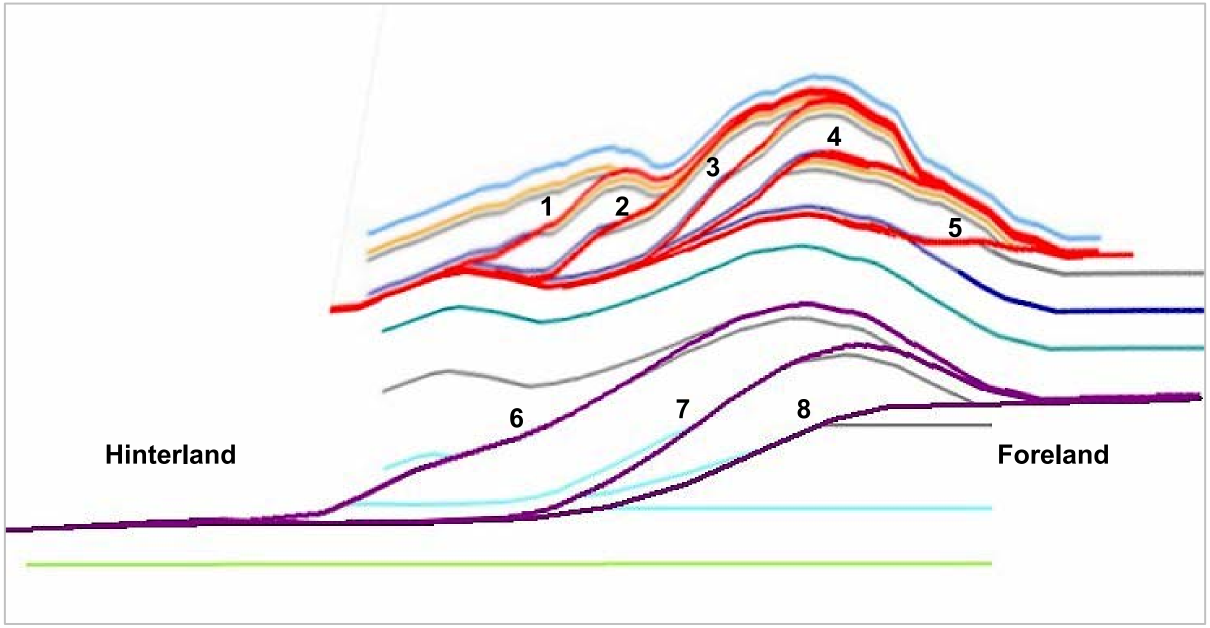
Exploring in Fold-Thrust Belts

Most thrust belts (FTBs) are under-explored. Whilst they have a high density of traps they typically have low-density seismic control, and the quality of older 2D seismic (and/or the processing) tends to be poor. FTBs with prolific source rocks offer potential for discoveries which can be very significant for small-medium sized companies.

•Excepting accretionary wedges and deep-water compression belts, FTBs are mostly onshore. Exploration costs are typically higher and success rates lower than in other, less-deformed play styles onshore, however.

•Are FTBs too difficult? FTBs are demanding technically: they need a long-term commitment and a sustained, confident spend on seismic acquisition, processing, other geophysics. Seismic shooting can be slow and difficult, processing expertise is critically important to reduce noise and stack data properly, reprocessing can take a significant effort and budget.

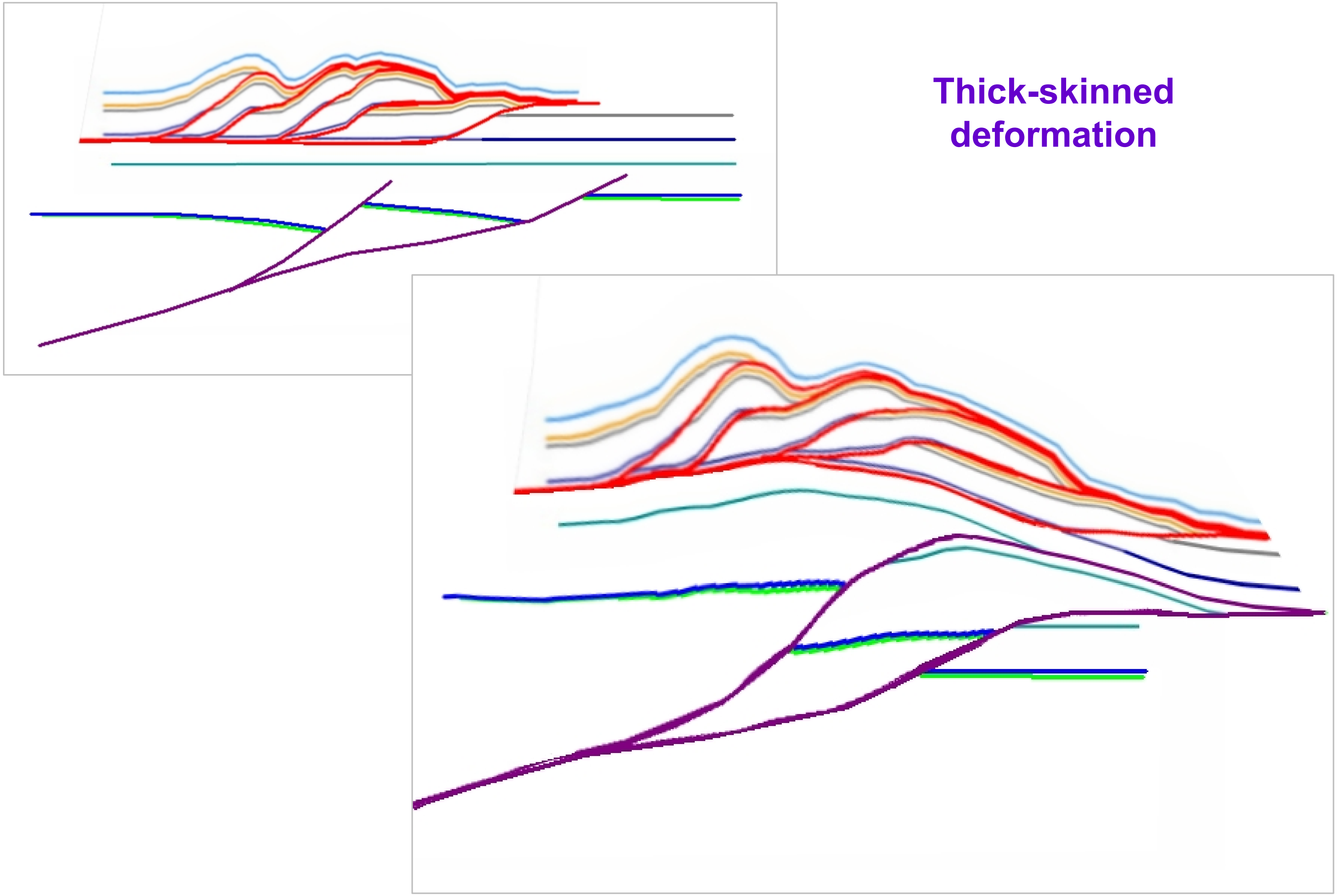
In thrust-fold belts the structure risk tends to increase towards the hinterland.



Many thrust belt models in the literature broadly look like this one. Its built with DepthCon, with the proviso that DepthCon is a simple shear program and it doesn't have a flexural slip algorithm. Shortening using the red thrust surfaces in the upper duplex is the same as in the lowerthrust set, the red thrusts formed in the order 1 through 5 have 50, 50, 50,100, 20 units inclined-shear displacement and the purple thrusts 6-8 have 80, 80, 110 units. It was made in two stages, the upper duplex was pulled back to left side of the diagram again after it was completed, using the red floor fault and a horizontal construction line; and then the purple thrust displacements were added underneath it, again using inclined shear. There is no presumption that pre-existing faults play any role in the deformation.

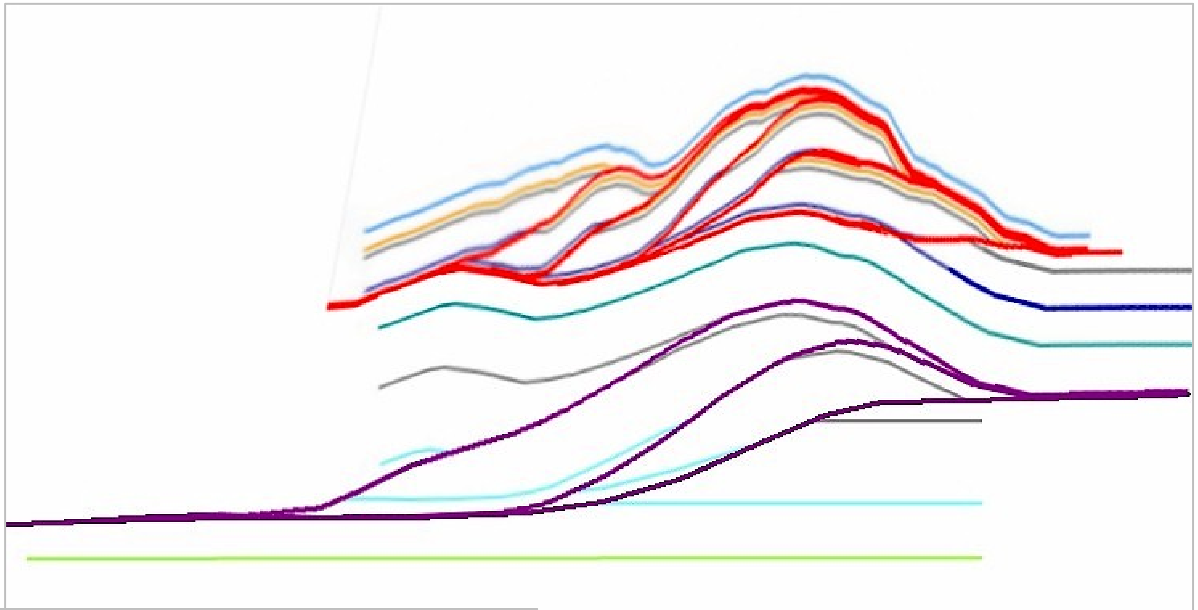
Its obviously a simplistic model, deformation wouldn't take place in discrete stages like this. What's more likely is that steeper ramps form first in stronger lithologies, and flats in the shales then link them. But it incorporates some of the "rules" thought to be critical in the 1980s. With deformation younging downwards (i.e. a successively-collapsing footwall) the earlier-formed potential closed structures are subjected to ongoing deformation as the deeper structures develop, and this is a principal cause of trap integrity risk in thrust-fold belts. Location of plays on the outer part of a thrust-fold belt is more favourable, traps there are the simplest and youngest and they are less prone to cracking after charge.

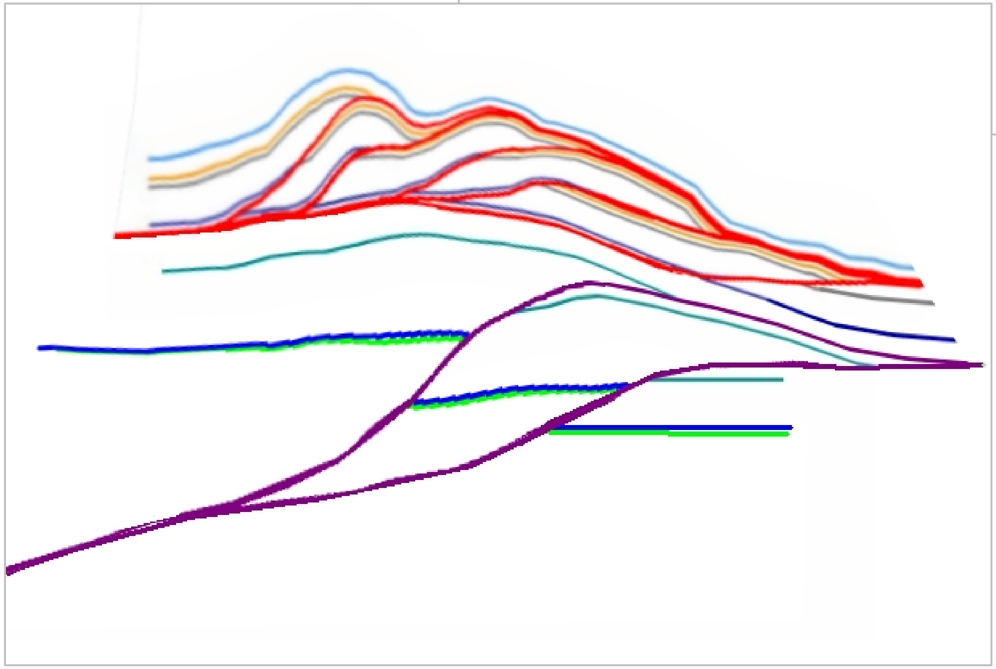
Thick-skinned deformation



An alternative shortening mode is to invert old extensional structures beneath the upper carapace of duplexes, and if this happens we get a thick-skinned system where the deeper faults may cut the basement.

The problem of seeing deeper structure





For the same shortening, deep targets can have quite different geometries and our challenge (and opportunity) in prospective fold-thrust belts is to decide what the deeper structure style really is.

The seismic available will largely influence our conclusion, and assessment of future possibilities for exploration. We've got to be able to see through the upper structure carapace and identify the potential targets beneath.

They may appear to be large, but its unlikely they will be simple. The more we know about them the more complex they will turn out to be, in detail.

Generalities about exploration potential in fold thrust belts

Deeper structures in FTBs tend to be bigger, which of course makes them attractive exploration targets, but they will be harder to delineate on seismic than the shallower traps. Whether we can reasonably-reliably map the deeper geometry largely depends on how well the seismic is shot and processed.

Deep structures will typically be expensive to drill, they may be over-pressured, demanding big rigs .

Do we have thin-skin tectonics with folds built on networks of low-angle ramping and flatting thrusts, and high degree of shortening, in which case a key question is where do the controlling detachments lie?

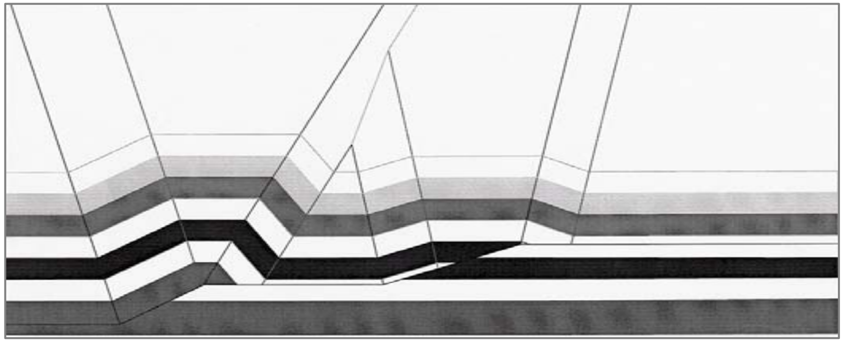
Or do we have predominantly thick-skinned tectonics, with deep (maybe crustal-penetrating) steep faults, which may be reactivated extensionals, defining the shapes of the major prospective folds? The shortening across the fold belt is then much less, the deep structure looks quite different.

Frontal zones form last, and because of this they may post-date the onset of generation of oil and gas, perhaps tilting expectation more towards gas.

If a trap has been found to contain oil and gas, there will be more like it, it starts a play. Its been suggested that older FTBs tend to be gas-prone, particularly if Palaeozoic rocks are the source sequences. If oil is the target, go to Tertiary FTBs with post-Jurassic source rocks. These rules are fine, but exceptions could make vast returns for smaller companies.

In thin-skin tectonics, three basic fold processes controlled by thrusting form prospective structures in thrust belts: these geometries are interactive in multi-phase deformation.

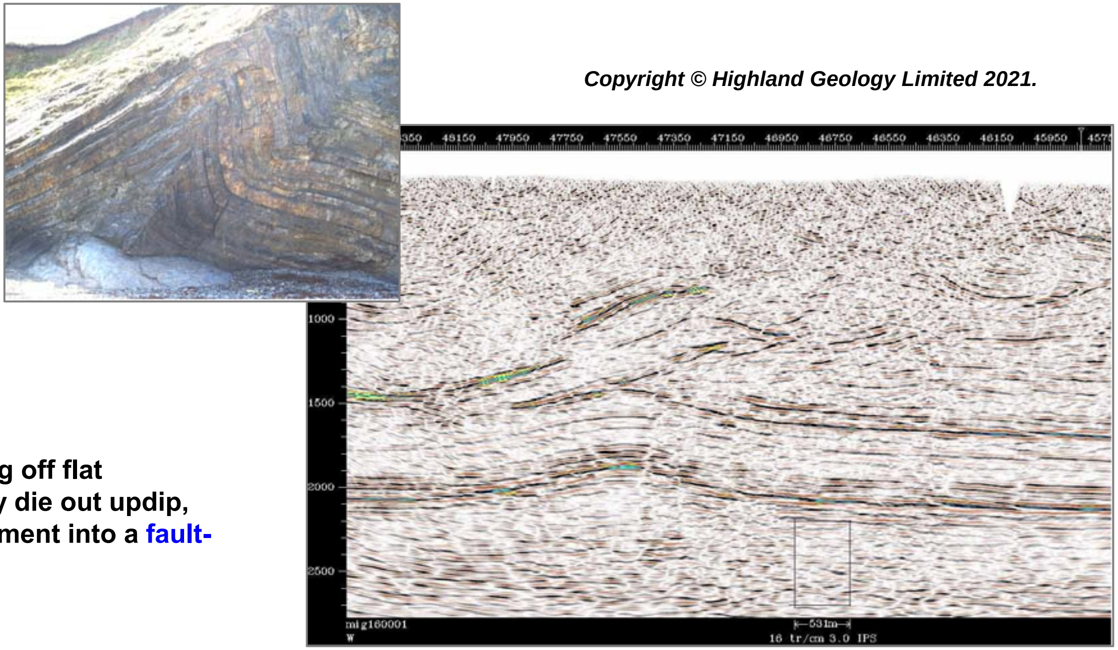
- **Fault-bend folds** are the consequence of movement of rocks over stepped ramps and flats. (They won't be angular, if ramps are smoothly gradational into flats).



- **Detachment folds** form above flat thrusts.

<u>Intergradational</u>: both types are likely to be dislocated by thrusts climbing through them.

- Thrusts climbing off flat detachments may die out updip, passing displacement into a **fault-propagation fold**.



Typical characteristics of thrust surfaces: basic rules

Deformation progresses towards the foreland, shallower structures were formed earlier than deeper ones. The stratigraphy has a very important role in end-structure: it controls where the main detachments go, and how many of them there are.

1. Steeper parts of thrusts (ramps) usually dip at around 25 degrees in hard rocks, and at much lower angles in incompetent rocks.

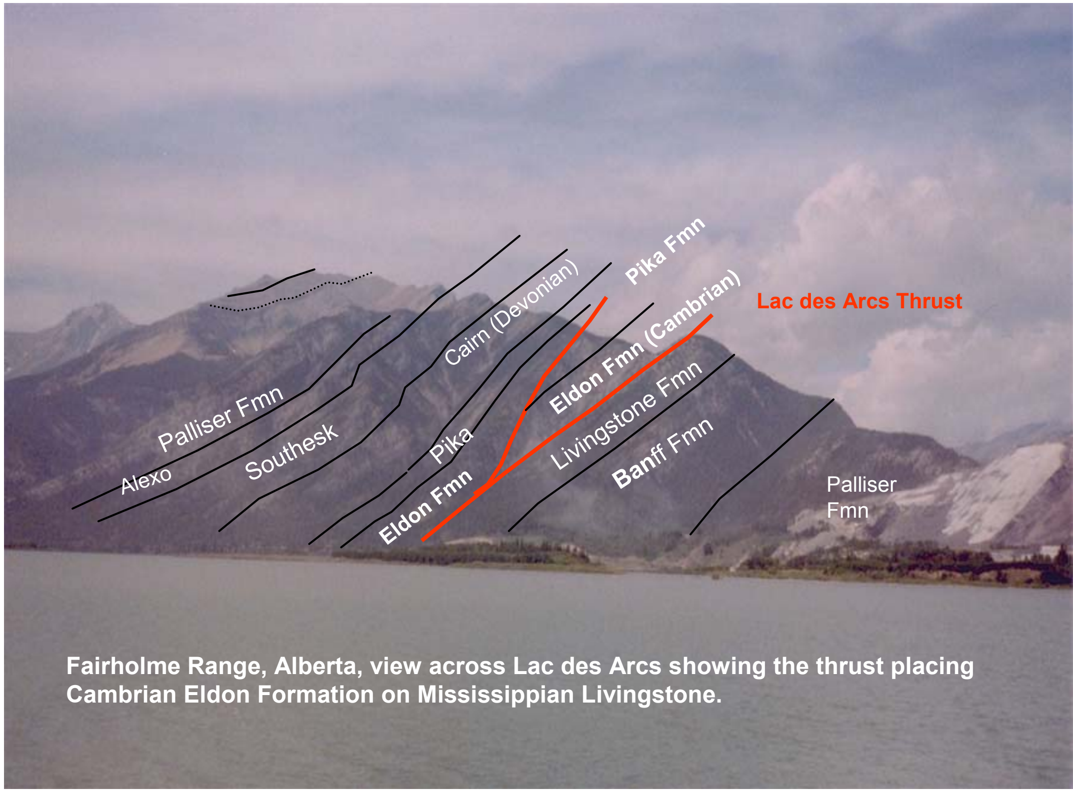
(When we see a thrust like the Lac Des Arcs (photo) dipping at 40 degrees or more, the implication is there must be younger, deeper thrusts, back-tilting it).

2. Ramps climb up-sequence in the transport direction <u>unless they cut a succession already folded</u>.

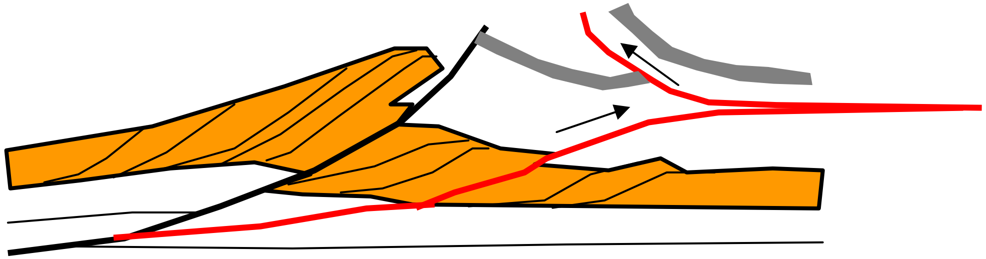
3. Thrusts place older rocks over younger rocks.

4. The displacement on thrusts is typically about 7-12 percent of the mapped strike length.

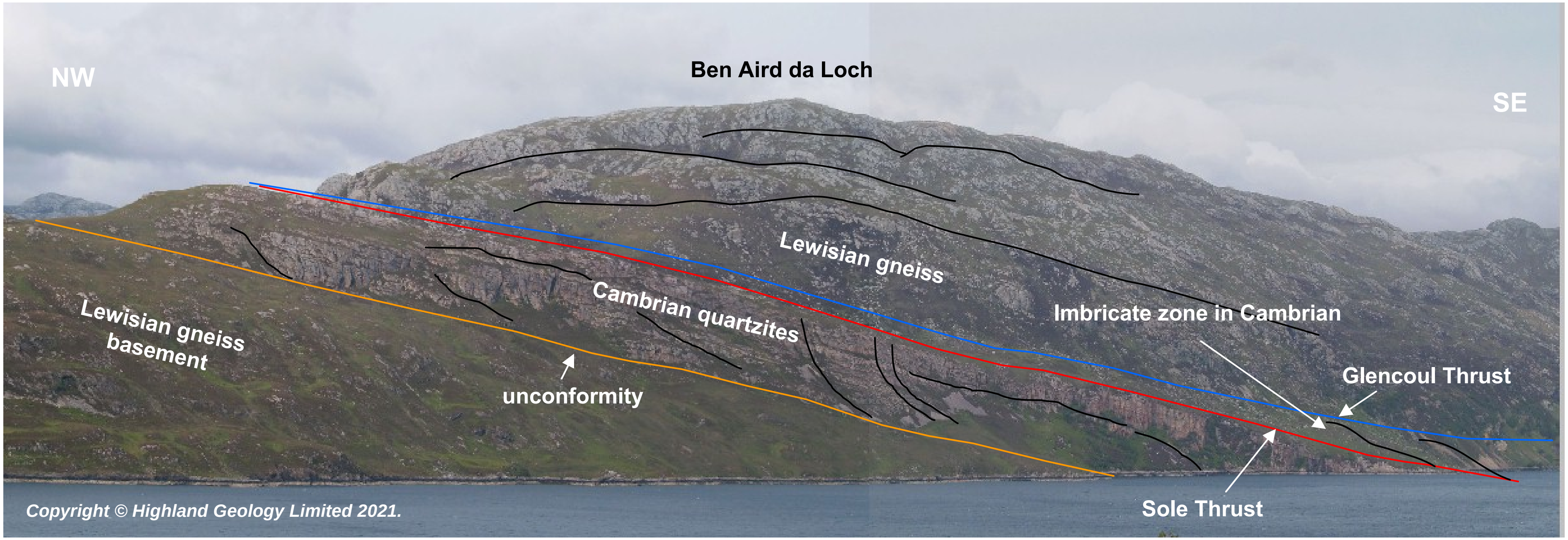
5. Thrusts tend to merge at depth onto a common detachment.



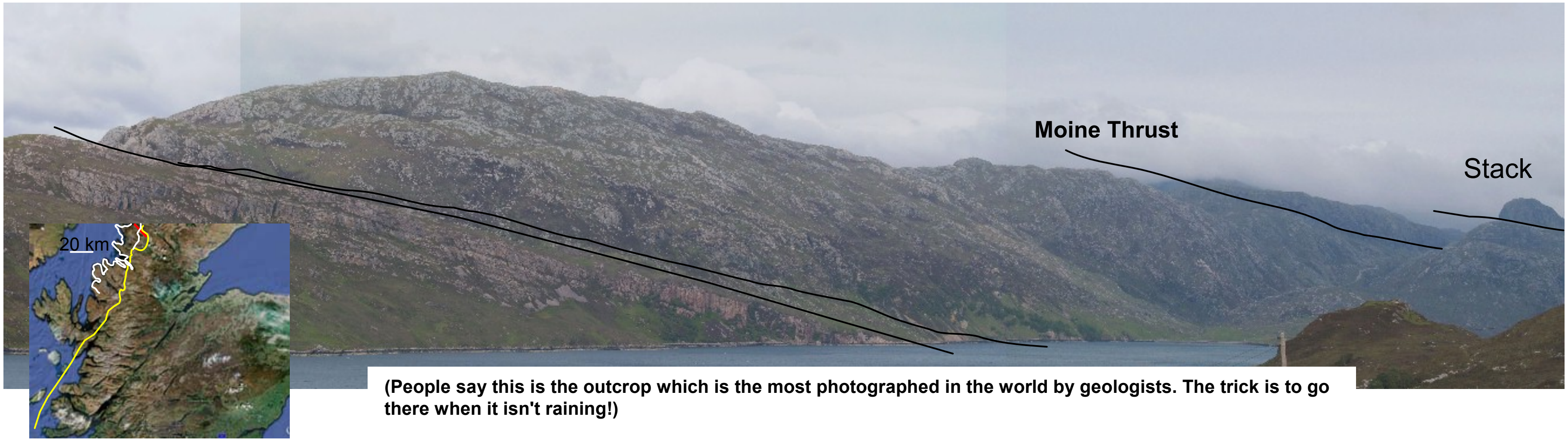
Fairholme Range, Alberta, view across Lac des Arcs showing the thrust placing Cambrian Eldon Formation on Mississippian Livingstone.



At the front of a thrust belt there may be a triangle zone, where foreland-vergent thrusts are paired with backthrusts, propagating from a tip.

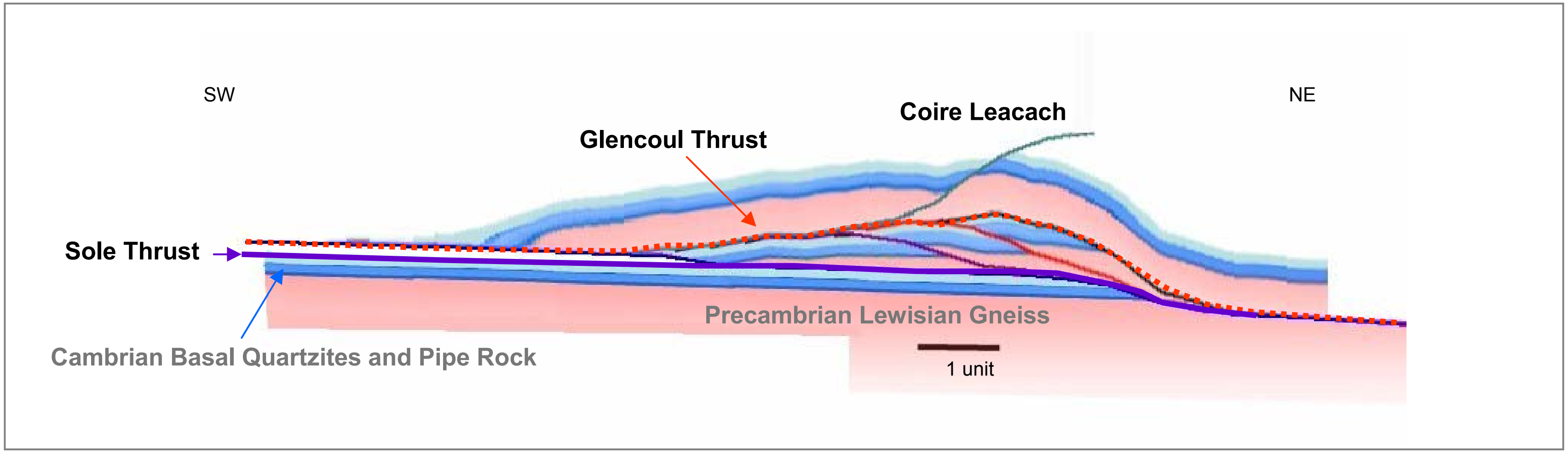


Assynt in NW Scotland is well exposed and has been significant historically for geologists trying to understand how thrust-belt structure geometries evolve. Around 1870 the Geological Survey officers working here discovered that Precambrian Moine metasediments are overthrust on top of Cambrian quartzites at this place, Loch Glencoul, and they found another huge thrust in the Stack of Glencoul, which is the Moine Thrust. This work triggered a revolution in scientific thinking. Current thinking suggests the Glencoul Thrust slip is around 30 km, and the Moine Thrust may have a displacement of more than 100 km.

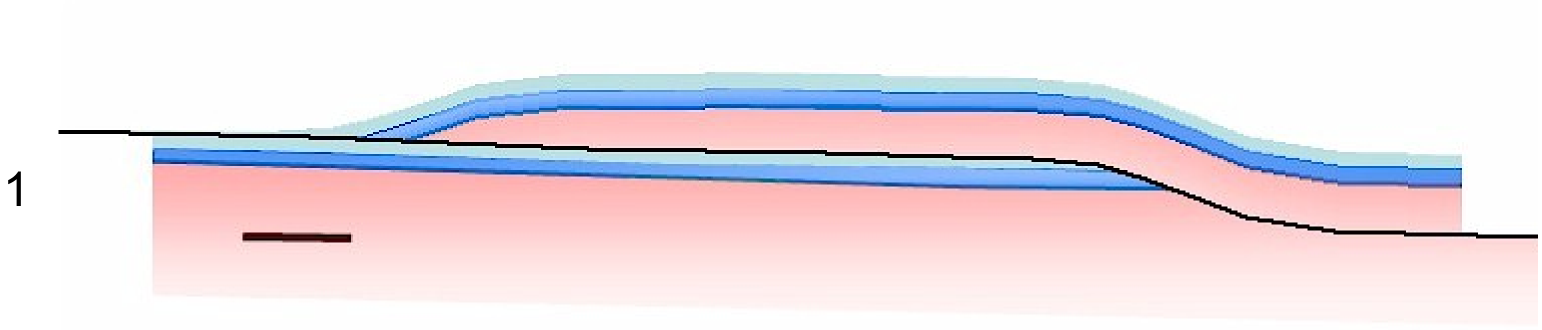


(People say this is the outcrop which is the most photographed in the world by geologists. The trick is to go there when it isn't raining!)

Thrust model for Inchnadamph, Assynt window, built using DepthCon.

