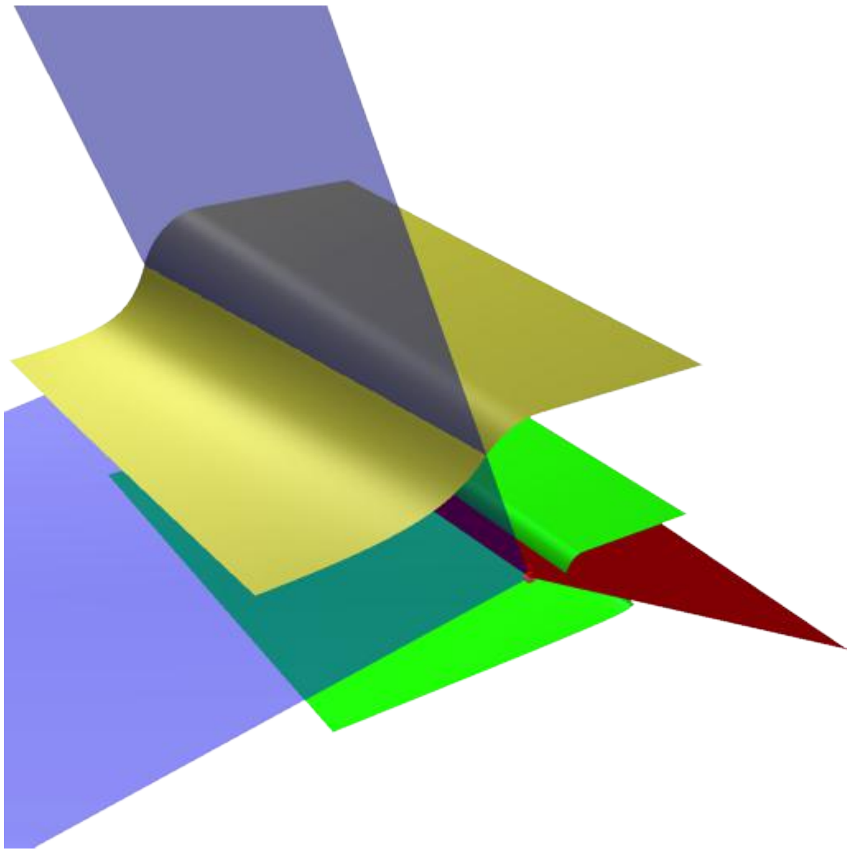

Trishear3D v. 7.1

3D trishear modelling

By Nestor Cardozo (University of Stavanger)

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Referencing this program

Please reference the program as: Trishear3D by Nestor Cardozo. Also, add the following reference in any publication or presentation:

Cardozo, N. 2008. Trishear in 3D: Algorithms, implementations and limitations. Journal of Structural Geology 30, 327-340.

Credits

I would like to thank Ernesto Cristallini from sharing his ideas and his code about trishear in 3D. Ernesto designed brilliant solutions for both pseudo 3D and true 3D trishear. I would also like to thank Richard Allmendinger for sharing his knowledge and his code about trishear. Rick implemented the most versatile computer program for trishear in 2D: FaultFold. **Trishear3D** is inspired on FaultFold.

Trishear3D is a Cocoa application written in Objective C. The program would have not been possible without the OpenGL library and the excellent OpenGL tutorials on the web, specially Nehe Productions.

Introduction

Trishear3D is a program to run 3D trishear models. Trishear is a kinematic model of fault-propagation folding in which the decrease in displacement along the fault is accommodated by heterogeneous shear in a triangular zone radiating from the tip line. Several publications describe the trishear model in 2D, including Erslev (1991), Hardy and Ford (1997), Allmendinger (1998), and Zehnder and Allmendinger (2000).

Trishear can be extended to 3D by solving either a series of 2D sections parallel to the slip vector (pseudo-3D trishear, Cristallini and Allmendinger, 2001), or a true-3D formulation (Cristallini et al. 2004). **Trishear3D** uses either one of these algorithms.

With **Trishear3D** you can set up a 3D trishear model, run it, modify it (i.e. modify model parameters, add beds, start a new fault), and examine its geometry and finite strain (either in 3D, cross section, or tables). You can also construct fault bends and use backlimb kinematic models such as layer-parallel slip or inclined shear to make fault-bend folds (including rollovers). Geometry and strain data can be exported to fracture and reservoir modeling programs.

Trishear3D can do forward and reverse modeling. You can deform and restore surfaces. However, an inverse modeling routine such as those in Allmendinger (1998) or Cardozo (2005, 2009, 2011) is not implemented in the program. **Trishear3D** is a great tool to visualize the effect of spatial and temporal variations of faulting on the geometry and finite strain of fault related folds.

Basic interface

When the program starts, it looks like Figure 1. The program's main window consists of three views: (i) A *Plot* view, (ii) a *Table* view, and (iii) a *Log* view. The *Plot* view displays the model in three-dimensions, the *Table* view lists the model's geometry and strain data, and the *Log* view is a record of the program's use. You can access any of these views using the tabs on top of the window, the Modules menu, or the keyboard combinations: ⌘1 for the plot view, ⌘2 for the table view, or ⌘3 for the log view.

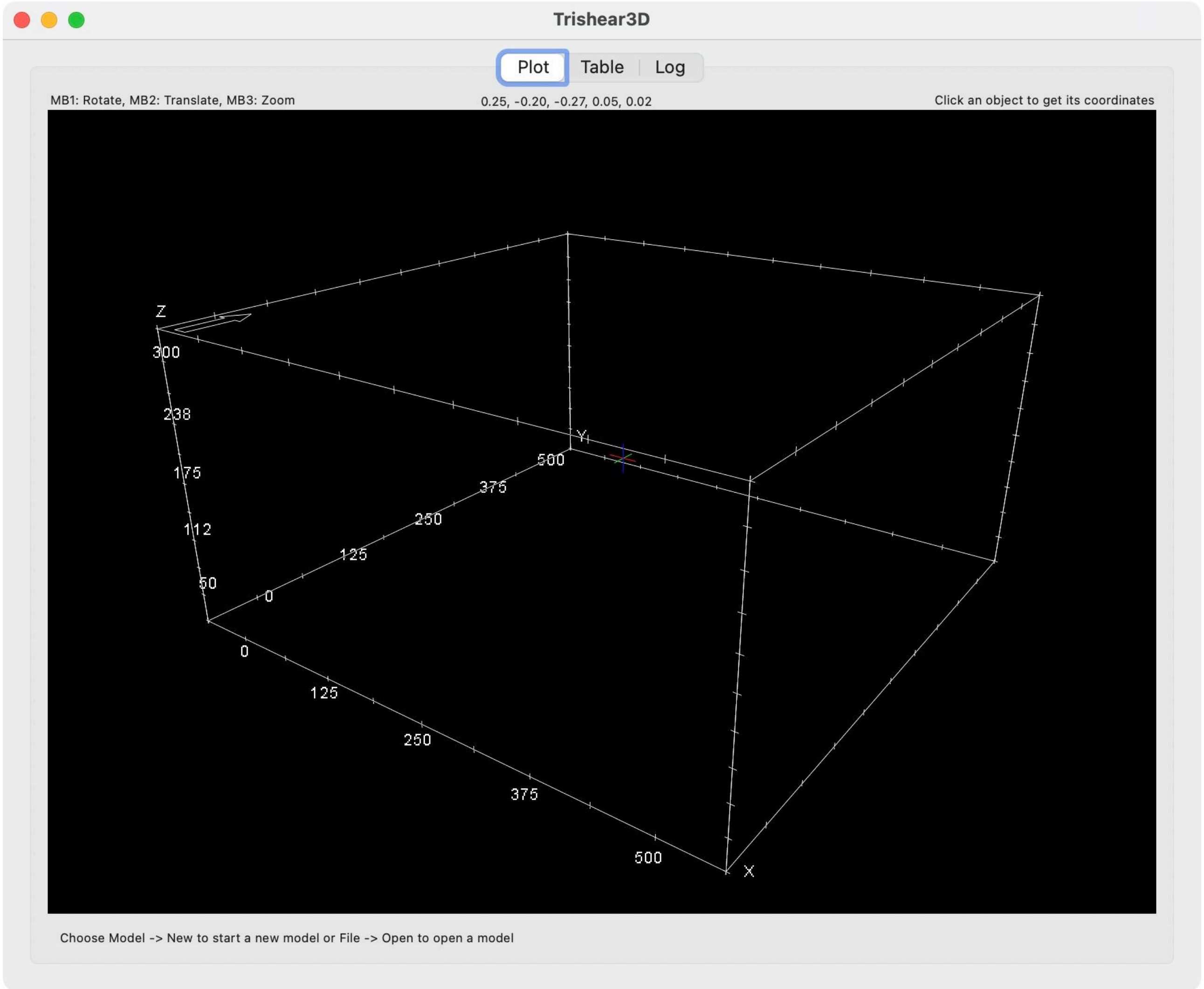


Figure 1. **Trishear3D** main window and the *Plot* view

Plot view:

The *Plot* view shows a white cube, a white arrow, and a triad (Figure 1). These objects indicate the reference coordinate system. You can toggle them using the *Plot* -> *Reference Frame* menus, or alternatively typing ⌥⌘B to toggle the cube, or ⌥⌘A to toggle the arrow and the triad. The reference coordinate system of **Trishear3D** is a right handed Cartesian coordinate system with *X* increasing to the east, *Y* increasing to the north, and *Z* increasing upward. The triad at the center of the cube indicates the orientation of the axes: the red line is parallel to the *X* axis, the green line to the *Y* axis, and the blue line to the *Z* axis. The white arrow points towards the positive *Y* axis (north). The ticks and labels at the sides of the cube indicate the model dimensions.

The *X*, *Y*, and *Z* coordinates of any non-transparent, solid object in the *Plot* view can be obtained by clicking the object. The coordinates are shown in the text field at the upper right corner of the view (Figure 1). The zoom and orientation of the view can be modified using the following keyboard combinations:

⌘+	Zoom in
⌘-	Zoom out
⌘→	Rotate model right
⌘←	Rotate model left
⌘↑	Rotate model up
⌘↓	Rotate model down
⌥⌘→	Translate model right
⌥⌘←	Translate model left
⌥⌘↑	Translate model up
⌥⌘↓	Translate model down

You can also modify the *Plot* view using a three buttons mouse. To rotate the model, press the left mouse button and drag the mouse. To zoom the model, press the right mouse button and drag the mouse. To translate the model, press the middle mouse button and drag the mouse. The settings of the Plot view are shown in the middle text field above the plot. This field contains five digits corresponding to the zoom, azimuth, inclination, vertical, and horizontal translation, respectively (Figure 1). You can reset the default view values using the *Plot* -> *View* -> *Reset* menu or the keyboard combination ⌥⌘R. The background can be changed from black to white (or vice versa) using the *Plot* -> *View* -> *Background Black* menu. By default the background is black. You can save the plot as a jpeg using the *File* -> *Save* -> *Plot as jpeg* menu or the keyboard combination ⇧⌘S .

Table and log views

The table view has two buttons at the base. These buttons are used to choose the bed/surface (left button), and the type of data: nodes or tetrahedrons (right button). You can also trigger these buttons using the *Table* menus or their corresponding keyboard combinations.

Every operation performed by the program is written to the log view. You can copy or drag results from the table or the log view to any application. You can save the table and the log as text files using the *File* -> *Save* -> *Table as text* (⌥⌘S), and *File* -> *Save* -> *Log as text* (^⌘S) menus. To learn more about the table and log views read the Tables and log section.

Preferences

Key parameters of the program can be set through the Preferences panel: *Trishear3D* -> *Preferences*, or keyboard combination ⌘, (Figure 2).

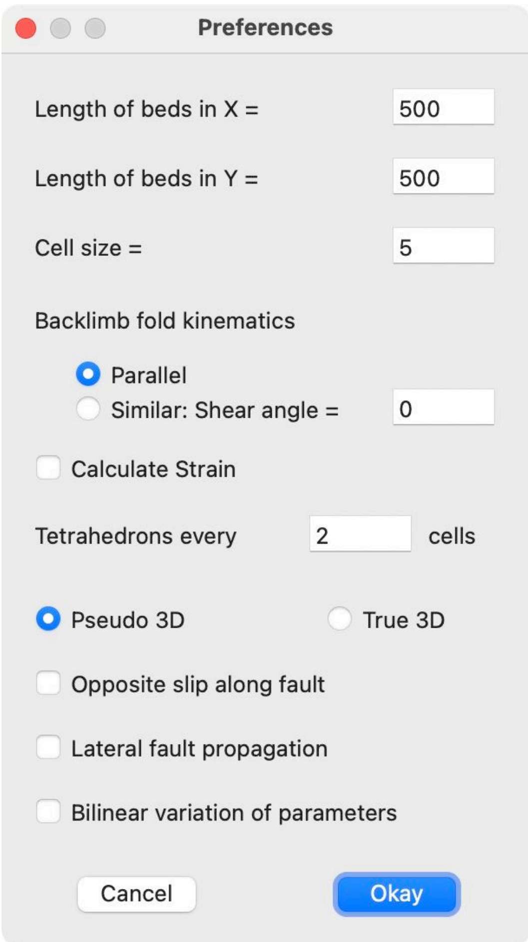


Figure 2. The *Preferences* panel

The parameters that can be set up in the Preferences panel are:

1. The extent of the beds in *X* and *Y*.
2. The size of the cells. **Trishear3D** undeformed beds are surfaces made of equal size quadrilaterals.
3. The type of backlimb kinematics, parallel or similar, and if the similar option is selected, the shear angle (see the Backlimb kinematics section). Notice that *backlimb kinematics* only works if fault slip is perpendicular to strike and *Lateral fault propagation* (point 7 below) is off.
4. The possibility to compute strain and the number of cells between tetrahedrons to compute strain. By default this option is off.
5. The option to use the pseudo-3D or the true-3D trishear algorithms. Please check Cardozo (2008) and the algorithms section to understand how these algorithms work. Use with caution the true-3D algorithm. It has some inconsistencies that make models questionable when the slip gradient along the fault is high and the tip line is oblique to the slip vector and/or to the fault strike (Cardozo, 2008). All models in this manual were made using the pseudo-3D algorithm.
6. The possibility to allow opposite slip along the fault. By default this option is off. This prevents interpolation ahead of fault tips. Toggle on this option if you want to model faults that change from reverse to normal along strike.
7. The possibility to model lateral (along strike) fault propagation. By default this option is off. This option can only be selected if the *Opposite slip along fault* option is off. To learn more about lateral fault propagation check Cardozo (2008) and the *Lateral propagation section*.
8. The possibility to use a symmetric, bilinear variation of parameters along the fault tip line from a point halfway from the fault to the fault tips. By default this option is off and the program uses a linear variation of parameters between the fault tips. This option only works in pseudo-3D models. To learn more about this, check the bilaterally growing fault example of the Lateral propagation section.

