

Fracture modelling in Move: Part 1 - Predicting fracture orientations based on strain

The **Strain Capture** tool and **3D Kinematic Modelling** module in Move™ can be used to capture and quantify strain as an essential precursor for fracture modelling. This monthly feature is the first of a two-part series that will illustrate the workflow steps to construct a discrete fracture network (DFN). Part 1 will use an example from the East Kaibab monocline in Utah (United States) to demonstrate the workflow for capturing strain during a sequential restoration. Part 2 will then focus on demonstrating the steps for evaluating the fracture forming mechanism and constructing a DFN.

3D Kinematic Modelling, Strain Capture and fracture orientations

Kinematic algorithms mimic movements associated with faulting and/or folding (e.g. Erslev 1991; Gibbs 1983; Griffiths *et al.* 2002), and are commonly used to restore the effects of deformation. Using these algorithms, the positions of points on the restored objects can be tracked in 3D space to calculate the strain experienced by the rocks through time.

In Move, the displacement for any point in 3D space is defined within the **3D Kinematic Modelling** module. For each surface vertex, a 'strain octahedron' is created from six points centred on the vertex (M in Figure 1). The displacements of all six octahedron points (x, x', y, y', z, z' in Figure 1) from undeformed to deformed geometry generate a strain tensor at each surface vertex. From the strain tensors, the principal strain directions ($\epsilon_1, \epsilon_2, \epsilon_3$) can be calculated and used to predict the orientations of the expected tensile and shear fractures, as shown in Figure 2.

Modules used:

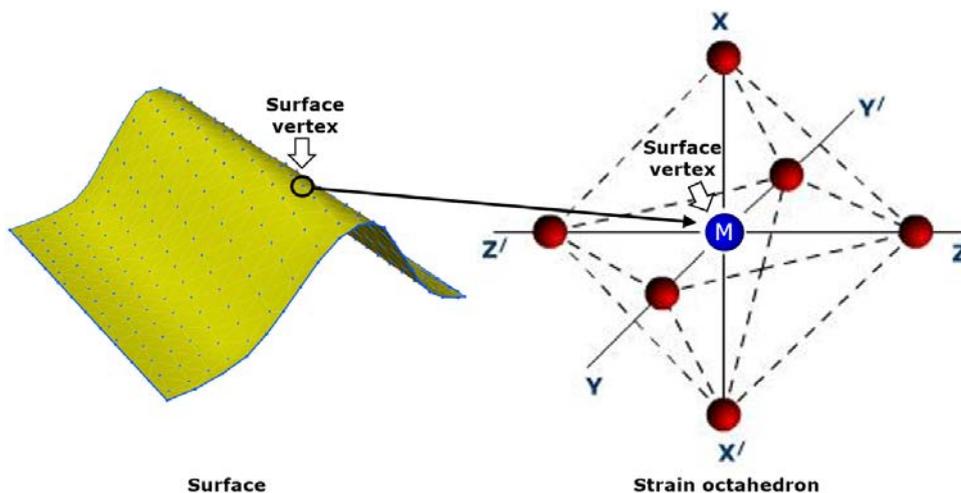


Figure 1. Definition of points surrounding a vertex M. The strain at point M is 'captured' by the displacement field of an octahedral shape around the point M that is deformed by the applied kinematic algorithm.

