
Introduction and software manual for
SG2PS
Platform independent structural geological data processing software
Coded by Ágoston Sasvári
Graphical User Interface coded by Ali Baharev
MANUAL: FEBRUARY, 2015

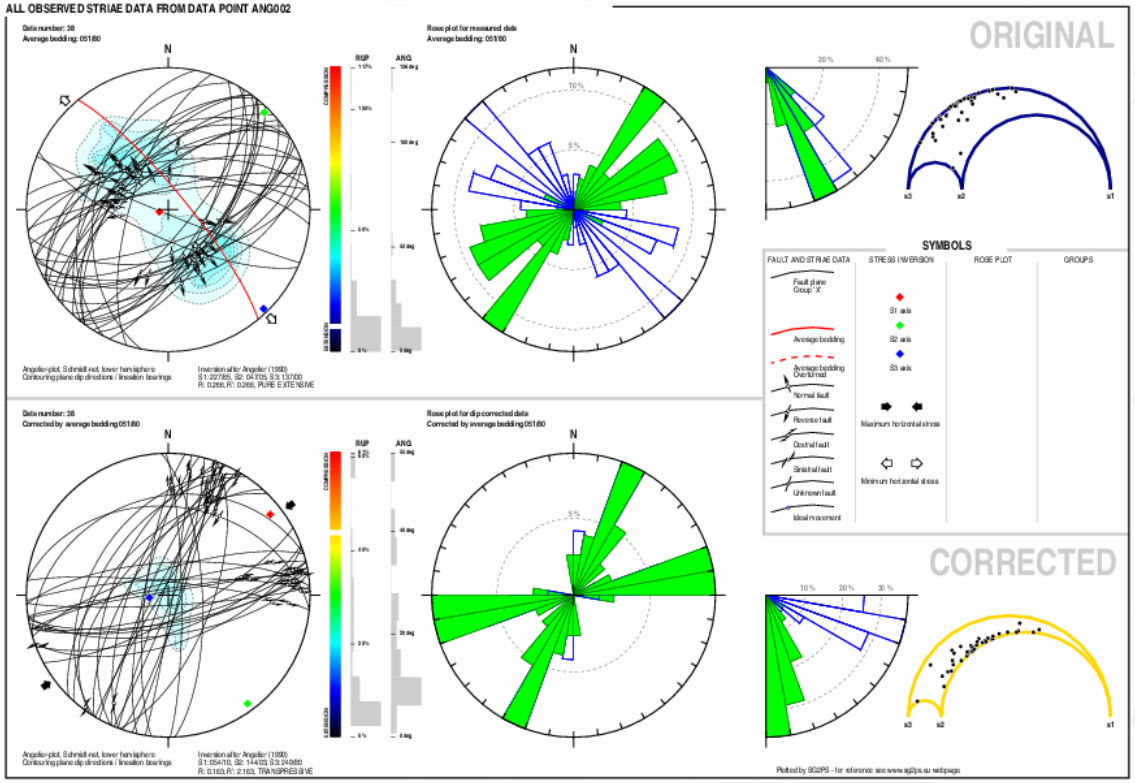
CONTENT

QUICK OVERVIEW

0.1 QUICK OVERVIEW

WHAT IS SG2PS?

- **SG2PS** is a **free** graphical application for **field** and **well** structural data evaluation and processing;
- Easy to use **Graphical User Interface**, data processing takes just a few clicks;
- Separate processing and plot for different **localities**, data **types** and data **groups**;
- Displays structural data on **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;
- Data **input in Excel** or any other spreadsheet application of your choice;
- Output in Adobe Portable Document Format (**PDF**).



CAPABILITIES

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

THE SOFTWARE

- Download SG2PS installer from the website **http://www.sg2ps.eu/download.htm** and install on unzip the application;
- Start either the Graphical User Interface (**SG2PS_GUI.EXE**) or the console application (**SG2PS.EXE**);
- **Create** your data spreadsheet what you want to evaluate using the **graphical version** of the program, or **copy-paste into a text file** in the working folder – this will be the **input (*.rgf)** file;
- You can store your **settings (*.set)** and **locality – coordinate – formation name pairs (*.xy)** in separated files;
- A **project folder** will be generated for the text and post script outputs;
- Evaluation results will be displayed on the **screen** in text format.
- If everything goes well, **couple of thousand data** from **some hundred data points** could be evaluated and plotted in **less than one minute**.

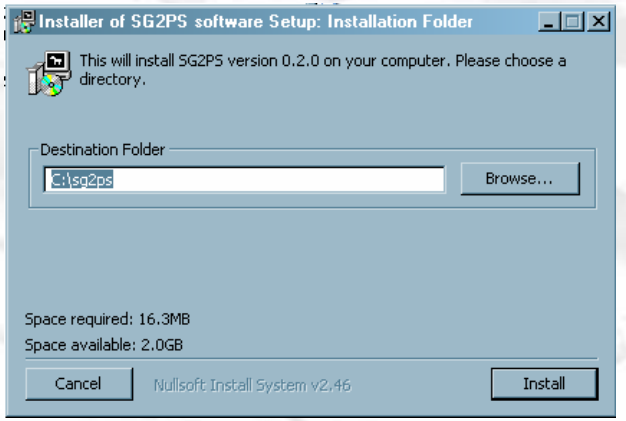
- To remove **evaluation results**, delete the project folder;
- To remove **SG2PS**, just delete the program folder.

THE MANUAL

- If you are interested in the software capabilities, or want to have a quick overview, read **INTRODUCTION** chapter; if you are interested is the result plot details, 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**.

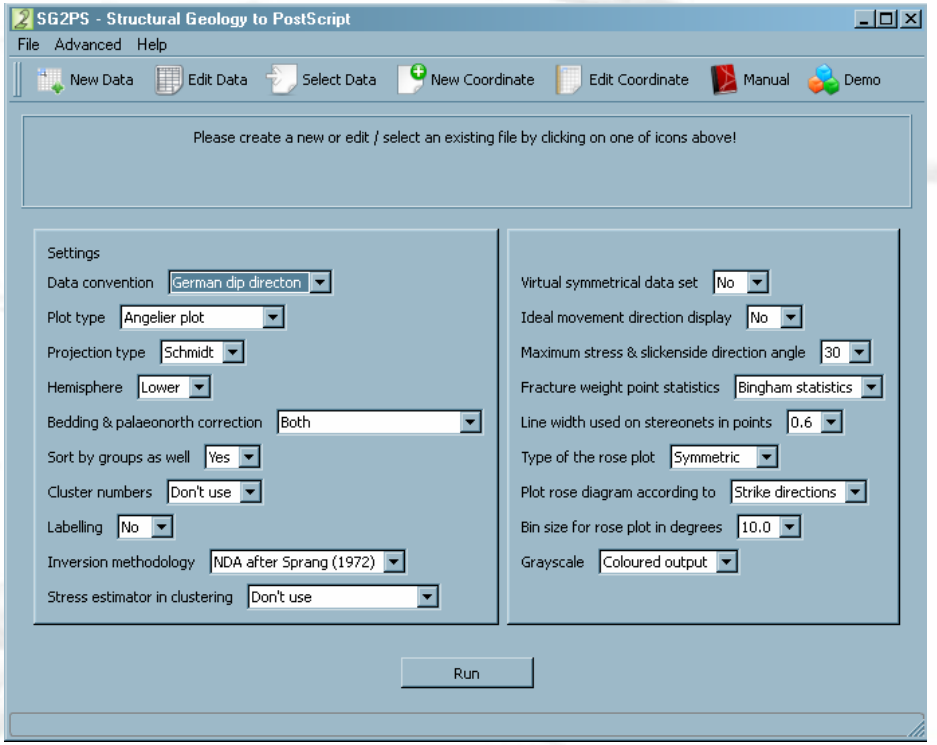
INSTALLATION

- 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 and press '**Install**'.
- If you are not allowed to run self extracting archives, simply download the installer in ***.zip** format and extract in the destination folder.



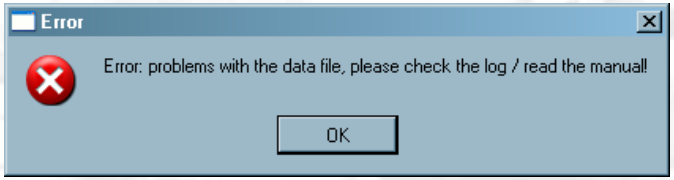
RUN – FILE MENU

- Start '**sg2ps_gui.exe**' to run the software;
- Use '**New data file**' to create a standard **input** (*.rgf) file;
- Use '**Edit Data**' to edit your own input file with the default spreadsheet editor;
- Use '**Select Data File**' to select input file to process;
- Use '**New Coordinate file**' and '**Edit Data**' to create/edit a standard **coordinate (*.xy)** file with the default spreadsheet editor;
- The software generates the **project name** and searches for project **settings (*.set)**; if found a correct one, will used, if not, standard defaults will be displayed;
- You can modify your settings;
- If **coordinate (*.xy)** file found will used, otherwise input file coordinates will processed;
- Push **RUN**;
- Settings will automatically saved in the project folder in a **setting (*.set) file**.
- **Processing result** and/or **working directory** with the project folder will displayed on the screen but will **NOT** be saved.



EDITING DATA FILES – MANUAL DISPLAY

- If a spreadsheet viewer and PDF viewer is installed on your computer, the software will open in to edit **input** (*rgf) and **coordinate** (*xy) file. If the software cannot find these programs, see Chapter 1.3.x how to install and configure them.

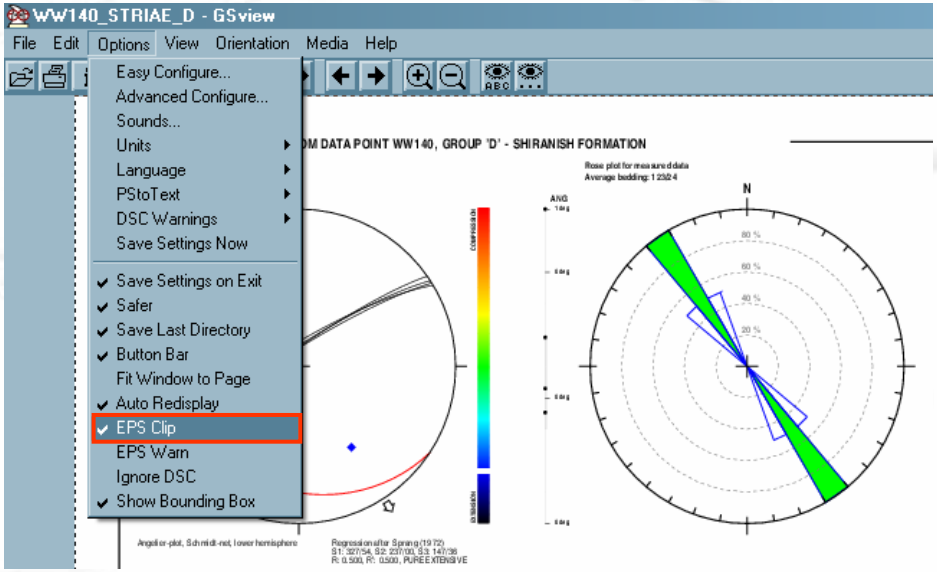


ERROR MESSAGE

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

DISPLAY RESULTS

- You can use free softwares (eq. **GSview**) to display generated *.eps files; if you want to use **GSview**, install **Ghostscript** before.
- If you are using GSView, please don't forget to thick **Options/EPS clip option**, otherwise a rotated and clipped view will displayed on the screen.
- You can convert the result vector graphs to ***.pdf** format and open it with a pdf viewer.



UNINSTALL

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

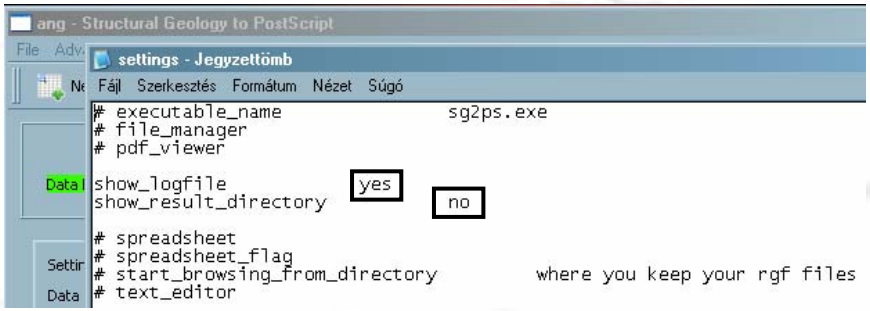
INTRODUCTION

EDITING DATA FILES – MANUAL DISPLAY

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

ADVANCED MENU – GUI SETTINGS

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



CONSOL INTERFACE – RUNNING USING SETTING FILE

```
D:\cpp_juno\SG2PS\Debug>sg2ps.exe

 ------------------------------------------------------------------
|                                                                  |
|                            SG2PS                                 |
|       Structural Geological data to PostScript converter         |
|                                                                  |
|        Data processing software coded by Agoston Sasvari         |
|                                                                  |
|             For further information check www.sg2ps.eu           |
|                                                                  |
|                        All rights reserved.                      |
|           This a free software under GNU LGPL licence.           |
|                                                                  |
 ------------------------------------------------------------------
|                                                                  |
|                   Built on: 12 Jan 2013, 23:01:02                |
|                                                                  |
|                         version: 0.2.0 beta                      |
|                                                                  |
 ------------------------------------------------------------------

RUNNING SG2PS IN COMMANDLINE MODE.

Enter RGF file (*.rgf) name without extension.....: ang  ❶
  - Input ANG.RGF file opened.

    - Input ANG.RGF file read, 33 record(s) imported.
    - Existing DATA_ID's in all records.
    - Correct DATA_ID's in all records.
    - Correct group code(s) in all records.
    - Correct color code(s) in all records.
    - Correct coordinate(s) in all records.
    - Correct datatype(s) in all records.
    - Correct strike/dip direction(s) in all records.
    - Correct dip angle(s) in all records.
    - Correct CS/striae(s) in all records.
    - Correct paleo north direction(s) in all records.

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

CHECKING OF SETTINGS OF 'ANG' PROJECT
  - Using 'ANG.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.....: do not use
  - Labeling.....: no labeling
  - Inversion.....: none
  - Virtual symmetrical striae set.....: do not use
  - Ideal slickenside movement.....: not display
  - 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_  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 will be 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.

CONSOL INTERFACE – PROCESSING AND DISPLAY OF RESULTS

```
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_017' has change from NORMAL to SINISTRAL.
    - 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_004' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_003' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_002' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_018' 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_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_020' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_009' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_011' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_028' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_027' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_012' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_010' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_016' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_015' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_014' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_013' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_038' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_037' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_036' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_035' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_034' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_033' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_032' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_031' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_030' has change from NORMAL to SINISTRAL.
    - Striae offset in record 'ANG_025' has change from NORMAL to DEXTRAL.
    - Striae offset in record 'ANG_029' has change from NORMAL to SINISTRAL.
  - 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,inversion after Angelier (1990):
    - Original : s1: 226/85, s2: 047/05, s3: 317/00,     PURE EXTENSIVE, R: 0.268, R': 0.268, av. misfit: 14.5 deg.
    - Corrected: s1: 053/10, s2: 143/03, s3: 248/80,      TRANSPRESSIVE, R: 0.167, R': 2.167, av. misfit: 18.3 deg.
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.
EVALUATION OF ANG2.RGF FILE COMPLETED.
  - Elapsed time: 1.31 seconds.

D:\cpp_juno\SG2PS\Debug>
```

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 lithology, slickenside and s-c data) is calculated for each location;
- **Re-tilting** of all data with the average bedding will be done and slickenside offset re-correction will be carried out;
- **Bingham statistics** and inversion results will be displayed for each data sets;

FILE OUTPUT

- **Postscript** files, completed **geodatabase** files, **average** files and **data type by data type 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 ⬇

DATA_ID	GROUP_CODE	COLOR_CODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIP_DIR	DIP	L_DIP_DIR	LDIP	SENSE	PALEONORTH	COMMENT
RW0508			RW226			LOWER BAKHTRIARI	bedding	162	7					
RW0509								171	20					
RW0510			RW228				bedding	228	8					
RW0511								194	10					
RW0512			RW230				bedding	165	18					
RW0513			RW232			QUATERNARY	LITHOLOGY							
RW0514			RW233				bedding	25	20					
RW0515							crossbedding	2	22					
RW0516			RW234				bedding	87	7					
RW0517								83	7					

DATA_ID	GROUP_CODE	COLOR_CODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIP_DIR	DIP	L_DIP_DIR	LDIP	SENSE	PALEONORTH	COMMENT
RW0508	X		RW226	36.1429	44.6694	LOWER BAKHTRIARI	BEDDING	162.0	7.0				0	
RW0509	X		RW226	36.1429	44.6694	LOWER BAKHTRIARI	BEDDING	171.0	20.0				0	
RW0510	X		RW228	36.1446	44.6724	LOWER BAKHTRIARI	BEDDING	228.0	8.0				0	
RW0511	X		RW228	36.1446	44.6724	LOWER BAKHTRIARI	BEDDING	194.0	10.0				0	
RW0512	X		RW230	36.145	44.6746	LOWER BAKHTRIARI	BEDDING	165.0	18.0				0	
RW0513	X		RW232	36.1449	44.6756	QUATERNARY	LITHOLOGY						0	
RW0514	X		RW233	36.1449	44.6756	QUATERNARY	BEDDING	25.0	20.0				0	
RW0515	X		RW233	36.1449	44.6756	QUATERNARY	CROSSBEDD	2.0	22.0				0	
RW0516	X		RW234	36.1433	44.6801	QUATERNARY	BEDDING	87.0	7.0				0	
RW0517	X		RW234	36.1433	44.6801	QUATERNARY	BEDDING	83.0	7.0				0	

```
 ------------------------------------------------------------
|                                                            |
|                          SG2PS                             |
|       Structural Geological data to PostScript converter   |
|                                                            |
|        Data processing software coded by Agoston Sasvari   |
|                                                            |
|            For further information check www.sg2ps.eu      |
|                                                            |
|                       All rights reserved.                 |
|           This a free software under GNU LGPL licence.     |
|                                                            |
 ------------------------------------------------------------
|                                                            |
|                  Built on: 12 Jan 2013, 23:01:02           |
|                                                            |
|                       version: 0.2.0 beta                  |
|                                                            |
 ------------------------------------------------------------

RUNNING SG2PS IN COMMANDLINE MODE.

Enter RGF file (*.rgf) name without extension.........:  ang
  - Input ANG.RGF file opened.

    - Input ANG.RGF file read, 33 record(s) imported.
    - Existing DATA_ID's in all records.
    - Correct DATA_ID's in all records.
    - Correct group code(s) in all records.
    - Correct color code(s) in all records.
    - Correct coordinate(s) in all records.
    - Correct datatype(s) in all records.
    - ERROR: incorrect strike/dip direction(s) in the following record(s):  ANG_002, ANG_004, ANG_006, ANG_009.
    - Input ANG.RGF file structure is incorrect; please enter file name again, or press 'X' to exit.

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, and an error message will displayed, and the program will continue the processing.
- If regression is required for the average calculation and the data set is singular (see Chapter xxxx), no average will be calculated, and a message will inform the user about the data set singularity.

CONSOL INTERFACE – 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 only exit (hitting 'x') 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, or to use the **graphical interface**.