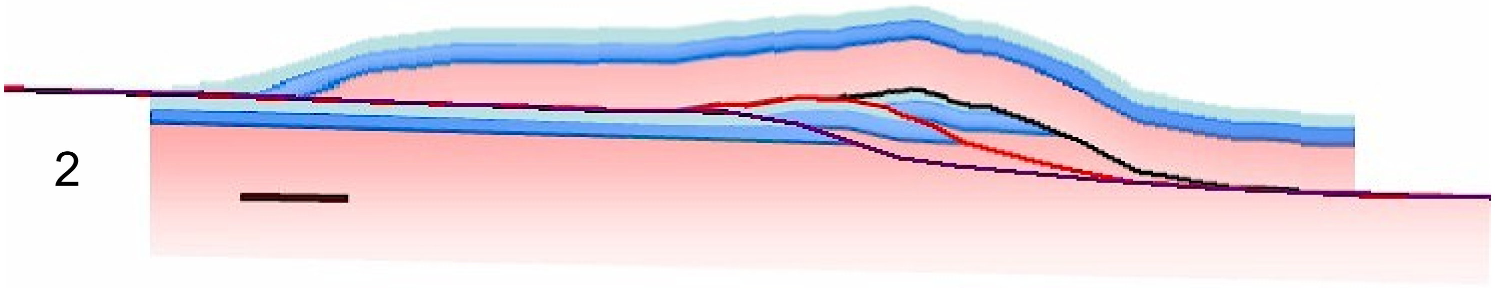


Some 10 km south of the classic Glencoul Thrust exposure at Beinn Aird da Loch, outcrops around Inchnadamph show the overthrusting in less dramatic setting but more of the story is evident. This model built with DepthCon is a very simple representation of the style: there are two slices of basement gneiss, one above the Glencoul Thrust sheet (red dotted) and the second on the Sole Thrust, purple. Under these two slices is the undisturbed foreland, the thrusts glide in the top of the Lower Cambrian. The maps are complex in detail but we can simulate this geology in a few stages:

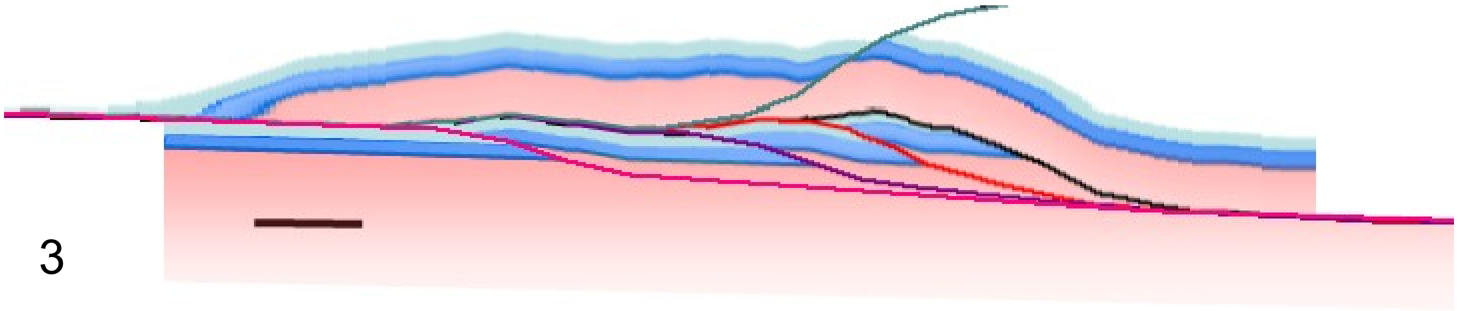


Starting with this, on the scale arbitrarily assigned as 1 unit the 7-unit displacement on the black ramp is intended to simulate the Glencoul Thrust surface.

Thrust model for Inchnadamph, Assynt window, stages 2, 3.

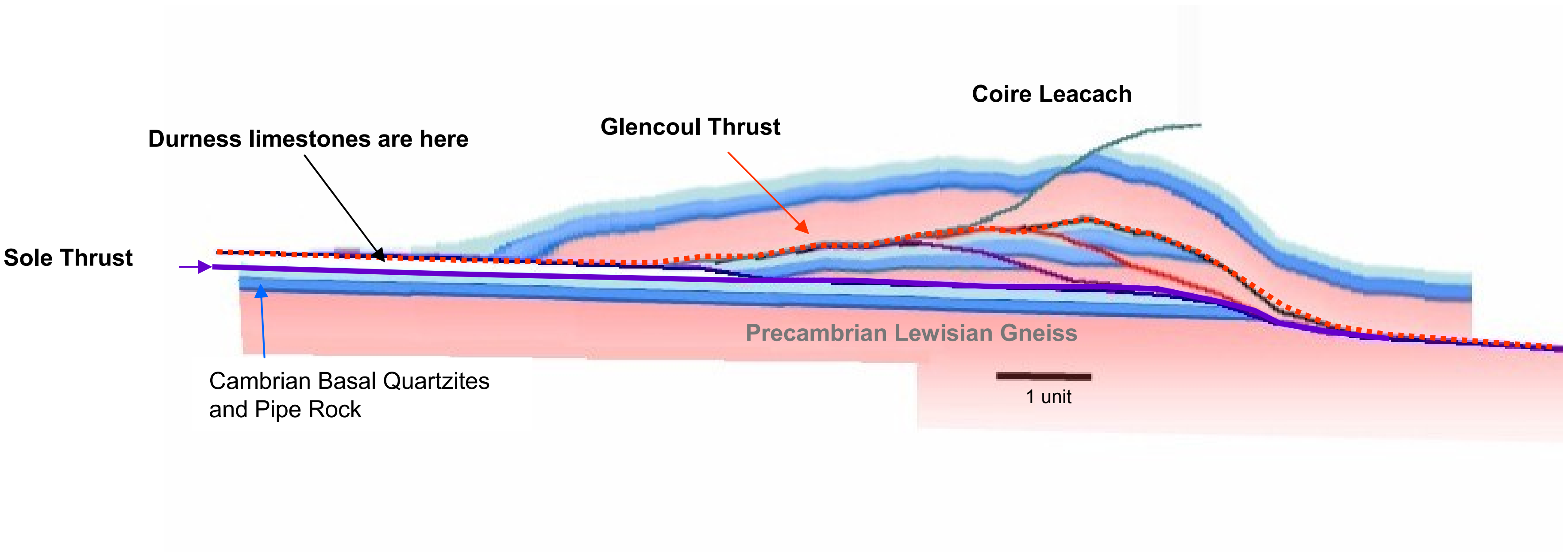


Next we add some imbrications to model those coming off the Sole Thrust, which is propagating west under the Glencoul surface, as a progressive footwall collapse. These faults link with the Glencoul Thrust, which is the roof fault for the Sole Thrust imbricates and passively folds in accordance with the red and purple ramp positions and shapes.



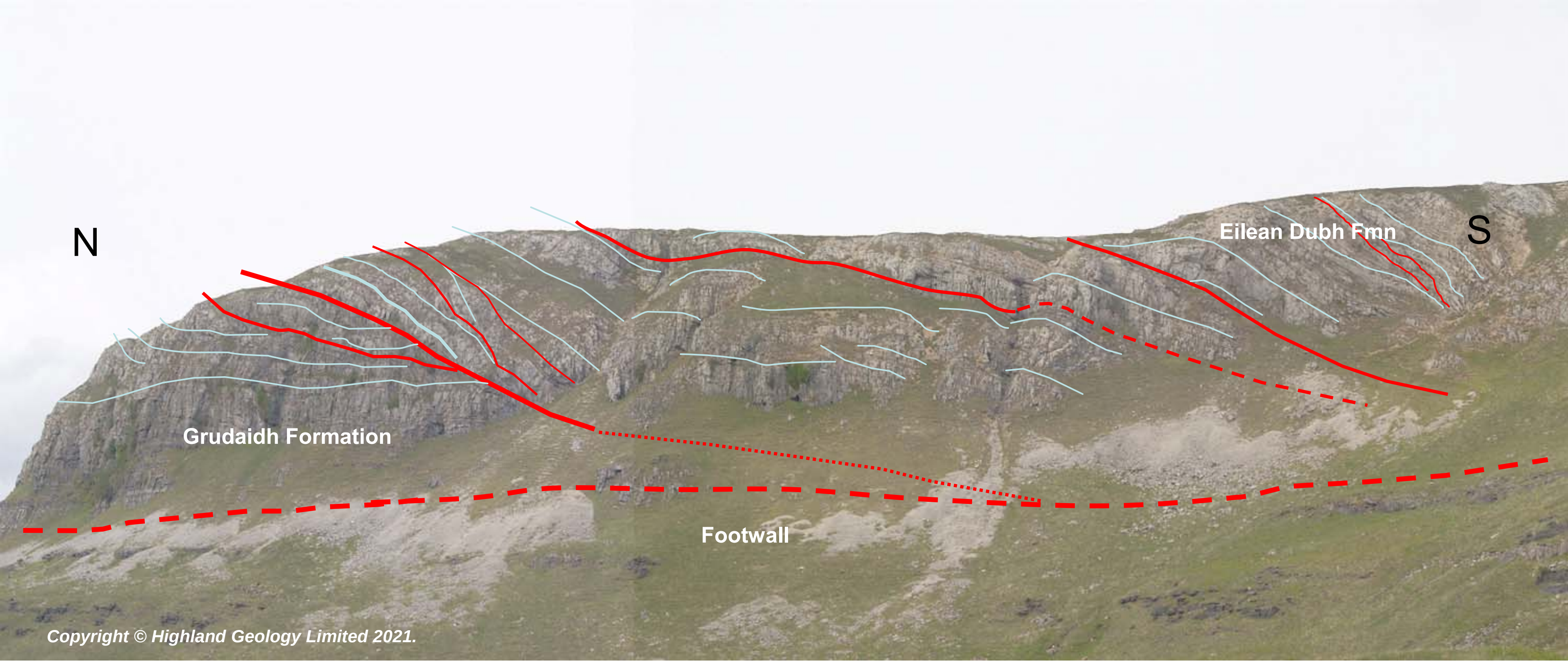
There is a series of extensional faults mapped in the Glencoul Thrust sheet, which have been partly inverted again by renewed compression. They are attributed to gravity collapse caused by the local steepening of the rock sheet over footwall collapse ramps, and they are interesting as plausible models for prospective traps in fault-fold belts. Its possible you'll see mixed extensional and thrust faults in translating thrust sheets. So I put one in (green-grey), along with another footwall flat and ramp, pink, being the next component of the Sole Thrust system. This is running at the top of the quartzites, in a unit called the Fucoid Beds, and I've got it joining with the Glencoul Thrust. We can see how the Glencoul Thrust is a roof fault for a train of duplexes, its displacement varies laterally, parts of it would only be reactivated if out-of-sequence thrusting were to develop.

Thrust model for Inchnadamph, Assynt window, stage 4.



And one last big move gets us to the final model stage. A major displacement of another 5 units on the purple fault carries the Glencoul sheet and the Sole Thrust sheet of duplexes farther west onto the foreland, adding another small ramp here to allow the Durness Limestones to appear as they do, in outcrop at the west end of the section. I made this final ramp using the Sole Fault, joining it with the Glencoul Thrust, but probably what really happens is that some part of the Sole Thrust slip does that and the rest is partitioned variously along the top of the quartzites.

Do we overestimate the amount of shortening in thin-skin fold belts? The answer would be yes, if what we do is measure and sum the individual shortening strain. We might presume that movement on thrusts is not successive really, they may be sharing the same shortening.



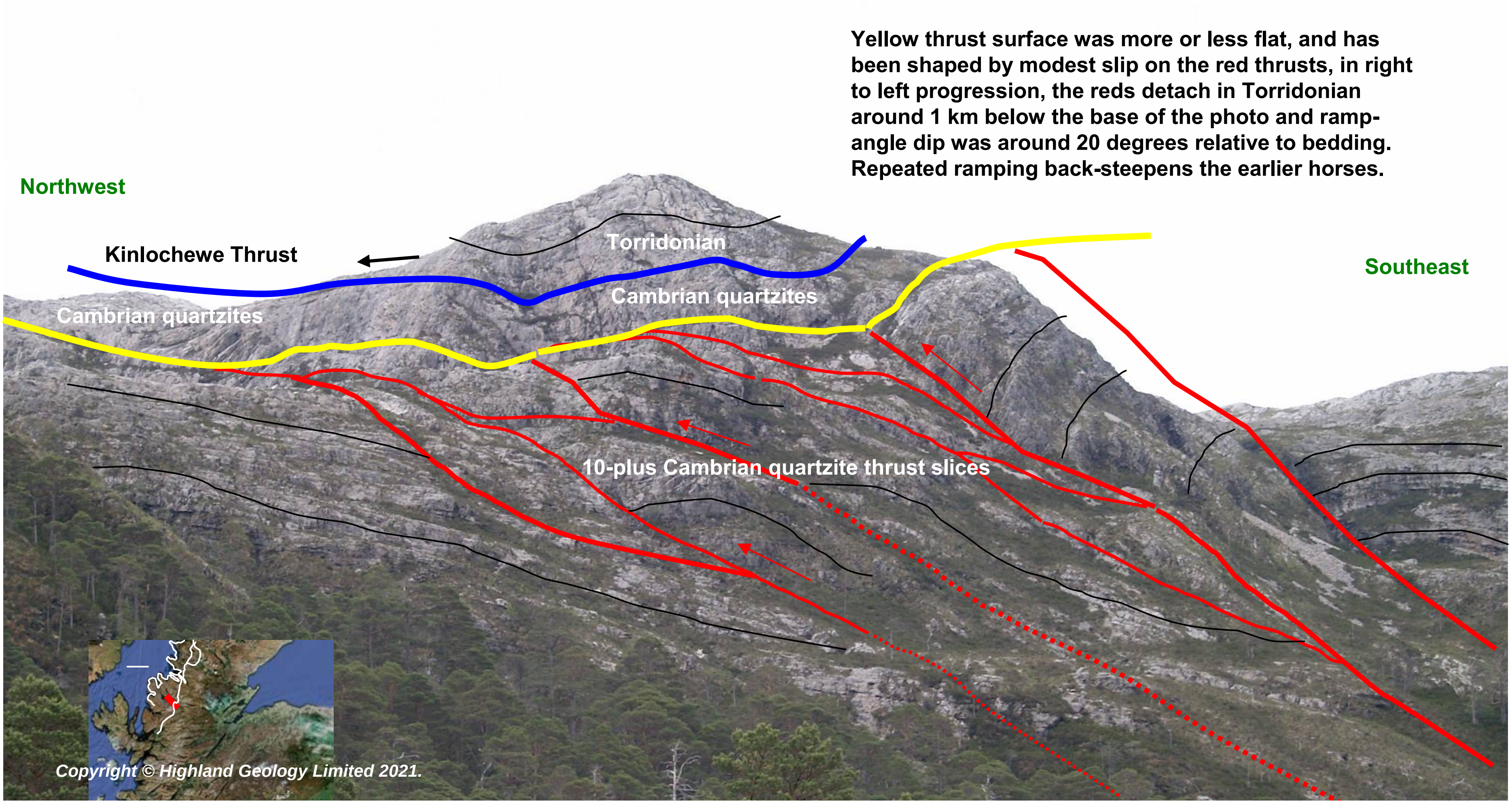
Stronchrubie escarpment a few km to the east of Inchnadamph shows the duplexing in the Ordovician Durness Group limestones above the Sole Thrust, which is detached in the 10-20 metre Fucoid Beds siltstone sequence, under scree. These duplexes are separated by frontal ramps dipping SE, into the plane of the photo. The photo shows about 1 km of the outcrop.

Moine Thrust at Knockan Crag, Sutherland, Scotland

Like many major thrusts the Moine is a very clean fracture, with only a few cm of carbonate-cemented gouge. The thrust is linked into younger thrust surfaces, climbing into it so that it no doubt moved repeatedly, eliminating irregularities.

The Durness Group dolomite footwall is highly sheared immediately below the thrust, but only for a few metres. Its a very different picture in the hangingwall, the Moine comprises highly strained schist which is foliated for 50-75 metres above the thrust surface: its mylonite, formed at depths of 10-15 km.

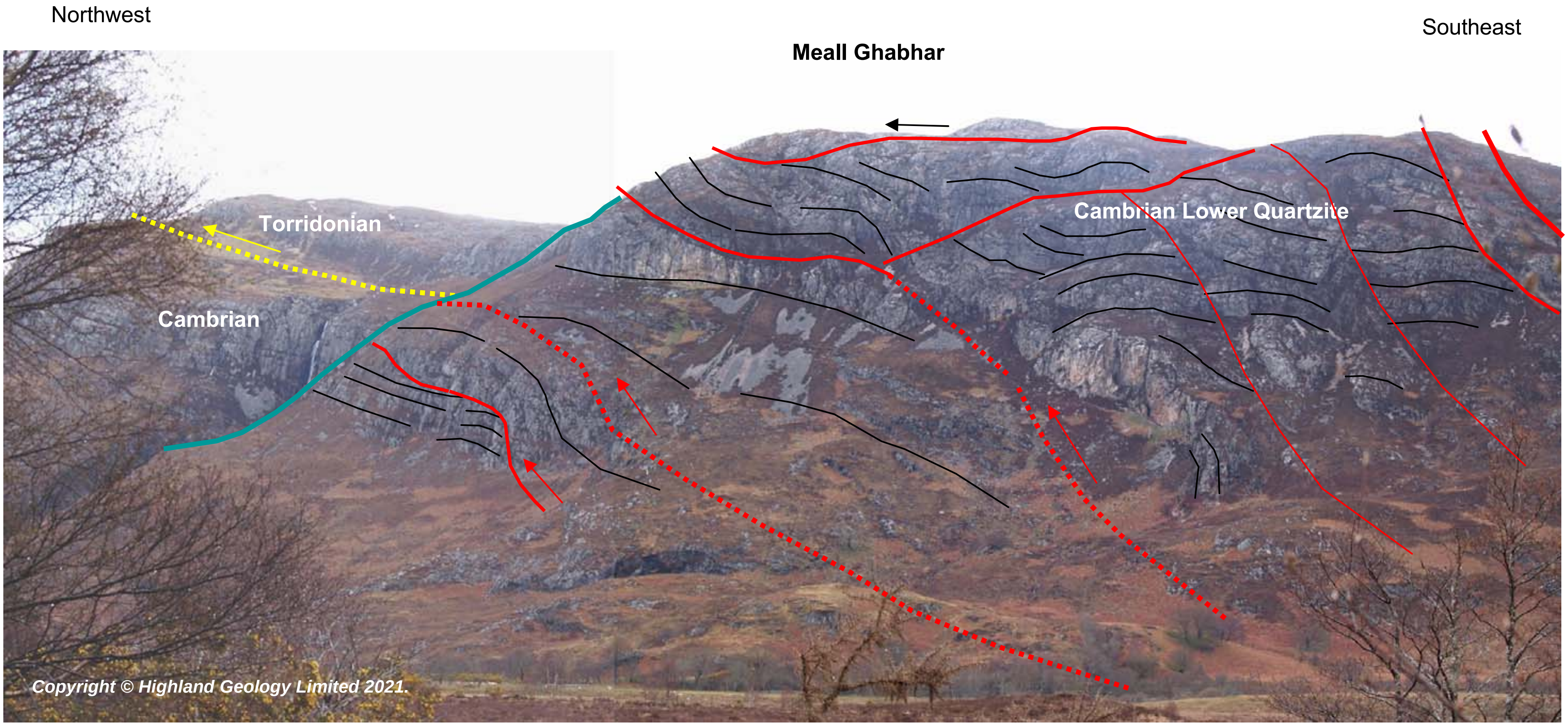
Imbricate thrust stack and klippe, classic duplexes in the Beinn Eighe range, Kinlochewe, Scotland



Yellow thrust surface was more or less flat, and has been shaped by modest slip on the red thrusts, in right to left progression, the reds detach in Torridonian around 1 km below the base of the photo and ramp-angle dip was around 20 degrees relative to bedding. Repeated ramping back-steepens the earlier horses.

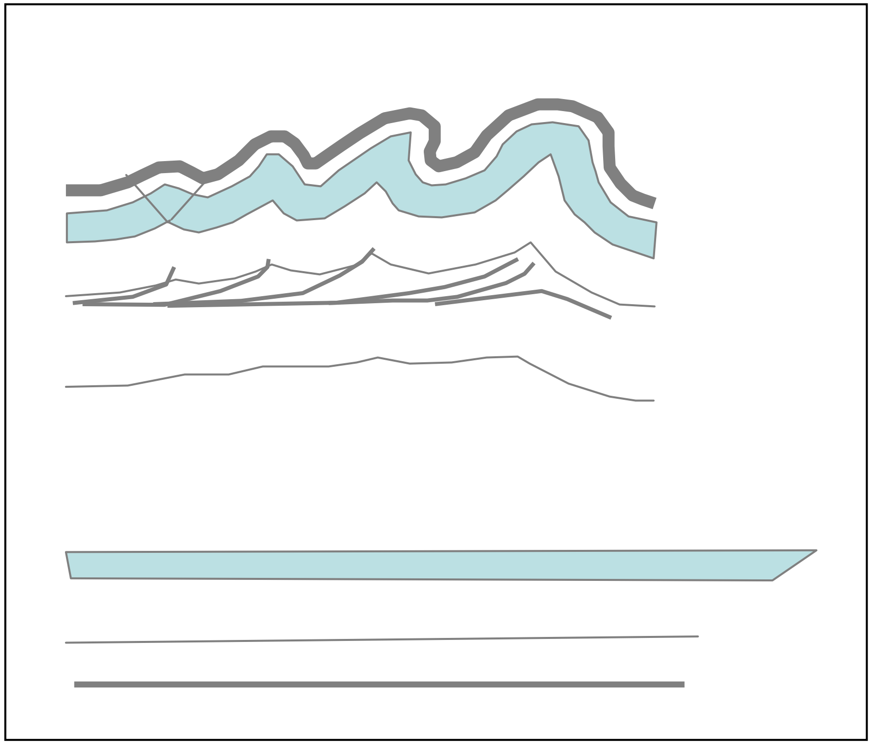
Meall a'Ghiubhais is a local top on Ben Eighe at the SE end of Loch Maree, Northwest Highlands of Scotland. The cliff face is about 500 metres high, it's mainly Cambrian quartzite with around a dozen imbricate thrust slices dipping towards the eye, detaching in the Proterozoic Torridonian, shortening in this stack is around 40 percent. Across these faults lie two thrusts, first the yellow and above that the much bigger Kinlochewe Thrust (blue) which places Proterozoic on Cambrian, mostly eroded off but the two slices remain as a klippe.

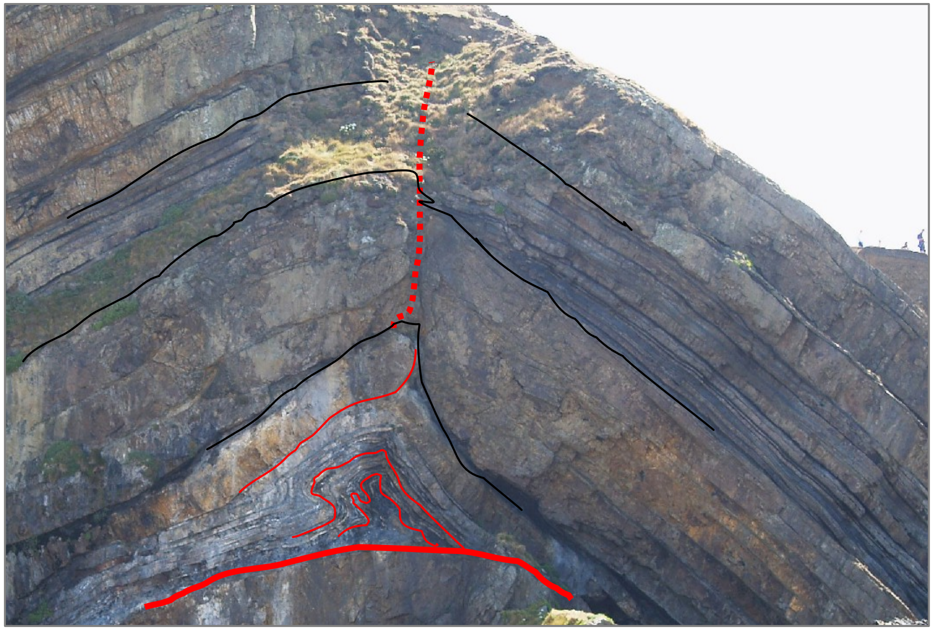
All these faults are in the footwall of the Moine Thrust and are younger than it, its trace at present surface is several km SE of this photo. The MT Zone is the northwest boundary of the Caledonian Orogeny in UK, around 190 km length onshore, tear faults indicate it moved WNW. The thrust belt is regionally tilted by around 10-15 degrees, as we see. Collectively the shortening across the MTZ is between 75-100 km.



On the opposite side of the valley the Kinlochewe Thrust is seen on the skyline (dotted yellow), the slope of Meall Ghabhar is made of imbricated Cambrian quartzites with ramp-related folding. The displacements on these ramps are around 500-1000 metres. The thrust sheet is the roof fault for these imbricates, it carries Torridonian rocks across the Cambrian footwall.

Butler et al (2007) in Geol Soc London Spec Pub 272, show that the Kinlochewe Thrust cuts down somewhat across Cambrian stratigraphy between the east side of the window, where it is in the Durness Limestone, and the west where it rides in the upper part of the quartzites. This isn't what simple thin-skin foreland-propagating thrust modelling predicts. Their explanation is that the imbricates uplifted the window and the Kinlochewe Thrust moved again, truncating the Durness and its ramp folds on the culmination. That is out-of-sequence thrusting, the roof fault is multi-phase. Its rare that we see out-of-sequence thrusting picked on seismic but the process may be much more common than classic thin-skin duplex models depict.





Drilling large tight anticlines, the maps become increasingly prone to error with depth.

"Similar" folding means that each bed's deformed shape is exactly the same as those above and below it: to achieve this result the thicknesses of beds (measured orthogonally) have to vary, with the limbs being much thinner than the crestal zones. A flow process is implied, and the areas of beds between pairs of flow lines stay constant. Bed lengths around the fold increase greatly. The fold could persist down the axial surface, indefinitely, it doesn't have (doesn't need) a basal detachment.

On the other hand, as this top-left sketch from Warren Carey proposed, "concentric" folds do need detachments to balance them. In concentric folds the deformation is bed-parallel, the process is flexural-slip in the same way as a deck of playing cards folds. If we presume parallel fold style the fold cannot continue indefinitely, and simple anticlines overlie complex thrusted structures.

Space problems in the cores of concentric folds are solved in a number of ways, this photo of a Bude, Cornwall structure shows processes working to accomodate excessive bed length on and below the centre of curvature:

- crenulation, the beds are thrown into high amplitude, short wavelength folds.
- out-of-core thrusts develop.
- detachments are formed on bedding planes

Signs of opportunity: and the key role for line-length checks.

Looking at given interpretations, e.g. Kingdom projects made by other explorationists, or notes to accompany data releases, may quickly tell us whether untested or poorly mapped traps are likely to be present.

- are the picked sections very local? You need reasonably long profiles, to interpret thrust-fold structure, a short dip line set won't be adequate.

- structure styles tend to repeat. Look at better-known anticlines, with wells, understand these, use them to test new ideas which may apply to your area of particular interest. Even structures 20-30 km distant may be highly relevant.

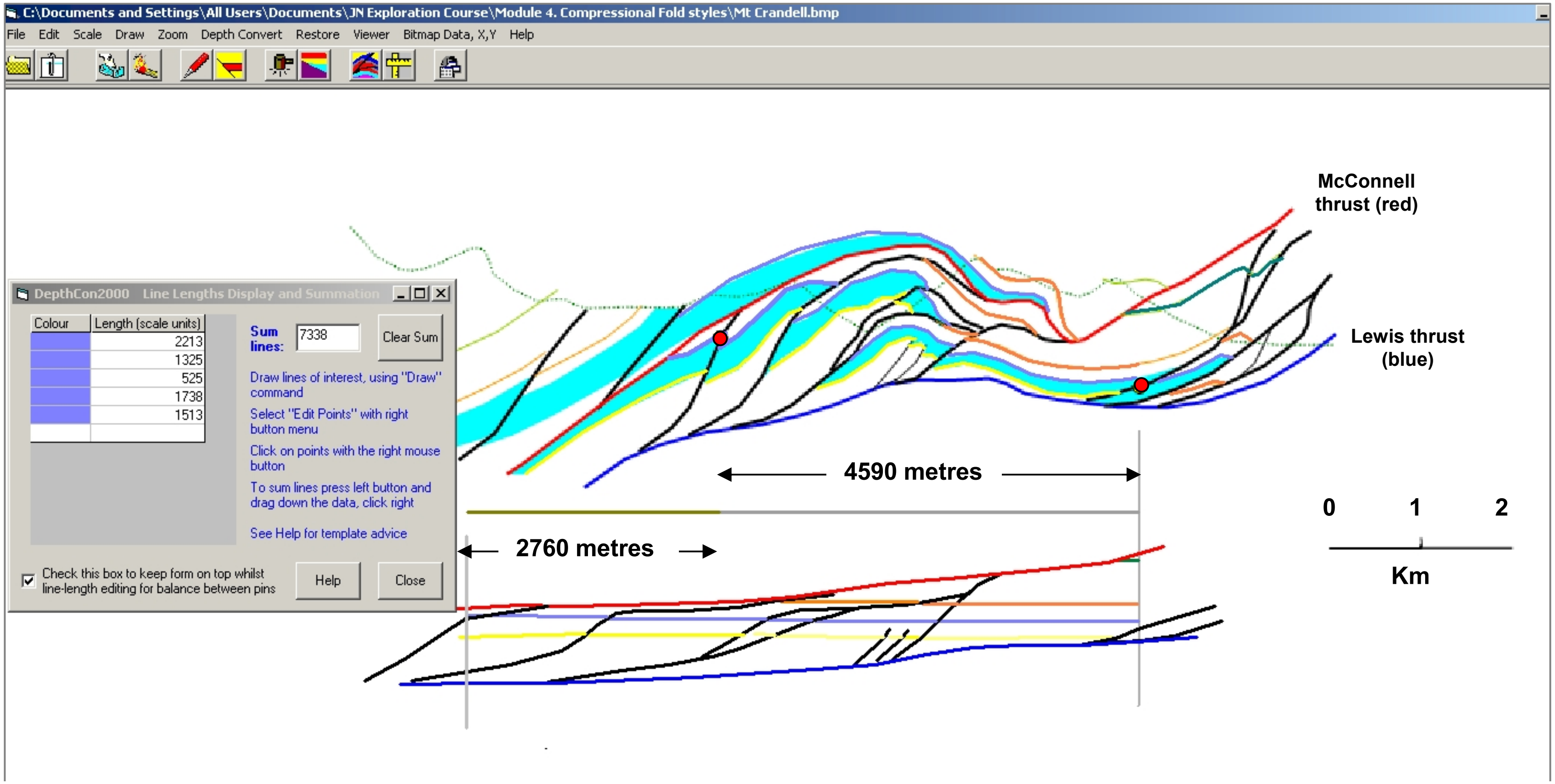
- do the bed lengths for the various picked units look the same, between pins, across the section? If they don't, if one horizon length is different from the rest, there may be an undetected duplex. Next slides show how this simple observation can be extremely effective.

- has the interpreter only picked steep faults? if these are not linked together by detachments the structure is incompletely interpreted.

- if there is a geological map, does the down-plunge view look like the section?

- can you visualise how the structures formed, or are there lumps and bumps which don't have a clear explanation. If there are, then good, these are unresolved structures which are things to focus on, they may be closed structures. Structures which you don't understand should be modelled, explained, don't quit till you have done this.

Duplexes, and line-length checks



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DepthCon2000 Line Lengths Display and Summation

Colour	Length (scale units)
🟦	2213
🟦	1325
🟦	525
🟦	1738
🟦	1513

Sum lines: 7338

Draw lines of interest, using "Draw" command

Select "Edit Points" with right button menu

Click on points with the right mouse button

To sum lines press left button and drag down the data, click right

See Help for template advice

☑ Check this box to keep form on top whilst line-length editing for balance between pins

For this given section at Mount Crandell in the Foothills, Alberta, our software is used here to measure the bed lengths in the various thrust slices (horses) interpreted in outcrop, and to sketch the undeformed template between two pin points (red). Line-length checks like this will show whether a horse or two may be missing. If the template faults have odd shapes, especially if they need to double back on themselves to honour the cut-off points, you know there's a problem with the interpretation, and where it is.

This interpretation of the structure was made by Douglas in the 1950s and has been variously published as a type example of duplexing. It works fine, because its been built using line-length checking. Lewis Thrust (dark blue) places Precambrian on Cretaceous. Pale blue marker formation is the Lower Altyn dolomite which is shortened between the floor and roof thrusts, and is flexed by transport over deeper (unshown) ramps. The shortening is 2760 metres, with the original length between pins (red points) found to be 7350 metres. The plane strain "contraction ratio" is therefore estimated at around 4590/7350, 62 percent, which is relatively high. The Lewis is one of North America's biggest thrust sheets.

Detachment folding at Moose Mountain, Alberta, upper thrust sheet of a series in Mississippian carbonates.

