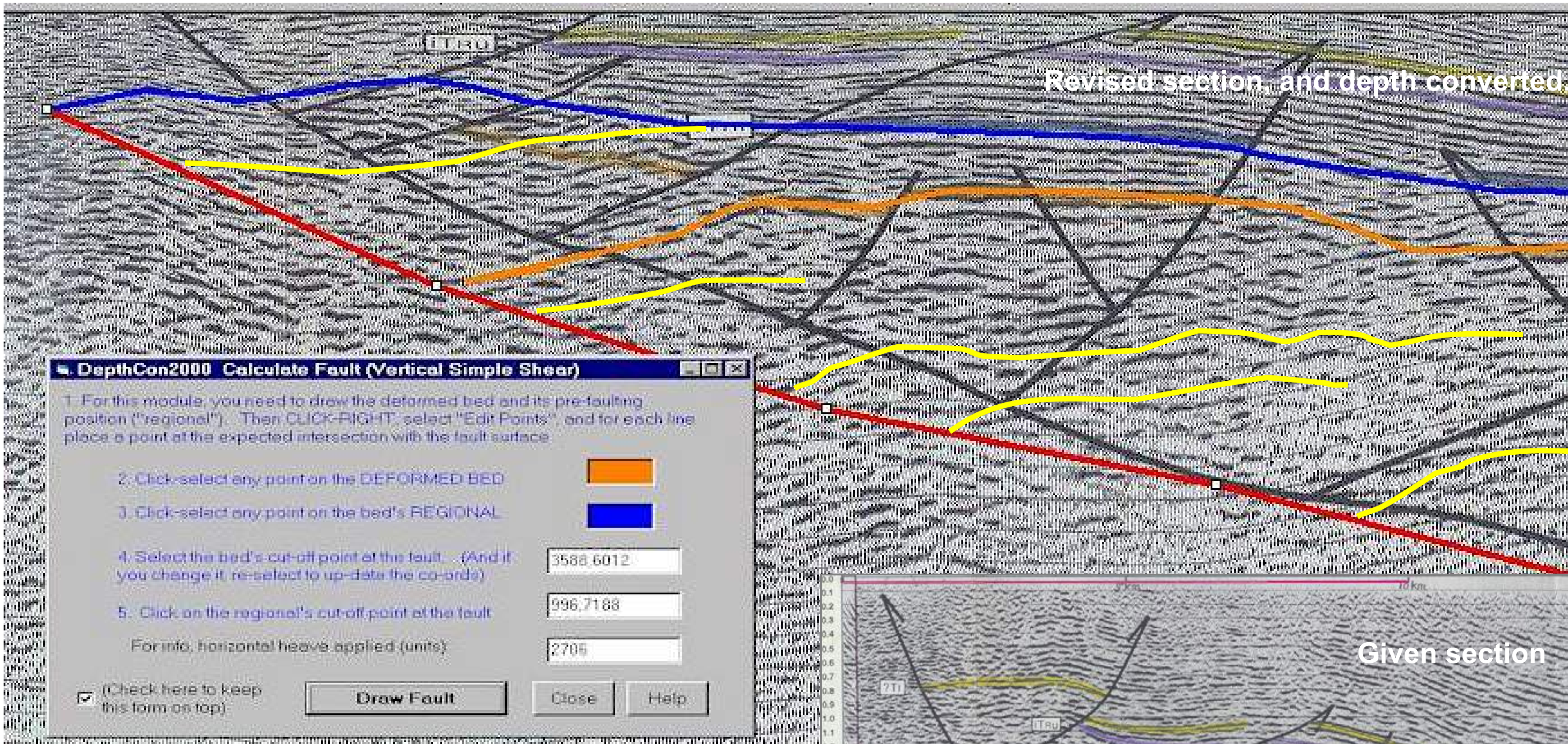
Draw one of the deformed beds, in this case green, in the hangingwall, and sketch its pre-faulting position. If looking at a growth fault this is easy, what you want is any pair of beds in the hanging wall sequence: the younger one is the regional to the other bed, because it was at the sediment-water 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.

You don't need to pick the known fault segment between footwall and hangingwall cut-offs, the program knows the horizontal heave as you will have mouse-input the respective cut-off positions (intersections on the fault) for the deformed bed and the regional.

It simply scans along the regional bed's trace file by an amount equal to the heave, finds the co-ordinates of the point where the next heave increment point lies, then drops a perpendicular to the deformed bed and likewise finds the co-ordinates of that point of intersection, and with this information it calculates the gradient of the dotted line, which is a segment parallel to the fault which we want to display. It projects that segment from the end of the known piece of fault, and repeats the exercise for the next segment, again looking along the regional by the amount of heave. It does this until it reaches the end of either of the given two lines.

The program 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. The regional and deformed bed lines have to be long enough to give at least one heave increment for the resulting construction, of course.

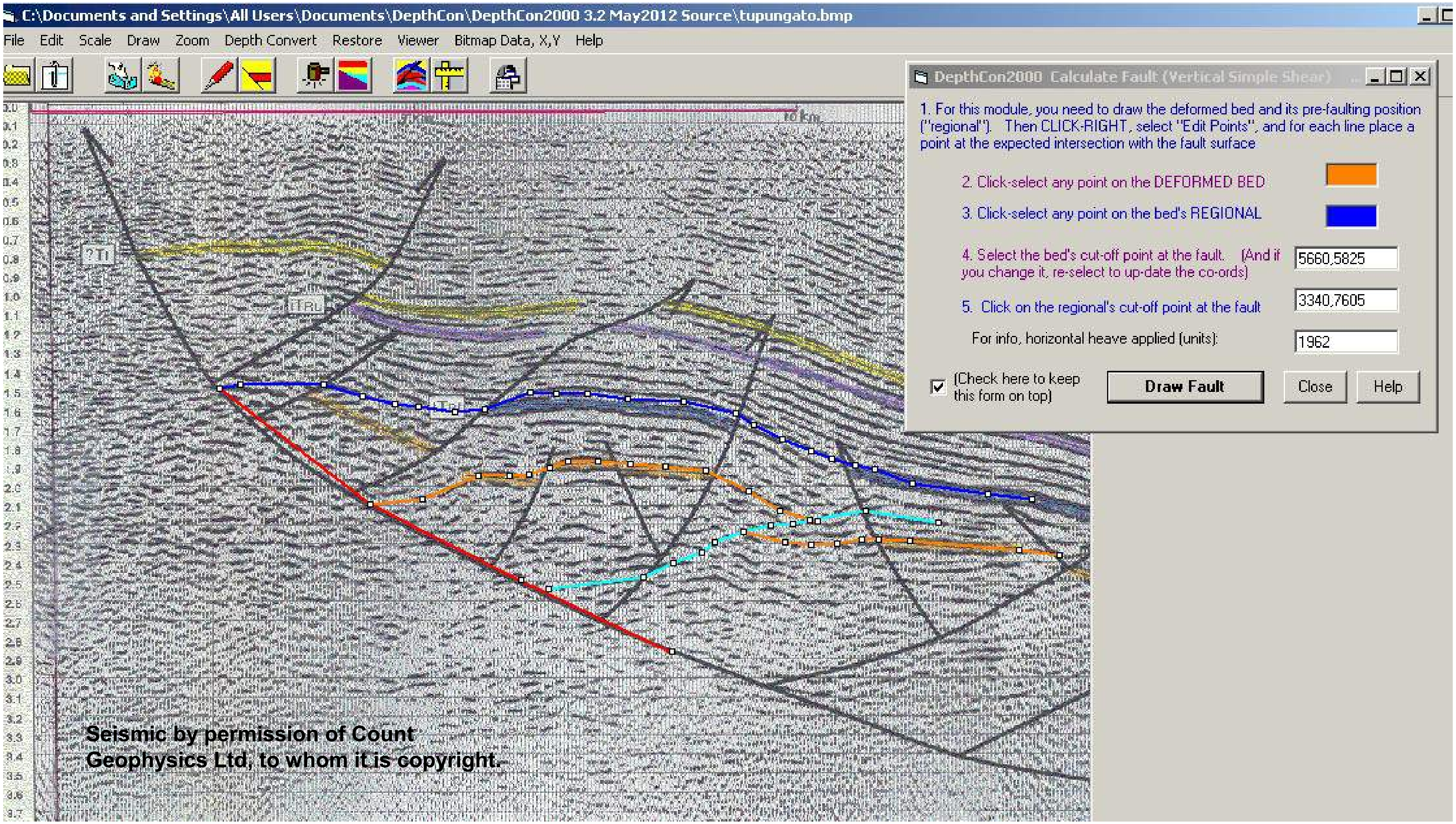
Fault construction



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 is 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 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.

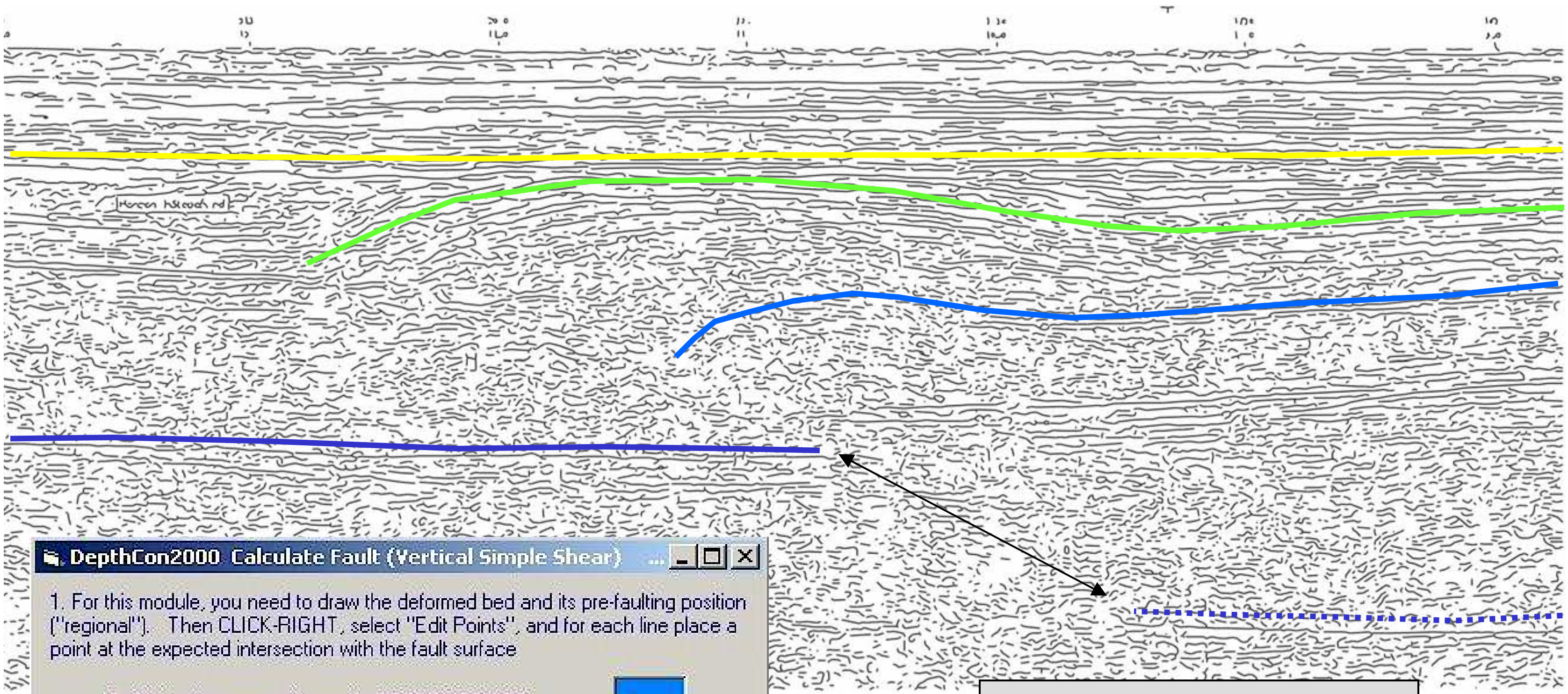
Suppose the master fault pick is correct?

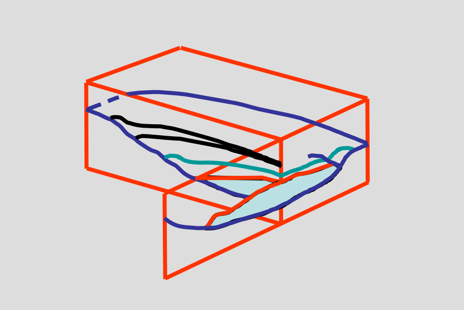


DepthCon is about experimenting, and I always push the interpretation to see what's reasonable and what isn't.

If you like to assume that the master fault drawn in black is more or less correct (perhaps you know it is, from well data or from some better, adjoining profiles), then we can experiment to see what bed shapes are compatible with constant-heave assumption. By trial and error I came up with this red fault for the pair of beds, dark blue and orange, and this model might seem more useful than the preceding one, in recognising some transpressional wedges which are consistent with the seismic. That gives me a turnover on orange, instead of the given model, and radically alters the way I think about orange prospectivity.

Calculating a fault for restoration and correlation checks

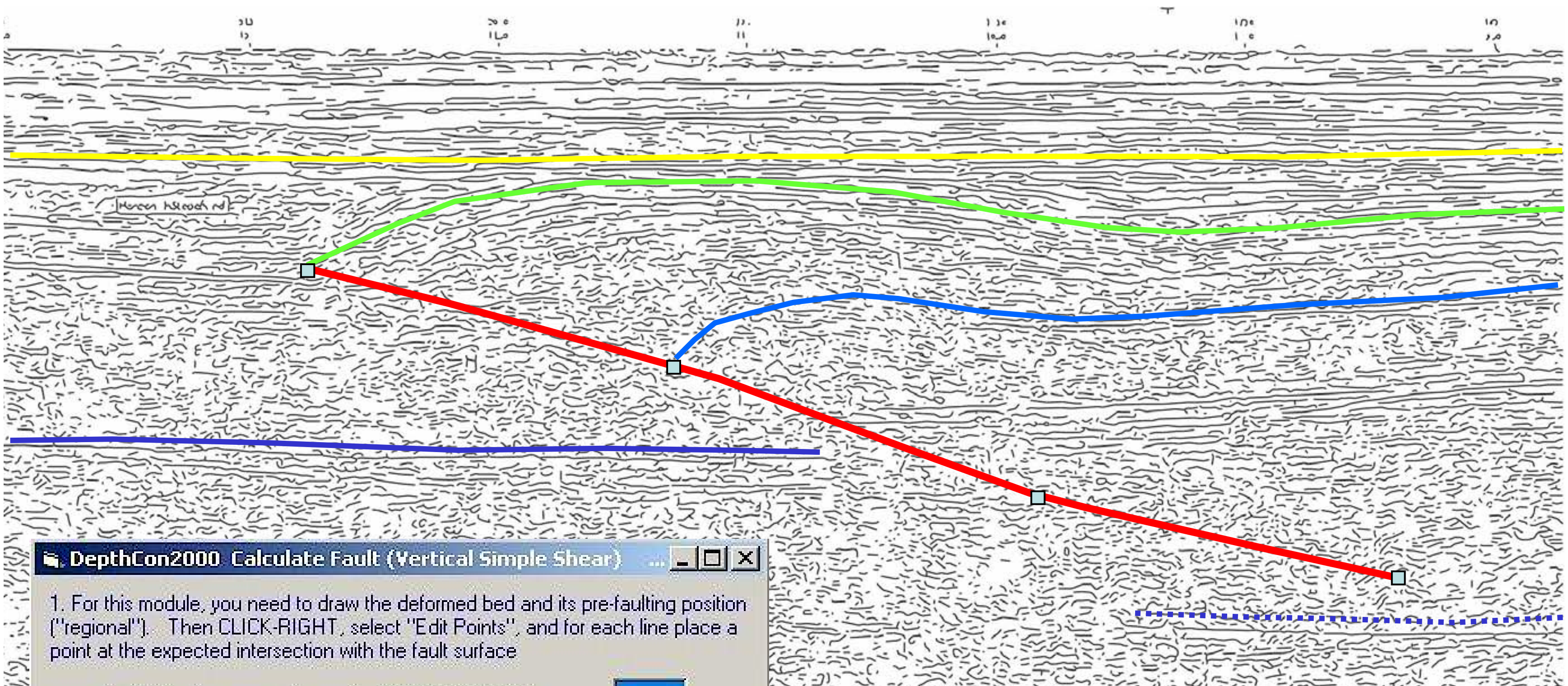


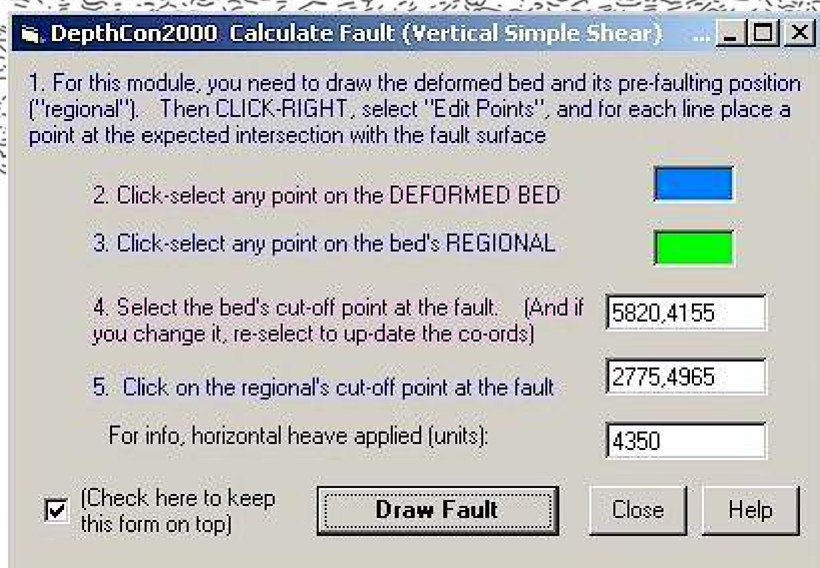


Growth faulting geometry

Here's a trace of a very poor quality old line. it shows a pair of beds which can be used to calculate a fault surface which isn't imaged. If we can compute a fault trace which looks reasonable and restore the displacement, we can then test the dark blue correlation, is it the same as the dotted horizon, which is what the interpreter thought.

