Characterizing fractures and their relation with the structural setting in 3D using novel photogrammetry tools

Bachelor project

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1. Abstract

The fracture patterns in an outcrop of the Alima anticline in central Tunusia is investigated. A 3D model of the outcrop is made in Photoscan. The fractures are digitized in 3D using OpenPlot software. OpenPlot can automatically calculate the orientation of every fracture. The length has to be calculated in Excel. Stereonet is used for further processing of the data. Gocad is used to calculate the fracture intensity of different areas of the outcrop.

There are two fracture sets in the outcrop, they are perpendicular to each other. One of the sets is perfectly vertical after back rotating, the other set has a dip angle of about 60 degrees after back rotating. Both sets consist of conjugate fractures with an angle of 40 – 50 degrees between the two systems. In large areas of the outcrop only one of the two conjugate systems is developed, so the conjugate fractures are not always visible. The fracture intensity can also show big differences throughout the outcrop, there are a few places with a much lower fracture intensity.

The software used in this project can cause some problems, which can result in deviations and errors in the data. The software actually is usable for 3D fracture modelling if the problems are known in advance and are taken into account.

2. Introduction

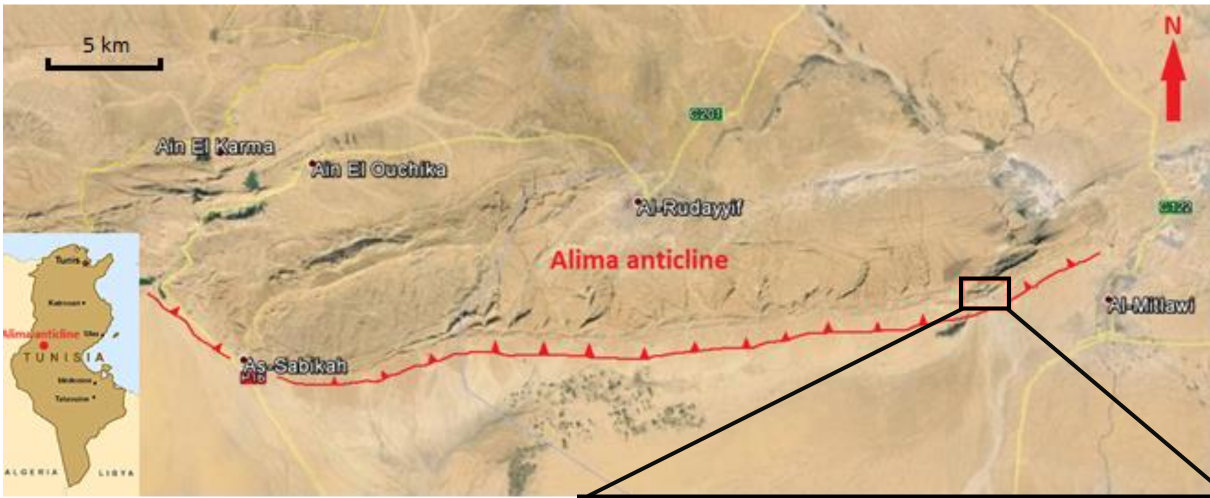
Oil and gas are two of the most important fossil fuels worldwide. All over the world people are searching for new and more efficient ways to get the oil and gas on the surface. Oil and gas are found in porous layers. They can flow around through the pores. Getting the oil and gas on the surface is a very complex process. A well is drilled into the layer containing oil or gas and it flows towards the well and to the surface. The flow through the porous rock is an essential part of the process and therefore it is very important to be able to predict the flow patterns in the layer. When the pores are connected, the oil can flow through the pores towards the well. In a fractured layer, the oil can also flow through the fractures. Usually the flow through the fractures is much larger than the flow through the pores. It is very important to determine the pattern of the fractures, because they contain most of the fluid flow.

It is mostly easy to determine the porosity of a layer. It can be calculated with a core sample or with the use of petrophysics. Determining the pattern of the fractures in the underground is very hard. Well logs can only give limited information about fractures. It is possible to determine the fracture density and orientation but it is impossible to get the fracture length. Fractures cannot be seen on seismics and using core samples is useless, because fractures are usually much longer than the samples. To get a good understanding of the fractures in a layer in the underground, it is best to look at a large area. This is not possible in the subsurface, so we have to look at formations with fractures at the surface and use this information to predict the fracture patterns in the subsurface.

In this paper we will look at the Kef Eddour formation in an outcrop in Central Tunisia. This outcrop is full of fractures that are very well visible at the surface. Normally such an outcrop will be analyzed in two dimensions, but in this paper we will try to map the fractures in 3D. OpenPlot software, Stereonet and Gocad will be used to make a 3D model of the outcrop. With this model the orientation of the fractures can be determined. First some information about regional geology of central Tunisia and the onset of the outcrop itself will be given. Second, all the software used during this project will be explained and the entire process of work we be discussed. We will look at the full process from creating the fracture planes to the data containing the orientation and length of each fracture. Also fracture intensity will be explained. In the next chapter the results will be presented. The presence of different fracture sets will be explained in multiple graphs and figures. We will also look at the accuracy of the model, how big is the deviation between the real outcrop and the model and how accurate are the fracture planes. A last the disadvantages of using the software during this project will be explained and some recommendations will be given.

