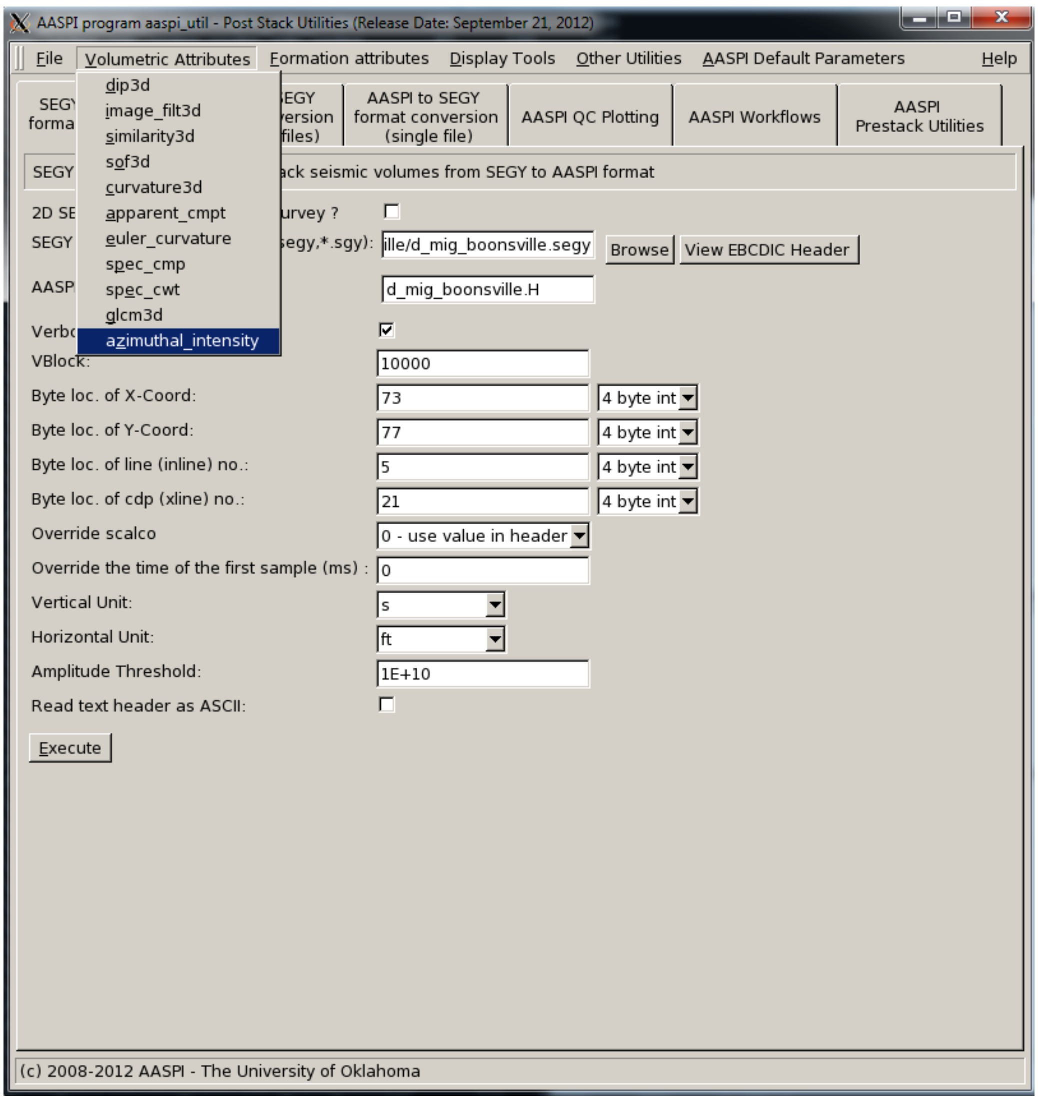
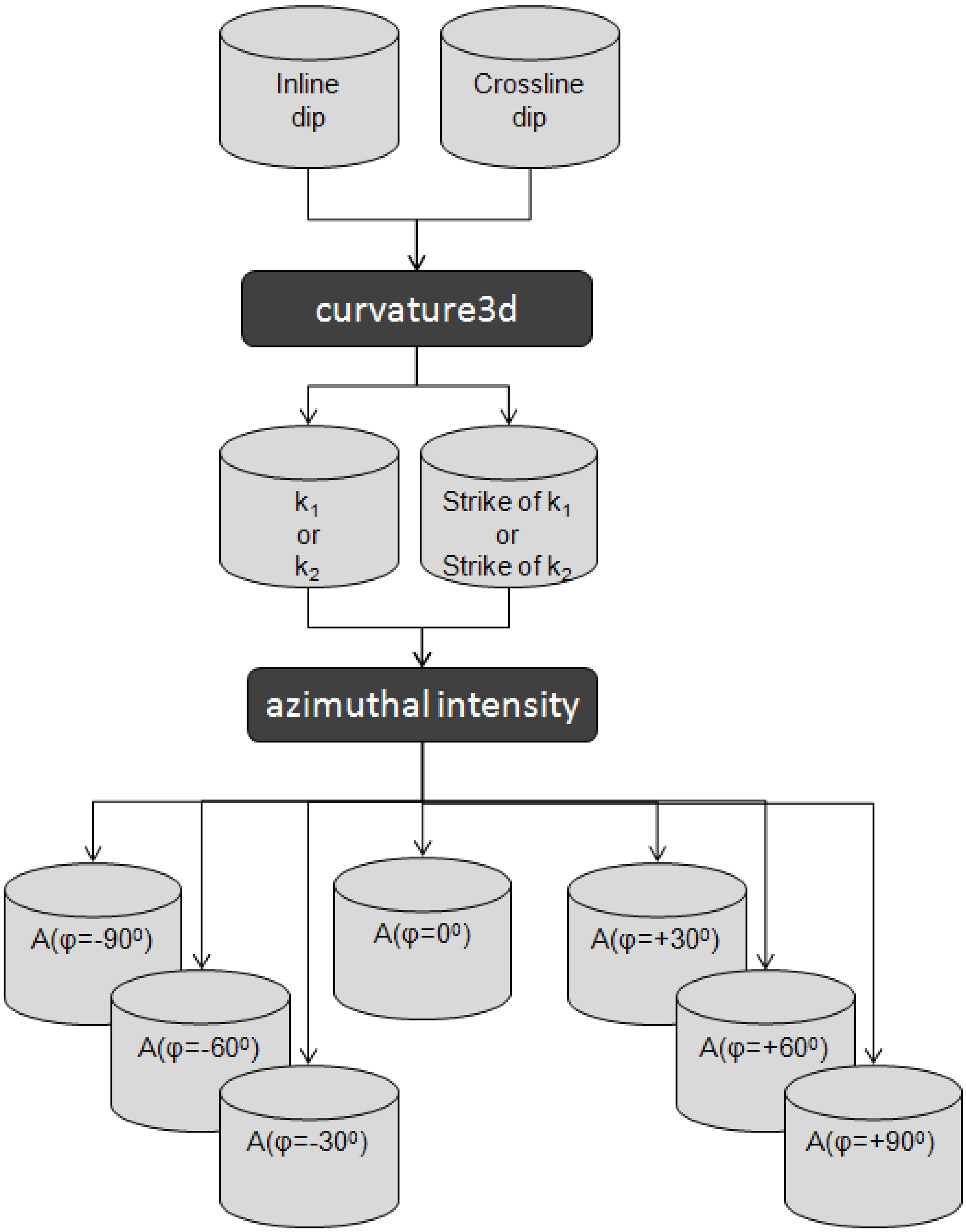
Generating volumes to correlate with production data – program azimuthal_fault_density

The GUI for **azimuthal_fault_density** is found under the *Volumetric attributes* tab on the **aaspi_util** GUI:



Computation flow chart

The input to program **azimuthal_fault_density** consists of pairs of either most-positive or most-negative principal curvature and their corresponding strikes, which previously had been computed using program **curvature3d**. The output will be a suite of smoothed, azimuthally-limited volumes that can be correlated with production, expected ultimate recovery, or other measurements sensitive to fluid flow. More direct measures of fractures from horizontal image logs, flow-and-temperature sensitive production logs, and microseismic event location and strength may also be correlated. Typically, these volumes are loaded into a commercial interpretation workstation package with values of each volume being extracted along the (horizontal or vertical) well bore. Depending on the interpretation workstation software you use, you may be able to correlate production to attributes directly on the workstation. If not, simply export the extracted attribute values and cross correlate production in excel or other statistics software packages. Correlation with horizontal wells requires some intuition and further hypothesis testing. Barring additional information about the success of the completion process, it may be simplest to assume that every portion of a horizontal well contributes equally to the total production, resulting in a workflow that divides the total production of a well into equal segments on the order of a seismic bin (say 110 ft or 25 m) followed by correlation with the extracted attributes.