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 option, 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 occurs, 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

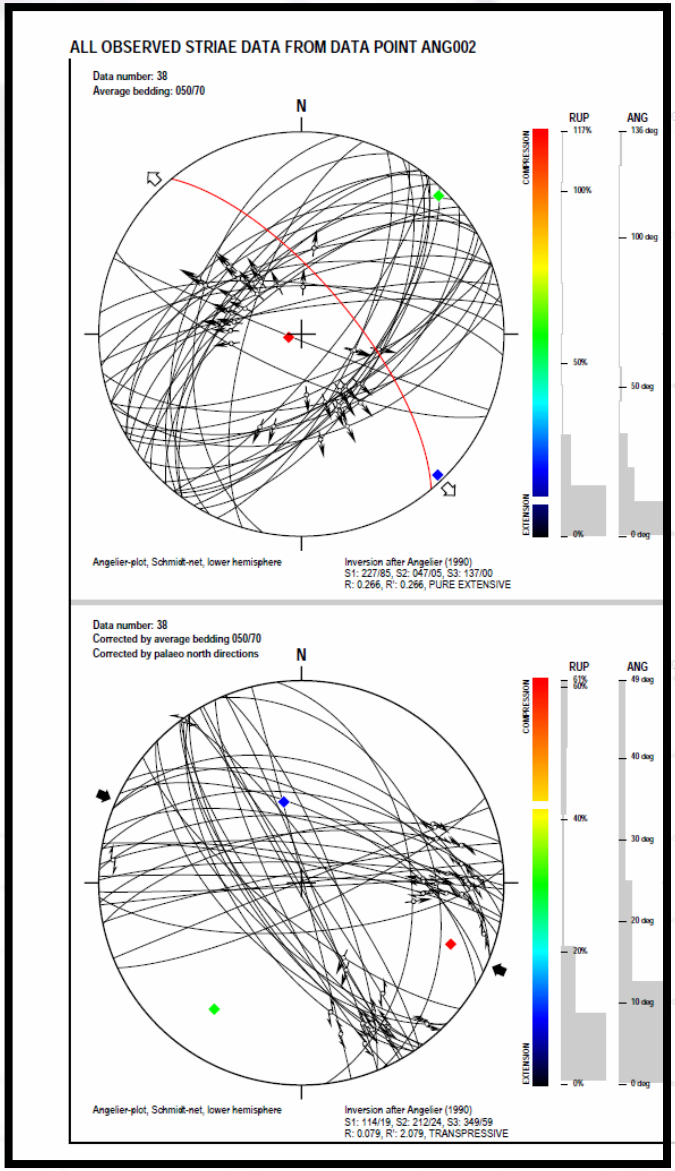
- It is possible to redirect screen output into text file format using '**>>**' operator on the following way:

```
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.

1.3.1 GRAPHIC OUTPUT

STEREOGRAPHICAL PROJECTIONS

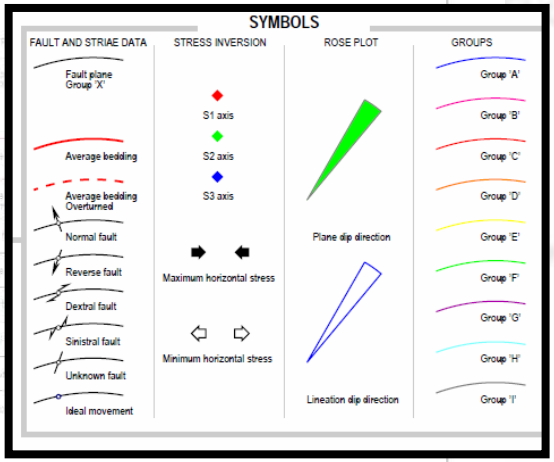


- You can use free softwares (e.g. **GSview**) to display generated *.eps files; if you want to use **GSview**, install **Ghostscript** before.
- If you are using GSView, please don't forget to thick **Options/EPS clip option**, otherwise a rotated and clipped view will displayed on the screen.

- At the left upper corner, **data type and data point locality** is indicated; if the option 'using groups' is selected, than **group name** is indicated there;
- Upper half of the final plot is to show **original** data set, lower half is for the **re-tilted** (bedding and/or palaeonorth corrected) visualization of them;
- Plot **type, projection and hemisphere** is displayed left below of stereonets;
- **Stress inversion result** is presented right below the stereonets:
  - stress inversion **methodology**,
  - stress axes **directions**,
  - **reduced stress tensors** value after Angelier (1979), after Delvaux et al. (1999) and
  - the **stress regime**;

- If fractures were processed, Bingham analysis could be displayed here:
  - density ellipsoid **axis directions** and
  - **axes length** (eigenvalues).

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



- For planes, Bingham statistics could be used; red, green and blue rectangles show the **maximum, intermediate and minimum weight axis** orientation;
- Black and white arrows show the **maximum and minimum horizontal stress** directions;
- Red great circle shows the **average bedding**.

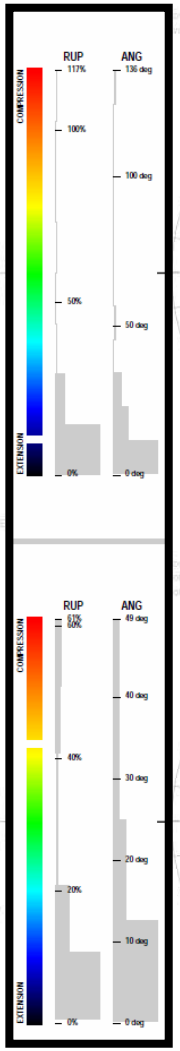
GRAPHIC OUTPUT

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.

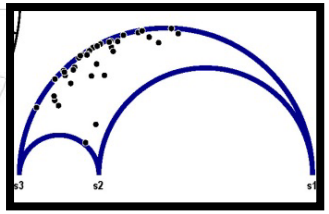
- RUP bar shows the **relative upsilon ratio** (theoretical / resolved shear stress vector length) from 0 to maximum RUP value (see chapter 4.8.2). Thickness of gray bars in the background shows the density of RUP values.

- 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.



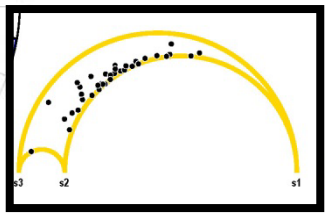
- ANG bar shows the **angular misfit** between the measured and calculated stress directions from 0 to the maximum ANG value. Thickness of gray bars in the background shows the density of ANG values;

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

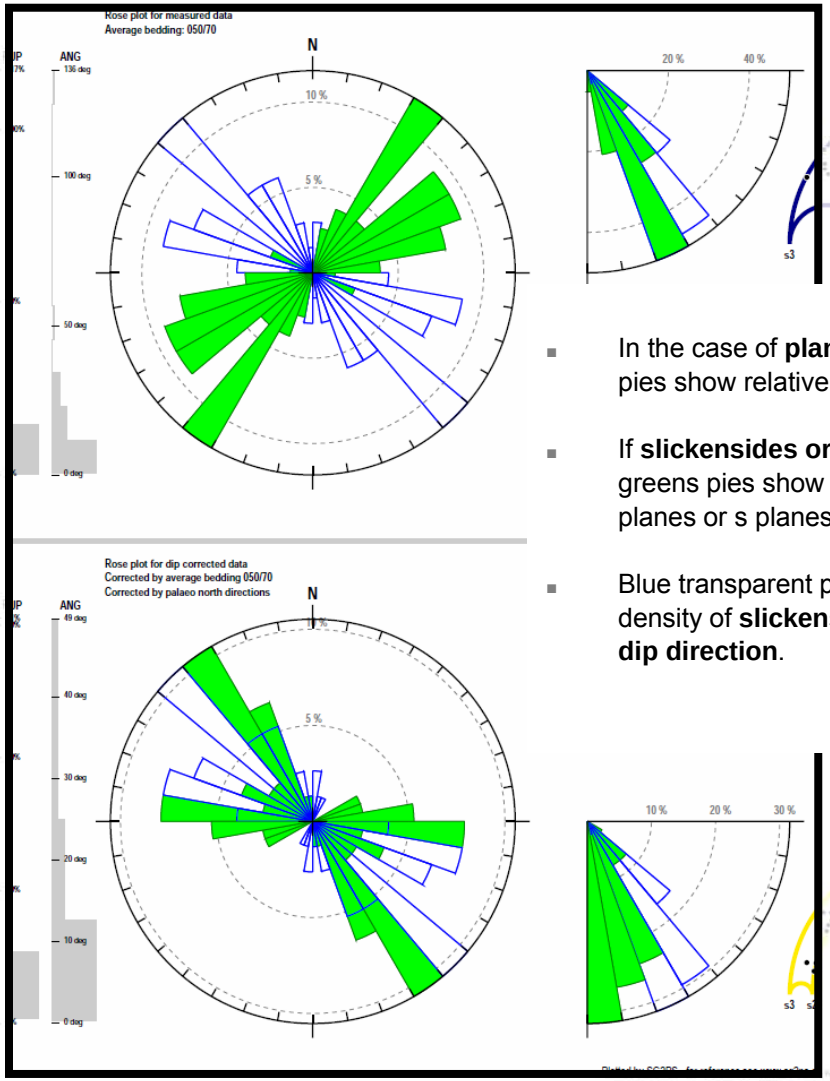


- Mohr circles show the **stress status** as well as normalized normal and shear stress values for each evaluated data;

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



- Equal bin size rose plots show the **directional density** change of the evaluated data set;
- Rose plots can show directional distribution of data **strikes** or **dip directions**;
- **Symmetric** and **asymmetric** plots with 2.5, 5, 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**.

GROUPS AND COLOR MANAGEMENT

GROUPS AND COLOR MANAGEMENT

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

⬇

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

⬇

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

⬇

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

ORIGINAL FILE

⬇

A__

⬇

K-MEANS CLUSTERING

⬇

AB_

⬇

RUP/ANG CLUSTERING

⬇

ABX

⬇

OUTPUT FILE

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

1) PROCESSING OF GROUPS

While exporting, you have the following options.

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

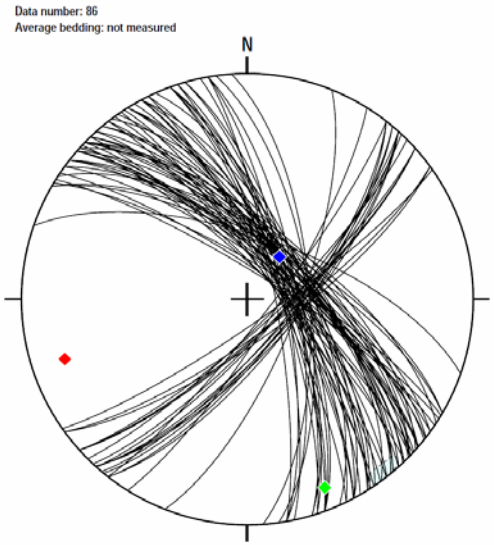
2) COLORING OF GROUPS

While coloring, you have the following options.

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

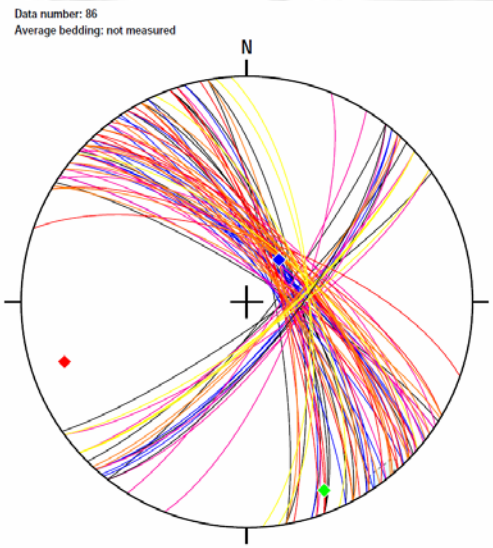
GROUPS AND COLOR MANAGEMENT

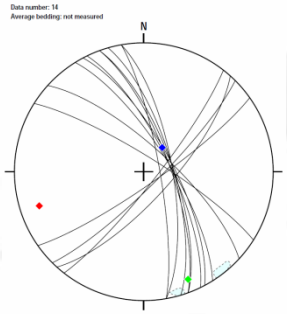
- It is possible to separate the processed data set 1) by user defined group codes, 2) by k-means clustering result, 3) by RUP/ANG clustering results (in the case of slickensides), or 4) display everything together.
- To find coloring options, please see 3.21.



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

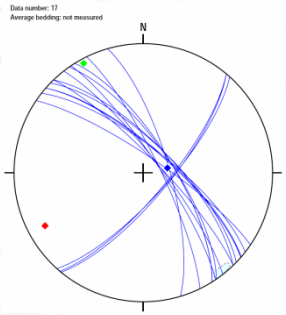
Data is colored by data sets group code. ➡

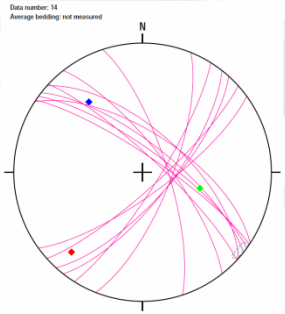


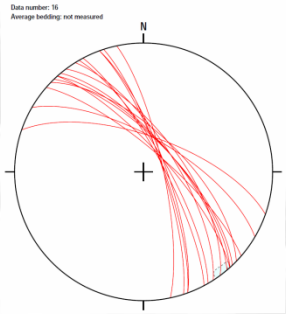


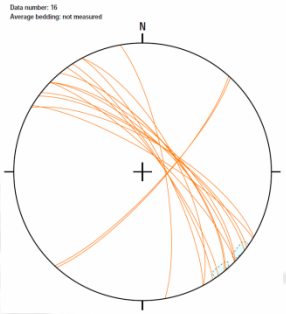
⬅ Exporting the same data set **separated by their user define groups**, resulting in 7 stereonets, one for each group code (A, B, C, D, E, F, X). Data is colored by data sets group code.

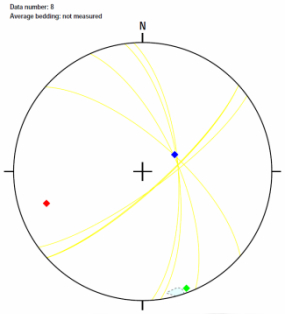
⬇

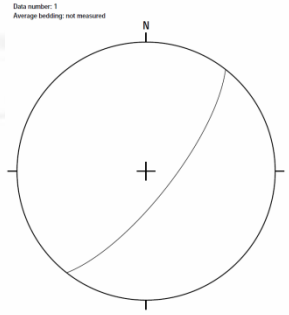












INPUT FILE FORMAT

3.1 INPUT FILE FORMAT

RGF DATA FORMAT I.

- RGF data file (*.rgf) is a text file. **First line is the header**, with **FIXED** content (used by the software to identify expected field content) to indicate column names; header column names are **bold and blue** below. Columns could be in arbitrary order; header is **case sensitive**, the file content is not. Please use ANSI characters for the file name and content.
- 1st column is for the **DATA_ID***; all of measurements entered in the RGF file **must** have an individual ID, which **must be different** from each other.