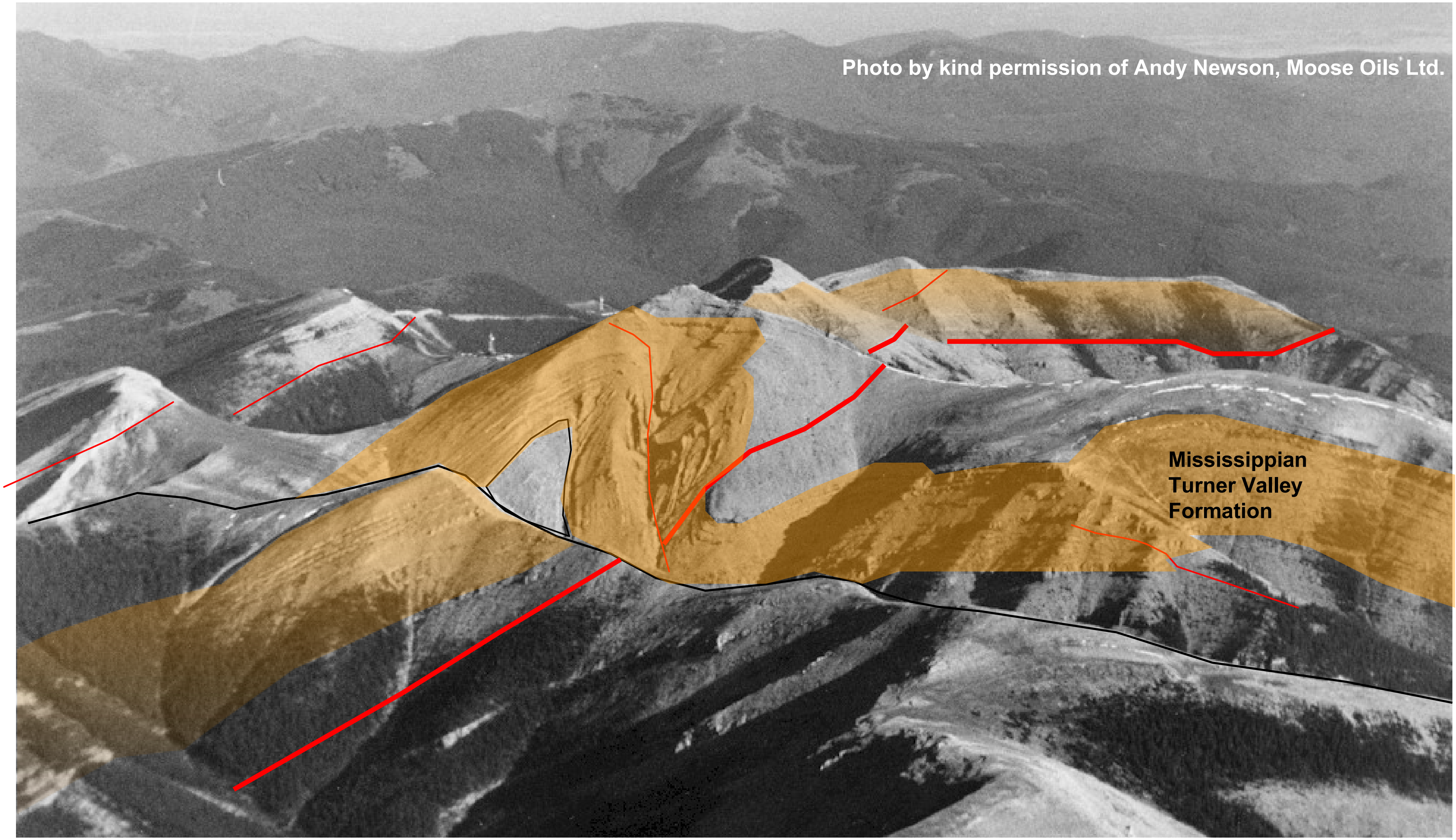


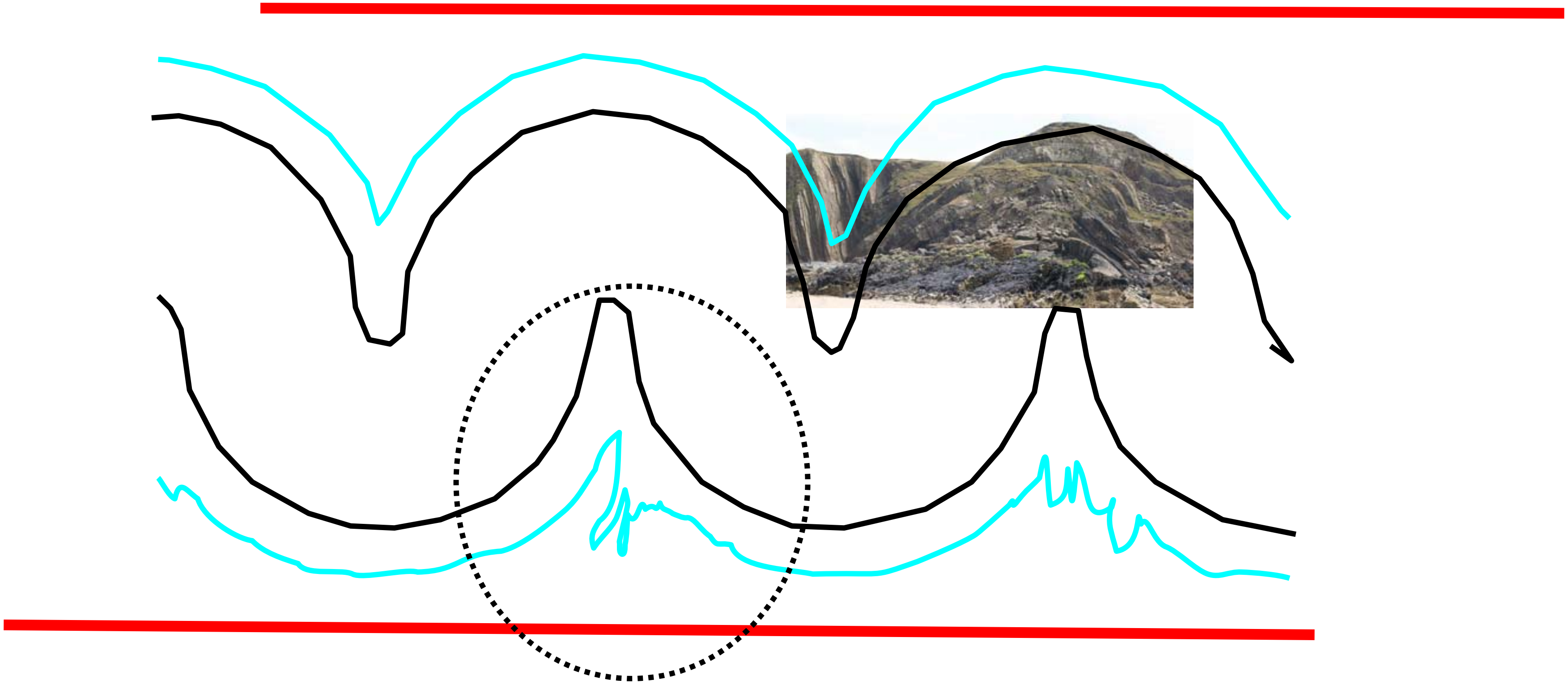
Photo by kind permission of Andy Newson, Moose Oils Ltd.

This outcrop is interpreted as a detached fold set elevated passively after its formation by a series of deeper, younger thrusts which form a duplexed antiformal stack. That is, a series of close-spaced thrusts each having relatively small displacement jacks-up the detachment fold. In the early 1990s Andrew Newson drew sections across this field, which was discovered in 1929, and realised the then-current published interpretation was line-length unbalanced and there was therefore potential for one or more undiscovered large Mississippian limestone horses to be present in closure. Subsequent seismic and drilling by Husky Oil showed his argument to be correct and an important oil reservoir was discovered. Very simple, very effective thinking led to a major success.

If we see only the outer part of a fold structure, what can we guess about its internal structure?

Anticline-syncline buckles, coastline just north of Bude in Cornwall UK, cliff height is about 30 metres. These folds were formed in the Upper Carboniferous of North Cornwall at high structural level in the Variscan thrust-fold belt, they are scraped off the Lower Carboniferous limestones and Devonian beds. What do they look like at depth?

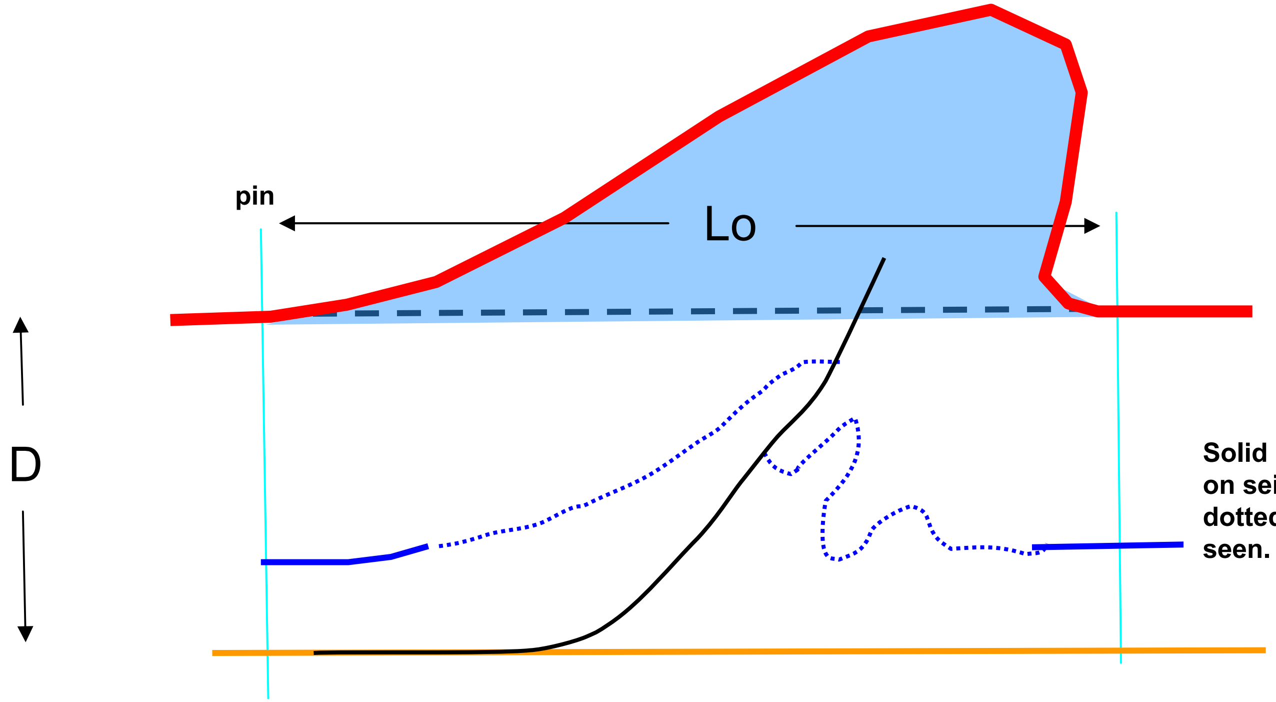
Presuming concentric behaviour a generalisation we see often is that basal detachment must be close when anticlines are steep-sided and widely separated by broad, flat synclines; and will be deep when anticlines are broad and separated by narrow, steep-sided synclines. That would commonly be a major decision-making principle, in selecting targets in fold belts. But they may not be concentric!



Presuming concentric behaviour, we expect depth to detachment must be shallow when anticlines are steep-sided and widely separated by broad, flat synclines; and will be deep when anticlines are broad and separated by narrow, steep-sided synclines. So according to that thinking, steer away from the widely-separated anticlines, ringed. That would commonly be a decision-making principle in selecting targets in fold belts, especially as these structures will tend to be poorly imaged on seismic.

We'll discuss this idea in the context of Tripura and Manipur, NE India, and see how it can be counter-productive.

Using a fold to estimate depth to a detachment surface



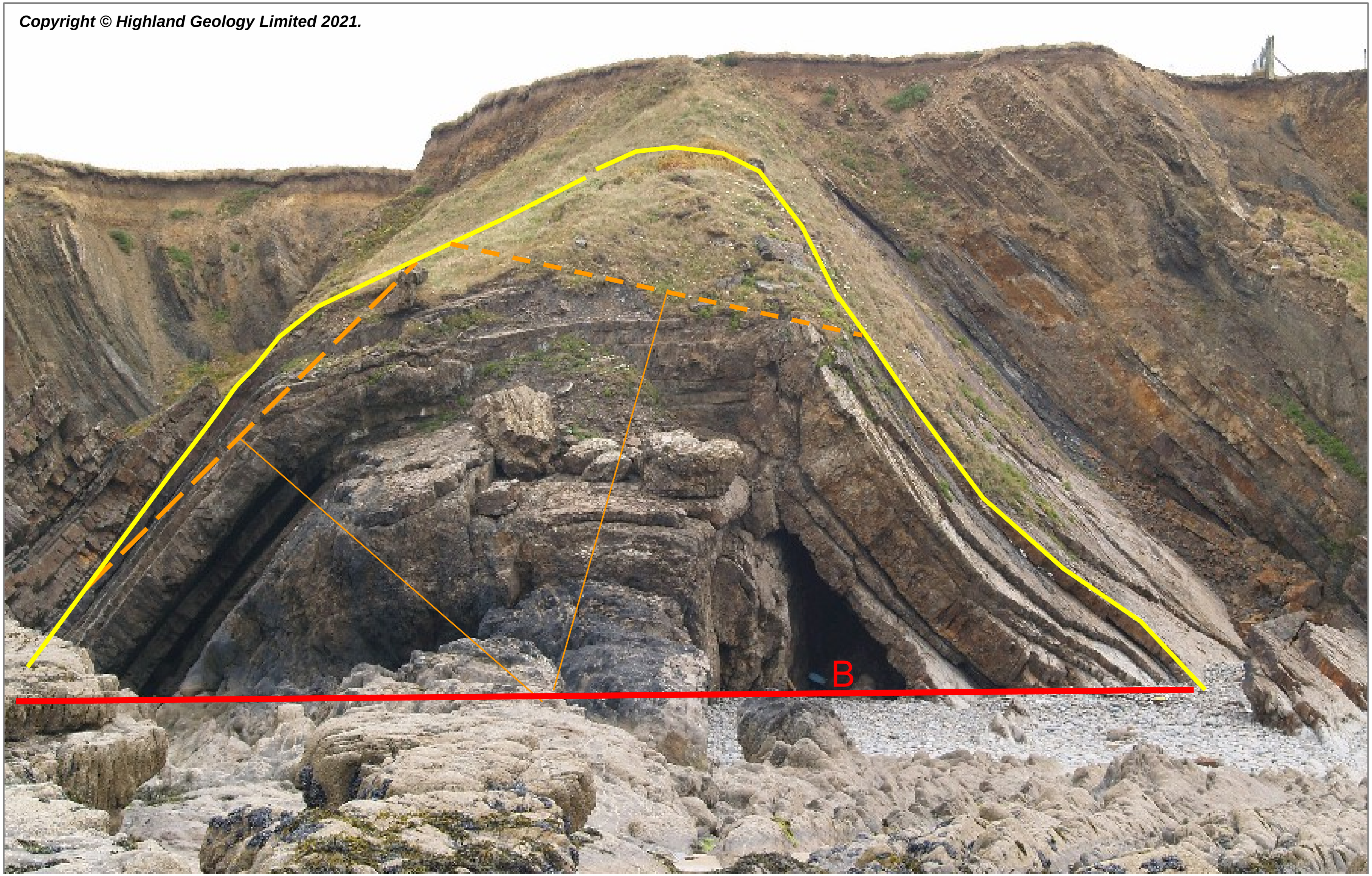
Solid blue, seen on seismic; dotted blue, not seen.

Draw the black regional dashed line for red, (it may be the line connecting base of red in synclines if no flat red segments are present), and measure the excess area (blue) generated above it under red in the formation of the fold. Measure the distance between the pins, and the dashed red-white fold line length between them, L.

The depth to detachment multiplied by the amount of shortening (L - Lo), divided into the area, gives D if the section is in the dip direction. To draw deeper structure such as the blue bed, its line length has to be the same as the red-white bed. Assume as a model that the shortening is in the footwall, and draw some fold pattern which gives the equivalent line length. There will probably be an axial thrust, detaching on the basal detachment, so sketch something appropriate.

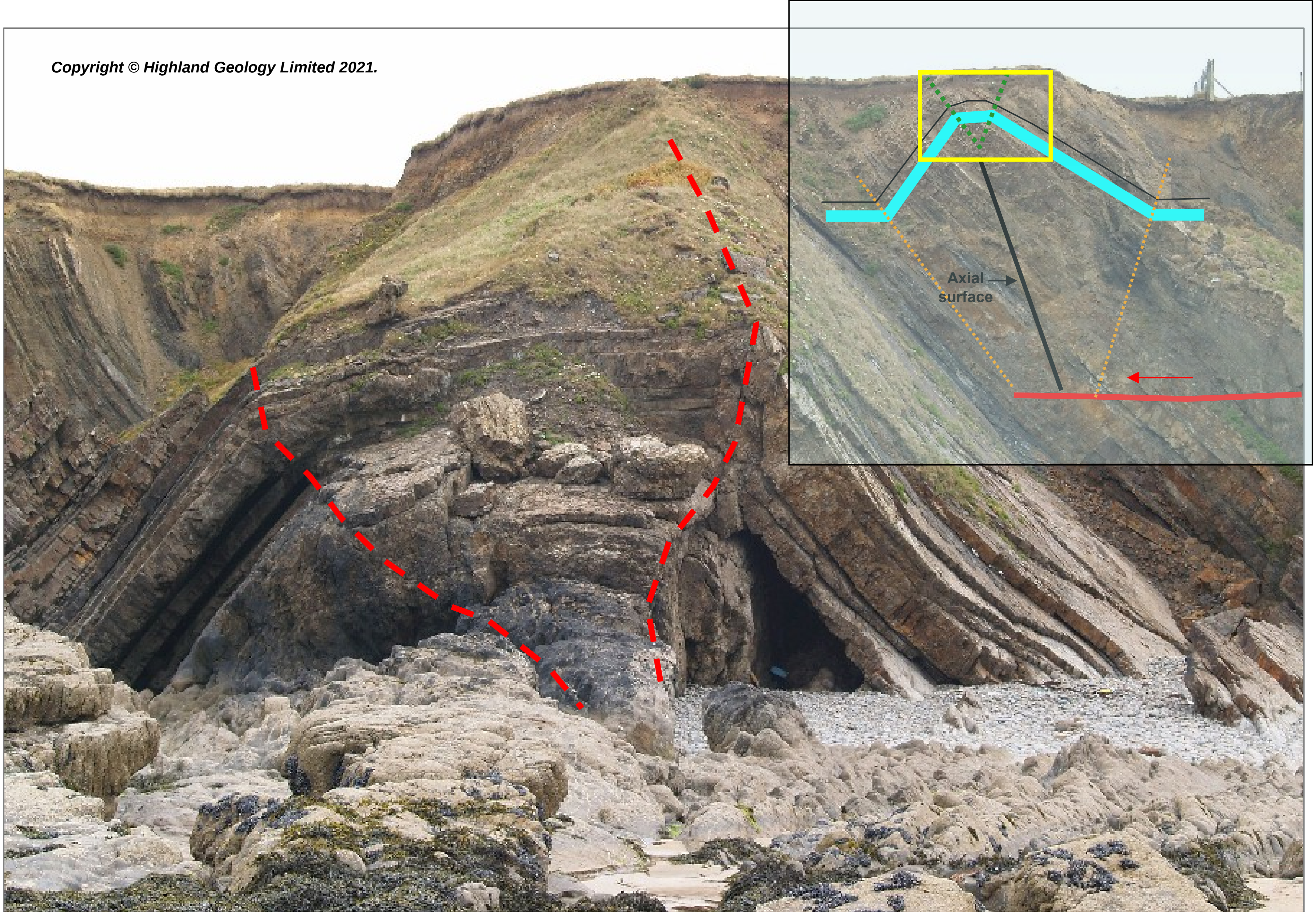
Units below the orange detachment surface won't conform to the geometry above it, they might not be shortened at all.

Does the seismic see anything like this? Maybe there are several thrusts cutting blue, there are lots of possibilities, its just a rough guide to what may be happening: but its a start!



A variation on this for parallel folds is to sketch the envelope of the bed (yellow), and draw any two chords (orange dashed), draw the orthogonals and where they intersect is the centre of curvature, below which bed shapes become cuspate. (This natural example is marginally convincing, although its a box fold). Draw the red reference line B for this point, the shortening is the yellow length minus the red. Measure the area between yellow and red, the detachment is predicted at {Area/(yellow-red)}.

Hmmm. Well we don't know the answer in this case, but that would be one approach to finding it.



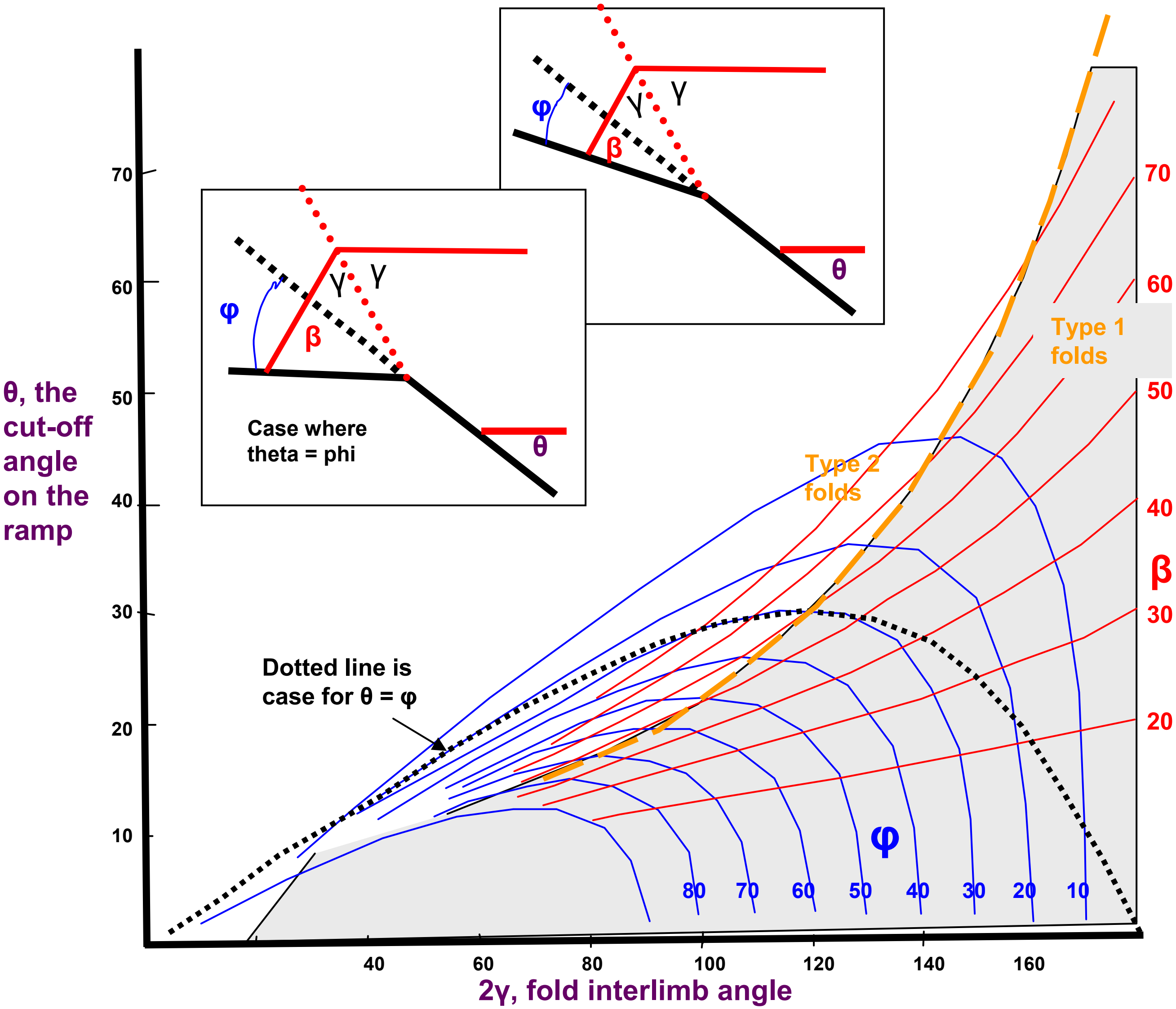
The apparent crest is flat and dipping towards us at 5-10 degrees, narrowing down-plunge as the axes converge. Is this a detachment fold, or might it be a fault-prop fold? It could be either, with this evidence. Inset is a detachment fold model. On the other hand if its a fault-prop fold we'd expect to see a steep ramp and upwardly-decreasing slip of markers across it. We can rarely get all the evidence we need, either on seismic or at outcrop, to demonstrate the style.

Fault-bend fold kinematics

Fault-bend folds, which are forced into rocks moved across stepped, flat and ramp thrust surfaces, were identified as such by Rich in the 1930s. In 1983 Suppe wrote the analysis which relates fault-bend fold interlimb angle to ramp angle, assuming conservation of layer thickness and bed length, and with this it became possible to predict the fold geometries which would develop with slip over particular ramp shapes. Suppe's key chart is drawn here, his equations define the evolution of the models shown in the following sequence.

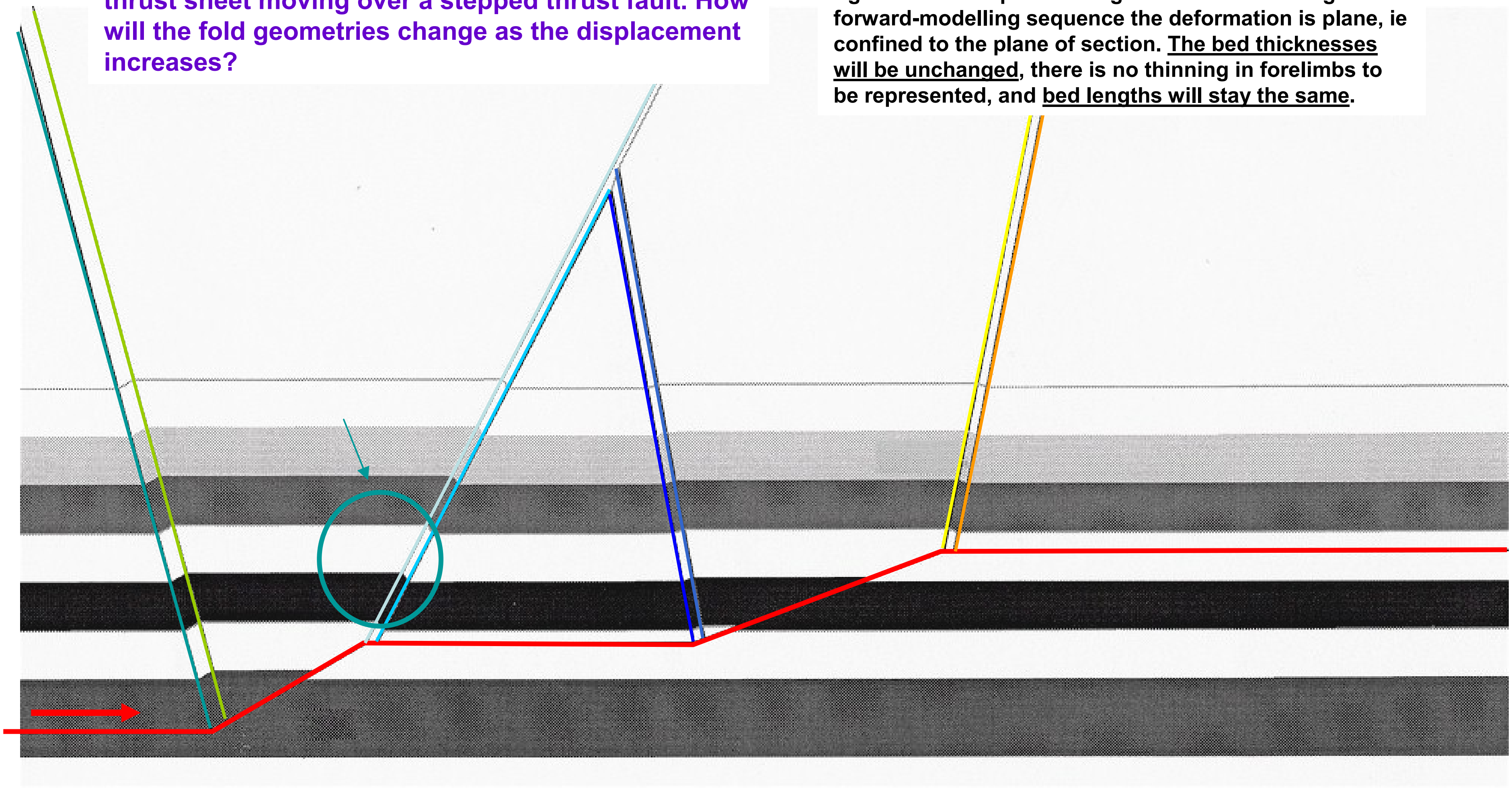
Part of the Suppe chart relating interlimb angle and ramp angle, to fold interlimb angle. See Suppe, J., 1983, Geometry and kinematics of fault-bend folding, Am J Science 283 (7), 684-721.

Notice that there are two possible solutions for a given theta cut-off angle, leading to the definition of Types 1 and 2 folds. Nearly all the folds we deal with as exploration prospects are Type 1.



Fault-bend folding: evolution of kink-band folds in a thrust sheet moving over a stepped thrust fault. How will the fold geometries change as the displacement increases?

The red ramp to the left has a 30 degree dip, the rightward one dips at 20 degrees. In the following forward-modelling sequence the deformation is plane, ie confined to the plane of section. The bed thicknesses will be unchanged, there is no thinning in forelimbs to be represented, and bed lengths will stay the same.

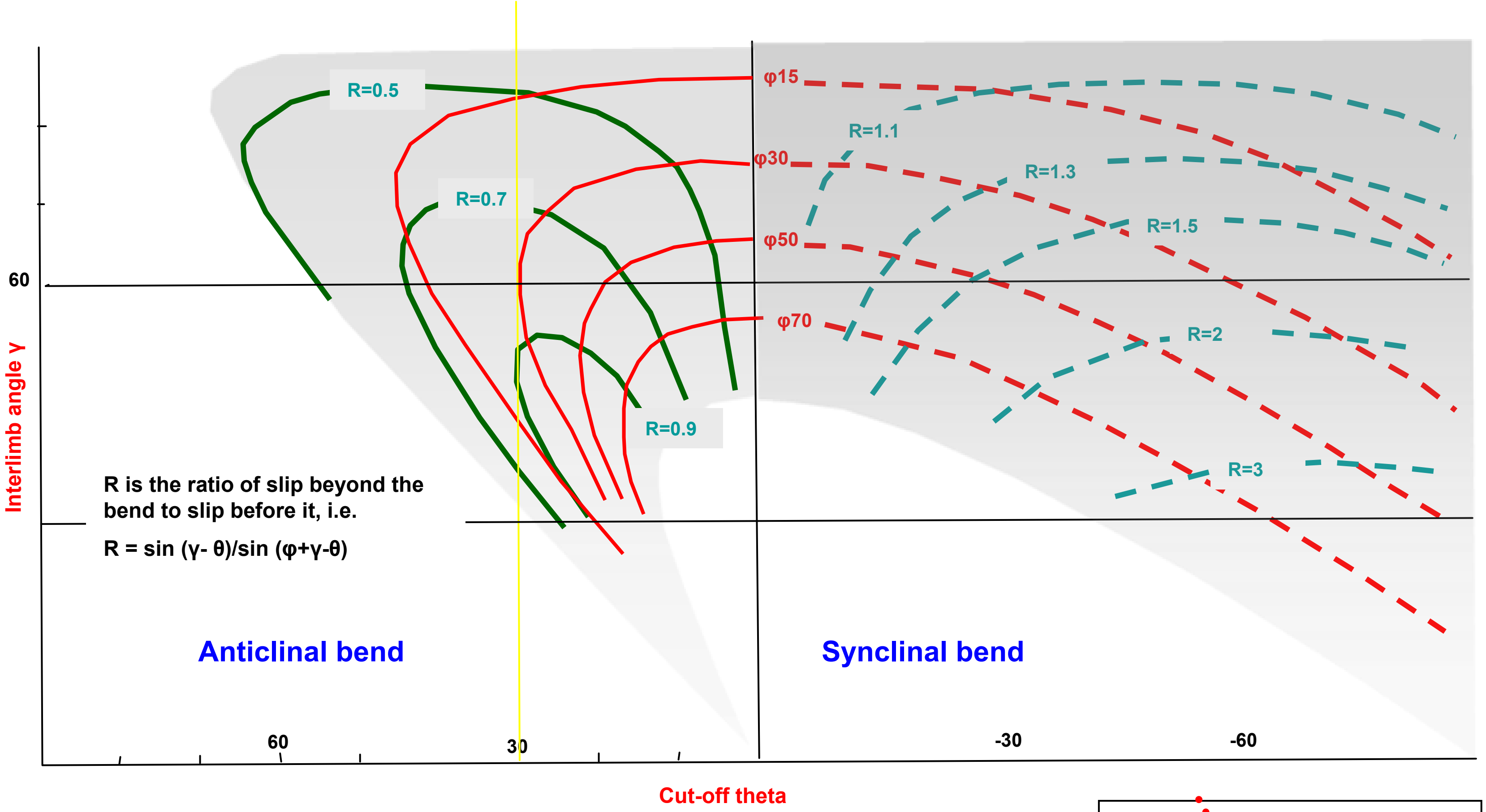


Stage 1:1000 units of slip from left side. As the first increment of slip is fed into the model the kinks in the red fault spawn fold axes, whose dips are known from Suppe's construction. They are the bisectors of the interlimb angle, and we get that angle from his cross-plot with the ramp dip. We also get the forelimb dip for each fold, from that graph.

Feeding in a given slip at left, that value is going to change at each bend: it will decrease as we go around an anticlinal bend and increase as we go around a synclinal bend, according to the "R" ratio of slips which is a function of interlimb angle and ramp angle.

So the four fold axis dips are known, green, grey, dark blue and yellow, they are anchored at the thrust's inflexion points, and we also know how to apportion the amount of displacement on red at each bend.

Slip changes on bends



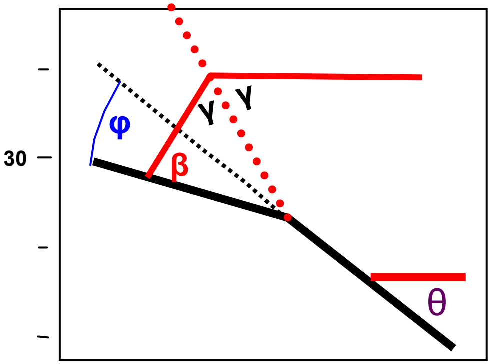
R is the ratio of slip beyond the bend to slip before it, i.e.

