

Introduction and software manual for SG2PS  
(**S**tructural **G**eology to **P**ost **S**cript)

SG2PS

Platform independent  
structural geological data processing software

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**MARCH, 2016**



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## 8 COPYRIGHT





# QUICK OVERVIEW

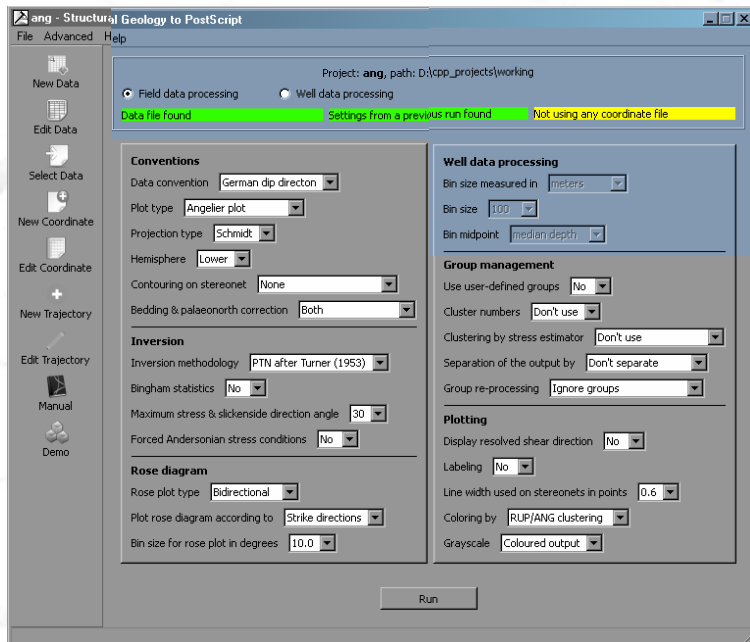


# QUICK OVERVIEW

## DATA PROCESSING MODES

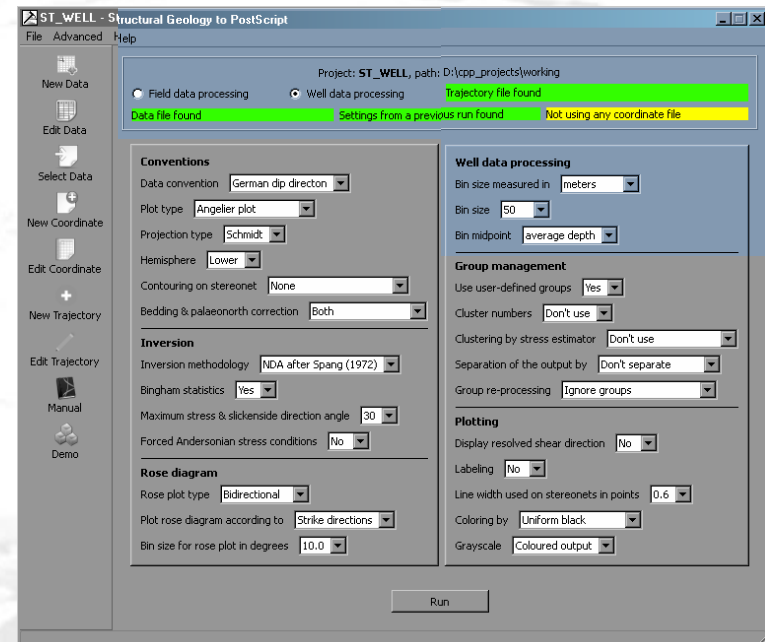
### FIELD PROCESSING MODE

- **Formation boundary, lineation, plane, striae** and **SC** schistosity data can be processed
- If a **coordinate file** is present for your field data locations (as data point – coordinate – formation name sets), it will be taken into agreement
- Using average dips, a **tilting test** is carried out
- **Stereonets** and **paleostress** calculation results are exported in \*.eps of \*.pdf format



### WELL PROCESSING MODE

- XRFI / FMI processing results, such as **bedding, fracture** and **borehole break out** data can be processed; striae and SC data are ignored
- **Trajectory correction** (using a depth – coordinate or depth – azimuth – plunge records) on the can be applied in the same time as the tilting test; no coordinate file is processed
- **Stereonets**, and **faults probability graphs** are exported in \*.eps of \*.pdf format



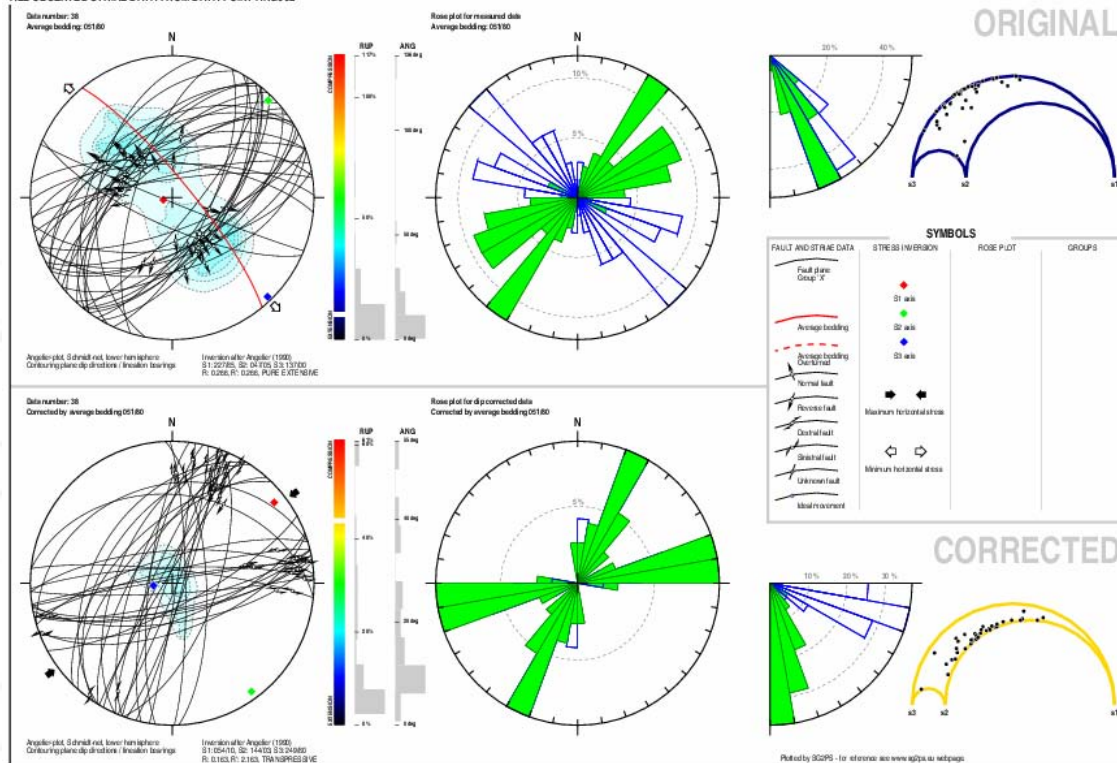


- **SG2PS** is a **free** graphical application for **field** and **well** structural data evaluation and processing
- Easy to use **Graphical User Interface**, data processing takes just a few clicks
- Separate processing and plot for different **localities**, data **types** and data **groups**
- Displays structural data on **stereonet**s and **rose diagrams**
- **Bedding correction** for tilting test available
- **K-means clustering** to identify data groups in an inhomogeneous data set
- Seven different **inversion** methodologies and fracture geometry statistics
- **Batch** processing for different input data sets
- Data **input in Excel** or any other spreadsheet application of your choice
- Output in Adobe Portable Document Format (**PDF**)

## CAPABILITIES

- **Angelier** or **Hoepfner** plot, **Schmidt** or **Wulff** net, as well as **upper** or **lower** hemisphere projections are possible
- **Symmetric / asymmetric** rose diagrams with different **bin size** are available to plot dip **direction** or **strike** of data
- Contouring data set using four different possible inputs
- **Slickenside data correction** on two ways
- **Full automatic** data processing option
- Simplified data input and **auto completion** of input database
- Average data (e.g. average bedding) calculation using **regression**
- Built in **k-means clustering** module
- **Stress tensor inversion** using
  - Turner (1953),
  - Spang (1972),
  - Michael (1984),
  - Angelier (1990),
  - Fry (1999),
  - Shan et al. (2003), and
  - Mostafa (2005) methodologies
- **Bingham directional statistics** for fracture sets
- **RUP** and **ANG** stress estimators display and slickenside clustering using them
- **Ideal movement** direction display
- Stress state display using **Mohr circle**

ALL OBSERVED STRIAE DATA FROM DATA POINT ANG002





## 1) AVERAGE CALCULATION FOR STRUCTURAL TRENDS

- **Average** feature dip / dip direction calculation along well bore using **fix data number bin** or **fix interval bins**
- **Standard deviation** and **relative error** calculation for the processed bins
- **Feature frequency** calculation

## 2) DERIVATE CURVE TO SHOW OUT-OF-TREND ZONES

- Investigation of **out-of-trend** zones using **first derivate curve** of the average and frequency curves

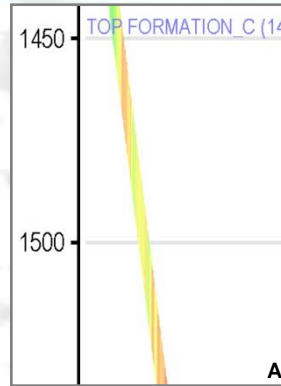
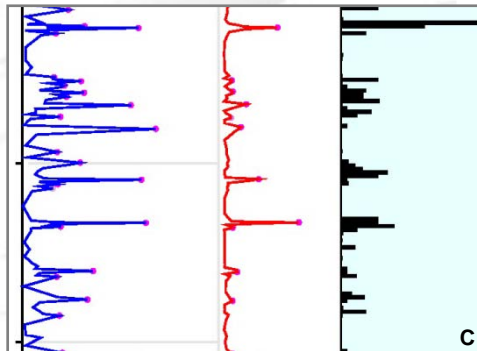
## 3) PEAK DETECTION FOR DEFORMATION ZONES

- **Changes** on average, frequency and derivate curve can indicate a zone of **deformation**
- **Peak recognition** of these curves can help to show the **reliability** of the assumed deformation zones

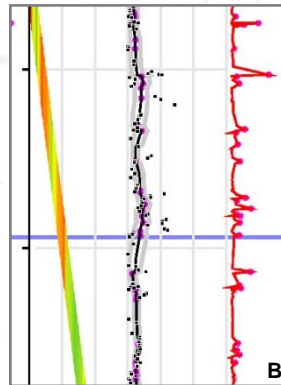
## 4) FAULTS PROBABILITY

- Abrupt **change** in feature geometry and/or frequency can indicate a **zone of deformation**;
- Using **changes** both of average and derivate curve, and **reliability** of those changes, **probability of fault zones** can be predicted

Measurements frequency (blue line) is plotted. Red line shows change in feature frequency as the first derivate of the frequency curve, indicative for faults. Reliability of peaks on the derivate curve are marked by colored dots. Faults probability (using average, frequency and derivate curves) is calculated for the well bore and displayed as black bars.

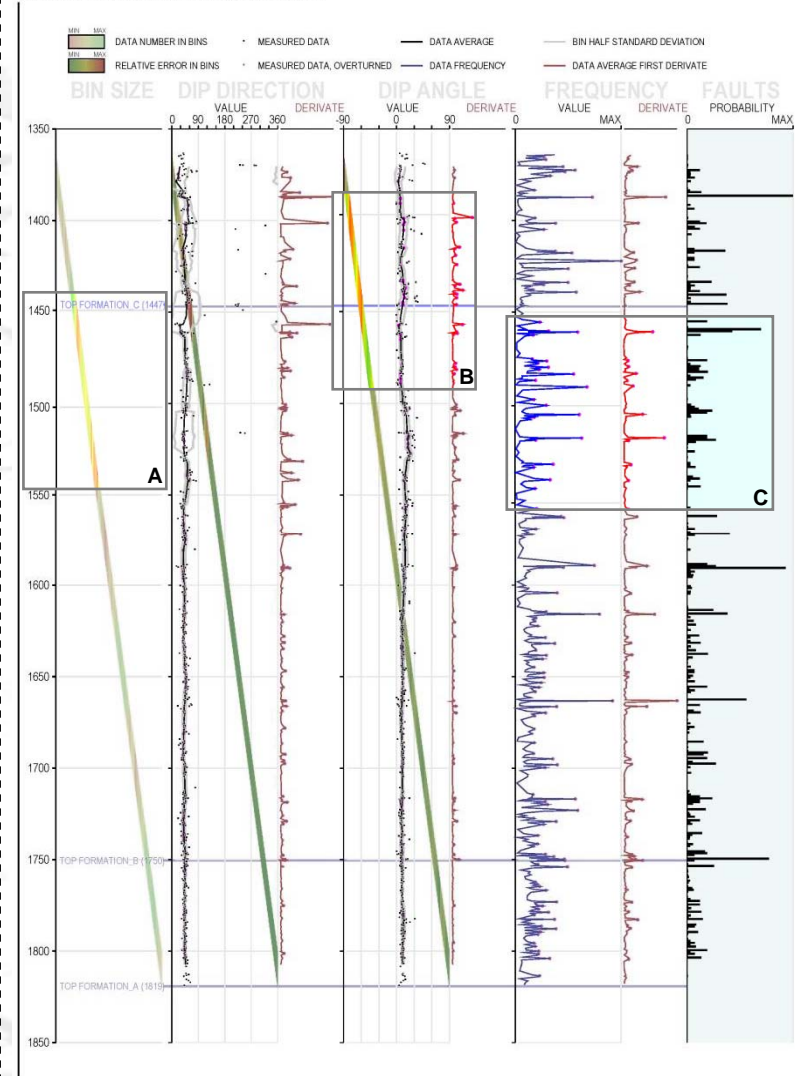


Bars showing relative data number in one bin: the higher the data number, the reliable the processing.



Measurements (dots), their moving average (black line) and standard derivate (gray line) plotted. Colored bars for relative error, and red line shows intensity of change in feature geometry as the first derivate of the average curve. Changes on the average and derivate curve are present as peaks, and their can indicate faults. Reliability of those peaks is marked by colored dots.

BEDDING FROM LOCATION TEST\_WELL - ORIGINAL DATA SET





## THE SOFTWARE

- Download SG2PS installer from the website <http://www.sg2ps.eu/download.htm> and install on unzip
- Start the Graphical User Interface (**SG2PS\_GUI.EXE**)
- **Create** your data spreadsheet what you want to evaluate using the **graphical version** of the program, or **copy-paste into a text file** in the working folder – this will be the **input (\*.rgf)** file
- You can store your **settings (\*.set)** and **locality – coordinate – formation name pairs (\*.xy)** in separated files
- For processing well data, you can use well trajectory (\*.trj) file for borehole deviation correction either in depth – azimuth – plunge or in depth – X – Y data format
- A **project folder** will be generated for the text and post script or pdf outputs
- Evaluation results will be displayed on the **screen** in text format
- If everything goes well, **couple of thousand data** from **some hundred data points** could be evaluated and plotted in **less than one minute**
- To remove **evaluation results**, delete the project folder
- To remove **SG2PS**, just delete the program folder

## THE MANUAL

- If you are interested in the software capabilities, or want to have a quick overview, read **INTRODUCTION** chapter; if you are interested is the result plot details, take a look at the **WELL AND FIELD DATA GRAPHICAL OUTPUT** chapter as well
- If you want to use the software to evaluate your own data, please have a look at the **INPUT FILE FORMAT** chapter to became familiar with the data input requirements
- Chapter **PROCESSING AND DISPLAY** gives a slightly detailed overview about the software capabilities presenting well data, and displaying different plot, net and hemisphere types as well as short description of used inversion methodologies
- **BACKGROUND** chapter describes all of the details what can help you to understand the source code. Please find here a brief summary about the different net calculation, Bingham statistics, clustering and inversion methodologies. This chapter don't repeat the published solutions, it is just a brief summary how to code them. Background theory and mathematics are published in the referred papers
- Feel free to use this software at any time, but please have a look at the **COPYRIGHT**

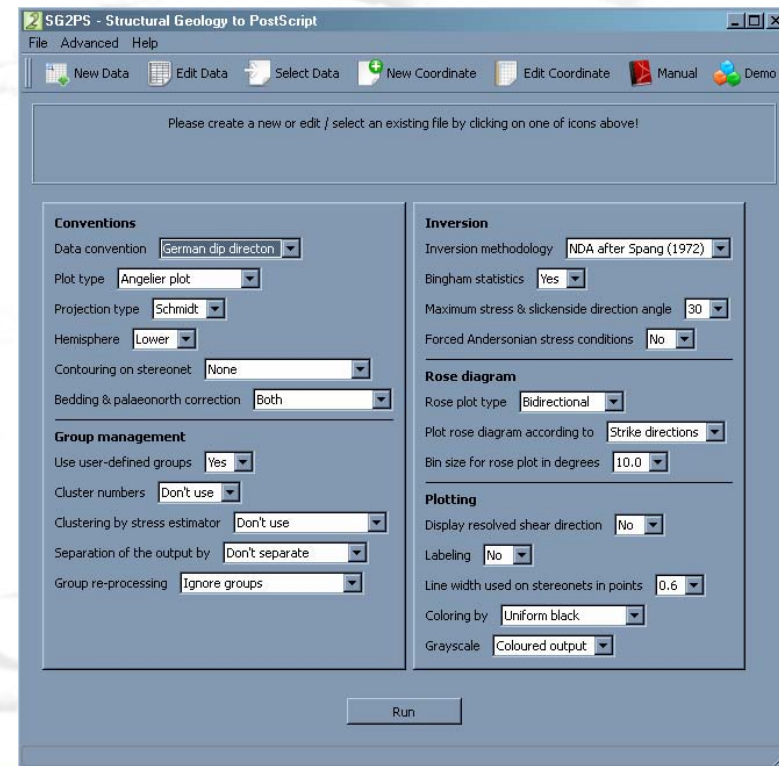
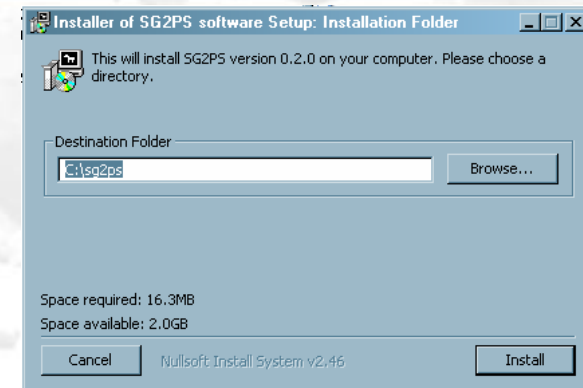


## INSTALLATION

- Download the install file from the [www.sg2ps.eu/download.htm](http://www.sg2ps.eu/download.htm) webpage and run 'sg2ps\_setup.exe'
- Choose the directory where you want to install the application and press 'Install'
- If you are not allowed to run self extracting archives, simply download the installer in \*.zip format and extract in the destination folder

## RUN – FILE MENU

- Start 'sg2ps\_gui.exe' to run the software
- Use 'NEW DATA' to create a standard input (\*.rgf) file
- Use 'EDIT DATA' to edit your own input file with the default spreadsheet editor
- Use 'SELECT DATA' to select input file to process
- Use 'NEW COORDINATE' or 'EDIT COORDINATE' to create/edit a standard coordinate (\*.xy) file with the default spreadsheet editor; if a coordinate (\*.xy) file is present that will be used, otherwise input file coordinates will be processed
- Use 'NEW TRAJECTORY' and 'EDIT TRAJECTORY' to create/edit a standard coordinate (\*.trj) file with the default spreadsheet editor; if a well data set is processed and a correct trajectory file is present, it will be used anyway
- The software generates the **project name** and searches for project **settings (\*.set)**; if a correct one is found that will be processed, otherwise standard defaults will be displayed
- You can modify your settings in the 'SETTINGS' field
- Push 'RUN'
- Settings will automatically be saved in the project folder in a **setting (\*.set) file**
- **Processing result** and/or **working directory** with the project folder will be displayed on the screen but will **NOT** be saved





## 0.3.2

# QUICK OVERVIEW

## RUN AND DISPLAY RESULTS

### EDITING DATA FILES – MANUAL DISPLAY

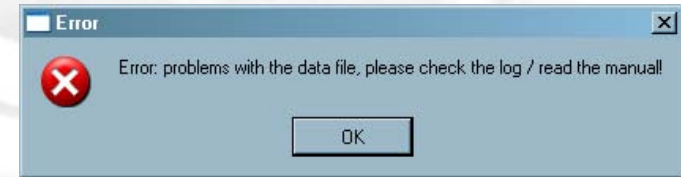
- If a spreadsheet viewer and a PDF viewer is installed on your computer, the software will open to edit **input** (\*.rgf), **coordinate** (\*.xy) and **trajectory** (\*.trj) file

### DEMO

- Use this button first to test everything is OK with your **installation** and **pdf** viewer
- This option will ask for the **demo.rgf** file location, starts the **processing** of it, opens the **output folder**, generates the **output files** first in \*.eps format and converts the into \*.pdf later on. As the last step, the stereoplot output will be displayed in the **default pdf viewer** to test it

### ERROR MESSAGE

- If the input (\*.rgf), coordinate (\*.xy) or trajectory (\*.trj) file is incorrect, it will be not processed, and an error message will displayed



### DISPLAY EPS RESULTS

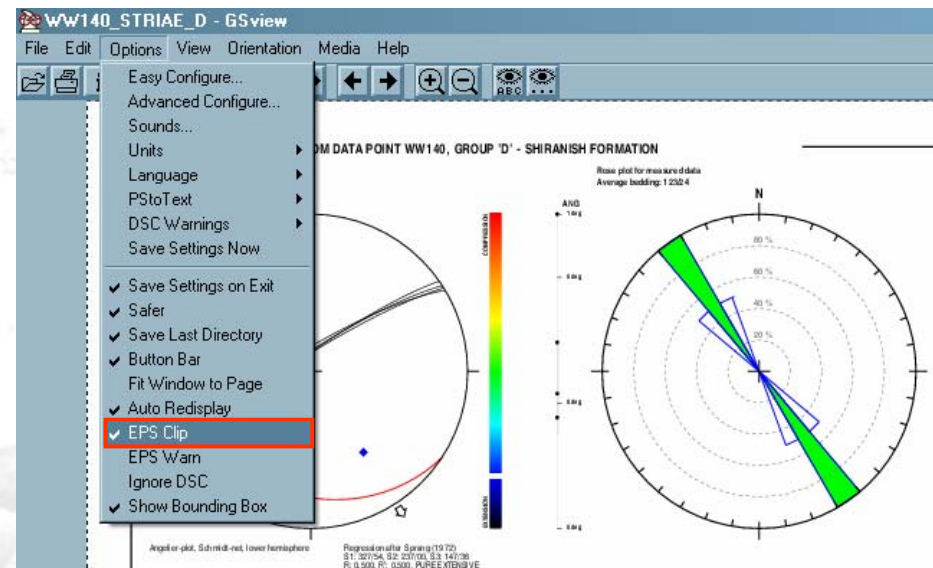
- If you have **no pdf viewer**, or want to **see the \*.eps file output**, you can use free softwares (e.g. **GSview**) to display generated \*.eps files; if you want to use **GSview**, install **Ghostscript** before
- If you are using GSView, please don't forget to tick **Options/EPS clip option**, otherwise a rotated and clipped view will displayed on the screen
- You can convert the result vector graphs to \*.pdf format and open it with a pdf viewer

### PDF OUTPUT

- Conversion of the generated pdf's is available for the user's choice. To make the user's life easier, merged version of the individual pdf's is generated and dumped into the project directory.

### UNINSTALL

- Simply delete the application folder; no registry components were modified







# INTRODUCTION

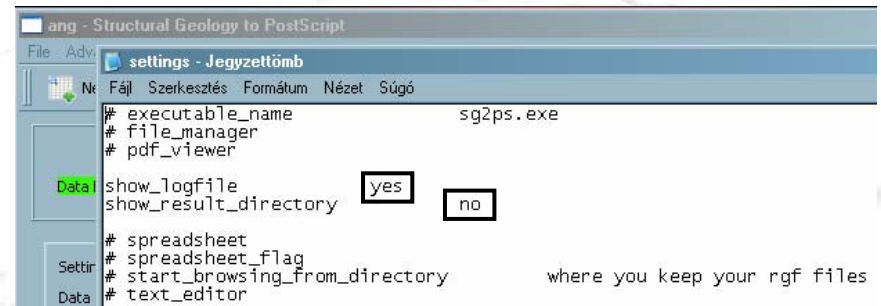


## EDITING DATA FILES – MANUAL DISPLAY

- If you don't have default spreadsheet editor and/or PDF viewer, you can download **Apache OpenOffice** to process spreadsheet and **Ghostscript** for PDF display

## ADVANCED MENU – GUI SETTINGS

- Here you can modify GUI settings
- Lines **with no # character** are active
- Use **yes/no** to display log file after processing, or to show working folder directory with the generated project folder
- After editing the settings, you **don't need** to restart the application





- For 'DO-03' location group, XXX, inversion after Angelier (1990):
  - Original : - Input data set separated into 2 clusters.  
s1: 241/19, s2: 145/16, s3: 017/65, PURE COMPRESSIVE, R: 0.325, R': 2.325, av. misfit: 1.6 deg.
- For 'HA-05' location group, XXX, inversion after Angelier (1990):
  - Original : - Input data set separated into 5 clusters.  
s1: 187/11, s2: 095/12, s3: 318/74, TRANSPRESSIVE, R: 0.138, R': 2.138, av. misfit: 42.4 deg.
- For 'KG-02' location group, XXX, inversion after Angelier (1990):
  - Original : - Input data set separated into 4 clusters.  
s1: 347/89, s2: 153/01, s3: 243/00, TRANSTENSIVE, R: 0.946, R': 0.946, av. misfit: 10.0 deg.
- For 'KG-04' location group, XXX, inversion after Angelier (1990):
  - Original : - Cannot cluster input data set using RUP / ANG values.  
s1: 119/09, s2: 022/33, s3: 223/55, PURE COMPRESSIVE, R: 0.479, R': 2.479, av. misfit: 45.5 deg.
- For 'MA-01' location group, XXX, inversion after Angelier (1990):
  - Original : - Input data set separated into 2 clusters.  
s1: 203/73, s2: 021/17, s3: 111/01, PURE EXTENSIVE, R: 0.536, R': 0.536, av. misfit: 32.0 deg.
- For 'NE-01' location group, XXX, inversion after Angelier (1990):
  - Original : - Input data set separated into 2 clusters.  
s1: 128/71, s2: 030/03, s3: 299/19, PURE EXTENSIVE, R: 0.374, R': 0.374, av. misfit: 51.4 deg.
- For 'NP-01' location group, XXX, inversion after Angelier (1990):
  - Original : - Input data set separated into 4 clusters.  
s1: 296/05, s2: 027/14, s3: 188/75, TRANSPRESSIVE, R: 0.206, R': 2.206, av. misfit: 40.6 deg.

### PRE-PROCESSING

- Empty records of the input (\*.rgf) file will be auto **completed**
- **Vectors** representing data input data will be generated

### PROCESSING

- Using pitch data format, slickenside data will be **converted** into lineation format
- Using lineation data format for slickensides, **misfit correction** will be done (see Chapter 6.3.2)
- Slickenside **offset correction** is carried out (see Chapter 6.3.2);
- If it was required, **k-means clustering** will be carried out and the results will be displayed on the screen

- **Average data** for each data types (except lithology, slickenside and s-c data) is calculated for each location
- **Re-tilting** of all data with the average bedding will be done and slickenside offset re-correction will be carried out
- In the case of a well data set, trajectory correction and bedding correction is applied, and four data set (original, bedding corrected, trajectory corrected and a data set with both corrections) will be processed
- **Bingham statistics** and inversion results will be displayed for each fault or fracture data sets

### FILE OUTPUT

- **Postscript** files, completed **geodatabase** files, **average** files and **data type by data type selected** files will be generated



# 1.2.2

## INTRODUCTION

### FILE OUTPUT

- In the working folder, a **project folder** will be generated named after the current datum, time and project name
- Five output **subfolders** will be created in the project folder
- '1\_ORIGINAL' folder contains the **copy of the original input** (\*.rgf) file with no modifications as backup
- '2\_COMPLETED' folder contains the **completed** version of the input (\*.rgf) file with no empty records
- 3\_AVERAGE** folder contains a file for the **average data** calculated for each different data types (except slickenside and s-c data) for each data points. This file is useful if you want to display average bedding in GIS
- '4\_RGF\_SEPARATED' folder has different subfolders containing input data **separated** by data points and data types
- The result **postscript** files are in '5\_PS\_SEPARATED' folder's subfolders, separated by data point, data types, groups and clusters (if this option was selected). No folder created if nothing to display.
- Folder '6\_WELL\_PS\_SEPARATED' folder and its subfolders are for the well processing output, separated by wells, data type, groups and clusters for your choice. No folder created if nothing to display.

Directory tree (right) generated after input processing ➔

```

—20150920-083701_ST_WELL
├──1_ORIGINAL
├──2_COMPLETED
├──3_AVERAGE
├──4_RGF_SEPARATED
│   ├──BEDDING
│   └──FRACTURE
├──5_PS_SEPARATED
│   ├──BEDDING
│   └──FRACTURE
└──6_WELL_PS_SEPARATED
    ├──BEDDING
    └──FRACTURE
    
```

Original (above) and completed (below) input file ↓

DATA_ID	GROUP_CODE	COLOR_CODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIP_DIR	DIP	L_DIP_DIR	LDIP	SENSE	PALEONORTH	COMMENT
RW0508			RW226			LOWER BAKHTRIARI	bedding	162.0	7.0					
RW0509								171.0	20.0					
RW0510			RW228				bedding	228.0	8.0					
RW0511								194.0	10.0					
RW0512			RW230				bedding	165.0	18.0					
RW0513			RW232			QUATERNARY	LITHOLOGY							
RW0514			RW233				bedding	25.0	20.0					
RW0515							crossbedding	2.0	22.0					
RW0516			RW234				bedding	87.0	7.0					
RW0517								83.0	7.0					

DATA_ID	GROUP_CODE	COLOR_CODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIP_DIR	DIP	L_DIP_DIR	LDIP	SENSE	PALEONORTH	COMMENT
RW0508	X		RW226	36.1429	44.6694	LOWER BAKHTRIARI	BEDDING	162.0	7.0				0	
RW0509	X		RW226	36.1429	44.6694	LOWER BAKHTRIARI	BEDDING	171.0	20.0				0	
RW0510	X		RW228	36.1446	44.6724	LOWER BAKHTRIARI	BEDDING	228.0	8.0				0	
RW0511	X		RW228	36.1446	44.6724	LOWER BAKHTRIARI	BEDDING	194.0	10.0				0	
RW0512	X		RW230	36.1445	44.6746	LOWER BAKHTRIARI	BEDDING	165.0	18.0				0	
RW0513	X		RW232	36.1449	44.6756	QUATERNARY	LITHOLOGY						0	
RW0514	X		RW233	36.1449	44.6756	QUATERNARY	BEDDING	25.0	20.0				0	
RW0515	X		RW233	36.1449	44.6756	QUATERNARY	CROSSBEDD	2.0	22.0				0	
RW0516	X		RW234	36.1433	44.6801	QUATERNARY	BEDDING	87.0	7.0				0	
RW0517	X		RW234	36.1433	44.6801	QUATERNARY	BEDDING	83.0	7.0				0	



```

                SG2PS
    Structural Geological data to PostScript converter
  
```

```

                Data processing software
  
```

```

    Copyright (C) 2012 - 2015 Agoston Sasvari.
    All rights reserved.
  
```

```

    This a free software, license: GNU LGPL.
  
```

```

    This software comes with NO WARRANTY.
  
```

```

    For further information check www.sg2ps.eu
  
```

```

    Built on: 18 Sep 2015, 13:16:24
  
```

Running 'SG2PS' in 'BATCH' mode.

```

=====
1) CHECKING OF SETTINGS FILE
=====
  
```

```

- CHECKING 230_ERR.SET SETTINGS FILE
- Correct key/value pair for 'DATARULE:' user input key.
- Correct key/value pair for 'PLOT:' user input key.
- Correct key/value pair for 'WELLINTERVAL:' user input key.
- Correct key/value pair for 'WELLINTERVAL_MIDDLE:' user input key.
- Correct key/value pair for 'WELLINTERVAL_LENGTH:' user input key.
- 230_ERR.SET SETTINGS FILE IS CORRECT.
  
```

```

=====
2) CHECKING OF INPUT DATA FILE
=====
  
```

```

- CHECKING 230_ERR.RGF INPUT DATA FILE
- The header (column names) of the data file has been processed.
- The following columns are reserved but unused:
  "DEPTH"
- Input 230_ERR.RGF file read, 89 record(s) imported.
- Existing DATA_ID's in all records.
- Correct DATA_ID's in all records.
- Correct group code(s) in all records.
- Correct color code(s) in all records.
- Correct coordinate(s) in all records.
- Correct datatype(s) in all records.
- ERROR: incorrect strike/dip direction(s) in the following record(s): BZ0098.
- Correct dip angle(s) in all records.
- Correct CS/striae(s) in all records.
- Correct paleo north direction(s) in all records.
  
