

## Using MOVE™ 3D Kinematic Modelling and Advanced Modules to generate strain-derived attributes

This month's feature will focus on the application of 3D Kinematic Modelling and Advanced Modules available in MOVE™ to enable greater understanding of reservoir properties, such as fracture porosity and permeability. Constraining reservoir fracture fairways in areas with little direct observation or well control can be problematic. In this feature we demonstrate how MOVE can be used to predict relative fracture intensities, orientations and associated zones of increased secondary porosity and permeability, using 3D Kinematic Modelling, Strain Capture and Fracture Modelling (**Figure 1**).

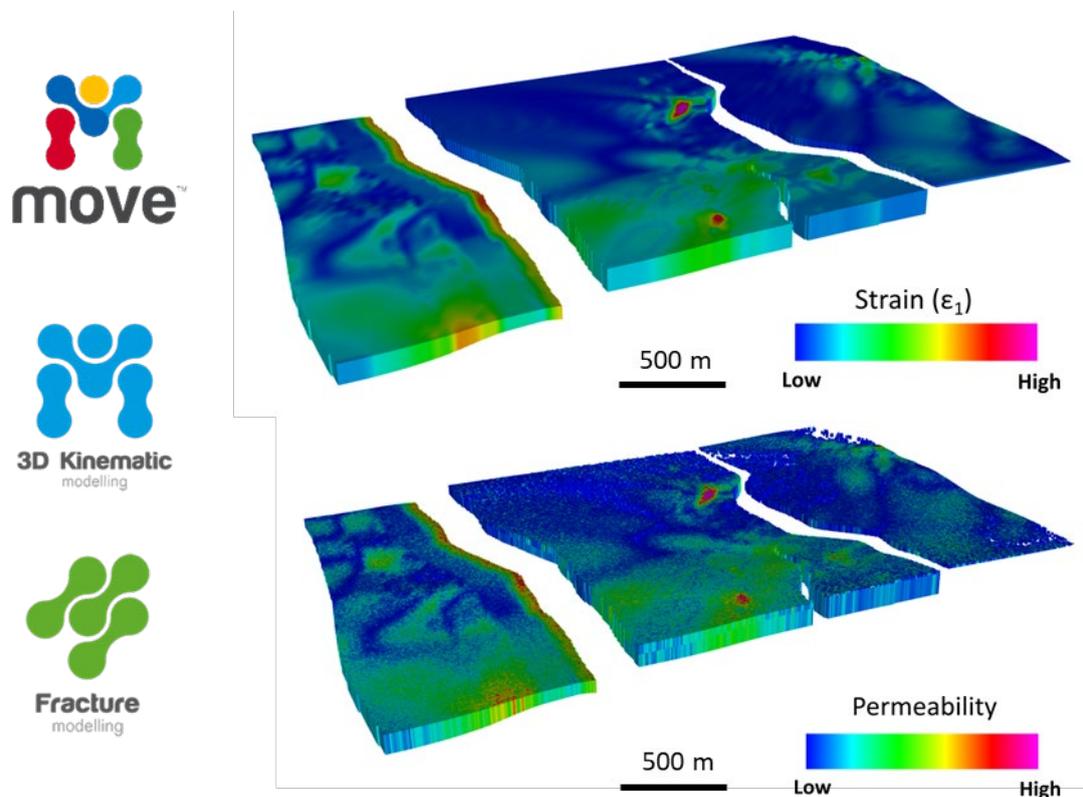


Figure 1: GeoCellular volume with captured strain (Top) and fracture modelling derived reservoir permeability (Bottom).

## Relationship between Strain and Fractures

The intrinsic role of geological history, strain and the expected types and orientations of fracture sets are well documented (e.g. Stearns, 1978; Price & Cosgrove, 1990; Nelson, 2001; Gudmundsson, 2012). Strain is defined as a change in length (1D) or shape (2D/3D) due to deformation (Fossen, 2010). Theoretical relationships between principal strain axes and common fracture types (**Figure 2**) can be used to define fracture characteristics (e.g. Anderson, 1905; Healy et al., 2012). Fracture intensity is often related to areas of high strain ( $\epsilon_1$ ), where the reservoir has undergone maximum distortion. In MOVE, the orientation of the principal axes ( $\epsilon_1$ ,  $\epsilon_2$  and  $\epsilon_3$ ) and strain magnitude are captured during forward modelling using the Strain Capture tool, and are assigned to each cell in a GeoCellular volume. This allows us to model the associated tectonic fracture systems.

This approach has three key advantages over other fracture modelling workflows (e.g. statistical approaches that extrapolate between data points):

1. **Reduced risk and uncertainty:** our approach aims to understand the cause for fracturing through time, and link observed fractures to a deformation phase.
2. **Modelling fractures in areas without direct measurements:** using the relationship between structural history and the expected fracture types and orientations, fracture modelling can be used in as a predictive tool in areas without direct measurements.
3. **Improved understanding of the geological history and structural evolution:** ability to model multiple scenarios and fine-tune the understanding of structural and strain histories.

