Introduction and software manual for

SG2PS

Platform independent structural geological data processing software

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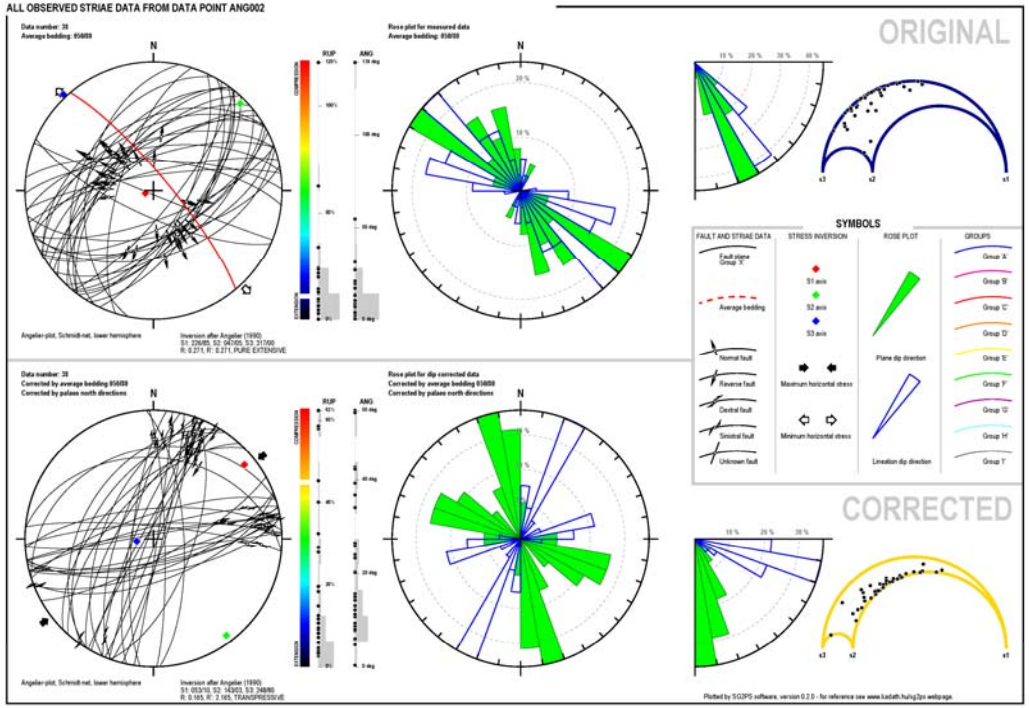
Graphical User Interface coded by Ali Baharev

CONTENT

1.1 INTRODUCTION

What is SG2PS?

- SG2PS is an **operating system independent** console application for field data evaluation and processing;
- **Separate processing** and plot for different localities, data types and data groups;
- Displays structural data on **stereonets** 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;
- **Post script** and text file output.



OTHER CAPABILITIES

- **Angelier** or **Hoeppner** plot, **Schmidt** or **Wulff** net, as well as **upper** or **lower** hemisphere projections are possible;
- **Slickenside data correction** on two different ways;
- **Full automatic** data processing option;
- Simplified data input and **auto completion** of input database;
- Built in **k-means clustering** module;
- **Stress tensor inversion** using
  - Turner (1953),
  - Sprang (1972),
  - Fry (1999),
  - Shan et al. (1984),
  - Michael (1984),
  - Angelier (1990) or
  - Mostafa (2005) methodologies;
- **Bingham directional statistics** for fracture sets;
- **RUP** and **ANG** stress estimators calculation and display;
- **Ideal movement** direction display on stereonet;
- Stress state display on **Mohr circle**.

1.2 INTRODUCTION

How does it works?

THE SOFTWARE

- Download SG2PS from the website **http://www.sg2ps.eu/download.htm**;
- Create a new empty folder (**working folder**) and copy the application into;
- Create your data spreadsheet what you want to evaluate, and **copy-paste into a text file** in the working folder;
- Start **SG2PS** using your console application;
- A **project folder** will be generated for the text and graphic 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 working 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, have a look this 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 input requirements;
- Chapter **PROCESSING AND DISPLAY** gives a slightly detailed overview about the software capabilities presenting different plot, net and hemisphere types as well as short description of used inversion methodologies;
- Fourth **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**.

INTRODUCTION

1.3 INTRODUCTION

Install, run and display results

INSTALLATION

- Download the install file from the **www.sg2ps.eu/download.htm** webpage and run '**sg2ps_setup.exe**';
- Choose the directory where you want to install the application, or use default C:\Program Files\sg2ps directory.

RUN

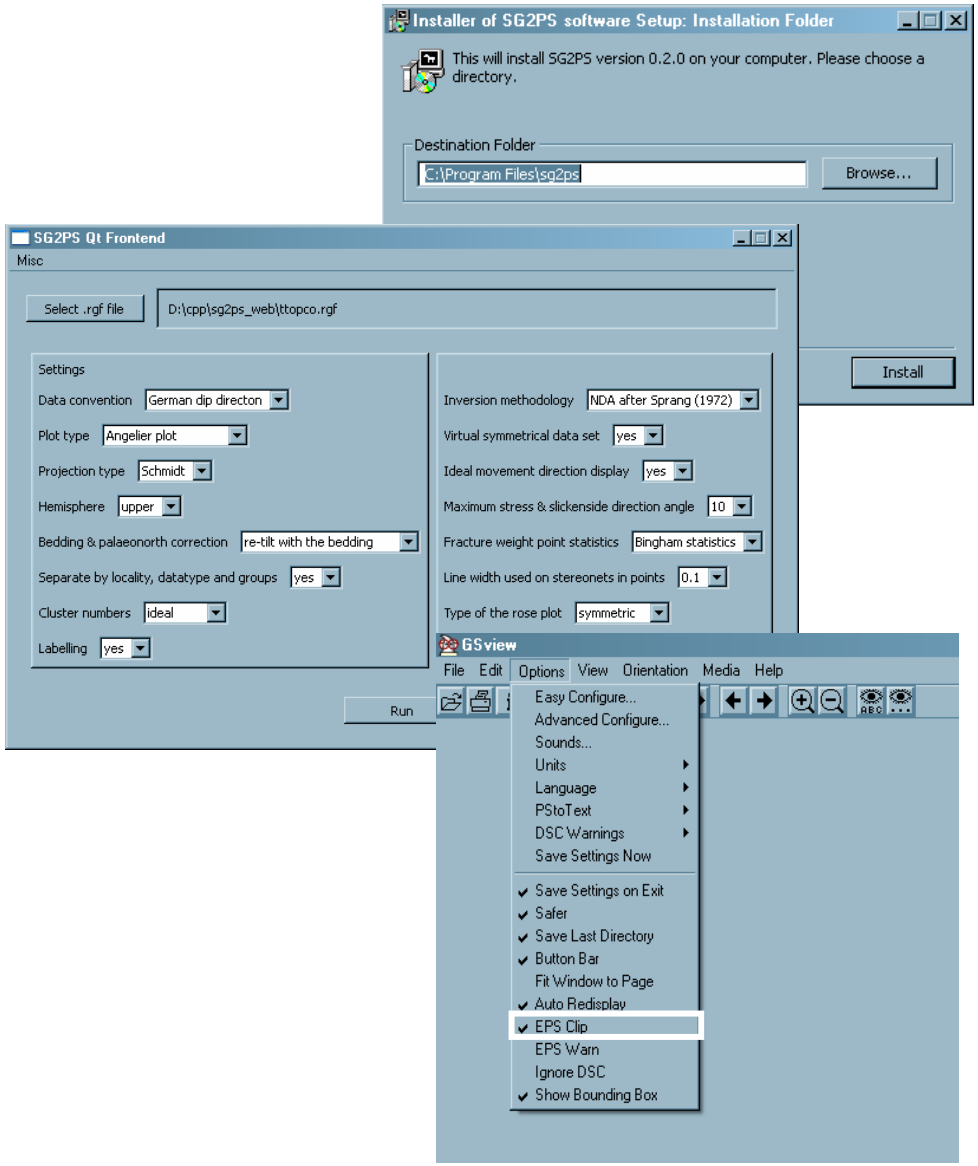
- Start '**sg2ps_gui.exe**' to run the software;
- Select the **data input (*.rgf) file** what you want to process;
- Use the project settings (if it is existing), use the default settings or create your evaluation settings; they will be saved in the project folder in a **setting (*.set) file**.
- Push **RUN**;
- Processing result will displayed on the screen but will **NOT** be saved;
- **SG2PS** working directory will displayed in a separate window.

DISPLAY RESULTS

- You can use free softwares (eq. GSView) or other ones (eq. Adobe Acrobat professional) to display the generated *.eps files;
- If you are using GSView, please don't forget to thick Options/EPS clip option, otherwise a rotated and clipped view will displayed on the screen.

UNINSTALL

- Simply delete the application folder; no registry components will be modified.



```
D:\cpp\sg2ps_1>sg2ps

+-----------------------------------------------------------------+
|                                                                 |
|                            SG2PS                                |
|       Structural Geological data to PostScript converter        |
|                                                                 |
|                     Coded by Agoston Sasvari                    |
|                       All rights reserved                       |
|                                                                 |
|                       version: 0.2.0 beta                       |
+-----------------------------------------------------------------+


Enter RGF file (*.rgf) name without extension.....: ang2
  - Input ANG2.RGF file opened.

CHECKING INPUT FILE(S) INTEGRITY
    - Input file opened successfully.
    - Correct file structure in all of 39 records.
    - Correct ID's in all of 39 records.
    - Correct group codes in all of 39 records.
    - Correct color codes in all of 39 records.
    - Correct location data in the first record.
    - Correct data types in all of 39 records.
    - Correct dip directions in all of 39 records.
    - Correct dips in all of 39 records.
    - Correct striae/SC data in all of 39 records.
    - Correct paleo North data in all of 39 records.
  - Input ANG2.RGF file structure is correct.

COORDINATE FILE

Do You want to use own coordinates in XY data format...[Y],
or use coordinate data in RGF file.....................[N].....? n

CHECKING OF SETTINGS OF 'ANG2' PROJECT
  - Using 'ANG2.SET' setting file.
  - Data convention.............................: german dipdir-dip
  - Plot type ..................................: Angelier plot
  - Net type....................................: Schmidt-net
  - Hemisphere..................................: lower hemisphere
  - Tilting by..................................: bedding and paleo-north
  - Groupcode...................................: do not use
  - Clustering..................................: 2 clusters
  - Labeling....................................: no labeling
  - Inversion...................................: using Angelier's method
  - Virtual symmetrical striae set..............: used
  - Angle between s1 and fault plane (if needed): 30 degs
  - Fracture statistics.........................: Bingham statistics
  - Linewidth:..................................: 0.6 points
  - Rose plot type..............................: symmetrical
  - Data bin size on rose plot..................: 10 deg


Do You want to use and save these settings....[S],
use default values............................[D],
input new ones................................[N],
or exit.......................................[X].....? s
```

❶ ❷ ❸

- Open the **console** of the operating system and navigate to the working folder;
- Type '**sg2ps**' to run the software;
- Enter the **name of the data input (*.rgf) file** what you want to process ❶; use small or large caps. After hitting ENTER, input file will be checked for errors and the result of the cross check will be displayed (see Chapter 1.6);
- If the input file is correct, next question is about the **coordinate (*.xy) file**; enter 'y' is you want to use a user-defined coordinate file to associate with the input file, otherwise hit 'n' and press ENTER ❷;
- If you are using coordinate (*.xy) file, it will be cross checked, and the result will displayed;
- Third step is to cross check the **setting (*.set) file** (if it is existing). If setting file is correct, settings wiill displayed on the screen, otherwise the 'hard coded' defaults are visible. You can choose ❸
  - to use a setting file to set up evaluation methodologies, type 's',
  - to use 'hard coded' default setup type 'd', or
  - manually create a new setting file, type 'n' (see Chapter 1.7);
- If the setting file is saved, the processing starts and results of the data evaluation will be displayed on the screen.

```
GEODATABASE PROCESSING FOR 'ANG2.RGF' DATABASE FILE

  - Geodatabase completed for 39 records.
  - Normal, dip and strike vectors were computed for 39 records.
  - Pitch to lineation conversion has done for 38 pitches of 38 striae data.
  - No striae to correcting.
  - Striae offset correction
    - No striae offset to correct.
K-MEANS CLUSTERING OF 'ANG2.RGF' DATABASE FILE
  - No clustering of geodatabase was required.
AVERAGE BEDDING COMPUTATION FOR 'ANG2.RGF' DATABASE FILE
  - Data set averages were computed for 2 independent data group(s) in 39 records.
  - Average bedding was computed for 1 independent data group(s) in 39 records.
RETILTING OF 'ANG2.RGF' DATABASE FILE
  - Striae offset correction
    - Striae offset in record 'ANG_010' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_011' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_002' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_003' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_004' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_005' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_006' has change from NORMAL to INVERSE.
    - Striae offset in record 'ANG_007' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_008' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_009' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_019' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_001' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_012' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_013' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_014' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_015' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_016' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_017' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_018' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_029' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_030' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_021' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_022' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_023' has change from NORMAL to INVERSE.
    - Striae offset in record 'ANG_024' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_025' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_027' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_028' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_038' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_020' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_031' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_032' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_033' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_034' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_035' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_036' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_037' has change from NORMAL to DEXTRAL.
  - Data set averages were computed for 2 independent data group(s) in 39 records.
  - Average bedding was computed for 1 independent data group(s) in 39 records.
DATA EVALUATION AND EXPORT FROM 'ANG2.RGF' DATABASE FILE
  - For 'ANG002' location, 'X', pseudo-inversion after Sprang (1972):
    - Original : s1: 066/83, s2: 233/06, s3: 323/02,     PURE EXTENSIVE, R: 0.423, R': 0.42
    - Corrected: s1: 228/16, s2: 059/73, s3: 319/03,   PURE STRIKE SLIP, R: 0.423, R': 1.57
DATA EXPORT FROM 'ANG2.RGF' DATABASE FILE
  - Postscript output completed for 2 file containing 39 records.
  - RGF output completed for 2 file containing 39 records.
  - Tilted RGF output completed for 2 file containing 39 records.
  - Average RGF output completed.
  - Completed RGF file exported.
  - Elapsed time: 1.61 seconds.

EVALUATION OF ANG2.RGF FILE COMPLETED.

D:\cpp\sg2ps_1>_
```

PRE-PROCESSING

- Empty records of the input (*.rgf) file will be **completed** as described in Chapter 2.1;
- **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 4.3.2);
- Slickenside **offset correction** is carried out (see chapter 4.3.2);
- 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 slickensides 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;
- **Bingham statistics** and inversion results will be displayed for each data sets;

FILE OUTPUT

- **Postscript** files, completed **geodatabase** files, **average** files and **datatype by datatype selected** files will be generated (see Chapter 1.5).

- 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 type and groups (if this option was selected, see Chapter 1.7 and 2.2).