If you change the preferences in the middle of a run, the model is deleted and the New Model panel (see Making a model section) shows up.

Making a model

To create a new model, open the *New Model* panel (*Model* -> *New* or keyboard combination ⌘N, Figure 3).

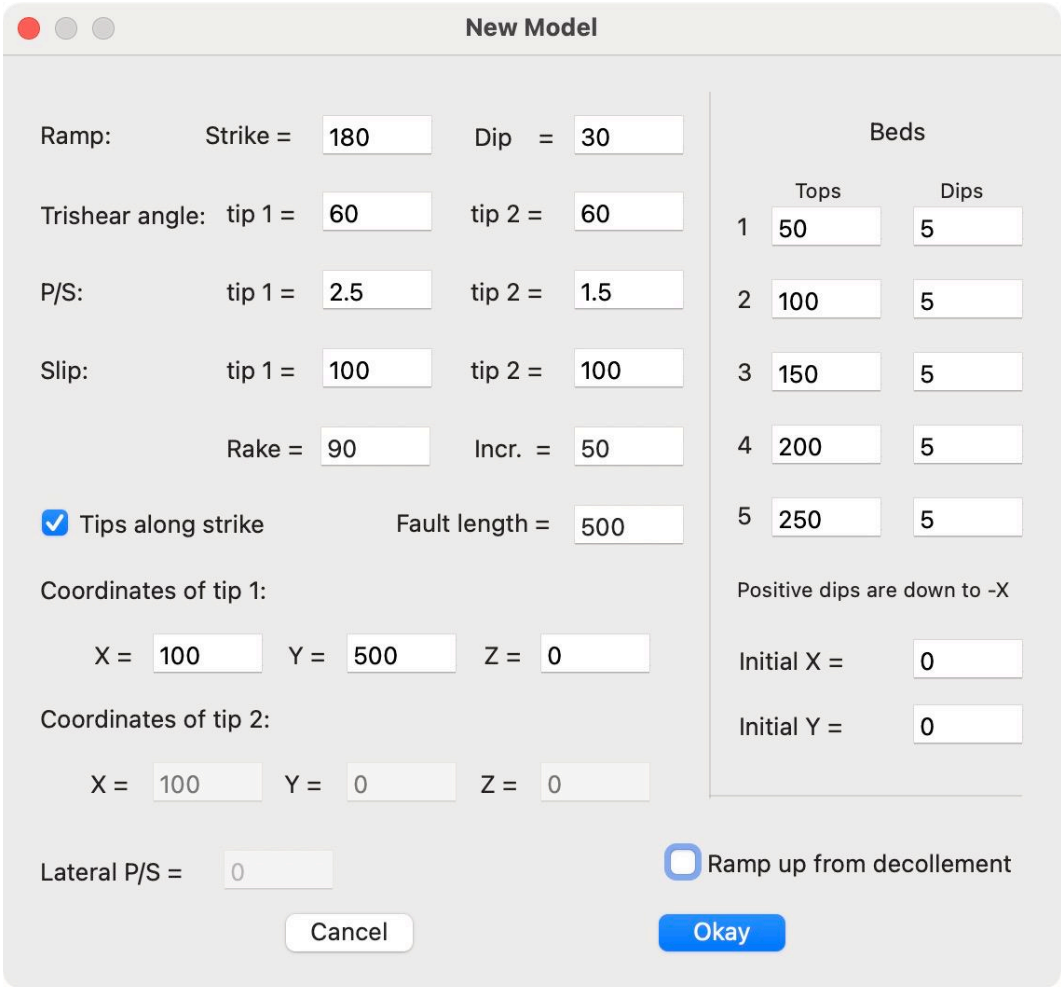


Figure 3. The *New Model* panel

Input parameters

A model is defined by the following parameters (Figure 3):

1. The strike and dip of the fault. **Trishear3D** uses a right-hand convention. In this convention, the fault dips to the right (+ 90°) of the input strike direction. The strike is an azimuth angle measured from the North (white arrow in Figure 1).
2. The trishear angle or apical angle of the triangular zone at the fault tips, or at the tips and at a point halfway the tips if the bilinear variation of parameters option is on.
3. The across-strike fault propagation to fault slip ratio (P/S) at the fault tips, or at the tips and at a point halfway the tips if the bilinear variation of parameters option is on.

4. The fault slip at the fault tips, or at the tips and at a point halfway the tips if the bilinear variation of parameters option is on. Use positive slip for reverse faults and negative slip for normal faults.
5. The rake or orientation of the fault slip vector with respect to the fault strike. The rake is measured clockwise from the strike direction and its value should be between 0 and 180°. A rake of 90° corresponds to a slip vector perpendicular to the fault strike. Figure 4 shows a map view of two thrust faults (red rectangles) with strike and dip 0/30 (left) and 180/30 (right). In both cases slip vectors with rake 30 and 150° are shown. If the rake is 0 or 180°, the fault is strike-slip. **Strike slip faults cannot be modeled with the pseudo-3D algorithm.** If you enter a rake of 0 or 180 in pseudo-3D mode, you will get a warning message and the rake will be deleted.

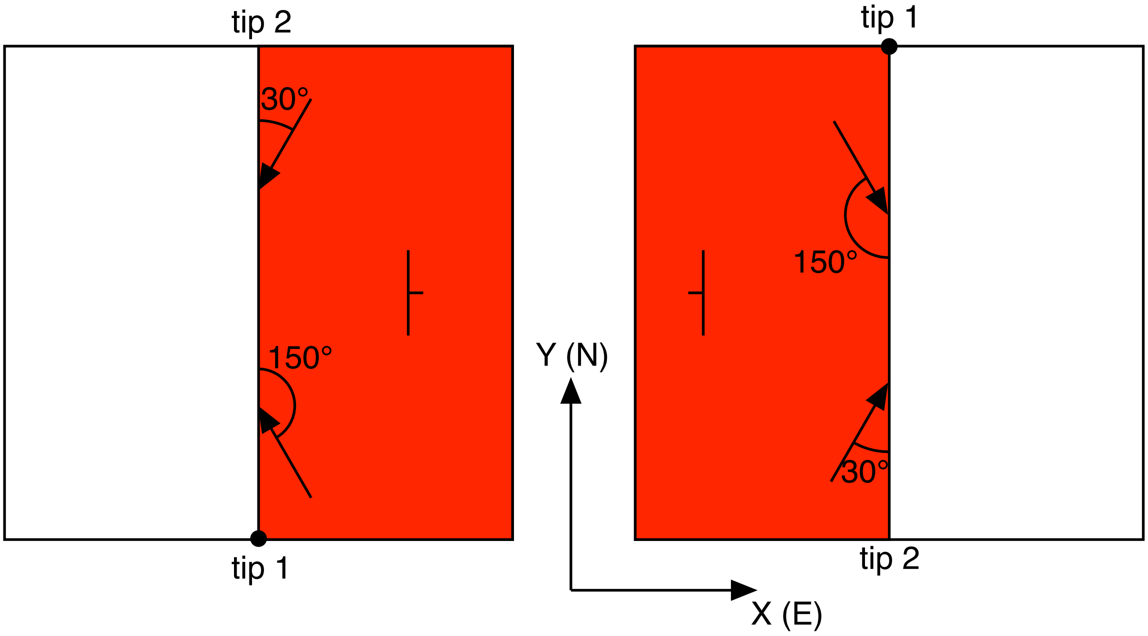


Figure 4. Map view of two thrust faults (red rectangles) with strike and dip 0/30 (left) and 180/30 (right). In both cases, slip vectors with rakes 30 and 150 are shown.

6. The number of slip increments (Incr). **Trishear3D** computes the deformation incrementally. You should use a number of slip increments that ensures a smooth geometry.
7. The *XYZ* coordinates of the fault tips. There are two options to define these coordinates: a. The tip line is horizontal and the tips are along the fault strike, and b. The tip line may not be horizontal and the tips are not necessarily along the fault strike. To select the first option, toggle on the *Tips along strike* button (Figure 3). You will

need to enter the length of the tip line and the *XYZ* coordinates of the fault tip 1. The tip 2 is then computed from tip 1 along the strike direction. For clarity, the tip 1 is shown as a red dot on the fault plane in the plot view. Figure 4 shows the location of the tips 1 and 2 for thrusts with strike and dip 0/30 (left side) and 180/30 (right side). To select the second option, toggle off the *Tips along strike* button. In this case you need to input the *XYZ* coordinates of the tips 1 and 2. The length of the tip line is computed by the program. If the strike of the fault is not consistent with the coordinates of the tips, the program shows an alert message with the correct strike value and sets this value in the *Strike* field. If the tip line is horizontal, it is more convenient to use the *Tips along strike* option. This is because the fault strike, length of the tip line, and coordinates of the tip 1 define the coordinates of the tip 2.

8. The lateral or along-strike fault propagation to fault slip ratio (Lateral P/S). This field can only be edited if the *Lateral fault propagation* option in the *Preferences* is on and the slip is zero in one of the tips (or at both tips if a bilinear variation of parameters). Lateral fault propagation operates on the tip (or tips if a bilinear variation of parameters) that has zero slip. If the lateral P/S is greater than zero, the location along strike of the tip with zero slip will change as the structure grows, so that the length of the tip line will increase with deformation. To learn more about along strike fault propagation check the Lateral propagation section.
9. The option to start the fault from a decollement. If you choose the parallel shear option in the Preferences panel (see basic interface section), the ramp from the decollement should not have a dip higher than 30 degrees. If that is the case, you will get a warning message and the dip of the ramp will be set to 30 degrees (see Backlimb kinematics section). Notice that this option is only available if the fault slip is perpendicular to strike (rake = 90) and the *Lateral fault propagation* option in the *Preferences* panel is off.
10. The tops and dips of the beds. Before the deformation the beds strike parallel to the *Y* axis. Positive dips are down to the negative *X* axis, and vice versa. In Figure 3 the beds dip 5 degrees down to the negative *X* axis.
11. Finally the *X* and *Y* coordinates of the origin of the layers.

Variation of parameters along the fault

Trishear3D assumes a linear variation of the P/S, trishear angle, and fault slip between the fault tips, or between the fault tips and the point halfway the tips if the bilinear variation of parameters is on. The P/S, trishear angle, and fault slip at any node are computed based on this interpolation, even if the node is outside the extent of the fault. For example, if the fault slip is 100 units at the tips (i.e. constant slip) and the fault does not cover the entire beds, the slip at the nodes not covered by the fault is 100 units, not zero. This ensures continuity.

If the *Opposite slip along fault* option is off (see interface section), the fault can't have opposite slip along strike. If you enter opposite slip values at the tips (or at the tips and at the point halfway the tips), the model will not be created and an error message will be displayed. Toggling off the *Opposite slip along fault* option also ensures that the program does not interpolate beyond a fault tip. Along strike nodes beyond the tip will have zero displacement. This is crucial for the lateral fault propagation algorithm.

You won't be able to change the dip of the fault (ramp angle) along its strike. **Trishear3D** can only model fault propagation folding ahead planar faults. Backlimb folding due to non-planar, multi-bend faults can be modeled using simple kinematics such as layer parallel slip or inclined shear (see Backlimb kinematics section).

Refined models with several tips between end tips

In pseudo-3D non laterally propagating models, you can introduce as many tips as you want between the end tips (tips 1 and 2 in Figure 3) using the *Refine Model* panel. At each of these tips, you can define the P/S, trishear angle, and fault slip. These parameters will vary linearly between the tips. This way, you can approximate any variation of P/S, trishear angle or fault slip along the fault using piecewise linear functions (see the example in the Refining a Model section).

Notice that in the *New Model* panel you can only set the parameters at the end fault tips (tips 1 and 2 in Figure 3). If there are several tips between the end tips from a previous run and you create a new model, the program will ask if you want to reuse these tips. In addition, if you want to modify the values of the parameters at these tips, you can use the *Refine Model* panel.

The new model

Once you fill the fields of the *New Model* panel, click the *Okay* button. A progress panel will appear. Please wait until the progress panel disappears to continue using the program. For the example of Figure 3 the initial model looks like Figure 5a.

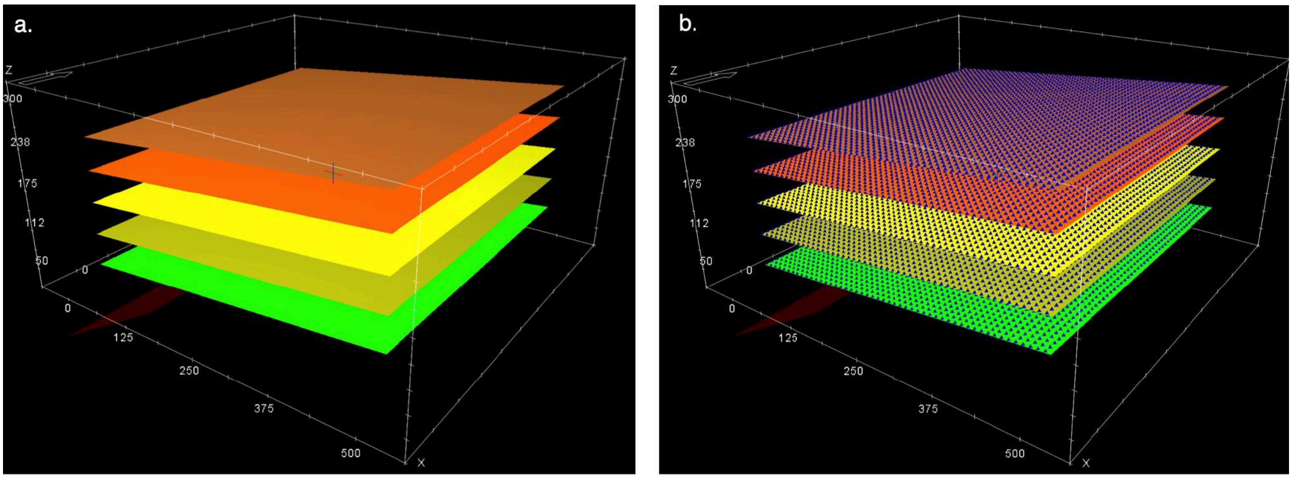


Figure 5. Initial model from Fig. 3, without (a) and with (b) tetrahedrons

Examine the model from different viewpoints. Toggle on and off the fault (*Plot* -> *Fault* or keyboard combination ⌥⌘F). Toggle on and off the trishear zone (*Plot* -> *Trishear zone* or keyboard combination ⌥⌘Z). Toggle on and off the *View* -> *Filled* option (⇧⌘O) to see the model in filled or wireframe mode. Change the transparency of the fault, trishear zone, or beds using the *Plot* -> *View* -> Transparency menus. Open the light panel (*Plot* -> *View* -> *Light* or keyboard combination ⇧⌘L) and change the light settings.