3. Geology

The investigated outcrop is part of an anticline in central Tunisia. This anticline is part of the southern Tunisian Atlas which originated from the Atlas orogeny. During this orogeny the European and the African tectonic plates collided. The southern Tunisian Atlas is a foreland fold and thrust belt. It consists of several big ENE-WSW trending fold bend faults, such as Metlaoui, Chotts and Orbata. There have been two main periods of Atlas orogeny. The first one in the late Eocene has been mainly reconstituted in Algeria. The second orogeny spans from the Middle Miocene to the present [*Said, 2011*]. It is separated into two periods of contraction, the first period in the Serravalian-Tortonian resulted in thrust sheets in northern Tunisia and big folds in central/eastern Tunisia. The second period in the Post-Villafranchian resulted in the folding of the northern thrust sheets and the enlargement of the structures in central/eastern Tunisia [*Said, 2011*]. The largest deformation of the thrust faults in central Tunisia occurred in the Post-Villafranchian period [*Said, 2011*]. The folded structures in Central Tunisia are fault propagation folds. They have a steep southern limbs and a very gentle dipping northern limb.



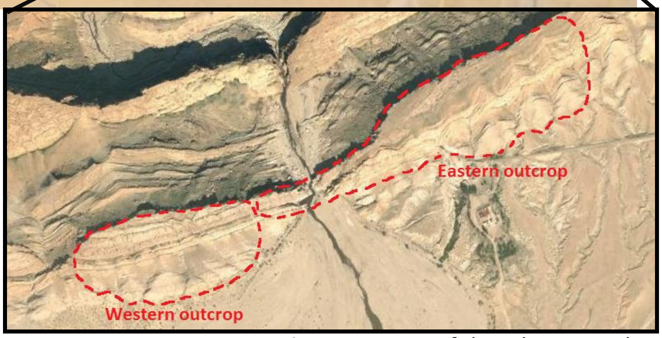


Figure 1: *map of the Alima anticline*

We are looking at the Alima anticline in central Tunisia. The Alima anticline is one in a series of en echelon folds that together form the Metlaoui range [*Riley, 2011*]. The main deformation of this fold range took place in the Post-Villafranchian. Close to the city Al-Mitlawi the southern limb of the Alima anticline forms a small extra fold. This causes that the Alima anticline is very tightly folded in this area [*Riley, 2011*]. The outcrop we are investigating is located on this tight fold and is displayed in the highlighted square in figure 1. The outcrop largely consists of rock from the Kef Eddour formation. This is a chalky and oyster rich limestone originated from the middle Eocene and is about 50 meter thick [*Riley, 2011*].

3.1 Outcrop

The outcrop investigated is located about 6 kilometers from city Al-Mitlawi in central Tunisia. It is part of the southern flank of the Alima anticline. The entire anticline is about 45 kilometers long. It has a gentle dipping northern flank and a steep southern flank. The anticline is a thrust fold and the associated fault is displayed in figure 1. The investigated outcrop is located in the black square in figure 1. The layers in the outcrop have the same dip as the outcrop surface. It is split into two parts, between them is a gorge that leads through the anticline. The western part is the best part of the outcrop. Almost this entire part is good enough to see fractures from the photos and it completely consists of rocks from the Kef Eddour formation. The bedding has a dip of about 60 degrees to the south. The orientation of the bedding is the same as the outcrop, so when you look at the outcrop you look at the top of the layer. The outcrop is approximately 350 meters wide and 90 meters high. The eastern part of the outcrop is much bigger than the western part. It is 650 meter wide and 130 meter high. There are two parts of the outcrop that are certainly part of the Kef Eddour formation. It is the part completely on the left at the entrance of the gorge and the part on the top of the outcrop, they are circled in yellow in figure 2. The area on the left is at ground level and is approximately 130 meter wide and 40 meter high. The orientation of the bedding is fairly steep, it dips to the south with a dip angle of about 80 degrees. We will call this part 1. The other part of the outcrop with the Kef Eddour formation is at the top in the middle. It is 170 meter wide and 30 meter high, we will call this part two. In this part of the outcrop, the bedding dips to the south with an orientation of about 65 degrees. This part will be called part 2.

