Stress inversion and maximum shear direction in Move™

Determining the palaeo- or present-day stress field is important in understanding regional deformation events and natural hazard assessment. Under the assumption that a fault slips parallel to the direction of maximum resolved shear stress (Wallace-Bott hypothesis), fault kinematic data can be inverted to calculate palaeo-stress fields and fault-related deformation can be forward modelled to validate possible stress field scenarios. In this Move feature, the Wallace-Bott hypothesis is discussed and two workflows in Move that rely on the maximum shear direction calculation to determine palaeo-stress fields are presented.

The Wallace-Bott hypothesis

The Wallace-Bott hypothesis states that the most likely orientation for a fault to slip is parallel to the maximum resolved shear stress on the fault plane (maximum shear direction; Bott 1959; Wallace 1951). The slip direction on a fault plane is expressed as slickenlines and striations, which can be measured and plotted on a stereographic projection (Figure 1).
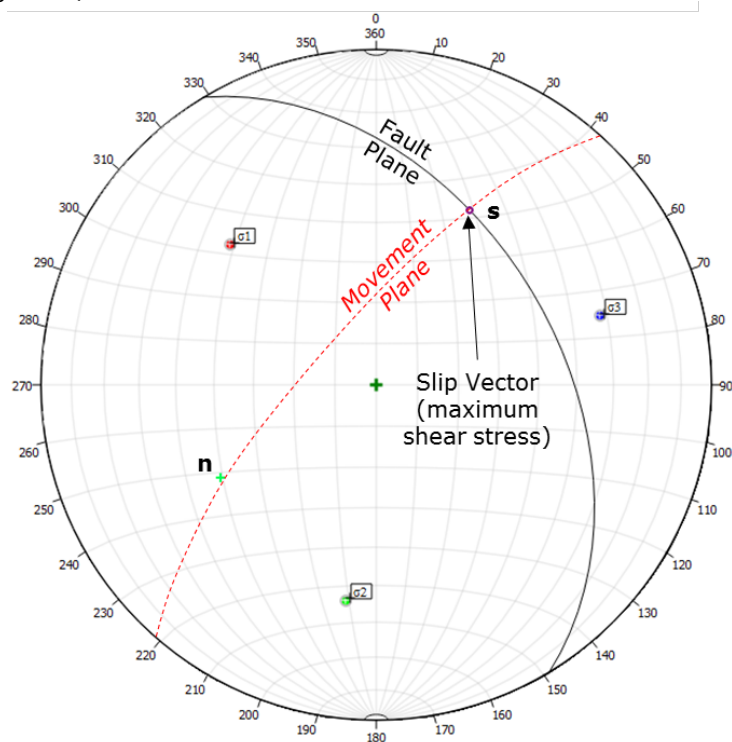

*Figure 1: The slip vector (**s**), or maximum resolved shear stress on a fault plane (black) resulting from an applied stress system (σ1>σ2>σ3) can be plotted on a lower hemisphere stereographic projection (Allmendinger et al. 2011). The vector normal to the fault plane (**n**) and the slip vector define a movement plane (dashed red line).*

The maximum shear direction on a fault plane (slip vector or **s**) is defined by the relationship between the orientation of the principal stress axes, the ratio of the principal stress magnitudes (shape ratio), and the fault plane (normal to the fault plane or **n**; Allmendinger *et al.* 2011; Angelier 1990). If the orientation of the fault plane is known, this relationship can be used to either: 1) Apply a known stress field to a fault plane and calculate the maximum shear direction (Allmendinger *et al.* 2011); or, 2) Invert observed fault kinematic data to calculate the orientations of the principal stress axes and the shape ratio during deformation (Angelier 1990). As such, the relationship between the fault plane, principal stress axes and the maximum shear direction provides a method to investigate present-day and palaeo-stress fields. The results can be applied to further studies such as hazard assessment and fracture prediction.

Inversion of fault kinematic data

If fault kinematic data are available (e.g. slickenline or striation measurements), the orientations of the principal stress axes (σ1>σ2>σ3) and the shape ratio can be calculated using the **Stress Analysis** module in Move. This can be done by either: 1) Manually adjusting the orientations and shape ratio of the principal stress axes until a suitable match between the observed slip vectors and the maximum shear direction calculations is found; or, 2) Calculating the principal stress axes using a direct analytical inversion which minimises the angle between the theoretical maximum shear direction and the observed data (Angelier 1990). Here, a stress inversion will be conducted to predict the orientation and shape ratio of a palaeo-stress field.

