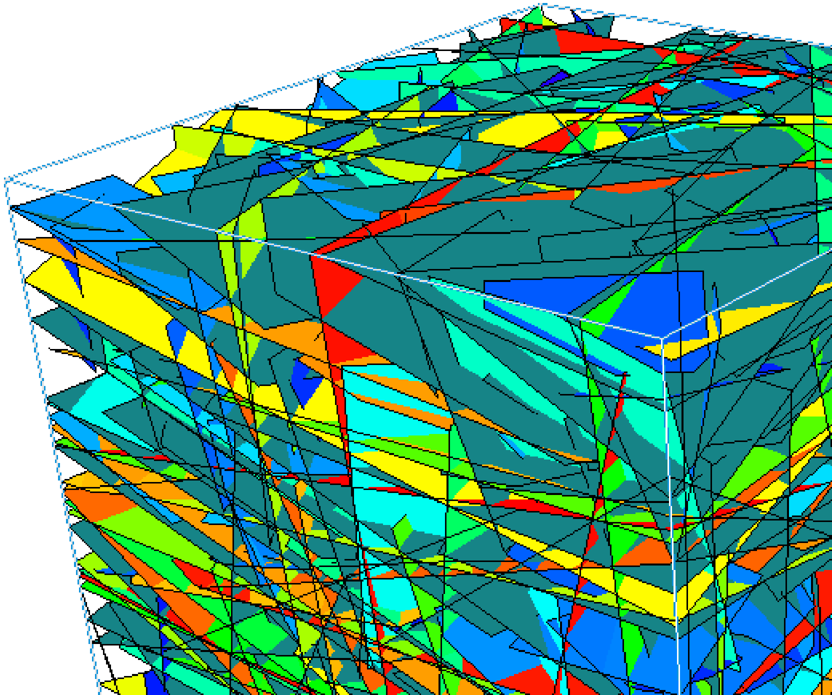
Derivation of Basic Fracture Properties



Contents

- Constraining your fracture model
- Key Fracture Properties
- Defining Fracture Orientation Distribution
- Defining Fracture Size Distribution
- Defining Fracture Intensity
- Defining Fracture Transmissivity

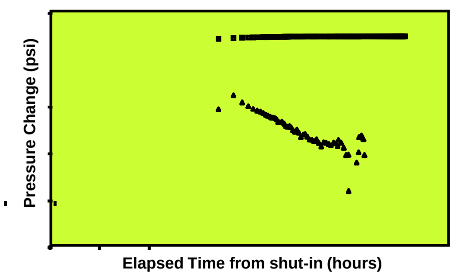
Constraining your Fracture model

- Fracture models can be constrained by using a range of data sources/types such as:
  - <u>1D Data</u>. Borehole/scan line Data (used for defining fracture orientation, intensity, aperture, mechanical zonation)
  - <u>2D Data</u>. Face, Bench, Outcrop Mapping, Photogrammetry (used for defining orientation, intensity, termination %, length scale, mechanical zonation)
  - <u>3D Data</u>. Geocellular input from structural restoration, 3D seismic data (e.g. velocity, coherency), curvature analysis etc

Outcrops

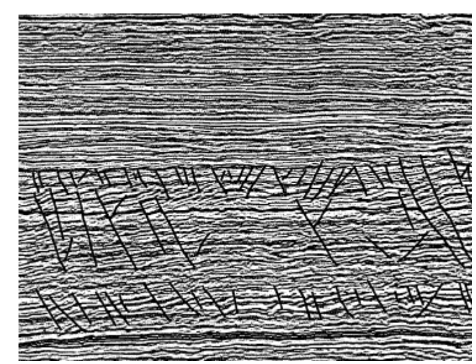
Image Logs

Well Test Data



Core

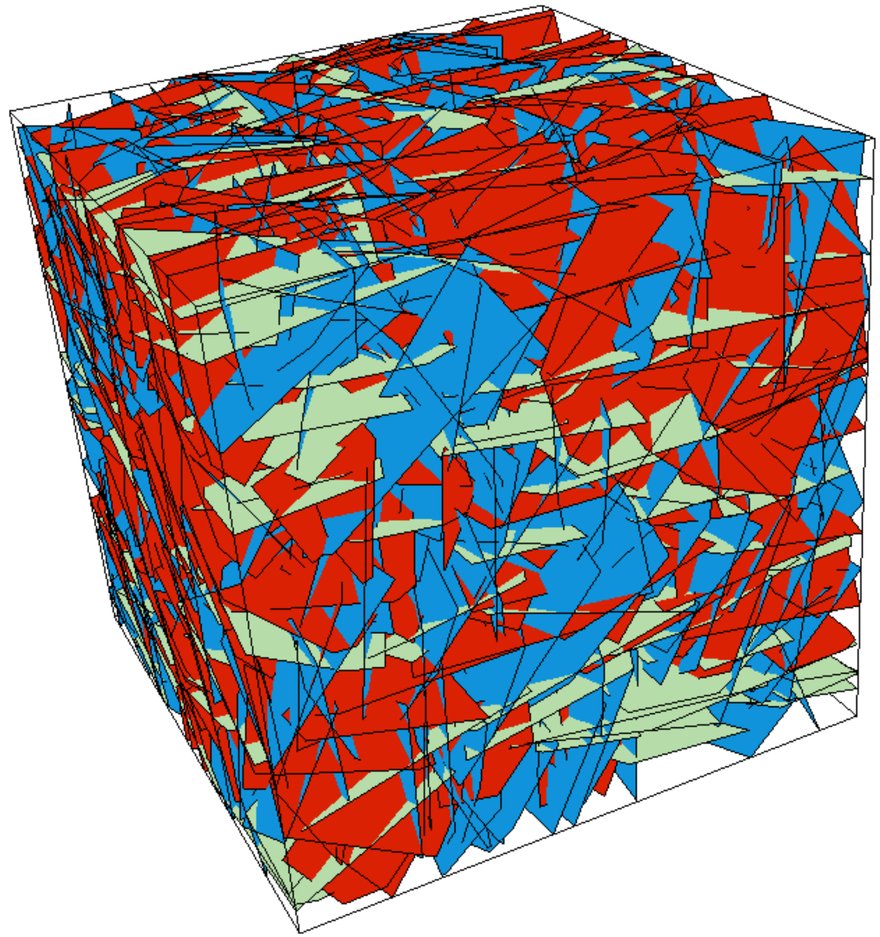
Seismic Sections



Key properties to be defined

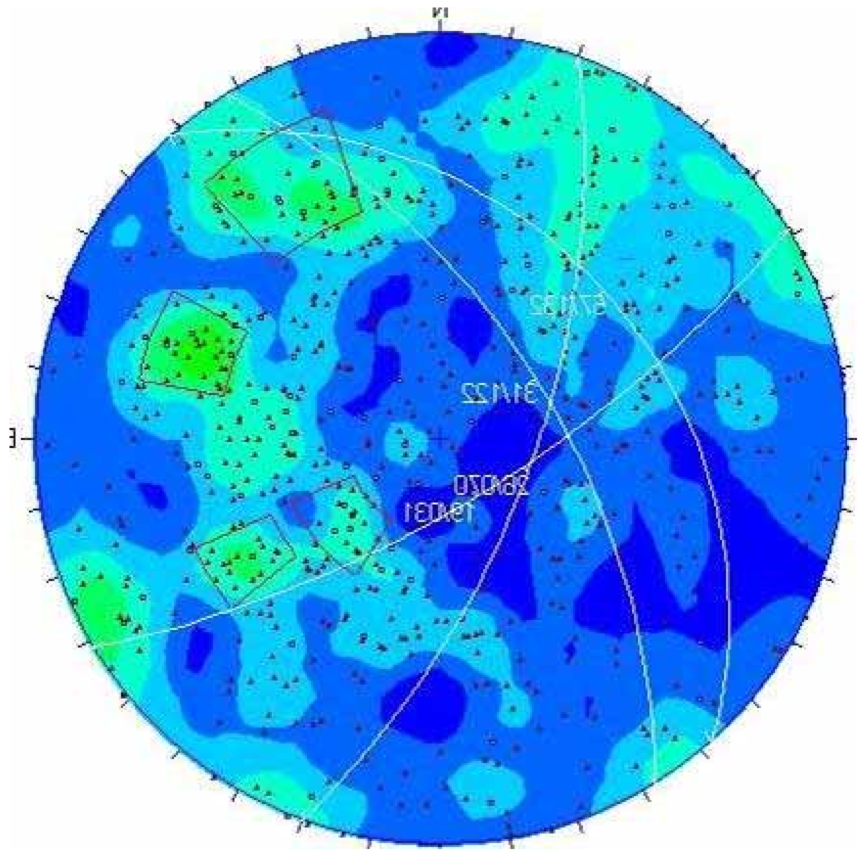
The 3 key properties to be defined for a DFN model are:

- –Fracture Orientation
- –Fracture Size
- –Fracture Intensity
- –For flow:
  - Fracture Transmissivity
  - Fracture Aperture