- 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' – 'I', 'X', 'a'-'i' and 'x' are accepted here. If the field is empty, group will became default group 'X'. Use one digit for an original input file; the output will get a three digits GROUP_CODE, first character for the user defined groups, second one for the k-means clustering, and a third one for the RUP/ANG clustering results. If no e.g. RUP/ANG clustering, the third digit will became 'X'.
- 3rd column is for the **COLOR_CODE**; use characters 'A' – 'J', 'a' – 'j' or numbers 0 – 9 to plot different colors. Empty cell, A and 0 is for default black color, other characters are for the colors at the right;
- 4th column is for the **LOCATION** of the data point where the measurement has done. You just need to enter the **new** data point name, otherwise the data point name of the previous record will be used. At least the first record must contain data.

1	DATA_ID	GROUP_CODE	COLOR_CODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIP_DIR	DIP	L_DIP_DIR	L_DIP	SENSE	PALEONORTH	COMMENT
2	D5_0084	a	e	230	1587663	2863928	FARS	fracture	44	66					
3	D5_0085	a	e	230	1587663	2863928	FARS	fracture	33	65					
4	D5_0086	a	e	230	1587663	2863928	FARS	fracture	42	64					
5	D5_0087	a	e	230	1587663	2863928	LOWERFARS	bedding	20	60					reliable
6	D5_0088	a	f	230	1587663	2863928	LOWERFARS	bedding	40	60			O		overturned
7	D5_0089	b	f	ANG001	7663871	9282365		striae	329	71	328	72	N		
8	D5_0090	b	f	ANG001	7663871	9282365		striae	315	65	310	14	N	15	
9	D5_0091	b	f	ANG001	7663871	9282365		striae	312	70	68	N	N		

- 5th and 6th columns are for the **LOC_X** and **LOC_Y** **coordinates** of the data point; just enter **new** data, otherwise previous record will be used. The following solutions are useful:
  - leave these fields empty if you do not have coordinates or do not need them;
  - fill them manually, or
  - if you want to process the final spread sheet with GIS / database manager softwares, use **coordinate** (*.xy) file (see Chapter 2.3) – 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 **DATATYPE**. Enter new data type if changed, otherwise it will be filled by content of previous record:
  - for **lithology**: 'lithology';
  - for **lineations**: 'boudain', 'foldaxis', 'kink', 'lineation', 'userlineation1', 'userlineation2', 'userlineation3', 'userlineation4' and 'userlineation5';
  - for **planes**: 'bedding', 'contact ', 'crossbedding', 'foldplane', 'foldsurface', 'fracture', 'lithoclase', 'plane', 'userplane1', 'userplane2', 'userplane3', 'userplane4', 'userplane5', 's1', 's2', 's3', 's4', 's5' and 'vein';
  - for **slickensides**: 'striae', and
  - for **s-c schistosity**: 'sc';

1	DATA_ID	GROUP_CODE	COLOR_CODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIP_DIR	DIP	L_DIP_DIR	L_DIP	SENSE	PALEONORTH	COMMENT
2	D5_0084	a	e	230	1587663	2863928	FARS	fracture	44	66					
3	D5_0085	a	e	230	1587663	2863928	FARS	fracture	33	65					
4	D5_0086	a	e	230	1587663	2863928	FARS	fracture	42	64					
5	D5_0087	a	e	230	1587663	2863928	LOWERFARS	bedding	20	60					reliable
6	D5_0088	a	f	230	1587663	2863928	LOWERFARS	bedding	40	60			O		overturned
7	D5_0089	b	f	ANG001	7663871	9282365		striae	329	71	328	72	N		
8	D5_0090	b	f	ANG001	7663871	9282365		striae	315	65	310	14	N	15	
9	D5_0091	b	f	ANG001	7663871	9282365		striae	312	70	68	N	N		

- 9th **DIP_DIR** column is for the **strike/dip direction** (depending on input settings) of lineations, planes, planes with slickenside, or s planes of s-c data sets. All of records must be filled except the case of 'lithology' datatype. Values between 0.0 – 360.0 are accepted.

- 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 **L_DIP_DIR** column is
  - for the **strike/dip direction** either **c planes** of s-c data sets, or for the bearing of **striae lineation** (values between 0.0 – 360.0 are accepted), or
  - for the **pitch angle** of the striation in the case of using pitch convention. All of records must be filled in the case of 'striae' or 'sc' data type; enter values between 0.0 – 90.0 for the pitch angle.

- 12th **L_DIP** column is
  - for the **dip angle** of **c plane** or plunge of **slickenside lineation**. All records must filled if using 'striae' or 'sc' data types (values between 0.0 and 90.0 are accepted), or;
  - in case of **pitch** convention this column indicates the **dip direction of the pitch** (enter 'n', 'nne', 'ne', 'ene', 'e', 'ese', 'se', 'sse', 's', 'ssw', 'sw', 'wsw', 'w', 'wnw', 'nw' or 'nnw' for pitch direction);

1	DATA_ID	GROUP_CODE	COLOR_CODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIP_DIR	DIP	L_DIP_DIR	L_DIP	SENSE	PALEONORTH	COMMENT
2	D5_0084	a	e	230	1587663	2863928	FARS	fracture	44	66					
3	D5_0085	a	e	230	1587663	2863928	FARS	fracture	33	65					
4	D5_0086	a	e	230	1587663	2863928	FARS	fracture	42	64					
5	D5_0087	a	e	230	1587663	2863928	LOWERFARS	bedding	20	60					reliable
6	D5_0088	a	f	230	1587663	2863928	LOWERFARS	bedding	40	60			O		overturned
7	D5_0089	b	f	ANG001	7663871	9282365		striae	329	71	328	72	N		
8	D5_0090	b	f	ANG001	7663871	9282365		striae	315	65	310	14	N	15	
9	D5_0091	b	f	ANG001	7663871	9282365		striae	312	70	68	N	N		

- 13th **SENSE** column is for the 1) **movement direction** along slickenside, and 2) to indicate **normal/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 for slickensides:
  - '+', 'thrust', 'up', 'inverse', 'u' or 'i' for **inverse/reverse** offset,
  - '-', 'normal', 'fault', 'down', 'downward', or 'n' for **normal** movement,
  - 'dextral', 'dx' or 'd' for **dextral** movement,
  - 'sinistral', 'sn' or 's' for **sinistral** movement, and
  - 'x' or 'none' for **unknown** offset;

