

## Modelling realistic fold shapes using dip-isogon relationships

The accurate representation of fold styles is one of the most challenging aspects of geological model building. The Isogon (Ramsay Fold Classes) construction method (Construct Horizon from Template tool) in Move™ offers an ideal solution to model realistic fold shapes based on established geological concepts (Figure 1). The Isogon method uses the geometric relationship between layer thickness and dip angles to represent fold shapes according to the fold classification scheme of Ramsay (1967). Like other fold construction methods, the Isogon construction method reproduces parallel and similar folds. However, it also allows the construction of complex or hybrid folds, and it can represent sequences in which geomechanical properties vary between beds. This results in fold models that are both objective and reproducible, models that capture important differences in the capacity of a reservoir horizon or changes in thickness of an orebody across the fold.

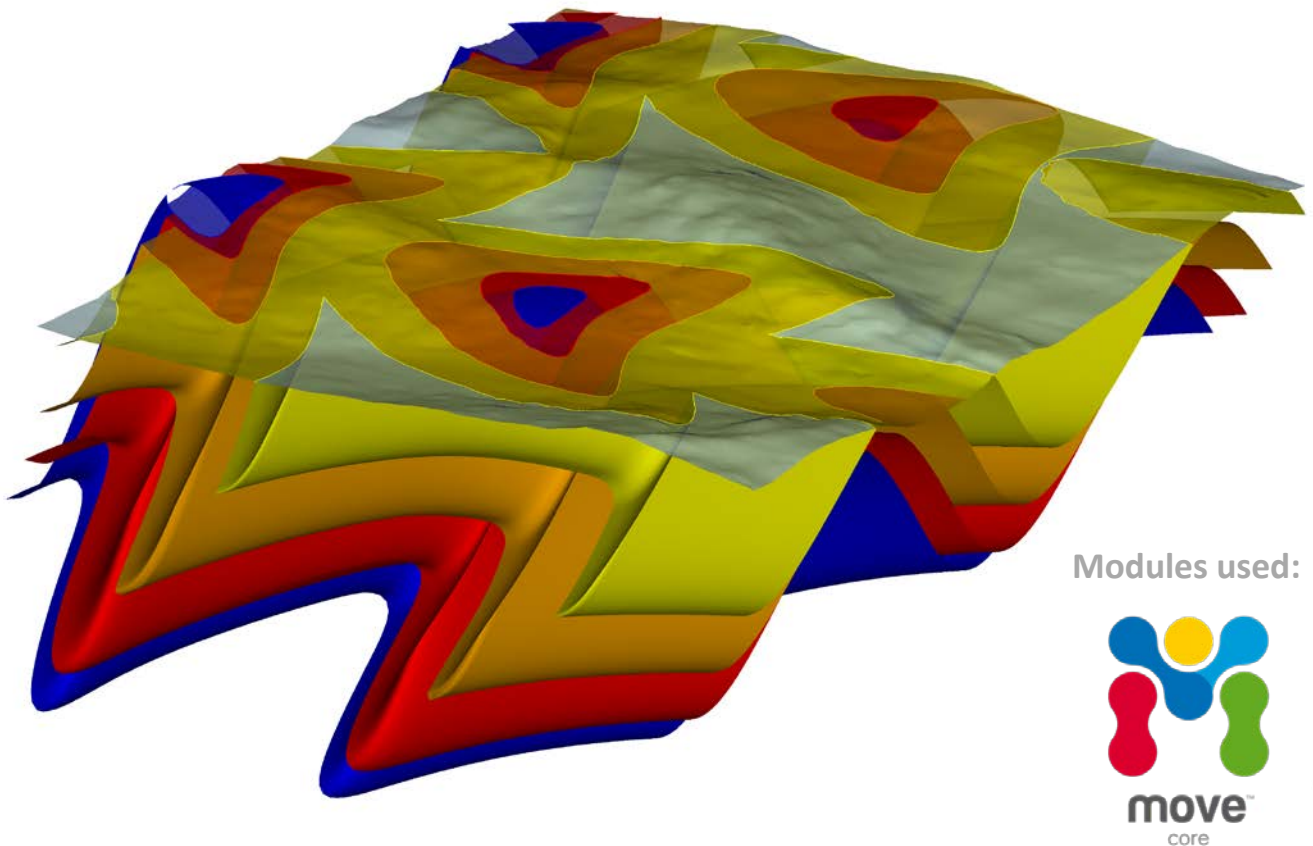


Figure 1: 3D model of a layered sequence that has experienced three separate folding events. At the surface, the folds show the characteristic outcrop pattern of Type 2 fold superposition.

## Fold classification using dip isogons

Historically, folds were classified using two geometric models: *parallel folds*, in which bed thickness remains constant throughout the fold, and *similar folds*, in which layer thickness is constant