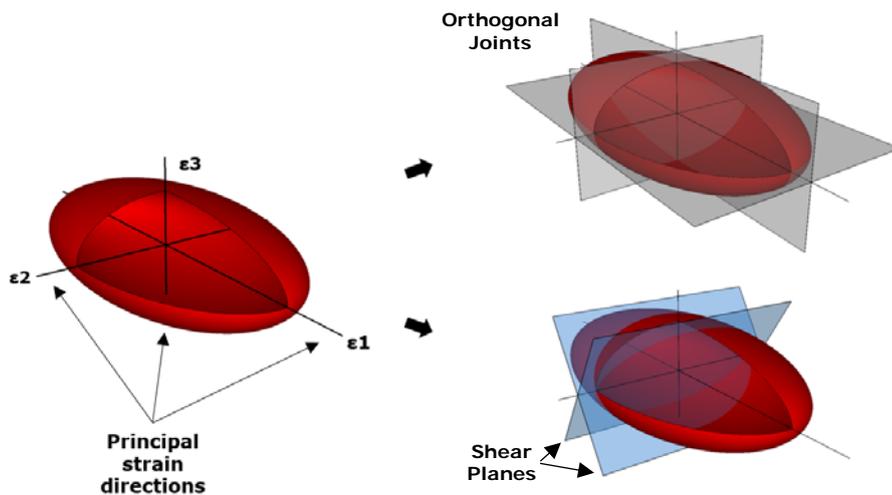


Figure 2. Idealised tensile and shear fracture orientations derived from principal directions of strain ellipse.

The East Kaibab Monocline case study

An example from the East Kaibab monocline, which forms the eastern margin of the Kaibab Uplift in southern Utah (Figure 3a) will be used to illustrate the workflow for strain capture. The monocline developed as a result of reactivation of basement faults during the Late Cretaceous (Brandenburg *et al.* 2012). Using Move, a 3D geological model of the northern sector of the East Kaibab monocline (see location in Figure 3a) was created and validated. Figure 3b shows the Base Dakota unit (Upper Cretaceous), the main basement fault and the location of two field sites (A and B) with cataclastic and shear band measurements (from Brandenburg *et al.* 2012). Data from A and B will be considered for Fracture modelling in Move: Part 2.

The model fault strikes NNE-SSW and dips at 70° to the WNW, with a roughly planar shape and a length of ~50 km. Sensitivity testing showed that the structural evolution of the East Kaibab Monocline can be reproduced by fault propagation folding using the **Move-on-Fault** tool with the **Trishear** kinematic algorithm, applying a constant dip-slip on the model fault of 1300 m. Other **Trishear** parameters include a **Trishear Angle** of 70°, a **Triangle Angle Offset** of 0.50 and a **Propagation/Slip Ratio** of 4.

