

Forward modelling backthrusts in Move™

Accurately interpreting backthrust structures can be tricky, however Move, and more specifically, the **2D Kinematic Modelling** module, provides the user with some simple forward modelling tools and techniques to aid or correct initial interpretations. Forward modelling in Move using a powerful workflow tests if an interpretation balances and if the amount of displacement is consistent with the interpreted amount of fault-related folding. This approach is particularly effective as steeply-dipping structures associated with thrusts and backthrusts are often poorly imaged in seismic data.

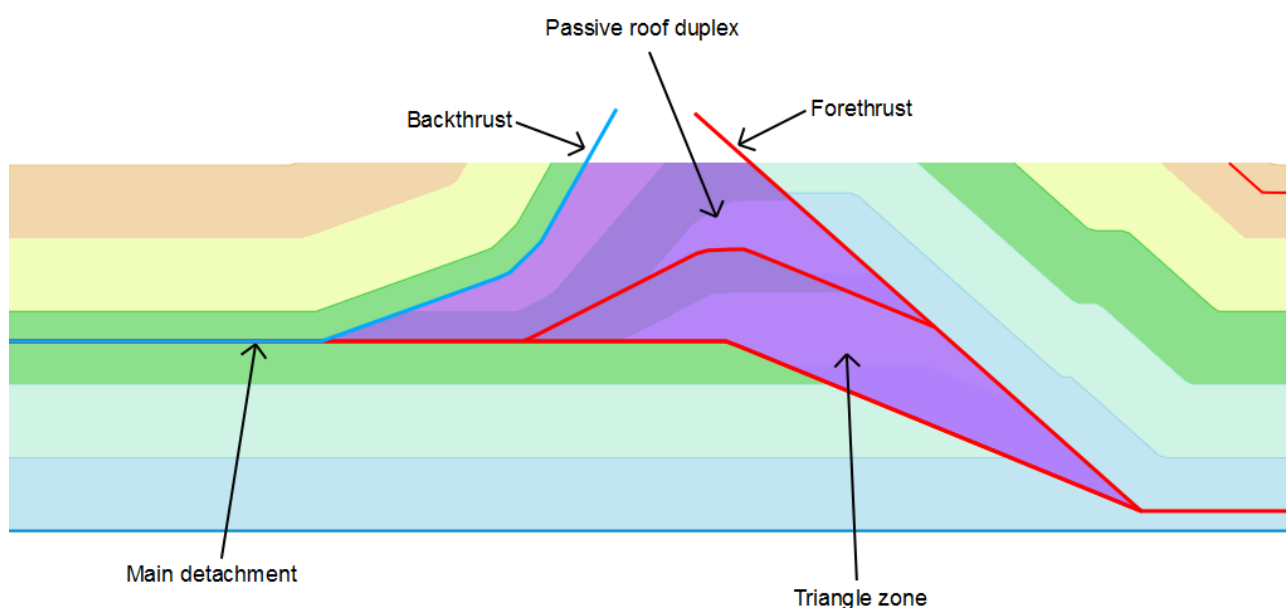


Figure 1: Triangle zone modelled in Move (area in purple).

