Statistical Curvature Analysis Technique (SCAT) in Move

Geological interpretations are often hindered by poor quality subsurface data or local structural complexity. In such areas, a lack of interpretational constraint can directly increase risk during oil and gas exploration. The **SCAT** tool in Move uses dip and dipmeter data as an aid for understanding structural geometry where other constraints are unreliable or unavailable. Plotting dipmeter data to analyse structural style was devised in the early 1980's following the publication of two papers that outlined how graphical plots could be prepared to best interpret folded structures (Bengtson 1980, 1981).

SCAT in Move

The SCAT tool allows the user to carry out multiple analyses of dip and dipmeter data in order to gain a more complete understanding of complex structural settings where other data was unable to do so. There are nine plots available to the user to carry out these analyses (Table 1). The use of multiple data plots and dense data (i.e. dipmeter data) enables the user to 'see through' the scatter and identify true structural dips amid otherwise erratic data. This article looks at the tangent plot, dip/azimuth plot and the dip analysis plots in more detail and demonstrate how they can be used to aid structural interpretation when solely reliant on dip or dipmeter data. All of the plots and interpretations outlined in this article are based solely on information derived from wells and show how, with minimal data, the geometry of subsurface structures can begin to be understood.

Table 1. Plot types available in the SCAT tool in Move.

Circular Plots	Orientation Plots	Dip Analysis plots
Rose Plot	Azimuth/Frequency	Azimuth/Depth
Stereo Plot	Dip/Azimuth	Dip/Depth
Tangent Plot		Transverse Dip/Depth
		Longitudinal Dip/Depth

Theory of folds and fold analysis

Bengtson (1981) identified seven basic categories of bulk structural curvature into which, the majority of structures can be classified: zero dip, low dip, moderate to steep dip, plunging fold, doubly plunging fold, non-plunging fold and circular dome. Figure 1 shows block diagrams of the structural settings that will be examined in this article. The directions of most structural change and least structural change in any structure are known as the transverse and longitudinal dip directions, respectively, or T- and L-directions. These are shown in Figure 1 as green and blue arrows. Calculating the T- and L-directions of a structure allows it to be orientated and helps to understand the geometry of a structure at depth.

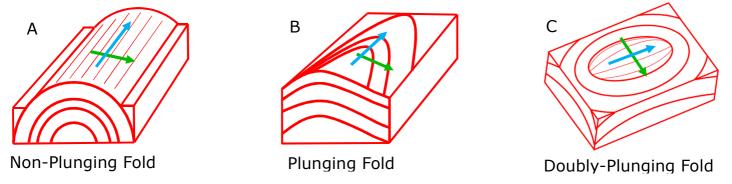A   Non-Plunging Fold   B   Plunging Fold   C   Doubly-Plunging Fold

Figure 1. Block diagrams displaying three of the seven categories of bulk curvature described by Bengtson (1981). The green and blue arrows denote the T- and L-directions, respectively.

Three surfaces that can help to more fully understand the geometry of a fold, beyond simply its bulk orientation, are the crestal plane, the axial plane and inflection planes. The crestal plane of a fold is a plane that bisects the highest points of a fold (Figure 2A); the axial plane is the plane that divides the fold as symmetrically as possible at its hinge (Figure 2B); and inflection planes define the parts of a fold with least curvature, or where concavity reverses (Figure 2C). Interpretation of each of these surfaces and knowing the orientation of bulk curvature of a folded structure, the user can begin to develop a valid 3D interpretation of the structure.