Defining Orientation Distributions

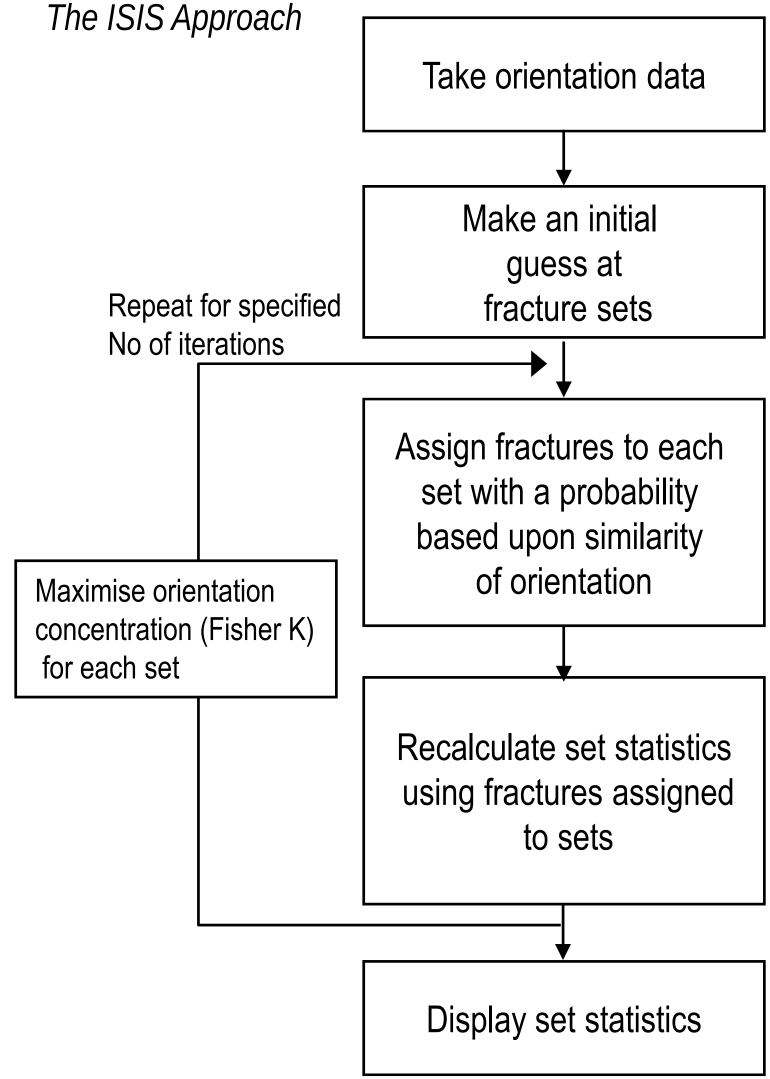
- Conventional “DIPS” orientation analysis concentrates upon the main clusters of orientation data rather than the whole distribution
- This can result in as little as 50% of the data being categorised
- DFN based orientation analysis seeks to fully define 100% of the data into their appropriate sets based upon a range of differing orientation distributions



Fracture Set Identification Approach

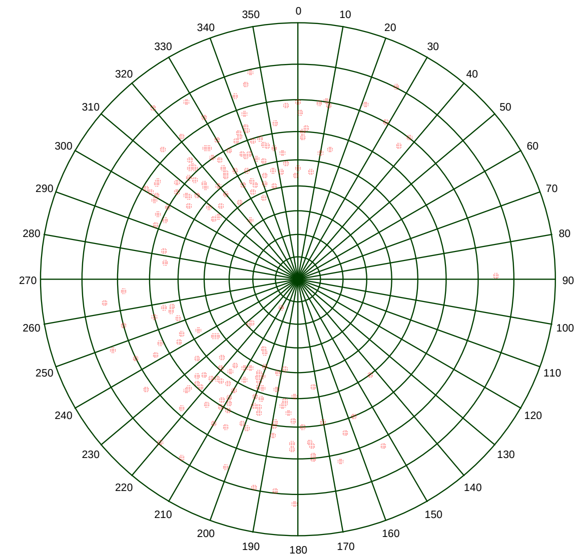
- Fractures sets are defined as groups of fractures with similar orientations
- FracMan uses an interactive set identification approach (ISIS) to determine the set orientation statistics
- In the future this will include other properties such as infilling, size, termination,….
- ISIS uses an adaptive, probabilistic, pattern recognition algorithm
- ISIS optimises the membership of fracture sets to maximise the concentration for each set

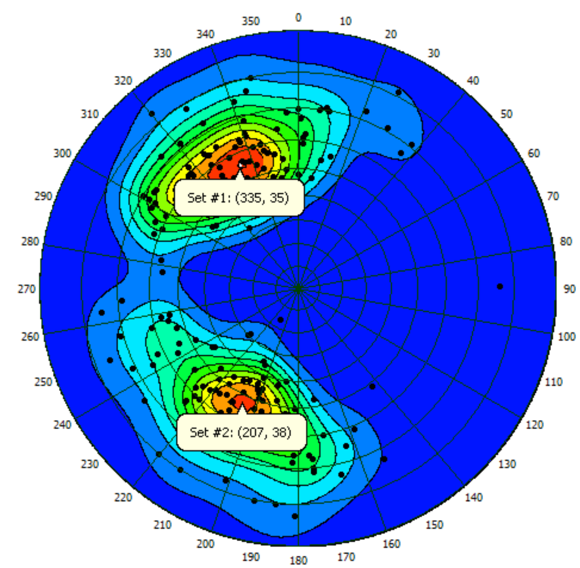
The ISIS Approach



Simple Example

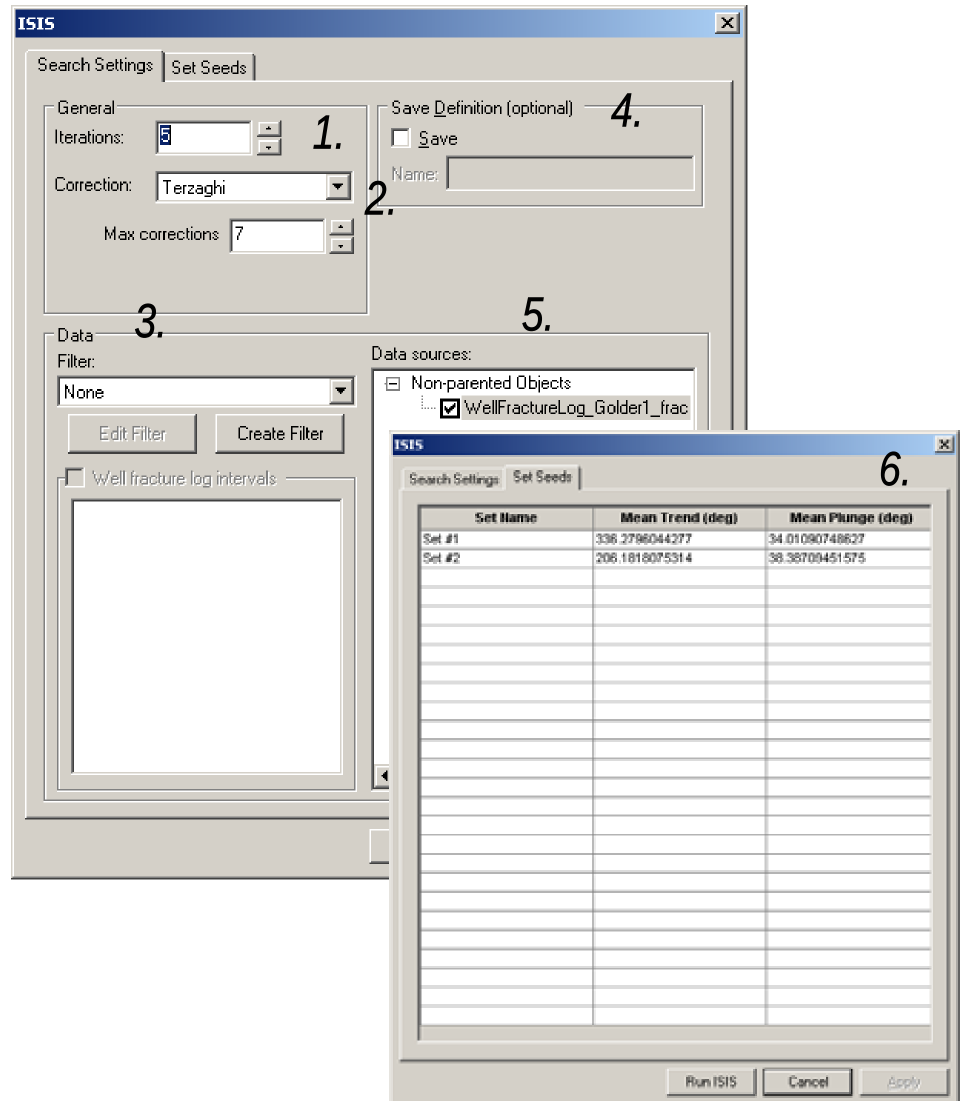
- Consider this example with two clear fracture sets
- Display the data on a stereoplot (e.g Menu>Fracture>Stereoplot)
- Contour the stereoplot to highlight the main fracture clusters
- Left Click on the centres of those clusters – FracMan will add Set No Flags with orientation
- Right click on stereoplot and launch ISIS





ISIS Controls

1. Select No of iterations. Recommended No is 50
2. Apply Terzaghi correction if required
3. Apply a fracture filter if required
4. Save the fracture definition for later reuse
5. Edit data sources to use
6. On the “Set Seeds” tab, view the starting orientations defined from the stereoplot



