Tutorial D (Geothermal and Microseismic)

Parent topic: User Manual and Tutorials

This short course provides:

- An introduction to building and updating a 3D geology model using 3D GeoModeller.
- A demonstration of 3D GeoModeller's geothermal modelling capability.

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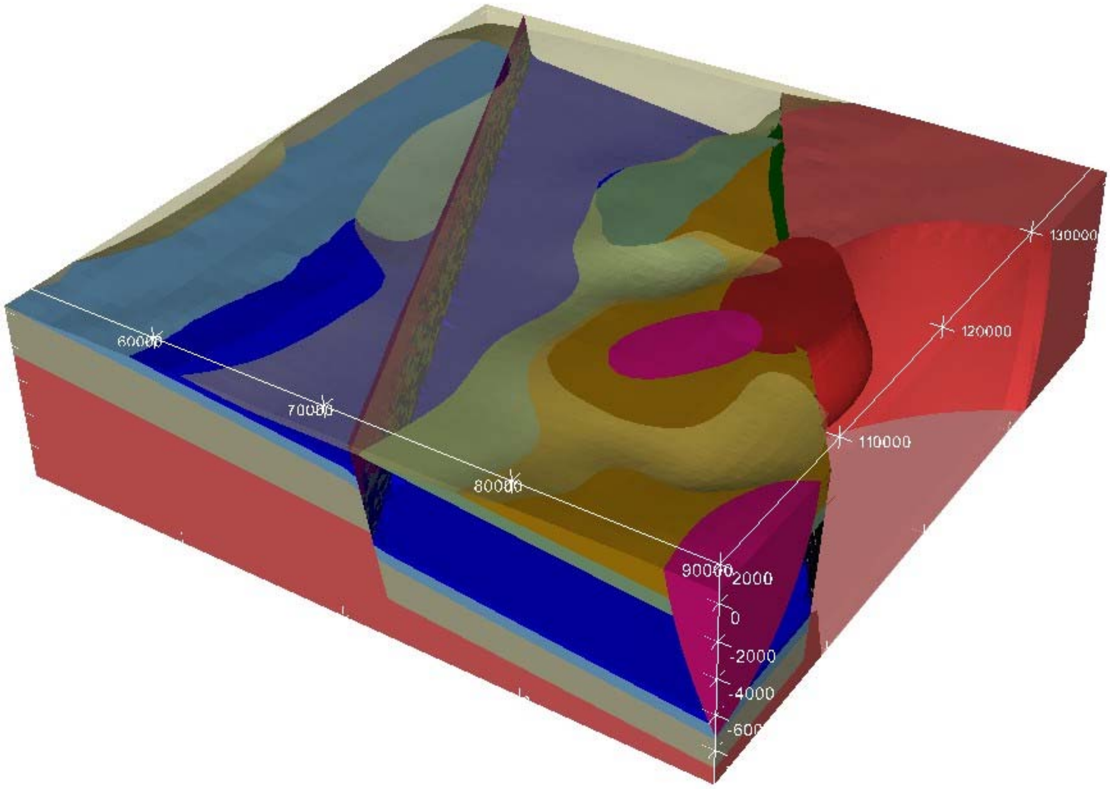

Disclaimer

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In this case study:

Introduction to Tutorial D

Parent topic: **Tutorial D (Geothermal and Microseismic)**

In this case study we calculate the equilibrated, steady state temperature distribution of the modelled geology in our project area. Given certain assumptions and boundary conditions (described below), the distribution of resulting in-situ formation temperatures is related to the 3D distribution of lithologies in our model, and their related thermal properties (thermal conductivity and heat production rate). At present the geothermal module accounts for heat contributions from conductivity and internal heat production. This is considered to be adequate for many geological settings involving 'hot dry rock' geothermal resources. However, improved 3D temperature estimation will be available in the future through implementation of advection considerations.

HotRox Project scenario

Geothermal energy company geologists have established from outcrop samples that the HotRox Project granite has anomalously high heat-producing properties due to its radiogenic mineralogy (heat production rate of 15 $\mu W/m^3$). The granite outcrops east of a major basin-margin fault, but interpretation of seismic and gravity data indicate that the granite also extends further west beneath the basin sediments in the vicinity of Section sCC. The Upper Palaeozoic unit of the basin sequence is a fine grained shale with low thermal conductivity (1.5 W/m/K—based on analysis of samples from drillhole DDH3 on Section sCC). This shale unit is potentially a thermal insulator.

With encouraging results from heat flow data and geothermal gradients measured in drillhole DDH3, the company has begun a 3D geology and temperature modelling study to:

- Investigate the geothermal potential of their tenement, and to
- Estimate the total heat resource of their project 'volume'

Course Structure

Parent topic: Tutorial D (Geothermal and Microseismic)

This case study has two main sections:

- Build and Revise a 3D Geology Model
- Perform Geothermal Modelling

Build and Revise a 3D Geology Model

Parent topic: Course Structure

Tutorial D1: Load the HotRox 3D GeoModeller Project

We load an existing project, and examine the main elements of the user interface

Tutorial D2: Examine the Project Geology Map and the 3D Geology Model

First examine the geology map for the project, and review the project's stratigraphic pile. Compute the geology model. Plot the geology model in map and section views in the **2D Viewer**. Build the 3D shapes of the geology model and examine in the **3D Viewer**.

Tutorial D3: Geo-register the Geology Map

Existing geology maps and sections are easily geo-registered, and contacts digitised. We geo-register the geology map on the TopoMap (surface) section.

Tutorial D4: Add Geology 1—Create a Formation, Update Stratigraphy

We want to add the LateGranite1 intrusive to our geology model. We must first create a geology object, and update the stratigraphic pile.

Tutorial D5: Add Geology 2—Digitise and Recompute the Model

We can now digitise the LateGranite1 contact, and build a revised 3D geology model. And again examine the 3D geology model in 2D and 3D views.

Tutorial D6: Import Drillhole Data and Recompute the Model

We import data for three drillholes, and project the drillhole geology onto vertical cross-sections. Note the inconsistency between the new data and the existing 3D model and consider the implications. Introduce a new fault to the project, compute the new 3D geology model. Again examine the 3D geology model in 2D and 3D views.

Perform Geothermal Modelling

Parent topic: Course Structure

Tutorial D7: Add the Geothermal Physical Property Data

We now add geothermal physical property data for each geology unit—the thermal conductivities and heat production rates.

Tutorial D8: Compute Geothermal Solutions

Set up boundary conditions, and compute in situ temperatures throughout the volume of our 3D geology model. Examine the results for temperature and other temperature-related parameters (heat flow and geothermal gradient) on selected sections.

Import and Analysis Microseismic Data

Parent topic: Course Structure

Tutorial D9: Microseismic 3D modelling and analysis

We now import Microseismic data from Enhanced Geothermal Stimulation within its geological context. Using Geomodeller analysis tools helps to understand the fracking system.

Tutorial D1: Load the HotRox 3D GeoModeller Project

***Parent topic:* Tutorial D (Geothermal and Microseismic)**

In this tutorial we load a 3D GeoModeller project and examine the components of the 3D GeoModeller workshops.

In the tutorial:

- D1 Steps
- D1 Discussion
- D1 More information

D1 Steps

***Parent topic:* Tutorial D1: Load the HotRox 3D GeoModeller Project**

1 Launch 3D GeoModeller from the desktop icon

The 3D GeoModeller welcome screen appears with a main menu and toolbars arranged across the top, left and right sides.

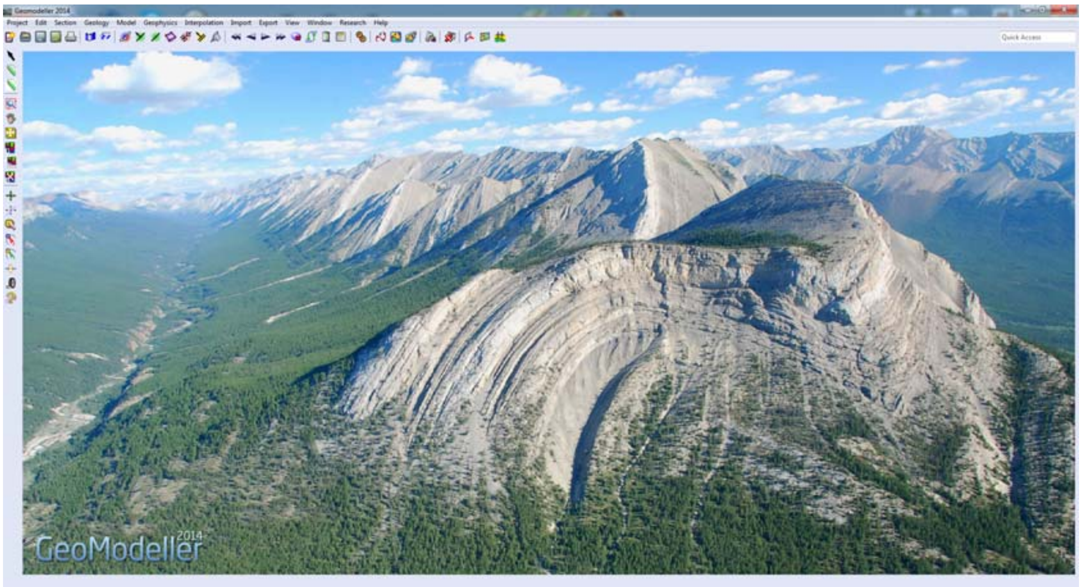


Figure 1. 3D GeoModeller welcome screen.

2 Open the start-point 3D GeoModeller project.

From the main menu choose **Project > Open** or
from the **Project** toolbar choose **Open** or
press CTRL+O

In the **Open a project** dialog box navigate to the 3D GeoModeller Project **`.xml`** file. In a typical installation this will be in:

`Tutorial_D\Tutorial_D1\D1Beginning_Project\HotRox_Start_Ex1.xml`

Choose **Open**.

3 Save your own copy of this project, so that you don't accidentally overwrite the original files. The file name you choose should not contain any spaces (e.g. **`My_Tutorial_D1`**). It is important to save your progress regularly.

From the main menu choose **Project > Save as** or
from the **Project** toolbar choose **Save As** or
press CTRL+SHIFT+S.

D1 Discussion

Parent topic: **Tutorial D1: Load the HotRox 3D GeoModeller Project**

Examine the main elements of the 3D GeoModeller workspace.

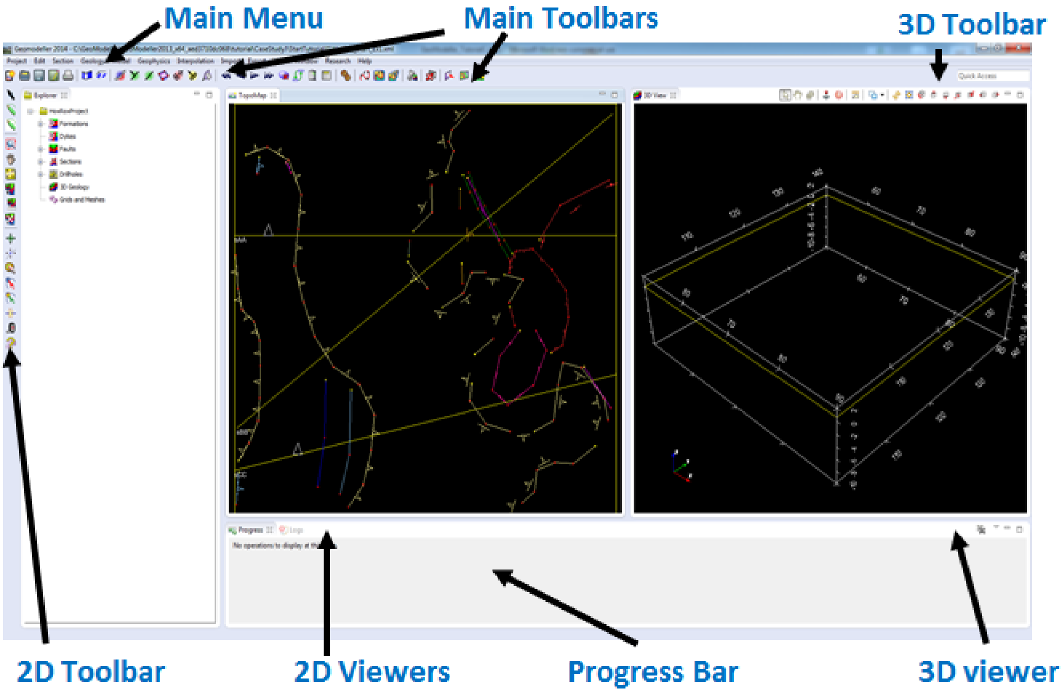


Figure 2. Main elements of the 3D GeoModeller workspace.

Note in particular:

- **Project Explorer**—this has a tree structure containing the many objects that make up our 3D geology project: Formations, Faults, Models, Sections, Drillholes, etc.
- **2D Viewer**—contains 2D sections. This Tutorial D1 project contains several sections—a special one—the 'geological map view' (labelled as TopoMap in this project), and four vertical cross-sections. We use the sections for data input, and for examining 2D plots of our 3D model.
- **3D Viewer**—contains the 3D view of our project. At this stage it shows only the bounding extents of the project. The yellow lines are the outlines of the TopoMap section (the topography of the project area) in the 3D Viewer, and the four vertical sections.

D1 More information

Parent topic: **Tutorial D1: Load the HotRox 3D GeoModeller Project**

Some comments about the 3D GeoModeller project space:

- X (East), Y (North) and Z (Elevation, positive upwards) are a standard coordinate framework according to a right-hand rule
- X, Y and Z are all in the same units—metres (Cannot be degrees of latitude or longitude)
- X and Y would typically be real world projected coordinates, but could be a local mine grid, etc.
- Z is Elevation, and is positive upwards. It also would typically use a real world vertical datum such as mean sea level

- You can (and should) define the Projection (actually a Coordinate System, consisting of a Datum and Projection)
- All data must be within the project limits; data outside those limits cannot be imported or created
- Likewise all modelled results—geology lines, polygons and surfaces—are within those limits

So, when you create your own project, make the project dimensions large enough to include all geology data used in the project.

Remember to allow for the full topographic height of the project area:

- We recommend that you leave, say, 5–10% extra space at the top of the project, above the highest point of the topography
- Allow sufficient project space at the bottom for the entire range of modelled geology that you are interested in. Don't, however, make it too large or you will take extra time to compute model shapes that are of no interest

For this project the project dimensions and coordinate system (Datum and Projection) are:

- **Projection**—**Local**
- **Height Datum**—**Local**
- Extents

	Minimum	**Maximum**	**Range**
East	50,000	90,000	40,000 m
North	100,000	140,000	40,000 m
Z-axis	–10,000	2,000	12,000 m

The topography map view (TopoMap) in a 3D GeoModeller project is a special (pseudo-non-planar) section, and it is an essential part of the project. You cannot do any practical work in a 3D GeoModeller project until the map view section has been created. Since topography defines the natural upper limit of a typical 3D geology model, we use a digital terrain model (DTM) file to correctly define the shape of this special TopoMap section. Using the correct topographic shape has geology mapping advantages, and we recommend it.

If a DTM is not available, the map view section can simply be a horizontal plane at a specified height. (We don't recommend this. If you don't have your own DTM, download DTM data from the Shuttle Radar Topographic Mission website.)

Once the DTM (topography) has been loaded, and the map view section created (called TopoMap in this project), the 3D GeoModeller project dimensions cannot be changed.

Tutorial D2: Examine the Project Geology and the 3D Geology Model

Parent topic: Tutorial D (Geothermal and Microseismic)

The HotRox_Start_Ex1 3D GeoModeller Project that we loaded in Tutorial_D1 has a geological model of most of the HotRox project area.

In this section:

D2 Overview

Parent topic: Tutorial D2: Examine the Project Geology and the 3D Geology Model

In this tutorial we:

1. Examine the geology map for the project, and review the Project's stratigraphic pile
2. Compute the geology model, and plot modelled geology in map and section views (**2D Viewer**)
3. Build 3D shapes of the geology model and examine (**3D Viewer**)

D2 Stage 1—Compute and view the 3D model

Parent topic: Tutorial D2: Examine the Project Geology and the 3D Geology Model

1. If it is not already open, open your project, or the supplied start-point 3D GeoModeller project for Tutorial D1.

   From the main menu choose **Project > Open** or
   from the toolbar choose **Open** or
   press CTRL+O

   (For the start-point project supplied) In the **Open a project** dialog box navigate to the 3D GeoModeller Project **`.xml`** file

   `Tutorial_D\Tutorial_D1\D1BeginningProject\HotRox_Start_Ex1.xml`

2. *(If you have not already done so)* Save your own copy of this project, so that you don't accidentally overwrite the original project files

   From the main menu choose **Project > Save as** or
   from the toolbar choose **Save As** or
   press CTRL+SHIFT+S.

   Save your project work (e.g. **`My_Tutorial_D2)`** in a folder outside the original **`StartTutorial`** folder.

3 Examine the geology map and stratigraphic column (Figure 3).

Consider the rock relationships, including:

- Cross-cutting relationships
- Timing implications
- Conformable sequences

From the main menu choose **Geology > Stratigraphic Pile: Visualise** to open the **Stratigraphic Pile Viewer**.

Compare the stratigraphic pile in the 3D GeoModeller Project (Figure 4) with the geology map. Note the important geological details that are recorded in the stratigraphic pile (Figure 4)—the chrono-stratigraphic order of geological events, the onlap or erode relationships, etc. You may spot that LateGranite1 in the geology map is not yet in the model—we will add that in Tutorials D4 and D5.

4 Compute the 3D geology model for the Project that we have loaded (to be constrained by the geological data existing within the current Project).

From the **Model** toolbar, choose **Compute** or press CTRL+M

In the **Compute the Model** dialog box:

- **Faults only**—Clear check box in top left corner (therefore DO compute faults)
- **Series to interpolate**—Select All
- **Faults to interpolate**—Select All
- **Sections to take into account**—Select All
- Choose **OK**

3D GeoModeller computes the model. (Nothing to see yet.) The model is a mathematical model—a set of interpolator equations that are computed from the geology contacts and orientation data. There is an interpolator equation for each series in the stratigraphic pile, and also an equation for each fault.

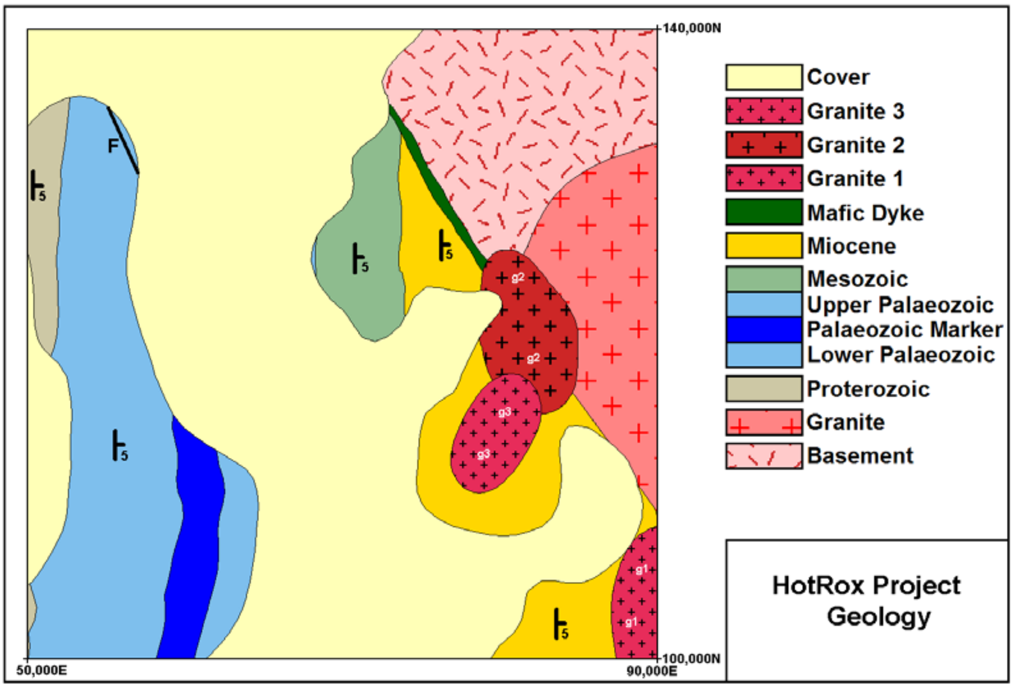


Figure 3. Geology map of the HotRox Project.

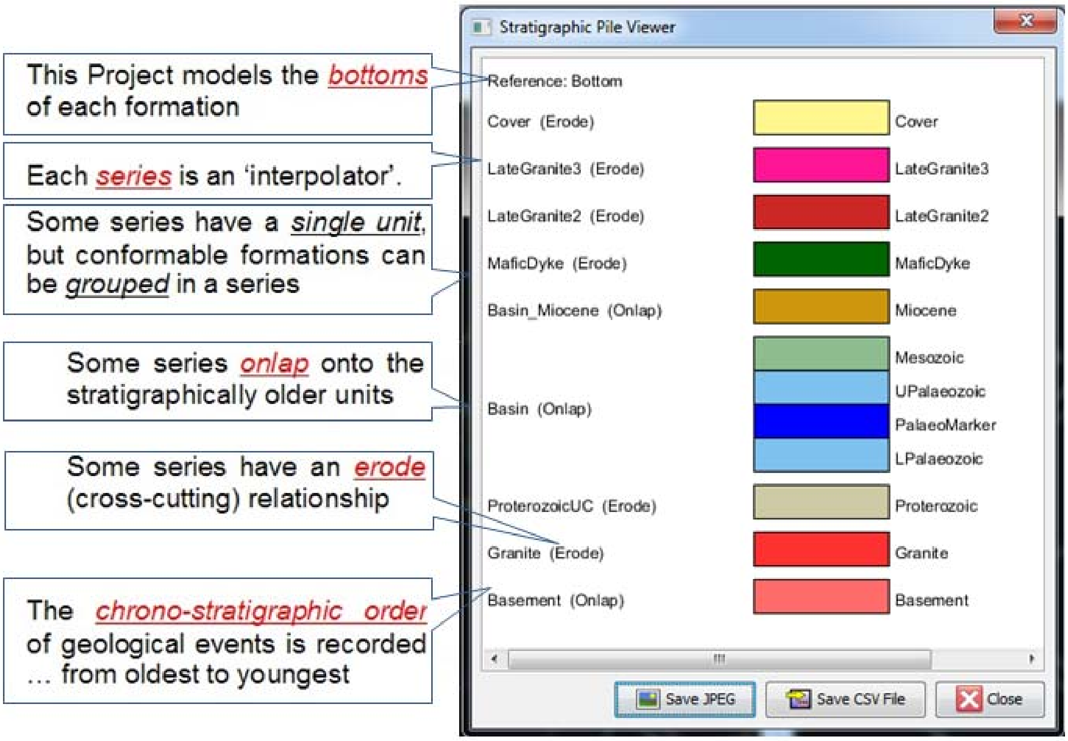


Figure 4. Stratigraphic Pile for the HotRox (Tutorial D1) Project.

View the modelled geology

To see the modelled geology, we need to interrogate the model equations. We can:

- Plot the modelled geology on the TopoMap 2D section (the Project's geological map)
- Plot the modelled geology on any other 2D cross-section
- Build the 3D shapes of the modelled geology, and view in the **3D Viewer**

5 Select **TopoMap** in the **2D Viewer** (click it)

6 From the **Model** toolbar, choose **Plot the model settings** or press CTRL+D

In the **Plot the model settings** dialog box:

- Check **Show lines**
- Choose **OK**

The lines of the modelled geology are plotted on the TopoMap 2D Section (map).

7 Repeat these steps and plot the modelled geology on some of the vertical cross-sections.

e.g. **Right-click on sAA section > Open 2D Viewer**

Click on **sAA section tab** in 2D Viewer, then repeat step 6 above.

8 Save your project

From the main menu choose **Project > Save** or
from the toolbar choose **Save** or
press CTRL+S.

D2 Stage 2—Explore model plotting options

Parent topic: **Tutorial D2: Examine the Project Geology and the 3D Geology Model**

1 Experiment with other options in the **Plot the model settings** dialog box:

- Check **Show fill** to plot 'solid' geology
- Choose **Apply to All** (sections) to plot all (open) 2D sections
- For **Show lines** or **Show fill**, select or de-select various combinations of formations
- Choose **Show trend lines** in combination with **Show lines** or **Show fill**
- Modify the Plotting resolution from the default u=50, v=50 to, say, 100 x 100

2 Experiment with the three plot buttons in the **Model** toolbar:

- **Plot the model settings** or press CTRL+D
- **Plot the model on the current section**
- **Plot the model on all sections**

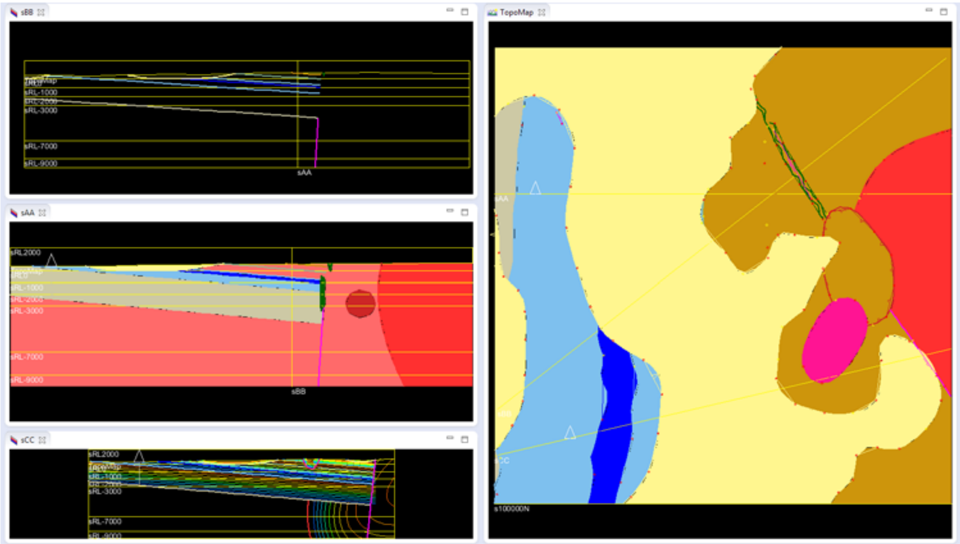


Figure 5. Various plots options displaying the 3D geology model on Sections TopoMap, sAA, sBB and sCC. Further display options can be found in Tutorial A.

3 Save your project

From the main menu choose **Project > Save** or from the toolbar choose **Save** or press CTRL+S.

D2 Stage 3—Explore the 3D Viewer

Parent topic: **Tutorial D2: Examine the Project Geology and the 3D Geology Model**

1 View the model in 3D:
   - From the **Model** toolbar choose **Visualise 3D Formations and Faults**
   - In the **Build 3D Formation and Fault Shapes** dialog box:
     - Check **Build**—**Formations**
     - Check **Build**—**Faults**
     - Select **Type**—**Volume**
     - Check **Draw Shapes after building**
     - Adjust the **Resolution**—**Render quality** to High
     - Choose **OK**

   3D GeoModeller computes the 3D shapes of the geology model as 'volumes' defined by triangle mesh surfaces, which it displays in the 3D Viewer.

2 Use the **Project Explorer** (typically on the left-side of your work space) to manage the display of modelled objects in the 3D Viewer. To rotate the view of the modelled object, click and drag the cursor in any direction within the 3D Viewer.
   - In the **Project Explorer** right-click **3D Geology >** and select **Hide**—to hide the entire modelled geology
   - In the **Project Explorer** right-click **3D Geology >** and select **Show**—to show again the entire modelled geology

     The **Hide** or **Show** options toggle from one to the other.
   - In the **Project Explorer** right-click **3D Geology >** and select **Wireframe**—to change the displayed 3D volumes to wireframes
   - In the **Project Explorer** right-click **3D Geology >** and select **Shading**—to toggle the 3D display of geology back to shaded

     The **Wireframe** or **Shading** options toggle from one to the other.

3 Display the plotted geology (2D) sections in the **3D Viewer**
   - With any **2D Viewer** window selected (for example, sAA) from the shortcut (right-click the background of the 2D viewer), and choose from the Menu:
     - **Show modelled geology polygons in 3D Viewer**
     - or, **Show modelled geology lines in 3D Viewer**
     - **Hide modelled geology polygons in 3D Viewer**

     These menu items toggle between **Hide** and **Show**.

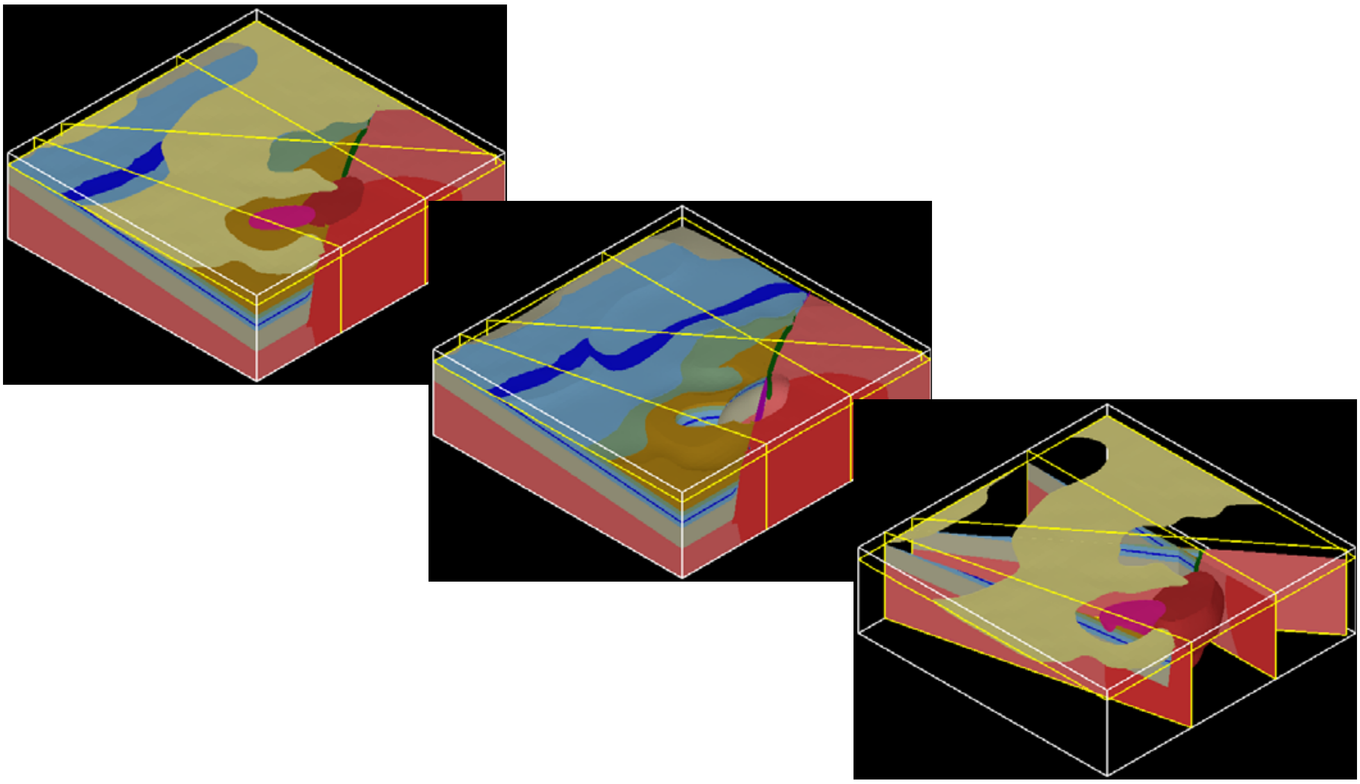


Figure 6. Various 3D plots of the 3D geology model.

4 Save your project

From the main menu choose **Project > Save** or
from the toolbar choose **Save** or
press CTRL+S.

Discussion—What data have been used to make this model?

We have now examined this project in traditional 2D views, and also in a 3D Viewer, but what data have been used to make this model?

We have used the following geological facts and interpretive data:

- The stratigraphic order of events and the rock relationships—both recorded in the stratigraphic pile
- Mapped geology contacts on the TopoMap surface section
- Some field-measured orientation data, also on the TopoMap section
- Drilled geology intervals from two drillholes
- Some additional interpretive data on other vertical and horizontal slice sections

To examine these actual data, use the **Project Explorer** to investigate the geology interface and orientation data catalogued within, and find the corresponding data for each lithology stored in structures linked to either: 2D Sections, or Drillholes.

D2 Stage 4—Visualising drillholes

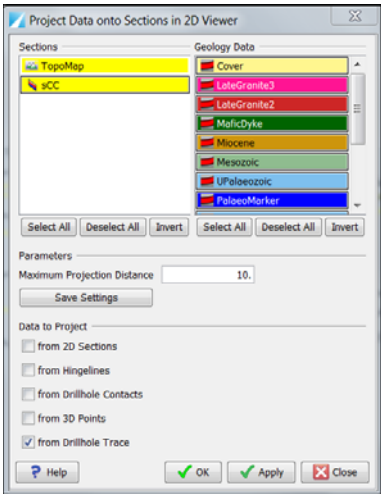
Parent topic: **Tutorial D2: Examine the Project Geology and the 3D Geology Model**

In this section we learn about viewing drillholes.

Show and Hide drillholes in the 3D Viewer

1. First, in the **Project Explorer** right-click **Models > 3D Geology** and select **Hide**—to hide the entire modelled 3D geology (so the drillholes will be visible)
2. In the **Project Explorer**, right-click **Drillholes >** and select **Show**—shows all drillholes in the 3D Viewer
3. In the **Project Explorer**, right-click **Drillholes >** and select **Hide**—hides them again from the view

You can also show or hide individual drillholes, by first expanding the list of drillholes in the Project Explorer.



Show drillholes in a 2D Viewer (Project them onto a Section)

1. From the **Model** toolbar, choose **Project Data Onto Sections in 2D Viewer**
   or press CTRL+I
2. In the **Project Data Onto Sections in 2D Viewer** dialog box
   - **Sections**—Select sCC, for example
   - **Geology Data**—**Select All**
   - **Maximum Projection Distance**— e.g. try 10m
   - **Data to project**—Check **from Drillhole Trace**
   - Clear all other check boxes
   - Choose **OK**

The trace of HRW2 can now be seen in the 2D Viewer for sCC, because the drillhole is located less than 10m off that section.