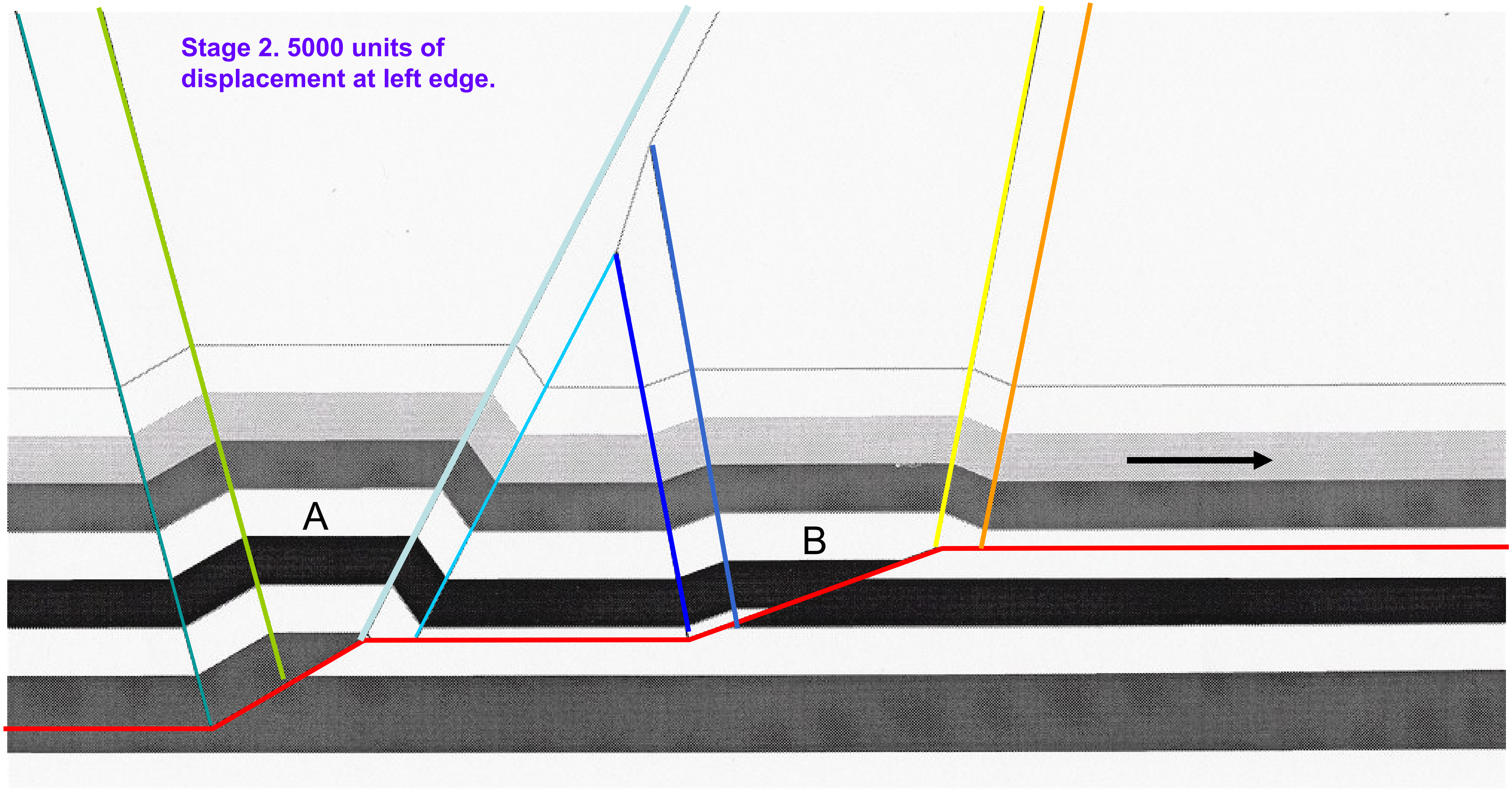
R = sin (γ- θ)/sin (φ+γ-θ)

Slip on the fault surface changes from segment to segment, according to Suppe's expression R.

This is his method for estimating slip change on the detachment surface at an anticlinal bend and at a synclinal bend.

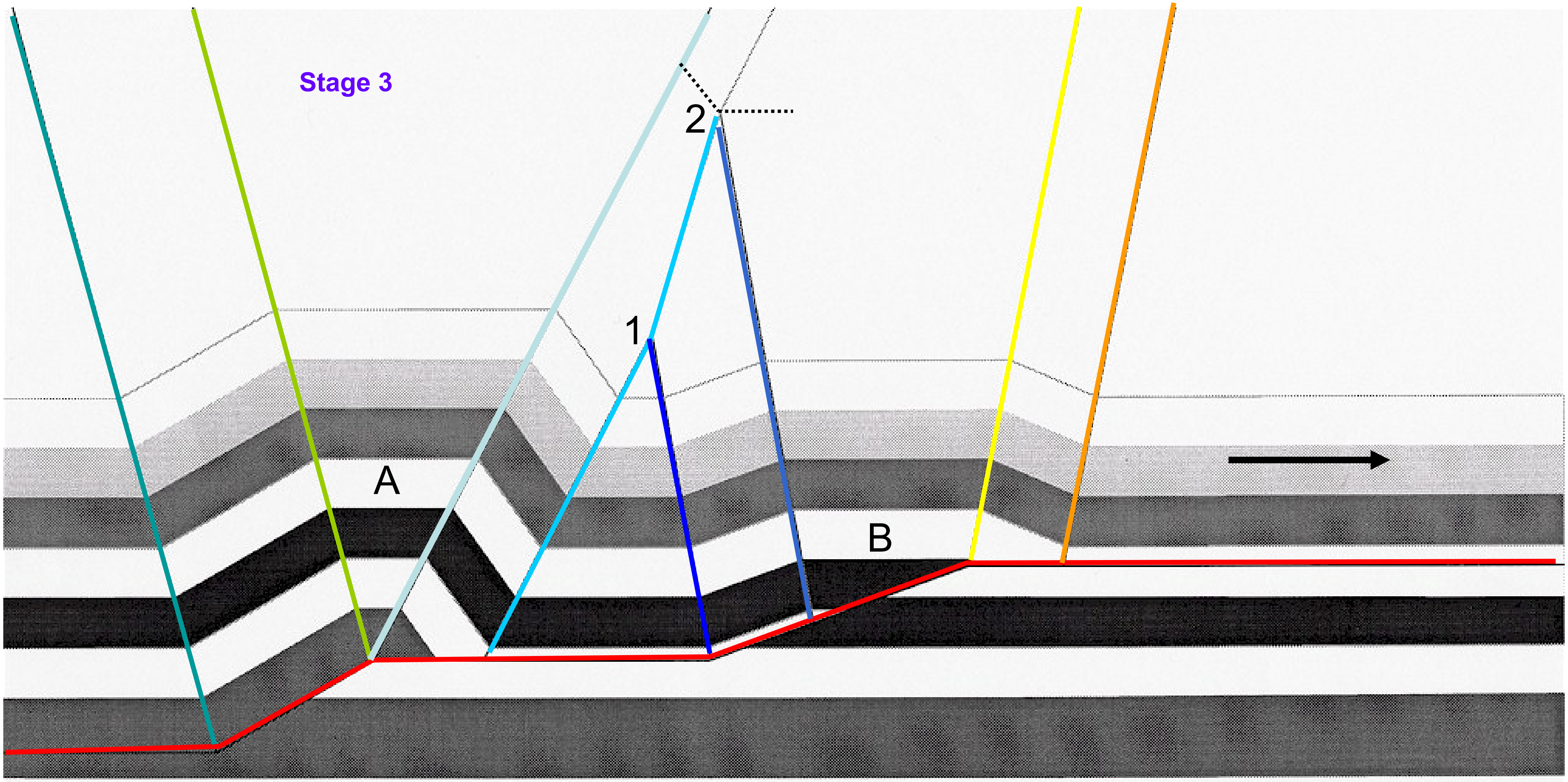
The anticline consumes slip, so R is less than unity. Synclines release slip, R is greater than 1.





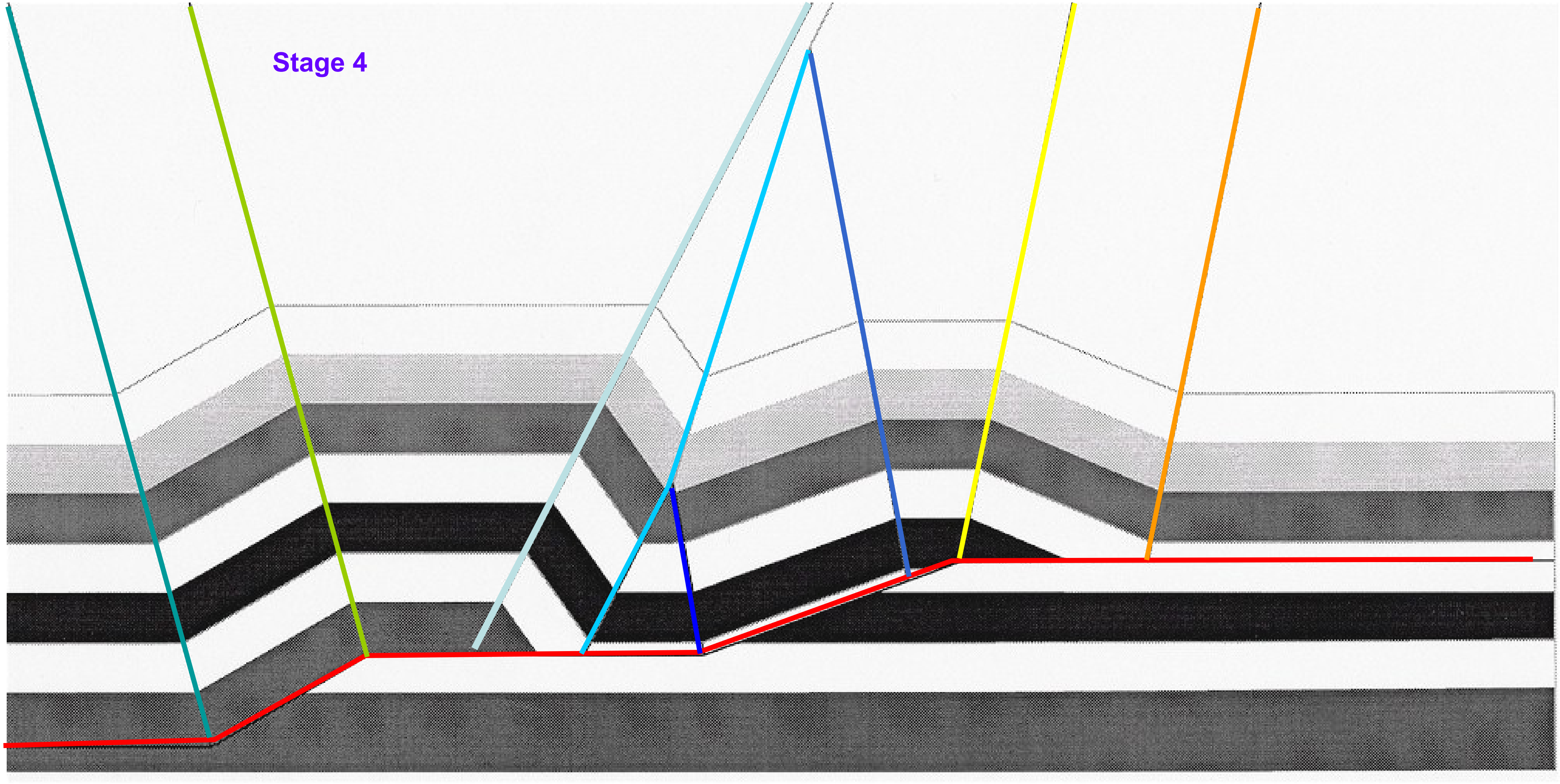
The kink bands are widening and the moving fold axes show variable separation from their origin, for the same amount of input slip. For the 30-degree ramp, with interlimb angle of 120 degrees, R = 0.7 meaning slip is lost going around the top of ramp A, some 30 percent of the slip is passed into the fold as bed-parallel shear. This process is "flexural slip".

The 30-degree ramp fold A is a box with a steeper and shorter leading limb, fold B on the gentler ramp has subdued expression at this stage.



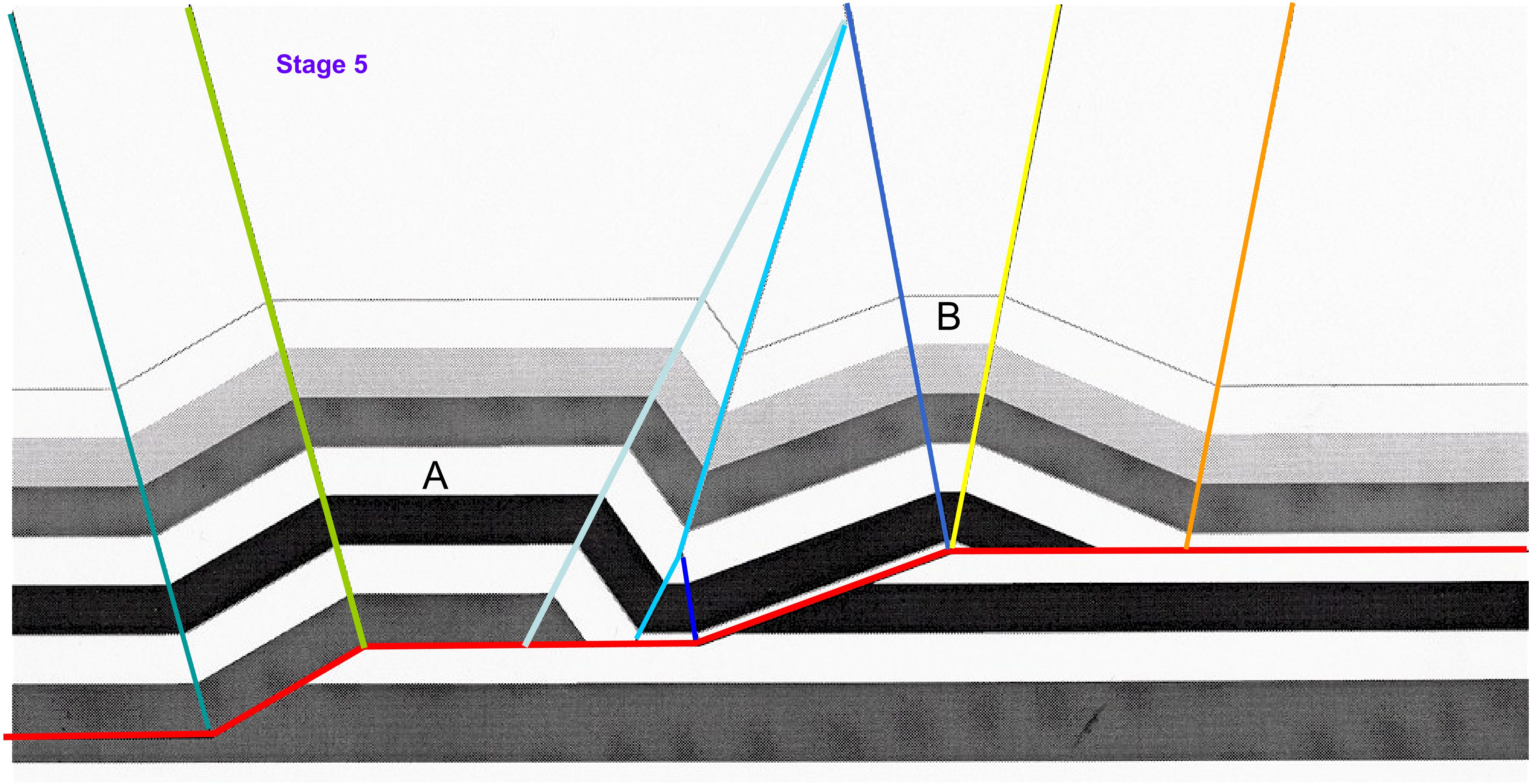
10000 units of rightward displacement is a particular case where the light green moving fold axis has just reached the top of ramp A and met the anchored grey axis, grey will now be released to move off rightwards and green stays fixed at the top of the ramp. As displacement continues rock passes through the fixed-axis positions.

(Fold axes are initiated as bisectors of the interlimb angle. A new axis made by upward converging axes is drawn for example from the intersection point 1 to the next intersection of axes at point 2: not as a bisector of the two axes joining. The points joined are the positions where an underlying panel ceases to exist).

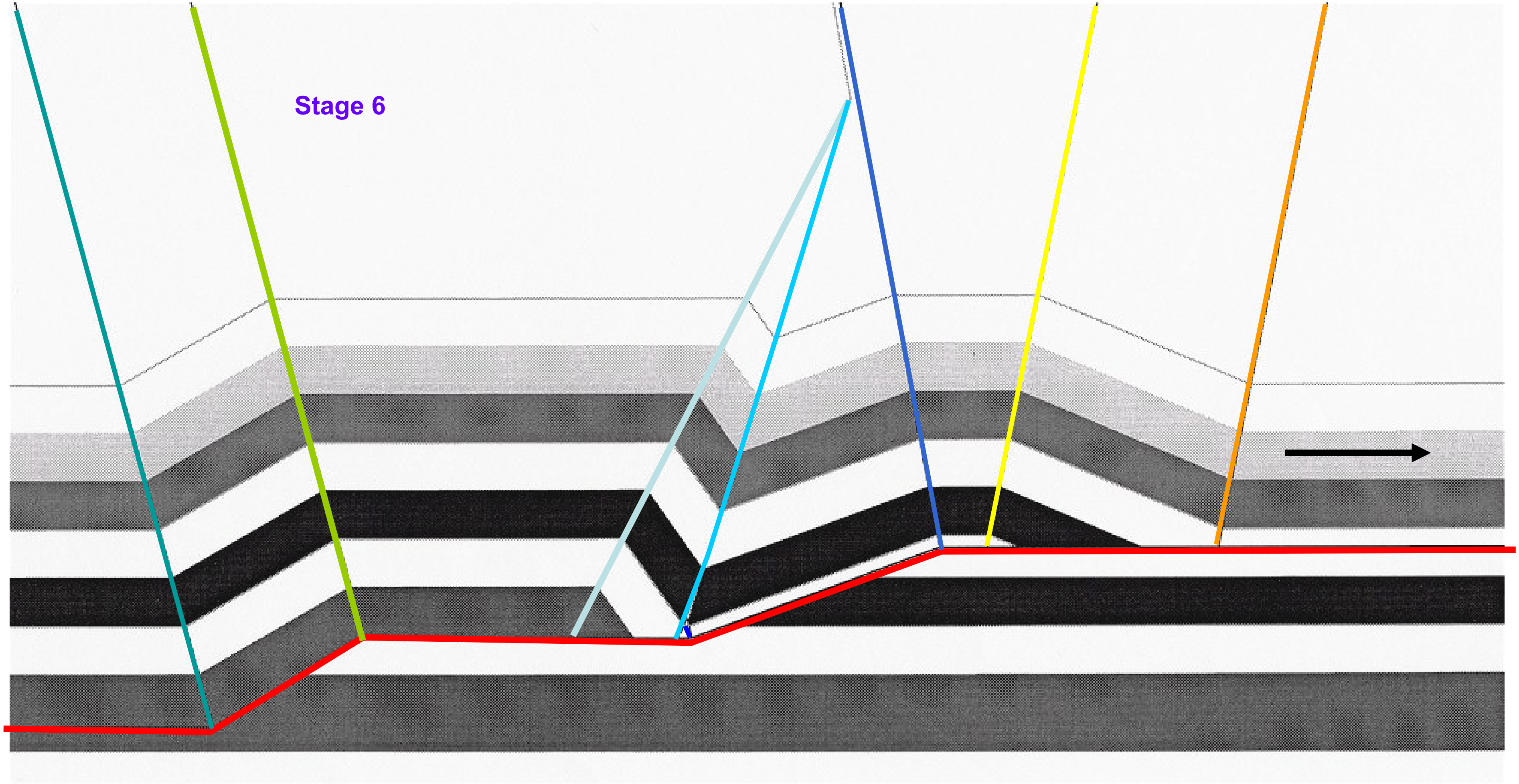


16000 units of displacement, A has its full amplitude and is broadening, whilst fold B is still to reach its maximum height, the lower ramp angle means that the floating blue axis has not yet reached the top of ramp B.

Stage 5

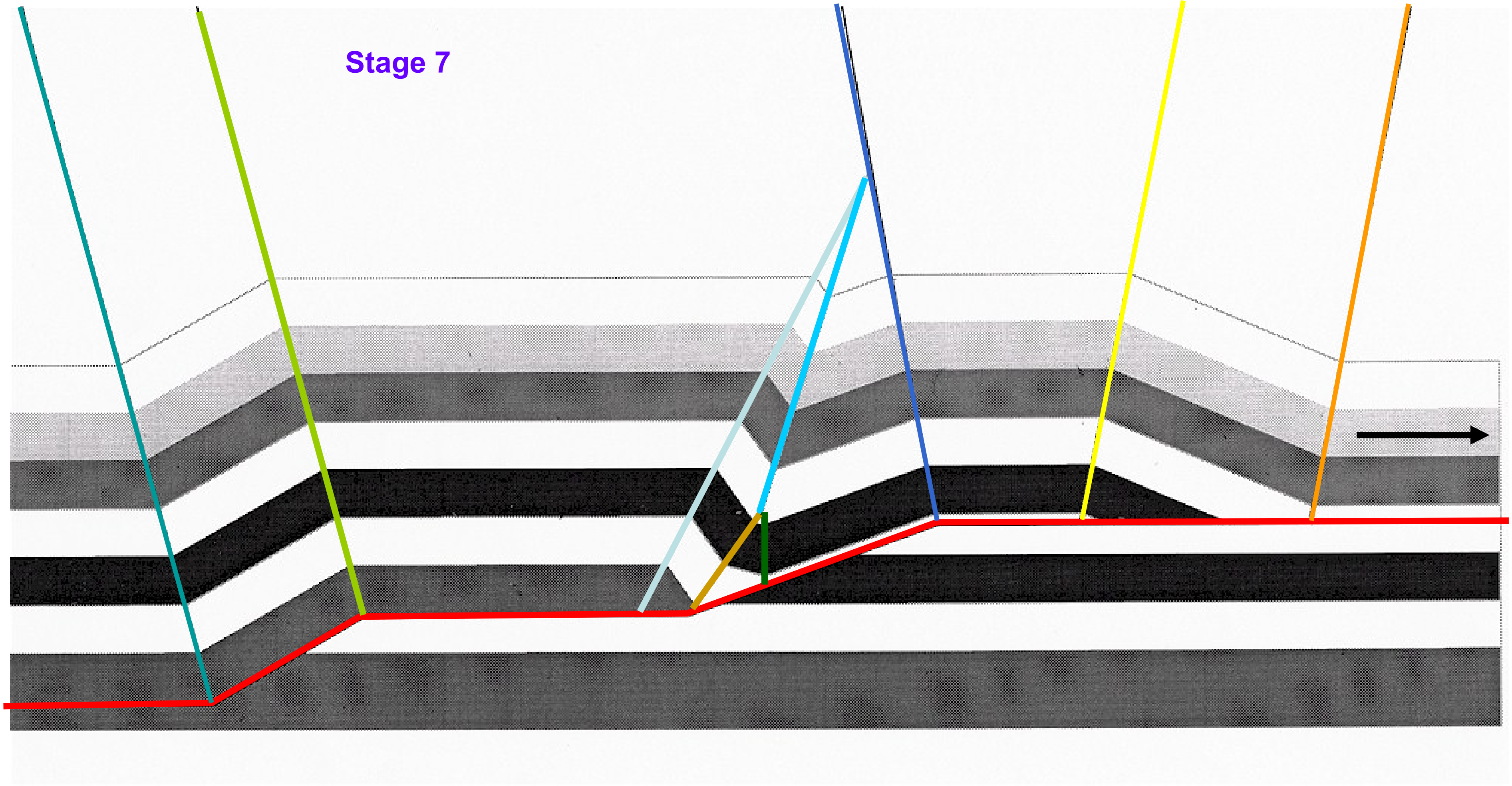


19000 units, structure B height is now the same as A's and it will start to widen. The travelling light blue axis of A has nearly eliminated the dark blue axis anchored at the foot of ramp B.



22000 units, original dark blue is almost merged with and replaced by light blue and I'm going to re-colour this axis now because it will sub-divide as a new structure element. The travelling blue fold axis at the top of ramp B is now anchored and has released yellow.

Stage 7

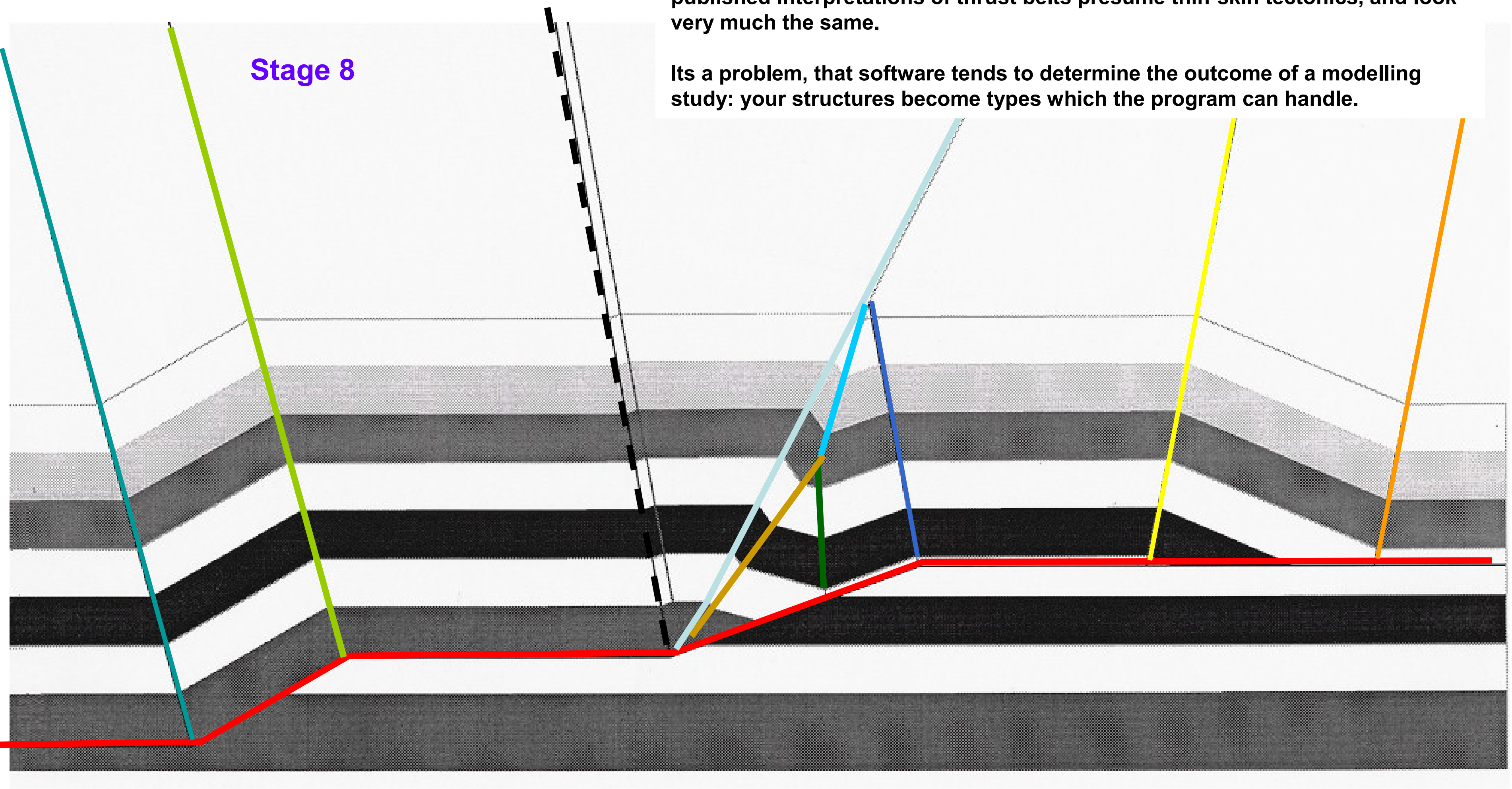


26000 units, synclinal bend at the foot of ramp B has generated a downward bifurcation of the light blue axis, dark green will travel up the ramp with the effect that the forelimb of the B ramp fold will unwind and disappear.

Suppe's construction became the basis of section-construction and balancing software packages, such as Geosec and Lithotect, treating folds as flexural-slip folds according to the equations. One consequence has been that many published interpretations of thrust belts presume thin-skin tectonics, and look very much the same.

Its a problem, that software tends to determine the outcome of a modelling study: your structures become types which the program can handle.

Stage 8

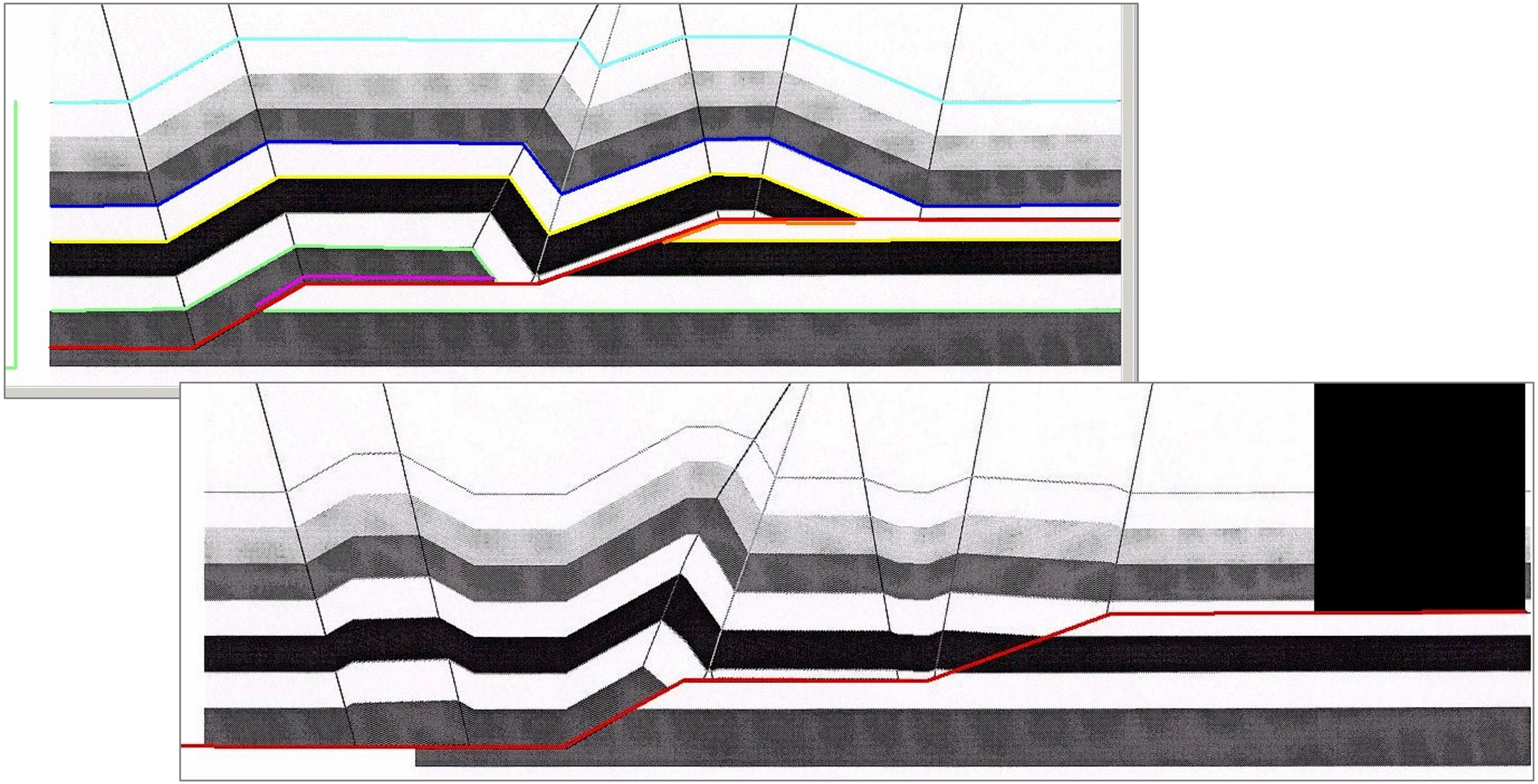


30000 units. The leading edge of the A fold is almost unwrapped, A is merging with B and unless the red fault surface is a reflector on seismic the local perturbation in the broad, flat composite crest is the only clue to ramp B's presence. What will happen with further slip, is simplification of the hangingwall in the bottom and mid parts of the B ramp, the dashed black will become the anchored fold axis there, whilst B fold will gain more amplitude, the various left-leaning fold axes will travel up the B ramp and release blue. A new local ridge will form over the top of B ramp.

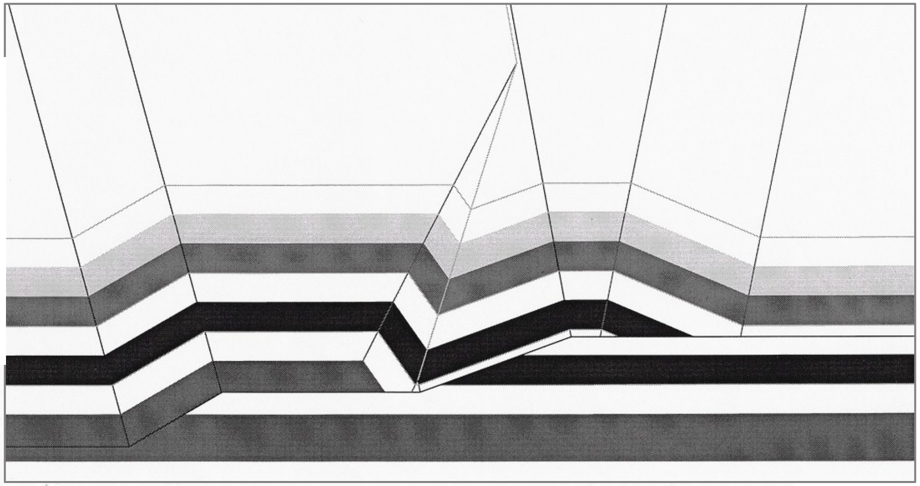
Can the DepthCon software restore interpretations made with flexural slip assumption?

No. DepthCon uses a vertical/inclined shear, constant-heave algorithm which preserves area, not bed length. Horizontal displacement on the fault is kept constant whereas the Suppe models preserve line length and allow variable slip along the fault.