parallel to the axial plane. However, not all natural folds can be represented by these two models, leading Ramsay (1967) to propose a now widely adopted fold classification scheme that is based on the geometric relationship between layer thickness and dip angles (Figure 2a). In order to account for arbitrary fold orientations, dip angles ( $\alpha$ ) are measured relative to the axial surface normal. Layer thickness is represented by the ratio between the orthogonal thickness of layer-parallel tangents ( $t_\alpha$ ) relative to the thickness in the fold hinge ( $t_0$ ; Figure 2a).

This classification scheme groups folds into three main classes depending on the pattern produced by their isogon lines, which connect points of equal dip on two layers (Ramsay & Huber, 1987; Figure 2b):

- **Class 1** folds are represented by convergent isogons, i.e. isogons that converge from the outer towards the inner arch of the folded horizon. Class 1 folds are further subdivided into three sub-classes in which isogons are either strongly convergent (Class 1A), perpendicular to layering (Class 1B), or weakly convergent (Class 1C).
- **Class 2** folds have isogons that are consistently parallel to the axial plane.
- **Class 3** folds are represented by divergent isogons, i.e. isogons that diverge from the outer towards the inner arch of the folded horizon.

In this definition, parallel and similar folds are simply two special cases (Class 1B and Class 2) in a broad spectrum of possible fold styles.