Now examine the geology intervals in a drillhole using drillhole properties

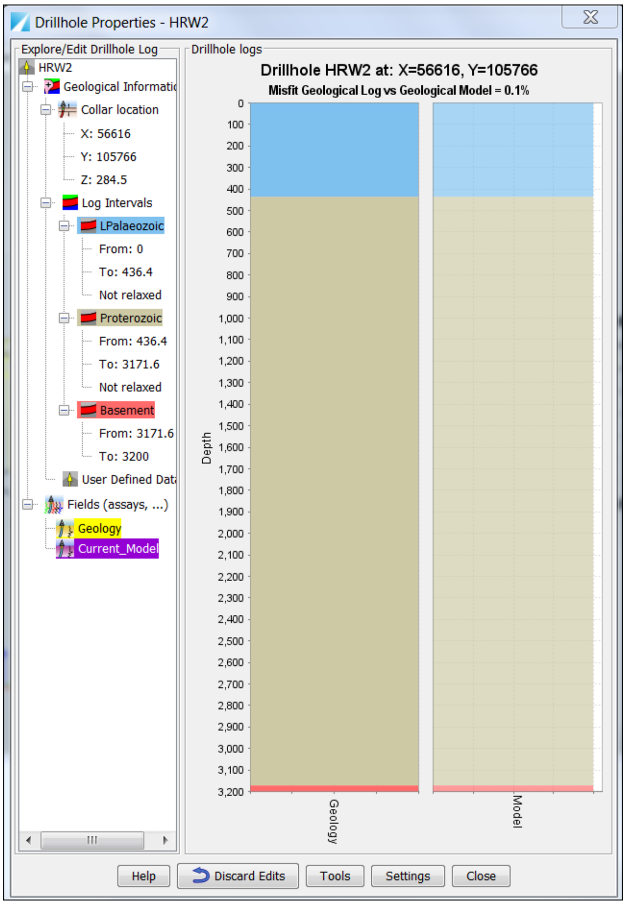
Either:

In the **Project Explorer**, choose and expand **Drillholes > (**select a **Drillhole** name**) >** right-click and choose **Properties**. This opens the **Drillhole Properties** table for a drillhole, showing the downhole depths and the intersected geology for each interval.

Alternatively:

1. From the **2D toolbar**, choose **Select**
2. Make sure Project Data Onto Sections is shown for at least one drillhole, on at least one section, as explained above.
3. Right click on any projected drillhole trace or triangle symbol in a section in the **2D Viewer** and select **Edit**

This opens the **Drillhole Editor** table for a drillhole:



4 Save your project

From the main menu choose **Project > Save** or from the toolbar choose **Save** or press CTRL+S.

Tutorial D3: Geo-register the Geology Map

Parent topic: Tutorial D (Geothermal and Microseismic)

Existing geology maps and sections are an important source of geology data. These are easily geo-registered onto sections, and geology contacts can be digitised.

In this tutorial we geo-register the geology map on to the project's TopoMap Section.

In this section:

- D3 Steps

D3 Steps

Parent topic: Tutorial D3: Geo-register the Geology Map

1 If it is not already open, open your project.

2 Save a new copy of your project with a new name

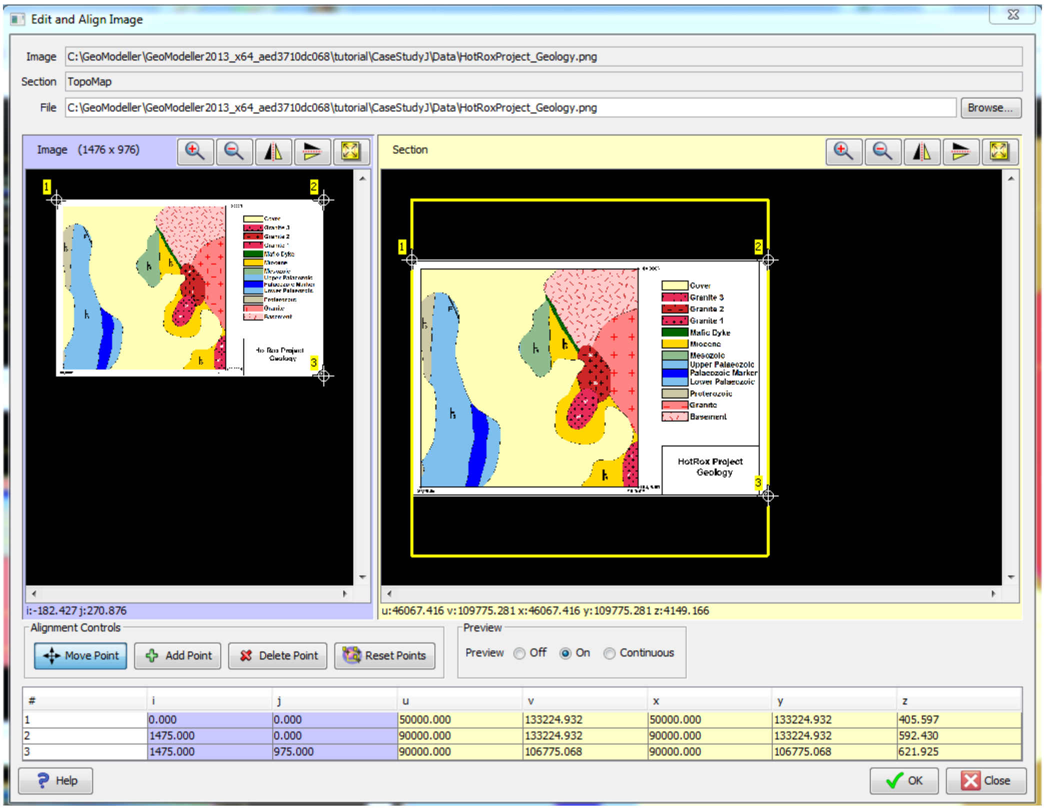
From the main menu choose **Project > Save as** or from the toolbar choose **Save As** or press CTRL+SHIFT+S.

In the **Save the project** dialog box, change the name (e.g. from `My_Tutorial_D2` to `My_Tutorial_D3`) and then choose **Save**.

3 In the **TopoMap** section in the **2D Viewer,** right click and choose **Image Manager** from the context menu.

4 In the **Image Manager** dialog box, choose **+** in the lower left corner to launch the **Edit and Align Image** tool.

5 From the **Edit and Align Image** tool, browse to the image file `Tutorial_D3\Data\HotRoxProject_Geology.png.` Select and **Open**.



#	i	j	u	v	x	y	z
1	0.000	0.000	50000.000	133224.932	50000.000	133224.932	405.597
2	1475.000	0.000	90000.000	133224.932	90000.000	133224.932	592.430
3	1475.000	975.000	90000.000	106775.068	90000.000	106775.068	621.925

Figure 7. Geo-registration of the geology map image onto the TopoMap section.

The **Edit and Align Image** tool displays the image in two windows:

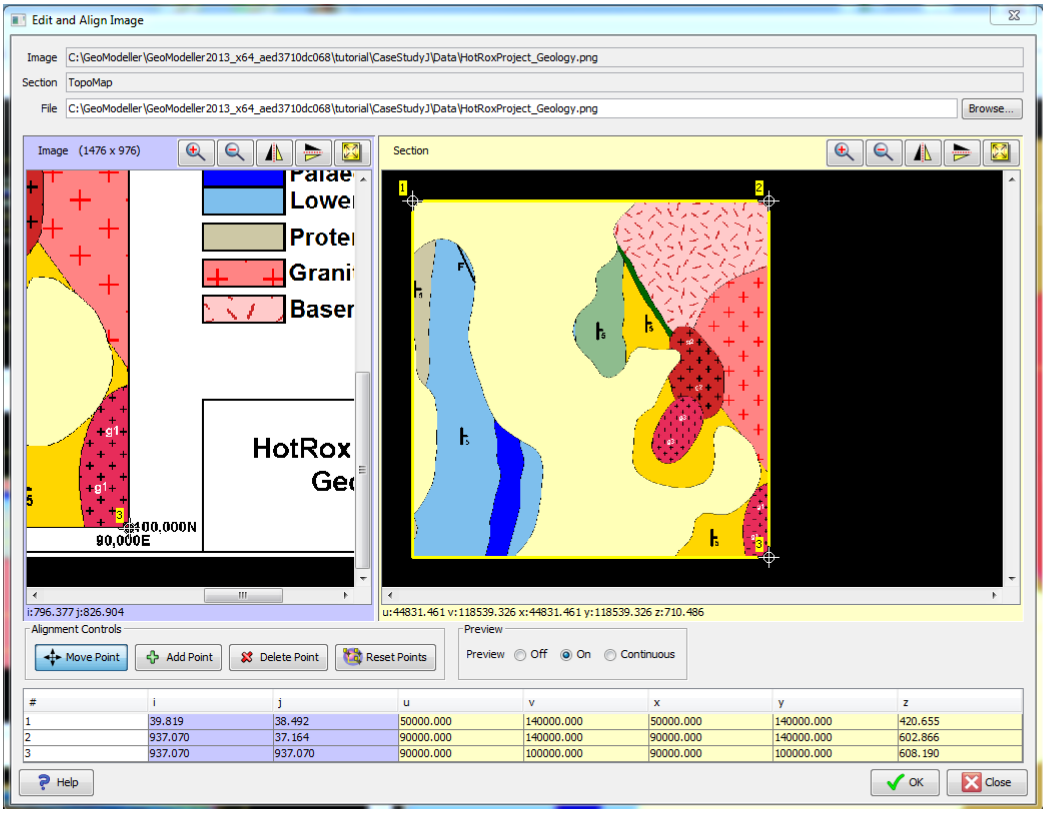
- An **Image** display on the left, which operates in terms of the image’s (i, j) pixel coordinates. There are three moveable image markers on this display, which are linked one-to-one to corresponding section markers of the **Section** display (on the right). The (i, j) coordinates of the three image markers are tabled below the display.
- A **Section** display on the right, which operates in terms of the section’s (u, v) coordinate space. There are three moveable section markers on the display. The (u, v) coordinates and corresponding (x, y, z) coordinates of the three section markers are tabled below the display.

6 Examine the image and note that map corners can be used as geo-registration marks as they have known coordinates. Press the magnifier icon to zoom; use the two sliders to pan horizontally or vertically to read map corner coordinates..

	Bottom or Left	Top or Right
East	50,000	90,000
North	100,000	140,000

7 In **Image** display (pale blue area, left side), move the three image markers to three known geo-registration marks at the corners of the map (1 = top left, 2 = top right and 3 = bottom right). Zoom in, and pan to each mark, and position the image markers precisely on the geo-registration marks. You can also directly edit the (i, j) coordinates in the table to move the image markers to specific pixel coordinates.

8 In the **Section** display (yellow area, right side), you can move the three corresponding section markers, but the recommended practice is to edit the entries for the (u, v) coordinates in the table below, inputting the known (u, v) coordinates (e.g. 90,000) corresponding to each of the geo-registration marks on the image. The section markers will move as you do this. Again, zoom and pan if you want to. You can also directly edit the (x, y, z) real coordinates in the table. The (x, y, z) option is useful when geo-registering an image on a vertical section.



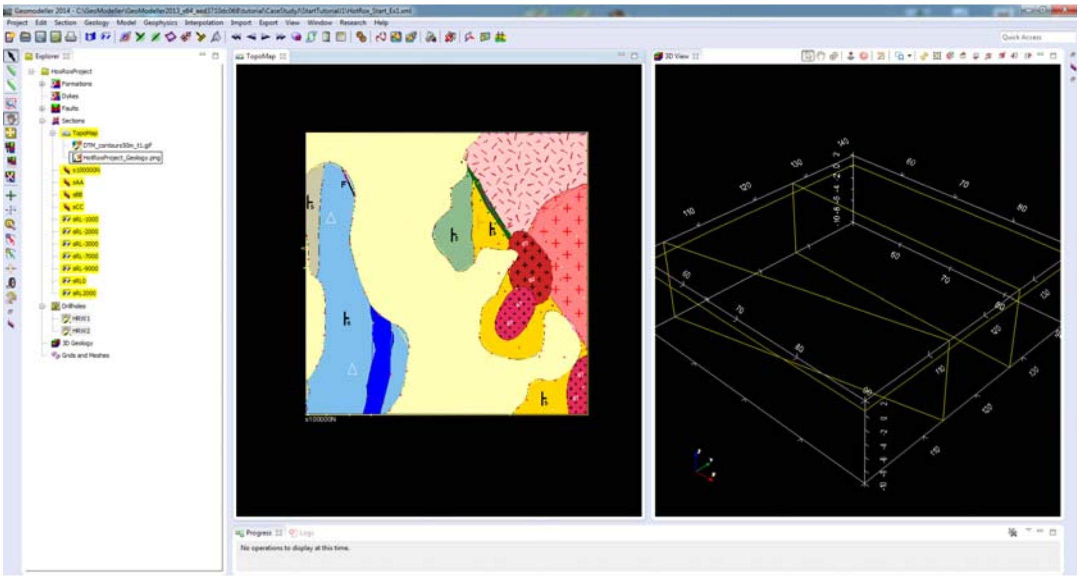
9 Additional marker points can be added (they are added to both displays).

As both the image markers and the section markers are moved, the image is continually ‘distorted’ in the **Section** display, illustrating the proposed geo-registration warping based on the current set of marker positions on the two displays.

10 With the image markers correctly placed precisely on the known geo-registration marks on the **Image** (left), and the known coordinates corresponding to each of the section markers correctly entered in the table below, choose **OK**.

11 Back in the **Image Manager** dialog box, check `HotRoxProject_Geology.png` and choose **Close**.

Having geo-registered the geology map image, you can plot the current model on the TopoMap Section. Compare the modelled geology—as developed to this point—with the map. Notice that the late-stage granite intrusive in the south-east corner of the map has not yet been modelled. We will add that unit in Tutorials D4 and D5.



12 Save your project

From the main menu choose **Project > Save** or from the toolbar choose **Save** or press CTRL+S.

Tutorial D4: Add Geology 1—Create a Formation, Update Stratigraphy

Parent topic: Tutorial D (Geothermal and Microseismic)

We want to add the LateGranite1 intrusive to our geology model. We must first create a geology object, and update the stratigraphic pile. In Tutorial D5 we digitise the LateGranite1 contact, and build the revised 3D geology model.

In this section:

- D4 Overview
- D4 Steps

D4 Overview

Parent topic: Tutorial D4: Add Geology 1—Create a Formation, Update Stratigraphy

In this tutorial we:

1. Create the LateGranite1 geology object
2. Place this in the correct chrono-stratigraphic order in stratigraphic pile for the Project
3. Declare the rock relationship. In this case it cuts across the older stratigraphy

D4 Steps

Parent topic: Tutorial D4: Add Geology 1—Create a Formation, Update Stratigraphy

1. If it is not already open, open your project or the supplied start-point 3D GeoModeller project for Tutorial D4.

   From the main menu choose **Project > Open** or
   from the toolbar choose **Open** or
   press CTRL+O

   (For the start-point project supplied) In the **Open a project** dialog box navigate to the 3D GeoModeller Project **.xml** file

   Tutorial_D\Tutorial_D4\D4Beginning_Project\D4Beginning_Project.xml

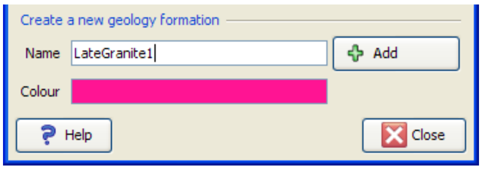
2. Save a copy of this project in your own data area.

   From the main menu choose **Project > Save** as or
   from the toolbar choose **Save As** or
   press CTRL+SHIFT+S.

   Save your project work (e.g. **My_Tutorial_D4)** in a folder outside the original **StartTutorial** folder.

3. From the main menu choose **Geology > Formations: Create or Edit**

4. From the **Create or Edit geology formations** dialog box (Create a new geology formation):



   - **Name**—LateGranite1 (No spaces!)
   - **Colour**—(pink (RGB = 255,20,147) used in this document)
   - Note: Many geology formations already exist in this project.
   - Choose **Add** and then **Close**

5. If prompted, in the **Create Formation** dialog box:

   - Choose **Yes, start Stratigraphic Pile editor**

   Alternatively:

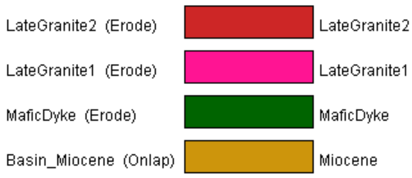
   - From the main menu choose **Geology > Stratigraphic Pile: Create or Edit**

6. In the **Create or Edit geology series and the stratigraphic pile** dialog box:

- For future reference, note that **Bottom** is the chosen option; for this project we model 'bottoms' of formations (i.e., all data entered is assumed to relate to the chronologically, bottom-boundary of the given geology unit, where it contacts with the unit below).
- Choose **New series**

7 In the **Create Geology Series** dialog box, confirm default entries, or change the following to:

- **Name of the series**—LateGranite1; remove '*_Series*' from the default name
- **Relationship**—Erode
- **Formations in Series**—LateGranite1 (Ensure this formation is in the right-side list. Select formation(s) and use the **Add to Series** or **Remove from Series** buttons as required)
- **Commit** then **Close**
- Back in the **Create or Edit geology series and the stratigraphic pile** dialog box:
- Check that the series are in the correct stratigraphic order, with this late-stage granite intrusive placed towards the top of the list, above the Mafic Dyke and below the LateGranite2 (select the new series, and use the **Move up** and **Move down** buttons as required).



- Then **Close**

8 From the main menu choose **Geology > Stratigraphic Pile: Visualise**

9 In the **Stratigraphic Pile Viewer** dialog box, review and then **Close**

10 Save your project

From the main menu choose **Project > Save** or
from the toolbar choose **Save** or
press CTRL+S.

Tutorial D5: Add Geology 2—Digitise and Recompute the Model

***Parent topic:* Tutorial D (Geothermal and Microseismic)**

Having created a geology object, and updated the stratigraphic pile in Tutorial D4, we can now digitise the LateGranite1 contact, and build a revised 3D geology model.

In this section:

- D5 Overview
- D5 Stage 1—Digitise the LateGranite1 geology contact
- D5 Stage 2—Recompute and visualise in 2D and 3D

D5 Overview

***Parent topic:* Tutorial D5: Add Geology 2—Digitise and Recompute the Model**

In this tutorial we:

1. Digitise the LateGranite1 geology contact
2. Recompute the 3D geology model
3. Again examine the 3D geology model in 2D and 3D views

D5 Stage 1—Digitise the LateGranite1 geology contact

***Parent topic:* Tutorial D5: Add Geology 2—Digitise and Recompute the Model**

D5 Stage 1—Steps

1. If it is not already open, open your project (e.g. `My_Tutorial_D4`) or the supplied start-point 3D GeoModeller project for Tutorial D5.

   From the main menu choose **Project > Open** or
   from the toolbar choose **Open** or
   press CTRL+O

   (For the start-point project supplied) In the **Open a project** dialog box navigate to the 3D GeoModeller Project `.xml` file

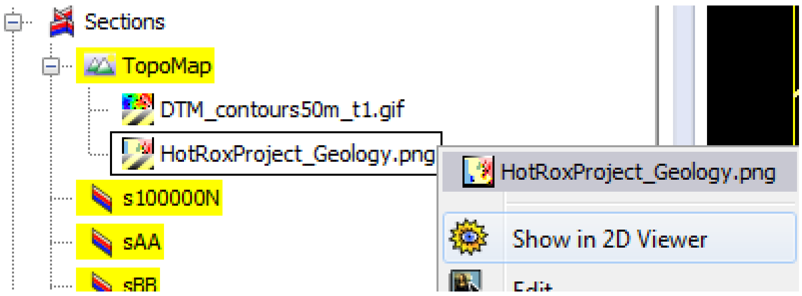
   `Tutorial_D\Tutorial_D5\D5Beginning_Project\D5Beginning_Project.xml`

   Save a copy of this project in your own data area.

   From the main menu choose **Project > Save** as or
   from the toolbar choose **Save As** or
   press CTRL+SHIFT+S.

   Save your project work in a folder outside the original folder.

2. Show the geo-registered image of the geology. From the **Explorer menu**, TopoMap section shortcut menu, choose `HotRoxProject_Geology.png`

   Please make sure the model is not plotted on the TopoMap or it will overlap the image.

   Note the granite body mapped in the south-east corner of the project area, labelled ‘g1’. We will model this granite as LateGranite1.

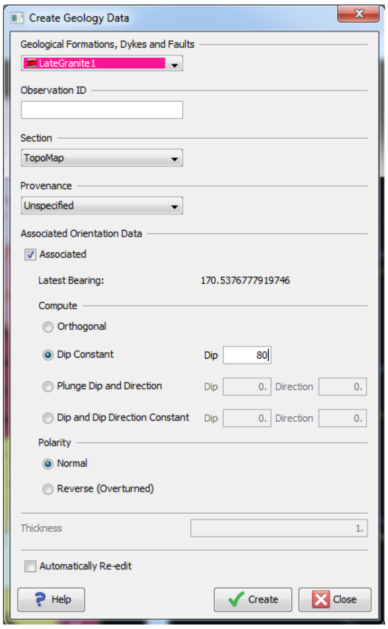
   In Tutorial D4 we created the LateGranite1 geology object. We are now ready to use that object when digitising a few contact data points along the granite boundary. We also want create some orientation data to define that contact as steeply dipping to the south-east.

3 From the **2D toolbar**, choose **Create (Lines)** or press C

4 From the **Points List Editor** toolbar, choose **Delete all Points**

5 Starting at the north-east end, click five or six points along the contact between the granite labelled ‘g1’, and the Miocene unit in dark yellow, located in the south-east corner of the geology map (Figure 8).

6 From the **Structural toolbar** choose **Create geology data** or press CTRL+G



7 In the **Create geology data** dialog box:

- **Geological Formations and Faults**—select LateGranite1
- This dialog box allows us to create some associated orientation data, too—these are orientation data created between each pair of digitised data points.
- Check on **Associated**
- Select **Dip constant**, and set Dip = 80 (degrees)
- **Polarity**—select **Normal**
- Choose **Create**, and then **Close**

8 Save your project. From the main menu choose **Project > Save** or from the toolbar choose **Save** or press CTRL+S.

D5 Stage 1—Discussion

The four or five points that we clicked along the contact using the **Create function** have been used to create geology contact data which define the edge of the LateGranite1 at the TopoMap surface. In addition, associated orientation data have been created between each pair of points, each dipping at 80 degrees, in a direction orthogonal to each line segment (approx. south-east). Note that in the Float or Dock the **Points List Editor** is now empty; the points have been committed to LateGranite1, and removed from the list.

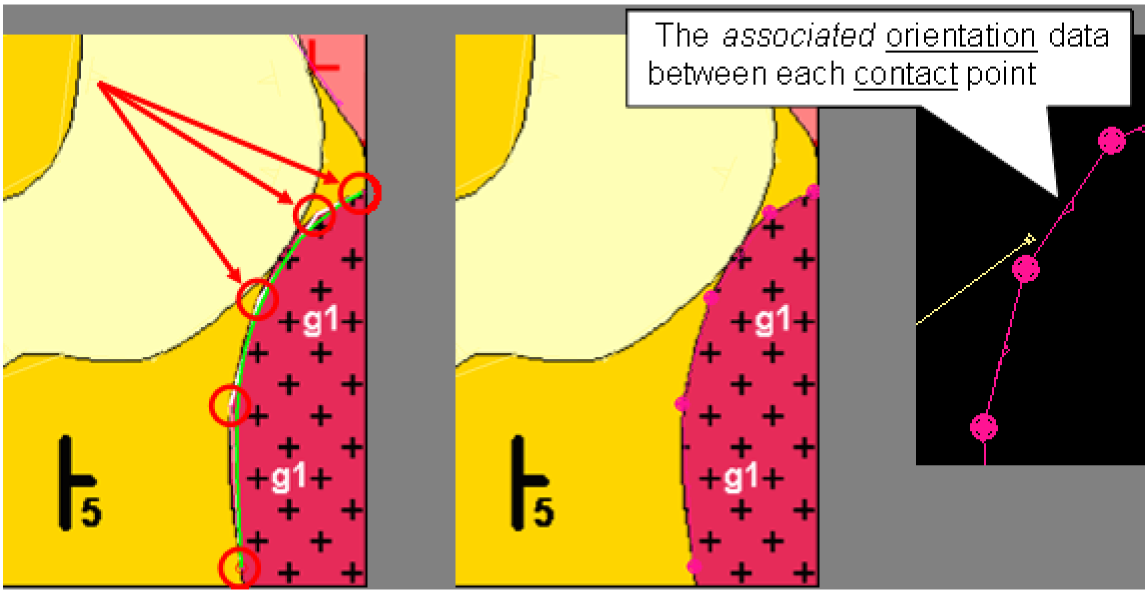


Figure 8. Digitised points (left) in the Points List (of the Points List Editor) are made into 'observations' of the position of the lower contact (geology) of the LateGranite1 (middle and right) by using the **Create geology data** dialog box.

In order to build the 3D model of any surface—either fault or geology formation—3D GeoModeller requires at least one point of contact (or fault position) data, and at least one point of orientation data, describing the attitude of that geology surface. Note that orientation data (of a surface) are entered by 'dip, and dip-direction' protocol in 3D GeoModeller.

Because we used the 'associated orientation data' case above, we have met the criteria, above, for building surfaces (need at least one point of contact [or fault position] data, and at least one point of orientation data).

Alternatively, we could have chosen to create orientation data independently of the contact data using **Create geology orientation data** in the **Structural** toolbar (or press CTRL+R).

D5 Stage 2—Recompute and visualise in 2D and 3D

Parent topic: Tutorial D5: Add Geology 2—Digitise and Recompute the Model

D5 Stage 2—Steps

1 From the **Model** toolbar, choose **Compute** or press CTRL+M

2 In the **Compute the Model** dialog box:

- Note that a new series—the LateGranite1—is now available to be computed:
- Clear the 'Faults only' box
- Series to interpolate—**Select All**
- Faults to interpolate—**Select All**
- Sections to take into account—**Select All**
- Choose **OK**

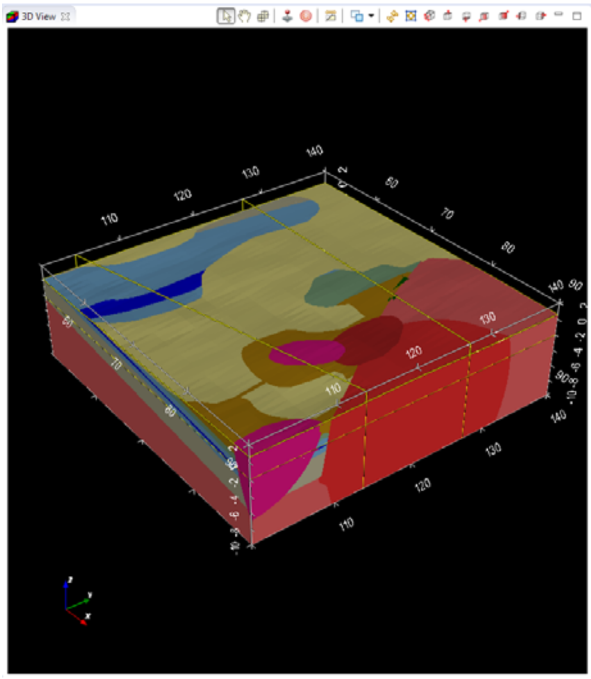
3 From the **Model** toolbar, choose from the available plotting options

- **Plot the model settings** or press CTRL+D
- **Plot the model on the current section**
- **Plot the model on all sections**

Repeat these steps, choosing different options to plot the geology model in different ways on one or more of the sections.

4 From the **Model** toolbar, choose **Visualise 3D Formations and Faults** . Set the **Render Quality** slider to High.

Visualise the revised geology model in the **3D Viewer**. Use the **Project Explorer** to **Show** or **Hide** different formations or units of the 3D geology model.



5 Save your project

From the main menu choose **Project > Save** or from the toolbar choose **Save** or press CTRL+S.

D5 Stages 1 and 2—Discussion

Did your revision produce the expected granite body in the south-east corner of the project area? To check this you need to plot 'solid geology' rather than 'lines', and compare your result with Figure, below.

If your solid geology map looks like the figure below (a), your 3D geology model is correct; the LateGranite1 body is a 3D body in the south-east corner of the project.

If your map looks like (b):

- what has gone wrong?
- how did this happen?
- how do you fix it?

What has gone wrong?

Essentially the problem is the 'facing direction' of the geology boundary that you created to model LateGranite1. If you look closely at the 'associated orientation data' that we created, you will see that—for the incorrect case—the dips are steeply dipping towards the north-west (Figure 9b). This is also the 'facing' direction, and, as a result, the modelled LateGranite1 body lies to the north-west side of the digitised contact.

How did this happen?

At Step 6 of Stage 1 (above) we stated "Starting at the north-east end, click four to five points along the contact". The key point is 'Starting at the north-east end'. In creating 'associated orientation data' with a constant dip of 80 degrees—as we did in Step 8 of Stage 1—those orientation data are generated to be dipping in a direction which is locally orthogonal to each line-segment of the digitised line—and to the left. If you digitised the line starting at the north-east end and working towards the southern end, then 'left' would be 'towards the south-east', which would be correct. But, if you digitised the line in the other direction—starting at the southern end—then 'left' would be 'towards the north-west', yielding the wrong result.

How do you fix this?

This small problem is easily fixed.

1. Move the mouse pointer over the LateGranite1 digitised data points and right click to open the shortcut menu
2. Choose **Flip Order of Points**

The 'associated dips' will be changed to now dip at 80 degrees towards the south-east. When the model is re-computed and re-plotted, the modelled geology map will now be correct.

Remember, the alternative method of adding orientation data (slower, but perhaps more foolproof) is not to use the 'associated orientation data' method, but the independent method: From the **2D toolbar**, choose **Create (Lines)** or press C. Digitise two points in the approximate position along the strike-direction of the dipping surface. In the **Structural** toolbar choose **Create geology orientation data** (or press CTRL+R).

In the **Create geology orientation data** dialog box:

Geological Formations and Faults—select LateGranite1

Direction—select dip direction=105 degrees, and select Dip=80 degrees

Polarity=Normal. Choose **Create** and **Close.**

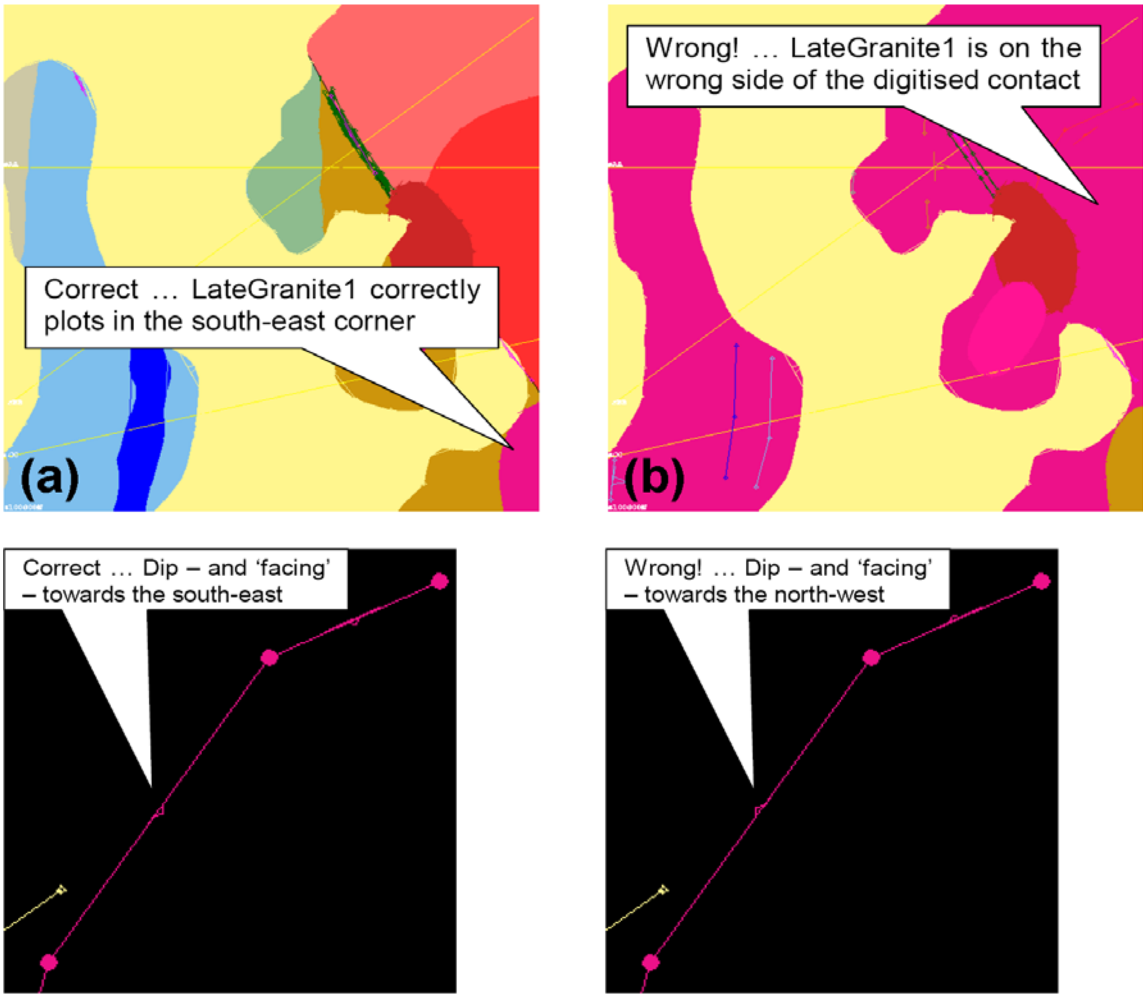


Figure 9. The geology map of the revised 3D geology model is correct in (a), with the LateGranite1 appearing in the south-east corner. In (b) the 'associated' orientation data are dipping in the wrong direction, and the modelled LateGranite1 plots on the incorrect side of the digitised contact.

Tutorial D6: Import Drillhole Data and Recompute the Model

***Parent topic:* Tutorial D (Geothermal and Microseismic)**

The geology model at this point has been developed using geology observations derived mainly from surface geological mapping, together with data from two drillholes. But things are about to change.

- Gravity data indicate a central, deeper basin—a graben?
- Towards the north-west, field mapping shows evidence for a fault. This is interpreted to lie along the western edge of a postulated graben.
- Three deep drillholes are now available, in addition to the existing two drillholes, confirming the deeper sedimentary section, and consequently the model requires major revision.

Change is easily implemented in 3D GeoModeller. Let's now make the changes.