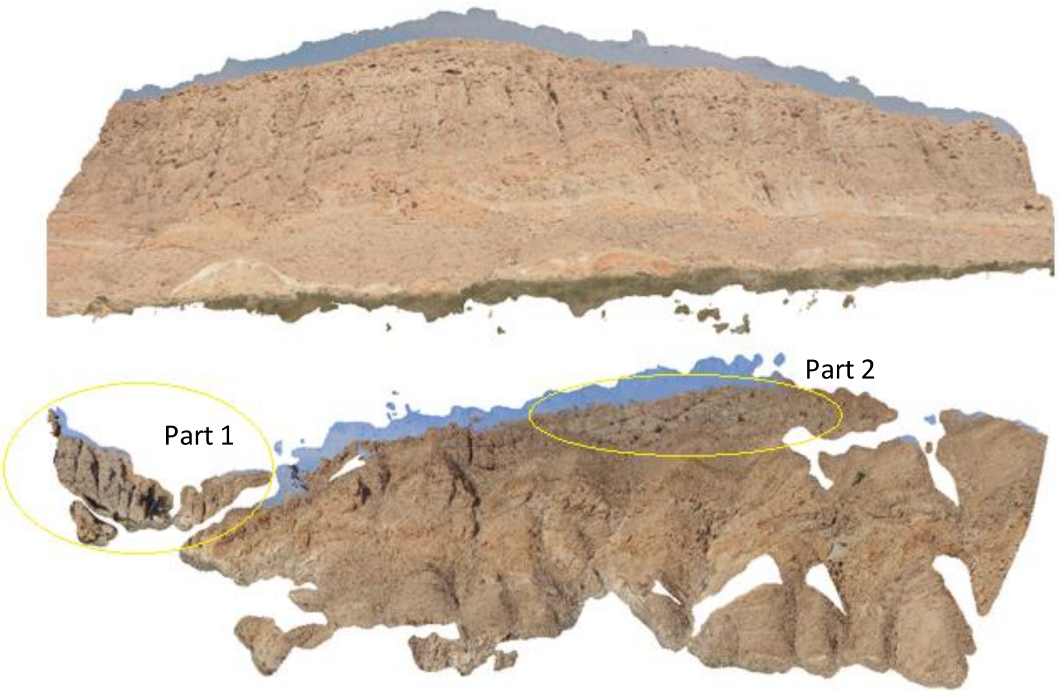


***Figure 2**: Top: the western outcrop. Bottom: the eastern outcrop.*

4. Methods

In this chapter the software that is used to collect and process the data will be explained. Every step of the process from the raw data to the results will be explained in detail. We want to interpret fractures in 3D, so first they must be digitized with OpenPlot software. After digitizing we want to know length and orientation, for which we use Stereonet and Excel. We also want to know the spacing, so for that we use Gocad. The outcrop consists of two different parts. These parts have a different model, so they must be processed separately. In this chapter, we will use the western part of the outcrop as an example to explain the steps.

4.1 Photoscan

Several pictures are taken from the outcrop in Tunisia. They are taken from ground level at different angles with respect to the outcrop. The pictures of the outcrop in Tunisia can be imported into the program Photoscan. This program can combine the pictures and form a 3D model of the outcrop. To make a 3D model, the program needs multiple photos from the same object from different angles. On every picture characteristic and recognizable objects are marked. The orientation and position of the pictures is known, so the pictures can be placed in a 3D space. The marked objects in the different pictures are combined and the position of the different object can be determined. Now the orientation of the pictures is known and a 3D model of the outcrop can be created. This 3D model consists of the complete structure with relief of the outcrop and it has the pictures draped on the outcrop surface. It is important that this is done well, because a wrong orientation of the outcrop surface can influence the results of the entire project. The model can be exported to the next software which is OpenPlot.

4.2 OpenPlot software

OpenPlot software is a program for structural data analysis. The software can display 3D geological models. These models can be analyzed with different tools. The software can perfectly be used to interpret fractures in 3D.

The 3D outcrop model of the Kef Eddour formation in Tunisia created in Photoscan can be imported into OpenPlot. The outcrop can be rotated in every desired direction and you can zoom into the outcrop surface until very close. A big advantage of OpenPlot is that the resolution of the pictures stays very high when you zoom into the model. This makes it perfect for finding fractures in the outcrop, because the smallest details can be seen. For this project the most important feature of the software is the option “Draw polyline”. With this option a 3D plane can be drawn into the 3D space of the model representing the fractures. The model is georeferenced, meaning that it is accurately positioned in real X, Y, Z coordinates. Based on that, OpenPlot can automatically calculate the fracture orientation of each plane.

A plane can be placed by selecting at least three points on the outcrop surface. The coordinates of these points are known so a plane can be placed through the points. When more than three points are selected the software makes a plane that best fits all the points. The more points on the fracture line are selected, the better is the approximation of the fracture plane. The fractures in the investigated formation cut through the outcrop. Due to weathering and erosion, the fracture line in the outcrop will not be as straight as a line anymore, but it will have some relief. Figure 3 shows how such a plane can be placed in the outcrop. At the left of the picture, the outcrop is displayed and it is clear that there are a few vertical fractures going through the formation. On pictures it is very hard to see at what angle the fracture dips into the rocks. However in OpenPlot the relief of the outcrop is displayed in 3D, so the dip angle and the dip

Figure 3: *a fracture plane*

direction of the fracture can be distinguished. On the right side of figure 3 the fracture plane is drawn in the model. The orientation of the plane can be seen clearly, something that would be almost impossible to determine from just a picture. The goal is to model every visible fracture with such a plane, so that the orientation of every fracture is known. From this information it will be possible to distinguish different fracture sets and a complete model can be made from the fractures in this formation. The dip angle and the dip direction are saved and can be exported as text files into, for instance, excel for further processing.