Directory tree (right) generated after input processing

```
├──20121002-073607_-_DEMO_02
│  ├──1_original
│  ├──2_completed
│  ├──3_average
│  ├──4_rgf_separated
│  │  ├──bedding
│  │  ├──boudain
│  │  ├──foldaxis
│  │  ├──lineation
│  │  ├──plane
│  │  ├──s1
│  │  └──striae
│  └──5_ps_separated
│  ├──bedding
│  ├──boudain
│  ├──foldaxis
│  ├──lineation
│  ├──plane
│  ├──s1
│  └──striae
```

Original (above) and completed (below) input file

ID	GROUPCODE	COLORCODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIPDIR	DIP	LDIR	LDIP	SENSE	PALEONORTH	COMMENT
AM_0001			AM456			BEKHME	s0	47	17					_
AM_0002								40	28					_
AM_0003								27	27					_
AM_0004	A						STRIAE	272	85	24	25	S		_
AM_0005	A							282	80	26	32	S		_
AM_0006	A							274	84	14	24	S		_
AM_0007	A							246	85	15	24	S		_
AM_0008	B						STRIAE	166	74	241	0	S		_
AM_0009	B							152	80	238	0	S		_
AM_0010	B							162	74	60	4	S		_
AM_0011	B							149	80	64	4	S		_
AM_0012	A		AM457				STRIAE	107	85	191	10	S		_

ID	GROUPCODE	COLORCODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIPDIR	DIP	LDIR	LDIP	SENSE	PALEONORTH	COMMENT
AM_0001	X		AM456	0	0	BEKHME	BEDDING	47.0	17.0				0	_
AM_0002	X		AM456	0	0	BEKHME	BEDDING	40.0	28.0				0	_
AM_0003	X		AM456	0	0	BEKHME	BEDDING	27.0	27.0				0	_
AM_0004	A		AM456	0	0	BEKHME	STRIAE	272.0	85.0	359.9	23.1	SINISTRAL	0	_
AM_0005	A		AM456	0	0	BEKHME	STRIAE	282.0	80.0	6.1	30.4	SINISTRAL	0	_
AM_0006	A		AM456	0	0	BEKHME	STRIAE	274.0	84.0	1.4	23.5	SINISTRAL	0	_
AM_0007	A		AM456	0	0	BEKHME	STRIAE	246.0	85.0	334.3	18.7	SINISTRAL	0	_
AM_0008	B		AM456	0	0	BEKHME	STRIAE	166.0	74.0	256.0	0.0	SINISTRAL	0	_
AM_0009	B		AM456	0	0	BEKHME	STRIAE	152.0	80.0	242.0	0.0	SINISTRAL	0	_
AM_0010	B		AM456	0	0	BEKHME	STRIAE	162.0	74.0	73.1	3.9	SINISTRAL	0	_
AM_0011	B		AM456	0	0	BEKHME	STRIAE	149.0	80.0	59.7	4.0	SINISTRAL	0	_
AM_0012	A		AM457	0	0	BEKHME	STRIAE	107.0	85.0	196.1	10.0	SINISTRAL	0	_

```
D:\cpp\sg2ps_1>sg2ps


+------------------------------------------------------------------+
|                                                                  |
|                            SG2PS                                 |
|       Structural Geological data to PostScript converter         |
|                                                                  |
|                     Coded by Agoston Sasvari                     |
|                       All rights reserved                        |
|                                                                  |
|                       version: 0.2.0 beta                        |
+------------------------------------------------------------------+


Enter RGF file (*.rgf) name without extension.........:  ang2
  - Input ANG2.RGF file opened.

CHECKING INPUT FILE(S) INTEGRITY
    - Input file opened successfully.
    - Correct file structure in all of 39 records.
    - Correct ID's in all of 39 records.
    - Correct group codes in all of 39 records.
    - Correct color codes in all of 39 records.
    - Correct location data in the first record.
    - Correct data types in all of 39 records.
    - Correct dip directions in all of 39 records.
    - ERROR: incorrect dip(s) in following record(s):  ANG_037.
  - Input ANG2.RGF file structure is incorrect; please enter file name again, or press

Enter RGF file (*.rgf) name without extension.........:
```

❶

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 4) **type** its name again ❶ for a new cross check;
- Because input database error check is carried out column by column, it can occur need to **repeat** error fixing for other columns as well.

PROCESSING

- If data number is **less** than required by the slickenside inversion procedure or Bingham statistics (see Chapter 4.5 and 4.6.1 – 4.6.6), the software is unable to calculate stress field or statistics parameters – error message will displayed.

INTRODUCTION

Manually create setting file

```
INPUT USER SETTINGS - to exit: press [X]
  - Data convention:
    - german with dip direction.....[G],
    - or right-hand rule with strike.....[r]?  g
  - Plot type:
    - Angelier plot with planes.....[A],
    - or Hoeppener plot with poles.....[h]?  a
  - Net type:
    - equal are Schmidt-net.....[S],
    - or equal angle Wulff-net.....[w]?  s
  - Hemisphere:
    - upper hemisphere.....[u],
    - or lower hemisphere.....[L]?  l
  - Correction of measured data with:
    - bedding.....[b],
    - paleo-north direction.....[p],
    - or bedding and paleo-north direction.....[A]?  b
  - Using group codes:
    - use and evaluate groups independently.....[Y],
    - or do not use and evaluate groups together.....[n]?  n
  - Clustering:
    - no clustering.....[N],
    - automatic cluster number.....[a],
    - or 2..9 clusters.....[2..9]?  n
  - Labeling of stereonet:
    - labeling of measured data using data ID.....[y],
    - or none.....[N]?  y
  - Inversion of slickenside data:
    - pseudo-inversion using Sprang's (1972) NDA method....[D],
    - pseudo-inversion using Turner's (1953) PTN method....[p],
    - regression using Fry's (1999) method.....[f],
    - regression using Shan et al's (2003) method.....[s],
    - regression using Michael's (1984) method.....[m],
    - inversion using Angelier's (1984) method.....[a],
    - inversion Mostafa's (2005) method.....[o],
    - or none.....[n]?  d
  - Virtual symmetric striae set:
    - use virtual symmetric striae set.....[Y],
    - or do not generate virtual symmetric set.....[n],  y
  - Ideal movement display for slickensides:
    - display.....[Y],
    - or do not display.....[n],  n
  - Angle between s1 and fault plane for pseudo-inversion:
    - 10 to 80 degrees.....[10..80]?  30
  - Fracture statistics:
    - Bingham statistics for weight point computation.....[B],
    - or none.....[n]?  b
  - Linewidth in points (1/72 inch):
    - 0.1 to 1.0.....[1...9, 0 for 1.0]?  6
  - Rose plot for data sets:
    - symmetrical.....[S],
    - or asymmetrical.....[a]?  s
  - Bin size on rose plot:
    - 2.5 degrees.....[a],
    - 5.0 degrees.....[b],
    - 10.0 degrees.....[C],
    - or 22.5 degrees.....[d]?  d
```

- If **no setting (*.set)** file and **don't want to use hard coded** defaults, it is possible to **manually create** own setting (*.set) file for the project;
- To do, hit '**n**' after asking for input settings ❶;

```
Do You want to use and save these settings....[S],
use default values.....[D],
input new ones.....[N],
or exit.....[X].....?  n
```

❶

- To enter new settings, you have to set up the new settings **one by one**, entering the character code of the desired options one by one. No 'cancel' or 'undo' possibility, you can exit or complete setting generation;
- After some experience using the software, the easiest way is to **manually modify** the setting (*.set) file using a text editor.

1.9 INTRODUCTION

Running with arguments and redirecting of screen output

RUNNING WITH ARGUMENTS

- Is it possible to run the software with **arguments** in the following format:

```
D:\cpp\sg2ps_1>sg2ps ang ang2
```

- Use this potion, if you want to process **large** data sets (>10000 records) or more files;
- If running with arguments (and all of input *.rgf files are corrects), **no user input** is needed;
- The software checks all of input files one by one; if any error occures, it is possible to fix it **before** starting the processing;
- After checking input files, processing starts. If coordinate (*.xy) files are present, they will be **used**; if setting file(s) are present, will be **used**; if no setting file, **hard coded settings** were used but not saved;
- Input (*.rgf) file check takes some seconds, but after the fixing of any errors, the software works **automatically** and processes the input without user's contribution.

REDIRECTING OF SCREEN OUTPUT

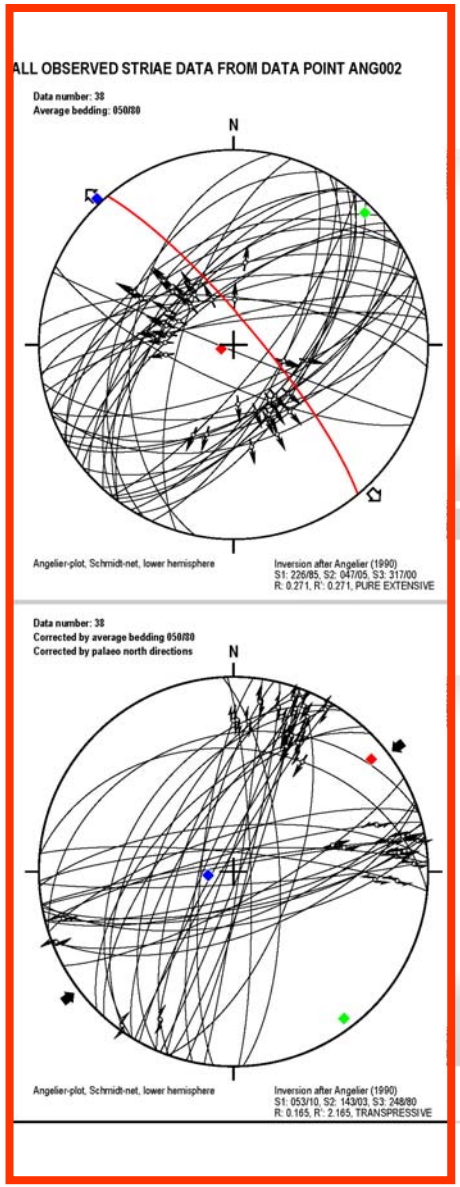
- It is possible to redirect screen output into text file format using '**>>**' operator on the following way:

```
D:\cpp\sg2ps_1>sg2ps ang ang2 >> output.txt
```

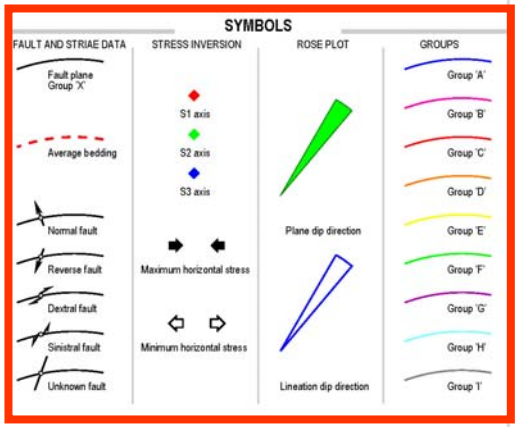
- This type of data processing is ideal if the user want to keep displayed evaluation results for future processing or report;
- Please note **ALL** of screen outputs will be re-directed by the operating system into the user defined file; if the input (*.rgf) file has any error, the warnings will be re-directed as well, and **no possibility** to correct any data – in this case the software is waiting for user input, but the user is not informed about;
- It is recommended to use this option just with correct, **cross checked** files.

GRAPHIC OUTPUT

Stereographical projections



- 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**.

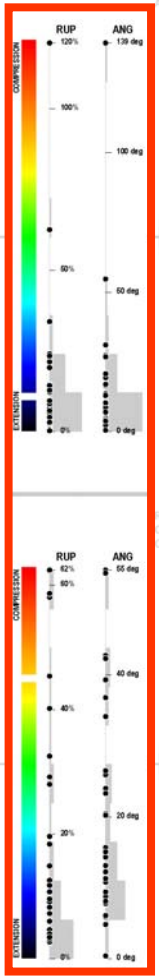
GRAPHIC OUTPUT

Stress field properties, stress estimators

- 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.

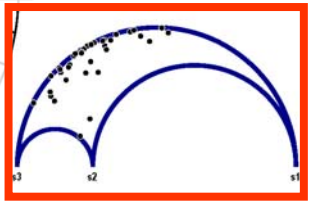
- RUP bar shows the **relative upsilon ratio** (theoretical / computed shear stress vector length) from 0 to maximum RUP value (see chapter 4.8.2). Thickness of gray bars in the background shows the density of RUP values.

- 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.



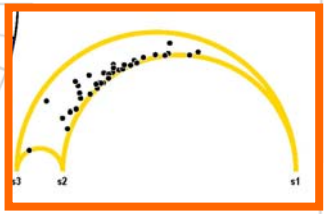
- ANG bar shows the **angular misfit** between the measured and calculated stress directions from 0 to the maximum ANG value. Thickness of gray bars in the background shows the density of ANG values;

- 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;

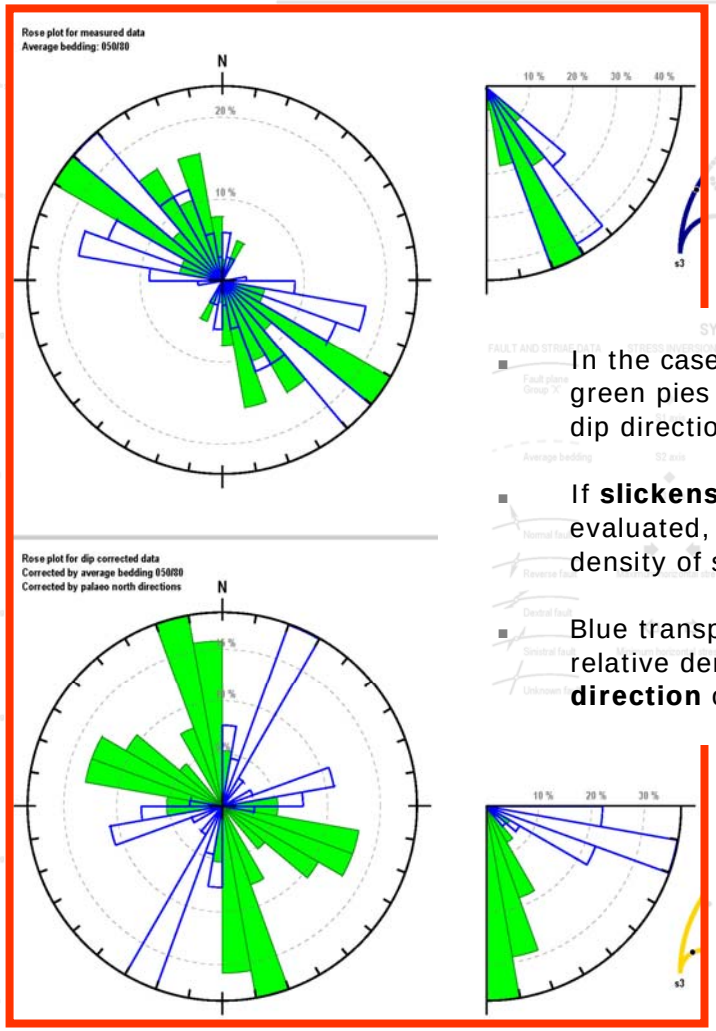
- Mohr circles color refers on **stress regime**.



GRAPHIC OUTPUT

Rose plots

- Equal bin size rose plots show the **directional density** change of the evaluated data set;
- **Symmetric** and **asymmetric** plots with 2.5, 5, 10 and 22.5 degrees bin size are available;
- Large stereonets 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.



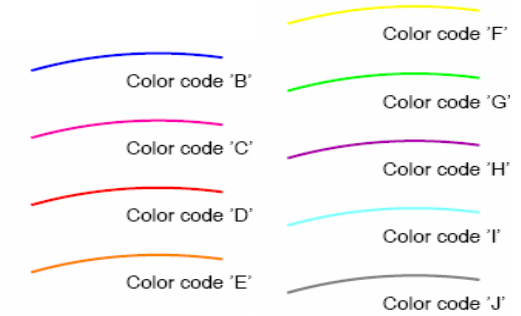
- In the case of **planes and lineations**, green pies show relative density of data dip direction;
- If **slickensides or s-c planes** are evaluated, greens pies show relative density of striated planes or s planes;
- Blue transparent pies are displaying relative density of **slickenside slip direction** or **c plane dip direction**.

INPUT FILE FORMAT

2.1 INPUT FILE FORMAT

RGF data format I.

- RGF data file (*.rgf) is a **tab separated** text file with the following properties:
  - Has **minimum** 15 columns;
  - **First line is the header**, with arbitrary content (to indicate column names is recommended here);
  - **Do not has new empty line at the end**;
- 1st column is for the **data ID**; all of measurements entered in the RGF file has to have an individual ID, which **must be different** from each other;
- 2nd 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 – J are accepted here. If the field is empty, group will became default group X;
- 3rd column is for the **color code**; use characters 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;
- 4th column is for the **name** 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;



ID	GROUPCODE	COLORCODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIPDIR	DIP	LDIR	LDIP	SENSE	PALEONORTH	COMMENT
P_S_0158			P067			KOLOSH	BOUDAIN	018	37					
P_S_0159			P068			KOLOSH	LITHOLOGY							
P_S_0160			P069			PILA SPI	LITHOLOGY							
P_S_0161			P070			GERCUS	BEDDING	009	74			O		
P_S_0162	A						STRIAE	012	85	187	77	I		
P_S_0163	A							198	71	204	71	I		
P_S_0164	A							202	78	24	N	I		
P_S_0165	A							187	62	55	SW	I		
P_S_0166	B						SC	182	70	252	40			

- 5th and 6th columns are for the **coordinate** 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 xy coordinate file (*.xy) – in this case the content of these columns will be **overwritten** by the content of xy coordinate file;
- 7th column is for the **formation name**; not required to fill. Enter new formation name, otherwise it will be filled by content of previous record;
- 8th column is for the data type. 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', 'crossbedding', 'contact', 'foldplane', 'foldsurface', 'lithoclase', 'plane', 's1', 's2', 's3', 's4', 's5', 'vein', 'userplane4' and 'userplane5';
  - for **slickensides**: 'striae', and
  - for **s-c schistosity**: 'sc';

ID	GROUPCODE	COLORCODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIPDIR	DIP	LDIR	LDIP	SENSE	PALEONORTH	COMMENT
ANG2_033			TYM033				striae	115	68	87	N	N		_
ANG2_034			TYM034				striae	161	48	85	E	N		_
ANG2_035			TYM035				striae	340	69	88	W	N		_
ANG2_036			TYM036				striae	287	68	80	N	N		_
ANG2_037			TYM037				striae	6	70	72	W	N		_
ANG2_038			TYM038				striae	359	71	89	E	N		_
ANG2_039			TYM039				bedding	50	80					_
AM_0001			AM456			BEKHME	bedding	47	17					_
AM_0002								40	28					_
AM_0003								27	27					_
AM_0004	A						STRIAE	272	85	24	25	S		_

2.1 INPUT FILE FORMAT

RGF data format III.