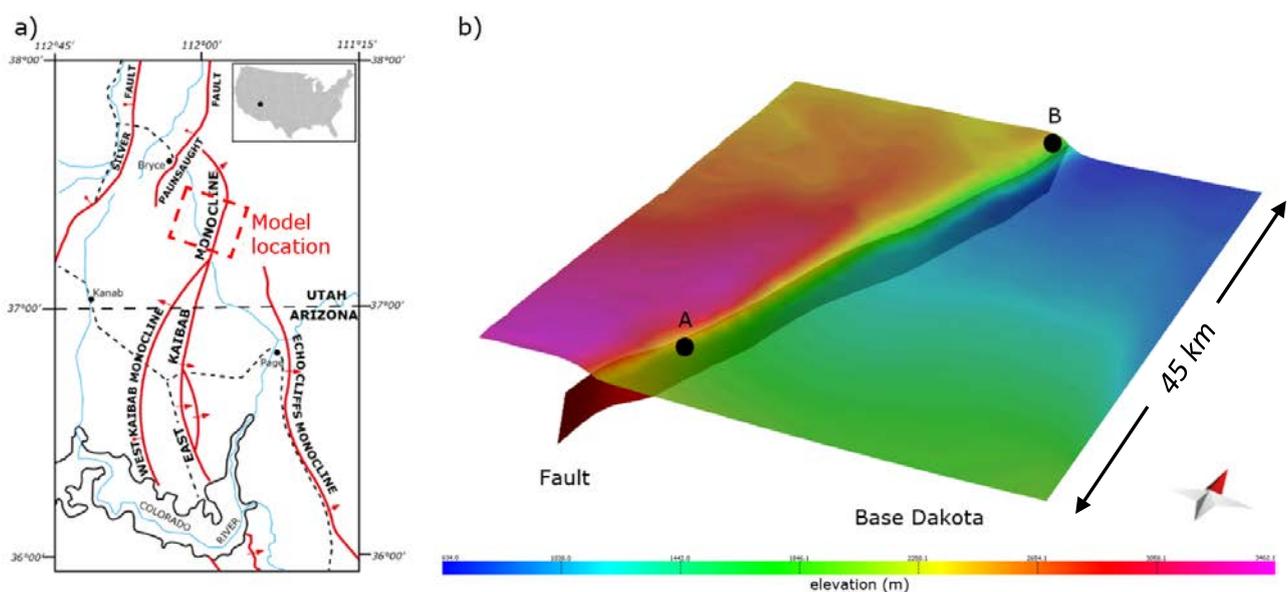


Figure 3. a) Location of the East Kaibab monocline and Move model location b) 3D model of the northern East Kaibab monocline, including the Base Dakota horizon (Upper Cretaceous), the main basement fault and two field sites with measured fracture data (A and B).

Predicting fracture orientations

The following workflow describes the steps to restore the East Kaibab Monocline using the Trishear algorithm, capture the strain associated with its modelled evolution and predict fracture orientations:

1. On the Modules tab, click on the **Strain Capture** tool and collect the horizon surface to be restored into the toolbox.
2. Click on the **3D Move-on-Fault** tool on the Modules tab, select **Trishear** as **Method** and collect the fault into the toolbox. Then collect the horizon surface to be restored into the **Objects to be Moved** box.
3. Set up the parameters for the **Trishear** restoration (outlined earlier) and **Apply**.
4. Go back to the **Strain Capture** tool, which has tracked the displacement of the surface vertices from the undeformed to the deformed state.

In the **Strain Capture** tool, finite or infinitesimal strain tensors can be calculated relative to the deformed (Eulerian strain) or undeformed (Lagrangian strain) state. As illustrated in Figure 4, the Trishear restoration automatically generates five strain states (*Trishear 1* to *Trishear 5*) between the present-day (*Initial state*) and the restored (*Trishear 6*) states.

In this case study, the aim was to capture strain from the pre-tectonic stage to the present-day structure. Therefore, in **Strain Calculation and Visualization**, *Trishear 6* must be chosen as the **Un-Deformed State (Starting Geometry)**; this corresponds to the pre-tectonic geometry. *Initial State* must be selected as the **Deformed State (Ending geometry)**; this corresponds to the present-day geometry. Finally, select *Initial State* in **Display Attributes on Geometric State**.

A number of strain attributes are calculated, which can be colour mapped in the 3D model. These include the amount of displacement or the principal strain orientations and magnitudes, as well as strain ratios for finite and/or infinitesimal strain.

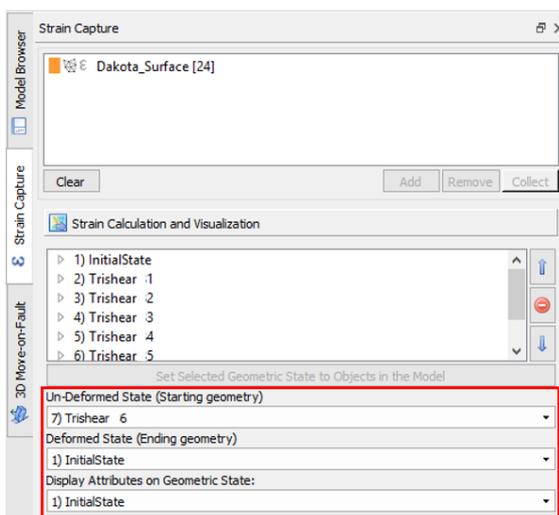


Figure 4. Setting up strain states for calculating strain attributes.