  For bedding planes, use
  - 'o' or 'overturned' to indicate **overturned** bedding, otherwise it will be handled as normal one;
  - it is allowed (but not necessary) to use 'n' or 'normal' to indicate **normal** bedding;
- 14th column is for the **PALEONORTH direction**; if it is known, can be indicated and used, otherwise leave empty. Values between 0.0 – 360.0 are accepted here;
- 15th column is for your **COMMENTS**.
- 16th and other columns: will be not processed by the software. Everything **behind** the 14th column will be exported with no modification, so it is possible to store here as many data as you want.

1	DATA_ID	GROUP_CODE	COLOR_CODE	LOCATION	LOC_X	LOC_Y	FORMATION	DATATYPE	DIP_DIR	DIP	L_DIP_DIR	L_DIP	SENSE	PALEONORTH	COMMENT
2	D5_0084	a	e	230	1587663	2863928	FARS	fracture	44	66					
3	D5_0085	a	e	230	1587663	2863928	FARS	fracture	33	65					
4	D5_0086	a	e	230	1587663	2863928	FARS	fracture	42	64					
5	D5_0087	a	e	230	1587663	2863928	LOWERFARS	bedding	20	60					reliable
6	D5_0088	a	f	230	1587663	2863928	LOWERFARS	bedding	40	60			O		overturned
7	D5_0089	b	f	ANG001	7663871	9282365		striae	329	71	328	72	N		
8	D5_0090	b	f	ANG001	7663871	9282365		striae	315	65	310	14	N	15	
9	D5_0091	b	f	ANG001	7663871	9282365		striae	312	70	68	N	N		

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

1) PLOT

DATARULE (4.1): '**g**' for German dip direction/dip convention, and 'r' for right hand rule input (output will be in the same format as the input).

PLOT (4.2): '**a**' for classic Angelier plot, and 'h' for Hoeppner pole point plot.

PLOTTYPE (4.3): '**s**' for equal area Schmidt projection, and 'w' for equal angle Wulff projection.

HEMISPHERE (4.4): 'u' in the case of upper, and '**l**' for lower hemisphere.

CONTOURING (4.5): enter '**n**' do not use, 'd' to contour dip direction/lineation bearing, 's' for strike/lineation bearing, 'o' for plane normal/lineation bearing and 'b' for slickenside/lineation bearing.

TILTING (4.6): 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.

2) INVERSION

INVERSION (4.7): for the striae **inversion** methodology:

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

BINGHAM (4.8): for fracture **weight point statistics**: enter '**b**' to use Bingham statistics, or 'n' if you do not need.

STRESSANGLE (4.9): for the **angle** between the maximum stress direction and the slickenside direction, and will be used only by NDA and PTN methodologies; enter a number between 10 and 80 (**30** deg is the default setting).

VIRTUAL (4.10): for the **virtual symmetrical data set**: enter 'y' to use them, otherwise input '**n**'.

3) DATA GROUP MANAGEMENT

INPUTGROUP (4.11): this option is used while opening the result of a previous interpretation loop. The output file has a three digits group code (1st built up by the user defined one, 2nd is the k-means clustering result and 3rd for the RUP/ANG clustering). You can ignore them ('**n**'), use the first digit ('f') to group your data for the original user defined group, or use the second digit ('s') to group your data using the former the k-means clustering results,(if it exists at all), or use the third digit ('t') to group your data using the former RUP/ANG clustering clustering results.

GROUP (4.12): if you want to use user defined groups (if they are indicated in 2nd column of RGF file), all data will be separated by locality, by datatype **plus by your groups**, and processed/displayed on this way. Input '**y**' to use groups, or 'n' to do not use them.

CLUSTERNUMBER (4.13): enter '**n**' do not use, 'a' to find the ideal cluster number, or 2 – 9 for the required number of clusters. Either the entire data set will be processed, or clustering will be done group by group.

RUP_CLUSTERING (4.14): enter '**n**' do not use, 'a' to do a clustering using the angular misfit (ANG) values of the stress inversion, or enter 'r' to use the relative upsilon (RUP) value (see Chapter 4.8.2) in the clustering procedure.

GROUPSEPARATION (2.1-2.2): you had the chance to group everything by a user defined group code, by k-means clustering result and later by RUP/ANG clustering. While creating the output files, group codes can be ignored ('**i**') and each groups will handled together, or your data set will be displayed on different stereonets, separated by the user defined group code ('g'), by the k-means clustering results ('k') or by the results of the RUP/ANG clustering ('r').

4) ROSE DIAGRAM

ROSETYPE (4.15): enter '**s**' for symmetric (bidirectional) and 'a' for asymmetric (unidirectional) one.

ROSEDIRECTION (4.16): enter '**s**' or 'd' to show strike or dip direction distribution on the rose plot.

ROSEBINNING (4.17): enter 'a', 'b', '**c**' or 'd' for 2.5, 4.0, 10.0 and 22.5 deg bin sizes on the rose plot.

5) OTHER

IDEALMOVEMENT (4.18): enter 'y' if you want to display ideal movement direction of slickensides, otherwise use '**n**'.

LABELING (4.19): enter 'y' to label all of your data on the stereonet, otherwise use '**n**'.

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

COLORING (2.1-2.2): you had the chance to group everything by a user defined group code, by k-means clustering result and later by RUP/ANG clustering, and you had the chance to use color codes for different records, too. While coloring the output stereonets, either any codes are ignored ('**i**') to generate uniform black colors, or data records can be colored using their color codes ('c'). It is possible to color them using their user defined group code ('g'), using their the k-means clustering results ('k') or using their the results of the RUP/ANG clustering ('r').