In this section:

- D6 Overview
- D6 Stage 1—Add drillhole data
- D6 Stage 2—Add a fault
- D6 Stage 3—Consideration of the Proterozoic offset by the Western Fault

D6 Overview

***Parent topic:* Tutorial D6: Import Drillhole Data and Recompute the Model**

In this tutorial we:

1. Import data for three drillholes, and project the drillhole geology onto vertical cross-sections
2. Note and respond to discrepancy between the new drillhole data and the existing 3D model
3. Introduce a new fault to the project, and recompute the 3D geology model

D6 Stage 1—Add drillhole data

***Parent topic:* Tutorial D6: Import Drillhole Data and Recompute the Model**

In this stage we add and examine the drillhole data

Load the project

1. If it is not already open, open your project or the supplied start-point 3D GeoModeller project for Tutorial D6.

   From the main menu choose **Project > Open** or
   from the toolbar choose **Open** or
   press CTRL+O

   (For the start-point project supplied) In the **Open a project** dialog box navigate to the 3D GeoModeller Project **`.xml`** file

   `Tutorial_D\Tutorial_D6\D6Beginning_Project\D6Beginning_Project.xml`

2. Save a copy of this project in your own data area.

   From the main menu choose **Project > Save as** or
   from the toolbar choose **Save As** or
   press CTRL+SHIFT+S.

   Save your project work in a folder outside the original **`StartTutorial`** folder.

3. In the **Explorer tree,** right-click on **3D Geology > Hide**

Load the drillhole data

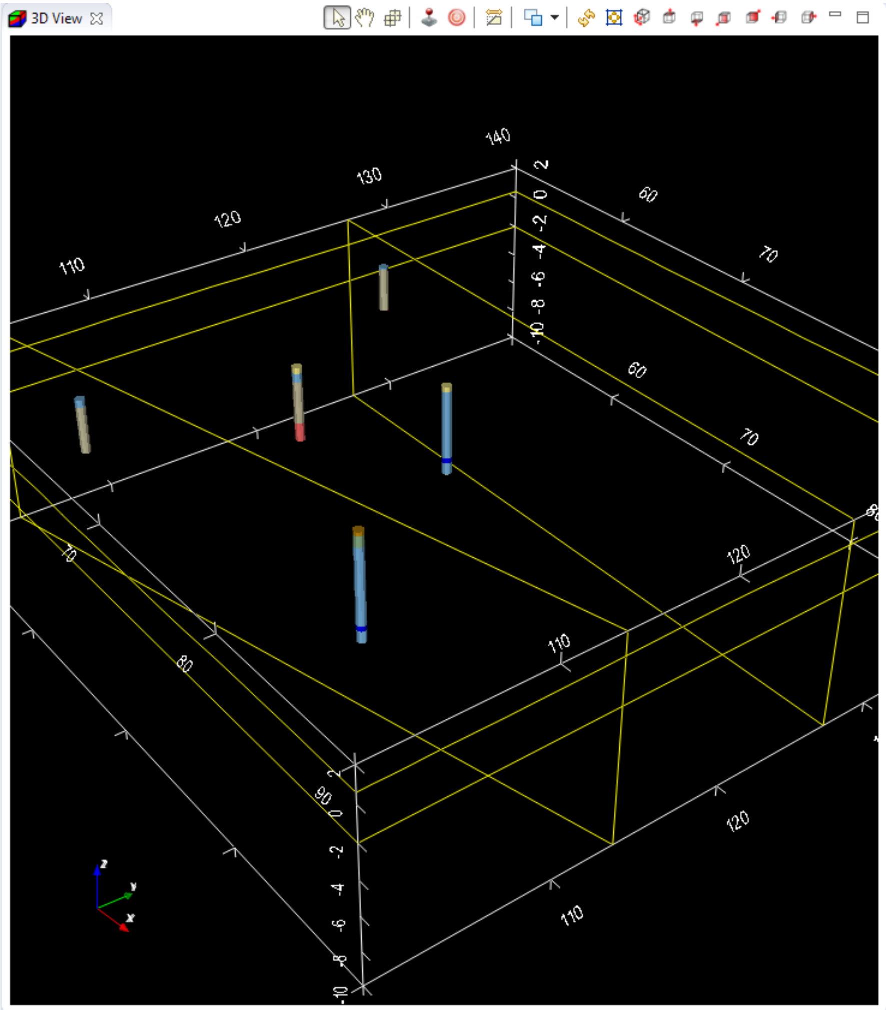
4 From the main menu choose **Import > Drillhole > 3 Files (Collars, Surveys, Geology)**

5 In the **Load Drillhole CSV dataset** dialog box:

- **Browse** to the 'Collar Table' file and select **`HotRox_DDH_Collars.csv`** in the **`Tutorial_D6\Data\`** folder, then 'Survey Table' file **`HotRox_DDH_Surveys.csv`** and 'Geology Table' file **`HotRox_DDH_Geology.csv`**.
- Select **Next >**
- Use the drop-down lists of labelled 'columns' at each step to assign the correct file columns to the fields required by 3D GeoModeller—e.g. the drillhole's Hole ID, its (X, Y, Z) collar coordinate and the Hole Depth. You can navigate these steps using **Next >** or **< Back** buttons.

6 At the final step, choose **Finish**

The 3 additional drillholes, DDH1, DDH2 and DDH3 are now loaded, and a brief load report is presented. All five drillholes can be displayed in the 3D Viewer.



Show or Hide drillholes in the 3D Viewer

7 In the **Explorer tree**, choose **Drillholes > Show**—shows all drillholes in the 3D Viewer

8 Choose **Drillholes > Shading** to increase the diameter of the holes

9 Change the thickness of drillholes with **Drillholes > Appearance**

10 In the **Explorer tree**, choose **Drillholes > Hide** to hide them from the view

Or, for a chosen drillhole either **Show** or **Hide** it

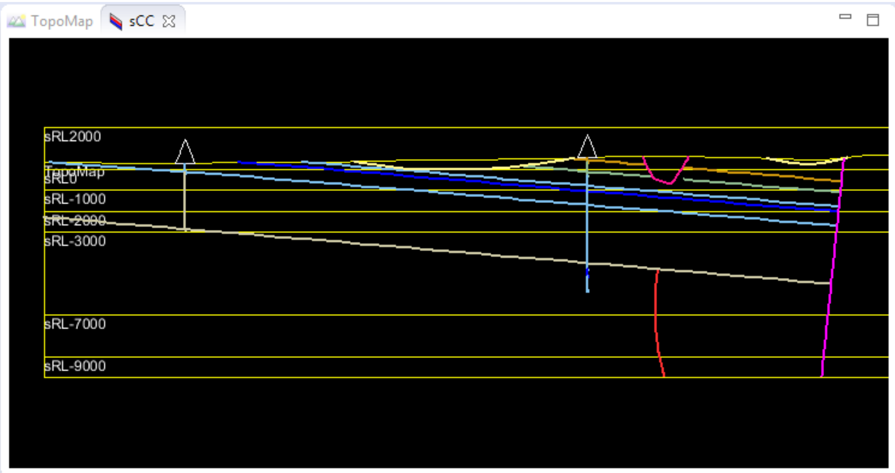
Show Drillholes in a 2D Viewer and project them onto a Section

11 In the main menu select **Model > Plot the Model Settings**, untick **Show Fill** and click on **Apply To All**

12 From the **Model** toolbar, choose **Project Data Onto Sections** or press CTRL+I

13 In the **Project Data Onto Sections** dialog box:

- **Sections: Select** section **sCC**, for example
- **Geology Data**: **Select All**
- **Data to Project**: Check **from Drillhole Trace**
- **Data to Project:** Uncheck all other options
- **Maximum distance of projection**: try 10m
- Choose **OK**



14 Check the drillhole projection by activating the 2D viewer for Section sCC.

Right-click on the drillhole trace for DDH3 within Section sCC (it's the deepest one, furthest east) and select **Edit..** to access the Drillhole Editor.

15 Next, let's examine the drillhole data relative to the original 3D geology model.

Examine these by plotting and visualising the 5 drillholes in 2D (Section) and 3D (Viewer). Consider the interpretive changes that you need to make to best accommodate the new drillhole data (Figure 10).

Use the same plotting options that we have used previously.

- Project the drillholes onto **Sections**
- Plot the geology on **Sections**
- Show the drillholes in the **3D Viewer**
- Display the section plots in the **3D Viewer**

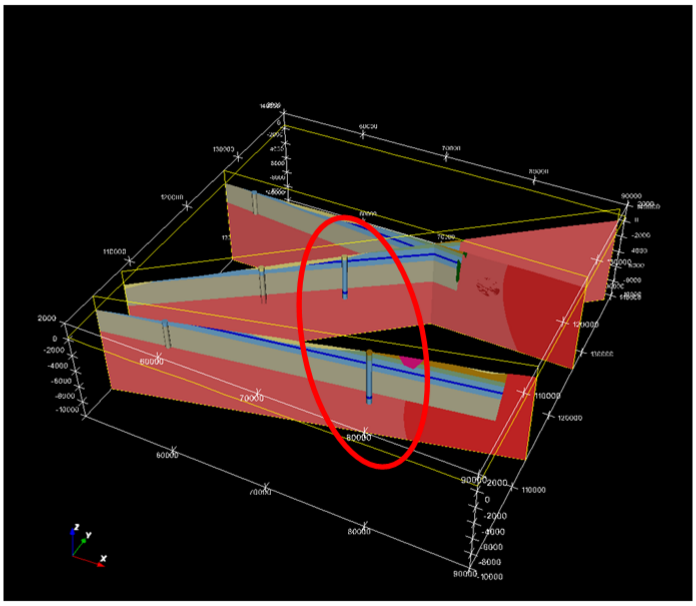


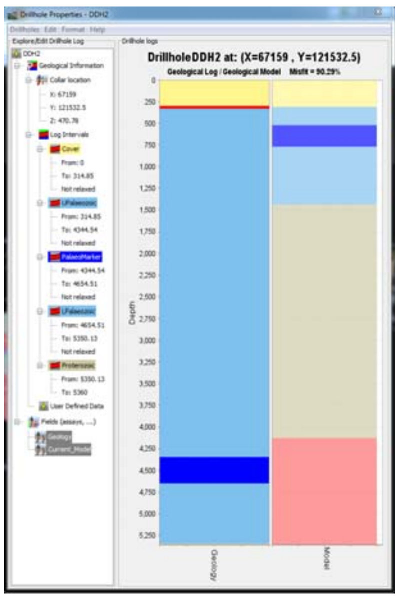
Figure 10. Plan showing Sections sAA, sBB, and sCC, and drillhole locations. The 3D view (right) shows the drillholes relative to the 3D modelled geology. Two of the new drillholes: DDH2 and DDH3 show a much deeper sedimentary section.

It is also possible to compare the current Geological model with the new drillholes data in the Drillhole Editor

16 In the **Explorer tree**, right-click on the **Drillhole DDH2** and choose **Edit**.

The misfit between the current model on the right and the drillhole data on the left is really high (**90.29%**) due to the deeper Paleozoic sedimentary section in the drillhole data.

Now let's recompute the model so that all 5 drill holes are taken into account.



17 From the **Model** toolbar, choose **Compute** or press CTRL+M

In the **Compute the Model** dialog box:

- **Series to interpolate**—Select All
- **Faults to interpolate**—Select All
- **Sections to take into account**—Select All
- **Drillholes to take into account**- Select All

Choose **OK**

18 Now re-plot and review the Recomputed, modelled geology. The geological interpretation-discrepancies will be confirmed (see Figure 10).

Perform steps as before (as in previous parts of this tutorial, for example, Tutorial D2 stages 1 to 3):

For 2D: From the **Model** toolbar, choose **Plot the model settings** or press CTRL+D

And for 3D: From the **Model** toolbar choose **Build 3D Formations and Faults**

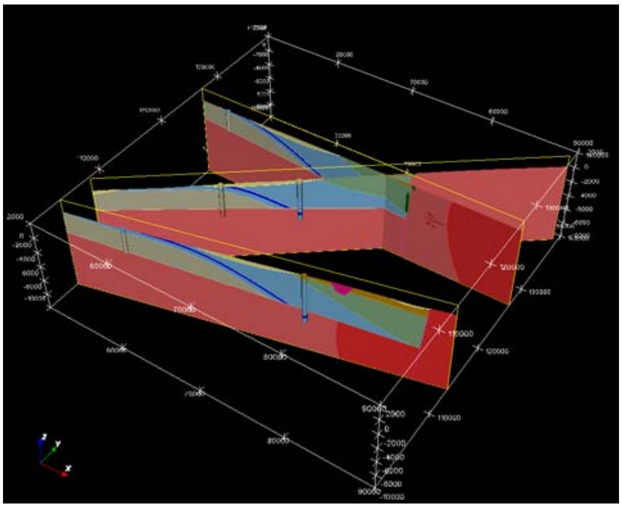
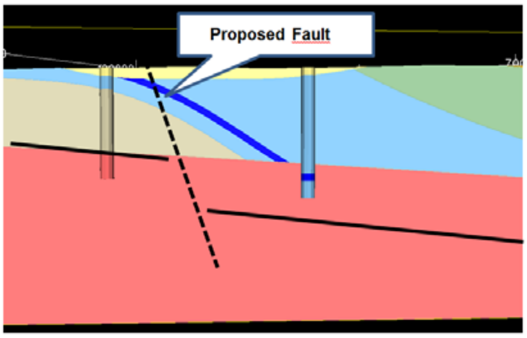


Figure 11. The TopoMap and Section sBB showing geology for the recomputed model. A fault is proposed to achieve a model which is more consistent with surface mapping.

The Sedimentary Basin now goes deeper, however the drillhole DDH2 still doesn't fit exactly with the current model. The Basement remains too high. A fault is proposed to achieve a model which is more consistent with surface mapping



19 Save your project

From the main menu choose **Project > Save** or
from the toolbar choose **Save** or
press CTRL+S.

D6 Stage 2—Add a fault

Parent topic: **Tutorial D6: Import Drillhole Data and Recompute the Model**

In this section, we add a fault to the geology model.

In fact a Western Fault geology object already exists in the Project, and some data describing the position and attitude of the Western Fault are already included in the north-west corner of the TopoMap section. This fault currently does not exist in the model because the fault is not linked to any of the geology series in the Project.

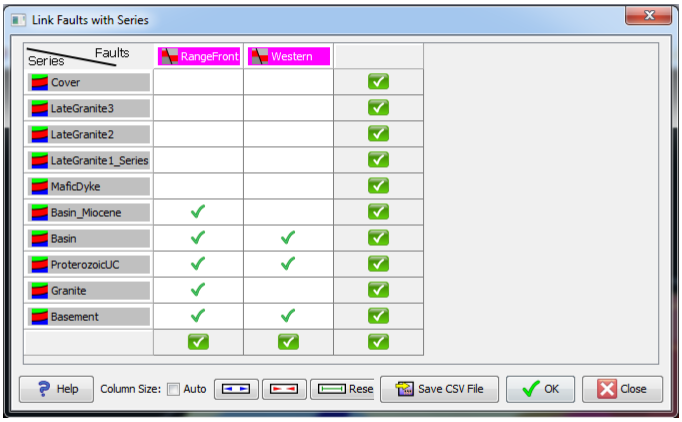
Consider that the proposed fault offsets the Basement, Proterozoic and Basin series.

D6 Stage 2—Steps

1 From the main menu choose **Geology > Link faults with series**

2 In the **Link faults with series** dialog box (table):

- Click the cells of the table to link Basement, ProterozoicUC and Basin (**Series**) to the Western (**Fault**)
- Choose **OK**

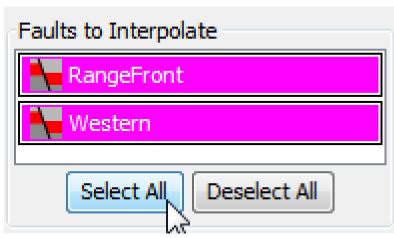


Recompute the 3D geology model for the Project

3 From the **Model** toolbar, choose **Compute** or press CTRL+M

4 In the **Compute the Model** dialog box:

- **Series to interpolate**—**Select All**
- **Faults to interpolate**—**Select All**
- **Sections to take into account**—**Select All**
- **Drillholes**—**Clear Selection** (Select None)
- Clear the **Faults only** check box
- Choose **OK**



D6 Stages 2—Discussion

When we try to compute the model at this point, we get a message saying 'unable to solve ProterozoicUC' and 'unable to solve Basin'. We examine this in the following stage.

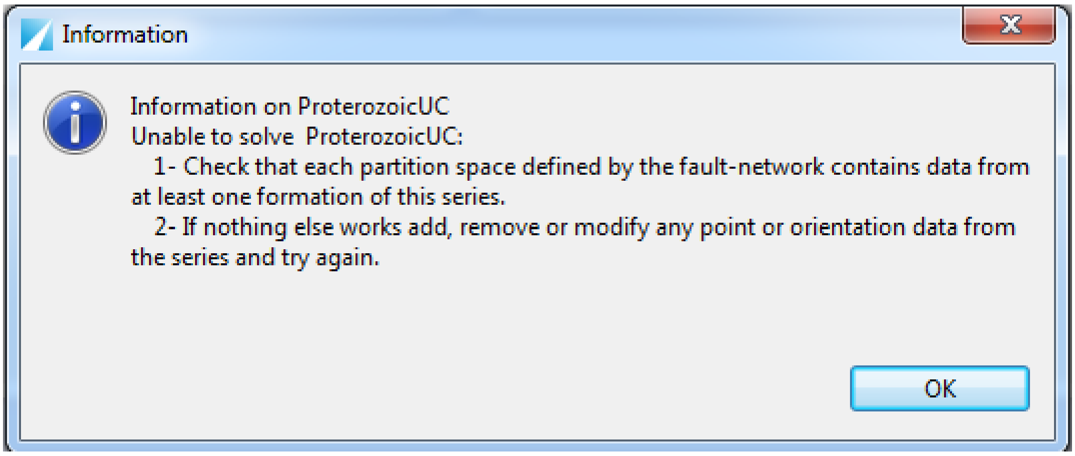
D6 Stage 3—Consideration of the Proterozoic offset by the Western Fault

Parent topic: **Tutorial D6: Import Drillhole Data and Recompute the Model**

In this section we find that we need to add some interpretive contact data for the (bottom of) Proterozoic. We know that this contact must be beneath the two deep basin drillholes.

D6 Stage 3 Having enough information about the geology horizon

As noted above, when we try to compute the model at this point, we get a message saying 'unable to solve ProterozoicUC' series.



The reason for this is that we do not have enough information about this geology horizon, particularly within the 'model compartment' created by the new fault. Consider the following:

To the west of the Western Fault:

- There is some outcrop of Proterozoic which provides information about the top of the unit; the interpolator for the ProterozoicUC cannot use that information because it relates to a different horizon. Recall that you are modelling 'bottoms' of formations, not 'tops'.
- Three drillholes penetrated the Proterozoic and intersected the Basement—thus providing three geology contact data points for the bottom of the Proterozoic, which can be used by the ProterozoicUC series interpolator.
- You can see that an orientation data point occurs on Section sAA, describing the ProterozoicUC as dipping 5° to the east. This is also used by the ProterozoicUC series interpolator.

These data—some contact and orientation data—provide sufficient information on the western side of the newly proposed fault—sufficient to satisfy the needs of the mathematical solver for the ProterozoicUC series.

To the east of the Western Fault:

- There is no outcrop of Proterozoic
- Two deep (central) drillholes intersected the top of the Proterozoic

This is the problem. We have postulated that the Western Fault produces an offset to the Proterozoic but we have no data to the east of the fault that says anything about where the bottom of the down-faulted of Proterozoic unit is. The mathematical solver cannot solve this. You, the interpreting geologist, either have to find the required data (shoot some seismic? Expensive!) or interpret (geologists are paid to interpret geology!)

D6 Stage 3 What do we know about the Proterozoic?

From three drillholes in the west we know the thickness of Proterozoic:

- 2641m in drillhole HRW1
- 2735m in drillhole HRW2
- 2525m in drillhole DDH1

In the two deeper ‘basin’ drillholes we know the depth to the top of the Proterozoic:

- 5350m in drillhole DDH2
- 6405m in drillhole DDH3

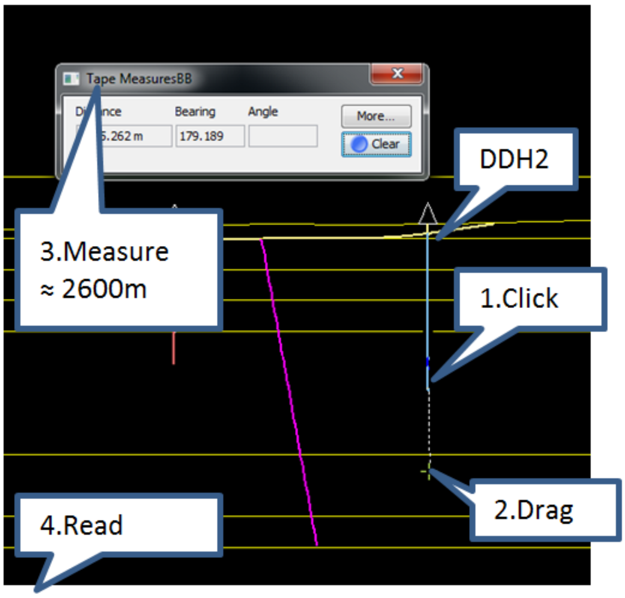
D6 Stage 3—The solution—adding interpretive contact data

On the basis of this information, we can reasonably estimate that the bottom of the Proterozoic is some 2600m below the points where the top of Proterozoic was intersected in drillholes DDH2 and DDH3. Let’s add one interpretive geology contact data point for Proterozoic on the Section sBB—below DDH2.

1 In the **2D Viewer**, select Section sBB

2 Project the drillhole traces onto this section (use the **Project** tool)

3 From the **2D toolbar**, choose **Tape Measure** (the **Tape Measure** tool)



Using the **Tape Measure** tool, click near the bottom of DDH2 in Section sBB, and drag downwards until the measured distance in the **Tape Measure** dialog box shows approximately 2600m (Figure 12, right).

Note the approximate position, or read off the Z-elevation value from the mouse coordinates displayed at the lower left edge of the **2D Viewer**

Create the contact data point

4 Change the mouse mode to **Create**. From the **2D** toolbar, choose **Create (Lines)** .

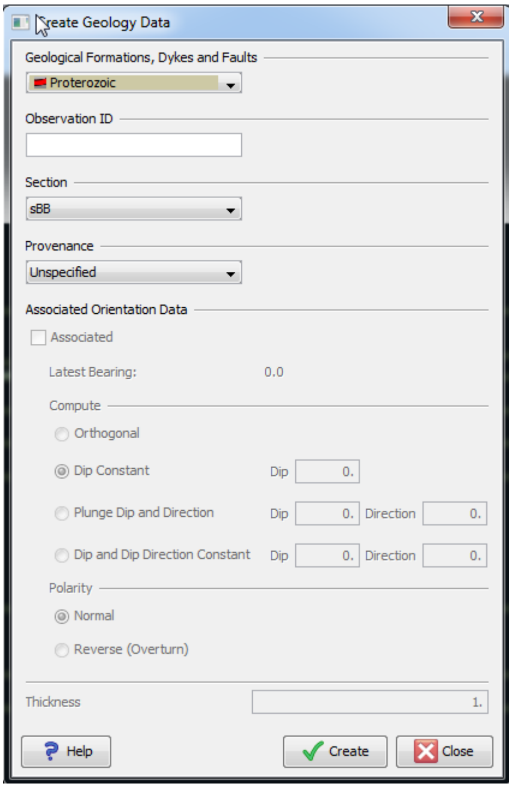
From the **Points List Editor** toolbar, choose **Delete all Points**

Click to place a single ‘point’ at the interpreted bottom of Proterozoic beneath DDH2

5 From the **Structural** toolbar, choose **Create geology data** or press CTRL+G.

In the **Create geology data** dialog box:

- **Geological Formations and Faults**—Choose Proterozoic
- Choose **Create**—You have created a single interpreted geology contact data point for the bottom of Proterozoic.



Recompute the 3D geology model

6 From the **Model** toolbar, choose **Compute** or press CTRL+M

In the **Compute the Model** dialog box:

- **Series to interpolate**: **Select All**
- **Faults to interpolate**: **Select All**
- **Sections to take into account**: **Select All**
- **Drillholes**: **Select All**
- Clear the **Faults only** check box
- Choose **OK**

7 Re-plot the geology. Use the same plotting options that we have used previously.

- Project the drillholes onto sections
- Plot the geology on sections ; set the 2D Plot the Model resolution to 100x100 cells for improved rendering quality.
- Show the drillholes and section plots in the **3D Viewer**
- **Build 3D shapes** and manage the **3D Viewer** display using the **Project Explorer;** build the 3D model at 1000x1000x500m resolution

8 Save your project

From the main menu choose **Project > Save** or from the toolbar choose **Save** or press CTRL+S.

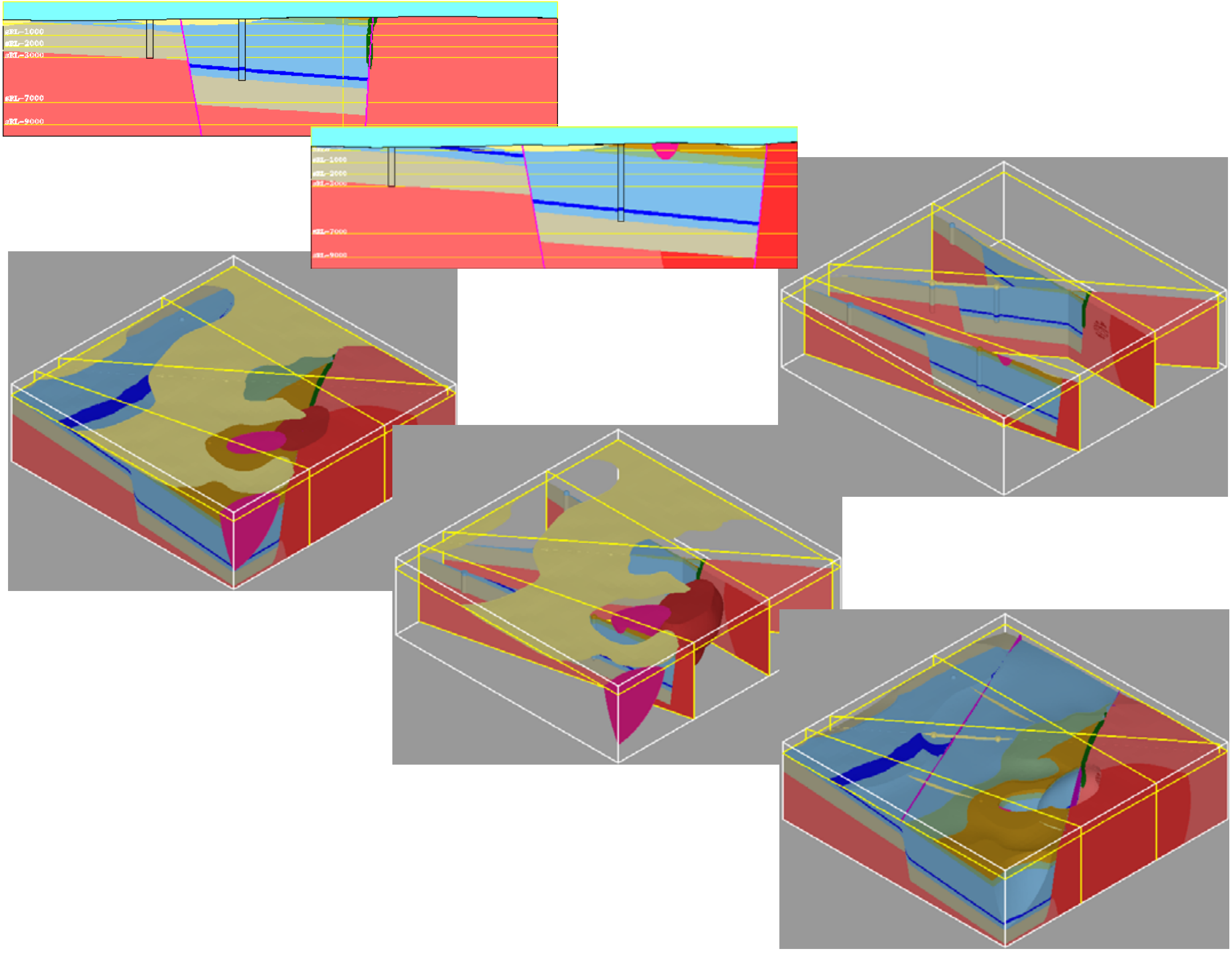


Figure 13. Various 2D and 3D plots of the revised 3D geology model.

Tutorial D7: Add geothermal physical property data

Parent topic: **Tutorial D (Geothermal and Microseismic)**

Tutorials D7 and D8 take the user through a typical sequence of tasks for performing forward modelling of 3D temperature distribution directly from a 3D geology model. In this instance, we are forward modelling from an existing 3D GeoModeller project (HotRox_) which we modified during exercises in tutorials D1–D6.

It is also possible to perform forward temperature modelling starting from a supplied voxet, for example, one exported from a GoCad project (steps not described here).

In this section:

- D7 Overview
- D7 Steps

D7 Overview

Parent topic: **Tutorial D7: Add geothermal physical property data**

In this tutorial we enter physical (thermal) properties for each geology unit in the model.

Assigning a single constant thermal property to each formation is not ideal, given that knowledge of real-world geology tells us heterogeneity within every formation is common. Nonetheless, the current software module takes only a mean value for the purpose of forward modelling 3D temperatures.

The best way to estimate the most representative mean value is to statistically consider a large number of samples from many locations within the project area.

If estimates of the variability (spread of values) are available, we suggest entering this additional information (standard deviation, multi-modal population statistics), because future innovations potentially planned for 3D GeoModeller may use these in estimating uncertainty in 3D temperature modelling, and / or performing inversion.

D7 Steps

Parent topic: **Tutorial D7: Add geothermal physical property data**

1. If it is not already open, open your project or the supplied start-point 3D GeoModeller project for Tutorial D7.

   From the main menu choose **Project > Open** or
   from the toolbar choose **Open** or
   press CTRL+O

   (For the start-point project supplied) In the **Open a project** dialog box navigate to the 3D GeoModeller Project **.xml** file

   Tutorial_D\Tutorial_D7\D7Beginning_Project\D7Beginning_Project.xml

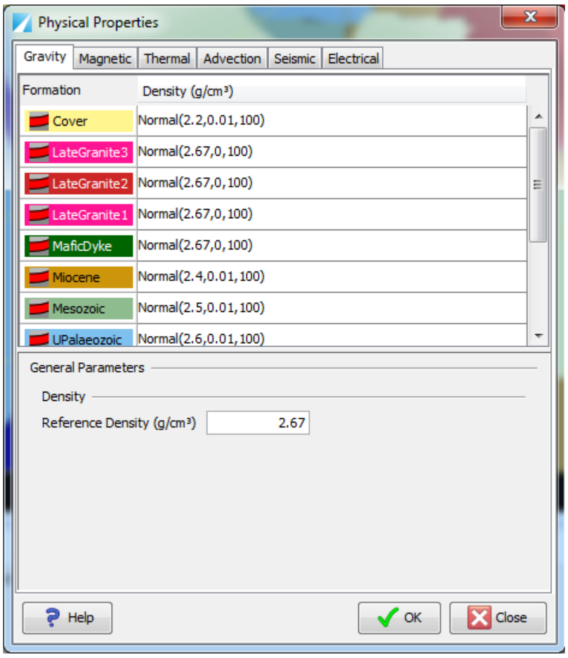
2. Save a copy of this project in your own data area.

   From the main menu choose **Project > Save as** or
   from the toolbar choose **Save As** or
   press CTRL+SHIFT+S.

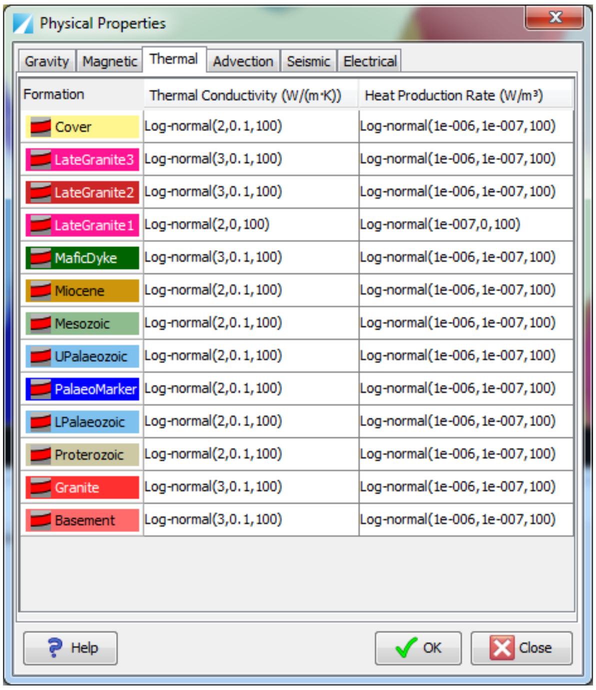
   Save your project work in a folder outside the original folder.

3. Choose menu option **Geophysics > Define physical properties**.

3D GeoModeller displays the **Physical properties of a geological formation** dialog box. Six tabs appear in the upper part of the dialog box.



4 Drop down the **Thermal** menu. Two thermal properties are available in this menu—**Thermal Conductivity** and **Heat Production Rate**.



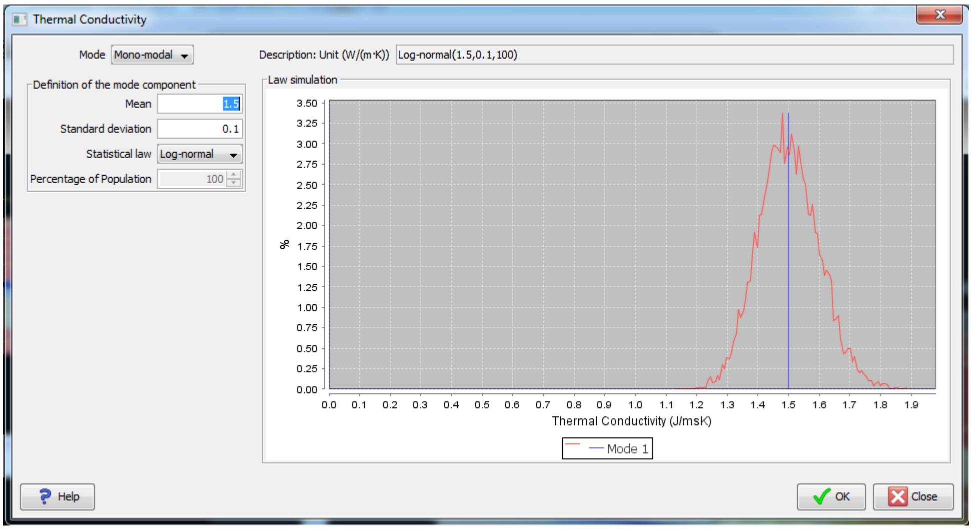
Note that default thermal conductivities values of 2 W/(mK) are assigned to all sedimentary units, and values of 3 W/(mK) are assigned to all igneous and basement rocks except for LateGranite1. The Thermal Conductivity and Heat Production Rate properties of LateGranite1 must be edited as follows:

- LateGranite: Thermal Conductivity = 3 W/(mK) and StdDev = 0.1.
- LateGranite: Heat Production Rate = 0.000001 and StdDev = 0.0000001

  The latter is the same as for all the other units.