4.3 Creating fracture planes

The outcrop contains vertical and horizontal fractures. This is a first observation and will be used to assign fractures to the fracture sets in OpenPlot. It is not yet based on data, but in this stage of the project it is necessary to make a first separation of fractures, because OpenPlot cannot change anything afterwards. In figure 4 an example is shown of how the fractures are digitized. They are digitized in two sets. The yellow lines are the vertical fractures, we will call them **set A**. The green lines are the horizontal fractures, we will call them **set B**. In this stage of the project, the only information that can be used is the visual information of the pictures and the 3D model. Considering that most of the horizontal fractures have about the same length, most of them stop when they hit a vertical fracture and they seem to have the same orientation when looking at the pictures of the outcrop, the assumption is made that they are from the same set, namely set B. The fractures from set A are vertical, long and clearly visible. Some of these big vertical fractures leave a trench that is opened very wide. These big trenches can be originated due to erosion or weathering. The large amount of relief makes it fairly easy to distinguish the orientation of the fracture planes. The most horizontal fractures are smaller and do not have as much relief as the vertical fractures, so the horizontal fractures are much harder to digitize in OpenPlot software. Sometimes these fractures do

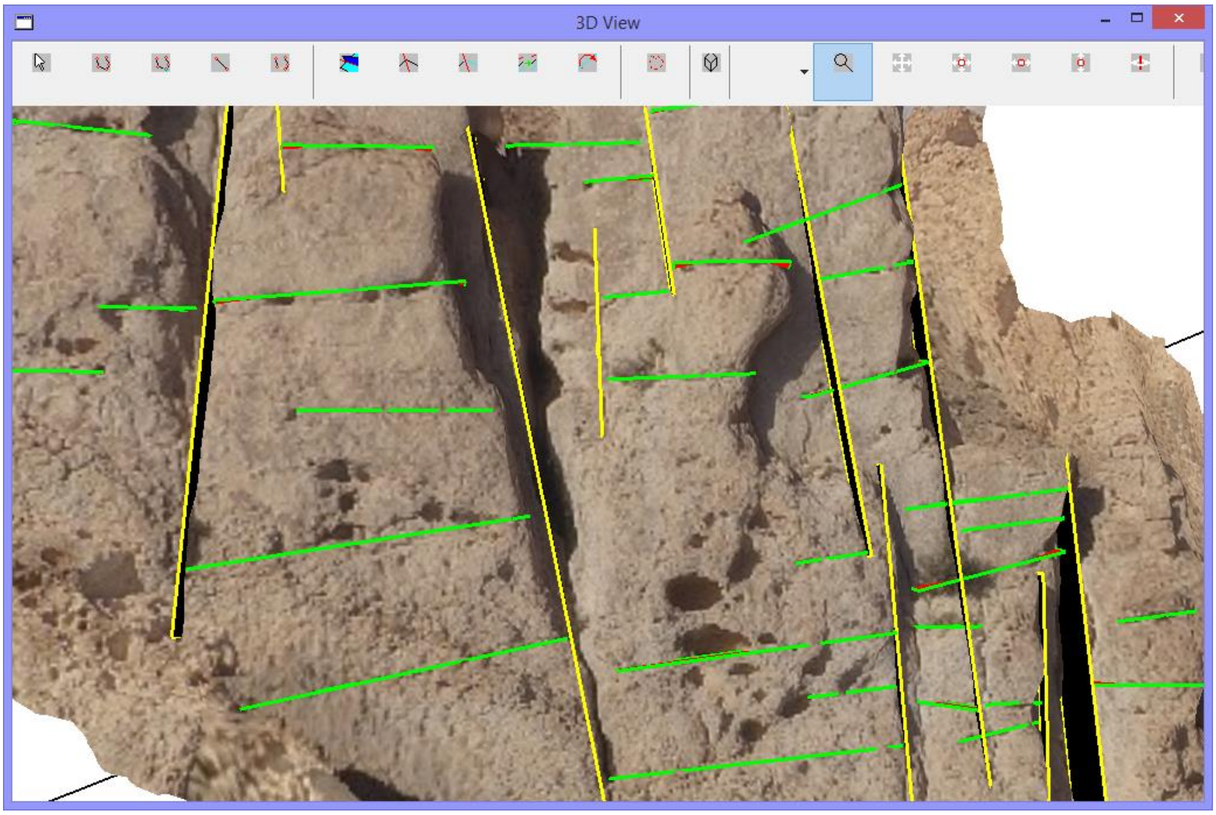


Figure 4: *OpenPlot*

not have relief at all and in the 3D model they can only be distinguished as a small black line on the outcrop.

The length of the fractures is easiest to determine. It can also be seen on pictures that give a 2D image of the outcrop. In reality it is the intersection between the fracture and the bedding, so we do not know the shape of the fracture. The fractures from set B are not deeply eroded and they do not have much relief as can be seen in figure 4. However there are a few fractures that do have some relief. Some of them continue through a trench, so an orientation can be specified. There are around 10 - 15 of these fractures in the western outcrop. This is not much, but the orientation of these horizontal fractures can be chosen as an example for the ones for which it was impossible to find an orientation. So most of the fractures from set B for which it was hard to distinguish the orientation have gotten the same orientation as the 10 – 15 fractures with the clearest orientation. Of course the uncertainty will be large when using this method, but it is the only way to model all the fractures in the software. The orientations will not deviate extremely much from the real value. The error of the dip angle of the horizontal fractures is estimated to be at maximum about 30 degrees. In a later stage, we will look deeper into the data and distinguish the different fracture sets with more certainty. We will also look at the uncertainty of the data. Moreover, the disadvantages of this method and the software will be discussed more specific.