ISIS Statistics

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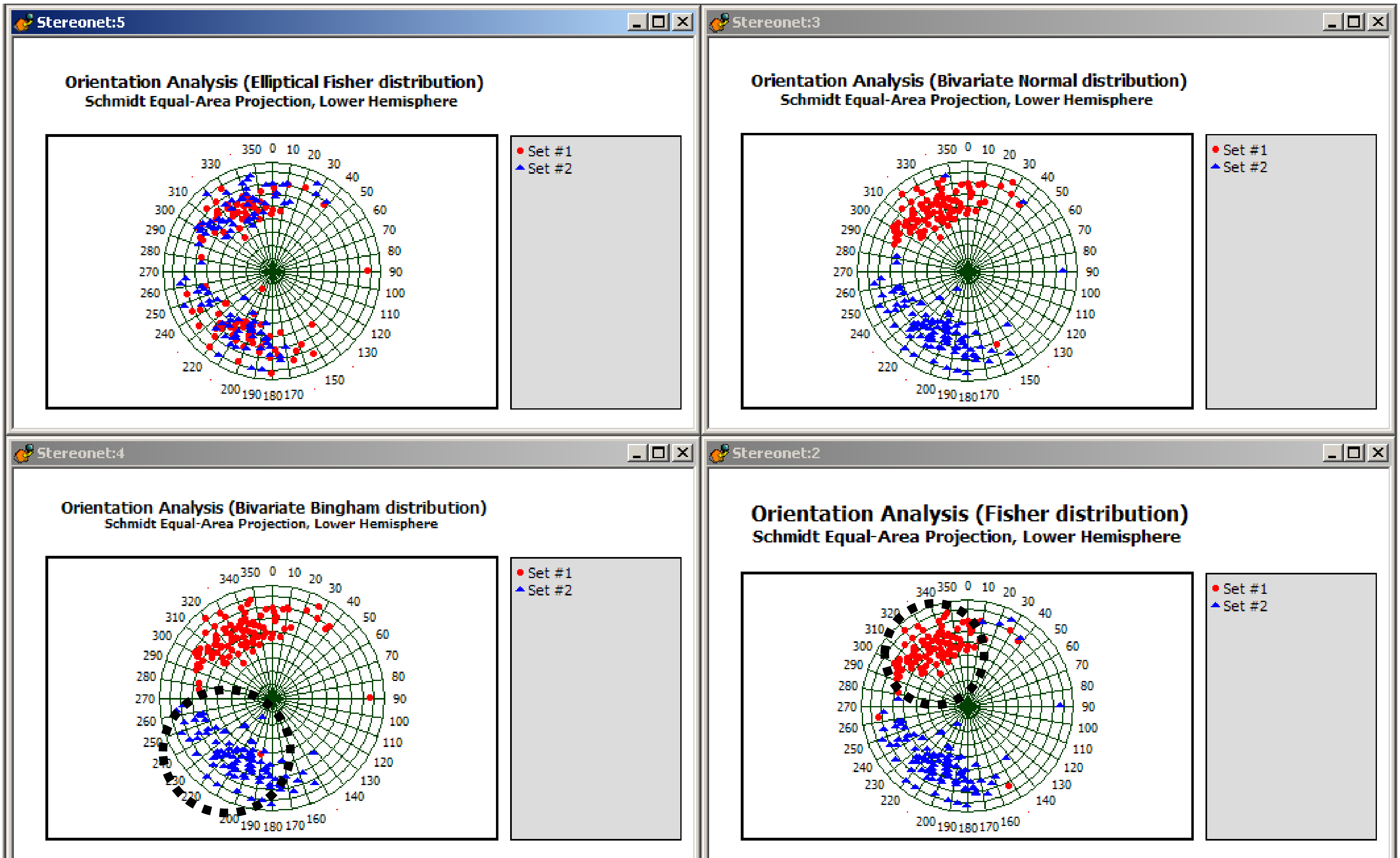
- ISIS automatically calculates the goodness of fit for the identified fracture sets for 4 different orientation distributions:
  - Fisher
  - Bivariate Normal
  - Bivariate Bingham
  - Eliptical Fisher
- Statistics summary show that Set 1 best described with a Fisher distribution and Set 2 with a Bivariate Bingham

	Fisher distribution	Bivariate Normal distribution	Bivariate Bingham distribution	Elliptical Fisher distribution
"Set #1"				
Fracture Count	99	99	104	99
Relative Intensity	49.5 %	49.5 %	52 %	49.5 %
Mean Pole	331.000, 32.817	333.707, 30.364	332.282, 33.160	349.702, 9.935
Major Axis	151.000, 57.183	153.588, 57.393	150.548, 56.828	247.491, 50.373
Minor Axis	61.000, 0.000	63.588, 0.000	241.763, 0.794	87.534, 37.880
K1	13.1967	22.9929	-14.8792	6.407
K2		11.4464	-4.66455	3.26833
K12		-0.0863723		
Kolmogorov-Smirnov	0.0644103	0.0944444	0.0842692	0.0827731
K_S Probability	95.371 %	61.9103 %	73.7404 %	77.3963 %
"Set #2"				
Fracture Count	101	101	96	101
Relative Intensity	50.5 %	50.5 %	48 %	50.5 %
Mean Pole	209.153, 33.703	210.634, 31.416	207.947, 35.593	340.215, 21.447
Major Axis	29.153, 56.297	30.155, 55.191	35.144, 54.192	230.335, 40.881
Minor Axis	299.153, 0.000	300.155, 0.000	300.396, 3.417	90.505, 41.436
K1	9.22459	27.973	-14.418	4.12984
K2		14.2317	-4.52339	2.45417
K12		0.00416297		
Kolmogorov-Smirnov	0.114468	0.0709571	0.058	0.135318
K_S Probability	36.4761 %	90.0495 %	98.4389 %	18.6929 %
Total Fracture Count	200	200	200	200
Data Pedigree				
Filter	-			
Data Source:	WellFractureLog_Golder1_frac			
Well Log Intervals:	-			

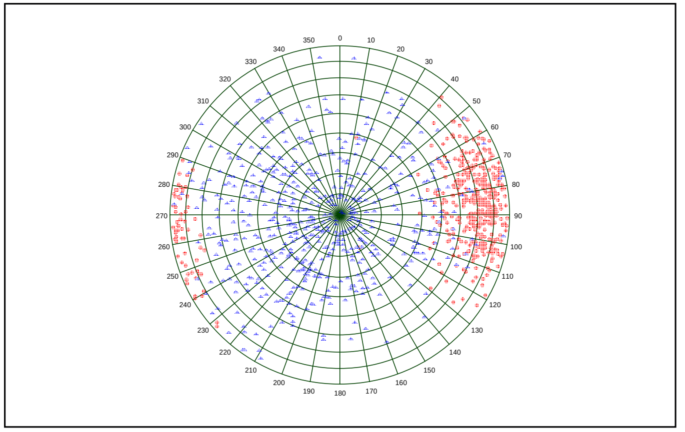
Best Fit Distributions



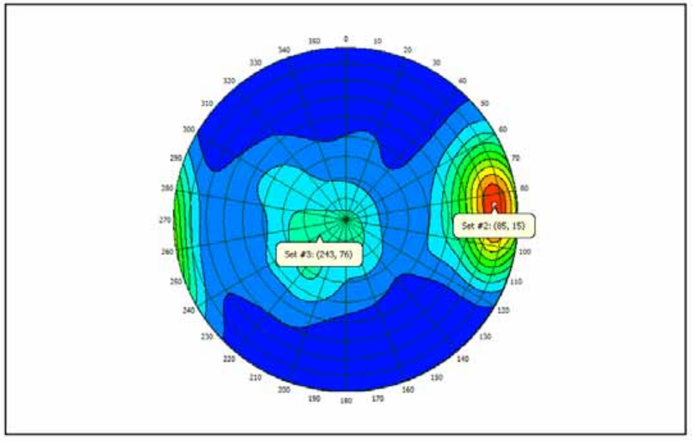
More complicated example

- 2 fracture sets (Fisher Distribution) generated in FracMan with reasonably high dispersion
  - Set 1: 085/15 k=15
  - Set 2: 250/75 k= 5
- Pole centres estimated by clicking on the stereoplot
- ISIS predicts the following distributions:
  - Set 1: 085/15 k=17
  - Set 2: 255/77 k= 4

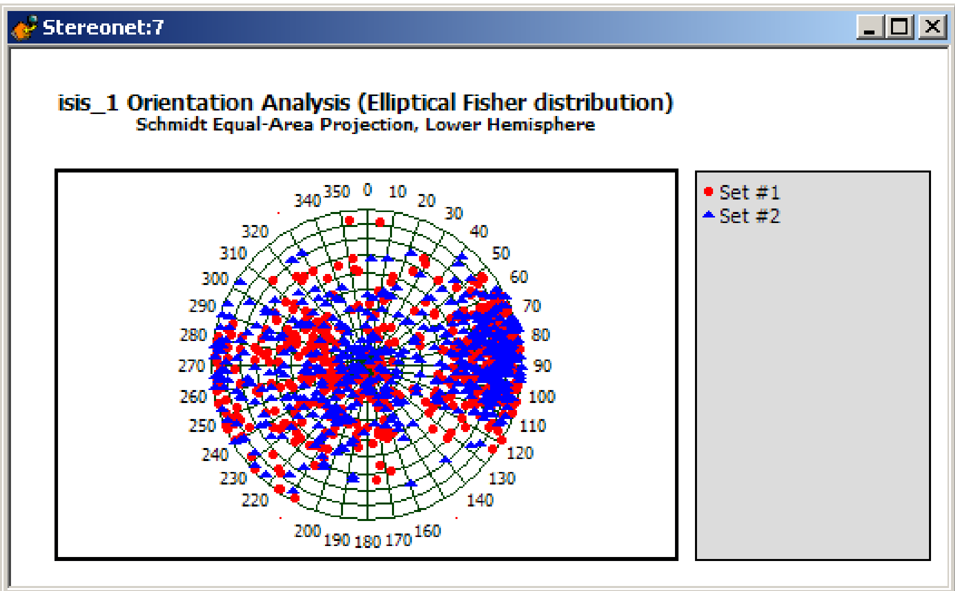
Orientation Analysis (Fisher distribution)
Schmidt Equal-Area Projection, Lower Hemisphere