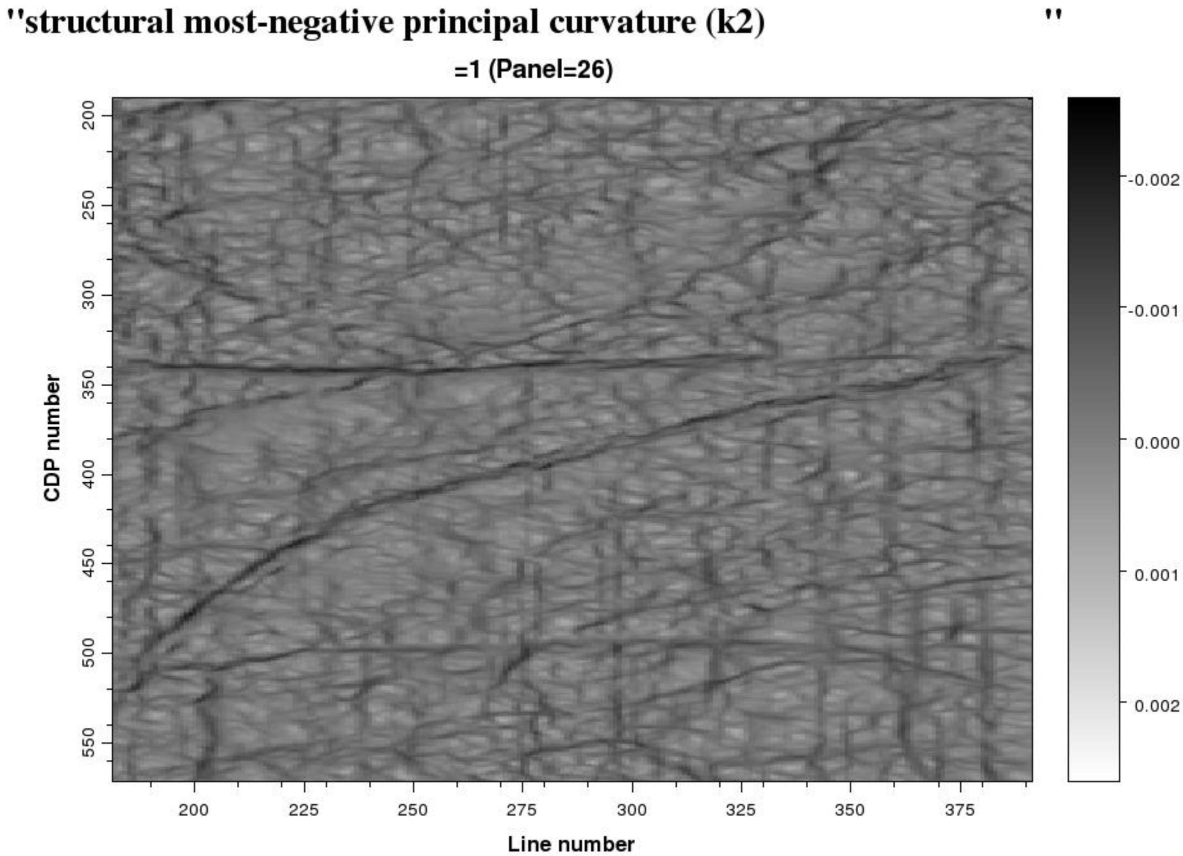


Example – Correlating production of oil and water to hypothesized fractures, Dickman Field, KS

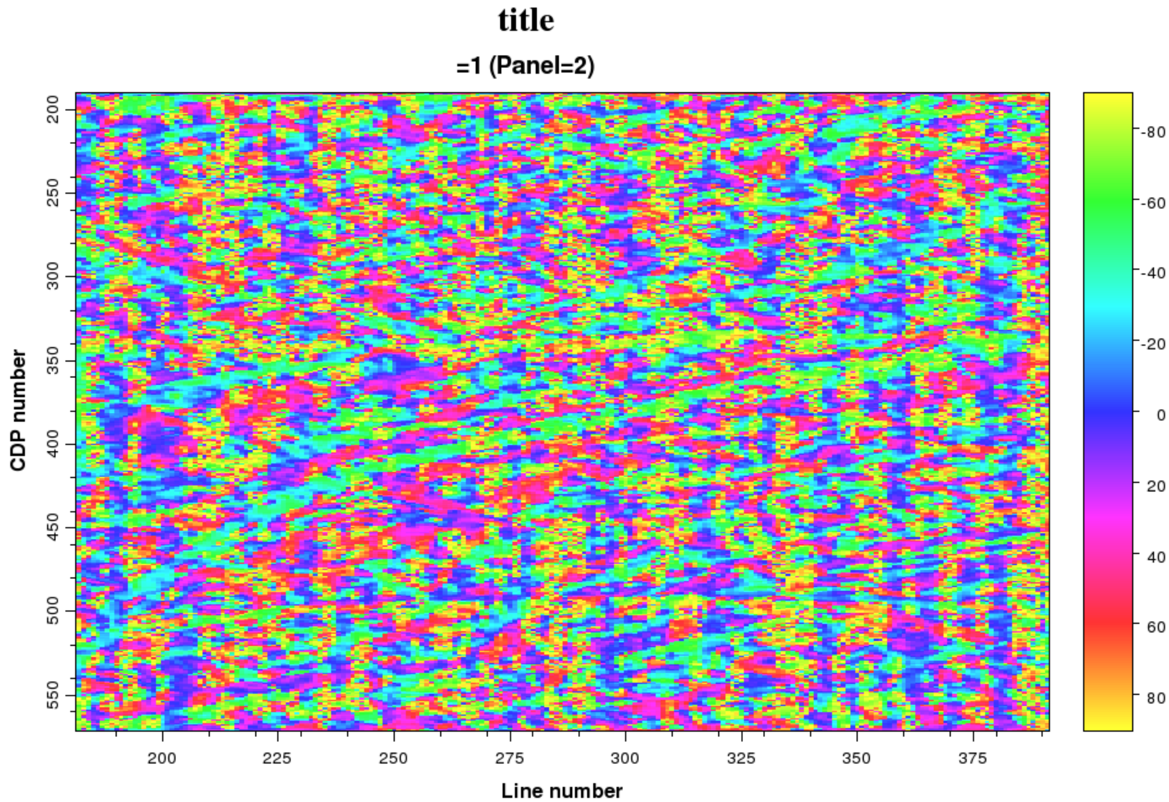
One of the earliest, Nissen et al. (2005, 2009) published a workflow that correlated production of oil and water from a mature oil field to most-negative principal curvature lineaments seen in the Mississippi Lime and deeper Gilmore City formations of central Kansas, USA. These curvature images are dominated by NE-SW trending and NW-SE trending lineaments, one of which was diagenetically enhanced by karstification during the Mississippian. This first application was achieved in a hard way, with Sue Nissen picking lineaments by hand, measuring the differences to the nearest NE-trending and NW-trending lineaments, and then correlating these distances to the amount of karstification (evidenced by the thickness of chert nodules estimated using conventional logs) and initial 5-year production of oil and water.

Encouraged by these results, we have implemented components of this workflow in the AASPI software. To illustrate these components, we reapply the workflow to the Westcam survey. Guo et al. (2010) have applied this same workflow to production of the Woodford Shale in the Ardmore Basin of Oklahoma. Singh et al. (2008) show an alternative workflow using Petrel's AntTracker image-processing software coupled with a Schmidt Stereonet to correlate fractures seen in image logs to curvature and coherence lineaments for a seismic survey acquired in Kuwait.