We calculate a fault consistent with green being regional to underlying lighter blue. Just these two markers, define the red fault trajectory.





The calculated fault agrees closely with cut-offs and dip indications.

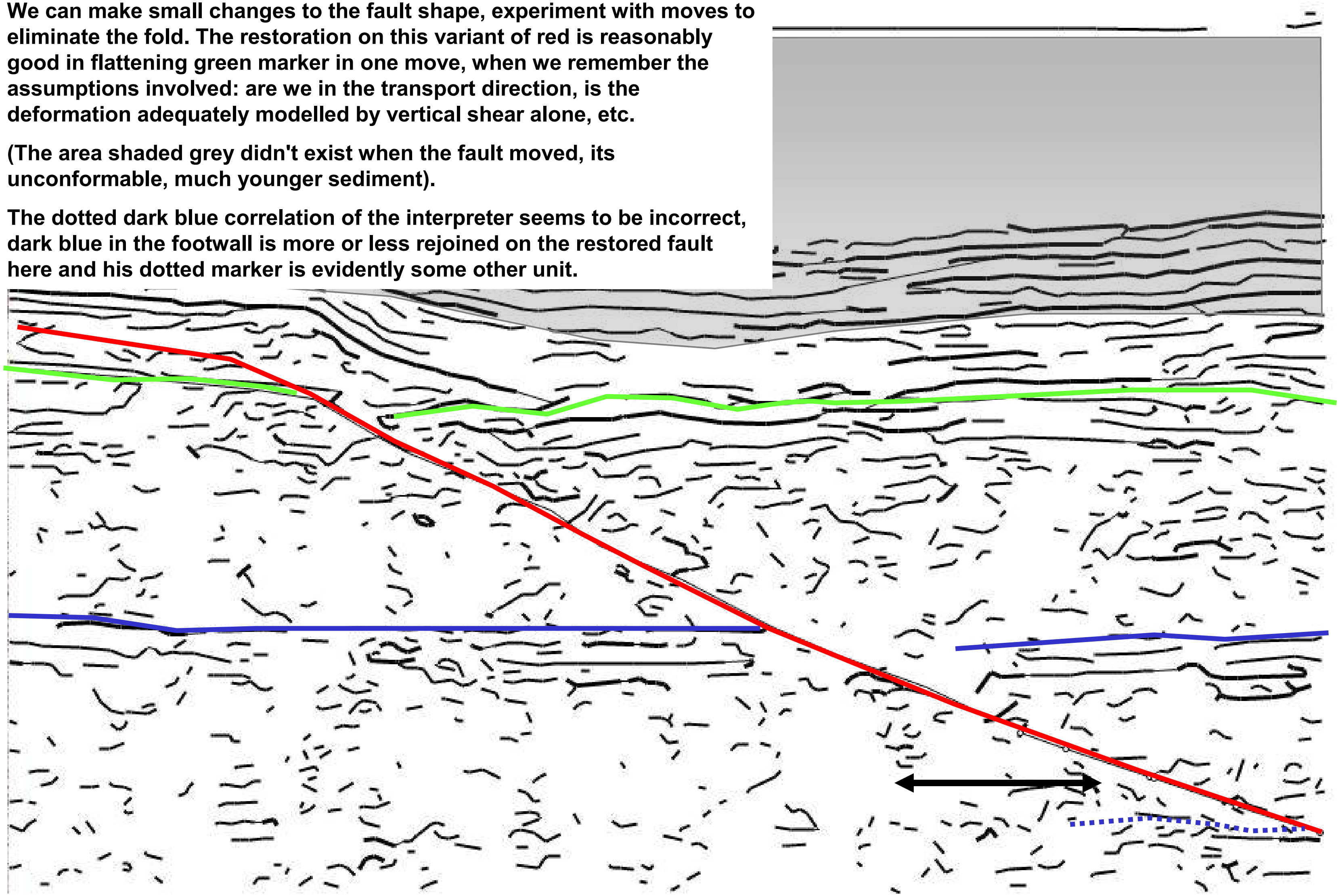
These calculations are quite sensitive to the heave value, changing the cutoff positions can alter the result a lot, but in this case the answer is constrained. Is the dotted line the dark blue horizon?

Now restore the inversion and check the horizon matching

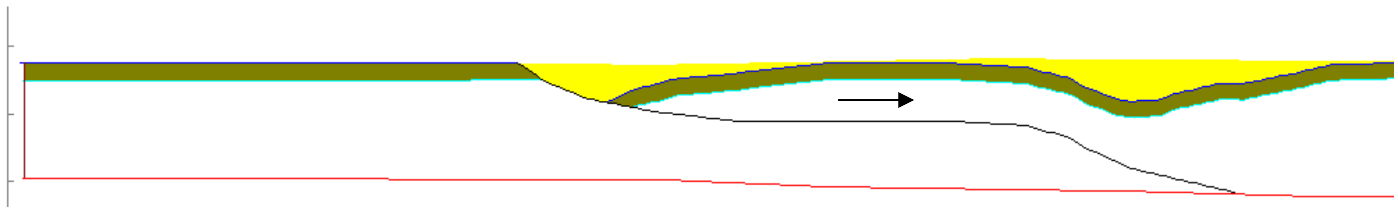
We can make small changes to the fault shape, experiment with moves to eliminate the fold. The restoration on this variant of red is reasonably good in flattening green marker in one move, when we remember the assumptions involved: are we in the transport direction, is the deformation adequately modelled by vertical shear alone, etc.

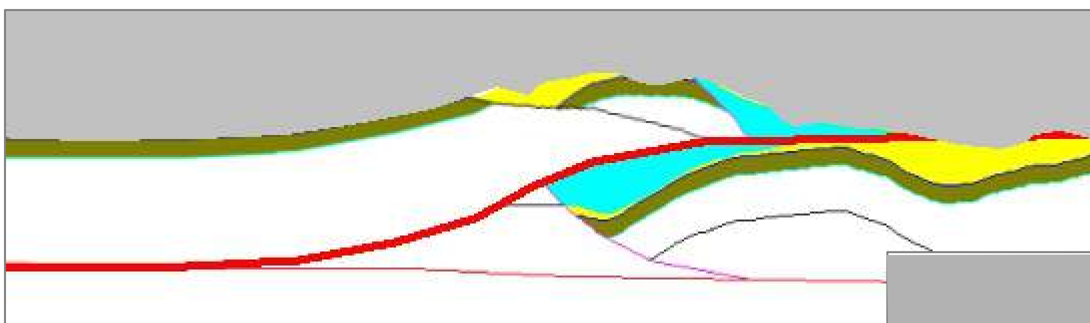
(The area shaded grey didn't exist when the fault moved, its unconformable, much younger sediment).

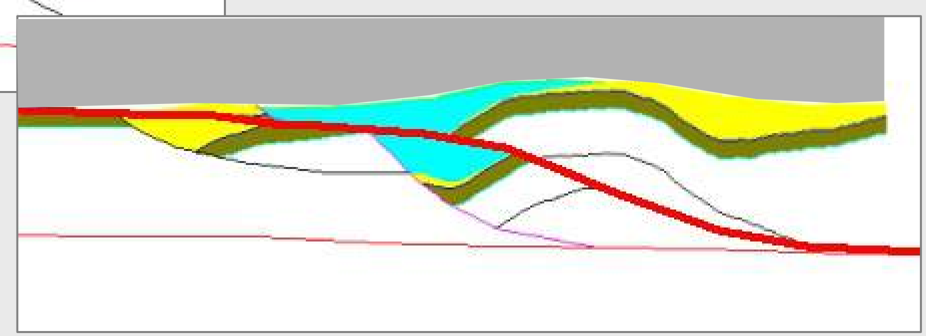
The dotted dark blue correlation of the interpreter seems to be incorrect, dark blue in the footwall is more or less rejoined on the restored fault here and his dotted marker is evidently some other unit.



DepthCon models to assist interpretation of inversion geometries

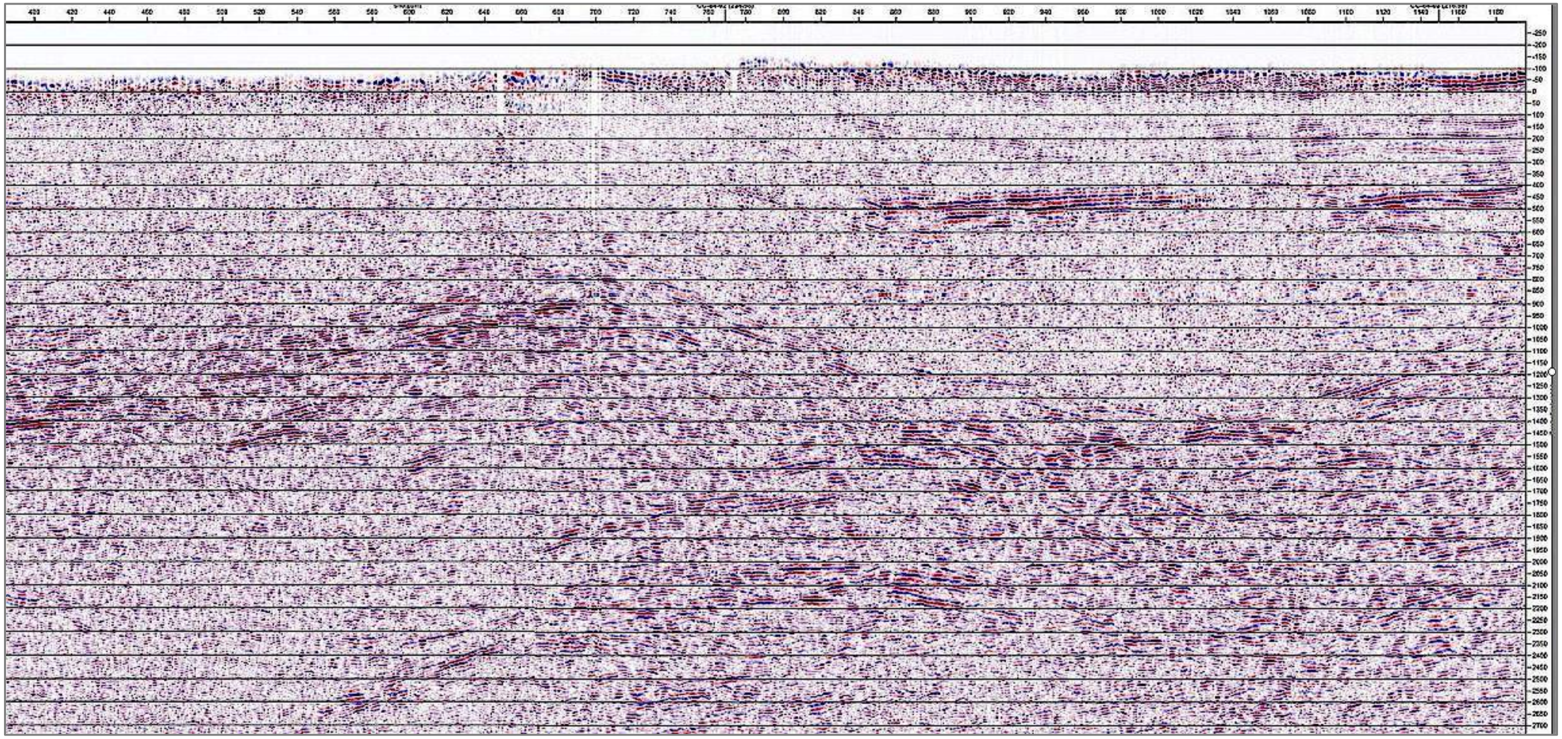






If the seismic isn't of good quality you can focus on the few lines which do provide clues, and model structure development: and when you have a match, the less-clear lines become more valuable. Here, growth faults produce local basins which fill with sediment as the faults continue to move. Several 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.

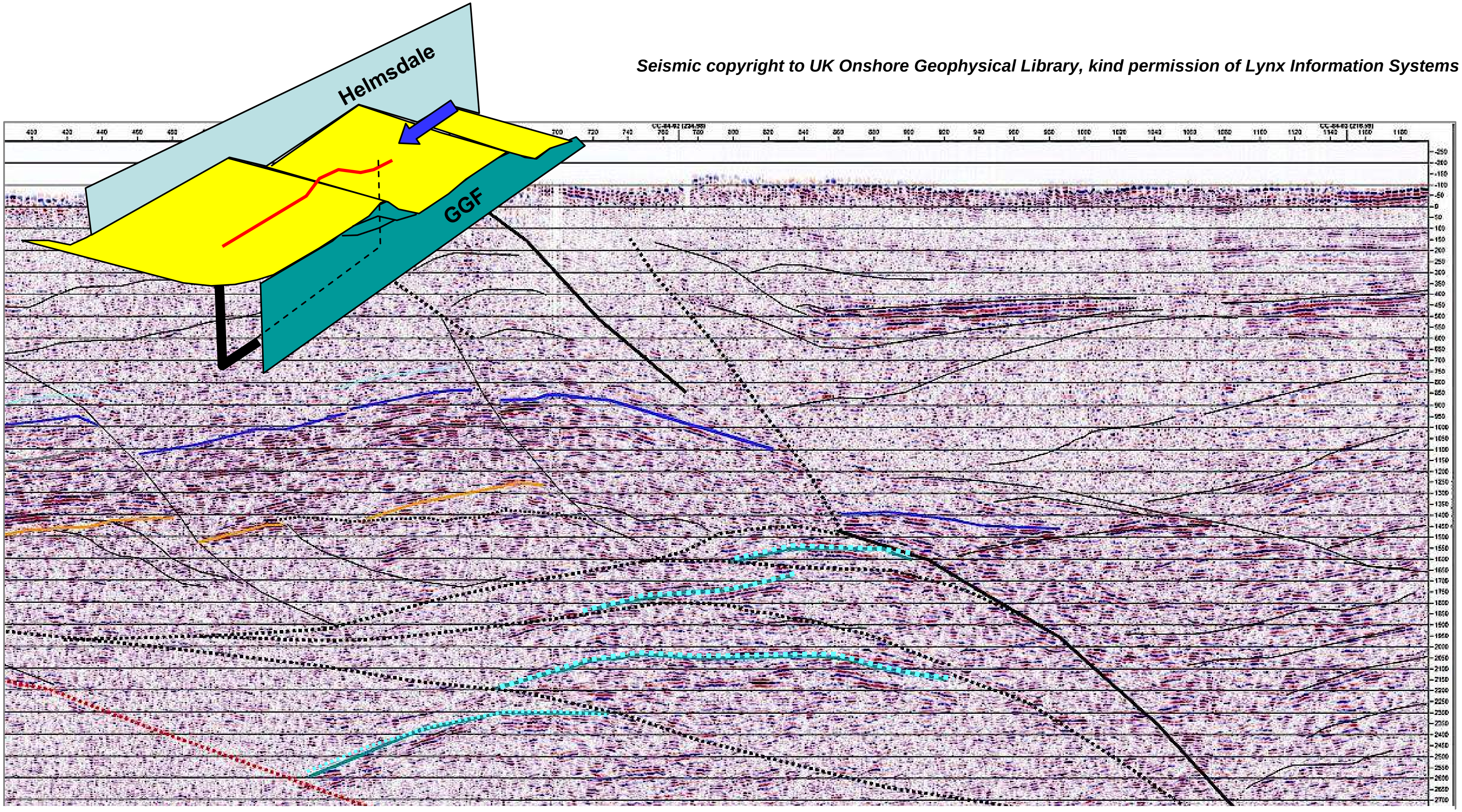
Challenging interpretation jobs: is this block one of those we should get excited about, or is it unprospective?



Presuming we are in a basin with proven source rocks, large structures call for careful and imaginative review. Apparently complex structure becomes attractive when we figure out how it works. If we can understand what kind of structure style we are dealing with, we are justified in picking it in an adventurous way; and in shortlisting it for acquisition if a large closure is identified.

In tackling a line like this one, most people will make the obvious picks, draw some simple fault pattern and the end product is going to be a conservative one. It will be data-driven.

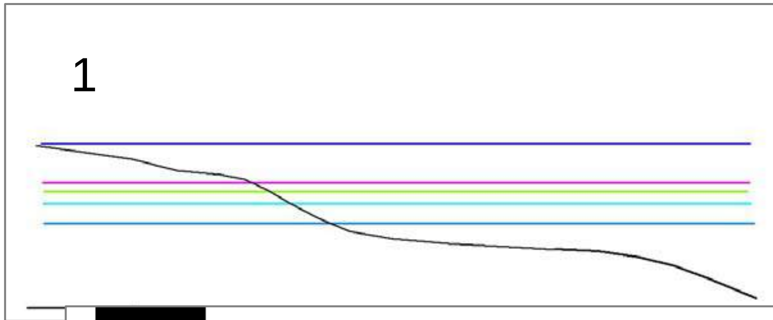
The alternative is to say, what if? Can we speculate on how these geometries developed, make some starting model and test it, alter it, until we get a result which looks like the seismic? Then we have a predictive model and can reasonably interpret the line. Let's see how DepthCon can be used for this result.