- 9th column is for the **strike** or **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. Please note to input **zero**, use '0', '00', '000', '0.0' or '0.00'; other numerical formats are not accepted by the software;

- 10th 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;

- 11th column is
  - for the **strike** or **dip direction** either **c planes** of s-c data sets, or for the **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.

- 12th column is
  - for the **dip angle** of **c plane** or **slickenside lineation**. All of records must be 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', 'wsw', 'w', 'wnw', 'nw' or 'nnw' for pitch direction);

ID	GROUPCODE	COLORCODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIPDIR	DIP	LDIR	LDIP	SENSE	PALEONORTH	COMMENT
ANG2_037			TYM037				striae	6	70	72	W	N		_
ANG2_038			TYM038				striae	359	71	89	E	N		_
ANG2_039			TYM039				s0	50	80					_
AM_0001			AM456			BEKHME	S0	47	17					_
AM_0002								40	28					_
AM_0003								27	27					_
AM_0004	A						STRIAE	272	85	24	25	S		_
AM_0005	A							282	80	26	32	S		_
AM_0006	A							274	84	14	24	S		_
AM_0007	A							246	85	15	24	S		_
AM_0008	B						STRIAE	166	74	241	0	S		_

- 13th column is for the 1) **movement direction** along slickenside, and 2) to indicate **overturned** geometry of bedding. Must be filled in the case of slickensides and in the case of overturned beds, otherwise it is empty. The following characters are accepted here:
  - '+', '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;
  - use 'o' or 'overturned' to indicate **overturned** bedding, otherwise it will be handled as normal one;
  - it is allowed to use 'n' or 'normal' to indicate **normal** bedding;
- 14th column is for the **palaeonorth direction**; if it is known, can be indicated and used, otherwise leave empty. Values between 0.0 – 360.0 are accepted here;
- 15th column is for your **comments**. Using Microsoft Excel, **do not leave empty** this column, because it will be not exported during the copy-paste process;
- 16th and other columns: will be not processed by the software. Everything **behind** the tab character after the 14th column will be exported with no modification, so it is possible to store here as many data as you want.

ID	GROUPCODE	COLORCODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIPDIR	DIP	LDIR	LDIP	SENSE	PALEONORTH	COMMENT
OR0960	A						STRIAE	272	85	24	25	S		first set
OR0961	A							282	80	26	32	S		first set
OR0962	A							274	84	14	24	S		first set
OR0963	A							246	85	15	24	S		first set
OR0964	B						STRIAE	166	74	241	0	S		second set
OR0965	B							152	80	238	0	S		second set
OR0966	B							162	74	60	4	S		second set
OR0967	B							149	80	64	4	S		second set
OR0968	A		O1457				STRIAE	107	85	191	10	S		first set
OR0969	A							118	90	202	10	S		first set

2.2 INPUT FILE FORMAT

SET data format

- SET data file (*.set) is a tab separated text file with 16 rows storing the settings used during data processing. Default settings (hard coded in software) are bold characters.
- 1st row is for the **data convention**: '**g**' for german dip direction/dip convention, and 'r' for right hand rule input (output will be in the same format as the input);
- 2nd row for **plot** type: '**a**' for classic Angelier plot, and 'h' for Hoeppner pole point plot;
- 3rd row for **projection** type: '**s**' for equal area Schmidt projection, and 'w' for equal angle Wulff projection;
- 4th row for the **hemisphere**: 'u' in the case of upper, and '**l**' for lower hemisphere;
- 5th row 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.
- 6th row refers to using **groups**. If you want to use groups (if they are indicated in 2nd column of RGF file), all data will be **separated** by locality, datatype **and groups**, and processed/displayed on this way. Input '**y**' to use groups, or 'n' to do not use them.
- 7th row refers to the **cluster numbers** used during k-means clustering. Enter '**n**' do not use, 'a' to find the ideal cluster number, or 2 – 9 for the required number of clusters.
- 8th row is for **labeling**: enter 'y' to label all of your data on the stereonet, otherwise use '**n**'.
- 9th row is for the striae **inversion** methodology:
  - '**d**' for NDA after Sprang (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).
- 10th row is for **virtual symmetrical data set**: enter 'y' to use them, otherwise input '**n**'.
- 11th row is for the **ideal movement direction display.** Enter 'y' if you want to display ideal movement direction of slickensides, otherwise use '**n**'.
- 12th row is 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).
- 13th row is for fracture **weight point statistics**: enter '**b**' to use Bingham statistics, or 'n' if you do not need.
- 14th row is for the **line width** used on stereonets in points; enter 1 - 9 for 0.1 – 0.9, or 0 for 1.0. Default is **0.6** points.
- 15th row is for the **type of the rose plot**: enter '**s**' for symmetric and 'a' for asymmetric one.
- 16th row is for the **bin size** for rose plot: enter 'a', 'b', '**c**' or 'd' for 2.5, 4.0, 10.0 and 22.5 deg bin sizes.

2.3 INPUT FILE FORMAT

XY data format

- XY data file (*.xy) is a tab separated text file with the following properties:
  - Has **3 columns**;
  - **First line of the header**, with arbitrary content (it is recommended to indicate column names here);
  - **Do not have new empty line** at the end;

- 1st column is for the **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;

- 2nd and 3rd columns are for **coordinates** in user defined **numeric format** and order. Just numeric format will checked but otherwise not processed by the software just merged with the opened *.rgf file content.

NAME	LATITUDE	LONGITUDE
001	37.221830	42.837230
002	37.224040	42.838040
003	37.224080	42.838070
004	37.225180	42.838510
005	37.227340	42.857490
006	37.230770	42.852360
007	37.232400	42.848140
008	37.232610	42.847570
009	37.220530	42.837570
010	37.221420	42.838400
011	37.220210	42.837760
012	37.219630	42.837410
013	37.219220	42.838030
014	37.218550	42.837370
015	37.217430	42.836310
016	37.215310	42.834780
017	37.214830	42.833950
018	37.213120	42.832940
019	37.210490	42.829390
020	37.204010	42.828900
021	37.205500	42.830200
022	37.203020	42.827920
023	37.258800	42.778080
024	37.247350	42.778340
025	37.239920	42.777410

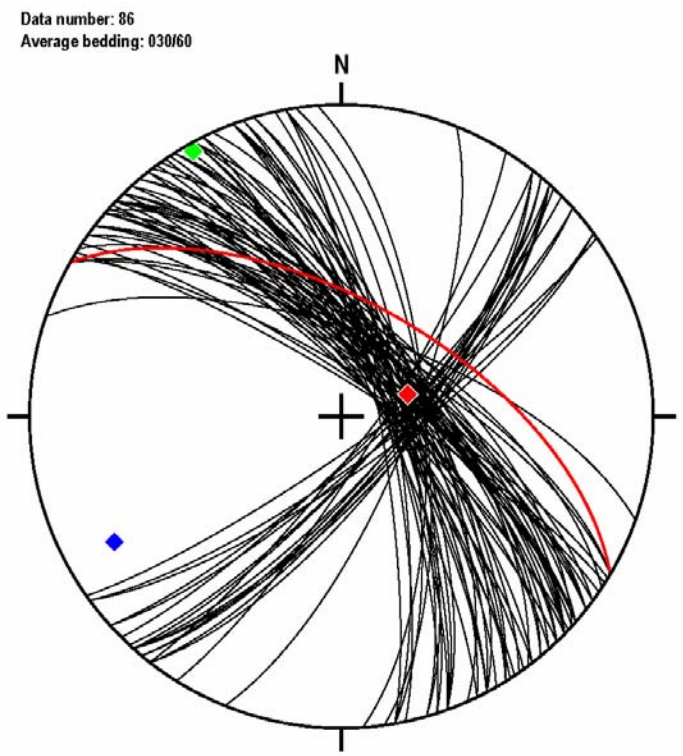
PROCESSING AND DISPLAY

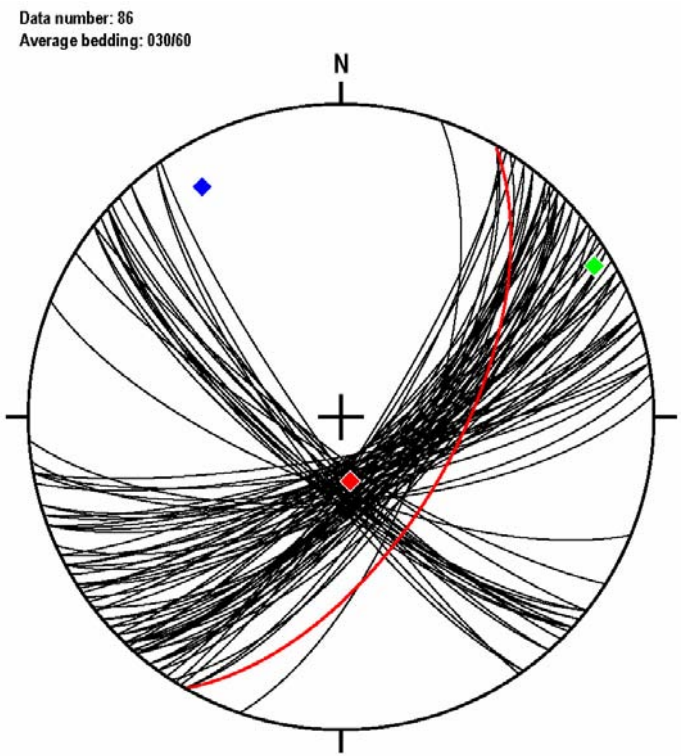
GERMAN DIP DIRECTION

- 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.





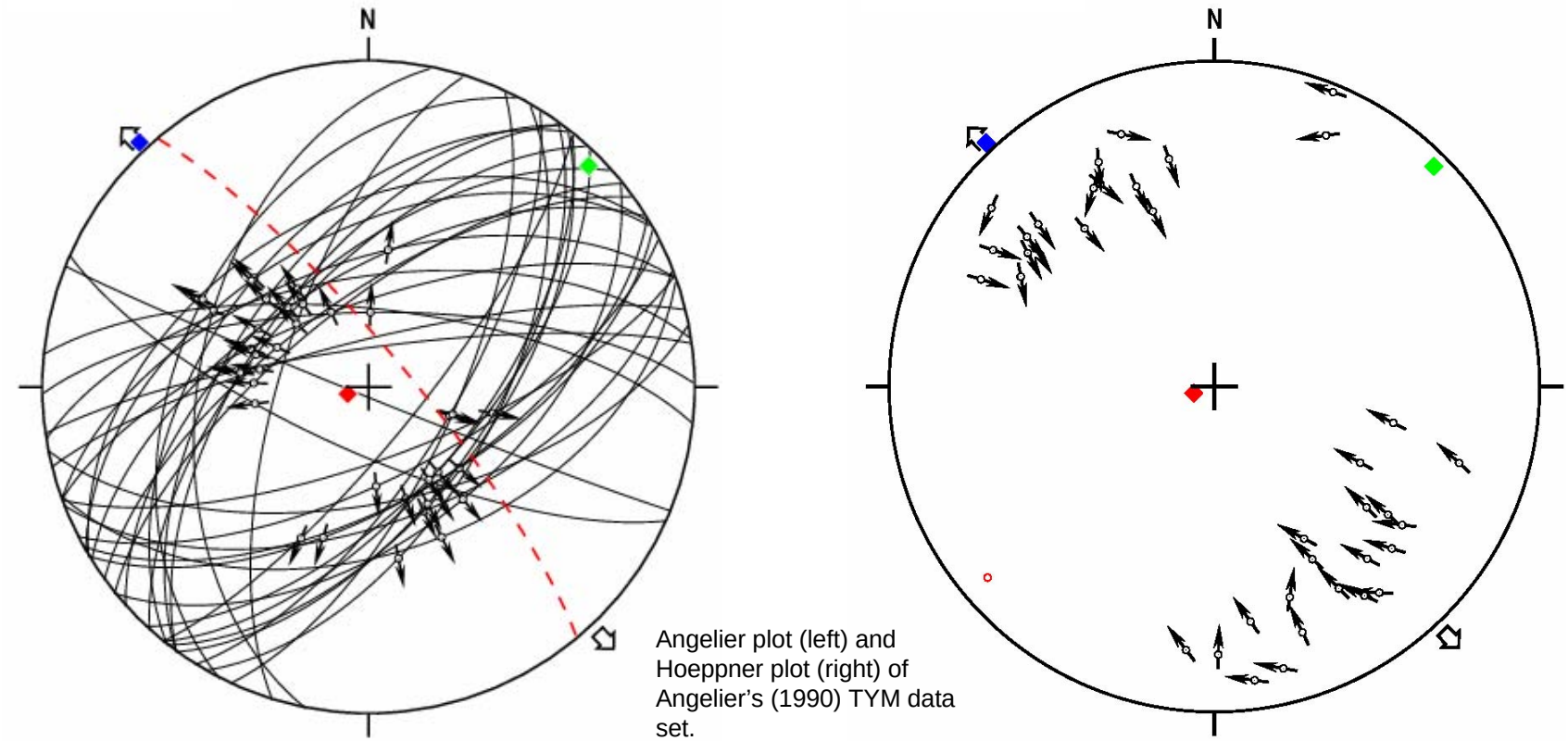
Same fracture data set processed as german convention data (left) and right hand rule data (right).

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.

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.



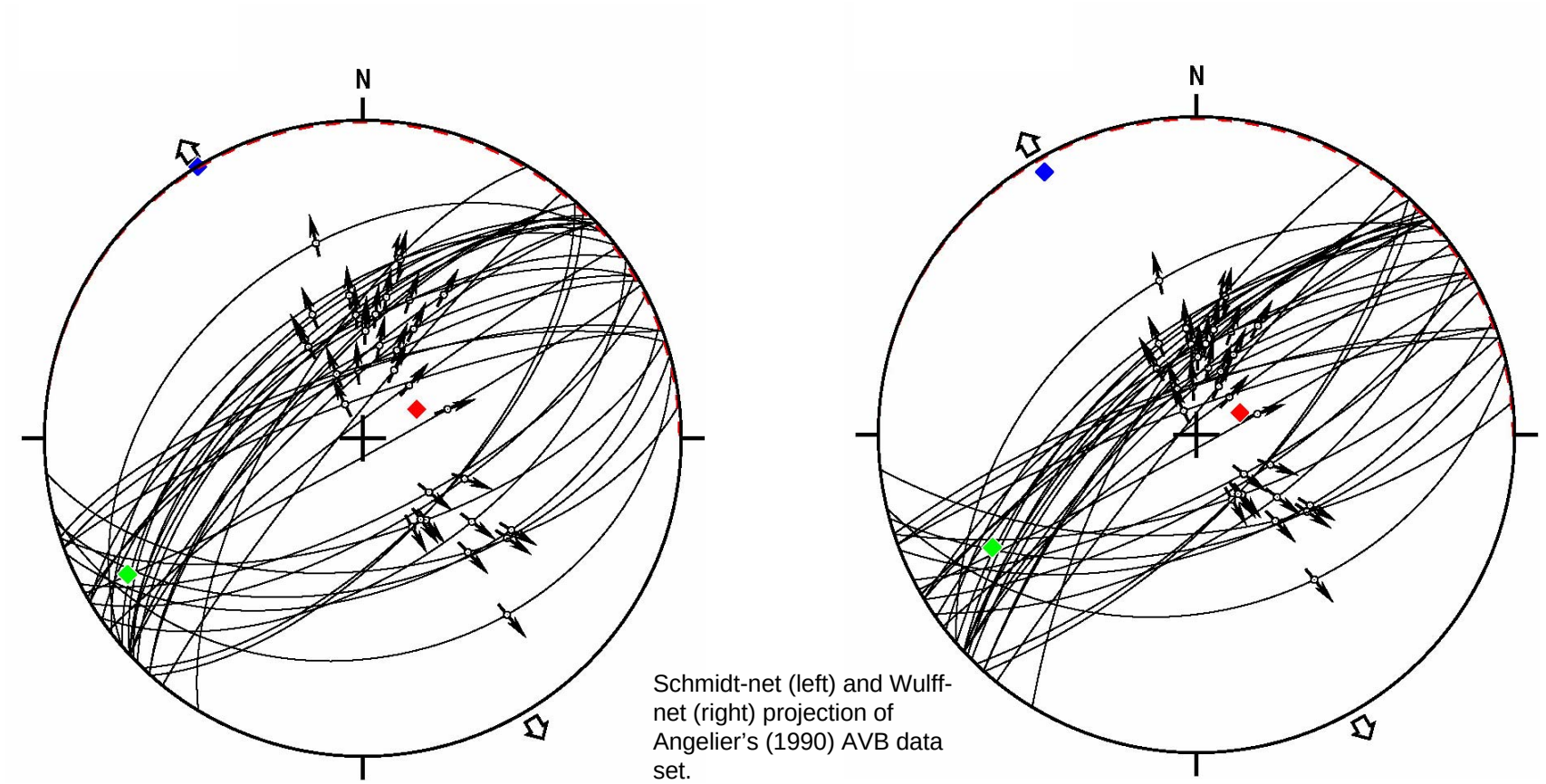
Angelier plot (left) and Hoeppner plot (right) of Angelier's (1990) TYM data set.