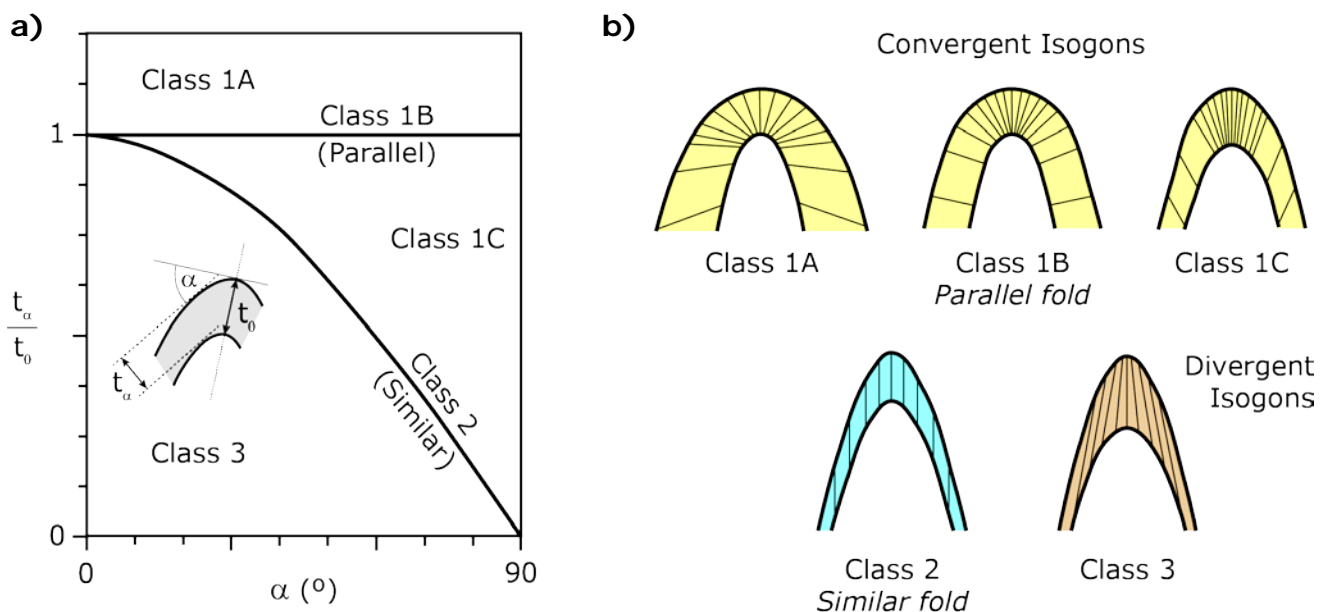


Figure 2: a) Fold classification scheme based variations in layer thickness around a fold. b) Three main fold classes can be defined according to their isogon patterns: convergent (Class 1, yellow), similar (Class 2, blue) and divergent (Class 3, orange). Class 1 folds are subdivided into strongly convergent (Class 1A), parallel (Class 1B) and weakly convergent (Class 1C). Modified from Ramsay and Huber (1987).

## Constructing folds using dip isogons

Once the fold class representing a specific fold style has been determined and the corresponding isogon patterns are known, the relationship between dip and layer thickness can be used to construct geometrically constrained folds. If there is evidence that fold styles at the surface are representative of those at depth, observed fold classes can be used to constrain fold shapes in the subsurface. This is particularly useful when the availability of subsurface data is poor.

To model folds using dip isogons, a dip isogon relationship has to be characterised for each layer of the fold. This is done using a graph that plots the dip of a bed ( $\delta$ ), corrected for fold axial surface inclination, against the angle ( $\phi$ ) between the isogon line and the bedding normal at each point along a fold (Figure 3). Homogenous folds of a single fold class are represented by straight lines that intersect at the graph's origin. Hybrid folds, in which the fold class varies between different portions of the fold (e.g. chevron folds), result in more complex and non-linear correlations.