If the *Calculate Strain* option is on, tetrahedrons spaced by the number of cells specified in the *Preference* panel, will be created. If this is the case, toggle on and off the tetrahedrons using the *Plot* -> *Strain* -> *Tetrahedrons* menu (⌥⌘T). Toggle on and off the ellipsoids (they should all be spheres) using the *Plot* -> *Strain* -> *Ellipsoids* menu (⌘0), or the principal axes of strain (they should all have the same length) using the *Plot* -> *Strain* -> *Principal axes* menu (⌥⌘0). Figure 5b shows the tetrahedrons in the initial model.

Running a model

To run a model use the *Model* -> *Run* menu or type the keyboard combination ⌘R . A progress panel will appear. Please wait. When the run is finished, the program updates the plot, table, and log views. Figure 6a shows the model of Figure 5 after running.

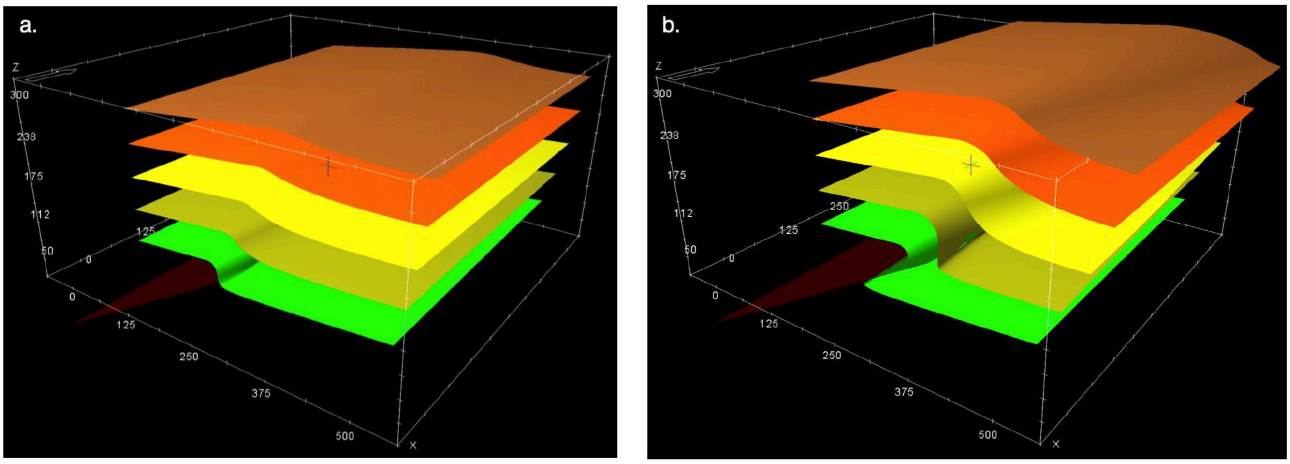


Figure 6. Model of Figure 5 after (a) One run, (b) Two runs.

The current values of the model parameters are shown below the plot. The parameters listed are the total slip, the total propagation, the strike and dip of the ramp, the trishear angle, the P/S, and the rake of the slip vector. The values of these parameters are shown at the fault tips, or at the fault tips and the point halfway these tips if using a bilinear variation of the parameters. The parameters and the coordinates of the fault tips are also shown in the Log view.

The *Run* menu plots the model at the end the run. If instead you want to see the incremental deformation of the model, use the *Model* -> *Run Incrementally* menu or keyboard combination Shift-⌘-R. To run the model again, choose *Model* -> *Run* (⌘R). Figure 6b shows the model after the second run.

You may notice that at places where the fault cuts the beds, the beds look rather jagged. Modeling bed-fault intersections is not easy. In Trishear3D only the quadrilaterals that have all nodes on one side of the fault are drawn. Quadrilaterals whose diagonals have been stretched more than three times are not drawn either. In general fault-bed intersections improve by selecting a smaller slip increment.

Trishear3D does not have Undo-Redo capabilities. However, a model with one ramp can be run backwards using the *Model* -> *Run Backwards* menu. This will retrodeform the model to its previous run step with a minor glitch: Quadrilaterals and tetrahedrons not showing (because they are cut by the fault) are not drawn in the restored state.

Modifying parameters

The parameters of the model can be modified after a run using the *Model* -> *Modify* menu (⇧⌘M). The *Modify model* panel will show up (Figure 7).

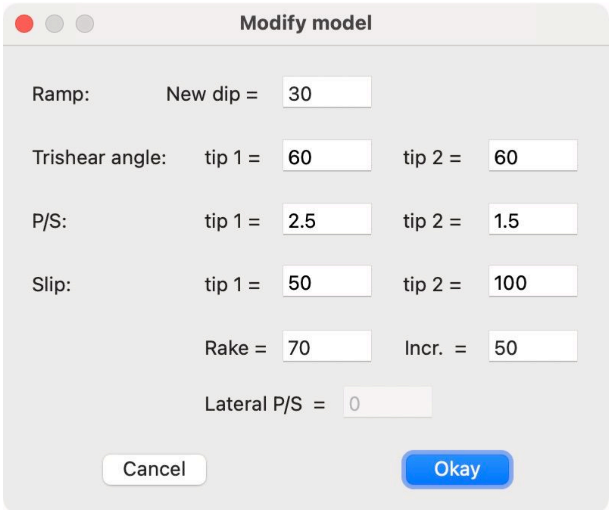


Figure 7. The *Modify model* panel.

In Figure 7, the fault slip was modified to 50 units at the tip 1, and the fault slip rake was modified to 70°. The backlimb kinematics section illustrates the use of the *Modify model* panel to construct multi-bend faults and fault-bend folds. Please notice that:

- It the *Lateral fault propagation* option in the *Preferences* panel is on, backlimb kinematics does not work and the ramp angle cannot be modified.
- If the fault has multiple bends (i.e. backlimb kinematics), the fault slip rake would be 90° and it cannot be modified.
- If the *Opposite slip along fault* option in the *Preferences* panel is off and opposite slip values are entered, you will get an error message.
- If you are running a model with several tips between the end tips, you can use the *Refine model* panel to modify the values of the parameters at these tips.

Figure 8 shows the model after modifying the trishear parameters and running it.

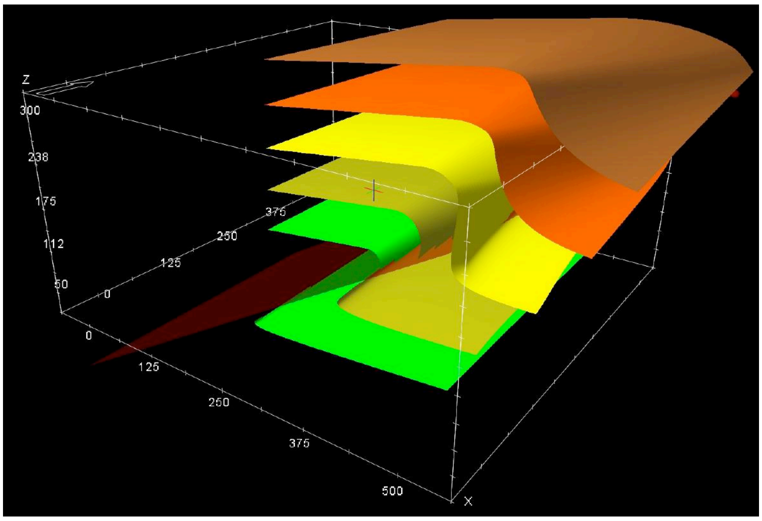


Figure 8. Model after modifying parameters and running it.

Adding beds

You can add beds after a run. This is a way to simulate growth strata. To add beds choose the *Model* -> *Add beds* menu or keyboard combination ⇧⌘A. The *Add beds* panel will show up (Figure 9). The panel shows the tops (the highest node) of the current beds. To add a bed simply fill one of the empty *Tops* boxes. You can also set the origin of

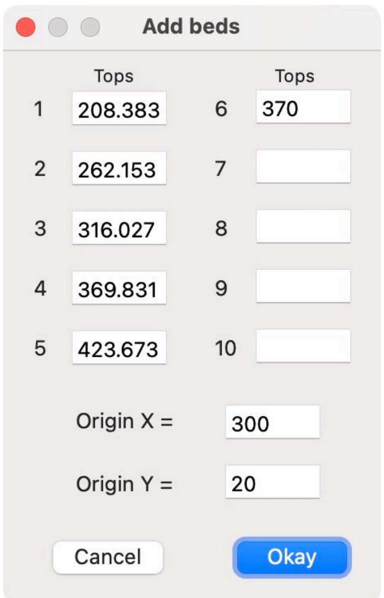


Figure 9. The *Add beds* panel.

the new bed. The extent of the new bed is taken from the Preferences (see Basic interface section).

Enter the top and origin of the new bed, click *Okay*. If you don't like the location of the new bed, open the Add beds panel again and modify the entries. You can do this with one or several new beds. Note that only horizontal beds above the lowest point of the youngest deformed bed can be added. Also, you can add beds up to a maximum of 10 beds.

Trishear3D can model intersections (pinchouts) of new beds against the deformed beds, but not against irregular surfaces or faults. The algorithm computes bed intersections reasonably well. However, when a new bed intersects more than one deformed bed along strike, the algorithm does not work. Figure 10 shows the model after adding the bed number 6 of Figure 9 and running the model.

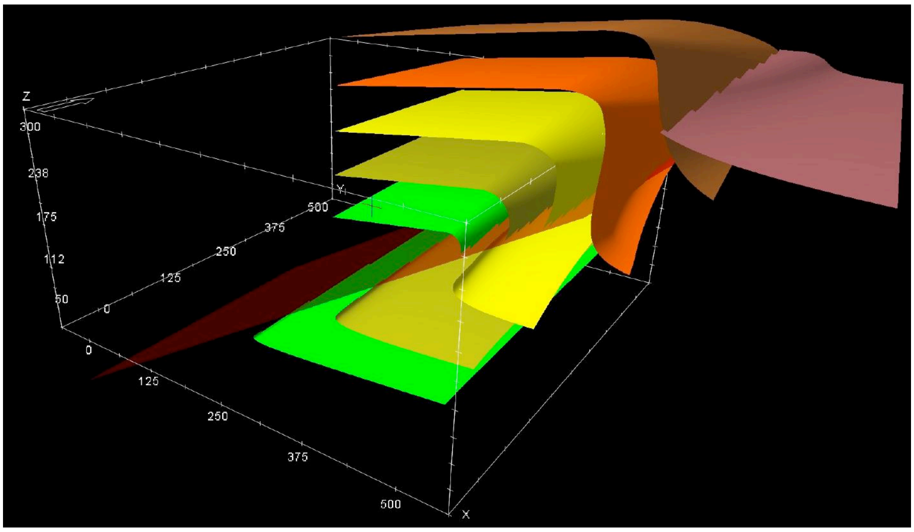


Figure 10. Model after adding one bed and running it.

Starting a new fault

To start a new fault choose the *Model -> Start New Fault* menu or keyboard combination ⇧⌘F. The *New Fault* panel will appear (Figure 11). Once a new fault is made, it will replace the previous fault. Older fault(s) are not considered or shown. You can see how the beds get deformed by the new fault, but no how older fault(s) get deformed by the new fault.

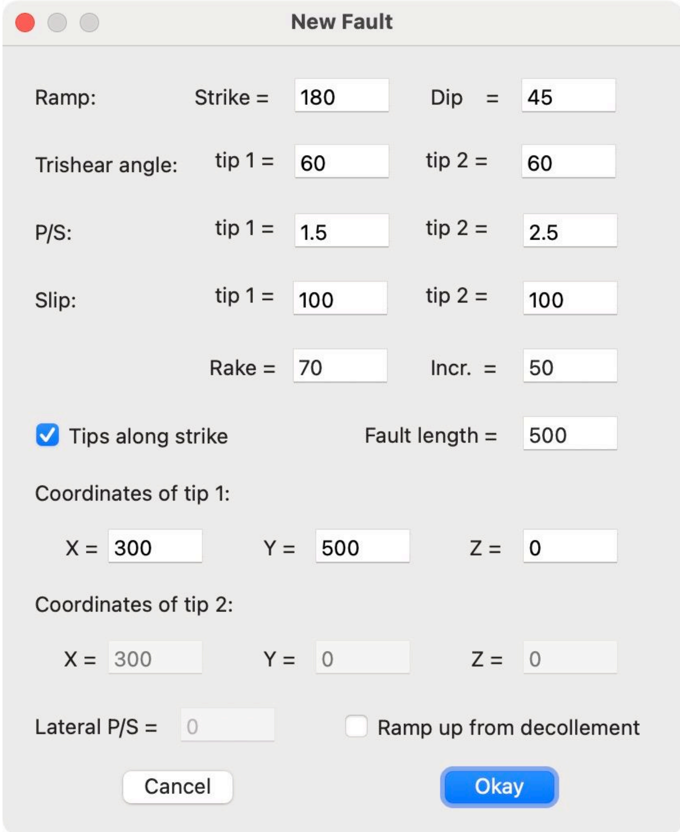


Figure 11. *New Fault* panel.

Please notice that:

- If the *Opposite slip along fault* option is off and opposite slip values are entered, you will get an error message.
- In the *New Fault* panel you can only modify the end fault tips (tips 1 and 2). If there are several tips between the end tips of a current fault, the program will ask you if you want to use the intermediate tip locations for the new fault. If you want to modify these intermediate tips, you can use the *Refine model* panel.
- Ramp up from decollement only works if the fault slip rake is 90° and there is no lateral fault propagation.

Figure 12 shows the model after starting the new fault with the parameters of Figure 11 and running it.

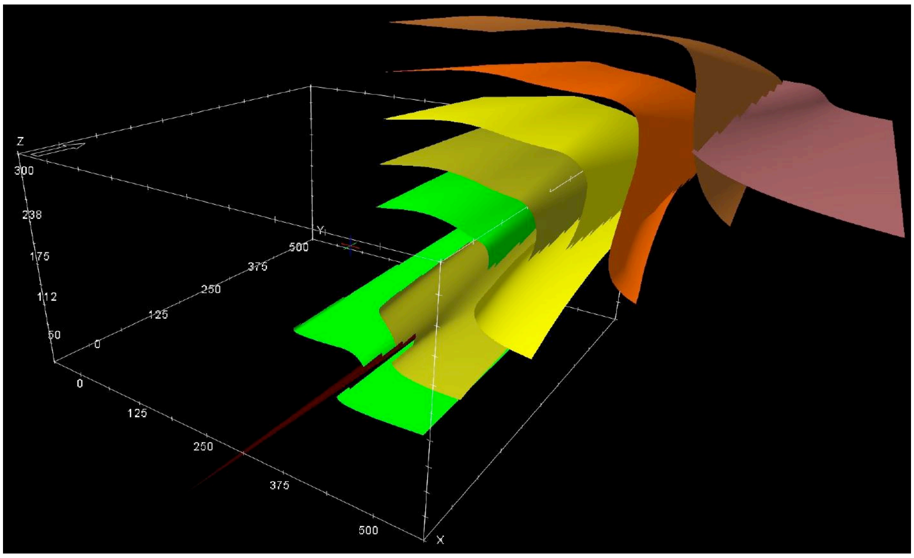


Figure 12. Model after making new fault and running it.