```

```

WARNING, RGF_ERROR: the input 230_ERR.RGF file structure is incorrect,
the file will not be processed.
- Elapsed time: 47.00 milliseconds.
  
```

## PRE-PROCESSING

- Before processing, input (\*.rgf) file will be **checked**
- If the file contains error(s), **type** of error and the incorrect **record ID** (from input file) will displayed
- In the case of any error, 1) **open** your input file with text editor application, 2) **fix** the incorrect record, 3) **save** the input file and process it again
- Because input database error check is carried out column by column, a need to **repeat** error fixing for other columns can easily arise

## PROCESSING

- If data number is **less** than required by the slickenside inversion procedure or Bingham statistics, the software is unable to calculate stress field or statistics parameters, and an error message will displayed, but the program will continue the processing
- If regression is required for the average calculation and the data set is **singular**, no average will be calculated, and a message will inform the user about the data set singularity





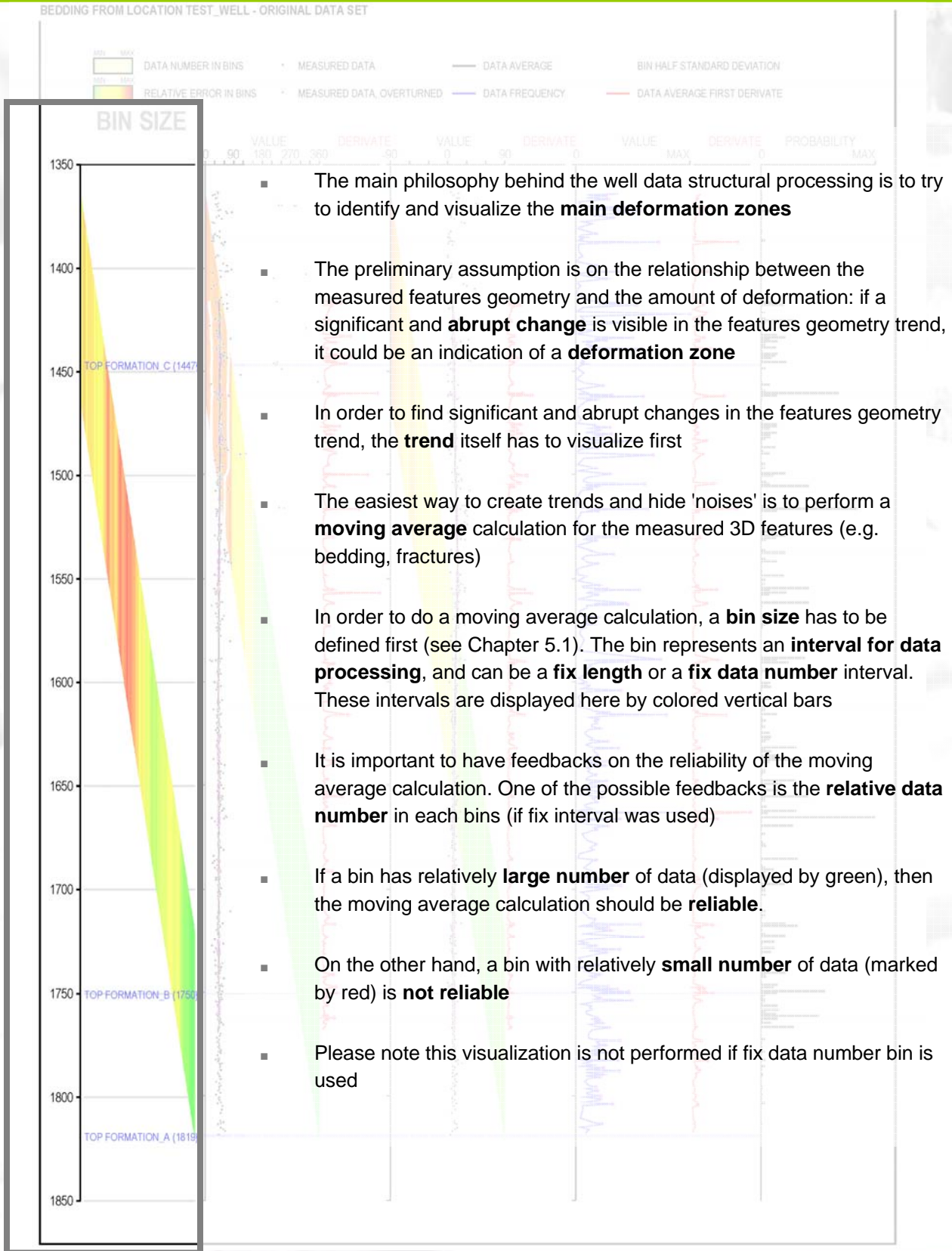
# **WELL AND FIELD DATA GRAPHICAL OUTPUT**



## 2.4.1

# WELL DATA GRAPHICAL OUTPUT

## BIN SIZE PANEL





## 2.4.2

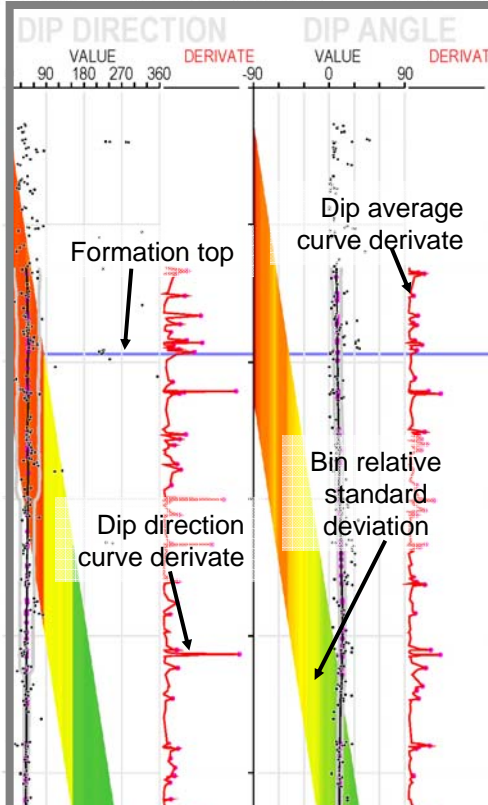
# WELL DATA GRAPHICAL OUTPUT

## DIP DIRECTION AND DIP ANGLE PANEL

BEDDING FROM LOCATION TEST\_WELL - ORIGINAL DATA SET

### DIP DIRECTION AND DIP

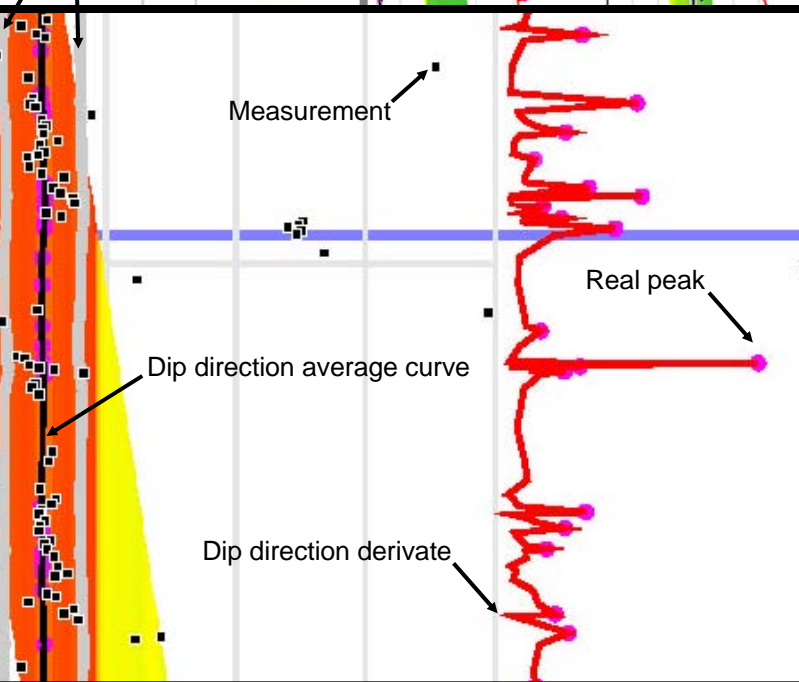
DATA NUMBER IN BINS MEASURED DATA DATA AVERAGE  
RELATIVE ERROR IN BINS MEASURED DATA OVERTURNED DATA FREQUENCY



The easiest way to create trends and hide 'noises' is to perform a **moving average calculation** for the measured 3D features (e.g. bedding, fractures)

Because the feature trend line has a **3 dimensions** geometry but the paper has only 2 dimensions, further adjustments are required

Dip direction standard deviations



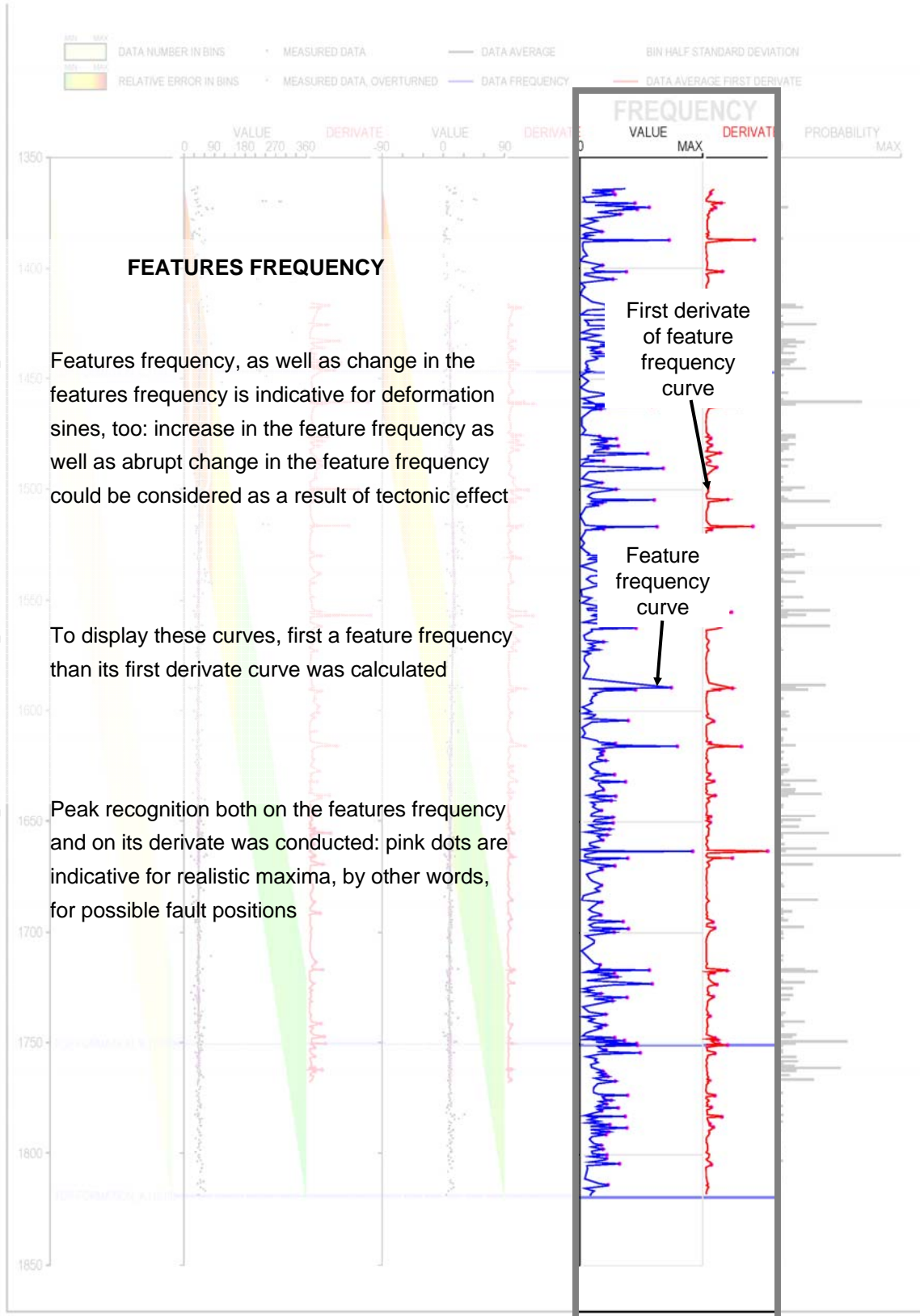
- To follow classic geological data handling, the average 3D feature trend line is '**decomposed**' into two lines and displayed on two panels: one for the **dip direction** and one for the **dip angle**
- Abrupt changes** (=positive or negative local maxima) of the average feature trend line could be indicative for **structural effects**
- It is important to have feedbacks on the **reliability** of the moving average calculation. The method is to calculate the **standard deviation curve** for the dip direction and dip angle in each data bins, and display it together with the trend line curve
- Here a **relative standard deviation** is displayed by colored bars for each bins, too: if a bin has relatively large error (displayed by red), then the moving average calculation should not be reliable. On the other hand, a bin with relatively small error (marked by green) could be reliable
- To visualize **how intensive** the change in the structural trend, **first derivate** of both the dip direction the dip average trend line is displayed
- Abrupt changes (=positive or negative local maxima) of the first derivate of the average features trend line could be indicative for **structural effects**
- Individual **measurement** have to be indicated on the same 'decomposed' way: measurement dip direction on the first panel, and measurement dip on the second one
- Peak recognition** both on the average features trend line and its derivate was carried out
- Pink dots on the average features trend line are indicative for realistic maxima or minima, by other words, for **possible fault positions**
- Pink dots on the first derivate of the features trend line are indicative for realistic maxima, by other words, for **possible fault positions**



## 2.4.3

# WELL DATA GRAPHICAL OUTPUT FEATURE FREQUENCY PANEL

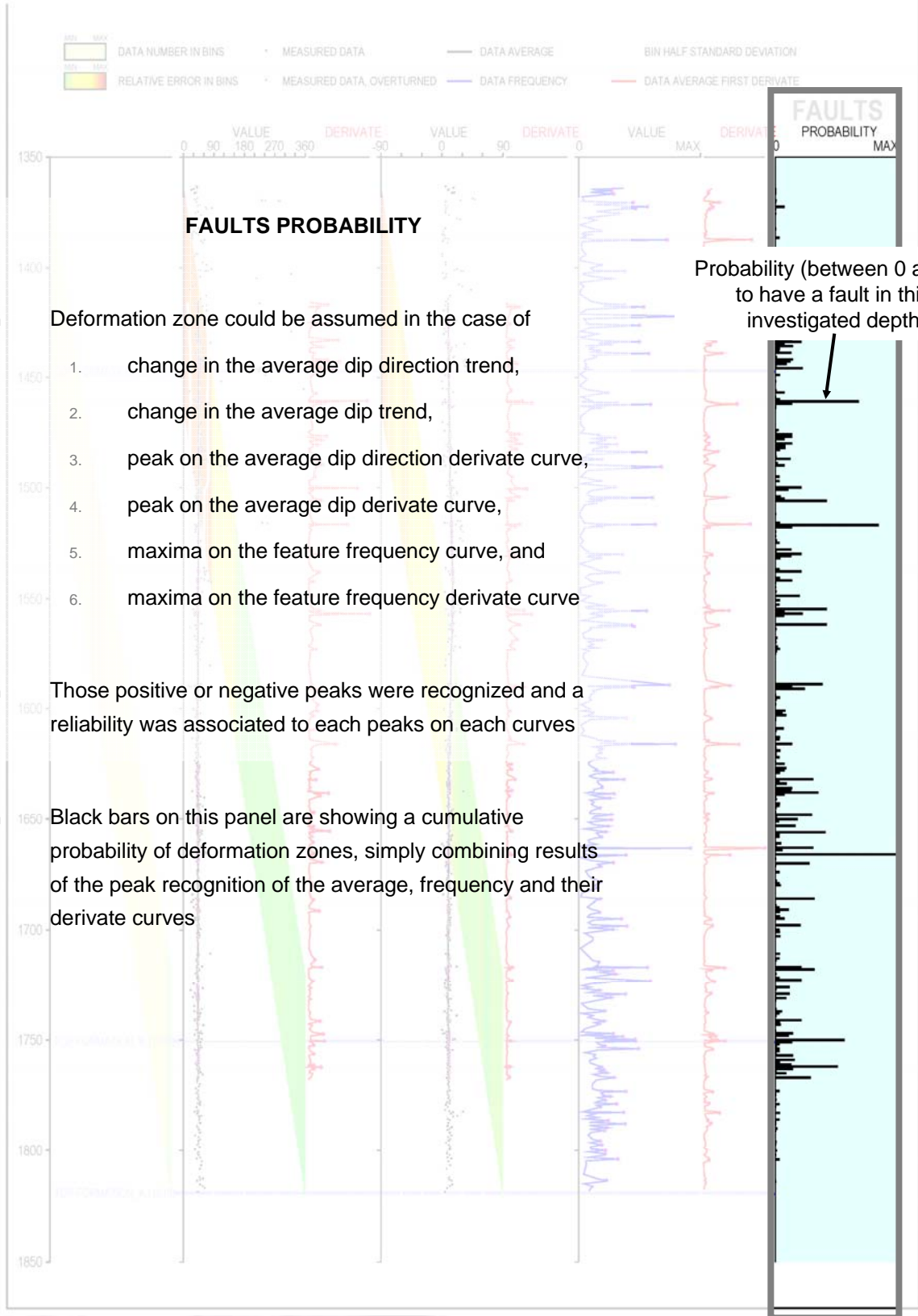
BEDDING FROM LOCATION TEST\_WELL - ORIGINAL DATA SET





## WELL DATA GRAPHICAL OUTPUT

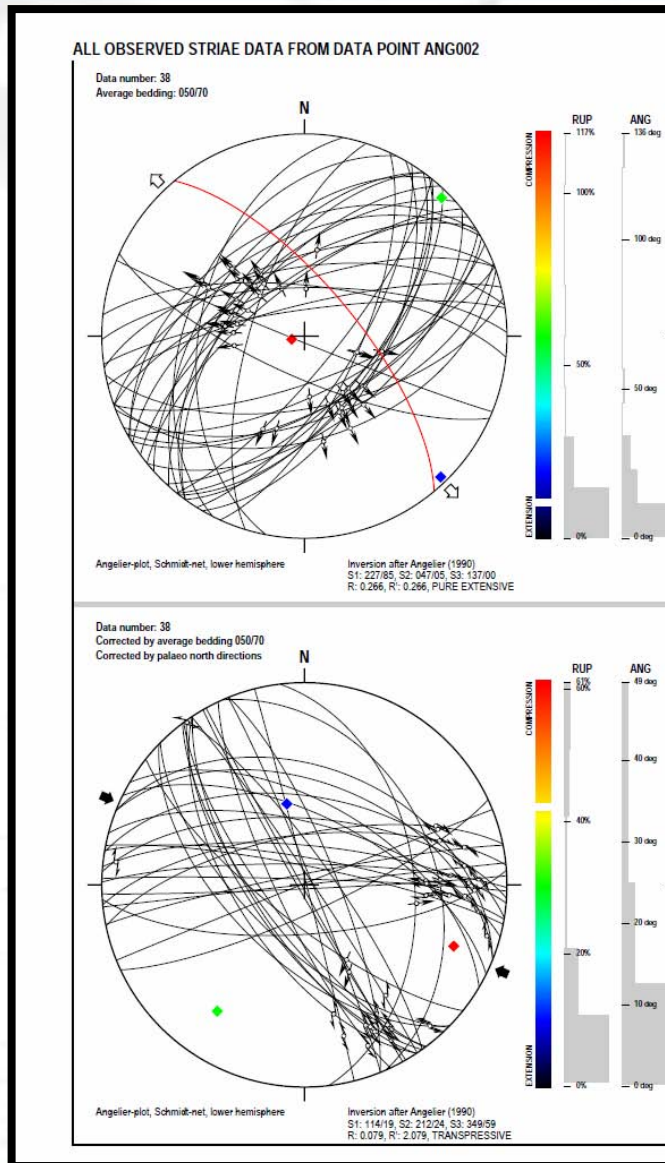
### FAULTS PROBABILITY PANEL





## 2.2.1

# FIELD DATA GRAPHIC OUTPUT STEREOGRAPHICAL PROJECTIONS



- You can use free softwares (e.g. **GSview**) to display generated \*.eps files; if you want to use **GSview**, install **Ghowsript** before
- If you are using **GSview**, please don't forget to tick **Options/EPS clip option**, otherwise a rotated and clipped view will displayed on the screen

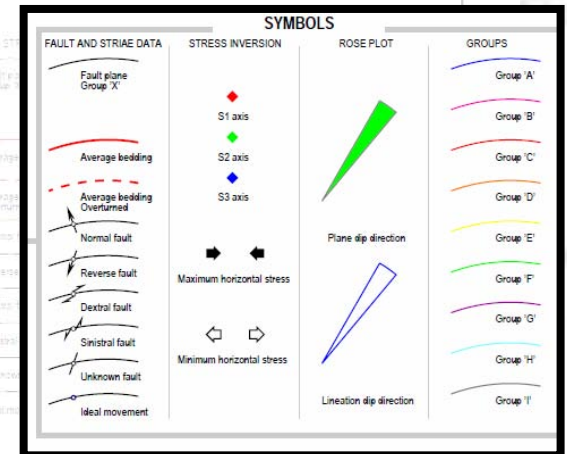
- At the left upper corner, **data type** and **data point locality** is indicated
- If the option 'using groups' is selected, than **group name** is indicated there
- Upper half of the final plot is to show **original** data set, lower half is for the **re-tilted** (bedding and/or palaeonorth corrected) visualization of them
- Plot type, projection and hemisphere** is displayed left below of stereonets
- Stress inversion result** is presented right below the stereonets:

- stress inversion **methodology**,
- stress axes **directions**,
- reduced stress tensors** value after Angelier (1979), after Delvaux et al. (1999) and the **stress regime**

If fractures were processed, Bingham analysis could be displayed here:

- density ellipsoid **axis directions** and **axes length** (eigenvalues)

For slickensides, stress inversion is carried out, red, green and blue rectangles show the **maximum, intermediate and minimum stress axis orientation**



For planes, Bingham statistics could be used; red, green and blue rectangles show the **maximum, intermediate and minimum weight axis** orientation

Black and white arrows show the **maximum and minimum horizontal stress** directions

Red great circle shows the **average bedding**



## 2.2.2

# FIELD DATA GRAPHICAL OUTPUT

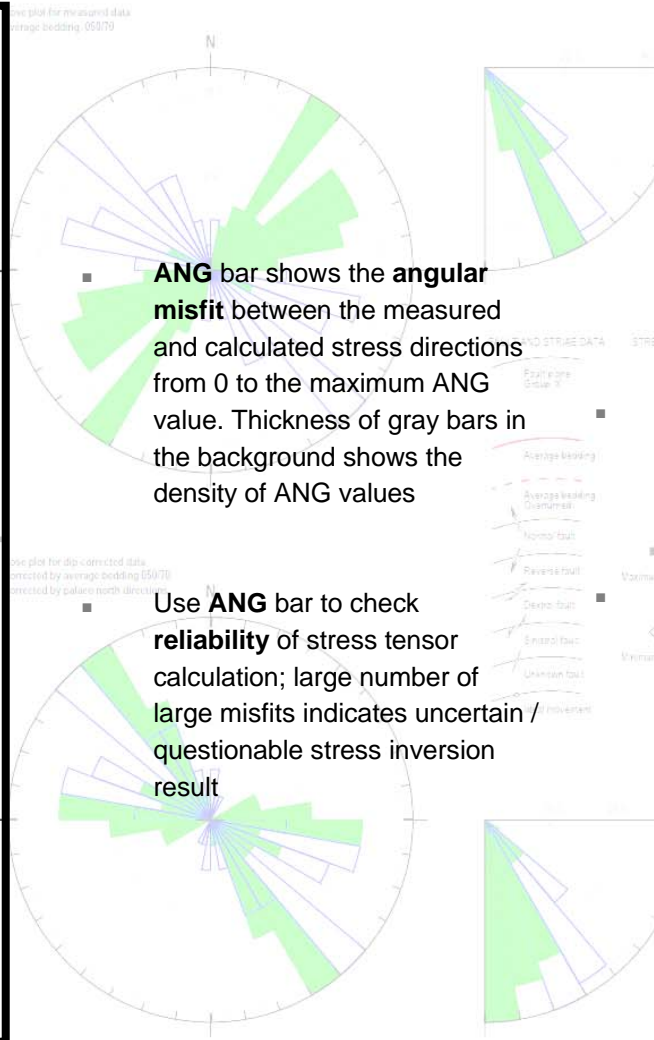
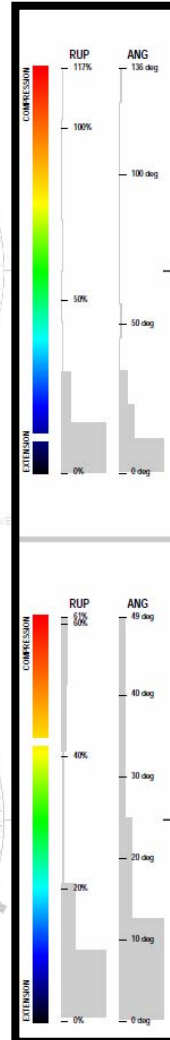
## STRESS FIELD PROPERTIES, STRESS ESTIMATORS

ALL OBSERVED STRIAE DATA FROM DATA POINT ANG002

Rainbow colored bar shows the possible stress regimes from radial extensive (black) to radial compressive (red). White line shows the **current stress regime** after inversion

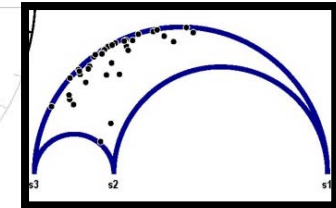
**RUP** bar shows the **relative** **upsilon ratio** (theoretical / resolved shear stress vector length) from 0 to maximum RUP value (see Chapter 6.9.2). Thickness of gray bars in the background shows the density of RUP values

If different clusters are visible on the **RUP** chart, they can show different striae sets working in different stress fields; use RUP bar to **identify possible striae sets** in a mixed data set



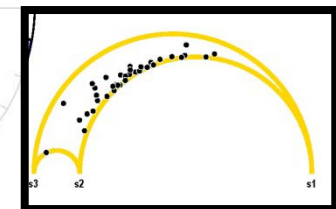
**ANG** bar shows the **angular misfit** between the measured and calculated stress directions from 0 to the maximum ANG value. Thickness of gray bars in the background shows the density of ANG values

Use **ANG** bar to check **reliability** of stress tensor calculation; large number of large misfits indicates uncertain / questionable stress inversion result



**Mohr circles** show the **stress status** as well as normalized normal and shear stress values for each evaluated data

Mohr circles color refers on **stress regime**





## 2.2.3

# FIELD DATA GRAPHIC OUTPUT

## ROSE PLOTS

ALL OBSERVED STRIAE DATA FROM DATA POINT ANG002

Data number: 38  
Average bedding: 050/70

Equal bin size rose plots show the **directional density** change of the evaluated data set

Rose plots can show directional distribution of data **strikes** or **dip directions**

**Symmetric** and **asymmetric** plots with 2.5, 5.0, 10.0 and 22.5 degrees bin size are available

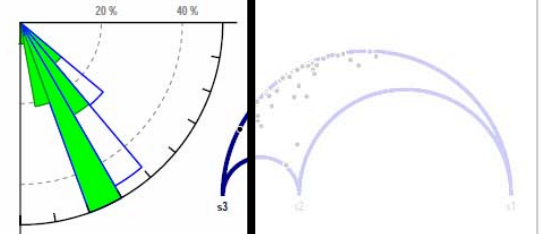
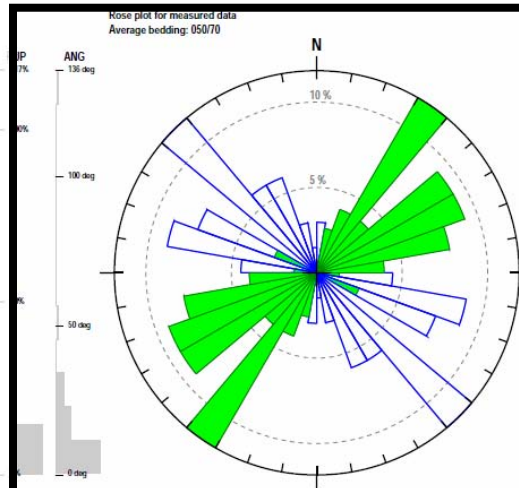
Large stereonet are for **horizontal** (strike or dip direction) distribution

Small quadrant plots show **vertical** (dip angle or plunge) directional statistics

Relative density of processed data is indicated by numbers and dashed gray lines

100%  
50%  
0%  
0 deg  
10 deg  
20 deg  
30 deg  
40 deg  
50 deg  
60 deg  
70 deg  
80 deg  
90 deg  
100 deg  
110 deg  
120 deg  
130 deg  
140 deg  
150 deg  
160 deg  
170 deg  
180 deg

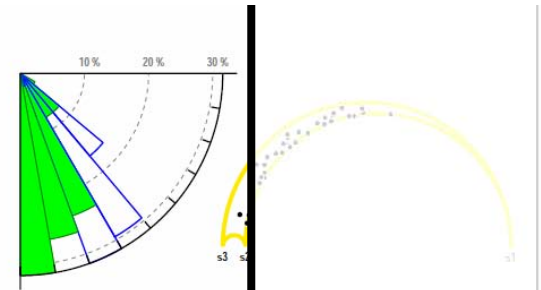
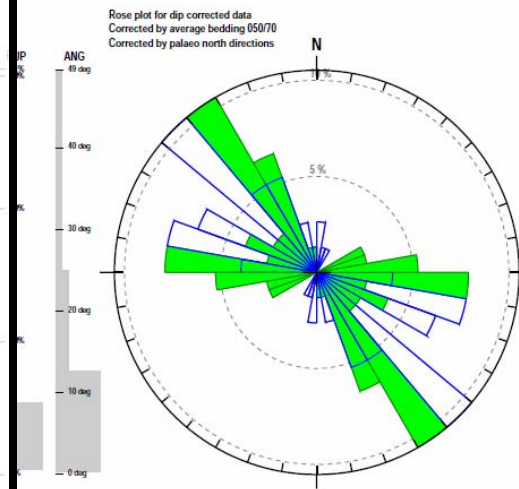
100%  
50%  
0%  
0 deg  
10 deg  
20 deg  
30 deg  
40 deg  
50 deg  
60 deg  
70 deg  
80 deg  
90 deg  
100 deg  
110 deg  
120 deg  
130 deg  
140 deg  
150 deg  
160 deg  
170 deg  
180 deg



In the case of **planes and lineations**, green pies show relative density of data dip direction

If **slickensides or s-c planes** are evaluated, greens pies show relative density of striated planes or s planes

Blue transparent pies are displaying relative density of **slickenside slip direction** or **c plane dip direction**







# **GROUPS AND COLOR MANAGEMENT**



- Each user-created input file could have a **user defined 1-digit group code**, in the range of A – J. If any record has no group code, will get a default 'X' character. The user can choose use these group codes during the processing or not



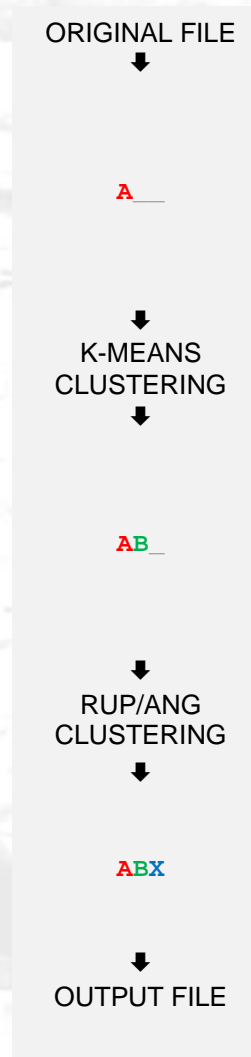
- While k-means clustering, a **second character will be added in the range of 'A' – 'J', referring to each clusters**, resulting in a **2-digits group code**. If no clustering, a default 'X' character will be added each data set



- While RUP/ANG clustering of slickensides, a **third character will be added in the range of 'A' – 'J', referring to each clusters**, resulting in a **3-digits group code**. If no clustering or no striae to process, a default 'X' character will be added each data set



- Each output file will have a **3-digits group code**: the first character will be the **user-define one**, the second one shows the result of the **k-means clustering**, and the third one is for the **RUP/ANG clustering of slickensides**



- You can process your groups, and in the next step while exporting, you can color them on many different ways

### 1) PROCESSING OF GROUPS

While exporting, you have the following options

1. **Ignore** your groups, and put everything into the same output file
2. Use the **first** character (user defined group), to separate your data by **the original user defined groups**
3. Use the **second** character (k-means clustering result), separate your data by the **k-means clustering result**
4. Use the **third** character (RUP/ANG clustering result), separate your data by the **RUP/ANG clustering result**