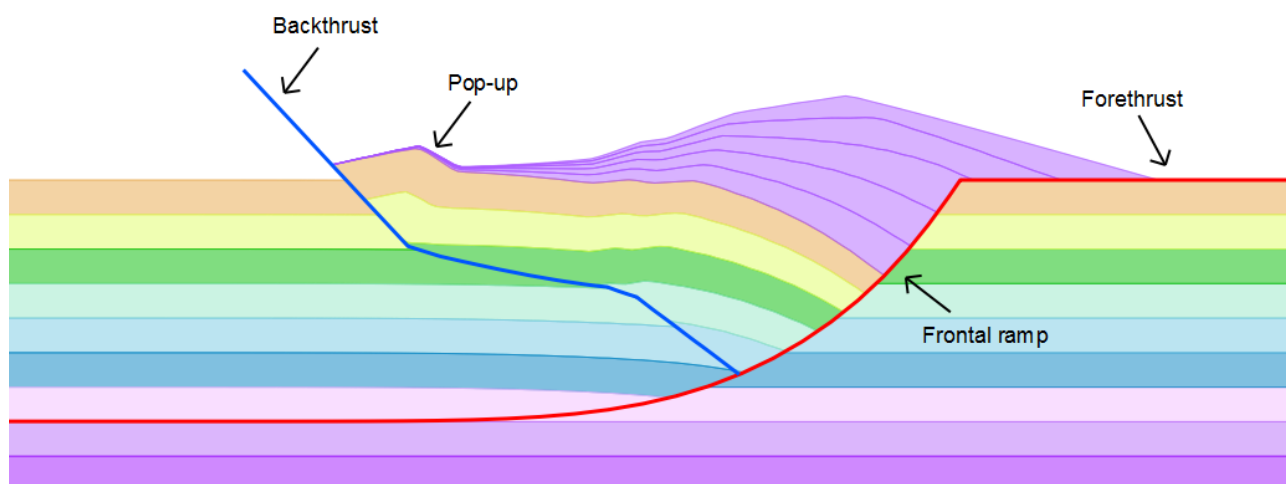


Figure 2: Pop-up (labelled) associated with antithetic backthrust.

Backthrusts commonly form in foreland fold-and-thrust belts or during basin inversion, often creating passive roof duplexes, 'triangle' zones (Banks & Warburton 1986; Couzens-Schultz *et al.* 2003) (Fig. 1), or pop-up structures (McClay & Buchanan 1992) (Fig. 2). The ability to model backthrusts is vital because, as previously mentioned, they generally fall in areas of poor seismic recovery and quite often contain significant hydrocarbon reserves (e.g. MacKay *et al.* 1996).

Move **Tutorial 22 Exercise 4** provides a detailed workflow for modelling passive roof duplexes - also called intrusive wedges - which form the basis of triangle zones.

Testing and refining interpretations that include backthrusts is of economic interest because backthrusts contribute to the development of hanging wall pop-up structural traps, formed during inversion (McClay & Buchanan 1992). They also occur in subduction settings (*e.g.* Xu *et al.* 2015) and are associated with large magnitude (>7.0 Mw) shallow earthquakes (<10 km depth) (Lee *et al.* 2002).

This Move feature focusses on the forward modelling of antithetic backthrusts that develop during frontal ramp climb, commonly associated with inversion tectonics (Butler 1982; Nieuwland *et al.* 2000) (Fig.2). Depending on basal friction conditions, backthrusts develop at a flat to ramp transition or during reactivation of a normal fault (Dahlen *et al.* 1984; Nieuwland *et al.* 2000); a workflow to forward model backthrusts associated with reactivation of normal faults is presented here.

Forward modelling backthrusts

Move offers the complete range of tools to build, balance, restore and analyse cross-sections at a local and regional scale through the **2D Kinematic Modelling** module, which can be accessed from the **Modules** tab. Forward modelling backthrusts requires the **2D Move-on-Fault** and **2D Unfolding** tools. More information about the **2D Kinematic Modelling** module is available from the **Move Knowledge Base**.

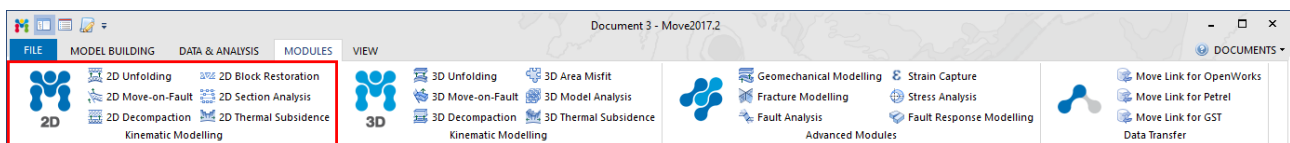


Figure 3 Modules tab in Move with the 2D Kinematic Modelling modules outlined in red.