Saving and opening a model

To save a model use the *File* -> *Save* -> *Model* menu or keyboard combination ⌘S. A progress panel will show up. Please wait. **Trishear3D** models are saved as files with extension trish. To open a model use the *File* -> *Open* menu or keyboard combination ⌘O. A progress panel will show up. Please wait.

Visualizing a model

There are several options to visualize the geometry and strain of models.

Selective display of beds

Often you would like to display on/off some beds. Let's take as example the model of Figure 8:

1. Highlight the currently selected bed using the *Plot* -> *Beds* -> *Show Selected* menu (⌘\). A thick line around the bed will show up.
2. Move up or down to the bed you want to select using the *Plot* -> *Beds* -> *Up* or *Down* menus, or keyboard combinations ⇧⌘↑ and ⇧⌘↓, respectively. For example select the top bed (Figure 17 left).

3. Draw (*Plot* -> *Beds* -> *Draw* or keyboard combination ⌘D), or not (*Plot* -> *Beds* -> *Don't draw* or keyboard combination ⇧⌘D) the bed. Figure 13 (right) shows the model with the selected bed not displayed.

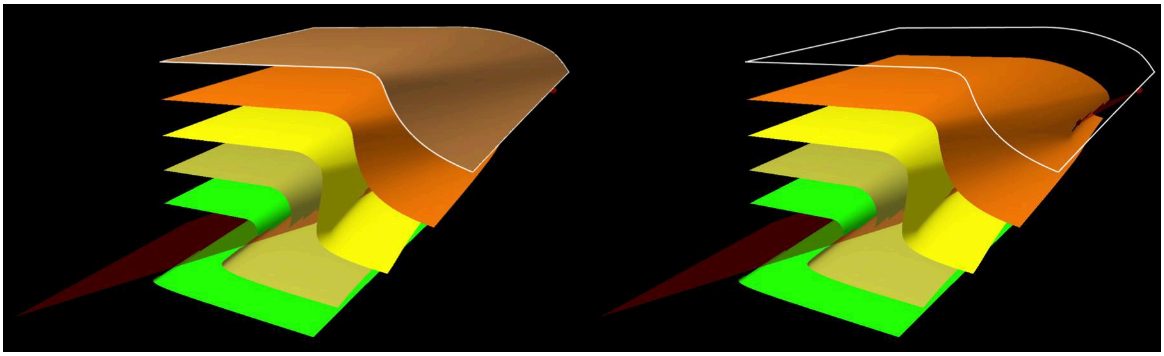


Figure 13. Selecting and toggling off uppermost bed

Repeat this procedure for several beds. You can display all beds again using the *Plot* -> *Beds* -> *Draw all* menu (keyboard combination ⌥⌘L).

Coloring beds

Beds (and irregular surfaces) can be colored by their height or displacement. To color the beds by elevation, select the *Plot* -> *Beds* -> *Color* -> *By Height* menu or keyboard combination ⌘[. Figure 14a shows the model of Figure 8 colored by elevation.

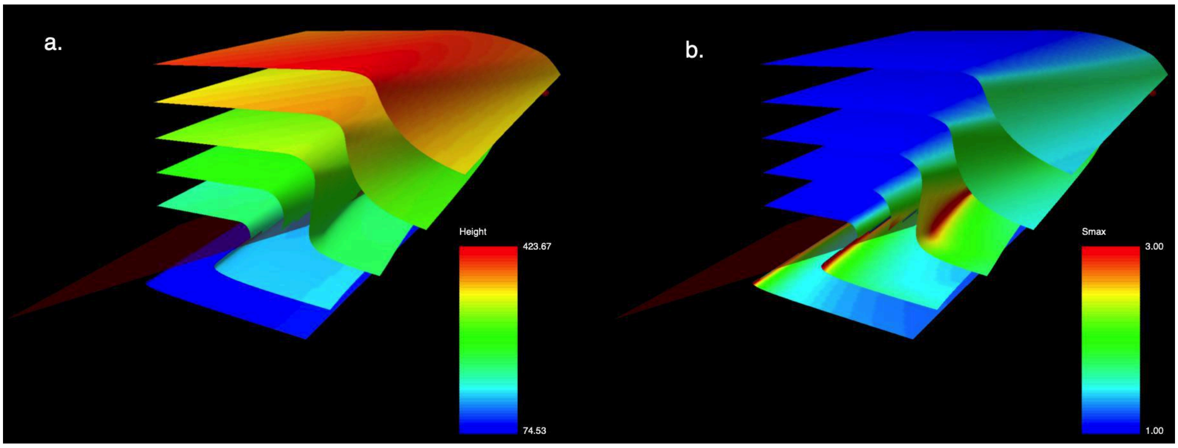


Figure 14. a. Beds colored by elevation. b. Beds colored by strain.

To color the beds by displacement select any of the *Plot -> Beds -> Color -> By Displacement* menus. Beds can be colored X, Y or Z displacement or displacement magnitude.

By default the limits for coloring the beds (and irregular surfaces) by height or displacement are the current minimum and maximum values. Fixed minimum and maximum values can be set using the *Plot -> Beds -> Color -> Set Height & Displ. Limits* menu.

If the *Calculate Strain* option is on, the beds can be colored by the magnitude of finite strain. Select the *Plot -> Beds -> Color -> By Strain* menu or keyboard combination ⌘] . Figure 14b shows the model of Figure 8 colored by strain, specifically the maximum principal stretch.

Trishear3D uses a simple algorithm to color the beds by strain. Each node is assigned a strain value based on the values and distances to the four tetrahedrons closest to the node. Thus, the quality of the strain contours depends on the number of tetrahedrons and their spacing.

You can set the strain parameter to plot, and the minimum and maximum contour values using the *Plot -> Strain -> Set parameter* menu or keyboard combination ⌘. . This will open the *Strain Parameter* panel (Figure 15).

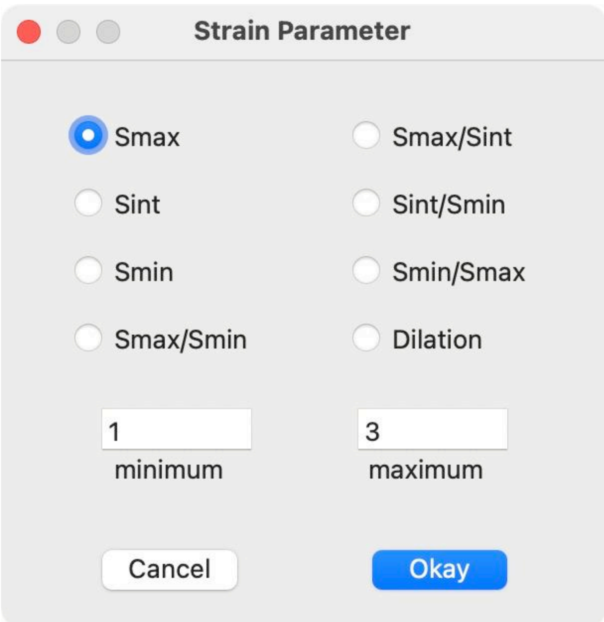


Figure 15. *Strain Parameter* panel.

To get a scale bar like those in Figure 14, select the *Plot -> Scale bar* option or keyboard combination ⌘/. You can drag the scale bar to any application or the desktop to save it as a pdf.

You can also modify the color map. Select the *Plot -> View -> Color Map* menu or keyboard combination ⌥⌘M. The *Color Map* panel will show up. For example, try coloring the beds by height (Figure 14a) using the *Elevation* color map.

Tetrahedrons, ellipsoids and principal strain axes

To plot tetrahedrons select the *Plot -> Strain -> Tetrahedrons* menu or keyboard combination ⌥⌘T . To plot ellipsoids select the *Plot -> Strain -> Ellipsoids* menu or keyboard combination ⌘0. To plot principal strain axes select the *Plot -> Strain -> Principal axes* menu or keyboard combination ⌥⌘0. The tetrahedrons or ellipsoids are colored by strain. The principal strain axes are colored red, green and blue for the maximum, intermediate and minimum principal axes, respectively. Figures 16 shows one bed with tetrahedrons (a) and ellipsoids (b).

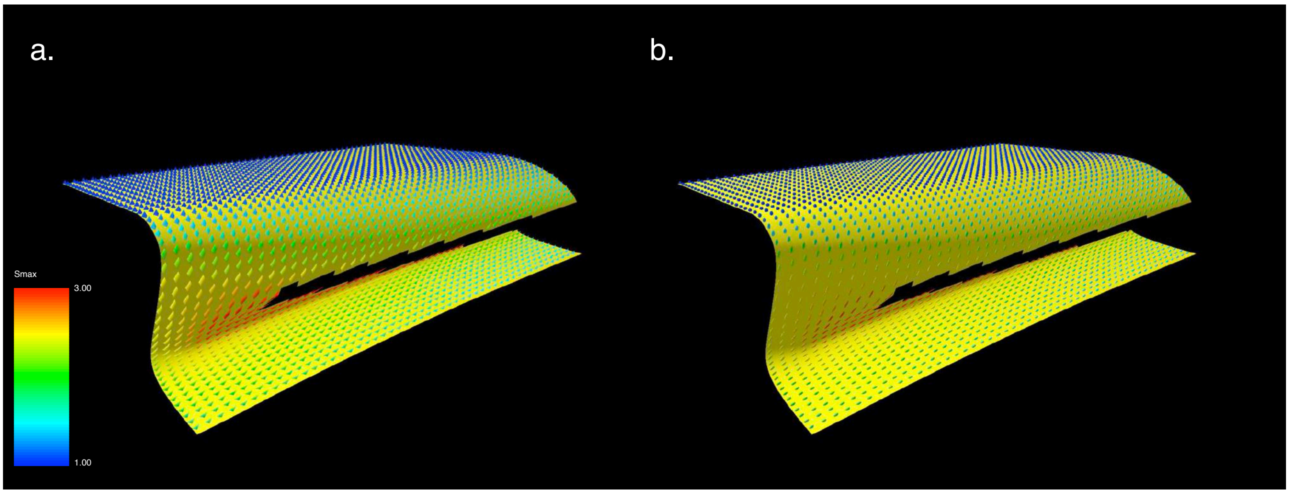


Figure 16. Bed with (a) tetrahedrons, and (b) ellipsoids.

Querying the plot view

There are four ways to query the Plot view:

1. By clicking any solid, non-transparent object in the view. The coordinates of the object will show up in the text field at the upper right corner of the view.

2. By opening the *Bed Info* panel (*Model* -> *Get Bed/Surface Info* or keyboard combination ⇧⌘B).
3. By opening the *Strain Info* panel (*Model* -> *Get Strain Info* or keyboard combination ⇧⌘E).
4. By opening the *Cross Section* panel (*Model* -> *Cross Section* or keyboard combination ⇧⌘X).

The Bed Info panel

The Bed Info panel (*Model* -> *Get Bed/Surface Info* or keyboard combination ⇧⌘B, Figure 17) reports key parameters of the selected bed, specifically its: (i) lowest node, (ii) highest node, (iii) area, (iv) volume with respect to a datum, and if the strain is computed (v) the bed's maximum stretch, (vi) minimum stretch, and (vii) dilation.

The area of the bed is computed by adding the area of the quadrilaterals that have not been segmented by the fault. The volume with respect to a datum is computed by adding the product of the quadrilaterals area times their height to a datum. This is a convenient way to compute the volume between two beds. For example, if you want to compute the volume between two beds, compute the volume of each bed to the same datum. The volume between the beds is the difference of the computed beds' volumes.

The strain parameters are based on the tetrahedrons that have not been segmented by the fault. The bed's dilation is the sum of the dilation of the tetrahedrons. The bed information is updated after running a model. This is a nice way to see how the parameters of a bed change with deformation.

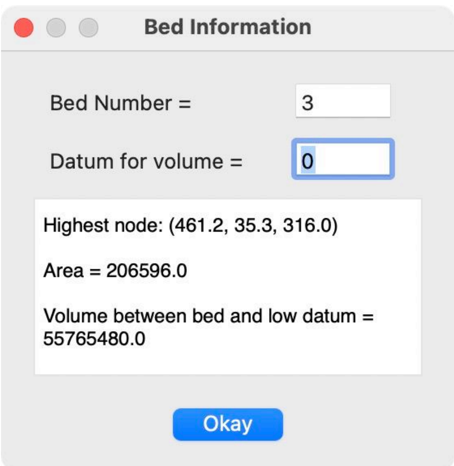


Figure 17. The *Bed Info* panel.

The Strain Info panel

The strain of any tetrahedron or ellipsoid can be queried in the Plot view using the Strain Info panel (*Model* -> *Get Strain Info* or keyboard combination ⇧⌘E, Figure 18). Open the *Strain Info* panel and click any tetrahedron or ellipsoid in the view. The principal stretches and the bedding at the tetrahedron or ellipsoid location are plotted in an equal angle, lower hemisphere stereonet. The magnitude and orientation (trend and plunge) of the principal stretches, and the strike and dip (right hand rule convention) of bedding, are written below the stereonet. These elements can be toggled using the buttons below the stereonet. The *Strain Info* panel updates every time a new tetrahedron or ellipsoid is clicked. This is great way to explore the variation of strain across the structure.

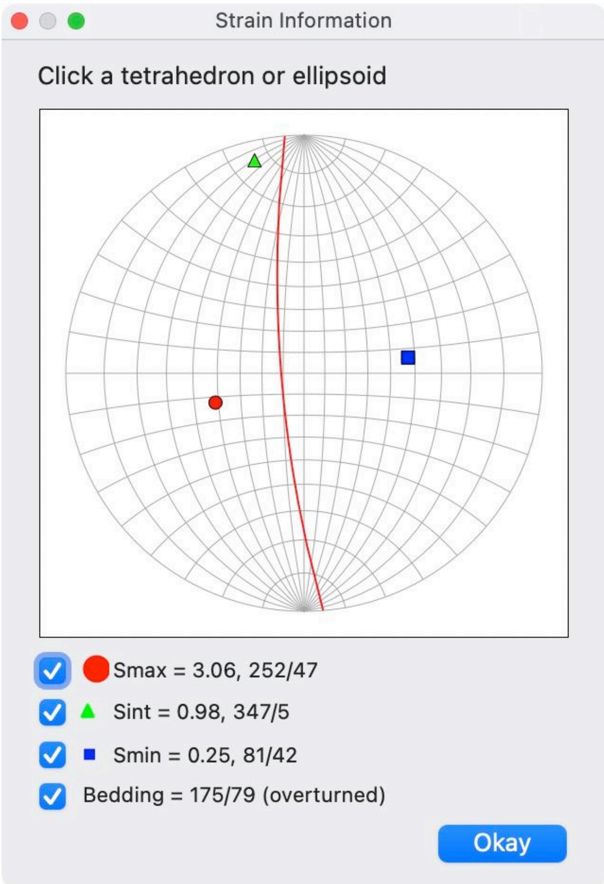


Figure 18. *Strain Info* panel after clicking one ellipsoid in the overturned forelimb of the bed in Figure 16.