4.4 Fracture length

OpenPlot software does not calculate the length of the fractures automatically, so the lengths have to be calculated in a different program. It can best be done in Excel. The length we calculate are parallel to the bedding. The data from OpenPlot can be saved in a text file. This text file contains the dip angle, the azimuth and the coordinates of the corners of the fracture planes. The text file can be imported into Excel and the data can be processed. Some changes in the data have to be made before they are ready to use. The azimuth values have to be converted to dip direction values, so 90 degrees has to be added up to the data. There must be a correction when the dip direction gets a value higher than 360 degrees.

The length of the fractures can be determined by using the coordinates of the corner of the fracture planes. These coordinates are displayed with an x, y and z-coordinate. Using the following formula the distance in 3D space can be calculated between point 1 and point 2.

$$L_{1-2} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$

In figure 5 there is a plane that represents a fracture. When the distance 1-2 would be completely parallel to the bedding, the length of the fracture is the distance from point 1 to point 2, but usually the plane is tilted a little bit. When the plane is tilted to its maximum, the distance 2-4 is parallel to the bedding. This depends on the amount of relief and what points are chosen on the fracture in OpenPlot. The real distance of the fracture will be between the

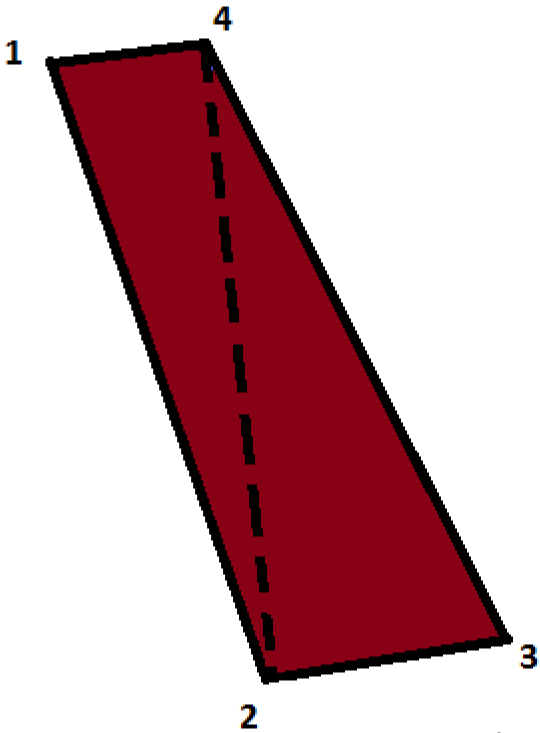
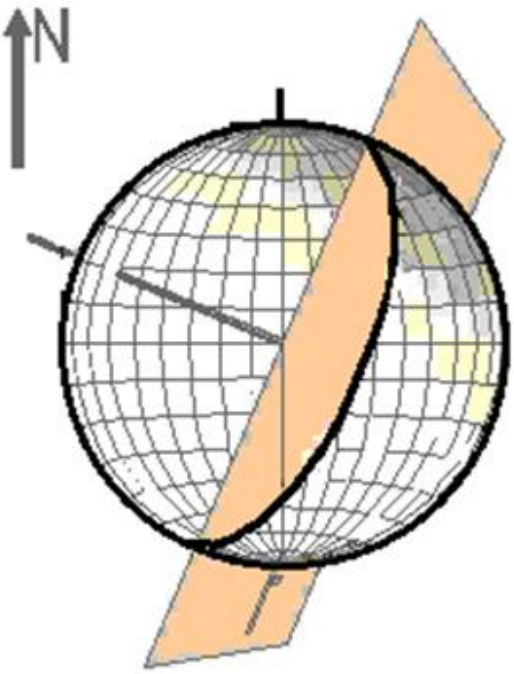


Figure 5: *fracture plane*

distances of 1-2 and 2-4 in. We approximate the real length of the fracture to just take the average between the lengths 1-2 and 2-4. This is accurate enough, because the distance 1-4 is mostly much smaller than the distance 1-2. The deviation can be from a few millimeters to 50 centimeters. This sounds like a lot but the big errors occur only at the largest fractures. Percentage wise, the deviation will usually be under 1% with some outliers to a maximum of 5%.

4.5 Stereonet

Stereonet is a program in which three-dimensional planes with a dip angle and a dip direction can be displayed in a stereonet. The planes can be edited and analyzed in every possible way. The stereonet is actually the underside of a sphere. All the planes go through the center of the sphere and they cut through the underside of the sphere, this is shown in figure 6. The left image shows a 3D plane that cuts through the underside of a sphere. This gives the cutting line shown in the right image of figure 6. The pole is the point where the line perpendicular to the plane and through the center of the sphere cuts the sphere.