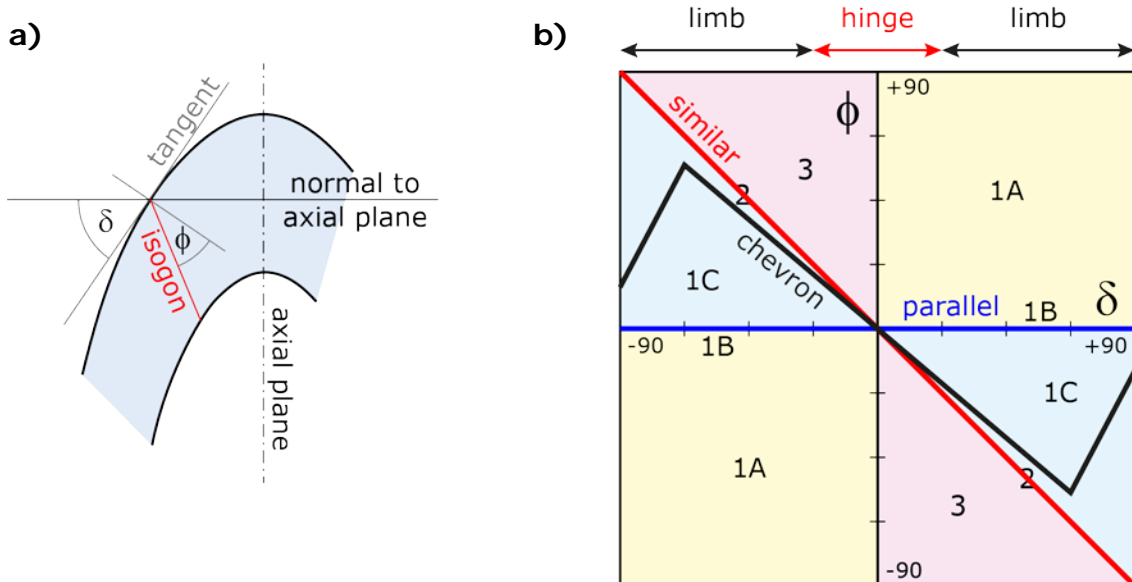


Figure 3: a) Method of constructing isogon lines and determining dip isogon relationships. b) Dip isogon graph showing examples of isogon relationships for parallel (horizontal blue line), similar (diagonal red line) and chevron (zig-zag black line) folds. In this plot, dips are corrected for the inclination of the axial surface, so the fold hinge and limbs correspond to low and high values of  $\delta$ , respectively.

The correlation between dip and isogon orientations in Figure 3b can then be used to predict the orientation of strata at depth based solely on surface dip measurements (corrected for fold inclination). In a paper-based workflow (Figure 4), this involves the manual construction of isogon lines for each dip measurement at the surface (Figure 4a) according to the exposed horizons' dip isogon relationship (Figure 4b). A series of parallel dip markers are then drawn at depth along the isogon line (Figure 4b). A lithological contact, constrained at the surface or in a borehole, is then extrapolated laterally to suitable dip markers on the isogon lines (Figure 4c). This process is repeated for all layers until the entire fold is constructed (Figure 4d).