The Cross Section panel

To make a section across the model open the Cross Section panel (*Model* -> *Cross Section* or keyboard combination ⇧⌘X, Figure 19a). To define the section plane, you need to enter the following parameters: (i) The strike of the plane, (ii) the dip of the plane,

(iii) The length of the plane along its strike, (iv) The length of the plane along its dip direction, and (v) the *XYZ* coordinates of the upper corner of the plane. Click the *Update* button.

The section plane is drawn in gray in the *Plot* view. The upper corner of the section plane is indicated by a red dot, and the lower corner by a green dot (Figure 19b). The cross section is drawn in the panel (Figure 19a). Like in the 3D view, the upper and lower corners of the section plane are shown by a red and a green dot, respectively. The origin of the cross section is at the lower corner of the section plane (green point, Figure 19a). The abscissa of the cross section increases from the origin to the right and its extent is equal to the length of the section plane along its strike. The ordinate increases from the origin up and its extent is equal to the length of the section plane along its dip direction. The beds are drawn as black lines, and the fault as a red line.

a. b.

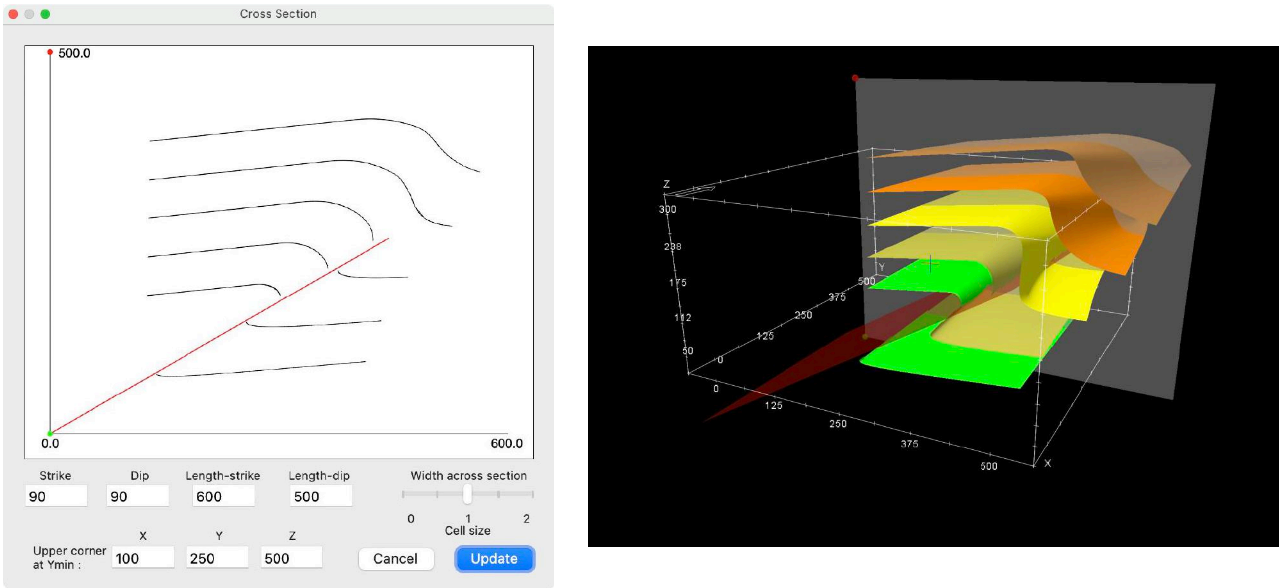


Figure 19. *Cross Section* panel and section plane in Plot view.

When making a cross section it is important to remember that every bed is made of nodes spaced at finite distances. To draw the cross section, **Trishear3D** converts the nodes to a local coordinate system *X'Y'Z'*, with *X'* parallel to the strike of the section, *Y'* parallel to the dip of the section, and *Z'* normal to the section plane. The program then plots in the section, the nodes with an absolute value of *Z'* lower than a defined width across the section plane, and within the *X'*, *Y'* limits of the section plane. By default nodes with an absolute value of *Z*' lower or equal than the undeformed cell size are plotted in the cross section.

Sometimes in a cross section a bed is not a single line but several lines. In this case the width across the section might be too high. You can change the width using the slider at the lower right corner of the panel (Figure 19a). It can be reduced down to 0 (i.e. only nodes that are exactly at the section plane are plotted), or increased up to twice the cell size. In the cross section, adjacent points that are a distance lower than twice the average distance between all adjacent points are joined by a line, otherwise a new line is started.

You can drag the contents of the *Bed Info*, *Strain Info*, or *Cross Section* panel to any application. Dragging the stereonet (Figure 18) or cross Section (Figure 19a) to the desktop creates a pdf.

Refining a model

In the pseudo-3D model, the solution coordinate system is associated to the fault slip vector. Thus, contrary to the true-3D formulation, in pseudo-3D the solution coordinate system is not attached to the tip line and does not rotate with deformation (Cardozo, 2008). This makes possible to implement in pseudo-3D any kind of variation of trishear parameters (P/S, trishear angle, and/or fault slip) along the fault tip line. In pseudo-3D mode, complex, non-linear variations of parameters along the tip line can be introduced using the *Refine Model* panel (*Model* -> *Refine*, Figure 20).

The *Refine Model* panel contains a table with the tips and their parameters, and buttons to add or delete intermediate tips (Figure 20). The table contains five columns: A tip column, with the ids of the tips. This column cannot be edited. A location column with the location of the tips expressed as the ratio: (distance from tip 1 along tip line) / (tip line length). The tip 1 has therefore a location value of 0.0 and the tip 2 a location value of 1.0. Any tip between the end tips 1 and 2 should have a location between 0.0 and 1.0 (in fact you will only be able to enter values between 0.0 and 1.0 in the location column). The last three columns are for the P/S, trishear angle, and fault slip at the tips. The trishear angle should be entered in degrees.

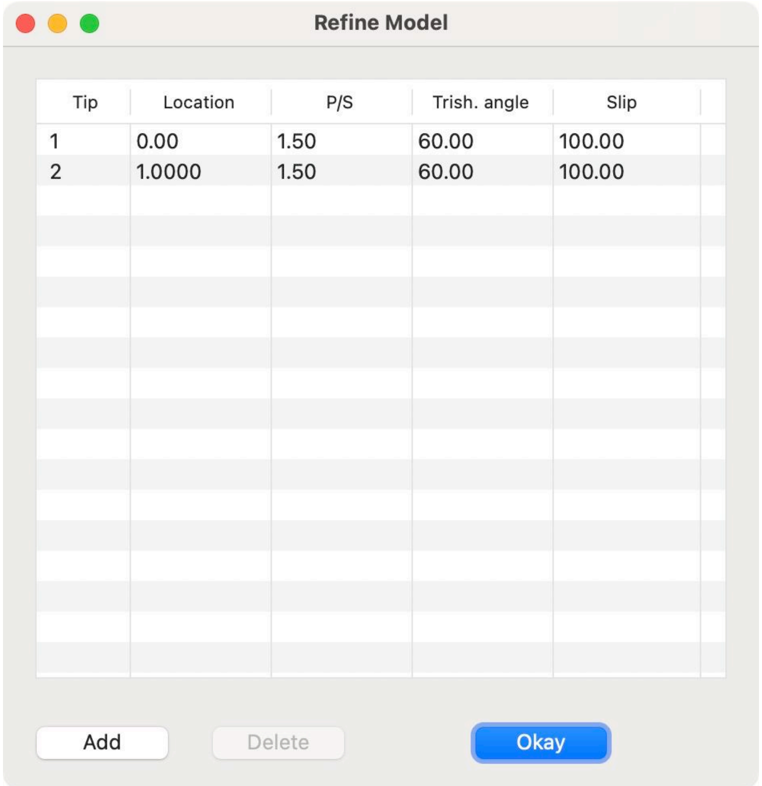


Figure 20. The *Refine Model* panel.

The first two rows in the table of the *Refine Model* panel, correspond to the end tips 1 and 2. These rows cannot be edited or deleted. The only way you can modify the parameters at the end tips is through the *New Model* (Figure 3), *Modify Model* (Figure 7), or *New Fault* (Figure 11) panels. After creating a new model, you can add (or delete) as many tips you want. Once the model is run, these tips cannot be deleted. You will still be able to modify the P/S, trishear angle, and/or fault slip at the intermediate tips in the *Refine Model* panel. To modify these parameters at the end tips, you should use the *Modify Model* panel (Figure 7).

As an example, create a new model with the default values of the program. Make sure that in the *Preferences* panel, the pseudo-3D option is on, and the lateral propagation and bilinear variation of parameters options are off. Open the *Refine Model* panel. Add the following tips to the panel before running the model:

Tip	Location	P/S	Trish. angle	Slip
3	0.04	1.5	60	139
4	0.08	1.5	60	155

5	0.12	1.5	60	165
6	0.16	1.5	60	173
7	0.2	1.5	60	180
8	0.24	1.5	60	185
9	0.28	1.5	60	190
10	0.32	1.5	60	193
11	0.36	1.5	60	195
12	0.4	1.5	60	198
13	0.44	1.5	60	199
14	0.5	1.5	60	200
15	0.56	1.5	60	199
16	0.6	1.5	60	198
17	0.64	1.5	60	195
18	0.68	1.5	60	193
19	0.72	1.5	60	190
20	0.76	1.5	60	185
21	0.8	1.5	60	180
22	0.84	1.5	60	173
23	0.88	1.5	60	165
24	0.92	1.5	60	155
25	0.96	1.5	60	139

The slip between the end tips varies in an elliptical, symmetrical manner from 100 at the end tips to 200 at the mid tip. Run the model. The uppermost bed colored by elevation should look like Figure 21. The possibilities offered by the *Refine Model* panel are endless. You can approximate any variation of P/S, Trishear angle, and/or fault slip along strike using this panel.

Lateral propagation

Trishear3D can model fault growth along strike. To do this, you need to toggle on the *Lateral fault propagation* option in the *Preferences* panel (Figure 2). Notice that this option can only be selected if the *Opposite slip along fault* option is off.

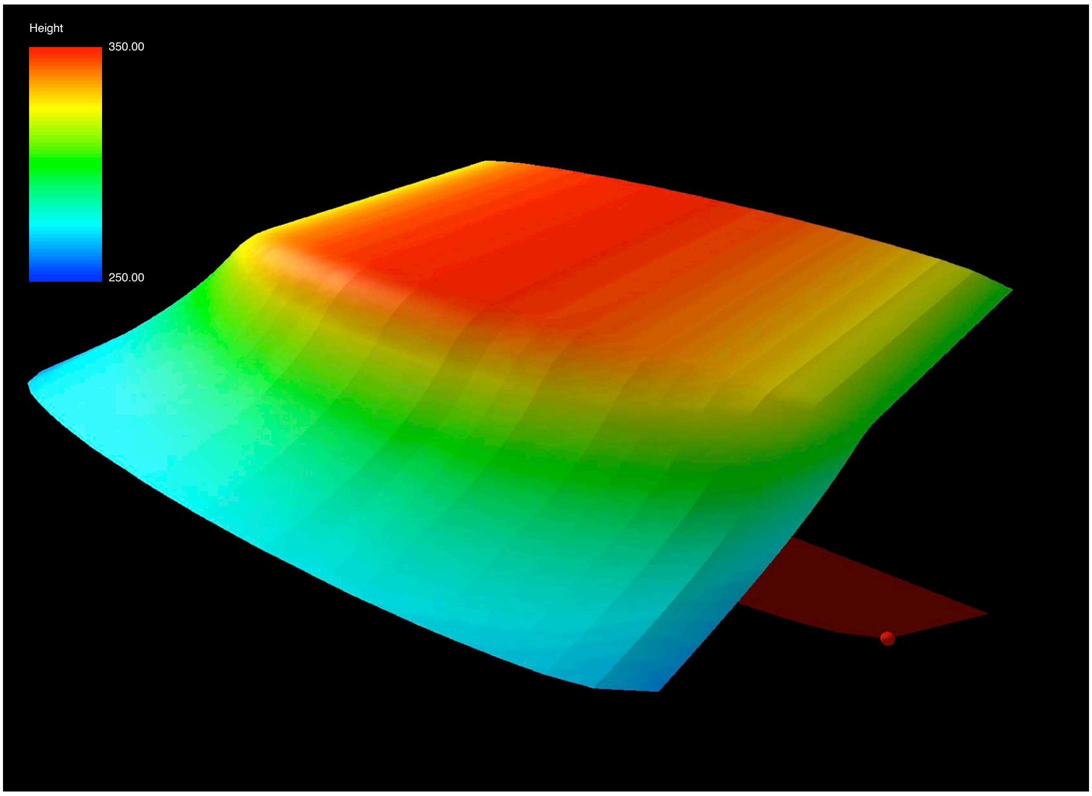


Figure 21. Elliptical variation of slip along the fault. Bed is colored by elevation.

Laterally growing faults

Make sure that in the *Preferences* panel, the Lateral fault propagation option is on. Create a model with the following parameters (Figure 22):

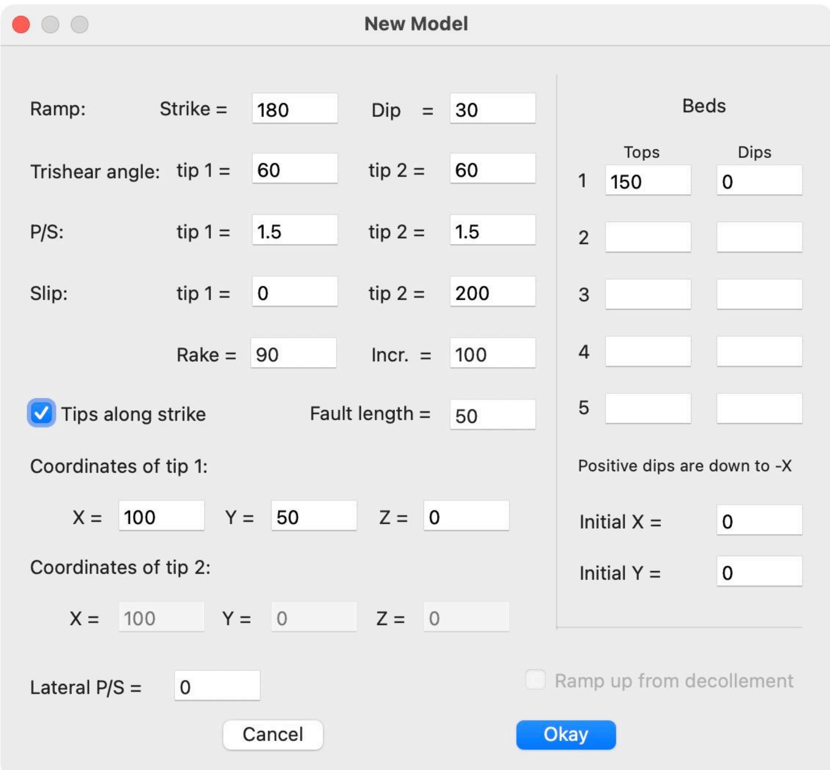


Figure 22. New model with lateral fault propagation.