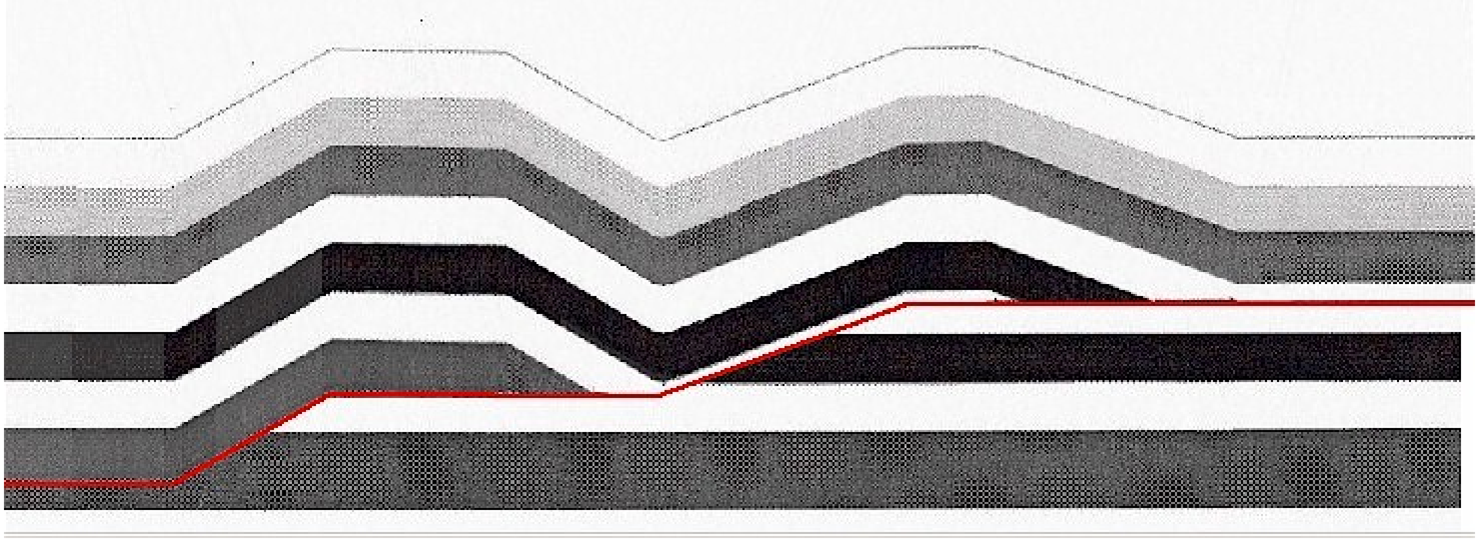
Here is the Stage 6 interpretation, restored in the lower diagram using vertical shear and constant heave. DepthCon does a moderately good job in re-joining the severed beds on the 20-degree ramp but leaves a substantial spurious residual fold on the left-hand ramp.



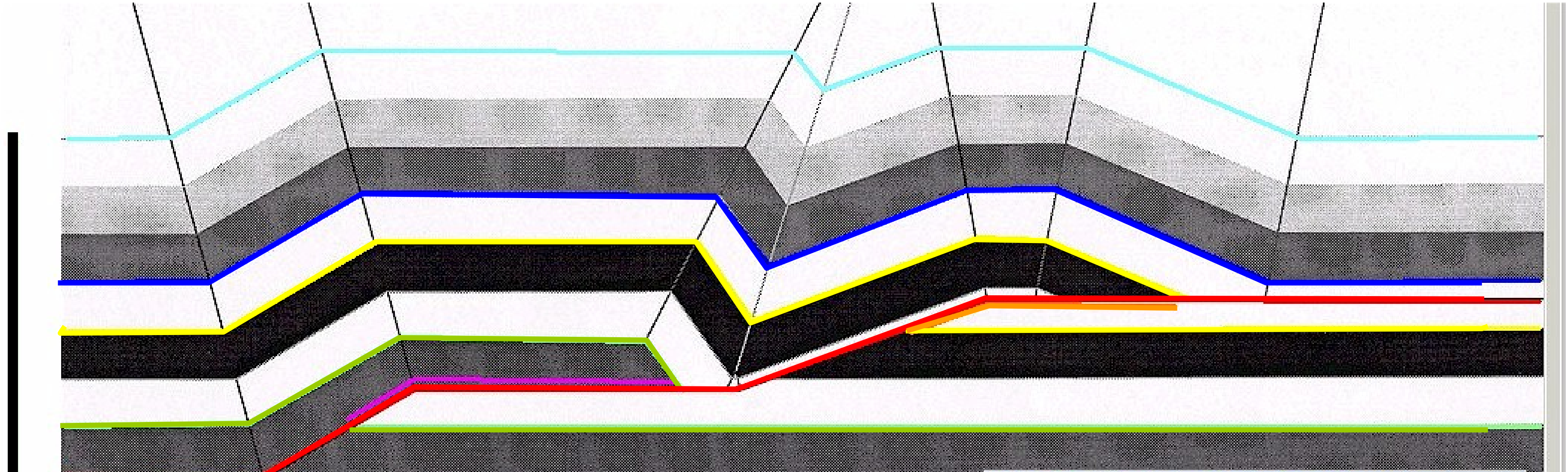
If we forward model to Stage 6 with Depthcon's simple shear, how does the result compare with the flexural slip method?

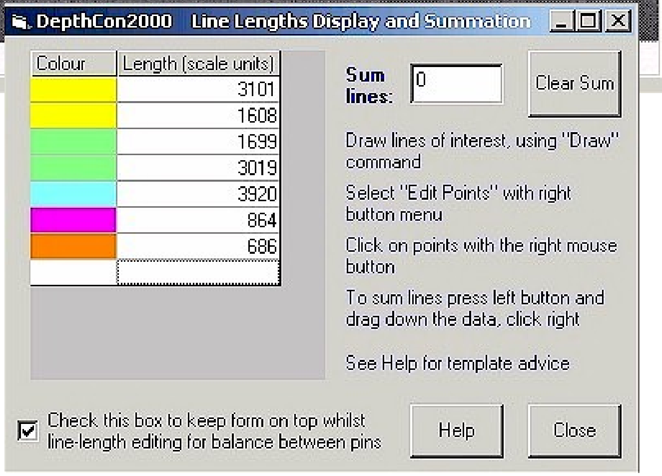


Not too good! See the lower diagram, DepthCon is designed for analysing extensional and inverted extensional geometries. This forward model is done in vertical shear, so the fold axes are all vertical, which means kink band widths don't match the flexural slip model, bed lengths have not been kept constant and the important role of bed-parallel shear is not recognised; and the forelimb cut-off angles' discrepancy becomes greater on steeper ramps.



Measuring line lengths in DepthCon





DepthCon2000 Line Lengths Display and Summation

Colour	Length (scale units)
🟨	3101
🟨	1608
🟩	1699
🟩	3019
🟦	3920
🟪	864
🟧	686

Sum lines: 0

Draw lines of interest, using "Draw" command

Select "Edit Points" with right button menu

Click on points with the right mouse button

To sum lines press left button and drag down the data, click right

See Help for template advice

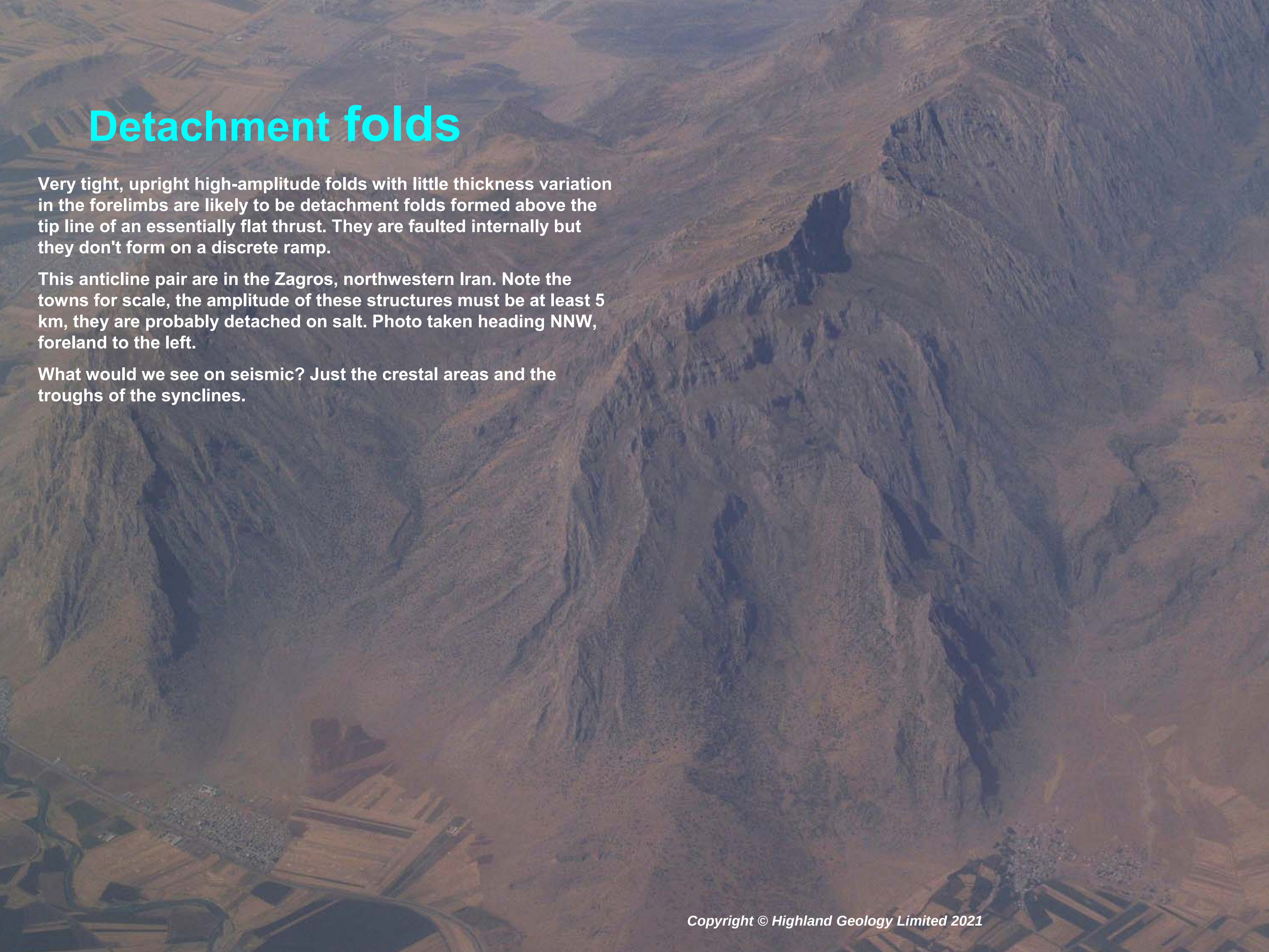
☑ Check this box to keep form on top whilst line-length editing for balance between pins

DepthCon can't model flexural-slip folds but as already noted for Moose Mountain, it can do line-length summations between reference points and that's very useful in evaluating plane-strain (2D) compressional structure interpretations.

For instance, in the Stage 6 fault-bend folding model if we input a notional scale (black vertical line at left is 1000 metres) and trace the two beds yellow and green between the edges of the section, which will act as "pins", the program reports the sum of line lengths to be the same at 4709/4718 units. (Blue lines, which aren't severed by the fault, likewise report common length of around 3920 units).

The separation measured along the fault on green bed cut-offs is 864 units, whilst on yellow marker its 686 units, this difference accounts for the inability of constant-heave DepthCon to restore all markers severed by the thrust.

Detachment folds



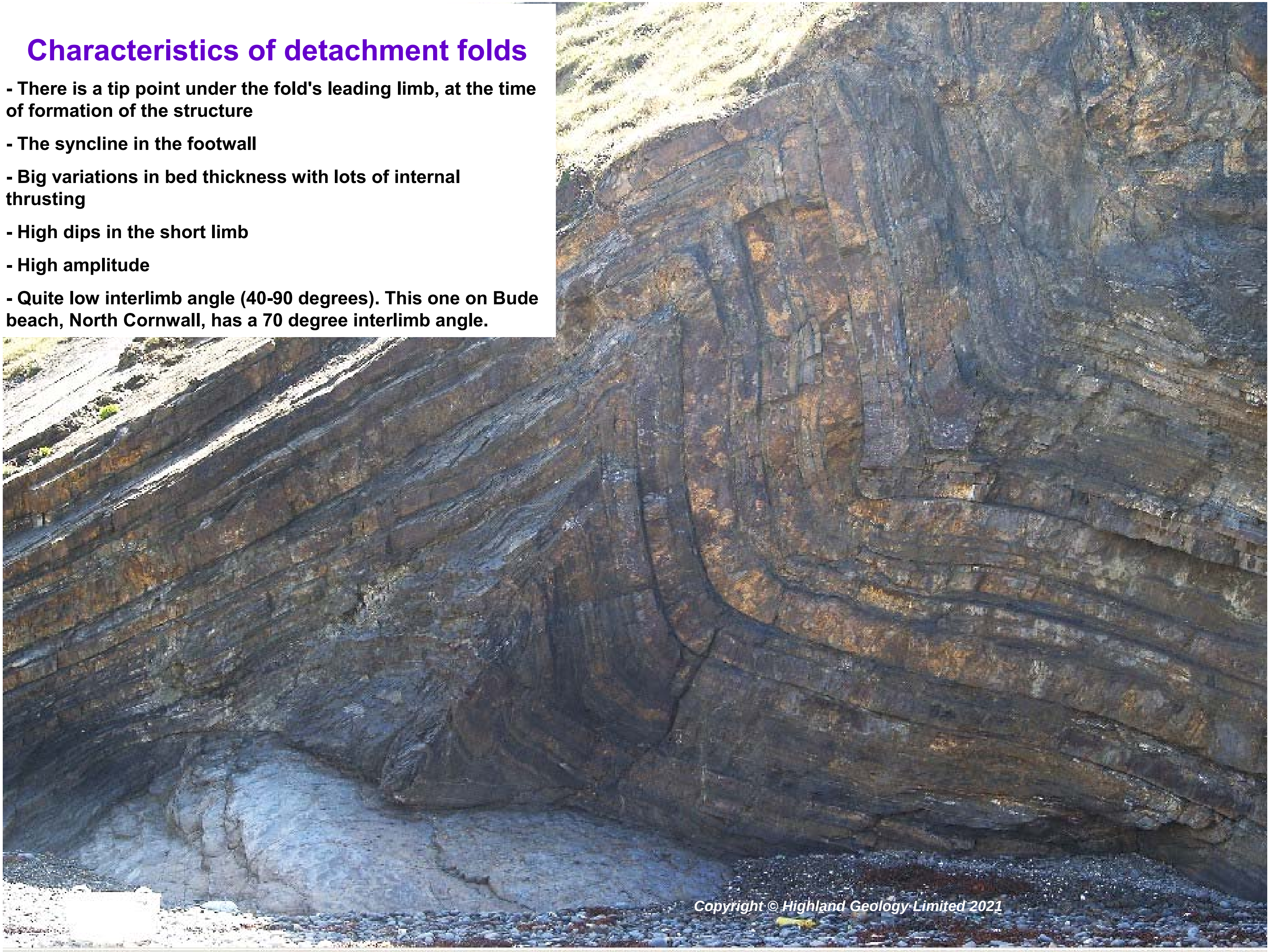
Very tight, upright high-amplitude folds with little thickness variation in the forelimbs are likely to be detachment folds formed above the tip line of an essentially flat thrust. They are faulted internally but they don't form on a discrete ramp.

This anticline pair are in the Zagros, northwestern Iran. Note the towns for scale, the amplitude of these structures must be at least 5 km, they are probably detached on salt. Photo taken heading NNW, foreland to the left.

What would we see on seismic? Just the crestal areas and the troughs of the synclines.

Characteristics of detachment folds

- There is a tip point under the fold's leading limb, at the time of formation of the structure
- The syncline in the footwall
- Big variations in bed thickness with lots of internal thrusting
- High dips in the short limb
- High amplitude
- Quite low interlimb angle (40-90 degrees). This one on Bude beach, North Cornwall, has a 70 degree interlimb angle.



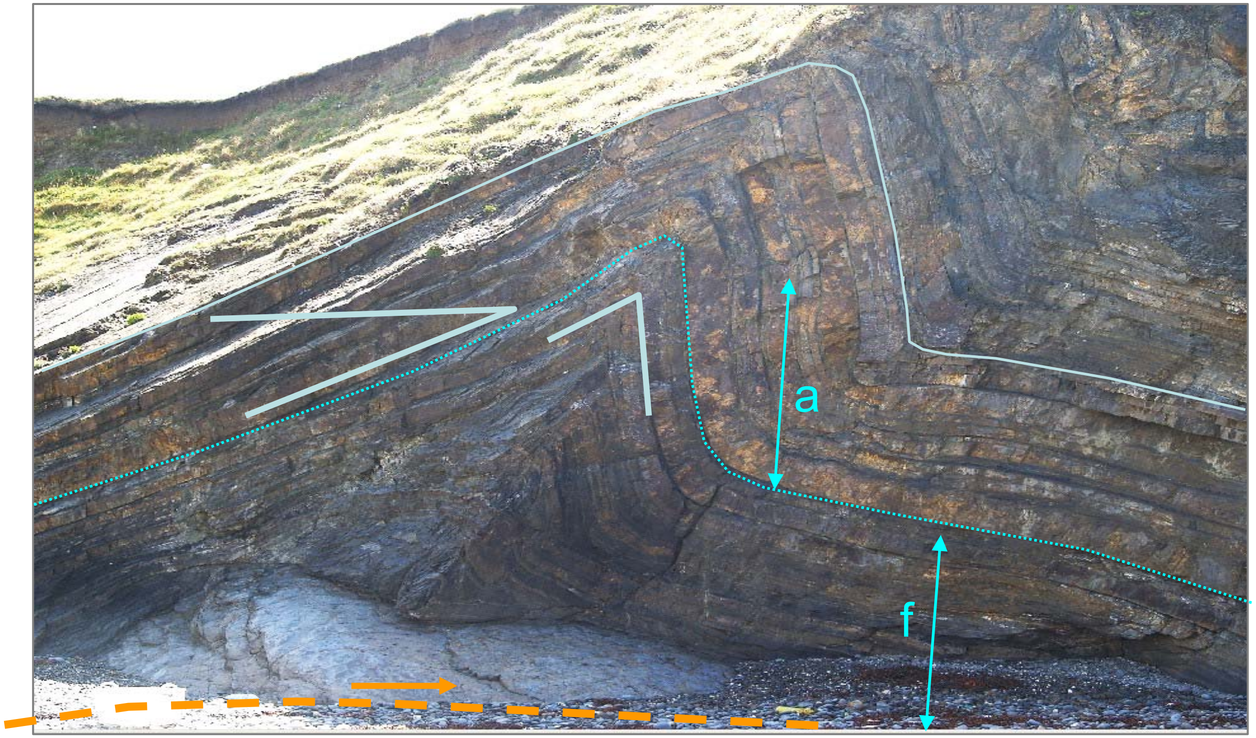
Detail of the ductile core over the detachment zone. There is no fault ramp climbing off the basal detachment: the core is a complex folded domain. Material moves from the flanks into the anticline, the limbs rotate as it grows.

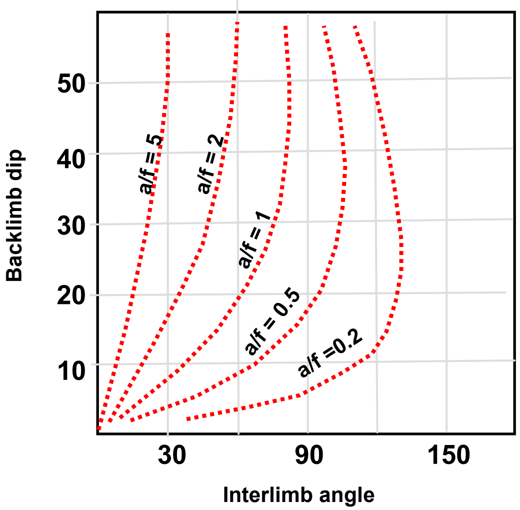
This is scale-independent, a very large structure will look much the same and of course much of the detailed structure would be beyond seismic resolution.

Bedding sketched here shows the interlimb angle is around 75 degrees at the top of the ductile unit. The backlimb dip is about 20 degrees.

Jamison (1987) in J Struct Geol 9(2) suggested a relationship between these angle values and the ratio a/f, "a" being the amplitude and "f" the thickness of the ductile unit.

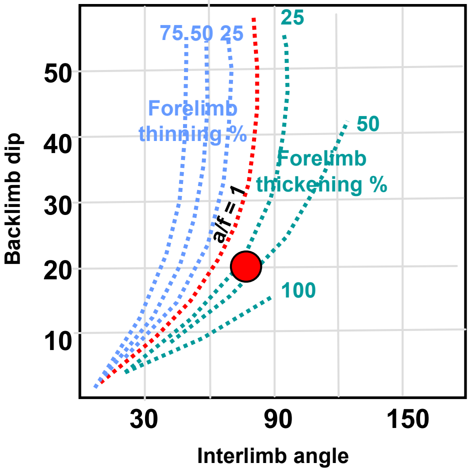
Its not easy in this case to decide on a figure for amplitude, as the left limb is inflated by shale flow. But from his graph given below, a/f for the parameters chosen is about 0.8, a value which then predicts "f" and indicates the basal flat thrust and tip will be at or around the dashed orange line: which looks reasonable.



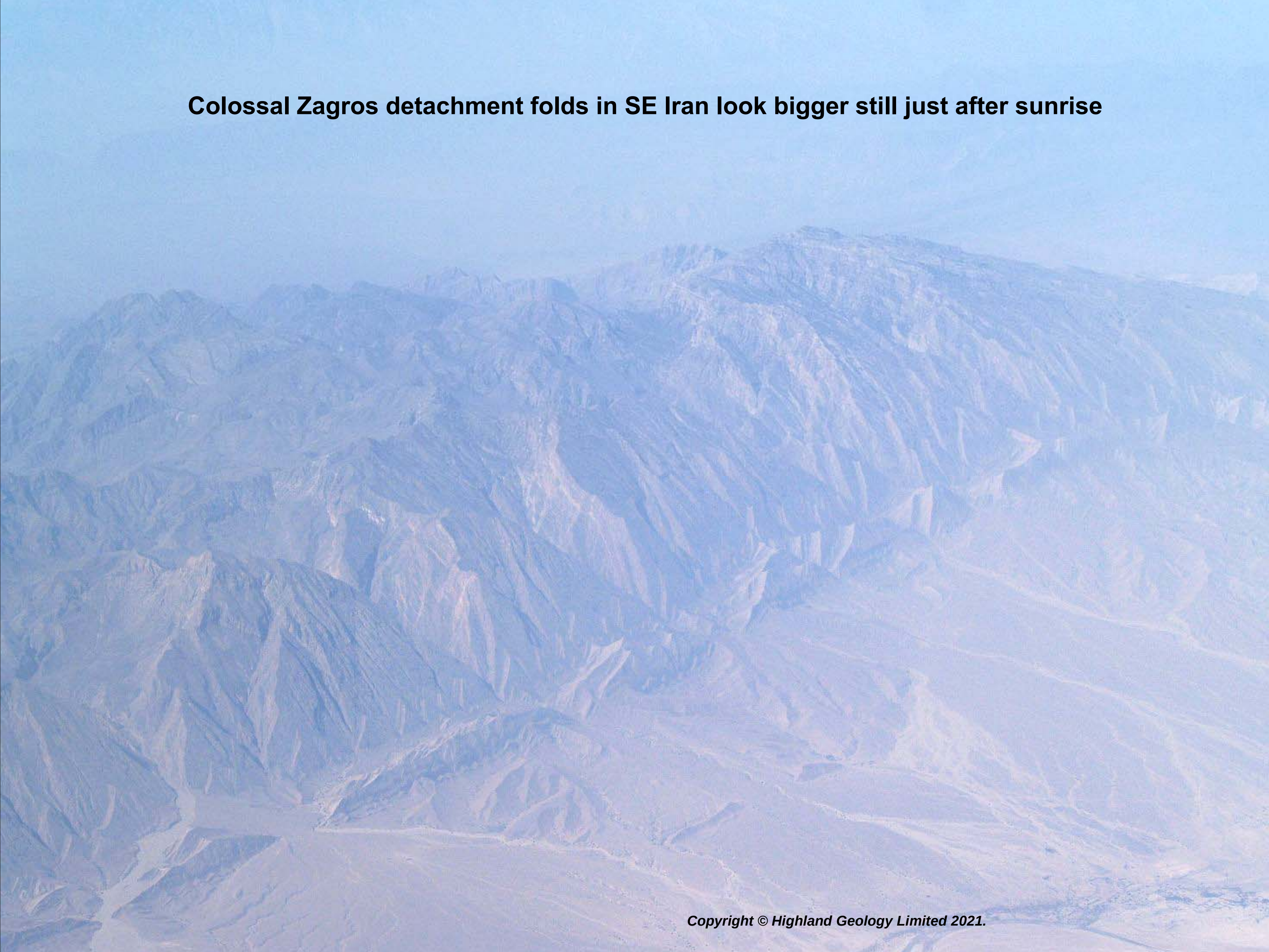


This left graph assumes uniform bed thickness, but variable forelimb thickness is common in detachment folding. We can see quite substantial thickening in the forelimb here. Its unrealistic to assume and predict constant bed thickness.

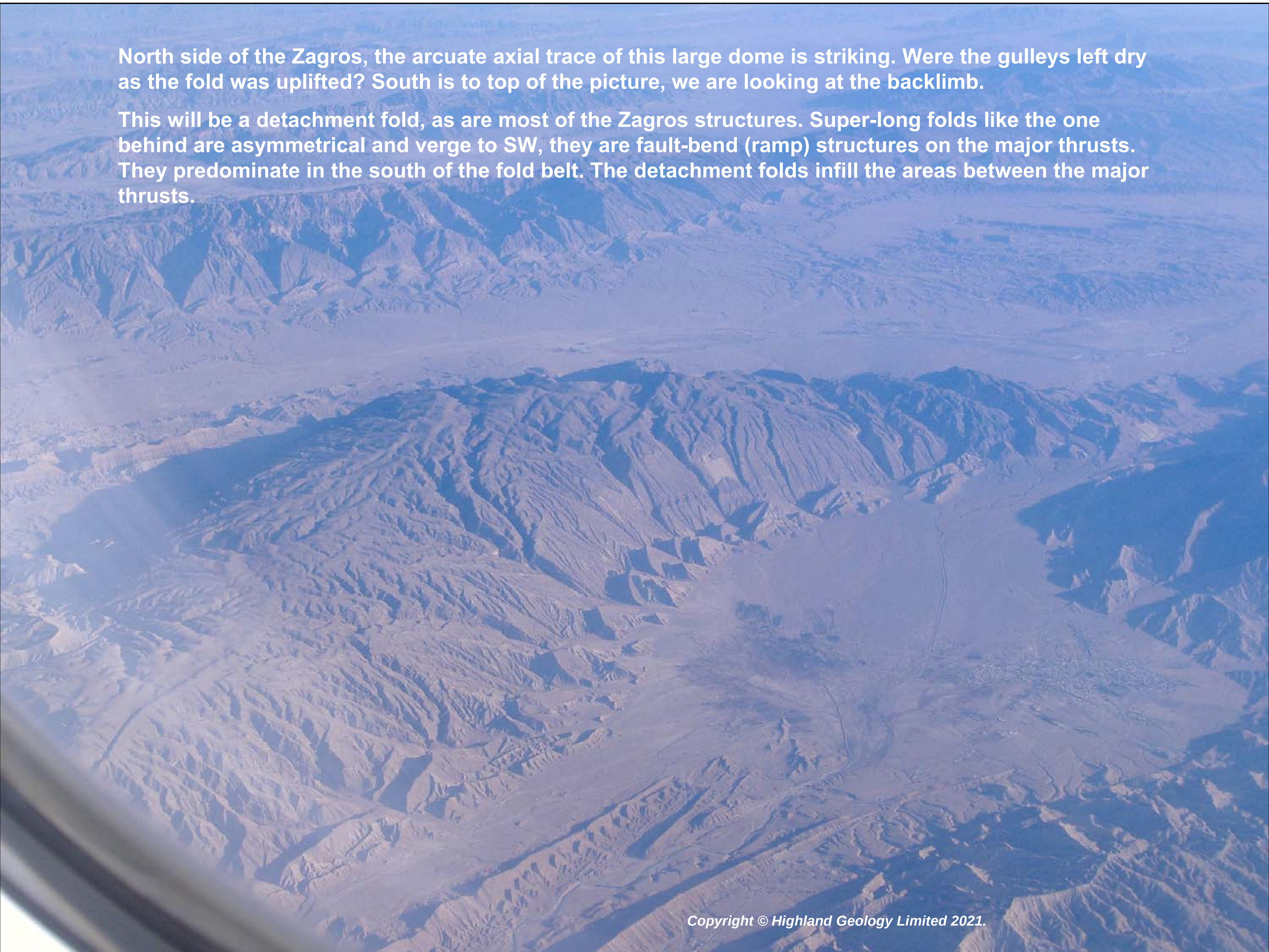
Jamison suggested a relationship like this, right, for backlimb, interlimb and percentage-thickening models. His paper has more crossplots. For the case where a/f is 1, red dot is the Bude fold and it does fall in the thickening-forelimb sector of the plot. This is one line of thinking, for sketching steep limb geometries on seismic where the imaging fails.



Colossal Zagros detachment folds in SE Iran look bigger still just after sunrise



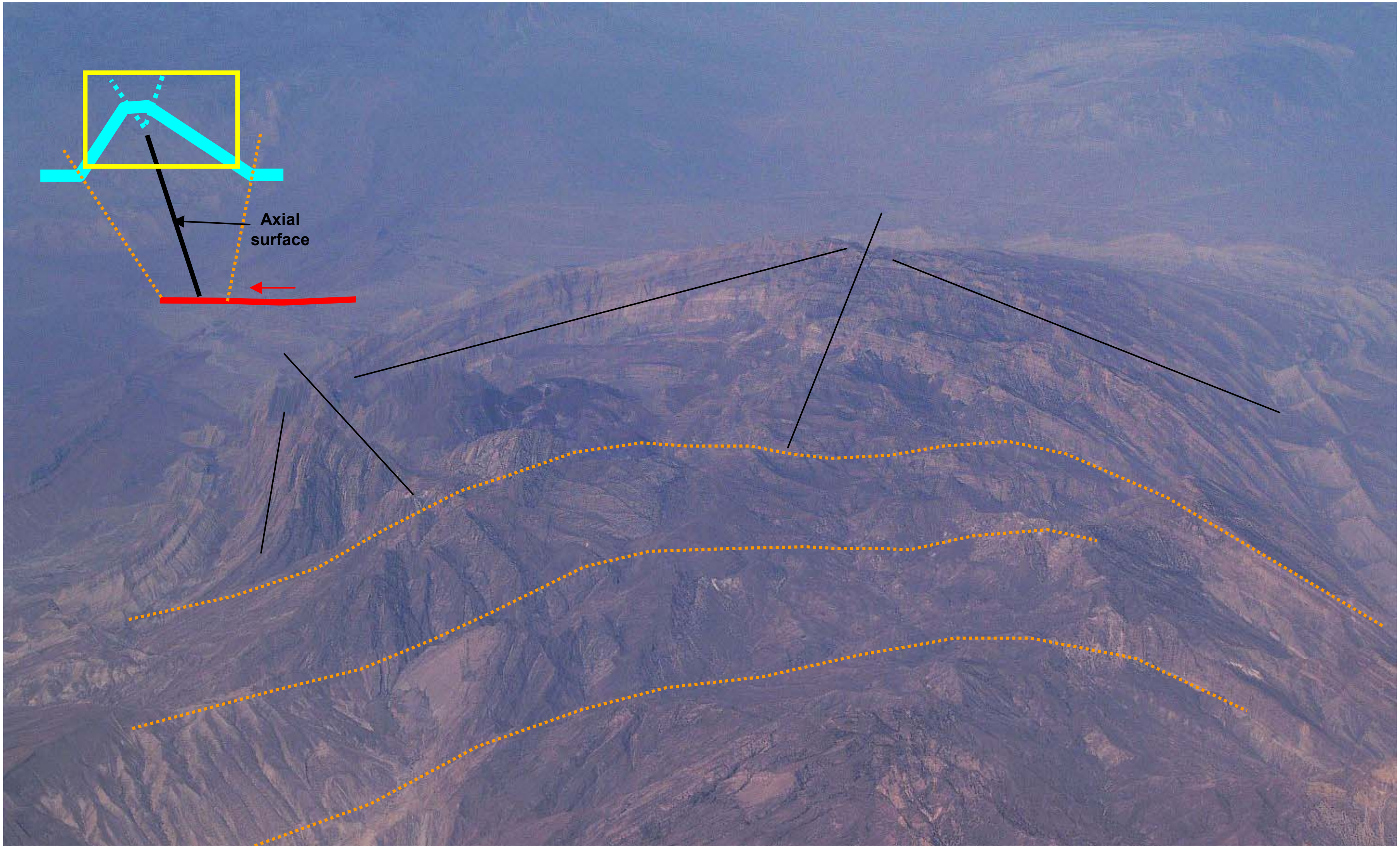
Closing end of a huge dome, SE Iran, the hinge length is short compared with the width of the fold , as is typical for a detachment. For scale notice the road running up the axis, there's a probable former rig site on the crest.



North side of the Zagros, the arcuate axial trace of this large dome is striking. Were the gulleys left dry as the fold was uplifted? South is to top of the picture, we are looking at the backlimb.

This will be a detachment fold, as are most of the Zagros structures. Super-long folds like the one behind are asymmetrical and verge to SW, they are fault-bend (ramp) structures on the major thrusts. They predominate in the south of the fold belt. The detachment folds infill the areas between the major thrusts.