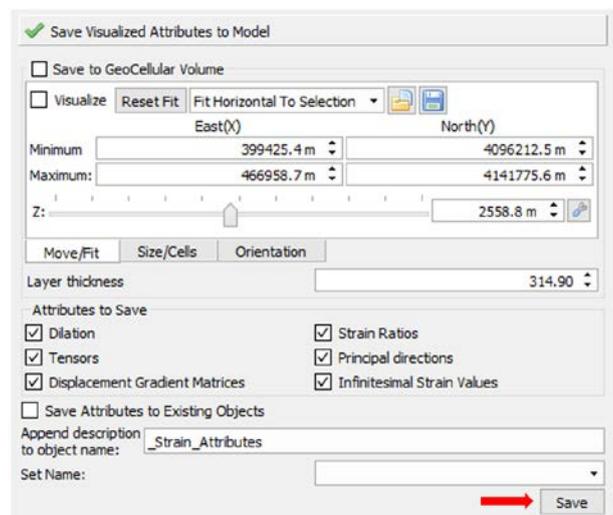


Figure 5. Saving calculated strain attributes to the model. Red arrow highlights the Save button.

5. To save calculated strain, click on the **Save Visualized Attributes to Model** sheet, check all the **Attributes to Save** and click **Save** (see right-hand side of Figure 5).

- In the Kaibab example, the maximum calculated strain intensity (warmer colours) is in the hinge area (Figure 6). To predict fracture orientations restricted to the high strain intensity areas, open the **Attribute Selection Filter** (highlighted in green in Figure 6) and set up an **Attribute Filter** for $fe1 > 0.001$. Then, holding down the **Shift** key, click and drag to loop select the desired area. The surface vertices that honour the attribute filter will be selected. Then, on the Data & Analysis tab, click **Vertex Attributes**.
- In the **Vertex Attributes** window, click on **Create Principal Strain Planes** (ϵ) to generate predicted orientations for joints, ϵ_2 -normal fractures, ϵ_3 -normal fractures and shear fractures.

