

ESTIMATION OF FAULT CONNECTIVITY USING AN EDGE-DETECTING ATTRIBUTE AS PROXY FOR HYDRAULIC CONDUCTIVITY – PROGRAM fault_connectivity

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Overview

This programs assumes that the 3D volumetric result of an edge detecting attribute such as coherence is directly proportional to the hydraulic conductivity of the investigated region. Then the program uses the attribute as a proxy of conductivity to simulate the steady-state flow between two horizons. Mapping the flux between two horizons (or two time/depth slices) is sufficient to highlight the faults that connect both horizons (or time/depth slices). The disjoint faults will be suppressed showing a weaker flow response.

Computation Flow Chart

To compute the fault connectivity attributes, the inline and crossline dip components of the seismic amplitude data need to be computed first, via the program, **dip3d**. The second step is to generate the edge detecting attribute through **similarity3d**. The chosen attribute can be filtered through **fault_enhancement** and can also be submitted to **skeletonize3d**. Finally, **fault_connectivity** program will perform the potential and flow computations on the input hydraulic conductivity proxy, and outputs the potential hydraulic head and flow estimations. The user can also provide horizons as input to limit the computations.



How to run

Fault_connectivity program is located under the *Image Processing Attributes* -> fault_connectivity of the main aaspi_util window (Figure 1). The user needs to specify the input edge detecting attribute data, unique project name, and suffix (Figure 2). The *Primary parameters* are *Maximum number of iterations, Percent iteration change that signifies convergence, iteration weight, Head value condition (top), Head value condition (bottom), Conversion, Pseudo sand-shale conductivity and the check-box <i>Input is inversely proportional to conductivity.* The second tab shows options for the Horizon parameters (discussed under Define the operation window section). Under the *Parallelization parameters* tab, the user can specify mpi-related parameters, such as the number of processors (Figure 3). Click the *"Execute fault_connectivity"* button, on the

right lower corner, to run the program. The potential head volume has "head_" prefix, and the flux result file name has "flux_" prefix.

aaspi_util GUI - Post Stack Utilities (Release Date: October 6, 2017)		_		×
Eile Geometric Attributes Spectral Attributes Single Trace Attributes Formation Attributes Volumetric Classification	Image Processing			Help
Attribute Correlation Tools Display Tools Other Utilities Set AASPI Default Parameters	stat3d			
SECULA AACRU AASPI to SEGY AASPI to SEGY	kuwahara3d			-
format conversion (multiple files) (single file) AASPI QC Plotting AASPI Workflows Prestack Utilities	fault_enhancement			
SEGY to AASPI - Convert Poststack seismic volumes from SEGY to AASPI format	 skeletonize3d fault_connectivity 			
SEGY Header Utility : SEGY Header Utility	compute f	' ault connect	ivityd im	age
2D SEG-V Line rather than 2D Suprey 2				

Figure 1. The fault_connectivity program is under *Image Processing* dropdown of the aaspi_util window.

Primary parameters	Horizon parameters	Parallelization parameters
Maximum number of itera	tions:	2000
Percent iteration change	that signifies convergence:	0.005
Iteration weight:		0.6667
Pseudo sand-shale condu	uctivity?:	
Head value condition (top):	0
Head value condition (bot	ttom):	1000
Conversion velocity:		4000
Input is inversely proporti	onal to conductivity?:	
Reset		

Figure 2. Main windows of the **fault_connectivity** program. Browse for input file (edge detecting attribute / hydraulic conductivity proxy), and specify unique project name and suffix. *Maximum number of iterations, Percent iteration change that signifies convergence, iteration weight, Head value condition (top), Head value condition (bottom) and Conversion velocity are completed with average values that were used during development testing. The user can choose to change if appropriate. <i>Pseudo sand-shale conductivity* linearly converts the input to range from 0.01 to 1000 (useful when data might have negative or zero values). *Input is inversely proportional to conductivity* is an option for the program to assume low values of the input attribute to be proportional to high values of hydraulic conductivity and vice-versa (a fault has low values compared with the background in **outer_product_similarity** but the same fault has high values of **fault_probability**).

The Maximum number of iterations and Percent iteration change that signifies convergence are the parameters with higher impact on processing cost and significance of the results and are sensitive to input data. A higher number of iterations will yield a better image, but will take longer. The opposite can be said to the Percent iteration change that signifies convergence – a high number indicates that a rough approximation is good enough and the program will stop iterating sooner. The iteration weight is set to 2/3, a number traditionally optimal for the weighted Jacobi method used in the **fault_connectivity** program. With noisy data as an input, the

solution might diverge, and setting this value to 1.0 will require more iterations to approximate the solution, (making the whole process slower) but may (or may not) solve the divergence.