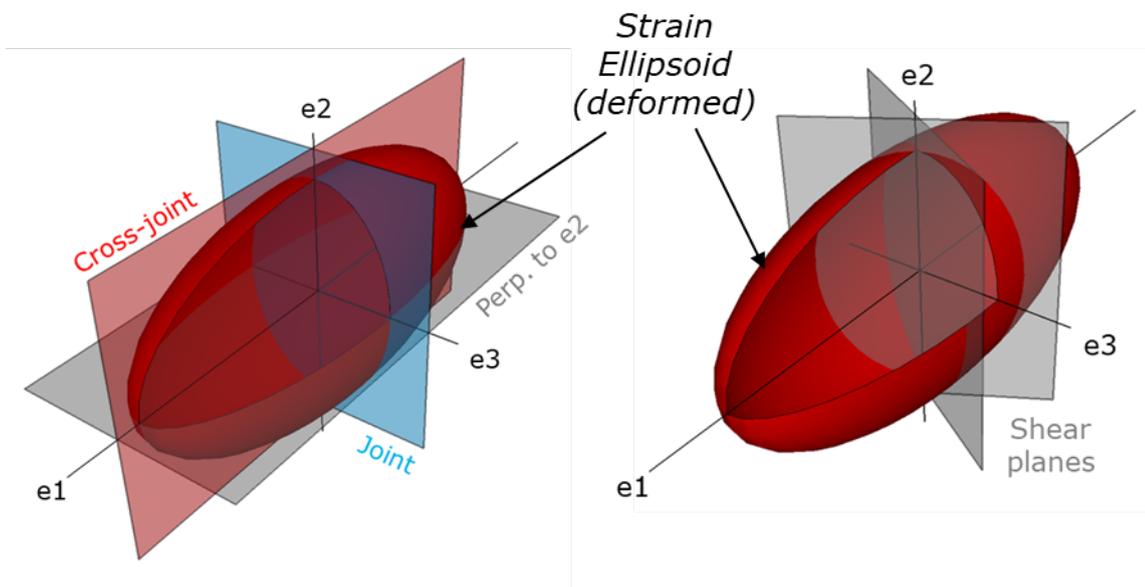


Figure 2: Relationship between principal strain axes and common fracture types.

## Strain Capture

The Strain Capture tool [Strain Capture](#) provides a simple interface which can be used to track the displacement of objects as they are deformed, and calculates the resultant strain. The methodology and equations used in Strain Capture are based on the work of Means (1976) and Allmendinger et al. (2011). MOVE converts the strain captured during forward modelling to an appropriate coordinate system (Eulerian or Lagrangian), then applies an average of the strain tensor components for each triangle on a mesh surface onto the triangle's vertices. The results of the tool can be visualised in 3D or Map View and assigned as Vertex Attributes for each mesh surface or Cell Attributes for a GeoCellular volume.

## Fracture Modelling

The Fracture Modelling Module [Fracture Modelling](#) provides a workflow driven approach to generating a 3D Discrete Fracture Network (DFN). The structured workflow design allows the user to quickly generate and analyse fracture sets, and test multiple models. Previous monthly features have focused in detail on the theory behind the Fracture Modelling module and the application of DFN models in hydrocarbon, mining and engineering industries. In this case study, strain captured through the previous steps in the workflow are used as a proxy for fracture characterization.

## Workflow

The following workflow describes the steps used to forward model deformation using 3D Kinematic Modelling, capture the strain associated with the modelled structural evolution and predict fracture orientations and relative intensities (**Figure 3**). Captured strain attributes are used to define fracture orientations and relative intensities in a Discrete Fracture Network (DFN). To do this in MOVE, the 3D distribution of strain is created as attributes in a 3D GeoCellular volume, using the Strain Capture tool. This Geocellular volume and its associated attributes are used as an input to create a DFN, using the Fracture Modelling Module. Through the generation of a DFN additional reservoir properties can be calculated, in this case secondary porosity and permeability. Properties calculated can be analysed interactively across the study area, and validated with any available well or analogue data.

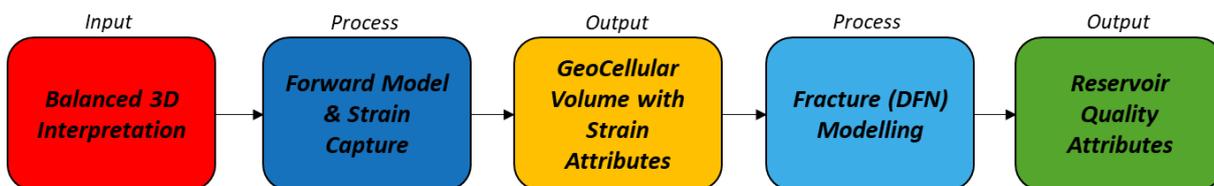


Figure 3: Workflow combining 3D Kinematic Modelling, Strain Capture and Fracture Modelling tools to generate strain and reservoir quality attributes.