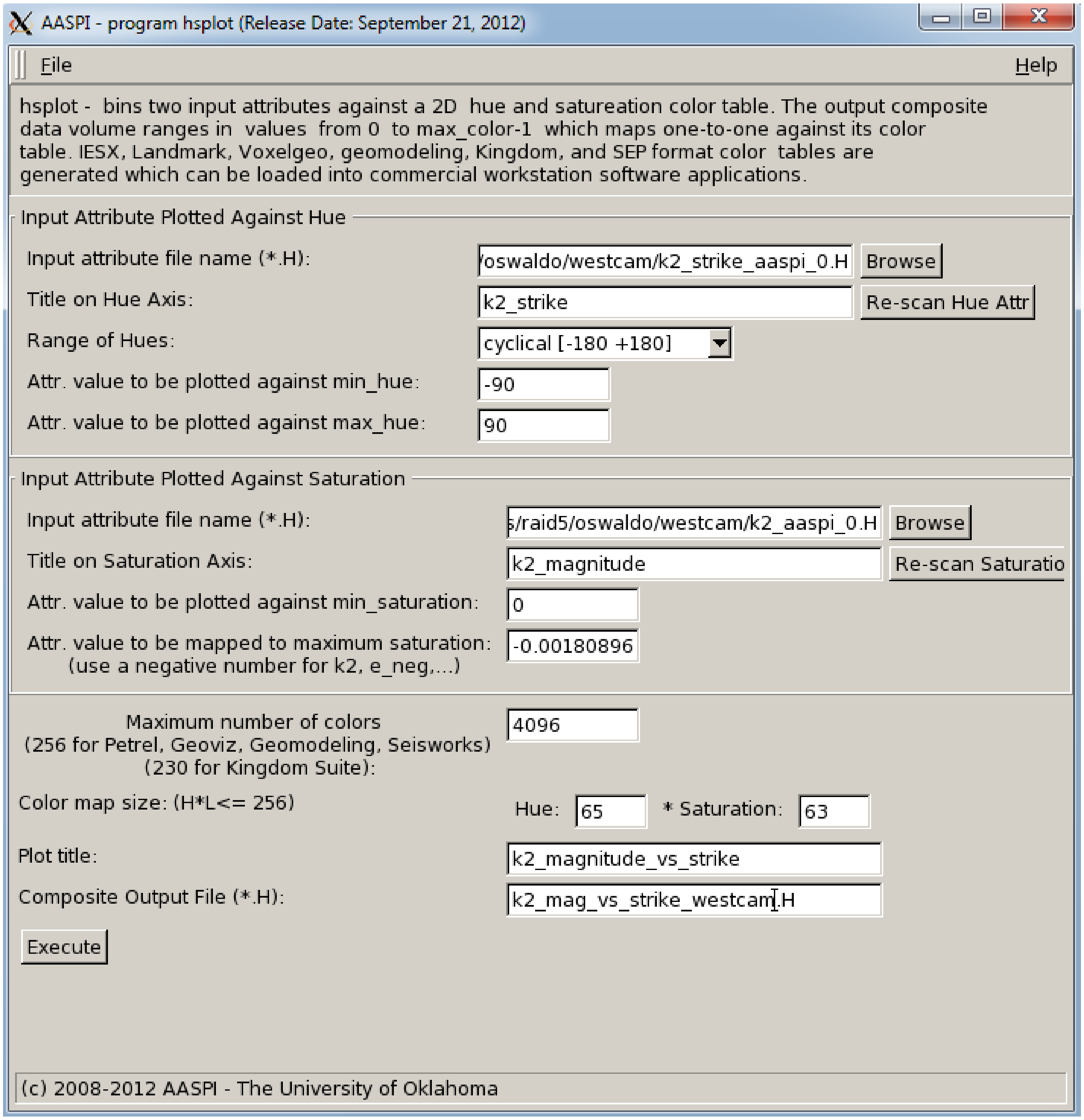
The workflow is quite simple. We start with the computation of the most-positive or most-negative curvature and their strikes. The image below is of the most-negative principal curvature, k_2. Note the color scale of k_2, varies from +/- 0.003 on the right.



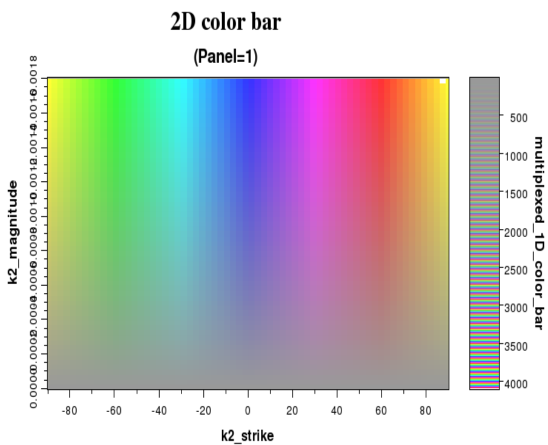
Plotting the strike of k_2, ψ_{k2} , against a cyclical color bar gives the following image:

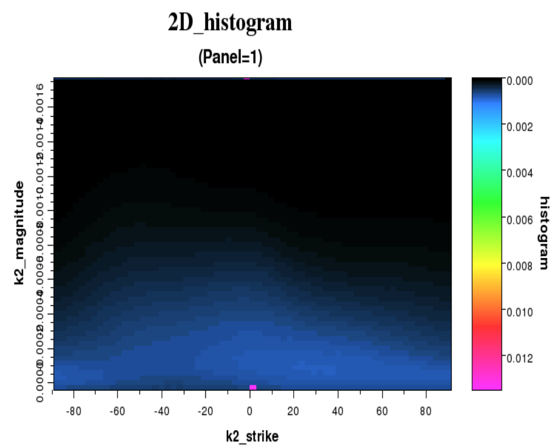


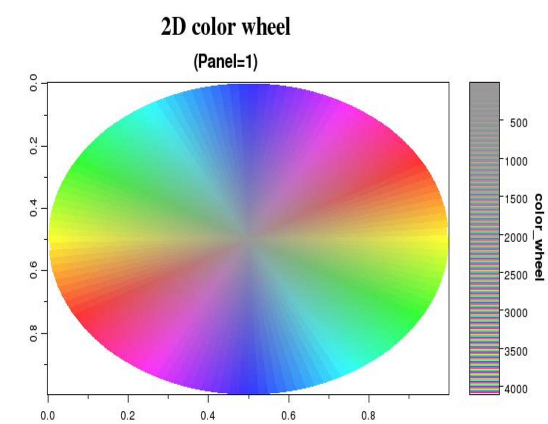
Note that every voxel in the seismic volume has a value of strike, even if the geology is perfectly planar. To address this issue, use program **hsplot** under the AASPI display tools to modulate the strike by the value of k_2 as shown by the GUI below. Note -2e-03 has been entered as the value to be plotted against the darker colors, while all values of strike whose magnitude is greater than or equal to 0 will be mapped to grey:

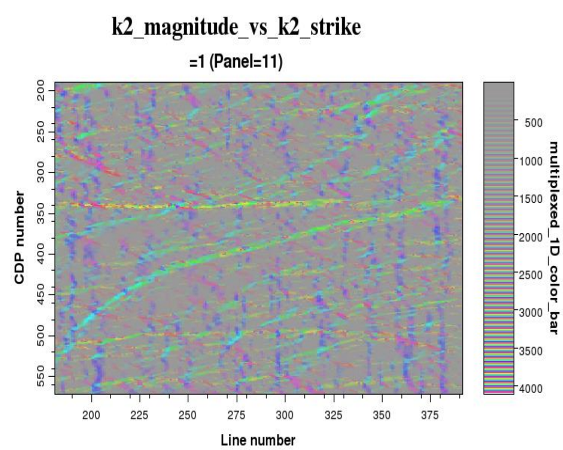

AASPI - program hsplot (Release Date: September 21, 2012)
File
Help
hsplot - bins two input attributes against a 2D hue and satureation color table. The output composite data volume ranges in values from 0 to max_color-1 which maps one-to-one against its color table. IESX, Landmark, Voxelgeo, geomodeling, Kingdom, and SEP format color tables are generated which can be loaded into commercial workstation software applications.
Input Attribute Plotted Against Hue
Input attribute file name (*.H):
/oswaldo/westcam/k2_strike_aaspi_0.H
Browse
Title on Hue Axis:
k2_strike
Re-scan Hue Attr
Range of Hues:
cyclical [-180 +180]
Attr. value to be plotted against min_hue:
-90
Attr. value to be plotted against max_hue:
90
Input Attribute Plotted Against Saturation
Input attribute file name (*.H):
s/raid5/oswaldo/westcam/k2_aaspi_0.H
Browse
Title on Saturation Axis:
k2_magnitude
Re-scan Saturatio
Attr. value to be plotted against min_saturation:
0
Attr. value to be mapped to maximum saturation:
(use a negative number for k2, e_neg,...)
-0.00180896
Maximum number of colors
(256 for Petrel, Geoviz, Geomodeling, Seisworks)
(230 for Kingdom Suite):
4096
Color map size: (H*L<= 256)
Hue:
65
* Saturation:
63
Plot title:
k2_magnitude_vs_strike
Composite Output File (*.H):
k2_mag_vs_strike_westcam.H
Execute
(c) 2008-2012 AASPI - The University of Oklahoma