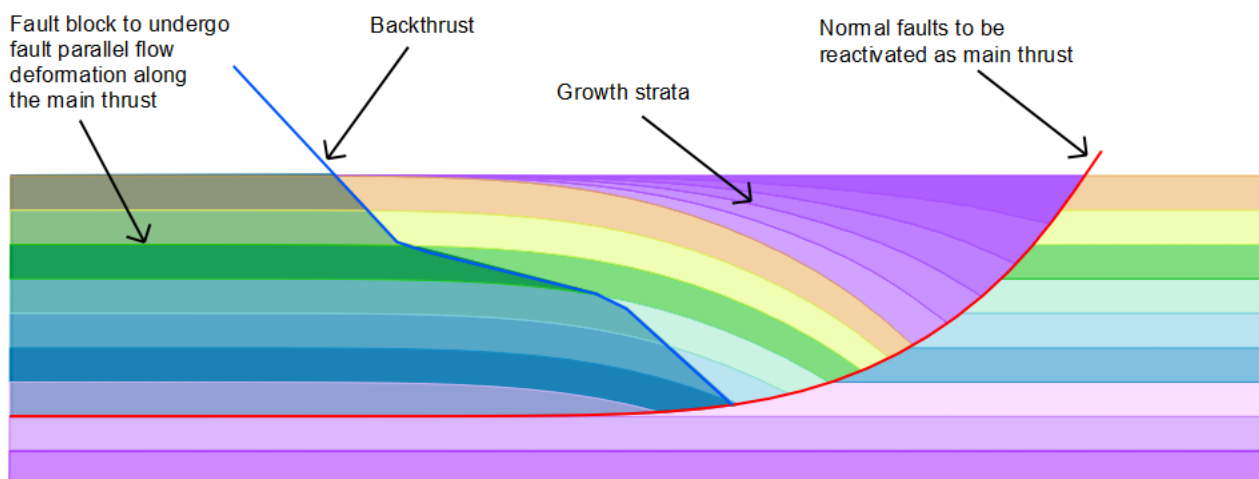


Figure 4: Block in backthrust footwall and main thrust hanging wall shaded in blue.

An inverted sedimentary basin is used for the purposes of this demonstration however, the workflow can be adapted to suit any backthrust system. The workflow is carried out in two stages: firstly, deformation of horizons in the footwall of the backthrust and the hanging wall of the main thrust (outlined by blue shape on Fig. 4) is simulated using **Move-on-Fault** algorithms; secondly, deformation of horizons in the hanging wall of the backthrust (outlined by blue shape on Fig. 5) is simulated using **2D Unfolding** algorithms.

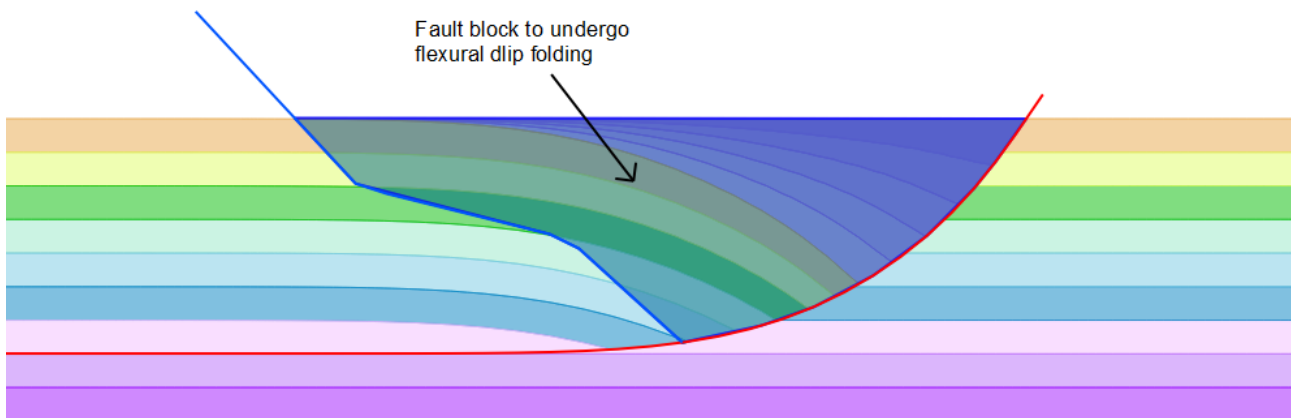


Figure 5: Block in backthrust hanging wall shaded in blue.