SCHMIDT NET

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

WULFF NET

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



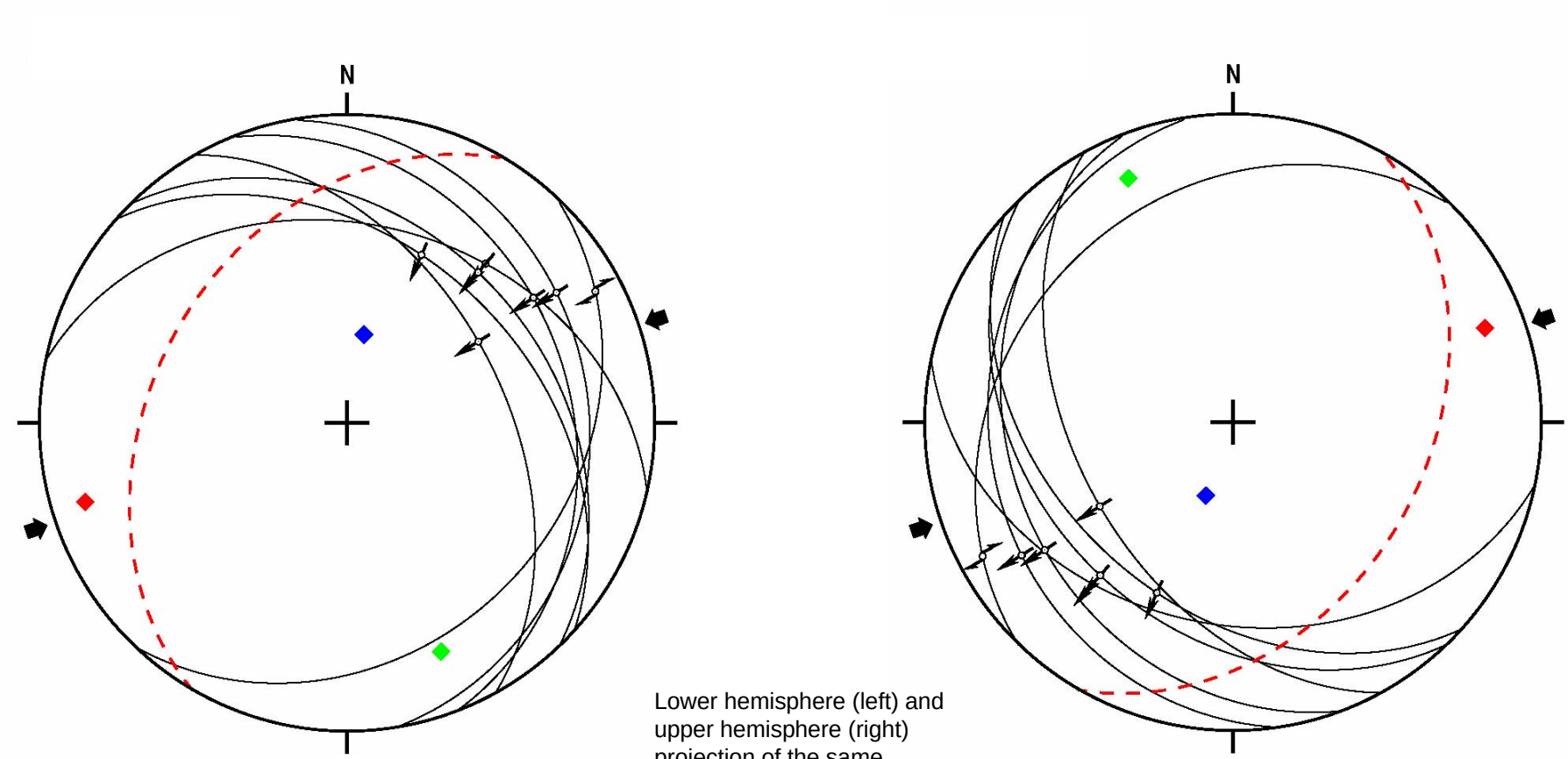
Schmidt-net (left) and Wulff-net (right) projection of Angelier's (1990) AVB data set.

LOWER HEMISPHERE

- Projects on **lower** hemisphere

UPPER HEMISPHERE

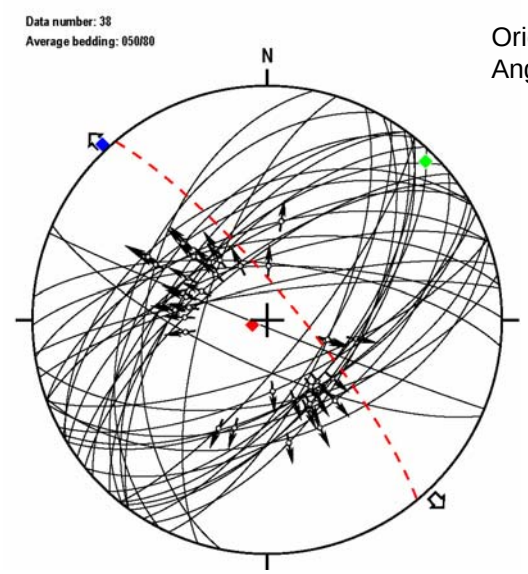
- Projects on **upper** hemisphere



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

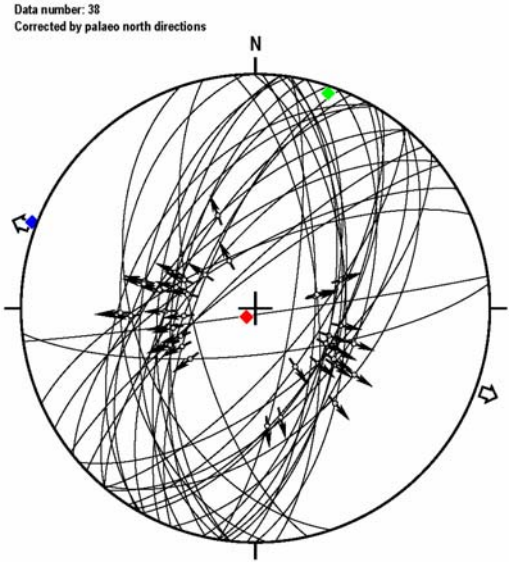
PROCESSING AND DISPLAY

Correction with average bedding and palaeonorth direction

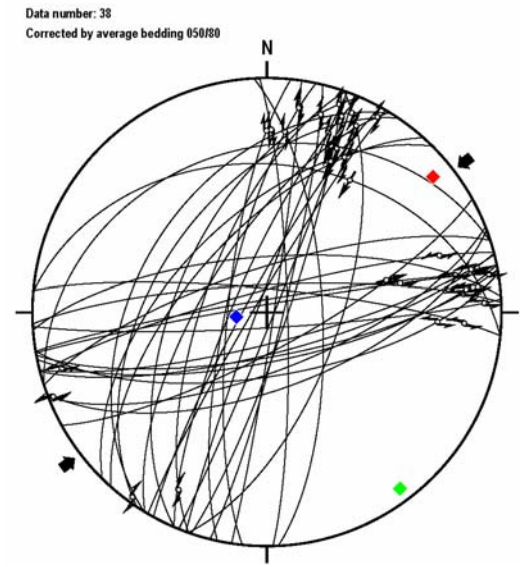


Original TYM dataset of Angelier (1990)

Original TYM dataset of Angelier (1990) corrected by 30 deg palaeonorth direction for all of data

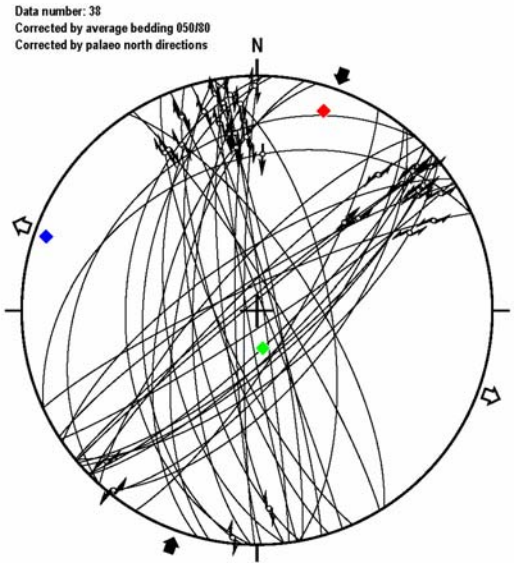


- Selecting **bedding correction** option, all data will be re-tilted by the **average bedding** measured in the outcrop. If no bedding data, the plot for measured and corrected data will be the **same**.
- Selecting **palaeonorth direction correction**, all data will be corrected with the palaeonorth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



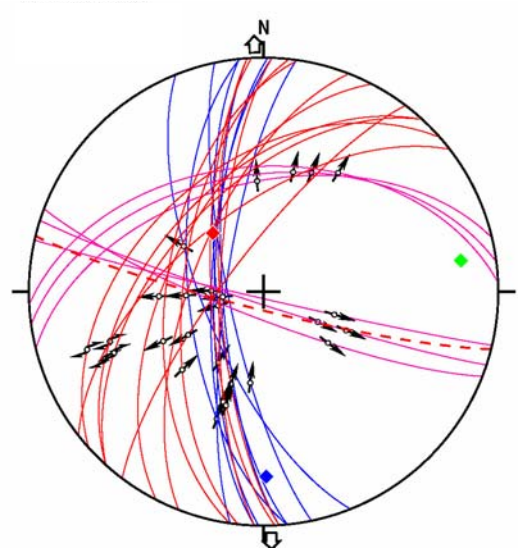
Original TYM dataset of Angelier (1990); all data corrected by 050/80 average bedding direction

Original TYM dataset of Angelier (1990) corrected by 050/80 average bedding and by 30 deg palaeonorth direction.



PROCESSING AND DISPLAY

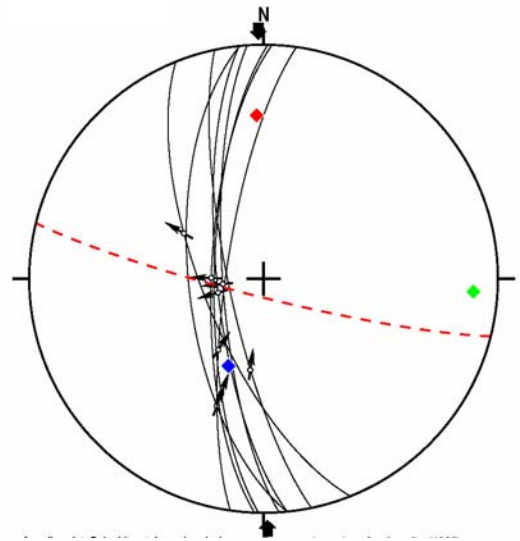
Processing with and without using groups

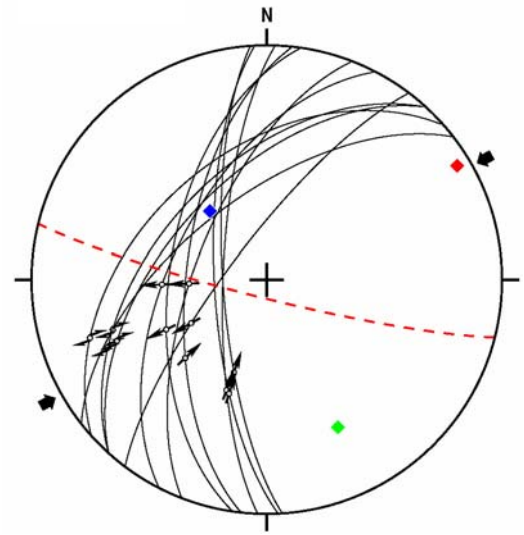


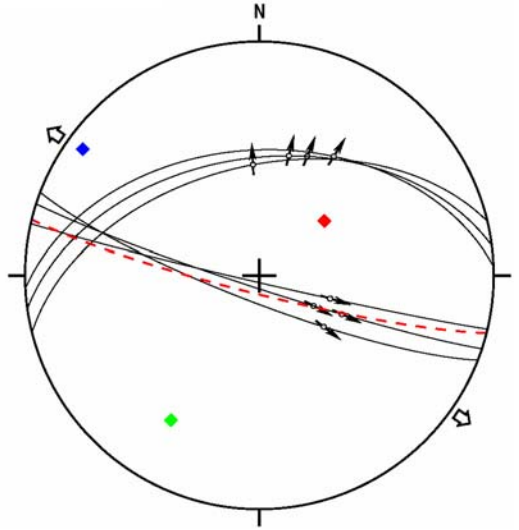
Data set with three different groups *not using groups processing* option – all data will be processed altogether and displayed using different colors

- Before processing, it is possible to sort the data in different groups (using **group codes** in input *.rgf file) and evaluate them **separately**.
- If group processing option is **not** is use, data from different groups will displayed with **different colors**, and will be processed **altogether**;
- Using groups setting option, groups will be processed and displayed **group by group** using **default** black line color.

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



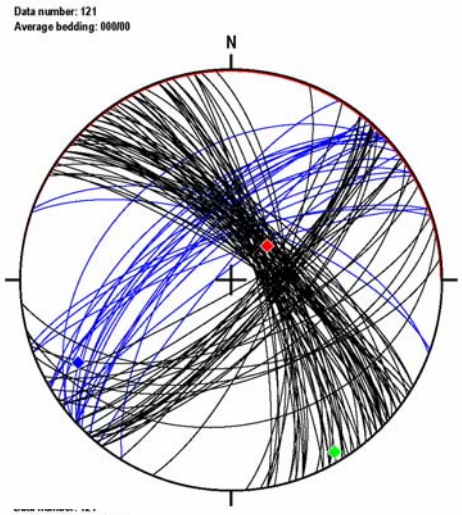




PROCESSING AND DISPLAY

K-means clustering

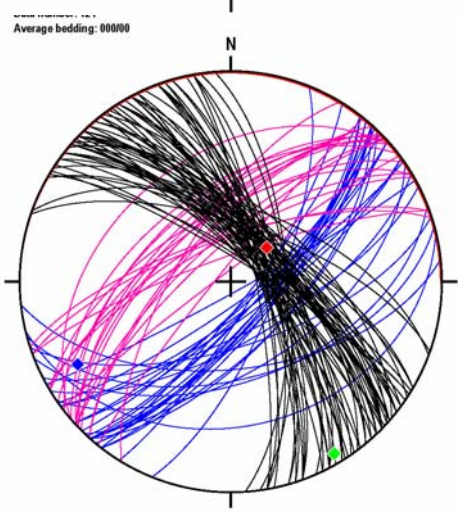
- Built in k-means clustering module is coded to identify **different clusters** of an inhomogeneous data set;
- Normal k-means clustering sorts all of data into **k user defied groups**.