The following four images appear:



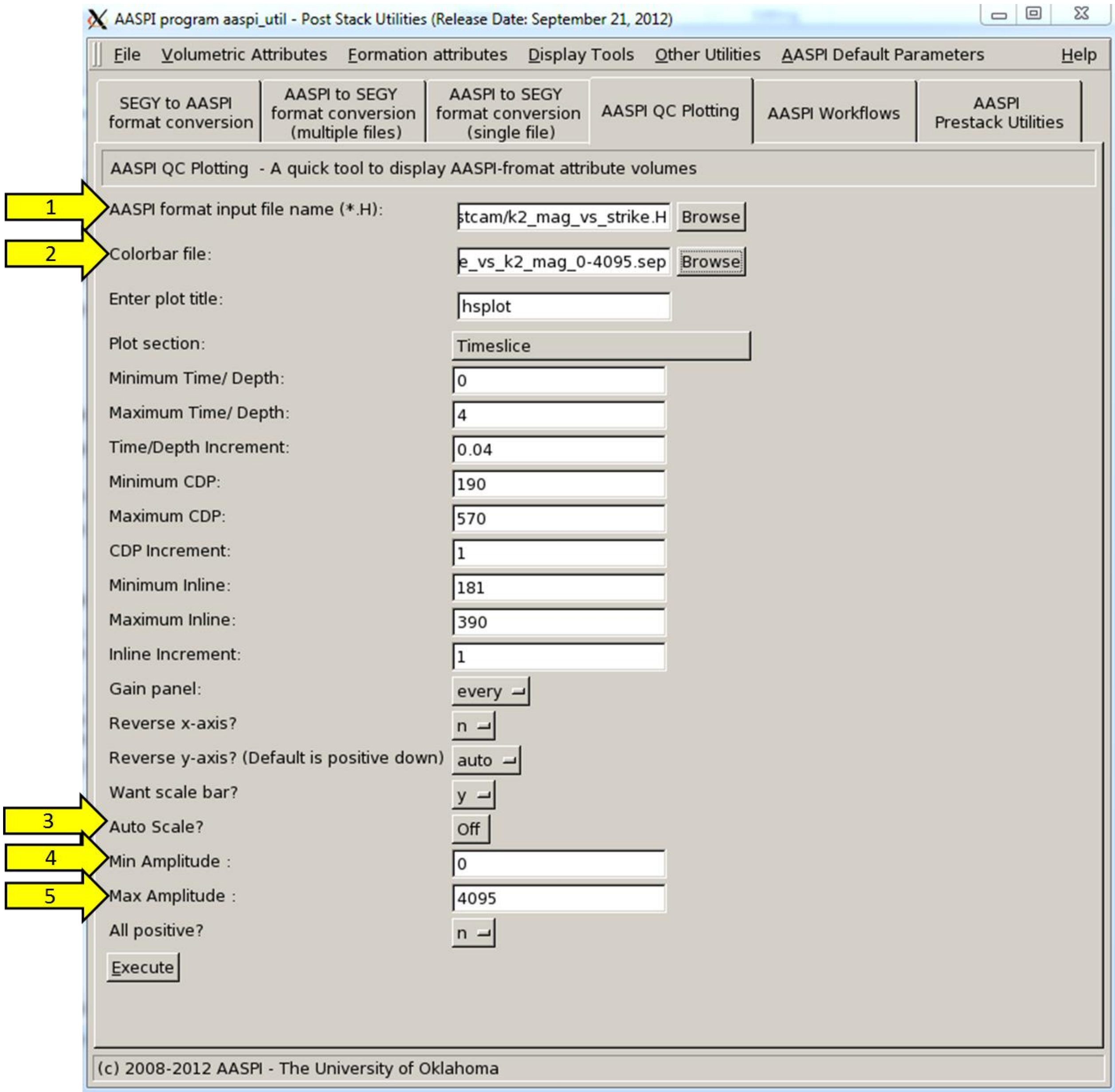






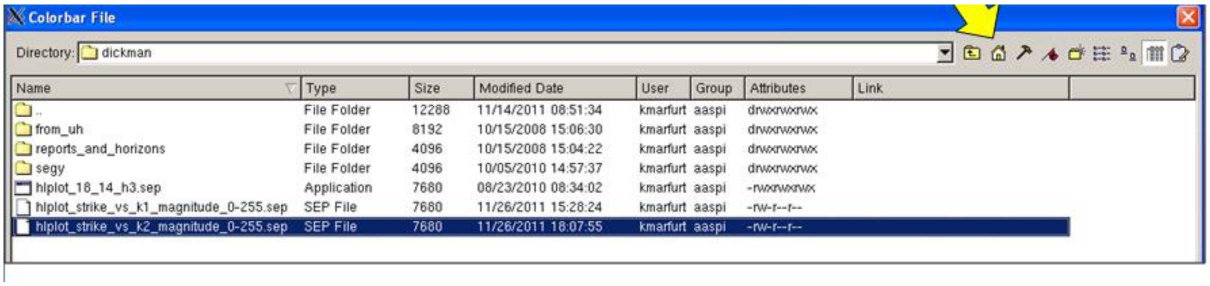
The upper and lower left images are 2D color bar showing the strike of the most negative principal curvature ψ_{k2} plotted against the hue axis and the magnitude k_2, plotted against the lightness axis. Strongly deformed negative curvature lineaments will appear as darker colors. Values that are less negatively deformed appear as pastel colors, while those that have a value of $k_2 \geq 0$ will appear as gray. The image on the upper right shows the corresponding 2D histogram. The image in the lower right is a representative time slice of the modulated data. These data can be loaded into your workstation software along with the corresponding color bar.

To plot the data using *AASPI QC Plotting*, fill in the parameters as follows:



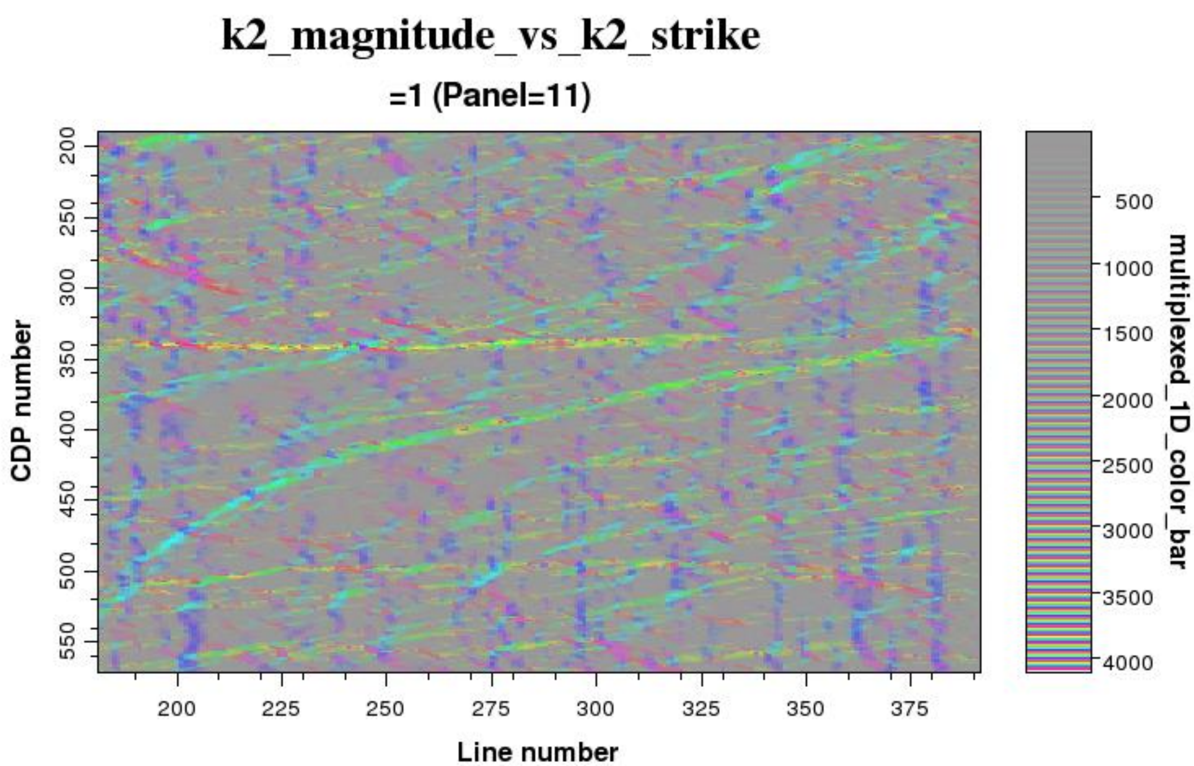
where (1) *k2_mag_vs_strike.H* is the name of the file creating using hlplot, (2) *strike_vs_k2_magnitude_0-4095.sep* is the SEP-format color table in my local project directory, (3) indicates that I turn the default Auto Scale to 'off', and I scale the data to range between (4) Min Amplitude 0 and (5) Max Amplitude 4096, representing the 4096 colors available in the *AASPI QC Plotter*.

To find the *.sep color bar in my Westcam subfolder, I can click the home icon as shown below:



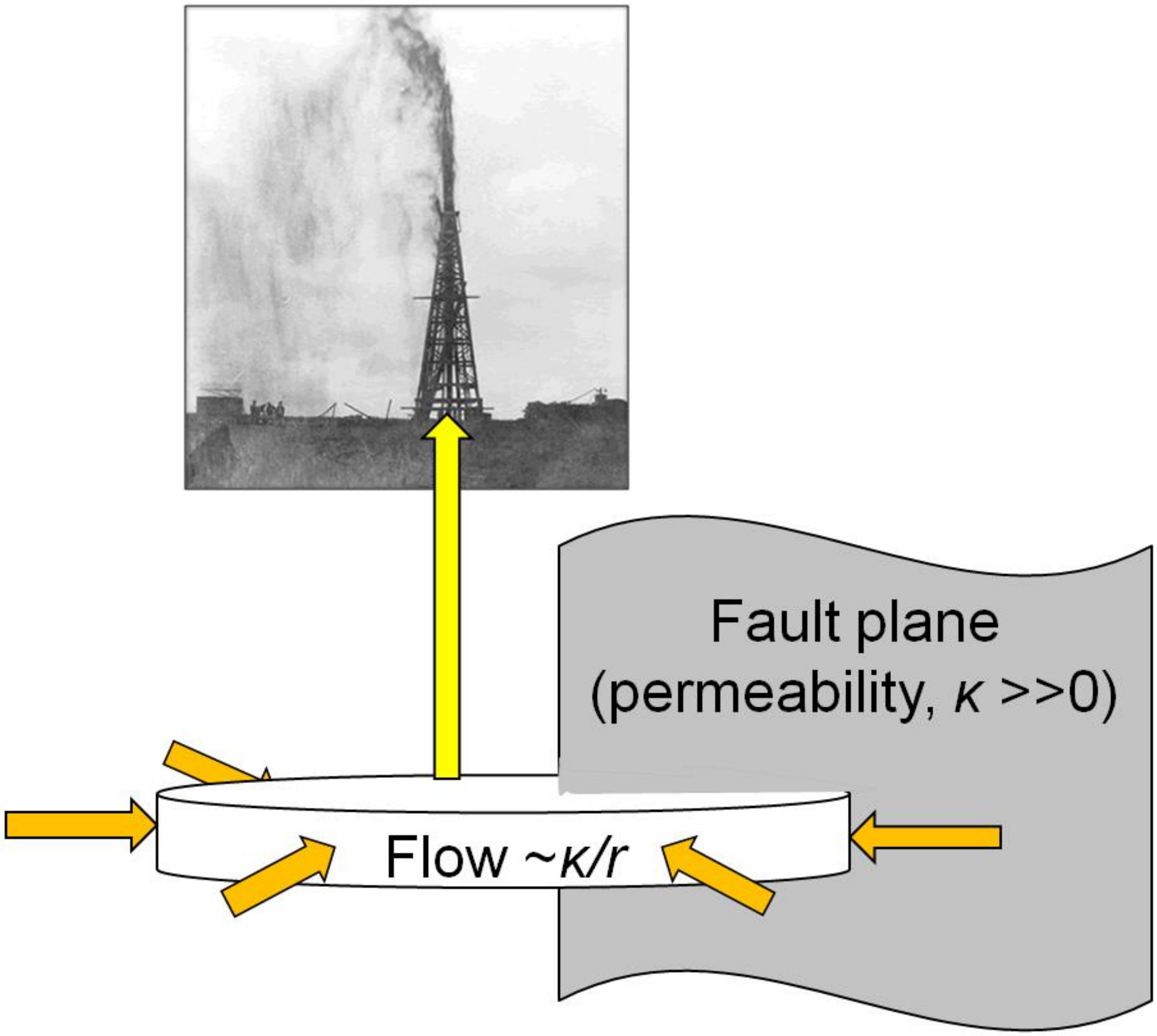
This takes me relatively quickly to the AASPI directory containing the default color bars.

The slice at *t*=0.840 s (k_2 magnitude vs strike plotted above) appears like this:

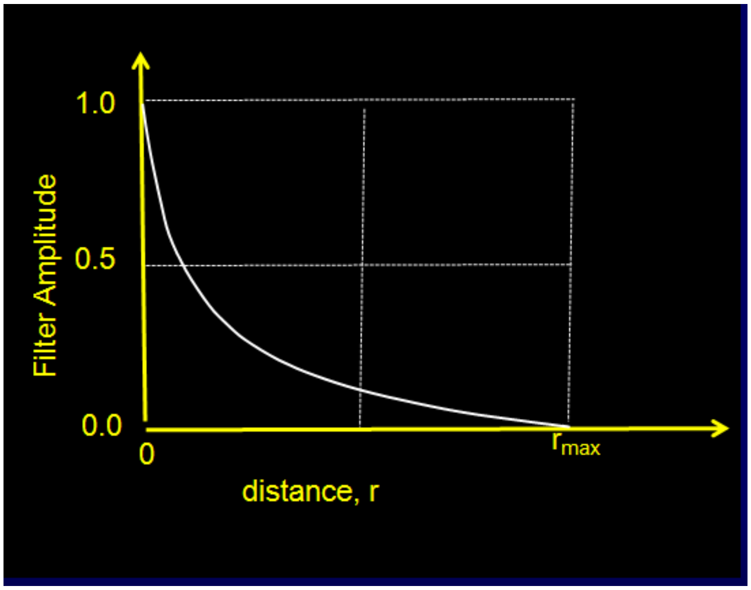


Note that the lineaments are color-coded to the 2D colorbar previously shown.