A knowledge of fold orientation and geometry is essential to understand the deformation history of a structure and to enable more detailed structural analysis, such as fracture generation and resource estimation. Unfortunately, high quality 3D data enabling easy visualization of structures at depth is not always readily available. However, dipmeter data from wells drilled through structures, visualized on the plots listed above, are an extremely powerful tool in interpreting folded structures. The theory behind this process is detailed by Bengtson (1980, 1981) and the SCAT tool in Move has been developed to allow these analyses to be carried out quickly and easily. The tool can utilise one or multiple wells, straight or deviated, that intersect a structure or structures.
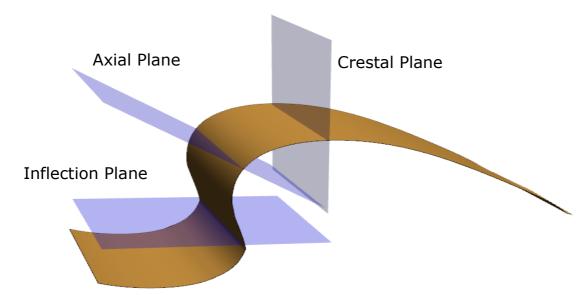

Figure 2. A folded surface with the crestal, axial and inflection planes visualized.

Identifying fold types with Tangent plots in Move

Most folds in nature can be classified as cylindrical or conical (Wilson 1967). Provided that the data are not taken from structures that plunge in various directions, random dip data taken from such folds will define a smooth, statistical curve when plotted on a tangent diagram.

Upon opening the SCAT tool in Move, the **tangent plot** will be visible on the right-hand side of the tool while the left-hand side is occupied by the two orientation plots (Figure 3). Dipmeter data from wells selected in Move when the SCAT tool is opened will automatically be displayed on all plots.

Tangent plots are polar coordinate graphs that allow analysis of 3D planar data on a 2D image, including the quick and easy identification of true dip and apparent dip, and identification and orientation of cylindrical or conical folds (Figure 4). Dip direction is read from the circumference of a tangent diagram and angle of dip from the concentric circles within it (Figure 4 D-F).

Cylindrical folds will define a straight line on a tangent plot with the line passing through the origin for non-plunging folds. If a cylindrical fold is tilted to become a plunging fold, it will also plot as a straight line, parallel to its non-plunging equivalent. The angle and direction of plunge is defined by the perpendicular vector from the centre point of the tangent plot to the data line.

In contrast to cylindrical folds, dip data plotted from conical folds will define curved lines on tangent diagrams. The plotted curve for an ideal type I (vertex down-plunge) conical fold will be a hyperbola that is open toward the centre, whereas a type II fold (vertex up-plunge) plot as a curve opening away from the origin (Figure 3 D and E). The shortest line from the centre point of the tangent plot to the curve defines bearing and plunge of the crestal line.
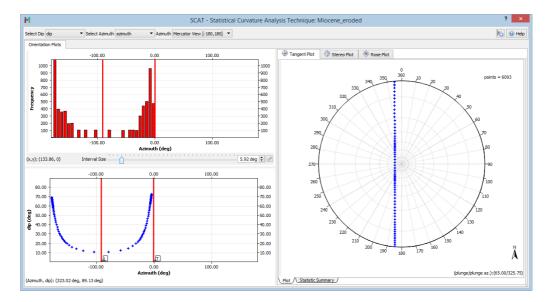

Figure 3. Orientation plots in the SCAT tool. The right-hand side displays the tangent diagram, plotting dip direction on the circumference and angle of dip is read from the internal concentric circles. The top graph on the left-hand side plots the frequency of azimuth measurements whilst underneath, dip is plotted against azimuth for all data. The pattern on the dip vs. azimuth plot can inform the variety of bulk curvature of the structure intersected by the well. T- and L-dip directions are given by the red lines on both orientation plots.
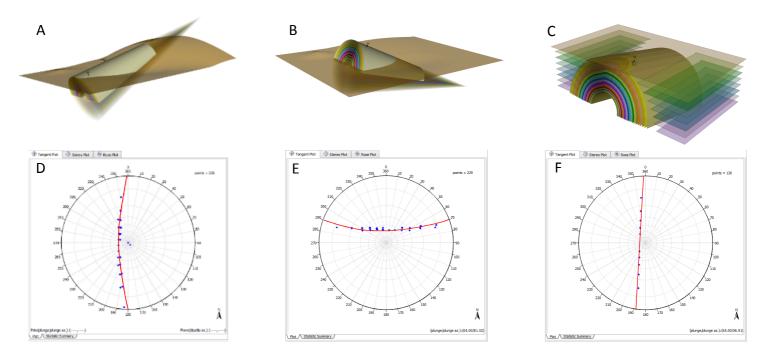

Figure 4. 3D models of vertex-up and vertex-down conical folds (A and B respectively) and a plunging cylindrical fold (C). D, E and F show tangent diagrams plotting dipmeter data from wells intersecting each of the structures. Note the open toward the origin nature of the curve representing the vertex-up fold (D) and the open away nature of the curve representing the vertex-down fold (E). The dipmeter data for the cylindrical fold falls on a straight line (F). The plunge angle and direction of each fold is given by a vector from the origin to the closest point on the best-fit curve to the dipmeter data.