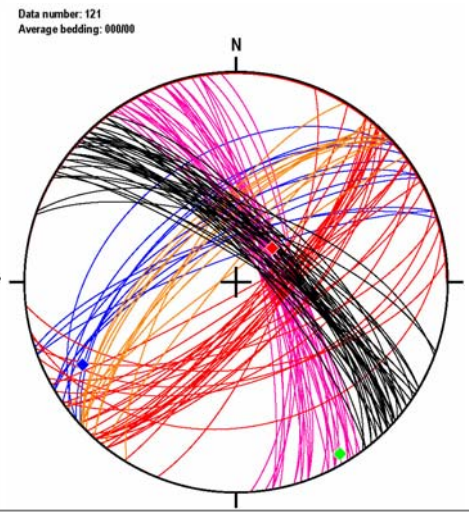


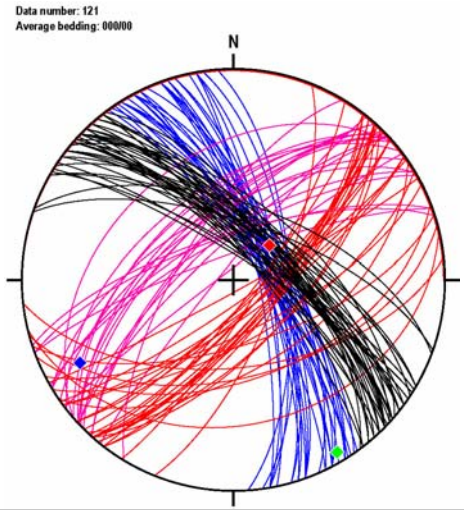
Clustering of the same data set into two, three, four five and six clusters with 32.16%, 1,29%, 0.73%, 0.68% and 0.20% relative error. Last solution with six clusters and 0.20% relative misfit is the best fitting solution.

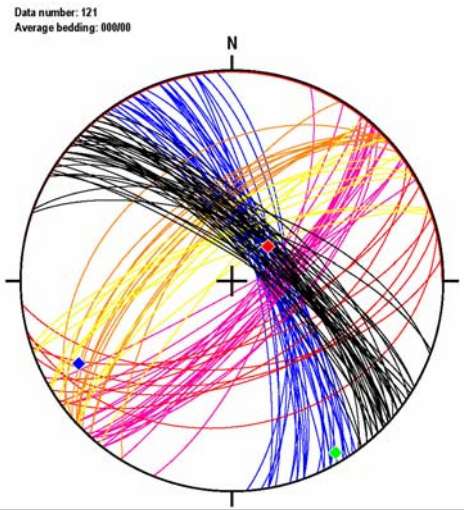
LIMITATIONS:

- 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 became **empty** (all data fits better to other groups). If data group becomes empty, group numbers was overestimated.

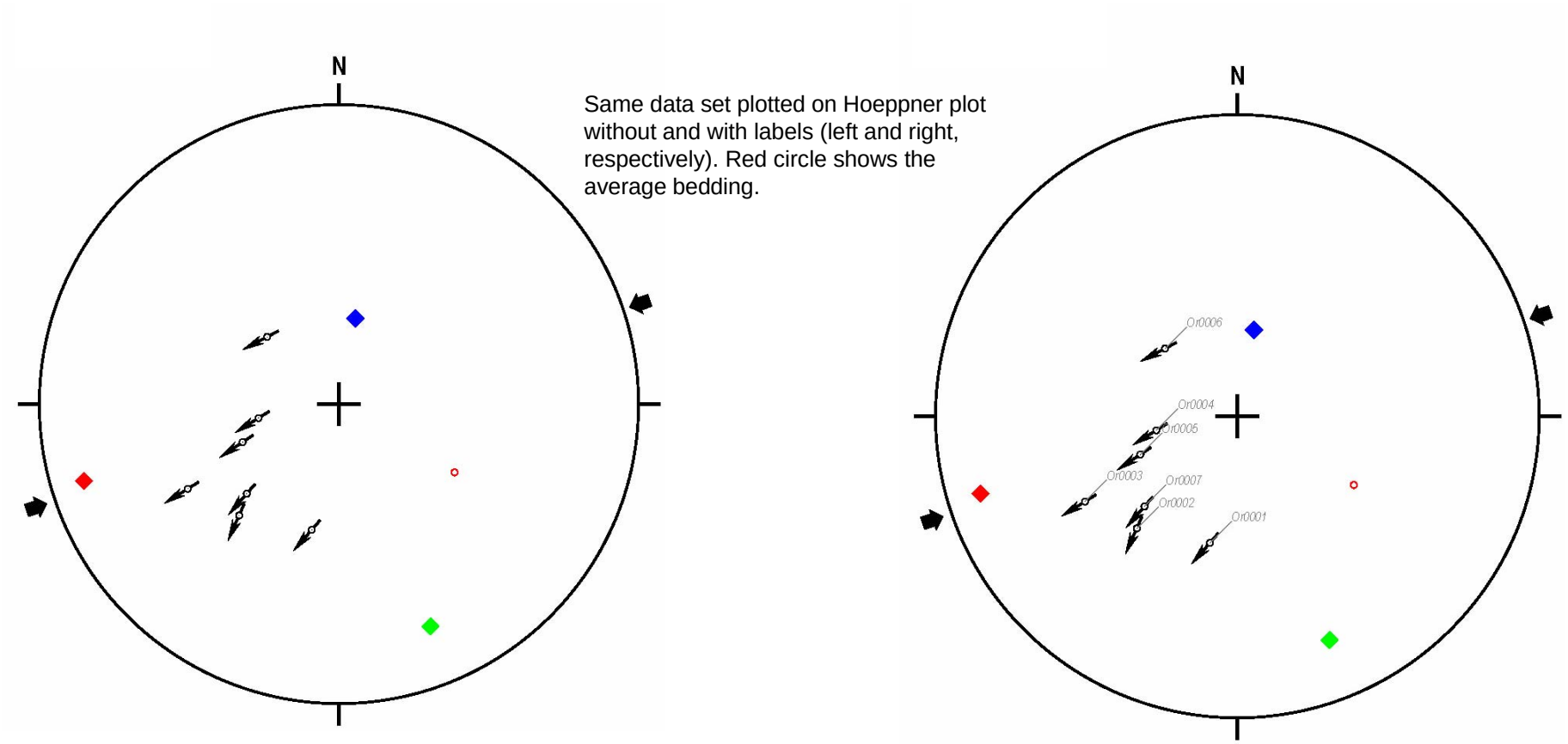








- Labeling option can help to **identify** data one by one;
- Labeling of large number of data is not recommended because the possible **overlapping**.



Same data set plotted on Hoeppner plot without and with labels (left and right, respectively). Red circle shows the average bedding.

PROCESSING AND DISPLAY

Inversion I. – regression with a priori assumption

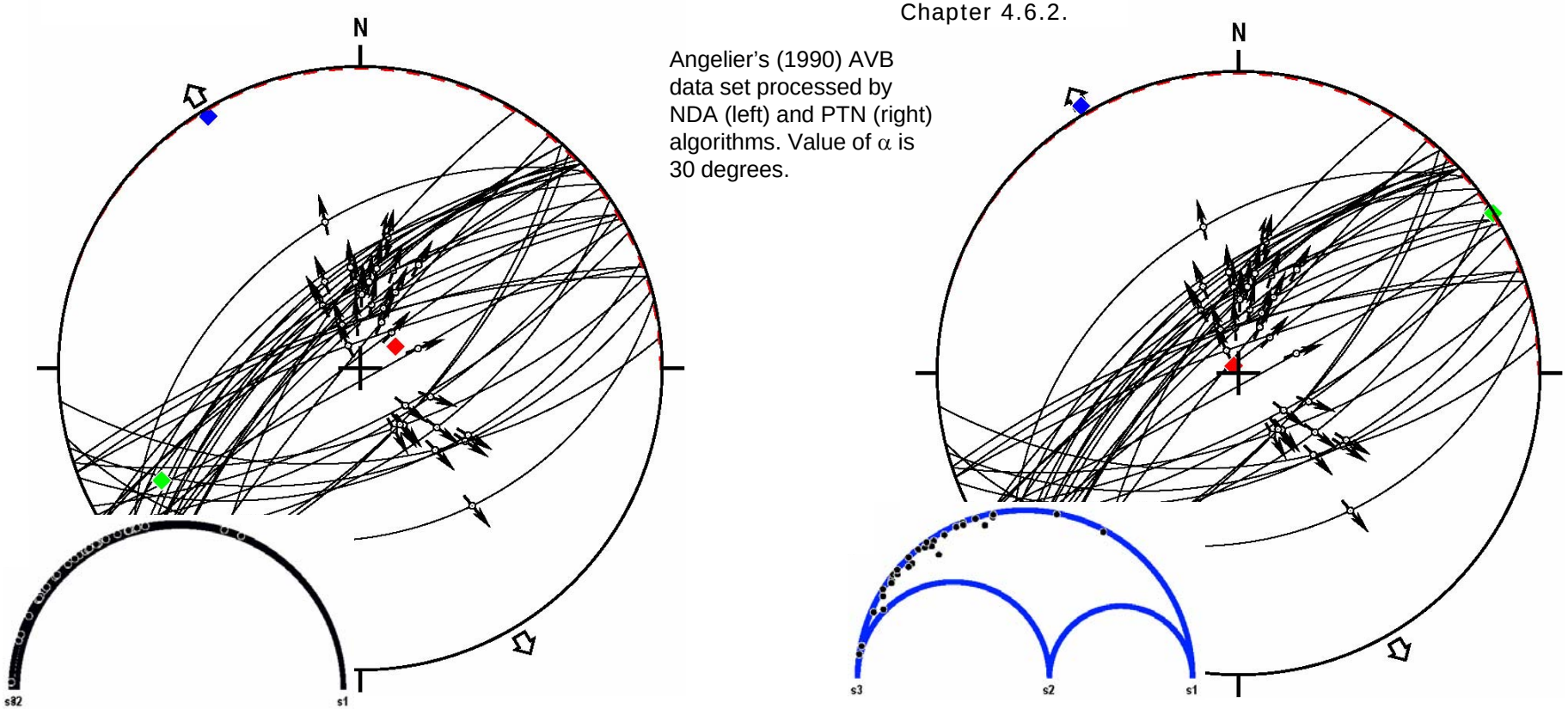
- Regression methodologies with a priori assumption are calculating maximum and minimum stress orientations for each slickenside **based on fault plane and striae geometry**, and searching for the best fitting stress tensor;
- To calculate stress axes direction, **a priori assumption is required** about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

NDA after Sprang (1972)

- NDA methodology calculates the best fitting stress tensor on this way for the **entire** data set. For details see Chapter 4.6.1.

PTN after Turner (1953)

- PTN methodology calculates the best fitting tensor for **maximum, minimum and intermediate stress orientations** and processes this tensor. For details see Chapter 4.6.2.



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

PROCESSING AND DISPLAY

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^{th} data.

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

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 4.6.3);

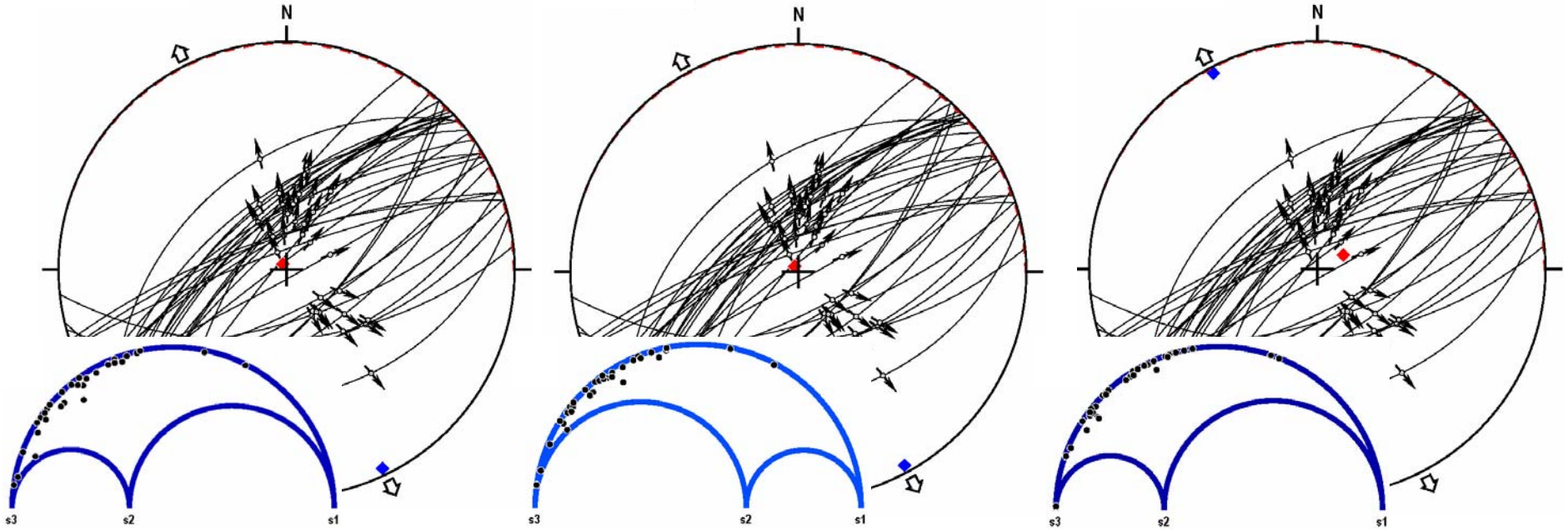
SHAN ET AL (2003)

- Shan et al's (2003) solution is five dimensional regression assuming $\sigma_{11} + \sigma_{22} + \sigma_{33} = 0$; use for minimum 5 data at the same set (see Chapter 4.6.4);

MICHAEL (1984)

- Michael's (1984) solution is to calculate the shear vector with assumed unit length (see Chapter 4.8.1) and find the best fitting stress tensor using five dimensional regression.

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



PROCESSING AND DISPLAY

Inversion III. – 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 $\sigma_{11} + \sigma_{22} + \sigma_{33} = 0$ and $\sigma_{11}^2 + \sigma_{22}^2 + \sigma_{33}^2 = 3/2$; the stress tensor below fits to these criteria;
- To minimize the misfit, create **partial derivates** of the stress estimator, and solve the equations.

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

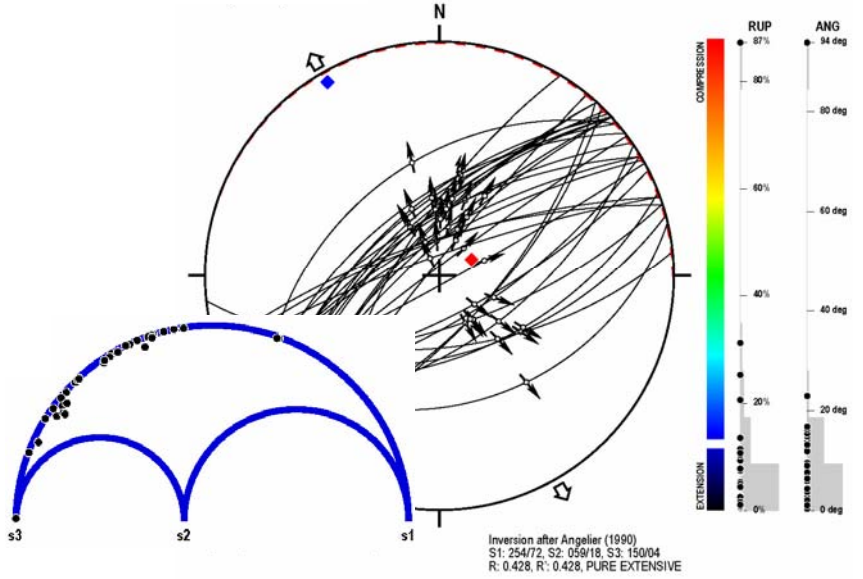
ANGELIER (1990)

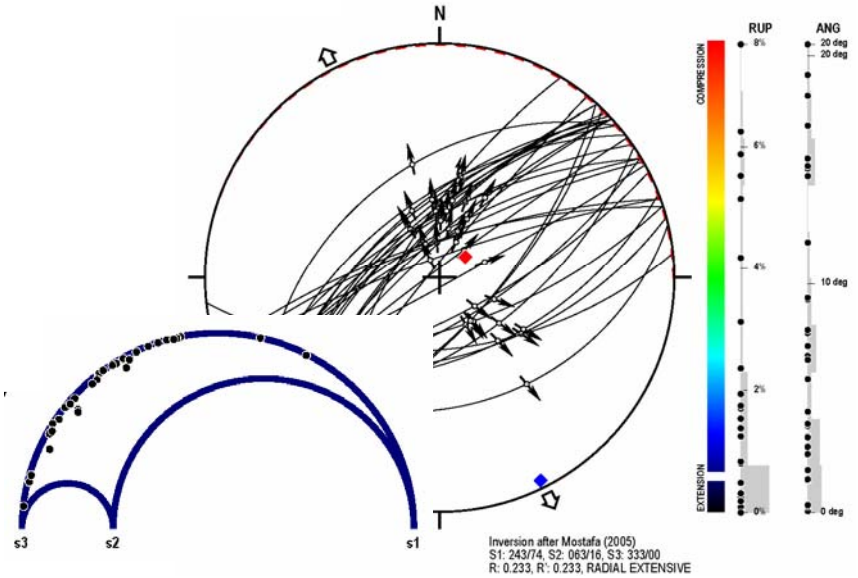
- Angelier's (1990) methodology calculates a **misfit vector** ν between the **measured** and **calculated** shear vector, and minimizes its length (see Chapter 4.6.6).