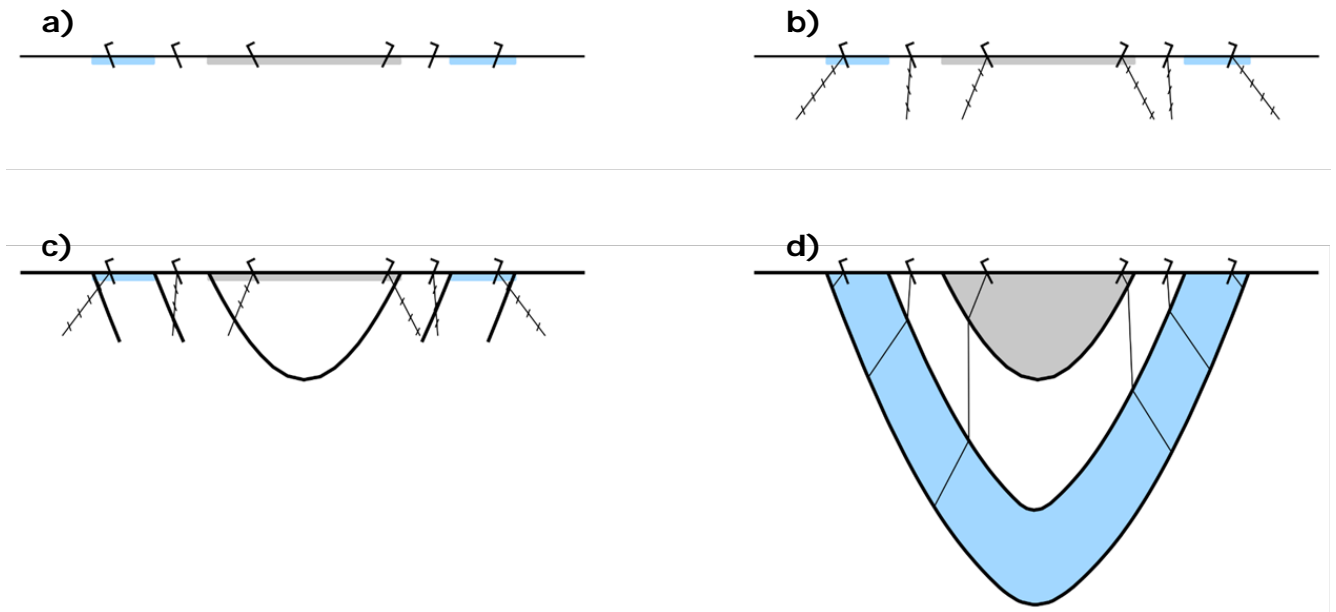


Figure 4: Manual construction of folds using dip isogon relationships. a) Input data consists of lithological contacts at the surface and dip measurements; b) Isogon lines and a series of parallel dip markers are constructed based on the dip isogon relationships of each layer; c) Horizons segments of exposed beds are constructed; d) Entire fold is constructed. Note the varying dip isogon relationship of each layer.

## Isogon construction method in Move

The Isogon construction method in Move automates the laborious process of manually constructing isogons and joining adjacent dip measurements. It is part of the Construct Horizons from Template tool and allows dip isogon relationships to be defined separately for each layer; these can be input either numerically or graphically by manipulating the graph shown in Figure 3b. Folds can be constructed from either dip data or a template line, which is approximated as a series of dips with a user-defined spacing, or sampling interval. For isogon constructions from 3D surfaces, Move uses a 2.5D approach, in which a series of closely spaced virtual cross-sections are used to define the fold shape in 3D.

## 2D fold construction

This section shows how folds can be constructed in cross-section view using the Isogon method in Move. The available data consists of a topographic surface intersection, lithological contacts mapped at the surface, dip measurements as well as the location of the fold hinge as determined by vergence indicators (Figure 5a). Based on outcrop-scale folds, the folding style has been determined to be chevron folding with the dip isogon relationship shown by the black line in Figure 3b.

The workflow to model the fold involves:

1. Open the **Horizons from Template** tool on the **Model Building** panel. Select **Dip Data** as the **Template Type** and **Isogon (Ramsay Fold Classes)** as the **Construction Method**.
2. In the **Template Dip Data** sheet, collect the available dip data into the toolbox and define a starting dip (mapped lithological contact for the template horizon).
3. Click on the **Horizon Construction (Isogon Relationship)** sheet and set up the stratigraphy, the chosen template horizon and all the horizons that are to be modelled.
4. Click on the **Add Interpolated Dip Data** check box; this will interpolate virtual dips between existing data points. With the isogon relationship set to 0 (Class 1B), adjust the **Sample Interval** until layers retain a constant bed thickness throughout as expected for Class 1B folds. This can easily be checked by clicking on **Show Thickness Ellipses** on the **Options** sheet (Figure 5b).