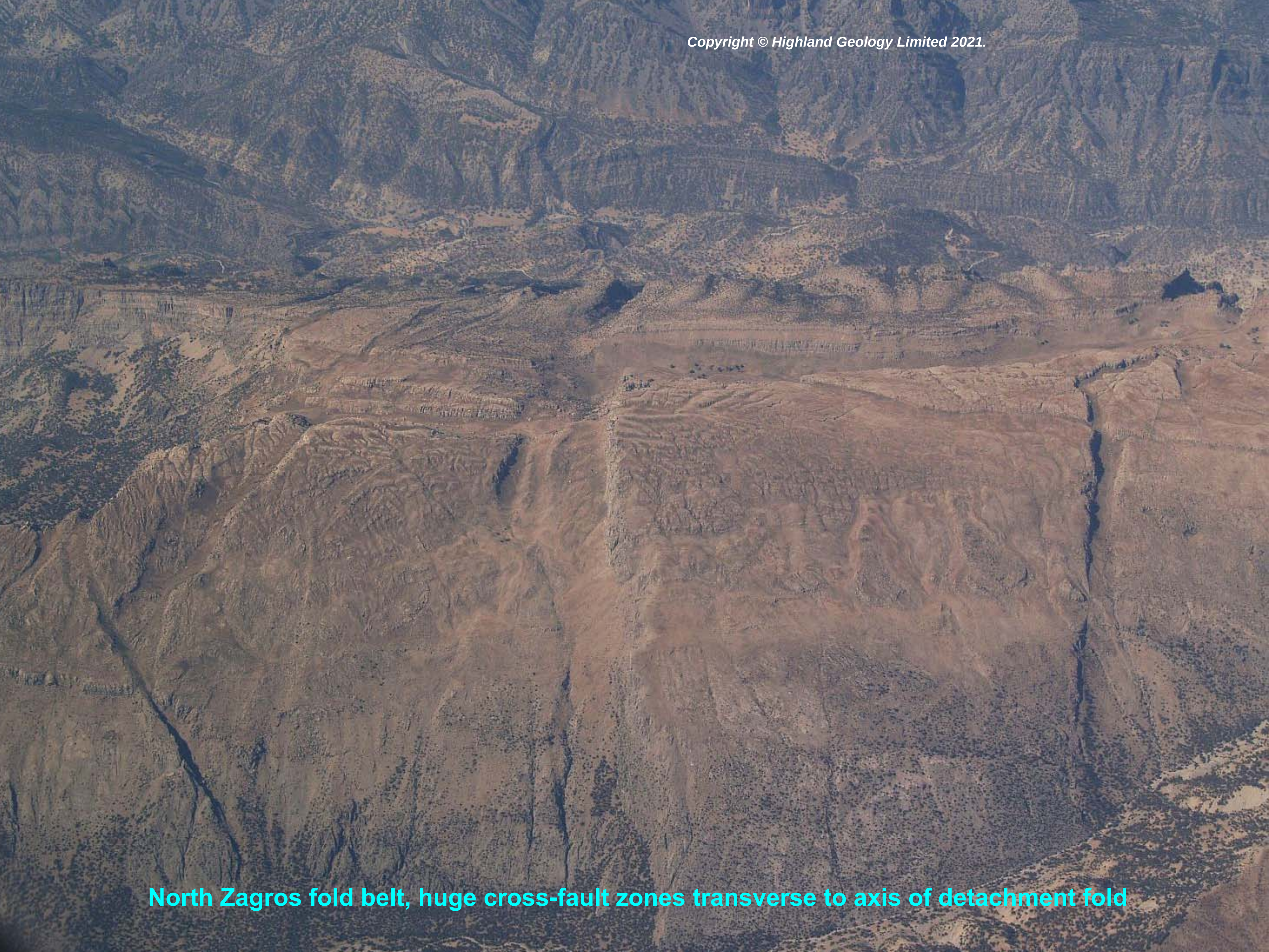
Another closure, probable detachment fold, deeply dissected.



Is this huge Zagros anticline a detachment fold? Probably. Its asymmetrical, with steeper limb to southwest. The implication would be that the basal flat thrust's vergence is to southwest. One plausible model is that the flat fold crest would locate early in the growth history, because the axes would fix, and the fold would grow in height by fore and back-limb rotation (steepening) as the shortening increased. That means the interlimb angle and fold axes dips increased with time. If we let ductile material flow in under the backlimb, the detachment depth would increase. An alternative is that the fold axes did migrate, keeping the same dips and interlimb angle as at the outset: the fold limbs would have to get longer and likewise the detachment depth would increase, it could double as the fold limb lengths double (roughly).

Zagros folds are underlain by salt, they show widely variable vergence and there probably isn't a simple tip line at depth.

Orange lines represent a family of large cross-faults trending transversely to this structure's main fold axis.



North Zagros fold belt, huge cross-fault zones transverse to axis of detachment fold

Passive roof duplexing

These DepthCon models show development of “passive-roof duplexes” in the style Chris Morley summarised in his paper on buried thrust fronts, in AAPG 70(1) of 1998.

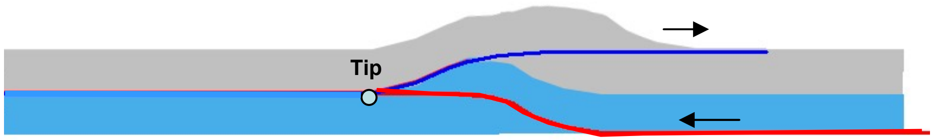
In stage 1 the active shortening fault is red. Let’s say red is running west in overpressured claystones down at 4-5 km, and its a flat, bed-parallel detachment. (Overpressuring reduces the weight of the hangingwall rocks by maybe 90 percent and allows them to ride without breaking up). Red flat ramps up to base of another regionally developed claystone, where it progresses a short distance westwards again, ending at a tip.

There must be a compensating displacement back to east, because the thrust is “blind” ending, this balancing backthrust is drawn in dark blue. The backthrust climbs east up-sequence, it either loses displacement by forming a fold and stopping eventually at another tip, or it hands its slip to another fault which transfers its displacement, or else it reaches topographic surface, as shown here.

Roughly, the amount of slip on red equals the slip on dark blue backthrust plus the shortening achieved by the fold which forms above blue: thus there is balance.

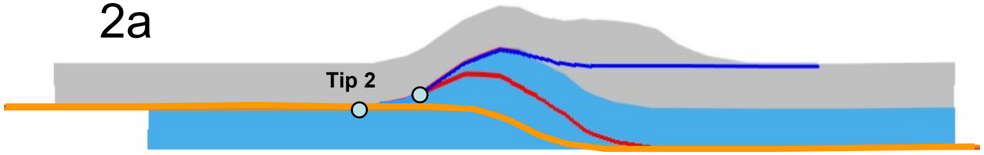
In stage 2a, 2b a new fault forms west of red, in the footwall. Why? Probably because red ramp loses its hydraulic pressure into the backthrust as the length and displacement of that compensating fault increases, and it eventually becomes easier for the westward shortening to switch onto a new footwall ramp of simpler shape, which takes pressure from the red flat. The westerly movement on the red ramp stops, we’ve redrawn the whole active flat and ramp as orange. The tip for orange is shifted some way west, and the backthrust from orange's tip is drawn in pale blue, its got a new western part and it joins dark blue eastwards, then prefes to climb to topo surface rather than follow dark blue over the fold crest. The wedge has moved west.

1

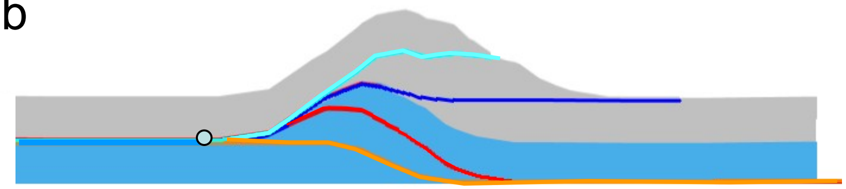


(DepthCon can't model a tip, We have to draw the fault as through-going and overlay it with a compensating thrust of the same but opposing throw, to make a fault "stop").

2a



2b



We now have a wedge of rock wholly bounded by red, pale blue and orange thrusts, and this is a "horse". Its roof fault is a mix of surfaces, and its displacement is variable because it has a polyphase history. The floor fault is orange.

The process can repeat, building the wedge westwards by adding more “horses” to make a composite duplex. Duplex systems can be very extensive along strike and are prime prospects if they have crestal closure.

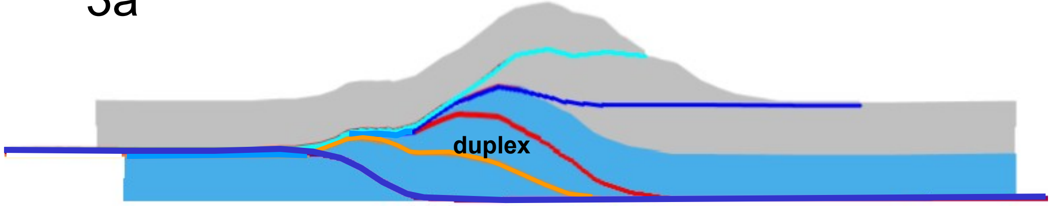
By stage 3a the orange ramp has failed and the new active frontal ramp is purple, and in 3b its accompanied by a new backthrust (also coloured purple) taking a simpler trajectory than the old pale blue one, which has been passively refolded by purple ramping, its easier to break new rock than to persist with the old backthrust surface. The backthrusting has now become duplexed as well.

In stage 4 we've added a final leading edge ramp, and this time instead of adding a backthrust which follows the again-folded roof thrust system we've locked the roof and made a reverse fault propagate westwards, these structures can act as seals and generate structural traps which look like sand pinchouts.

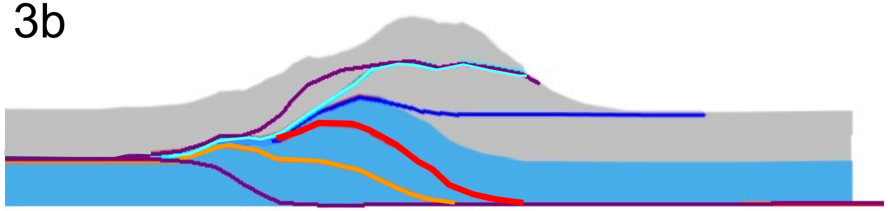
As the wedge broadens it gets less efficient, finally the whole structure may freeze. The soler fault will then propagate ten or so km west and start a new ramp.

There is a way for the duplex to prolong its life, and that is by forming an antiformal stack. This is simply a closely-spaced pack of ramps, on each of which displacement is high relative to the separation from the next ramp. They pile up, the original backthrust surface gets progressively more deformed as new ramps underneath it fold it. You might expect the core of an anticline of this type to be heavily fractured and it could have ductile shale thickening under pressure. An antiformal stack is of course strongly reverse-faulted and wells drilled into these will see many repeat sequences.

3a



3b



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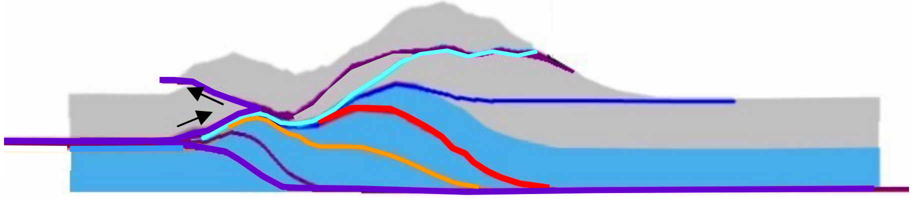
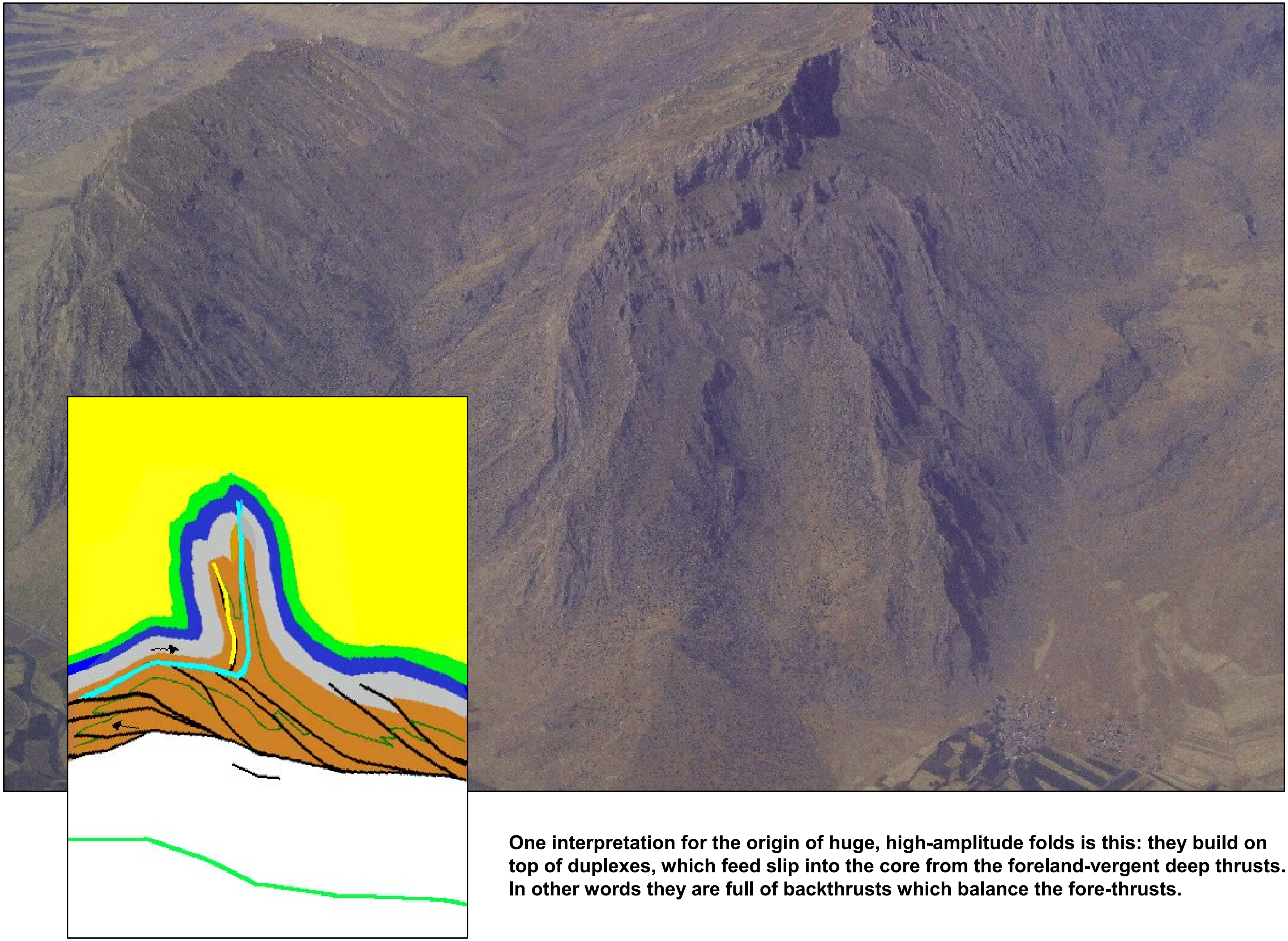
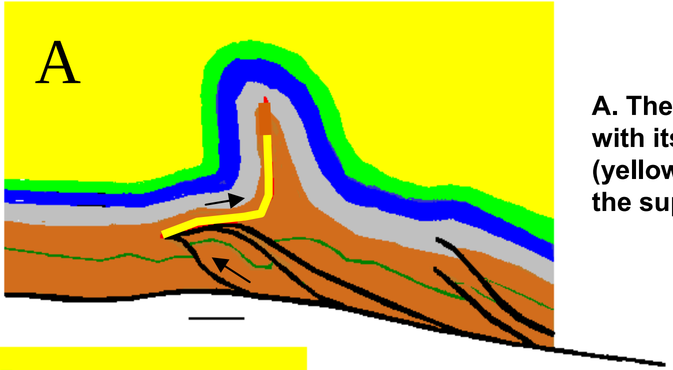
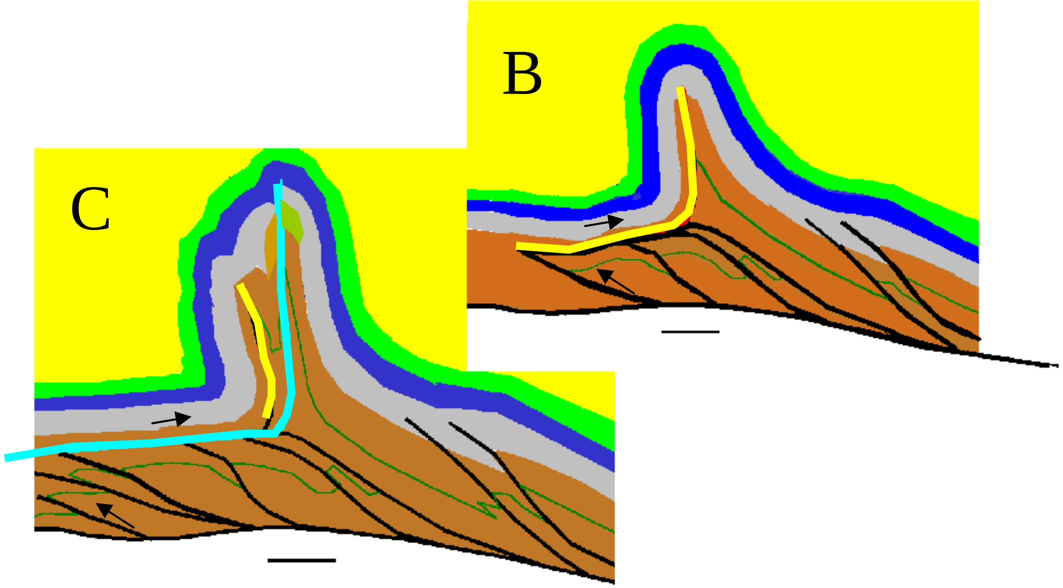




One interpretation for the origin of huge, high-amplitude folds is this: they build on top of duplexes, which feed slip into the core from the foreland-vergent deep thrusts. In other words they are full of backthrusts which balance the fore-thrusts.

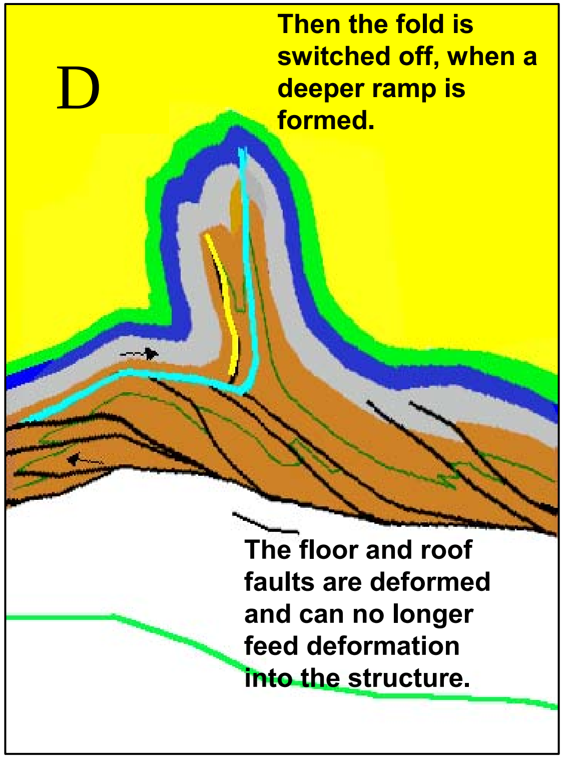


A. The duplex is established, along with its compensating back-thrust (yellow). The fold grows upwards in the superstructure.



B. The duplex grows westwards, and the fold becomes taller as extra horses are added and more displacement is passed into it via the yellow back-thrust

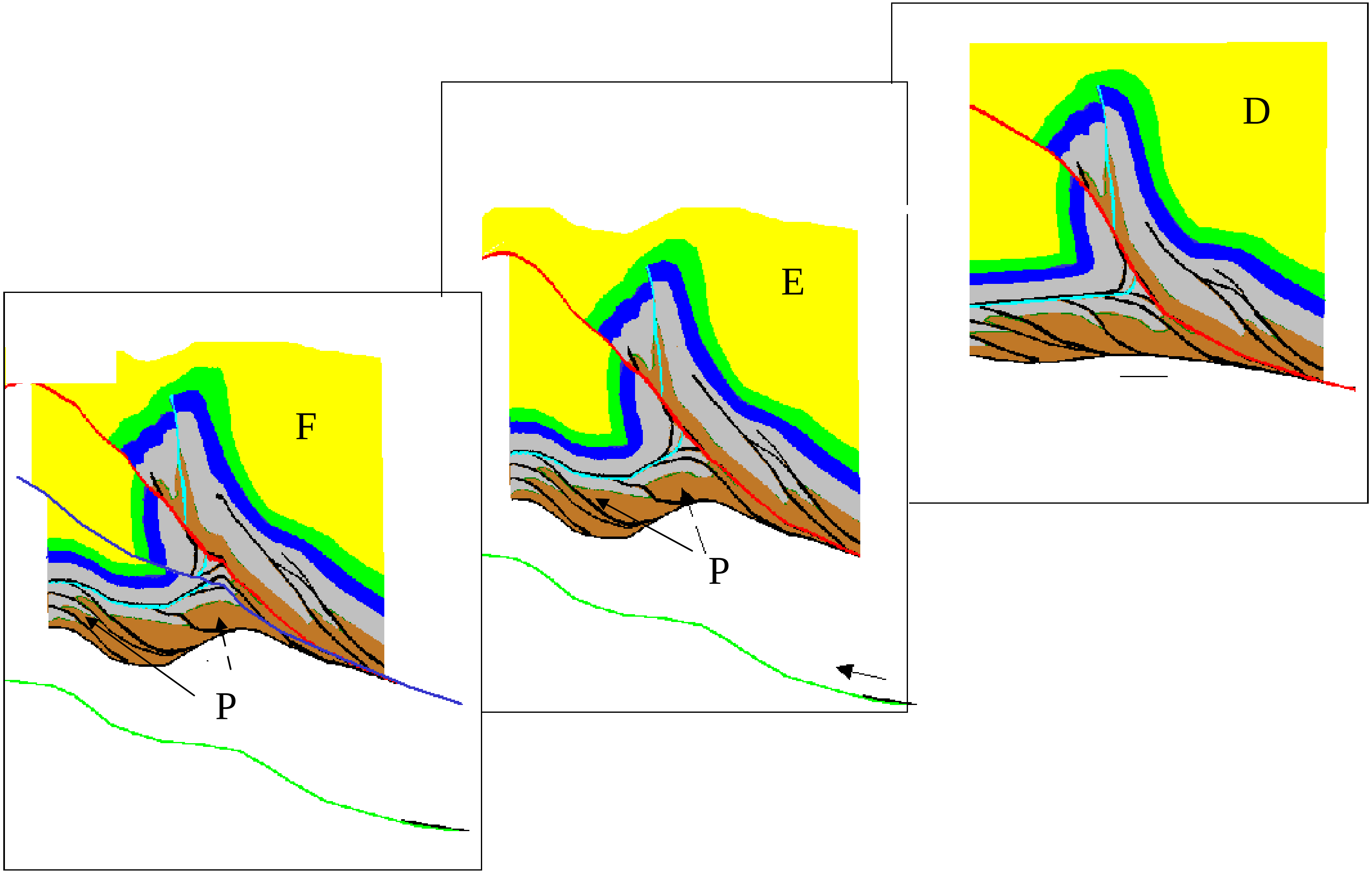
C. The fold becomes over-steepened because back-limb thrusts feed westward slip into it. The back-thrust therefore locks and a new one forms (pale blue), to balance the continuing shortening in the duplex. In this way the core of the fold fills with vertical to overturned thrusts. There might be dozens of thrust surfaces.



Then the fold is switched off, when a deeper ramp is formed.

The floor and roof faults are deformed and can no longer feed deformation into the structure.

Evolution of upright high-amplitude passive-roof duplexes: growth of the fold as the duplex evolves.

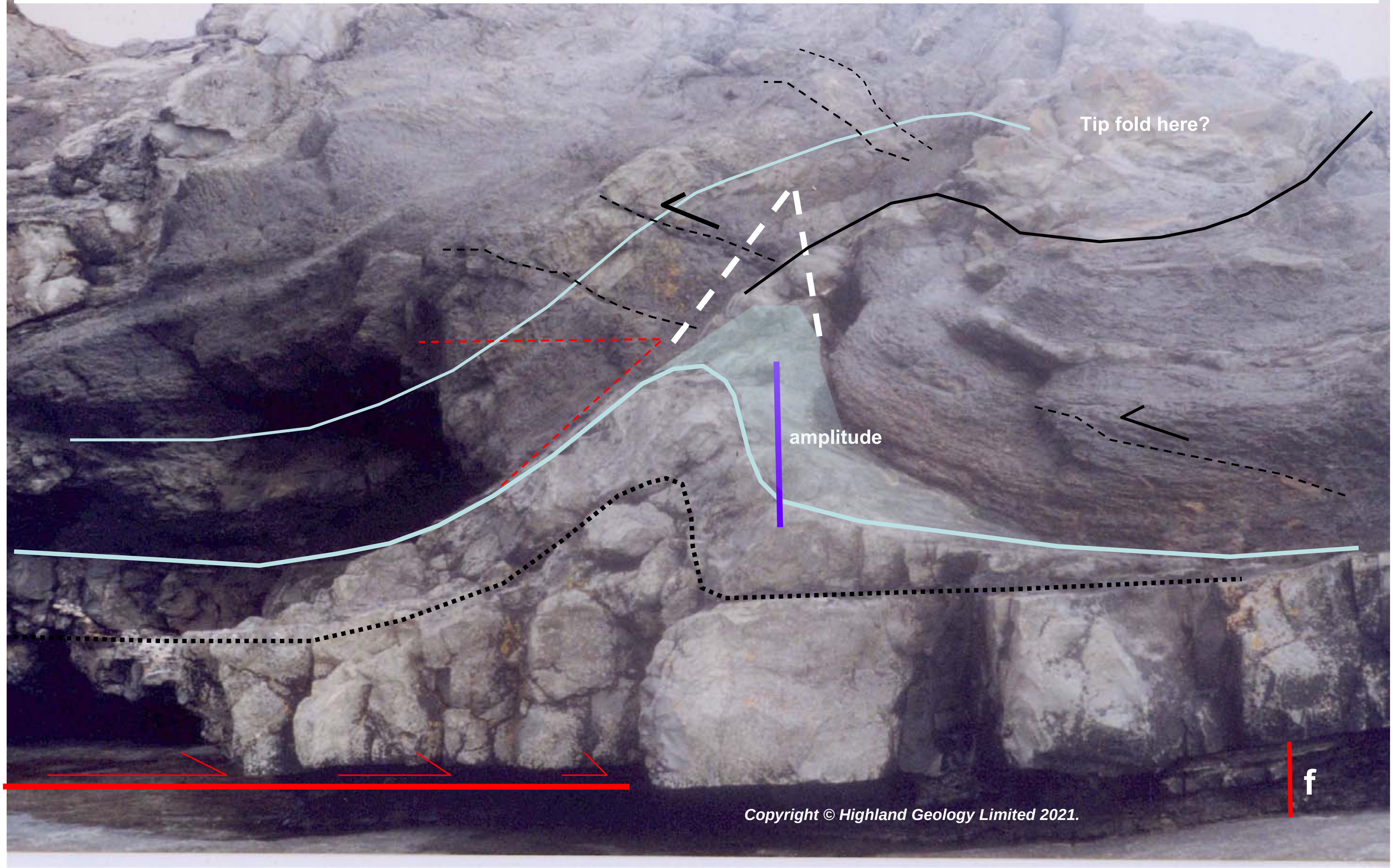


Passive-roof duplex-cored geometries, the duplex roof fault is in the grey unit. Steep thrusts cross the fault-prop fold. The duplex becomes folded on new ramps, to produce prospects under the superstructure of the fault-propagation folds. We can also predict prospects under the synclines.

At Bridges of Ross just north of the Shannon Estuary in western Ireland, the Namurian deepwater Ross Formation comprises a well-exposed 50-metre sequence of slumps infilled by lobes of silty mudstone, followed by channels and more lobes. This is a fold in the main slide sheet.

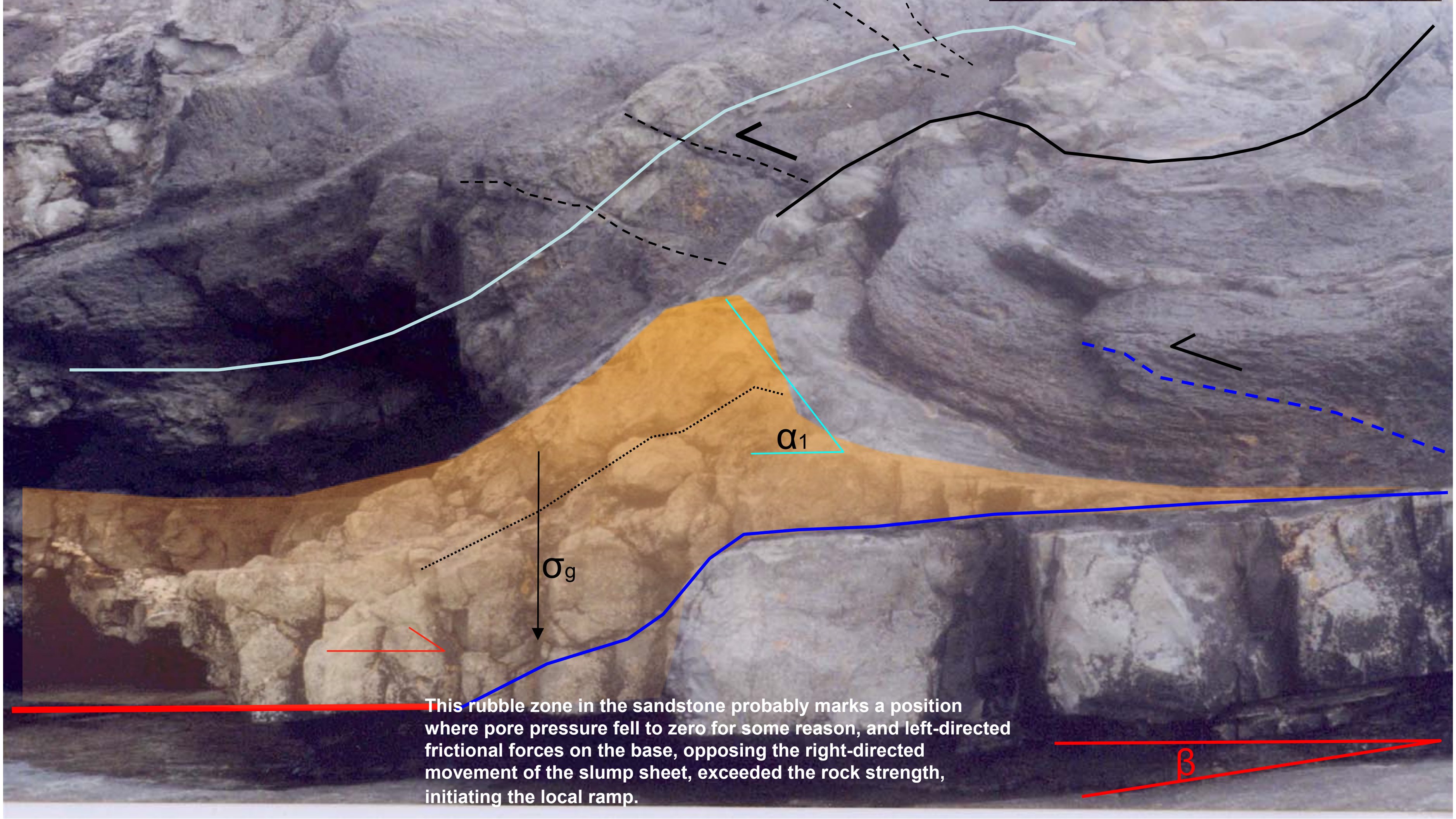
Is it a detachment fold? Maybe: the a/f is about 2, backlimb dip is 35 degrees, Jamison's chart suggests interlimb angle should be about 50 degrees and depending on where we choose to measure it, that's possible.

There are big flute-like scours on the slide surface, this sediment was probably moving like wet cement, it was stiff enough to back-thrust.



This outcrop suggests a key process in thrust sheet development. A wedge, which built when the base of the slump sheet became sticky, provided greater side force to overcome the friction, piling up sediment until the force applied restored the sliding. Repeated wedging and new slide-surface inception is a mechanism for internal deformation of this slump sheet, contributing to sidewards propagation of the whole slide.

"Critical taper" is the sum of surface slope angle and the detachment slope angle, β. The pile-up in orange gives a local taper angle of α1 plus β which is probably exceeding the critical value needed to be to keep the mass moving. On attainment of this local wedge shape, blue thrust would move and restore rightward transport, trying to bring the orange wedge front back to critical angle again.



This rubble zone in the sandstone probably marks a position where pore pressure fell to zero for some reason, and left-directed frictional forces on the base, opposing the right-directed movement of the slump sheet, exceeded the rock strength, initiating the local ramp.