### 2) COLORING OF GROUPS

While coloring, you have the following options

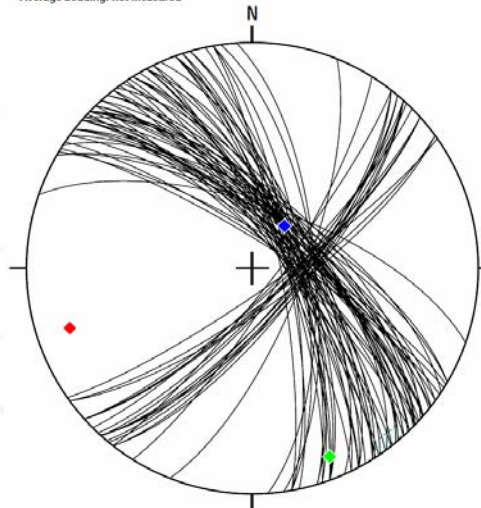
1. **Ignore** any groups and color code, and color everything black
2. Use the **color code** to color everything
3. Use the **first** character of the group code (user defined group), to separate your data by **the original user defined groups**
4. Use the **second** character of the group code (k-means clustering result), separate your data by the **k-means clustering result**
5. Use the **third** character of the group code (RUP/ANG clustering result), separate your data by the **RUP/ANG clustering result**



- It is possible to separate the processed data set 1) by user defined group codes, 2) by k-means clustering result, 3) by RUP/ANG clustering results (in the case of slickensides), or 4) display everything together

- To find coloring options, please see Chapter 2 and 5.21

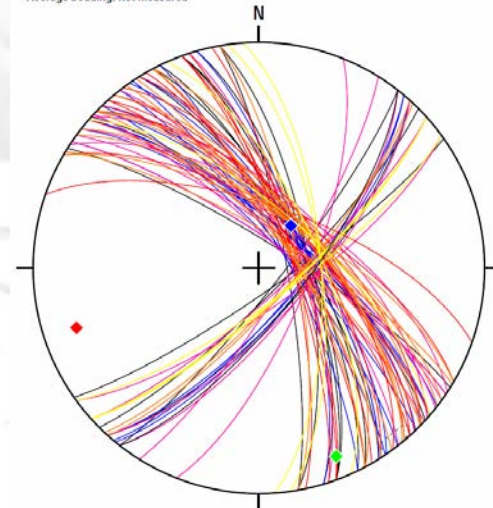
Data number: 86  
Average bedding: not measured



Exporting a data set **without** separation by user define groups, showing everything (used defined groups A, B, C, D, E, F and X) on the same stereonet

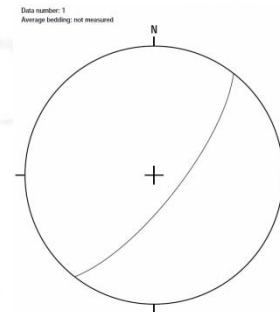
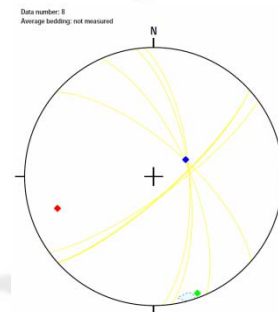
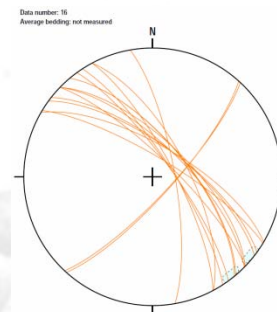
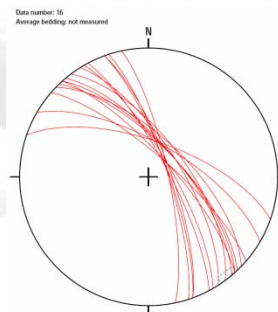
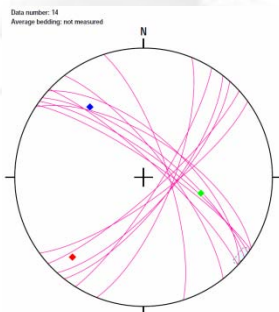
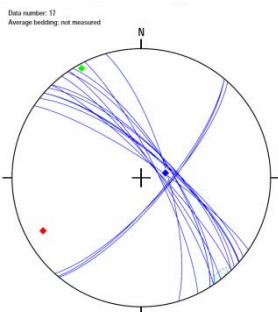
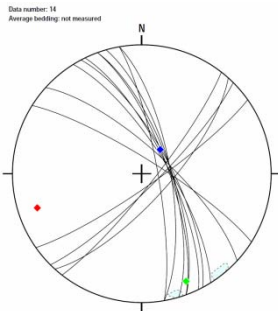
Data is colored by data sets group code ➡

Data number: 86  
Average bedding: not measured



➡ Original data set, ignoring both user defined color codes and groups

➡ Exporting the same data set **separated by their user define groups**, resulting in 7 stereonets, one for each group code (A, B, C, D, E, F, X). Data is colored by data sets group code







# INPUT FILE FORMAT



# 4.1.1

## INPUT FILE FORMAT

### RGF DATA FORMAT I.

- RGF data file (\*.rgf) is a text file. **First line is the header**, with **FIXED** content (used by the software to identify expected field content) to indicate column names; header column names are **bold and blue** below. Columns could be in arbitrary order; header is **case sensitive**, the file content is not. Please use ANSI characters for the file name and content
- 1<sup>st</sup> column is for the **DATA\_ID**; all of measurements entered in the RGF file **must** have an individual ID, which **must be different** from each other
- 2<sup>nd</sup> column shows the **GROUP\_CODE**; use if you want to process more than one group (ie. different slickenside sets on the same location); characters 'A' – 'I', 'X', 'a'-'i' and 'x' are accepted here. If the field is empty, group will become default group 'X'. Use one digit for an original input file; the output will get a three digits GROUP\_CODE, first character for the user defined groups, second one for the k-means clustering, and a third one for the RUP/ANG clustering results. If no e.g. RUP/ANG clustering, the third digit will become 'X'
- 3<sup>rd</sup> column is for the **COLOR\_CODE**; use characters 'A' – 'J', 'a' – 'j' or numbers 0 – 9 to plot different colors. Empty cell, A and 0 is for default black color, other characters are for the colors at the right

4<sup>th</sup> column is for the **LOCATION** of the data point where the measurement has done. You just need to enter the **new** data point name, otherwise the data point name of the previous record will be used. At least the first record must contain data



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	DATA_ID	GROUP_CODE	COLOR_CODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIP_DIR	DIP	L_DIP_DIR	L_DIP	SENSE	PALEONORTH	DEPTH	COMMENT
2	P_S_0019	a	e	547	1436887	366576	Dachstein	Striae	258	78	188	58	D			
3	P_S_0020	a	e						271	73	198	N	D			reliable
4	P_S_0021	a	e					Bedding	264	64						overturned
5	P_S_0022	a	e						278	77						
6	P_S_0029	a	f						266	76						
7	P_S_0030	a	f	Well-2	1436656	355889	Dachstein	Bedding	264	74				12	1345.55	
8	P_S_0031	b	f				Kossen	Fracture	248	69				12	1445.76	
9	P_S_0032	b	f						272	72				12	1657.99	



## 4.1.2

# INPUT FILE FORMAT

## RGF DATA FORMAT II.

- 5<sup>th</sup> and 6<sup>th</sup> columns are for the **LOC\_X** and **LOC\_Y coordinates** of the data point; just enter **new** data, otherwise previous record will be used. The following solutions are useful:
  - leave these fields empty if you do not have coordinates or do not need them
  - fill them manually, or
  - if you want to process the final spread sheet with GIS / database manager softwares, use **coordinate** (\*.xy) file (see Chapter 4.3) – in this case the content of these columns will be **overwritten** by the content of xy coordinate file
- 7<sup>th</sup> column is for the **FORMATION** name; not required to fill. Enter new formation name, otherwise it will be filled by content of previous record
- 8<sup>th</sup> column is for the **DATATYPE**. Enter new data type if changed, otherwise it will be filled by content of previous record:
  - for **lithology**: 'lithology'
  - for **lineations**: 'boudain', 'foldaxis', 'kink', 'lineation', 'userlineation1', 'userlineation2', 'userlineation3', 'userlineation4' and 'userlineation5'
  - for **planes**: 'bedding', 'borehole break-out' or 'bbo', 'contact', 'crossbedding', 'foldplane', 'foldsurface', 'fracture', 'lithoclase', 'plane', 'userplane1', 'userplane2', 'userplane3', 'userplane4', 'userplane5', 's1', 's2', 's3', 's4', 's5', 'stress-induced fracture' or 'sif', and 'vein'
  - for **slickensides**: 'striae', and
  - for **s-c schistosity**: 'sc'

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	DATA_ID	GROUP_CODE	COLOR_CODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIP_DIR	DIP	L_DIP_DIR	L_DIP	SENSE	PALEONORTH	DEPTH	COMMENT
2	P_S_0019	a	e	547	1436887	366576	Dachstein	Striae	258	78	188	58	D			
3	P_S_0020	a	e						271	73	198	N	D			reliable
4	P_S_0021	a	e					Bedding	264	64						overturned
5	P_S_0022	a	e						278	77						
6	P_S_0029	a	f						266	76						
7	P_S_0030	a	f	Well-2	1436656	355889	Dachstein	Bedding	264	74				12	1345.55	
8	P_S_0031	b	f				Kossen	Fracture	248	69				12	1445.76	
9	P_S_0032	b	f						272	72				12	1657.99	



## 4.1.3

# INPUT FILE FORMAT

## RGF DATA FORMAT III.

- 9<sup>th</sup> **DIP\_DIR** column is for the **strike/dip direction** (depending on input settings) of lineations, planes, planes with slickenside, or s planes of s-c data sets. All of records must be filled except the case of 'lithology' datatype. Values between 0.0 – 360.0 are accepted
- 10<sup>th</sup> column is for the **DIP angle** (plunge) of lineations, planes, planes with slickensides, or s planes of s-c data sets. All of records must be filled except the case of 'lithology' datatype with values between 0.0 – 90.0
- 11<sup>th</sup> **L\_DIP\_DIR** column is
  - for the **strike/dip direction** either **c planes** of s-c data sets, or for the bearing of **striae lineation** (values between 0.0 – 360.0 are accepted), or
  - for the **pitch angle** of the striation in the case of using pitch convention. All of records must be filled in the case of 'striae' or 'sc' data type; enter values between 0.0 – 90.0 for the pitch angle
- 12<sup>th</sup> **L\_DIP** column is
  - for the **dip angle** of **c plane** or plunge of **slickenside lineation**. All records must filled if using 'striae' or 'sc' data types (values between 0.0 and 90.0 are accepted), or
  - in case of **pitch** convention this column indicates the **dip direction of the pitch** (enter 'n', 'nne', 'ne', 'ene', 'e', 'ese', 'se', 'sse', 's', 'ssw', 'sw', 'ws', 'w', 'wnw', 'nw' or 'nnw' for pitch direction)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	DATA_ID	GROUP_CODE	COLOR_CODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIP_DIR	DIP	L_DIP_DIR	L_DIP	SENSE	PALEONORTH	DEPTH	COMMENT
2	P_S_0019	a	e	547	1436887	366576	Dachstein	Striae	258	78	188	58	D			
3	P_S_0020	a	e						271	73	198	N	D			reliable
4	P_S_0021	a	e					Bedding	264	64						overturned
5	P_S_0022	a	e						278	77						
6	P_S_0029	a	f						266	76						
7	P_S_0030	a	f	Well-2	1436656	355889	Dachstein	Bedding	264	74				12	1345.55	
8	P_S_0031	b	f				Kossen	Fracture	248	69				12	1445.76	
9	P_S_0032	b	f						272	72				12	1657.99	



## 4.1.4

# INPUT FILE FORMAT

## RGF DATA FORMAT IV.

13<sup>th</sup> **SENSE** column is for the 1) **movement direction** along slickenside, and 2) to indicate **normal/overtured** geometry of bedding. Must be filled in the case of slickensides and in the case of overtured beds, otherwise it is empty. The following characters are accepted here for slickensides:

- '+', 'thrust', 'up', 'inverse', 'u' or 'i' for **inverse/reverse** offset
- '-', 'normal', 'fault', 'down', 'downward', or 'n' for **normal** movement
- 'dextral', 'dx' or 'd' for **dextral** movement
- 'sinistral', 'sn' or 's' for **sinistral** movement, and
- 'x' or 'none' for **unknown** offset

For bedding planes, use

- 'o' or 'overtured' to indicate **overtured** bedding, otherwise it will be handled as normal one
- it is allowed (but not necessary) to use 'n' or 'normal' to indicate **normal** bedding

14<sup>th</sup> column is for the **PALEONORTH** direction; if it is known, can be indicated and used, otherwise leave empty. Values between 0.0 – 360.0 are accepted here

15<sup>th</sup> column is for the well data **DEPTH** which must be present for each well data sets

16<sup>th</sup> column is for your **COMMENTS**

17<sup>th</sup> and other columns: will be not processed by the software. Everything **behind** the 17<sup>th</sup> column will be exported with no modification, so it is possible to store here as many data as you want

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	DATA_ID	GROUP_CODE	COLOR_CODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIP_DIR	DIP	L_DIP_DIR	L_DIP	SENSE	PALEONORTH	DEPTH	COMMENT
2	P_S_0019	a	e	547	1436887	366576	Dachstein	Striae	258	78	188	58	D			
3	P_S_0020	a	e						271	73	198	N	D			reliable
4	P_S_0021	a	e					Bedding	264	64						overtured
5	P_S_0022	a	e						278	77						
6	P_S_0029	a	f						266	76						
7	P_S_0030	a	f	Well-2	1436656	355889	Dachstein	Bedding	264	74				12	1345.55	
8	P_S_0031	b	f				Kossen	Fracture	248	69				12	1445.76	
9	P_S_0032	b	f						272	72				12	1657.99	



## 4.2.1

# INPUT FILE FORMAT

## SET DATA FORMAT I.

SET data file (\*.set) is a **non case sensitive**, **tab separated** text file storing the settings **keys** and **values** used during data processing. It is not necessary to have all settings; if any correct setting is found in the file will be used, otherwise default settings were applied. The order of these settings in the file is arbitrary. Default keys are **bold and blue**, and default settings values (hard coded ones in software) are **bold** characters

### 0) PROCESSING MODE

**WELLDATA:** 'n' to evaluate input file as a field data set, and 'y' to process the input file as a well data set

#### 1) WELL

**WELLINTERVAL (4.1)** while processing well data (e.g. fractures or bedding), a moving average of the processed data set is calculated. The interval, used for the step-by-step moving average calculation is called *bin*. Size of this bin can be either defined in **meters** and you can use 'm', or if you like, you can create fix data number interval applying 'd' in the settings file

**WELLINTERVAL\_LENGTH (4.2)** here you can define the length of your bin: how many meters or how many piece of data can belong to one bin between 1 and 5000 (**100** meters or piece of data as default). We recommend to have at least 50-100 bins, so divide the complete data number or your logged interval by 50-100

**WELLINTERVAL\_MIDDLE (4.3)** here the question is how to calculate the middle depth of the processed bin: it can be either the median depth of each interval (use 'm'), or the arithmetic average (use 'a') of each intervals

#### 2) PLOT

**DATARULE (4.4):** 'g' for German dip direction/dip convention, and 'r' for right hand rule input (output will be in the same format as the input)

**PLOT (4.5):** 'a' for classic Angelier plot, and 'h' for Hoeppner pole point plot

**PLOTTYPE (4.6):** 's' for equal area Schmidt projection, and 'w' for equal angle Wulff projection

**HEMISPHERE (4.7):** 'u' in the case of upper, and 'l' for lower hemisphere

**CONTOURING (4.8):** enter 'n' do not use, 'd' to contour dip direction/lineation bearing, 's' for strike/lineation bearing, 'o' for plane normal/lineation bearing and 'b' for slickenside/lineation bearing

**TILTING (4.9):** refers to the **bedding and palaeonorth direction correction**: use 'b' to re-tilt everything with the bedding, 'p' to correct by palaeonorth direction, and 'a' to do both of them

### 3) INVERSION

**INVERSION (4.10):** for the striae **inversion** methodology:

- 'n' for no inversion,
- 'b' for brute force inversion,
- 'd' for NDA after Spang (1972),
- 'p' for PTN after Turner (1953),
- 'f' for Fry (1999),
- 's' for Shan et al (2003),
- 'm' for Michael (1984),
- 'a' for Angelier (1990), and
- 'o' for Mostafa (2005)

**BINGHAM (4.11):** for fracture **weight point statistics**: enter 'b' to use Bingham statistics, or 'n' if you do not need

**STRESSANGLE (4.12):** for the **angle** between the maximum stress direction and the slickenside direction, and will be used only by NDA and PTN methodologies; enter a number between 10 and 80 (**30** deg is the default setting)

**VIRTUAL (4.13):** for the **virtual symmetrical data set**: enter 'y' to use them, otherwise input 'n'



### 4) DATA GROUP MANAGEMENT

**INPUTGROUP (4.14):** this option is used while opening the result of a previous interpretation loop. The output file has a three digits group code (1<sup>st</sup> built up by the user defined one, 2<sup>nd</sup> is the k-means clustering result and 3<sup>rd</sup> for the RUP/ANG clustering). You can ignore them ('n'), use the first digit ('f') to group your data for the original user defined group, or use the second digit ('s') to group your data using the former the k-means clustering results, (if it exists at all), or use the third digit ('t') to group your data using the former RUP/ANG clustering results

**GROUP (2, 4.15):** if you want to use user defined groups (if they are indicated in 2<sup>nd</sup> column of RGF file), all data will be separated by locality, by datatype **plus by your groups**, and processed/displayed on this way. Input 'y' to use groups, or 'n' to do not use them

**CLUSTERNUMBER (4.16):** enter 'n' do not use, 'a' to find the ideal cluster number, or 2 – 9 for the required number of clusters. Either the entire data set will be processed, or clustering will be done group by group

**RUP\_CLUSTERING (4.17):** enter 'n' do not use, 'a' to do a clustering using the angular misfit (ANG) values of the stress inversion, or enter 'r' to use the relative epsilon (RUP) value (see Chapter 6.9.2) in the clustering procedure

**GROUPSEPARATION (2):** you had the chance to group everything by a user defined group code, by k-means clustering result and later by RUP/ANG clustering. While creating the output files, group codes can be ignored ('i') and each groups will handled together, or your data set will be displayed on different stereonet, separated by the user defined group code ('g'), by the k-means clustering results ('k') or by the results of the RUP/ANG clustering ('r')

### 5) ROSE DIAGRAM

**ROSETYPE (4.18.1):** enter 's' for symmetric (bidirectional) and 'a' for asymmetric (unidirectional) one

**ROSEDIRECTION (4.18.2):** enter 's' or 'd' to show strike or dip direction distribution on the rose plot

**ROSEBINNING (4.18.3):** enter 'a', 'b', 'c' or 'd' for 2.5, 4.0, 10.0 and 22.5 deg bin sizes on the rose plot

### 6) OTHER

**IDEALMOVEMENT (4.19):** enter 'y' if you want to display ideal movement direction of slickensides, otherwise use 'n'

**LABELING (4.20):** enter 'y' to label all of your data on the stereonet, otherwise use 'n'

**LINEWIDTH:** used on stereonets in points; enter 1 - 9 for 0.1 – 0.9, or 0 for 1.0. Default **6** is for 0.6 points

**COLORING (2):** you had the chance to group everything by a user defined group code, by k-means clustering result and later by RUP/ANG clustering, and you had the chance to use color codes for different records, too. While coloring the output stereonets, either any codes are ignored ('i') to generate uniform black colors, or data records can be colored using their color codes ('c'). It is possible to color them using their user defined group code ('g'), using their the k-means clustering results ('k') or using their the results of the RUP/ANG clustering ('r')

**GRAYSCALE (4.21):** RGB colored ('n') and grayscale ('y') outputs are possible for the user's choice; grayscale output is recommended for publications



- XY data file (\*.xy) is a tab separated text file with the following properties:
  - Has **4 columns**;
  - First line is the header**, with arbitrary content (it is recommended to indicate column names here)
- 1<sup>st</sup> column must be **data point name**. The software will use this field to search for coordinates to merge with the original input (\*.rgf) file content. In the case of repetition of data point names, error message will displayed
- 2<sup>nd</sup> and 3<sup>rd</sup> columns must be **coordinates** in user defined **numeric format** and order. Just correct numeric format will checked but otherwise not processed by the software just merged with the opened \*.rgf file content. These values will overwrite the relevant rows of LOC\_X and LOC\_Y columns
- 4<sup>th</sup> column is for the (optional) **formation name**; the software will use this field to complete the original input (\*.rgf) file content and overwrite the **FORMATION** field if it has any record

	A	B	C	D
1	LOCATION	LOC_X	LOC_Y	FORMATION
2	001	35.167340	44.696108	FARS
3	002	35.060867	44.589635	FARS
4	003	34.689926	44.218694	FARS
5	004	35.323870	44.852638	FARS
6	005	34.704831	44.233599	FARS
7	006	34.589101	44.117869	FARS
8	007	34.833382	44.362150	FARS
9	008	34.840982	44.369750	FARS
10	009	34.724930	44.253698	FARS
11	230	35.168929	44.697697	BEKHME
12	ANG001	35.169656	44.698424	BEKHME
13	ANG002	35.171196	44.699964	BAKHTIARI
14	ANG003	35.173050	44.701818	KAREEM
15	ANG004	36.164102	45.692870	KAREEM
16	ANG005	35.769995	45.298763	KAREEM
17	ANG006	35.758512	45.287280	KAREEM
18	ANG007	35.708102	45.236870	KAREEM
19	ANG008	35.708104	45.236872	KAREEM
20	ANG009	36.457510	45.986278	KAREEM
21	ANG010	35.708932	45.237700	KAREEM
22	ANG011	35.725867	45.254635	KAREEM
23	BE-03	35.742802	45.271570	QAMCHUQA
24	BE-04	35.759736	45.288504	QAMCHUQA
25	BE-05	35.776671	45.305439	QAMCHUQA
26	BE-06	35.793606	45.322374	QAMCHUQA
27	BE-07	35.810541	45.339309	BEKHME
28	BE-08	35.827475	45.356243	BEKHME
29	BE-09	35.844410	45.373178	BEKHME



- TRJ data file (\*.trj) is a tab separated text file with the following properties:
  - Has **3 columns**
  - First line is the header**, with arbitrary content (it is recommended to indicate column names here)
- 1<sup>st</sup> column is for the **data point depth**. Only numeric values are accepted here
- 2<sup>nd</sup> and 3<sup>rd</sup> columns are for **coordinates** in user defined **numeric format** and order. The following data conventions are accepted here:
  - azimuth – plunge data set: the 2<sup>nd</sup> row has numeric values less than 360 but greater than 0, and the 3<sup>rd</sup> row has numeric values less than 90 but greater than 0
  - X – Y: any numbers in the coordinate data format of the project
  - The software identifies **automatically** which data convention is in use. Is the content of the trajectory file fulfills the first criteria, then it will be handled as an azimuth – plunge data set, otherwise it will be handled as an X – Y coordinate pair

	A	B	C
1	DEPTH	LOC_X	LOC_Y
2	1181.27	35.167340	44.696108
3	1198.57	35.060867	44.589635
4	1210.65	34.689926	44.218694
5	1212.55	35.323870	44.852638
6	1215.19	34.704831	44.233599
7	1217.23	34.589101	44.117869
8	1217.55	34.833382	44.362150
9	1221.93	34.840982	44.369750
10	1229.11	34.724930	44.253698
11	1231.16	35.168929	44.697697
12	1233.14	35.169656	44.698424
13	1241.48	35.171196	44.699964
14	1242.06	35.173050	44.701818
15	1243.51	36.164102	45.692870
16	1252.33	35.769995	45.298763
17	1253.15	35.758512	45.287280
18	1265.42	35.708102	45.236870
19	1265.97	35.708104	45.236872
20	1280.33	36.457510	45.986278
21	1281.85	35.708932	45.237700
22	1292.46	35.725867	45.254635
23	1300.51	35.742802	45.271570
24	1303.99	35.759736	45.288504
25	1312.55	35.776671	45.305439
26	1314.06	35.793606	45.322374
27	1330.94	35.810541	45.339309
28	1335.92	35.827475	45.356243
29	1341.43	35.844410	45.373178





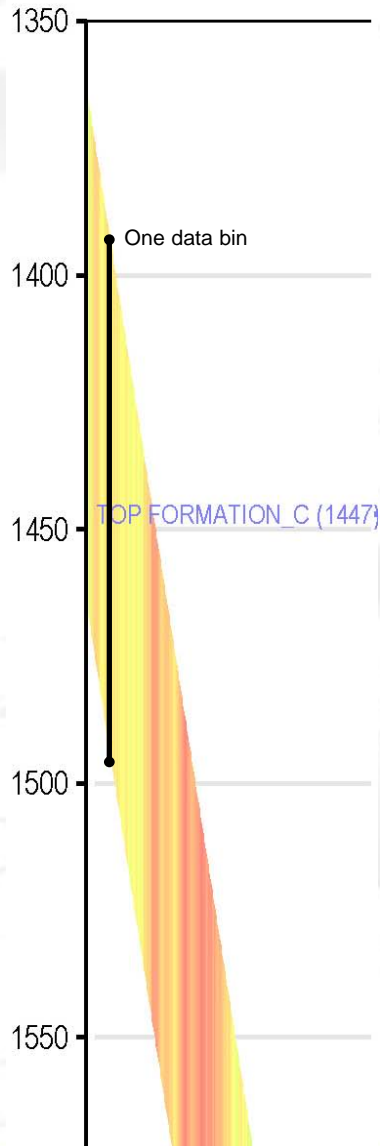
# PROCESSING AND DISPLAY



# 5.1

## PROCESSING AND DISPLAY

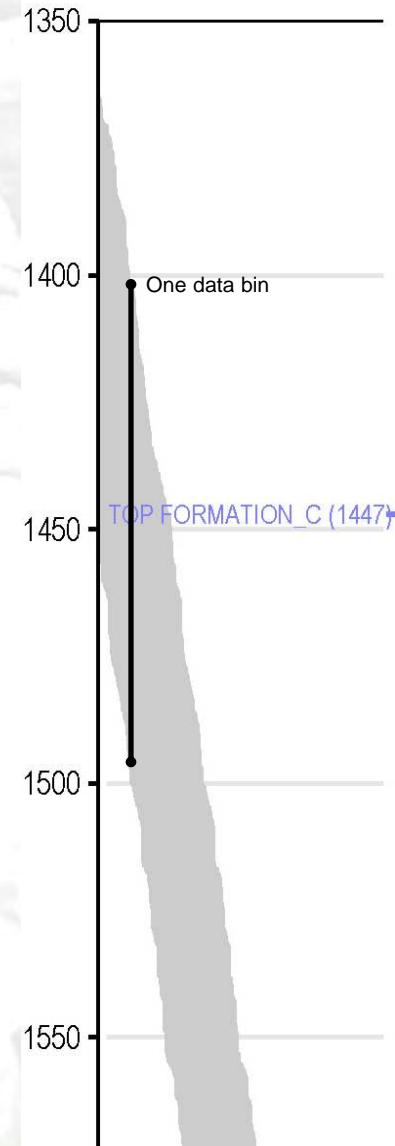
### WELL INTERVAL



- While well data processing, a **moving average curve** is calculated to highlight changes in the features geometry and/or frequency
- In order to do a moving average calculation, a processing interval (=bin) and the step have to be defined
- Bin size can be given by the user either in **meters** (e.g. 50m) or in **pieces** (e.g. 100 data). Different settings are resulting in different data bins, which generates different results
- Step size is default: 1m if the bin size is in meters, and 1 piece of data if the interval length is defined by data number

◀ Test data set, with 100m data bin value. Step interval during moving averages calculation is 1m. Vertical colored bars are showing each bin intervals. Color of the bars refers to the relative data number (green: many data, red: less data)

Test data set, with 100 piece data bin value. Step interval during moving averages calculation is 1 piece of data. Vertical gray bars are showing each bin intervals. No coloring: each bins have identical number of data ➡

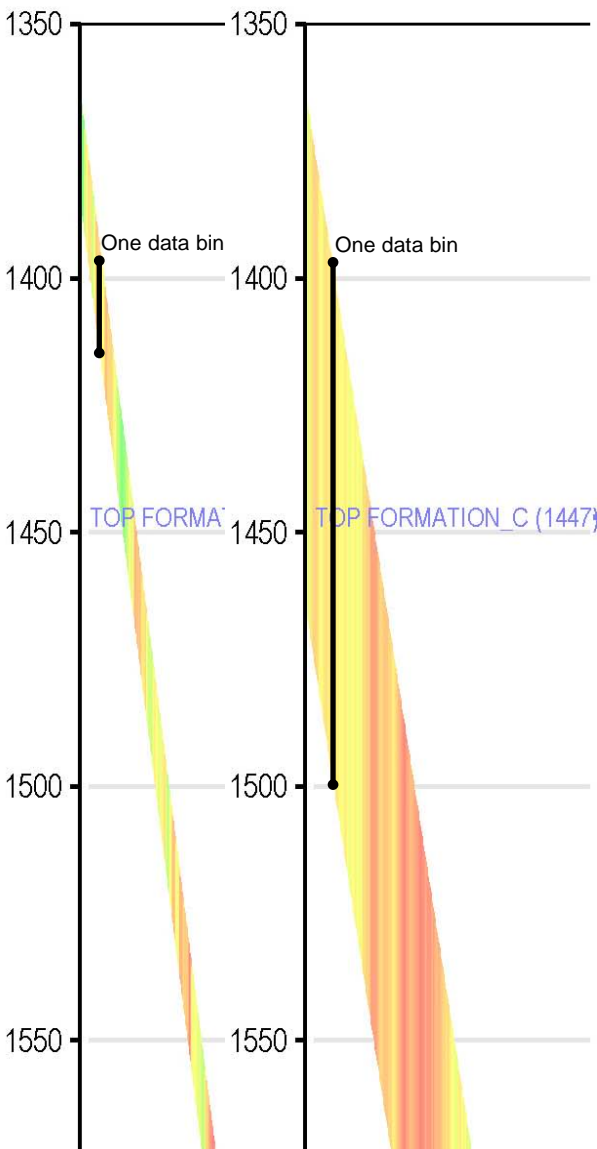




## 5.2.1

# PROCESSING AND DISPLAY

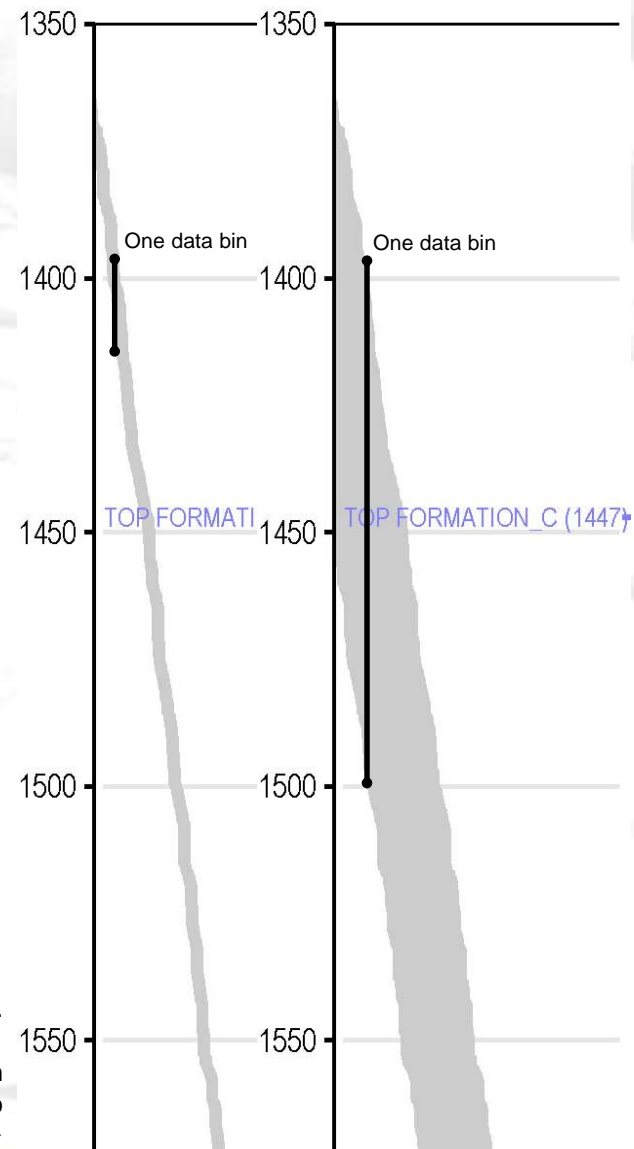
## WELL INTERVAL LENGTH $I$ .