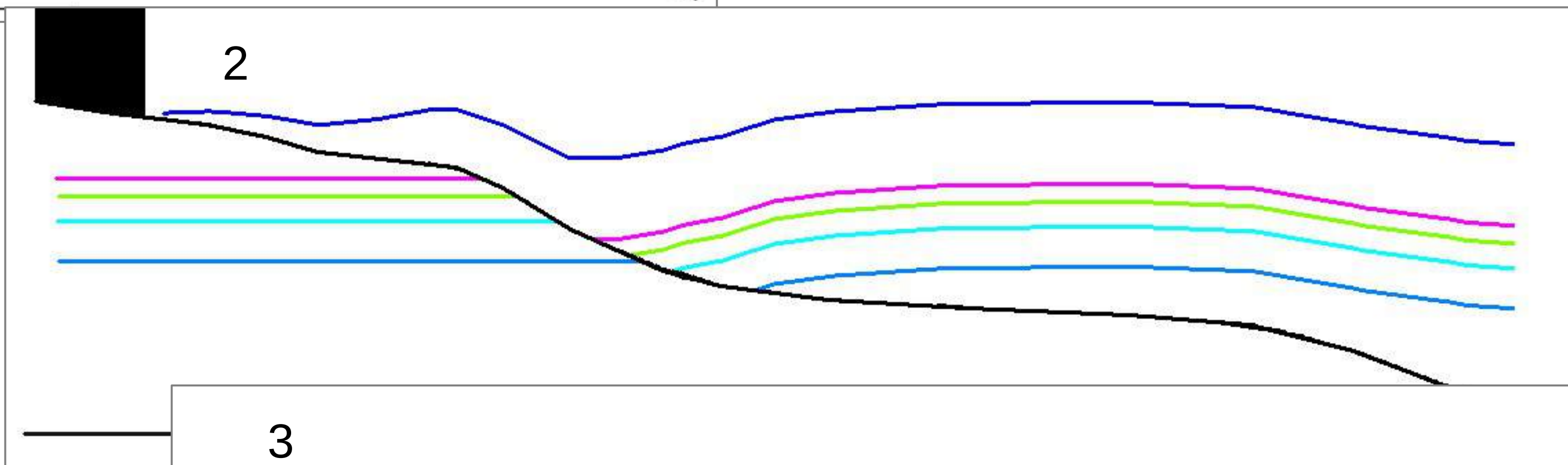


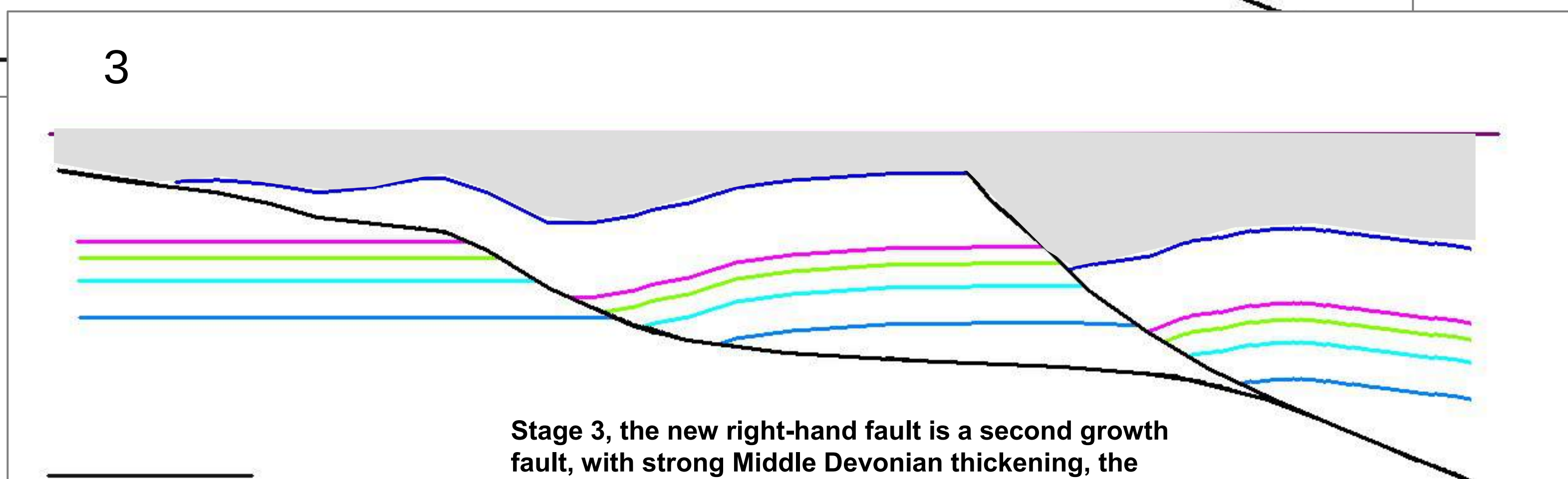
Here is an instance where I can use the course software, DepthCon. We can only get a limited understanding of this profile by picking the markers and character-correlating. We have to make some plausible assumptions and test them. We need some clues as to the sort of geometries which might result, and when we have a defensible model we can justify making picks which will seem adventurous or just puzzling to people who make purely observational picks.

The rocks are Devonian and this line is a profile shot between two more or less parallel strike-slip faults in the Great Glen system, Scotland. I think the line is imaging a major extensional fault linking the wrench faults, it has undergone some shortening in basin inversion, as the blue arrow suggests. Partial reversal of the fault is accompanied by some sequence repetition in the footwall. Can I get some support for the idea that the pale blue events drawn dotted really might be the same marker repeating on low-angle thrusts, as shown? And what could I do to improve my understanding of the likely shapes of the faults which are not imaged? A forward modelling exercise applying it is shown in the following slides, to clarify the geometries will might result in an extension-inversion cycle of this type.

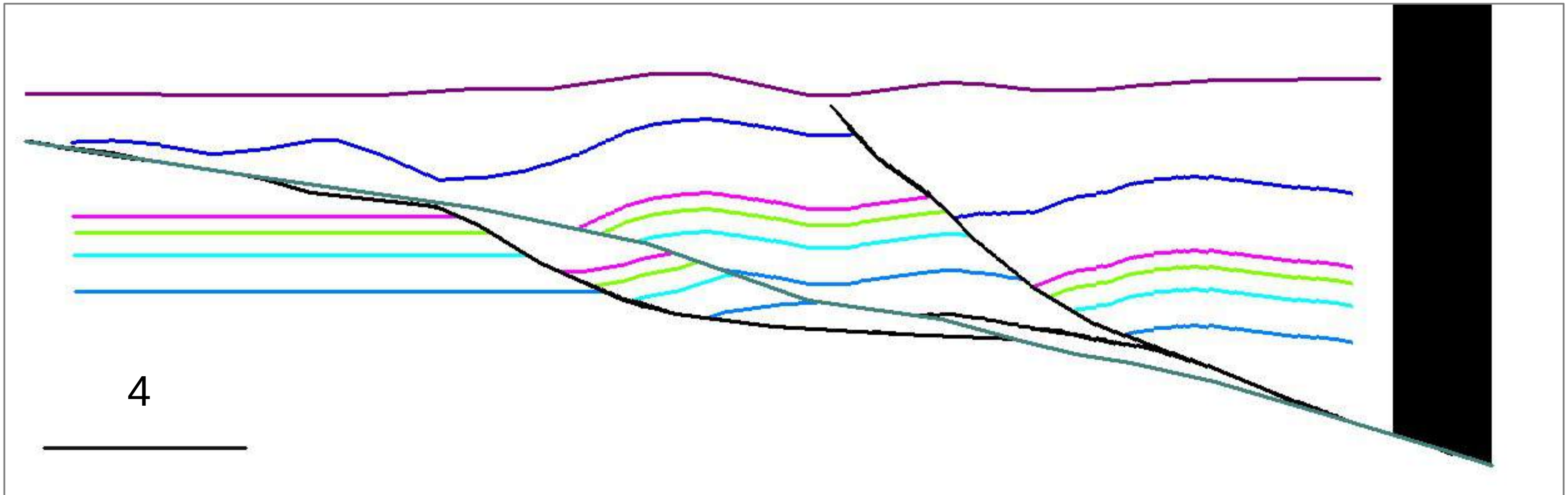
Model for Black Isle fold. A Lower Devonian template is drawn (1) and a growth fault will operate as we add more sediment. Next we'll put the Middle Devonian in, the fault will extend to the right and sustain the Middle Devonian depocentre as more sediment comes in (2).



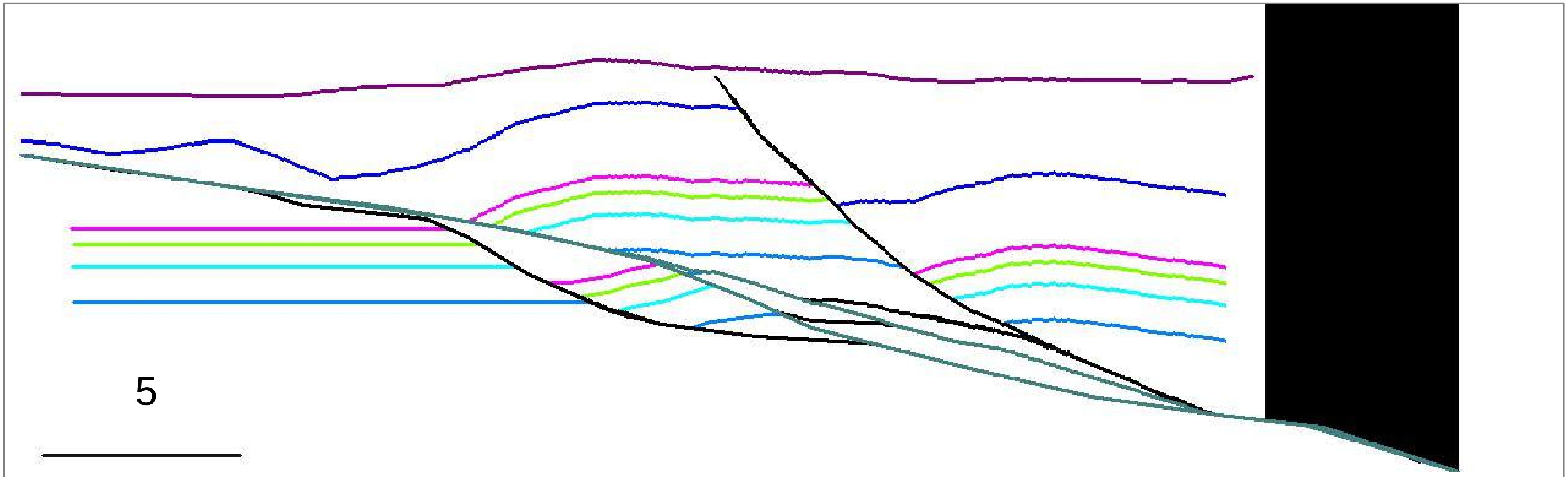




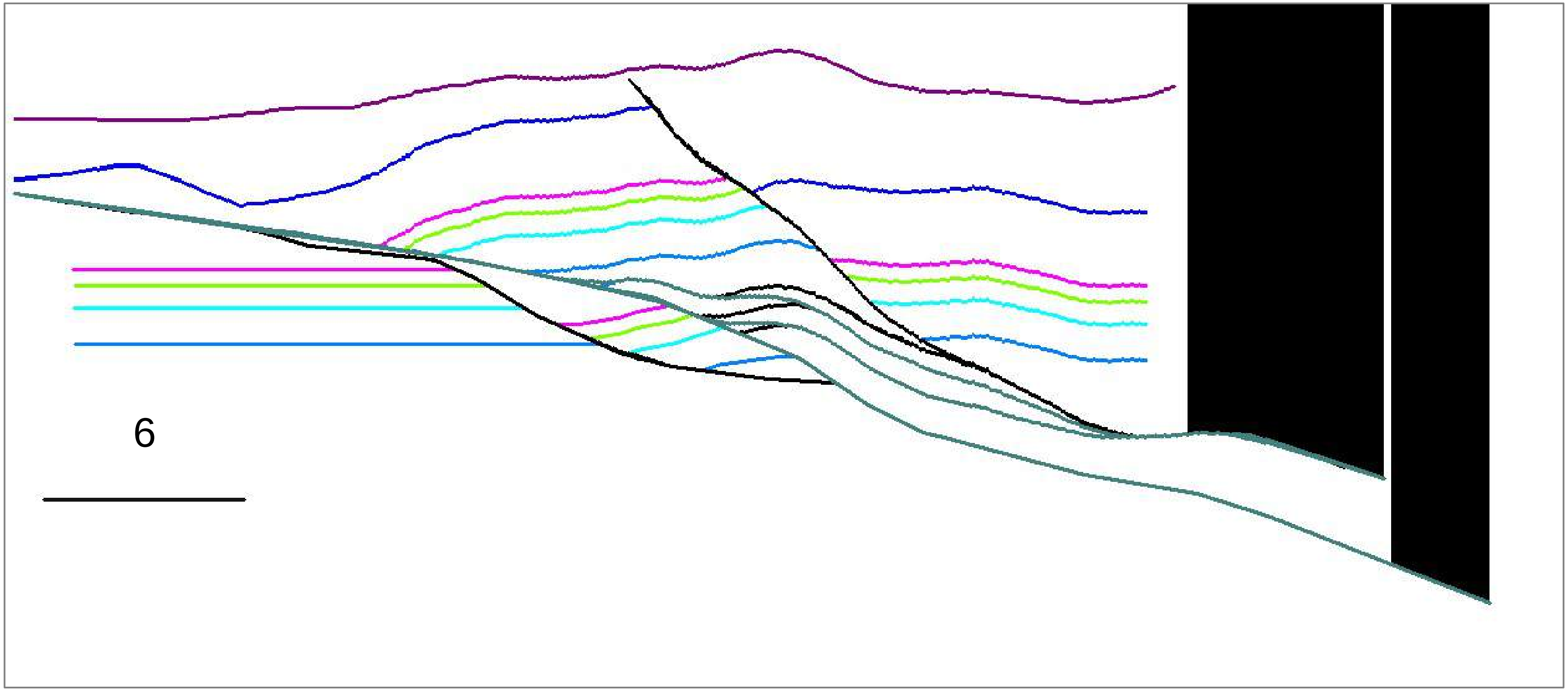
Stage 3, the new right-hand fault is a second growth fault, with strong Middle Devonian thickening, the grey sequence post-blue. What I want to do next is initiate a ramp inversion and see how the geometry develops.



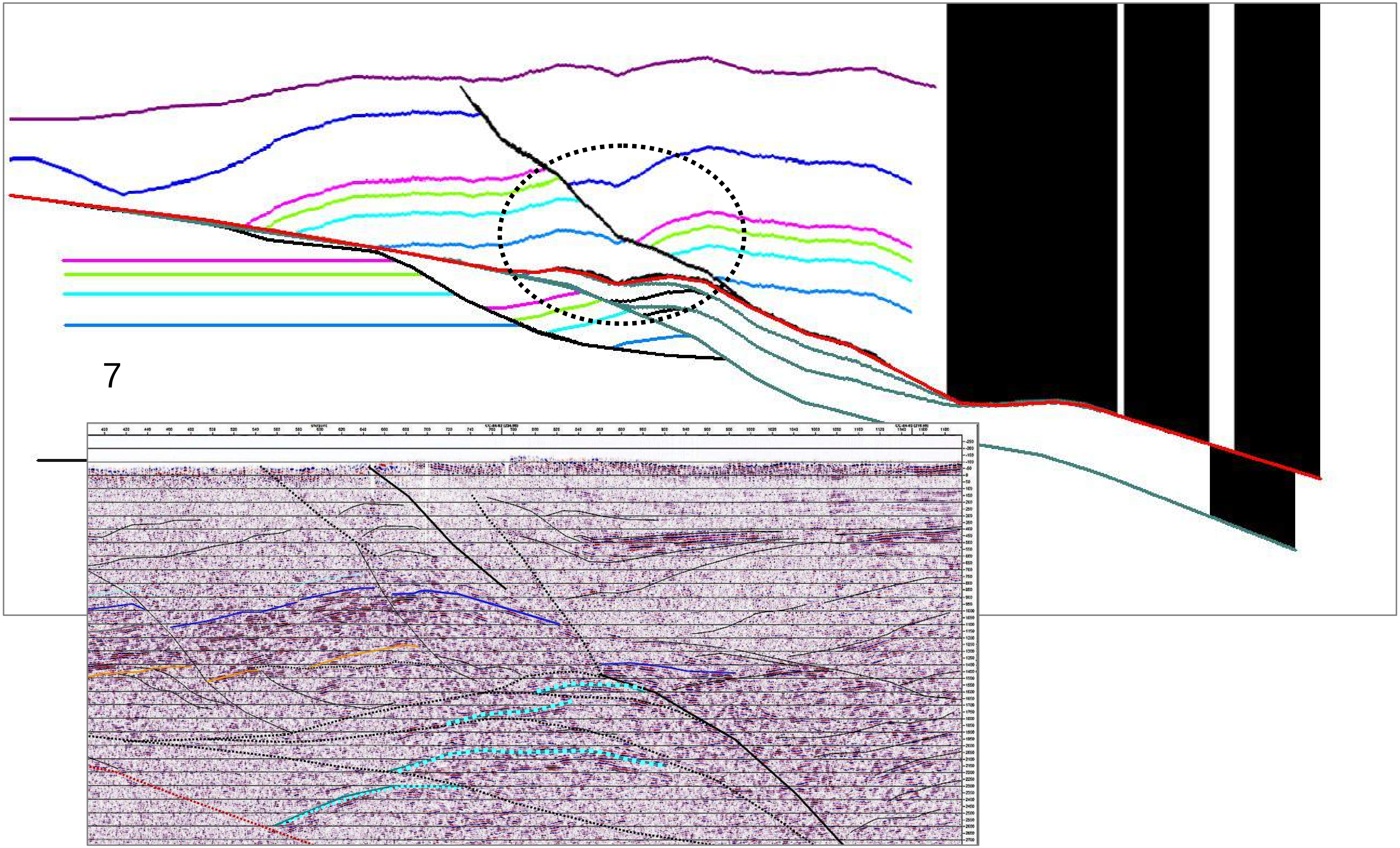
Stage 4 adds a footwall collapse fault, dark green, reversing the main ramp slip sense.