Your exploration team has direct measurements from core samples of the Upper Palaeozoic (shale). This unit has a mean thermal conductivity of ~ 1.5 W/(mK), so we will edit this now.

5 Scroll down through the geology units. Double click within the thermal conductivity cell for the 'UPalaeozoic' unit. This will open the **Thermal Conductivity** dialog.



Note this dialog box (below) contains a number of features including:

- Parameters to define the distribution
- Number of modes
- Proportions (if more than one mode)
- Statistical 'law' or distribution type

However, as noted above, the module takes only the mean value for the purpose of forward modelling 3D temperatures. (Tools for the inversion of potential field data adopt these distributions, see Tutorial C (Forward & Inverse Modelling of Potential Fields))

6 Change the mean value to **1.5**, ignoring all other entries for now. Close with the **OK** button to go back to the'Physical Properties' dialog.

7 Next, for heat production rates note that a default value of 1 $\mu W/m^3$ has been assigned to all units. However, we now have direct measurements indicating that the 'granite' unit should instead be assigned a heat production rate of **~15 μW/m3**, so we edit this now.

8 Scroll back up through the geology units. Double click within the heat production rate cell for the 'granite' unit, and change the mean value to **15 μW/m3**.

Note you may enter this value in a number of ways depending which units you wish to display in the right-hand cell of the Parameters dialogue box (for example, enter 0.000015 if " W/m^3 " units are selected rather than $\mu W/m^3$).

9 Now, close this dialog box for granite. Choose **OK**, which saves your edits and returns you to the **Thermal** menu of the physical properties table.

10 Now close 'Physical Properties' dialogue box. Choose **OK**

11 Save your project

From the main menu choose **Project > Save** or from the toolbar choose **Save**

Tutorial D8: Compute geothermal solutions

Parent topic: Tutorial D (Geothermal and Microseismic)

In this section:

D8 Overview

Parent topic: Tutorial D8: Compute geothermal solutions

In this tutorial we:

1. Run the Geothermal Forward Modelling Wizard
2. Set model parameters using the wizard
3. Visualise the 3D results within GeoModeller
4. Examine Colour tables and Data Clipping of MeshGrids using the results
5. Examine Contours and Iso-Surfaces of MeshGrids using the results
6. Examine the Data Statistics of the results.

D8 Stage 1—Project Setup

Parent topic: Tutorial D8: Compute geothermal solutions

D8 Stage 1 Steps

1. If it is not already open, open your project or the supplied start-point 3D GeoModeller project for Tutorial D8.

   From the main menu choose **Project > Open** or
   from the toolbar choose **Open** or
   press CTRL+O

   (For the start-point project supplied) In the **Open a project** dialog box navigate to the 3D GeoModeller Project **.xml** file

   Tutorial_D\Tutorial_D8\D8Beginning_Project\D8Beginning_Project.xml

2. Save a copy of this project in your own data area.

   From the main menu choose **Project > Save** as or
   from the toolbar choose **Save As** .

   Save your project work in a folder outside the original folder.

D8 Stage 2—Forward Model Temperature Wizard

Parent topic: Tutorial D8: Compute geothermal solutions

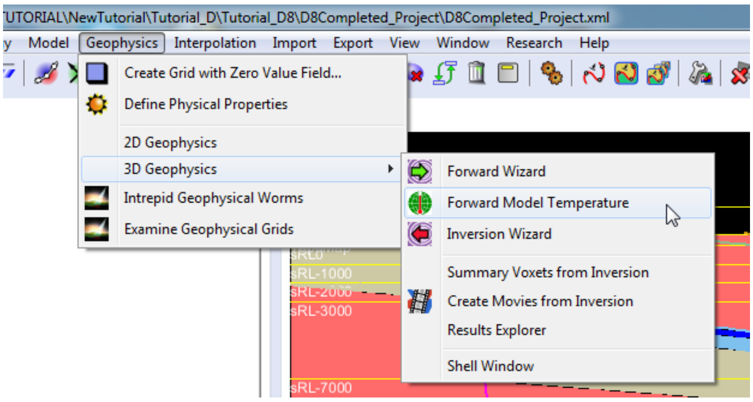
D8 Stage 2 Overview

The heat transport equations we are going to solve make use of 3D GeoModeller's ability to generate a cartesian voxelised 3D grid of the geology model we already have loaded for this tutorial. The 3D temperature approximation then proceeds by an explicit finite difference method, which iteratively solves for temperature in every voxel, using a Guass-Seidel iteration scheme until the sum of the residual errors (in °C) is small, or the maximum defined number of iterations is met (whichever occurs first).

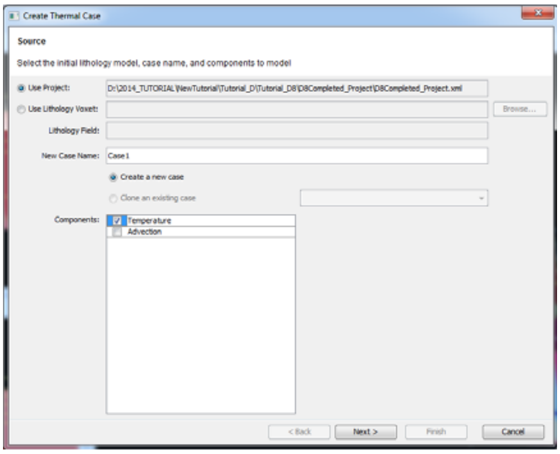
Providing suitable parameters are entered, the point of convergence should represent a 3D temperature model which is in thermal equilibrium (steady state), having solved for variance, and met all the boundary conditions.

D8 Stage 2 Steps

1 Choose menu: **Geophysics > 3D Geophysics > Forward Model Temperature**



2 This begins the **Forward Model Wizard**.



On this first page you can:

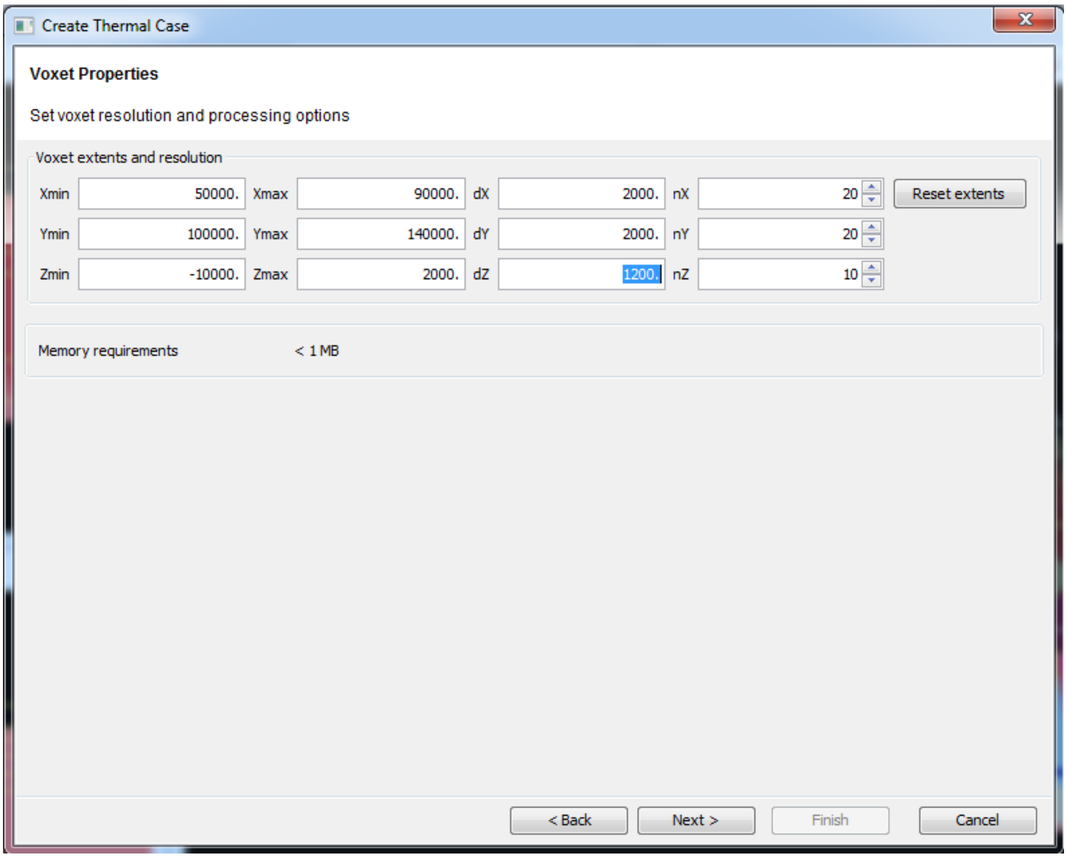
- Set the forward model case and run
- Clone an existing case, if you have one. With case cloning you can quickly reuse parameters when you only wish to change a few for comparison.
- Set the fields to compute. Only Temperature should be available in this instance.

3 Check the **Temperature** box and give a case name, then choose **Next** to move onto page 2 of the wizard.

4 **Compute Grid Resolution**

Look at the cell/voxel size by which our geology model will be discretised. Values for dX, dY, and dZ cell dimensions are given in metres. These defaults correspond to fixed defaults which divide the model into a total of 4,000 voxels: 20 cells in the X direction, 20 in the Y direction and 20 in the Z direction (depth).

5 Change the dZ cell to be 1200. The number of cells in the Z direction should now be 10.



Editing the division-rate or discretisation scheme (nX, nY or nZ) will change the cell/voxel sizes automatically.

We suggest accepting the default X and Y cell sizes for this project: dX=2000m, dY=2000m in order to keep run-time short, for this exercise.

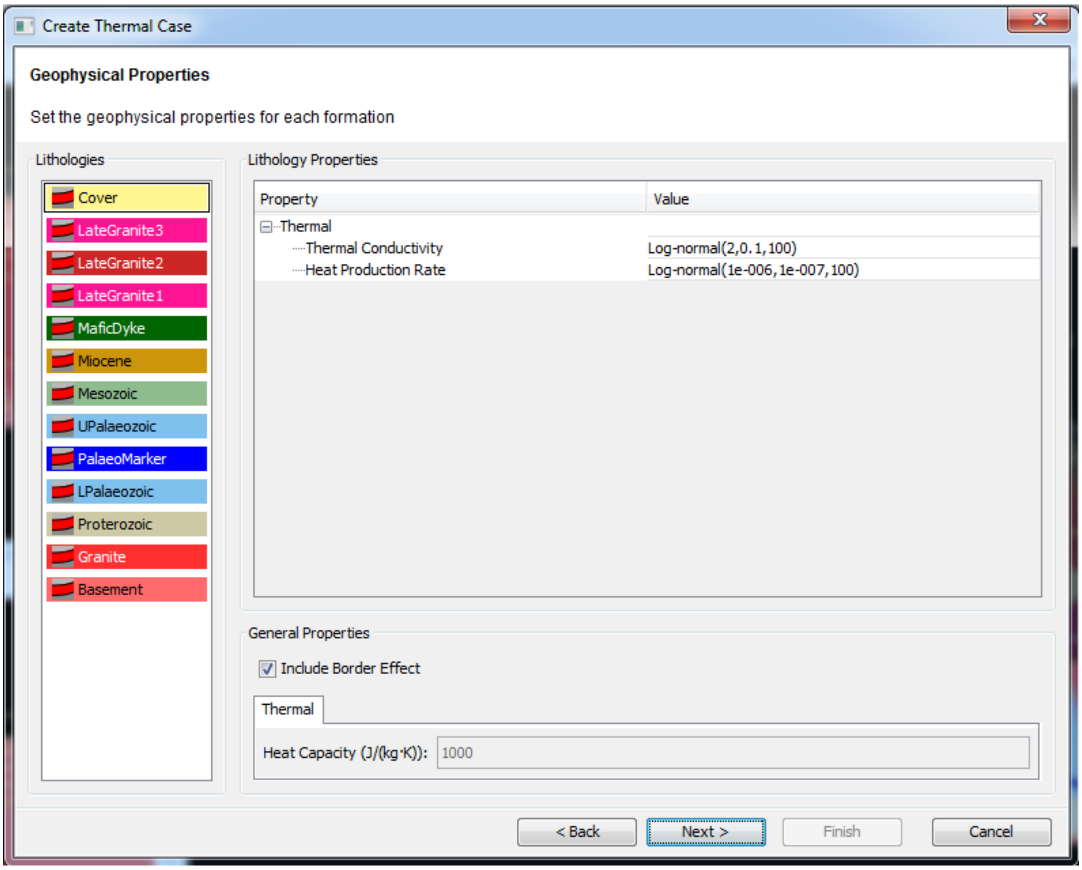
So, no further editing is required. (Click **Next >**)

Concerning run times, it is useful to note that the using a standard PC:

- 4,000 voxels combined with 20,000 iterations takes ~ 1 minute to compute
- 32,000 voxels combined with 20,000 iterations takes ~ 2 minute to compute
- 108,000 voxels combined with 20,000 iterations takes ~ 20 minutes to compute

6 **Physical Properties**

The third page of the wizard sets the physical properties for the geology units. This is linked to the values set from the **Geophysical Properties** dialog. If you are not cloning an existing case then the values from the dialog will be used as defaults here in the wizard.



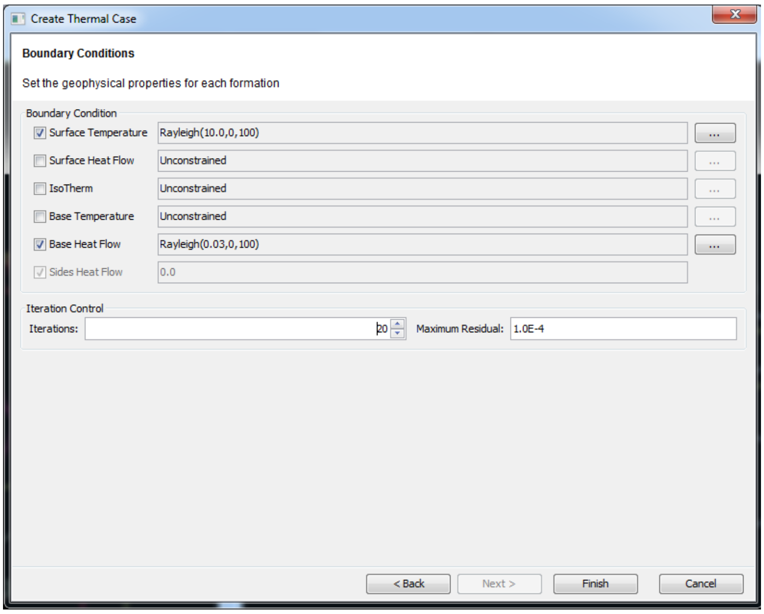
Check the values for each unit to ensure they correspond to the values set previously via the **Geophysical Properties** dialog.

7 Choose **Include Border Effect** then **Next** to continue.

8 **Physical Properties - Boundary Conditions**

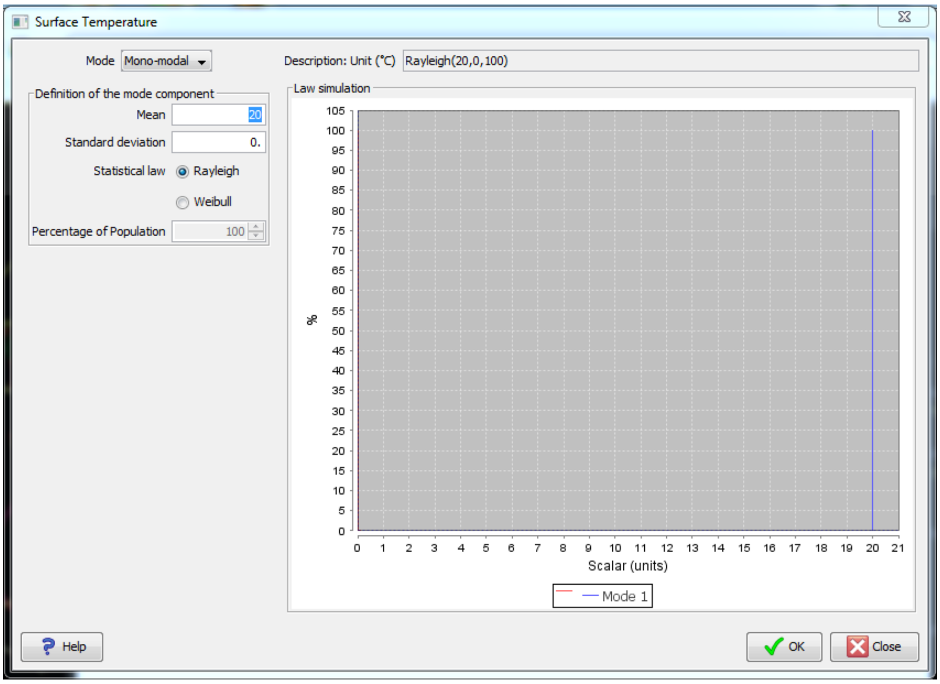
Like any other differential equation, the heat transport equations we are going to solve need boundary conditions to evaluate the integration constants. On the four vertical sides, it is assumed that no heat flows through the model boundaries (Neumann-type boundary conditions). This implies that all lithologies and ambient temperatures are mirrored beyond the model boundaries and therefore the temperature gradient across the boundary is zero.

For the surface boundary condition (rock/air interface), a constant temperature must be applied. We suggest the mean annual air temperature for your local project area (available from the Australian Bureau of Meteorology website), minus ~5°C. Note that some thermal modellers have alternative methods of deriving and correcting-for surface temperature, and you will need to consider what is suitable for your own project area.



Our HotRox project (this tutorial) is representative of a typical hot dry rock (EGS) geothermal energy target, in medium latitudes of Australasia, but comprises synthetic data. For the purpose of this tutorial, we decided to adopt a constant surface temperature of 20°C.

9 Choose the **'...'** button for **Surface Temperature**. This will open a new dialog allowing you to set the distribution parameters of the boundary condition.



10 Change the **Mean** value to **20°C**. Leave all other fields as their defaults for now.

Choose **OK** to accept the changes and return to the properties dialog.

For the entire bottom boundary condition of the model, we have currently implemented code to apply either a constant heat flow or constant temperature. We suggest this treatment is satisfactory in most scenarios and, in any case, it would be unusual to have constraints / data on temperature or heat flow variability for a deep horizon (near the bottom of the model). If there is evidence for basal boundary temperature variability, then we might suggest that a more meaningful approach may be to increase the vertical extent of the geology model into depth zones where isotherms are predicted to flatten-out, as is the conventional approach amongst many modellers.

Typical heat flow values at the Earth's surface range between 0.001 and 0.1 W/m^2 although extreme values such as 0.129 W/m^2 have been recorded in Australia (for example, in the zone of the South Australian Heat Flow Anomaly). The question is, what is a suitable heat flow value to apply at the bottom of our geology model? (That is, at -10 km for the HotRox project—from the main menu choose **Project > Properties** and look at **Z min**) Even for regions displaying high heat flow at surface, the heat flow values at the base of any given geology model would be typically predicted to be much lower, as Uranium and other radiogenic elements become depleted, deeper in the crust.

For our HotRox project (this tutorial), we suggest accepting the default heat flow value of 0.03 W/m^2. In the lower part of the **Thermal** menu of the **Physical Properties** table, find the active cell for **Base** in the **Boundary Conditions** area.

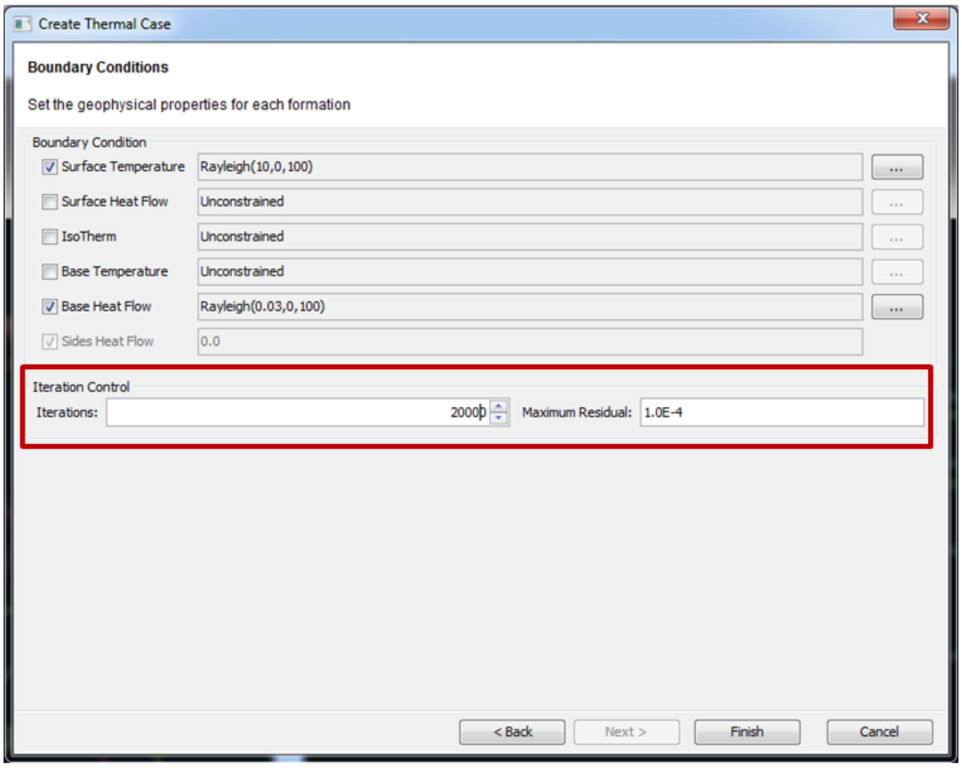
11 Ensure the value is 0.03 W/m^2.

Note the remaining item in the lower part of the **Thermal** menu of the **Physical Properties** table, is **Heat Capacity** in the **General parameters** area. This is assumed to be a constant, and is not currently editable.

Typical heat capacities of rocks are between 800 J /(kg°C) and 1000 J /(kg°C) and because the variation is so much less than that of conductivitiy, few thermal modellers worry about this variation and simply assume cp = 1000 J /(kg°C) (Stüwe, 2008).

12 The last step of the wizard is to define the stopping criteria. At the bottom of the properties wizard page you can specify:

- The maximum number of iterations
- The maximum residual.



Next look at the **Iterations** default value in the **Iteration Control** area of the dialogue box. (By definition, one iteration has occurred after every voxel in the entire model is visited once).

13 Change this value to 20,000.

We can accept the default value for the **Max Residual** of the errors (0.0001°C), so no editing is required. For reference, this value sets the maximum allowable change in temperature in any cell. When this condition is met, the variance is said to have been solved (by finite difference approximation), and calculations stop (unless they have already stopped because the maximum number of iterations condition has been met first.)

Run the computation by selecting Finish

D8 Stage 3—The results directory

Parent topic: **Tutorial D8: Compute geothermal solutions**

Stage 3 Steps

1 The forward model wizard will place the results in a folder directory under the project directory. The name of the folder will be the same as the case name you specified on the first page of the wizard. If you used the defaults then this will be **Case1.**

D8 Stage 4—Examine the results

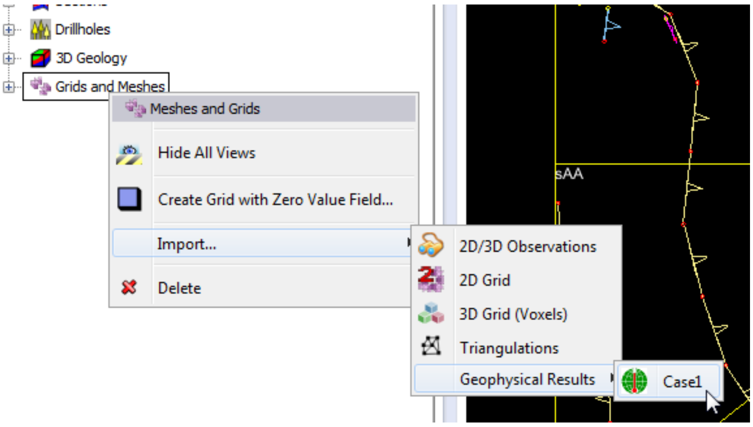
Parent topic: **Tutorial D8: Compute geothermal solutions**

D8 Stage 4—Introduction

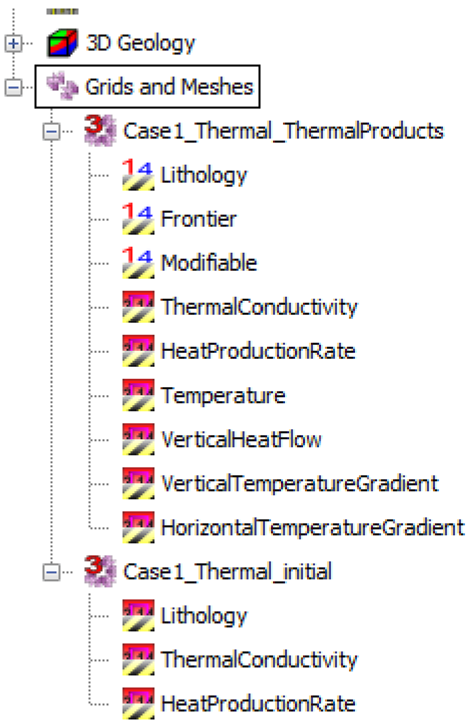
At completion of the run, a dialog will inform you if the compute was successful or not. If successful then two voxel grids in GoCAD format will be produced.

You are now ready to explore the results using the **GeoModeller** Grid and Mesh visualisation tools.

1 In the **Explorer tree** > right-click on Grids and Meshes. Choose **Import > Geophysical Results > Case1**



2 Once imported you should now have a voxet grid under the **Grids and Meshes** branch, the Initial Geothermal voxet grid **Case1_Thermal_Initial** and a **Case_1_Thermal_ThermalProducts** which contains all of the thermal products.



Geothermal Modelling Products

Solved 3D temperature and other derived output parameters	
Lithology	Lithology units at each voxel in the grid.
Modifiable	Flag indicating if a cell was fixed for the forward modelling computation. For this tutorial all cells above Topo should be fixed. All below should be modifiable.
Thermal Conductivity	The thermal conductivity at each cell.
Temperature	(°C) Solved for every cell/voxel centre by Finite Difference approximation
Vertical Heat Flow	(W/m^2) Flow of heat measured in energy per time per unit area. Solved for each cell/voxet centre with respect to the centre of the cell immediately above.
Vertical Temperature Gradient	(°C/km) Change of temperature over a distance. Solved for each cell/voxet centre with respect to the centre of the cell immediately above.
Total Horizontal Temperature Gradient	(°C/km) Change of temperature over a distance of one cell. Equal to the square root of the sum of the squares of the horizontal temperature gradients in the x and y directions.

D8 Stage 5—Visualising a MeshGrid

A MeshGrid in GeoModeller is visualised by its fields. A field contains the data which is associated with each 'primitive' of the mesh or grid. In V2014 **GeoModeller** supports the following MeshGrid primitive types:

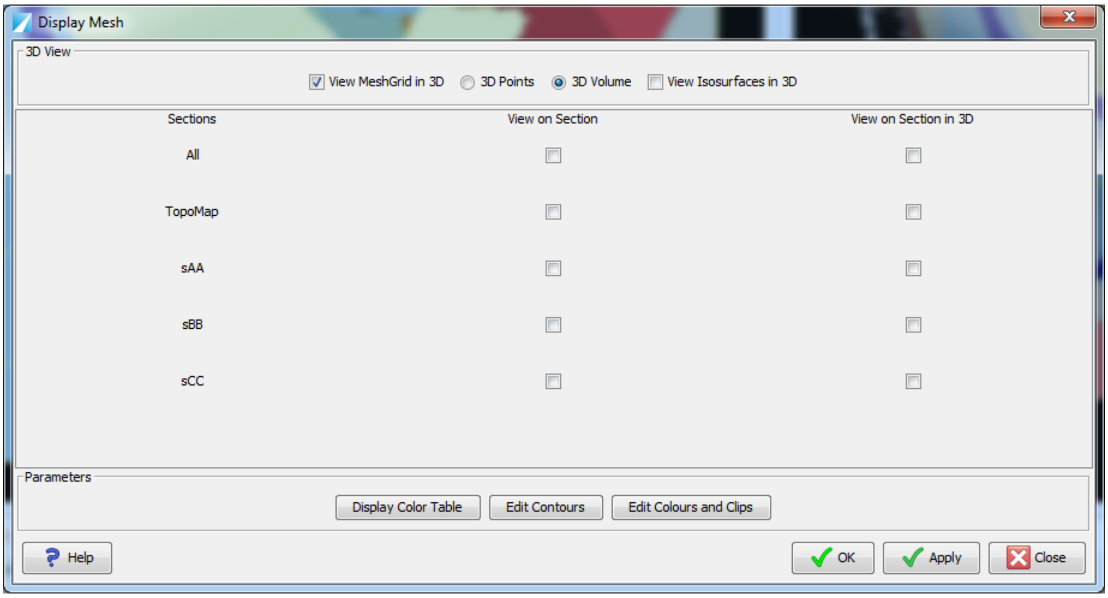
- **3D Voxet grid (Cube primitives)**
- **2D Quad grid (2D planar quads which can be located in 2D or 3D space)**
- **Triangle Mesh**
- **Point Observations**

In the case of this tutorial the primitive type is a voxet.

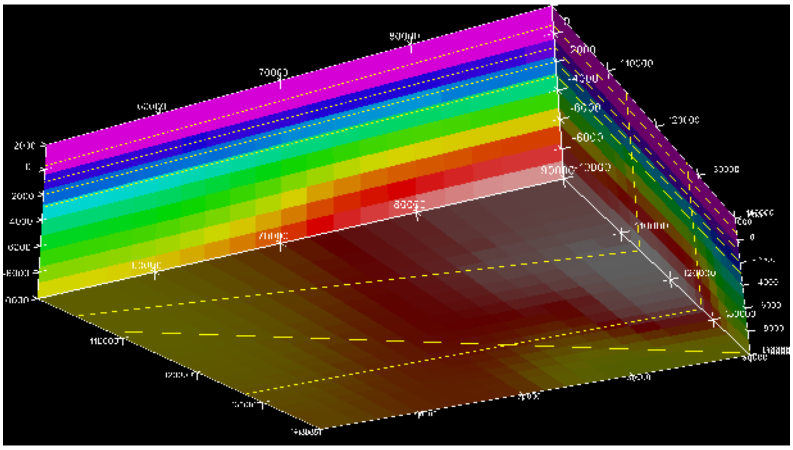
1 In the **Explorer tree** select **3D Geology > Hide** to remove the 3D geology model from the **3D Viewer**

2 To visualise the **Temperature** field, right click on **Grids and Meshes > Case1_Thermal_ThermalProducts > Temperature** in the **Explorer tree**.

3 Choose **Field Visualisation Manager** to display the 'Display Mesh' dialog. Check the **View MeshGrid in 3D** and **3D Volume** options**.**



Press **OK** to visualise the grid in 3D.



In the voxet grid shown the surface temperature (and above topo) is everywhere 20°C, as expected.

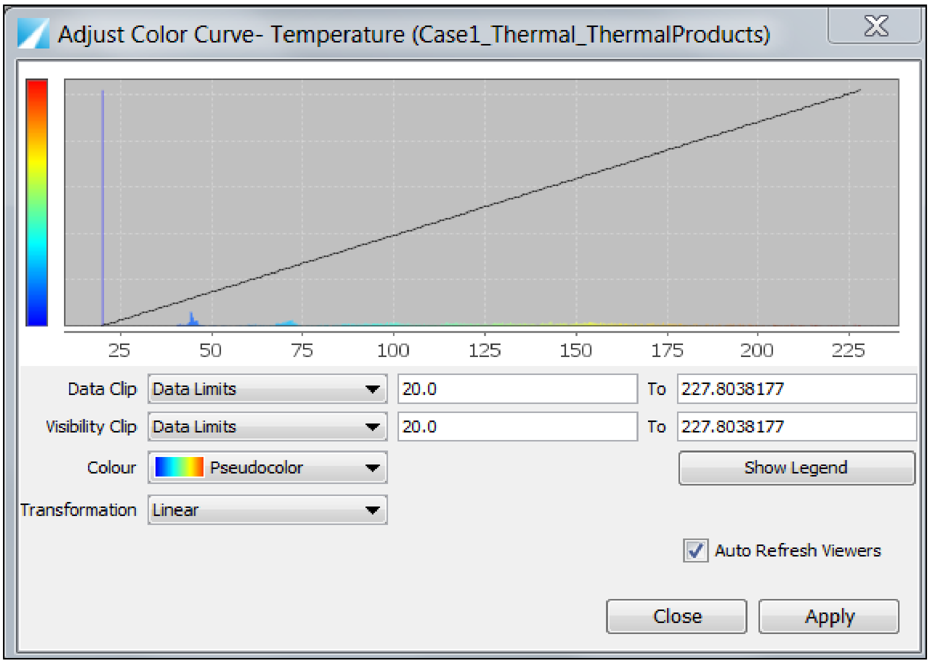
D8 Stage 6—MeshGrid Colours and Data Clipping

Parent topic: Tutorial D8: Compute geothermal solutions

The Grids and Meshes **Colours and Clips** dialog is where you can control the colour table, colour transform and data or visual clipping.