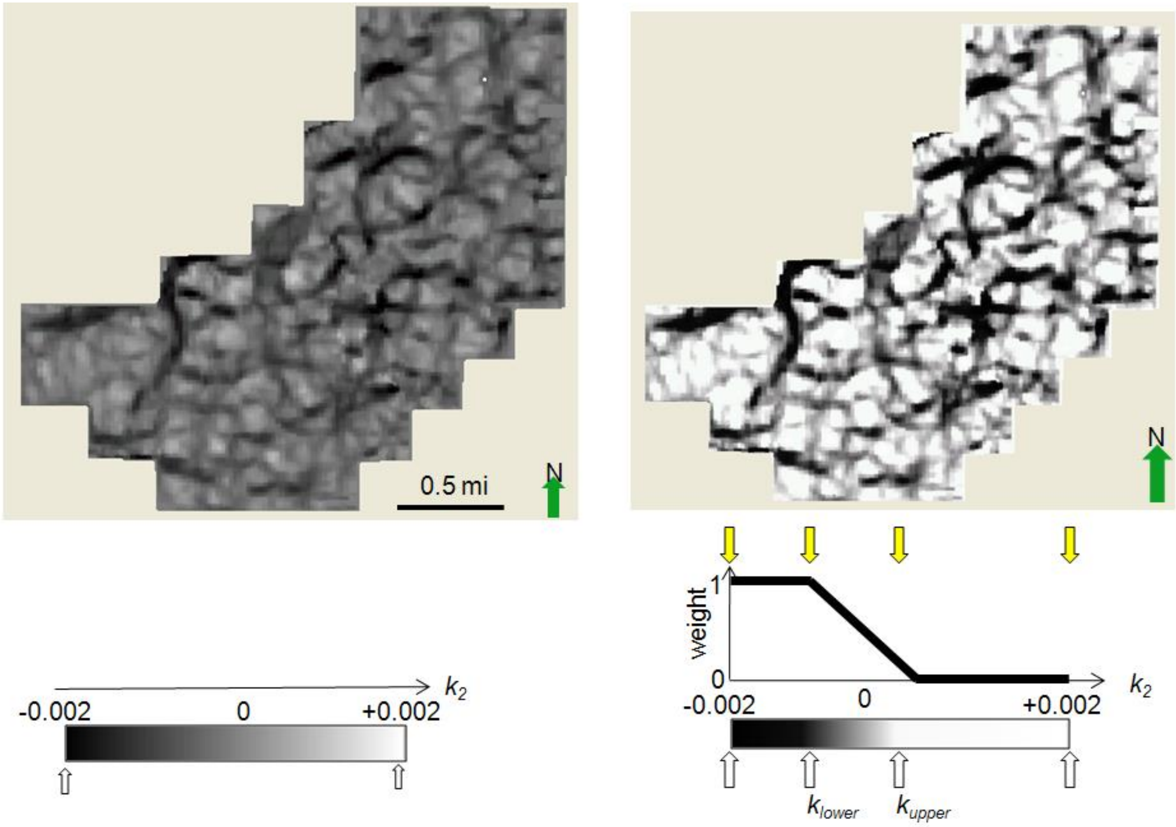
We now wish to formulate alternative hypotheses about the correlation of a given set of azimuthally-limited lineaments to the presence of open fractures, and hence to production. To do so we invoke a simple model (Guo et al., 2010):



We assume that the reservoir has a constant, finite permeability κ, while the hypothesized open fractures have an extremely large permeability. At present, the software provides two simple models – fluid flow that varies as *1/r*, or as $1-r/r_{max}$ from a 'fault element' .All of the fault elements will then be integrated to form azimuthally-limited components of the fault surface.

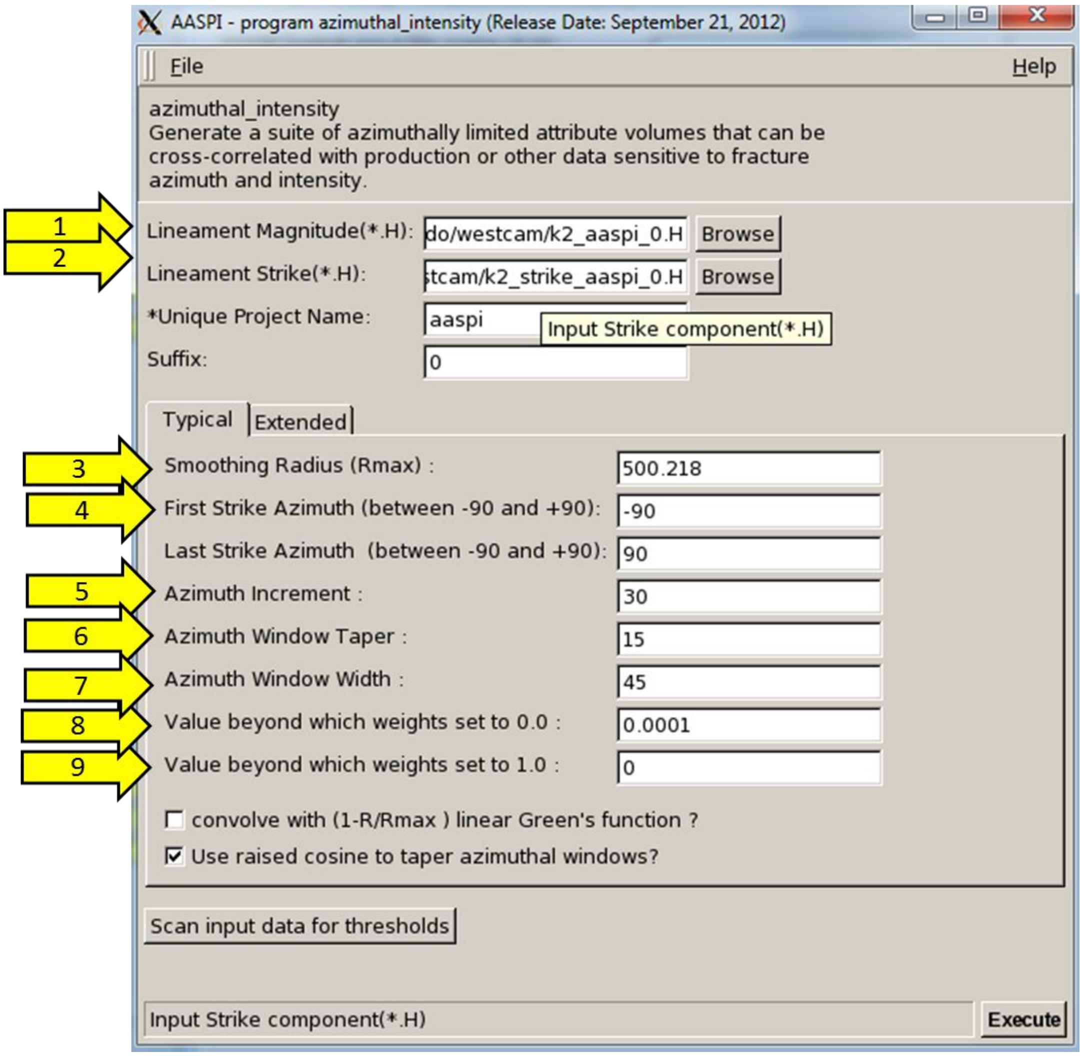


While the shape of lineaments seen on the k_2 time slices might appear to be open fractures, the amplitude of curvature has at best a nonlinear relationship to the fault intensity. Our workflow uses conventional workstation colorbar manipulation to set these relationships.