Preparing a 2D cross-section

The initial cross-section is constructed using a simple layer cake stratigraphy and the fault digitization tools found on the **Model Building** tab. Growth strata are modelled using fault kinematic algorithms. The workflow applies the concept of the 'working section', where all modelling operations are carried out on one section and duplicated at each step, thus creating a record of steps performed.

1. Using the **Create Section** tools on the **Model Building** tab, create an empty 2D cross-section (using the **Section** tool) and, then click on **Layer Cake** to create the stratigraphy.
2. Based on the underlying data or the initial interpretation, digitize a listric fault (comparable to that shown in Fig. 5), using the **Fault** tool. Make sure to resample this fault, ideally using the **Bézier** method followed by **Along Length**.
3. Right-click in the **Section View** and select **Duplicate Section**. Name it *Working_Section* and click **Create and Open**.

A. Modelling growth strata in a listric normal fault

As mentioned above, antithetic backthrusts often develop in inversion settings, therefore, how to forward model some growth strata using the **2D Move-on-Fault** tool from the **2D Kinematic Modelling** module is now demonstrated. Using the *Working_Section*:

1. In the 2D Move-on-Fault tool, select the **Simple Shear** method to simulate growth strata. Sediment thicknesses should be based as closely to available data as possible. In this case, five steps of -100 m slip on the listric fault are simulated, adding a single sediment layer at elevation 0.0 m after each fault step (Growth strata can also be simulated using the **Horizons from Fault** tool).
2. Add a Sedimentation horizon to **Stratigraphy** in the **Data & Analysis** tab and assign the growth strata to this horizon using the **Quick Editor**.
3. Create polygons for these horizons using the **Polygon** tool on the **Model Building** tab. Apply some transparency to your growth strata polygons for easy viewing.
4. Based on the underlying data or the interpretation, digitize a backthrust like that in Figure 5 and **Split** the pre-tectonic horizons (lines and polygons) with it. If growth strata have been created, Move will already have split the pre-tectonic horizon lines and polygons with the listric fault; otherwise, if modelling a thrust system without growth strata, the section will have to be split using the main thrust. This separates the section into fault blocks.

5. Create fault block sets for the horizon lines and polygons forming the backthrust footwall (Fig. 4) and backthrust hanging wall (Fig. 5), for ease of selection when forward modelling.
6. Create a duplicate of the section and name it appropriately.

B. Forward modelling slip on the main thrust

This part of the workflow simulates deformation of the block of horizons that are in the footwall of the backthrust and hanging wall of the main thrust (shown in blue on Fig. 4). The workflow applies **Fault Parallel Flow** to model reverse slip on the listric fault, which has been reactivated during inversion to form the main thrust.

1. Select and hide the fault block set for the backthrust hanging wall (shown in blue on Fig. 5).
2. With the *Working_Section* active, click on **2D Move-on-Fault** on the **Modules** tab and select the **Fault Parallel Flow** algorithm.
3. Collect the main thrust as the **Fault**.
4. Collect the horizon set for the backthrust footwall (shown in blue on Fig. 4) and the backthrust into the **Objects to Be Moved** box.
5. Select and copy (Ctrl+C) the backthrust.
6. Enter a slip value based on the existing data or interpretation (here, a slip value of 400 m has been used; positive slip values indicate reverse movement) and click **Apply**.
7. Paste (Ctrl+V) the copied backthrust to the forward modelled section and use the **Quick Editor** to change the style of the line from solid to dashed. Figure 6 shows the original and forward modelled positions of the backthrust following 400 m of fault parallel flow faulting on the reverse reactivated listric fault.
8. Create a duplicate of the section and name it appropriately.