And a second one is added, order right to left. What I want to do now, 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 me think its more or less on the right track. I've now got a huge jump in my confidence in the interpretation, I have a viable model and its giving predictive ability.

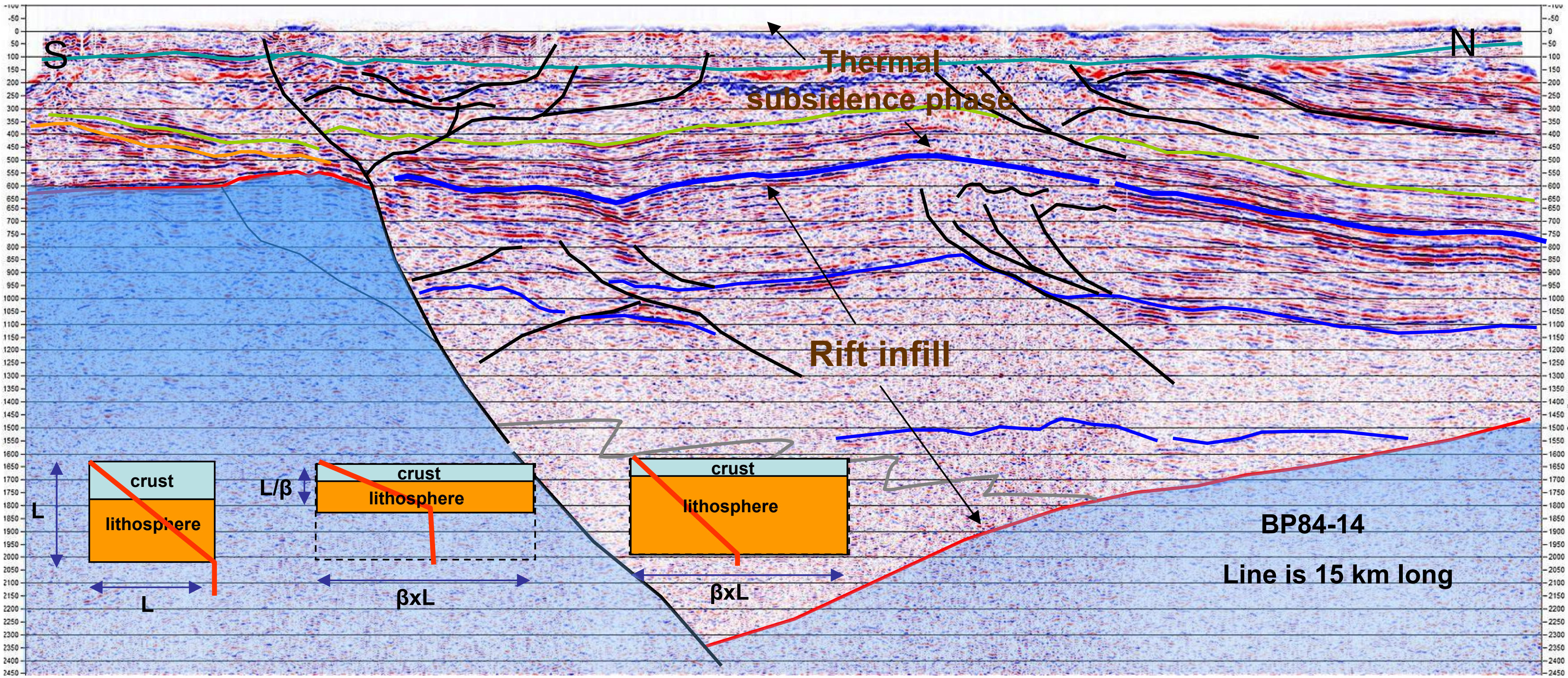
I can look at more of the dip lines and check for additional features supporting the concept. I can improve it, for example by adding a bit more rightward extensional displacement using the roof fault on the collapse duplex (red) I can reposition the fault blocks to give that kink we see, in the black fault. I could run a depth conversion too.

So that is what DepthCon is for.

With this software you've got the ability to model the many possible outcomes of extensional and inversion faulting. You can also constructively review an interpretation given to you. Is it reasonable, are the hangingwall geometries sensible with respect to fault shapes interpreted, are the correlations confirmed when severed horizons of interest are rejoined? If not, what is the problem: should the faults be drawn differently, are the horizons wrongly picked, does the section I'm looking at actually allow me to make these tests, is the geological model just plain wrong? If there is salt in the section, when you depth convert does the interpretation still look sensible?

Many times when you look at farm-in opportunities or new acreage for licensing, given interpretations will immediately be flagged as implausible. But in the process of making these tests you may see prospectivity in a different way. Larger structures become apparent, perhaps, or different rollover geometries are suggested, and explanations appear for discordant reflectors which the interpreter has not picked ("bad processing") or has incorrectly mapped.

And in technical meetings, its helpful to be able to show that your picks are geologically sensible: they may not be right but they aren't going to be shot down by somebody saying, "That doesn't balance!"



Rifting followed by thermal subsidence: Widmerpool Basin, UK

McKenzie in the late 1970s envisaged basin development in terms of stretching crust and lithosphere (beta in this sketch is his stretch factor) in a rifting phase, causing the peridotite solidus isotherm 1333 degrees C to rise and so the heat flow (red line) increases. The upper crust extends by brittle fracturing, the lower crust and top of mantle deforms in ductile style. When the stretch finishes the isotherms return slowly to original configuration and the mean density of interval L is now greater, so there is subsidence and a broad depocentre is sustained, overlapping the edges of the rift. This generates "steer's head" geometry, which actually is only evident in cross sections which are strongly exaggerated in depth. The subsidence phase produces re-activation of the rift faults.

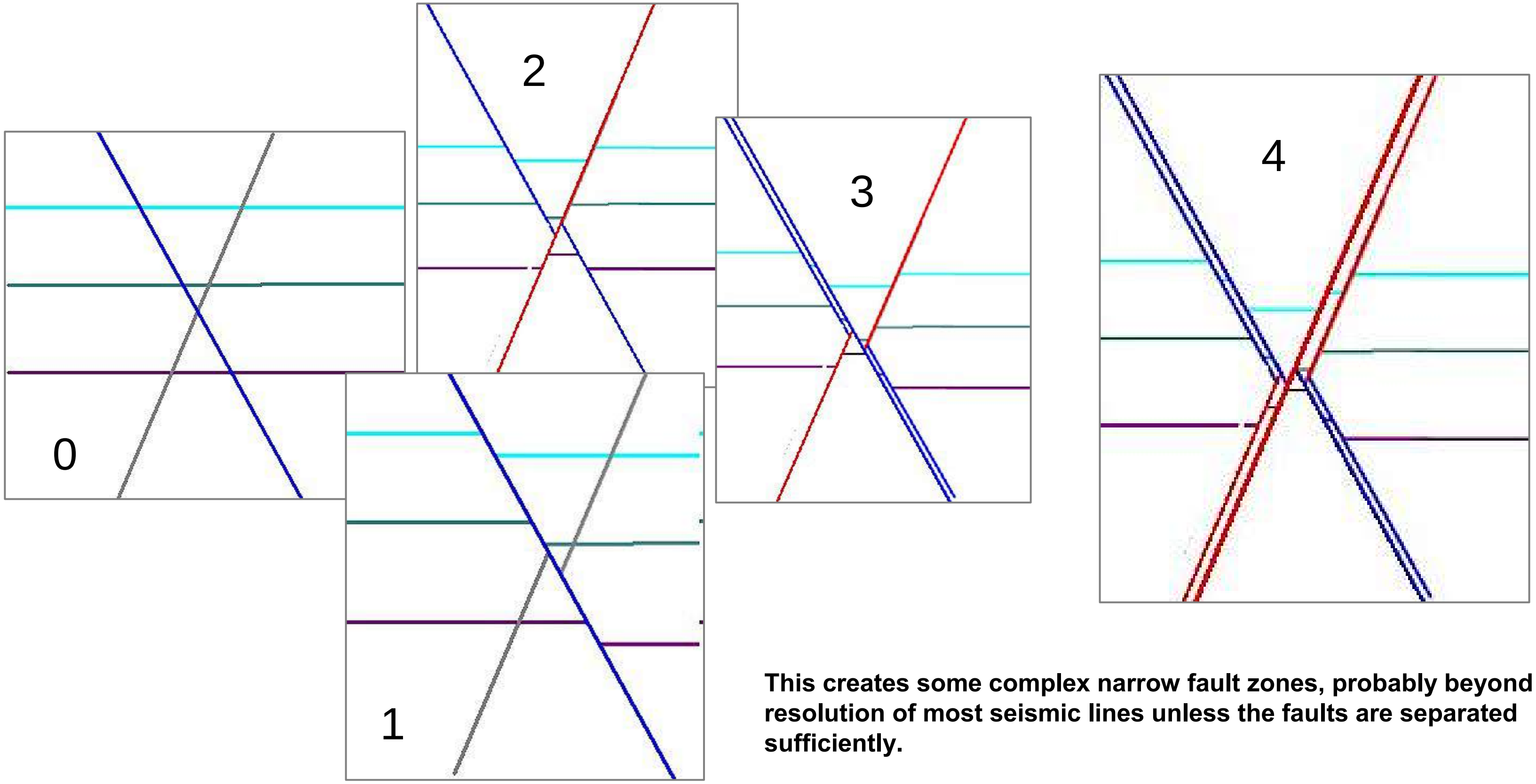
McKenzie didn't address inversion. Real basins are more complex, this Early -Late Carboniferous example from UK East Midlands has an inversion phase at the end of rifting (Dinantian) and indeed a second inversion in the Tertiary. But the McKenzie model is a very successful one, which integrates source rock maturation with extensional structural history.

Extensional basin margins (1)

Extensional faults which initiated and grew with the max effective stress being vertical, are "normal". We tend to think of them as dip-slip faults but often they will have a multi-phase history and acquire a significant component of oblique slip.

Although conjugate faults are predicted in rock failure theory, with sigma 1 bisecting the acute angle between them, usually we see one fault set dominant with the other very subsidiary. Why? Several possible reasons.

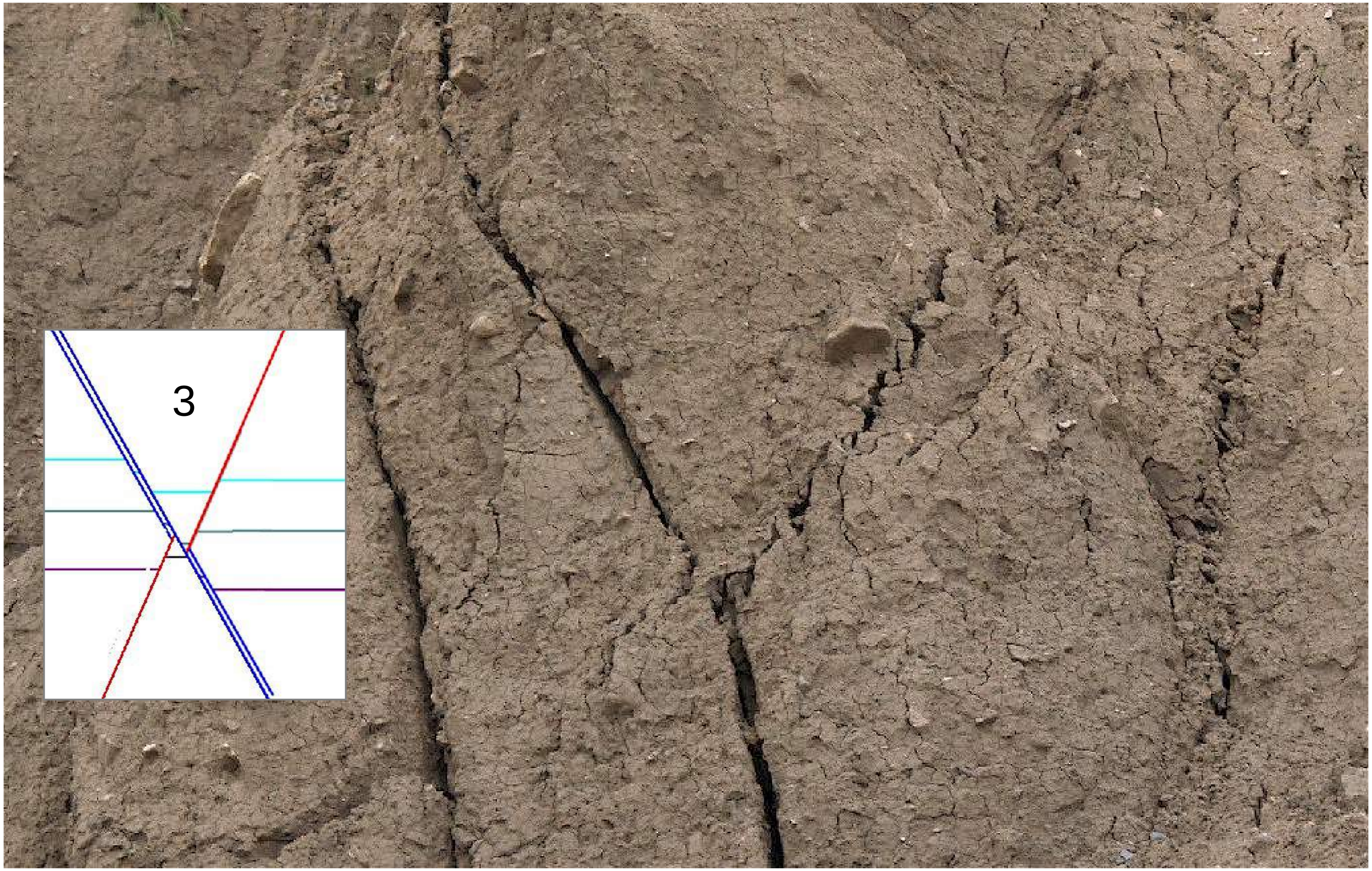
One is, there's a space problem in allowing both faults to move more or less at the same time. We can solve it by alternately slipping on the faults, thus:



This creates some complex narrow fault zones, probably beyond resolution of most seismic lines unless the faults are separated sufficiently.

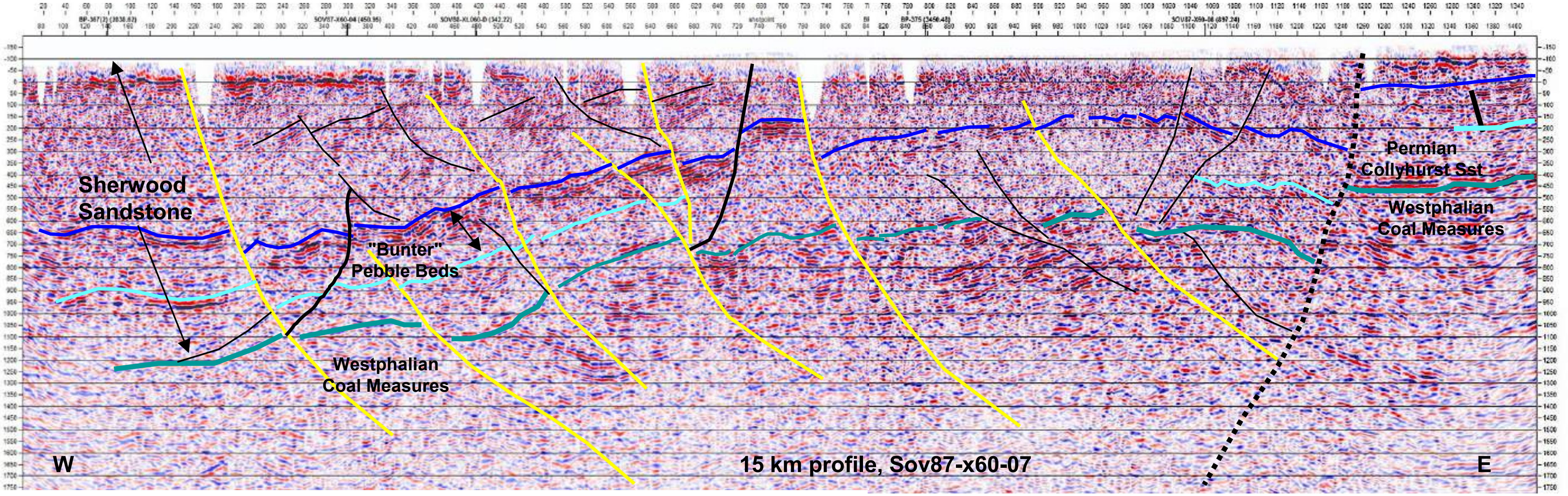
Extensional basin margins (1)

Stage 3 in the process might be exemplified by this section, in boulder clays at Robin Hood's Bay, Yorkshire. Load in this instance was ice. The dominant shear is probably multi-phase, the other shear is arrested, made of intersecting near-vertical segments which have not fully combined into a single surface.



Extensional basin margins (2)

A probably more important reason is that initiation of slip reduces the differential stress field around the active fault, to a lateral distance of something like 40 percent of the fault length, so the theoretical conjugate has a much smaller scope to develop. This instance shows a dominant fault pattern with only limited sign of conjugates developed.