GRAYSCALE (4.20): RGB colored ('**n**') and grayscale ('y') outputs are possible for the user's choice; grayscale output is recommended for publications.

XY DATA FORMAT I.

- XY data file (*.xy) is a tab separated text file with the following properties:
  - Has **4 columns**;
  - **First line is the header**, with arbitrary content (it is recommended to indicate column names here);

- 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 correct numeric format will checked but otherwise not processed by the software just merged with the opened *.rgf file content.

- 4th column is for the (optional) **formation name**; the software will use this field to complete the original input (*.rgf) file content and overwrite the **FORMATION** field if it.

LOCATION	LOC_X	LOC_Y	FORMATION
001	36.129135	44.677941	SHIRANISH
002	36.117464	44.692926	TANJERO
003	36.118041	44.695327	TANJERO
004	36.117797	44.696108	TANJERO
005	36.117485	44.697697	TANJERO
006	36.119754	44.698424	TANJERO
007	36.116457	44.699964	SHIRANISH
008	36.115977	44.701818	SHIRANISH
009	36.113235	44.703591	SHIRANISH
010	36.112914	44.703981	SHIRANISH
011	36.111820	44.704590	SHIRANISH
012	36.111597	44.703153	TANJERO
013	36.121436	44.721826	TANJERO
014	36.120050	44.720542	TANJERO
015	36.117612	44.719546	TANJERO
016	36.116089	44.720087	TANJERO
017	36.115622	44.719530	TANJERO
018	36.113558	44.714509	TANJERO
019	36.109844	44.713332	TANJERO
020	36.142698	44.680661	TANJERO
021	36.143330	44.680070	TANJERO
022	36.144300	44.677833	TANJERO
023	36.144910	44.675580	TANJERO
024	36.145046	44.674649	FARS
025	36.145050	44.673880	SHIRANISH
026	36.144580	44.672364	SHIRANISH
027	36.144252	44.671924	FARS
028	36.142930	44.669365	SHIRANISH
029	36.141660	44.668470	SHIRANISH
030	36.140685	44.666966	BAKHTIARI

PROCESSING AND DISPLAY

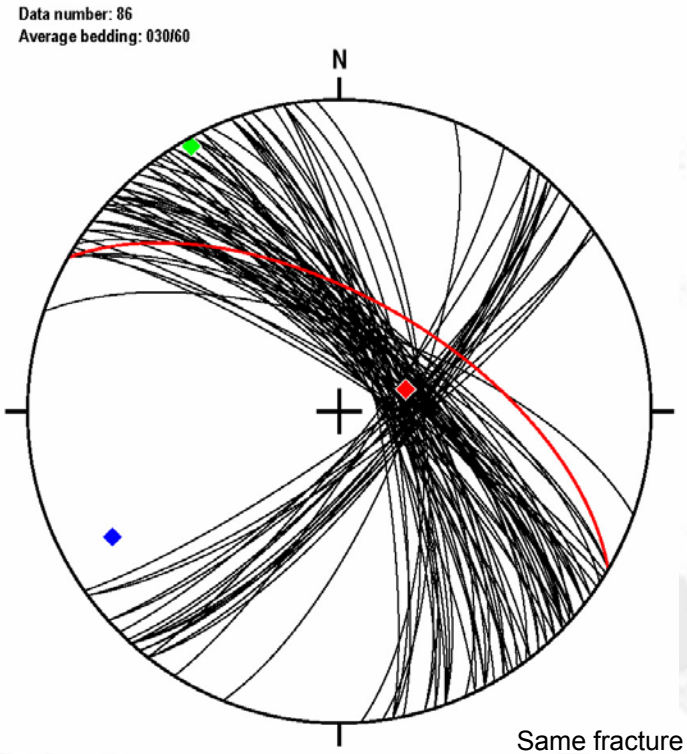
GERMAN DIP DIRECTION AND RIGHT HAND RULE

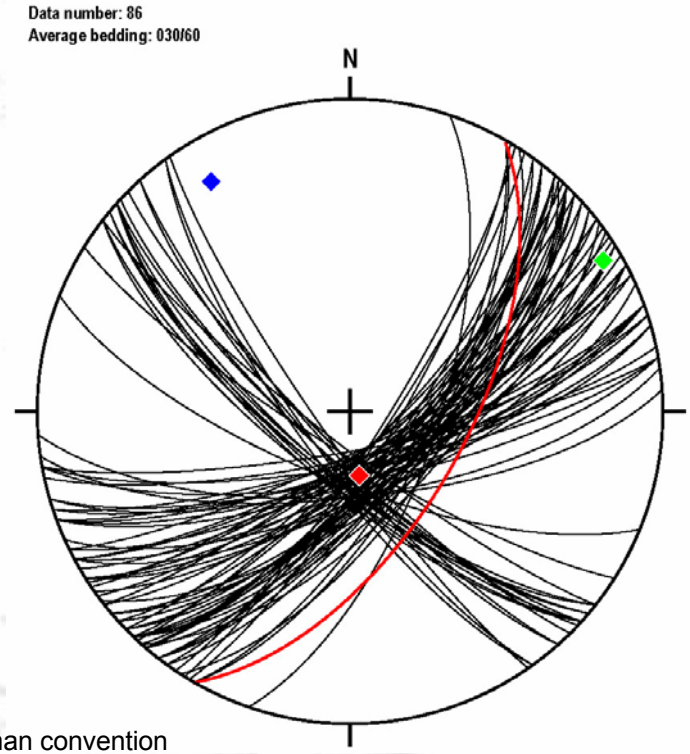
DIP DIRECTION

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

RIGHT HAND RULE

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





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

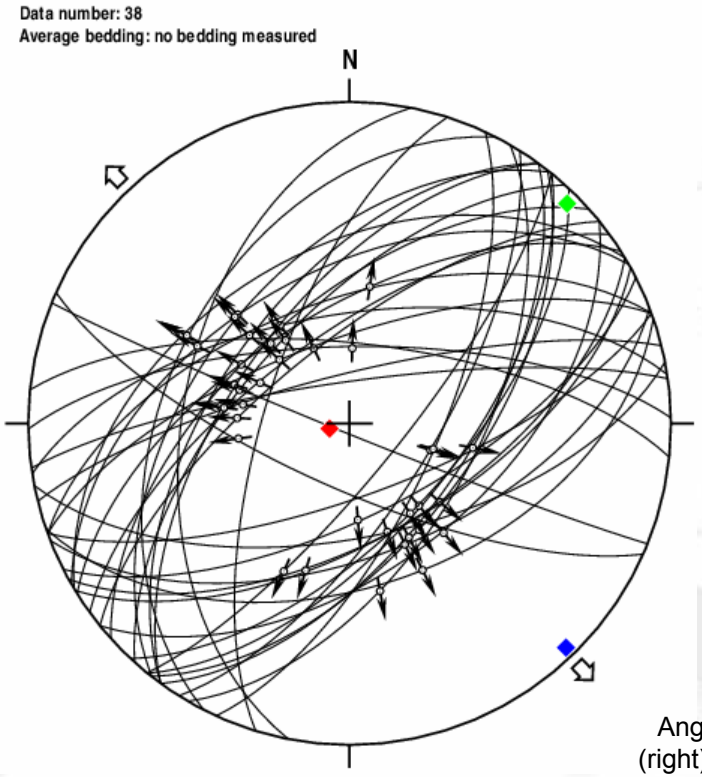
ANGELIER AND HOEPPNER PLOT

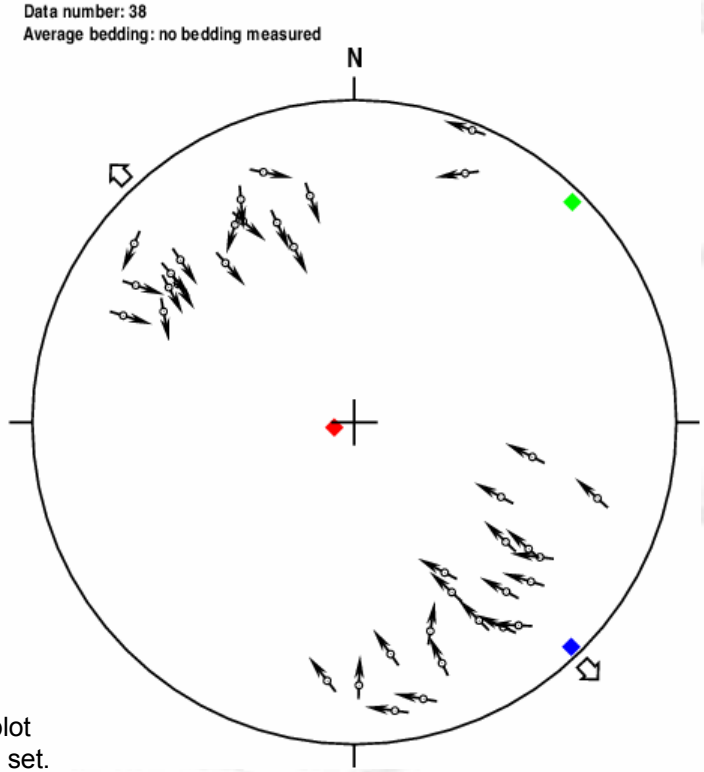
ANGELIER PLOT

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

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.





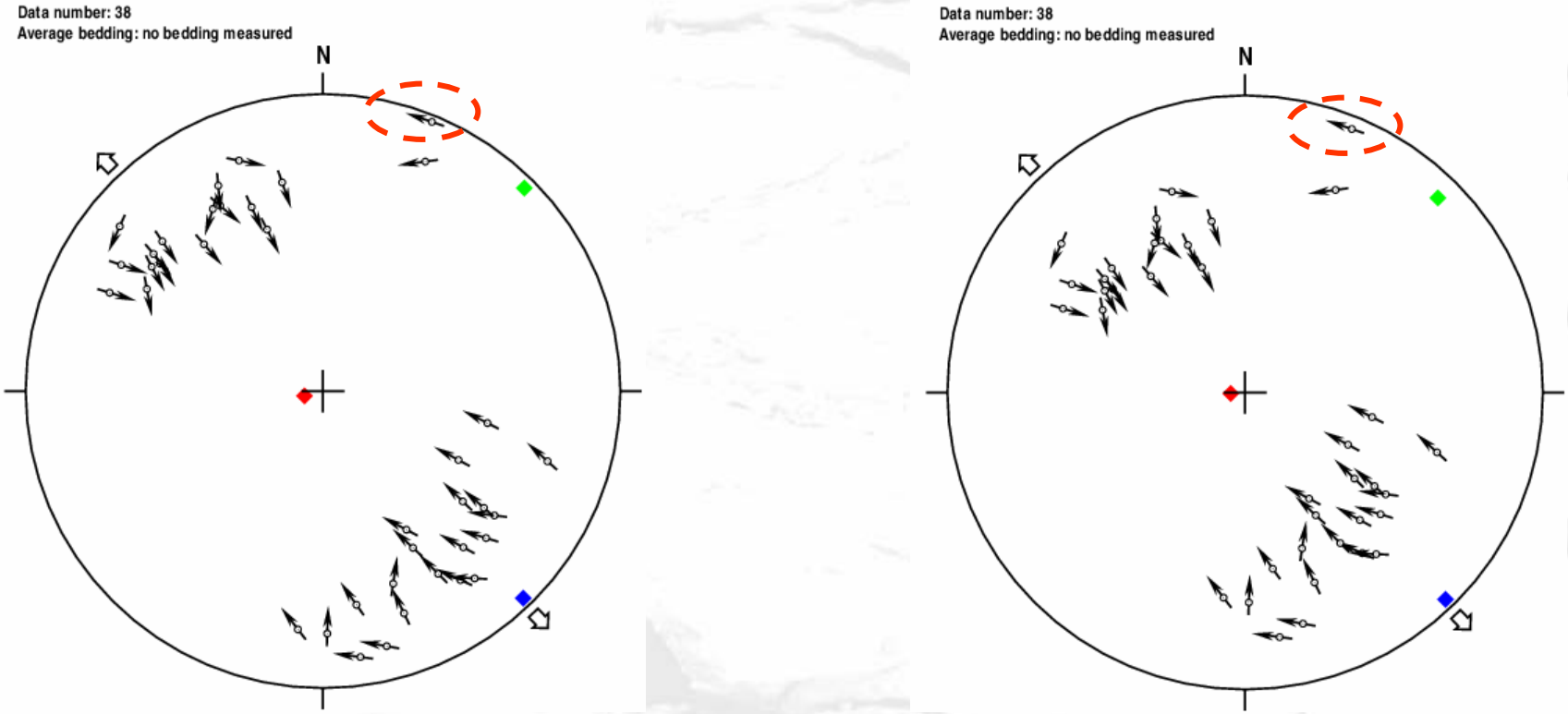
Angelier plot (left) and Hoeppner plot (right) of Angelier's (1990) TYM data set.

SCHMIDT NET

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

WULFF NET

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



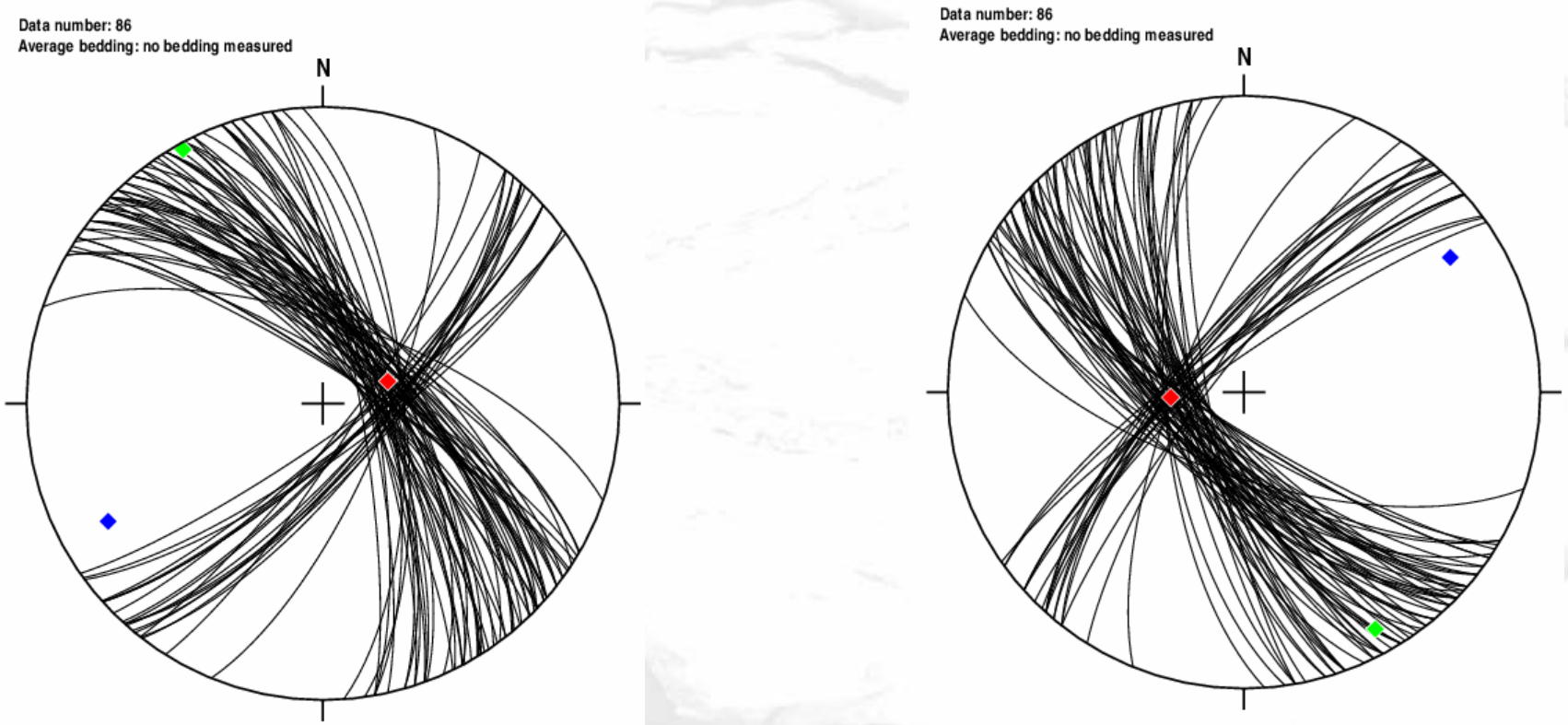
Schmidt-net (left) and Wulff-net (right)
projection of Angelier's (1990) AVB data set.

LOWER HEMISPHERE

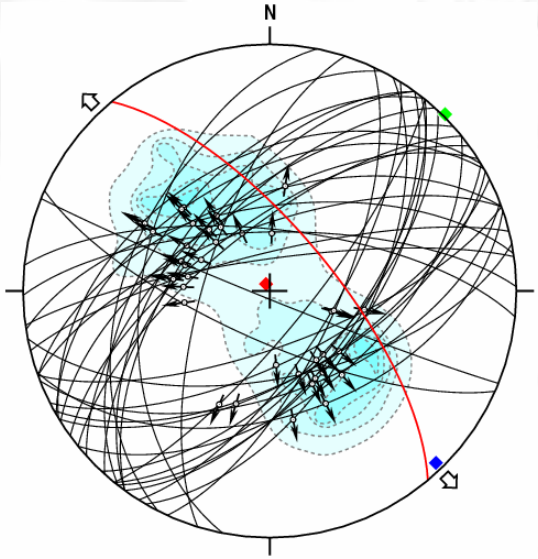
- Projects on **lower** hemisphere

UPPER HEMISPHERE

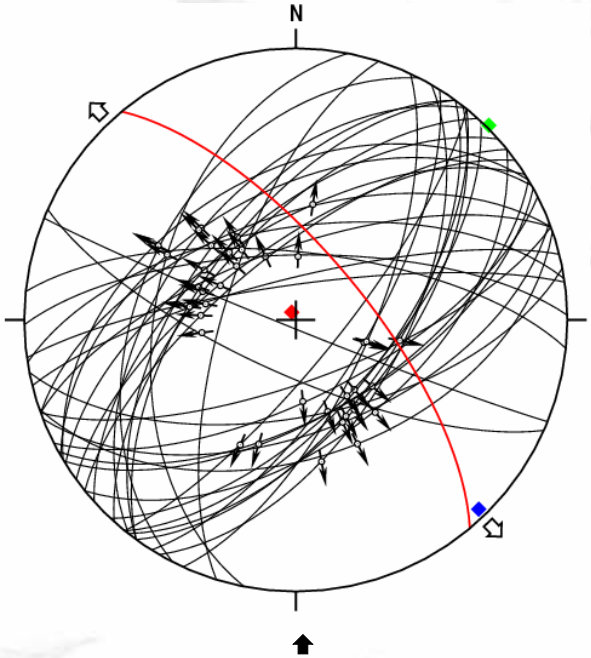
- Projects on **upper** hemisphere



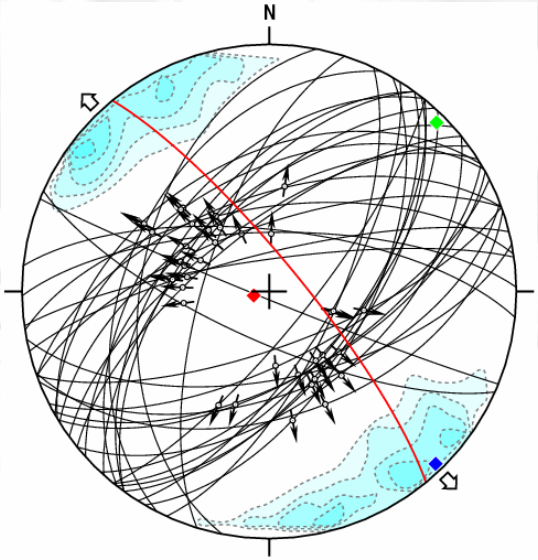
Lower hemisphere (left) and upper hemisphere (right) projection of the same inverse slickenside data set.



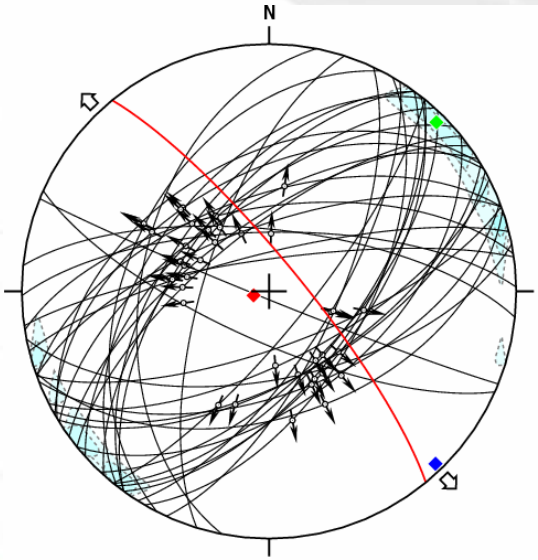
Contouring of the input data set using plane **dip direction** or lineation **bearing** as input.



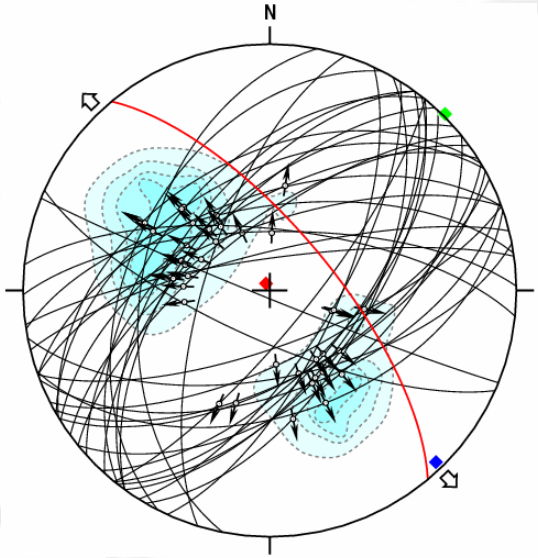
Original input data set, **no contouring** method was chosen



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



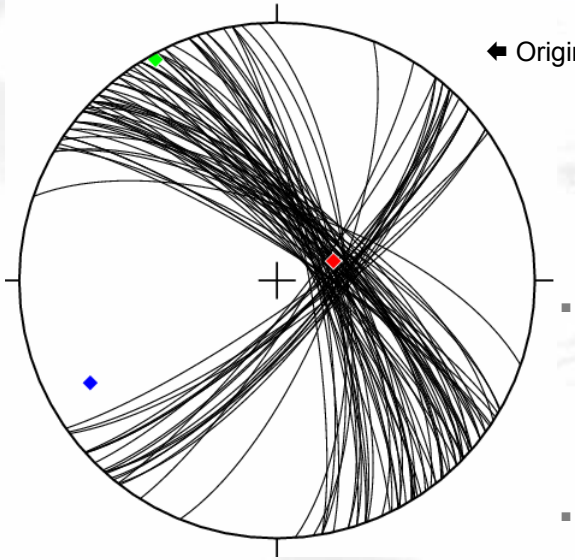
Contouring of the input data set using plane **strike** direction or lineation **bearing** as input.



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

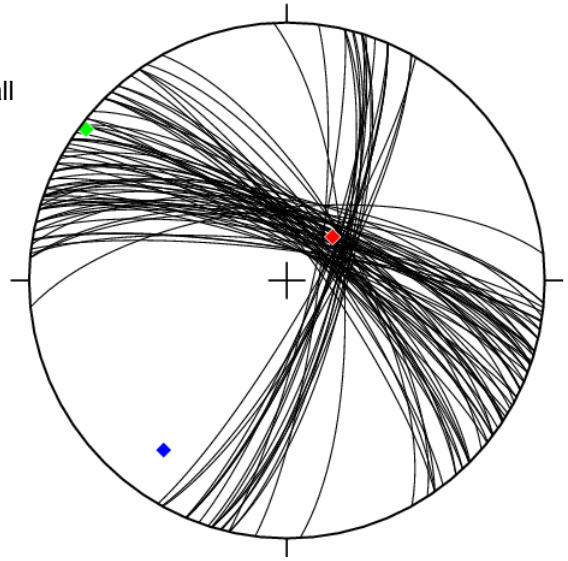
PROCESSING AND DISPLAY

CORRECTION WITH AVERAGE BEDDING AND PALAEONORTH DIRECTION

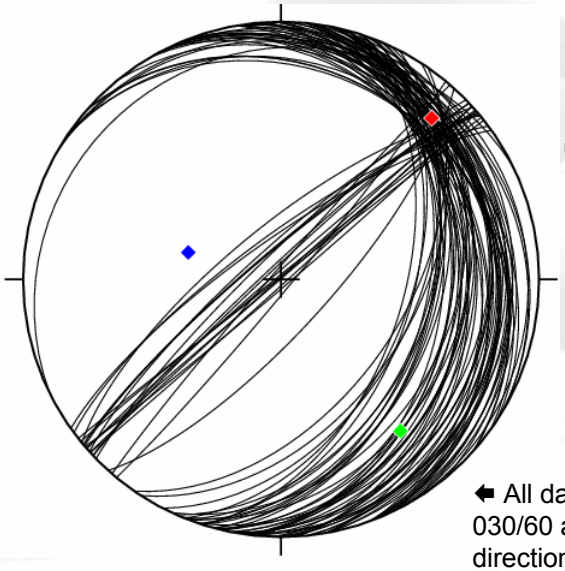


⬅ Original dataset

Corrected by 30 deg palaeonorth direction for all of data. ➡

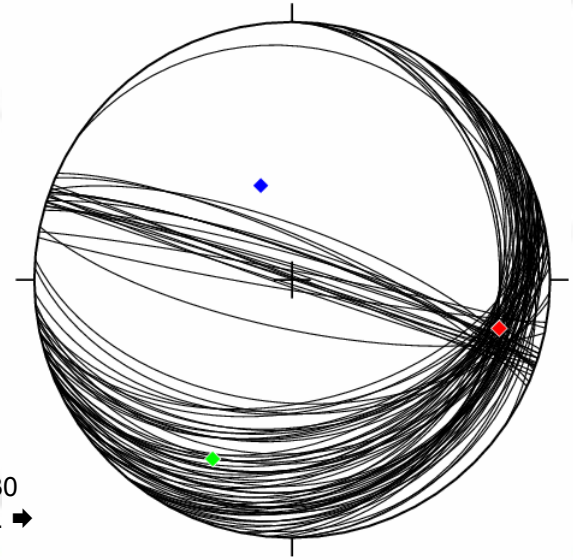


- Selecting **bedding correction** option, all data will be re-tilted by the **average bedding** measured in the outcrop. If no bedding data, the plot for measured and corrected data will be the **same**.
- Selecting **palaeonorth direction correction**, all data will be corrected with the palaeonorth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



⬅ All data corrected by 030/60 average bedding direction

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



PROCESSING AND DISPLAY

INVERSION I. – REGRESSION WITH A PRIORI ASSUMPTION

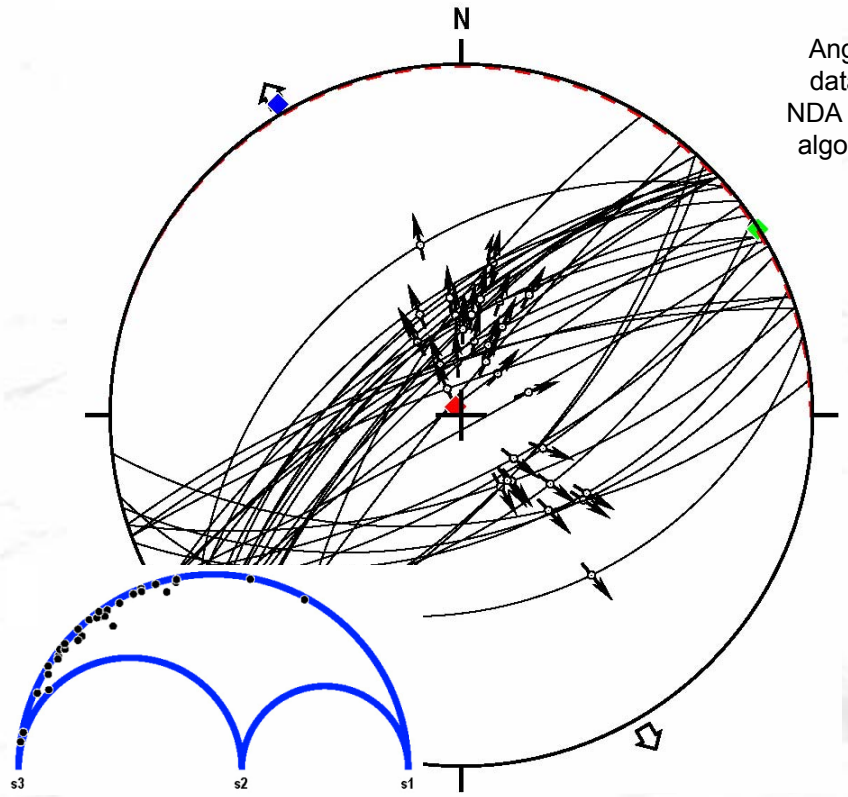
- Regression methodologies with a priori assumption are calculating maximum and minimum stress orientations for each slickenside **based on fault plane and striae geometry**, and searching for the best fitting stress tensor;
- To calculate stress axes direction, **a priori assumption is required** about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

NDA after Spang (1972)

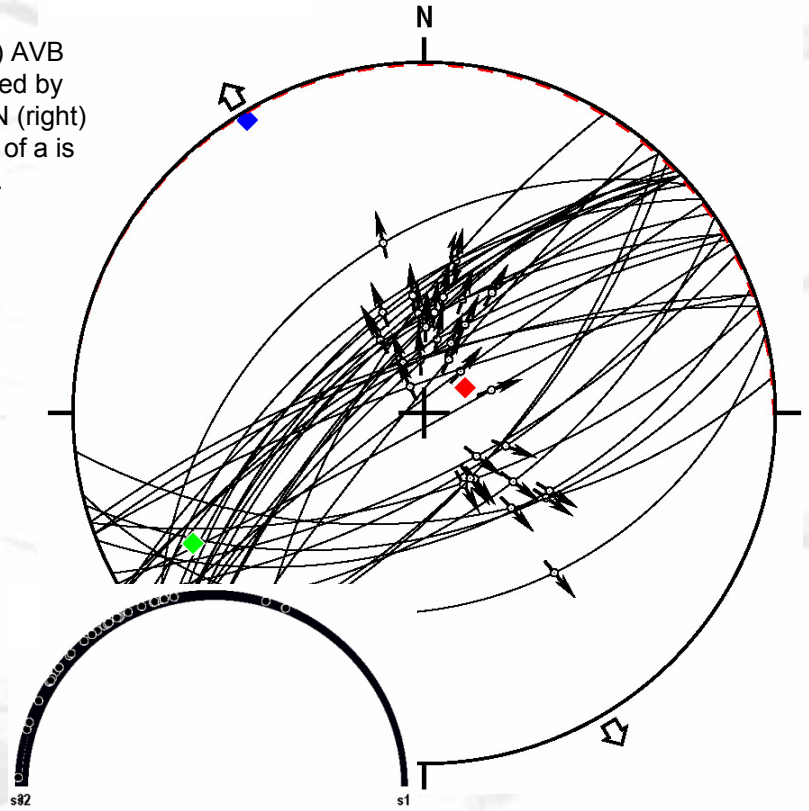
- NDA methodology calculates the best fitting stress tensor on this way for the **entire** data set. For details see Chapter 4.6.1.

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 a is 30 degrees.



- 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);

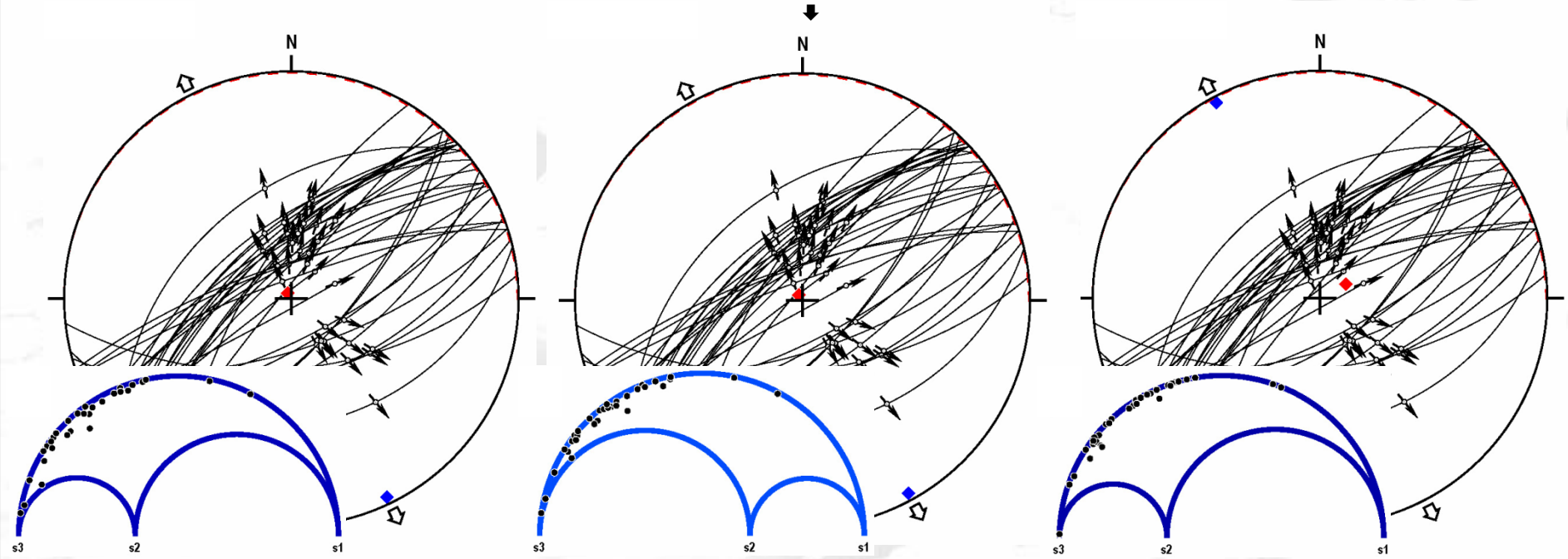
SHAN ET AL (2003)

- Shan et al's (2003) solution is five dimensional regression assuming $s_{11} + s_{22} + s_{33} = 0$; 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.



INVERSION III. – DIRECT INVERSION, BRUTE FORCE INVERSION