The **Orientation plots** are on the left-hand side of the tool window. These graphs plot a histogram of the frequency of dip-azimuth and dip vs. azimuth for each data point. Identification of fold categories (Figure 1) can be given by the pattern of dip measurements plotted on the dip vs. azimuth orientation plot. Different fold types show quite different patterns, and are most easily identified on the dip vs. azimuth plots.
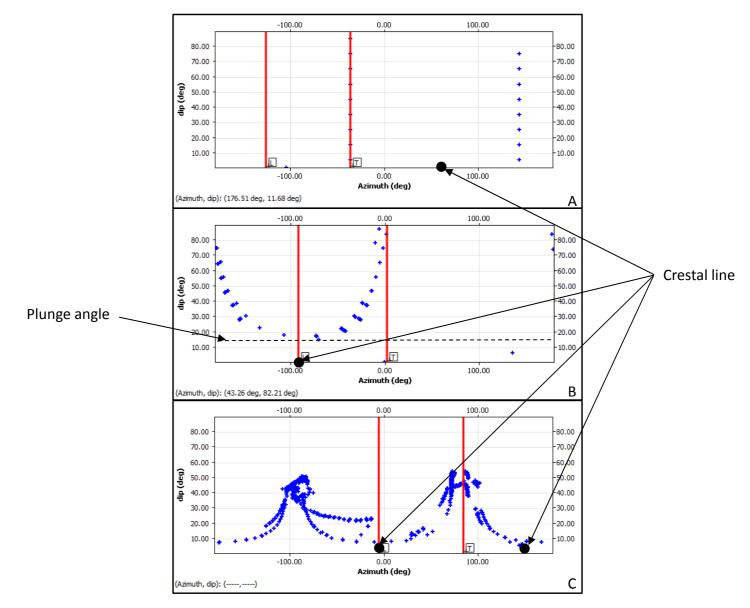

Figure 5. Dip vs. azimuth plots representing (A) a plunging fold, (B) a non-plunging fold and (C) a doubly plunging fold (C). The crestal line orientation for each can be read from the x-axis midway between the data extents and fold plunge is given by the data point with the lowest y-axis value. The T- and L-directions are given by the red lines on each plot.

Non-plunging folds will define two straight lines (Figure 5A). The azimuth of the crestal line can be read from the x-axis (azimuth) at the midway point between the two vertical data point trends. The T-direction will be coincident with the data point trends, which will be 180□ from one another and the L-direction 90□ either side of these.

Plunging folds will give a horseshoe-shape (Figure 5B). The sides of the horseshoe pattern for a plunging fold describe the T-directions. The L-direction will be defined by the midway point between the sides of the horseshoe, which will also be the crestal line. The angle of plunge can be read from the y-axis at the lowest data point of the horseshoe.

A plunge-reversal setting, or a doubly plunging fold, will show two horseshoe patterns which link to show a 'christmas tree' pattern (Figure 5C). Similar to the plunging fold setting, the T-direction is given by the sides of the horseshoes, or the top of the 'christmas tree' and the L-direction by the midway point between them. The angle of plunge is again given by the lowest point of the horseshoes but may be different for each of the two horseshoes that make up the pattern, the fold may plunge more steeply on one side or the other.

Calculation of the T- and L-directions from a dataset is carried out automatically in the SCAT tool and immediately allows structural orientation to be determined (red lines in Figure 5). The T- and L-directions will influence how data are plotted on the dip analysis plots.