This is a profile from the NE part of Cheshire Basin, UK, where the Permian and Lower Triassic is a post-rift infill unconformable above another, inverted Carboniferous rift basin. This is a multi-inverted basin, with end-Carboniferous uplift, erosion, and a major Tertiary phase of inversion too, which domed the Triassic and led to removal of Jurassic sequences deposited here.

In this section the yellow faults cutting Permian and Triassic don't show much evidence of Permo-Trias growth, they were mainly active in the mid-Jurassic North Sea stretch. (In contrast, the Upper Triassic to the south of this line thickens greatly and is a second rift infill sequence in the basin, it reaches 3000 metres or so and shows growth faults). They run north-south and tend to be easterly-downthrowing, more or less evenly spaced, they probably link with a deep westerly-dipping floor fault at basement level. Their repetition interval may be controlled by the width of the differential stress reduction area. They are antithetic to the east boundary fault for the Triassic depocentre, dotted, here its relatively minor at 400-450 metres throw but it increases dramatically in displacement southwards.

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!

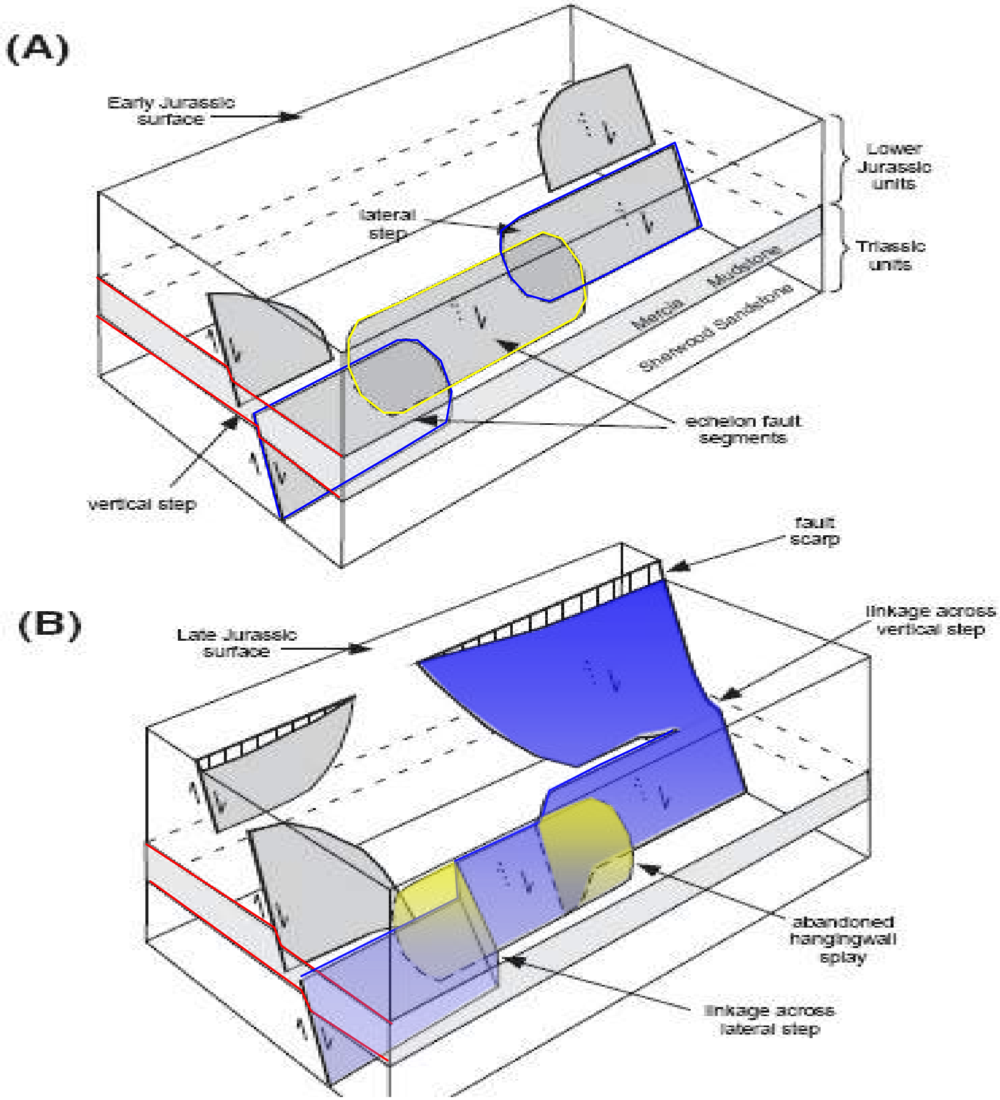
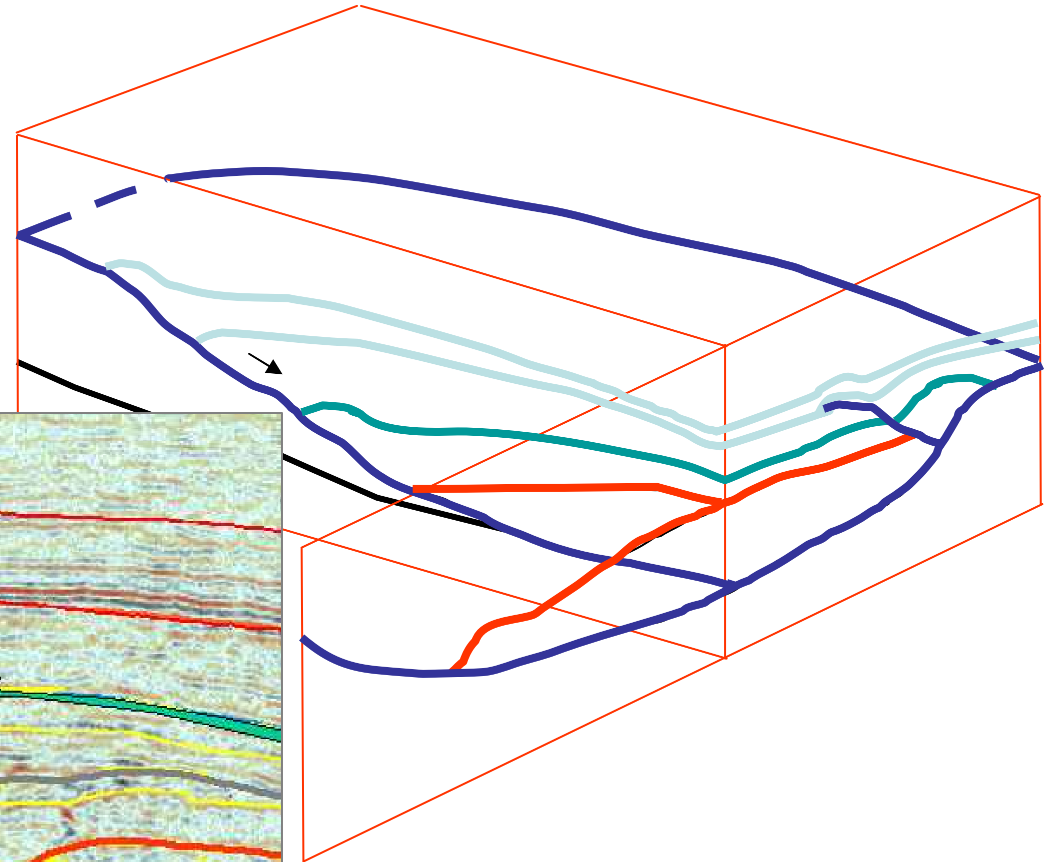
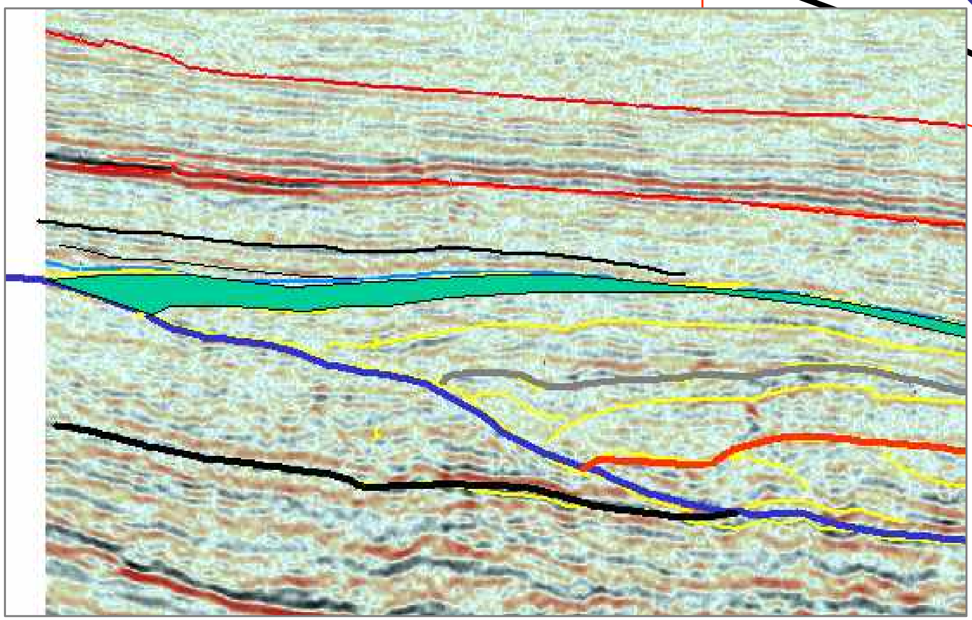


Figure 20 (page 1207), Kattenhorn, S.A. and D.D. Pollard, 2001, *Integrating 3-D Seismic Data, Field Analogs, and Mechanical Models in the Analysis of Segmented Normal Faults in the Wytch Farm Oil Field, Southern England, UK,* AAPG Bulletin v. 85/7, 1183-1210. AAPG © 2001, this figure is reprinted by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

Listric Faults

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

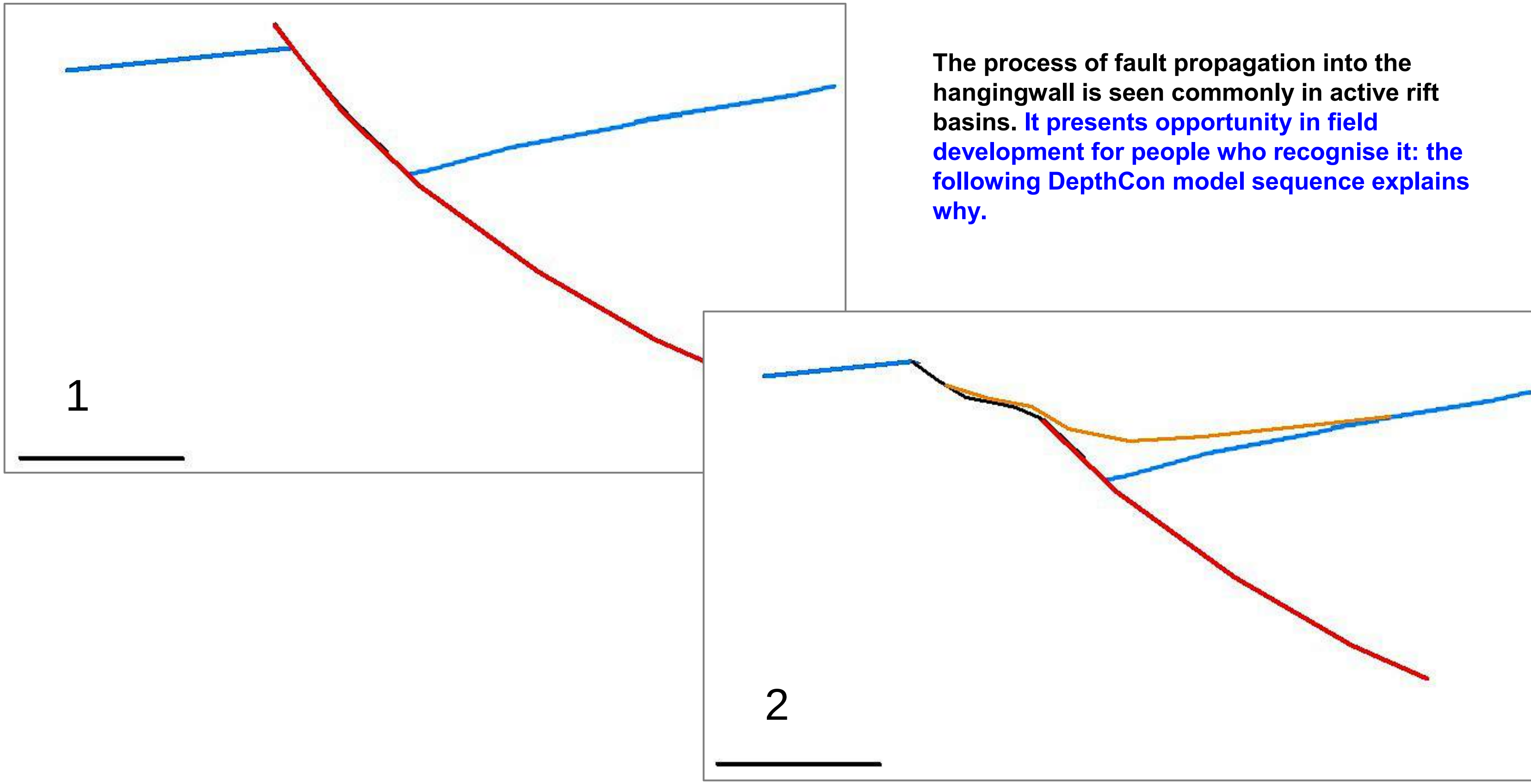




An arcuate growth fault will have a rollover in its hangingwall, which is early-formed. Compared to footwall stratigraphy this closure will have an expanded sequence, probably with reservoirs which haven't been seen in the footwall.

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!



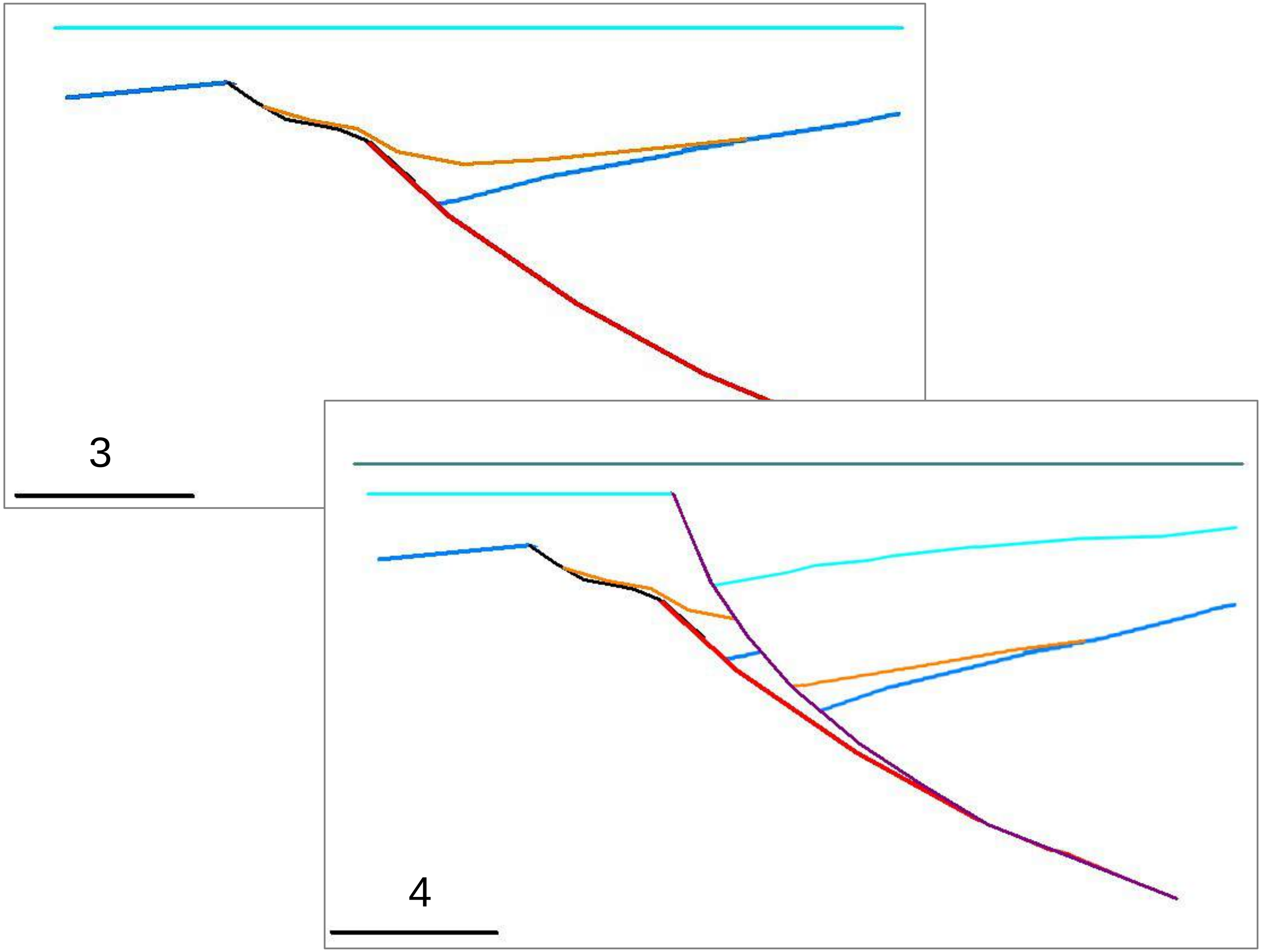
The process of fault propagation into the hangingwall is seen commonly in active rift basins. It presents opportunity in field development for people who recognise it: the following DepthCon model sequence explains why.

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.