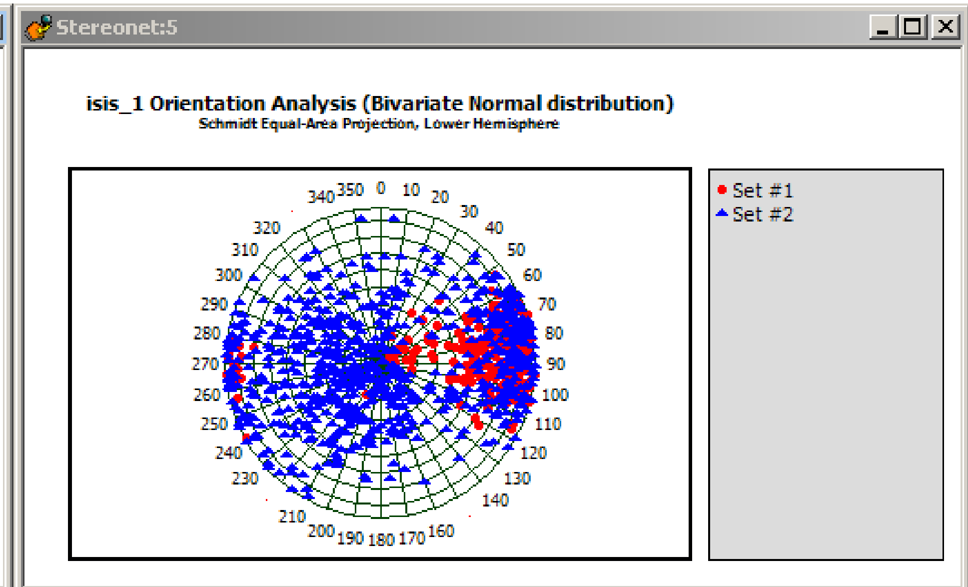


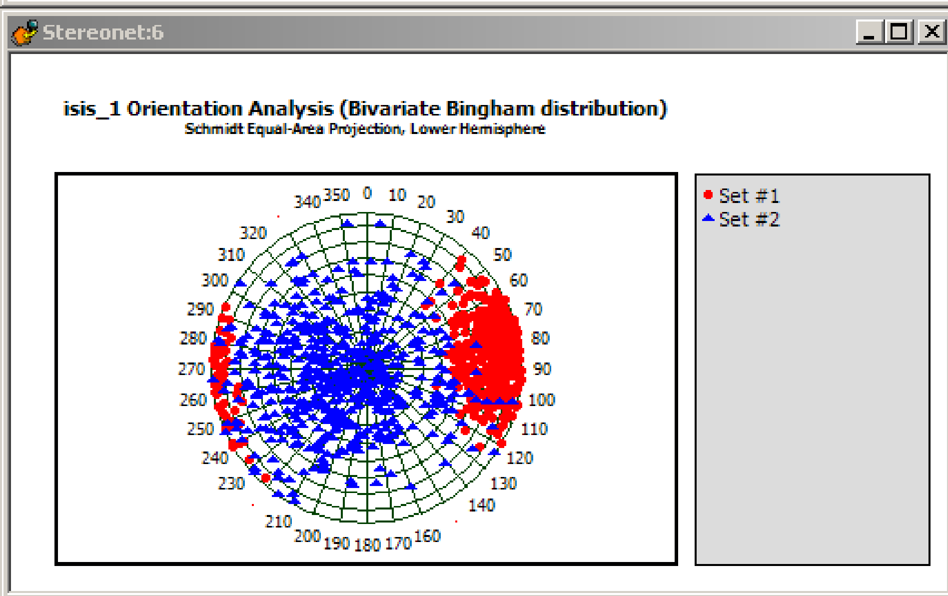
Fracture Pole Orientation
Schmidt Equal-Area Projection, Lower Hemisphere