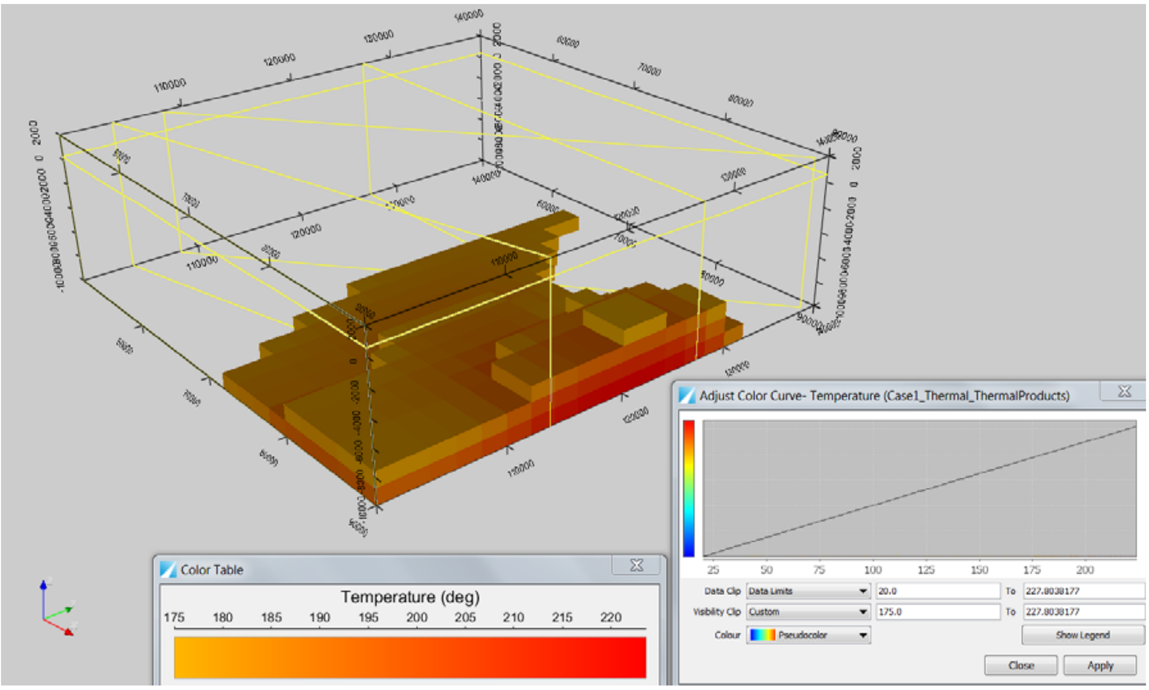
1 In Explorer menu, right-click on **Temperature** field and choose **Edit Colours and Clips...**

2 This will open the **Colours and Clips** dialog.

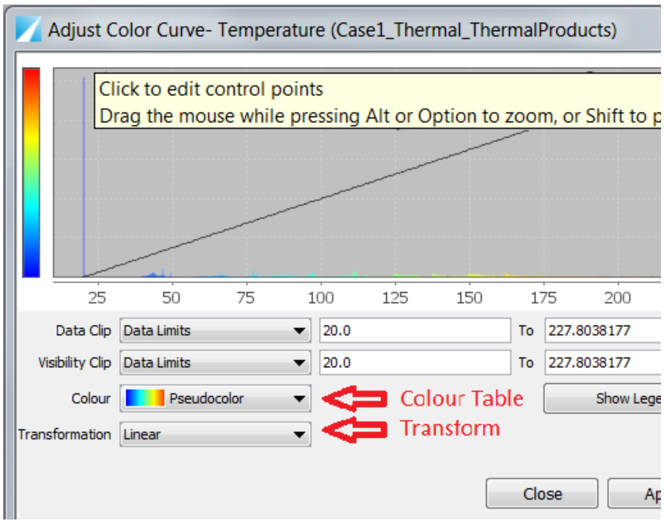


3 You will notice the temp range is approximately 20°C to 227.80°C. This can be adjusted so that only a specified data range is visible. To visualise temperatures between 175°C to 227.80°C, type 175 into the **Visibility Clip** minimum edit box.

4 Click on **Show Legend** to display the Temperature colour scale bar legend



5 You can also change the colour table for a MeshGrid as well as the transform for the colour table lookup. from the **Colours and Clips** dialog. This is done via the **Colour** drop-down list and the **Transform** drop-down list.

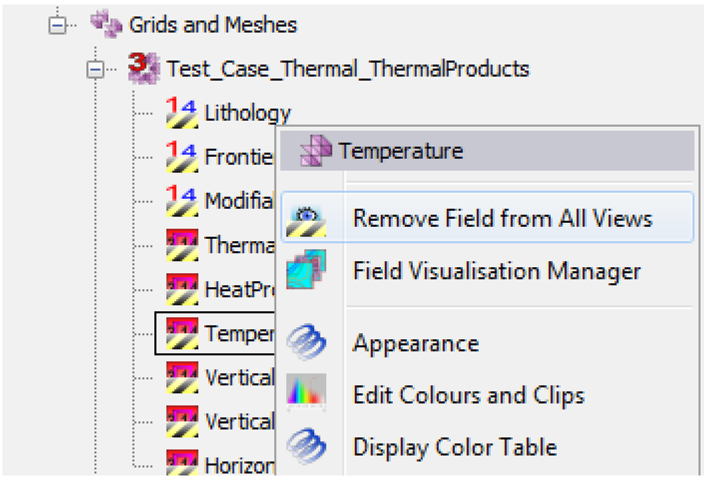


D8 Stage 7—3D Clipping Planes

Parent topic: **Tutorial D8: Compute geothermal solutions**

As well as data clipping for visualisation you can slice the model along the X, Y and Z axis. The 3D clipping planes are not exclusively for MeshGrids. They are applied to all 3D objects except sections.

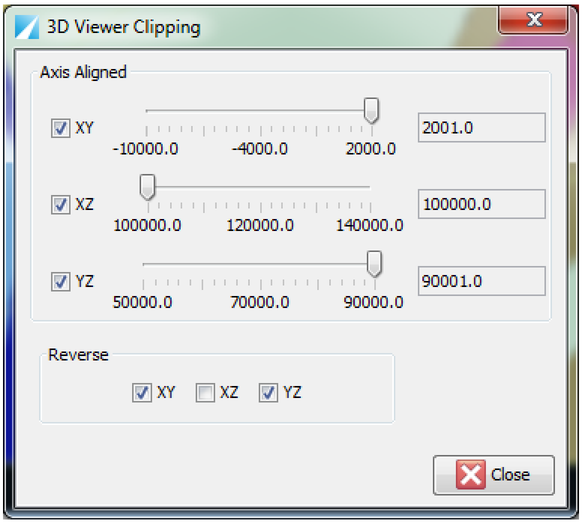
1 To begin, hide all views of the **ThermalProducts MeshGrid**



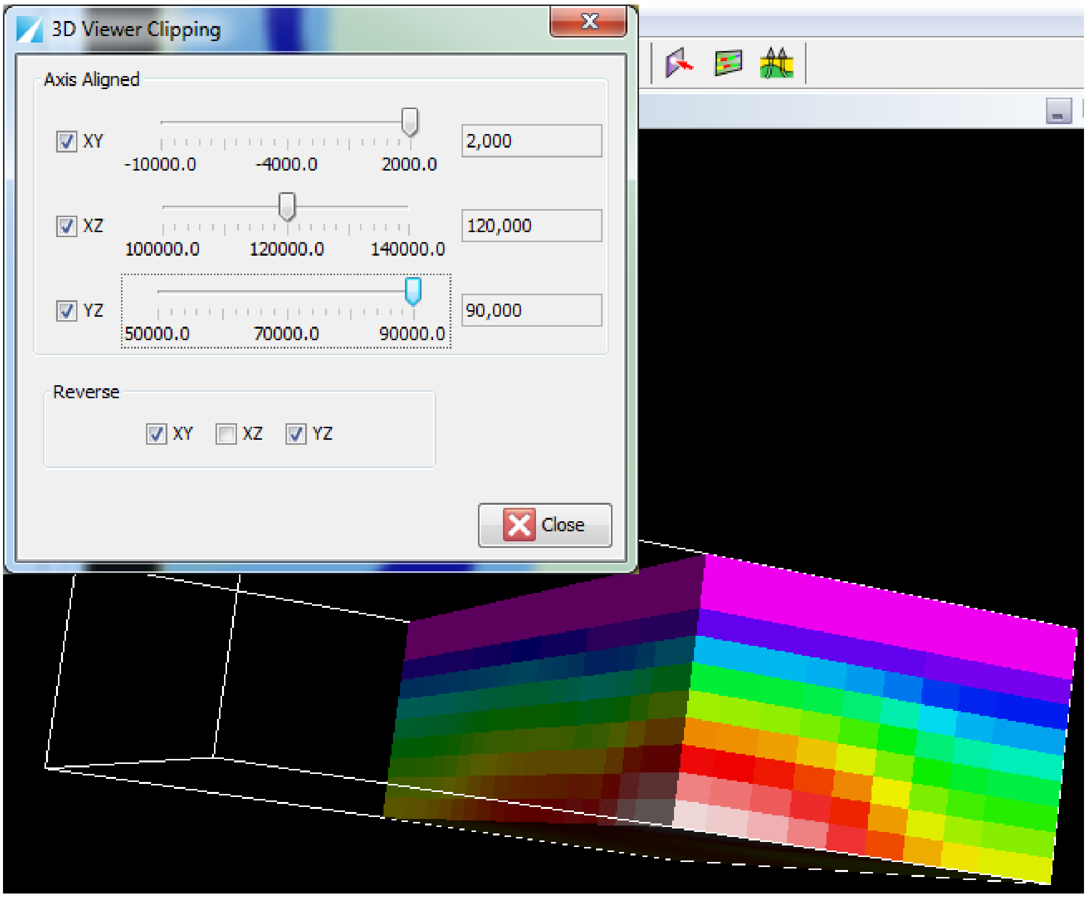
2 Display the **Temperature** field, or any other field you wish, using the methods previously described.

3 On the 3D viewer toolbar choose the **Set Clipping Parameters** button: 

4 This will bring up the **Clipping Parameters** dialog:



5 Slide the **XZ** slider to approximately half way along. You should see the 3D viewer slice the MeshGrid voxet allowing you to view the interior.



6 Now check the **YZ** check box under the **Reverse** group of radio buttons and slide the **YZ** slider approximately 3/4 along its length.

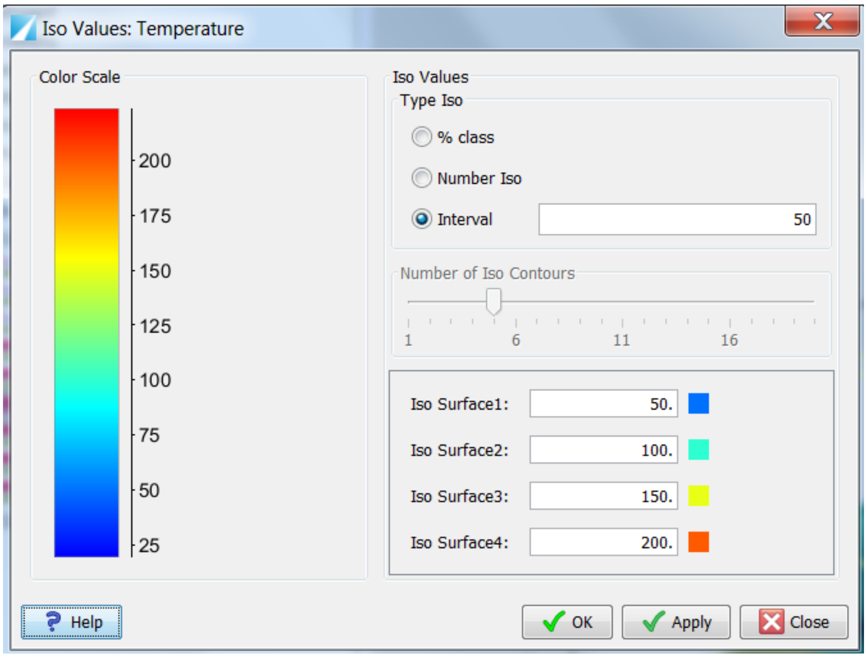
D8 Stage 8—*MeshGrid Contours and Iso-Surfaces*

Parent topic: **Tutorial D8: Compute geothermal solutions**

1 Before proceeding, **Remove All Views** of the '**ThermalProducts**' MeshGrid

2 To view contour iso-surfaces of the MeshGrid data right-click on any Grids and Meshes field in Explorer menu and choose the **Edit Contours** option. For this tutorial the Temperature field will be used.

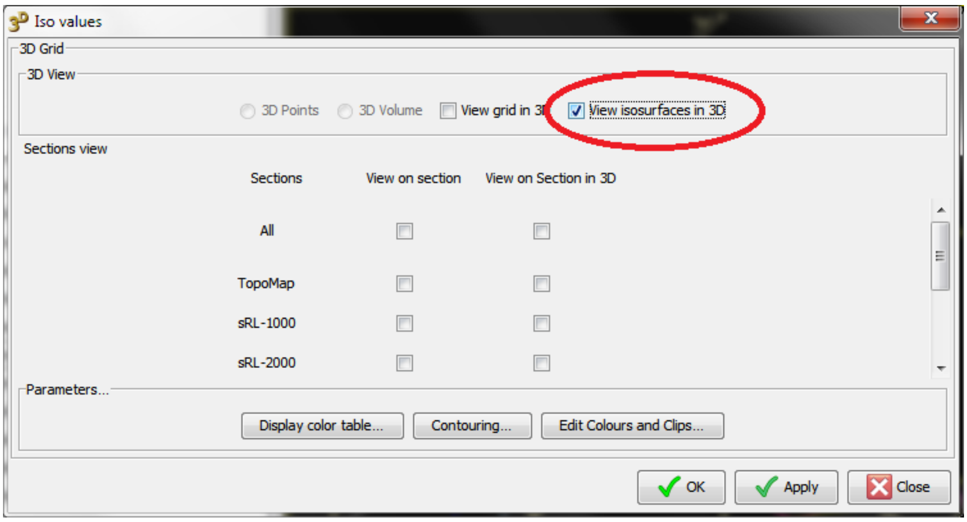
3 This will open the **Iso Values** dialog box. Choose **Interval** from the 'Iso values...' button group and enter a value of 50 as the interval. The dialog should appear something like the one shown here.



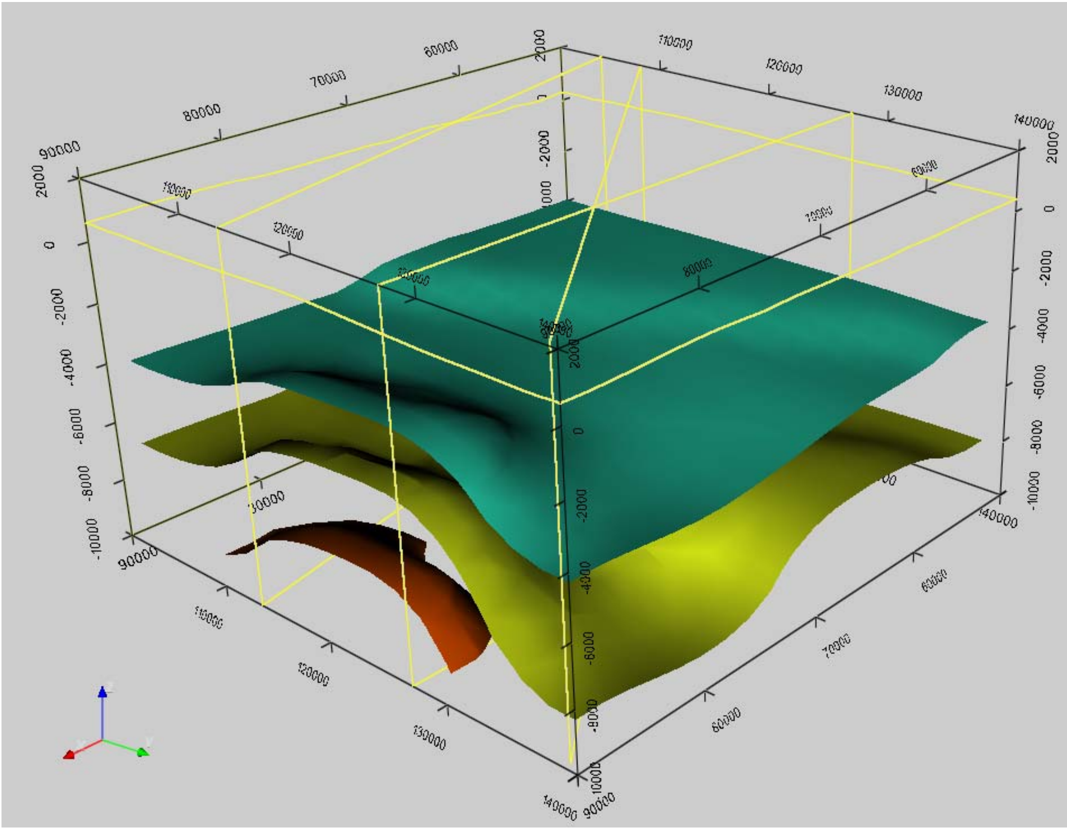
4 Click on the **OK** button to set the iso-surface values.

5 Right-click to open the MeshGrid **Field Visualisation Manager** via the context menu of the MeshGrid field

6 In the visualisation manager, check the **View isosurfaces in 3D** check box.



7 Make sure all other views are unchecked and choose **OK** to close the dialog and display the iso-surfaces.



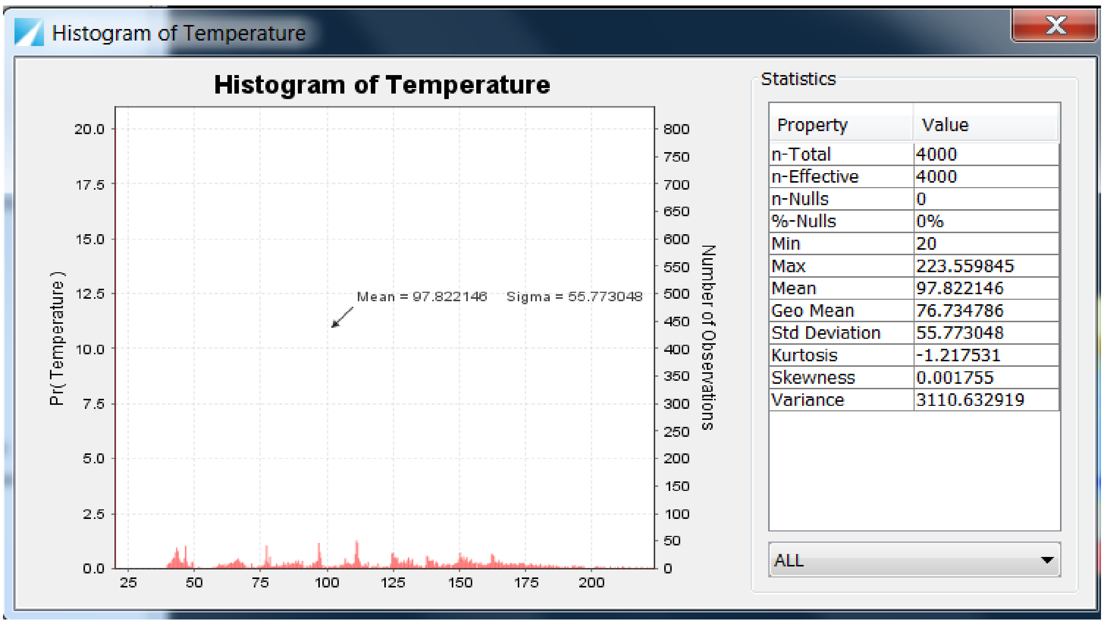
D8 Stage 9—Data Statistics of a MeshGrid

Parent topic: Tutorial D8: Compute geothermal solutions

MeshGrid data can also be analysed using histograms, cross-plots, multi-field analysis and polynomial data fitting. In this tutorial only the histogram dialog will be presented in any detail.

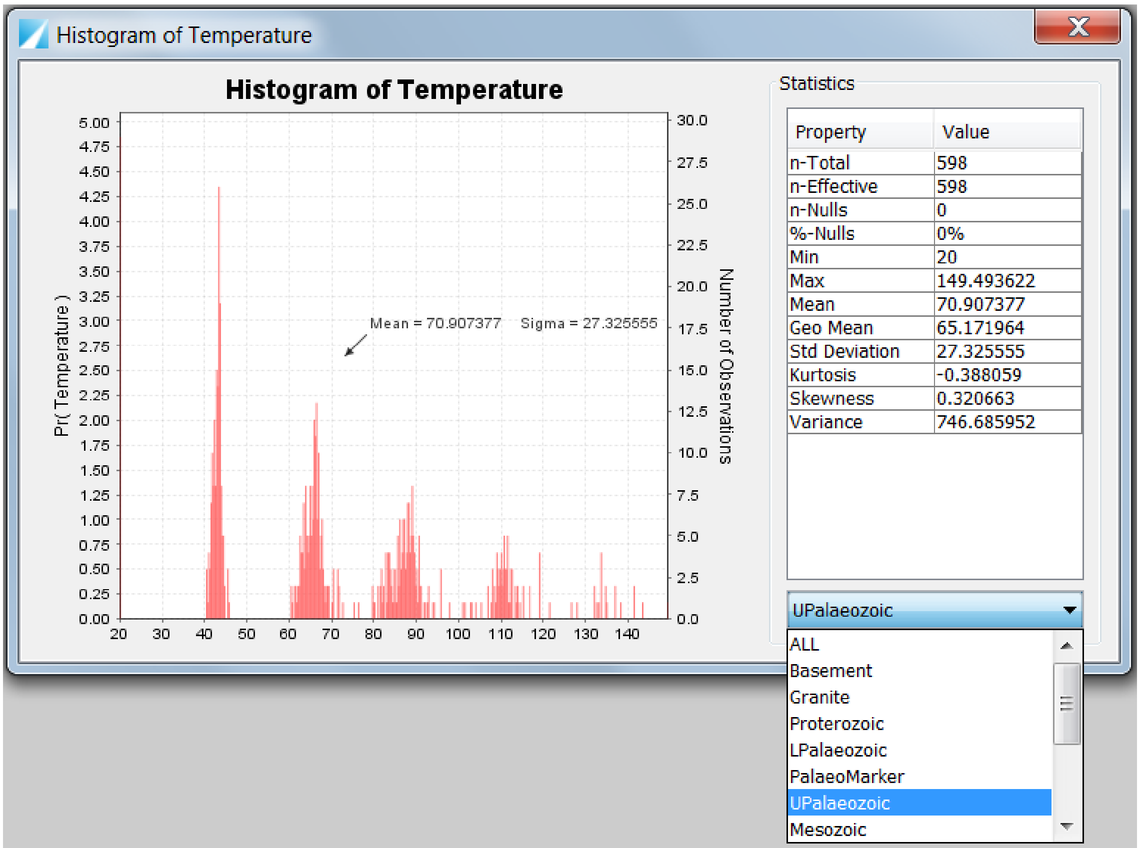
1 Open the Temperature field context menu and select **Histogram**

2 This will open the **MeshGrid Field Histogram** dialog box which contains a histogram plot and on the right a set of statistical measures of the data.



3 By default the statistics are calculated for all geological units. However this can be refined to a single geological unit. Open the pull-down list and select 'UPalaeozoic'.

4 The histogram plot should change, along with the computed statistics.



5 *(For the end-point project supplied)* In the **Open a project** dialog box navigate to the 3D GeoModeller Project **`.xml`** file

`Tutorial_D\Tutorial_D8\D8Completed_Project\D8Completed_Project.xml`

Tutorial D9: Microseismic 3D Modelling and Analysis

Parent topic: **Tutorial D (Geothermal and Microseismic)**

In this section:

D9 Overview

Parent topic: **Tutorial D9: Microseismic 3D Modelling and Analysis**

In this tutorial we:

1. Import the Microseismic database
2. Discover the meshes and grids environment
3. Plot the seismic cloud within 3D viewer
4. Open and play with Interpretation tools
5. Import flow-rate database and open graph
6. Filter the data types with a multi-filter manager

D9 Stage 1 - Import EGS drillholes

Parent topic: **Tutorial D9: Microseismic 3D Modelling and Analysis**

D9 Stage 1 overview

After analysis of the Geothermal forward modelling solution and plotting the geology data superimposed above the temperature results, it is clear that the source of heat in the project corresponds to the intrusion called "Granite" in the right hand side of the project box (see Tutorial D8 stage 6). With a vertical temperature of 40°C/km the granite is hot enough at 4km to host an EGS (Enhanced Geothermal System). Three geothermal boreholes have been drilled to reach 5.2 km depth. The drillholes are not vertical.

D9 Stage 1 Steps

1. If it is not already open, open your Tutorial D8 project or the supplied start point GeoModeller project for Tutorial D9.

   From the main menu choose **Project > Open** or

   From the toolbar choose **Open** Or press CTRL+O

   (For the start-point project supplied) In the **Open a project** dialog box navigate to the **`3D GeoModeller Project.xml file`**

   `Tutorial_D\Tutorial_D9\D9Beginning_Project\D9Beginning_Project.xml`

2. Save a copy of this project in your own data area.

   From the main menu choose **Project > Save** as or from the toolbar choose **Save As** or press CTRL+SHIFT+S

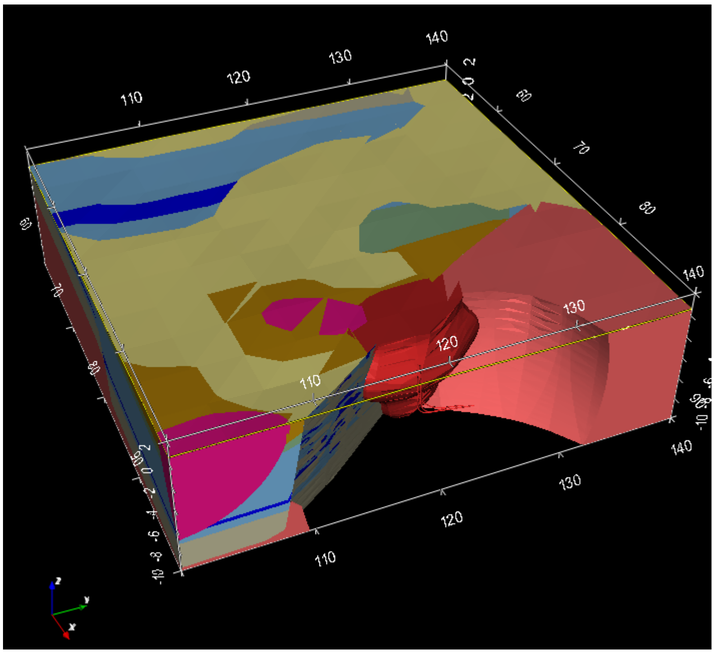
   Save your project work in a folder outside the original folder.

3. If required, compute the model and build 3D Geological model:

   From the main menu choose **Model > Compute** or

From the Model toolbar choose **Compute** or Press CTRL+M

In the **Explore Menu** extend **3D Geology** and hide the formation **Granite**. (That will help to see the drillholes imported in their geological context)



4 Import the EGS drillholes:

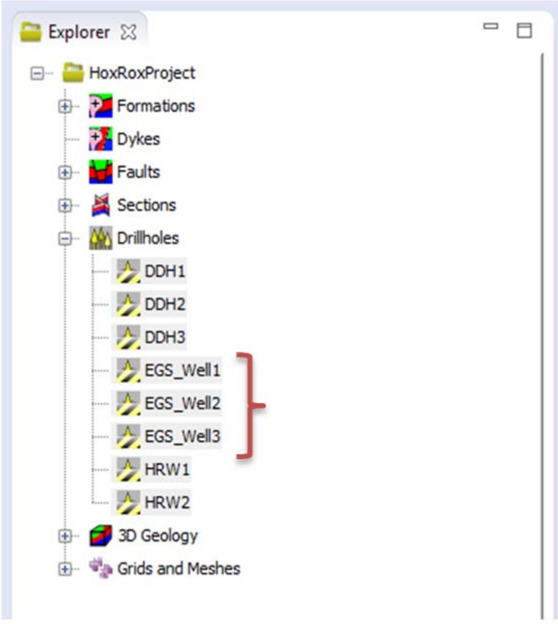
From the main menu choose **Import > Drillhole > 3 Files (Collars, Surveys, Geology)**

In the **Load Drillhole CSV dataset** dialog box:

- **Browse** to the 'Collar Table' file, `Geothermal_Wells_EGS_Collars.csv` in the `Tutorial_D\Tutorial_D9\Data\` folder, then browse 'Survey Table' file `Geothermal_Wells_EGS_Surveys.csv` and 'Geology Table' file `Geothermal_Wells_EGS_Geology.csv`.
- Select **Next >**
- Use the drop-down lists of labelled 'columns' at each step to assign the correct file columns to the fields required by GeoModeller i.e. the drillhole Hole ID, (X, Y, Z) collar coordinate and Hole Depth. You can navigate these steps using **Next >** or **< Back** buttons.

5 At the final step, choose **Finish**

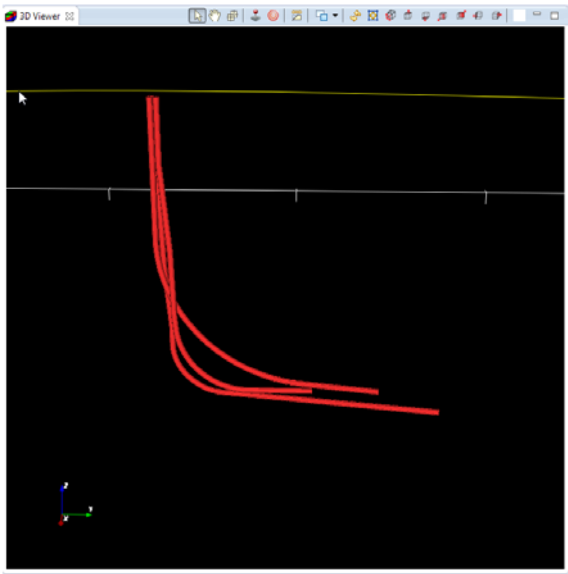
The 3 additional drillholes (EGS_Well1, EGS_Well2 and EGS_Well3) are now loaded, and a brief load report is presented. All drillholes are now displayed in the 3D Viewer (see right).



In the **Explorer tree** > Right-click on **Drillholes** and choose **Shading** to render the holes in the **3D Viewer**. The default display is wireframe.

You can also set the radius of the displayed drillholes from the drillhole context menu **Drillholes >Appearance**.

Show or Hide drillholes in 3D Viewer



1 In the **Project Explorer**, choose **Drillholes > Show**—shows all drillholes in the 3D Viewer

2 In the Project Explorer, choose **Drillholes > Hide**—hides them from the view

Or, for a chosen drillhole either **Show** or **Hide** it

D9 Stage 2 - Analyze the dataset format of the micro-seismic events

Parent topic: **Tutorial D9: Microseismic 3D Modelling and Analysis**

D9 Stage 2 overview

Enhanced Geothermal Systems (EGS) are geothermal reservoirs formed by hydraulic stimulation of low permeability rock (in our case the Granite). In faulted crystalline formations, the mechanism of stimulation is induced shear on pre-existing fractures, which increases their transmissibility by orders of magnitude.

In this tutorial, the granite has been stimulated 3 times between 2008 and 2010 and the micro-seismic activity recorded. The pressure and flow rate of the water injected through the wells during the stimulation has also been monitored and will be imported later in the tutorial.

Our HotRox project (this tutorial) is a typical hot rock (EGS) geothermal energy target from medium latitudes of Australasia. The micro-seismic database presented below is a synthetic database based on real granite stimulations.

1 The micro-seismic database is located in the directory:

   Tutorial_D\Tutorial_D8\Data\Microseismic_Database_Stim_08_10.csv

   The database is in CSV format and can be opened with any spread-sheet editor. **Open** the database with your spread-sheet editor.

   The measurements of induced micro-seismicity from the 2008 and 2010 stimulations were ‘treated’. GeoModeller doesn't support untreated seismic data from geophones.

   There are 17850 seismic events in this database. Each event records the following:

   - The location of the hypocenter XYZ in **WGS84/UTM zone 54N Projection** (the same as used in the GeoModeller project to locate the data in the 3D Geological Model).
   - The event ID to identify each seismic event. It corresponds to a number from 1 to 17850.
   - The recorded time of each seismic event is defined by 2 columns/fields; **Date** (in the format dd/mm/yyyy) and **hour** (in decimal format).
   - The X, Y and Z locational Errors in 3D space, in metres.
   - The Magnitude of each induced seismic event in local magnitude scale (M).
   - The Focal mechanism data defined in three columns:
     - **strike** (with a range of 0-360°); the fault trace direction in decimal degrees (0 to 360 relative to North) defined so that the fault dips to the right side of the trace.
     - **dip** (0-90°); the angle of the fault in decimal degrees (0 to 90, relative to the horizontal).
     - **rake** (+/-180°); or pitch, the direction the hanging wall moves during rupture, measured relative to the fault strike (between -180 and 180 decimal degrees.

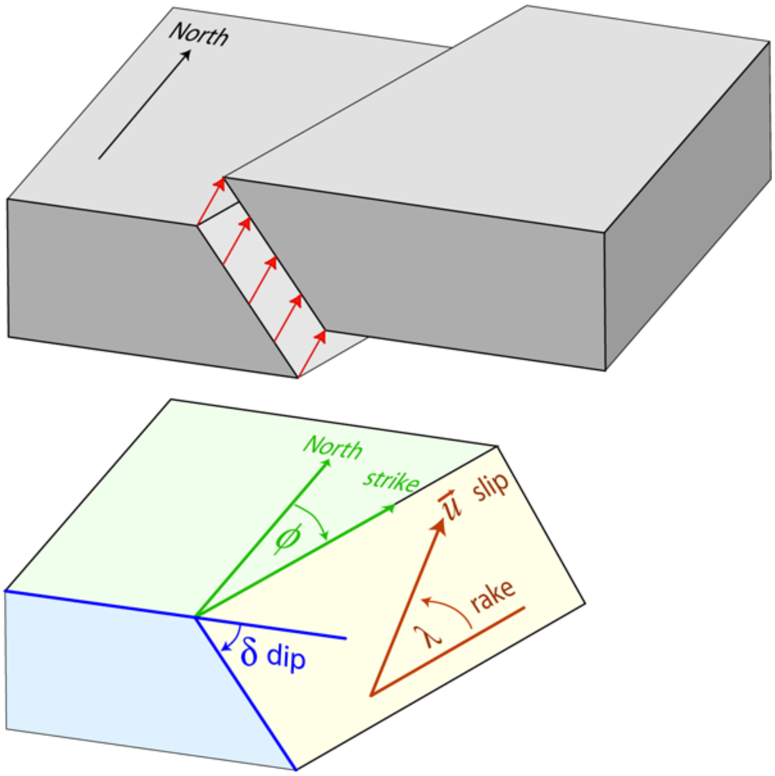
       Basic Examples:

       Dip=90 & Rake=0------> left lateral strike slip

       Dip=90 & Rake=180---> right lateral strike slip

       Dip=45 & Rake=90-----> reverse fault

       Dip=45 & Rake=-90----> normal fault



Waveform data are not available but a column (WID) is included in the database for addition of waveforms in the future. **The word "NAN" is present in the database where data for a field is not available for a seismic event.**

X	Y	Z	ID	date	hour	Xerr	Yerr	Zerr	M	Strike	Dip	Rake	WID
87245.4	121262.7	-3824.8	1	8/04/2008	17.926	25.1	24.5	52.3	0.4	NAN	NAN	NAN	NAN
87307.4	121275.3	-3831.8	2	8/04/2008	17.945	35	33.8	66.1	-0.3	NAN	NAN	NAN	NAN
88666.1	122502.6	-3840.4	3	9/04/2008	19.088	40.2	35.7	66.6	-0.5	NAN	NAN	NAN	NAN
87122.7	122160.1	-3856.3	4	11/04/2008	10.323	34.1	33.1	63.3	0.1	2	43	60	NAN
87110.5	122159.9	-3863.3	5	11/04/2008	11.382	47.9	61.8	88.6	0	NAN	NAN	NAN	NAN
87075	122157	-3864.5	6	11/04/2008	12.478	51.6	53.9	109.1	0.5	NAN	NAN	NAN	NAN
87159.6	120219.3	-3865.5	7	11/04/2008	13.003	41.3	41.1	81.5	0	NAN	NAN	NAN	NAN
87107	122165.6	-3868.2	8	11/04/2008	13.101	24.4	25	50.1	0.1	NAN	NAN	NAN	NAN
87111.3	122156.4	-3868.3	9	11/04/2008	23.166	28.8	28	54	0.9	NAN	NAN	NAN	NAN
87127.9	122150.3	-3873.5	10	12/04/2008	15.528	36.3	38.4	91.4	0.1	0	45	175	NAN
87114.4	122183	-3873.6	11	14/04/2008	16.259	34.4	35.9	73	0.2	0	42	160	NAN
87122.6	122158.9	-3874.4	12	14/04/2008	16.365	34.8	35.6	72	0.4	1	40	142	NAN
87311.1	121314.7	-3875.5	13	15/04/2008	4.135	23	21.8	38.7	0.3	0	43	142	NAN
87137.7	122192.3	-3879.5	14	15/04/2008	9.207	28.8	30.5	72.1	-0.4	8	45	178	NAN
87132.6	122197.5	-3880	15	15/04/2008	9.495	35.4	36.9	75.4	-0.3	0	40	9	NAN
87125.2	122139.2	-3880.7	16	16/04/2008	23.476	40.2	42	84.5	-0.3	1	40	140	NAN
88338.1	121836.4	-3882.1	17	17/04/2008	0.821	18.3	17.8	34.7	-0.3	2	42	150	NAN
88389.5	121805	-3884.8	18	17/04/2008	0.822	12.5	12.4	23.9	0	3	41	162	NAN
87282.6	121282.8	-3887.3	19	22/04/2008	8.145	35	28.6	49.5	0.5	4	41	175	NAN
87248.9	121361.4	-3888.8	20	22/04/2008	20.994	46.5	43.8	99.6	-0.3	5	41	125	NAN
87271.3	121336.8	-3889	21	9/07/2008	7.548	30.4	32.3	57.3	-0.5	6	42	104	NAN
87291.2	121293.3	-3889.4	22	21/07/2008	12.155	27.2	25.5	48.7	-0.8	0	45	150	NAN
87555.1	121286.4	-3890.2	23	26/07/2008	18.424	95.9	81.2	120.3	-0.8	6	43	150	NAN

The csv format is a simple text file with a comma separating each field. In Stage 3 we import this database into GeoModeller.