MOSTAFA (2005)

- Because the measured stress vector length is **unknown**, Angelier (1990) assumed constant measured shear vector length λ; Mostafa's (2005) methodology is the same as Angelier's (1990) one, with **iteration in the measured shear vector length λ** to decrease ν misfit vector length (see relative upsilon RUP bars below, and Chapter 4.6.7).

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

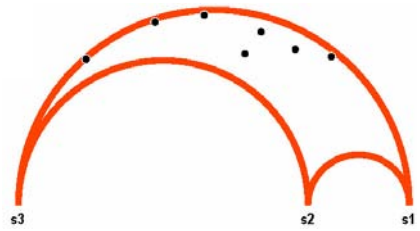


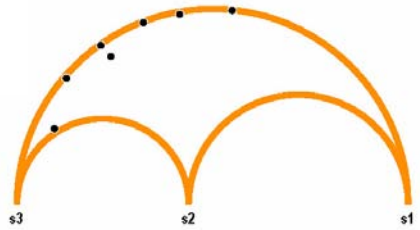


PROCESSING AND DISPLAY

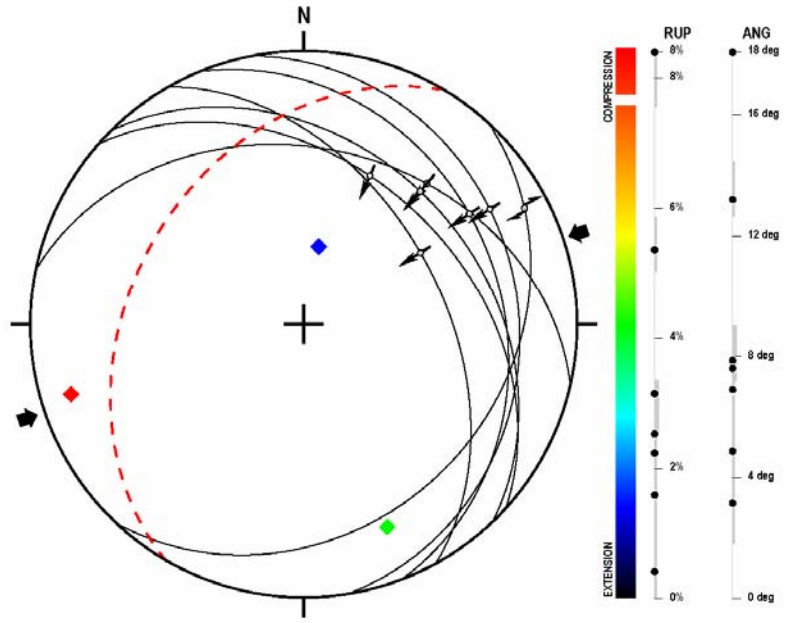
Virtual symmetrical data set

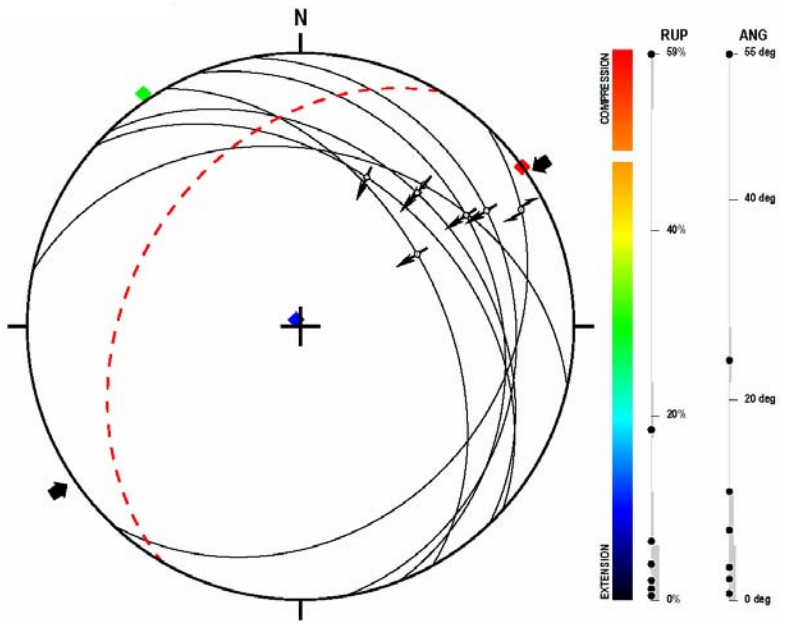
- Some inversion methodologies are sensible on the **symmetry** of the input data set; in some case of asymmetry the result is mathematically correct, but not from geological point of view;
- One of the possible solutions could be to generate a **virtual, symmetrical data set**; this virtual set is composed 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.



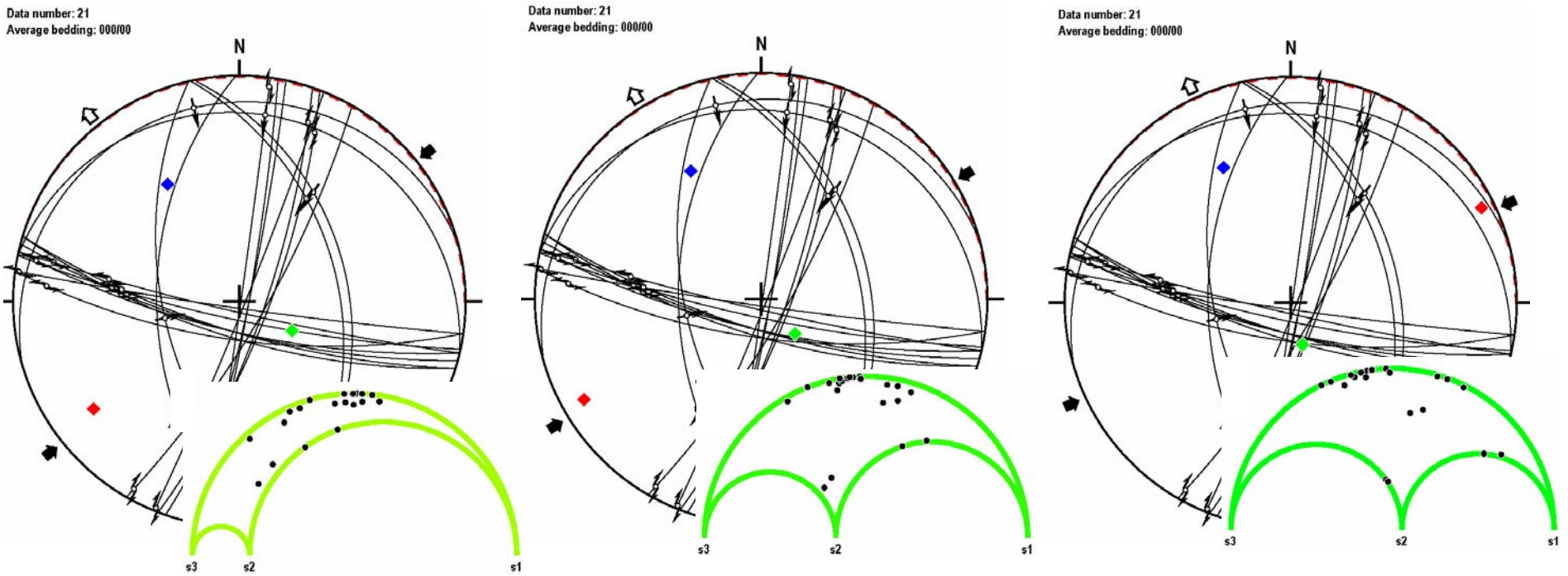


PROCESSING AND DISPLAY

Stress angle

- Regression technologies with **a priori** assumptions are using α **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 (Ortner et al. 2002).

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

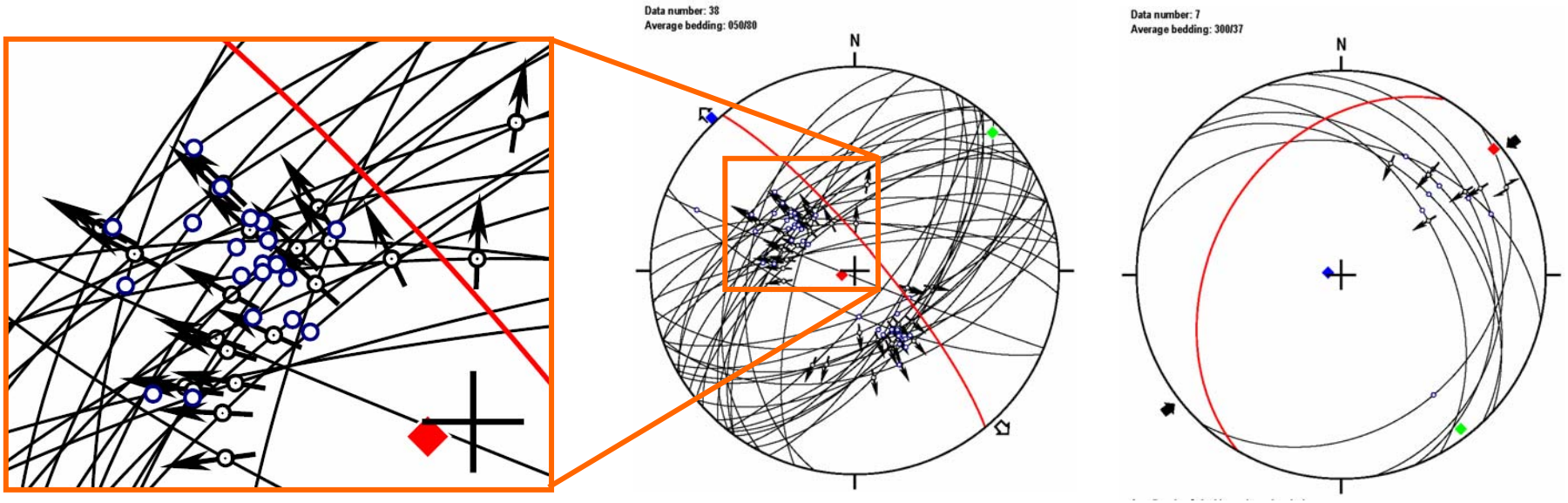


PROCESSING AND DISPLAY

Ideal movement direction display

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

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



PROCESSING AND DISPLAY

Bingham statistics and fold great circle calculation

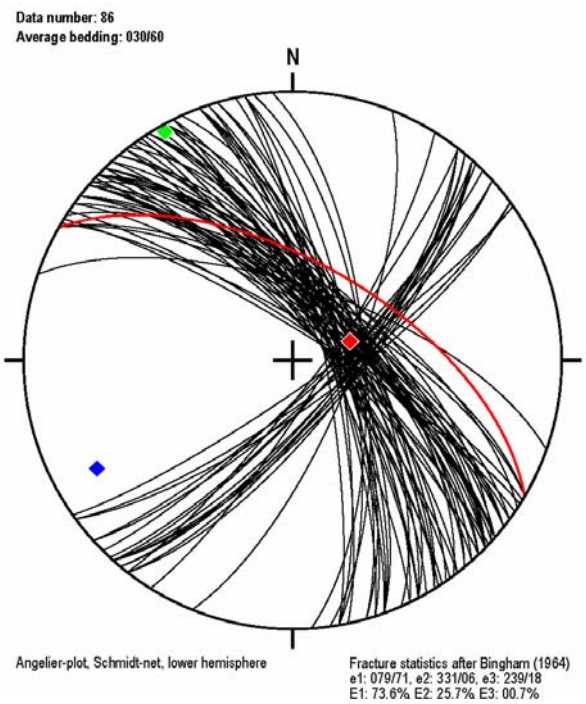
BINGHAM STATISTICS

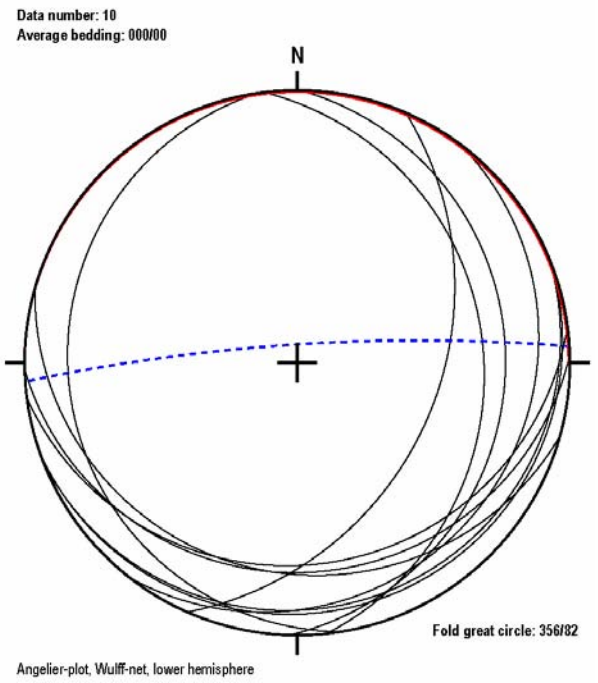
- Average computation can be carried out on different ways; one of them is to calculate **arithmetic average**, or median;
- In the case of **directional data** (eq. stress vector direction) this methodology might be misleading (average of compression vectors of 040/10 and 220/10 is ~220/90 and not 040/00 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.

Bingham statistics result for a fracture set (below).



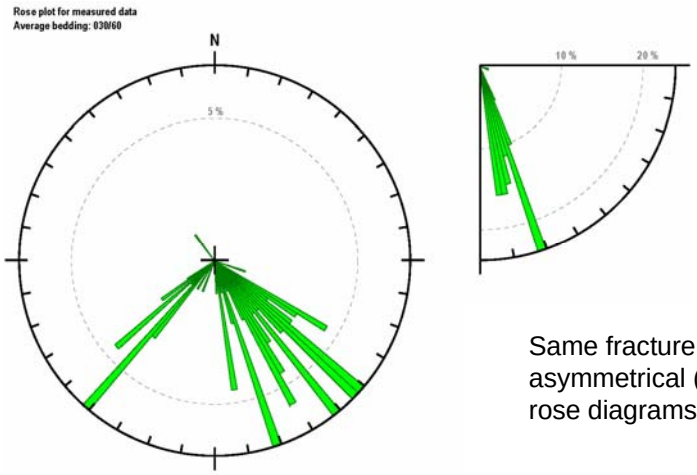


Fold great circle of a 'foldsurface' data set using Bingham statistics to find the best fitting plane.