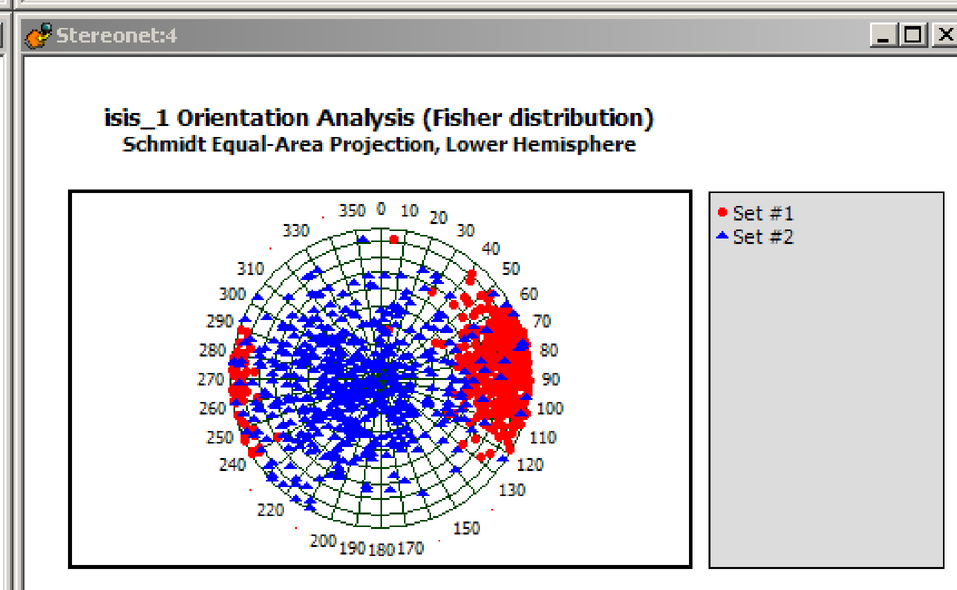


Best fit distributions





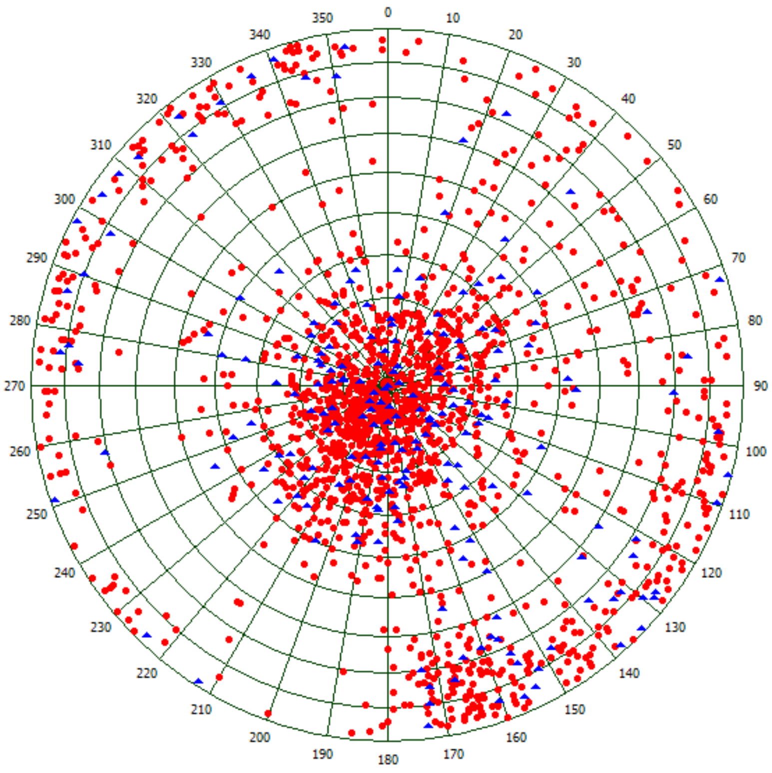




Bootstrapping

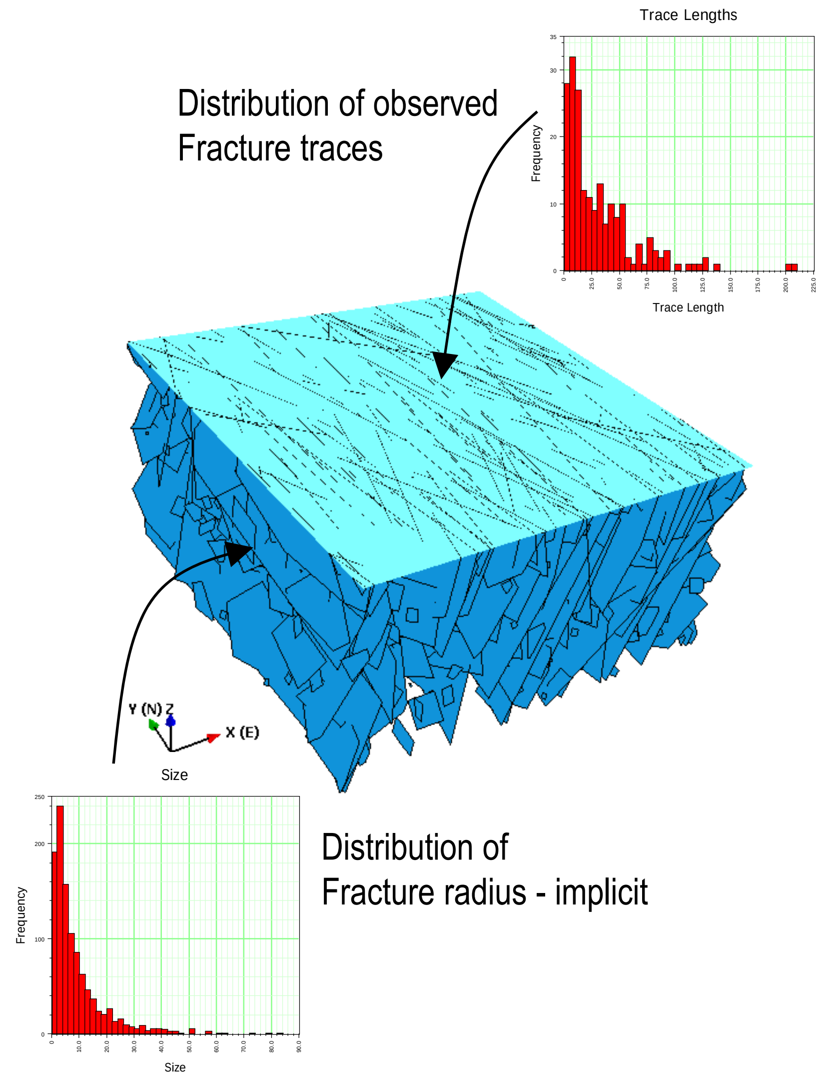
- When the data are highly dispersed and fracture set definition hard, use *Bootstrapping.*
- This is a statistical method based upon multiple random sampling with replacement from an original sample to create a pseudo-replicate sample of fracture orientations.
- Basically use your data to produce a similar but slightly different fracture population

Red dot – Field Data
Blue Triangles – simulation



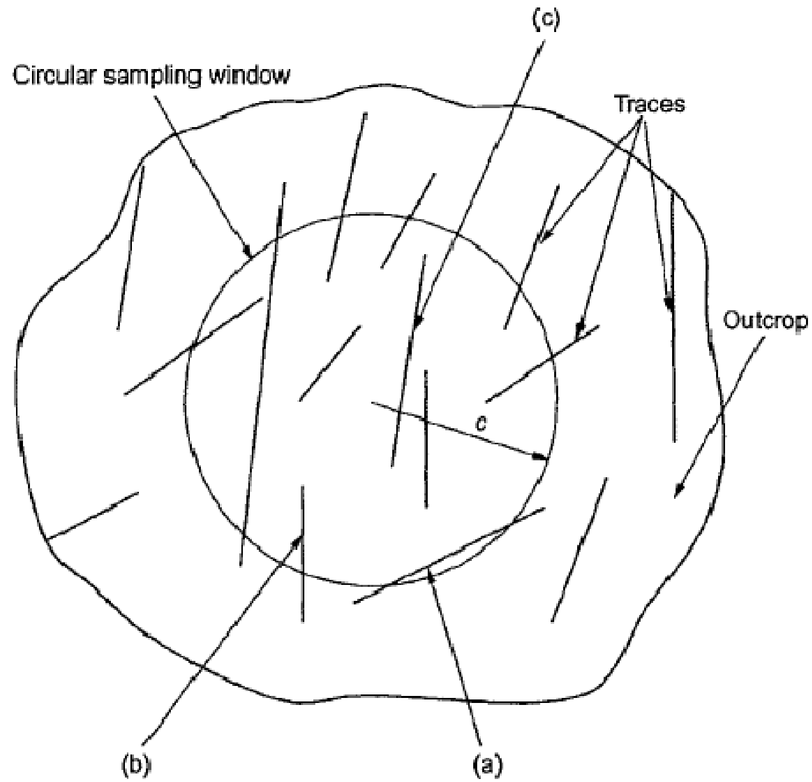
Defining Size Distributions

- Defining fracture size has always been problematic
- Fracture traces observed on tunnel walls or benchfaces not actually fracture size
- They are a Cord to a “disc”
- Need to determine the underlying fracture size distribution that results in the observed trace length distribution
- There are a number of ways that can be done:
  - Analytical Method
  - Scaling Laws
  - Manual Simulated Sampling
  - Automated Simulated Sampling



Analytical Method

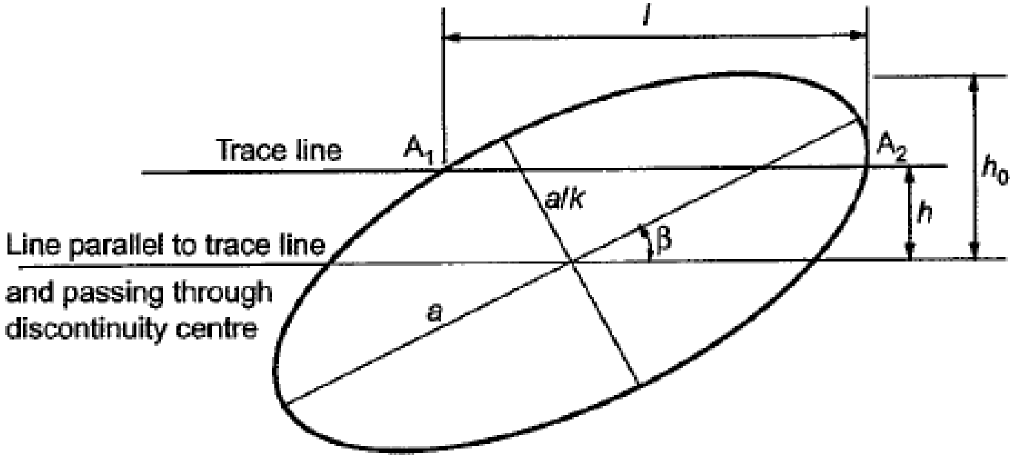
- Zhang, Einstein, and Dershowitz (2002) derived a method for taking the distribution of trace lengths observed in a circular window and deriving the distribution of fracture radius
- It will work on a bench or tunnel wall but the aspect ratio (i.e. height to width needs to remsin close to 1)
- You need to be aware of the type of censoring that is occuring when measuring trace length



<u>Censoring Types</u>

- Both ends censored
- One end censored
- Both ends visible

Elliptical Fracture Size and Shape



- Trace Length
  - Mean μ_L
  - Standard Deviation σ_L
- Fracture Radius
  - Mean μ_a
  - Standard Deviation σ_a
- Elliptical Fractures
  - Ratio of major axis to minor axis k
  - k is one for circular fractures
- Fracture Orientation Relative to trace line
  - Angle β relative to major axis

After Zhang, Einstein, and Dershowitz (2002)

Convert Trace Length to Radius

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Table 1. Expressions for determining μ_a and σ_a from μ_l and σ_l

Distribution form of $g(a)$	μ_a	$(\sigma_a)^2$
Log-normal	$\dfrac{128(\mu_l)^3}{3\pi^3 M[(\mu_l)^2+(\sigma_l)^2]}$	$\dfrac{1536\pi^2[(\mu_l)^2+(\sigma_l)^2](\mu_l)^4-128^2(\mu_l)^6}{9\pi^6 M^2[(\mu_l)^2+(\sigma_l)^2]^2}$
Negative exponential	$\dfrac{2}{\pi M}\mu_l$	$\left[\dfrac{2}{\pi M}\mu_l\right]^2$
Gamma	$\dfrac{64(\mu_l)^2-3\pi^2[(\mu_l)^2+(\sigma_l)^2]}{8\pi M\mu_l}$	$\dfrac{\{64(\mu_l)^2-3\pi^2[(\mu_l)^2+(\sigma_l)^2]\}\times\{3\pi^2[(\mu_l)^2+(\sigma_l)^2]-32(\mu_l)^2\}}{64\pi^2 M^2(\mu_l)^2}$

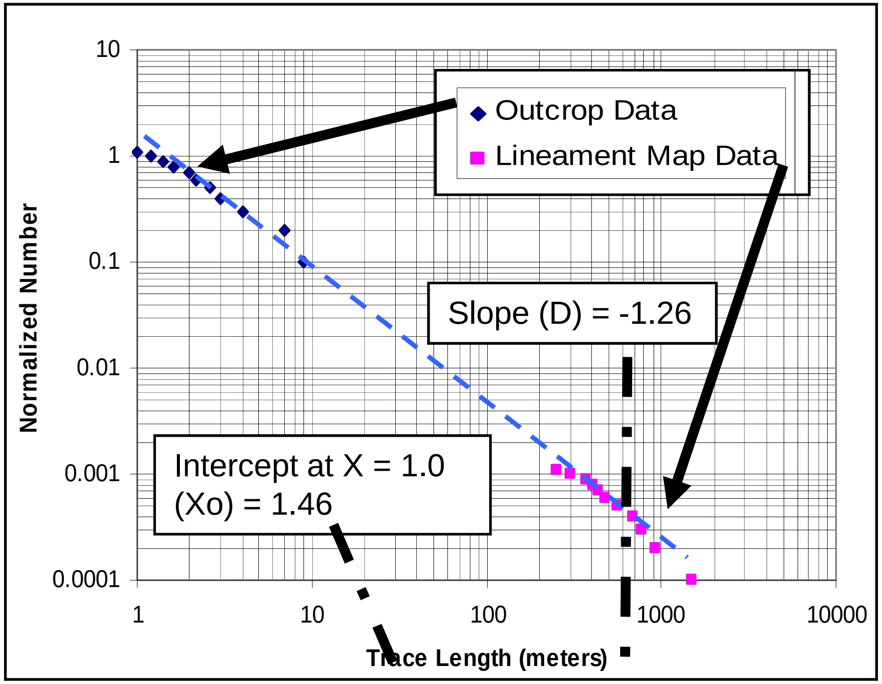
$$M=\frac{\sqrt{\tan^2\beta+1}}{\sqrt{k^2\tan^2\beta+1}}$$