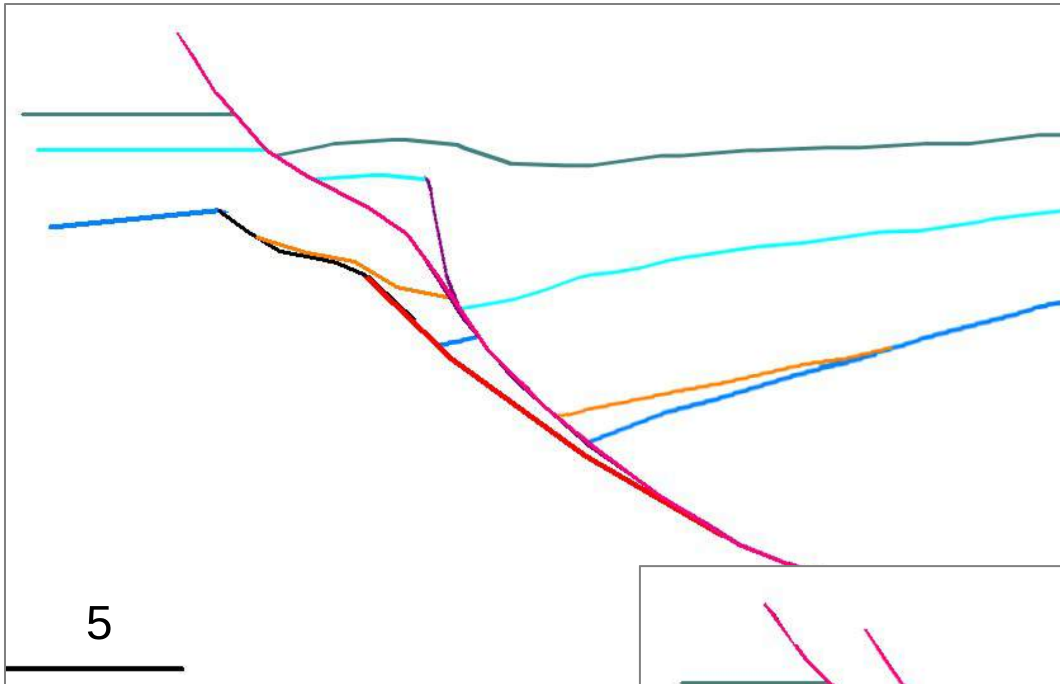
Stage 1 is the establishing of tilted fault block topography, and in Stage 2 there is erosion of the upstanding footwall and deposition of sediment on the hangingwall, this could be alluvial sediments or we might be in a marine environment with slumping off the footwall.

Fault propagation into the hangingwall (2)



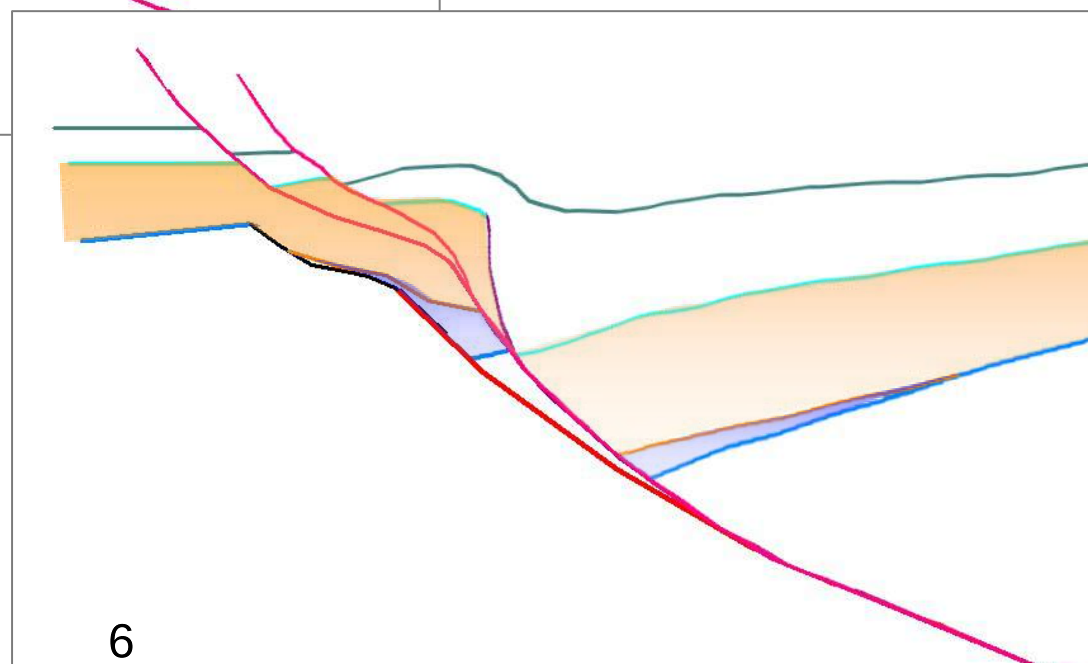
Stage 3 sees sediments blanket the high, as the red fault has gone quiescent. In Stage 4 it reactivates but the upper segment of the fault surface is new, shifted towards the hangingwall, its the purple surface. Upper red segment will not move again.

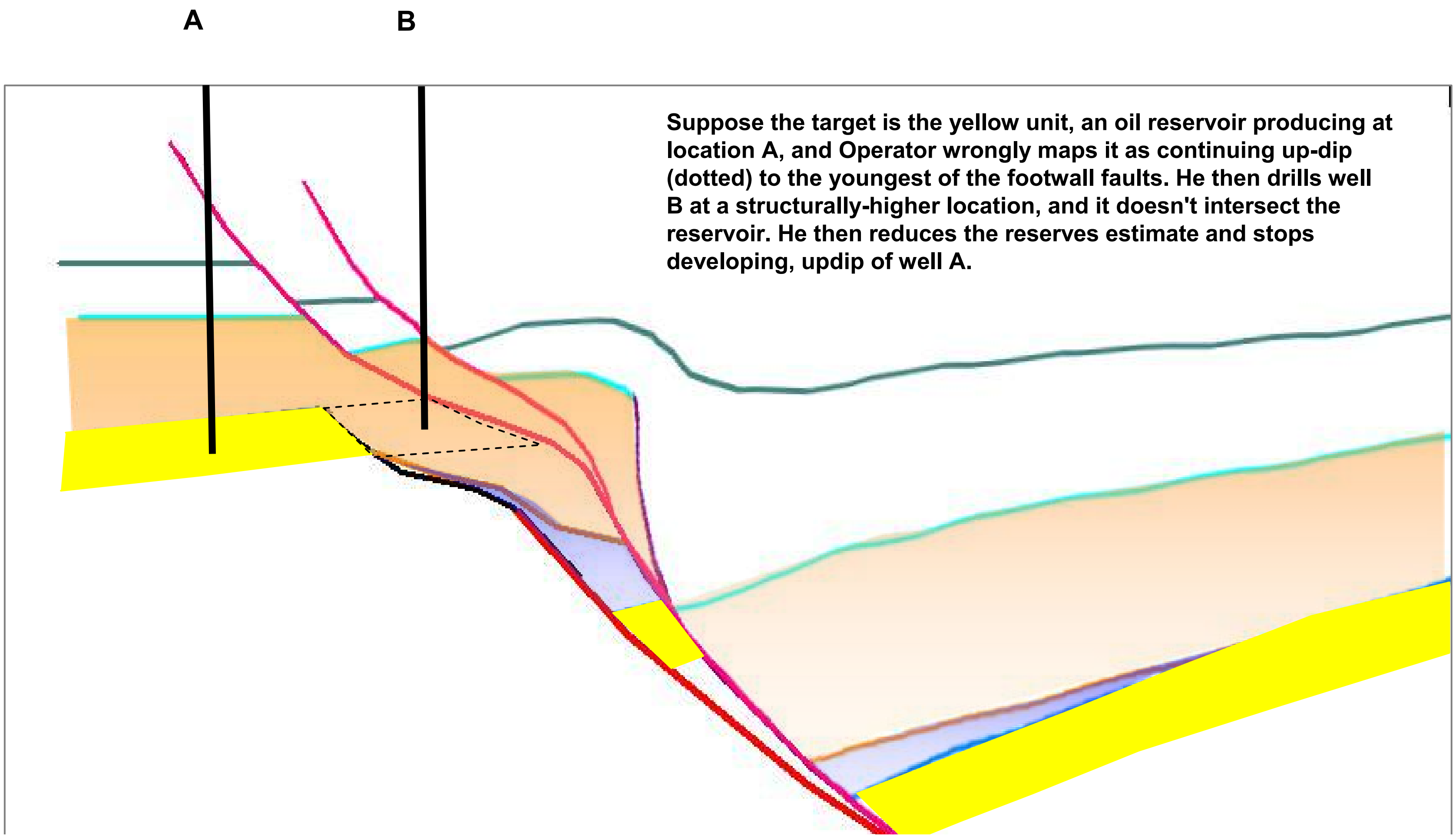
Fault propagation into the hangingwall (3)



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 a fine 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 were 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 potential is more interesting than disappointed early operators supposed.

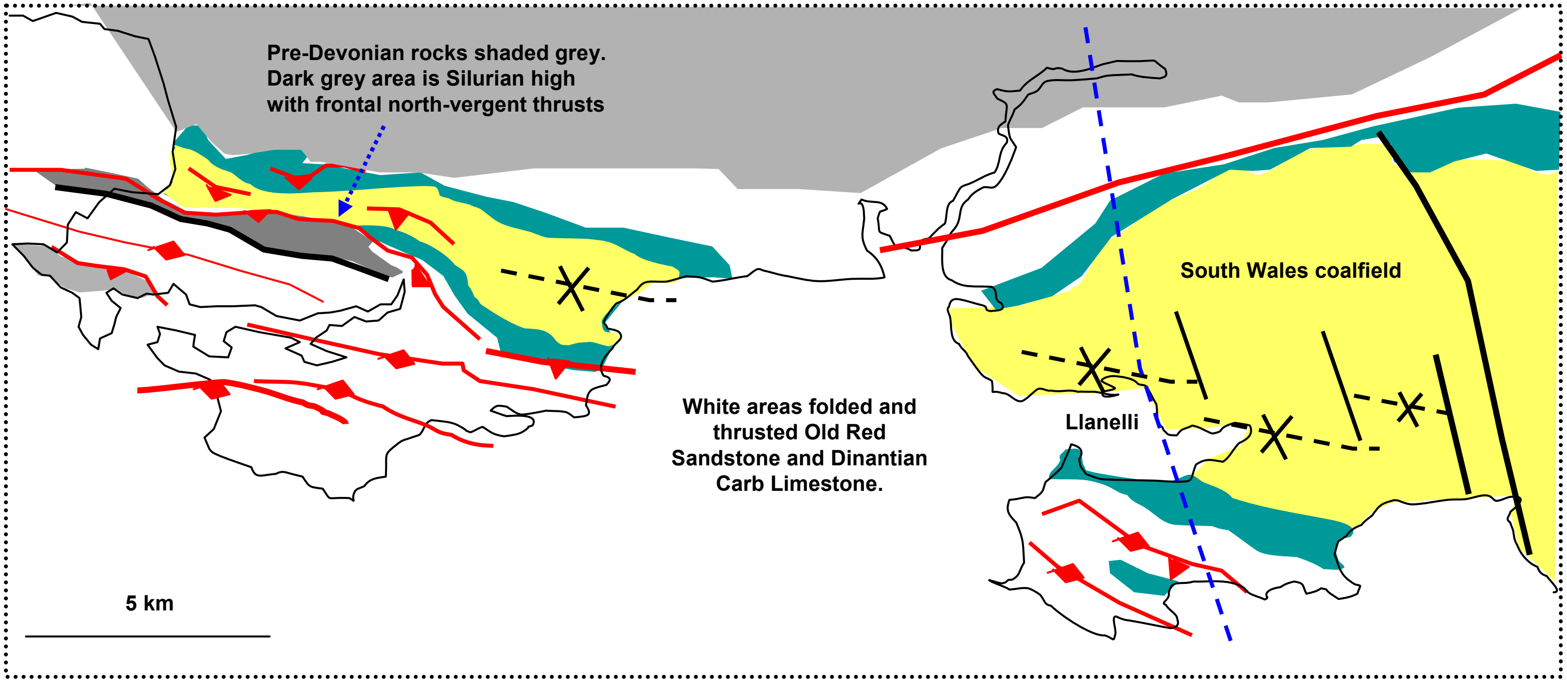
Ultimate Inversion: extensional detachment surface at summit of Everest

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.

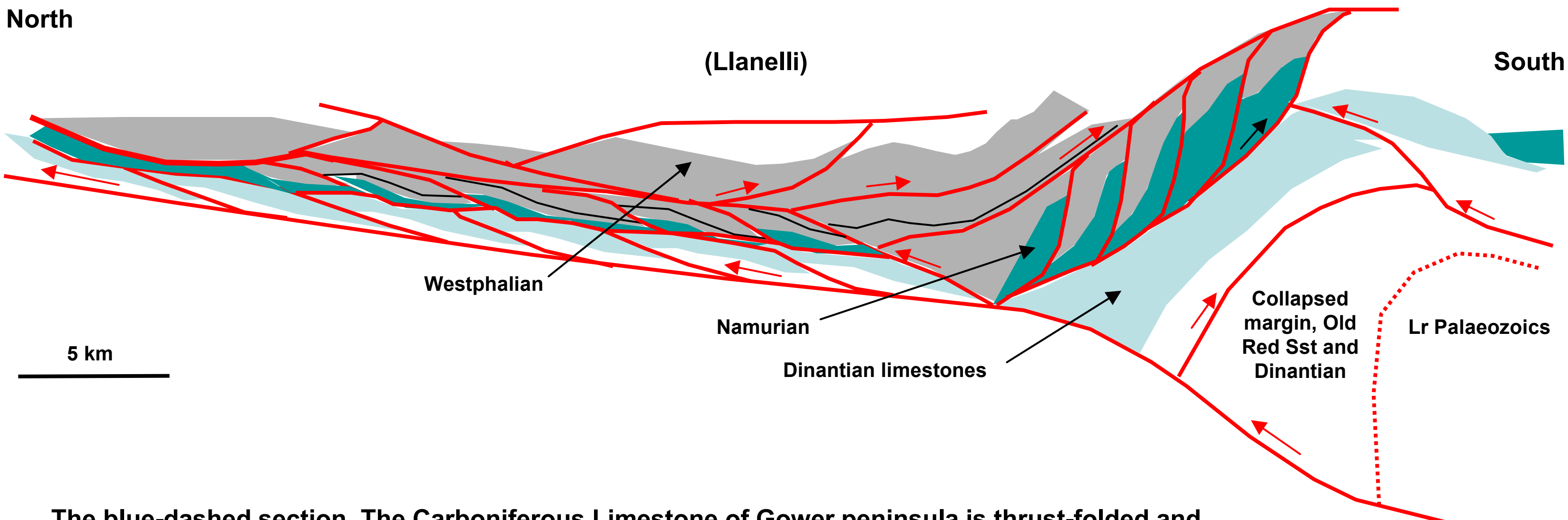
Inversion processes have various origins and effects, many petroliferous basins have been regionally or locally inverted above original regional depositional surface, some markedly so. Severe uplift of a basin has happened here: South Wales, UK, exposes late Carboniferous (Variscan) northward-vergent 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.