Suggested workflow:
1. Load the kinematic data into Move (**File** - **insert** – **ASCII data** – select **Lineation Data**);
2. Open the **Stress Analysis** toolbox and collect the lineation data into the **Select Objects to Analyse** box;
3. Expand the **Lineation** sheet and toggle either **Plunge/Azimuth** or **Plane/Pitch** depending on the format of the lineation data;
4. Select the appropriate parameters from the drop-down lists (e.g. Dip is defined by the dip parameter);
5. Expand the **Annotation/Display Settings** sheet;
6. Toggle on **All Planes** and toggle off **Show Colour Filled Stress State**;

The lineation data should now be plotted on the Stereo Plot. With the data loaded it is now possible to calculate the orientations and shape ratio of the principal stress axes (σ1>σ2>σ3).

7. Expand the **Display: Stress Overlay Control** sheet and toggle on **Show Max Shear Directions from Planes**;
8. Click on one of the principal stress axes in the Stereo Plot window and manually adjust the plunge and trend of the stress axis by dragging the axis around the Stereo Plot. The orientation (plunge and plunge azimuth) of each of the principal stress axes can also be defined on the **Regional Stress Field** sheet;
9. Adjust the orientations and shape ratio of the principal stress axes until a satisfactory visual match between the observed lineation data and the maximum shear direction calculated for each fault is achieved. On arriving at this visual match, the parameters can be read from the **Regional Stress Field** sheet.
10. The orientations and shape ratio of the principal stress axes can also be calculated automatically (Angelier 1990) by expanding the **Lineation** sheet and clicking on **Calculate Stress State** (Figure 2).

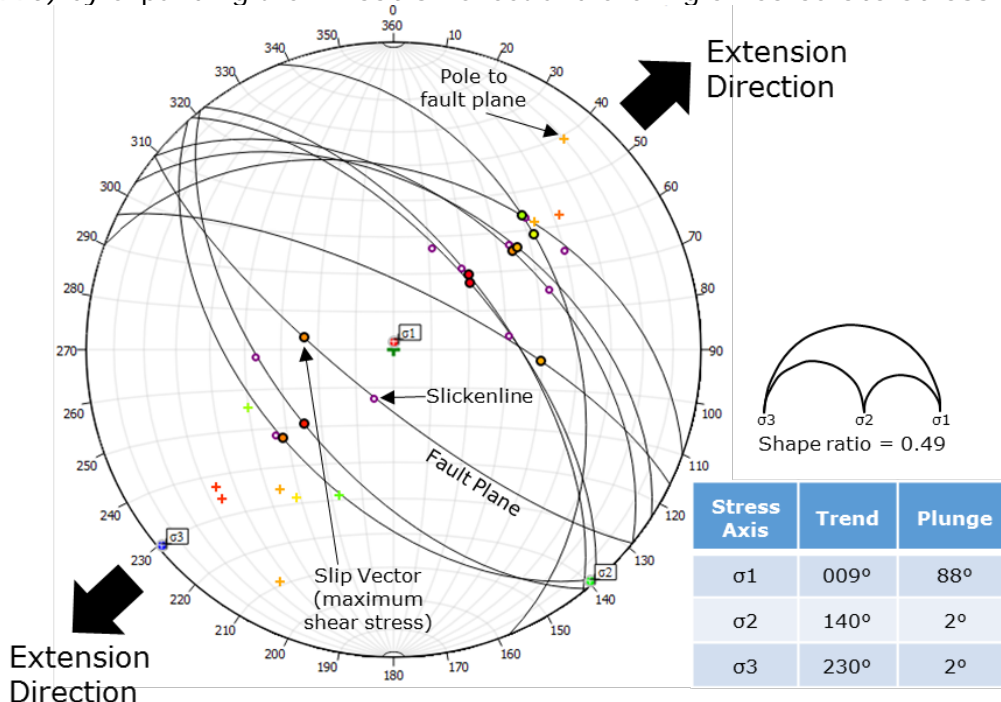| Stress Axis	Trend	Plunge
σ1	009º	88º
σ2	140º	2º
σ3	230º	2º

Shape ratio = 0.49

Figure 2. Inversion of observed fault kinematic data using the angular misfit calculation (Angelier 1990). The data suggests that the fault network evolved under a NE-SW orientated extension direction.

Forward modelling palaeo-stress fields using Fault Response Modelling

Where kinematic data are unavailable (e.g. subsurface datasets), forward modelling of fault-related deformation can be conducted to test and validate possible stress field scenarios obtained from alternative sources. This involves applying a number of stress field scenarios to fault surfaces and modelling the resulting fault displacements, which are defined from the maximum shear direction calculation. Different scenarios can be tested until a close match is obtained between the observed horizon surface and the model results.

Here, a regional stress field interpreted from in-situ well-bore breakout data in the La Concepción field, NW Venezuela (Colmenares and Zoback 2003) will be applied to fault surfaces adjacent to the La Concepción field using the **Fault Response Modelling** module. Slip vectors will be defined using the maximum shear direction calculation (Allmendinger *et al.* 2011) and the fault-related deformation will be recorded on a horizontal observation horizon. The validity of the stress field will be assessed by visually comparing a vertical displacement (dZ) map of the simulation results with the observed horizon surface.