Assume equal to one for circular fractures

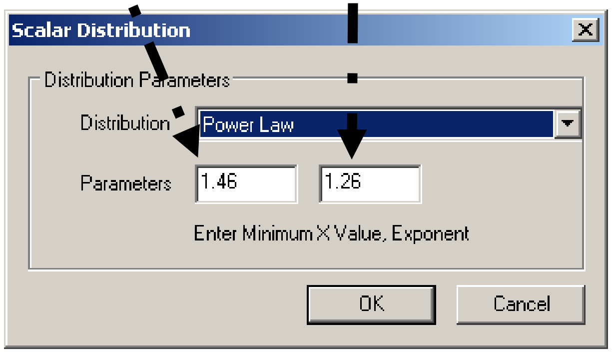
After Zhang, Einstein, and Dershowitz (2002)

Scaling Laws

- Field studies have shown that in many rock masses, fractures and faults scale according to power laws
- By taking fault/fracture length data taken at different scales (e.g. regional, mine scale or district faults & fractures), power law function can often be fitted
- The data have to be normalised with respect to the area of the particular sample
- This is not a universal solution and care needed to not mix up data types (e.g. faults and joints)



Power law function directly input to FracMan



Scaling Laws - Worked Example

<u>Steps</u>

- Take raw trace length data
- Sort into order from smallest to biggest
- Calculate the cumulative number greater than or equal to the trace
- normalize this cumulative number by the area of the outcrop or map
- Plot normalised number (y axis) against trace length (x axis) for both trace data and map data

Trace Map Data

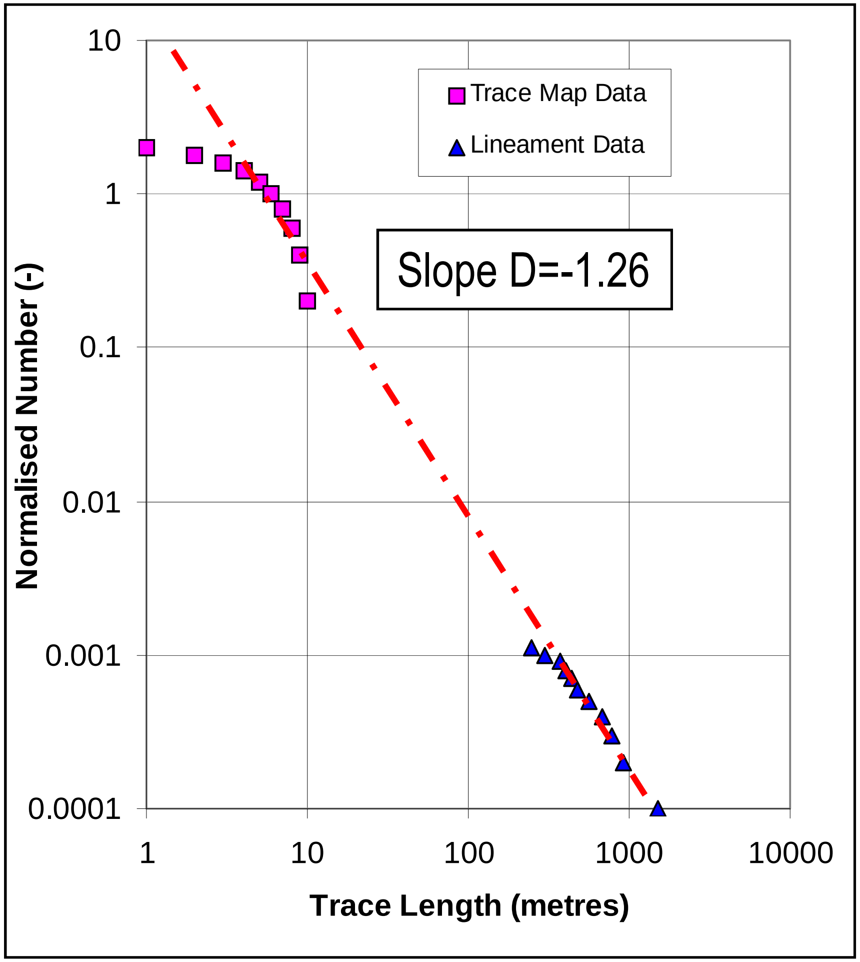
Trace Length [1]	Sorted Trace Length [2]	Cumulative Number [3]	Normalised Cumulative Number [4]
1.2	0.6	10	2
2.1	1.1	9	1.8
3.5	1.2	8	1.6
0.6	1.2	7	1.4
1.1	2.1	6	1.2
4.5	2.1	5	1
2.1	3.2	4	0.8
3.2	3.5	3	0.6
3.6	3.6	2	0.4
1.2	4.5	1	0.2

Area = 5 m2

Lineament Data

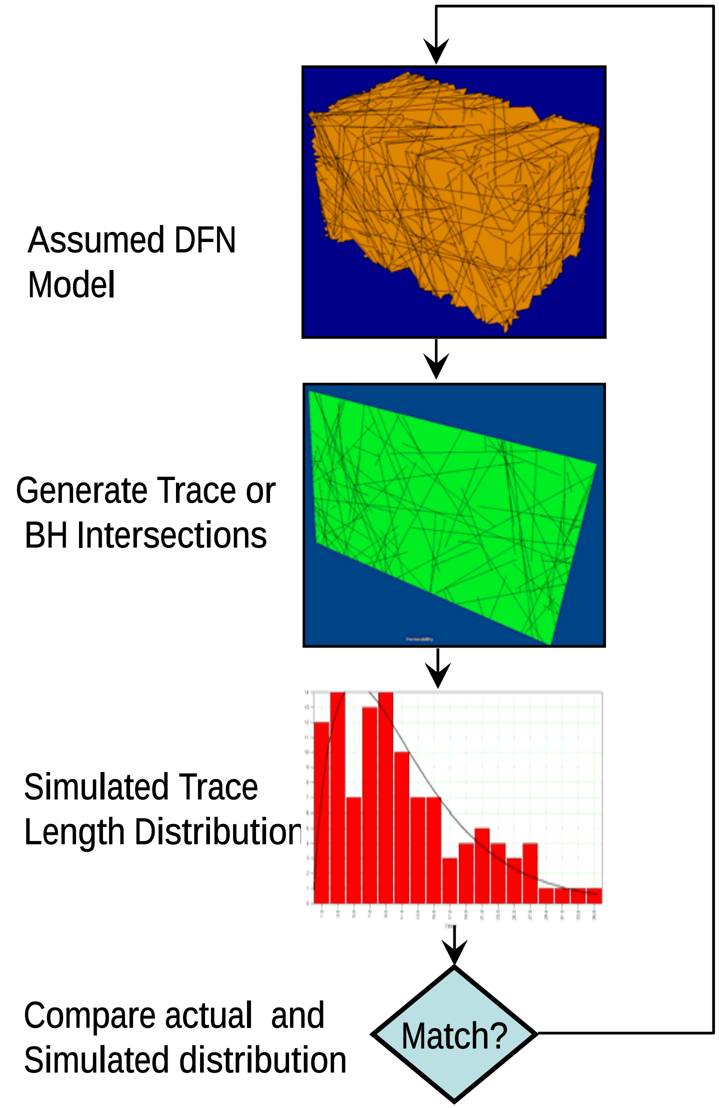
Trace Length	Sorted Trace Length	Cumulative Number	Normalised Cumulative Number
250	250	11	0.0011
1500	300	10	0.001
920	370	9	0.0009
300	410	8	0.0008
410	440	7	0.0007
480	480	6	0.0006
690	560	5	0.0005
560	690	4	0.0004
780	780	3	0.0003
440	920	2	0.0002
370	1500	1	0.0001