The fault slip varies from 200 units at the tip 2, to zero at the tip 1. The initial length of the fault along strike is 50 units and the along-strike, lateral fault propagation to fault slip ratio (P/S) is twice the across-strike P/S. You can only edit the lateral P/S field if the slip at one tip is zero. Lateral fault propagation works such that the tip with zero slip moves along strike as the structure grows, so that the along-strike length of the fault increases with deformation. Run the model, you should get a geometry like Figure 23a.

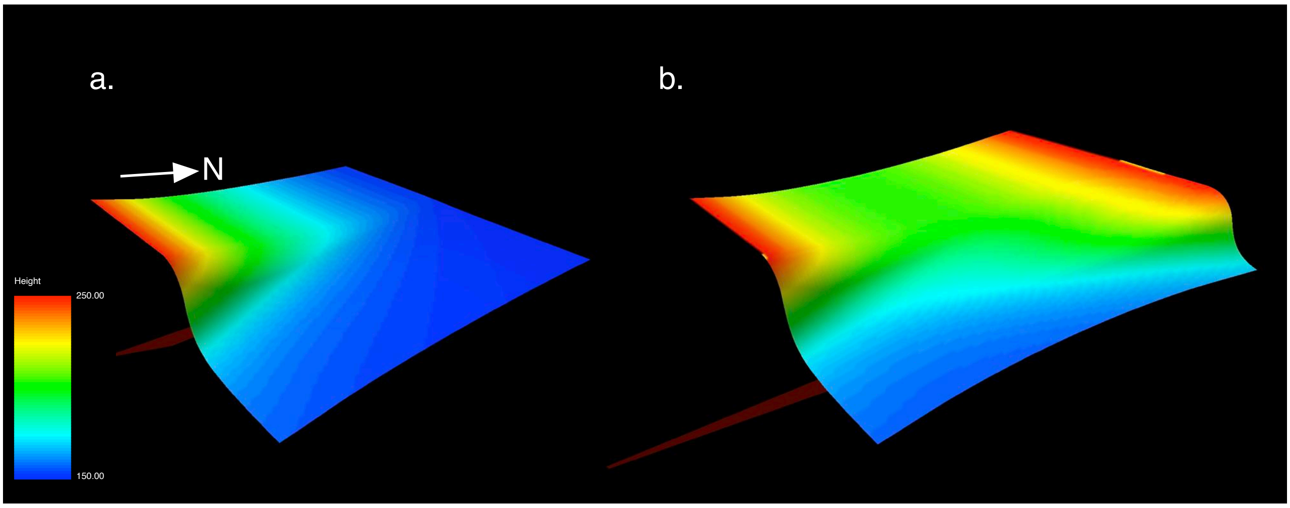


Figure 23. a. Lateral fault propagation to the North. b. A new fault propagating in the opposite direction.

The fault grew along strike in the positive Y (north) direction, and the elevation is higher at the location where the fault accumulated more slip. Let's start another fault on the opposite side, but growing along strike in the opposite direction (south). Open the *New Fault* panel (⇧⌘F). Fill the fields of the panel as in Figure 24.

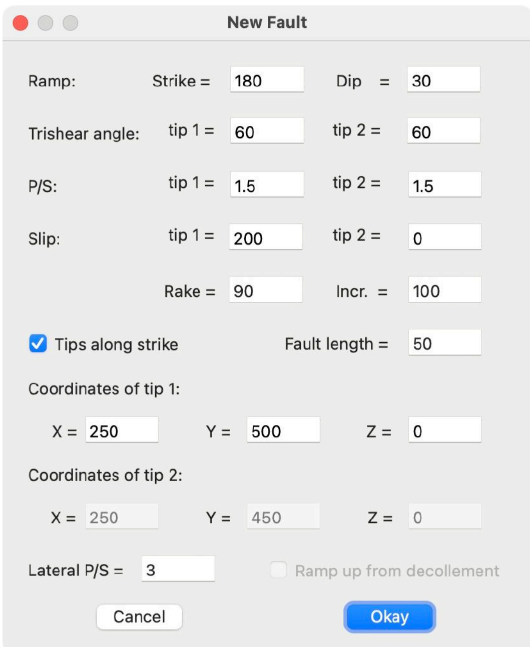


Figure 24. Second fault propagating to the negative Y (south) direction.

Fault slip varies from 200 units at the tip 1 to zero at the tip 2. The initial length of the fault along strike is 50 units and the lateral, along-strike P/S is twice the across-strike P/S. The tip 2 will move to the south (negative Y), so that the fault length will increase as slip accumulates. Run the model. You should get a geometry like in Figure 23b.

Bilaterally growing faults

Let's model a fault that propagates along strike in two, opposite directions. Open the *Preference* panel and turn on the *Lateral fault propagation* and the *Bilinear variation of parameters* options. Now, create a model with the following parameters (Figure 25).

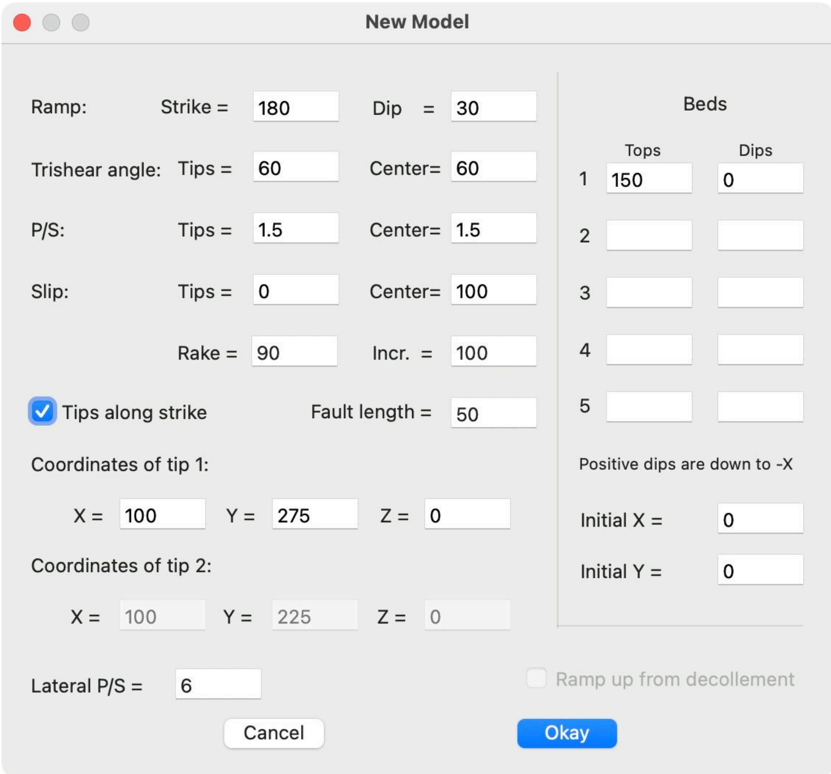


Figure 25. New model for lateral fault propagation in two opposite directions.

In this case the slip is zero at the tips and 100 units at the point halfway from the tips. The lateral P/S is six times the across strike P/S. The fault will propagate six times as much along strike as across strike. Each tip will propagate along strike, in opposite directions, three times as much as the propagation across strike. Run the model, you should get a geometry like Figure 26.

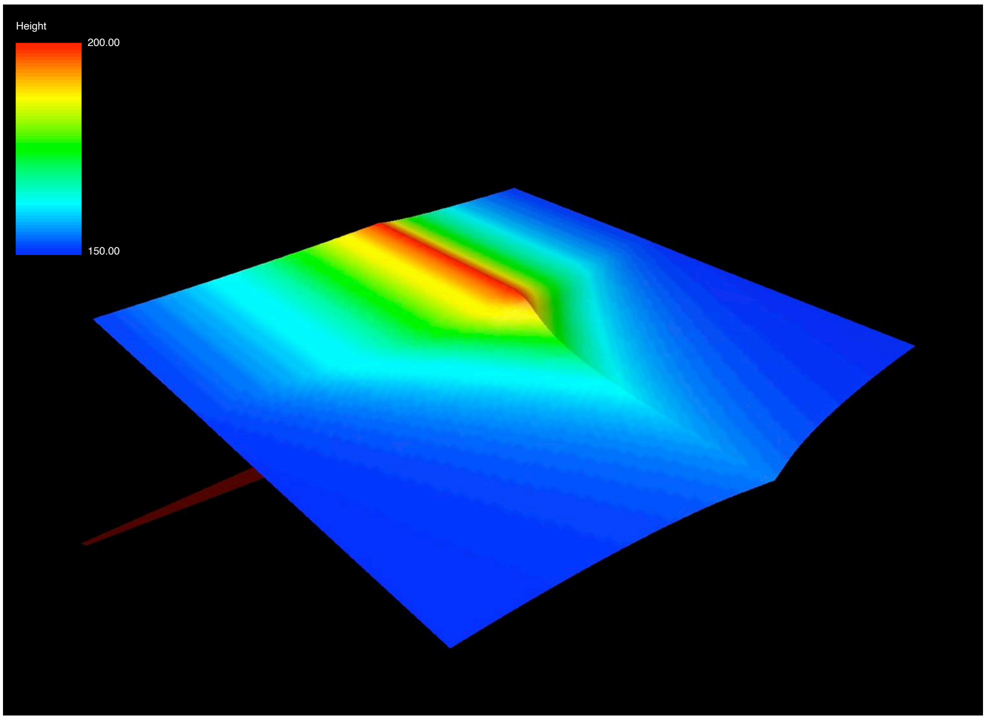


Figure 26. Bilateral fault propagation after one run. The bed is coloured by elevation.

Backlimb kinematics

Trishear3D can model folding behind the trishear zone using simple kinematics such as inclined and parallel shear. These algorithms are based on a two-dimensional velocity formulation (Hardy, 1995). Backlimb kinematics only works if fault slip is perpendicular to strike (rake = 90°) and the *Lateral fault propagation* option is off. Also the kink axes of backlimb kinematics and the trishear zone should not cross. There are some interesting things you can do in Trishear3D using backlimb kinematics:

Ramp from decollement

Create a model using the following parameters (Figure 27a). Make sure *Parallel* backlimb kinematics in the *Preferences panel* is on. You should get a model like Figure 27b. Toggle the fault kink using the *Plot* -> *Fault kinks* menu or keyboard combination ⌥⌘K. Run a model with variable slip along the fault. Change the backlimb kinematics to inclined shear. Use different shear angles.

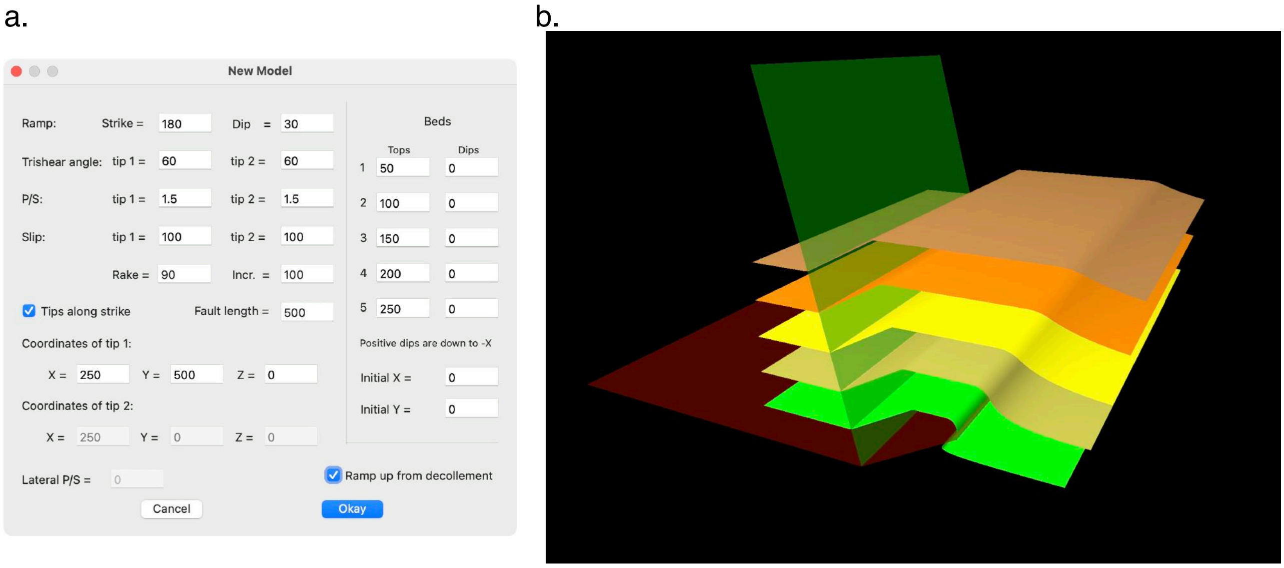


Figure 27. Ramp from decollement. a. New model, and b. Model after one run.

Fault bend folding

Trishear3D can generate a fault bend fold. The trick is to think about how fault bend folds form: first the fault trajectory is formed with very little slip, and then the hanging wall slips over the multi-bend fault plane. To generate the fault trajectory with little slip use a large propagation to slip ratio (P/S). Create a model using the parameters of Figure 28a.