- During the moving average calculation, the bin size can be changed by the user
- Bin size can change on a 0 - 5000m or 0 - 5000 piece of data scale
- Using too small bins, maybe you will see a noisy outcome because 'over zooming' the data set
- Using too large bins, you can easily hide the real changes because having less resolution than required
- It is proposed to try to do many processing loops, varying both the bin size and bin type (meters or piece of data) to study the same data set with different resolutions

◀ Test data set, with 20m and 100m data bin value. Step interval during moving averages calculation is 1m. Vertical colored bars are showing each bin intervals. Please compare the intervals taken into account while processing

Test data set, with 20 and 100 piece data bin value. Step interval during moving averages calculation is 1 piece of data. Vertical gray bars are showing each bin intervals. Please compare the intervals taken into account while processing ➡



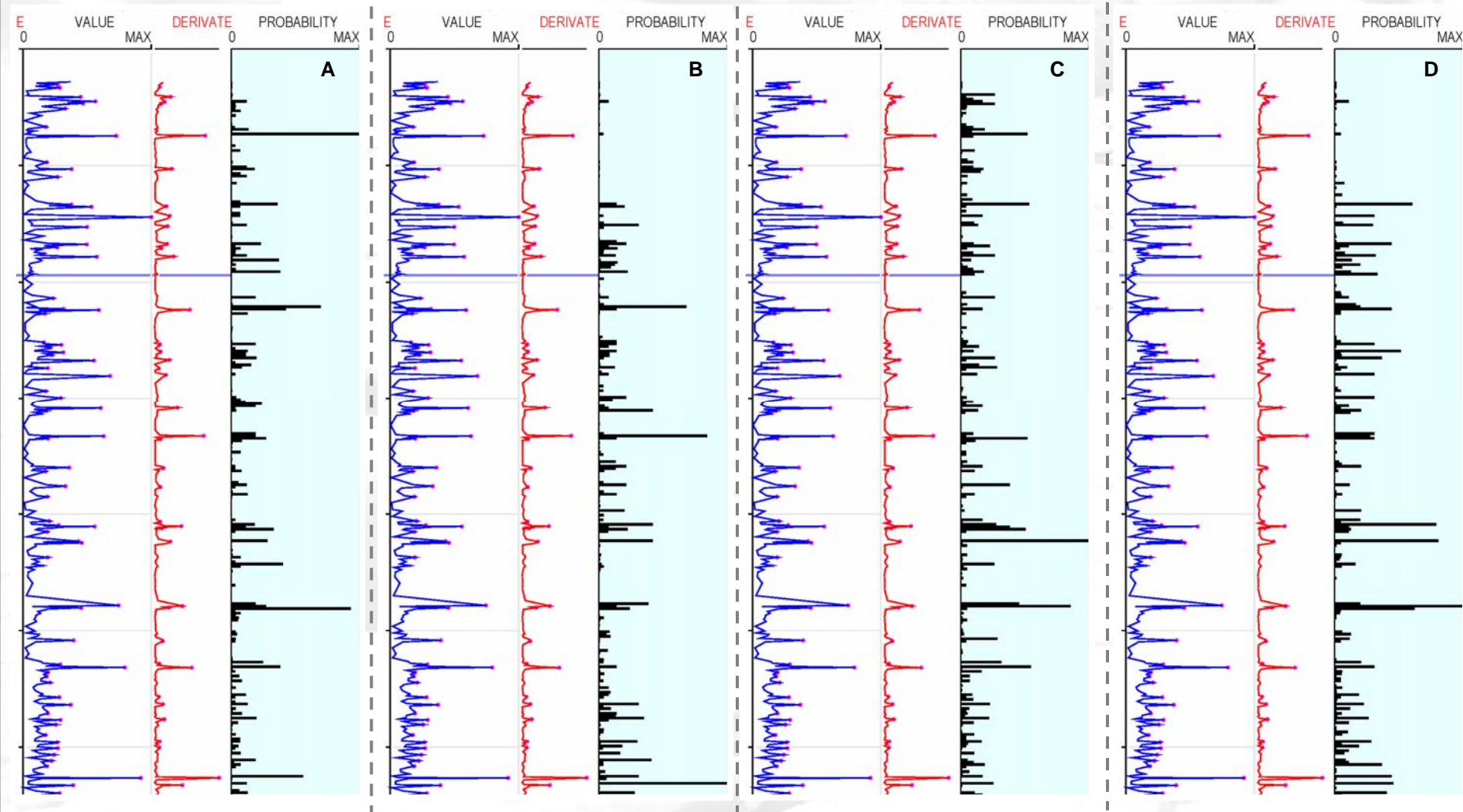


## 5.2.2

# PROCESSING AND DISPLAY

## WELL INTERVAL LENGTH II.

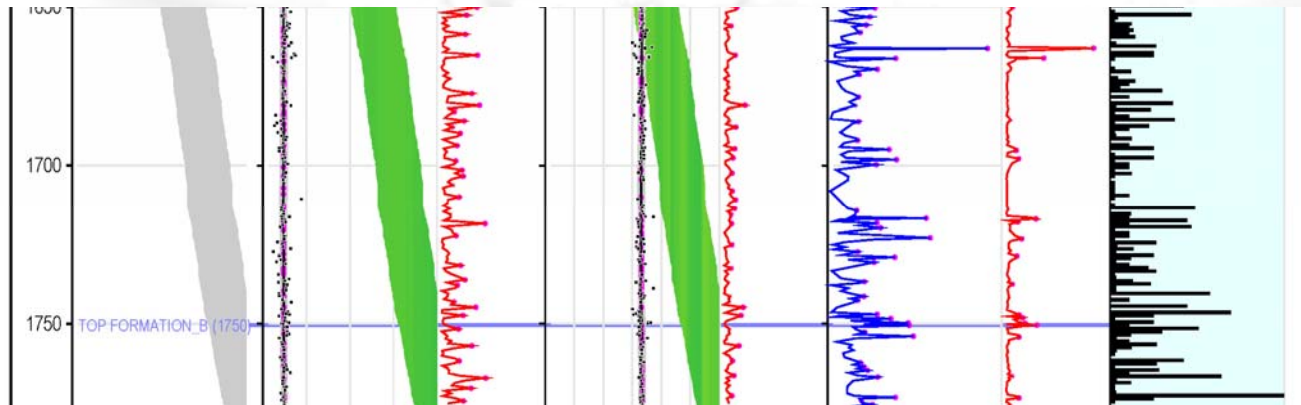
Fault / deformation zone reliability graph for the same data set, using 20m and 100m, and 0 and 100 piece data bin size  
Please note the same data set was processed on different resolutions



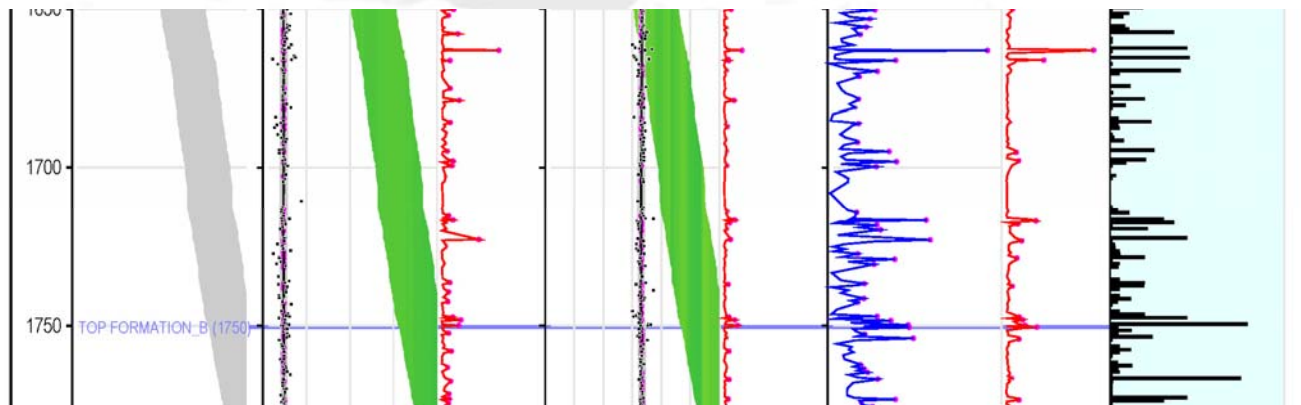


# 5.3

## PROCESSING AND DISPLAY WELL INTERVAL AVERAGE



Test data set, with 100 piece of data bin value. Bin interval middle point is the *average depth* of the binned data



Test data set, with 100 piece of data bin value. Bin interval middle point is the *median depth* of the binned data

- During the moving average calculation, one of the questions is about the **middle point depth** of the used bins
- In the case of a **dense** and **homogeneous** set, the **arithmetic average** depth of the binned data can be used
- In the case of **inhomogeneous** data set, and especially having significant **gaps**, **median depth** of the binned data is recommended to use



# 5.4

## PROCESSING AND DISPLAY

### GERMAN DIP DIRECTION AND RIGHT HAND RULE

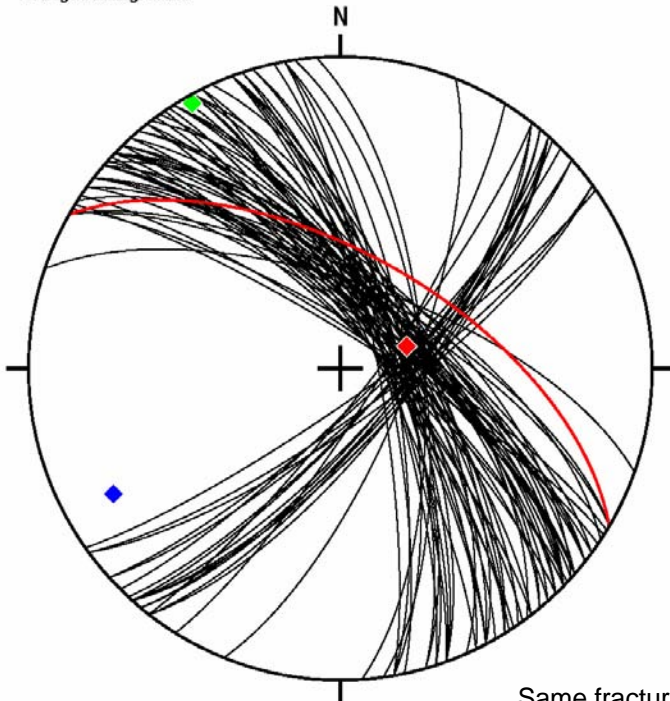
#### DIP DIRECTION

- In this case the planes and lineations are described by the **dip direction** and **dip angle** of the element, in this order
- To convert German convention data set to right hand rule data, add -90 degrees to the dip direction

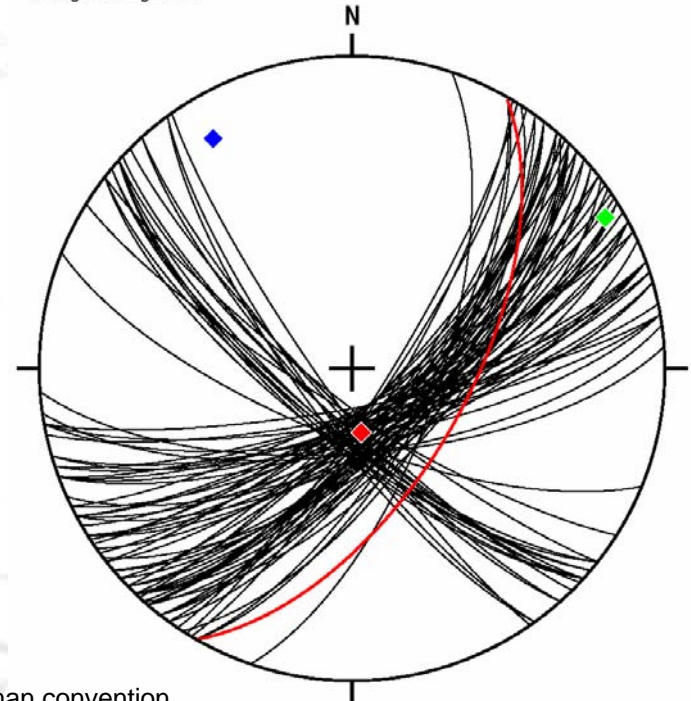
#### RIGHT HAND RULE

- In the case of right hand rule, planes are described with **strike** direction (-90 degrees from dip direction) and **dip angle** of the planar object, in this order
- Lineations are presented by **bearing and plunge**, which are the **equivalents** of dip direction and dip angle

Data number: 86  
Average bedding: 030/60



Data number: 86  
Average bedding: 030/60



Same fracture data set processed as German convention data (left) and right hand rule data (right)



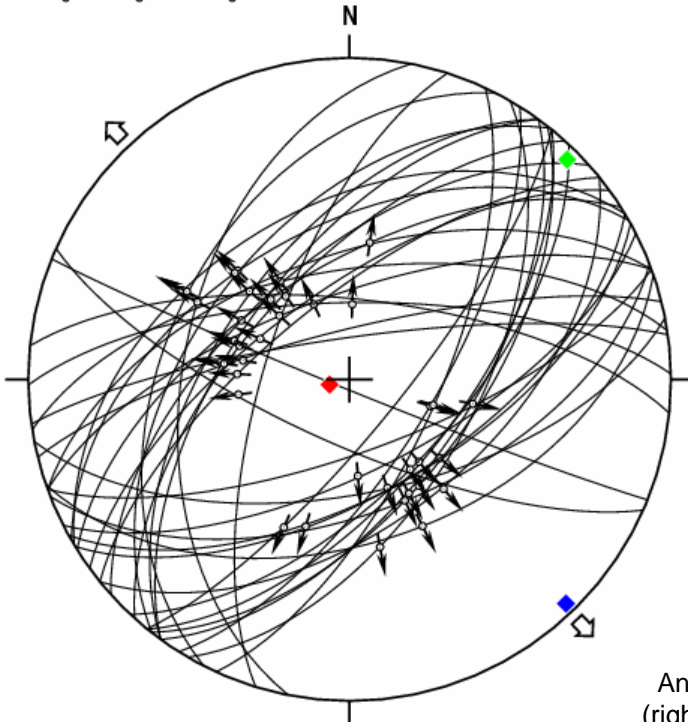
# PROCESSING AND DISPLAY

## ANGELIER AND HOEPPNER PLOT

### ANGELIER PLOT

- Angelier plot shows all planes as **great circles**, and all lineations as **points**
- In the case of slickenside visualization, fault plane and the **movement direction** along it is displayed
- Easy to read in the case of **homogenous** data sets, or in the case of **small** number of data

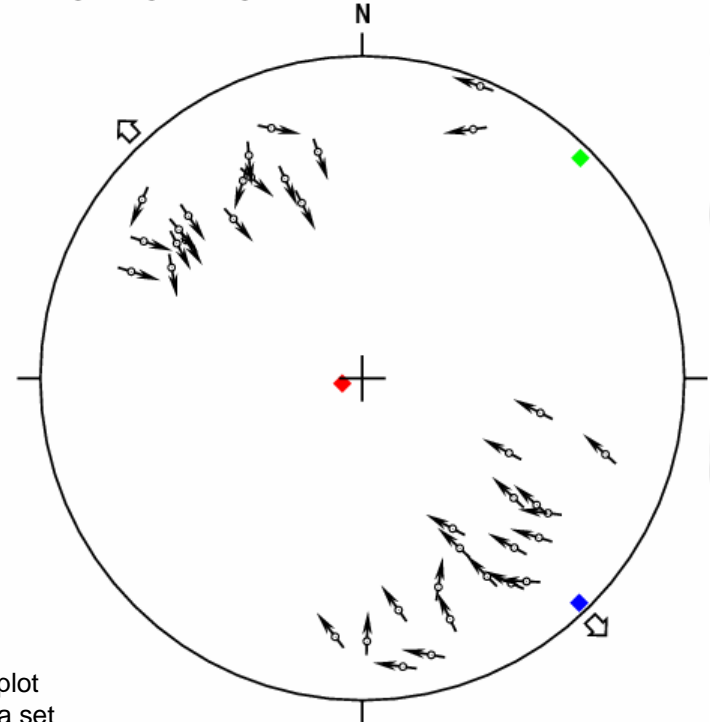
Data number: 38  
Average bedding: no bedding measured



### HOEPPNER PLOT

- Hoeppner plot shows **pole point of the planes**
- Lineations are displayed as **points** as well
- Striae are plotted as **pole points** pointing in the **movement direction of the hanging wall**
- This representation is really useful in the case of **large** or **inhomogeneous** data sets

Data number: 38  
Average bedding: no bedding measured



Angelier plot (left) and Hoeppner plot (right) of Angelier's (1990) TYM data set



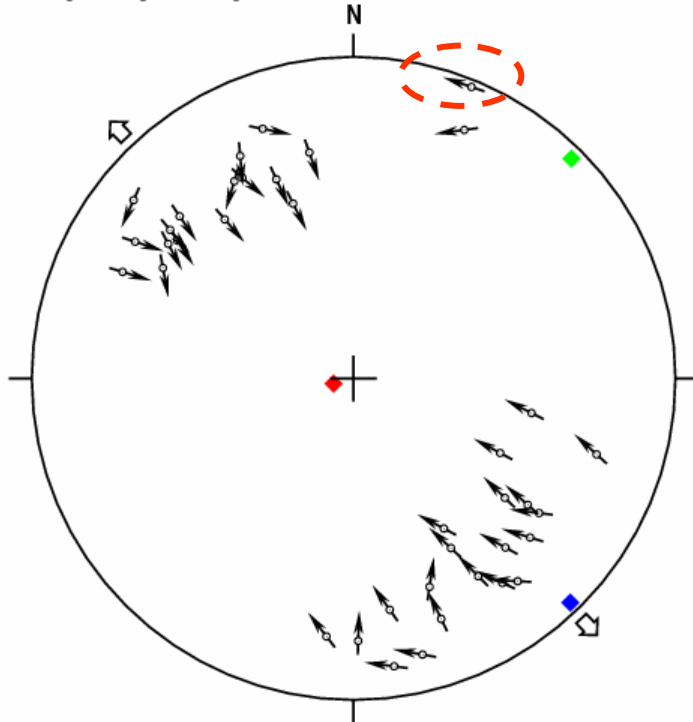
# 5.6

## PROCESSING AND DISPLAY SCHMIDT AND WULFF NET

### SCHMIDT NET

- Equal area projection
- Great circles are **Bezier** curves

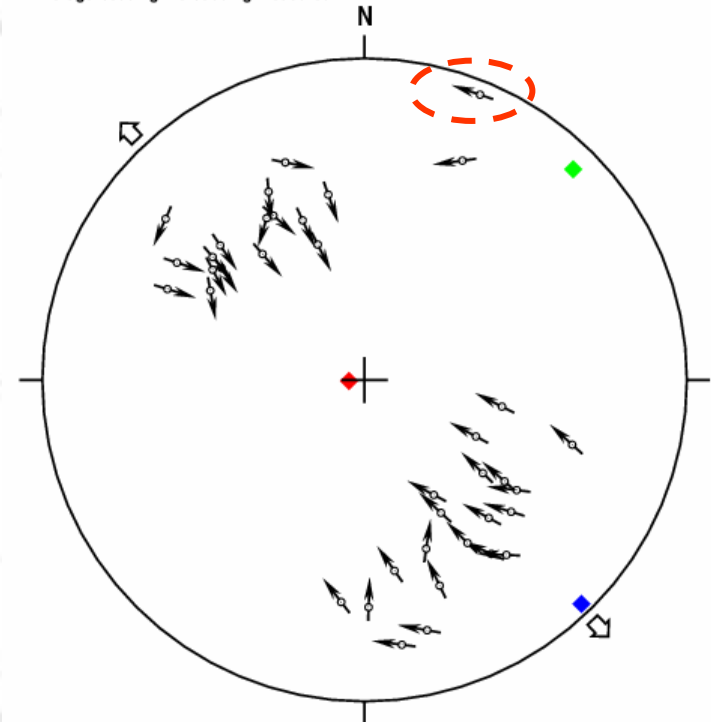
Data number: 38  
Average bedding: no bedding measured



### WULFF NET

- Equal angle projection
- Great circles are **arcs**

Data number: 38  
Average bedding: no bedding measured



Schmidt-net (left) and Wulff-net (right)  
projection of Angelier's (1990) AVB data set



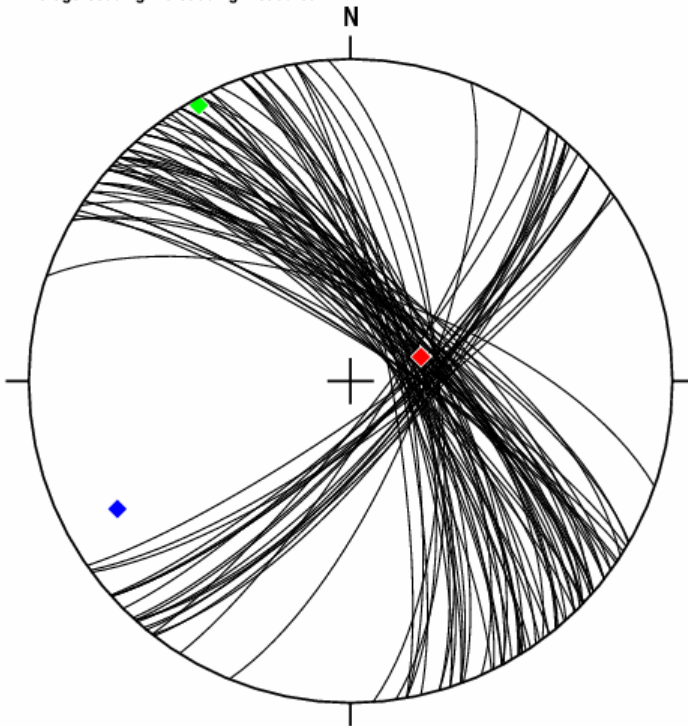
# 5.7

## PROCESSING AND DISPLAY LOWER AND UPPER HEMISPHERE

### LOWER HEMISPHERE

- Projects on **lower** hemisphere

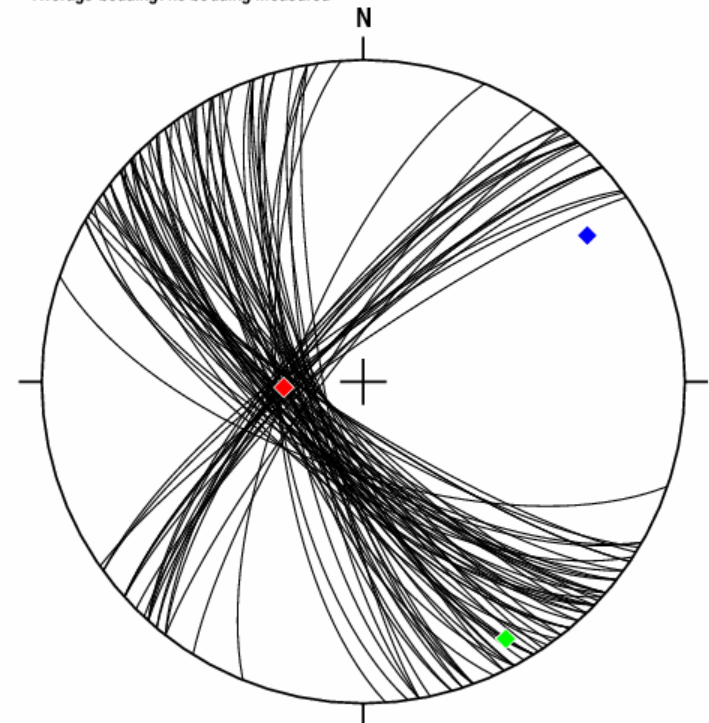
Data number: 86  
Average bedding: no bedding measured



### UPPER HEMISPHERE

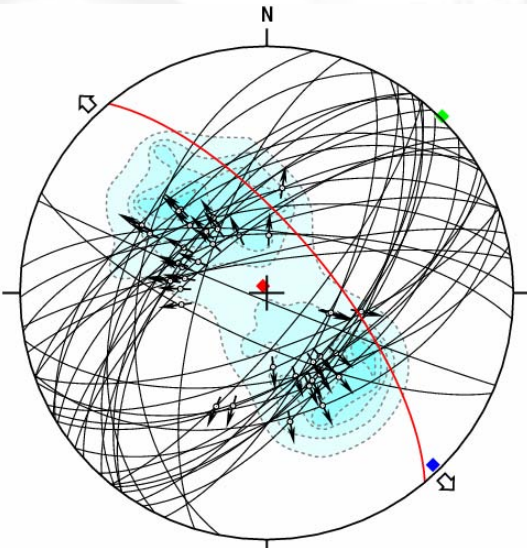
- Projects on **upper** hemisphere

Data number: 86  
Average bedding: no bedding measured



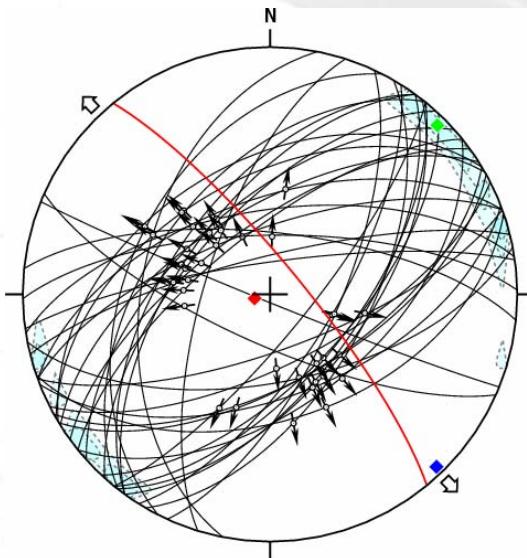
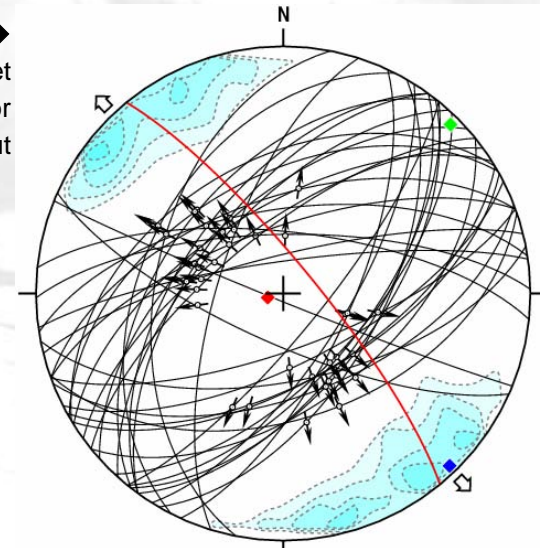
Lower hemisphere (left) and upper hemisphere (right) projection of the same inverse slickenside data set





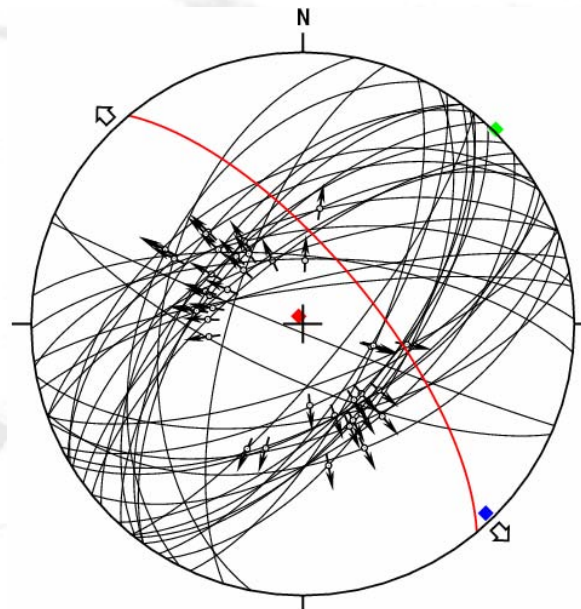
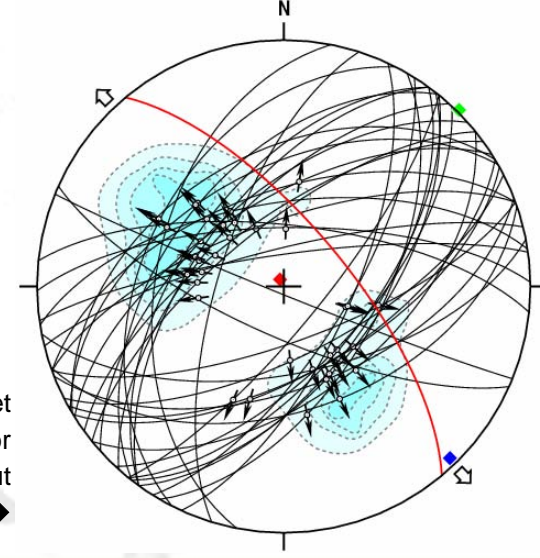
←  
Contouring of the input data set  
using plane **dip direction** or  
lineation **bearing** as input

→  
Contouring of the input data set  
using **plane normals** or  
**lineation bearing** as input



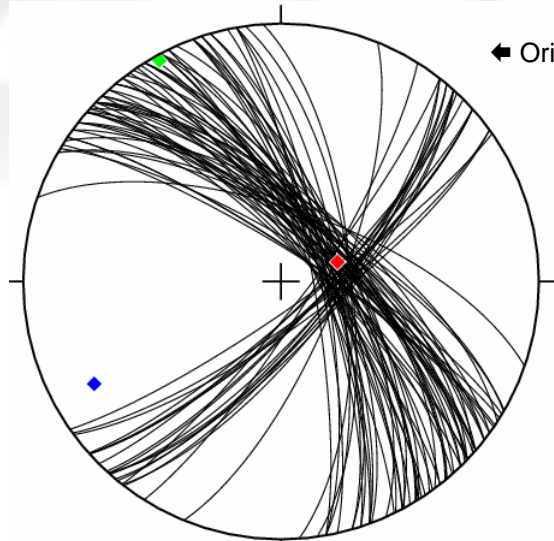
←  
Contouring of the input data set  
using plane **strike direction** or  
lineation **bearing** as input

→  
Contouring of the input data set  
using **striae bearing** or  
**lineation bearing** as input



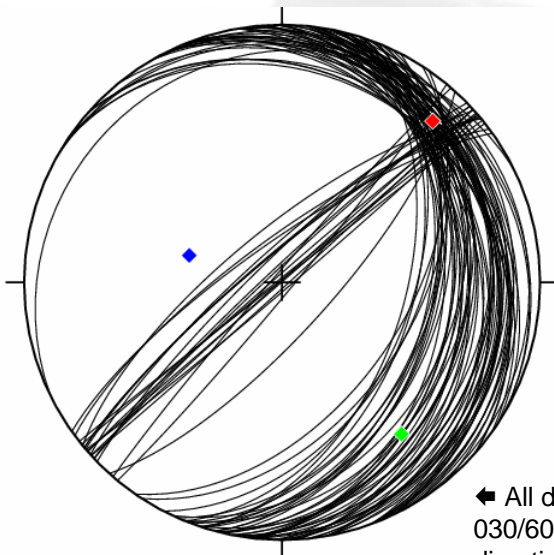
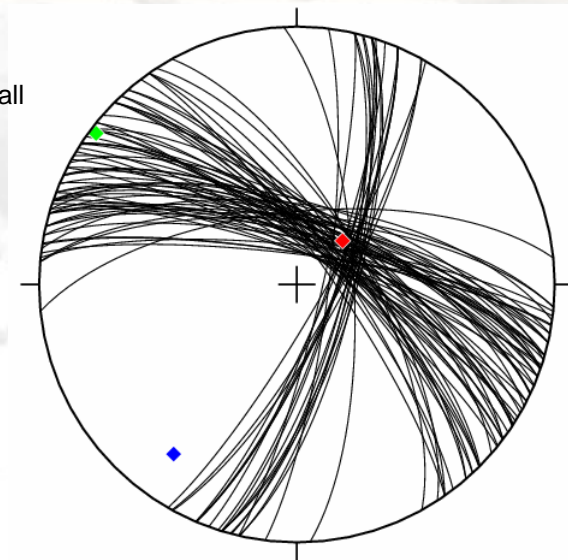
↑  
Original input data set, **no**  
**contouring** method was chosen





← Original dataset

Corrected by 30 deg  
palaeonorth direction for all  
of data ➡



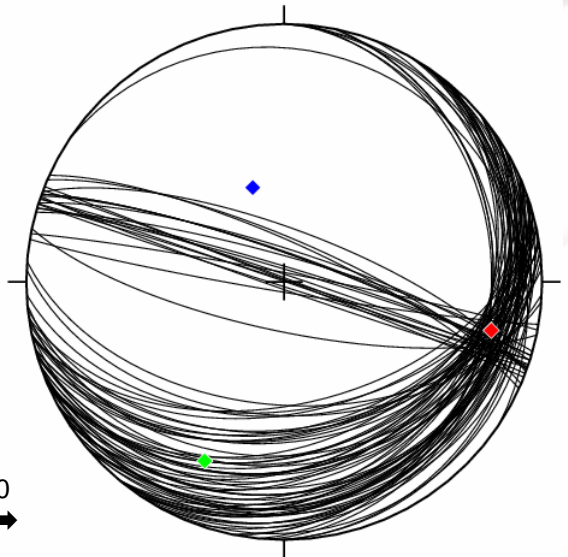
← All data corrected by  
030/60 average bedding  
direction

- Selecting **bedding correction** option, all data will be re-tilted by the **average bedding** measured in the outcrop. If no bedding data, the plot for measured and corrected data will be the **same**