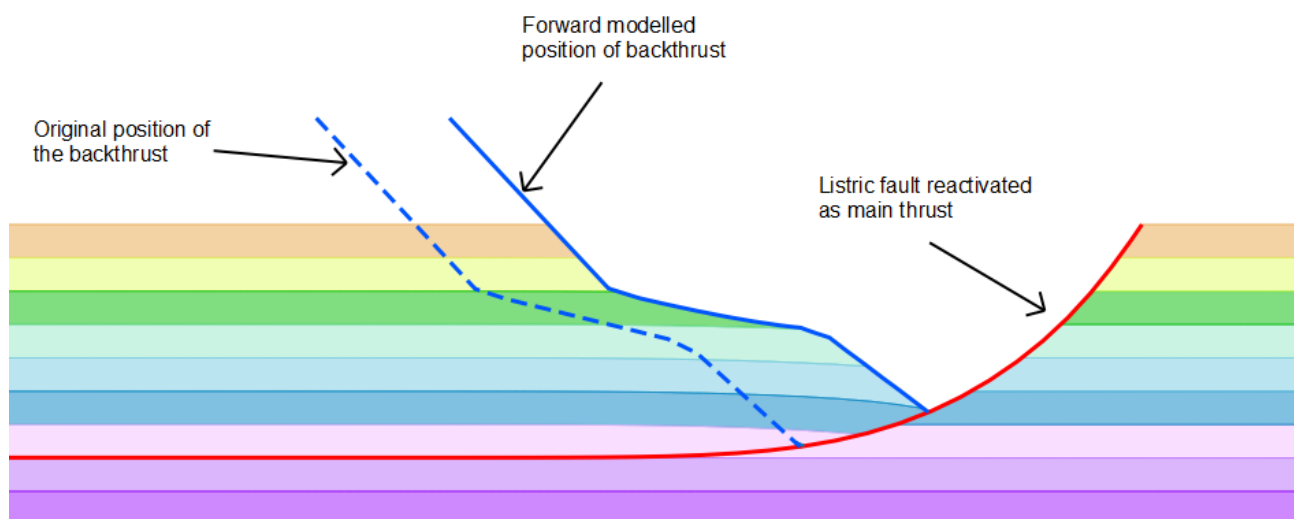


Figure 6: Change in position of backthrust following 400 m of reverse slip on listric fault reactivated as main thrust.

C. Forward modelling slip on the backthrust

This part of the workflow simulates slip on the backthrust and deformation of the backthrust hanging wall block to form a pop-up structure (Fig. 5). The workflow uses the **Flexural Slip Folding** algorithm in the **2D Unfolding** tool, which is part of the **2D Kinematic Modelling** module.

1. With the *Working_Section* active, hide the backthrust footwall fault block set and make the backthrust hanging wall fault block set visible (Fig. 7). Make sure that the backthrust in its original position is visible; copy (Ctrl+C) and paste (Ctrl+V) it from a duplicated section created earlier in the workflow if necessary – if so, choose 'model coordinates' when prompted while pasting.
2. Use the **Extend** tool on the **Model Building** tab with the **At Angle (No Snap)** option selected, to extend all the faults as shown in Figure 7. The reactivated listric fault will act as the pin, i.e. a line along which strain is modelled to be zero.
3. In the **2D Unfolding** toolbox (Fig. 8), using the **Flexural Slip** method, choose **Unfold to Target** and collect the forward modelled backthrust as the target to unfold to. Select the main thrust as the **Pin**.
4. Collect the pasted copy of the backthrust in its position prior to fault parallel flow deformation as the **Template Beds**. Collect the contents of the backthrust hanging wall fault block set into **Passive Objects**.
5. Click **Apply**.
6. Create a duplicate section and name it appropriately.