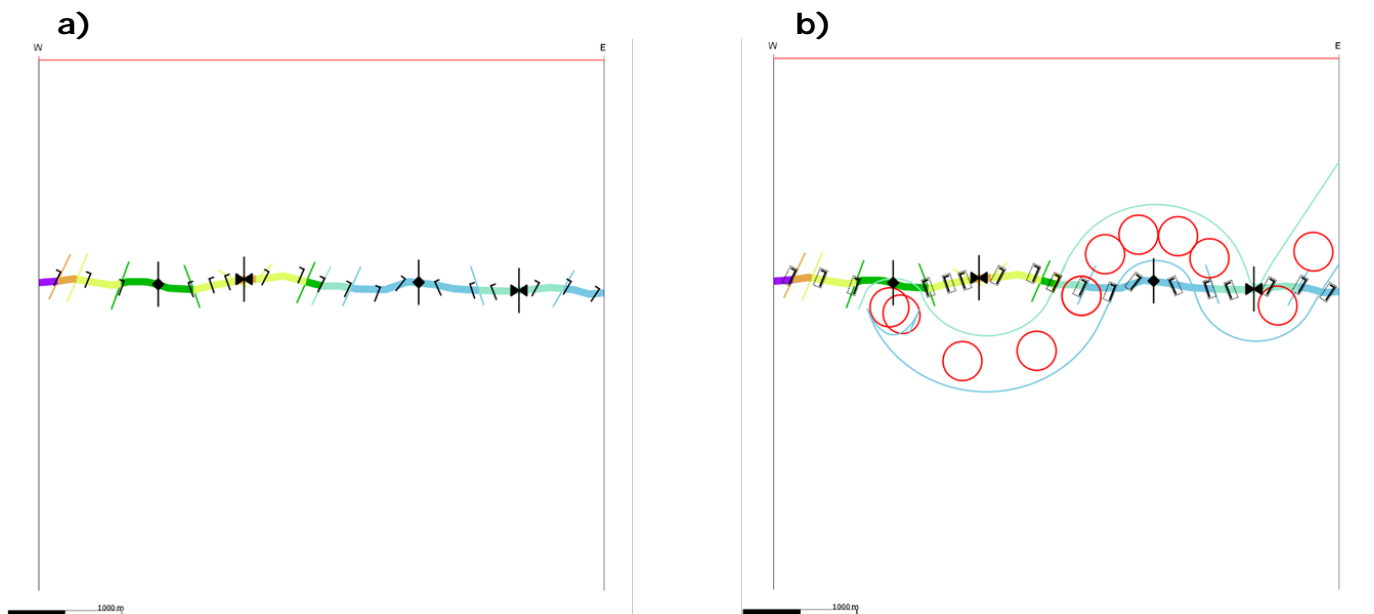


Figure 5: a) Input data for fold construction; b) The correct sampling interval is determined by ensuring that thickness ellipses remain circular for a parallel fold.

At this stage, the dip isogon relationship observed from outcrop data are defined. This is done for each layer individually to allow for differences in the competence of different layers.

5. On the **Construction** tab, select the **Isogon** value of the layer for which the dip isogon relationship will be defined and click on the **Relationships** tab. Define the dip isogon relationship for the selected layer; both linear (default) and non-linear relationships can be defined. In this example, the relationship for chevron folds (Figure 3b) is used.
6. Proceed with other layers that are to be modelled. If dip isogon relationships are identical between different layers, they can be copied across different **Isogon** rows in the **Construction** tab.

Even with isogon relationships defined, modelled horizon intersections may not exactly correlate with mapped lithological contacts (Figure 6a). This may be due to variations in horizon thickness, isogon relationships, or it may reflect measurement uncertainties of observed dip data. A better match can be obtained by iterative adjustments to stratigraphic thicknesses as well as the virtual dip data, shown by black dotted rectangles, which are used in the isogon construction method (Figure 6a).

7. Layer thickness is adjusted by modifying the corresponding value in the **Thickness** column on the **Construction** tab.
8. Virtual dip data are adjusted until lithological contacts match. Relevant keyboard shortcuts are:
  - **Shift+Click**: Select a virtual dip measurement;
  - **Shift+Scroll**: Rotate the selected virtual dip as required;
  - **Ctrl+Click**: Add a new virtual dip;
  - **Ctrl+Click** (middle mouse button/scroll wheel): Delete existing virtual dip.

Note that all of these operations are only performed virtually, so that the underlying field data will not be affected.

9. Click **Create** to add the modelled horizons as objects to the **Model Browser**. Clicking on the **Snap to Faults/Posts** or **Show Polygons** check boxes prior to creating model objects may help in visualizing the results (Figure 6b).