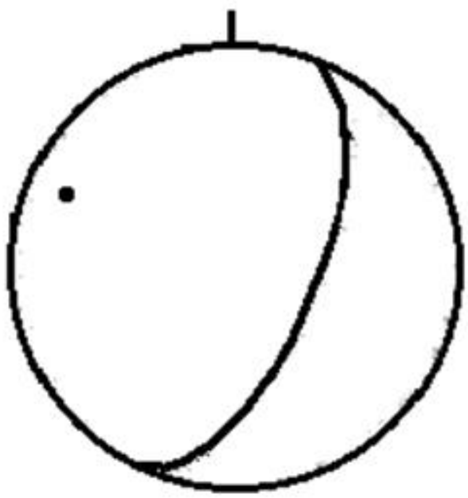


Figure 6: *stereonet*

The program stereonet can create arcs and poles from the data generated by OpenPlot. All the fractures will be displayed as an arc with a pole. The program can be used to analyze in detail the orientation distribution and it can identify different orientation sets. Every set of fracture planes can be rotated in every wished direction. The program also can determine angles between different planes.

4.6 Back rotated data

As explained before in the chapter about the geology, the outcrop is part of an anticline. The bedding has an average dip of about 60 – 70 degrees towards the south. Fractures that are perpendicular to the bedding may have already been formed before folding, when the layers were still horizontal, so it is interesting to know what the orientation of the fracture sets is with respect to the orientation of the bedding. This can be calculated by back rotating the bedding to the horizontal. The bedding has the same orientation as the outcrop surface, so we can just use the orientation of the outcrop for the back rotating of the fractures. The orientation of the outcrop can be determined in OpenPlot by just selecting points on the entire outcrop. OpenPlot makes a plane through these point which represents the average orientation of the outcrop. This has to be done separately for the western and eastern part of the outcrop, because they have a slightly different orientation. All the fractures have to be rotated with the same angle as the bedding. The back rotating can be done by the program Stereonet.

4.7 Gocad

Gocad is a multifunctional software for seismic, geological and reservoir modelling and much more. It is very useful for processing the data from OpenPlot software. OpenPlot is the best software for creating the fracture planes, but after that it cannot do much more with the data. For further processing Gocad is needed. The main reason we will be using Gocad is calculating the spacing. Different parts of the outcrop can be separated, so differences in spacing in the outcrop itself can be found. Another benefit of Gocad is that it can display the statistics in a very clear way. The length distribution of the different fracture sets can be displayed in graphs and histograms.

4.8 Fracture intensity

The orientation and the length of the fracture can describe exactly how the fracture is located in the outcrop. The next step is looking at the relation between the different fractures. The most important relation between the fractures is the fracture spacing. However, it makes a big difference whether the fractures are 10 meter long or only one meter long. Spacing won't make a difference between these two cases, but in terms of fluid flow they are very different. It can cause inaccurate results when only the spacing is calculated. That is why we look at the fracture intensity instead of the spacing.

The fracture intensity is the length of fractures per area of rock. This way of approach takes the length of fractures on a 2D surface into account, so it gives a value with much more significance. The best way to calculate the fracture intensity is by using Gocad. The 3D model with all the fractures can be imported into Gocad and displayed as a surface. It is possible to digitize all the intersections between the fractures and the outcrop surface. The area of interest has to be chosen. The length of all the fractures in this area can be automatically calculated by Gocad. The fracture intensity can be calculated to just divide the area by the length of the fractures in this area.

5. <u>Results</u>

The two outcrops that have been analyzed consist of a western and an eastern part. In between is a gorge where you can walk through the anticline. The two parts of the outcrop have a different model. Every result will be split between the two parts, so there will allways be a result for the western and the eastern part. In the end a total result will be given.

5.1 Western outcrop

The part of the outcrop that could be used to analyze the fractures is displayed in figure 7. A difference has been made between two different fracture sets. In figure 7 the yellow fractures belong to set A and the green fractures belong to set B. The difference between the two sets in figure 7 is made with the bare eye in OpenPlot. Later on we will look deeper into the different sets and look more specific to the orientation and length differences. An observation that can be made from figure 7 is that the fractures from set B often stop when they meet a fracture from set A. There is not a single fracture from set A that stops when it meets a fracture from set B. This could mean that set A is formed earlier than set B. Another presumption that can be made is the presence of conjugate fractures. Conjugate fractures are fractures that intersect with each other under angles significantly less than 90 degrees. They are very important for fluid flow, because the more intersections the more fluid flow can take place. Perpendicular fractures can only transport fluid in one direction, but conjugate fractures can transport fluid in two directions due to the intersections. The fractures from set A in the top left part of figure 7 show evidence of conjugate fractures. They are under an angle of about 40 – 50 degrees with each other.