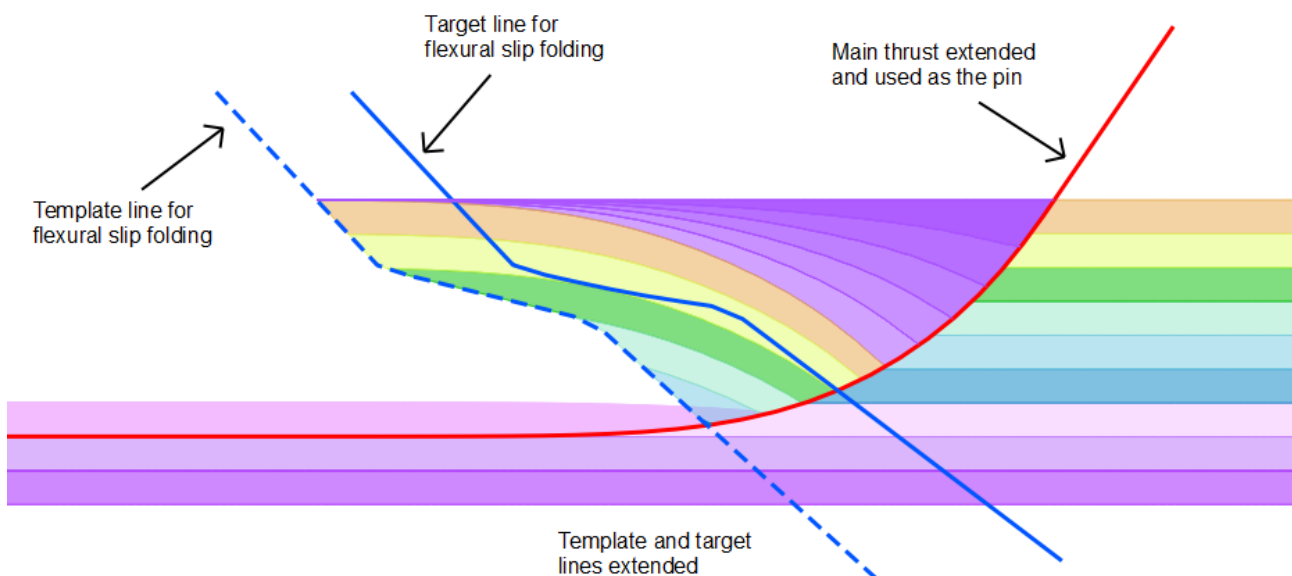


Figure 7: Backthrust hanging wall block prior to deformation showing template and target lines for flexural slip folding. Main thrust is extended to act as pin and template and target lines are also extended