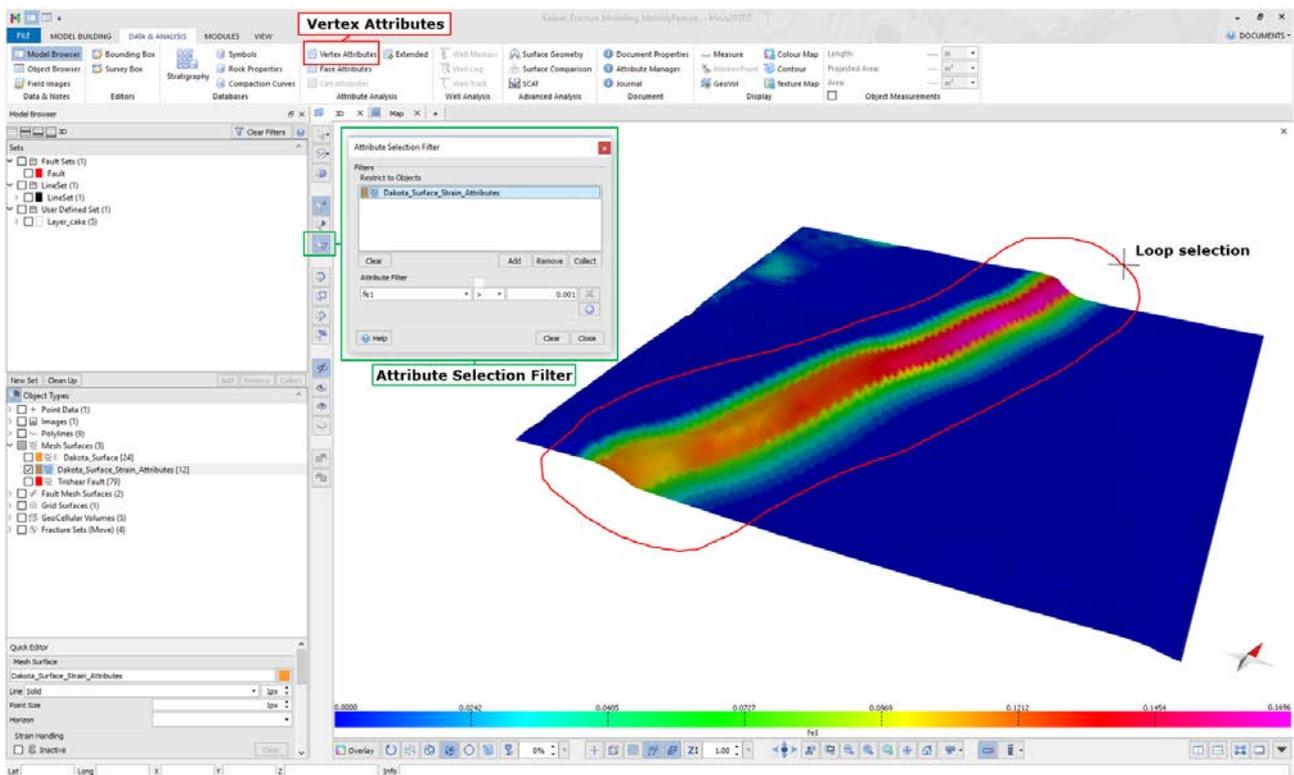


Figure 6. 3D model of the East Kaibab monocline, colour mapped for finite strain intensity ($fe1$). To generate fractures where the strain intensity is maximum, set up a $fe1 > 0.001$ filter in the Attribute Selection Filter (highlighted in green) and loop select the desired area. Then click on Vertex Attributes.

- The fracture orientations sets can now be analysed in the **Stereonet Plot** of the **Vertex Attributes** window by choosing the appropriate parameters as **Dip/Plunge** and **Azimuth**. Poles of joints (ϵ_1 -normal fractures) are displayed in Figure 7.

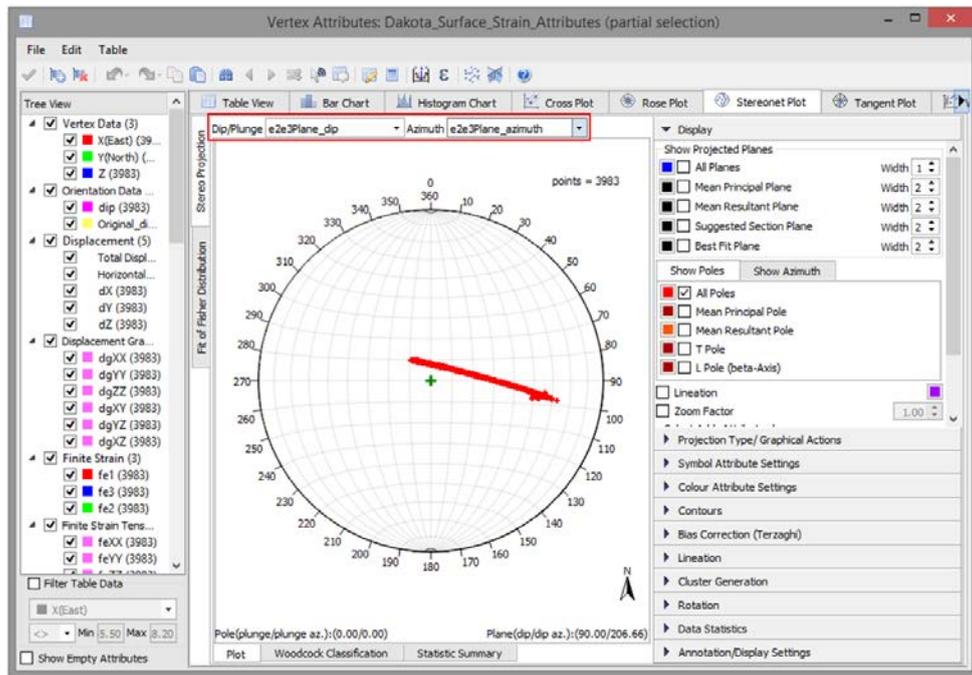


Figure 7. Analysis of predicted joint (ϵ_1 -normal fractures) orientations based on strain, using the Stereonet Plot. Different fracture sets can be selected using the Dip/Plunge and Azimuth menus (highlighted by red box).