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

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

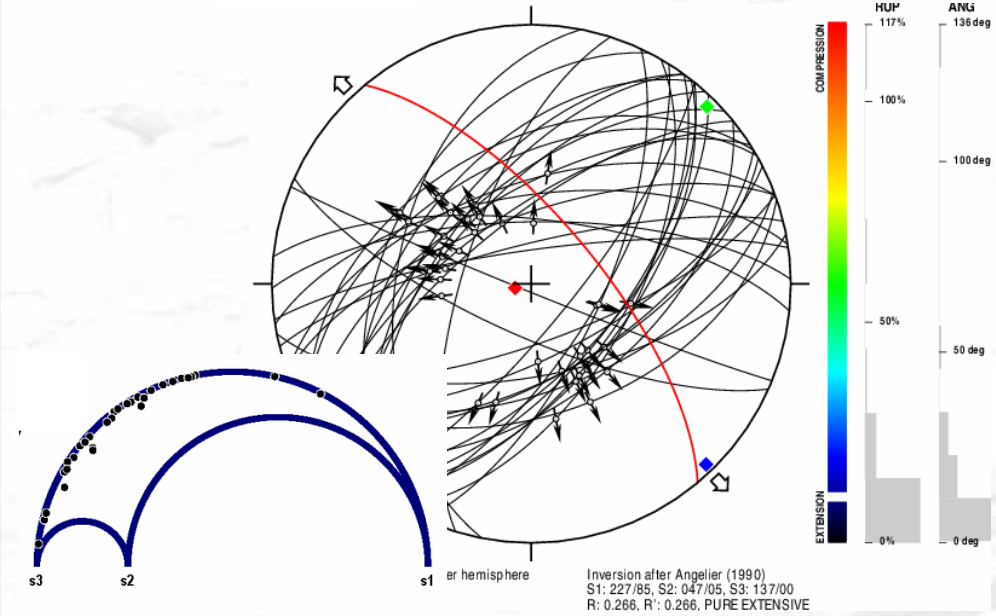
ANGELIER (1990)

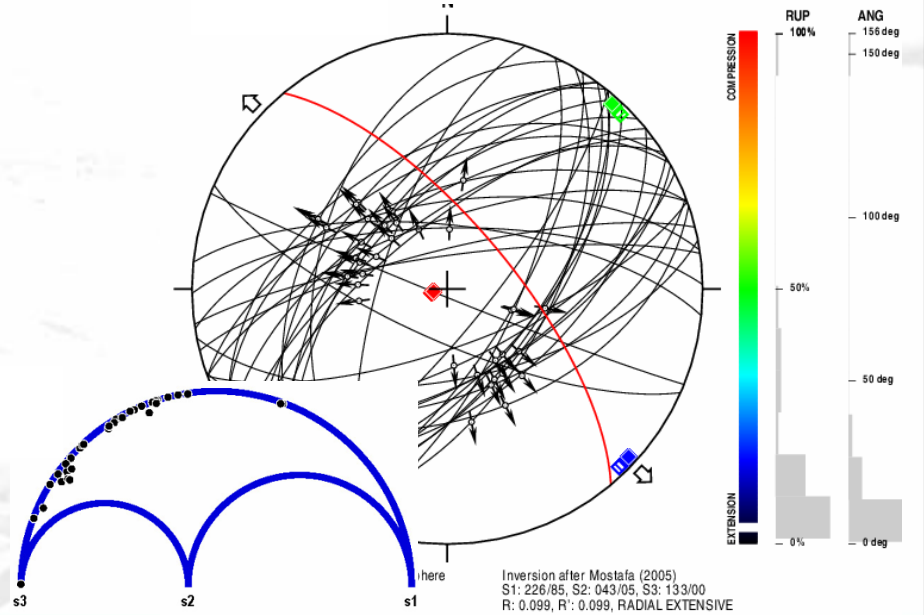
- Angelier's (1990) methodology calculates a **misfit vector** ν between the **measured** and **calculated** shear vector, and minimizes its length (see Chapter 4.6.6).

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. ⬇

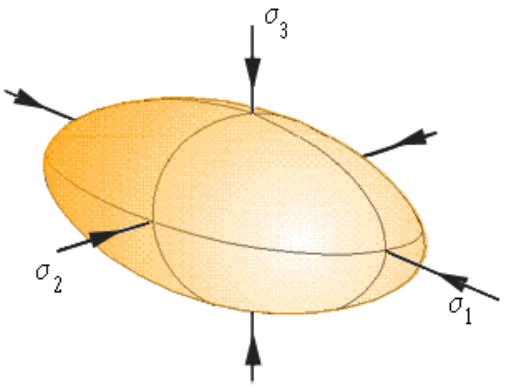


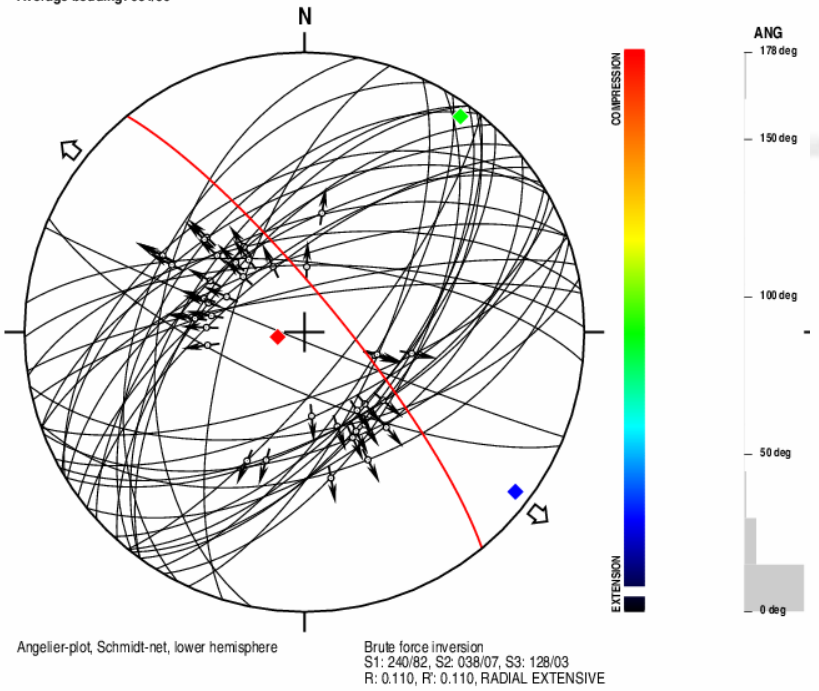


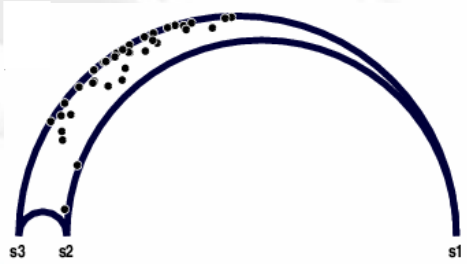
PROCESSING AND DISPLAY

INVERSION IV. – BRUTE FORCE INVERSION

- Brute force methodologies are really simple but time consuming technologies to find the best fitting stress tensor of the investigated data set.
- Brute force inversion is a **simple iteration** with **no preliminary assumption** and with **no heuristic approach**.
- This methodology has a ‘trial and error’ philosophy – the stress tensor with the **smallest cumulative misfit angle** (ANG) is the ‘best fitting’ stress tensor.
- Because the stress ellipsoid is characterised by the **stress axes direction** (perpendicular to each other) and the **stress axes length** (or stress ellipsoid shape), a number of stress tensor candidates with different geometry and orientation can be used.
- **Iterating** in these variables, and ‘**zooming in**’ on the local maxima, it is possible to find the best fitting stress tensor – this will be really the best fitting one, because all theoretical solutions were cross checked.







PROCESSING AND DISPLAY

BINGHAM STATISTICS AND FOLD GREAT CIRCLE CALCULATION

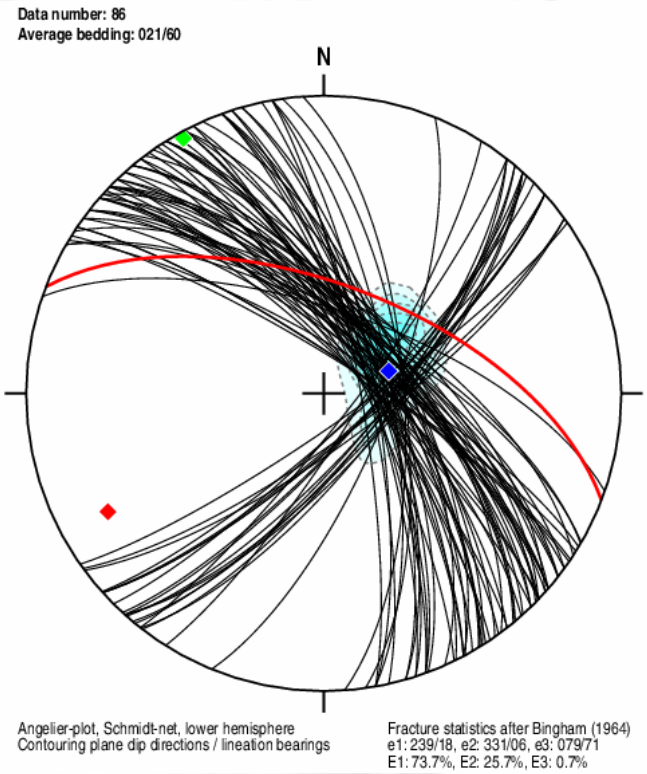
BINGHAM STATISTICS

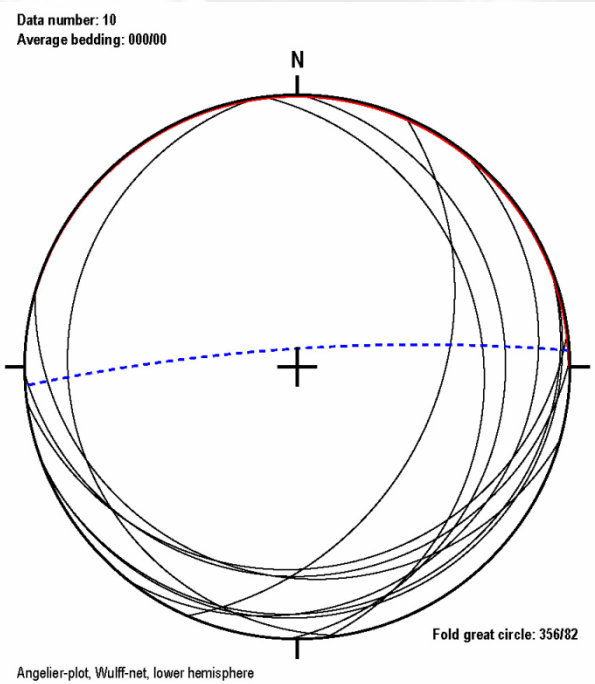
- Average computation can be carried out on different ways; one of them is to calculate **arithmetic average**, or median;
- In the case of **directional data** (eq. stress vector direction) this methodology might be misleading (average of compression vectors of 040/10 and 220/10 is ~220/90 and not 040/00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





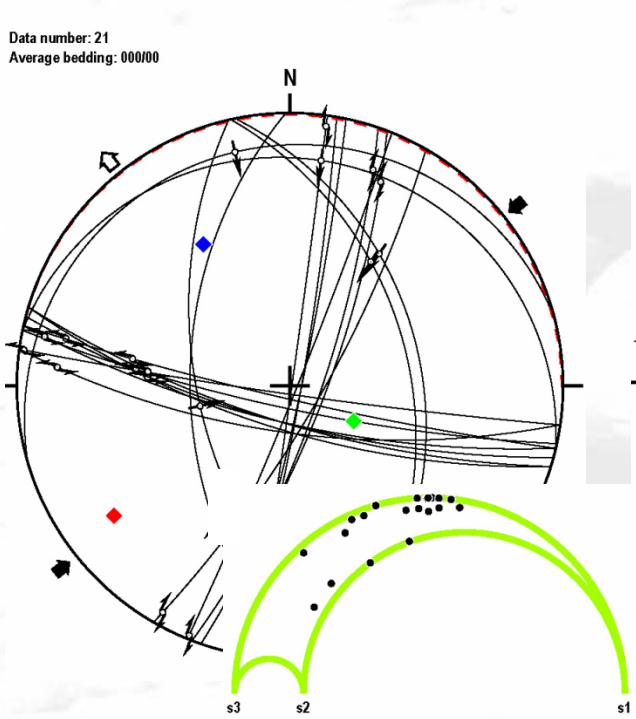
⬆ Fold great circle of a 'foldsurface' data set using Bingham statistics to find the best fitting plane.

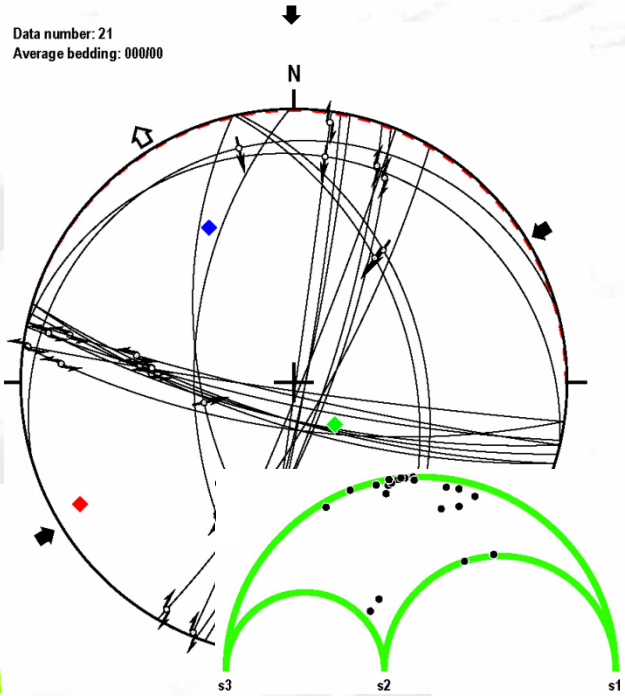
PROCESSING AND DISPLAY

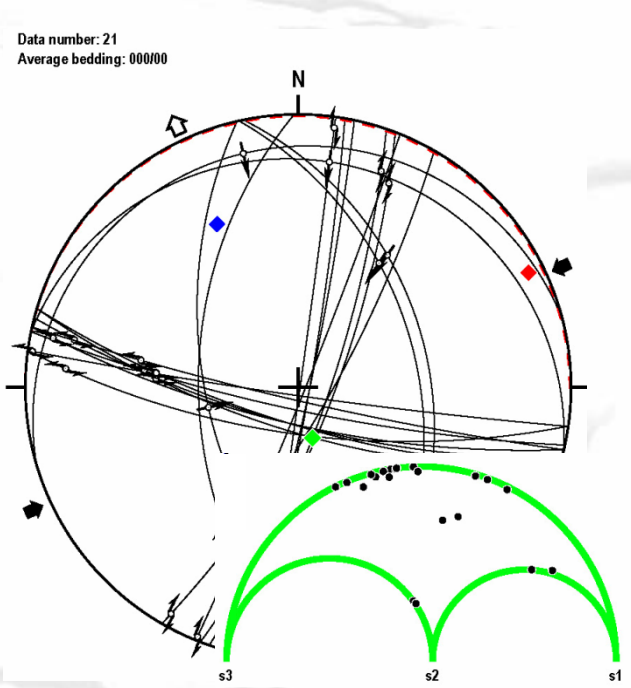
STRESS ANGLE

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

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



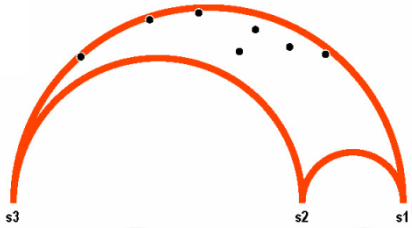


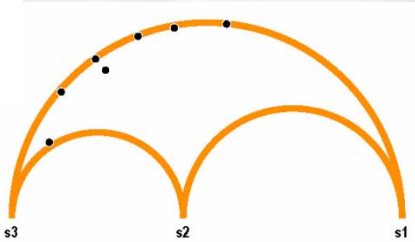


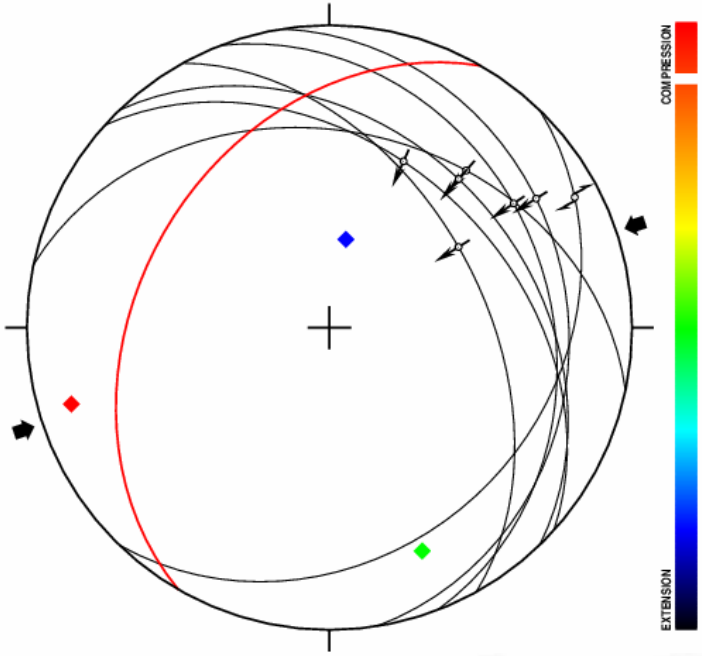
PROCESSING AND DISPLAY

VIRTUAL SYMMETRICAL DATA SET

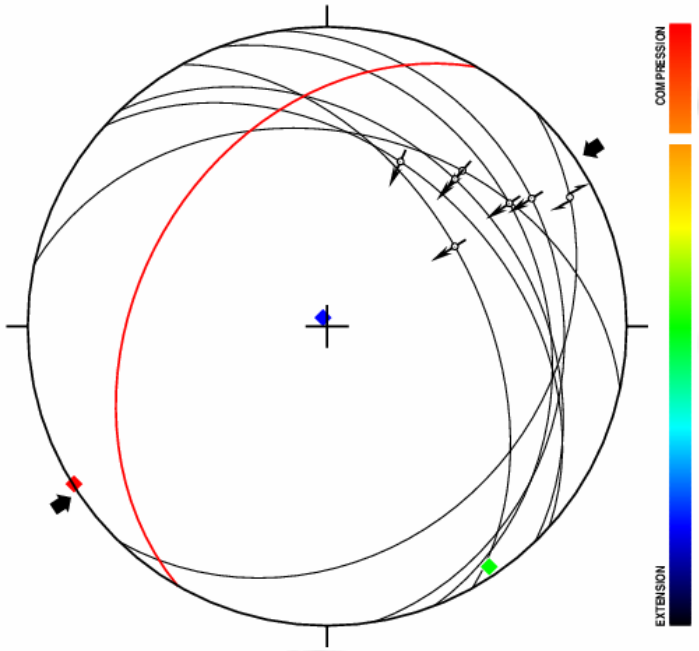
- Some inversion methodologies are sensible on the **symmetry** of the input data set; in some case of asymmetry the result is mathematically correct, but not from geological point of view;
- One of the possible solutions could be to generate a **virtual, symmetrical data set**; this virtual set is composed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





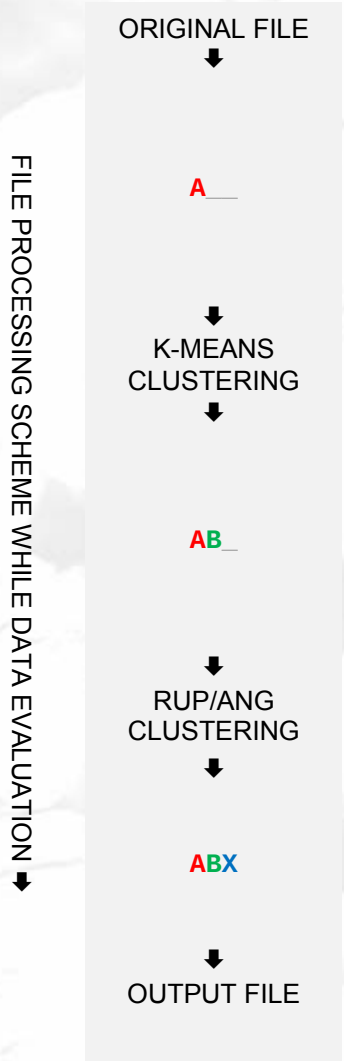


Same data set processed without (left) and with (right) virtual symmetric data set.



PROCESSING AND DISPLAY

IMPORTING GROUPS



- While importing, it is possible to choose which digit of the group code to import as a user defined group code.

1. Importing the **first** character (user defined group), you will keep the original user defined groups of the file you have been created for a while.

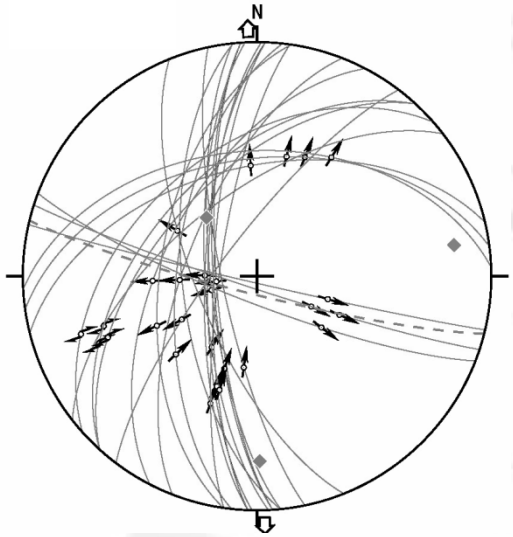
2. Importing the **second** character (k-means clustering result), you will keep the original k-means clustering result groups and use them as user defined group code.

3. Importing the **third** character (RUP/ANG clustering result), you will keep the original RUP/ANG clustering result groups and use them as user defined group code.

PROCESSING AND DISPLAY

PROCESSING WITH AND WITHOUT USING GROUPS

NOT USING USER DEFINED GROUPS

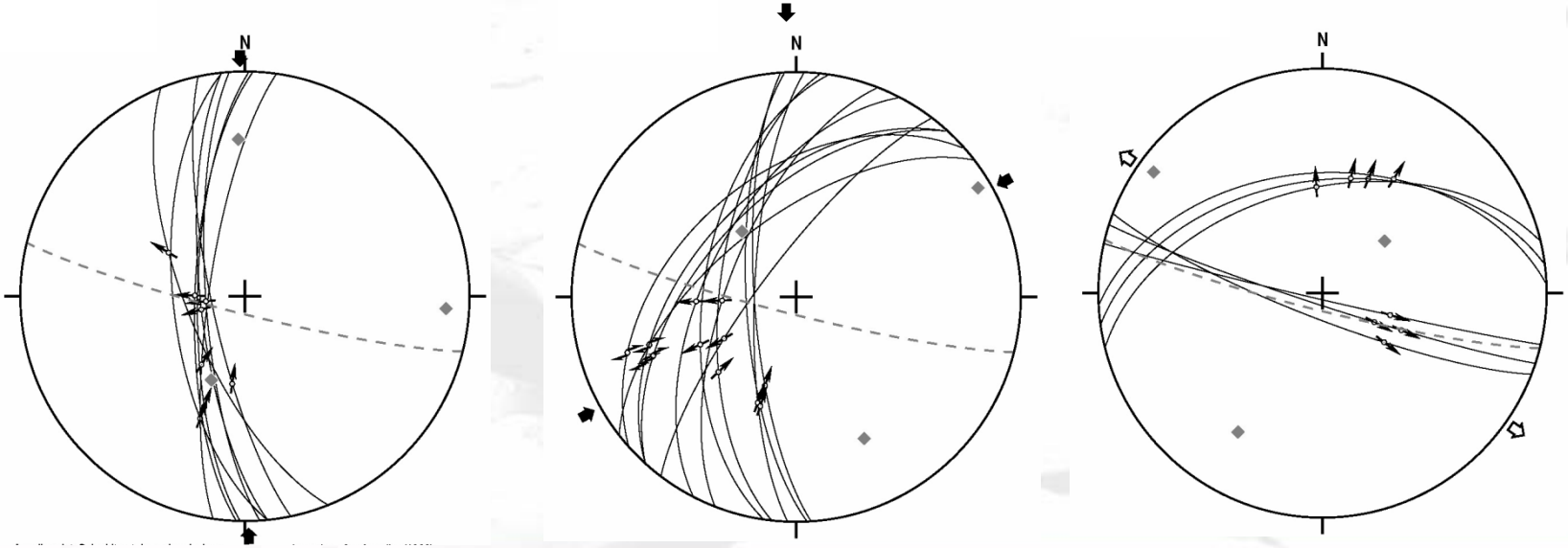


Data set with three different groups *not using groups processing* option – all data will be processed together.

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

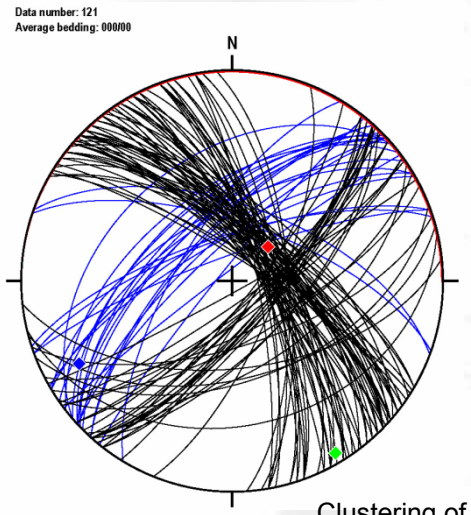
Same data set processed *using processing option* – all of three data groups defined in input file will be processed and displayed one by one.

USING USER DEFINED GROUPS



PROCESSING AND DISPLAY

K-MEANS CLUSTERING

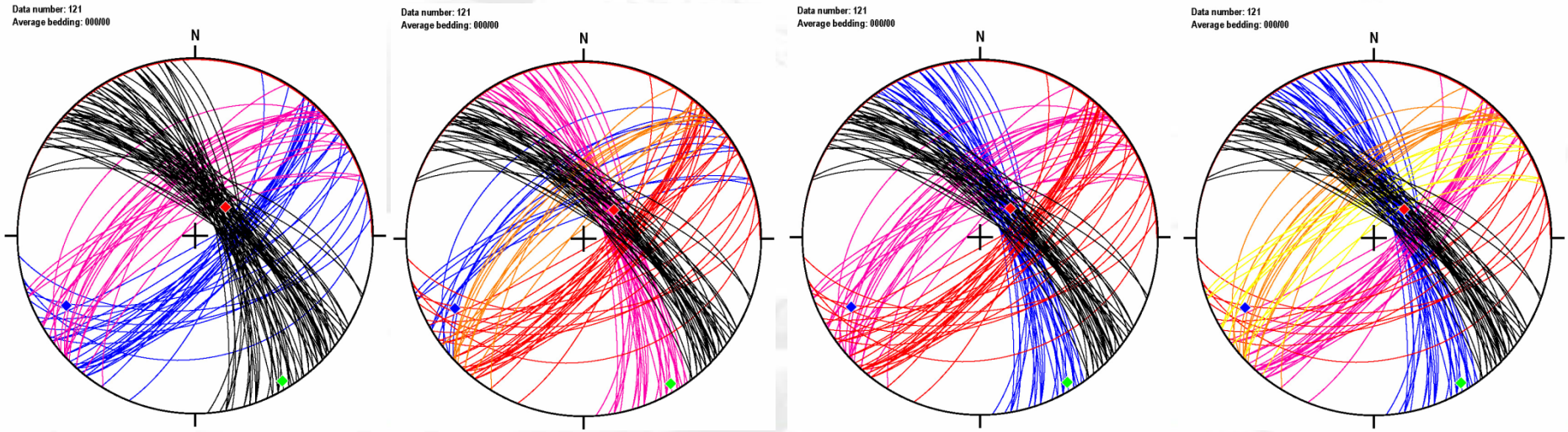


- Built in k-means clustering module is coded to identify **different clusters** of an inhomogeneous data set.
- Normal k-means clustering sorts all of data into **k user defied groups**.

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.

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.

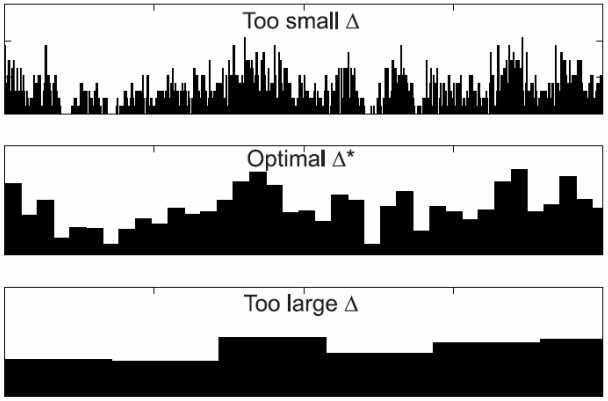


CLUSTERING USING RUP AND ANG VALUES

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

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

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



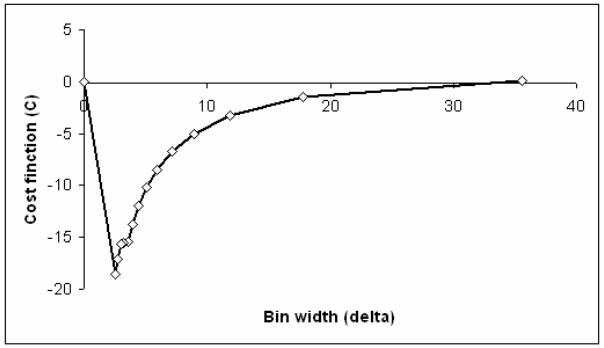
⬆ Histograms for the same data set with too small, optimal, and too large bin size. Figure of Shimazaki and Shinomoto (2007).

SHIMAZAKI AND SHINOMOTO (2007)

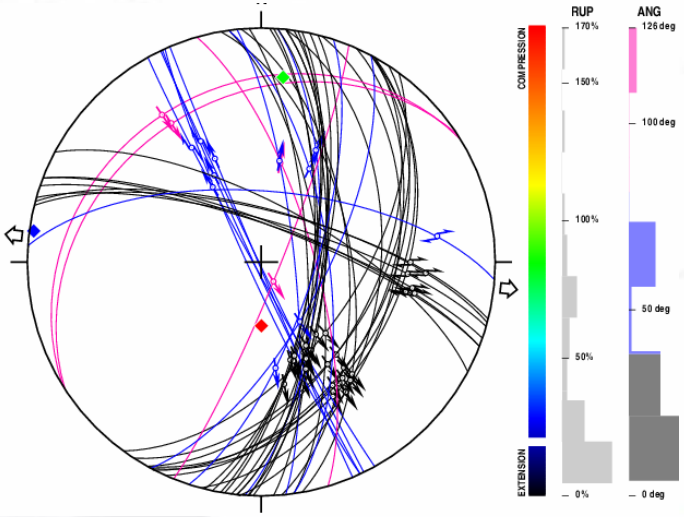
- Divide the data range into **N** bins of width **D**. Count the number of events k_i that enter the i^{th} bin;
- Calculate the **mean**, the **variance** and the 'cost function' of the number of events:

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