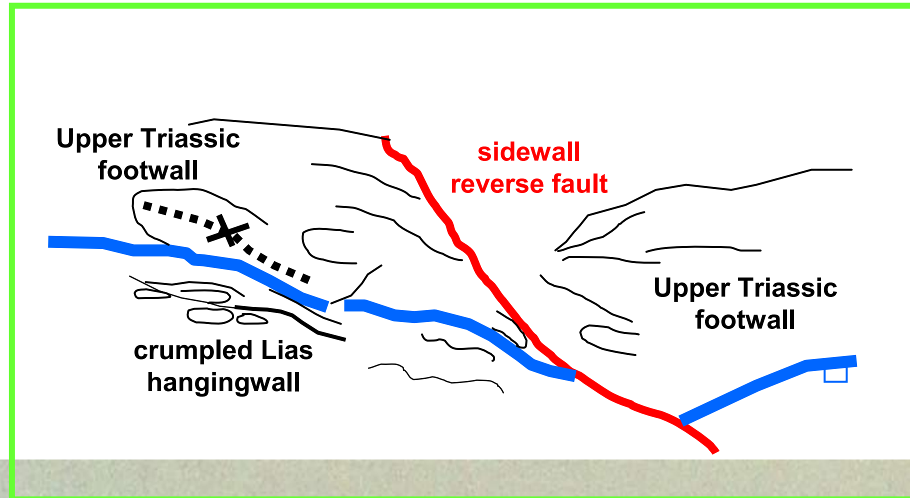
Section across the inverted South Wales coalfield



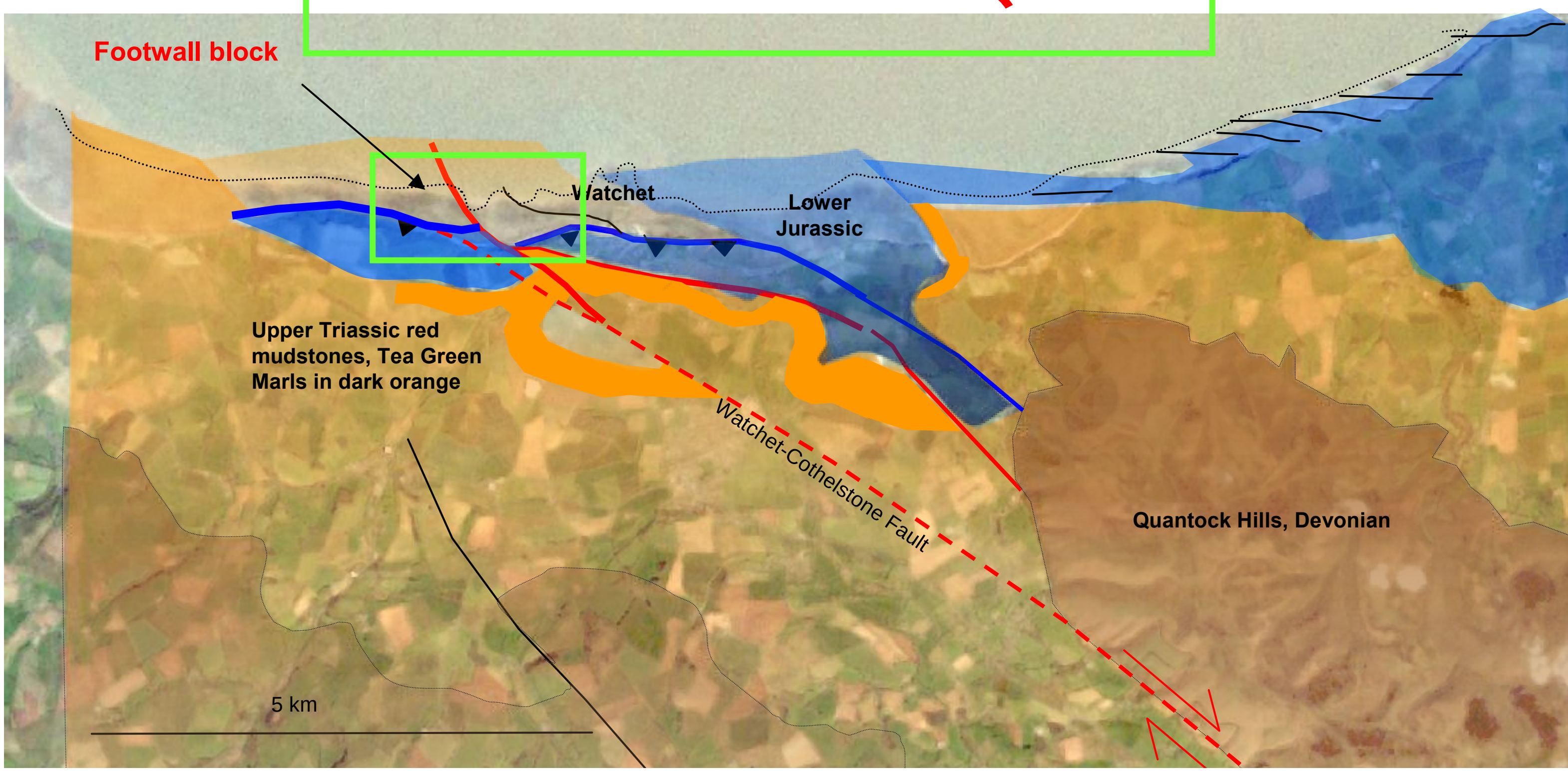
The blue-dashed section. The Carboniferous Limestone of Gower peninsula is thrust-folded and dips at around 60 degrees on the south side of the coalfield. Strong shortening is evident on what was a major extensional growth fault in the Dinantian and Namurian. Some of this propagates into the footwall, 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).



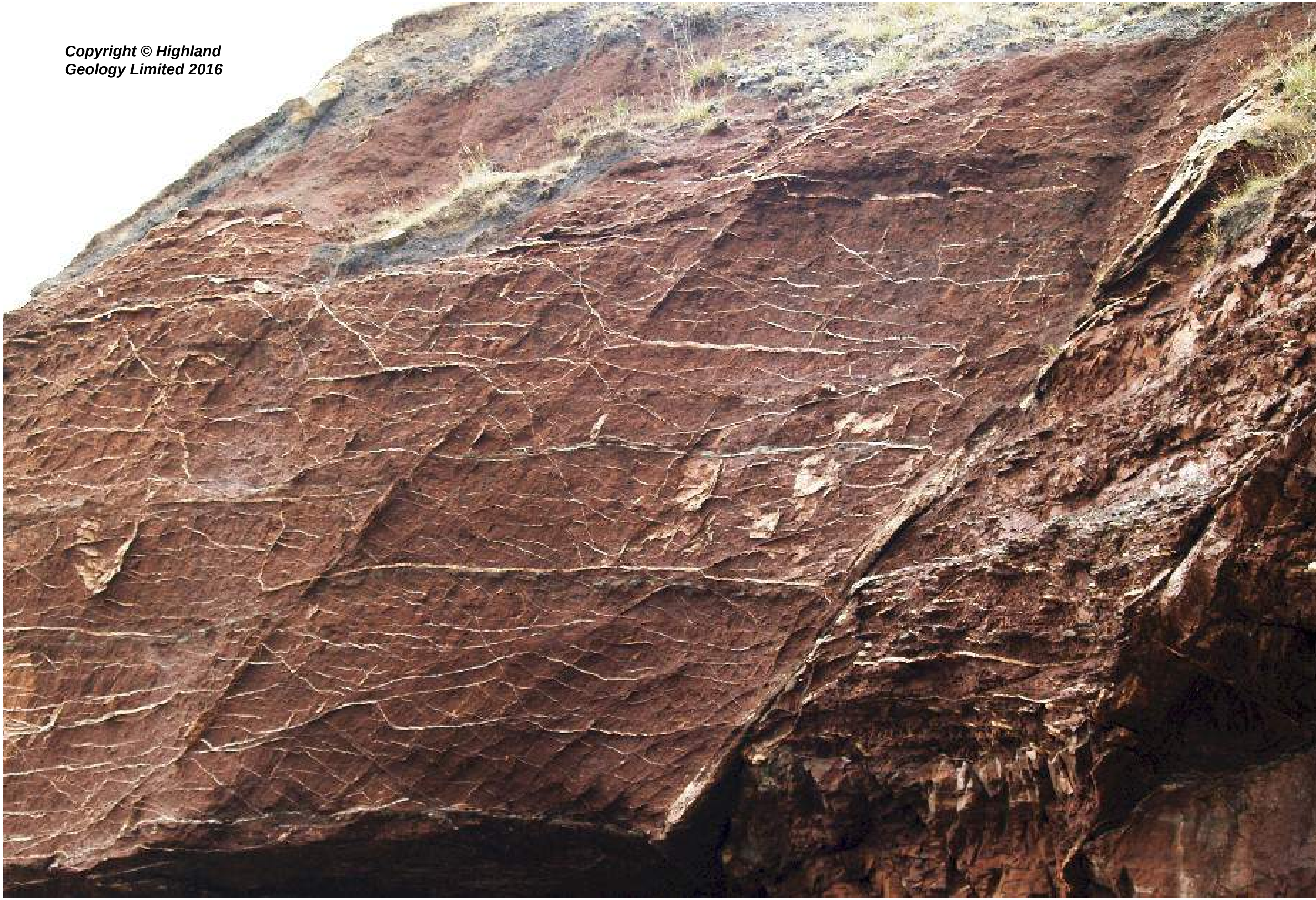
N-S Tertiary shortening inverts the late Jurassic extension



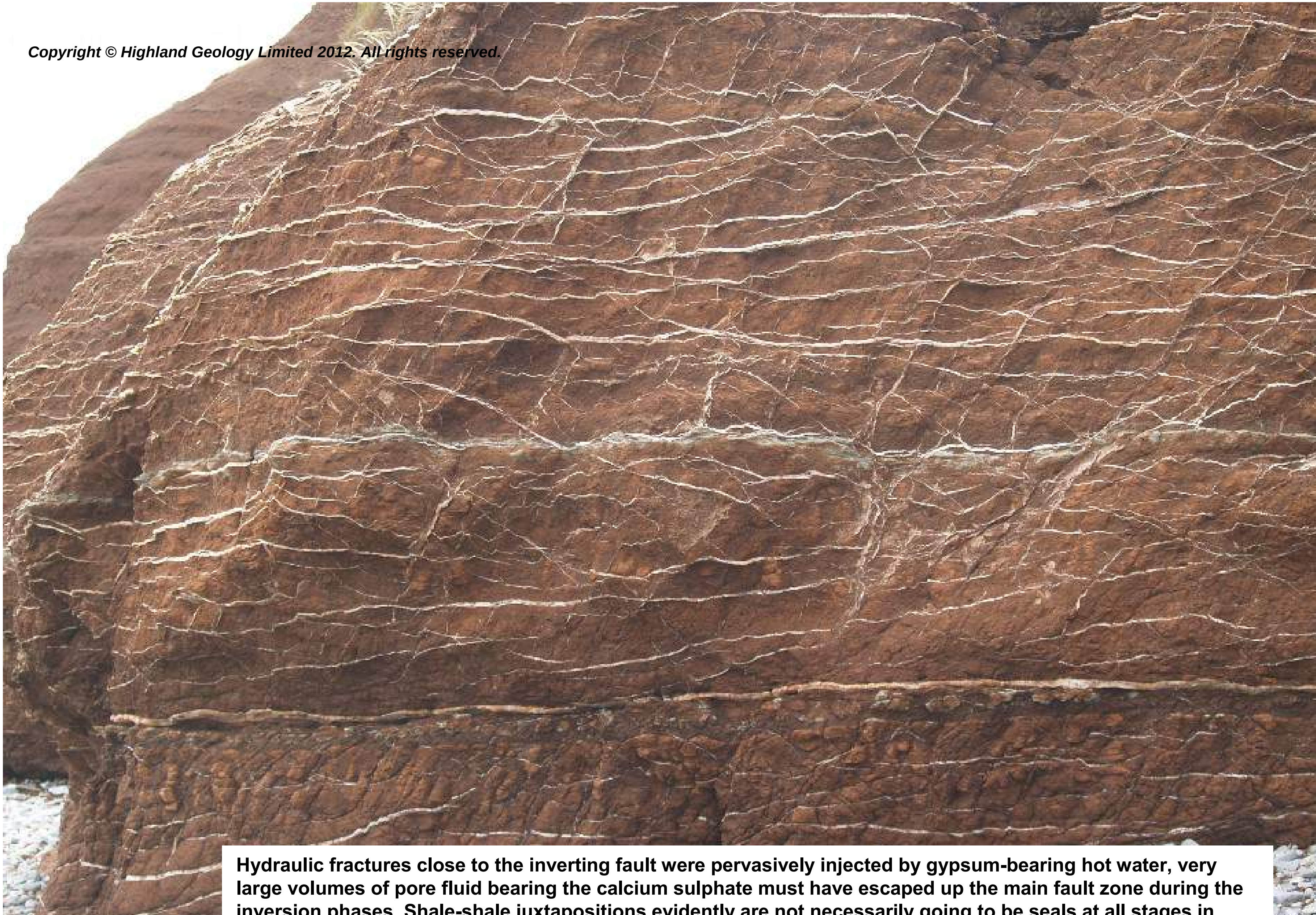
At Watchet on the north coast of Somerset, UK, an inverted fault block structure some 5 km long is well exposed. Its a high with Upper Triassic bounded southwards by the blue fault which is late Jurassic in age. Blue fault reversed some of its down-to-southward displacement in the Tertiary, when the footwall acted as a buttress to the weaker Lower Lias (blue shaded) which was compressed and crumpled against it. 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.

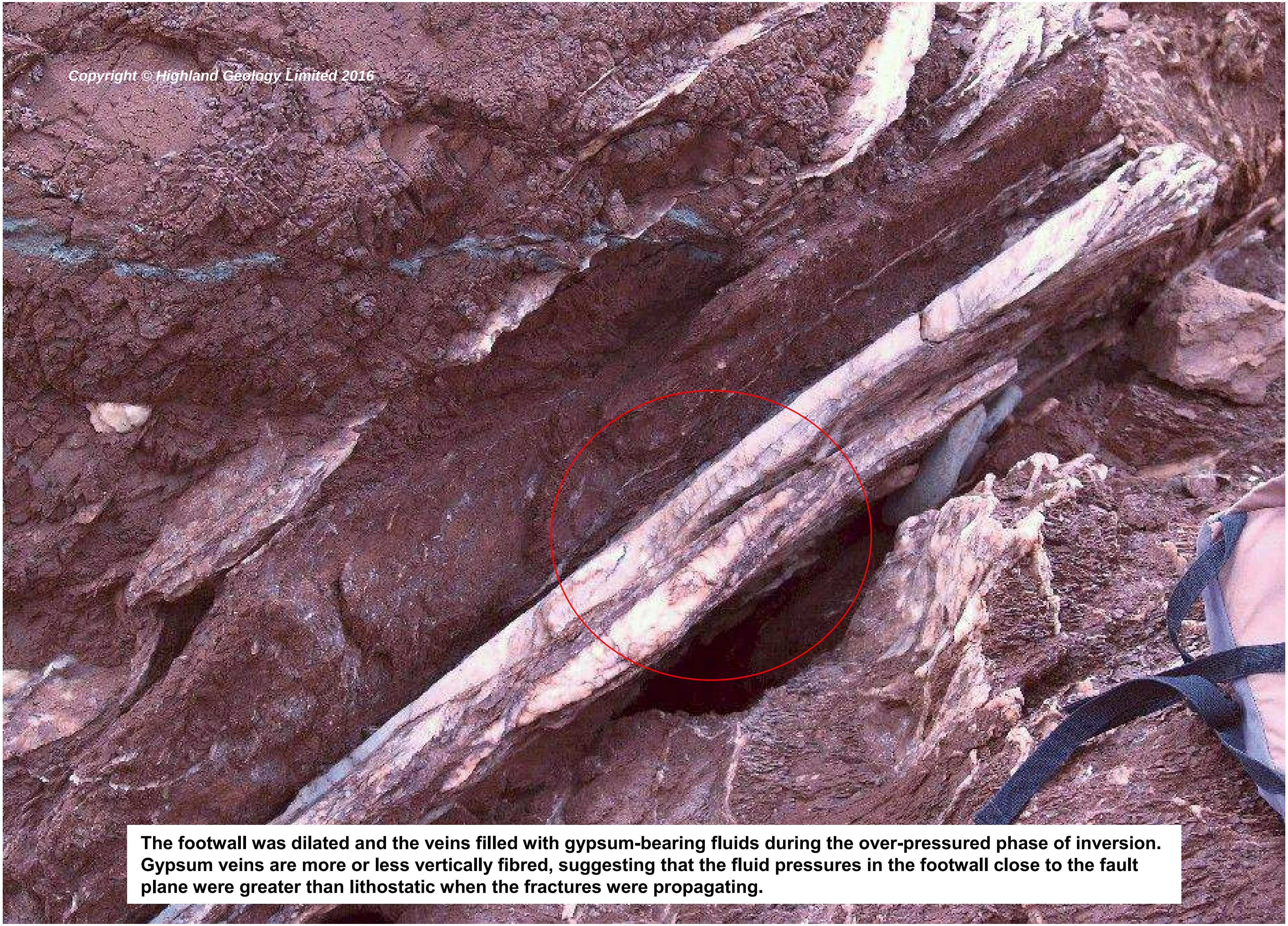
Detail of the Lower Lias deformation. This outcrop doesn't prove inversion, in itself, arguably the red mudstone footwall could just be acting as a buttress. But there is abundant evidence that Bristol Channel and South Wales have been regionally uplifted and this fault is highly likely to be one of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



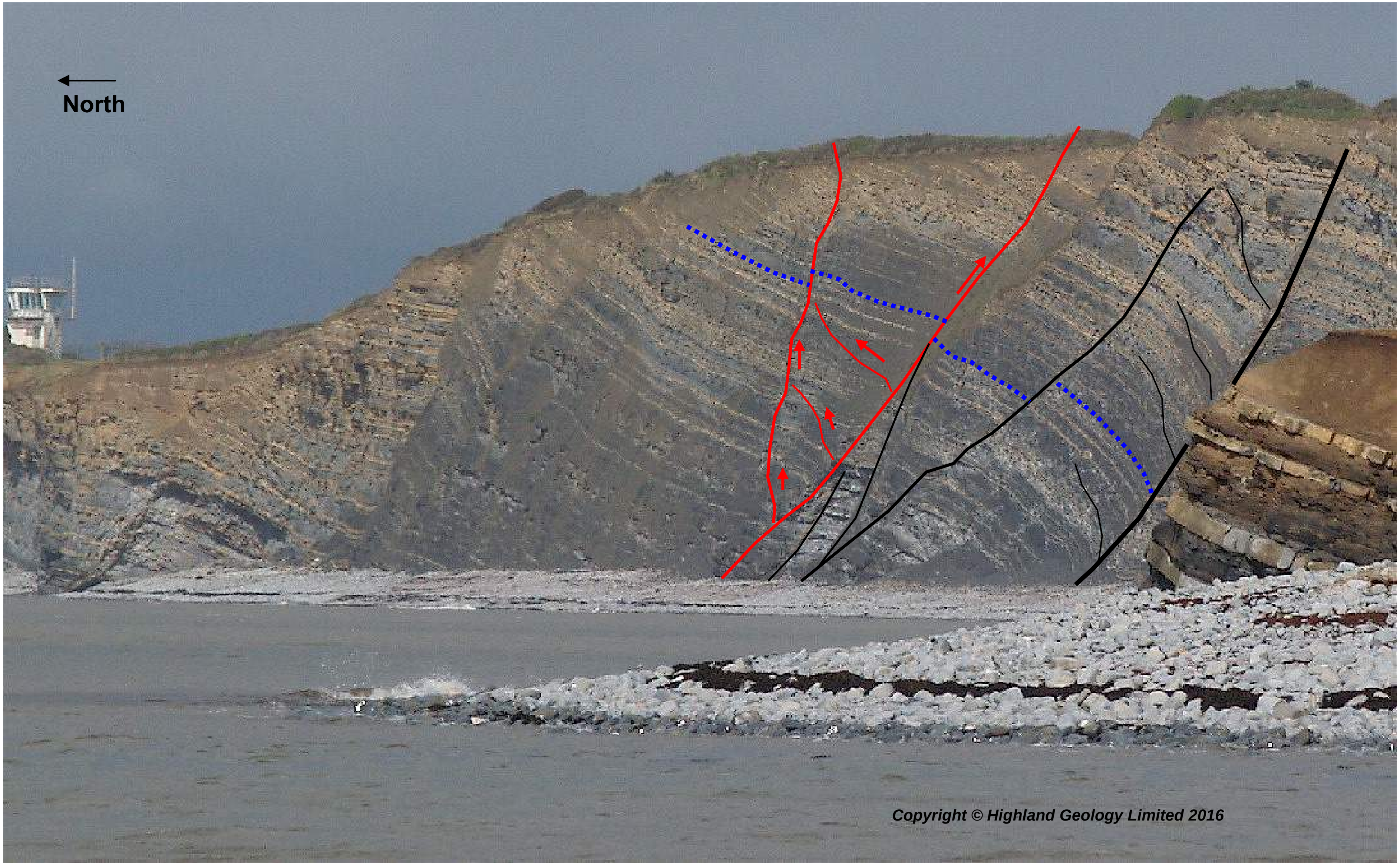
The inverted blue fault is just a few metres behind the outcrop face, dipping away from us. Subsidiary footwall faults and a maze of hydraulic fractures in the red footwall mudstones are sealed by gypsum.