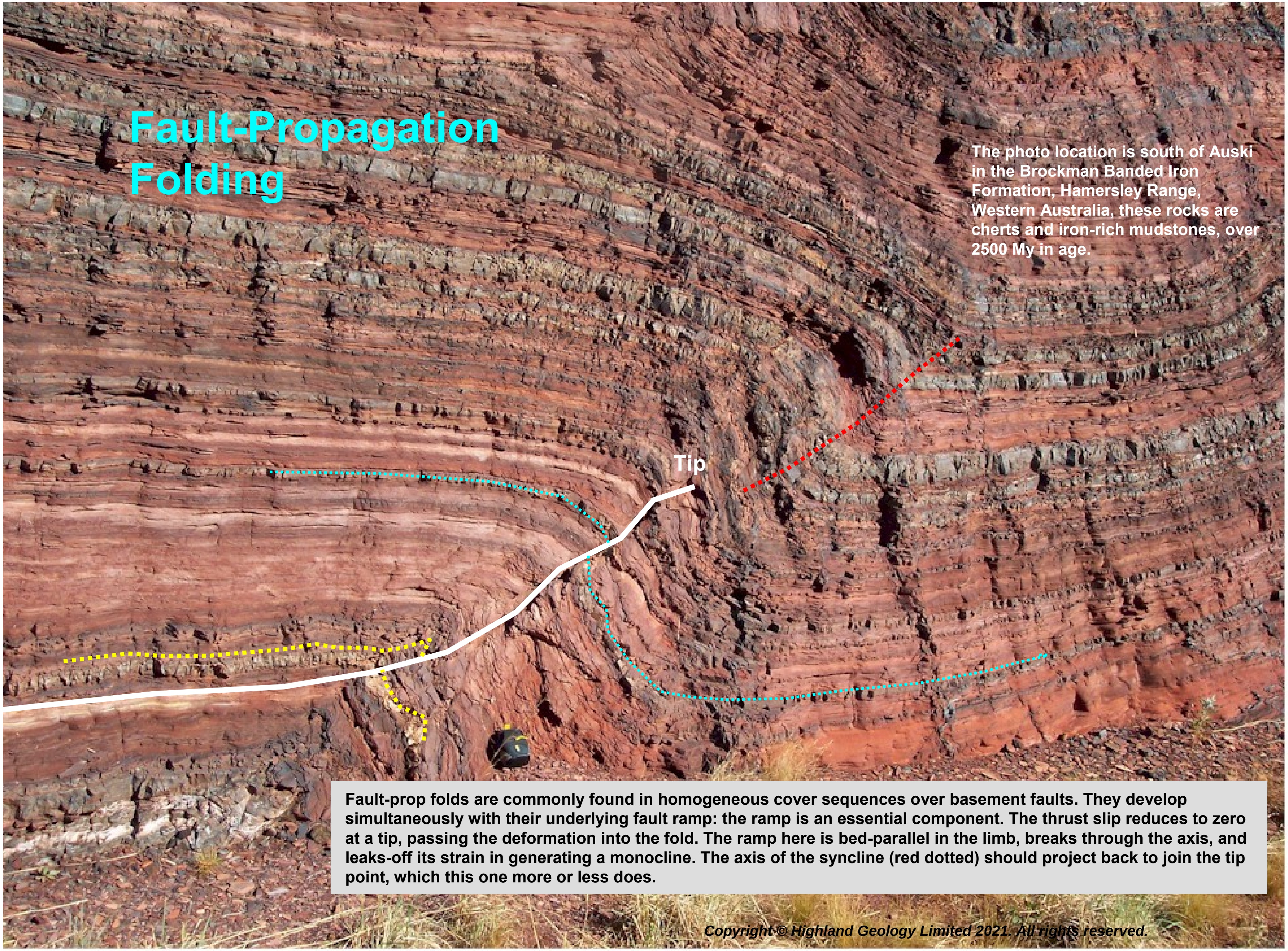
Papers on detachment folding:

DETACH: an Excel spreadsheet to simulate 2-D cross sections of detachment folds.
M. Scott Wilkerson,, Joshua M. Wilson, Josep Poblet, Mark P. Fischer, in Computers & Geosciences 30 (2004), 1069–1077.

2-D and 3-D modeling of detachment folds with hinterland inflation: A natural example from the Monterrey Salient, northeastern Mexico.
M. Scott Wilkerson, Sara M. Smaltz, Dannena R. Bowman, Mark P. Fischer, I. Camilo Higuera-Diaz, in Journal of Structural Geology xx (2006) 1-13.

Latter paper describes the method for modelling used in the spreadsheet.

Fault-Propagation Folding



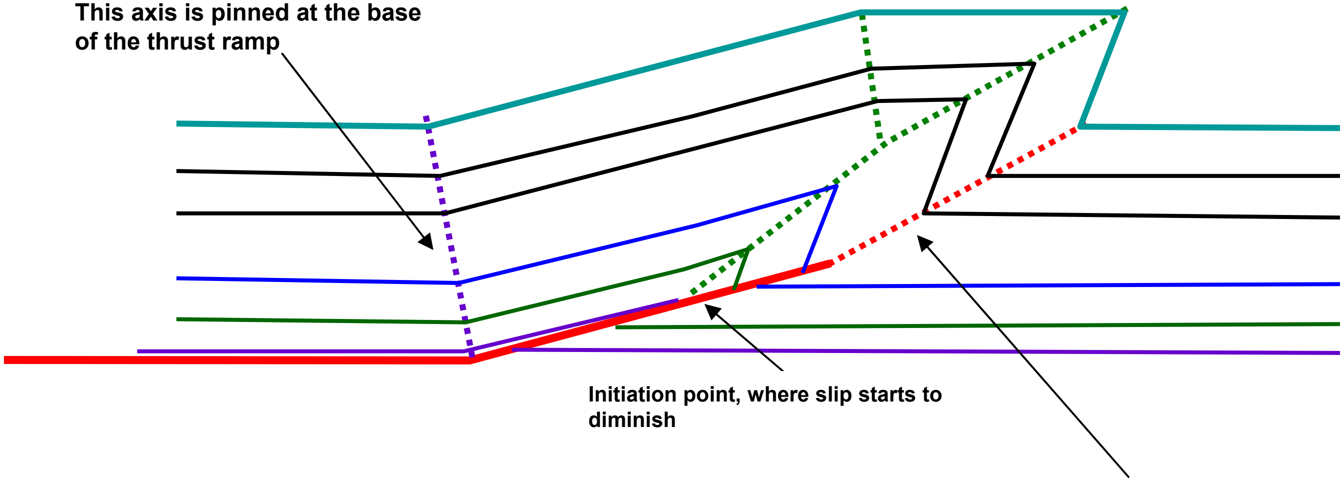
The photo location is south of Auski in the Brockman Banded Iron Formation, Hamersley Range, Western Australia, these rocks are cherts and iron-rich mudstones, over 2500 My in age.

Fault-prop folds are commonly found in homogeneous cover sequences over basement faults. They develop simultaneously with their underlying fault ramp: the ramp is an essential component. The thrust slip reduces to zero at a tip, passing the deformation into the fold. The ramp here is bed-parallel in the limb, breaks through the axis, and leaks-off its strain in generating a monocline. The axis of the syncline (red dotted) should project back to join the tip point, which this one more or less does.

Geometry of fault-prop folds

Fault prop folds grow by the progressive movement of the fault tip with a decrease in slip on the fault up-ramp, whilst the back-limb dip is fixed by the ramp dip. The bedlengths of the layers cut by the fault will change across the fault, to accomodate the decrease in slip. For the fold to grow in amplitude as the tip migrates into the syncline, with the limbs still retaining their thickness, the cut-off angles of beds intersecting the fault in the hangingwall must be greater than in the footwall.

Chester and Chester (1990) came up with a further modification of kink-band theory for fault-props, with area balance for the fold rather than line-length balance. The fold geometry was specified by inputting ramp dip, interlimb, backlimb dip, and forelimb thickness change. We used this algorithm to make the fold shown below:



This axis is pinned at the base of the thrust ramp

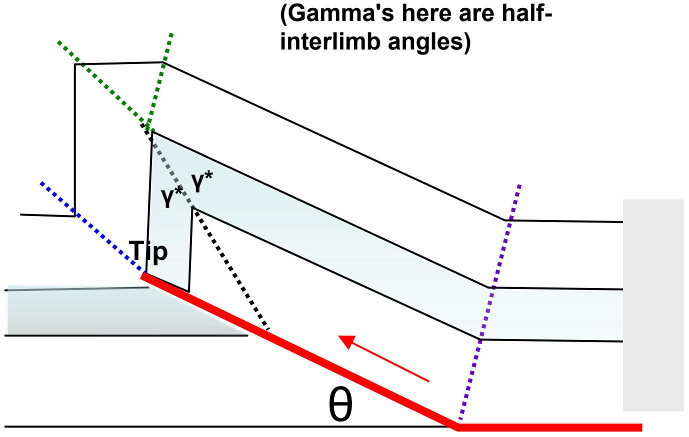
Initiation point, where slip starts to diminish

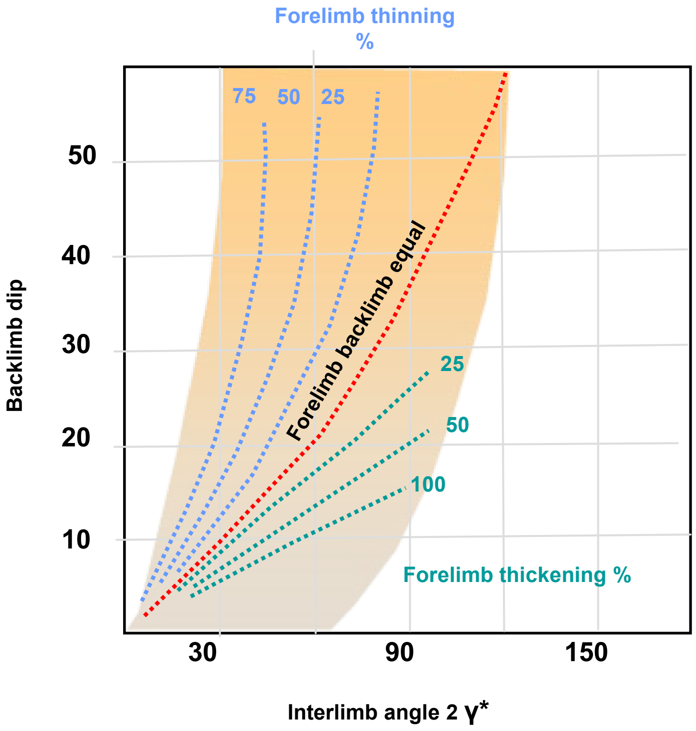
The two dotted green axes must converge in the bedding unit where the red tip is: if we can see that convergence on seismic, it helps us to pick the likely tip position.

This axis is pinned at the fault tip, for the duration of the fold growth, so the fault propagates through the syncline axis

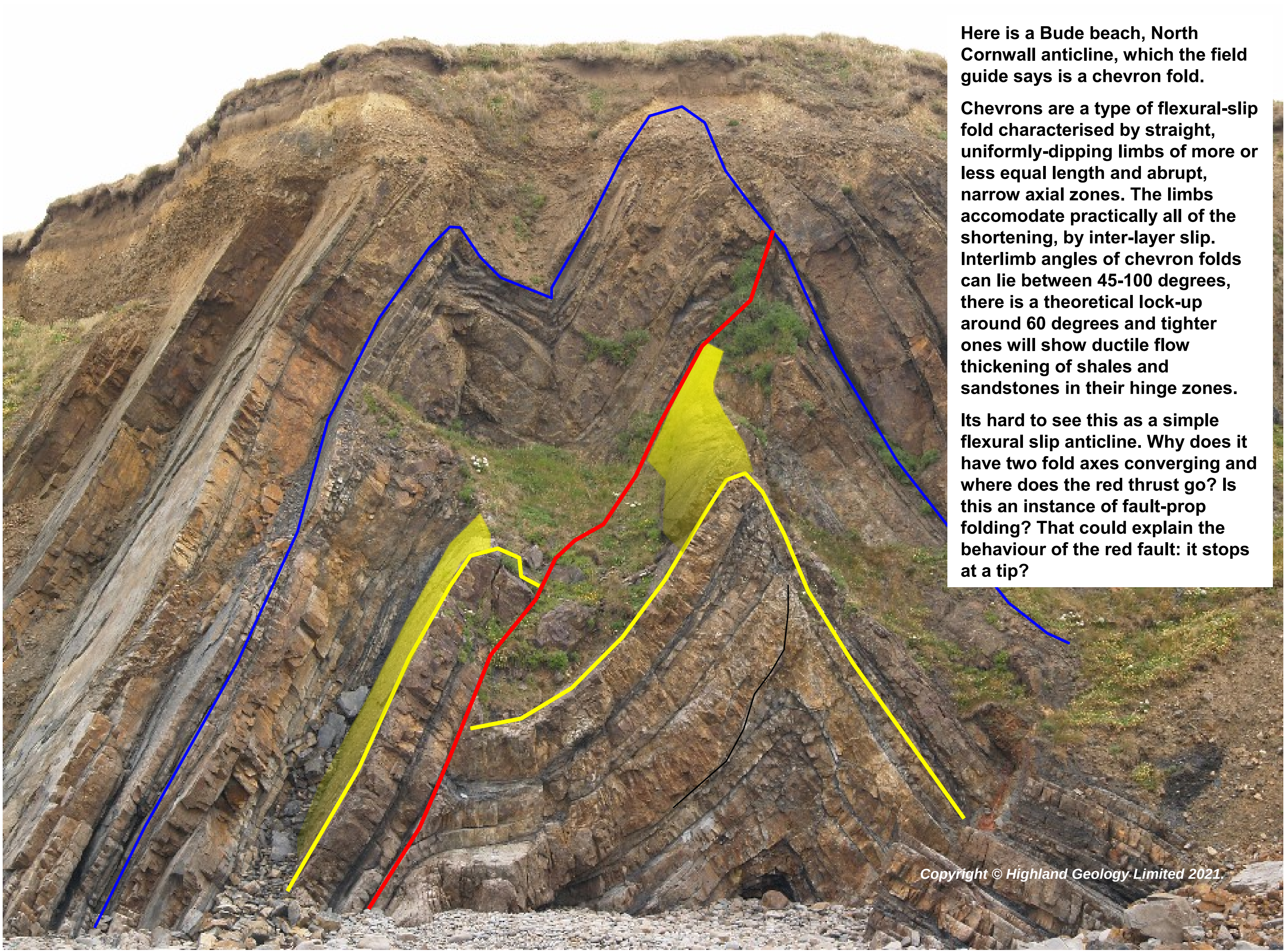
Fault-propagation folding

If the bed thickness is allowed to vary, for certain types of fault-prop folds Jamison showed the interlimb angle can vary for a particular ramp angle. His graph relating ramp and interlimb angles, given here, is similar to his detachment fold model: if you know those two angles it predicts forelimb thickness. If you only know the interlimb or axial-plane angle half-gamma, and assume no forelimb thickness change, you can read-off the cut-off angle for the associated fault ramp. Note that the interlimb angle to be used in the graph is for the formations cut by the ramp, not for overlying folded units.





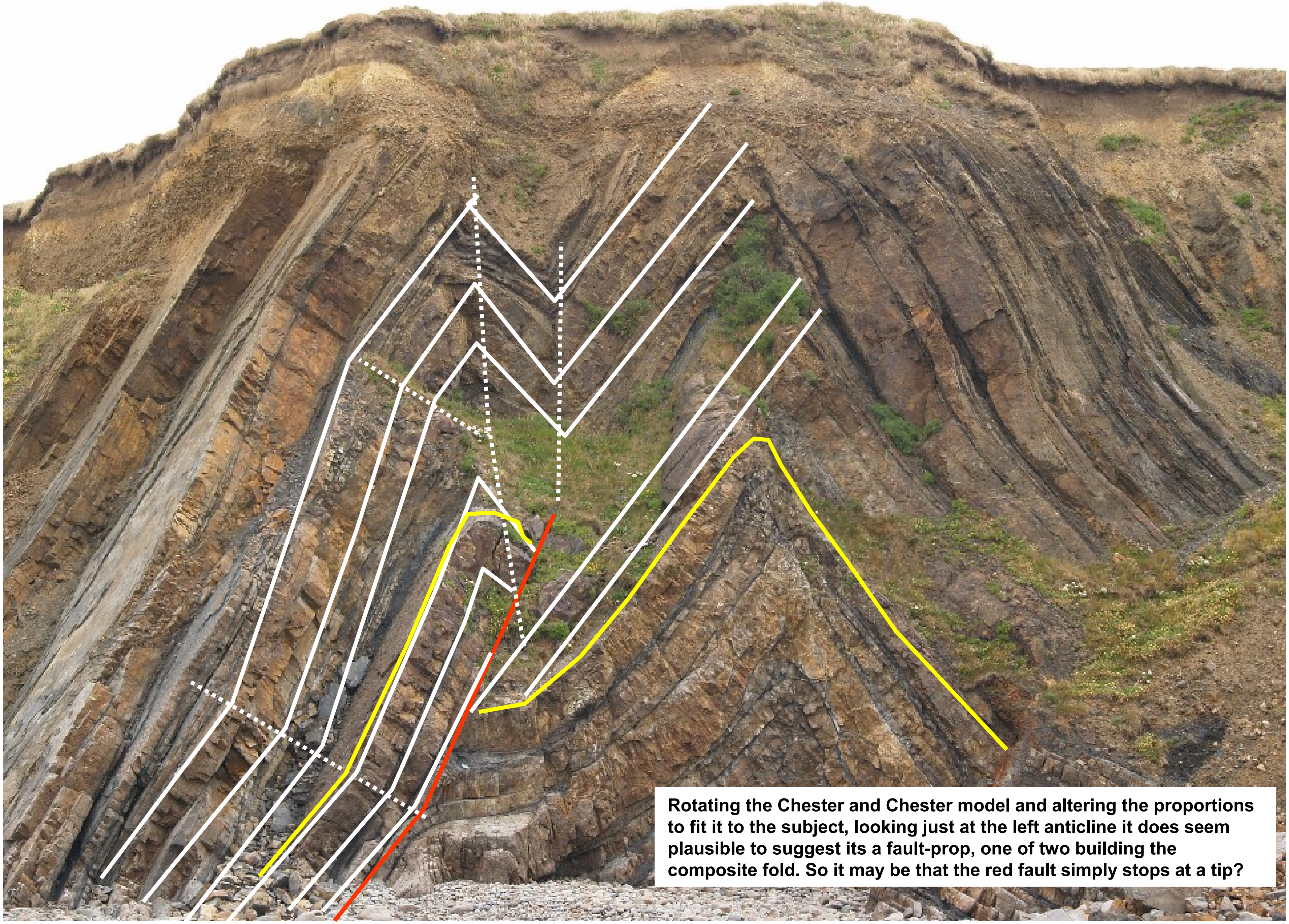
Real folds over ramps show strong bed-stretching near the fault, in the steep limb: they don't conserve bed length. They don't necessarily have angular fold hinges either. And, along the strike of a fault-prop fold the fold axis geometry will change according to the slip on the ramp. As the displacement increases on the thrust ramp we typically see the fold tighten, so that where the slip maximises the fold is tightest and the front limb is steepest. Also, fault-prop fold shapes evolve with time, often with progressive thinning of the front limb, and they may become translated over a breakthrough ramp. "Pure" fault props seem to be few and far between! Despite these limitations Jamison's chart is handy. See Mitra (1990), in AAPG 74(6) 921-945, an excellent paper, for models of thrust breakthrough in the fold syncline and anticline, and description of trap potential of these folds.



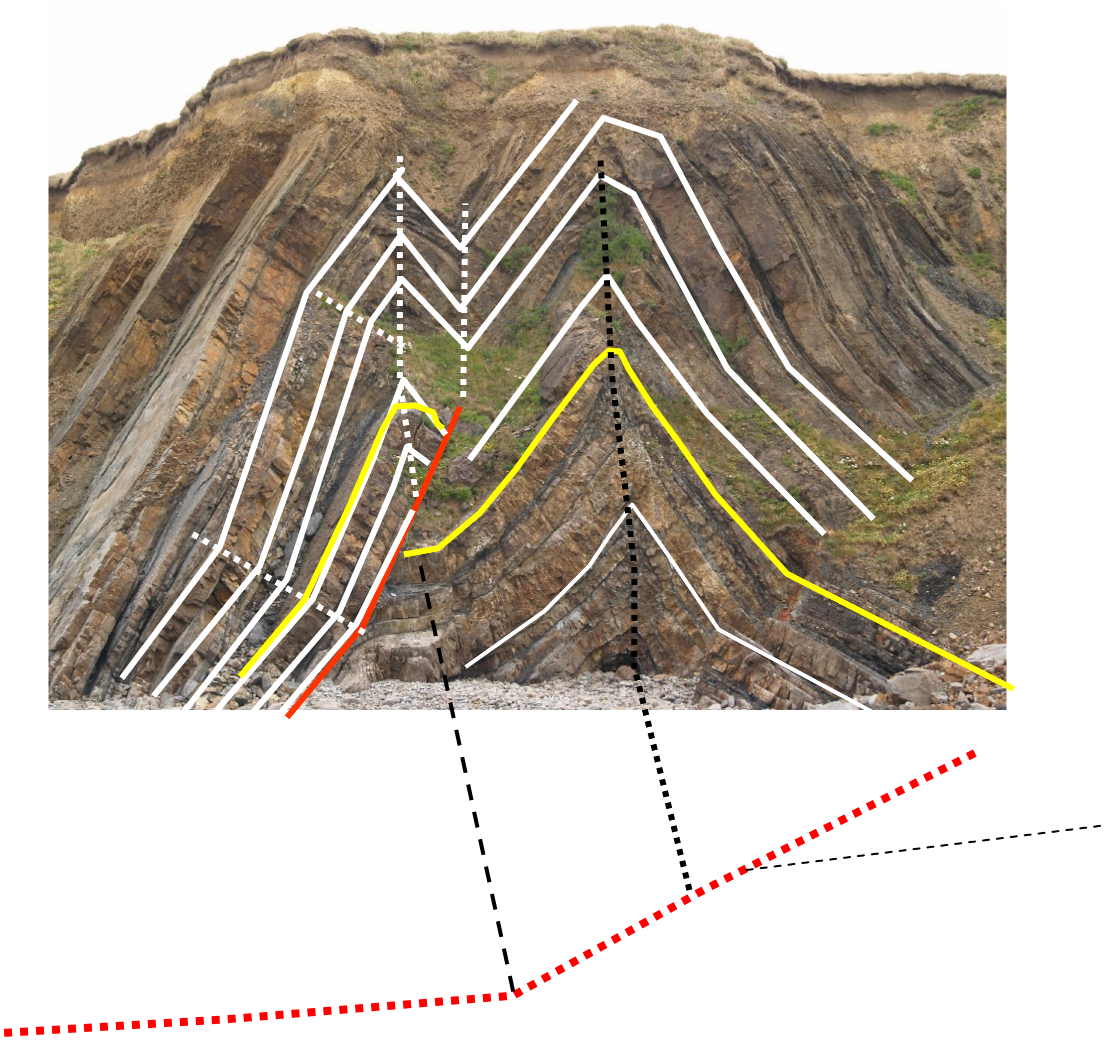
Here is a Bude beach, North Cornwall anticline, which the field guide says is a chevron fold.

Chevrons are a type of flexural-slip fold characterised by straight, uniformly-dipping limbs of more or less equal length and abrupt, narrow axial zones. The limbs accomodate practically all of the shortening, by inter-layer slip. Interlimb angles of chevron folds can lie between 45-100 degrees, there is a theoretical lock-up around 60 degrees and tighter ones will show ductile flow thickening of shales and sandstones in their hinge zones.

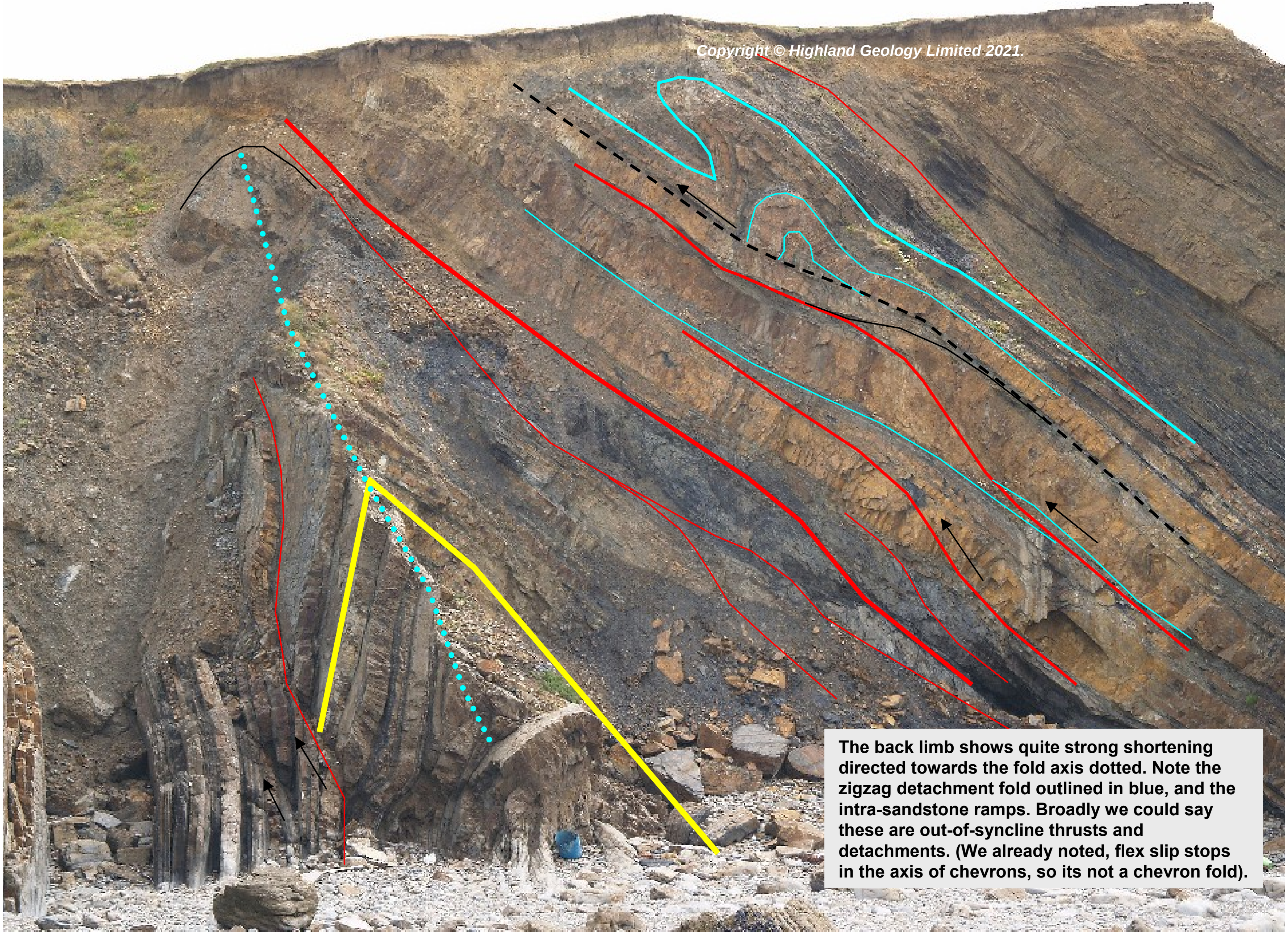
Its hard to see this as a simple flexural slip anticline. Why does it have two fold axes converging and where does the red thrust go? Is this an instance of fault-prop folding? That could explain the behaviour of the red fault: it stops at a tip?



Rotating the Chester and Chester model and altering the proportions to fit it to the subject, looking just at the left anticline it does seem plausible to suggest its a fault-prop, one of two building the composite fold. So it may be that the red fault simply stops at a tip?



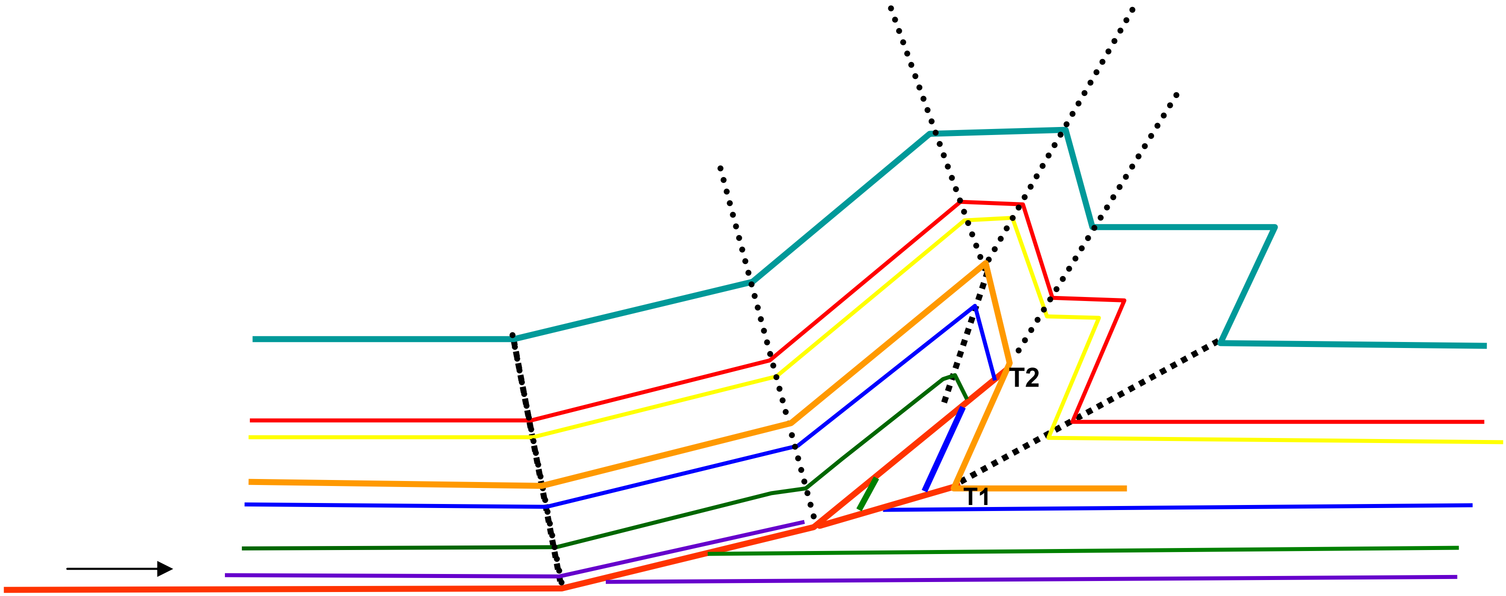
And something on these lines may be a plausible interpretation for the larger fold, its arguably a bigger fault-prop fold with the smaller one on its back limb. For this interpretation the deeper ramp has to be pushed down, to tip-out under the broad syncline flank to the right of the photo.



The back limb shows quite strong shortening directed towards the fold axis dotted. Note the zigzag detachment fold outlined in blue, and the intra-sandstone ramps. Broadly we could say these are out-of-syncline thrusts and detachments. (We already noted, flex slip stops in the axis of chevrons, so its not a chevron fold).

What about this overturned fold at Northcott Mouth near Bude, its got a vertical limb faulted against the tight fold core, so its more complex than the simple fault-prop model. Can we explain this extra geometrical feature?

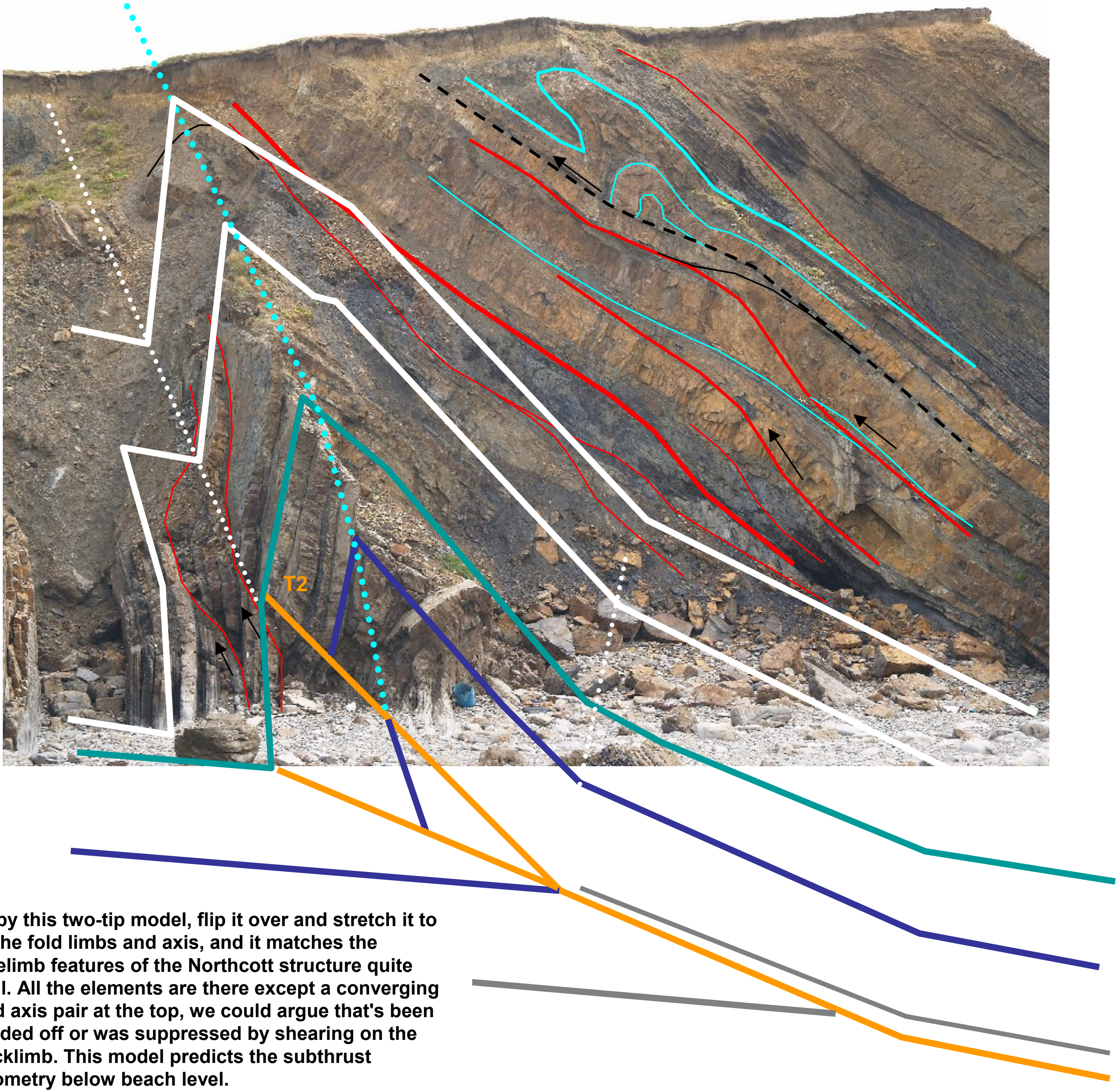
Multi-tip fault prop folding



Returning to the Chester model a plausible anwer is to introduce a second growth stage, with another ramp and second tip point, T2.