A total of 438 fractures are mapped in the western outcrop. 146 of them are from set A, set B has 292 fractures. The dip angle and the dip direction for every fracture are plotted against each other in graph 1. The dip direction is plotted with the south in the middle. The dots on the left are fractures that dip towards the west and the dots on the right are fractures that dip towards the east. In this graph you can see the different fracture sets. Now we can really subdivide the fractures into two sets based on data. There are clearly three groups of dots in graph 1. The fractures from set B have a low dip angle and a very wide range of dip directions. This is because a very small deviation in the orientation of a fairly horizontal fracture can easily give a big change in the dip direction. The fractures from set A are much more vertical, so they do not have this problem. These fractures have a much smaller range of dip directions. They are split into two groups that have an opposite dip direction. Set A consists of fractures that dip towards the east and fractures that dip towards the west. This is another proof of conjugate fractures.

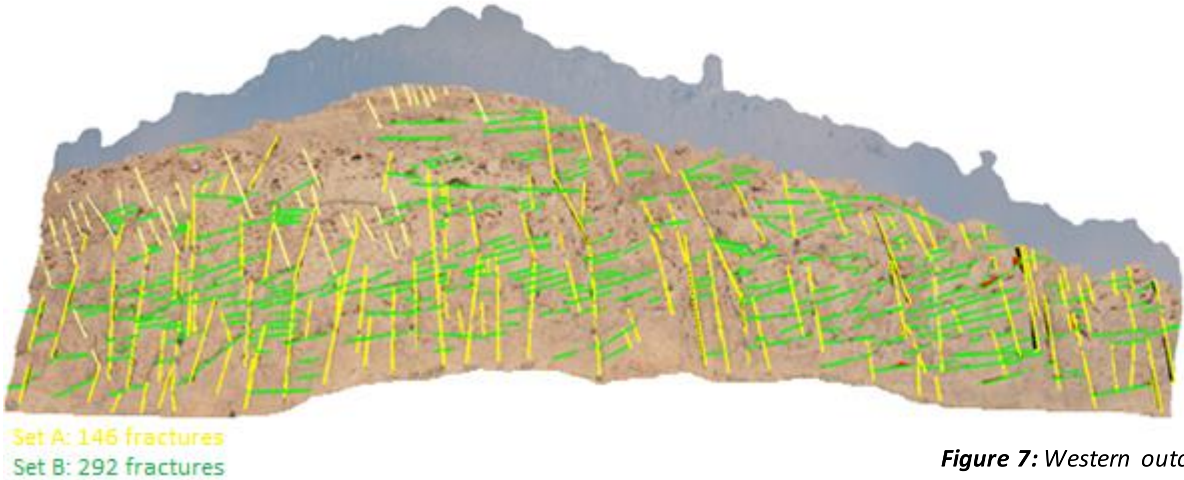
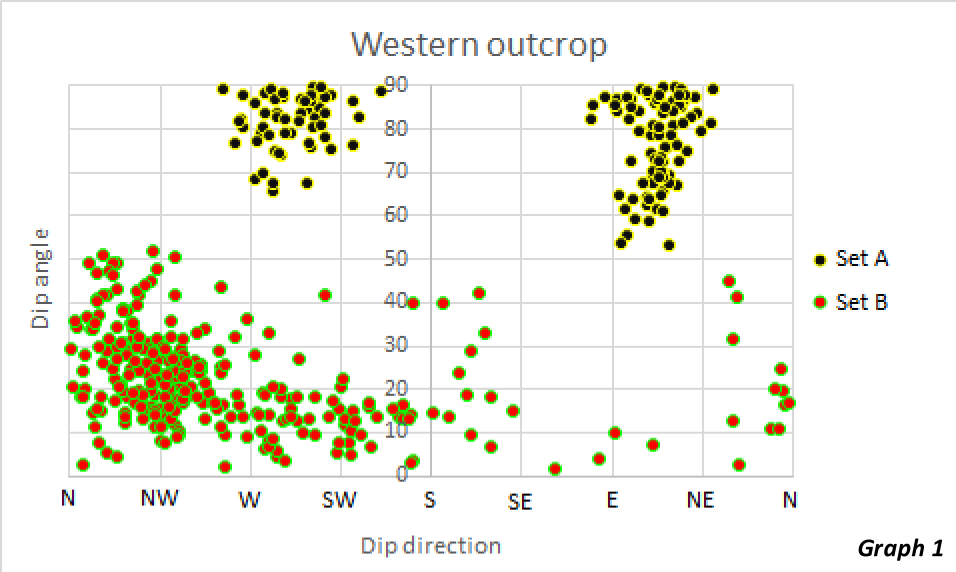


Figure 7: *Western outcrop*



Graph 1

The data in graph 1 can also be visually displayed in a stereonet. This makes it clearer and easier to manipulate. In figure 8 are all the fractures of the western part of the outcrop. The red dots are the poles from the fractures of set B and the black dots are poles from the fractures of set A. In the stereonet the two fracture sets can easily be distinguished. The blue dot is the pole of the bedding. The bedding in this part of the outcrop has an orientation of 162/52. We can back rotate the bedding back to the horizontal to see what the orientation of the fractures was before folding. These results are displayed in the right part of figure 8. The pole of the bedding is completely vertical now, so the bedding is horizontal. It is obvious that the vertical fractures do not change much, because they rotate in the direction of their strike. The fractures from set B rotate toward the vertical and get an orientation of about 340/60.