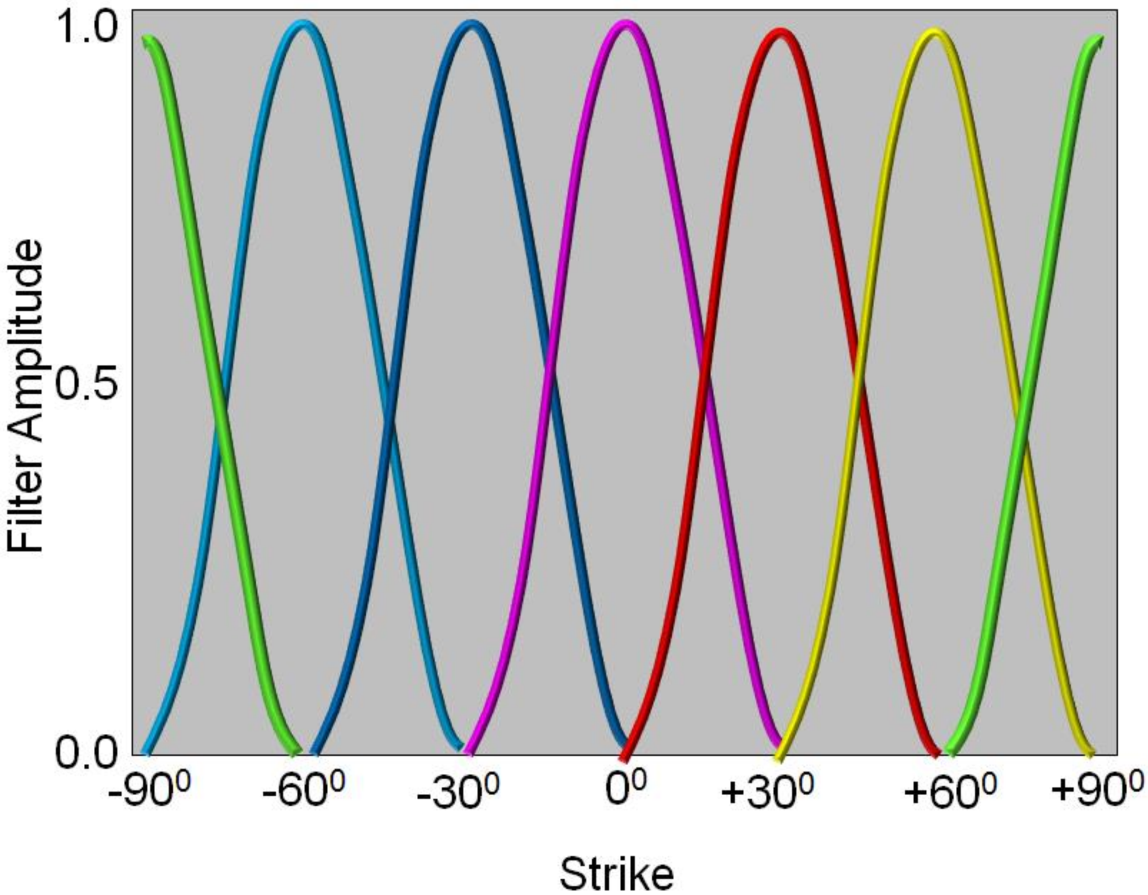


The figure on the left shows a horizon slice along the Mississippi Lime of the most-negative principal curvature, k_2, plotted against a conventional gray scale colorbar. The image on the right shows the same time slice, where two of the color control points (called ‘ramps’ in some software packages) are moved to ‘skeletonize’ the image. Specifically, values of $k_2 > k_{upper}$ are displayed as white and will be assigned a weight of 0.0. Values of $k_2 < kl_{ower}$ are displayed as black and will be assigned a weight of 1.0. Intermediate values are displayed in shades of gray and are assigned weights proportional to their distance from k_{upper} and kl_{ower}.

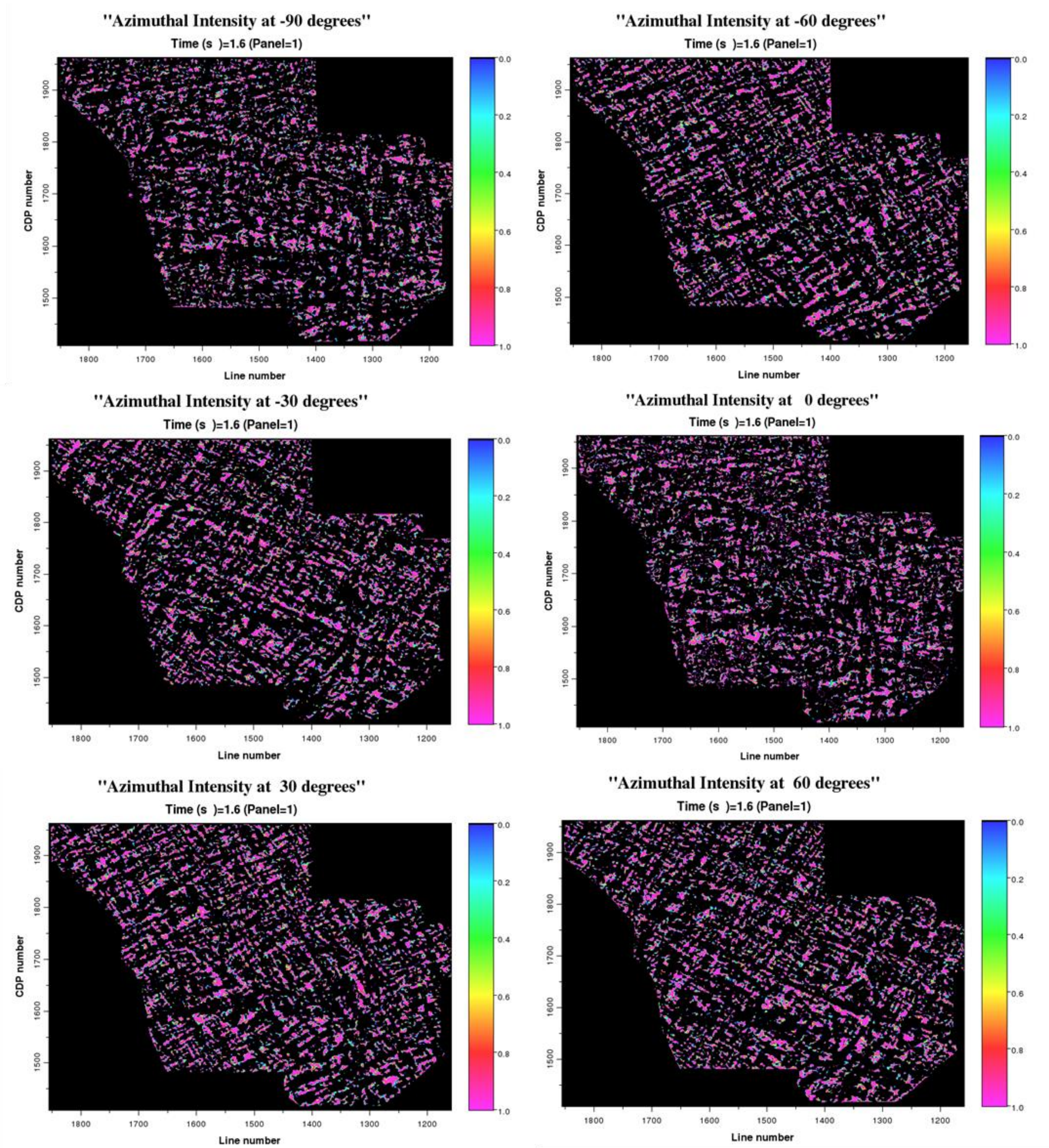
With this preamble, we now invoke the GUI azimuthal_fault_density:



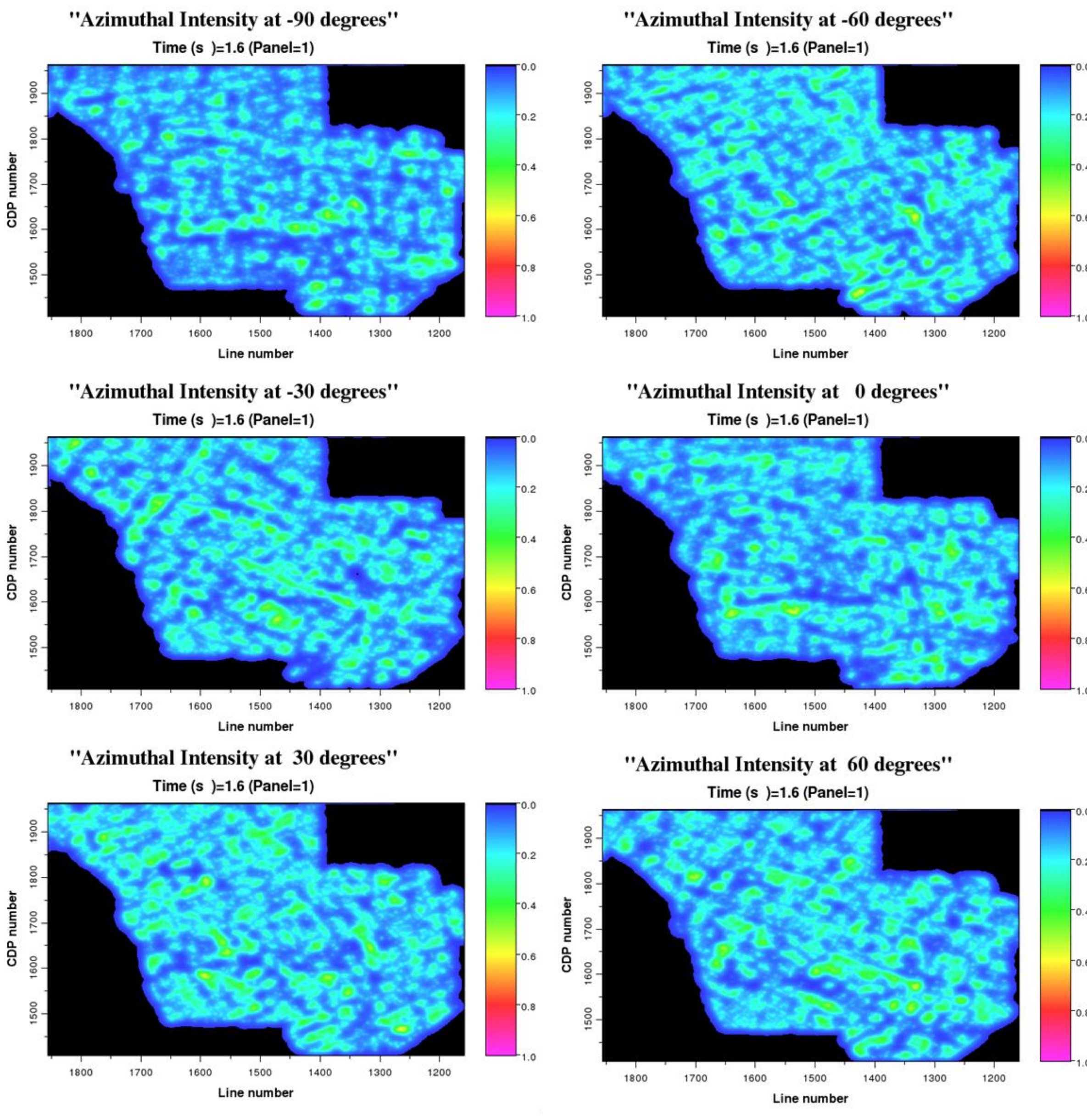
Here, I've entered (1) the lineament magnitude, *k2_aaspi_0.H*; (2) the lineament strike, *k2_ strike_aaspi_0.H*; (3) the default smoothing radius is *20*dcdp* or in this case, with *dcdp=25* ft, a value of 500 ft; (4) the default first and last strikes or azimuths to be analyzed are -90^0 and +90^0; (5) the azimuth increment of 30^0 will result in six output azimuthal volumes, centered about -90^0, -60^0, -30^0, 0^0, +30^0 and +60^0; (6) the taper of 15^0 and (7) the azimuth window width of 45^0 result in analysis windows that overlap as shown in the following diagram generated by plotting the file *azimuthal_filter.H* with **Graph** under *Display tools*. I've also entered the (8) minimum and (9) maximum color control points I used to skeletonize the most-negative principal curvature.


1.0
0.5
0.0
Filter Amplitude
-90⁰
-60⁰
-30⁰
0⁰
+30⁰
+60⁰
+90⁰
Strike

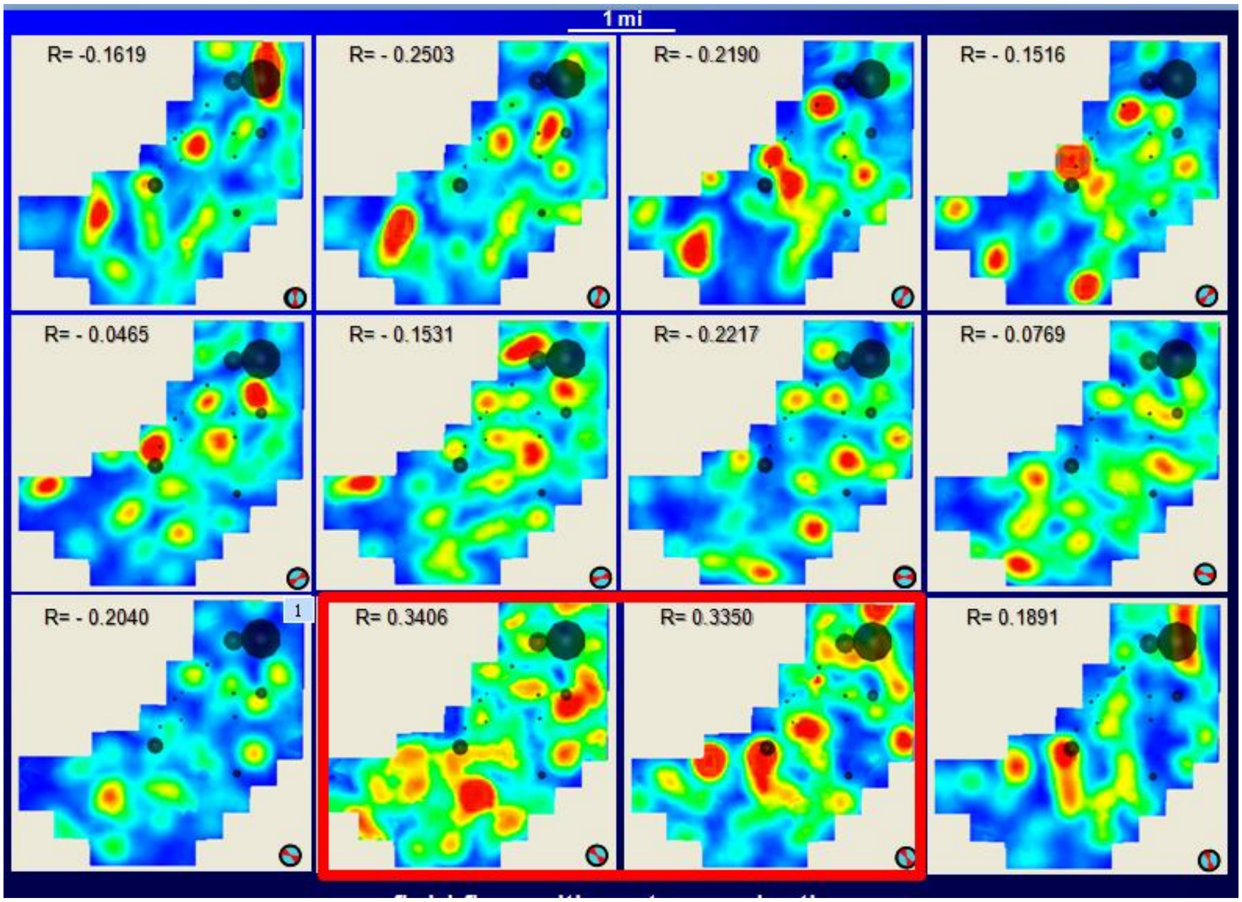
If the radius is limited to 25 ft (one bin), we obtain the following six azimuthally-limited images that look like simple pass-band images of the earlier figures.



Setting the radius to 500 ft (20 bins) smear the images, using the 1/r weighting function. These images can then be cross-correlated with the production data.



Guo et al. (2010) correlate the 5-year water production plotted as bubbles co-rendered with the azimuthally-limited volumes to obtain the following figure along the Mississippi Lime horizon:



The highest correlation occurs for the NW-SE lineaments, which concurs with the original measurements made by hand by Nissen et al. (2005, 2009).

References

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Hunt, L., S. Reynolds, T. Brown, S. Hadley, H. James, Jon Downton, and S. Chopra, 2010, Quantitative estimate of fracture density variations in the Nordegg with azimuthal AVO and curvature: a case study: The Leading Edge, **29**; 1122-1137.

Nissen, S. E., T. R. Carr, and K. J. Marfurt, 2005, Using new 3D seismic attributes to identify subtle fracture trends in mid-continent Mississippian carbonate reservoirs: AAPG Annual Meeting Abstracts.

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Singh, S. K.,H. Abu-Habbiel B. Khan, M. Akbar, A. Etchecopar and B. Montaron, 2008, Mapping fracture corridors in naturally fractured reservoirs: an example from Middle East carbonates: The First Break, **26**, 109-113.