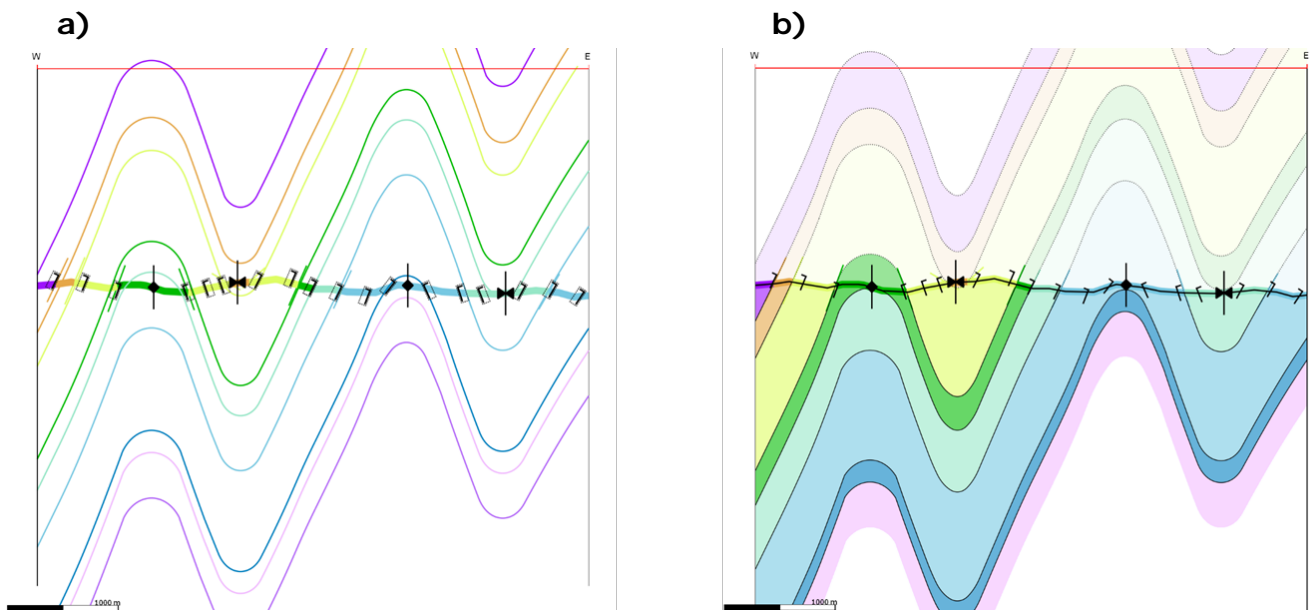


Figure 6: a) Layered fold constructed according to dip isogon relationships of a chevron fold. Minor adjustments in stratigraphic thickness and/or dip measurements are required to match the observed data; b) Final fold interpretation.

### Fold construction from 3D surfaces

Modelling the 3D geometry of folds based on individually constructed cross-sections is a time consuming process that may result in fold style inconsistencies along the strike of the fold. In some cases, such changes in fold class are expected from geological observations, so that individual cross-section construction is the only way to accurately model the structure. In other instances, fold classes – and by extension dip isogon relationships – are constant along the fold axis, and a more efficient and accurate way to model a multilayer fold is to use a 3D surface as the template when using the Isogon method of construction.

In this case, Move constructs a series of virtual cross-sections, which are shown as a series of parallel intersection lines that represent the template surface (Figure 7). The Isogon method is applied to all template lines simultaneously, according to the specified dip isogon relationship. The fold is modelled in exactly the same way as it would be when using lines as a template, providing full control over all parameters except the fold inclination correction. As shown in Figure 7, clicking on the **Add Horizon Surfaces** check box creates the associated horizon surfaces directly out of the Construct Horizons from Template tool, using either **Linear** or **Delaunay Triangulation** as the interpolation method. This makes the construction process of multilayer folds both fast and accurate.