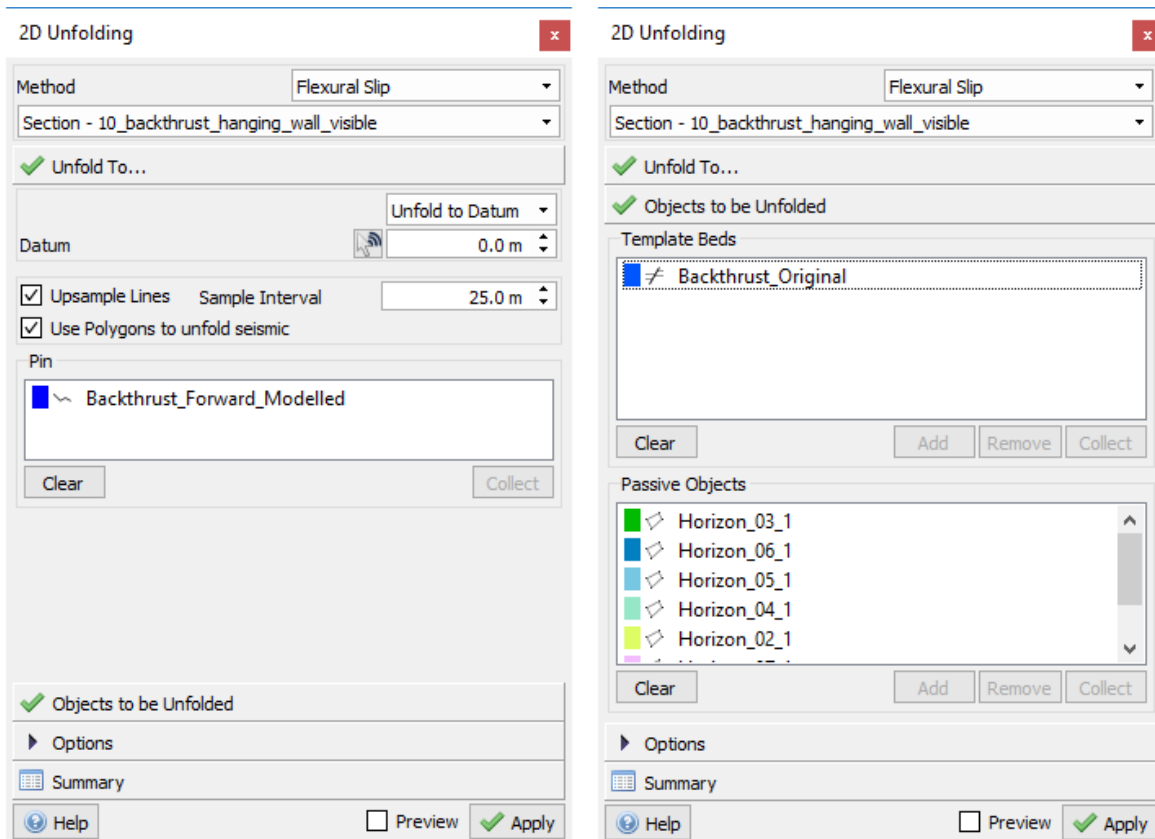


Figure 8: 2D Unfolding toolbox with Target and Pin selected (left), and Template Beds and Passive Objects selected (right)

D. Workflow variations and considerations

The shape of the backthrust hanging wall block after folding provides a key test for the interpreted shape and location of the main thrust (which controls the form of the pin), the shape of the backthrust, and the selected dip of the downward extension of the target line and template bed. Figure 9 shows an example where the main thrust has been extended at a steep angle with significant material on the right that has been uplifted above the land surface. The pop-up by the backthrust on the left of Figure 9 forms a potential anticlinal trap closed in 2D.

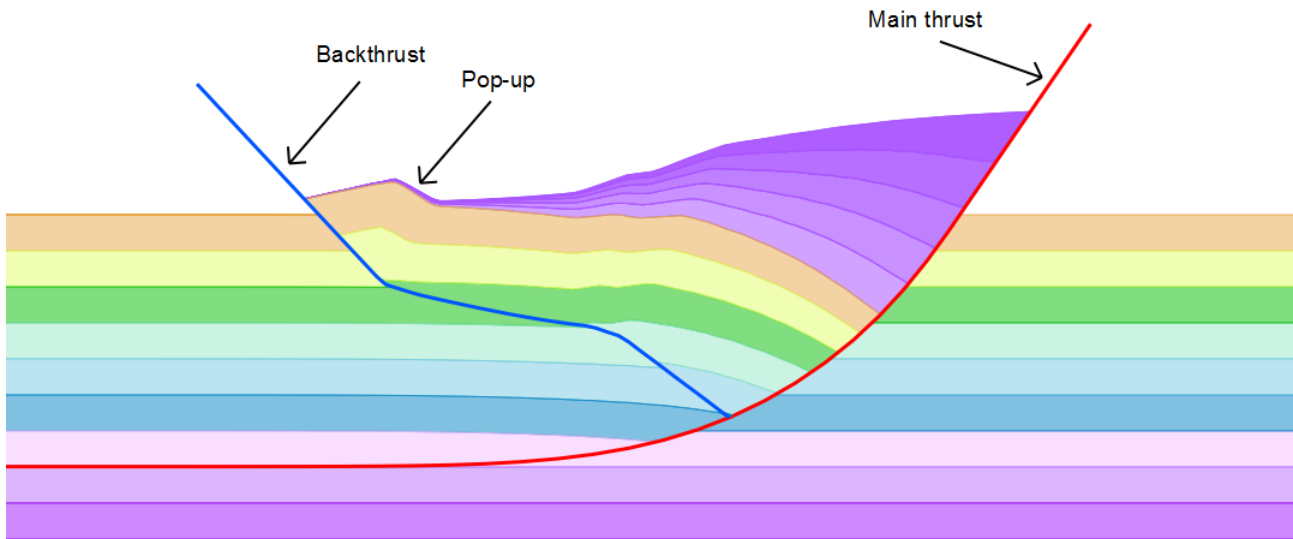


Figure 9: Backthrust modelled using steep main thrust

Processes of uplift and erosion are contemporaneous; however, for the purposes of modelling it is best to model all the deformation first and then account for erosion. The advantage of this is that it allows the user to quantify missing material. The amount of erosion will be defined by the present-day surface, or whatever surface bounds the top of the modelled succession.