Suggested workflow:
1. Load the fault surfaces to be investigated and a representative horizon surface into a Move project (Figure 3a);
2. Create a horizontal observation surface approximately coincident with the observed horizon surface (Figure 3b). This can be done from the **Surface** creation toolbox located on the **Model Building** panel. Select **Create New Planar Surface/Grid** and define appropriate parameters.

NOTE: Any deformation unrelated to faulting (e.g. regional tilting or thermal sagging) should be removed prior to comparing the observed horizon surface with the simulation results.
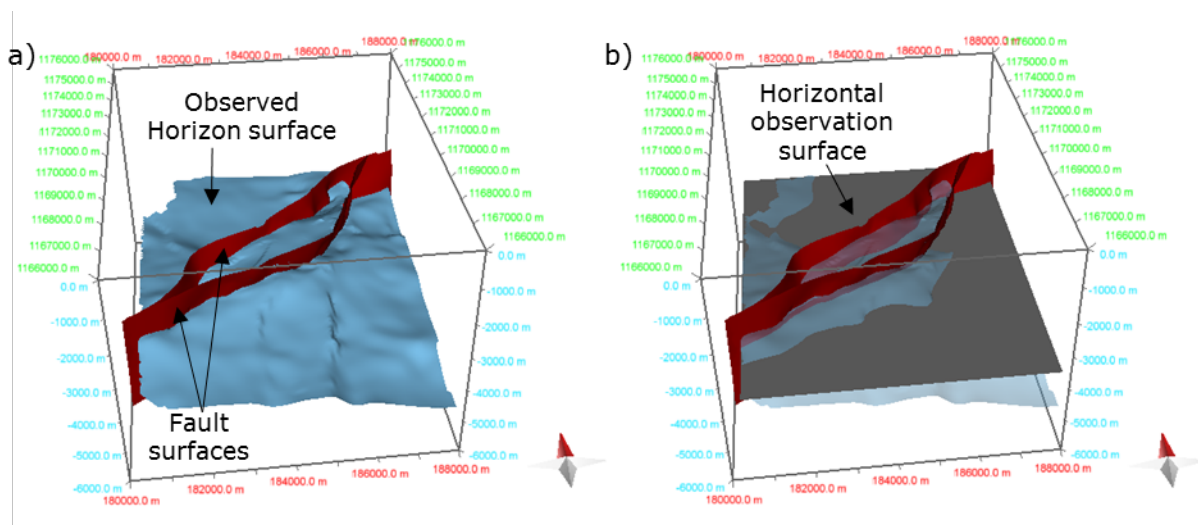

Figure 3. a) Observed horizon (blue) and fault (red) surfaces loaded in Move. b) A horizontal observation surface is created (grey) approximately coincident with the observed horizon surface.

3. Open the **Fault Response Modelling** toolbox from the **Modules** panel and collect the fault surfaces into the **Master Faults/Fracture Sets** box of the **Input: Master Faults/Fracture Sets** sheet.
4. Select all faults in the **Master Faults/Fracture Sets** box.
5. Ensure **Slip** is selected from the **Displacement Defined By** drop-down list.

To ensure that the magnitudes and orientations of the principal stress axes are the only variable, an arbitrary and uniform slip across the fault surfaces will be defined.

6. Toggle on **Max Shear Direction** on the **Slip Definition** tab and define a uniform **Slip Magnitude** of **1.0 m**.
7. Expand the **Input: Observation Objects and their Mechanical Properties** sheet.
8. Collect the horizontal observation surface you created into the **Observation Objects** box.

The fault and observation surfaces to be included in the simulation have now been loaded into the **Fault Response Modelling** toolbox. The slip magnitude has been defined and the slip vector on each triangle element of the fault surfaces will be defined from the maximum shear direction calculation. Before performing the simulation the regional stress field has to be defined.

9. Click on the **Regional Stress** tab at the top of the **Fault Response Modelling** toolbox.
10. Navigate to the **Pressure Profile** sheet. Ensure the **Profile Depth** is set to the approximate depth of the fault surfaces.
11. Expand the **Regional Stress Field** sheet. Define the magnitudes (or shape ratio) and orientations of each of the principal stress axes.
12. Click on the green tick in the upper left corner of the toolbox to save the updated parameters.

Now that the magnitudes and orientations of the regional stress field and the depth of the model have been defined, the **Fault Response Modelling** simulation is ready to begin.

13. Return to the **Fault Response Modelling** tab.
14. Click **Run Fault Response Simulation** to start the simulation.

Once the simulation is complete, it is necessary to colour map the observation surface for vertical displacement (dZ).

15. Expand the **Analyse Results: Displacement, Strain and Stress Colour Mapping** sheet.
16. On the Displacement tab, toggle on **Displacement Z** as the colour map option.