In this manner, identification of a folded structure can be carried out quickly and easily in areas where little data are available. Move also allows for a clearer picture of the subsurface to be visualized using the dip analysis plots in the SCAT tool.

Dip analysis plots and structural orientation

The SCAT tool in Move, as well as being used to identify the type of structure that has been intersected by a well, can also be used to identify the nature of folding and faulting at depth. This is done by interpreting the position of the folds crestal plane, axial plane and inflection plane by the well being analysed. The orientation of a fold's crest is possible on the dip vs. azimuth plots illustrated in Figure 4, but it is with dip analysis plots that identification of further surfaces, and creation of markers representing these surfaces in 3D space can be carried out.

The SCAT tool contains the following dip analysis plots: azimuth-depth, dip-depth, transverse dip-depth and a longitudinal dip-depth (Figure 6). Upon clicking on the dip analysis plots tab, the T- and L-directions are shown at the top of the window and can be adjusted if necessary.

The **Structural Interpretation** sheet is on the right-hand side of the dip analysis window (Figure 7) and is where interpretation of different planes that define the shape of a fold (Figure 2) can be carried out. The chosen plane is selected from under the **Create** options of the **Structural Interpretation** sheet, and the user can then click on any point on any of the dip analysis plots where the plane is interpreted to intersect the well. The data pattern that defines the position of each of these planes for each identified structural setting has been described by Bengtson (1981) and is described in Table 2 for non-plunging and plunging folds. It is important to note that a structure may have more than one inflection plane.

Table 2. Methods of identification of crestal planes, axial planes and inflection planes in folded settings from the available dip-analysis plots in Move.

Structural Setting	Crestal Plane	Axial Plane	Inflection Plane
Non-plunging fold	Point of change of dip (e.g. from E-W) nearest top of dip plot and transverse dip plot.	Max rate of change of dip on transverse dip plot.	Points of local maximum dip and zero rate of change of dip on dip plot and transverse dip plot.
Plunging fold	Maximum rate of change of azimuth on azimuth plot; point of max dip on dip plot.	Max rate of change of dip on transverse dip plot.	Point of maximum dip on dip plot.

For a non-plunging fold (Figure 1C), the interpretations of each of these planes can be seen in the plots on Figure 6. The crestal plane is interpreted as the point of change of dip (e.g. from E-W) nearest the top of the plot. A similar change of dip near the bottom of the plot could be interpreted as the intersection of a trough plane. The axial plane is interpreted as the point of maximum change of rate of dip on the transverse-dip plot. Inflection

planes are interpreted as points of local maximum dip and zero rate of change of dip on the transverse dip plot. As with a plunging fold, local maxima can define multiple inflection planes. On the longitudinal dip plot for a non-plunging fold (Figure 6), the data points will define a straight line with zero dip, while a plunging fold will define a straight line with a dip equivalent to the angle of plunge (Figure 7).

For a plunging fold (Figure 1B), the crestal plane is interpreted at the point of maximum dip on the dip plot and the point of maximum rate of change of azimuth on the azimuth plot. The axial plane is interpreted at the point of maximum rate of change of dip on the transverse dip plot. Inflection planes are interpreted at points of maximum dip on the dip plots. As there may be multiple inflection planes, local maxima will also define inflection planes. These interpretations can be seen on the plots in Figure 6.

When the interpretation of these planes has been carried out, the **Create/Update** button, will create well markers in the well being analysed at the interpreted depth with orientation attributes and names corresponding to the names of the interpreted planes. These can be examined and edited in the well marker data table and visualized in 3D. Following their creation, these interpreted intersections can be used to verify a 3D structural model or modify an interpretation (e.g. using the **Reshape** tool).

There are a variety of visualization options accessed via the **Display** sheet on the right-hand side of the tool and can be applied to each of the plots individually. The grid in each display can be toggled on/off; the data point display symbol can be changed in style, colour and size; the data points can be joined by a curve; and the data can be decimated by choosing a 'vertex sampling' value. Some of these options have been applied to the plots shown in Figures 6 and 7.