- Selecting **palaeonorth direction correction**, all data will be corrected with the palaeonorth direction entered in RGF file. Correction will be done **record by record**

- Third possibility is to apply **both** of these correction re-tilting everything by average bedding plane direction **and** by palaeonorth direction

Corrected by 030/60  
average bedding and by 30  
deg palaeonorth direction ➡





# 5.10.1

## INVERSION I.

### REGRESSION WITH A PRIORI ASSUMPTION

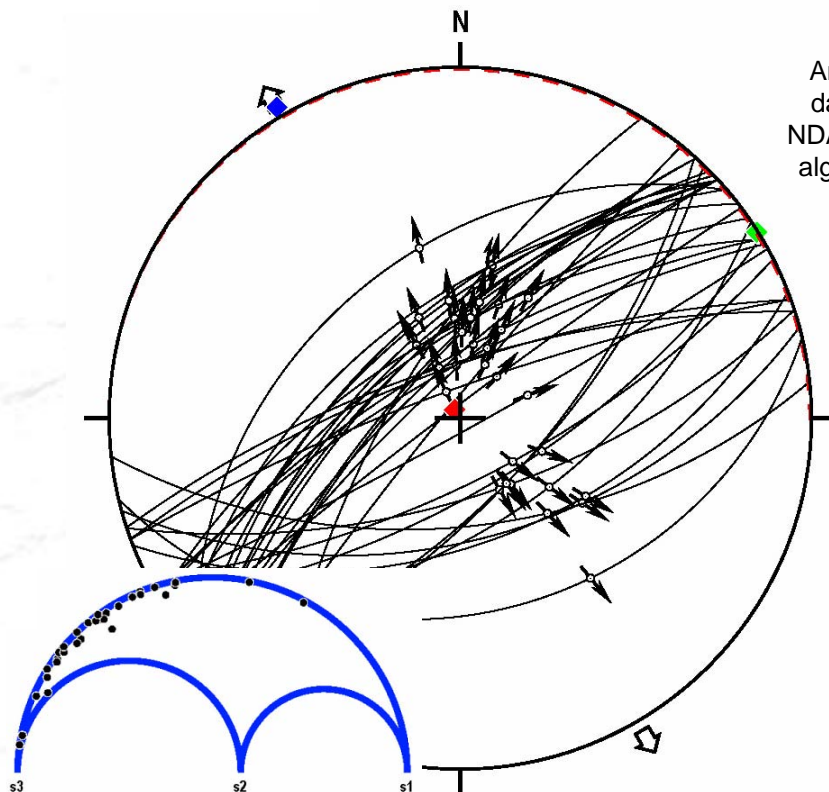
- Regression methodologies with a priori assumption are calculating maximum and minimum stress orientations for each slickenside **based on fault plane and striae geometry**, and searching for the best fitting stress tensor
- To calculate stress axes direction, **a priori assumption is required** about the  **$\alpha$  angle** between the fault plane (holding the slickenside) and the maximum stress axis direction
- Usually, a value could be approximately 30 degrees

#### NDA after Spang (1972)

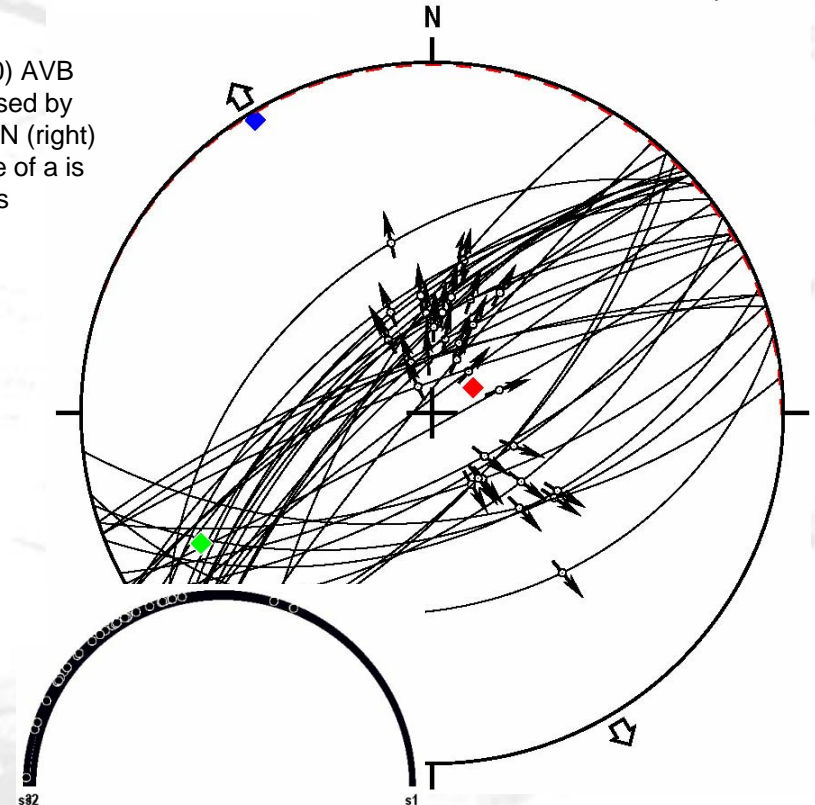
- NDA methodology calculates the best fitting stress tensor on this way for the **entire** data set with not less than **6** different data. For details see Chapter 6.7.1

#### PTN after Turner (1953)

- PTN methodology calculates the best fitting tensor for **maximum, minimum and intermediate stress orientations** and processes this tensor, for not less than **6** different data. For details see Chapter 6.7.2



Angelier's (1990) AVB data set processed by NDA (left) and PTN (right) algorithms. Value of  $\alpha$  is 30 degrees





## 5.10.2

### INVERSION II.

#### REGRESSION WITHOUT A PRIORI ASSUMPTIONS

- Inversion methodologies without a priori assumptions satisfying Angelier's (1979) basic equation about **no traction in direction perpendicular to striae direction**;  $b_i$  is perpendicular to the striation,  $T$  is the stress tensor and  $n_i$  is the plane normal of the  $i^{\text{th}}$  data

$$b_i \cdot T \cdot n_i = [b_1 \quad b_2 \quad b_3] \cdot \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix} \cdot \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix} = 0$$

#### FRY (1999)

- Fry's (1990) methodology is a classic six dimensional regression to solve the equation on the left hand side; use for minimum **6** data at the same set (see Chapter 6.7.3)

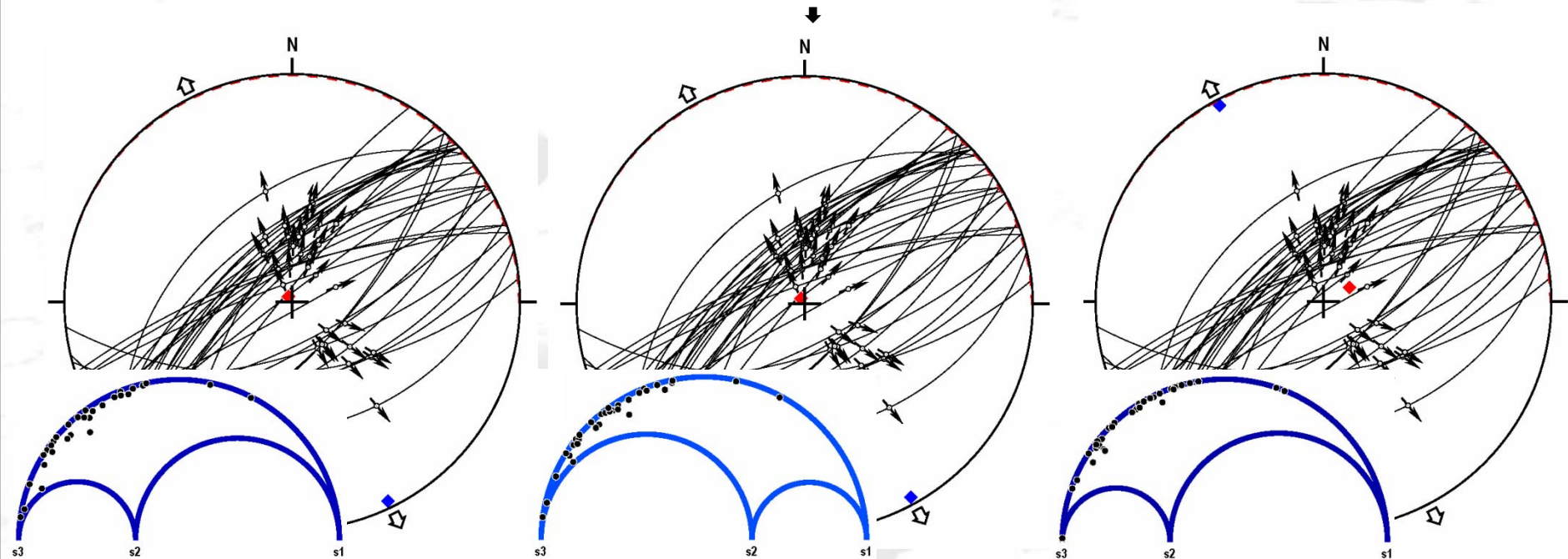
#### SHAN ET AL (2003)

- Shan et al's (2003) solution is five dimensional regression assuming  $s_{11} + s_{22} + s_{33} = 0$ ; use for minimum **5** data at the same set (see Chapter 6.7.4)

#### MICHAEL (1984)

- Michael's (1984) solution is to calculate the shear vector with assumed unit length (see Chapter 6.7.5) and find the best fitting stress tensor using five dimensional regression for no less than **6** different data

Angelier's (1990) AVB data set processed by Fry's (1999), Shan et al's (2003) and Michael's (1984) regression methodologies, respectively





# 5.10.3

## INVERSION III.

### DIRECT INVERSION, ITERATIVE DIRECT INVERSION

- Direct inversion technologies are expressing an **estimator** describing the cumulative misfit between the measured and computed slickenside movement direction (misfit angle, divergence vector, etc)
- Basic assumption after Angelier (1979) is to suppose  $s_{11} + s_{22} + s_{33} = 0$  and  $s_{11}^2 + s_{22}^2 + s_{33}^2 = 3/2$ ; the stress tensor below fits to these criteria;
- To minimize the misfit, create **partial derivatives** of the stress estimator, and solve the equations

$$T = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix} = \begin{bmatrix} \cos(\psi) & \alpha & \gamma \\ \alpha & \cos\left(\psi + \frac{2\pi}{3}\right) & \beta \\ \gamma & \beta & \cos\left(\psi + \frac{4\pi}{3}\right) \end{bmatrix}$$

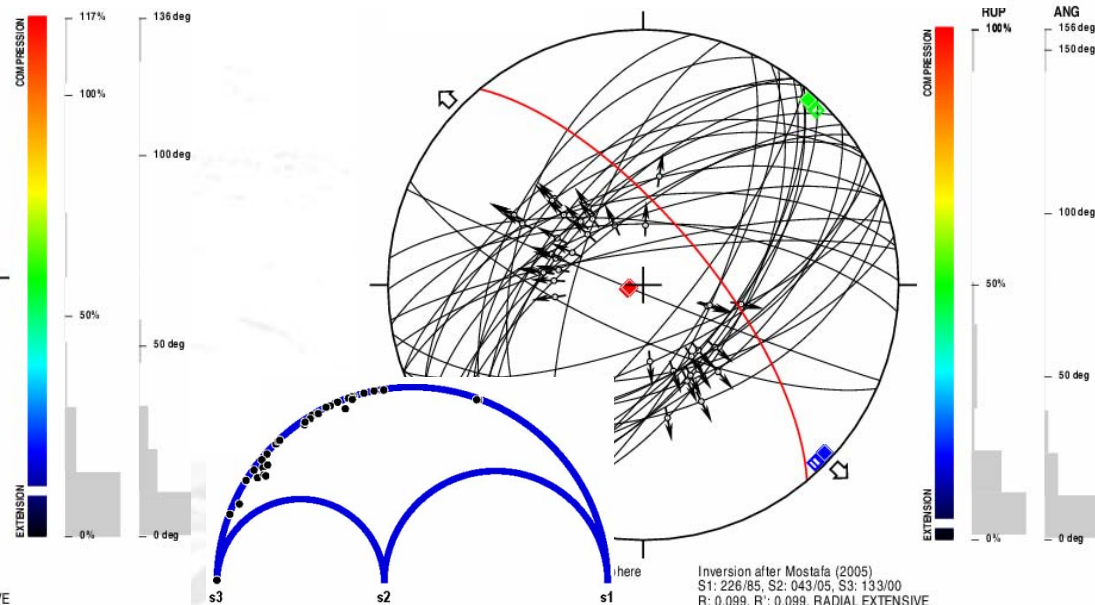
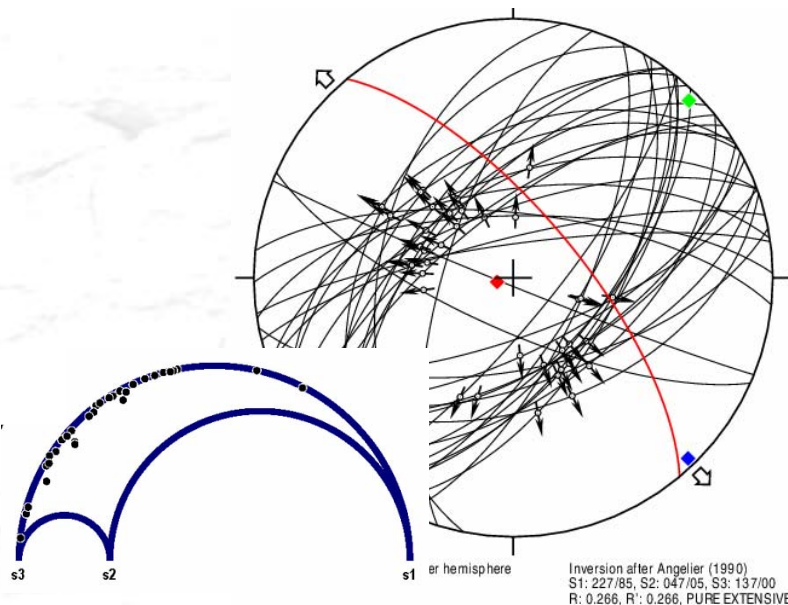
#### ANGELIER (1990)

- Angelier's (1990) methodology calculates a **misfit vector**  $v$  between the **measured** and **calculated** shear vector, and minimizes its length (see Chapter 6.7.6) for not less than 4 different data

#### MOSTAFA (2005)

- Because the measured stress vector length is **unknown**, Angelier (1990) assumed constant measured shear vector length  $\lambda$ ; Mostafa's (2005) methodology is the same as Angelier's (1990) one, with **iteration in the measured shear vector length  $\lambda$**  to decrease  $v$  misfit vector length (see relative epsilon RUP bars below, and Chapter 6.7.7) for not less than 4 different data

↓ Angelier's (1990) AVB data set processed by Angelier's (1990) and Mostafa's (2005) methodology ↓



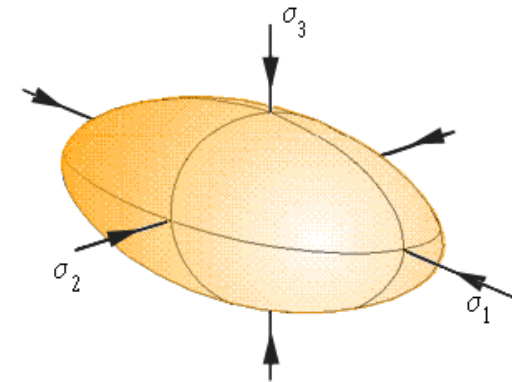


## 5.10.4

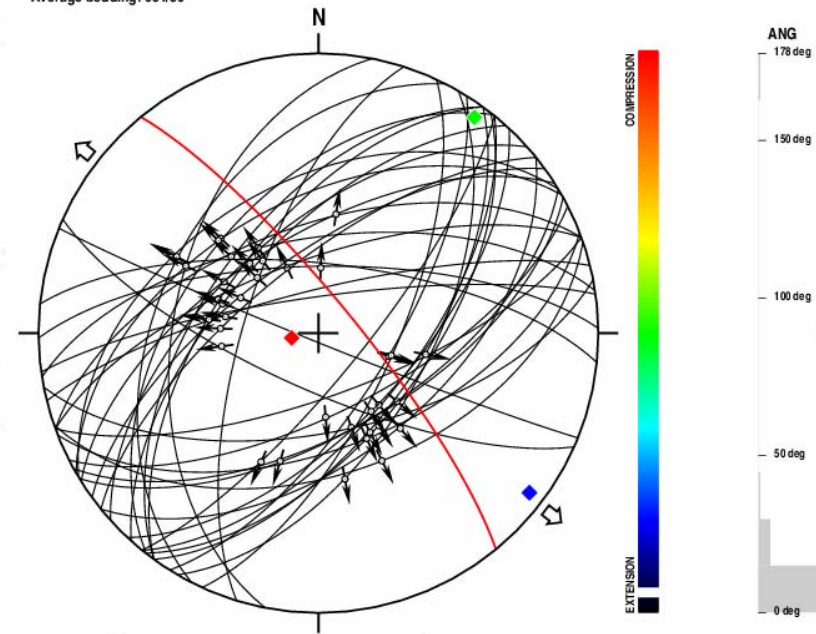
# PROCESSING AND DISPLAY

## INVERSION IV. – BRUTE FORCE INVERSION

- Brute force methodologies are really simple but time consuming technologies to find the best fitting stress tensor of the investigated data set with not less than **6** different data
- Brute force inversion is a **simple iteration** with **no preliminary assumption** and with **no heuristic approach**
- This methodology has a 'trial and error' philosophy – the stress tensor with the **smallest cumulative misfit angle (ANG)** is the 'best fitting' stress tensor
- Because the stress ellipsoid is characterised by the **stress axes direction** (perpendicular to each other) and the **stress axes length** (or stress ellipsoid shape), a number of stress tensor candidates with different geometry and orientation can be used
- Iterating** in these variables, and '**zooming in**' on the local maxima, it is possible to find the best fitting stress tensor – this will be really the best fitting one, because all theoretical solutions were cross checked

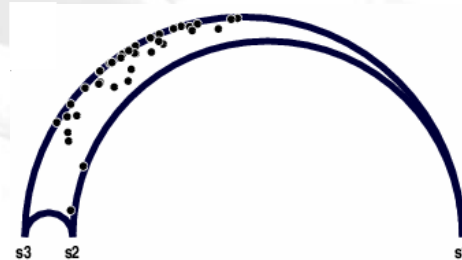


Data number: 00  
Average bedding: 051/80



Angelier-plot, Schmidt-net, lower hemisphere

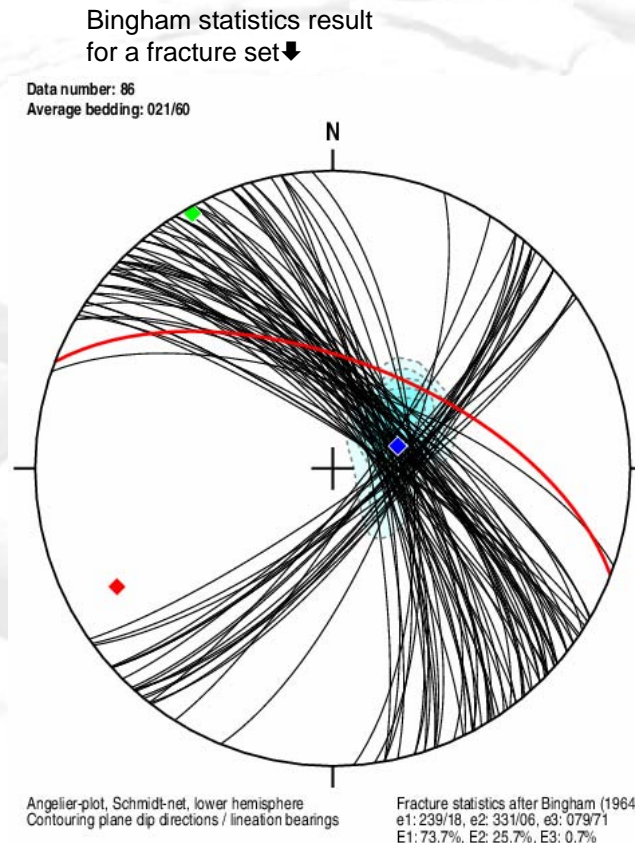
Brute force inversion  
S1: 240/82, S2: 038/07, S3: 128/03  
R: 0.110, R: 0.110, RADIAL EXTENSIVE





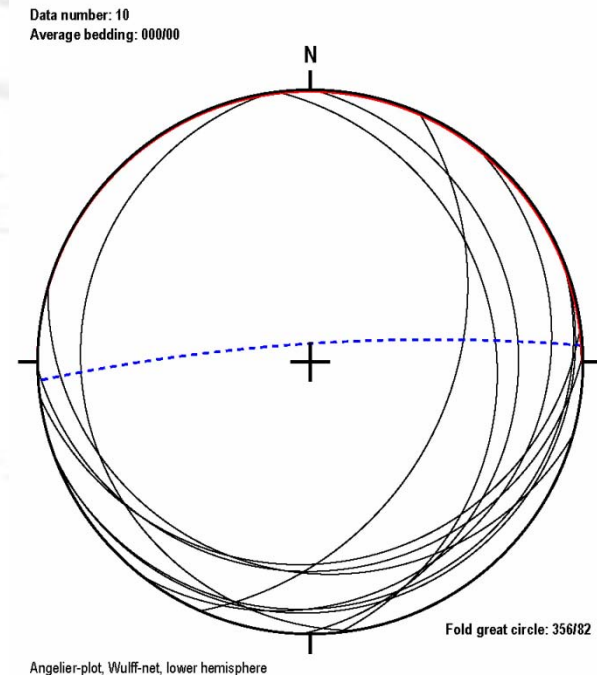
## BINGHAM STATISTICS

- Average computation can be carried out on different ways; one of them is to calculate **arithmetic average**, or median
- In the case of **directional data** (e.g. stress vector direction) this methodology might be misleading (average of compression vectors 040/10 and 220/10 is ~220/90 and not 040/00 or 220/00)
- One of the possible solution is the **regression** finding the best fitting 'average' directions of the processed data set
- Bingham directional statistics calculates **directional density** of the input fracture data set, resulting the maximum, intermediate and minimum density directions



## FOLD GREAT CIRCLE CALCULATION

- This methodology is used to find the best fitting plane of 'foldsurface' plane normals to calculate best fitting planes: the great fold circle

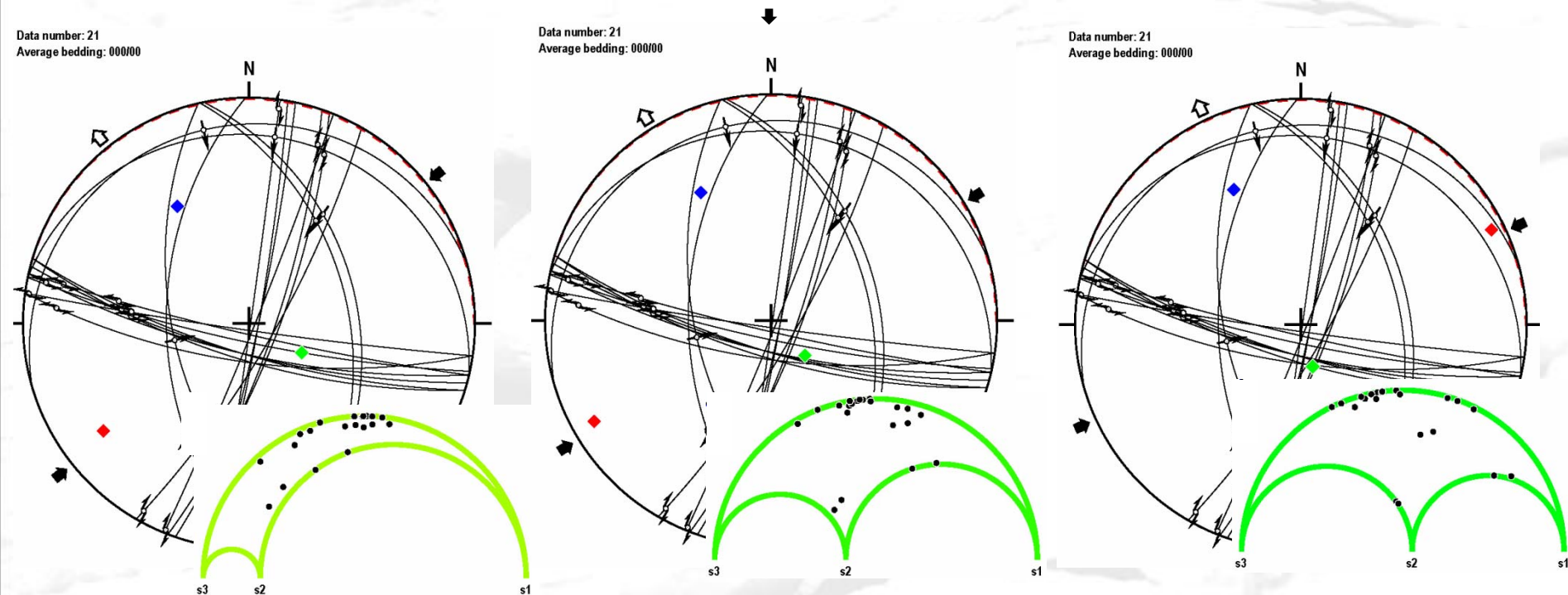


↑ Fold great circle of a 'foldsurface' data set using Bingham statistics to find the best fitting plane



- Regression technologies with **a priori** assumptions are using **a angle** to describe angle between the movement direction along the fault plane and the maximum stress direction
- This value can be constant, or the best fitting value can calculate using iteration methodologies (see Ortner et al. 2002)

Same data set processed with NDA technology using different **a** angles between movement direction and maximum stress axis direction, 15, 30 and 70 degrees, respectively



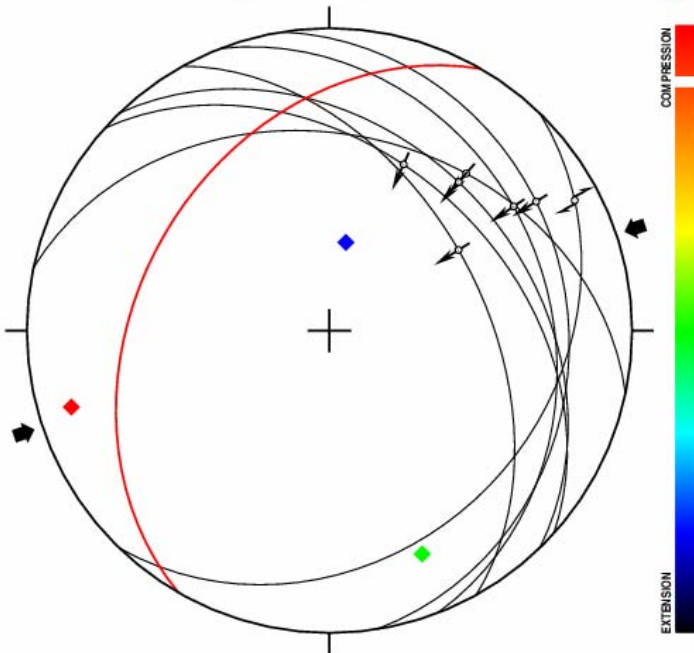
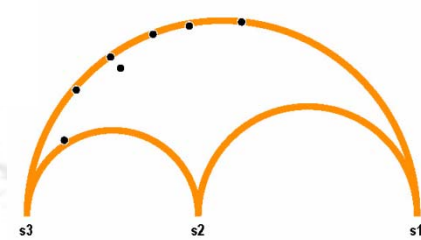
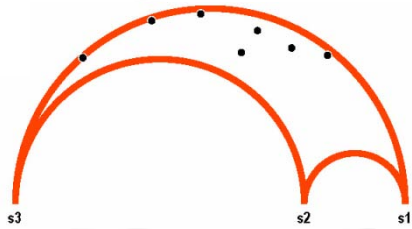


# 5.13

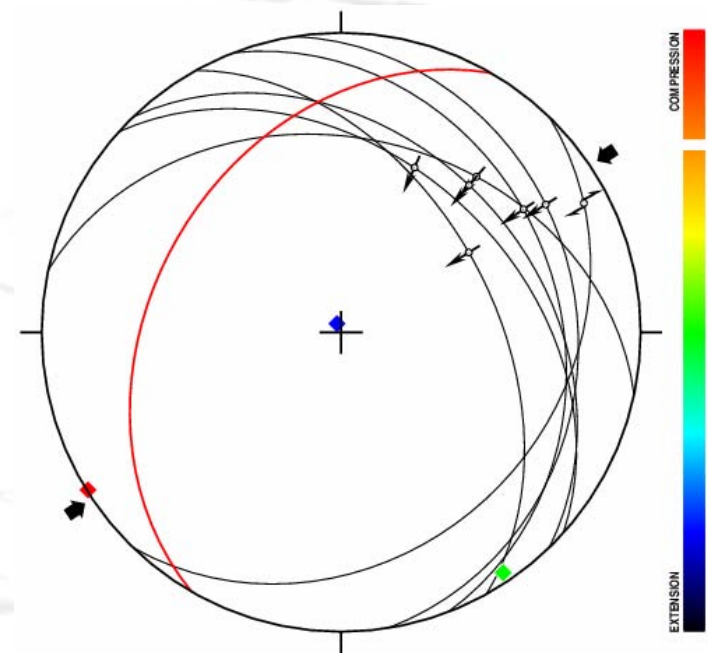
## PROCESSING AND DISPLAY

### FORCED ANDERSONIAN STRESS CONDITIONS

- Some inversion methodologies are sensible on the **symmetry** of the input data set; in some case of asymmetry the result is mathematically correct, but not from geological point of view
- One of the possible solutions could be to generate a **virtual, symmetrical data set**; this virtual set is composed by the original data rotated by **180 degrees** around a vertical axis
- The result stress field axes will be definitely **Andersonian** with two horizontal and one vertical stress axes



Same data set processed  
**without** (left) and **with** (right)  
virtual symmetric data set





FILE PROCESSING SCHEME WHILE DATA EVALUATION ↓

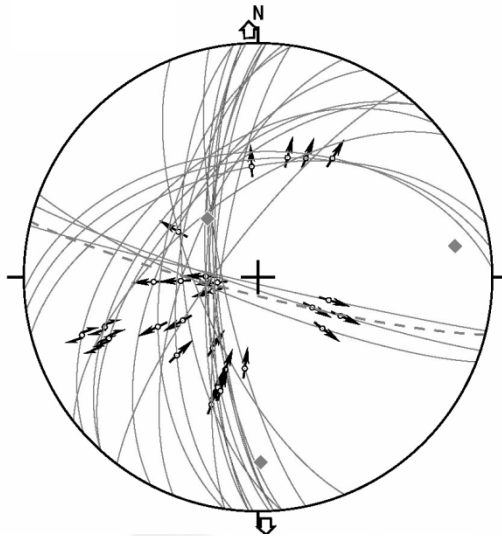


- While opening, it is possible to choose which digit of the group code to import as a user defined group code
- 1. Importing the **first** character (user defined group), **you will keep the original user defined groups** of the file you have been created for a while
- 2. Importing the **second** character (k-means clustering result), **you will keep the original k-means clustering result groups** and use them as user defined group code
- 3. Importing the **third** character (RUP/ANG clustering result), **you will keep the original RUP/ANG clustering result groups** and use them as user defined group code



USER DEFINED GROUPS

NOT USING



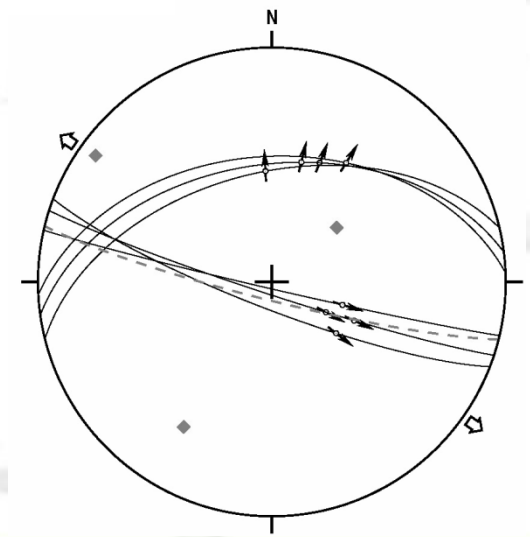
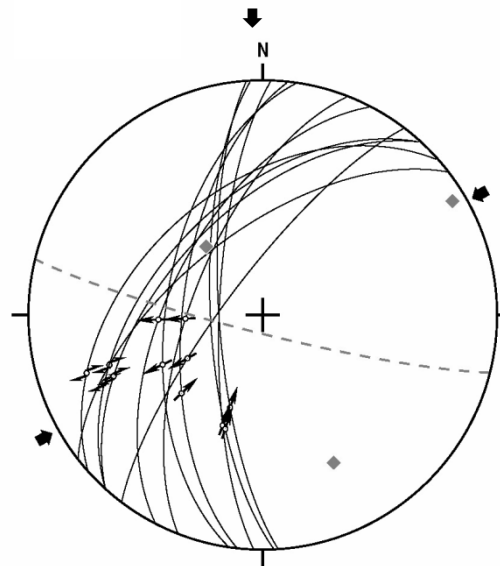
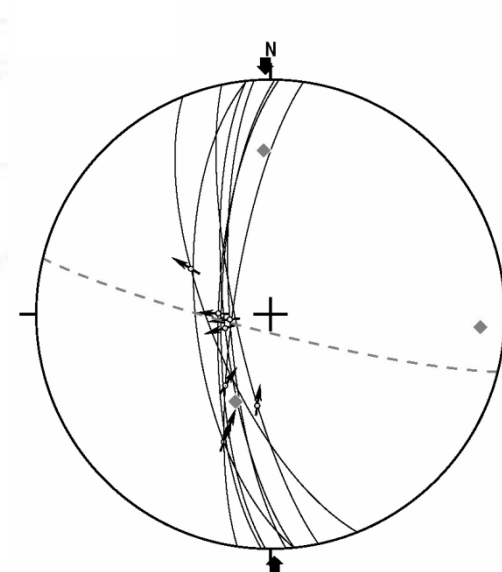
←  
Data set with three different groups *not using groups processing option* – all data will be processed together