The study area comprises a series of normal fault blocks, which form part of a wider extensional setting in the Norwegian North Sea. Following analysis of displacement distributions of faults in the area, a simple 3D forward model is chosen to capture strain in a fractured reservoir interval. Fractures are seen to affect production performance and knowledge of fracture systems will be used to inform future development. Strain can also be captured through a geometric or geomechanical restorations, however these will not be covered within the scope of this feature.

## A) Setting up Strain Capture

1. On the **Modules** tab, click **Strain Capture**.
2. In the **Strain Capture** toolbox, collect the horizon surfaces that you would like to record strain upon.
3. Leave the **Strain Capture** toolbox **open**. Leaving the toolbox open will allow MOVE to track strain during forward modelling or restorations. To check if a horizon has strain tracking toggled on, in the **Model Browser**, make sure the  $\epsilon$  icon    appears next to the object.

## B) Using 3D Move-on-Fault to forward model deformation and capture strain

The following section describes the steps to forward model horizons to their present day geometries. Regional observations of the fault systems indicate that deformation propagated from E-W, therefore the layer cake model is sequentially deformed from E-W using constant and variable heave of different faults.

1. On the **Modules** tab, click **3D Move-on-Fault**.
2. Under the **Active Fault** sheet, collect the fault surface (**Figure 4a**). For the **Method**, select the algorithm (e.g. Simple Shear).
3. In the **Objects to be Moved** sheet, collect horizon mesh surfaces (**Figure 4b**).
4. Under the **Movement** sheet, define the fault movement using Constant or Variable Heave (**Figure 4c**).
5. Deform horizons by clicking **Apply**.
6. **Repeat the workflow** for other faults, working sequentially from E-W (**Figure 5**). Ensure all previously deformed Faults are added to the **Objects to be Moved** sheet.