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



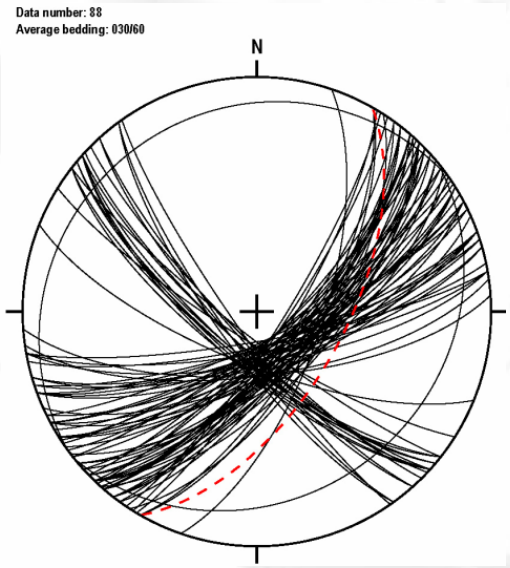
⬅ Bin size vs cost function graph for a test data set; cost function minimum is at ~-18, resulting ~2.5 ideal bin width for clustering.



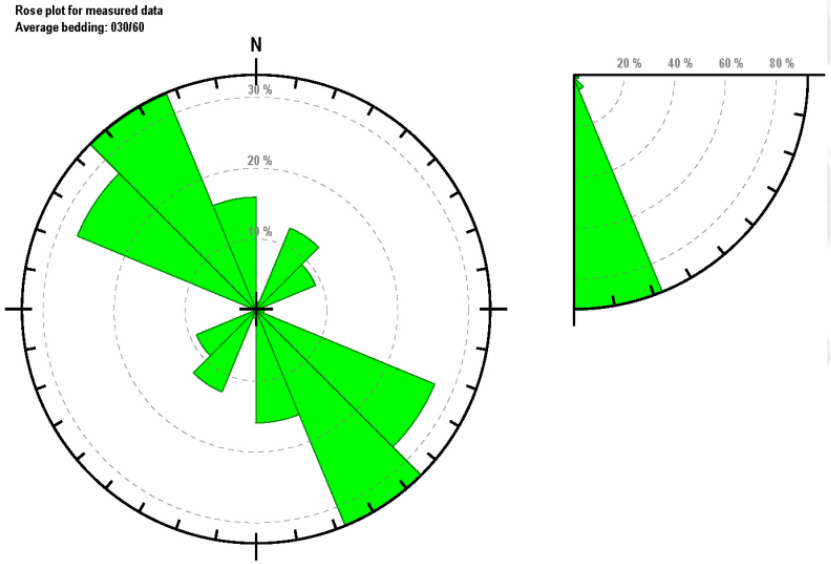
⬅ Clustering result of a test data set, based on ANG parameter distribution. The input data set could be a heterogeneous set, a mixture of at least two different striae set.

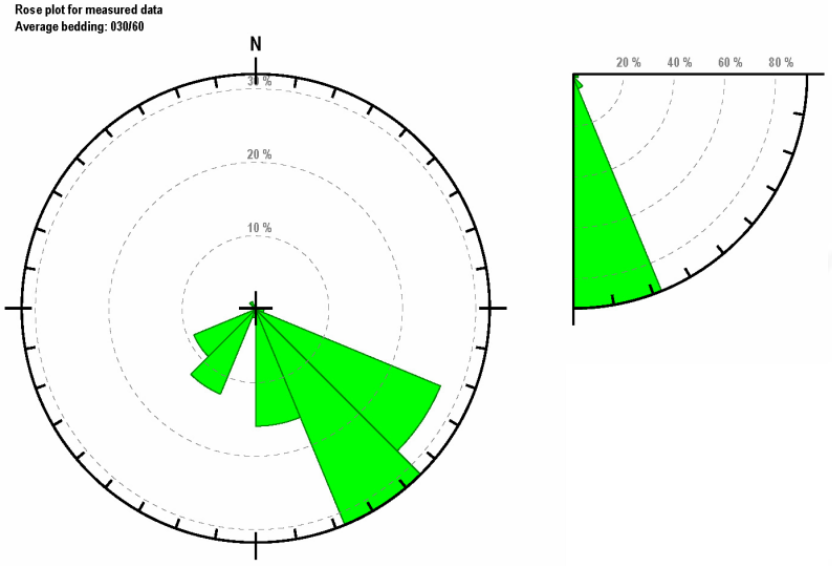
PROCESSING AND DISPLAY

ROSE PLOTS I. – ROSE DIAGRAM TYPE



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

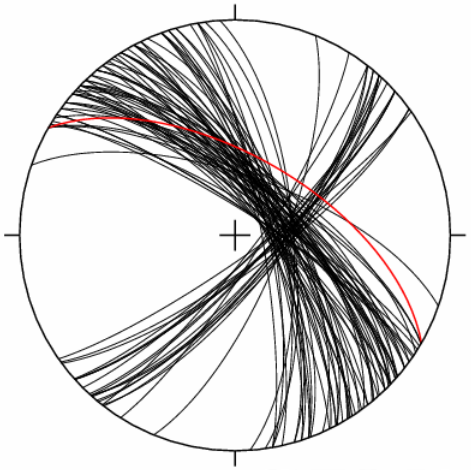


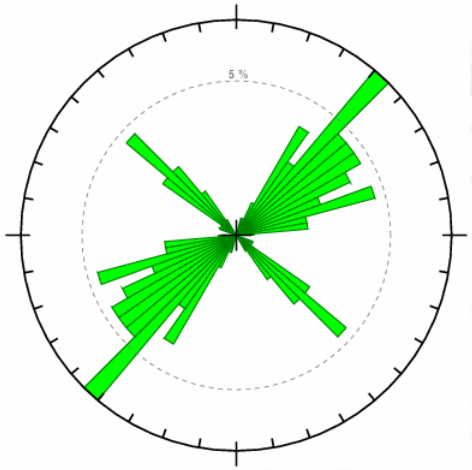


- Rose plots are presenting the **horizontal** and **vertical** distribution of data sets;
- Both asymmetric (unidirectional) and symmetric (bidirectional) plots are available.

PROCESSING AND DISPLAY

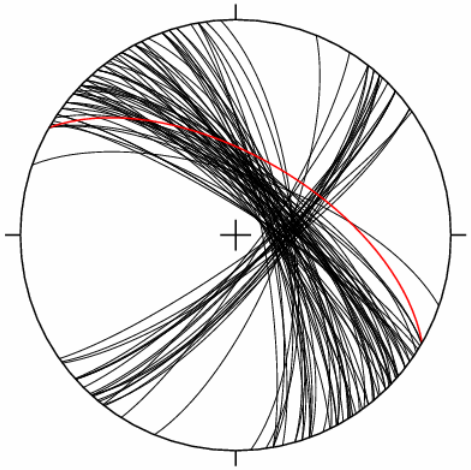
ROSE PLOTS II. – ROSE PLOT DIRECTION

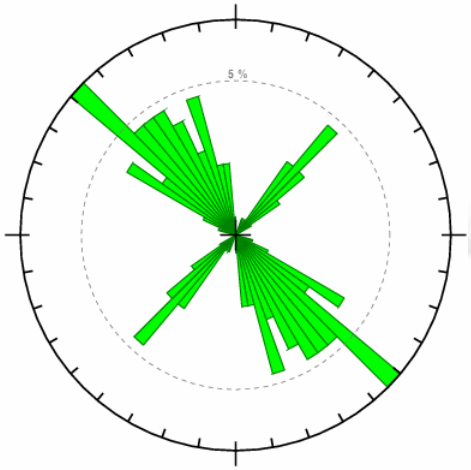




- Rose plot when **dip direction** of the input data is displayed (symmetrical rose plot with 5 degree bin size)

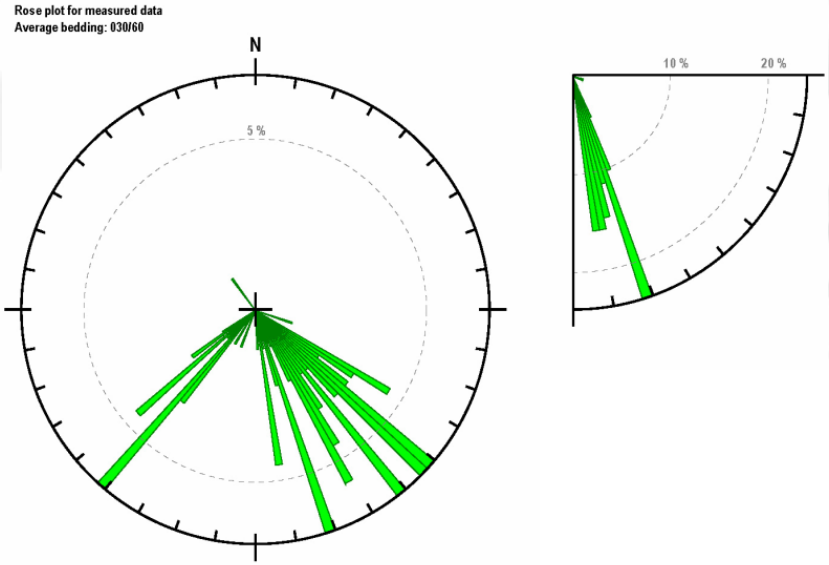
- Rose plot when **strike** of the input data is displayed (symmetrical rose plot with 5 degree bin size)

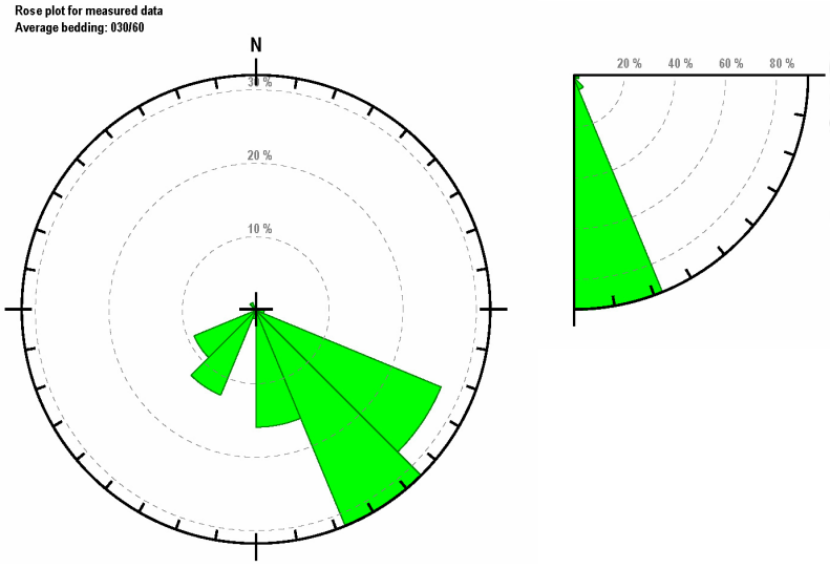




PROCESSING AND DISPLAY

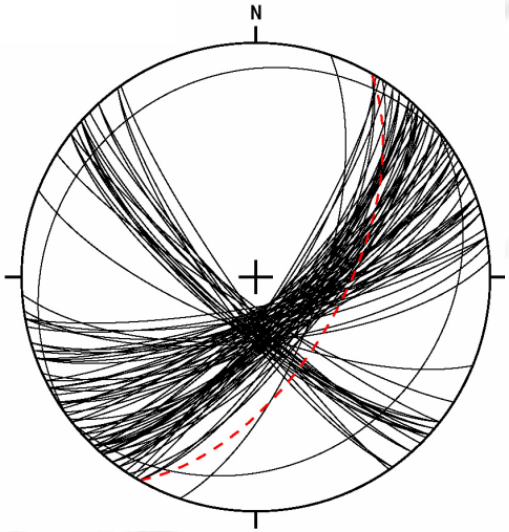
ROSE PLOTS III. – BIN SIZE





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

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

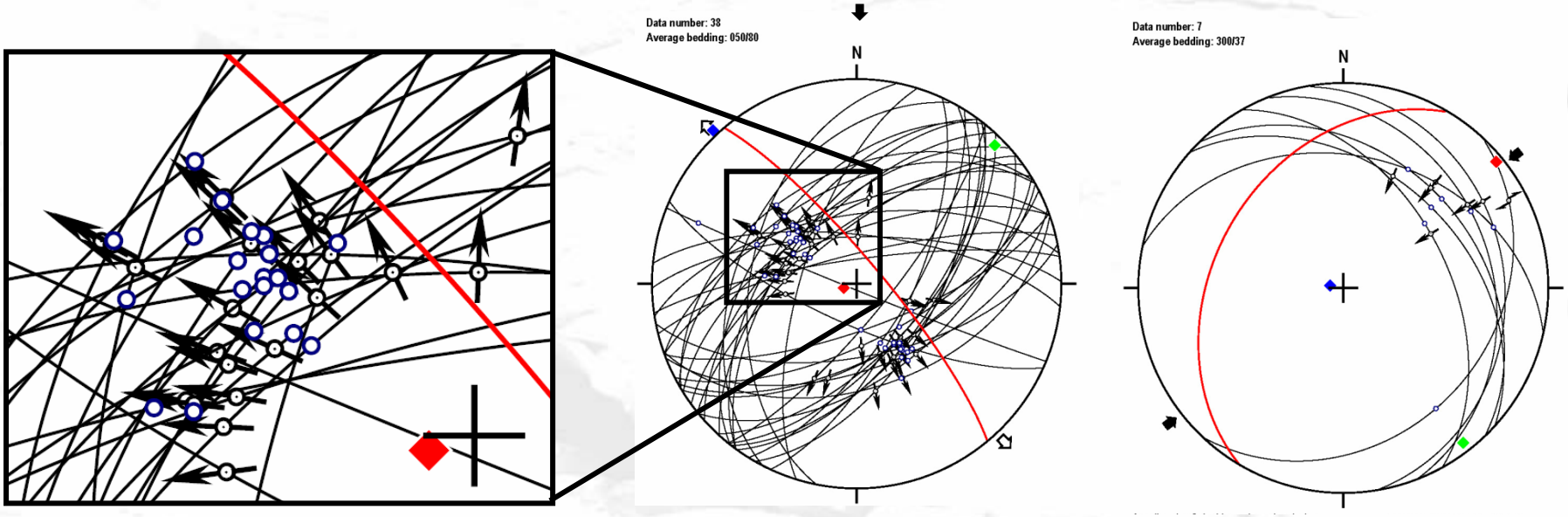


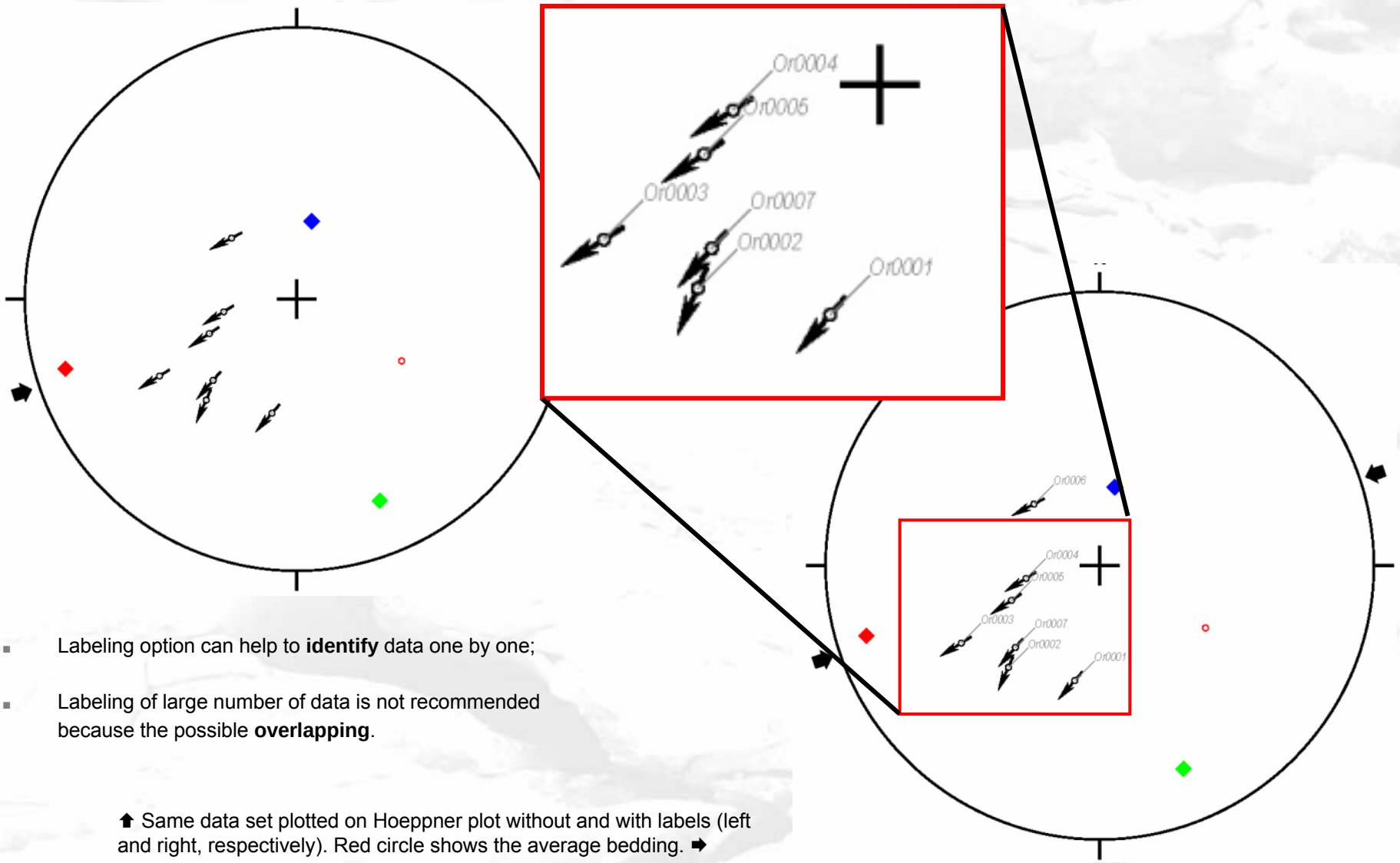
PROCESSING AND DISPLAY

Resolved shear 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.

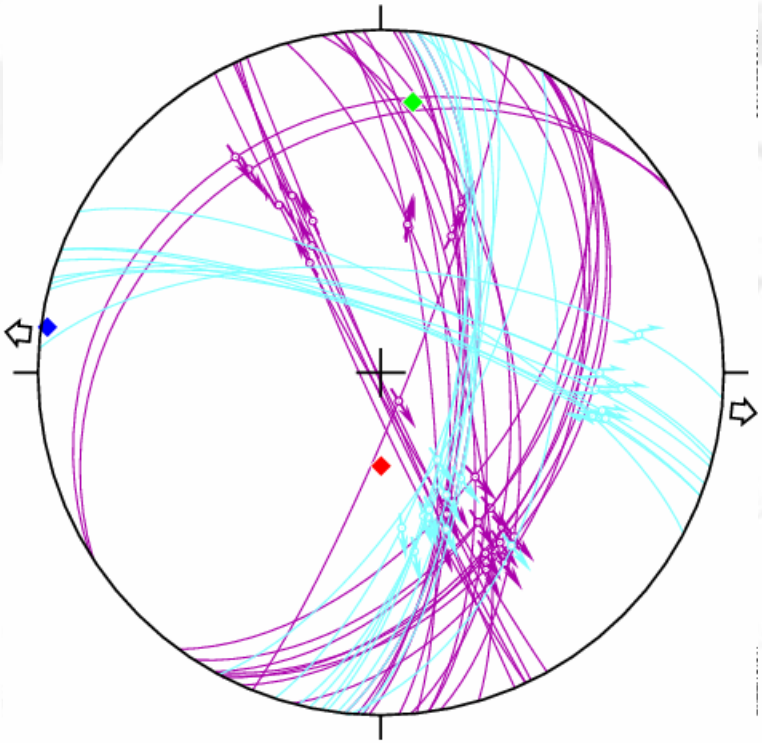


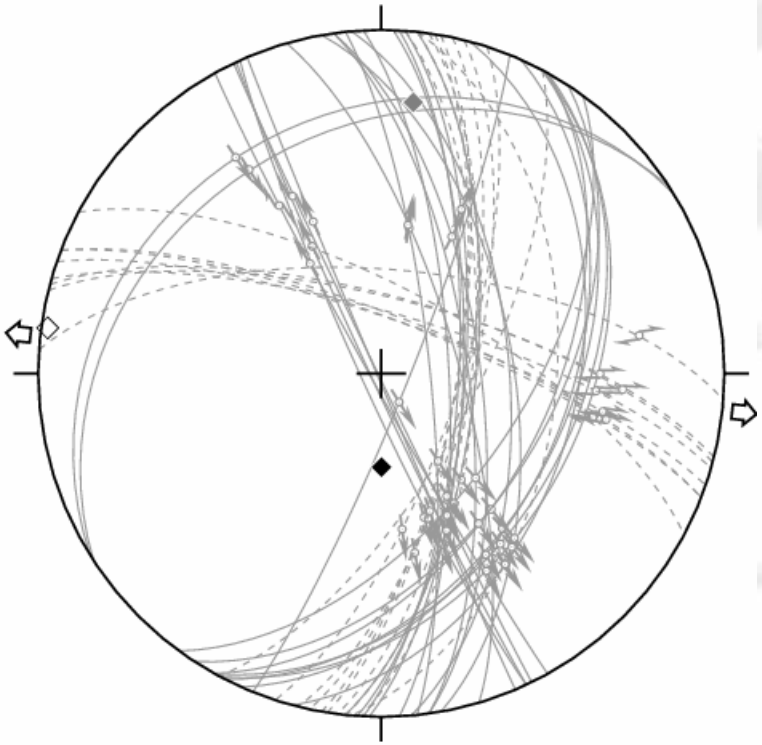


- Labeling option can help to **identify** data one by one;
- Labeling of large number of data is not recommended because the possible **overlapping**.

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

GRAYSCALE IMAGE





⬅ Same data set with RGB and grayscale output. ➡

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

BACKGROUND

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).

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

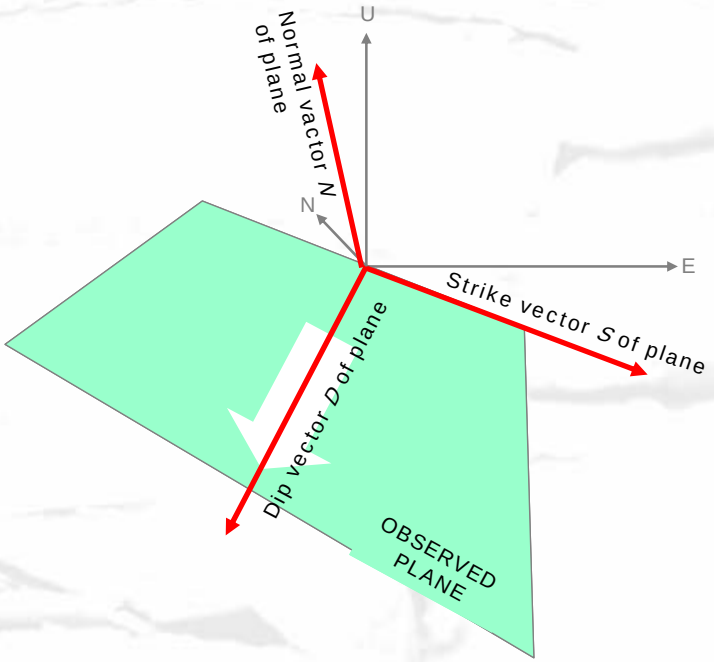
- D_i vector (dip vector) is a unit vector **parallel to the dip of the plane**, with Z coordinate ≥ 0 (in the case of overturned beds as well). Computation methodology of dip vector from dip direction and dip angle data is the following:

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

- 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.



COORDINATE SYSTEM AND VARIABLES I. – DC, NC, SC AND SV 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 referring 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:

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

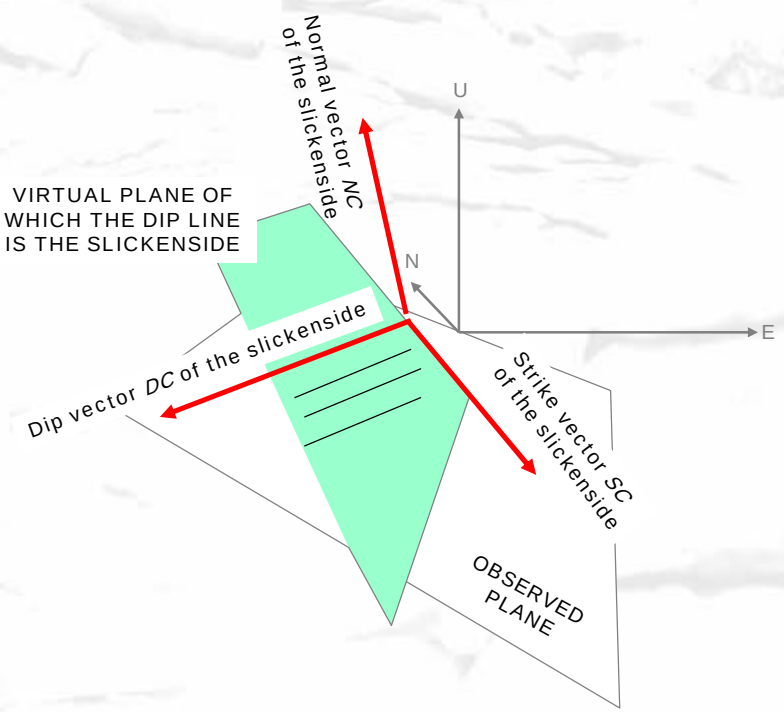
- NC_i unit vector is the **c plane normal**, or – in the case of slickensides – **normal vector of a plane of which DC_i vector the dip vector is**, with Z coordinate ≤ 0. Computation methodology of dip vector from dip direction and dip angle data is the following:

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

- 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.



- **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

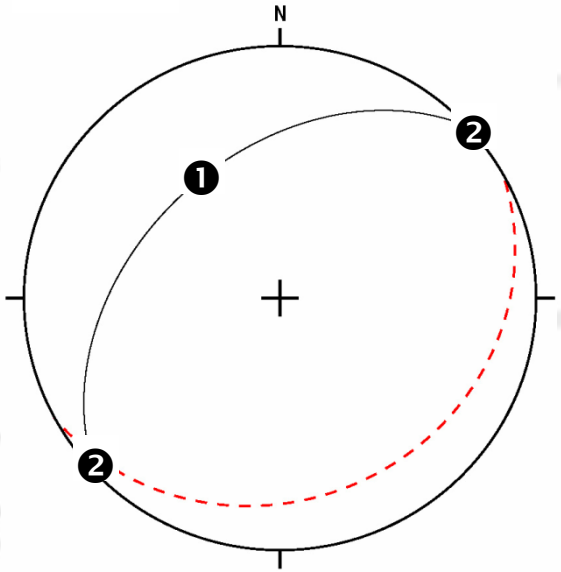
- To calculate x and y coordinates on the Schmidt stereonet , use the following equations:

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

WULFF-NET

- Wulff net point coordinates are the following:

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

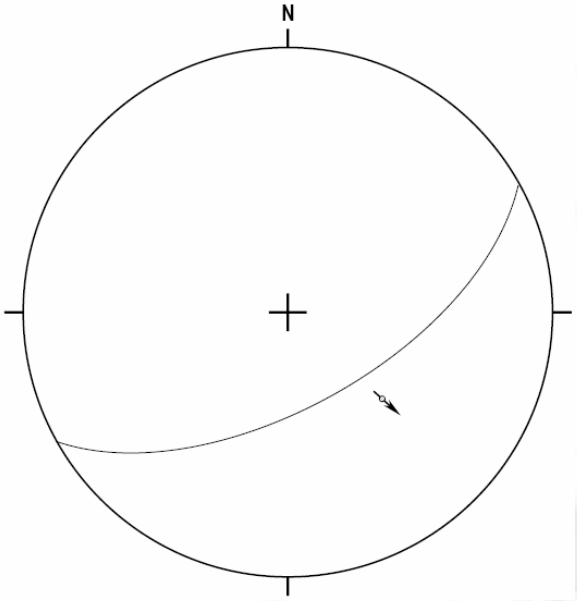


STRIAE MISFIT AND CORRECTION II. – MISFIT ANGLE

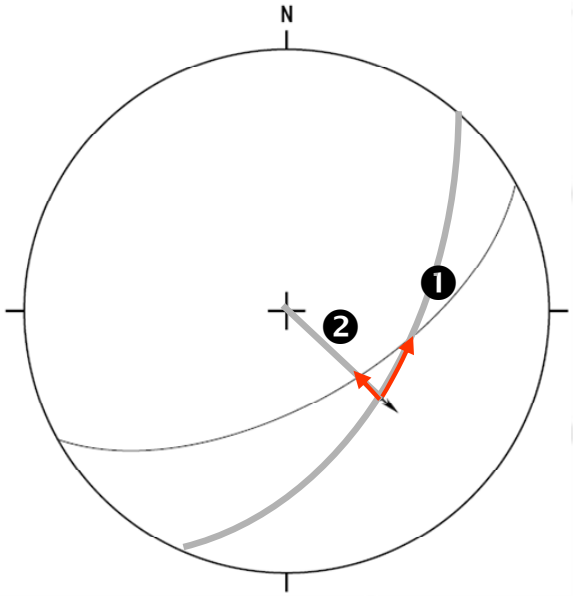
- In ideal case, the measured slickenside vector is on the fault plane surface, and dip vector DC_i of slickenside is **perpendicular** to the plane normal vector N_i.
- In the case of measurement as 'pitch', slickenside lineation is **definitely** on the fault plane because measurement methodology.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



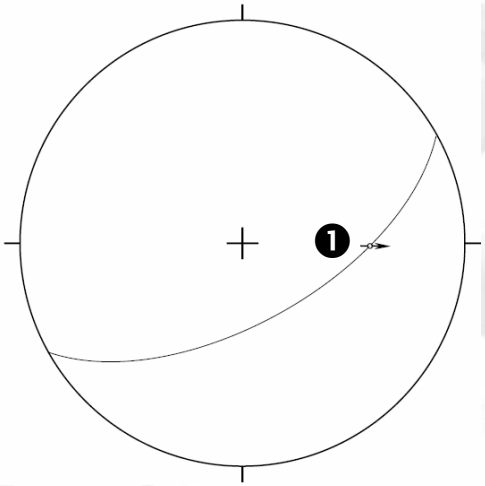
Possible striae misfit corrections ⬆

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

$$DC_i = SC_i \otimes N_i$$

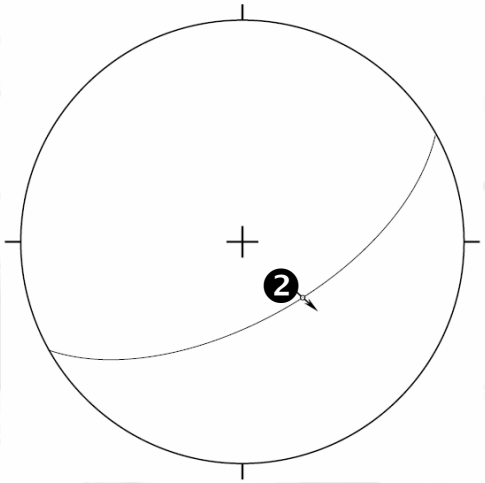


Result of dip direction correction

- 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;

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;

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

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

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

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

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:

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

- **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

AVERAGE CALCULATION AND SINGULARITY

- In the case of a **single** data set, the data set itself is the average;
- If two data forms the entire data set, **mathematical average** of their N vectors is the average. If N_1 is the opposite of N_2, no average is calculated (would be a null vector);
- **Bingham** directional statistics is used to calculate data average for data sets with more than 2 records. If the input data set is symmetrical, the final directional tensor will be singular, with a really small determinant more or less equal to zero.

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

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