- Before processing, it is possible to sort the data in different groups (using **group codes** in input \*.rgf file) and evaluate them **separately** (see Chapter 2)
- If group processing option is **not** is use, data from different groups will displayed and processed **together**
- Using groups setting option, groups will be processed and displayed **group by group**

Same data set processed *using processing option* – all of three data groups defined in input file will be processed and displayed one by one

USER DEFINED GROUPS

USING

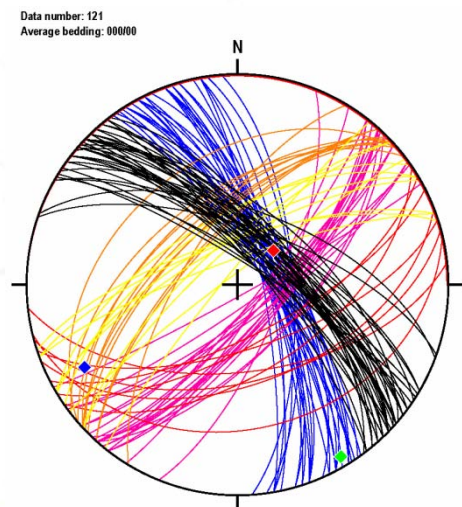
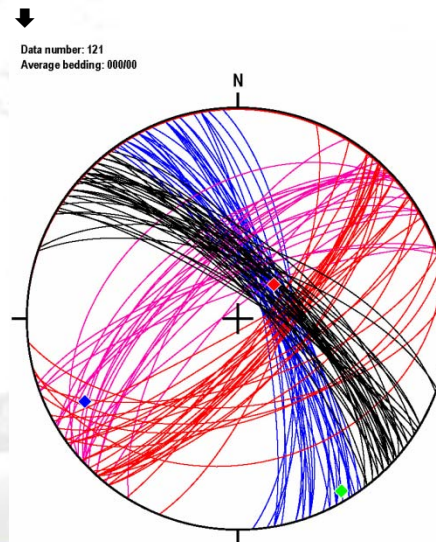
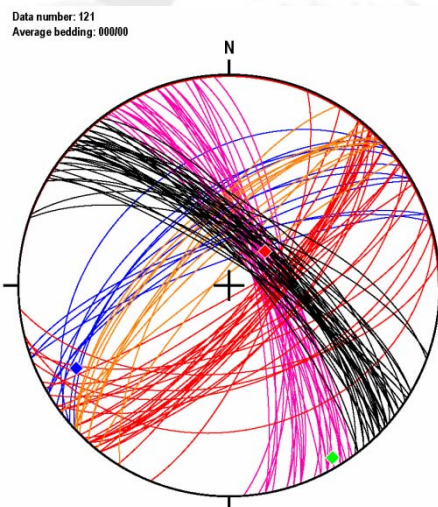
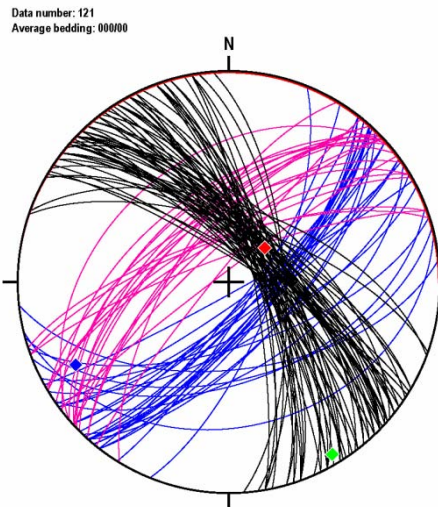
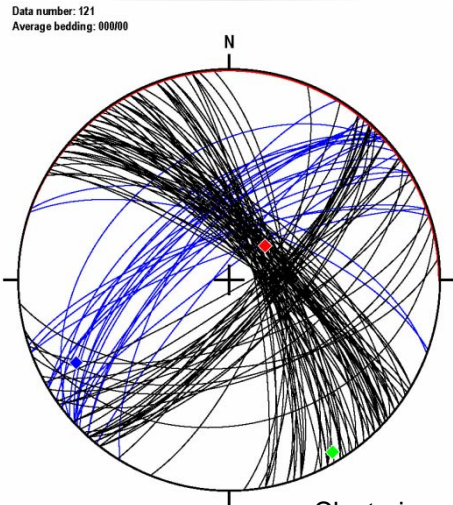




### LIMITATIONS

- Built in k-means clustering module is coded to identify **different clusters** of an inhomogeneous data set
- Normal k-means clustering sorts all of data into **k user defined groups**
- First step of k-means clustering is to **sort** the input data in k groups using different algorithms. Please note clustering result depends on this initial step, and sometimes the iteration algorithm produces a mathematically correct solution, but it is just a **local** and not global solution
- User defined k value is the maximum of possible group numbers; because the iteration methodology uses distance calculation, some groups can become **empty** (all data fits better to other groups). If data group becomes empty, groups number was overestimated

Clustering of the same data set into two, three, four five and six clusters with 32.16%, 1.29%, 0.73%, 0.68% and 0.20% relative error. Last solution with six clusters and 0.20% relative misfit is the optimum solution





# 5.17

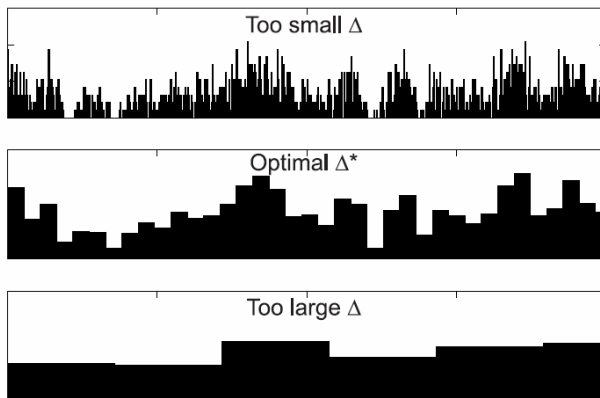
## PROCESSING AND DISPLAY

### CLUSTERING USING RUP AND ANG VALUES

This clustering methodology is based on Angelier's (1990) work; according to that, **single phase** slickenside data set has **unimodal** ANG and/or RUP distribution, and **mixed data** set has **bimodal** or **polymodal** ANG and/or RUP distribution. This assumption is checked for each data set, either for the ANG or for the RUP parameter

To find the **ideal number** of 'valleys' or 'peaks' (=number of clusters) in the distribution of the ANG or UP values, methodology of Shimazaki and Shinomoto (2007) was implemented

In this case, the main goal is to find the right **bin size** for a data set distribution or histogram. Small bin size results noise (extra, non-existing peaks will appear), too large bin size hides existing peaks



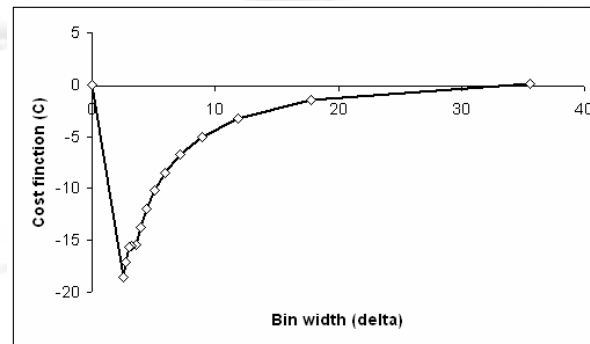
↑ Histograms for the same data set with too small, optimal, and too large bin size. Figure of Shimazaki and Shinomoto (2007)

#### METHODOLOGY OF SHIMAZAKI AND SHINOMOTO (2007)

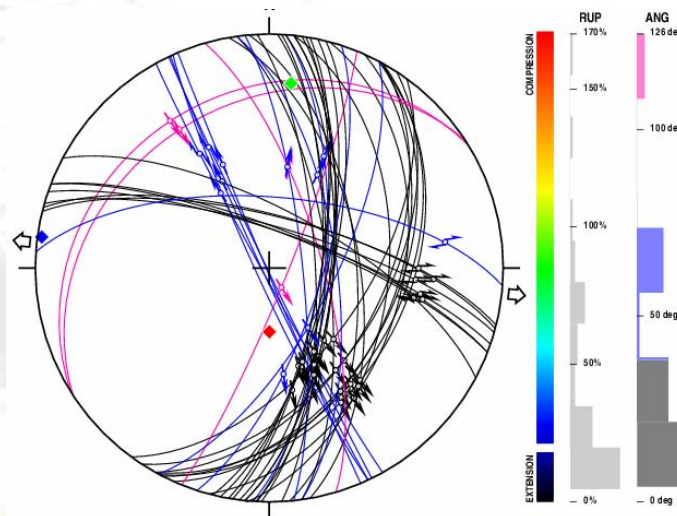
- Divide the data range into **N** bins of width **D**. Count the number of events  $k_i$  that enter the  $i^{\text{th}}$  bin
- Calculate the **mean**, the **variance** and the 'cost function' of the number of events

$$k = \frac{1}{N} \sum_{i=1}^N k_i, v = \frac{1}{N} \sum_{i=1}^N (k_i - k)^2, C = \frac{2k - v}{\Delta^2}$$

- Repeat these steps changing **D**, and find **minimum** of cost function 'C'



↖ Bin size vs cost function graph for a test data set; cost function minimum is at ~18, resulting ~2.5 ideal bin width for clustering



↖ Clustering result of a test data set, based on **ANG** parameter distribution. The input data set could be a heterogeneous set, a mixture of at least two different striae set

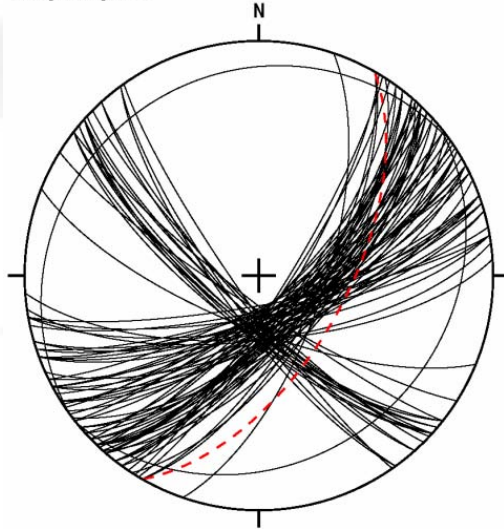


# 5.18.1

## ROSE PLOTS I.

### ROSE DIAGRAM TYPE

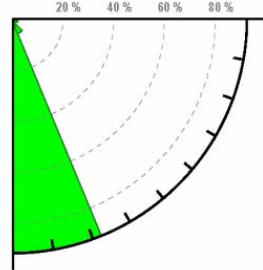
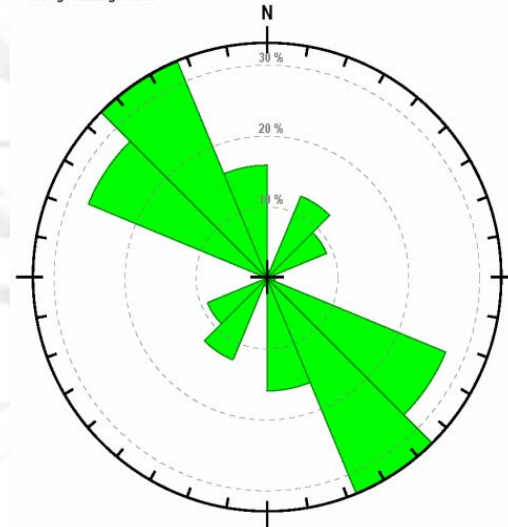
Data number: 88  
Average bedding: 030/60



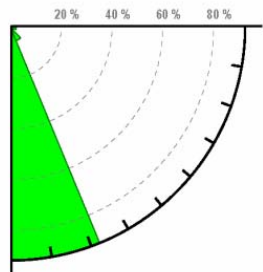
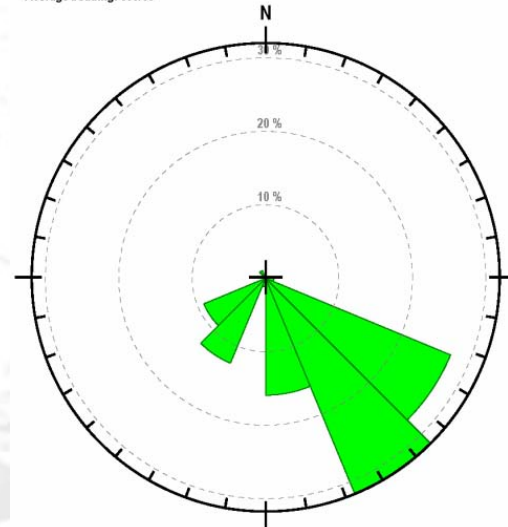
Same fracture data set plotted on asymmetrical (above) and symmetrical (below) rose diagrams using 22.5 deg bin sizes ➡

- Rose plots are presenting the **horizontal** and **vertical** distribution of data sets
- Both asymmetric (unidirectional) and symmetric (bidirectional) plots are available

Rose plot for measured data  
Average bedding: 030/60



Rose plot for measured data  
Average bedding: 030/60

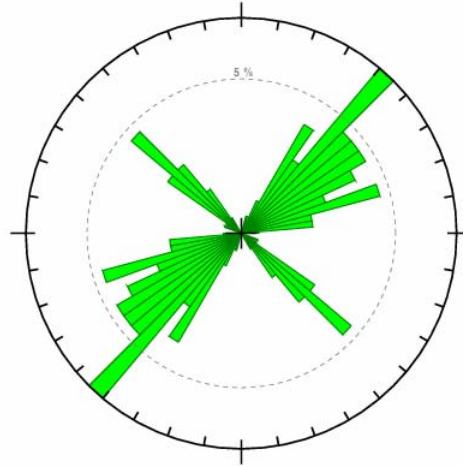
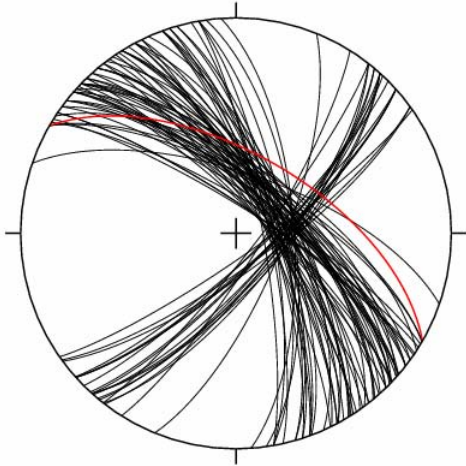




## 5.18.2

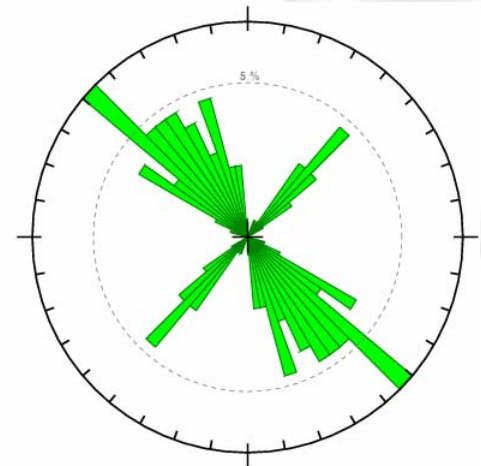
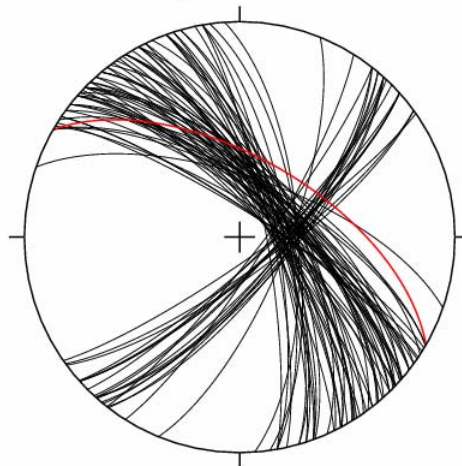
### ROSE PLOTS II.

#### ROSE PLOT DIRECTION



- Rose plot when **dip direction** of the input data is displayed (bidirectional rose plot with 5 degree bin size)

- Rose plot when **strike** of the input data is displayed (unidirectional rose plot with 5 degree bin size)



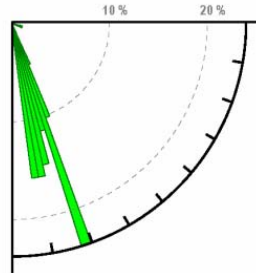
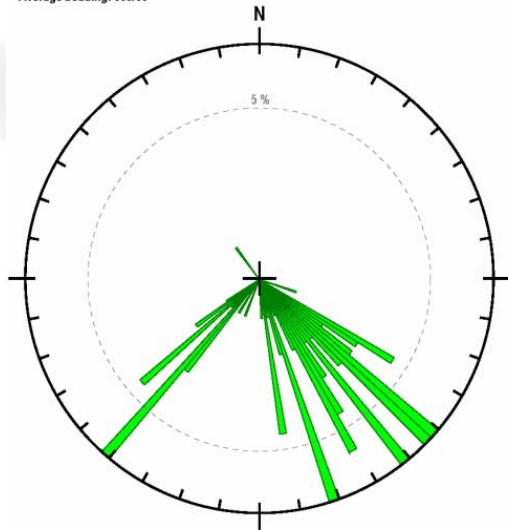


## 5.18.3

## ROSE PLOTS III.

### BIN SIZE

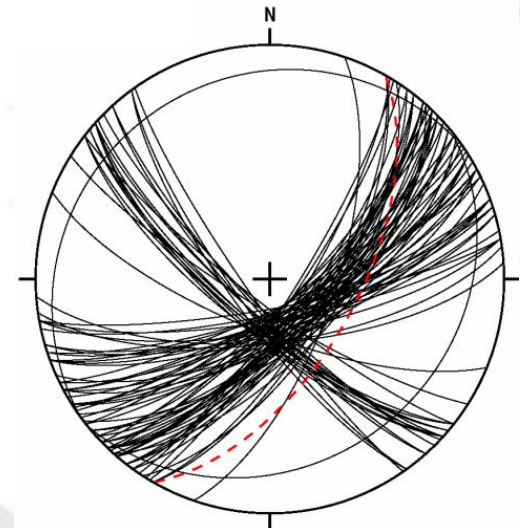
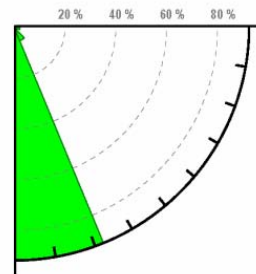
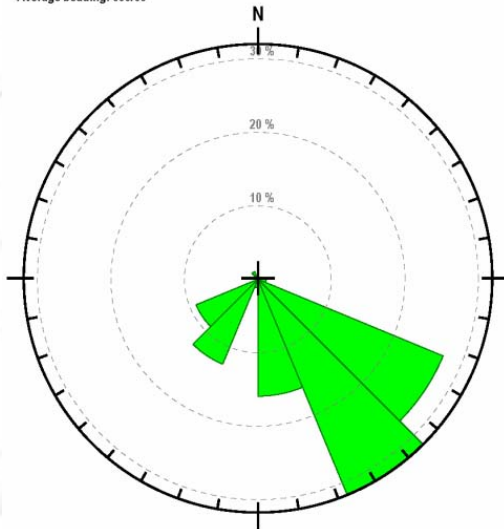
Rose plot for measured data  
Average bedding: 030/60



- Rose plots are presenting the **horizontal** and **vertical** distribution of data sets
- Bin size can be 2.5, 4.0, 10.0 and 22.5 degrees

◀ Same fracture data set plotted on unidirectional rose diagrams using 2.5 deg (above) and 22.5 deg (below) bin sizes

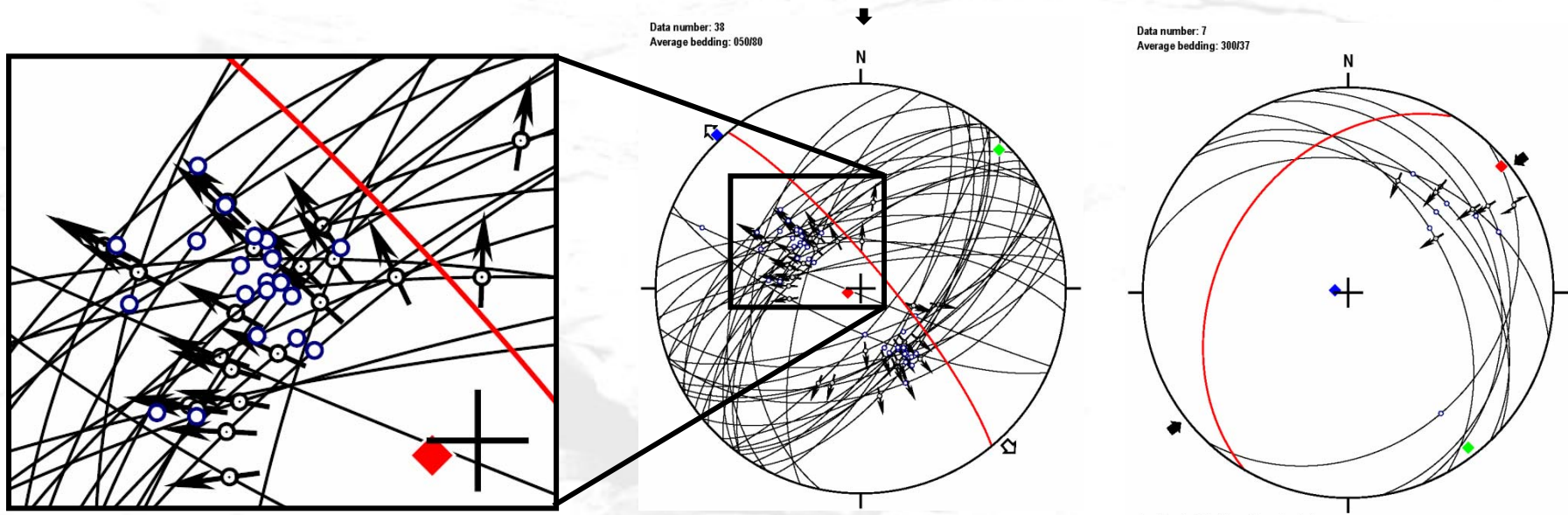
Rose plot for measured data  
Average bedding: 030/60



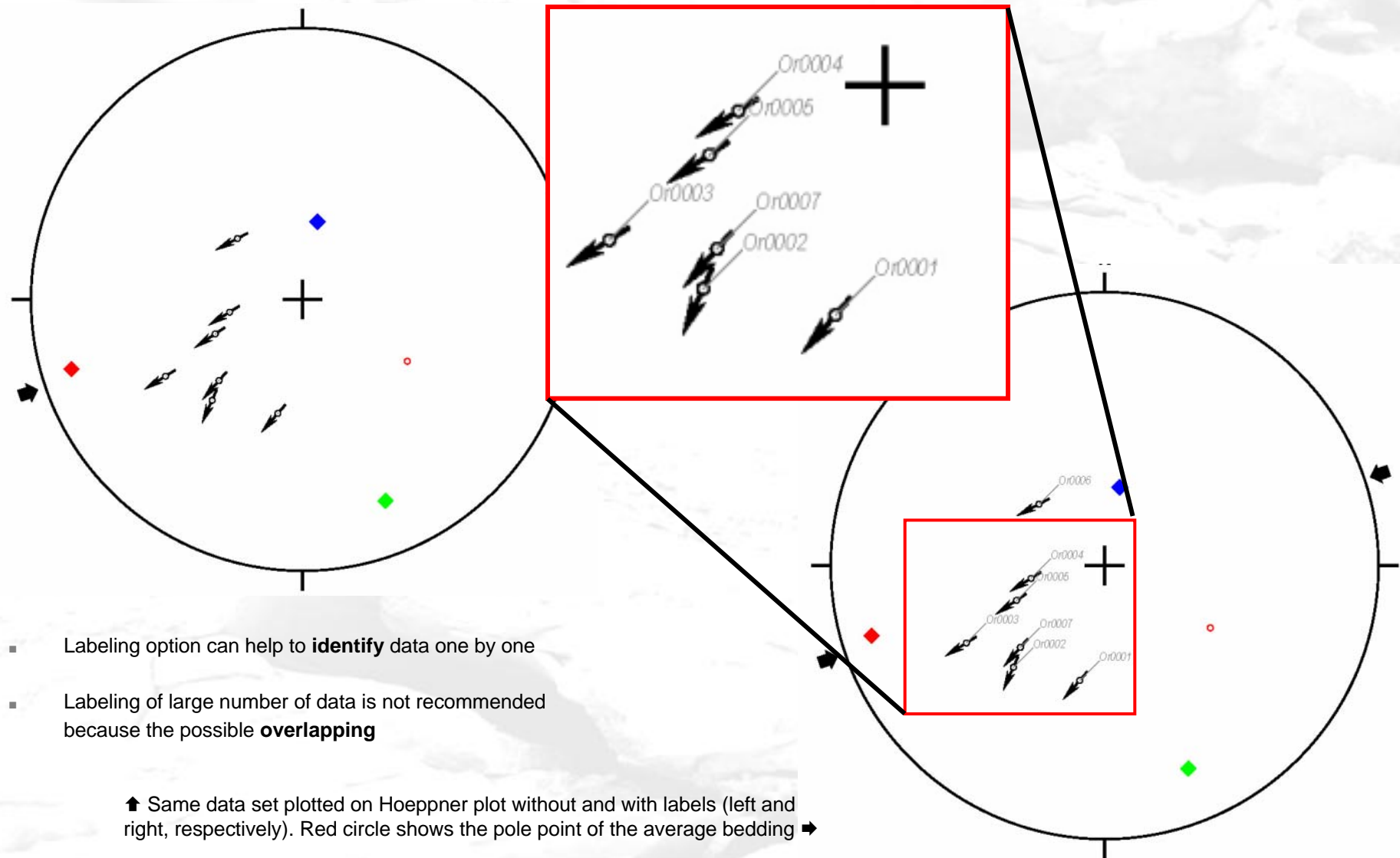


- Using stress inversion results, **ideal shear stress direction** is calculated and plotted
- Small blue circles resolved (ideal) **movement direction** (calculated stress direction) on each planes

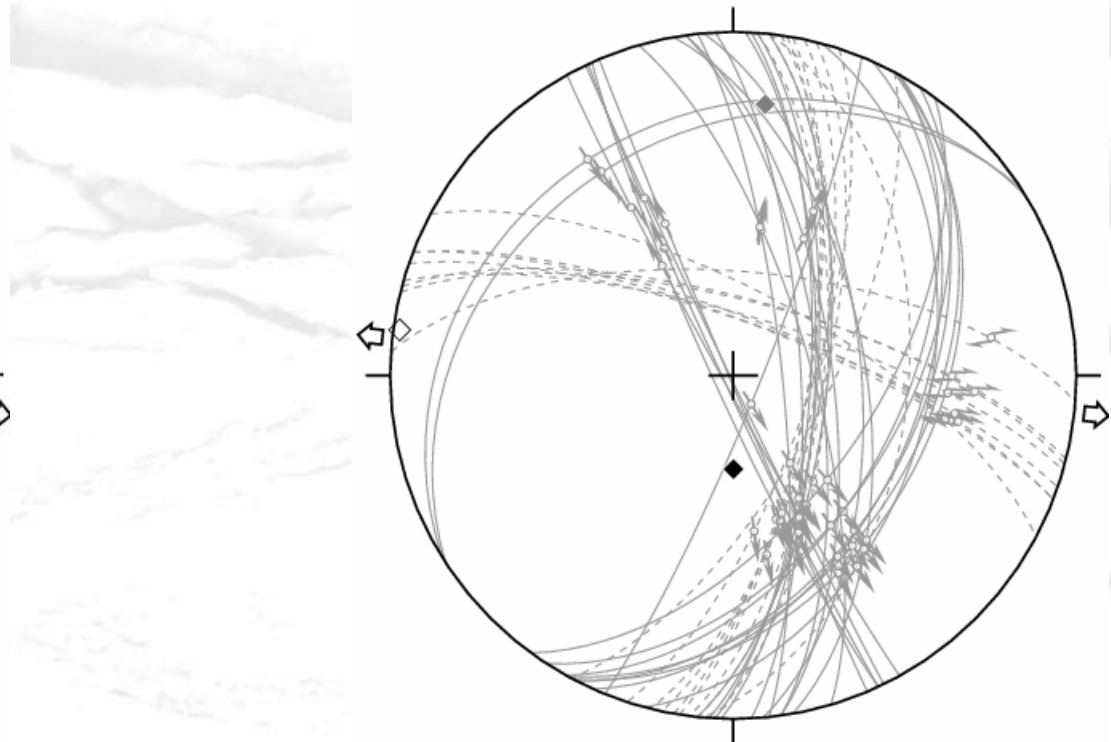
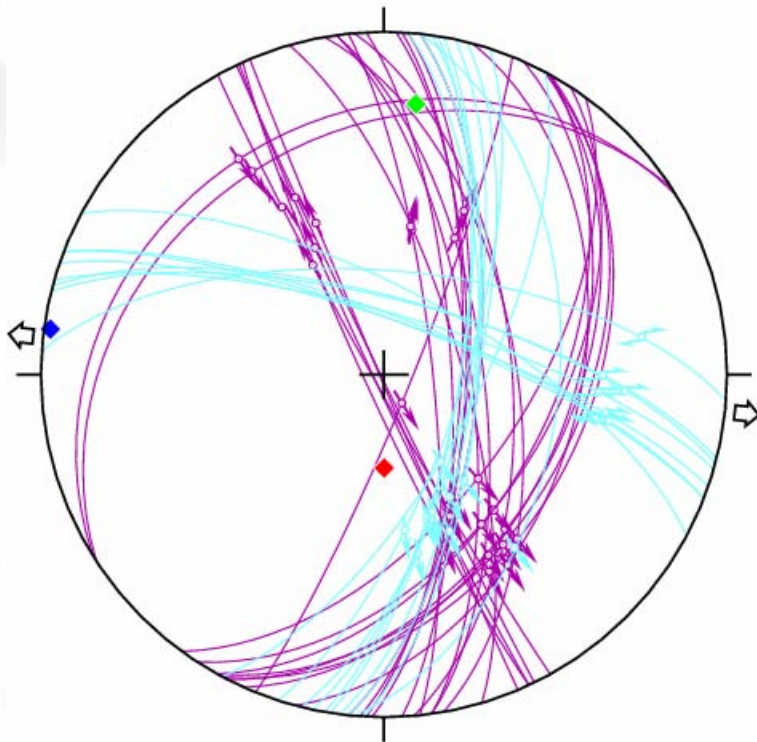
Resolved shear directions for two different data sets; small blue circles show the ideal movement direction on each fault planes in the calculated stress field











◀ Same data set with RGB and grayscale output ▶

- Grayscale option is ideal for **publications** or black and white printouts
- Different **dash** patterns and three different **grayscale colors** are used to differentiate data using group code or color code





# BACKGROUND



## 6.1.1

# COORDINATE SYSTEM AND VARIABLES I.

## D, N AND S VECTORS

- Coordinate system for all data processing is: **X** axis points to the **East**, **Y** points to the **North**, and **Z** points **upwards**. All coordinate axes are unit vectors
- All planes, lineations, striated planes and s planes of s-c sets are described using three unit vectors, perpendicular to each other
- In the case of a planar element,  $N_i$  unit vector is the **plane normal**, perpendicular to the plane, with Z coordinate  $\leq 0$  (in the case of overturned beds as well)

$$N = \begin{bmatrix} NX \\ NY \\ NZ \end{bmatrix} = \begin{bmatrix} \sin(\text{dipdir}) \cdot \sin(\text{dip}) \\ \cos(\text{dipdir}) \cdot \sin(\text{dip}) \\ \cos(\text{dip}) \end{bmatrix}$$