The file "**`Microseismic_Database_Stim_08_10.csv`**" has been saved with the spread-sheet editor (Excel) by selecting CSV(Ms-DOS)(*.cvs) format from the available list. It is already in the correct format for import.

D9 Stage 3 - Import the Microseismic database within GeoModeller

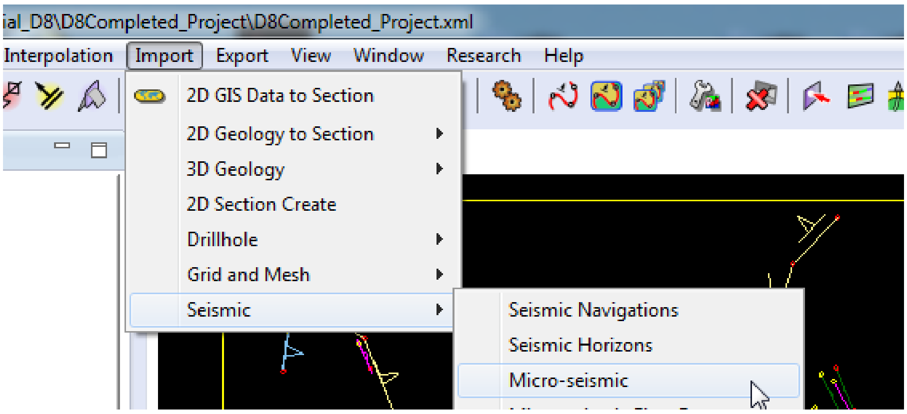
Parent topic: **Tutorial D9: Microseismic 3D Modelling and Analysis**

D9 Stage 3 overview

Once the micro-seismic database is saved in the correct CSV format it can be imported into the GeoModeller project as a Mesh Grid object. Then the seismic cloud can be plotted in 3D with the geology.

D9 Stage 3 Steps

1 From the Main menu of GeoModeller software
Click on: **Import > Seismic > Micro-seismic**

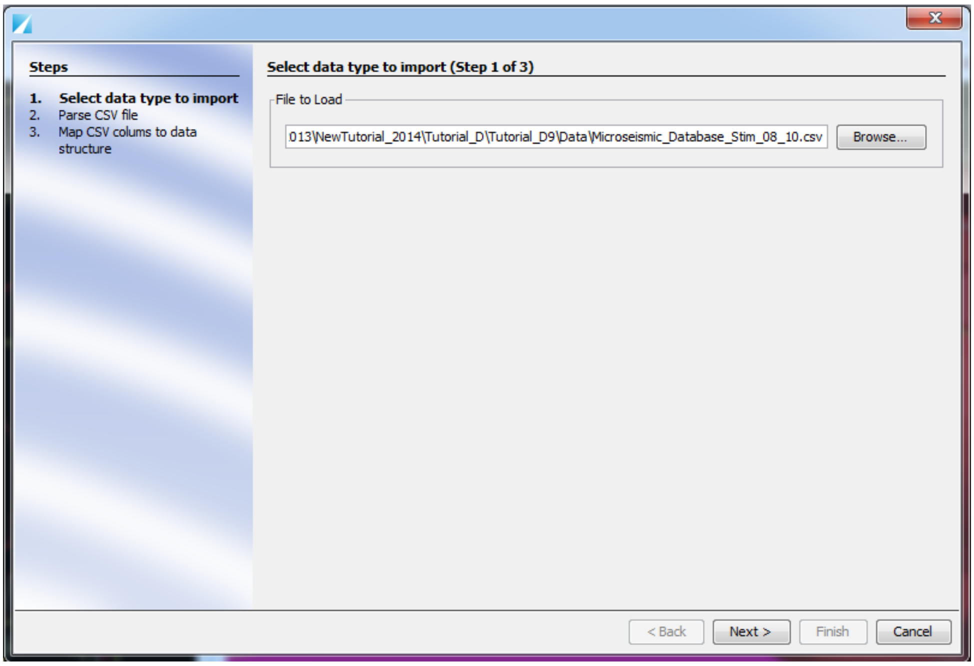


The dialog box of the CSV Data Importer will appear.

There are 3 steps to follow to import the micro-seismic database.

2 Step 1:

- Click **Browse** to navigate to the micro-seismic database directory.
  Tutorial_D\Tutorial_D9\Data\ Microseismic_Database_Stim_08_10.csv
- Click **Next >**.

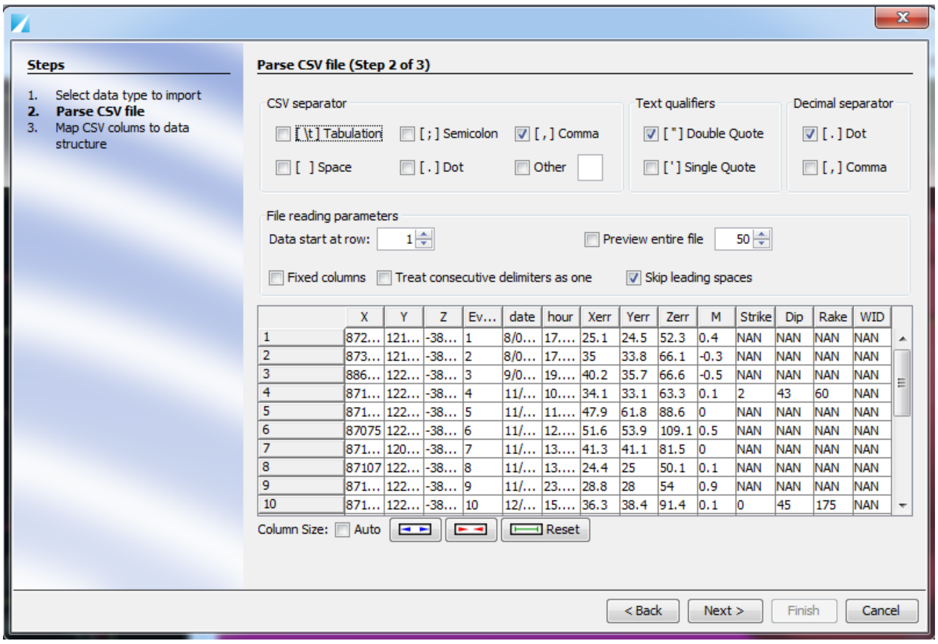


3 Step 2:

Parse CSV file allows the database import to be setup as required by GeoModeller. Import as follows:

- choose the **CSV separator, Text qualifiers** and **Decimal separator**
- choose the required **File reading parameters:**
  - **Data start at row:** (to eliminate text header lines).
  - **Fixed columns**
  - **Treat consecutive delimiters as one** (for space separated fields).
  - **Skip leading spaces**

For this micro-seismic database, nothing has to be changed at this step. The database is well organized and can be imported without modification.



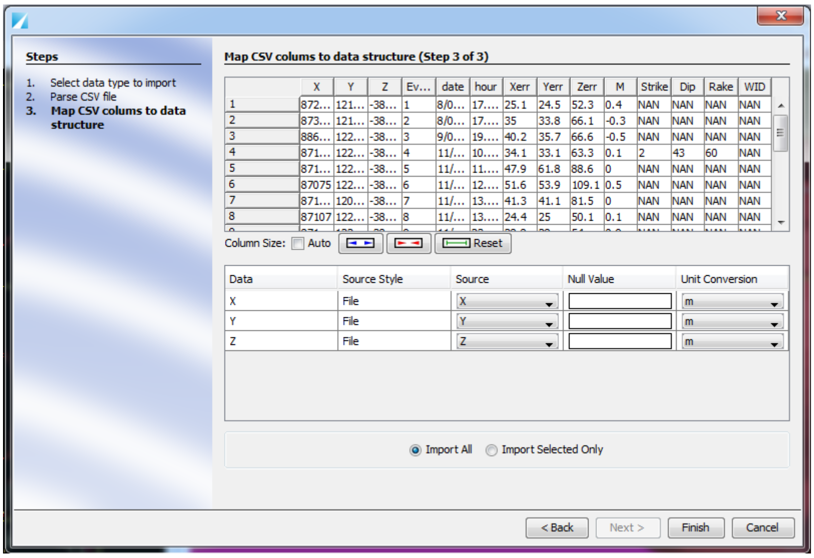
- Choose **NEXT**.

4 Step 3:

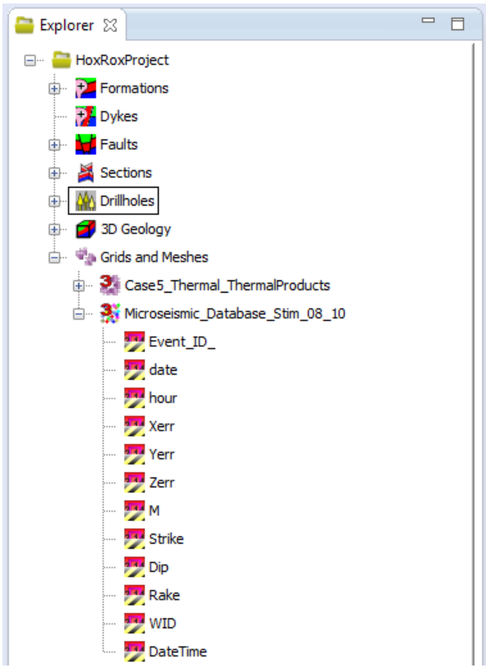
The last step required to import the micro-seismic database is:

Map CSV columns to data structure.

- Map the CSV file columns to the micro-seismic data fields expected by GeoModeller using the **Source** column name drop down selectors.



Only 3 fields must be defined in order for the software to import the micro-seismic events. These are the event locations X, Y and Z. The other imported fields are selected automatically using their column names.



Note: Fields named 'date' and 'hour' must be present in the csv import file. A field named DateTime is created on import!

The *date* and *hour* fields are expected to be in the following format:

date == 8/04/2008 (dd/mm/yyyy)

hour == 17.926 (decimal hours)

The other column names must match the list shown in the mesh grid tree to the right for them to be automatically recognised by the GeoModeller visualisation tools. Aliases can be assigned i.e. **XError**, **YError**, **ZError** are recognised and assigned on import. Aliases are set by Right clicking on the field and choosing **Properties.**

When the X, Y, Z file columns are correctly selected,

- Choose **Finish**.

It will take a few seconds, depending on the machine capacity, to import the 17850 seismic events and their associated fields.

Once the import process has finished the microseismic data will appear as an item under the **Grid and Meshes** tab in the **Explore** tree. A sign + (plus) on the left of

Grid and Meshes indicates that the data has been imported.

Expand the Explorer Grids and Meshes tree to reveal the micro-seismic database. All the imported fields are shown in the mesh grid tree above.

Using a **Right click** operation on the imported fields, various tools can be selected to analyze and interpret the observed Micro-seismicity. This is explained in the following stages.

5 Save your project. From the main menu choose **Project > Save** or from the toolbar choose **Save** or press CTRL+S

D9 Stage 4 - Plot the seismic cloud within 3D viewer

Parent topic: **Tutorial D9: Microseismic 3D Modelling and Analysis**

D9 Stage 4 overview

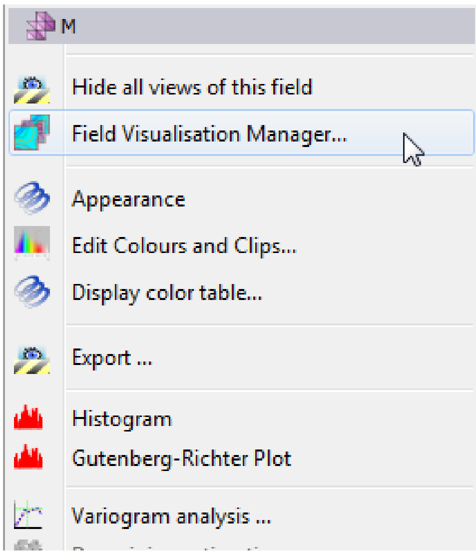
Now that the micro-seismic events and their attributes have been imported into the GeoModeller project, we will plot the micro-seismic cloud in the 3D viewer with the 3D geology model.

D9 Stage 4 visualise

1 Visualize the Magnitude of the micro-seismic cloud in the 3D viewer:

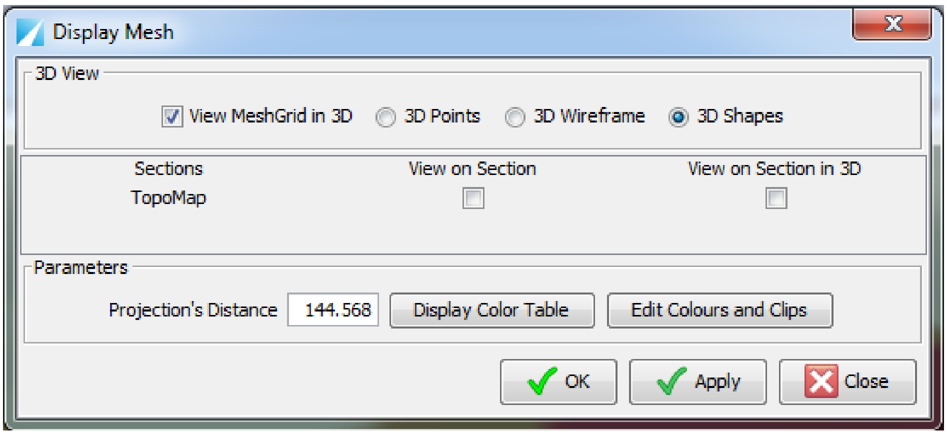
In the **Explore tree**

- Right click on field **Magnitude (M)** and
- Select **Field Visualisation Manager**

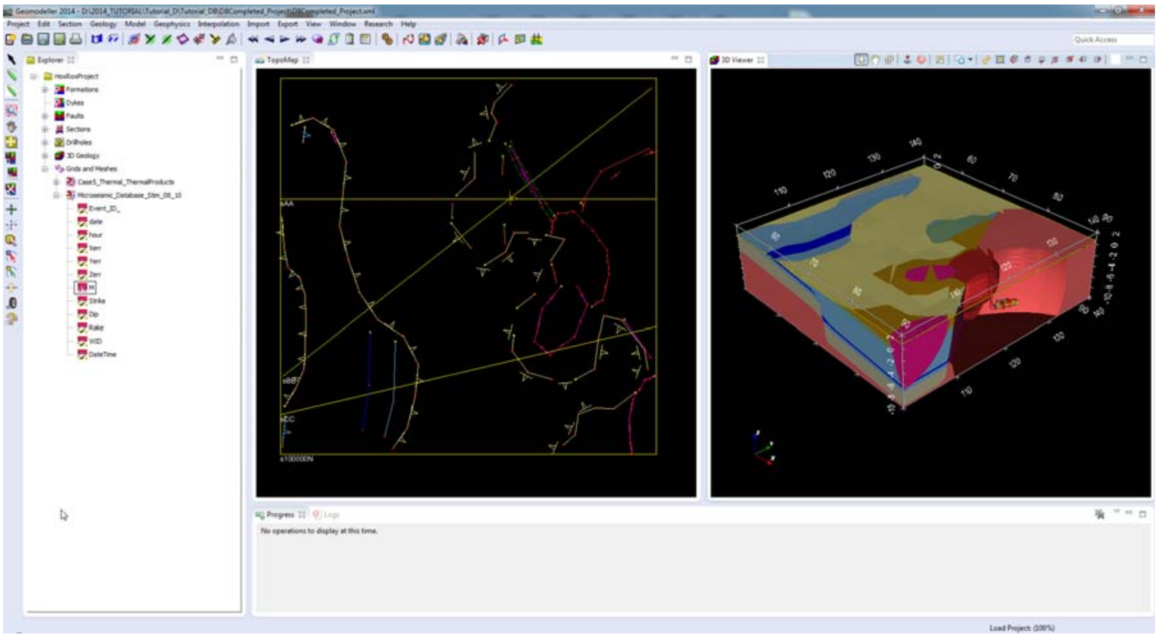


In the **Field Visualisation Manager** dialog toggle:

- **View MeshGrid in 3D** and **3D Shapes** then:
- Click on **OK** or **Apply**.

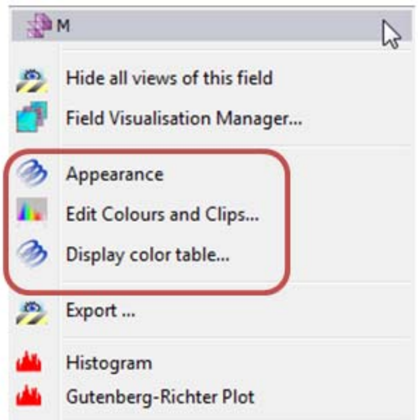


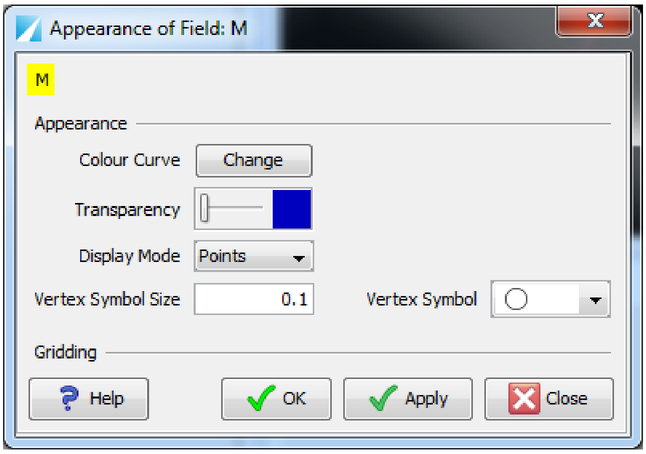
The seismic point cloud displays within the **Granite** formation in the 3D Viewer:



Changing the Appearance of the seismic events in the 3D Viewer.

1 **Right click** on the Magnitude field **M** and **select Appearance;** the following dialog will be displayed.





2 Choose from the following options:

- **Change** - allows the user to select the colour LUT and change the colour mapping limits. This function is also available from the field's Right click context menu as shown in the figure above right.
- **Transparency** - changes the transparency of the point cloud when shaded.
- **Display Mode** - changes the type of 3D display
  - **Shading** - balls are scaled according to the magnitude of M
  - **Wireframe** - hollow wireframe balls scaled as above.
  - **Points** - select this option
- **Vertex Symbol Size** - Set the Vertex Symbol Size to **0.1** (see below left).
- **Vertex Symbol** - Choose the symbol for wireframe or points from the dropdown list.

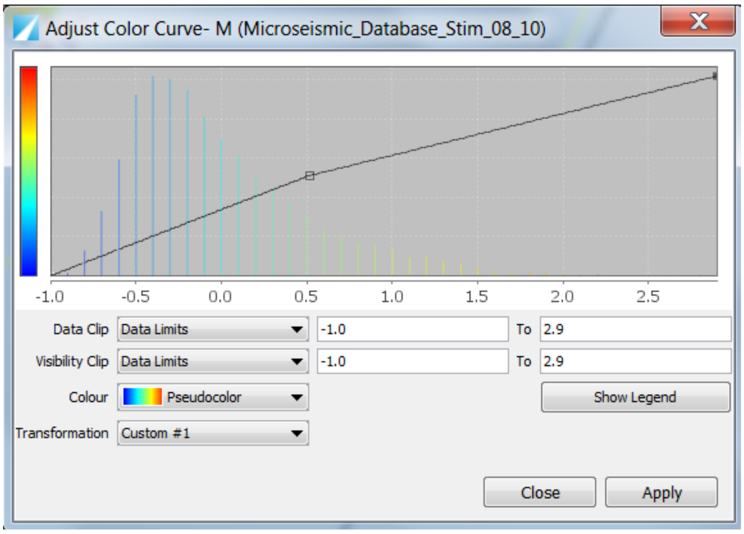
3 Click **Change** in the **Appearance** dialog shown above right or

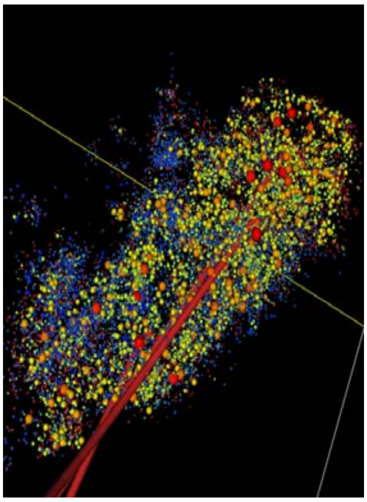
4 **Right click** on the Magnitude field **M** and select **Edit Colours and Clips...** to modify the color scale of the seismic cloud.

- A colorized histogram allows the user to adjust the color of the seismic events according to their magnitude. Choose from the **Colour** dropdown to change the colour lookup table.
- The type of colour mapping can be chosen under **Transformation** (Histogram, Linear, Stepped or Log) or
- by manually clicking and dragging points in the histogram panel to vary the colors as shown below.

Note: To view the seismic cloud as shown below right

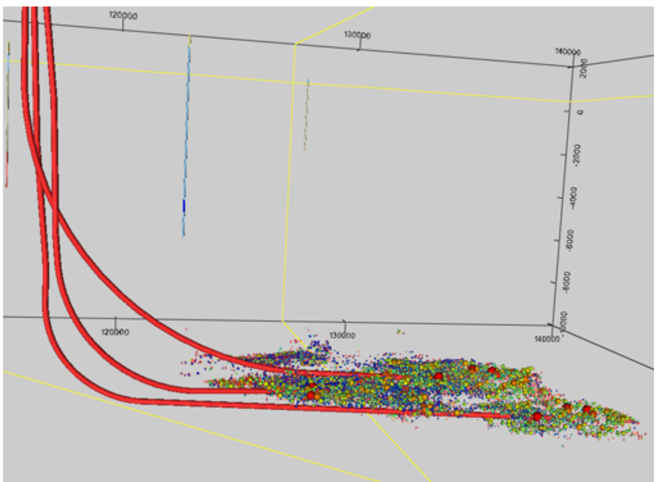
- Right click on **3D Geology** in the **Explorer** tree and select **Hide** to remove the geology from the **3D viewer**, then
- Zoom into the seismic cloud by tapping F on the keyboard. The viewer will zoom to your mouse cursor location
- Rotate the view as required.





5 The visual can be improved by modifying the background colour in the 3D Viewer

- Right click in the 3D Viewer, choose Background colour and then select the 3rd box down from the top left (pale grey).



D9 Stage 5 - Open and play with Interpretation tools

Parent topic: Tutorial D9: Microseismic 3D Modelling and Analysis

D9 Stage 5 general overview

In addition to 3D visualization of the micro-seismic cloud, a number of interpretation tools are avalable to help understand the behaviour of the formation of the fracturing network. These tools are:

- **Histogram**: To visualise the distribution of a field in the seismic cloud.
- **Visual Filter**: A general purpose filter which allows multilevel visual queries on mesh grid fields (i.e. *show all events in 2008 WHERE M>1.0 AND Zerr<50.1*)
- **Time Filter**: To observe the propagation in time of the seismic cloud and also to apply a simple filter to the data.
- **Gutenberg-Richter diagram**: To obtain an initial idea of the number of structures activated during the stimulation of the granite.
- **Focal Mechanisms Cartesian Plot**: To identify subsets of micro-seismic events and the activated structures.
- **Error in location visualisation**:

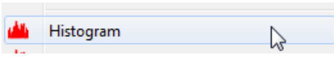
The Histogram tool overview

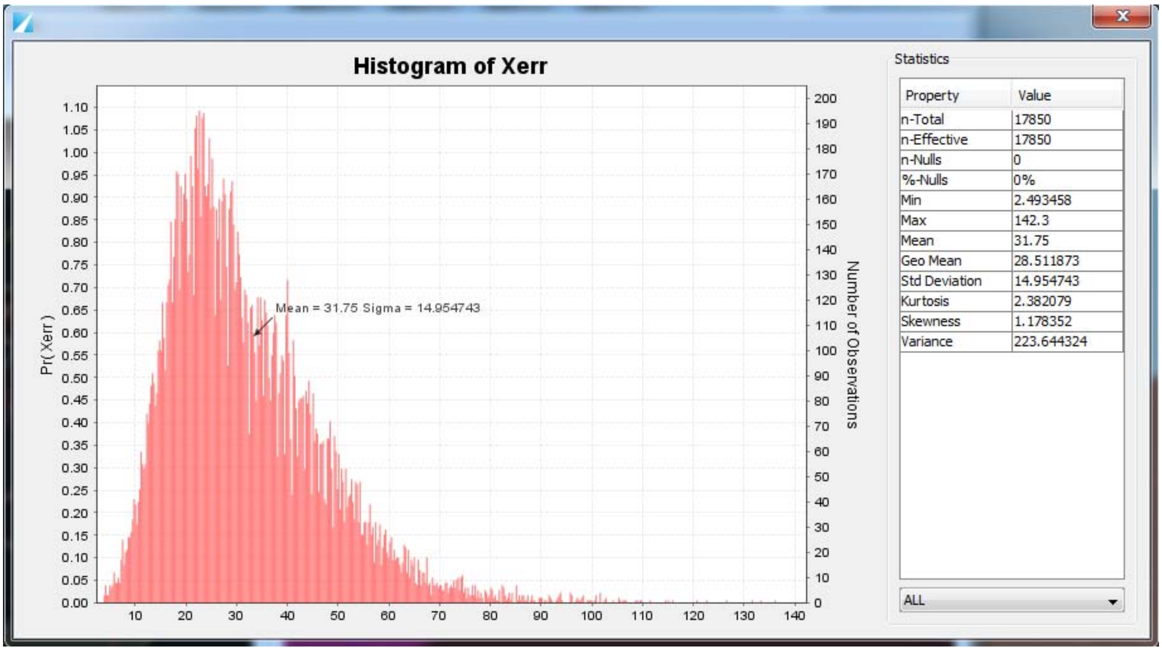
Once a micro-seismic database is imported to a Mesh Grid, the Histogram and Visual Filter tools are available for use on any numeric or date time field via context sensitive Right Click menus.

The Histogram tool usage

1 In the **Explorer tree**, right click on the field that you want to analyse; in this case choose the Error of x 

.

2 Select **Histogram** 



3 The popup dialog displays a statistical summary of the data in graphical and table form; it is possible to zoom into an area of the graph by using the mouse wheel, draggging the cursor or by right-clicking on the window and selecting **Zoom In**. The same method can also be used to **Zoom Out.**

Time Filter overview

A simple visual inspection in 3D of the cloud and its expansion over time can help to detect and draw mechanical barriers. These barriers could be structures that are working against the expansion of the seismic cloud.

The second utilisation of this tool enables filtering of the Histogram using other associated micro-seismic fields.

Time Filter usage

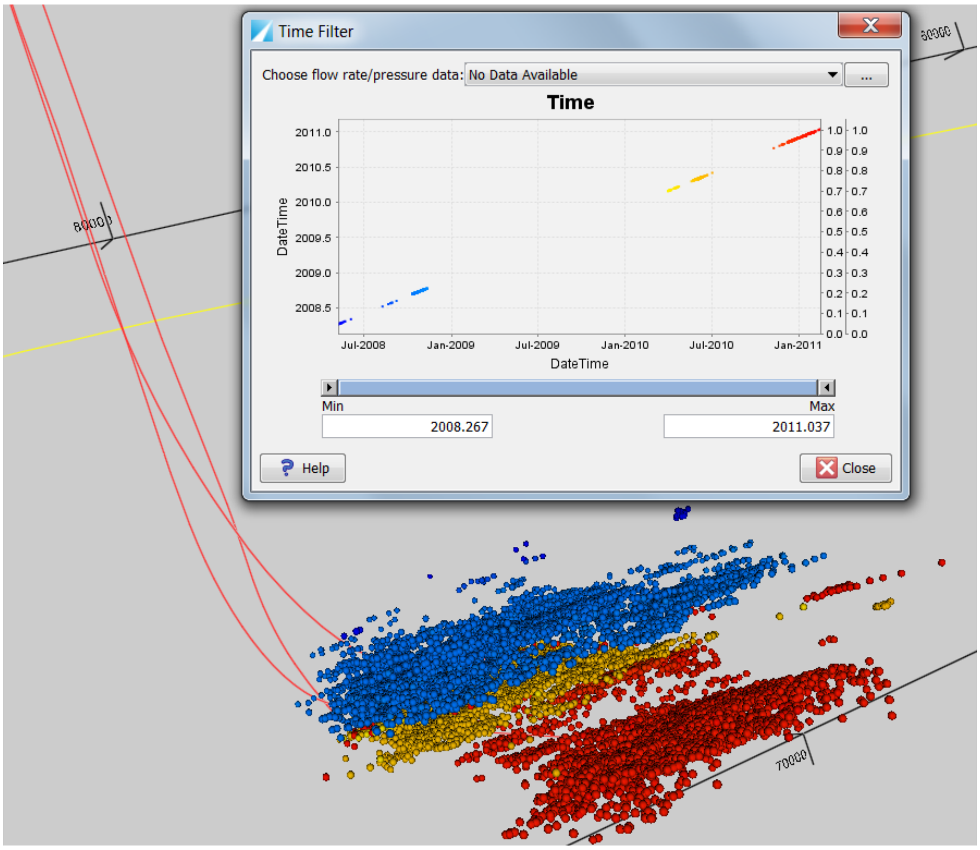
The time filter is located in the **Time Filter** window.

1 **Right-click** the field **DateTime** 

and adjust the visibility and appearance of the data using the **Field Visualisation Manager** and **Appearance** tools. This field is not present in the original database and is a created by combining the "date" and "hour" data fields together.

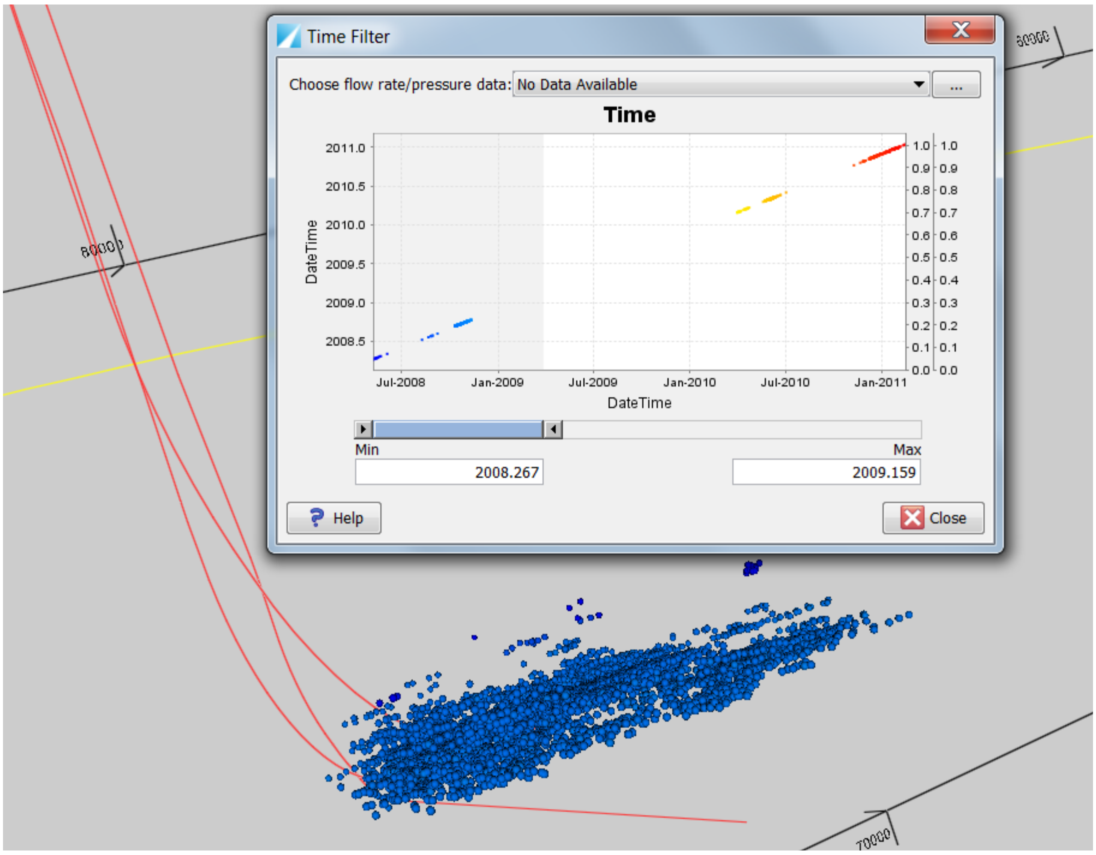
2 Now move up the Grids and Meshes tree one level and **Right-click** on the Mesh Grid, **Microseismic_Database_Stim_08_10** and select **Time Filter**.