Area = 10000 m2



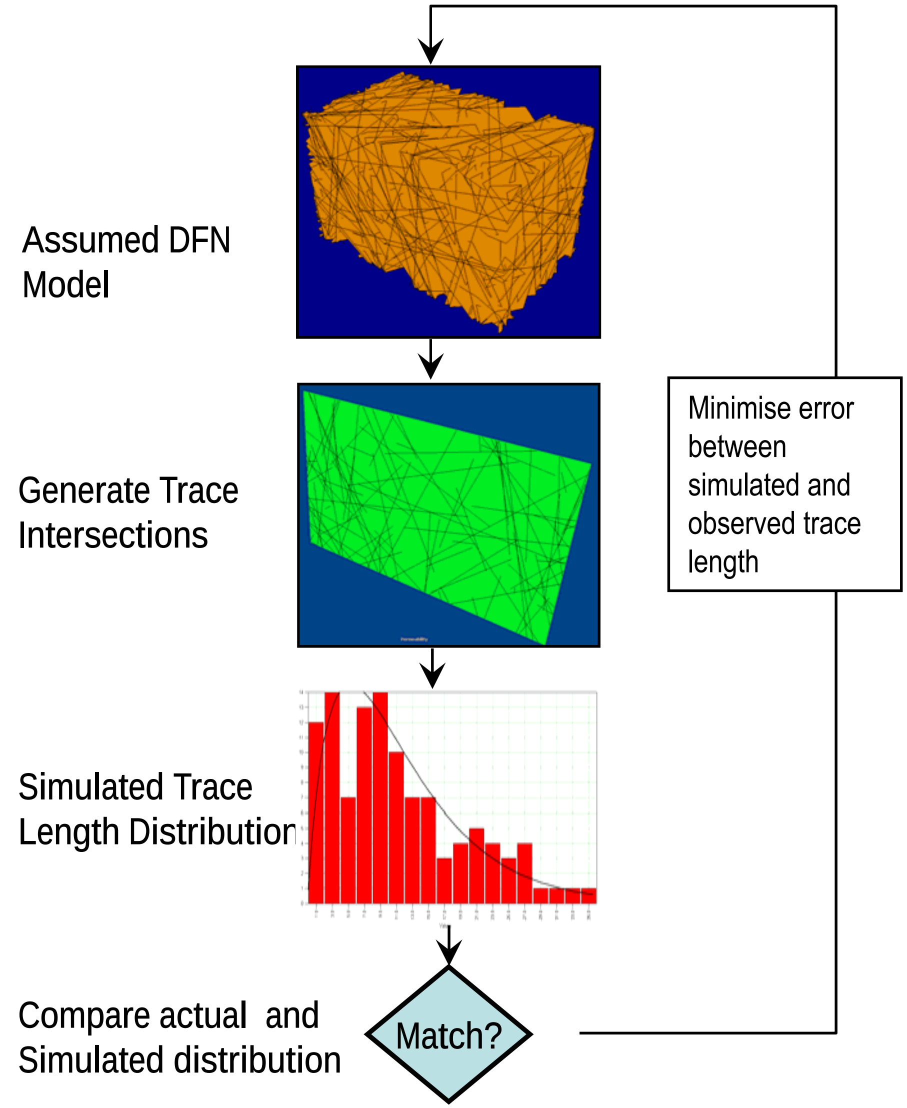
Manual Simulated Sampling

- Make a guess on the type of distribution (e.g. lognormal, exponential), and for the values for the parameters that describe the distribution (e.g. mean size, standard deviation of size)
- Generate a DFN model with these characteristics
- Sample the model with a borehole or plane
- Compare trace length statistics in simulated borehole or plane with measured data
- Change parameters until satisfactory match is achieved



Automated Simulated Sampling

- Coming late 2008 release, automated fracture size derivation
- FracMan will use simulated annealing technique to automatically optimise the match between estimated fracture size distribution and observed trace length distribution
- This will result provide faster and better constrained estimates of the underlying fracture size distribution

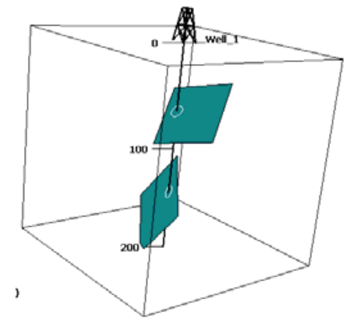


Determining Fracture Intensity

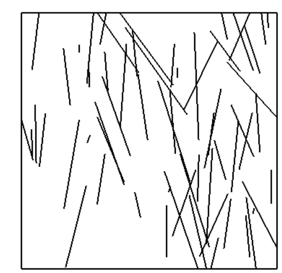
- The degree of fracturing means different things to different people
- There are many ways of defining fracture intensity, e.g:
  - Fracture intensity
  - Fracture density
  - Fracture Frequency
- They are all subjected to high degrees of bias and are highly directional

DFN based Fracture Intensity System

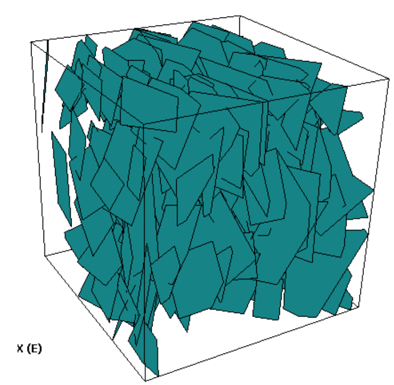
- The "Pxy" System of Fracture Intensity
- Two subscripts
  - x denotes sampling space dimension i.e. 1D line, 2D surface, 3D volume)
  - y denotes sample measure dimension (0D count, 1D line, 2D plane, 3D volume)



1D borehole or scan line



2D trace map



3D Volume

Fracture Density, Intensity & Porosity

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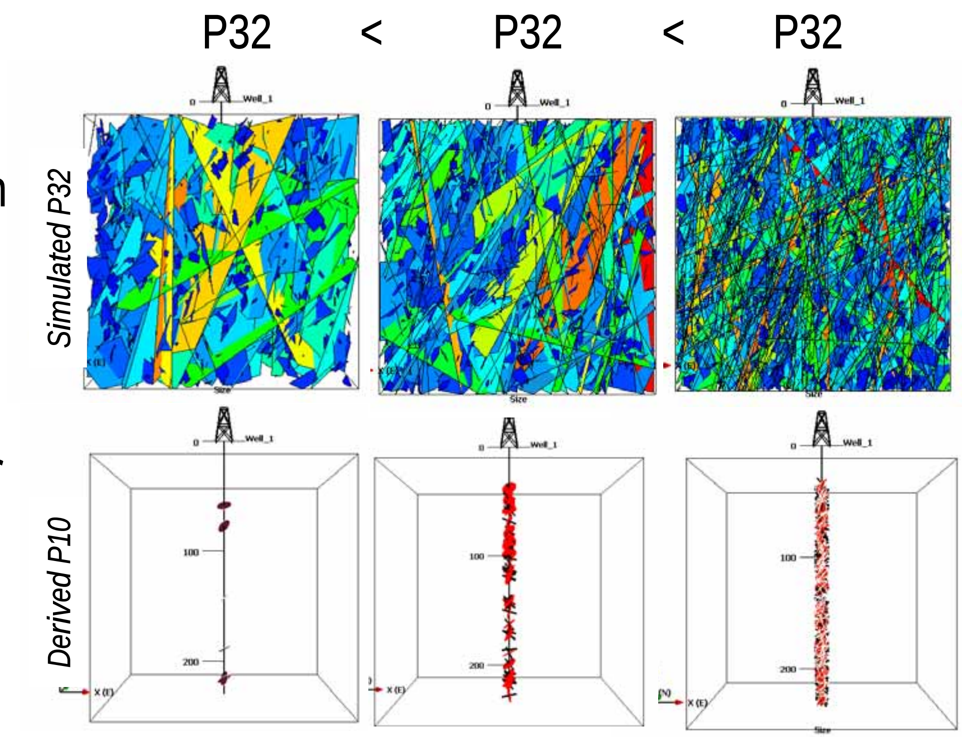
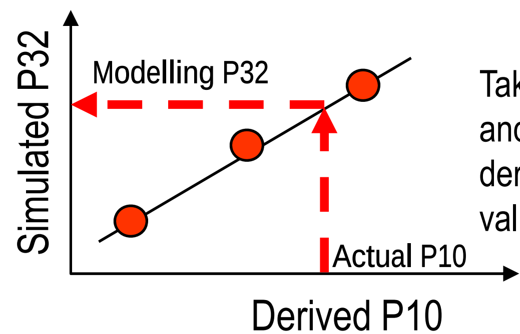
		Dimension of Measurement				
		0	1	2	3	
Dimension of Sample	1	P10 *No of fractures per unit length of borehole*	P11 *Length of fractures per unit length*			*Linear Measures*
	2	P20 *No of fractures per unit area*	P21 *Length of fractures per unit area*	*P22* *Area of fractures per area*		*Areal Measures*
	3	P30 *No of fractures per unit volume*		P32 *Area of fractures per unit volume*	P33 *Volume of fractures per unit volume*	*Volumetric Measures*
		Density		*Intensity*	*Porosity*	

Deriving Intensity inputs

- Determine P32 by simulation
  - Take orientation & size distribution data
  - Simulate a model with an initial P32 value
  - Sample the model in the same way as your data (e.g. borehole or trace plane) and derive P10 or P21 data
  - Repeat for a number of P32 values
- Specify P10 directly
  - FracMan allows you to set the P10 value for a well (or number of wells) and will generate fractures until the P10 value is reached