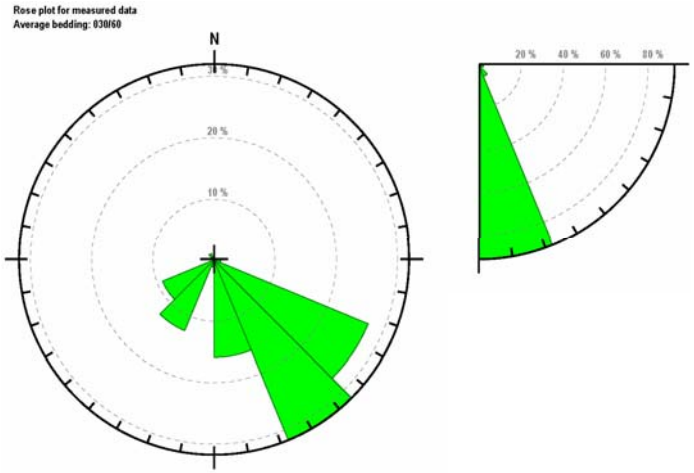
PROCESSING AND DISPLAY

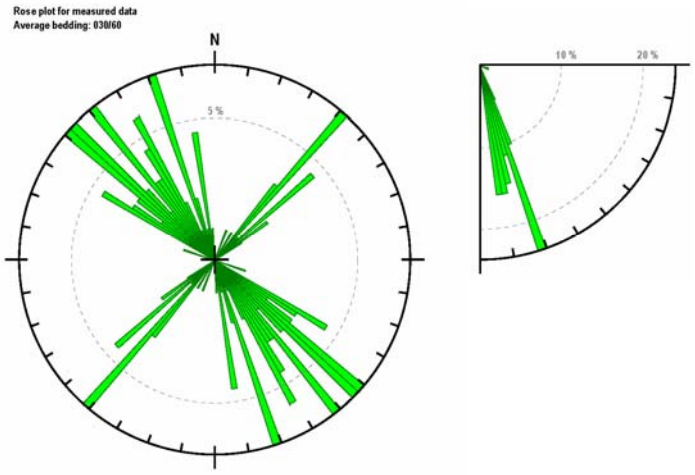
Rose plots

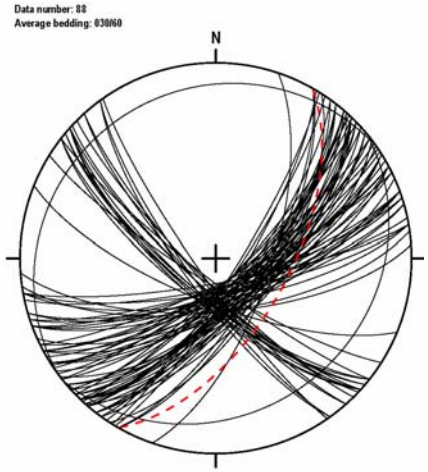
- Rose plots are presenting the **horizontal** and **vertical** distribution of data sets;
- Both **asymmetric** and **symmetric** plots are available;
- Bin size can be 2.5, 5.0, 10.0 and 22.5 degrees.

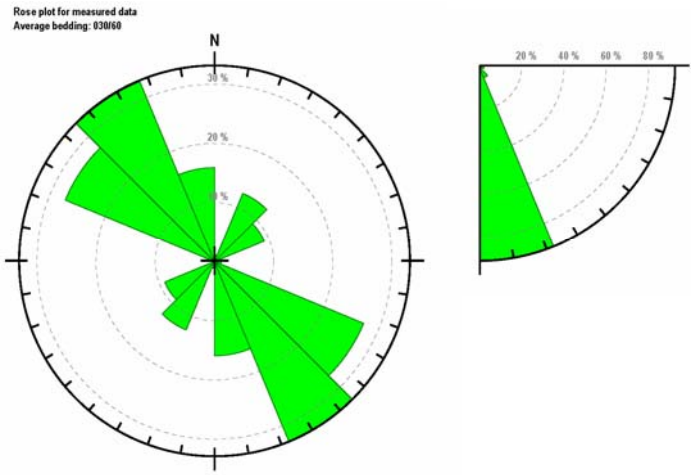


Same fracture data set (middle below) plotted on asymmetrical (above) and symmetrical (below) rose diagrams using 2.5 and 22.5 deg bin sizes.









BACKGROUND

4.1.1 BACKGROUND

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 ≤ 0 (in the case of overturned beds as well).

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

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

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

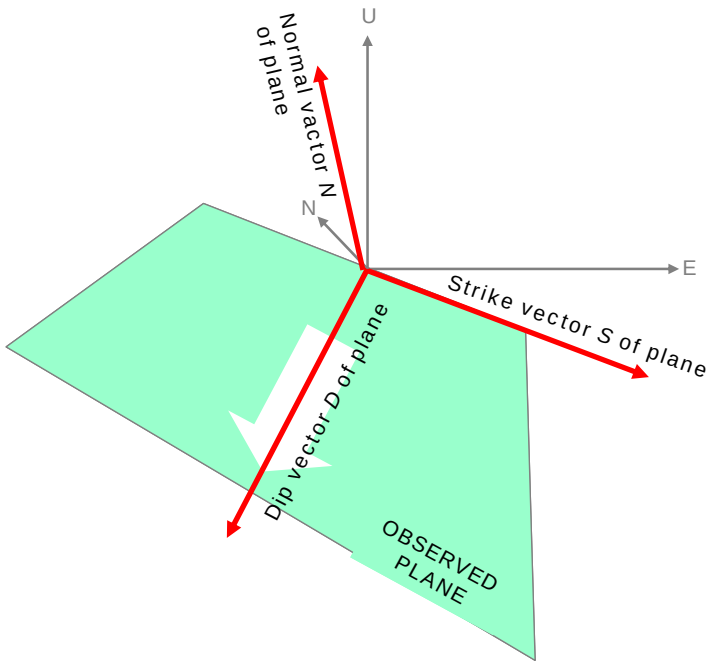
- Calculation of S_i **strike** unit vector (with Z=0) is the following:

$$S = N \otimes D$$

- 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.



- DC_i, NC_i, SC_i and SV_i vectors are used to describe **slickensides** and **s-c** data sets;
- In the case of s-c data sets, DC_i, NC_i and SC_i vectors are referring to the dip, normal and strike unit vectors of c plane; in the case of a slickenside, these vectors are refering to the slickenside as a **lineation;**
- DC_i 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:

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

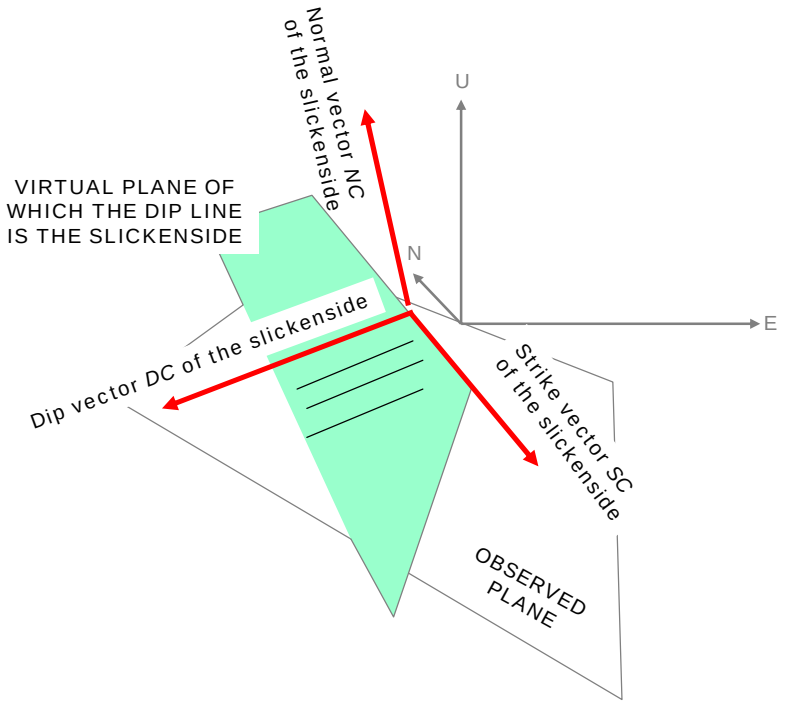
- NC_i unit vector is the **c plane normal**, or – in the case of slickensides – **normal vector of a plane of which DC_i vector the dip vector is**, with Z coordinate ≤ 0. Computation methodology of dip vector from dip direction and dip angle data is the following:

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

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

$$SC = NC \otimes DC$$

- SV_i vector is used to describe **movement direction** along the slickenside lineation. SV_i vector is exactly the same as DC_i with **$SVZ_i > 0.0$** in the case of **downward** movement along the slickenside, and **$SVZ_i < 0.0$** in the case of **upwards** movement.



BACKGROUND

Stereonet coordinates – Schmidt- and Wulff-net, upper and lower hemisphere

- **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, ❶), and
  - two **strike points** on the stereonet circle (S_i and –S vectors, ❷);

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:

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

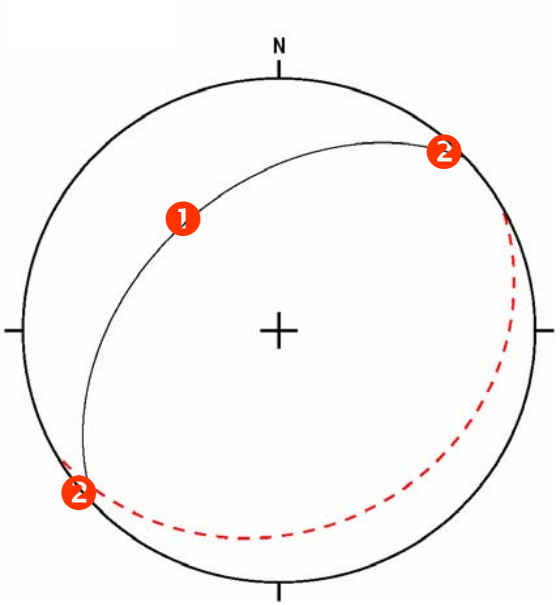
$$y = \frac{DY}{1.0 - DZ}$$

WULFF-NET

- Wulff net point coordinates are the following:

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

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



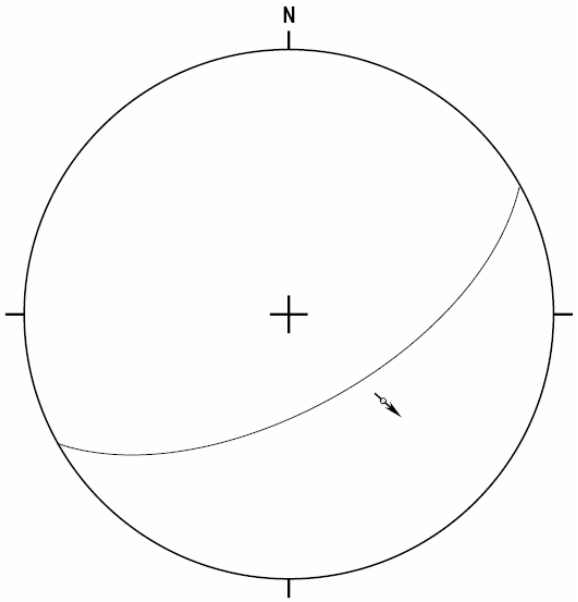
4.3.1 BACKGROUND

Striae misfit and correction I. – Misfit angle

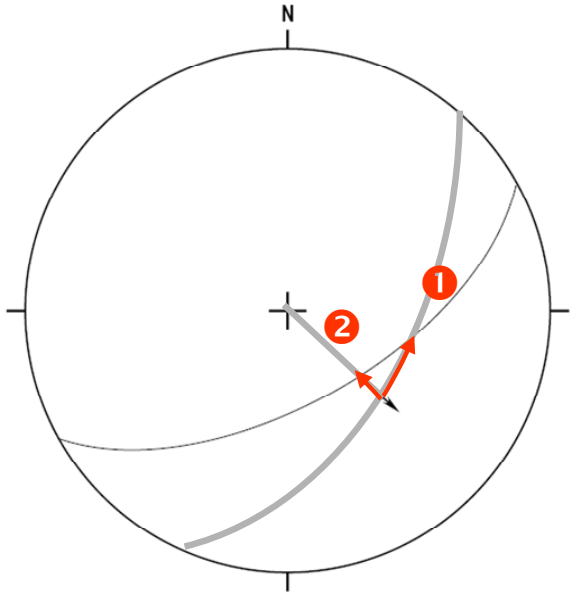
- In ideal case, the measured slickenside vector is on the fault plane surface, and dip vector DC_i of slickenside is **perpendicular** to the plane normal vector N_i.
- In the case of measurement as 'pitch', slickenside lineation is **definitely** on the fault plane because measurement methodology. 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

$$\alpha_i = \left|\arcsin(N_i \cdot DC_i)\right|$$

- It is required to correct 'lineation' measurements, but not 'pitch' observations. One of the possible correction is 1) 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



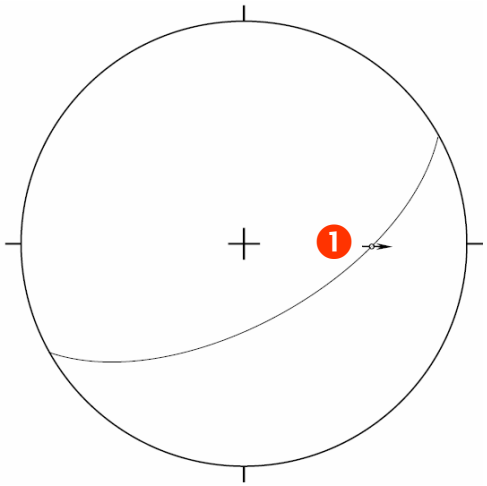
Possible striae misfit corrections

4.3.2 BACKGROUND

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

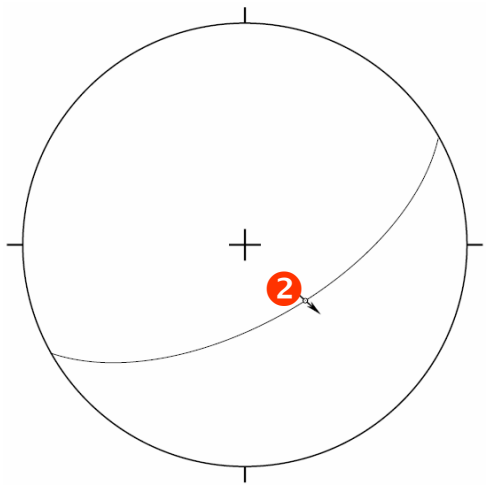
$$DC_i = SC_i \otimes N_i$$



Result of dip direction correction

- 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

$$DC_i = NC_i \otimes N_i$$



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;

4.4 BACKGROUND

K-means clustering

- 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;

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

- Eash 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.

1. Distance of each **data to** each **centroid** is calculated on the following way;

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

2. Each data is related to the **closest** centroid and became **member of centroid's group**;

3. **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 the iteration is **not definitely convergent**.

- Error of clustering is described by **relative error** (ERR) value:

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

4.5 BACKGROUND

Directional statistics – Bingham statistics

- **Bingham** directional statistics is used to display directional distribution of fractures;
- During Bingham procedure, 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 4.6.1 and 4.6.2).
- 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[th] data set (ang is the angle between two vectors):

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

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

- Calculate the following sum for th entire data set:

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

- **Eigenvectors** of matrice 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.

BACKGROUND

Inversion methodologies I. – Regression after Sprang (1972)

- Define angle α between the **movement direction** (slip vector, SV) 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:

$$p_i = \begin{bmatrix} (1-\alpha)SVX - \alpha NX \\ (1-\alpha)SVY - \alpha NY \\ (1-\alpha)SVZ - \alpha NZ \end{bmatrix},$$

$$t_i = \begin{bmatrix} (1-\alpha)NX + \alpha SVX \\ (1-\alpha)NY + \alpha SVY \\ (1-\alpha)NZ + \alpha SVZ \end{bmatrix},$$

- 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:

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

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

BACKGROUND

Inversion methodologies II. – Regression after Turner (1953)

- Define angle α 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 eash data:

$$p_i = \begin{bmatrix} (1-\alpha)SVX - \alpha NX \\ (1-\alpha)SVY - \alpha NY \\ (1-\alpha)SVZ - \alpha NZ \end{bmatrix}, t_i = \begin{bmatrix} (1-\alpha)NX + \alpha SVX \\ (1-\alpha)NY + \alpha SVY \\ (1-\alpha)NZ + \alpha SVZ \end{bmatrix}, n_i = p_i \otimes t_i$$

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

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

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

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

- 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.