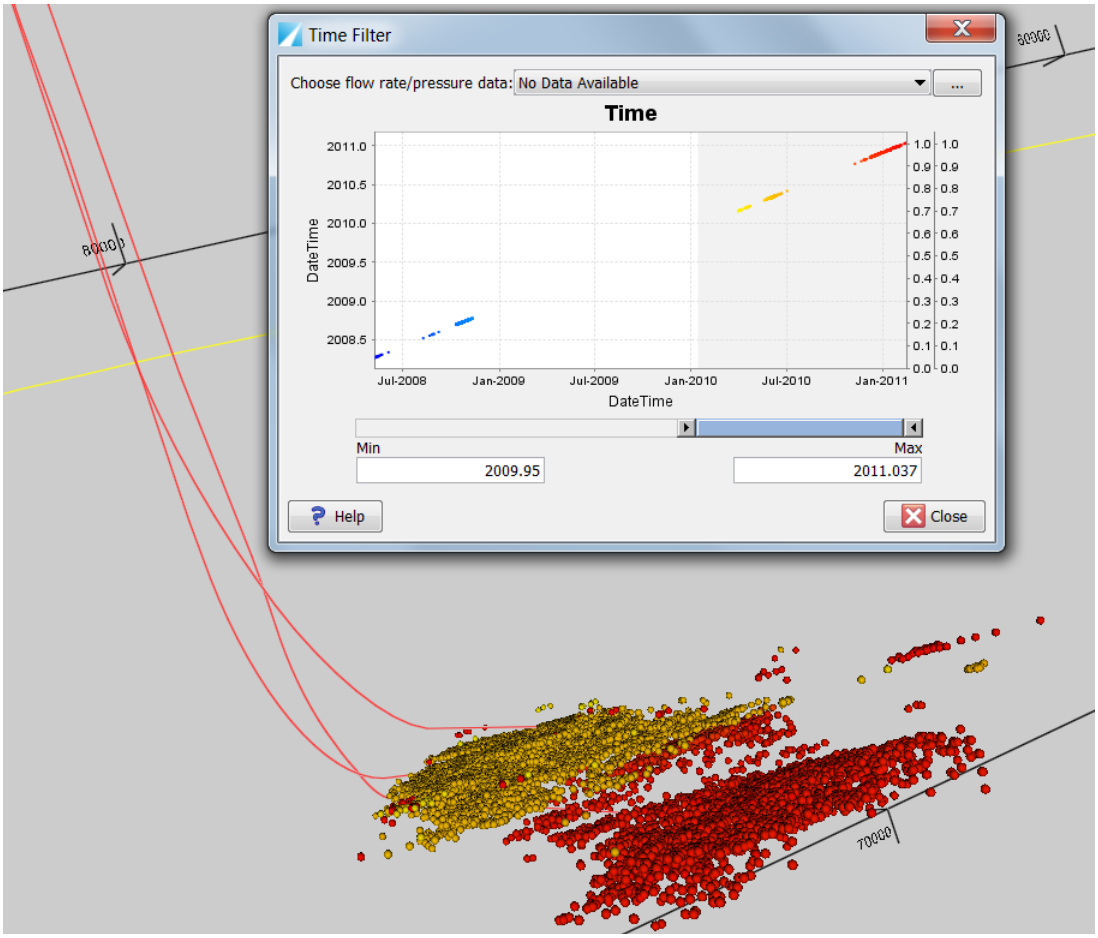
In the **Time Filter** dialog box, a min and max slider bar is located below the histogram. When you start dragging the max arrow cursor to the left along the time axis, the histogram and the seismic cloud update automatically. Events after the max cursor are removed from view. Dragging very slowly from left to right allows the user to visualise the propagation of the seismic cloud with time



The above figure shows default state of Time Filter with all seismic events visible.

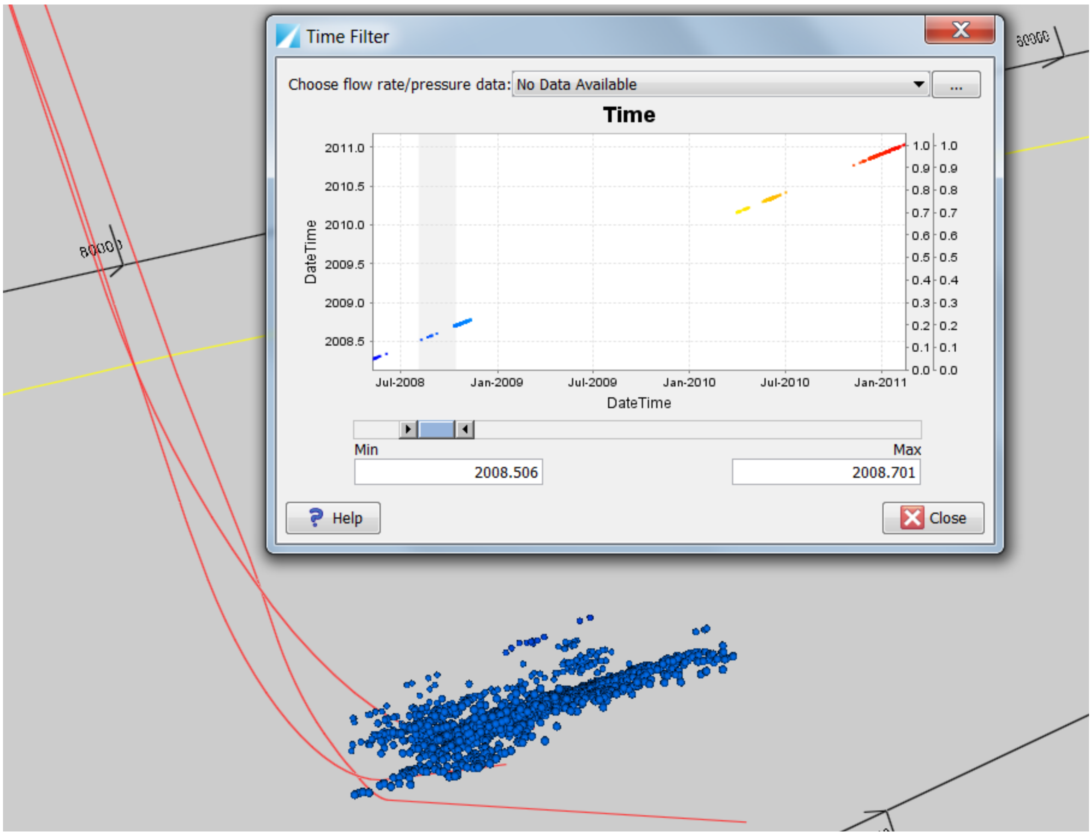
The next two figures show microseismic events before 2009.159 and microseismic events after 2009.95 respectively.

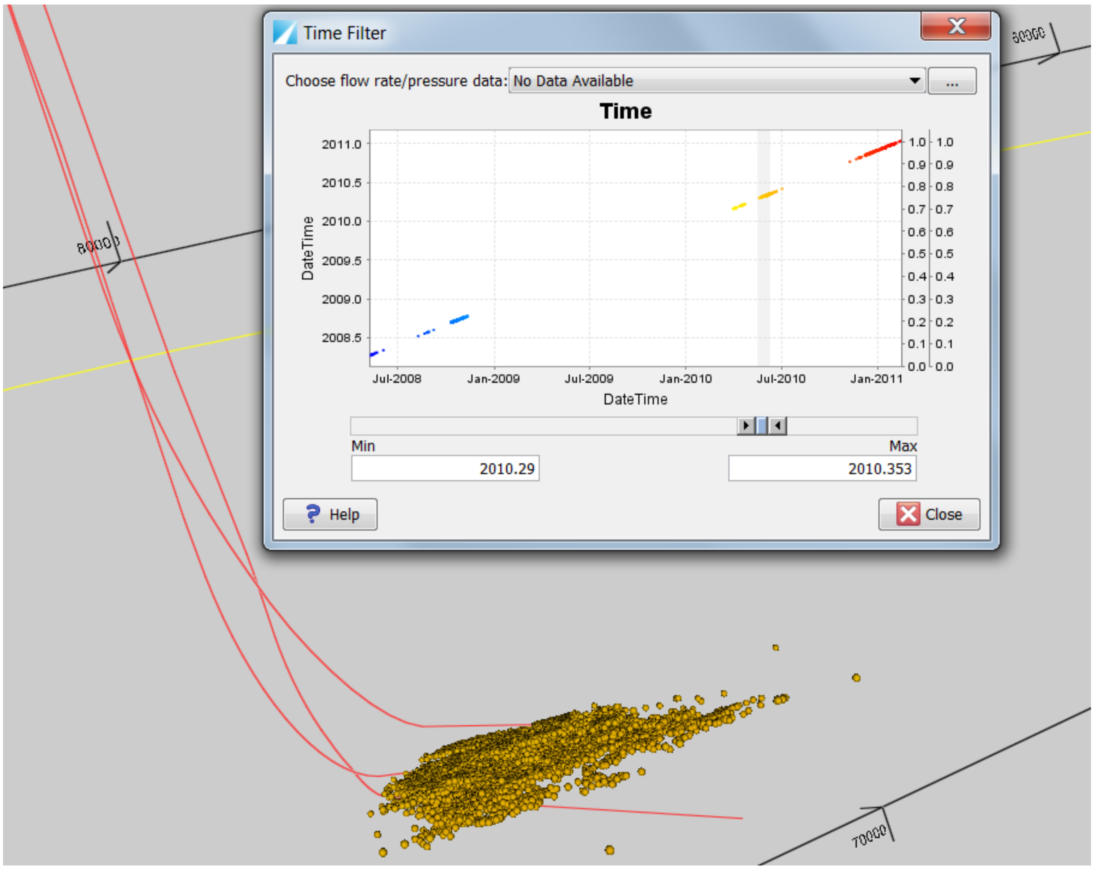




3 The Time Filter cursors can be used to create a narrow moving window for a more detailed examination of the seismic cloud migration during each stimulation.

For example: If we only want to see micro-seismic events from stimulation No.1 between 2008.505 & 2008.701 or stimulation No.2 between 2010.29 & 2010.353





Visual Filter Usage

The above Time filter operations can also be accomplished using the **Visual Filter** which is a more general purpose multilevel visual query tool.

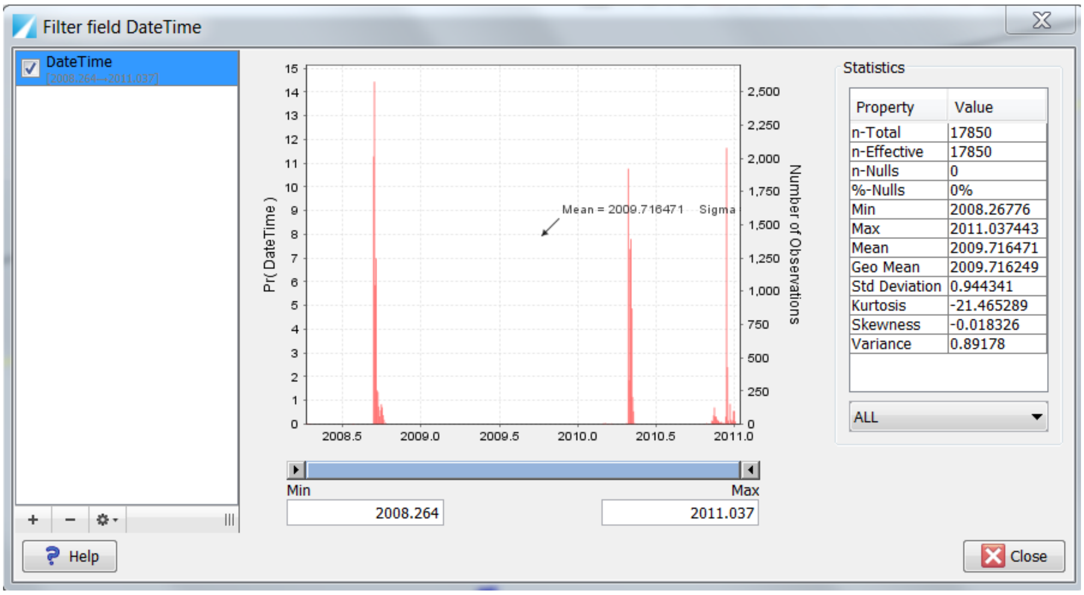
For example:

1 Right Click at the top level of the **Grids and Meshes** tree and select **Remove All Views**

2 Right Click on the **DateTime** field in the **Microseismic_Database_Stim_08_10** mesh grid, choose **Field Visualisation Manager** and display as previously in the **3D Viewer**

3 Right Click on the **DateTime** field in the **Microseismic_Database_Stim_08_10** mesh grid a second time and choose **Visual Filter**

We now see the following dialog with features of both the histogram and time filter tools with an extra variable list panel on the left.



The left panel with the **+**, **-** and cog wheel selectors allows the user to add new fields to the variable list and order them as required using the cog wheel dropdown. When each field is selected the user can choose a range with which to filter the variable which was selected for display (i.e. DateTime)

The central panel shows the histogram for the selected field in the variable list in the left panel.

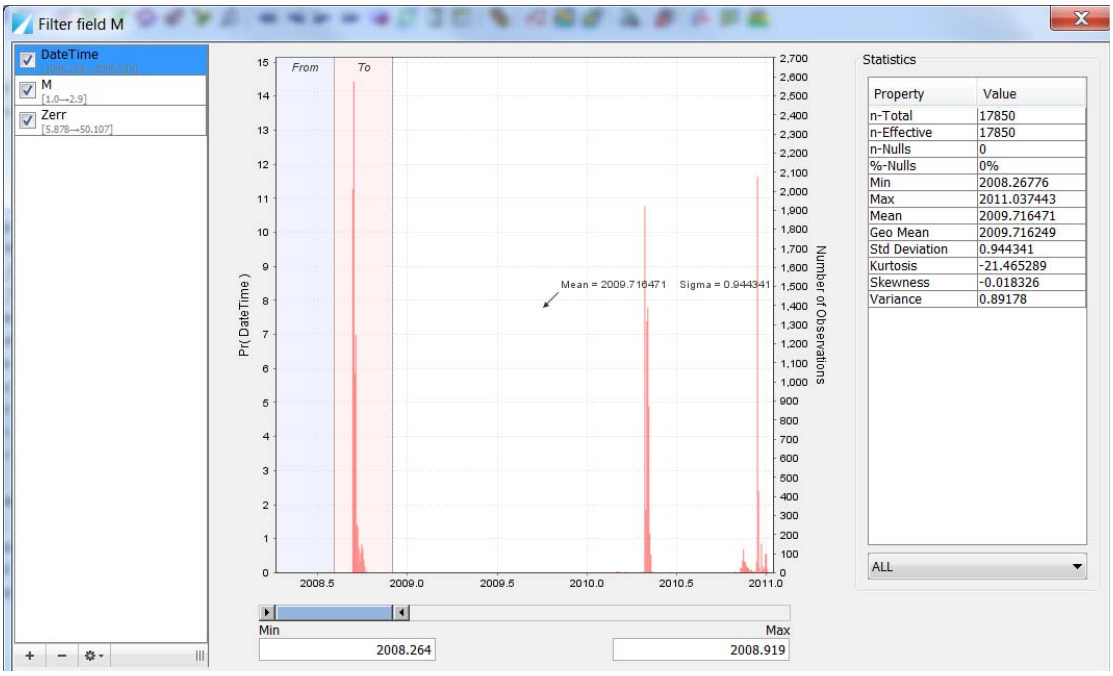
The right panel shows a statistical summary in the same way as the histogram tool and this statistical summary can be further filtered by Lithology if the GeoModeller geological model is added to the Mesh Grid being visualised.

4 Drag the Max button in the centre panel to the left so that only the 1st stimulation is visible.

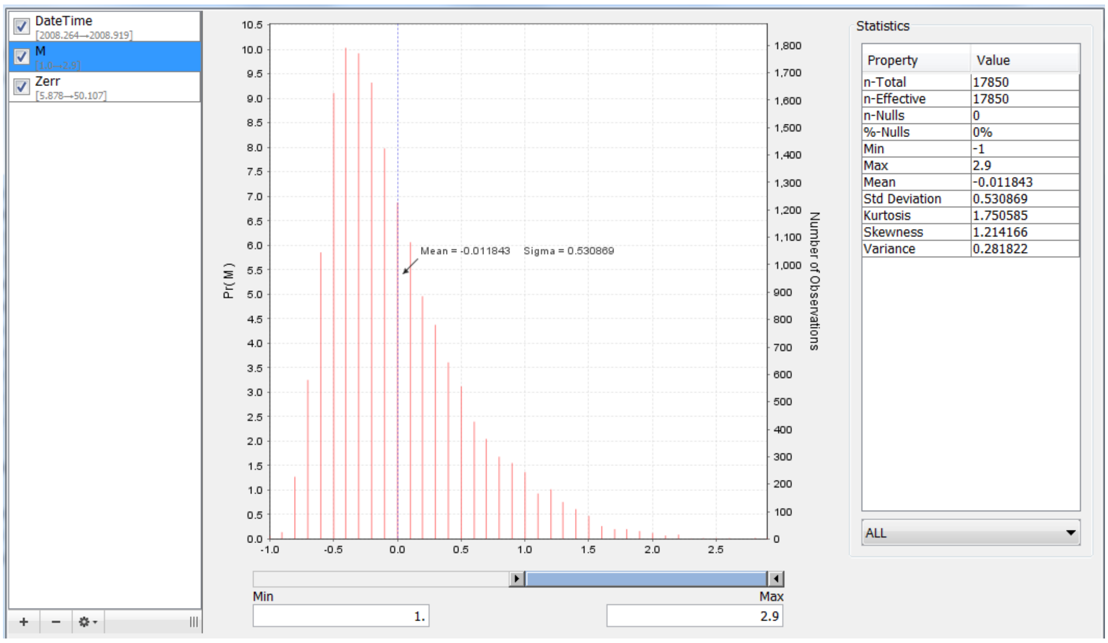
5 Click on the + button at the base of the variable list panel and choose M (Magnitude) to add it to the variable list

6 Click on the + button at the base of the variable list panel and choose Zerr

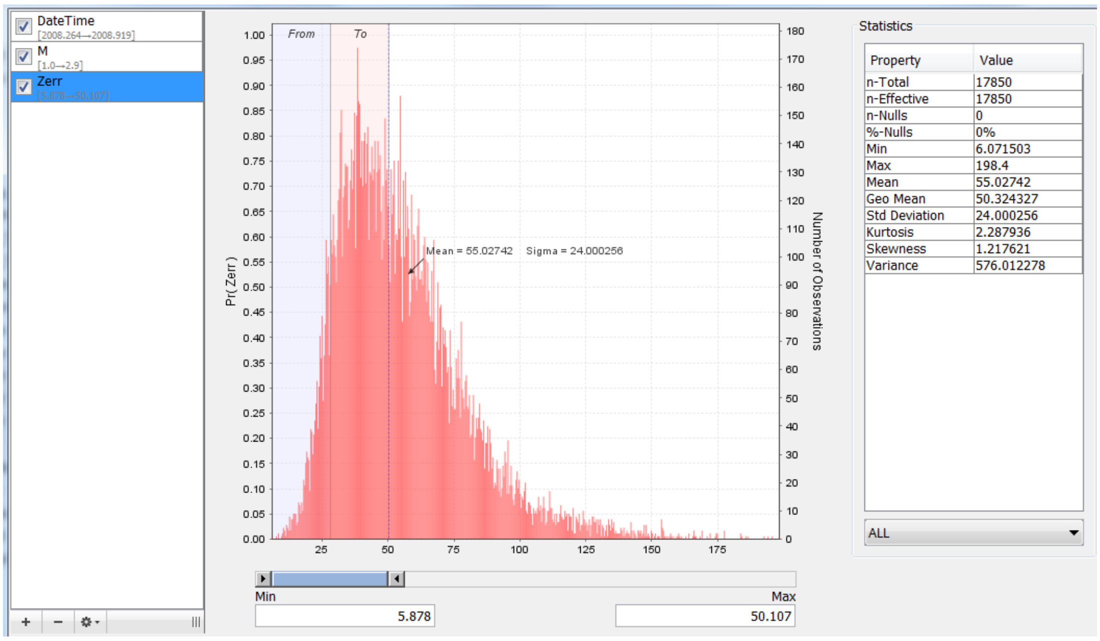
The Visual Filter will display as shown below:



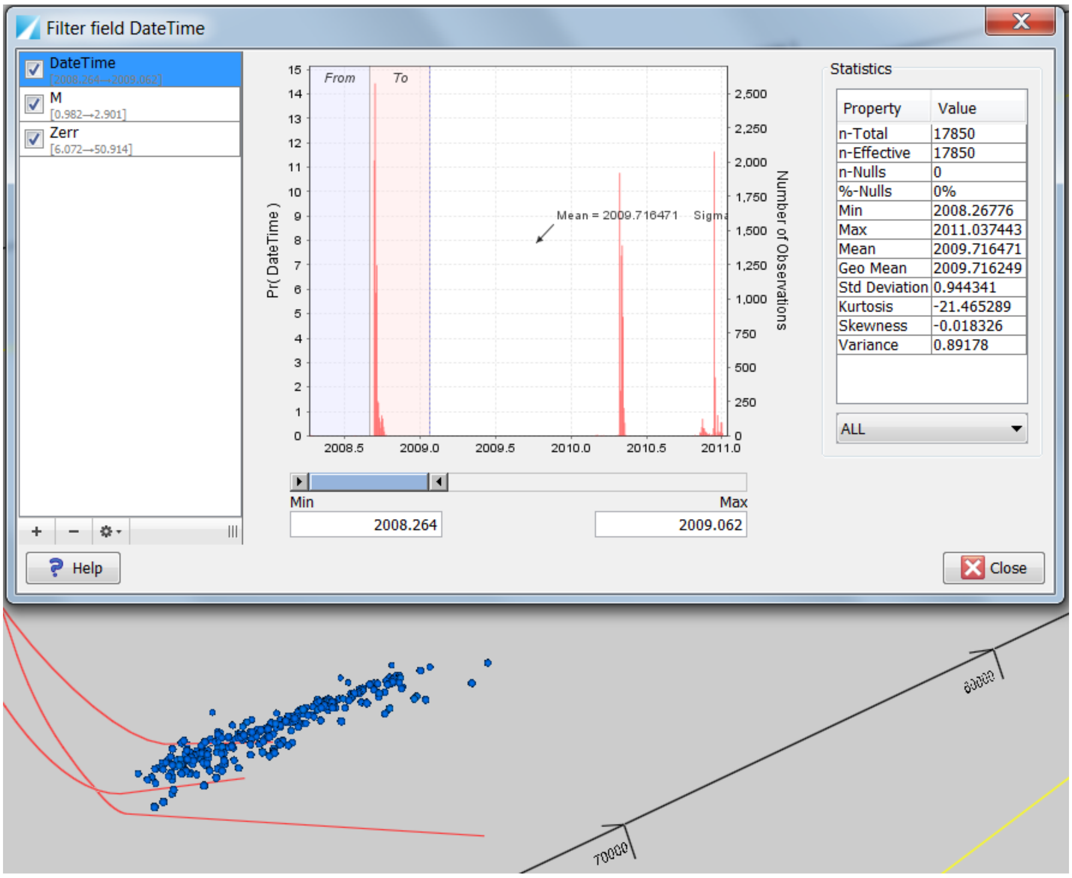
7 Click on the field M in the variable list and drag the Min button to the right to select a Magnitude range from 1 to the max 2.9



8 Click on the field Zerr in the variable list and drag the Max button to the left to select a Zerr range from the Min 5.878 to ~50.0.



9 The 3D display now looks like this:



We have chosen to display stimulation No.1 where local magnitude M >1.0 and Zerr <50.

The Gutenberg-Richter graph overview

The Gutenberg-Richter graph will help to characterize the number of structures activated during any stimulation. This tool expresses the relationship between the "magnitude" and "total number of earthquakes" with "*at least*" that magnitude in any given region and time period:

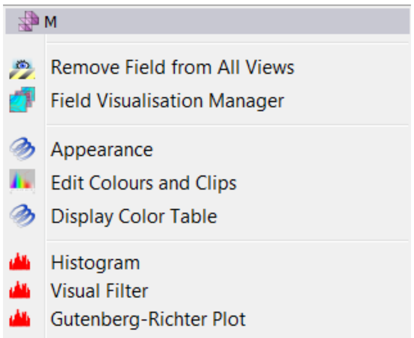
$$\log N = a - bM$$

- **N** is the number of events having a magnitude
- **a** and **b** are constants

The Steps Required To Display the Gutenberg-Richter graph are:

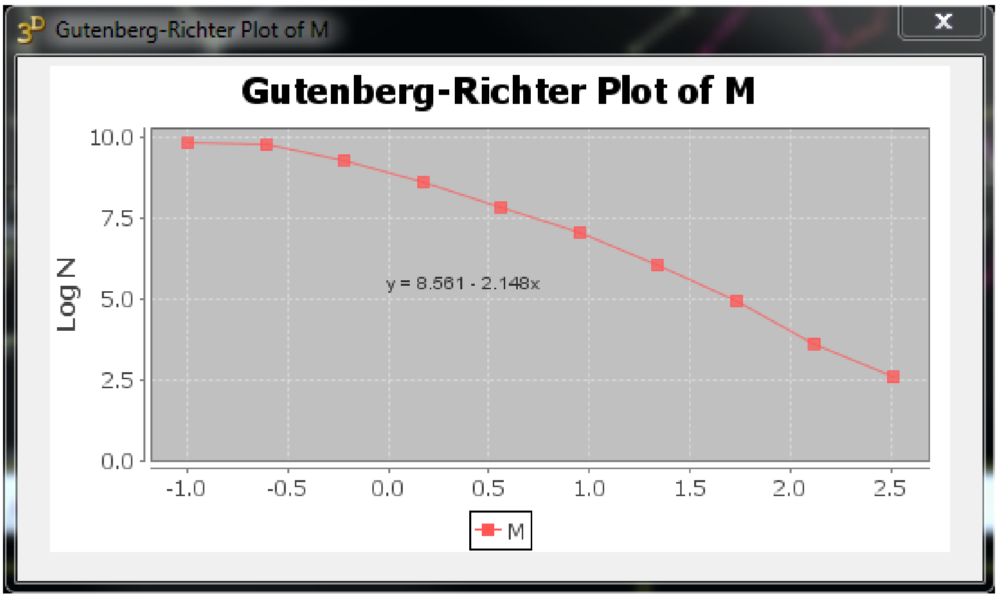
1 In the **Explore menu**, under mesh grid **Microseismic_Database_Stim_08_10**, right click field **Magnitude** M and display it in 3D using the **Field Visualisation Manager** as described previously.

2 Right click field **M** a second time and from the context menu select **Gutenberg-Richter Plot**.



3 The **Gutemberg-Richter** graph appears in a new non-interactive display window. We plot the curve *log(N) v's M* and calculate the constants *a* and *b*. The "b-value" corresponds to the relative proportion of "small" versus "big" events.

If only one structure is activated the relationship between magnitude and the total number of earthquakes will be linear. If more than one structure is activated the graph will be curved.



The Focal Mechanisms Cartesian display overview

A global focal mechanism analysis can help in the identification of the different fracture sets that have been reactivated within the stimulated area. To push this type of analysis further, detection of individual focal mechanisms can even lead to the identification of individual structures.

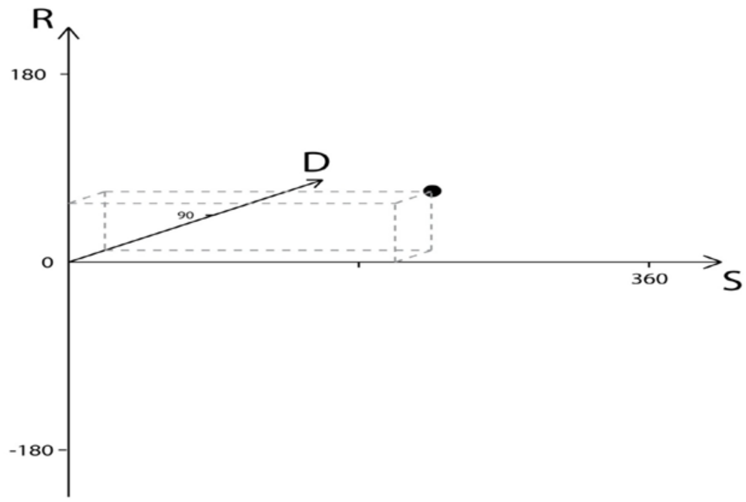
In terms of development, the identification and interpretation of individual focal mechanisms could be considered as an equivalent of the 3D seismic surveys operated in the oil & gas industry. It should clearly allow a better understanding of the geometry of the reservoir.

Focal mechanisms are usually represented as "beach balls" located at the focal point. However with this system, comparisons between "beach balls" becomes a challenge when the number of events increases. The other problem with the "beach ball" display is that each ball may actually represent two different fractures and displacements, so that additional information (geology, stress field, etc...) is required to determine which solution is the best one.

In the EGS case, if individual focal mechanisms are generated, their number could be quite high. Therefore, a different approach is required for their display. The main requirements are:

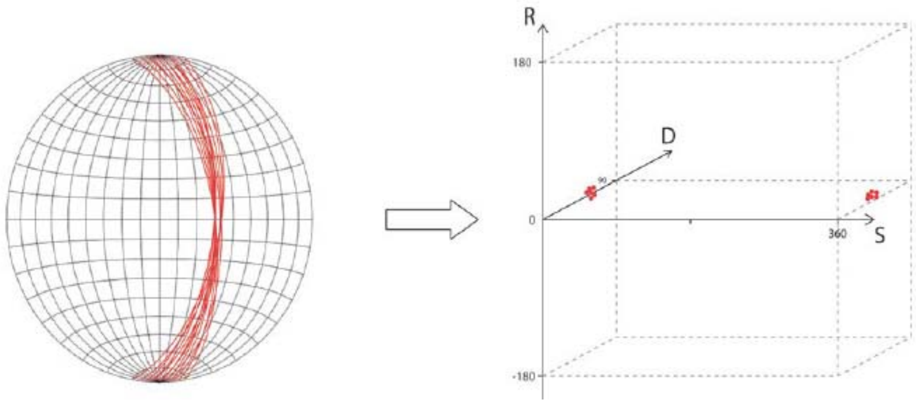
- The representation must be unique for a given fracture orientation and a given direction of displacement.
- The graphical representation should be an object that allows easy selection; most likely a point in the appropriate coordinate system.

A Focal mechanism is described by 3 parameters, Strike, Dip, and Rake, which give a fracture orientation (Strike and Dip) and a direction of slip along this fracture (Rake).

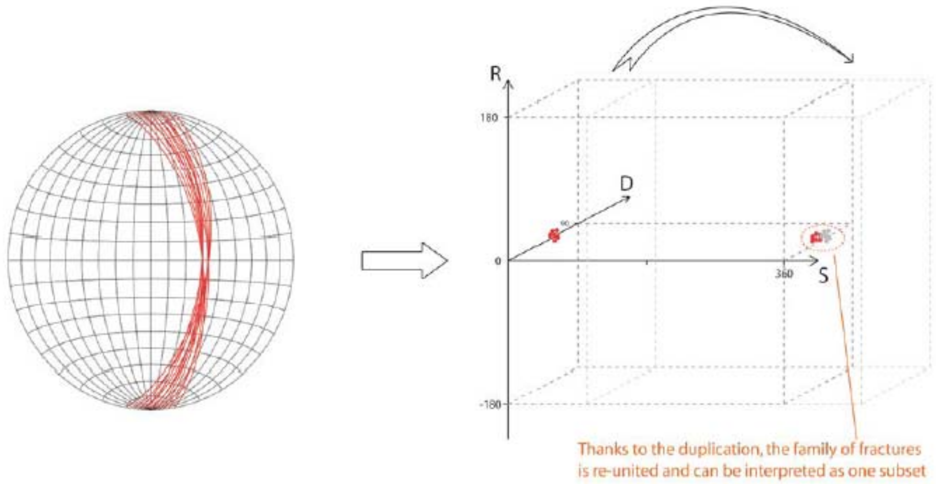


Even if displaying focal mechanisms in a Cartesian system is quite unusual, it remains the only solution that allows unique punctual representations. This last point is critical in terms of dataset analysis, subset detection and subset selection.

There is however a problem in terms of continuity of the dataset in the case of a family of fractures with orientations oscillating around zero degrees. In a Cartesian system, this family ends up being split into two subsets for visualisation.



To overcome the fact that the continuity of the dataset is broken in a non-spherical system, part of the original dataset will require duplication



In a spherical system, strike, dip and rake vary within the following ranges:

Strike	Dip	Rake
0° < S < 360°	0° < D < 90°	-180° < R < 180°

To allow dataset continuity in a Cartesian system, each range described above has to be divided into 3 parts. By doing this, the maximal volume that could be occupied by the original dataset ends up being split into 27 blocks. Because they are in contact with the periphery, 26 of these blocks will require duplication. Sometimes, more than one duplicate has to be considered: as an example, when a focal mechanism happens to be in one of the 8 corner blocks, 7 duplications of the same point are required to avoid a discontinuity in the dataset.