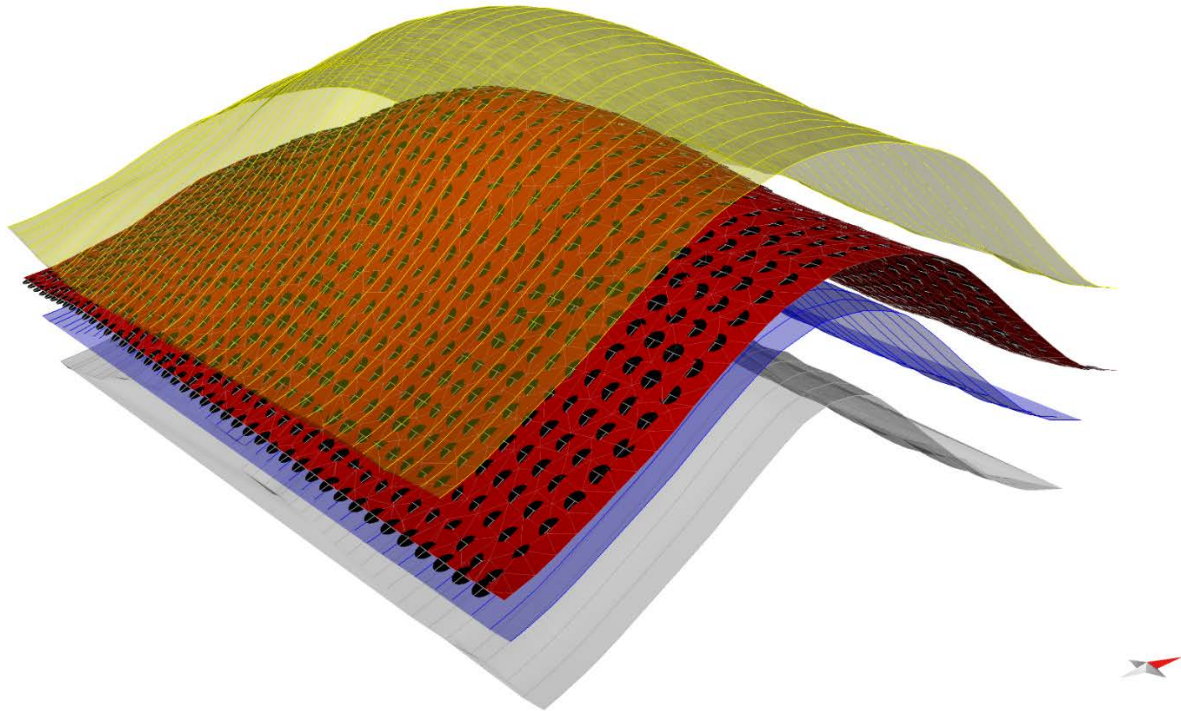


Figure 7: 2.5D construction of a structural trap defined by a multilayer fold using the Isogon construction method in Move.

### Inclined or refolded axial surfaces

Move also provides tools to model folds with inclined axial planes, or folds that have undergone more than one deformation event.

If the axial plane is inclined, a simple rotation of the input data around an appropriate rotation axis using either the **Basic** or **Advanced Transform** tools will correct for the inclination of the axial plane. Following rotation, the workflow, as described above, can be applied in order to model folds using the Isogon method. At the end, the model is rotated back to its original configuration and conditioned to match adjacent fault blocks as required. Model rotation can be avoided altogether if the input for the Isogon method is a template line. In this case, the inclination of the axial plane can be specified in the **Fold Axis** section of the **Horizon Construction** sheet of the **Horizon from Template** tool.

Folds with refolded axial surfaces can be constructed using the Isogon method only after the model has been retro-deformed to a time when the axial surface was planar. This can be done using the sequential restoration algorithms available in the **2D Kinematic Modelling** or **3D Kinematic Modelling** modules, such as the **Unfolding** or **Move-on-Fault** tools, which are applied on axial surfaces of sequentially older events.

### References

- Ramsay, J.G. 1967. *Folding and fracturing of rocks*. McGraw-Hill, New York and London.
- Ramsay, J.G. & Huber, M.I. 1987. *The Techniques of Modern Structural Geology. Volume 2: Folds and Fractures*. Academic Press, New York.