```
33/70 normal
34/71 normal
35/72 normal
33/70 overturned
34/71 overturned
35/72 overturned
```

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

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

INVERSION METHODOLOGIES I. – REGRESSION AFTER SPANG (1972)

- Define angle a 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:

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

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

INVERSION METHODOLOGIES I. – 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.

- 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 s_{11}, s_{22}, s_{33}, s_{12}, s_{23} and s_{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 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 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 p_1 – p_6**) will be the members of the stress tensor:

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

INVERSION METHODOLOGIES IV. – REGRESSION AFTER SHAN ET AL. (2003)

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

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

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

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

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

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

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

- 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:

$$\mathrm{M} = \begin{bmatrix} \mathrm{M}_1^{\mathrm{T}} \\ \vdots \\ \mathrm{M}_i^{\mathrm{T}} \\ \vdots \\ \mathrm{M}_n^{\mathrm{T}} \end{bmatrix}, \mathrm{B} = \begin{bmatrix} \mathrm{B}_1^{\mathrm{T}} \\ \vdots \\ \mathrm{B}_i^{\mathrm{T}} \\ \vdots \\ \mathrm{B}_n^{\mathrm{T}} \end{bmatrix},$$

- 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. 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 $s_{11} + s_{22} + s_{33} = 0$ and $s_{11}^2 + s_{22}^2 + s_{33}^2 = 3/2$; the stress tensor below satisfies these criteria;

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

- **Length of vector** 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**.

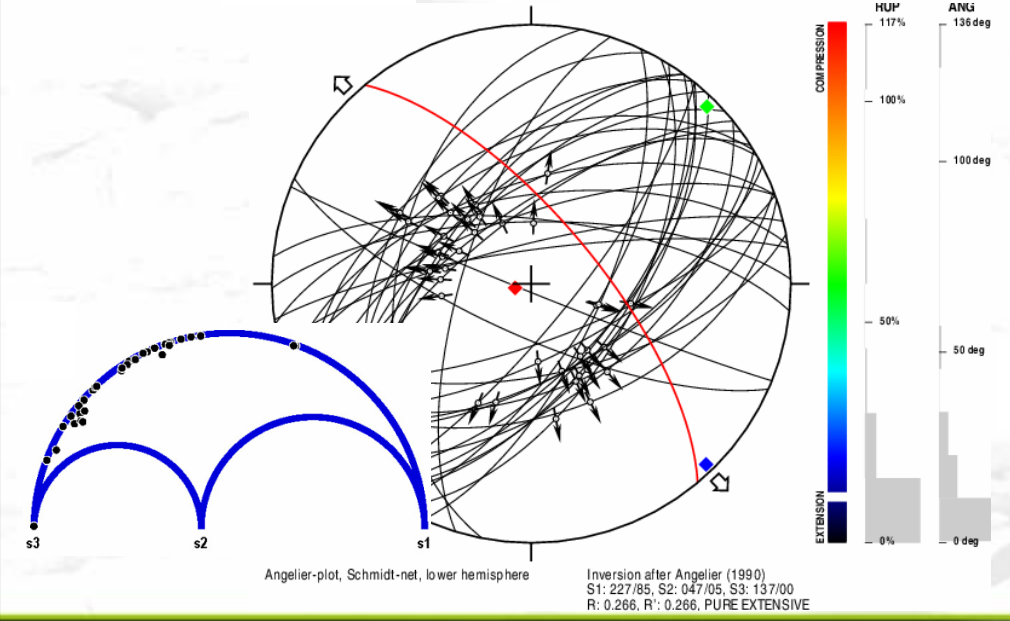
MOSTAFA (2005)

- 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 length;
- 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.

INVERSION METHODOLOGIES VII. – ITERATIVE INVERSION

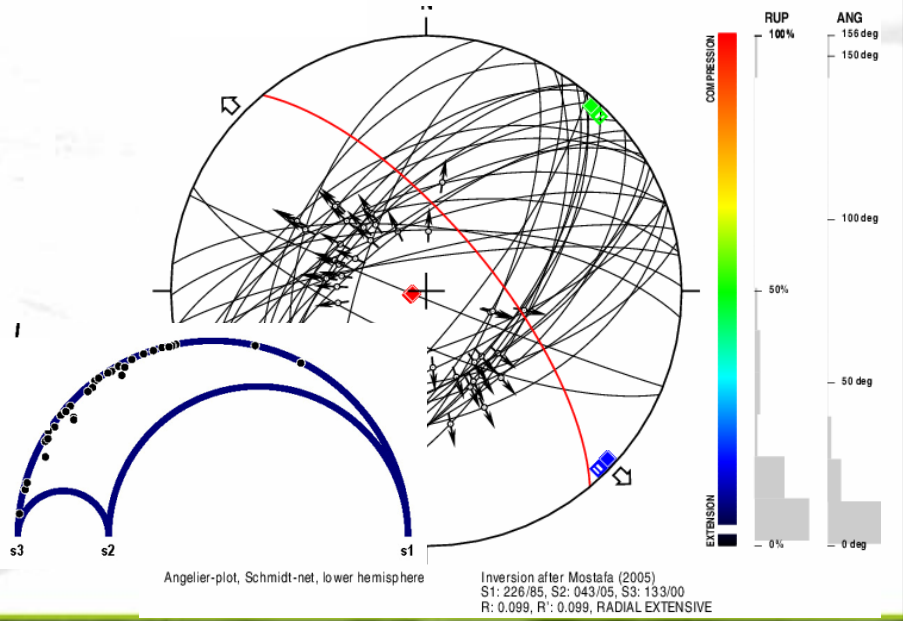
- One of the key problems of inversion methodologies is the measured shear vector (SV_i) length calculation.
- Because basic inversion equations are nonlinear in the sense of shear vector length, either 1) assumption on the original vector length is used (λ=1 in the case of Michael 1984 and $\lambda = \sqrt{3}/2$ was used by Angelier 1990), or 2) iteration in the shear vector length.
- Using Angelier 1990 methodology Mostafa (2005) proposed the following iteration 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 |t|,
  - use λ = |t| for the next iteration step.
- Using Michael's (1984) methodology, is it possible to use the same iteration methodology with λ=1 start criteria.

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



Angelier-plot, Schmidt-net, lower hemisphere

Inversion after Angelier (1990)
S1: 227/85, S2: 047/05, S3: 137/00
R: 0.266, R': 0.266, PURE EXTENSIVE



Angelier-plot, Schmidt-net, lower hemisphere

Inversion after Mostafa (2005)
S1: 226/85, S2: 043/05, S3: 133/00
R: 0.099, R': 0.099, RADIAL EXTENSIVE

INVERSION METHODOLOGIES VIII. – BRUTE FORCE INVERSION

GENERAL METHODOLOGY

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

STRESS TENSORS

- Use **Kaalsbeek counting net** to generate a series of σ_3 directions (331 points).
- **Rotate** σ_1 axes around σ_3 axis with 10 degrees steps (18 rotations, 0.0 – 170 degrees).
- **Calculate** σ_2 directions.
- Use **0.0 – 1.0 phi values** for the stress tensor geometry with 0.1 steps (11 different geometries).

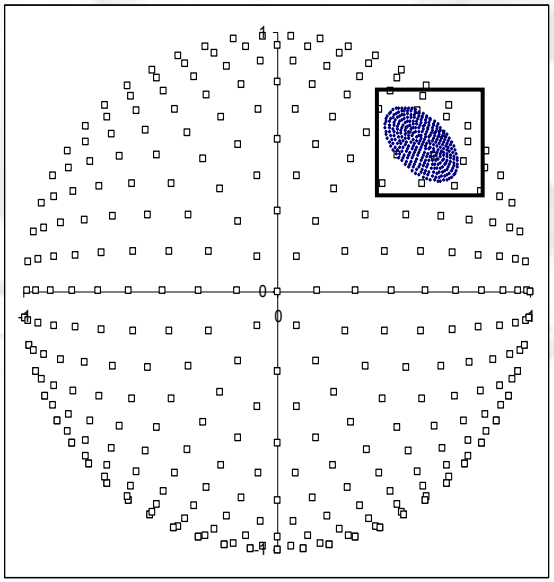
INITIAL ITERATION

- Calculate **resolved shear directions** on all fault planes; do altogether 331 x 18 x 11 = 65538 iterations.
- Calculate the **cumulative angular misfit** (ANG) between the observed and the resolved shear directions.
- Store stress tensor parameters for the **10 smallest misfit** values.

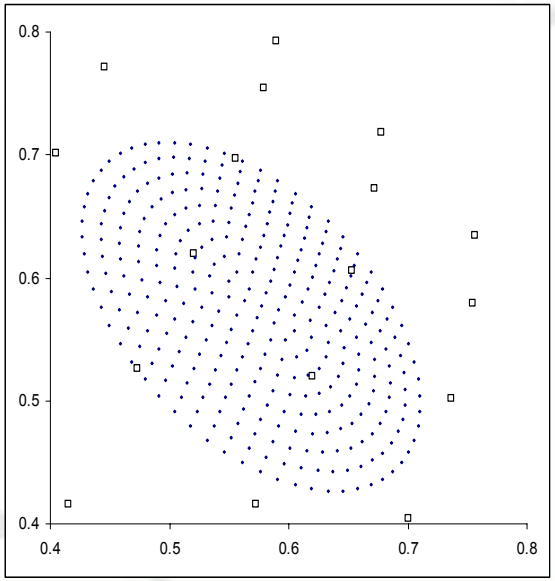
HIGH RESOLUTION ITERATION

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

➡ Kaalsbeek counting net to generate σ_3 directions



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



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.

BACKGROUND
STRESS VECTORS, ESTIMATORS I.
STRESS VECTOR, NORMAL AND SHEAR STRESS ON PLANE

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

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

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

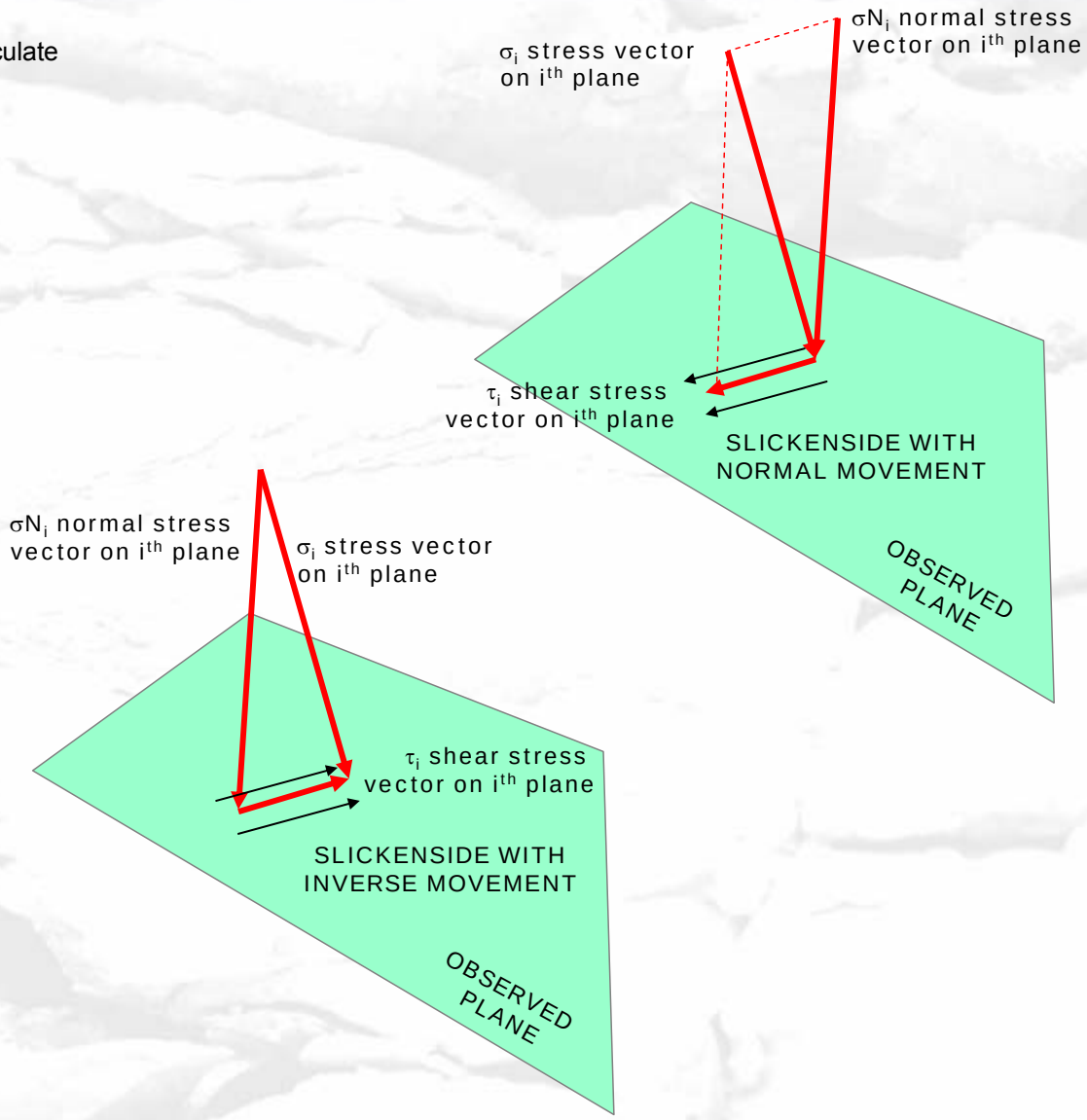
- **Normal stress** on the i[th] plane is the following:

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

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

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

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



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** length 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:

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

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

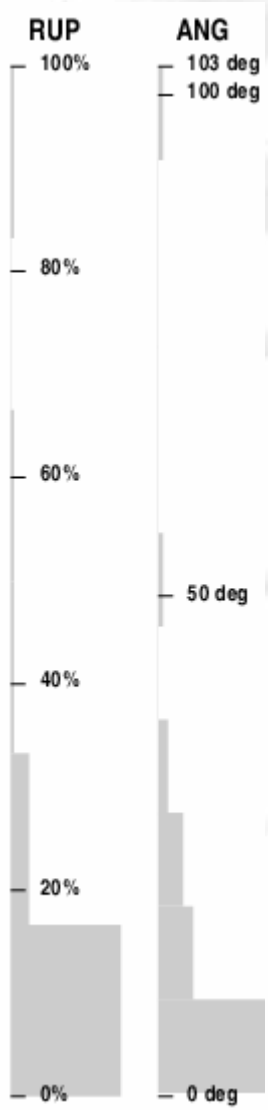
ESTIMATOR RUP

- 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 VISUALIZATION – MOHR-CIRCLE

- Because absolute stress magnitudes are **unknown**, Mohr circle parameters were **re-scaled to unit stress**;
  - $\sigma_1 = 1.0$,
  - $\sigma_2 = \varphi$, and
  - $\sigma_3 = 0.0$.

- Calculate **stress vector magnitude:**

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

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

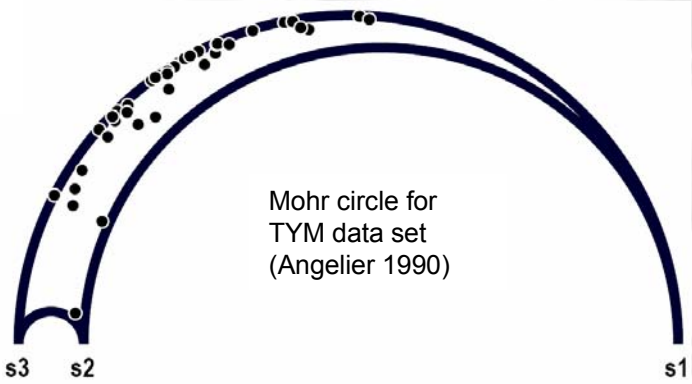
- **Normal stress value** will be computed on the following way:

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

- **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

TRIANGULAR GRID

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

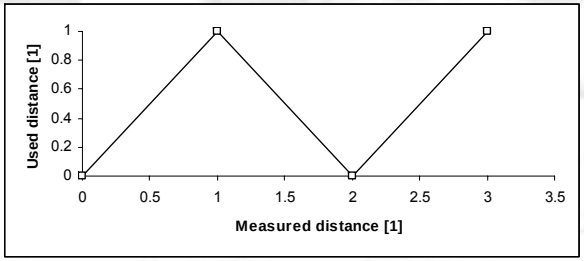
RECTANGULAR GRID

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

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

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

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



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

BINARY GRID

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

LINE SEGMENT PROCESSING

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

LINE PROCESSING

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

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