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 charging them, too.



The footwall was dilated and the veins filled with gypsum-bearing fluids during the over-pressured phase of inversion. Gypsum veins are more or less vertically fibred, suggesting that the fluid pressures in the footwall close to the fault plane were greater than lithostatic when the fractures were propagating.



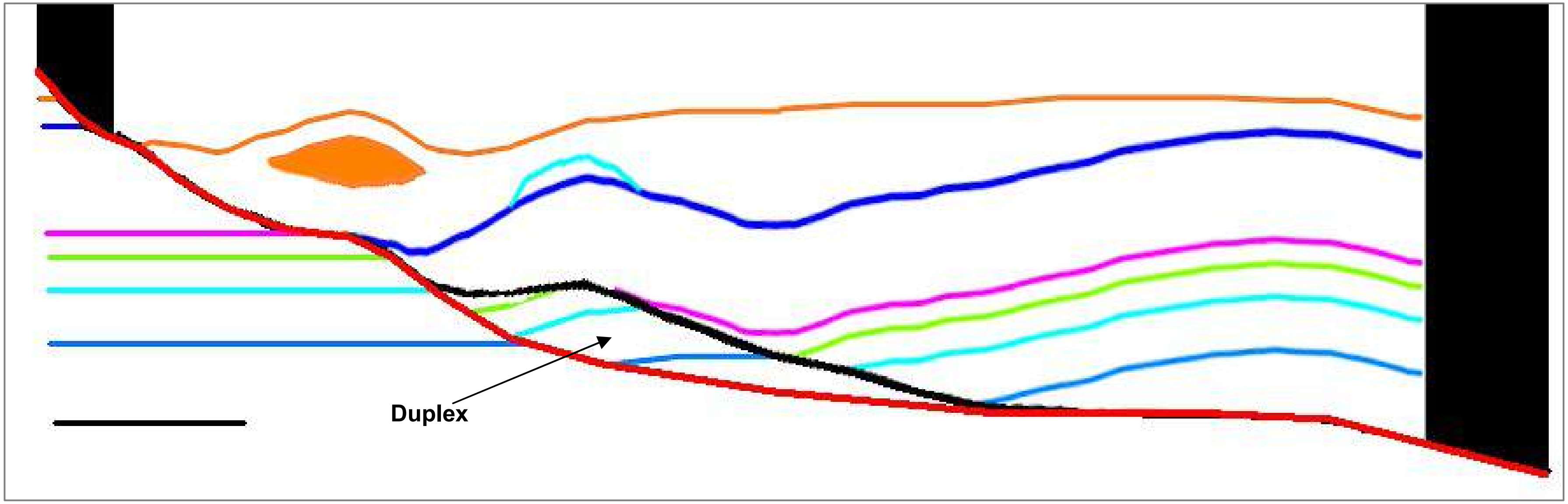
Bristol Channel Basin about 20 km east from Watchet, Somerset, UK, Lower Lias cliffs east of Kilve beach show extensional faults which formed in the mid-late Jurassic were partly inverted, in this case modest reversal by some 20-30 metres, during the Early Tertiary regional compression. This photo shows the effect of the shortening: buckling and local steepening of dips, local reverse faulting (red) and pop-ups, thickening and backthrusts against the footwalls, in the mainly-shale sequence.

This is one of the many small faults at Kilve introduced in the Tertiary N-S shortening of Bristol Channel Basin, its a down-to-the-west tear fault on a north-dipping fold limb, losing displacement to a tip at bottom-right of the photo. Tear faults are not necessarily strike-slip faults, though many of them are: not this one, in the few metres between the tip and the cliff its developed mainly vertical throw.

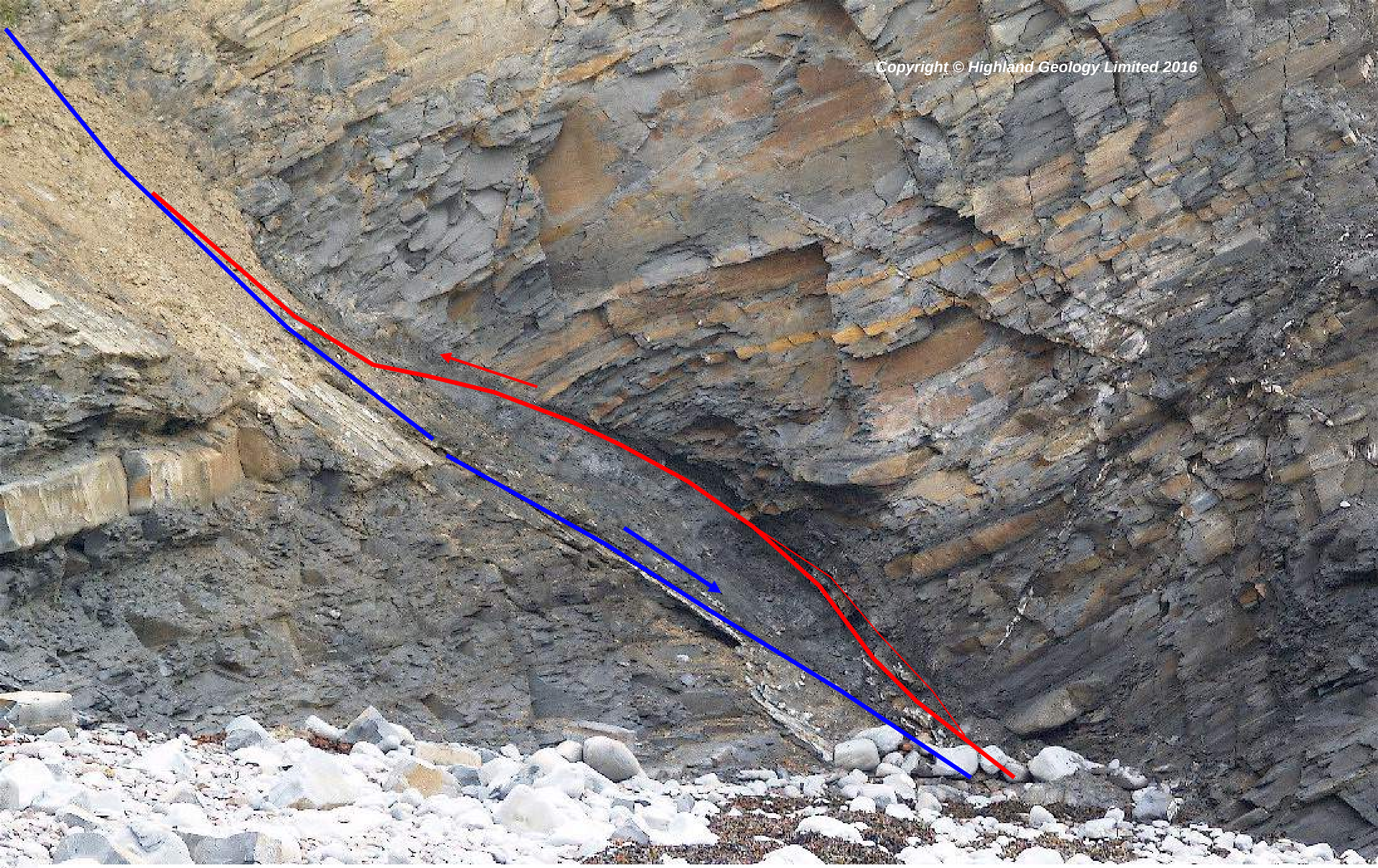
Extensional duplexes

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".

To model this one we simply form a new fault in the black fault’s footwall and slip rightwards on it, and if this 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.

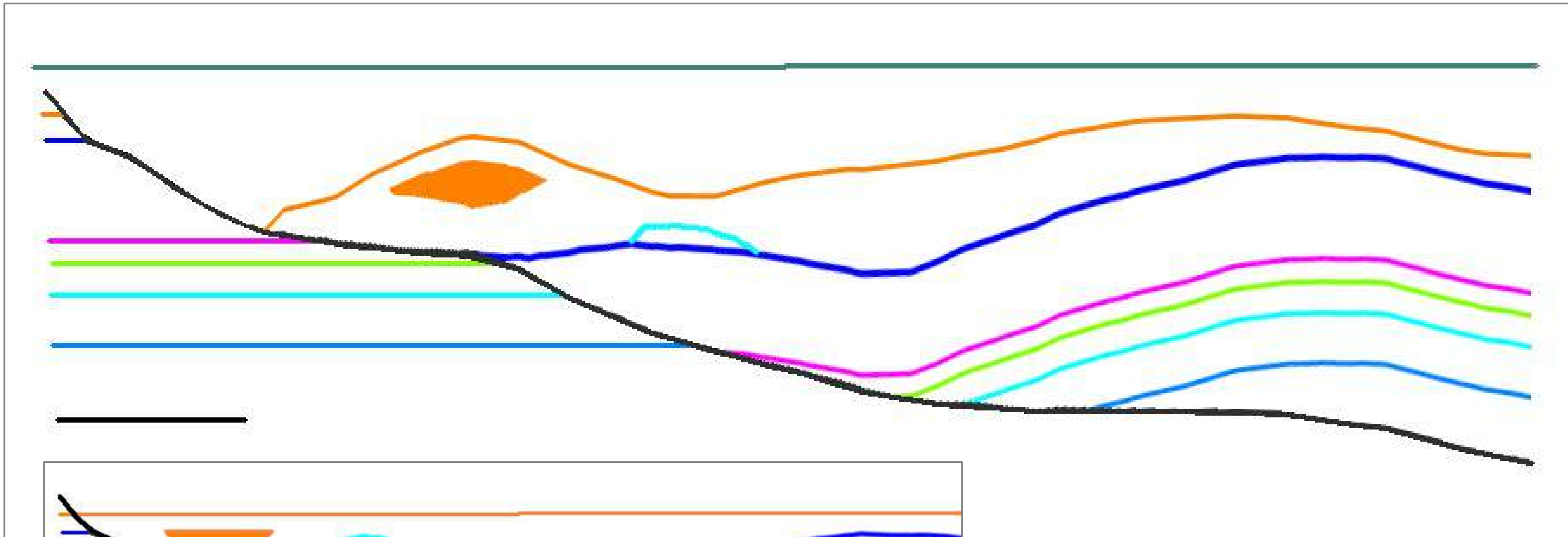
-The largest-displacement faults which have movement past a major shale unit, will reverse more readily.

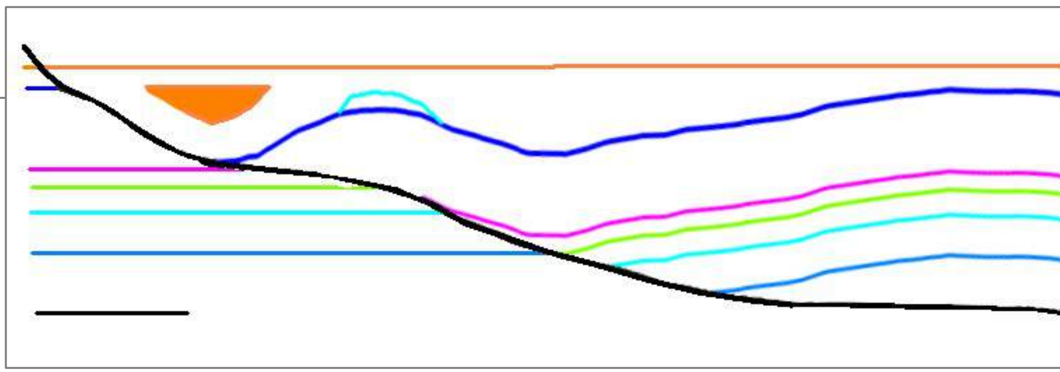
- Limited fault gouge means high frictional strength. Does inversion on a fault stop at the point when gouge thickness is reduced?

- 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?

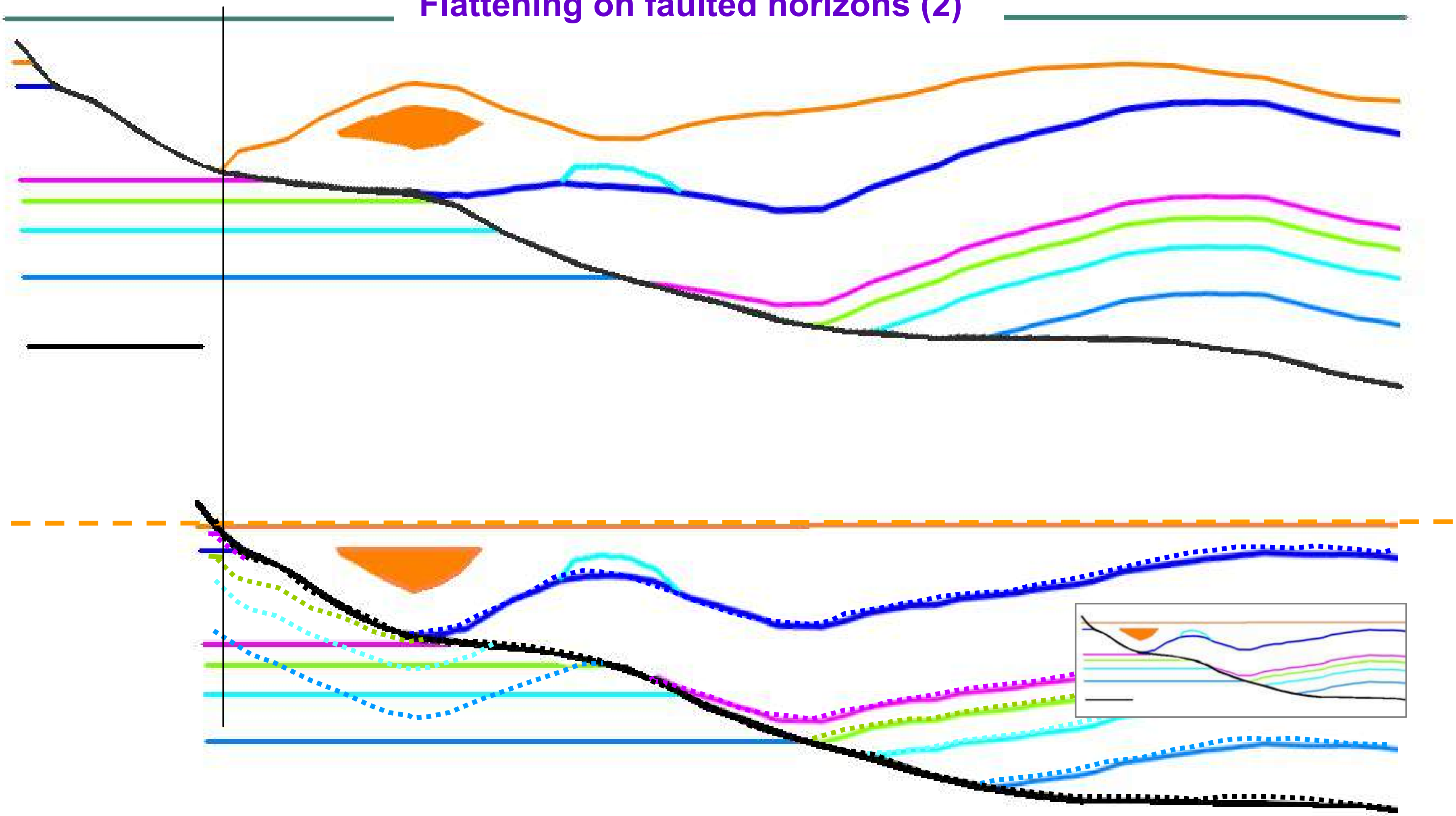




Many interpreters like flattening and re-datuming on seismic surfaces, workstations have automated flatteners for data cubes and 2D profiles, so its easy. These transforms shear the image vertically, all the data are pulled up or down. Some software developers recommend vector flattening to "minimise"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

A little thought shows that flattening on a horizon which is faulted can produce structure which never existed. Going back to our DepthCon model for growth faulting, in the next slide I flatten on the orange marker: will we return to the geometry orange bed had, at orange time? That's the inset picture.

Flattening on faulted horizons (2)



Flattening on orange marker is performed by shifting the picks vertically, dotted lines are the result. Above the black growth fault the results are OK, compare with the mini-inset, but in the footwall below it the dotted 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.

Think carefully about flattening, and don't trust bulk flattening on cubes of data unless you fully understand what it means for faulted beds. One can suspect there must be a lot of dry holes drilled on false structures made in this way.