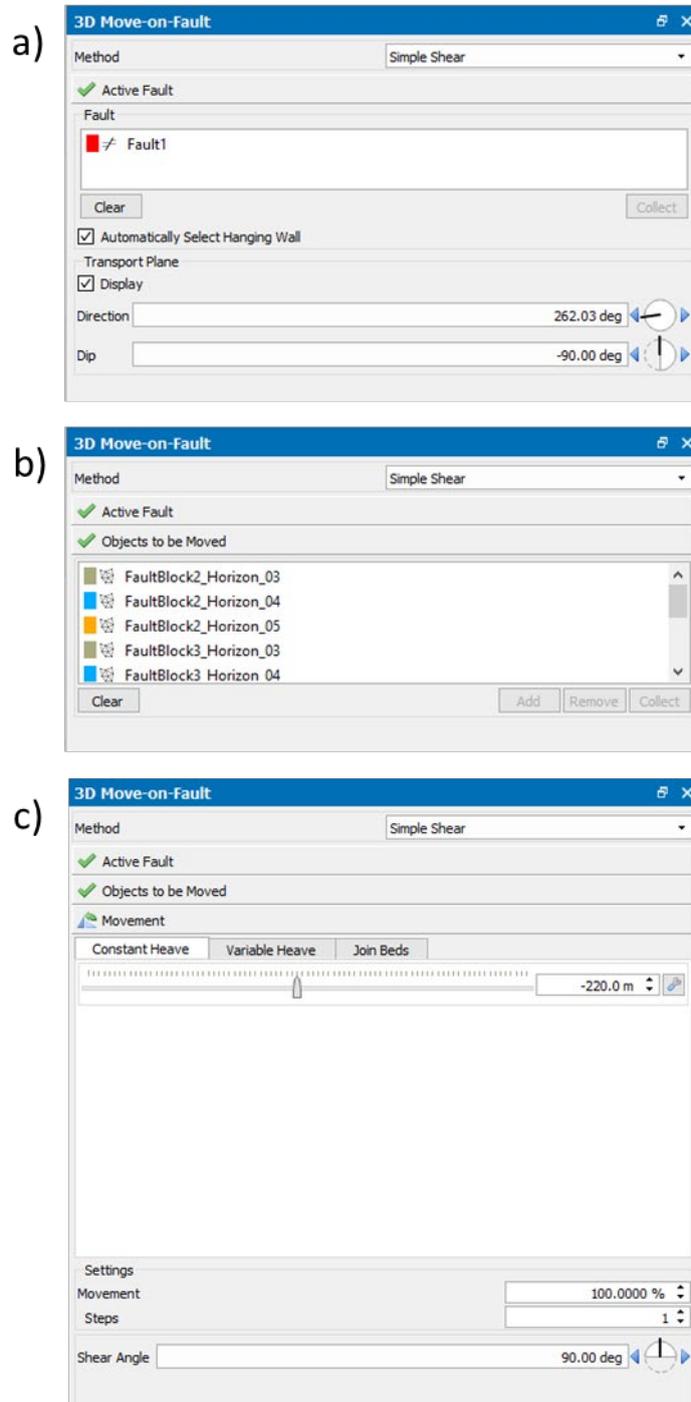


Figure 4: 3D Move-on-Fault toolbox set up for forward modelling. A) Active fault collected in Active Fault sheet. B) Horizon mesh surfaces collected in Objects to be Moved sheet. C) Defined fault movement in Movement sheet.

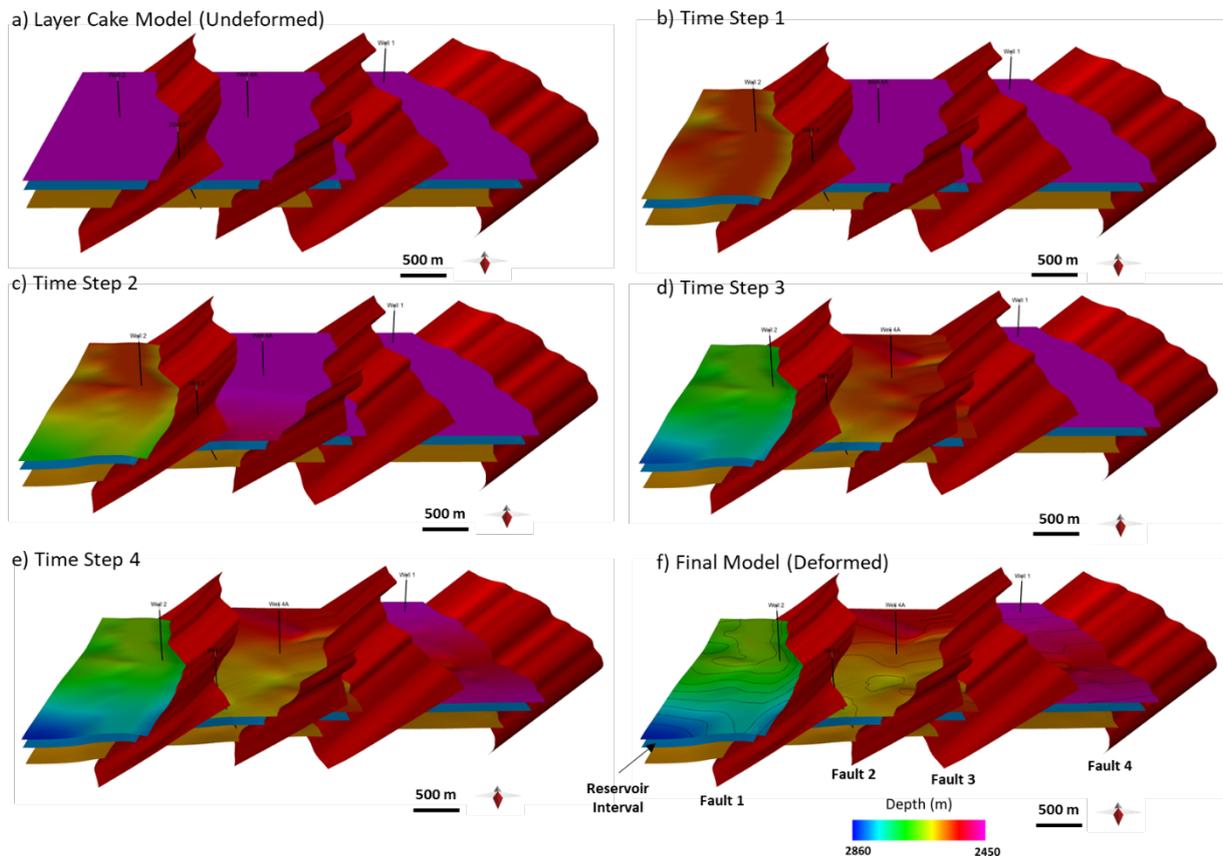


Figure 5: Forward model sequentially deformed from E-W (Faults 1-4).

### C) Using Strain Capture to produce a GeoCellular volume with strain attributes

The following section describes the steps to generate a GeoCellular volume with strain attributes, using the horizons upon which strain has been captured during forward modelling.