In practice, the duplication process simply consists of a translation, a central symmetry, a combination of translations or a combination of a translation and a central symmetry. If all possibilities are considered, then 98 sets of equations have to be generated to make sure that the continuity of the dataset is not broken

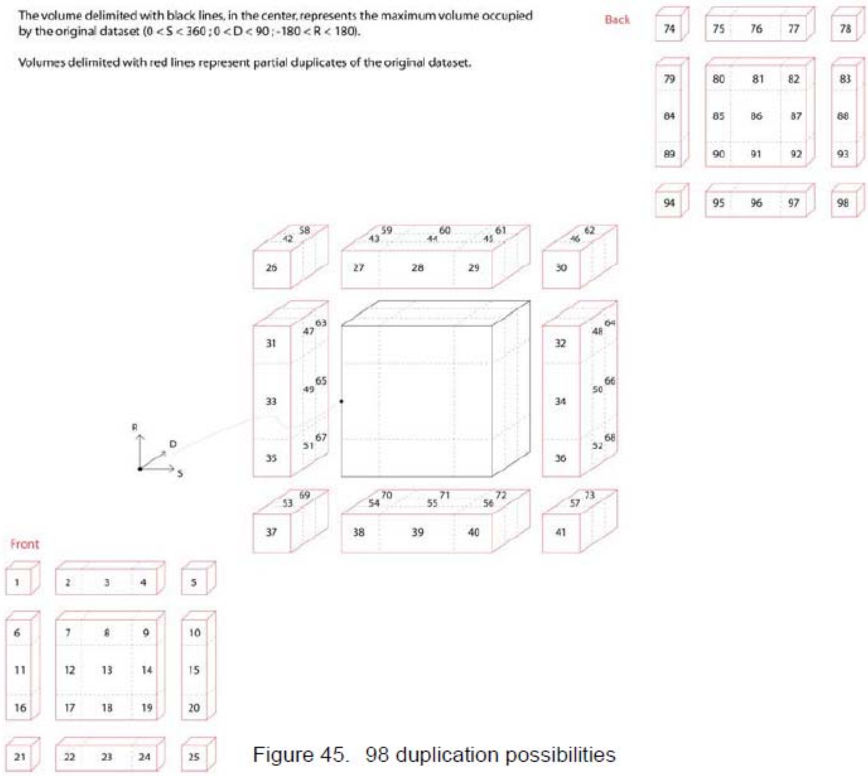


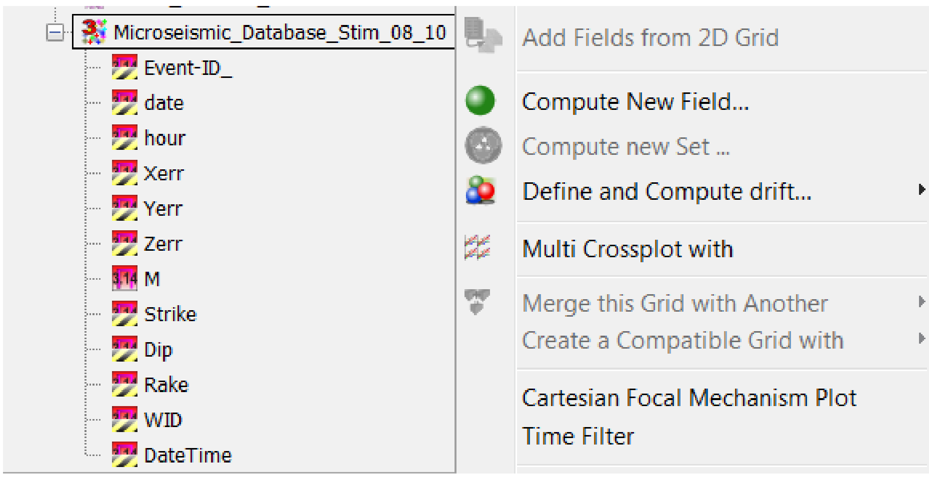
Figure 45. 98 duplication possibilities

To allow easier detection of focal mechanism subsets, and ultimately individual structures within the stimulated area, the development of a specific visualisation tool has been considered.

In this tool, focal mechanisms are displayed in a Cartesian system with strike, dip, and rake on the main axis. To avoid discontinuities of the dataset (related to the fact that the system is not spherical), all possible duplications have been identified and the related equations generated. Based on this information, the appropriate duplication algorithm has been generated.

Steps to display the Cartesian Focal Mechanisms are:

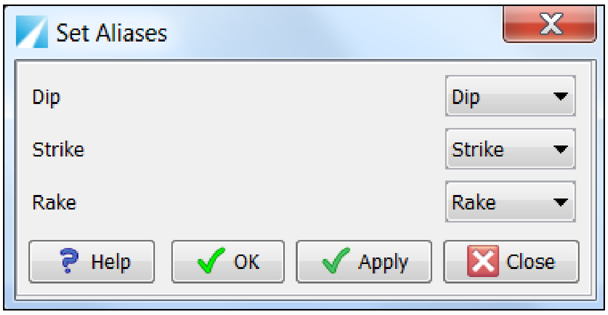
1 In the **Explorer menu,** right click on the micro-seismic database. A grids and meshes context menu pops up.



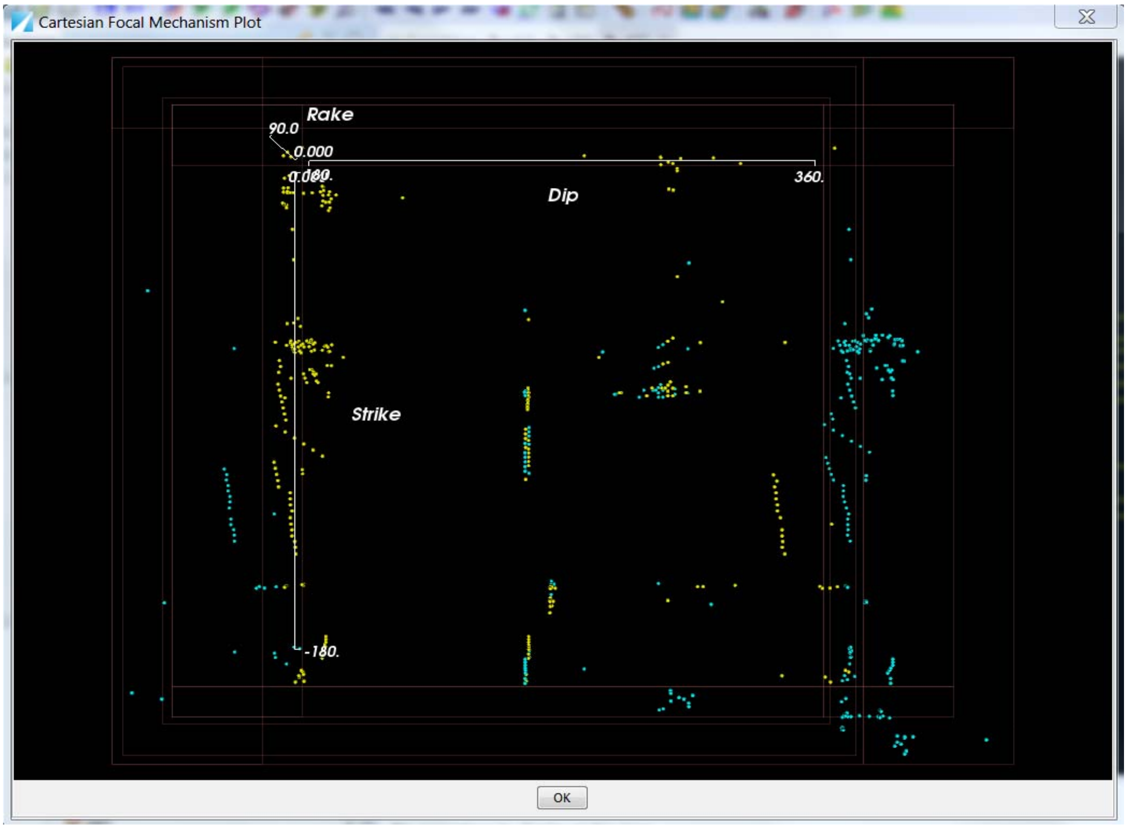
2 Click on **Cartesian Focal Mechanism Plot**.

3 In the ‘Set Aliases’ dialogue box, choose Dip, Strike and Rake from the drop down for each item.

4 Click **OK** to open a new window with the Cartesian Diagram.



The Yellow balls correspond to the original Focal Mechanisms and the blue ones correspond to all the duplication possible.



5 To move into the Cartesian Diagram :

Zoom in/out: scroll the middle mouse button forward/back.

6 To rotate the view in 3D drag inside the display window with the mouse.

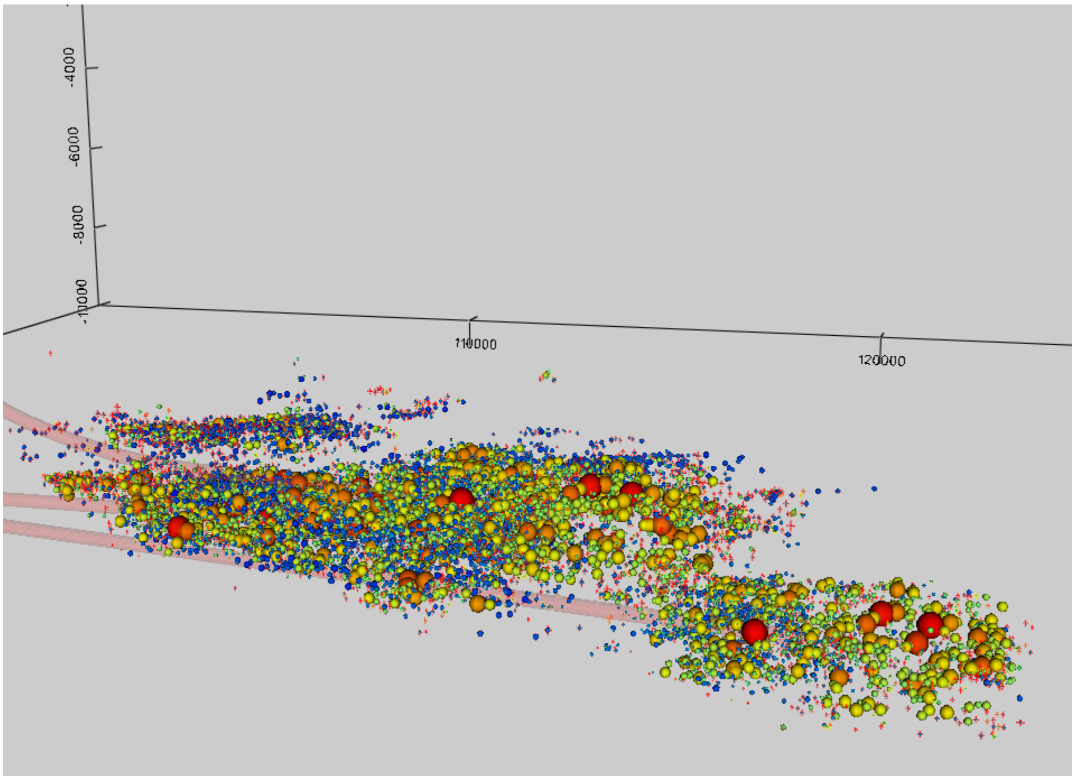
7 To close the window click on **OK**

Interactive Display of Microseismic balls

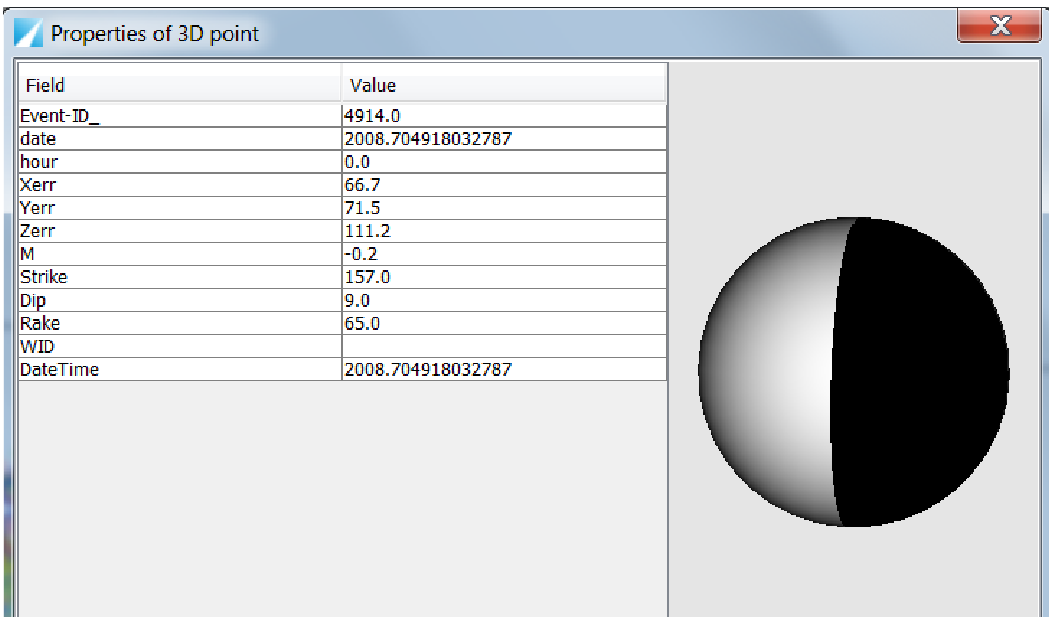
In addition to the Cartesian Focal Mechanism plot it is possible to graphically select and display the structural properties of any microseismic event by double clicking on it in the 3D Viewer.

1 In the **Explorer, Grids and Meshes tree**, right click and select **Remove All Views**. Locate mesh grid **Microseismic_Database_Stim_08_10**; right click field **M (Magnitude)** and display it in 3D using the **Field Visualisation Manager** as described previously.

2 Drag select to display only Stimulation 1 using the Visual Filter



3 Display the structural properties of any microseismic event by double clicking on it in the 3D Viewer. The following dialog will display.



The dialog shows a table of the microseismic fields for this event and a stereographic ball of the event structure (Strike, Dip,Rake).

D9 Stage 6 - Import flow-rate database

Parent topic: **Tutorial D9: Microseismic 3D Modelling and Analysis**

D9 Stage 6 overview

In an Enhanced Geothermal System (EGS) a diagram showing the monitoring of the pressure and flow rate inside the injection well during the stimulation can be useful.

The user can take a look at the pressure in the well and compare it with the activity of the micro-seismicity in the basement. A comparison can also be made between the flow rate and the location of the seismic event at a specific time of the stimulation, or after the stimulation.

The database for the monitoring of the stimulation is separated from the original micro-seismic database.

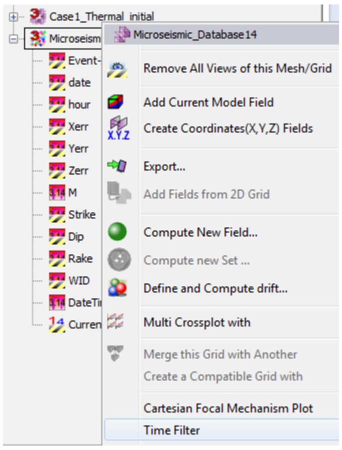
The stimulation monitoring database is a CSV file with 8 columns:

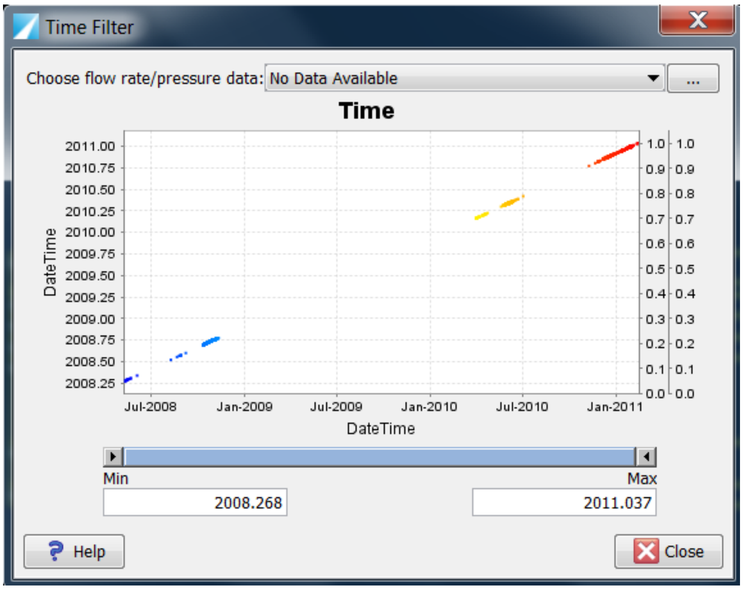
X	Y	Z	Event-ID#	date	hour	Flowrate	Pressure
87245.4	121262.7	-3824.8	1	8/04/2008	17.926	0	0
87307.4	121275.3	-3831.8	2	8/04/2008	17.945	0	0
88666.1	122502.6	-3840.4	3	9/04/2008	19.088	0	0
87122.7	122160.1	-3856.3	4	11/04/2008	10.323	0	0
87110.5	122159.9	-3863.3	5	11/04/2008	11.382	0	0

D9 Stage 6 - Steps

1 In the **Explorer, Grids and Meshes tree**, right click and select **Remove All Views**. Locate mesh grid **Microseismic_Database_Stim_08_10**; right click field **DateTime** and display it in 3D using the **Field Visualisation Manager** as described previously.

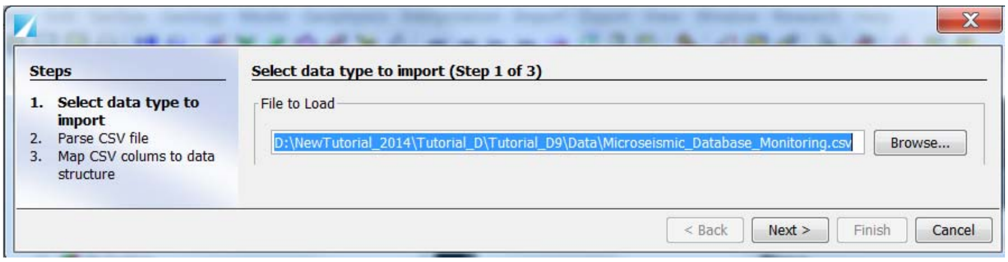
2 To Import the Monitoring database right click on mesh grid **Microseismic_Database_Stim_08_10** at the top level and choose **Time Filter**.





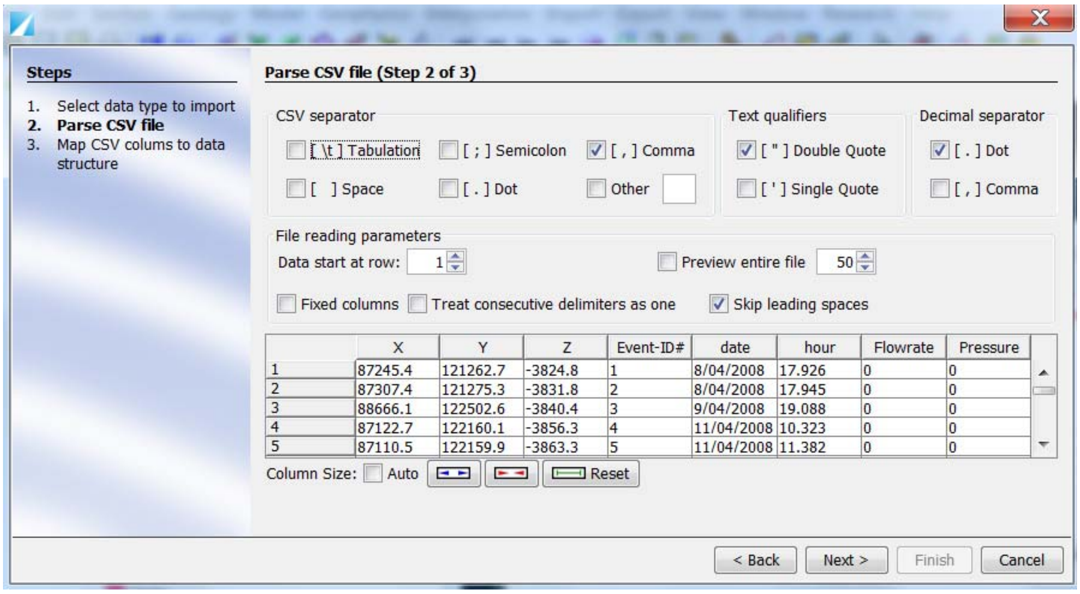
3 Select **'...'** button in top right hand corner. **Browse** to locate the Monitoring database. Then click on **Next >**. The micro-seismic database is located in the directory:

Tutorial_D\Tutorial_D9\Data\Microseismic_Database_Monitoring.csv

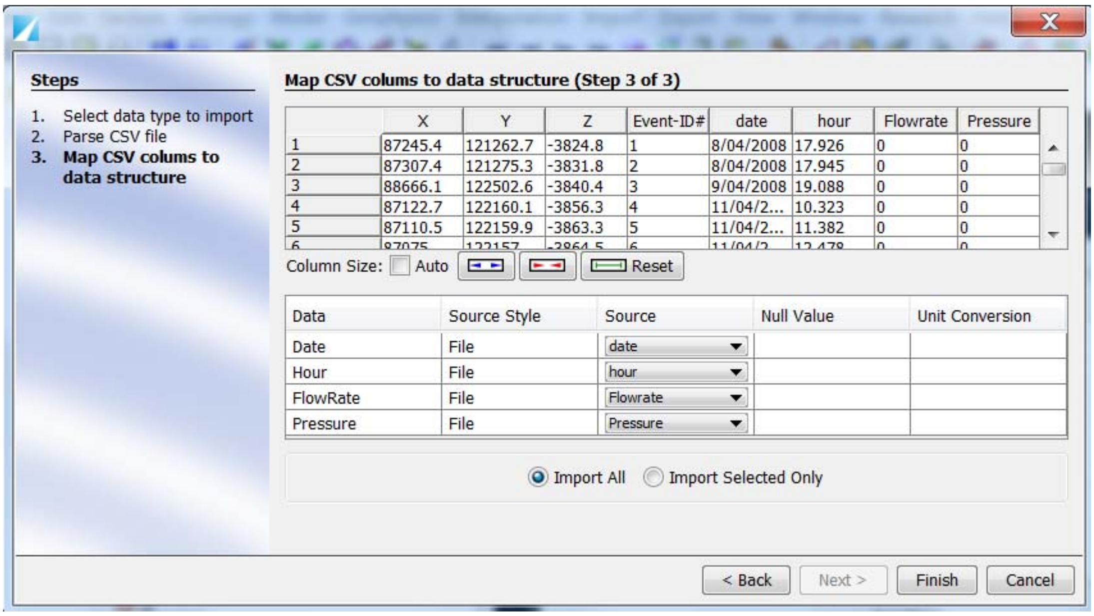


4 The next step is called "parse CSV file." It allows the database to be set up to the format of GeoModeller by choosing the separator, skipping text lines etc.

Accept the defaults.



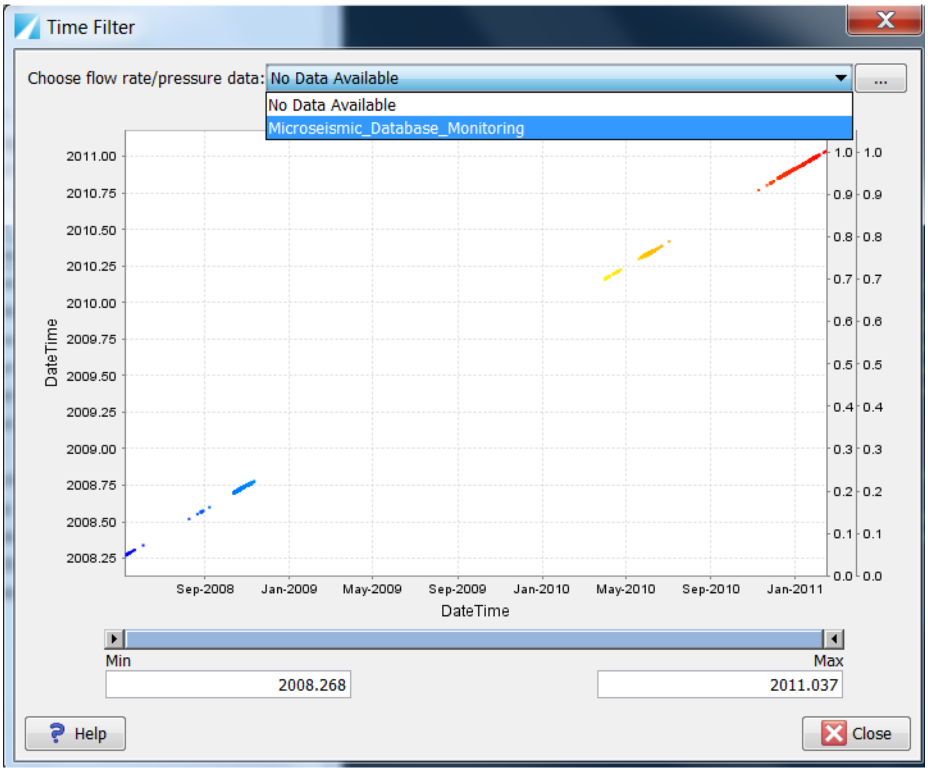
5 The third and last import step, "Map CSV columns to data structure" is used to indicate to GeoModeller the CSV column names (Source) that match the required database fields (Data).



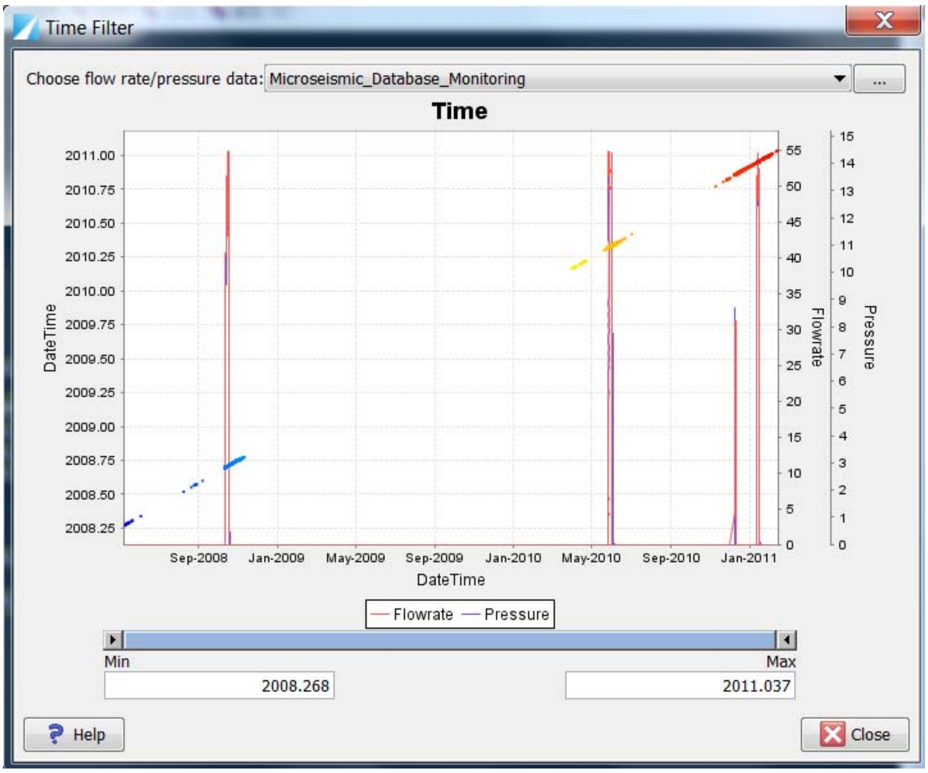
6 Source data for the fields, **Date, Hour, Flowrate and Pressure** must be present in the CSV file. Match the columns of your CSV file (last 4 columns) with the Data fields required. The importer will try to automatch fields using column headers.

When it's done click on **Finish**.

7 Once the Monitoring data are imported, the Monitoring database name will appear in the dropdown list at the top of the Time Filter. Choose it from the list

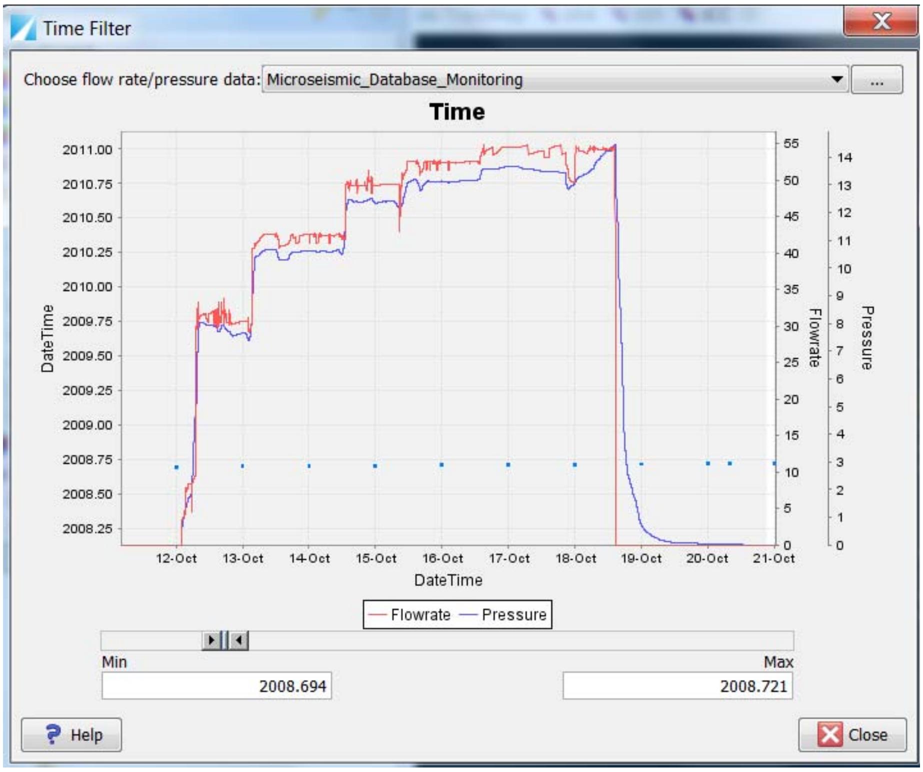


8 When the monitoring database is selected the Time Filter will update to show the Pump rate data



9 To visualise the flow-rate and the pressure in the Well1 during the stimulation 2008 drag zoom the red pump test spike in the Time Filter display window

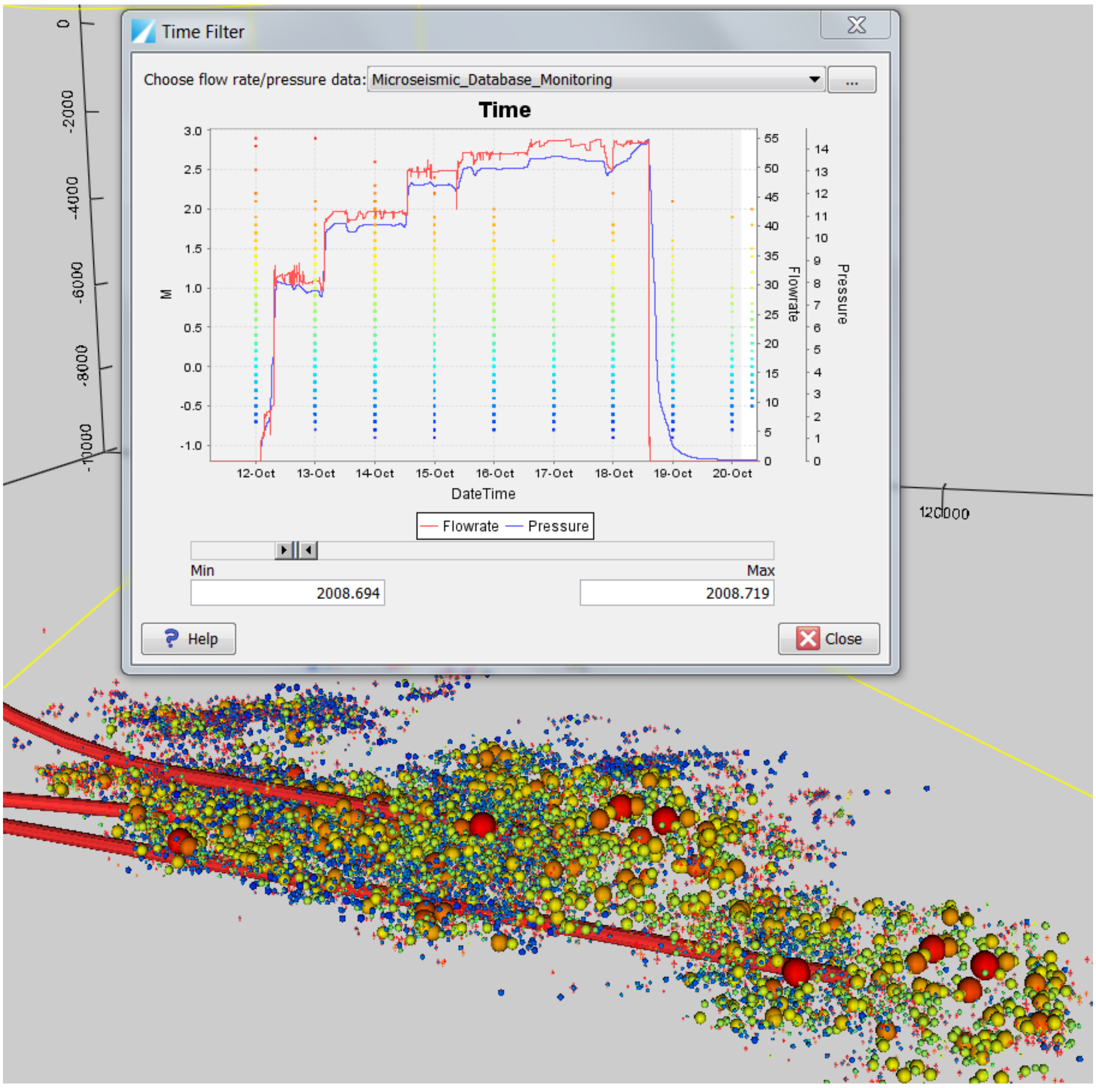
The Graph of the pressure and the flow-rate versus the time appear in a new window.



In this case the FlowRate/Pressure graph represents only the fluctuation in EGS_Well1 during Stimulation 1 in 2008. It is possible to visualise the monitoring of any stimulation by zooming to the appropriate time interval.

10 To visualise the flow-rate and pressure in EGS_Well1 during the 2008 stimulation with event Magnitude M as well as Time proceed as follows:

- Close the Time Filter
- Right click on Magnitude M and display in the 3D viewer
- Open the Time Filter
- Select the stimulation database from the dropdown menu
- Drag the Max cursor left to visualise Stimulation 1 events only in the 3D viewer
- Drag zoom the red Flowrate/Pressure peak for Stimulation 1. The graph will display as below:



Concluding points

Parent topic: Tutorial D (Geothermal and Microseismic)

In this Case study we have import a synthetic micro-seismic database within the 3D geology model of the Hotrox tutorial. By playing with the 3D view of the seismic cloud and use the interpretation tools we can start an interpretation of the fracturing of the granite during the three stimulations.

Case Study D References

Parent topic: Tutorial D (Geothermal and Microseismic)

Beardsmore G.R. and Cull J. P. (2001) Crustal heat flow: A guide to measurement and modelling. Cambridge University Press.

Cull J. P. and Beardsmore G.R. (1992) Statistical methods for estimates of heat flow in Australia, Exploration Geophysics 23, 83-86.

Gibson, H., Stüwe, K., Seikel, R., FitzGerald, D., Calcagno P., Argast D., McInerney P. and Budd A. (2008) Forward prediction of spatial temperature variation from 3D geology models. PESA Eastern Australasian Basins Symposium III, Sydney.

O'Neill, C., Moresi, L., Lenardic A. and Cooper C. (2003) Inferences on Australia's heat flow and thermal structure from mantle convection modelling results. Geol. Soc. Australia Spec. Publ. 22, and Geol. Soc. America Spec. Paper 372, 169-184.

Sass J. H. and Lachenbruch, A. H. (1979) Thermal regime of the Australian continental crust. In The Earth: It's origin, structure and evolution. M. N. McElhinny (ed.). Academic Press, London.

Stüwe K. (2008). Principles of heat flow modelling (Notes from a course on heat flow modelling given at Intrepid Geophysics in March 2008, and a summary of the subsequent implementation into GeoModeller software).

Stüwe K. (2007). Geodynamics of the lithosphere. An introduction. 2nd edition. Springer Verlag 493 pages.