Primary parameters	Horizon paran	neters Pa	arallelization pa	arameters		
						Help - Parallelization
Use MPI: 🔽						
Processors per node: 4 Determine Maximum Processors on localhost						
Node list (separated by bla	inks):	localhost				
Build an LSF Script?		Do Not Run	Under LSF			
Build a PBS Script?		Do Not Run	Under PBS			
Build a SLURM Script?		Do Not Run	Under SLURM			
Maximum LSF run time (hrs):	10				
Maximum number of proce	ssors per node:	40				
Available batch processors	:	2				
		Determine (Optimum Numb	er of Batch I	Processors	
Batch Queue:						

Figure 3. *Parallelization parameters* tab: specifies the number of processors used for parallel processing.

Define the operation window

The user has the option to use either a constant time/depth window or a window defined by top and bottom horizons. The functionalities in defining the operation window are discussed below.

Primary parameters Horiz	on parameters Parallelization parameters
	Help - Horizon Definition
Start Time in s:	
End Time in s:	1.5 2
Use horizons as limits?	USE HORIZON Click to change to Use Time
Input upper horizon filename:	ao7520/justin/psvm3d_test/P_012_Petrel.dat Browse
(Choose Horizon Type Below:)	5 View horizon file Convert DOS to Unix
Input lower horizon filename:	ao7520/justin/psvm3d_test/P_014_Petrel.dat Browse 7
(Choose Horizon Type Below:)	8 View horizon file Convert DOS to Unix 9
Choose horizon type:	gridded (e.g. EarthVision) 10
Number of header lines to skip:	□ <u>11</u>
Total number of columns:	5 12
Column number of line_no:	1 13
Column number of cdp_no:	2 14
Column number of time or depth picks:	5 15
znull value (indicates missing pick)	999999
Vertical axis of picked surface?	Positive Down 17 Vertical Units of ms 18
(c) 2008-2017 AASPI for Linux - The	University of Oklahoma

Figure 4. Horizon parameters tab: specify horizon or time/depth windows.

Horizon definition

The horizon definition panel will look the same for almost all AASPI GUIs:

- 1. Start time (upper boundary) of the analysis window.
- 2. End time (lower boundary of the analysis window.
- **3.** Toggle that allows one to do the analysis between the top and bottom time slices described in 1 and 2 above, or alternatively between two imported horizons. If *USE HORIZON* is selected, all horizon related options will be enabled. If the horizons extend beyond the window limits defined in 1 and 2, the analysis window will be clipped.
- 4. Browse button to select the name of the upper (shallower) horizon.
- 5. Button that displays the horizon contents (see Figure 1).
- 6. Button to convert horizons from Windows to Linux format. If the files are generated from Windows based software (e.g. Petrel), they will have the annoying carriage return (^M) at the end of each line (Shown in Figure 1). Use these two buttons to delete those carriage returns. Note: This function depends on your Linux environment. If you do not have the program **dos2unix** it may not work. In these situations, the files may have been automatically converted to Linux and thus be properly read in.
- 7. Browse button to select the name of the lower (deeper) horizon.
- 8. Button that displays the horizon contents (see Figure 1).
- 9. Button to convert horizons from Windows to Linux format. (see 6 above).
- 10. Toggle that selects the horizon format. Currently gridded (e.g. EarthVision in Petrel) and interpolated (ASCII free format, e.g. SeisX) formats are supported. The gridded horizon are nodes of B-splines used in mapping and have no direct correlation to the seismic data survey. For example, gridded horizons may be computed simply from well tops. The x and y locations are aligned along north and east axes. In contrast, interpolated horizons are defined by *line_no, cdp_no (crossline_no)* and *time* triplets for each trace location. Examples of both formats are shown in Figure 1. If interpolated is selected, the user needs to manually define each column in the file.
- **11.** Number of header lines to skip in the *interpolated* horizon files.
- **12.** Total number of columns in the *interpolated* horizon files.
- **13.** Enter the column number containing the *line_no (inline_no)* of the interpolated data triplet.
- **14.** Enter the column number containing the *cdp_no* (*crossline_no*) of the interpolated data triplet.
- **15.** Enter the column number containing the *time* or *depth* value of the interpolated data triplet.
- 16. Znull value (indicate missing picks) in the horizon files.
- **17.** Toggle to choose between *Positive Down* and *Negative Down* for the horizon files (e.g. Petrel uses *Negative Down*).
- **18.** Choose the vertical units used to define the horizon files (either *s*, ms, *kft*, *ft*, *km*, or *m*).