It is often also possible to identify dip slip faults on dip analysis plots. These may be shown by 'cusp' patterns on the transverse dip plot (Figure 8). The cusp pattern will point in the direction of the fault in the case of normal dip-slip faults and against the direction of dip in the case of reverse dip-slip faults. It is not possible identify if a fault is normal or reverse from dipmeter data alone. The reason for the 'cusp' pattern is due to the drag effect that faults have on the strata adjacent to the slip surface. Upon identification, faults can be created in the same way that other structural surfaces are created in the **Structural Interpretation** sheet of the SCAT tool.
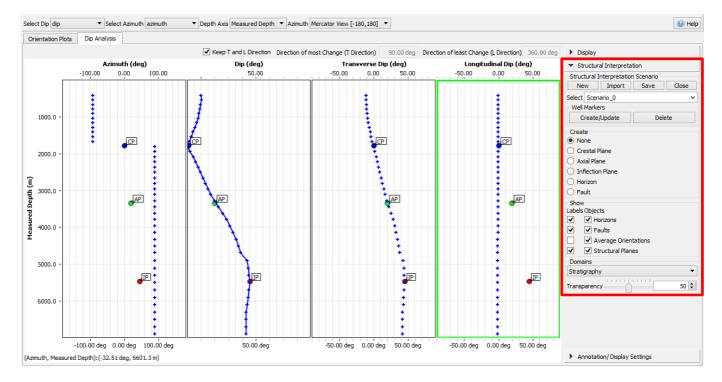

Figure 6. The four dip analysis plots available in the SCAT tool in Move shown for a well intersecting a non-plunging fold. From left to right: Azimuth-depth, Dip-depth, Transverse dip-depth and Longitudinal dip-depth. The azimuth dip-depth plot has had a trendline added. The structural interpretation sheet highlighted with a red box on the right-hand side of the window allows interpretation and creation of intersections of planes defining the fold geometry on the well. The crestal plane, axial plane and inflection plane interpretations have been made and are visualized as blue, green and red points, labelled CP, AP and IP.
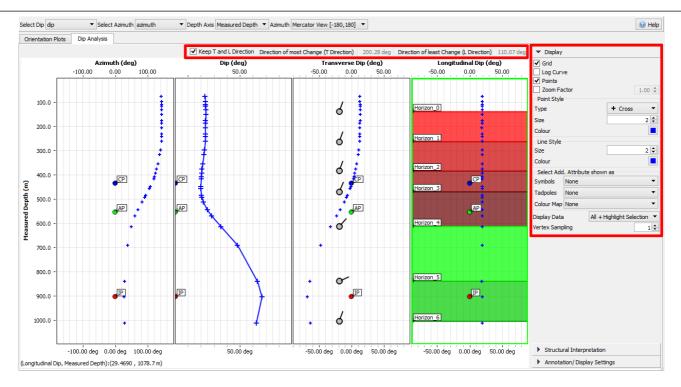
Figure 7. The four dip analysis plots available in the SCAT tool in Move shown for a well intersecting a plunging fold. The azimuth dip-depth plot has had a trendline added; the Transverse dip-depth plot is showing average orientation tadpoles and the Longitudinal dip-depth plot has been coloured for the stratigraphy in the model. The Display sheet on the right-hand side of the window allows visualization options to be user-defined. Crestal planes, axial plane and inflection plane interpretations have been made and are visualized as blue, green and red points, labelled CP, AP and IP. The red box at the top of the tool highlights the T- and L-directions and the red box on the right-hand side of the tool highlights the Display options.
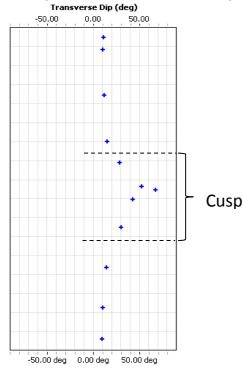

Figure 8. Transverse dip component plot displaying a cusp zone representing a fault with steepening drag.

References:

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Wilson, G., 1967. The geometry of cylindrical and conical folds. Proceedings of the Geologists' Association, 78(1), 179-IN11.

If you require any more information about the SCAT tool in Move, please contact us by email: enquiries@mve.com or call: +44 (0)141 332 2681.