Changing the shape and position of the pin will change the deformation in the backthrust hanging wall block. To test alternative pin configurations:

1. Create and name a duplicate of your working section.
2. Using the **Extend** tool on the **Model Building** tab, select the main thrust.
3. Using **Ctrl** on the keyboard to make sure that the fault is being extended at the top of the section (this key will swap the end of the line that is being extended), extend the main thrust horizontally or at an angle.

Or

4. Using the **Pin** tool on the **Model Building** tab, digitize a vertical pin through the point at which the backthrust and main thrust intersect, making sure that the ends of the pin extend to a good distance above and below all section objects.
5. Using the modified or newly created pin, follow the steps in section D.

Figure 10 shows an example of where the main thrust has been extended horizontally. This models deformation at shallow levels where the leading edge of the main thrust rolls over and hanging wall material is 'bulldozed' (e.g. Davis *et al.* 1983). In Figure 10, this has been modelled where the steep inverted fault intersects the land surface. As before, it is recommended that all deformation is modelled first and then erosion.

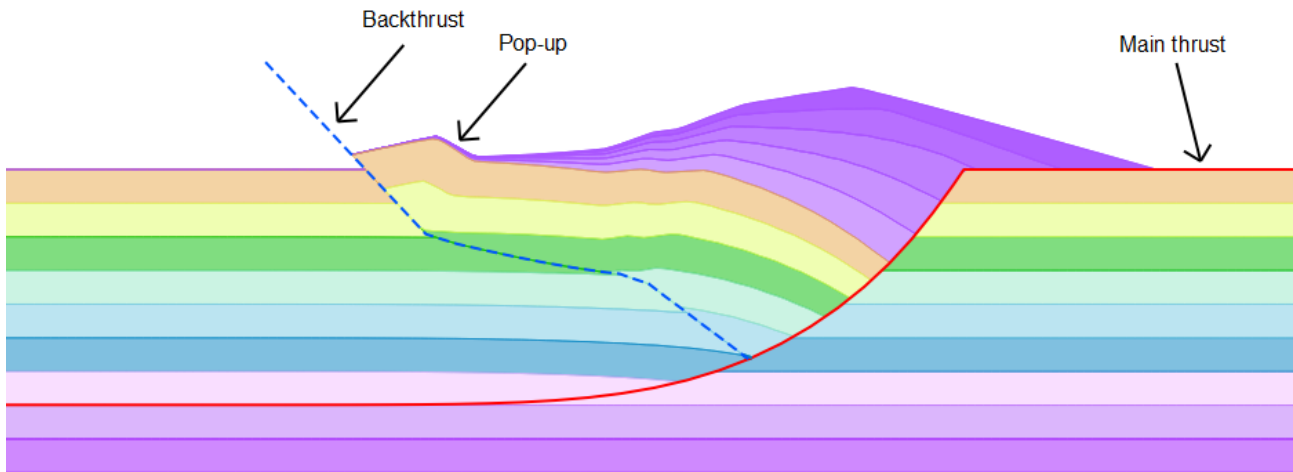


Figure 10: Backthrust modelled with main thrust parallel to land surface at shallow levels.

Conclusions

The strength of using this approach to test backthrust interpretation is that the faults and stratigraphy are based on the underlying data or the interpretation, producing a workflow that is quick to implement and resulting in a very manageable number of choices. The main decisions to be made relate to fine-tuning of fault shape and pin location. By providing feedback on the relationship between fault slip and backthrust hanging wall deformation, this workflow provides an important test for the scale and location of potential traps, or the expected magnitude of surface deformation during backthrust-related seismicity.

If you require any more information about forward modelling backthrusts, then please contact us by email: enquiries@mve.com or call: +44 (0)141 332 2681.

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