Take actual P10 value and from graph, derived modelling P32 value

Deriving fracture transmissivity

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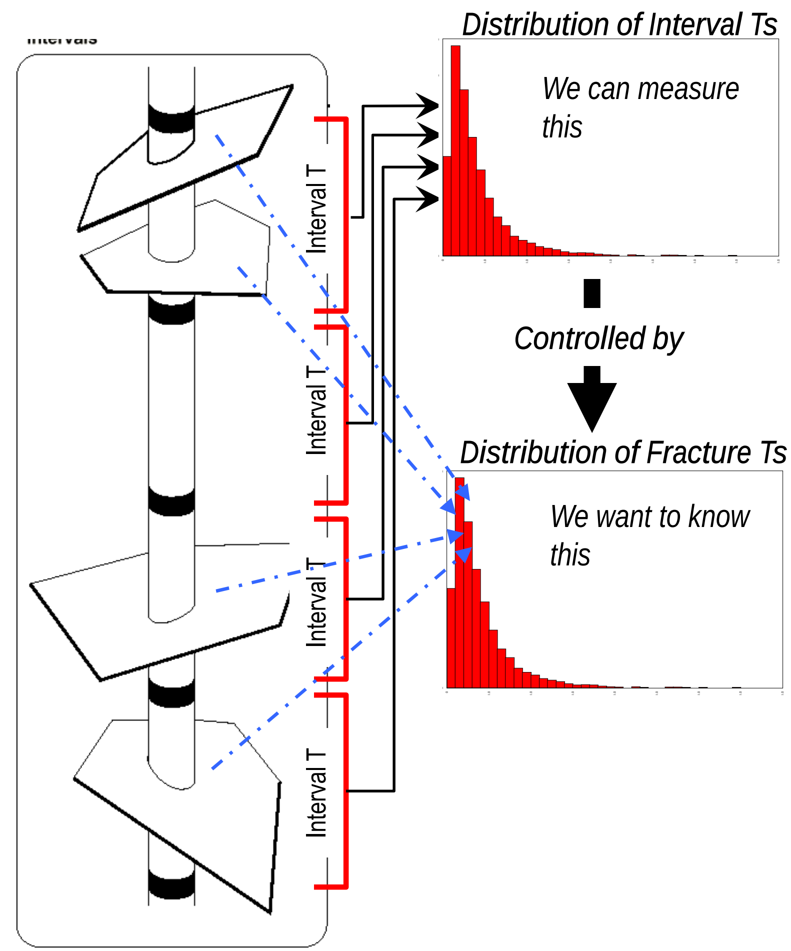
- The problem
  - Fracture transmissivity (T) not actually measured
  - Well tests (either open hole or packer tests) derive the interval transmissivity
- Therefore we need a method that will convert these interval T values into fracture T values
- The solution: the *OXFILET* method (Osnes Extraction of Fixed Interval Length Evaluation of Transmissivity)
- The distribution of packer test T values is controlled by the distribution of fracture T values

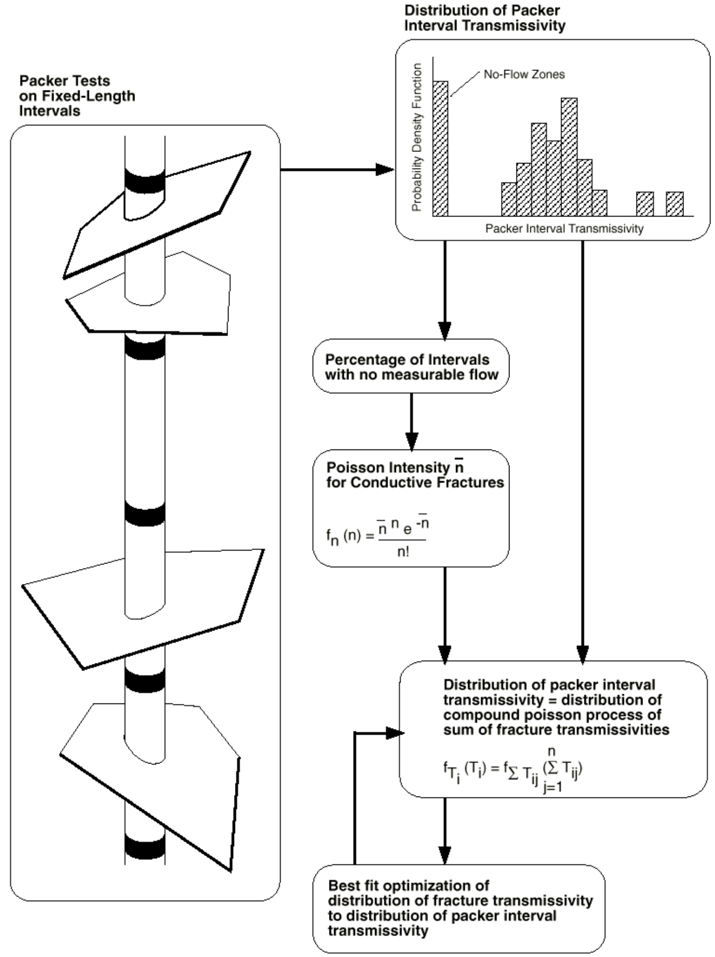


Oxfilet Method

- Analyze distribution of packer test results (Ts) for intensity and transmissivity distribution of single fractures
- The percentage of No-flow tests (or flow below cut-off) gives the conductive fracture frequency ($P10_c$)
- The T distribution of single fractures comes from fitting the T distribution of *tests* to a trial-and-error guess about the T distribution of *single fractures*
- Assumes random conductive fractures (Poissonian) and assumed distribution of single fracture Ts
- Most work shows that fracture T is Log Normally distributed

Oxfilet Workflow

- Guess *T* and P_{10} of Fractures
- Oxfilet generates fractures along hole
- Oxfilet calculates packer test transmissivities (for either fixed intervals or any combination of arbitrary test-zone lengths)
- Oxfilet compares measured and simulated packer test transmissivities, adjusting estimated fracture T distribution to optimise match to interval T distribution



$$P_{10} = \frac{-\ln(P_n)}{L}$$

P_n - # of no flows/# of tests

L - length of test zone

Oxfilet Results

Fracture Network Stats

```
**** OXFIL SIMULATION RESULTS ****

 Input File : allfracs.fil
 Single Fracture: m=1 r=1.0
 Min. Transimissivity:        1e-010
 Distribution option : LogNormal
Arith.(Mean,Dev):     1e-007     8e-006
Log10 (Mean,Dev):      -8.9        1.29
(# Frac/m, Length):    0.23        4.96

-------------------------------------

                Simulation  FIL Data

# of Intervals        1000       121
Mean             7.74e-008 7.67e-008
Std Dev          7.02e-007 2.98e-007
Log10 Mean           -8.88      -8.9
Log10 Std Dev         1.18      1.28
Skewness              18.4      6.24
Kurtosis               382      44.7
% Nonconductive       39.3      40.5

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(Smirnov, % Signif): 0.356 2.64e-010
(Chi-Sq , % Signif):  11.8      98.2

   ===> Print File (Y/N) ?

     Version: Fracsys 2.602
        Date: 09:41 Apr 11 1999
        File: allfracs.fil
```
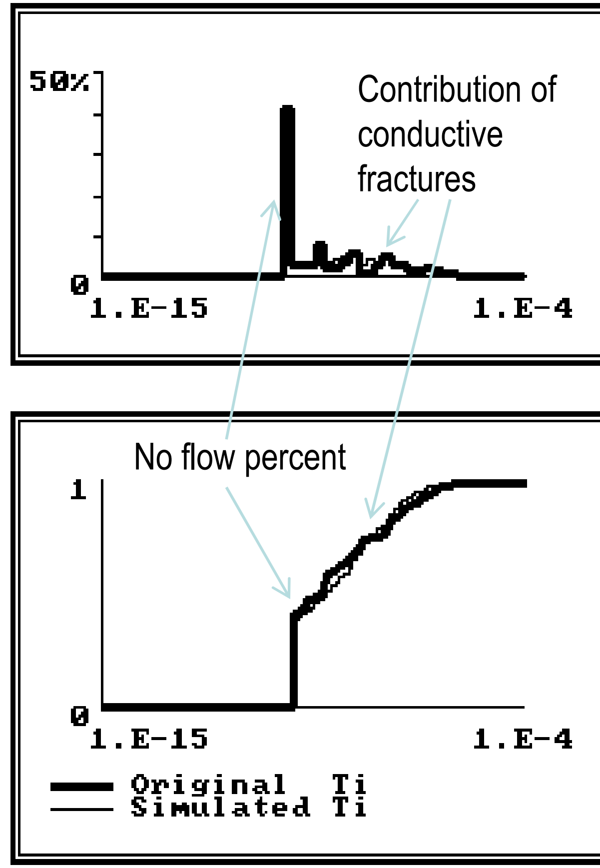

Packer Test Stats

Data and Simulated PDF's



Quiz 2 – Tuesday Jan 27th 3:35 to 4:00 pm

- *UNDERSTAND THE CONCEPTS OF FRACTURES, FAULTS, AND FOLDS*
  - *Fracture mechanics (Mode I, II, and III and ways to identify them from)*
  - *Measures of Orientation (Strike, Dip, Azimuth, Pole Trend, etc)*
  - *Measures of Intensity (P10, P21, P32)*
  - *Use of Lower Hemisphere Equal Area (Schmidt) Stereonets*
  - *Kinematic Analysis of Rock Slopes*
  - *Mechanical and Hydraulic Properties of Faults and Fractures (including roughness, strength, deformability, aperture, and transmissivity)*
  - *Understanding Fracture "chronology" based on termination modes and shear offsets*
  - *Hydraulic Properties: Hydraulic Conductivity, intrinsic permeability, etc*
  - *Relationship between in situ stress and faults and fractures*
  - *Definitions of types of faults (normal, reverse, etc) and types of folds (anticline, syncline) and their characteristics*
  - *Fracture characterization (surface roughness, types of surfaces for different Modes, infillings, etc)*
- *RESOURCES FOR STUDYING*
  - *Hoek 4, Watham Chapter 12 (particularly the definition of folds and the various kinds of folds)*
  - *Wikipedia pages for faults, folds, and horsts (links on our website)*
  - *Course notes (on our website), particularly:*
    - *Fracture Characteization*
    - *Fracture Intensity*
    - *Fracture Properties*
    - *Tectonics, Faults, and Stress*
    - *Stereonet Material*
    - *Structural Geology*