- $D_i$  vector (dip vector) is a unit vector **parallel to the dip of the plane**, with Z coordinate  $\geq 0$  (in the case of overturned beds as well). Computation methodology of dip vector from dip direction and dip angle data is the following:

$$D = \begin{bmatrix} DX \\ DY \\ DZ \end{bmatrix} = \begin{bmatrix} \sin(\text{dipdir}) \cdot \cos(\text{dip}) \\ \cos(\text{dipdir}) \cdot \cos(\text{dip}) \\ -\sin(\text{dip}) \end{bmatrix}$$

- Calculation of  $S_i$  **strike** unit vector (with Z=0) is the following:

$$S = N \otimes D$$

- The methodology is exactly the same for planes holding slickensides, and for s planes of s-c sets

- In the case of **linear** elements,  $D_i$  vector points in the dip direction of the linear element.  $N_i$  vector is perpendicular to it (as a normal vector of a virtual plane of which D vector is the dip vector), and  $S_i$  vector is perpendicular to both of them. Computation methodology is the same as for the planar elements
- In the case of **absolutely symmetric data set**, during eigenvalue computation division by zero can occur. To avoid this, small artificial error ( $\pm 10^{-6}$ ) is added randomly to X, Y or Z coordinates of each plane normal vectors





## 6.1.2

# COORDINATE SYSTEM AND VARIABLES II.

## DC, NC AND SC AND VECTORS

- DC<sub>i</sub>, NC<sub>i</sub>, and SC<sub>i</sub> and vectors are used to describe **slickensides** and **s-c** data sets
- In the case of s-c data sets, DC<sub>i</sub>, NC<sub>i</sub> and SC<sub>i</sub> vectors are referring to the dip, normal and strike unit vectors of c plane; in the case of a slickenside, these vectors are referring to the slickenside as a **lineation**
- DC<sub>i</sub> vector (dip vector) is a unit vector **parallel to the dip of c plane** or **parallel to slickenside direction**, with Z coordinate ≥ 0. Computation methodology of dip vector from dip direction and dip angle data is the following:

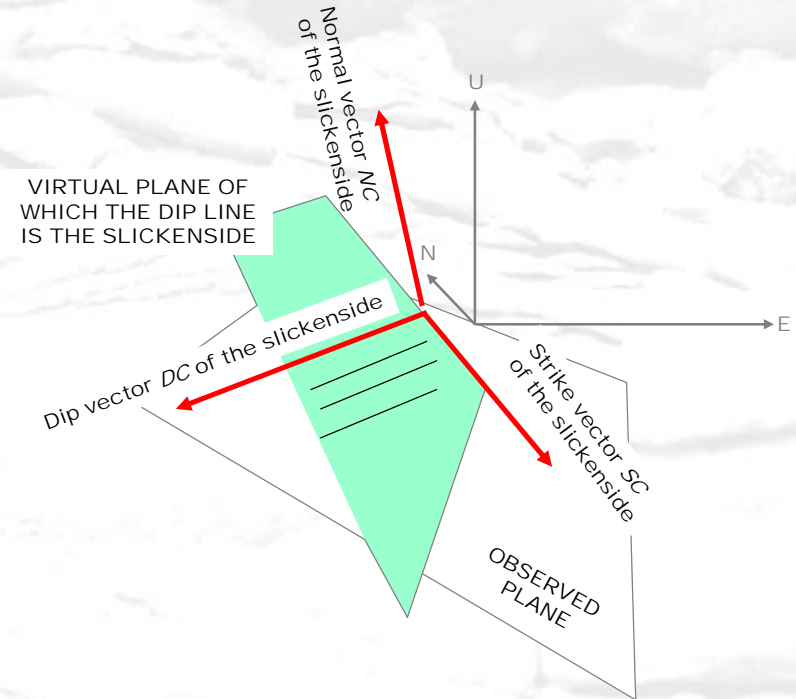
$$DC_i = \begin{bmatrix} DCX \\ DCY \\ DCZ \end{bmatrix} = \begin{bmatrix} \sin(\text{dipdir}) \cdot \cos(\text{dip}) \\ \cos(\text{dipdir}) \cdot \cos(\text{dip}) \\ -\sin(\text{dip}) \end{bmatrix}$$

- NC<sub>i</sub> unit vector is the **c plane normal**, or – in the case of slickensides – **normal vector of a plane of which DC<sub>i</sub> vector the dip vector is**, with Z coordinate ≤ 0. Computation methodology of dip vector from dip direction and dip angle data is the following:

$$NC_i = \begin{bmatrix} NCX \\ NCY \\ NCZ \end{bmatrix} = \begin{bmatrix} \sin(\text{dipdir}) \cdot \sin(\text{dip}) \\ \cos(\text{dipdir}) \cdot \sin(\text{dip}) \\ \cos(\text{dip}) \end{bmatrix}$$

- Calculation of **strike** unit vector (with Z=0) is the following:

$$SC = NC \otimes DC$$





- **Dip vector** is used to display lineations and planes on the stereographic projection:

$$D_i = \begin{bmatrix} DX \\ DY \\ DZ \end{bmatrix}$$

- All lineations are described by **x and y coordinates** on the stereographic projection; these point are calculated from the dip vector for Schmidt- and Wulff-net
- Planes are either **arcs** (in the case of Wulff-net) or **Bezier curves** (in the case Schmidt-projection) using three points to plot them:
  - **dip** of the plane ( $D_i$  vector, ①), and
  - two **strike points** on the stereonet circle ( $S_i$  and  $-S_i$  vectors, ②)

### LOWER HEMISPHERE

- On stereographic projection, **x axis** (with unit length) points to **East**, and **y axis** (with unit length) points to the **North**

### UPPER HEMISPHERE

- Coordinates above are in lower hemisphere; to use then in upper hemisphere projection, calculate expressions below using the **negative DX and DY** values of the dip vector:

$$D_i = \begin{bmatrix} -DX \\ -DY \\ DZ \end{bmatrix}$$

### SCHMIDT-NET

- To calculate x and y coordinates on the Schmidt stereonet, use the following equations:

$$x = \frac{DX}{1.0 - DZ};$$

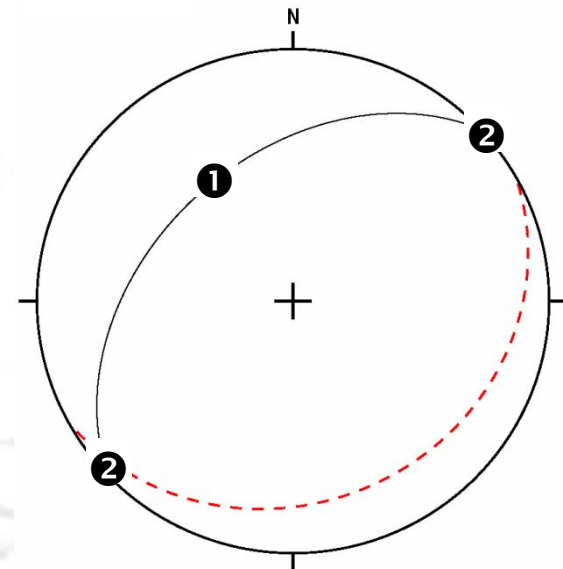
$$y = \frac{DY}{1.0 - DZ}$$

### WULFF-NET

- Wulff net point coordinates are the following:

$$x = \frac{DX}{\sqrt{1.0 - DZ}};$$

$$y = \frac{DY}{\sqrt{1.0 - DZ}}$$



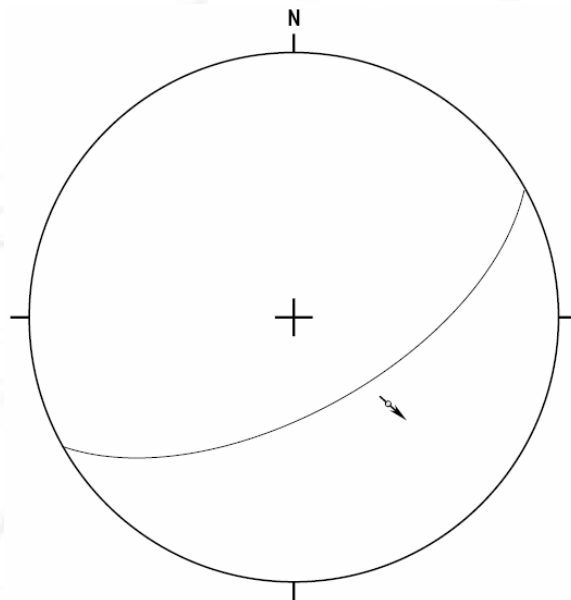


## 6.3.1

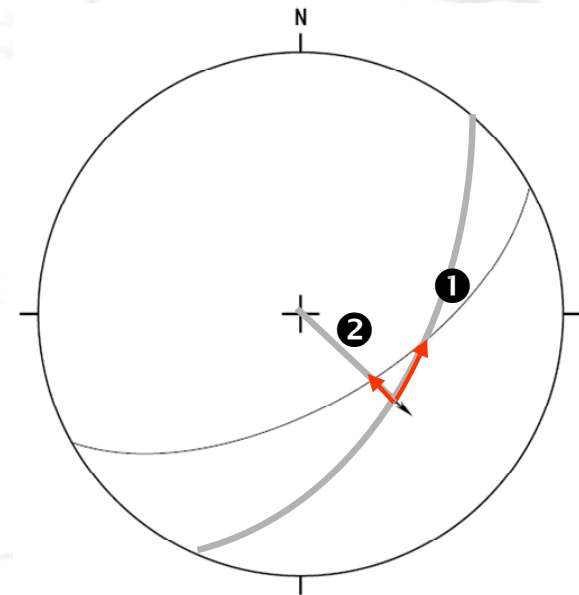
# STRIAE MISFIT AND ITS CORRECTION I.

## MISFIT ANGLE

- In ideal case, the measured slickenside vector is on the fault plane surface, and dip vector  $DC_i$  of slickenside is **perpendicular** to the plane normal vector  $N_i$
- In the case of measurement as 'pitch', slickenside lineation is **definitely** on the fault plane because measurement methodology. In the case of 'lineation' observation, a plane and a lineation is measured, which are **not** definitely fitting to each other
- To have the misfit angle between the plane normal  $N_i$  and the dip line  $DC_i$ , calculate
 
$$\alpha_i = |\arcsin(N_i \cdot DC_i)|$$
- It is required to correct 'lineation' measurements, but not 'pitch' observations. One of the possible correction is ① ② to accept dip angle to be correct, and calculate a **corrected dip direction**, or ② accept dip direction to be correct, and calculate a **corrected dip angle**



Original data set with misfit ↑



Possible striae misfit corrections ↑



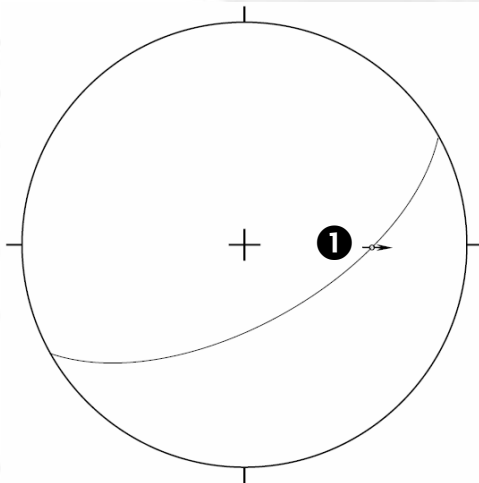
## 6.3.2

# STRIAE MISFIT AND CORRECTION II.

## DIP DIRECTION AND DIP CORRECTION, OFFSET CORRECTION

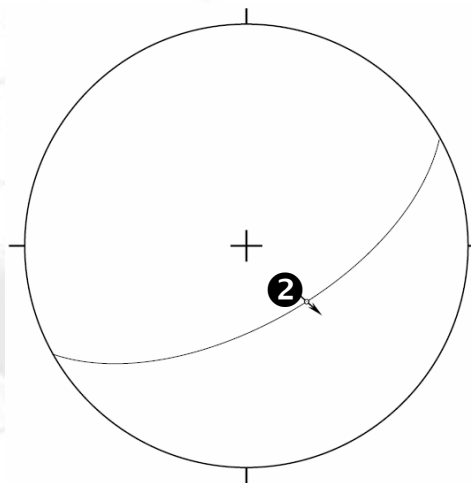
- The first possible correction is to accept dip angle to be correct, and calculate a new **dip direction** fitting on the measured plane
- In the reality, both  $N_i$  and  $SC_i$  vectors are **perpendicular** to the striae dip vector  $DC_i$ , but not necessarily perpendicular to each other. In an ideal case (ie. corrected striae), all of these vectors are perpendicular to each other. So to get the ideal movement direction, calculate the unit vector
- In the case of dip angle correction, one accepts dip direction to be correct, and calculate a corrected **dip angle**
- In this case, we are searching for the **intersection** line of two planes: one is the fault plane, and the other one is a virtual plane characterized by  $NC_i$ ,  $DC_i$  and  $SC_i$  vectors. The observed slickenside is in the plane, and in the ideal case, it is perpendicular to the plane normal  $N_i$ , so it is in the fault plane as well. The only lineation satisfying these two criteria is the intersection line of these planes. To calculate this intersection line, calculate new unit vector

$$DC_i = SC_i \otimes N_i$$



Result of dip direction correction

$$DC_i = NC_i \otimes N_i$$



Result of dip angle correction

- Despite several words are describing movement direction (offset) along a slickenside lineation, just two movement directions are visible in reality: the missing block has been moved **upwards** or **downwards** along the striae lineation
- To do the correction of the user defined offset, first the pitch angle (angle between strike and the slickenside direction, 0.0 – 90.0 degrees) will be computed
- During slickenside data processing, user input offset will be changed to be compatible with the followings:
  - if plane dip angle is less than 15 degrees, just 'normal' or 'inverse' offsets are used
  - if plane dip angle is more than 15 degrees:
    - if the pitch angle is less than 45 degrees, 'sinistral' or 'dextral' can be used
    - if the pitch angle is more than 45 degrees, 'normal' or 'inverse' is used



- At the initial step, **k data centers** (centroids) are defined; **three dimensional** centroids are used for lineation and plane data, and **six dimensional** ones for striae and s-c data sets. Centroids are unit vectors:

$$C_k = [C_X \quad C_Y \quad C_Z],$$

$$C_k = [C_U \quad C_V \quad C_W \quad C_X \quad C_Y \quad C_Z]$$

- Each plane and lineation data is described by a **three dimensional unit vector**, and each slickenside and s-c data is stored as **six dimensional unit vector**:

$$D_i = [NX \quad NY \quad NZ],$$

$$D_i = [NX \quad NY \quad NZ \quad NCX \quad NCY \quad NCZ]$$

- Input data will be **sorted into k groups** using
  - random grouping, or
  - one by one grouping: first data into the first group, second to the second, etc

- Distance of each **data** to each **centroid** is calculated on the following way:

$$\delta_i = ((C_X - NX)^2 + (C_Y - NY)^2 + (C_Z - NZ)^2),$$

$$\delta_i = ((C_U - NX)^2 + (C_V - NY)^2 + (C_W - NZ)^2 + (C_X - NCX)^2 + (C_Y - NCY)^2 + (C_Z - NCZ)^2)$$

- Each data is related to the **closest** centroid and became **member of centroid's group**
- Calculate new centroid** unit vector from centroid's data group average (n is the clustered database size):

$$C_k = \frac{1}{n} \sum_{i=1}^n D_i$$

- Repeat last three steps above either until a **convergence limit**, or user defined **m times**. **Please note that in the latter case the iteration can yield suboptimal results.**
- Error of clustering is described by **relative error** (ERR) value:

$$ERR = \frac{1}{n} \sum_{i=1}^n \delta_i \cdot 100\%$$



- **Bingham** directional statistics is used to display directional distribution of fractures

- During the Bingham statistics calculation, a three dimensional '**density ellipsoid**' is generated; the ellipsoid axes show the maximum, intermediate and minimum density direction, and ellipsoid axes length are referring to the geometry of the distribution

- The methodology is a three dimensional **regression**, and the background is almost the same as seen in the case of **PTN** and **NDA** inversion methods (see Chapter 6.7.1 and 6.7.2)

- First generate three unit vectors parallel to the **coordinate axes**:

$$n = \begin{bmatrix} 0.0 \\ 1.0 \\ 0.0 \end{bmatrix}, e = \begin{bmatrix} 1.0 \\ 0.0 \\ 0.0 \end{bmatrix}, u = \begin{bmatrix} 0.0 \\ 0.0 \\ 1.0 \end{bmatrix},$$

- Calculate the following **directional tensor** for each  $i^{\text{th}}$  data set (ang is the angle between two vectors):

$$E_i = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{12} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{13} & \varepsilon_{23} & \varepsilon_{33} \end{bmatrix},$$

$$\begin{aligned} \varepsilon_{11} &= \text{ang}(N, e) \cdot \text{ang}(P, e), \\ \varepsilon_{12} &= \text{ang}(N, e) \cdot \text{ang}(P, n), \\ \varepsilon_{13} &= \text{ang}(N, e) \cdot \text{ang}(P, u), \\ \varepsilon_{22} &= \text{ang}(N, n) \cdot \text{ang}(P, n), \\ \varepsilon_{23} &= \text{ang}(N, n) \cdot \text{ang}(P, u), \\ \varepsilon_{33} &= \text{ang}(N, u) \cdot \text{ang}(P, u) \end{aligned}$$

- Calculate the following sum for the entire data set:

$$E = \sum_{i=1}^n E_i,$$

- **Eigenvectors** of matrix E points to maximum, minimum and intermediate axes if the directional distribution ellipsoid
- **Eigenvalues** of matrix E can show the geometry of fracture distribution ellipsoid



- In the case of a **single** data set, the data set itself is the average

- If two data forms the entire data set, **mathematical average** of their  $N_1$  vectors is the average. If  $N_1$  is the opposite of  $N_2$ , no average is calculated (because it would be a null vector)

- **Bingham** directional statistics is used to calculate data average for data sets with more than 2 records. If the input data set is symmetrical, the final directional tensor will be singular, with a really small determinant more or less equal to zero

$$E_1 = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{12} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{13} & \varepsilon_{23} & \varepsilon_{33} \end{bmatrix} = 0$$

- During eigenvalue and eigenvector calculation, really small (almost zero) determinant can result in '**division by zero**' or in division by a really small number (generating unreliable result)

33/70 normal

34/71 normal

35/72 normal

33/70 overturned

34/71 overturned

35/72 overturned

Singular data set example – processing is not possible and the user is informed on that

- To avoid this problem, during data average calculation for each data sets with more than two records, directional tensor is calculated prior the eigenvalue and eigenvector computation
- If the determinant of the directional tensor is less than  $10^{-25}$ , no average is calculated, and the user is informed on the singularity of the input data set
- This singularity check makes sense from structural geological point as well: what is the average bedding of a 30/70 normal and 30/70 overturned bedding measurement?



# 6.7.1

## INVERSION METHODOLOGIES I.

### REGRESSION AFTER SPANG (1972)

- Define angle  $\alpha$  between the **movement direction** (slip vector) and the **maximum stress direction**

- Declare North, East and Upwards **unit vectors** below:

$$n_i = \begin{bmatrix} 0.0 \\ 1.0 \\ 0.0 \end{bmatrix}, e_i = \begin{bmatrix} 1.0 \\ 0.0 \\ 0.0 \end{bmatrix}, u_i = \begin{bmatrix} 0.0 \\ 0.0 \\ 1.0 \end{bmatrix},$$

- Calculate  $p_i$  and  $t_i$  vectors for each data set, referring to **compression** and **tension** directions:

$$p_i = \begin{bmatrix} (1-\alpha)DCX - \alpha NX \\ (1-\alpha)DCY - \alpha NY \\ (1-\alpha)DCZ - \alpha NZ \end{bmatrix},$$

$$t_i = \begin{bmatrix} (1-\alpha)NX + \alpha DCX \\ (1-\alpha)NY + \alpha DCY \\ (1-\alpha)NZ + \alpha DCZ \end{bmatrix},$$

- Calculate the following **sums**:

$$P = \sum_{i=1}^n p_i,$$

$$T = \sum_{i=1}^n t_i,$$

- The stress tensor **T** is the following:

$$T_i = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix},$$

$$\begin{aligned} \sigma_{11} &= \text{ang}(P, e) \cdot \text{ang}(P, e) - \text{ang}(T, e) \cdot \text{ang}(T, e), \\ \sigma_{12} &= \text{ang}(P, e) \cdot \text{ang}(P, n) - \text{ang}(T, e) \cdot \text{ang}(T, n), \\ \sigma_{13} &= \text{ang}(P, e) \cdot \text{ang}(P, u) - \text{ang}(T, e) \cdot \text{ang}(T, u), \\ \sigma_{22} &= \text{ang}(P, n) \cdot \text{ang}(P, n) - \text{ang}(T, n) \cdot \text{ang}(T, n), \\ \sigma_{23} &= \text{ang}(P, n) \cdot \text{ang}(P, u) - \text{ang}(T, n) \cdot \text{ang}(T, u), \\ \sigma_{33} &= \text{ang}(P, u) \cdot \text{ang}(P, u) - \text{ang}(T, u) \cdot \text{ang}(T, u) \end{aligned}$$



## 6.7.2

# INVERSION METHODOLOGIES II.

## REGRESSION AFTER TURNER (1953)

- Define angle  $\alpha$  between the **movement** and the **maximum stress** direction
- Define North, East and Upwards **unit direction vectors** below:

$$n = \begin{bmatrix} 0.0 \\ 1.0 \\ 0.0 \end{bmatrix}, e = \begin{bmatrix} 1.0 \\ 0.0 \\ 0.0 \end{bmatrix}, u = \begin{bmatrix} 0.0 \\ 0.0 \\ 1.0 \end{bmatrix},$$

- Calculate **pressure** (P), **tension** (T) and **neutral** (N) vectors for each data:

$$p_i = \begin{bmatrix} (1-\alpha)DCX - \alpha NX \\ (1-\alpha)DCY - \alpha NY \\ (1-\alpha)DCZ - \alpha NZ \end{bmatrix}, t_i = \begin{bmatrix} (1-\alpha)NX + \alpha DCX \\ (1-\alpha)NY + \alpha DCY \\ (1-\alpha)NZ + \alpha DCZ \end{bmatrix}, n_i = p_i \otimes t_i$$

- Calculate  $P_i$ ,  $T_i$  and  $N_i$  tensors for each data set referring to **compression**, **tension** and **neutral** directions:

$$P_i = \begin{bmatrix} \text{ang}(p_i, e) \cdot \text{ang}(p_i, e) & \text{ang}(p_i, e) \cdot \text{ang}(p_i, n) & \text{ang}(p_i, e) \cdot \text{ang}(p_i, u) \\ \text{ang}(p_i, e) \cdot \text{ang}(p_i, n) & \text{ang}(p_i, n) \cdot \text{ang}(p_i, n) & \text{ang}(p_i, n) \cdot \text{ang}(p_i, u) \\ \text{ang}(p_i, e) \cdot \text{ang}(p_i, u) & \text{ang}(p_i, n) \cdot \text{ang}(p_i, n) & \text{ang}(p_i, u) \cdot \text{ang}(p_i, u) \end{bmatrix},$$

$$T_i = \begin{bmatrix} \text{ang}(t_i, e) \cdot \text{ang}(t_i, e) & \text{ang}(t_i, e) \cdot \text{ang}(t_i, n) & \text{ang}(t_i, e) \cdot \text{ang}(t_i, u) \\ \text{ang}(t_i, e) \cdot \text{ang}(t_i, n) & \text{ang}(t_i, n) \cdot \text{ang}(t_i, n) & \text{ang}(t_i, n) \cdot \text{ang}(t_i, u) \\ \text{ang}(t_i, e) \cdot \text{ang}(t_i, u) & \text{ang}(t_i, n) \cdot \text{ang}(t_i, n) & \text{ang}(t_i, u) \cdot \text{ang}(t_i, u) \end{bmatrix},$$

$$N_i = \begin{bmatrix} \text{ang}(n_i, e) \cdot \text{ang}(n_i, e) & \text{ang}(n_i, e) \cdot \text{ang}(n_i, n) & \text{ang}(n_i, e) \cdot \text{ang}(n_i, u) \\ \text{ang}(n_i, e) \cdot \text{ang}(n_i, n) & \text{ang}(n_i, n) \cdot \text{ang}(n_i, n) & \text{ang}(n_i, n) \cdot \text{ang}(n_i, u) \\ \text{ang}(n_i, e) \cdot \text{ang}(n_i, u) & \text{ang}(n_i, n) \cdot \text{ang}(n_i, n) & \text{ang}(n_i, u) \cdot \text{ang}(n_i, u) \end{bmatrix}$$

- Calculate **sum** tensors

$$P = \sum_{i=1}^n P_i,$$

$$T = \sum_{i=1}^n T_i,$$

$$N = \sum_{i=1}^n N_i$$

- Calculate the **eigenvalues** and **eigenvectors** for all of **three** tensors:

$$EVAL_P = \begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix}, EVEC_P = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix},$$

$$EVAL_T = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix}, EVEC_T = \begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix}$$

$$EVAL_N = \begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix}, EVEC_N = \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix}$$

- The **reduced stress tensor** will be:

$$\begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix} = \begin{bmatrix} P_1 & 0 & 0 \\ 0 & N_2 & 0 \\ 0 & 0 & T_3 \end{bmatrix}$$

- The maximum, intermediate and minimum stress directions will be  $EVEC_P$ ,  $EVEC_T$ , and  $EVEC_N$ , respectively



## 6.7.3

# INVERSION METHODOLOGIES III.

## REGRESSION AFTER FRY (1999)

- Use Angelier's (1979) assumption for each slickenside data:  $\mathbf{b}_i \cdot \mathbf{T} \cdot \mathbf{n}_i = 0$ , where

$$\mathbf{b}_i = DC \otimes \mathbf{N} = [b_1 \quad b_2 \quad b_3],$$

$$\mathbf{T} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix},$$

$$\mathbf{n}_i = \begin{bmatrix} NX \\ NY \\ NZ \end{bmatrix} = \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix}$$

- In this case

$$[b_1 \quad b_2 \quad b_3] \cdot \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix} \cdot \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix} =$$

$$b_1\sigma_{11}n_1 + b_1\sigma_{12}n_2 + b_1\sigma_{13}n_3 + \\ b_2\sigma_{12}n_1 + b_2\sigma_{22}n_2 + b_2\sigma_{23}n_3 + \\ b_3\sigma_{13}n_1 + b_3\sigma_{23}n_2 + b_3\sigma_{33}n_3 = 0$$

- Use **regression** to search for the best fitting values of T; first compute the coefficients of  $s_{11}$ ,  $s_{22}$ ,  $s_{33}$ ,  $s_{12}$ ,  $s_{23}$  and  $s_{13}$ , and they are the values of a **six-dimensional unit vector**  $\mathbf{p}_i$ :

$$\mathbf{p}_i = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \\ p_6 \end{bmatrix} = \begin{bmatrix} b_1n_1 \\ b_2n_2 \\ b_3n_3 \\ b_1n_2 + b_2n_1 \\ b_2n_3 + b_3n_2 \\ b_1n_3 + b_3n_1 \end{bmatrix}$$

- Calculate the **sum of the inner products (second moment tensor)** of  $\mathbf{p}_i$  vectors:

$$\mathbf{P} = \sum_{i=1}^n \mathbf{p}_i \cdot \mathbf{p}_i^T$$

- Find the **eigenvalues and eigenvectors** of this 6x6 symmetrical matrice, e.g. use the Jacobi algorithm

- The eigenvector of the lowest eigenvalue will be:

$$\mathbf{E}_{vec} = [0.57735 \quad 0.57735 \quad 0.57735 \quad 0.00000 \quad 0.00000 \quad 0.00000]$$

- Choose the eigenvector of the **second** lowest eigenvalue:

$$\mathbf{E}_{vec} = [E_1 \quad E_2 \quad E_3 \quad E_4 \quad E_5 \quad E_6]$$

- These values (**the coefficients of  $\mathbf{p}_1 - \mathbf{p}_6$** ) will be the members of the stress tensor:

$$\begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix} = \begin{bmatrix} E_1 & E_4 & E_6 \\ E_4 & E_2 & E_5 \\ E_6 & E_5 & E_3 \end{bmatrix}$$



## 6.7.4

# INVERSION METHODOLOGIES IV.

## REGRESSION AFTER SHAN ET AL. (2003)

- Shan et al's (2003) methodology is really similar to Fry's (1999) solution; the most important difference is the **reduction in the dimension numbers** using basic assumption after Angelier (1979):  $s_{11} + s_{22} + s_{33} = 0$

- Calculate the **best fitting stress tensor** for the equation below:

$$b_i \cdot T \cdot n_i = [b_1 \quad b_2 \quad b_3] \cdot \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix} \cdot \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix} =$$

$$\begin{aligned} & b_1 \sigma_{11} n_1 + b_1 \sigma_{12} n_2 + b_1 \sigma_{13} n_3 + \\ & b_2 \sigma_{12} n_1 + b_2 \sigma_{22} n_2 + b_2 \sigma_{23} n_3 + \\ & b_3 \sigma_{13} n_1 + b_3 \sigma_{23} n_2 + b_3 \sigma_{33} n_3 = 0, \end{aligned}$$

$$\sigma_{11} + \sigma_{22} + \sigma_{33} = 0$$

- Use **regression** to search for the best fitting values of the stress tensor: first compute the coefficients of  $s_{11}$ ,  $s_{22}$ ,  $s_{12}$ ,  $s_{13}$  and  $s_{23}$ ; they are the values of a **five-dimensional unit vector**  $p_i$ :

$$p_i = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \end{bmatrix} = \begin{bmatrix} b_1 n_1 - b_3 n_3 \\ b_2 n_2 - b_3 n_3 \\ b_1 n_2 + b_2 n_1 \\ b_1 n_3 + b_3 n_1 \\ b_2 n_3 + b_3 n_2 \end{bmatrix}$$

- Calculate the **sum of the inner products (second moment tensor)** of  $p_i$  vectors:

$$P = \sum_{i=1}^n p_i \cdot p_i^T$$

- Find the **eigenvalues and eigenvectors** of this 5x5 symmetrical matrice, e.g. use Jacobi algorithm

- The eigenvector of the **lowest eigenvalue** will be:

$$E_{vec} = [E_1 \quad E_2 \quad E_3 \quad E_4 \quad E_5]$$

- These values (the coefficients of  $p_1 - p_6$ ) will be the **members of the stress tensor**:

$$\begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix} = \begin{bmatrix} E_1 & E_3 & E_4 \\ E_3 & E_2 & E_5 \\ E_4 & E_5 & 0 - E_1 - E_2 \end{bmatrix}$$



## 6.7.5

# INVERSION METHODOLOGIES V.

## REGRESSION AFTER MICHAEL (1984)

- Calculate the following **orientation matrix** using fault plane normal directions for each slickenside:

$$M_i = \begin{bmatrix} n_1 - n_1^3 + n_1 n_3^2 & n_2 - 2n_2 n_1^2 & n_3 - 2n_3 n_1^2 & -n_1 n_2^2 + n_1 n_3^2 & -2n_1 n_2 n_3 \\ -n_2 n_1^2 + n_2 n_3^2 & n_1 - 2n_1 n_2^2 & -2n_1 n_2 n_3 & n_2 - n_2^3 + n_2 n_3^2 & n_3 - 2n_3 n_2^2 \\ -n_3 n_1^2 - n_3 + n_3^3 & -2n_1 n_2 n_3 & n_1 - 2n_1 n_3^2 & -n_2^2 n_3 - n_3 + n_3^3 & n_2 - 2n_2 n_3^2 \end{bmatrix},$$

$$\begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix} = \begin{bmatrix} NX \\ NY \\ NZ \end{bmatrix}$$

- Calculate the **movement matrix** for each slickenside data:

$$B_i = \begin{bmatrix} DCX \\ DCY \\ DCZ \end{bmatrix}$$

- The matrix form of the **stress tensor** is:

$$X = \begin{bmatrix} \sigma_{11} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{22} \\ \sigma_{23} \end{bmatrix}, \sigma_{11} + \sigma_{22} + \sigma_{33} = 0$$

- Calculate following **hypermatrices** for all of  $n$  faults using orientation matrices and movement matrices:

$$M = \begin{bmatrix} M_1^T \\ \vdots \\ M_i^T \\ \vdots \\ M_n^T \end{bmatrix}, B = \begin{bmatrix} B_1^T \\ \vdots \\ B_i^T \\ \vdots \\ B_n^T \end{bmatrix},$$

- Linear equation system to be solved for  $X$  is  $MX = B$

- Rectangular** ( $n \times n$ ) form of matrix  $M$  is needed to solve this equation: calculate matrices  $A = M^T M$  and  $C = M^T B$ , and the equation system to be solved will be  $AX = C$

- To solve this equation system, use e.g. **LU decomposition** methodology to compute members of matrix  $X$ ; because matrix  $A$  is symmetrical, simple Gaussian elimination will be not working