The results of the simulation can be compared with the mapped (observed) horizon surface (Figure 4), and similarities and differences in the positioning of relative highs and lows can be used to assess the validity of the applied stress field. If there is uncertainty in the stress regime or multiple stress field scenarios exist, numerous simulations should be run and the results compared.
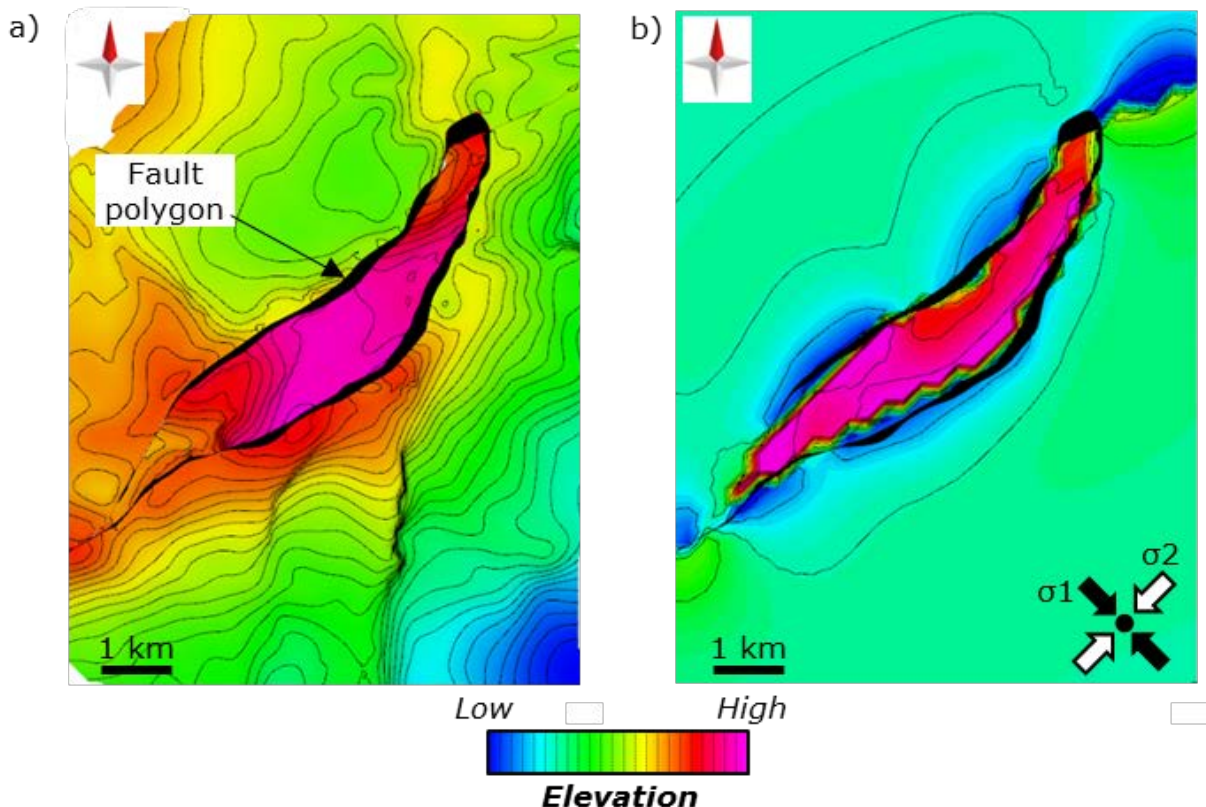

Figure 4. Comparison of the observed horizon surface (a) Colour mapped and contoured for elevation and rotated to remove regional tilting, with the results of Fault Response Modelling simulation (b) Colour mapped and contoured for vertical displacement (dz). The simulation results reproduce many features of the large-scale structure, suggesting that fault-related deformation occurred in a similar stress field to that of the present-day.

References

Allmendinger, R.W., Cardozo, N. & Fisher, D.M. 2011. Structural geology algorithms: Vectors and tensors. Cambridge University Press.

Angelier, J. 1990. Inversion of field data in fault tectonics to obtain the regional stress—III. A new rapid direct inversion method by analytical means. *Geophysical Journal International*, **103**, 363-376.

Bott, M.H.P. 1959. The mechanics of oblique slip faulting. *Geological Magazine*, **96**, 109-117.

Colmenares, L. & Zoback, M.D. 2003. Stress field and seismotectonics of northern South America. *Geology*, **31**, 721-724.

Wallace, R.E. 1951. Geometry of shearing stress and relation to faulting. *The journal of Geology*, 118-130.

If you require any more information about **Stress Analysis** or **Fault Response Modelling** in Move, then please contact us by email: enquiries@mve.com or call: +44 (0)141 332 2681.