1. Open the **Strain Capture** tool.
2. Define Geometric State to Objects: **Un-Deformed State** (geometry before deformation), **Deformed State** (geometry after deformation) and which horizon to **Display Attributes on Geometric State**.
3. Select **Strain Calculation Method** and **Radius**. This allows Move to convert and transform the strain captured to an appropriate coordinate system. In this study, **Eulerian** is selected as the **Strain Calculation Method**, as it models strain in a forward sense, to display strain on the deformed geometry.

4. Open the **Save Visualized Attributes to Model** for direct output as a **GeoCellular volume**.
5. Click **Calculate**, and toggle **Save to GeoCellular Volume**.
6. Click on **Visualize** to view the prospective grid that will be used for volume construction, and adjust grid or cell parameters. This allows the user to control the gridding and resolution of the Geocellular volume.
7. Select which **Attributes to Save**, and click **Save** to create a Geocellular volume with the strain attributes saved to each cell (**Figure 6**).

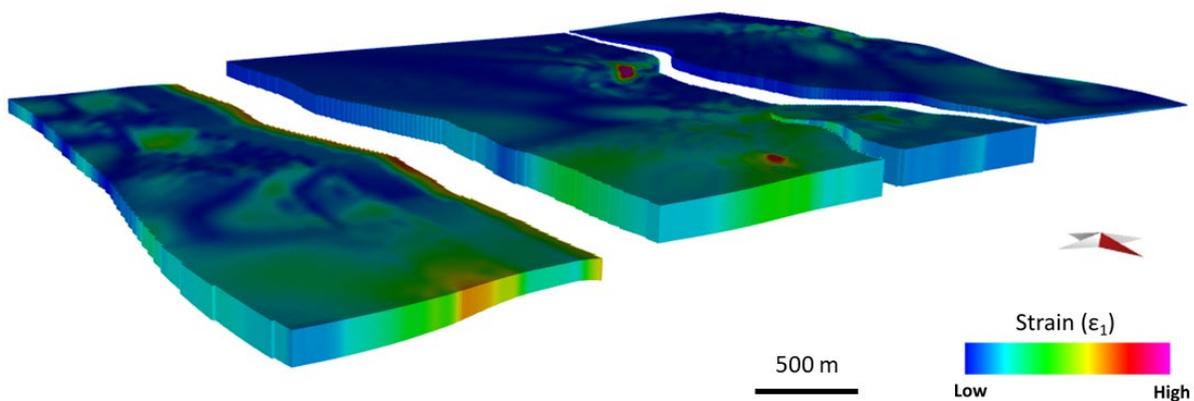


Figure 6: GeoCellular volume generated in Strain Capture.

## D) DFN construction using the Fracture Modelling Module

The following section describes the steps to use the Fracture Modelling Module to construct a DFN. Strain properties captured during forward modelling in Parts A-B are used as a proxy to define fracture parameters (i.e. relative intensity and orientations).

1. On the **Modules** tab, click **Fracture Modelling**.
2. Click **Create New Session**. The Fracture Modelling Module also allows the user to load a session, and the DFN model can be revisited at a later date, and calibrated using any fracture information.
3. In **Parameter Setup**, collect the **Geocellular Volume** and click **Create Fracture Sets**. In this case study, 2 shear plane sets and 1 joint set were defined based on relationships observed in extensional faulting analogues (e.g. Friedman and Wiltschko, 1992).

4. Set **Parameters for Fracture Sets**: Region, Intensity, Length, Orientation, Aspect Ratio and Aperture. The orientation of principal axes ( $\epsilon_1$  and  $\epsilon_3$ ) and magnitude of strain captured during forward modelling are used in the **Intensity** and **Orientation** sheets, to define relative intensity of fractures, and the dip and dip azimuth (**Figure 7**).
5. In the **Review Session** step, check the Parameters and continue.
6. In the **Compute Sets** step, ensure all fracture sets are selected, then click **Run**. This will generate fractures for each set.
7. Click **Next** to display the generated sets and visualise the fractures in the 3D View.
8. Continue through the Workflow steps, navigating through the **Connectivity Analysis**. Here the overall connectivity of fracture network, along with the connectivity between fractures and wells can be calculated and visualised. This is not covered within the scope of this feature.
9. To save the fracture sets to the model, click on **As Fracture Set**, in the **Save to Model** step.
10. In the **Calculate Properties from Fractures** reservoir quality indicators derived from the fracture sets can be calculated and assigned to the GeoCellular Volume. In this study fracture **Porosity** and **Permeability** were calculated.
11. In the **Report & Output** step, save the session report and **Close Workflow**.