X horizon file content)	Norizon file content	
Type: scattered data "M # Version: 6-M # Version: 6-M # Version: 6-M # Version: 6-M # Forescription: No description "M # Vertical, faults: Not, available "M # Vertical, faults: Not, available "M # Vertical, faults: Not, available "M # Z, fedit: "M # Vertical, faults: Not, available "M # Z, fedit: "M # Vertical, faults: Not, available "M # Z, fedit: "M # Vertical, faults: Not, available "M # Z, fedit: "M # Solowood 4393712 500000 1851 985962 500 4^M 1485455 000000 4393712 500000 1851 985962 500 4^M 1485455 000000 439373 500000 1851 1743408 409 6^M 1485455 000000 439373 500000 1851 1743454 500 6^M 1485455 000000 439373 500000 1851 174342 500 6^M 1485455 000000 439375 000000 1851 317874 499 7^M 1485455 000000 439375 00000 1851 317872 500 6^M 1485455 000000 4393750 00000 1851 317872 500 6^M 1485455 000000 4393750 00000 1851 318156 501 7^M 1485455 000000 4393750 00000 1851 381156 501 7^M 1485455 000000 4393750 00000 1851 381156 501 7^M 1485450 0000000 4393750 00000 1851 381156 501 7^M		1 2043410 510781 1239 705 ° M 1 2043520 510781 1242 7826 ° M 1 2043520 510781 1242 7826 ° M 1 2043503 510781 1242 7826 ° M 1 4 204370 510781 1242 7826 ° M 1 4 204370 510781 1244 7877 1 4 204470 510781 1248 9817 ° M 1 7 2044070 510781 1248 9817 ° M 1 2044105 510781 1248 9817 ° M 1 2044405 10781 1238 937 ° M 1 2044405 10781 1238 9587 ° M 1 14 2044705 10781 1237 9667 ° M 1 15 2044505 10781 1238 9034 ° M 1 2045405 10781 1238 9034 ° M 1 20454505 <td></td>	
	Close		lose

Figure 5. (left) A gridded horizon file (EarthVision format). (right) An interpolated horizon file with five columns (ASCII free format).

Mathematical Background

The program uses a finite-difference scheme to solve the steady-state three-dimensional saturated flow equation (1) assuming that the hydraulic conductivity is proportional to misalignment of the seismic reflectors (or inversely proportional to the seismic coherence attribute).

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial h}{\partial z} \right) = 0 \tag{1}$$

where K_x , K_y , and K_z are the conductivities of the media in the *x*, *y*, and *z* coordinate directions (LT-¹); *h* is the hydraulic head, a combination of potential energy due to elevation, and pressure energy (expressed in L units)

The flow between two adjacent voxels using the finite difference notation is giving by equation 2.

$$Q_{i+0.5,j,k} = KX_{i+0.5,j,k}\Delta z * \Delta y \frac{h_{i+1,j,k} - h_{i,j,k}}{\Delta x}$$
(2),

where $Q_{i+0.5,j,k}$ is the volumetric flow rate through the face between voxels i,j,k and i+1,j,k (with units L³T⁻¹); $KX_{i+0.5,j,k}$ is the hydraulic conductivity along the row between nodes voxels i,j,k and i+1,j,k (with units LT⁻¹); $\Delta x, \Delta y, \Delta z$ are the distance between nodes in the x, y, and z coordinate directions. These equations are arranged to for a linear system that is iteratively solved using the weighted Jacobi method. More details in Pires de Lima (2017).

Example: Syneresis and polygonal faulting (New Zealand)

The Great South Basin (GSB) is a highly faulted New Zealand Basin and which also shows the presence of syneresis. Morley et al. (2017) describes the syneresis as exhibiting a honeycomb-shaped morphology, with the structures approximately 200 m in diameter. The proxy for hydraulic conductivity input (Figure 6) was computed by applying a directional Laplacian of a

Gaussian (dLoG) filter (Machado et al., 2016) to an outer product similarity volume (Pires de Lima and Marfurt, 2017). This volume was then used as input to the **fault_connectivity** program.



Figure 6. (a) Time-slice and (b,c) cross-section of the dLoG filtered coherence. The purple triangle and purple ellipse point to depth restricted (not connected) syneresis formations. The red arrow points to a fault that extends from top to bottom (connected) of the analyzed volume.



Figure 7. (a) Time-slice and (b,c) cross-section of the computed flow. The purple triangle and purple ellipse point to areas that are not connected from t=1.2 s to t=2.2 s. The red arrow points to connected faults that became more visible on the flow computation results.

References

- Morley, C. K., A. Maczak, T. Rungprom, J. Ghosh, J.A. Cartwright, C. Bertonib, N. Panpichityota, 2017, New style of honeycomb structures revealed on 3D seismic data indicate widespread diagenesis offshore Great South Basin, New Zealand: Marine and Petroleum Geology, 86, 140-154.
- Pires de Lima, R. A. "Linking image processing and numerical modeling to identify potential geohazards", Master's thesis, The University of Oklahoma, 2017, <u>http://hdl.handle.net/11244/51902</u>.
- Pires de Lima, R. A. and K. Marfurt, 2017, Quantifying fault connectivity drilling hazards through simple flow computations: SEG Technical Program Expanded Abstracts, <u>https://doi.org/10.1190/segam2017-17786445.1</u>.