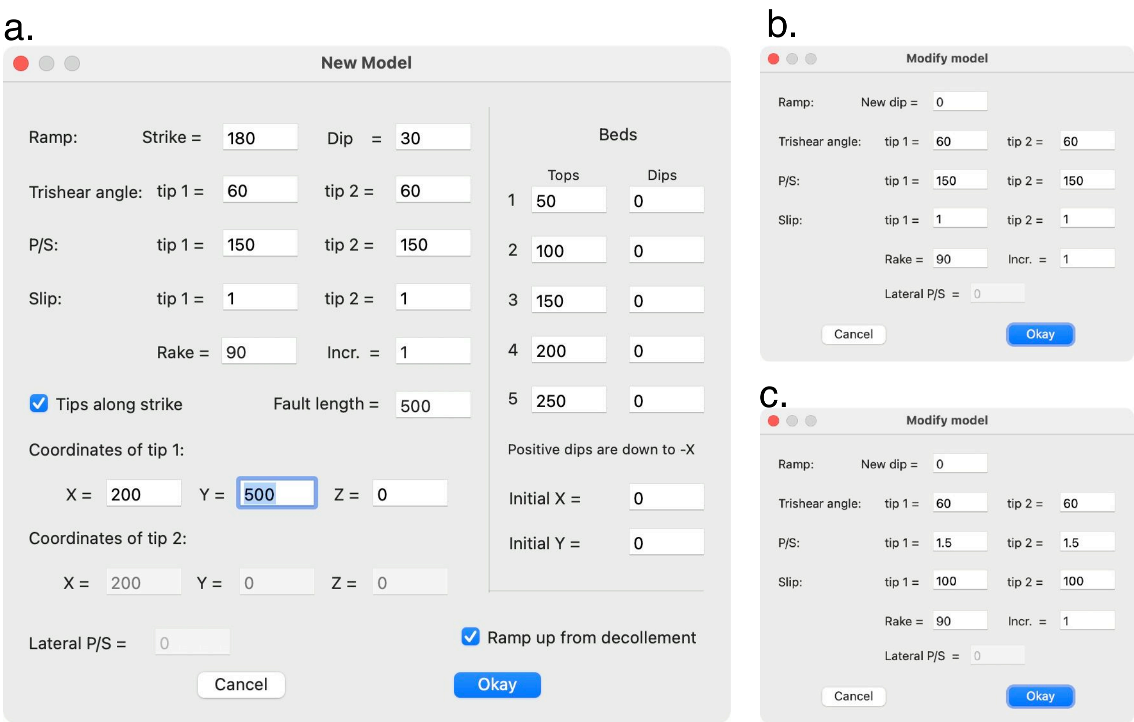


Figure 28. Steps to produce a fault-bend fold.

The P/S is very high (150), the slip is small (1), and there is only one slip increment. Also the ramp up from decollement option is selected. Run the model. You are creating the footwall ramp. The ramp should not dip more than 30°. Now modify the fault dip so that the fault is again parallel to the beds using the *Modify* panel (*Model* -> *Modify* or keyboard combination ⇧⌘M, Figure 28b). Run the model about five times so that the tip line is to the right of the beds. Now that the flat-ramp-flat fault geometry has been created, modify the slip and the P/S so that the hanging wall moves above the fault, as in Figure 28c. Run the model, Figure 29 shows the resultant fault bend fold.

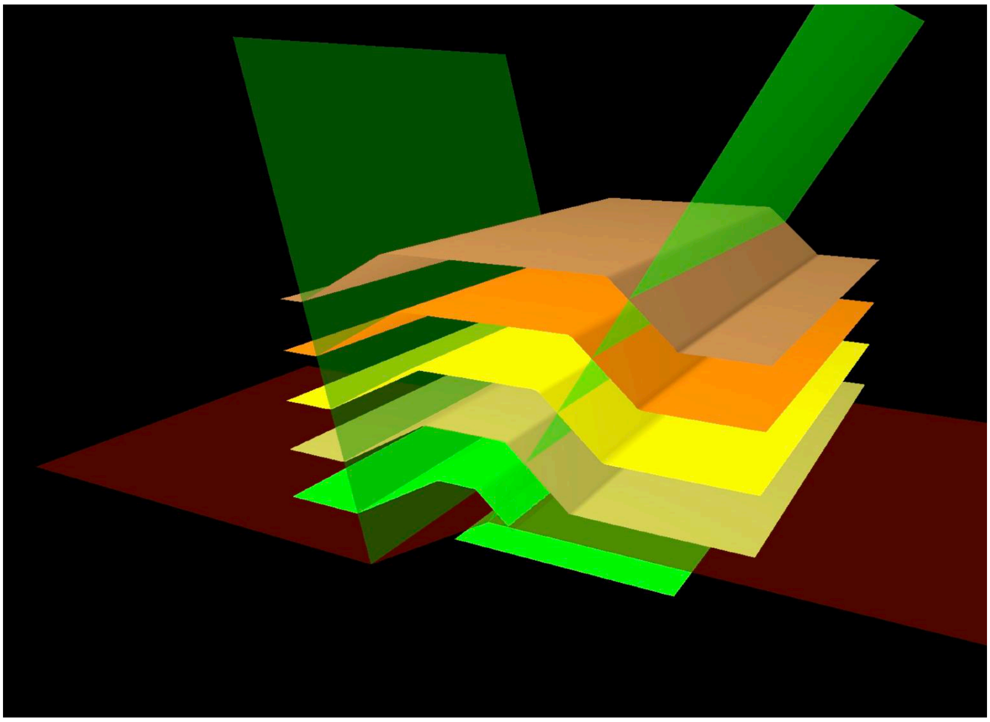


Figure 29. Fault-bend fold.

Toggle the fault kinks. **Trishear3D** only shows the active fault kinks (i.e. axial planes across which material particles rotate). Continue running the model. You will see how the active axial kink in the ramp-upper flat intersection, change in orientation. This happens when the cumulative slip is equal to the ramp length. Compute strain. The strain is simple compared to trishear folds. Run the same model but now with variable slip along the fault.

Rollover

Following the previous strategy, faults with multiple bends can be created. For example, a listric fault can be created by increasing the fault dip between runs using the

Modify panel. You can then move the beds over the listric fault. Figure 30 shows a rollover created by normal faulting over a listric fault, with inclined shear (*Similar* backlimb kinematics) and a shear angle of 30° (positive shear angles correspond to shear planes antithetic to the fault). The beds are colored by elevation. Run a similar model but with variable slip. Try also reversing the slip (fault inversion). Compute strain.

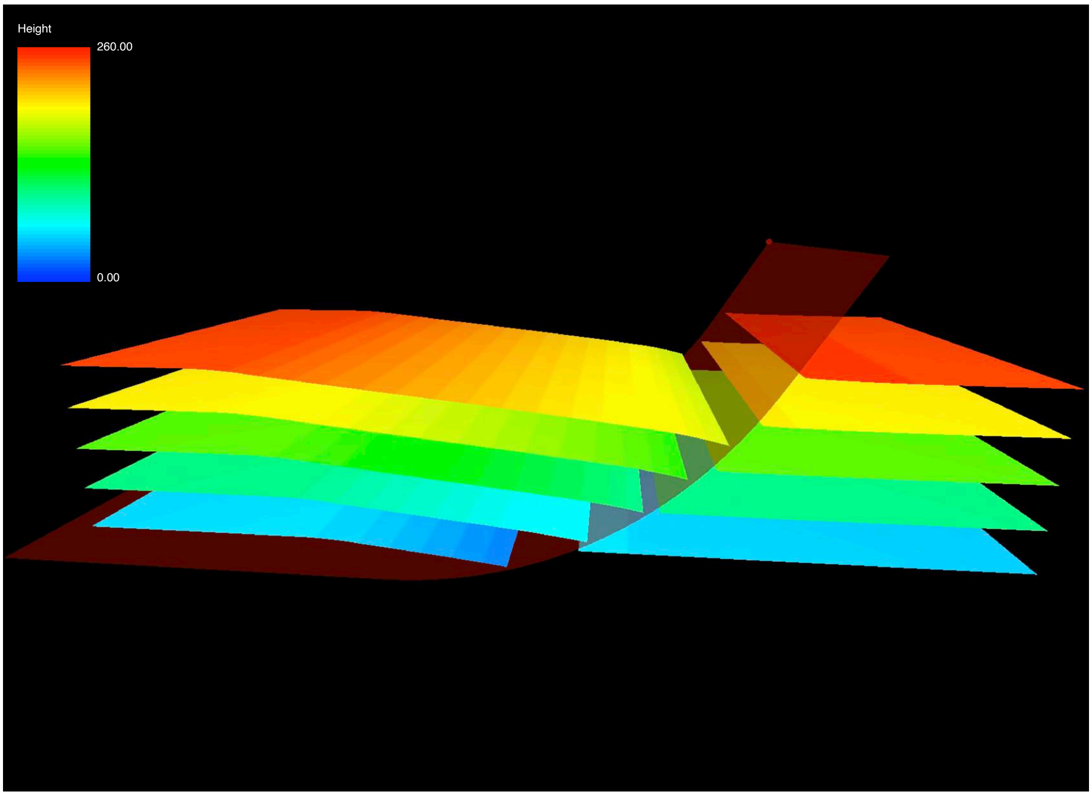


Figure 30. Rollover produced by 30° inclined shear over listric normal fault.

Irregular surfaces

Irregular surfaces are defined by scattered points. These surfaces can be loaded from text files using the *File* -> *Load Surface from text* menu or keyboard combination ⌥⌘O. The format of a surface text file is simple: The file should contain as many lines as the number of points lying on the surface, and each line should contain the *X*, *Y* and *Z* coordinates of each point. Entries on a line can be separated by tabs, commas, or spaces. There is no limitation in the number of points.

A maximum number of 10 surfaces can be loaded. Irregular surfaces are different from beds because instead of being made of regular quadrilaterals as the beds, they are a cloud of points which can be displayed as a triangular mesh. Irregular surfaces are detached from the model's beds. They are by default active (i.e. deform with the beds) and visible. These options can be modified for each surface using the *Surfaces Controller panel*: *Model* -> *Surfaces Controller* or keyboard combination ^⌘X (Figure 31a):

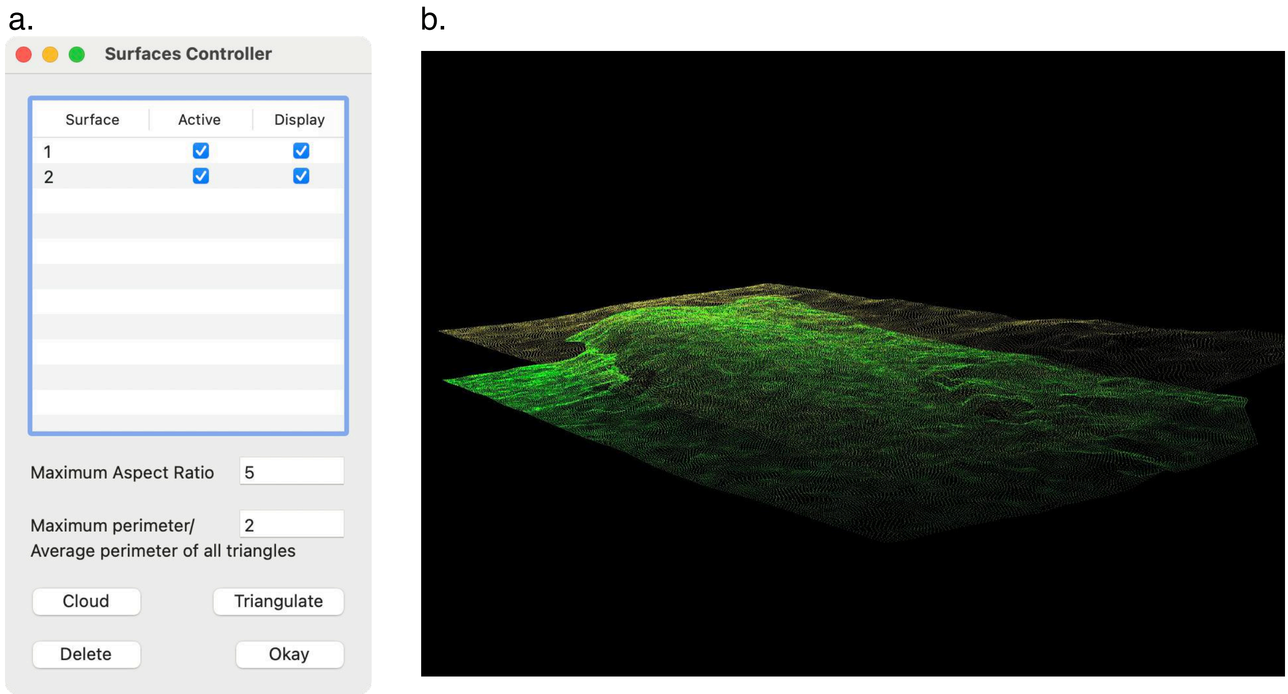


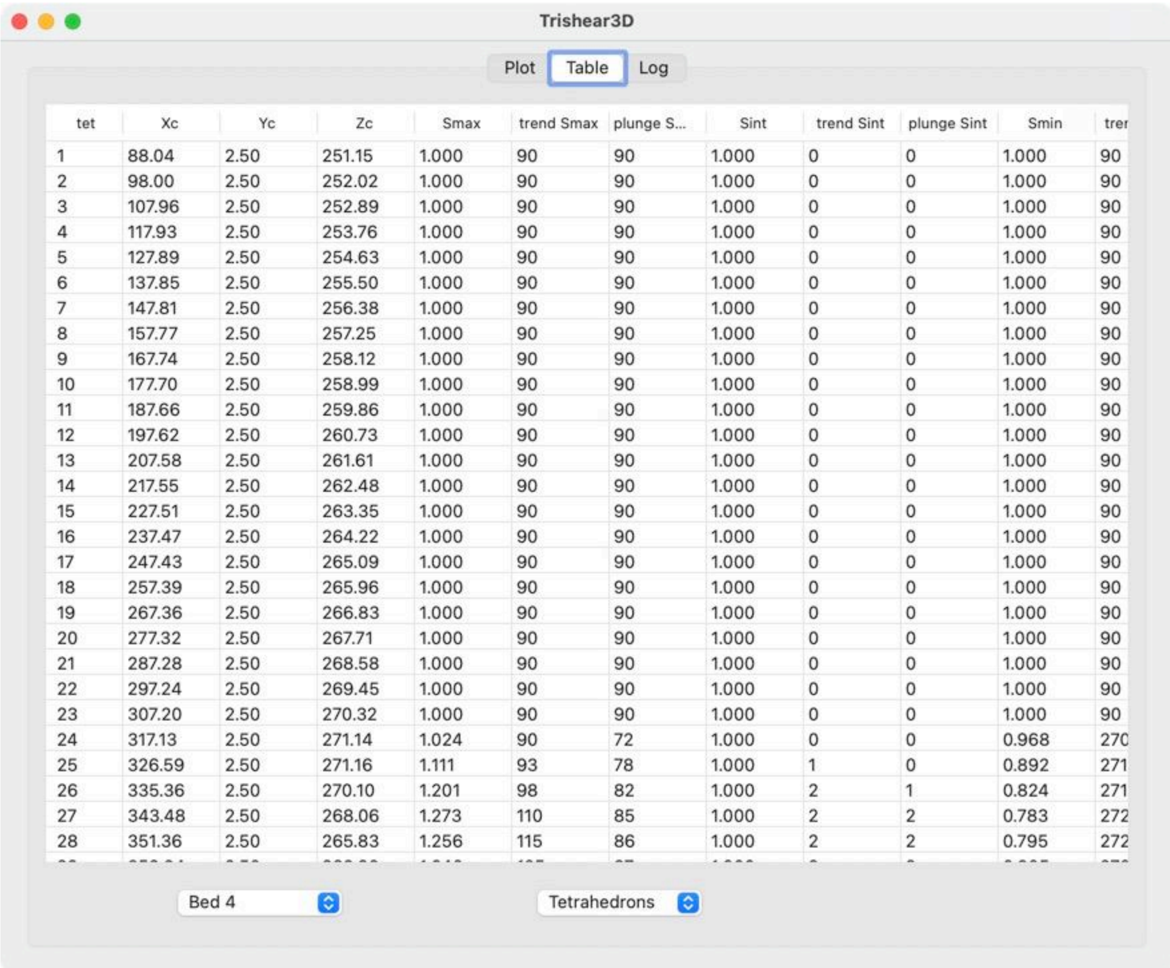
Figure 31. a. Surfaces Controller panel, and b. Two surfaces from a 3D seismic cube in the Niger Delta (courtesy of Andreas Plesch).