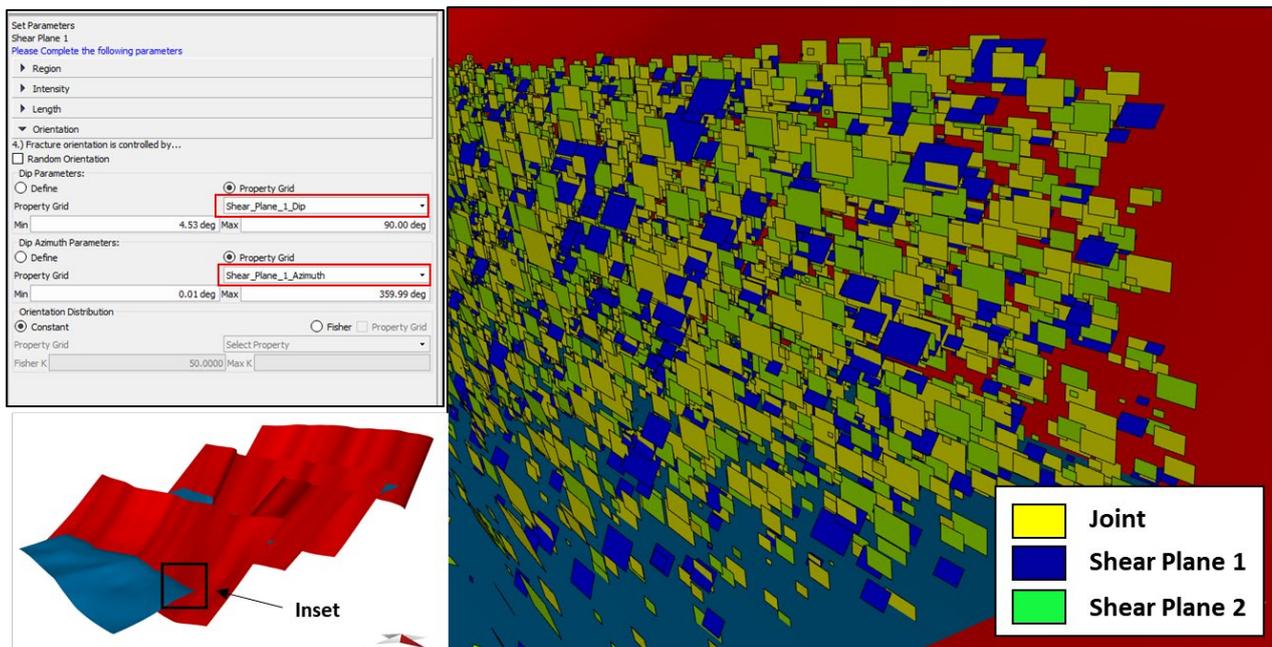


Figure 7: Fracture modelling workflow and calculated fracture sets. Left) Strain and fracture orientations attributes, calculated during strain capture, are used as an input to define fracture parameters. Right) Generated DFN model displaying joints and shear planes.

## Visualization of Results:

- Calculated strain attributes can be viewed under **Cell Attributes**, on the **Data Analysis** tab.
- To visualise results in **3D** or **Map View** select the GeoCellular volume and from the **Data & Analysis** tab, click **GeoVol**. Use the GeoVol tool to control the display of a volume and filter it based on specific regions or attribute ranges.

## Analysing Results & Calibration

Various factors have an effect on fault-related deformation and the way that strain is distributed close to fault zones, including:

- Fault initiation.
- Propagation.
- Displacement.
- Slip history.
- Fault surface profile (e.g. Planar, non-planar, fault corrugations).
- Mechanical stratigraphy.
- Topology of fault networks

Results of the strain capture identify regions of high strain in close proximity (damage zones) of the faults (**Figure 8**). High strain values are also observed where faults interact in areas of fault linkage, and in local regions along the fault plane where the surfaces are non-planar.