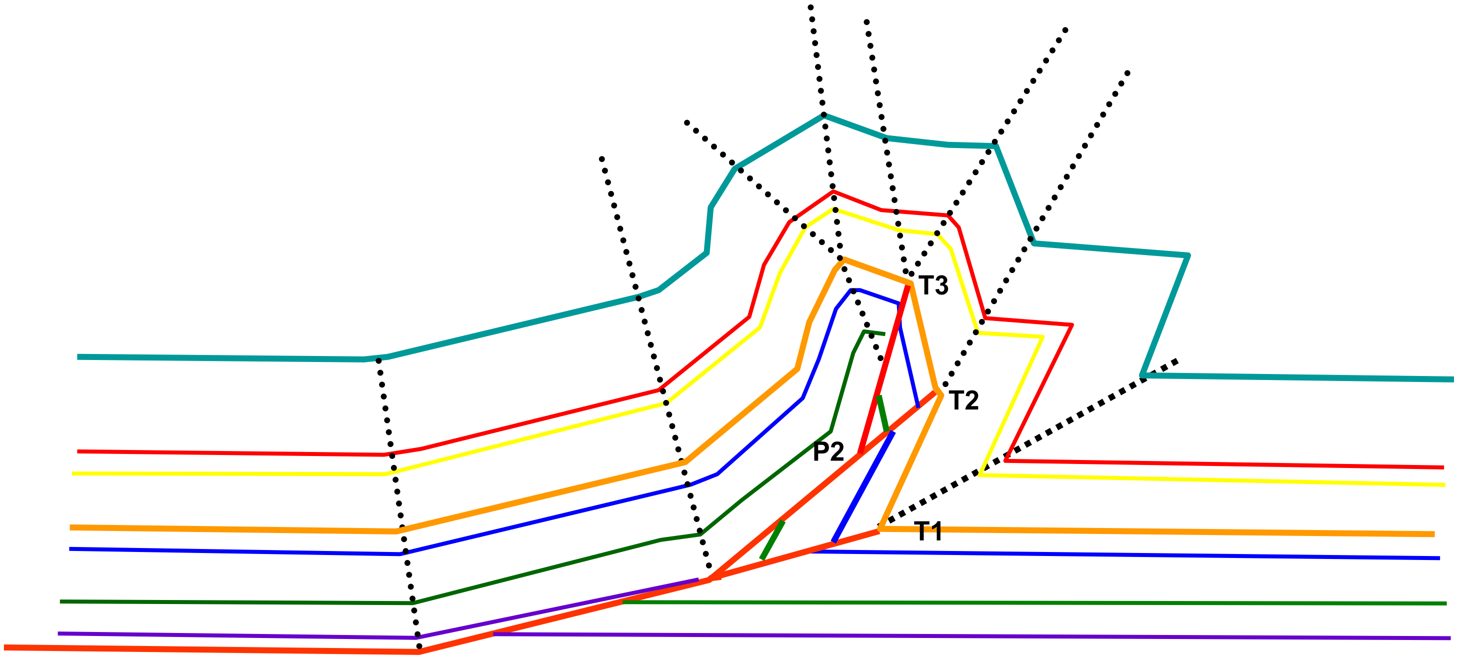
In stage 2 of this fold a further 1000 metres of slip is fed in via the red flat and lower ramp, but the tip T1 now sticks and the active ramp retreats to point P where a new steeper, upper ramp develops. It has a dip of 40 degrees, backlimb 40 degrees, interlimb angle 65 degrees, tip at T2. It follows the stage 1 fold axis, because the inner fold zone is mechanically weak.

This idea came from a paper by Al Saffar (1992) in Tectonophysics 223, 363-380, where he analyses Algerian examples.



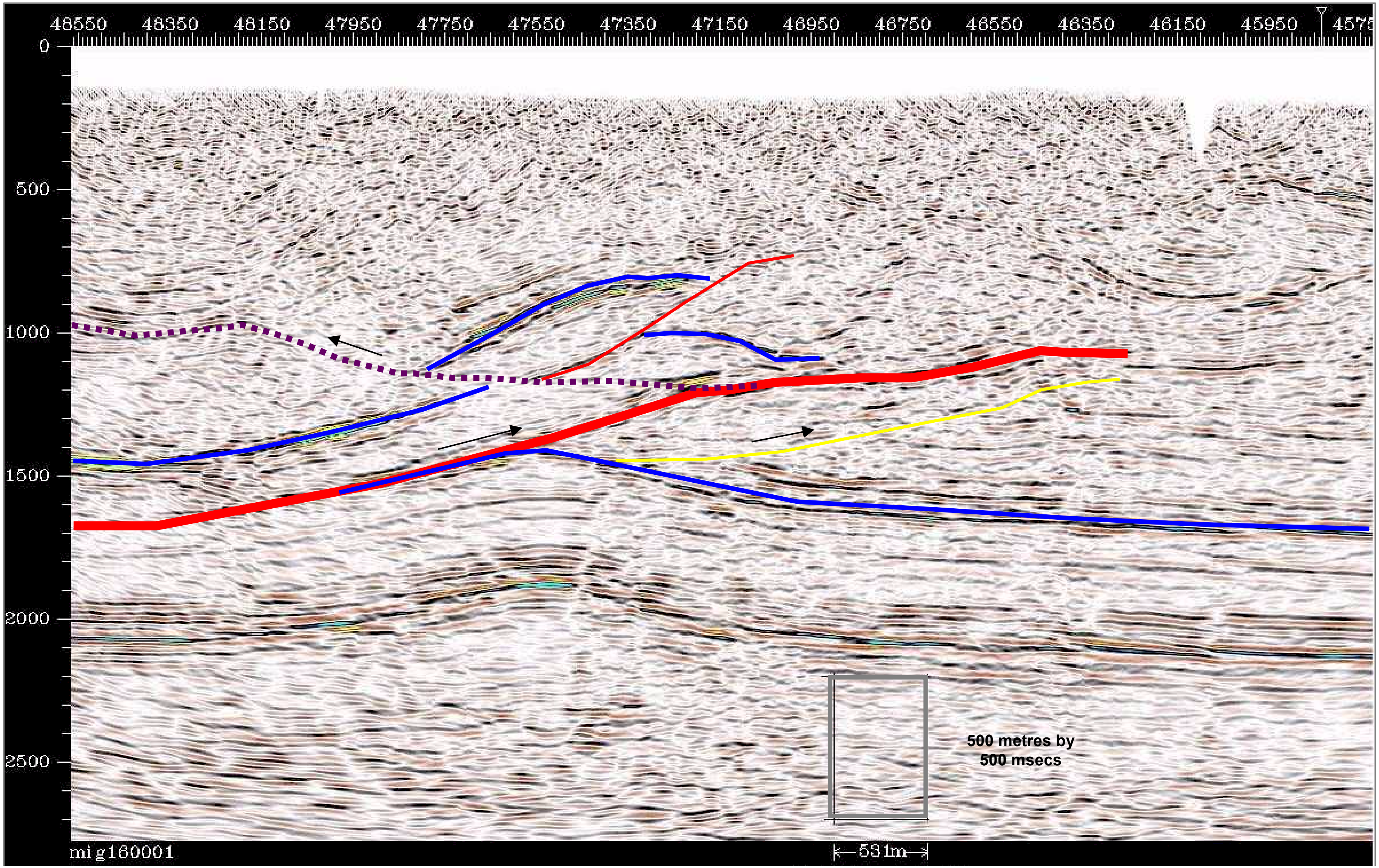
Copy this two-tip model, flip it over and stretch it to fit the fold limbs and axis, and it matches the forelimb features of the Northcott structure quite well. All the elements are there except a converging fold axis pair at the top, we could argue that's been eroded off or was suppressed by shearing on the backlimb. This model predicts the subthrust geometry below beach level.

Three-tip fault prop folding: is this getting too complex to demonstrate?



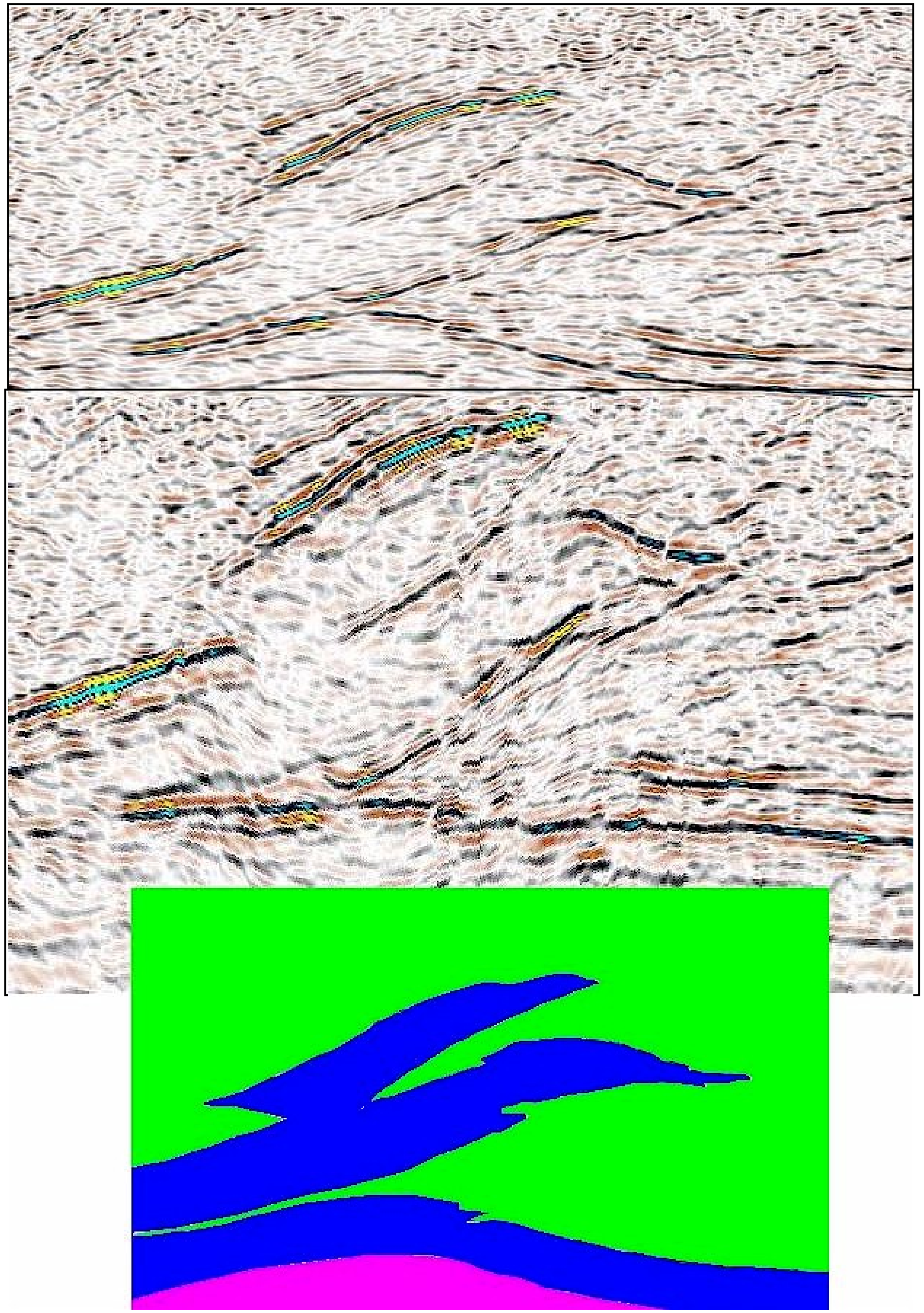
And a third tip point could be introduced, T3, when T2 stops propagating, with a ramp between P2 and T3. This final fold has a backlimb of around 65 degrees, forelimb of about 20-25 degrees, and an interlimb angle of 90 degrees. As with the second-stage fold, the initiation point (point where the slip on the ramp begins to reduce) is close to the tip, otherwise the fold can't develop on a steep ramp surface.

This process model predicts a very high amplitude, narrow structure with multiple internal ramps.



A famous old oilfield is the Turner Valley Anticline, south-central Alberta Foothills, its a dislocated fold which resides over a major thrust ramp (Turner Valley Fault, heavy red line), and has been much discussed as a fault-prop fold case example , its described as tipping-out in the Cretaceous. But does it, maybe it runs on eastwards bed-parallel? This is to make the point, even with reasonable quality seismic and many wells it can still be a matter of opinion how these structures are interpreted. A lot of imbricate thrusts are suggested here, transferring slip. The yellow thrust appears to be an important surface, plausibly younger than the Turner Valley thrust and maybe between it and the TVT there's a duplex panel with trapping potential?

Seismic section shows our picks for the top of the Mississippian carbonate reservoir in blue, the repetition of the fast blue unit and the backthrust pop-up causes a large velocity pull-up in the footwall. Next slide shows depth conversion of this image to flatten the velocity anomaly.



DepthCon depth converts a bitmap, by assigning velocities to the colour-filled polygons (carbonates of Mississippean in blue) and marrying them with the seismic image, pixel for pixel. When the geological model is experimented with and looks like its giving a sensible depth conversion, the image quality can be raised.

Chevron Folding

Just in passing, you'll see the term used.

Chevrons are a type of flexural-slip fold characterised by straight, uniformly-dipping limbs of more or less equal length and abrupt, narrow axial zones. (If asymmetrical, they are called kink folds).

They seem to form primarily in sequences of alternate harder and softer rocks, typically sandstones and shales, where no one unit is particularly thick. In other words, in ductility-contrasting successions which have been compressed along the beds. As soon as the bedding departs from uniform layered style, and significant thickness variations are introduced in say the sandstones, the fold limbs become curved.

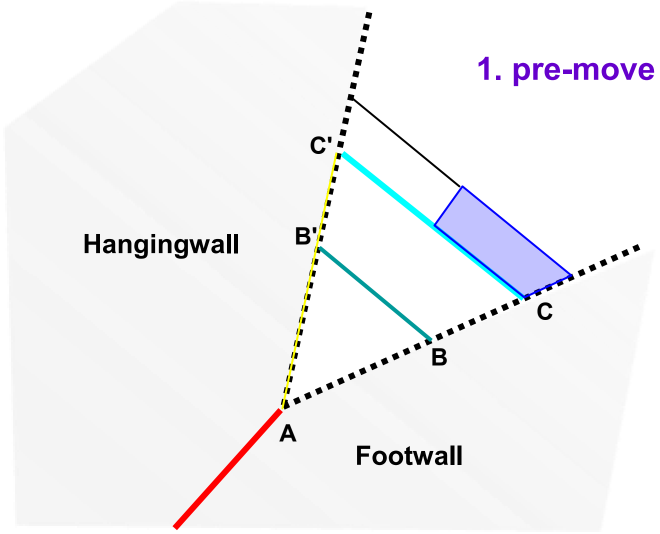
The limbs accomodate practically all of the shortening, by inter-layer slip. Interlimb angles of chevron folds can lie between 45-100 degrees, there is a theoretical lock-up around 60 degrees and tighter ones will show ductile flow thickening of shales and sandstones in their hinge zones.

In very thick turbidite sequences they may be large multi-reservoir structures and trap important fields. Good examples are the Huntingdon Beach, Long Beach, Potrero, Inglewood fields of the Inglewood trend, Los Angeles Basin, California.

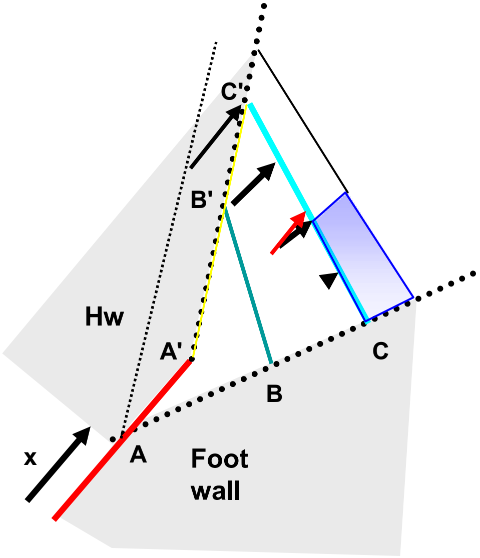
An alternative way to forward-model and restore fault-prop structures: Trishear

Trishear is "distributed, strain-compatible shear in a triangular shear zone", after Erslev 1991, in "Trishear fault propagation folding", Geology, 19, 617-620.

Let's say we have a fault, red, which will propagate into a symmetrical triangular shear zone, into which the fault will develop and within which reference lines such as green and pale blue are drawn. Any polygon we draw inside the zone between tie lines, will not change in volume (area) as the fault progresses. The blue polygon outlined, for example, is going to preserve its area.



1. pre-move

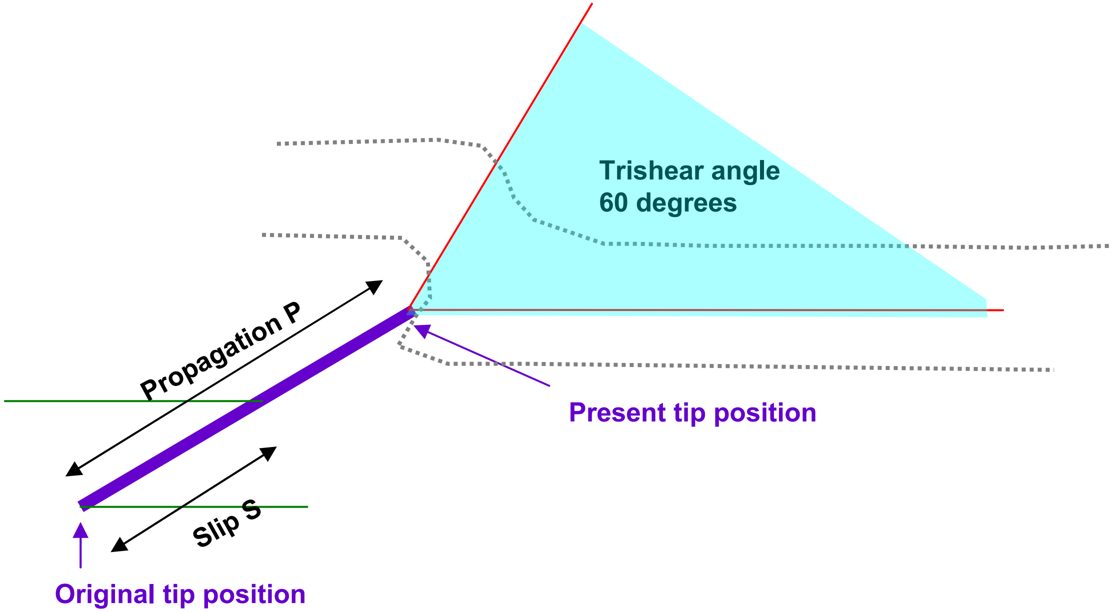


2. post-move

As the fault propagates by amount x units the footwall boundary of the trishear zone stays where it is but the hangingwall side migrates by that vector x. Tie-line end points on the hangingwall boundary line of the shear zone take up new locations as shown, e.g. length AB' in diagram 1 remains equal to A'B' of 2, and so the tie lines rotate. To keep areas unchanged the material paths are therefore oblique instead of parallel to the fault slip. The displacement of any point in the trishear zone increases from zero at the footwall side to maximum on the hangingwall side, where it equals the added displacement on the fault, x.

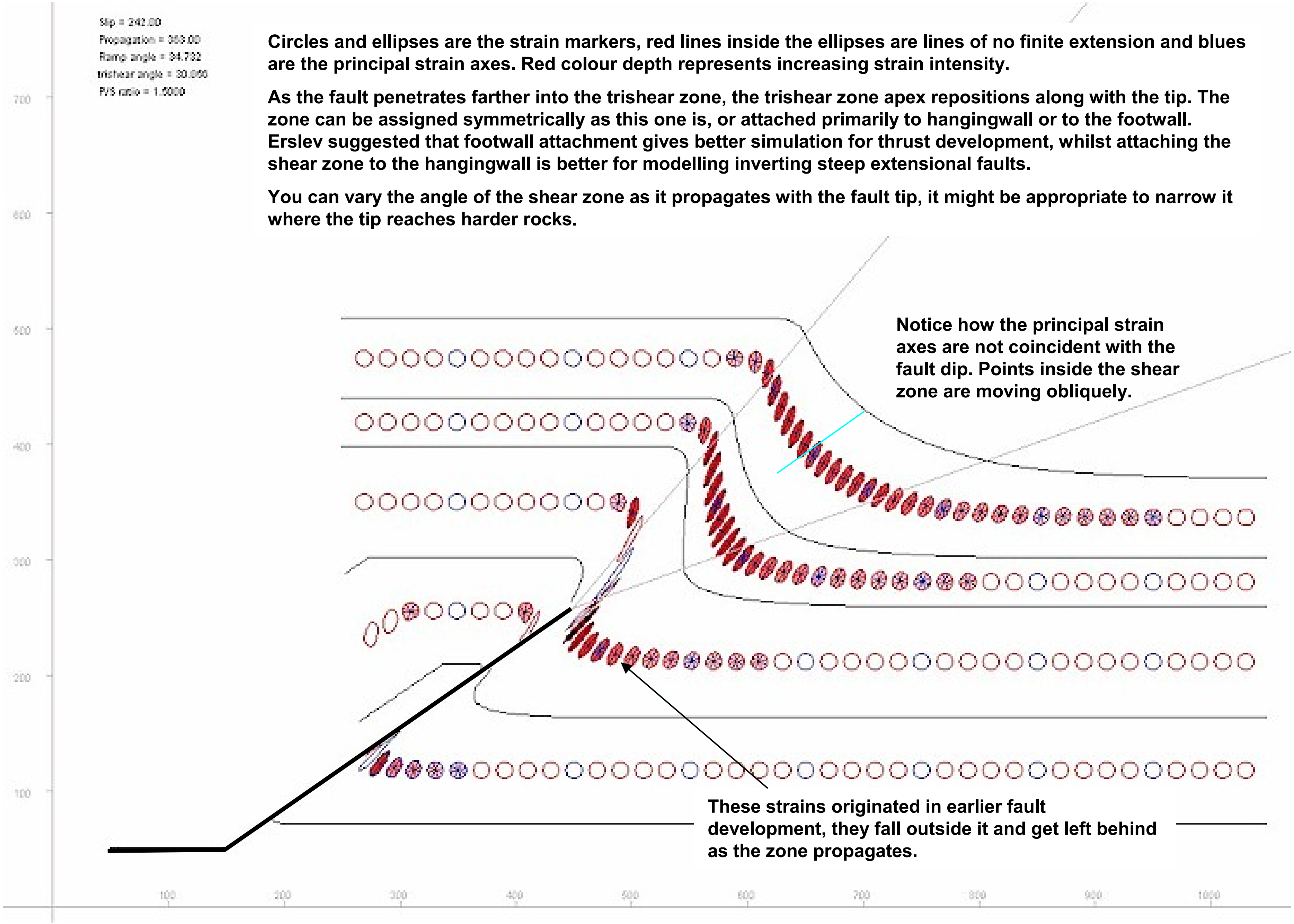
If we were seeing simple-shear displacement of points on these lines the move of every particle inside the shear zone would be parallel to the fault. But that creates volume imbalance. Compare the red fault vector direction with the actual one, at the corner of the polygon.

Trishear



Variables needed to simulate strain fields and to undeform a bed to flat dip are shown here: the position of the tip; the angle at the triangle apex; the slip; the ratio P/S; the ramp angle. P/S seems to be particularly important in controlling the results of modelling. The trishear angle is arbitrary, narrow wedges seem more appropriate for stronger rocks. For thrust folds, Erslev recommended that the apex should be fixed to the footwall side, whilst modelling inversion of normal faults is better done with a fix to the hangingwall side of the triangle.

Numerical analysis by "Trishear" implemented with finite-element simulation is an effective way to model fault-prop folds. See Cardozo et al (2003), J Struct Geol 25, 1-18. If you are going to drill a fault-prop target, or are appraising one, it is probably best to do trishear work in-house. There is now a 3D-enabled version of Trishear.



Circles and ellipses are the strain markers, red lines inside the ellipses are lines of no finite extension and blues are the principal strain axes. Red colour depth represents increasing strain intensity.

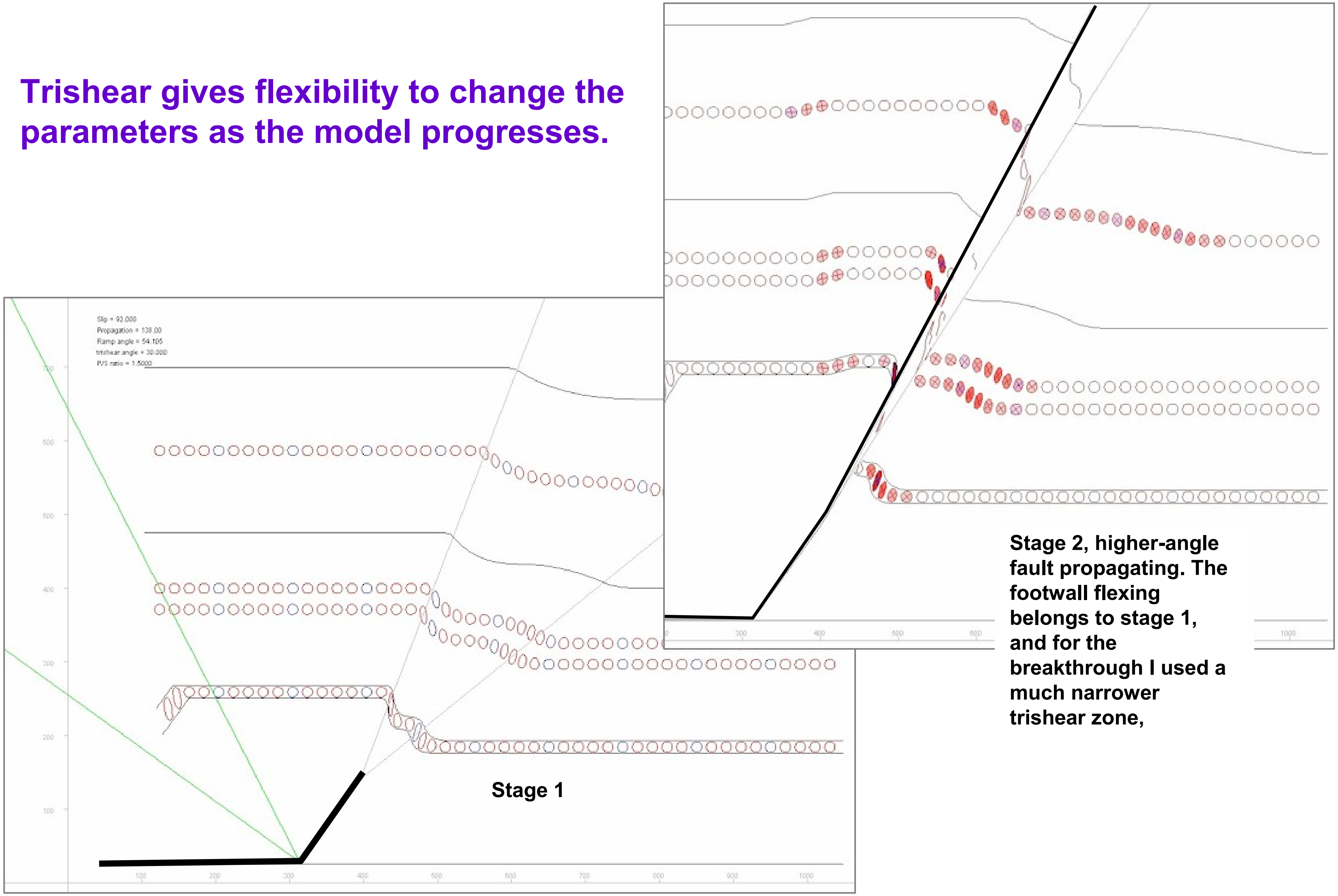
As the fault penetrates farther into the trishear zone, the trishear zone apex repositions along with the tip. The zone can be assigned symmetrically as this one is, or attached primarily to hangingwall or to the footwall. Erslev suggested that footwall attachment gives better simulation for thrust development, whilst attaching the shear zone to the hangingwall is better for modelling inverting steep extensional faults.

You can vary the angle of the shear zone as it propagates with the fault tip, it might be appropriate to narrow it where the tip reaches harder rocks.

Notice how the principal strain axes are not coincident with the fault dip. Points inside the shear zone are moving obliquely.

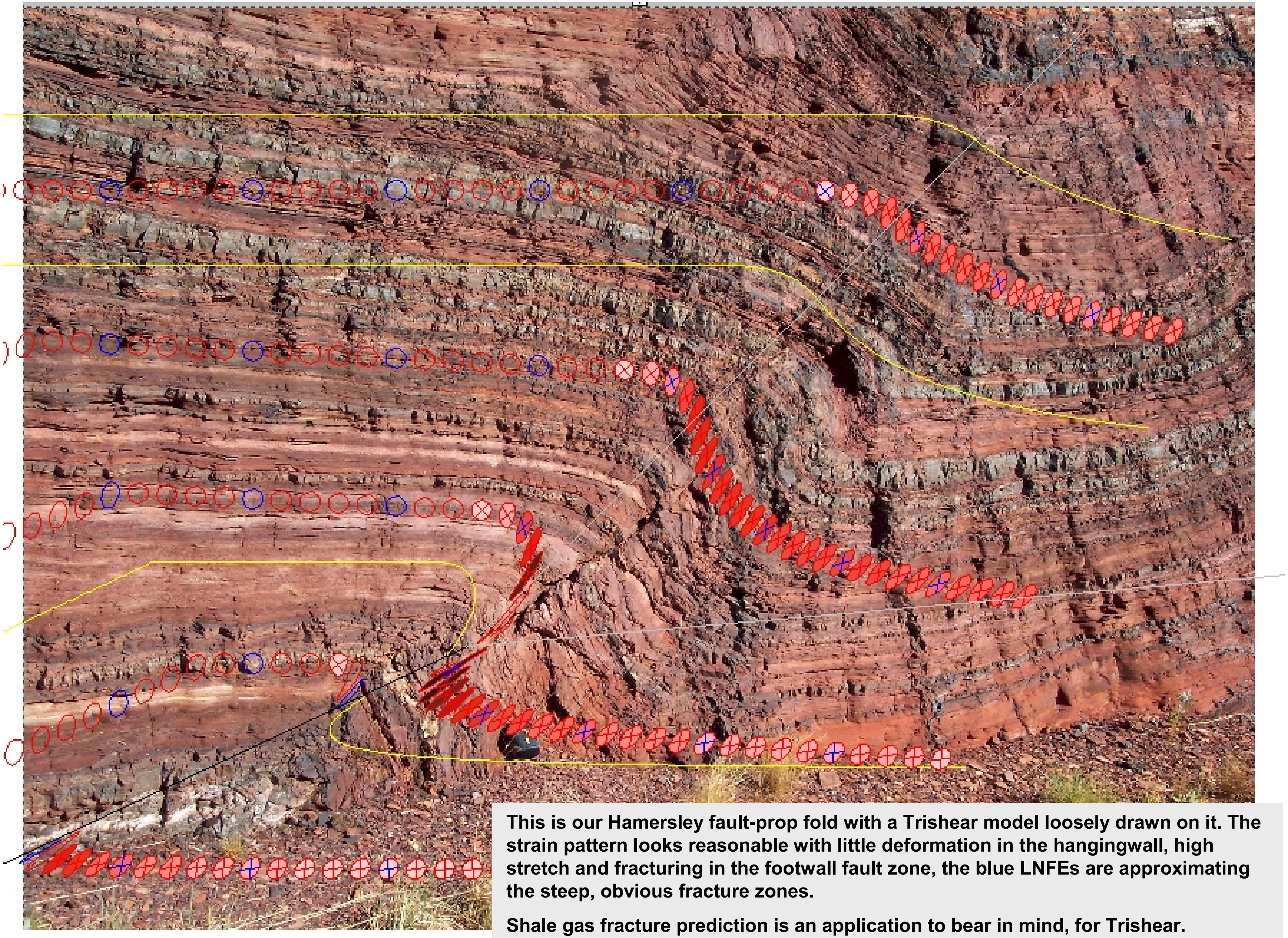
These strains originated in earlier fault development, they fall outside it and get left behind as the zone propagates.

Trishear gives flexibility to change the parameters as the model progresses.



Stage 1

Stage 2, higher-angle fault propagating. The footwall flexing belongs to stage 1, and for the breakthrough I used a much narrower trishear zone,



This is our Hamersley fault-prop fold with a Trishear model loosely drawn on it. The strain pattern looks reasonable with little deformation in the hangingwall, high stretch and fracturing in the footwall fault zone, the blue LNFEs are approximating the steep, obvious fracture zones.

Shale gas fracture prediction is an application to bear in mind, for Trishear.

Prospect evaluation: fold geometries

In summary, what do we need to know about anticlines, to map their deeper structure properly?

Seismic might not be definitive with respect to primary and/or secondary targets. Commonly the target isn't defined by a nearby marker, and complexity in hinge zones will defeat detail efforts. If we are going to be drilling progressively deeper into structure which is uncontrolled by seismic, how much confidence can we have in the deep maps?

Its critical that we know what is the fold structural style. Are we looking at fault-bend folds, detachment folds formed over flat thrusts, or fault-propagation folds? Or some hybrid type, deformed in several phases?

Whether we can reasonably reliably deduce the deeper geometry largely depends on how much of the story is evident from seismic.

- Broadly, do we have thin-skin tectonics with folds built on networks of low-angle ramping and flatting thrusts, and high degree of shortening, in which case a key question is where do the controlling detachments lie?
- Or do we have predominantly thick-skinned tectonics, with deep (maybe crustal-penetrating) steep faults which may be reactivated extensionals, defining the shapes of the major prospective folds? The shortening across the fold belt is then much less, the deep structure looks quite different.