Use the buttons in the *Active* and *Display* columns to activate/deactivate, or show/don't show a surface. Irregular surfaces are displayed by default as cloud of points (Figure 31b). However, they can also be displayed as triangulated surfaces. Just select a surface and click the *Triangulate* button in the *Surfaces Controller* panel (Figure 31a). Use the *Maximum Aspect Ratio* field to set the maximum aspect ratio of the triangles. Use the *Maximum perimeter/Average perimeter* field to set the maximum perimeter of the triangles as a multiple of the average perimeter of all triangles. (Figure 31a). **Trishear3D** uses a Delaunay subroutine by Paul Bourke to triangulate surfaces. This works fine if there are no points with different *Z* but identical *X* and *Y*. If the surface is vertical or overturned, the triangulation may not be as nice and the program may crash.

There are two main limitations with irregular surfaces: (i) They cannot have tetrahedrons and therefore strain cannot be computed on them, and (ii) Beds-Irregular surfaces intersections are not checked. Irregular surfaces are a convenient way to model actual data (Figure 31b). You can load an actual surface, make it inactive, and experiment with different models to see how they fit the surface. Alternatively, you can make the surface active and run different models backward (*Model* -> *Run Backwards* menu), to see how the models restore the surface. This needs to be done by trial and error. There is no inverse modeling routine in **Trishear3D** such as in Cardozo and Aanonsen (2009) and Cardozo et al. (2011).

Tables and log

You can review and export the information of a trishear model using the *Table* view (Figure 32). The use of this view is straightforward: (i) Choose the bed/surface to get information from using the left button at the base of the view, and (ii) Choose the type of information (nodes or tetrahedrons) using the right button at the base of the table. You can also perform these operations using the Table menus or their corresponding shortcuts.



tet	Xc	Yc	Zc	Smax	trend Smax	plunge S...	Sint	trend Sint	plunge Sint	Smin	trer
1	88.04	2.50	251.15	1.000	90	90	1.000	0	0	1.000	90
2	98.00	2.50	252.02	1.000	90	90	1.000	0	0	1.000	90
3	107.96	2.50	252.89	1.000	90	90	1.000	0	0	1.000	90
4	117.93	2.50	253.76	1.000	90	90	1.000	0	0	1.000	90
5	127.89	2.50	254.63	1.000	90	90	1.000	0	0	1.000	90
6	137.85	2.50	255.50	1.000	90	90	1.000	0	0	1.000	90
7	147.81	2.50	256.38	1.000	90	90	1.000	0	0	1.000	90
8	157.77	2.50	257.25	1.000	90	90	1.000	0	0	1.000	90
9	167.74	2.50	258.12	1.000	90	90	1.000	0	0	1.000	90
10	177.70	2.50	258.99	1.000	90	90	1.000	0	0	1.000	90
11	187.66	2.50	259.86	1.000	90	90	1.000	0	0	1.000	90
12	197.62	2.50	260.73	1.000	90	90	1.000	0	0	1.000	90
13	207.58	2.50	261.61	1.000	90	90	1.000	0	0	1.000	90
14	217.55	2.50	262.48	1.000	90	90	1.000	0	0	1.000	90
15	227.51	2.50	263.35	1.000	90	90	1.000	0	0	1.000	90
16	237.47	2.50	264.22	1.000	90	90	1.000	0	0	1.000	90
17	247.43	2.50	265.09	1.000	90	90	1.000	0	0	1.000	90
18	257.39	2.50	265.96	1.000	90	90	1.000	0	0	1.000	90
19	267.36	2.50	266.83	1.000	90	90	1.000	0	0	1.000	90
20	277.32	2.50	267.71	1.000	90	90	1.000	0	0	1.000	90
21	287.28	2.50	268.58	1.000	90	90	1.000	0	0	1.000	90
22	297.24	2.50	269.45	1.000	90	90	1.000	0	0	1.000	90
23	307.20	2.50	270.32	1.000	90	90	1.000	0	0	1.000	90
24	317.13	2.50	271.14	1.024	90	72	1.000	0	0	0.968	270
25	326.59	2.50	271.16	1.111	93	78	1.000	1	0	0.892	271
26	335.36	2.50	270.10	1.201	98	82	1.000	2	1	0.824	271
27	343.48	2.50	268.06	1.273	110	85	1.000	2	2	0.783	272
28	351.36	2.50	265.83	1.256	115	86	1.000	2	2	0.795	272

Figure 32. *Table* view showing the strain information for bed 4 of a model.

Navigate the table and get familiar with the type of information reported. For the *Nodes* option, the initial (X_i, Y_i, Z_i) and current (X_c, Y_c, Z_c) coordinates of each node, its displacements (u_X, u_Y, u_Z), and displacement magnitude ($|u|$) are reported. For the *Tetrahedrons* option, the current coordinates of the centroid of each tetrahedron (*Xc*, *Yc*, *Zc*), the magnitude and orientation (trend and plunge) of the principal stretches (S_{max}, S_{int}, S_{min}), and the dilation (the product of the principal stretches) are reported. Notice that in some rows the stretches in a tetrahedron are reported as NA. This corresponds to stretches greater than 5.0.

To sort the table by a column, click the header of the column. You can select several rows or columns, and drag them to any application. You can also save the table as text tab-delimited file using the *File* -> *Save* -> *Table as text* menu or keyboard combination ⌥⌘S.

Finally, every operation in **Trishear3D** is written to the log view. This is a nice way to keep a record of your work. As with the table view, you can select text in the log view and drag it to any application. You can also save the log using the *File* -> *Save* -> *Log as text* menu or keyboard combination ^⌘S .

Keyboard shortcuts

General:

Preferences	⌘,
Help	⌘?
Hide Trishear3D	⌘H
Hide others	⌥⌘H
Quit	⌘Q

Opening and saving a model:

Open a model	⌘O
Save a model	⌘S
Save plot as jpeg	⇧⌘S
Save table as text	⌥⌘S

Save log as text	^⌘S
Load surface from text	⌥⌘O

Modules:

Plot view	⌘1
Table view	⌘2
Log view	⌘3

Creating and running a model:

Create a model	⌘N
Run a model	⌘R
Modify a model	⇧⌘M
Add beds	⇧⌘A
Start new fault	⇧⌘F
Get bed information	⇧⌘B
Get strain information	⇧⌘E
Cross section	⇧⌘X
Run incrementally	⇧⌘R
Surfaces controller	^⌘X

Table:

Select next bed	⌘>
Select nodes	⌘N
Select tetrahedrons	⌘T

Plot:

Zoom in	⌘+
Zoom out	⌘-
Rotate model right	⌘→
Rotate model left	⌘←
Rotate model up	⌘↑
Rotate model down	⌘↓
Translate model right	⌥⌘→

Translate model left	⌥⌘←
Translate model up	⌥⌘↑
Translate model down	⌥⌘↓
Toggle black background	^⌘B
Reset model position	⌥⌘R
Toggle filled or wired mode	⇧⌘O
Toggle fault transparency	⌘4
Toggle fault kinks transparency	⌘5
Toggle trishear zone transparency	⌘6
Toggle beds/surfaces transparency	⌘7
Open light panel	⇧⌘L
Open color map panel	⌥⌘M
Toggle axes	⌥⌘A
Toggle bounding box	⌥⌘B
Show selected bed	⌘\
Select bed above	⇧⌘↑
Select bed below	⇧⌘↓
Draw selected bed	⌘D
Don’t draw selected bed	⇧⌘D
Draw all beds	⌥⌘L
Don't color beds/surfaces	⌘*
Color beds/surfaces by height	⌘[
Color beds/surfaces by vertical displacement	⌘(
Color beds/surfaces by displacement magnitude	⌘)
Set fixed limits for height and displacement	⌘:
Color beds by strain	⌘]
Toggle fault	⌥⌘F
Toggle fault kinks	⌥⌘K
Toggle trishear zone	⌥⌘Z
Toggle tetrahedrons	⌥⌘T
Toggle ellipsoids	⌘0

Toggle principal strain axes	⌥⌘0
Set strain parameter and its limits	⌘.
Show color scale bar	⌘/

Algorithms

The algorithms and implementation of **Trishear3D** are described in detail in Cardozo (2008). Below is a short summary of the algorithms.

Pseudo-3D trishear

In the pseudo-3D algorithm (Cristallini and Allmendinger, 2001) a number of serial 2D sections, all parallel to the fault movement plane, are solved. The fault movement plane is defined by the fault slip vector (*x*) and the pole to the fault (*y*) (Figure 33a). The velocity field in each section is computed in the local *xy* coordinate system, attached to the *z* axis (perpendicular to the fault slip vector) and with origin at the fault tip 1 (Figure 33a). The equations used to compute the velocity field are those of the simplest trishear model: A symmetric trishear zone with v_x linear in y (Zehnder and Allmendinger, 2000, their equations 2 and 6).

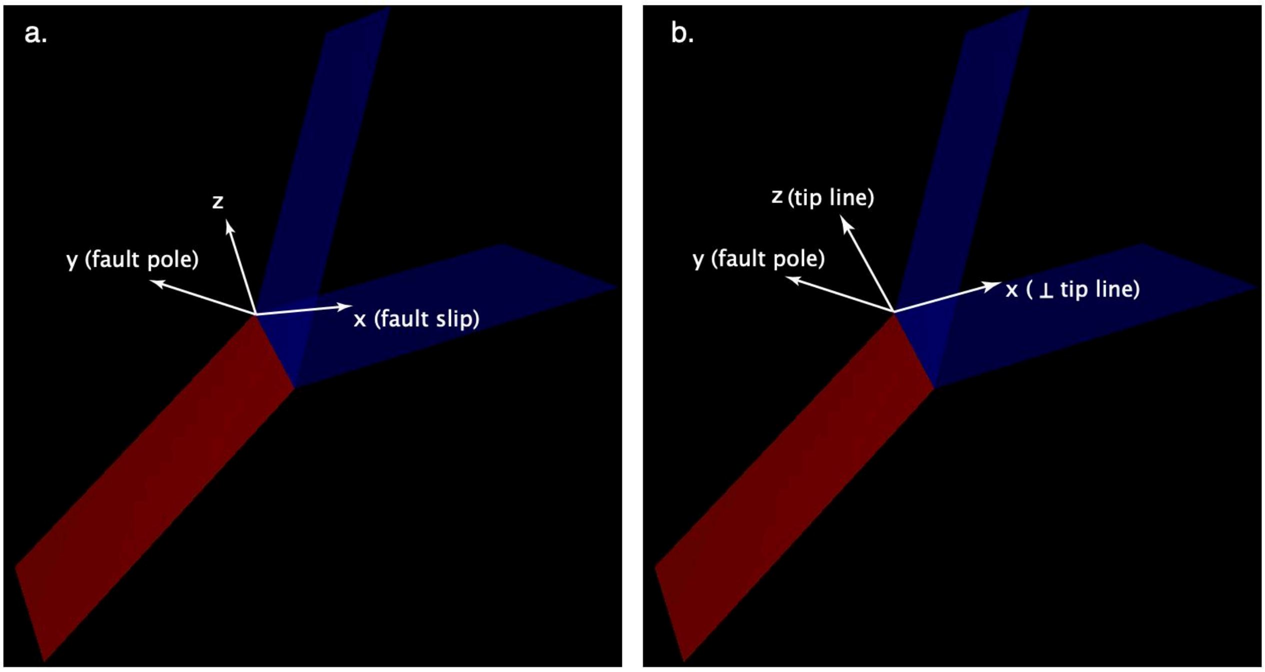


Figure 33. Coordinate systems for the a. Pseudo-3D and b. 3D trishear models.

The orientation of the *xyz* local coordinate system remains the same as long as the direction of the fault slip vector does not change. Therefore it is not necessary to update the length of the tip line and the variation of parameters along the *z* axis.

True-3D trishear

In the true-3D algorithm (Cristallini et al. 2004), a true 3D formulation is solved in a local coordinate system with *x* perpendicular to the fault tip line, *y* perpendicular to the fault plane, and *z* parallel to the fault tip line (Figure 33b).

The local *xyz* coordinate system is attached to the current location of the tip line. Therefore it is necessary to update the local xyz coordinate system, the length of the tip line, and the variation of trishear parameters along the *z* axis, every increment of slip. The equations of the true-3D algorithm are described by Cristallini et al. (2004), but as discussed by Cardozo (2008) there are some problems with this algorithm that can result in considerable volume changes. Please be cautious when using this algorithm.

Lateral fault propagation

In the pseudo-3D model, lateral fault propagation is implemented by augmenting the distance between the fault tips according to the lateral P/S. Notice that the local coordinate system is not changed, but rather the distance between the tips. In the true-3D model, since the local *xyz* coordinate system is attached to the fault tip line, it is just necessary to move the tips according to the fault slip and the across and along-strike P/S, and update the *xyz* local system according to the new position of the tips.

Backlimb kinematics

Backlimb kinematics is solved using the 2D velocity description of Hardy (1995). This formulation allows the computation of the velocity fields for both inclined shear, and mode I fault-bend folding (Suppe, 1983). Fault slip can be varied along strike. Variable fault slip, however, poses some problems in mode I fault-bend folding when in some sections the magnitude of the slip is equal or greater than the length of the footwall ramp, while in other sections it is lower. In this case the active and passive kinks that control the deformation (Suppe, 1983) may switch along strike.

Backlimb kinematics can only be modeled if fault slip is perpendicular to strike (rake = 90°) and the *Lateral fault propagation* option in the *Preferences* panel is off. Also make sure that the kink axes of backlimb kinematics and the trishear zone do not cross.

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