BACKGROUND

Inversion methodologies III. – Regression after Fry (1999)

- Use Angelier's (1979) assumption for each slickenside data: $\boldsymbol{b_i \cdot T \cdot n_i = 0}$, where

$$b_i = SV \otimes N = \begin{bmatrix} b_1 & b_2 & b_3 \end{bmatrix},$$

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

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

- In this case

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

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

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

$$p_i = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \\ p_6 \end{bmatrix} = \begin{bmatrix} b_1 n_1 \\ b_2 n_2 \\ b_3 n_3 \\ b_1 n_2 + b_2 n_1 \\ b_2 n_3 + b_3 n_2 \\ b_1 n_3 + b_3 n_1 \end{bmatrix}$$

- Calculate the **sum of the inner product s** (**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 6x6 symmetrical matrice, eq. use Jacobi algorithm;

- The eigenvector of the lowest eigenvalue will be:

$$E_{vec} = \begin{bmatrix} 0.57735 & 0.57735 & 0.57735 & 0.00000 & 0.00000 & 0.00000 \end{bmatrix}$$

- Choose the eigenvector of the second lowest eigenvalue:

$$E_{vec} = \begin{bmatrix} E_1 & E_2 & E_3 & E_4 & E_5 & E_6 \end{bmatrix}$$

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

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

BACKGROUND

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): $\sigma_{11} + \sigma_{22} + \sigma_{33} = 0$;

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

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

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

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

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

$$p_i = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \end{bmatrix} = \begin{bmatrix} b_1n_1 - b_3n_3 \\ b_2n_2 - b_3n_3 \\ b_1n_2 + b_2n_1 \\ b_1n_3 + b_3n_1 \\ b_2n_3 + b_3n_2 \end{bmatrix}$$

- 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, eq. use Jacobi algorithm;

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

$$E_{vec} = \begin{bmatrix} E_1 & E_2 & E_3 & E_4 & E_5 \end{bmatrix}$$

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

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

- 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:

$$B_i = \begin{bmatrix} SVX \\ SVY \\ SVZ \end{bmatrix}$$

- 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:

$$\mathrm{M} = \begin{bmatrix} \mathrm{M}_1^{\mathrm{T}} \\ \vdots \\ \mathrm{M}_{\mathrm{i}}^{\mathrm{T}} \\ \vdots \\ \mathrm{M}_{\mathrm{n}}^{\mathrm{T}} \end{bmatrix}, \mathrm{B} = \begin{bmatrix} \mathrm{B}_1^{\mathrm{T}} \\ \vdots \\ \mathrm{B}_{\mathrm{i}}^{\mathrm{T}} \\ \vdots \\ \mathrm{B}_{\mathrm{n}}^{\mathrm{T}} \end{bmatrix},$$

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

- **Rectangular** (nxn) form of matrice M is needed to solve this equation: calculate matrices $A = M^{\mathrm{T}}M$ *and* $C = M^{\mathrm{T}}B$, and the equation system to be solved will be *AX = C.*

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

BACKGROUND

Inversion methodologies VI. – Inversion after Angelier (1990) and after Mostafa (2005)

ANGELIER (1990)

- Angelier's (1990) methodology calculates the **misfit vector** υ between the measured (SV_i) and calculated (τ) shear stress vectors; length of SV_i is unknown, and it was assumed to be $\lambda = \sqrt{3}/2$;
- Basic assumption after Angelier (1979) is to suppose $\sigma_{11} + \sigma_{22} + \sigma_{33} = 0$ and $\sigma_{11}^2 + \sigma_{22}^2 + \sigma_{33}^2 = 3/2$; 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** υ is expressed as a function of the plane **normal vector**, the **slickenside lineation**, the assumed (a priori) shear stress vector length λ and the members of stress tensor (α, β, γ and ψ; see equations A6 and A8 in Angelier 1990).
- To minimize length of υ vector, Angelier (1990) calculates the following **partial derivates** (see equation A10 in Angelier 1990):

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

- The final equation (A15, using equation A11 in Angelier 1990) is the function of ψ 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** (ψ_1 and ψ_2) and two complex ones;
- Using ψ value, express α, β and γ and **generate the stress tensor** (see equation A12 in Angelier 1990);
- To find the best fitting stress tensor, generate two stress tensors using both ψ_1 and ψ_2 values and choose the **best fitting one**.

MOSTAFA (2005)

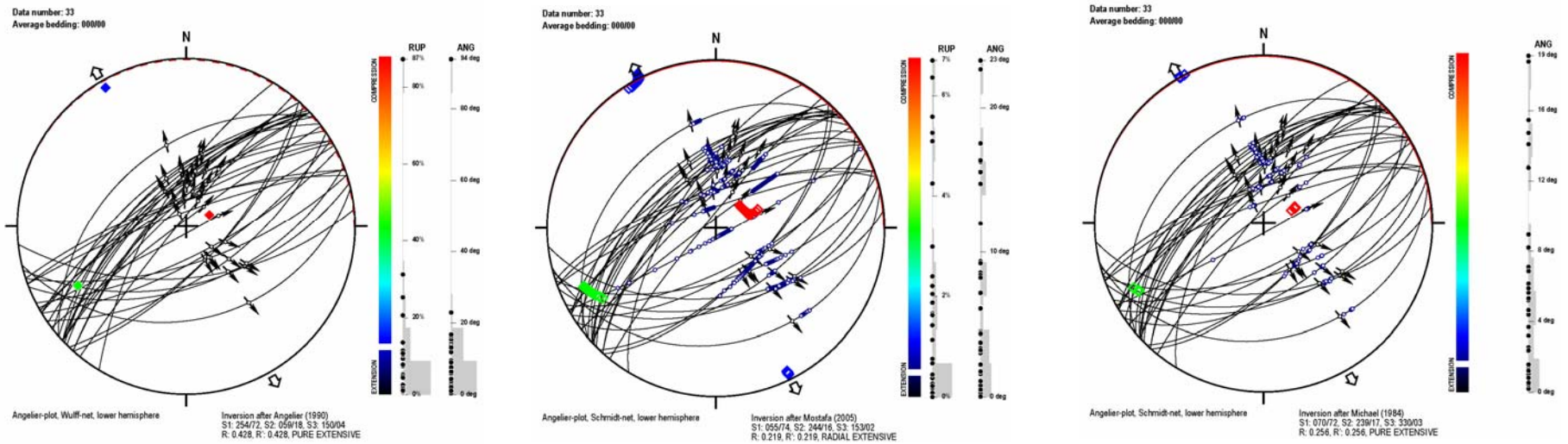
- Mostafa's (2005) methodology is an **iteration in shear stress vector length**. Value of λ was assumed by Angelier (1990) to be $\sqrt{3}/2$;
- Mostafa (2005) uses Angelier's (1990) solution to generate the stress field and calculate τ shear vector lenght;
- In the second iteration step, λ (measured shear stress vector length) is **replaced by the length of** τ (calculated shear vector) in all of equations, and a new stress tensor calculation is carried out;
- In the next steps, values of τ **are re-calculated**; after the 10-15th iteration no major change in stress estimators is visible.

BACKGROUND

Inversion methodologies VII. – Iterative inversion

- One of the key problems of inversion methodologies is the measured shear vector (SV_i) 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 1990 methodology Mostafa (2005) proposed the following itration methodology:
  - assume $\lambda = \sqrt{3}/2$,
  - calculate the stress tensor using Angelier's (1990) methodology,
  - calculate the stress vector, the normal stress and than the shear stress vectors;
  - calculate shear vector length $|\tau|$,
  - use $\lambda = |\tau|$ for the next iteration step.
- Using Michael's (1984) methodology, is it possible to use the same iteration methodology with $\lambda=1$ start criteria.

Inversion of Angelier's (1990) AVB data set using Angelier's (1990), Mostafa's (2005) and iterative Michael's (1984) methodology; average misfit is 13.0, 7.7 and 6.6 degrees. Iteratio has done for 100 steps.



4.7 BACKGROUND

Post-inversion manipulation – Negative of stress tensor, negative of stress vector

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 for all of the inputs 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 4.8.2) between observed and computed shear direction for the stress tensor and 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 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:

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

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

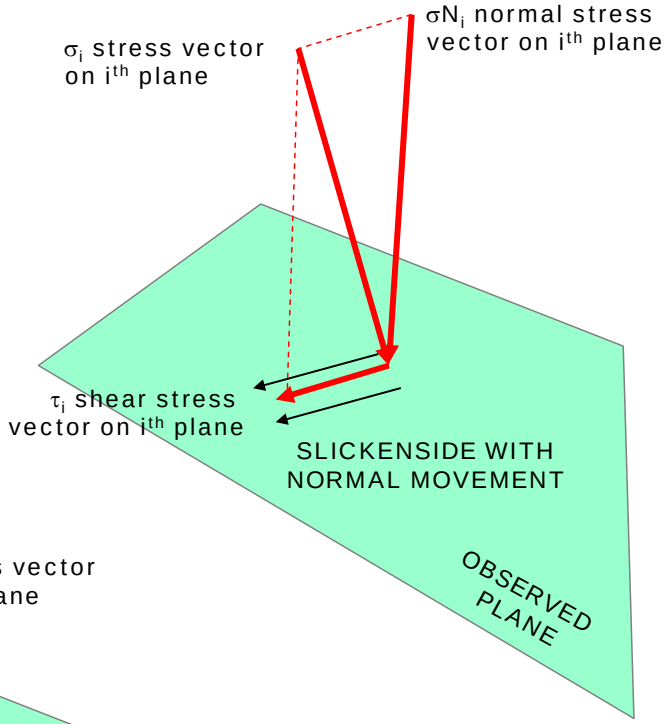
$$T = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix}, n_i = \begin{bmatrix} NX \\ NY \\ NZ \end{bmatrix} = \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix}$$

- If the inversion methodology produces the **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.

- To have the **stress vector** effecting the i[th] plane, calculate

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

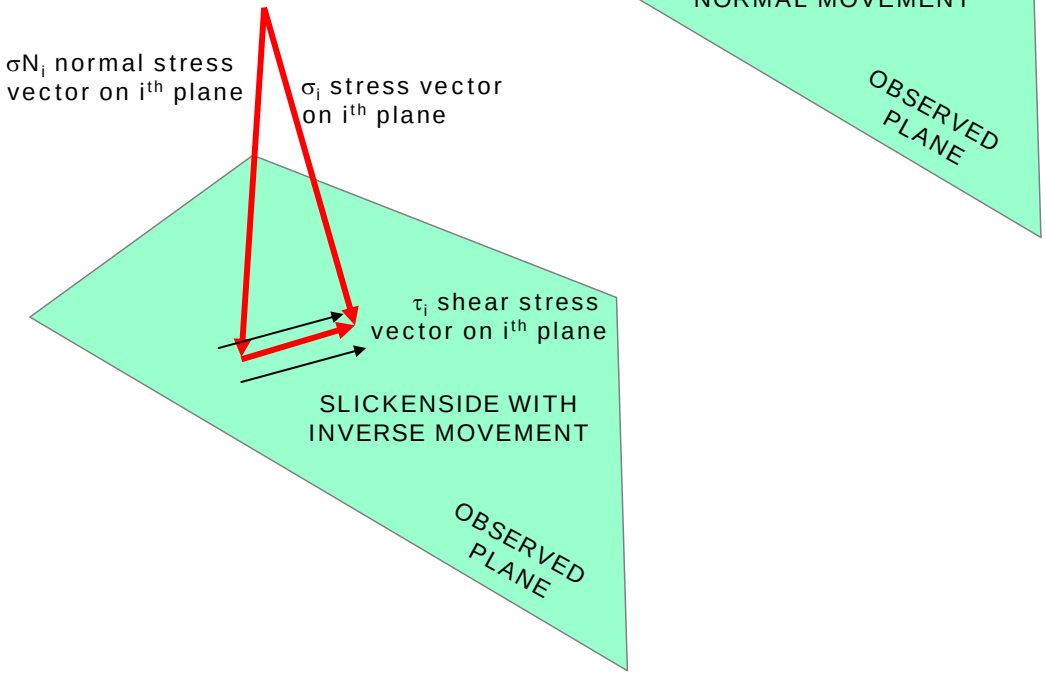
$$T = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix}, n_i = \begin{bmatrix} NX \\ NY \\ NZ \end{bmatrix} = \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix}$$



- **Normal stress** on the i[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[th] plane is:

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

BACKGROUND

Stress vectors, stress estimators II. – υ vector, λ_i RUP and ANG parameters

VECTOR υ

- Upsilon vector (υ) refers to the **divergence** between the **measured** (a priori, described by *SV* vector) and the **calculated** (a posteriori, τ vector) shear stress direction.

$$\upsilon_i = SV_i \cdot \lambda - \tau_i = \begin{bmatrix} SVX \cdot \lambda - \tau_X \\ SVY \cdot \lambda - \tau_Y \\ SVZ \cdot \lambda - \tau_Z \end{bmatrix},$$

$$SV_i = \begin{bmatrix} SV_iX \\ SV_iY \\ SV_iZ \end{bmatrix}, \tau_i = \begin{bmatrix} \tau_X \\ \tau_Y \\ \tau_Z \end{bmatrix}$$

SHEAR STRESS VECTOR LENGTH λ

- Angelier (1990) assumed shear vector length to be √3/2; this is the 0th iteration step of Mostafa's (2005) methodology. λ is the scale factor to get the **real** lenght of the slip vector instead the unit vector length; in Angelier's (1990) methodology its value is constant √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 (SV) and calculated (τ) shear stress vectors:

$$ANG = ang(s_i, \tau_i)$$

$$s_i = \begin{bmatrix} SVX \\ SVY \\ SVZ \end{bmatrix}, \tau_i = \begin{bmatrix} \tau_i X \\ \tau_i Y \\ \tau_i Z \end{bmatrix}$$

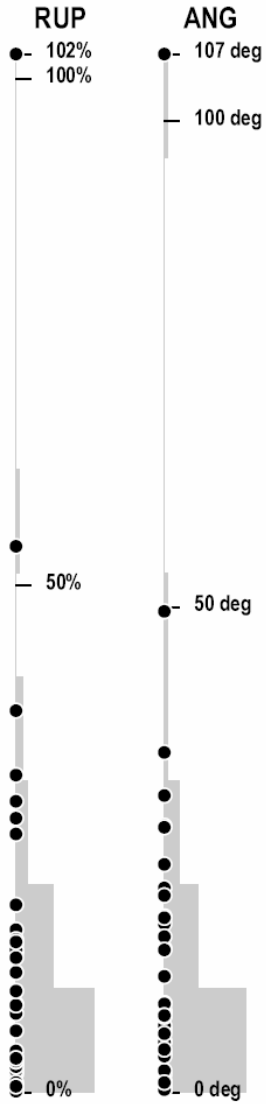
ESTIMATOR RUP

- Estimator **RUP** (relative upsilon) shows the calculated τ shear vector length relative to assumed λ = √3/2.

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

$$\frac{\sqrt{((\lambda^2 + \tau_i X^2 + \tau_i Y^2 + \tau_i Z^2) - 2 \cdot \lambda \cdot ANG)^2}}{\lambda} \cdot 100\%,$$

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



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

BACKGROUND

Stress visualisation – Mohr-circle

- Because absolute stress magnitudes are **unknown**, Mohr circle parameters were **re-scaled to unit stress**;
  - σ_1 = 1.0,
  - σ_2 = φ, and
  - σ_3 = 0.0.

- Calculate **stress vector magnitude:**

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

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

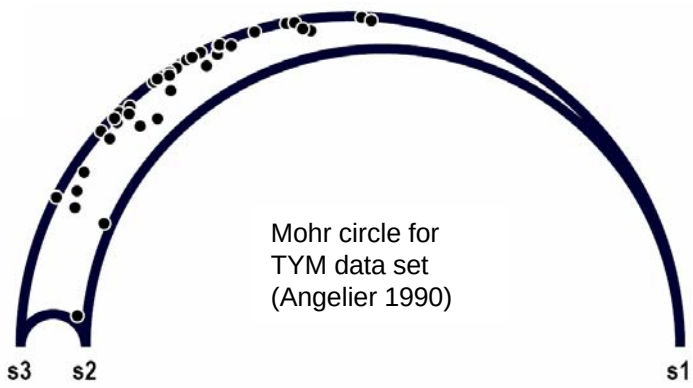
- **Normal stress value** will be computed on the following way:

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

- **Shear stress** on the i[th] plane is the following:

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

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



Mohr circle for
TYM data set
(Angelier 1990)

R' = 2.75 – 3.00: radial compressive

R' = 2.25 – 2.75: pure compressive

R' = 1.75 – 2.25: transpressive

R' = 1.25 – 1.75: pure strike slip

R' = 0.75 – 1.25: transtensive

R' = 0.25 – 0.75: pure extensive

R' = 0.00 – 0.25: radial extensive

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