- If desired, use the **Create Fracture Set** button () to generate fracture planes that can be visualized in the 3D View. As an example, Figure 8 shows joints colour mapped for strain intensity.

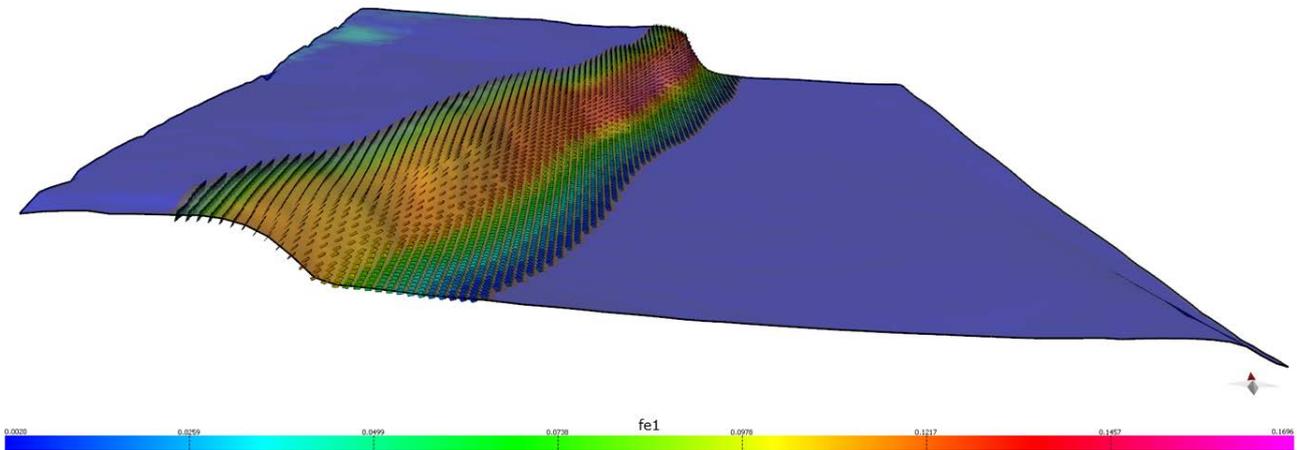


Figure 8. Predicted joints in the high strain intensity area ($fe_1 > 0.001$). Surface and joints colour mapped for strain intensity. Vertical exaggeration $\times 2$.

The next Move monthly feature will outline the workflow steps for constructing a discrete fracture network (DFN) model in Move, using the East Kaibab monocline data.

If you require any more information about **3D Kinematic Modelling** or **Strain Capture**, then please contact us by email: enquiries@mve.com or call: +44 (0)141 332 2681.

References

- Brandenburg, J.P., Alpak, F.O., Solum, J.G. and Naruk, S.J., 2012. A kinematic trishear model to predict deformation bands in a fault-propagation fold, East Kaibab monocline, Utah. *AAPG bulletin*, 96(1), pp.109-132.
- Erslev, E.A., 1991. Trishear fault-propagation folding. *Geology*, 19(6), pp.617-620.
- Gibbs, A.D., 1983. Balanced cross-section construction from seismic sections in areas of extensional tectonics. *Journal of structural geology*, 5(2), pp.153-160.
- Griffiths, P., Jones, S., Salter, N., Schaefer, F., Osfield, R. and Reiser, H., 2002. A new technique for 3-D flexural-slip restoration. *Journal of Structural Geology*, 24(4), pp.773-782.