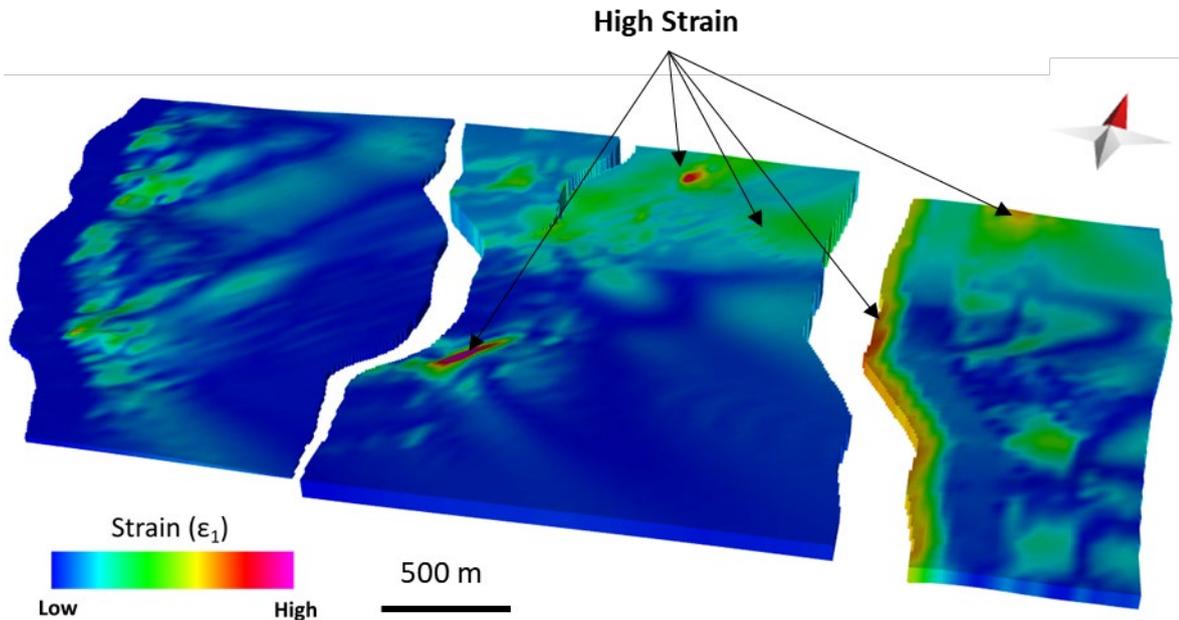
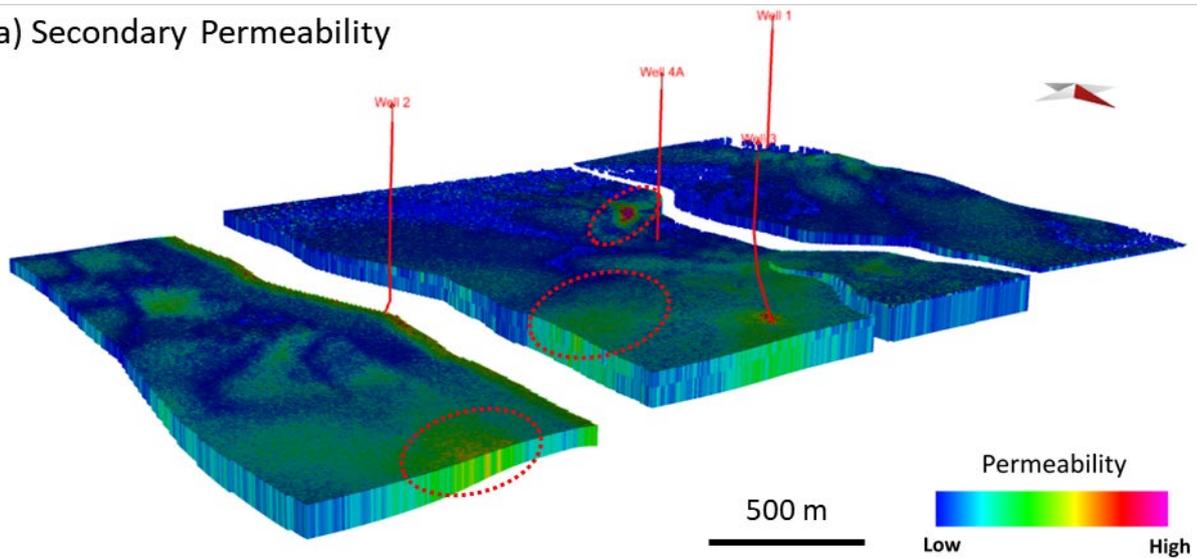


Figure 8: GeoCellular model displaying  $E_1$  strain values.

Strain captured during forward modelling is used as a proxy for fracture distribution and intensity. DFN generation allows different reservoir quality attributes to be calculated (**Figure 9**) to analyse the capacity for the fracture system to store (fracture porosity), and control on the fluid flow properties (fracture permeability) in fractured reservoirs (Nelson, 2001; Warren and Root, 1963). Directional permeability, connectivity and anisotropy across a region or between wells can also be quantified. In this study, we observe a correlation between high strain and areas of good secondary reservoir quality. This constrains the reservoir fracture fairways and allows the high-grading of identified prospects.