## 6.7.6

# INVERSION METHODOLOGIES VI.

## REGRESSION AFTER ANGELIER (1990)

- Angelier's (1990) methodology calculates the **misfit vector**  $\mathbf{v}$  between the measured ( $\mathbf{DC}_i$ ) and calculated ( $\tau$ ) shear stress vectors; length of  $\mathbf{DC}_i$  is unknown, and it was assumed to be  $\lambda = \sqrt{3}/2$

- Basic assumption after Angelier (1979) is to suppose  $s_{11} + s_{22} + s_{33} = 0$  and  $s_{11}^2 + s_{22}^2 + s_{33}^2 = 3/2$ ; the stress tensor below satisfies these criteria:

$$T = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix} = \begin{bmatrix} \cos(\psi) & \alpha & \gamma \\ \alpha & \cos\left(\psi + \frac{2\pi}{3}\right) & \beta \\ \gamma & \beta & \cos\left(\psi + \frac{4\pi}{3}\right) \end{bmatrix}$$

- Length of vector  $\mathbf{v}$**  is expressed as a function of the plane **normal vector**, the **slickenside lineation**, the assumed (a priori) shear stress vector length  $\lambda$  and the members of stress tensor ( $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\psi$ ; see equations A6 and A8 in Angelier 1990)

- To minimize length of  $\mathbf{v}$  vector, Angelier (1990) calculates the following **partial derivatives** (see equation A10 in Angelier 1990):

$$\frac{1}{2} \frac{\partial v^2}{\partial \alpha} = 0, \frac{1}{2} \frac{\partial v^2}{\partial \beta} = 0, \frac{1}{2} \frac{\partial v^2}{\partial \gamma} = 0, \frac{1}{2} \frac{\partial v^2}{\partial \psi} = 0$$

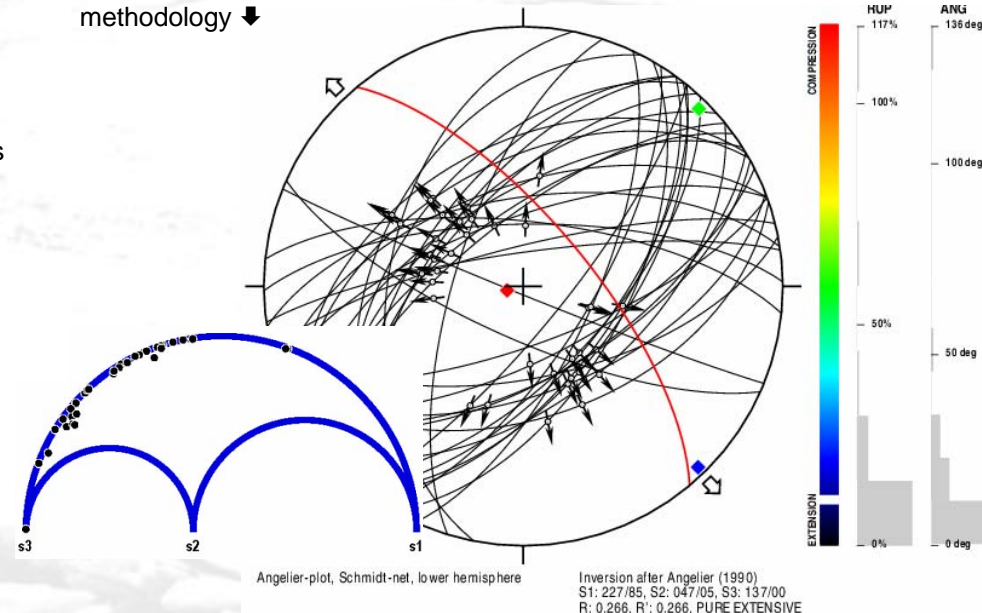
- The final equation (A15, using equation A11 in Angelier 1990) is the function of  $\psi$  on the fourth power

- A fourth power equation has 1) four real solutions, 2) two real and two complex solution, or 3) all solutions are zero; **usually**, this equation has **two real solutions** ( $\psi_1$  and  $\psi_2$ ) and two complex ones

- Using  $\psi$  value, express  $\alpha$ ,  $\beta$  and  $\gamma$  and **generate the stress tensor** (see equation A12 in Angelier 1990)

- To find the best fitting stress tensor, generate two stress tensors using both  $\psi_1$  and  $\psi_2$  values and choose the **best fitting one**

Angelier's (1990) AVB data set processed by Angelier's (1990) methodology ↓





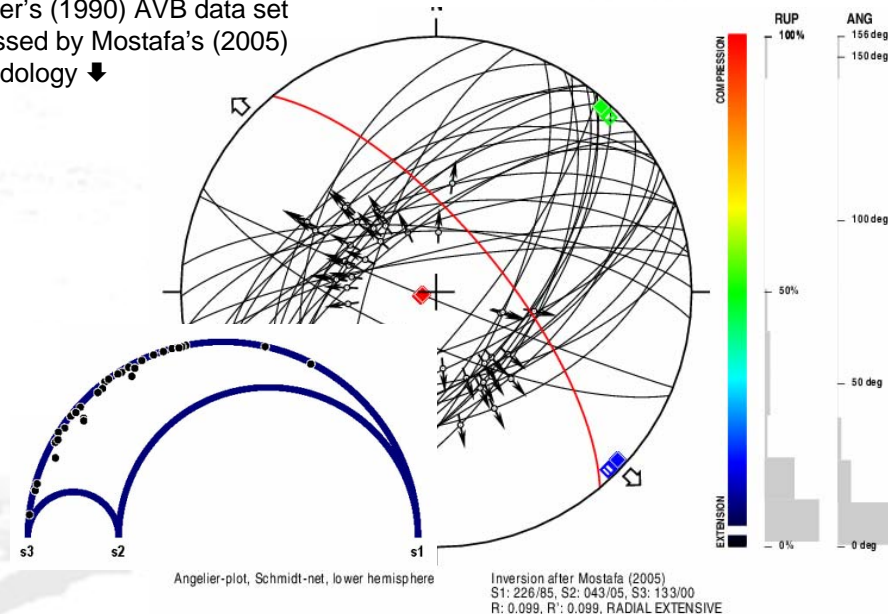
## 6.7.7

# INVERSION METHODOLOGIES VII.

## ITERATIVE REGRESSION AFTER MOSTAFA (2005)

- Mostafa's (2005) methodology is an **iteration in shear stress vector length**. Value of  $\lambda$  was assumed by Angelier (1990) to be  $\sqrt{3}/2$
- Mostafa (2005) uses Angelier's (1990) solution to generate the stress field and calculate  $\tau$  shear vector length
- In the second iteration step,  $\lambda$  (measured shear stress vector length) is **replaced by the length of  $\tau$**  (calculated shear vector) in all of equations, and a new stress tensor calculation is carried out
- In the next steps, values of  $\tau$  **are re-calculated**; after the 10-15<sup>th</sup> iteration no major change in stress estimators is visible
- One of the key problems of inversion methodologies is the measured shear vector (DCi) length calculation
- Because basic inversion equations are nonlinear in the sense of shear vector length, either 1) assumption on the original vector length is used ( $\lambda=1$  in the case of Michael 1984, and  $\lambda = \sqrt{3}/2$  was used by Angelier 1990), or 2) iteration in the shear vector length
- Using Angelier's 1990 methodology, Mostafa (2005) proposed the following iteration methodology:
  - assume  $\lambda = \sqrt{3}/2$
  - calculate the stress tensor using Angelier's (1990) methodology
  - calculate the stress vector, the normal stress and then the shear stress vectors
  - calculate shear vector length  $|t|$
  - use  $\lambda = |t|$  for the next iteration step
- Using Michael's (1984) methodology, is it possible to use the same iteration methodology with  $\lambda=1$  start criteria

Angelier's (1990) AVB data set processed by Mostafa's (2005) methodology ↓





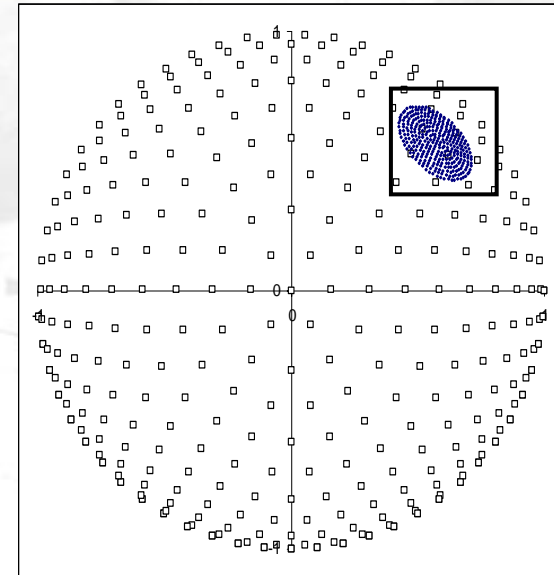
## GENERAL METHODOLOGY

- Generate a **set of stress tensors**, calculate the **resolved shear** on the given data set, choose the **10 best fitting tensors**, and do a **detailed investigation** in their proximity. Accept the **best fitting** stress tensor

## STRESS TENSORS

- Use **Kaalsbeek counting net** to generate a series of  $\sigma_3$  directions (331 points)
- **Rotate**  $\sigma_1$  axes around  $\sigma_3$  axis with 10 degrees steps (18 rotations, 0.0 – 170 degrees)
- **Calculate**  $\sigma_2$  directions
- Use **0.0 – 1.0 phi values** for the stress tensor geometry with 0.1 steps (11 different geometries)

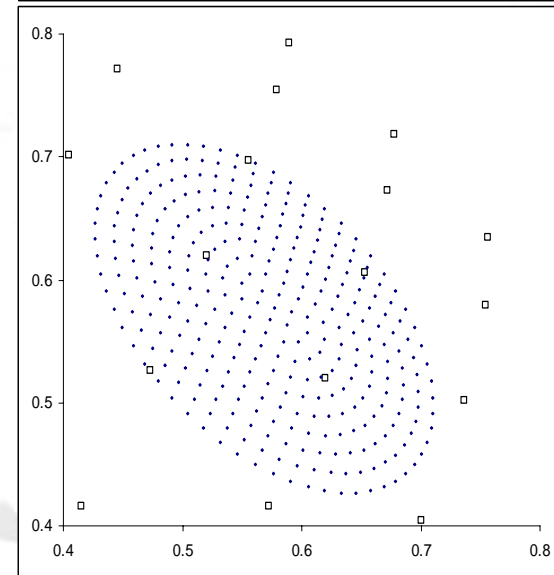
→  
Kaalsbeek counting  
net to generate  $\sigma_3$   
directions



## INITIAL ITERATION

- Calculate **resolved shear directions** on all fault planes; do altogether 331 x 18 = 65538 iterations
- Calculate the **cumulative angular misfit (ANG)** between the observed and the resolved shear directions
- Store stress tensor parameters for the **10 smallest misfit** values

High resolution 'zoom  
in' area with a high  
resolution Kaalsbeek  
counting net



## HIGH RESOLUTION ITERATION

- Generate a **detailed 'zoom in' Kaalsbeek net** around each local minima
- **Repeat the iteration** for the local maxima using the high resolution Kaalsbeek net
- Any stress tensor with the **smallest cumulative angular misfit** is the solution of the brute force inversion



## NEGATIVE OF STRESS TENSOR

- In several cases (ie. in the case of Fry 1999 and Shan et al. 2003 methodology) both **stress tensor** and the **negative of the stress tensor**:

$$T = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix}$$

and

$$T = \begin{bmatrix} -\sigma_{11} & -\sigma_{12} & -\sigma_{13} \\ -\sigma_{12} & -\sigma_{22} & -\sigma_{23} \\ -\sigma_{13} & -\sigma_{23} & -\sigma_{33} \end{bmatrix}$$

could be a good solution after stress field computation

- Because the coordinate conventions are the same for all of methodologies, it must be **checked** for each inversion technologies that the result stress tensor, or its negative is the correct one
- One of the possible solution to find the best fitting tensor, is to **calculate the sum of the angular misfits ANG** (see Chapter 6.9.2) between observed and computed shear direction 1) for the stress tensor and 2) for its negative, and choose the best fitting one

## NEGATIVE OF STRESS VECTOR

- Before stress estimator calculation, the right **stress vector orientation** must be checked for each data sets. Because the stress data convention, stress vector must be **positive if pointing into the deformed body**. After inverting a homogenous data group, this will be true for the majority of data sets, but not for all of them
- Calculate the stress vector and its magnitude for each slickensides:

$$\sigma = n_i \cdot T = \begin{bmatrix} \sigma_X \\ \sigma_Y \\ \sigma_Z \end{bmatrix} = \begin{bmatrix} n_1\sigma_{11} + n_2\sigma_{12} + n_3\sigma_{13} \\ n_1\sigma_{12} + n_2\sigma_{22} + n_3\sigma_{23} \\ n_1\sigma_{13} + n_2\sigma_{23} + n_3\sigma_{33} \end{bmatrix},$$

$$|\sigma| = n_1\sigma_X + n_2\sigma_Y + n_3\sigma_Z$$

$$T = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix}, n_i = \begin{bmatrix} NX \\ NY \\ NZ \end{bmatrix} = \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix}$$

- If the inversion methodology produces a **negative of stress vector** (pointing outside of the deformed body) **and magnitude of stress in positive**, or the **stress vector** is positive **and magnitude of stress in negative**, use the negative of stress vector



# 6.9.1

## STRESS VECTORS AND STRESS ESTIMATORS I.

### STRESS VECTOR, NORMAL AND SHEAR STRESS ON PLANE

- To have the **stress vector** effecting the  $i^{\text{th}}$  plane, calculate

$$\sigma = n_i \cdot T = \begin{bmatrix} \sigma_X \\ \sigma_Y \\ \sigma_Z \end{bmatrix} = \begin{bmatrix} n_1 \sigma_{11} + n_2 \sigma_{12} + n_3 \sigma_{13} \\ n_1 \sigma_{12} + n_2 \sigma_{22} + n_3 \sigma_{23} \\ n_1 \sigma_{13} + n_2 \sigma_{23} + n_3 \sigma_{33} \end{bmatrix}$$

$$T = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix}, n_i = \begin{bmatrix} NX \\ NY \\ NZ \end{bmatrix} = \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix}$$

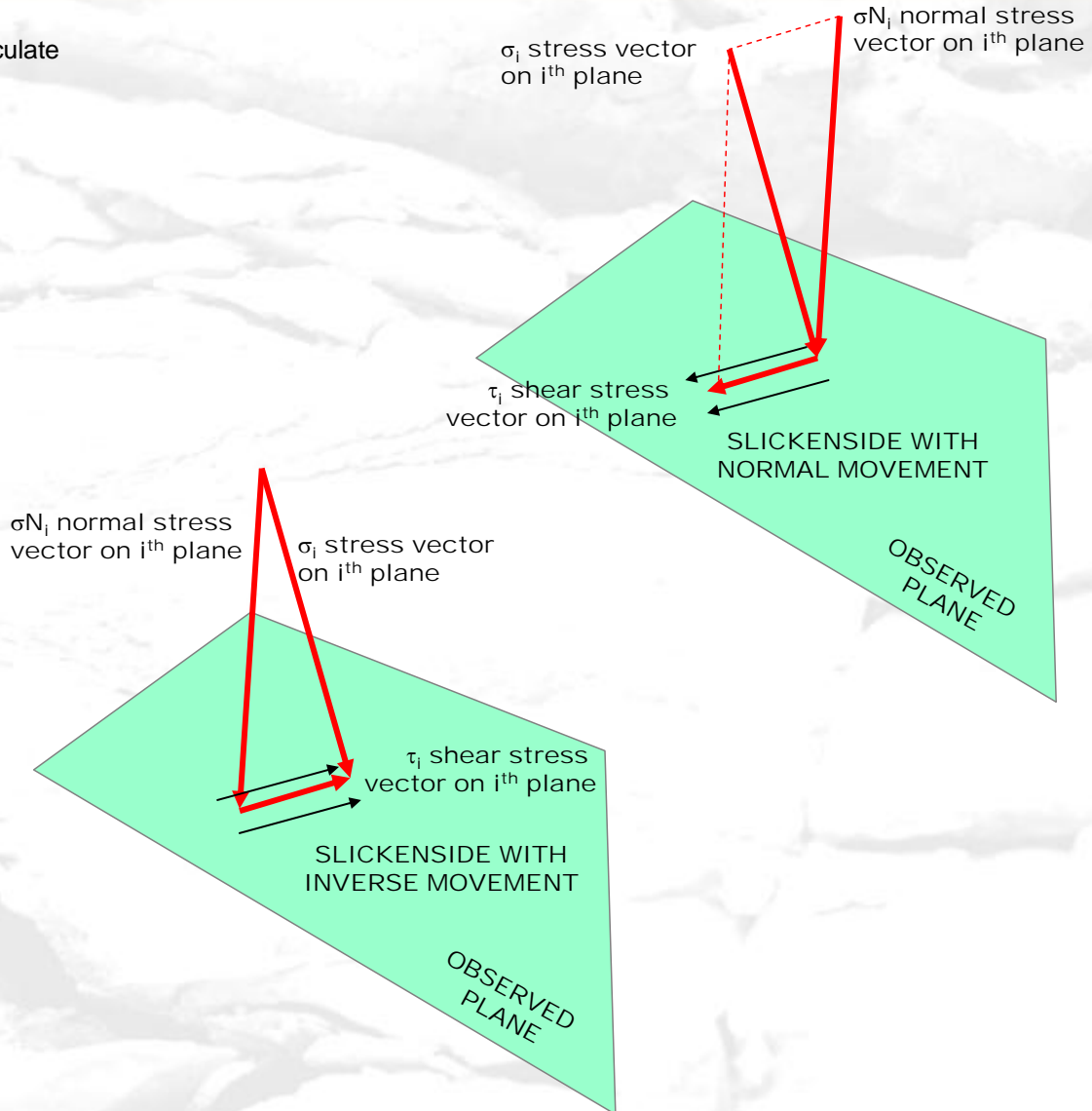
- Normal stress** on the  $i^{\text{th}}$  plane is the following:

$$\sigma N_i = n_i \cdot \sigma_i = \begin{bmatrix} \sigma_i X \cdot n_1 \\ \sigma_i Y \cdot n_2 \\ \sigma_i Z \cdot n_3 \end{bmatrix}$$

$$\sigma_i = \begin{bmatrix} \sigma_i X \\ \sigma_i Y \\ \sigma_i Z \end{bmatrix}, n_i = \begin{bmatrix} NX \\ NY \\ NZ \end{bmatrix} = \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix}$$

- The **shear stress** on the  $i^{\text{th}}$  plane is:

$$\tau_i = \sigma_i - \sigma N_i = \begin{bmatrix} \tau_i X \\ \tau_i Y \\ \tau_i Z \end{bmatrix} = \begin{bmatrix} \sigma_i X - \sigma N_i X \\ \sigma_i Y - \sigma N_i Y \\ \sigma_i Z - \sigma N_i Z \end{bmatrix}$$





## 6.9.2

# STRESS VECTORS AND STRESS ESTIMATORS II.

## $\nu$ VECTOR, $\lambda$ , RUP AND ANG PARAMETERS

### VECTOR $\nu$

- Upsilon vector ( $\nu$ ) refers to the **divergence** between the **measured** (a priori, described by DC vector) and the **calculated** (a posteriori,  $\tau$  vector) shear stress direction

$$\nu_i = DC_i \cdot \lambda - \tau_i = \begin{bmatrix} DCX \cdot \lambda - \tau_X \\ DCY \cdot \lambda - \tau_Y \\ DCZ \cdot \lambda - \tau_Z \end{bmatrix},$$

$$SV_i = \begin{bmatrix} DC_i X \\ DC_i Y \\ DC_i Z \end{bmatrix}, \tau_i = \begin{bmatrix} \tau_X \\ \tau_Y \\ \tau_Z \end{bmatrix}$$

### SHEAR STRESS VECTOR LENGTH $\lambda$

- Angelier (1990) assumed shear vector length to be  $\sqrt{3}/2$ ; this is the 0<sup>th</sup> iteration step of Mostafa's (2005) methodology.  $\lambda$  is the scale factor to get the **real** length of the slip vector instead the unit vector length; in Angelier's (1990) methodology its value is constant  $\sqrt{3}/2$ , in Mostafa's (2005) methodology it's value changes iteration by iteration

### ESTIMATOR ANG

- Estimator **ANG** shows the angular misfit between the measured (DC) and calculated ( $\tau$ ) shear stress vectors:

$$ANG = \text{ang}(s_i, \tau_i)$$

$$s_i = \begin{bmatrix} DCX \\ DCY \\ DCZ \end{bmatrix}, \tau_i = \begin{bmatrix} \tau_X \\ \tau_Y \\ \tau_Z \end{bmatrix}$$

### ESTIMATOR RUP

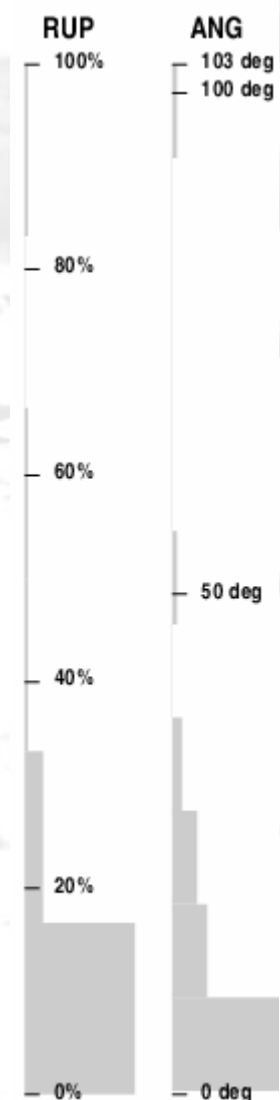
- Estimator **RUP** (**relative up**psilon) shows the calculated  $\tau$  shear vector length relative to assumed  $\lambda = \sqrt{3}/2$

$$RUP_i = \frac{\sqrt{\nu^2}}{\lambda} \cdot 100\% =$$

$$\frac{\sqrt{((\lambda^2 + \tau_X^2 + \tau_Y^2 + \tau_Z^2) - 2 \cdot \lambda \cdot ANG)^2}}{\lambda} \cdot 100\%,$$

$$\nu^2 = \lambda^2 + \tau^2 - 2 \cdot \lambda \cdot ANG$$

RUP and ANG diagram for TYM data set (Angelier 1990) →





- Because absolute stress magnitudes are **unknown**, Mohr circle parameters were **re-scaled to unit stress**:

- $\sigma_1 = 1.0$ ,
- $\sigma_2 = \varphi$ , and
- $\sigma_3 = 0.0$

- Calculate the **stress vector magnitude**:

$$|\sigma| = n_1\sigma_X + n_2\sigma_Y + n_3\sigma_Z,$$

$$\sigma = n_i \cdot T = \begin{bmatrix} \sigma_X \\ \sigma_Y \\ \sigma_Z \end{bmatrix} = \begin{bmatrix} n_1\sigma_{11} + n_2\sigma_{12} + n_3\sigma_{13} \\ n_1\sigma_{12} + n_2\sigma_{22} + n_3\sigma_{23} \\ n_1\sigma_{13} + n_2\sigma_{23} + n_3\sigma_{33} \end{bmatrix}$$

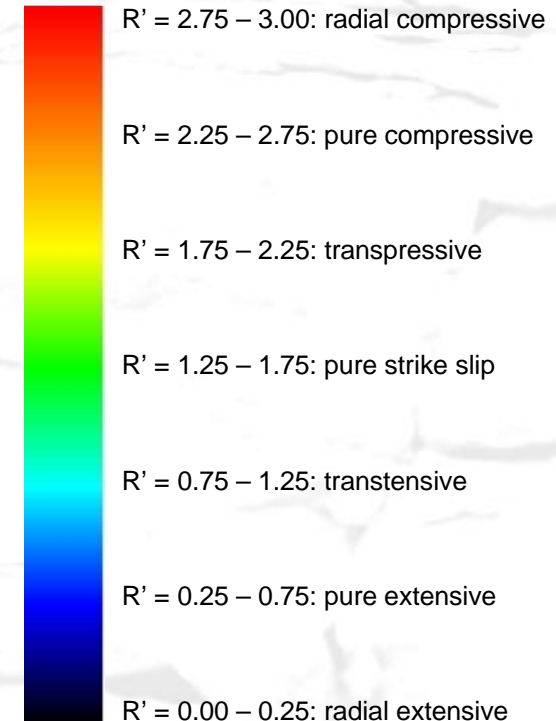
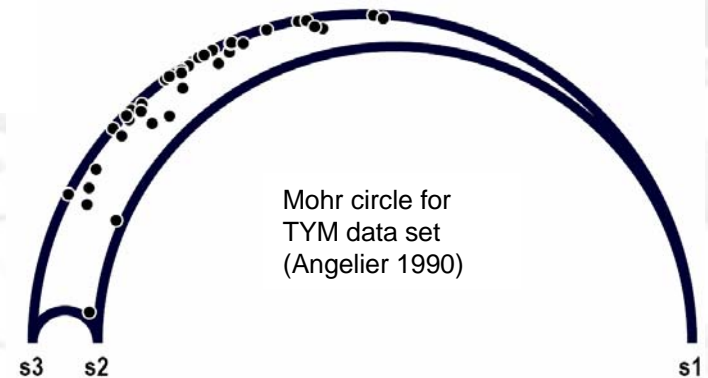
- Normal stress value** will be computed on the following way:

$$\sigma N_i = \frac{\sqrt{\sigma N_i X^2 + \sigma N_i Y^2 + \sigma N_i Z^2} - \sigma_3}{\sigma_1 - \sigma_3}$$

- Shear stress** on the  $i^{\text{th}}$  plane is as follows:

$$\tau_i = \frac{\sqrt{\tau_i X^2 + \tau_i Y^2 + \tau_i Z^2}}{\sigma_1 - \sigma_3}$$

- Mohr circle color refers to stress regime computed after Delvaux et al's (1999) reduced stress tensor





## TRIANGULAR GRID

- Generate a **Kaalsbeek counting net** (331 points), and convert in to Schmidt / Wulff net
- Identify **individual triangles** of the counting net (660 triangles)
- Decide which **input values** to count (dip, dip direction, strike, bearing, plunge), **count** data number in each triangle, and store them as a triangle center – count data set

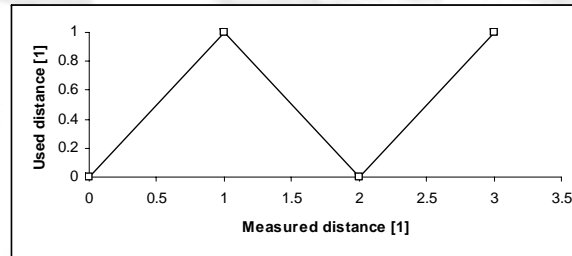
## RECTANGULAR GRID

- Generate a **rectangular grid** with the same number of data points in the unit circle as the Kaalsbeek triangle net has – use approximately  $\sqrt{(331 / 0.78)}$  cells
- **Re-scale** triangular grid's count data to the rectangular grid, calculating the count of each rectangular grid point  $C_R$  using each triangular counts  $C_T$ , where  $R_X$ ,  $R_Y$ ,  $T_X$  and  $T_Y$  are the rectangular and triangular grid point coordinates, respectively, and  $d$  is the distance of  $C_R$  and  $C_T$

$$C_R = \frac{C_T}{d},$$

$$d = \sqrt{(R_X - T_X)^2 + (R_Y - T_Y)^2}$$

- If a data set is close to the unit circle of the stereonet, the contour lines should appear on the opposite side of the stereonet as well because the projection method. To be able to visualize these contour lines, **re-calculate the measured distance**



- To avoid division by zero when  $C_R$  and  $C_T$  are close to each other, **define a minimum value for  $d$**
- Store as grid point – count data set
- Define **contouring values  $V$**  as a percentage of the maximum value of the rectangular grid

## BINARY GRID

- Generate **binary rectangular grid** using the original rectangular grid: cell value is 1 if the value in the cell is higher than the value of the contour line, otherwise keep it zero
- Use **marching squares** methodology to generate line segments, and re-calculate their relative position taking the contouring percentage into agreement

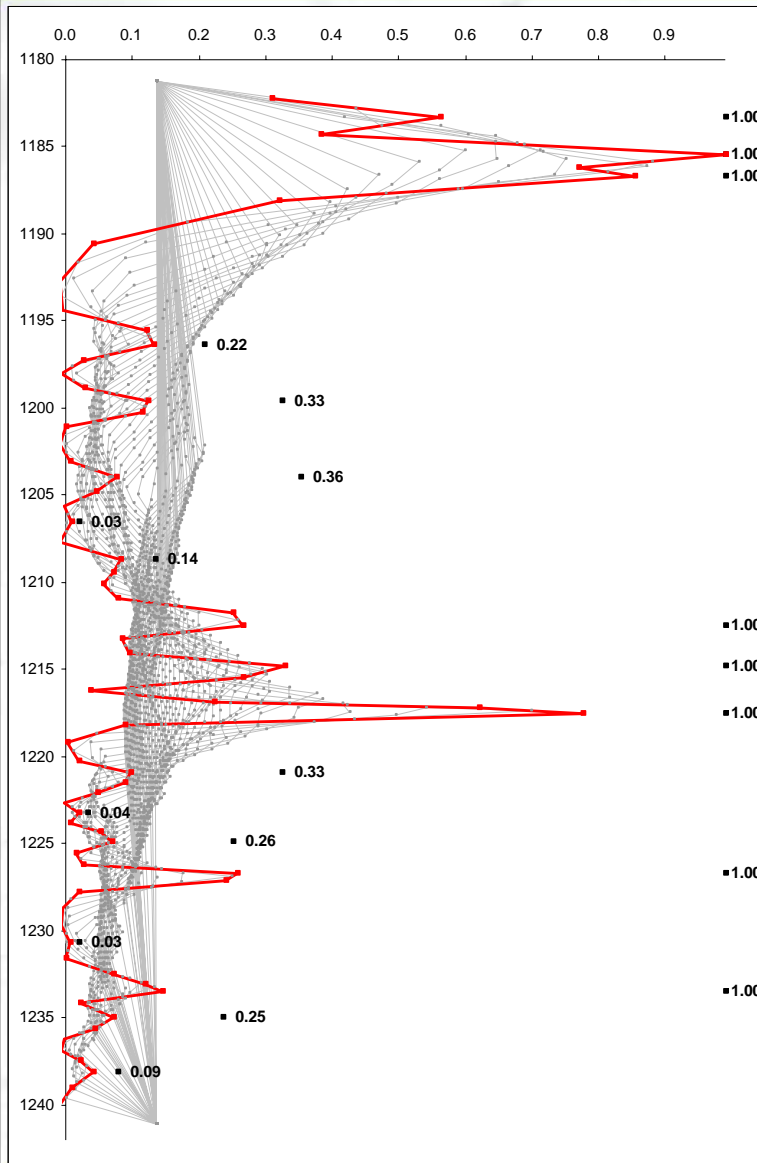
## LINE SEGMENT PROCESSING

- If a line is out of the unit circle, **ignore** it
- If a line crosses the unit circle, **clip** it
- If a line is not closed and does not cross the unit circle, linearly **extrapolate** first and/or last vertex coordinate to be at the unit circle
- **Eliminate** short lines (e.g. less than 5 vertex)

## LINE PROCESSING

- If a line terminates at the unit circle, it has to be **closed** either in the first  $\rightarrow$  last or last  $\rightarrow$  first vertex direction (nothing to do with the closed lines)
- Generate **two curves**, one is closed into the first  $\rightarrow$  last vertex direction, the other one in the last  $\rightarrow$  first vertex direction
- Each contour line has a value  $V$  (see above): **if any of the two lines** contains any grid point count value equal or higher than  $V$ , than use that line
- If **two contour lines** has any grid point equal or higher than  $V$ , than choose the one with the **smaller** area
- In **none** of the two contour lines has any grid point equal or higher than  $V$ , that's a bug
- Generate **2<sup>nd</sup> order Bezier curves** from the line segments, and plot them





- During deformation zones identification, it is important to visualize **changes** and **intensity of changes** in features geometry along the well bore
- The preliminary assumption is to correlate **intensity of changes in features geometry or frequency** with the **intensity of deformation**
- **These changes are displayed on curves, and 'intensive' change is visible as a peak in the data set. The question is how reliable the peak is, or on the other hand, which peaks are only noise**
- In order to do that, a **peak recognition** on the features dip, dip direction and frequency curve, as well as on their derivatives has to be carried out as follows

### PEAK RECOGNITION

- **Moving averages** are calculated for the investigated curve (=data set with  $n$  data)
  - The bin size for the moving average calculation changes one by one from **2 to  $n-1$** , and on the way,  $i$  different moving average curves are calculated
  - During each  $i^{\text{th}}$  moving average calculation, a boolean variable  $v$  is associated to each local maxima. The value of  $v$  is 1 if the local maxima is above the moving average curve, and 0 if below
  - The possibility (=chance) to have a real peak at any local maxima is the arithmetic average of  $\sum v$  for each peaks
- ◀ Feature frequency curve in red. Light gray curves are representing the result of a consecutive moving average calculation. Numbers above each maxima show the reliability of the investigated maxima to be a real peak. Please note maxima with 1.00 reliability are real peaks, but other maxima with e.g. 0.33 is maybe noise



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