a) Secondary Permeability



b) Fracture Porosity

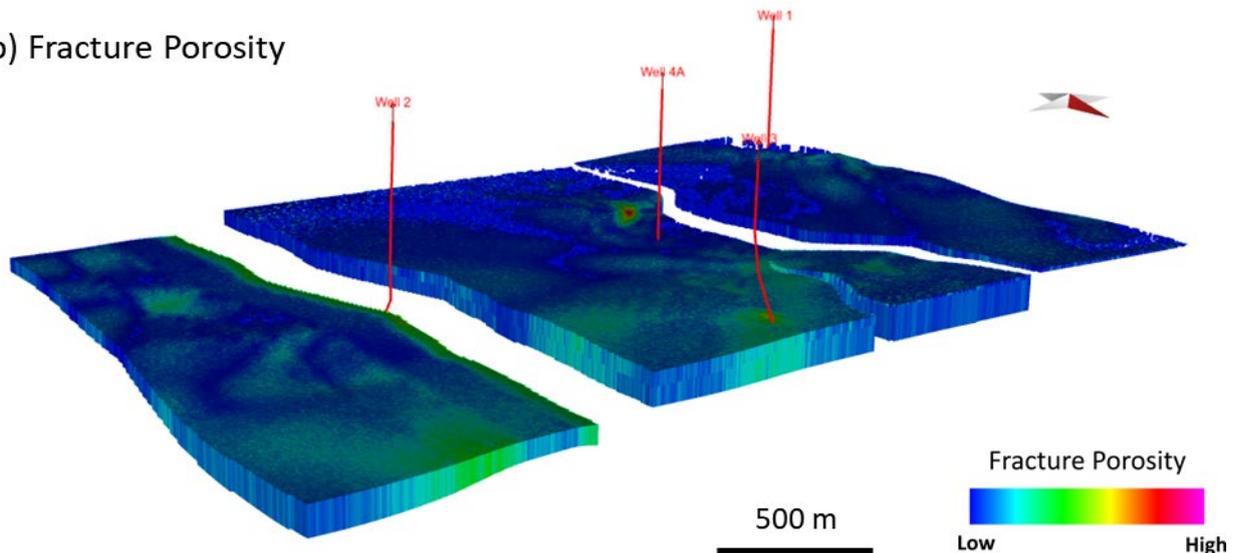
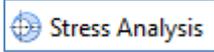


Figure 9: Reservoir quality attributes: a) Fracture (Secondary) Permeability; b) Fracture (Secondary) Porosity. These can be assigned to a GeoCellular volume for visualization. Areas that have not been drilled with higher permeability have been indicated with red ellipses.

Comparison of fracture sets with available well data can be used as a validation tool. Calibrating the modelled fracture networks in an area without well or direct observation can be difficult, therefore it is important to compare the results to analogues or theoretical models of the relationship between strain and fracture networks.

The analysis described here has identified three undrilled areas of high strain and secondary permeability (Figure 9) for future prospect evaluation. Results can also be output for reservoir simulation or to aid development and well planning studies. The workflow presented can be used in a range of structural settings. Further analysis can also be undertaken using the **Stress Analysis** Module  to analyse how the fracture sets may behave under present or paleo-stress fields, and identify areas of increased dilation or slip tendency.

**Detailed explanations of the theory and functionality of the Advanced Modules can be found in the MOVE Knowledge Base and previous MOVE Monthly Features.**

## References:

- **Allmendinger, R.W., Cardozo, N., and Fisher, D.M., 2011.** Structural Geology Algorithms: Vectors and Tensors. *Cambridge University Press*, 289p.
- **Anderson, E.M. 1905.** The dynamics of faulting. *Transactions of the Edinburgh Geological Society*, 8, 387– 402p.
- **Fossen, H. 2010.** Structural geology. *Cambridge University Press*. 463p.
- **Friedman, M., and Wiltschko, D.M. 1992.** An approach to exploration for naturally fractured reservoirs - a generic approach with examples from the Austin Chalk. **In:** Geological Studies Relevant to Horizontal Drilling: Examples from Western North America, J. W. Schmoker, E. B. Coalson, and C. A. Brown, eds. *Rocky Mountain Association of Geology, Denver, Colo.* 143-153p.
- **Gudmundsson, A. 2012.** Rock Fractures in Geological Processes. *Cambridge University Press*. 594p.
- **Healy, D., Butler, R.W.H., Shipton, Z.K. and Sibson, R.H. 2012.** Faulting, Fracturing and Igneous Intrusion in the Earth's Crust. *Geological Society, London, Special Publications*, 367, 1–6p.
- **Means, W.D., 1976.** Stress and Strain. Springer New York, New York, NY.
- **Nelson, R.A. 2001.** Geological Analysis of Naturally Fractured Reservoirs. 2<sup>nd</sup> Edn. *Gulf Professional Publishing, Elsevier, Oxford, UK.* 352p.
- **Price, N.J. and Cosgrove, J.W. 1990.** Analysis of Geological Structures. *Cambridge University Press, Cambridge*, 502p.
- **Stearns, D.W. 1978.** Faulting and forced folding in the Rocky Mountain foreland. *Geological Society of America Memoir*, 151, 1-38p.
- **Warren, J.E., and Root, P.J. 1963.** The behaviour of naturally fractured reservoirs. *Proceedings Society of Petroleum Engineers Fall Meeting*, 3(3), 245-255p.