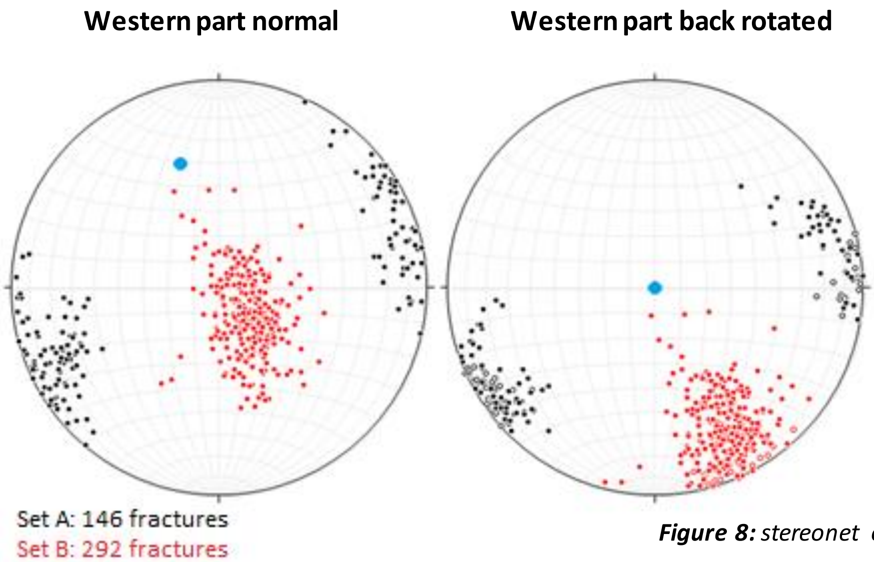
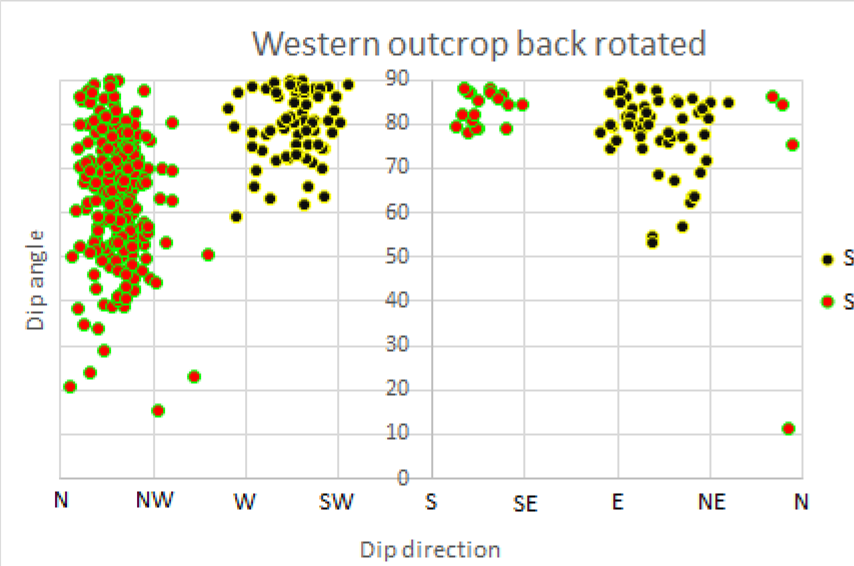


Figure 8: *stereonet of western outcrop*

The unfolded data are also plotted in graph 2. It is clear that the dip direction and dip angle of the fractures from set A does not change much compared to graph 1. They still show two groups dipping at the opposite direction with a difference of about 40 – 50 degrees. The point cloud of the fractures from set B does change. It has still a pretty big range of dip angles, but now the dip direction is concentrated around N – NW. The big difference in dip angles is probably due to the deviation of the fracture planes in OpenPlot. The average dip of the back rotated fractures from set B is about 65 degrees. This is not perfectly vertical like the fractures from set A. It could mean that they are not formed before folding, but after a period of deformation.



Graph 2

5.2 Eastern outcrop

The eastern part of the outcrop is displayed in figure 9. Most parts of this outcrop have a much lower resolution, which makes it harder to identify different fractures. The pictures taken from the outcrop have a better resolution and are really needed to determine where to put a fracture plane in OpenPlot software. The outcrop has two areas that give very clean data and are certainly part of the Kef Eddour formation. The rest of the outcrop does contain fractures, but it is almost impossible to determine a reliable orientation. We will focus on the two clean areas highlighted in figure 9. These area are part 1 and part 2. Part 1 contains 86 fractures. The bedding in this outcrop is fairly steep and has an orientation of 143/80. Part 2 contains 29 good fractures. At this part of the outcrop, the bedding has an orientation of 133/67. In figure 9 the yellow fractures are from set A and the green fractures are from set B.

It is striking that there are some differences between part 1 and part 2 in this outcrop. Part 1 clearly shows that the fractures from set B are smaller than the fractures from set A. Fractures from set B stop when they meet a fracture from set A, just as could be seen in the western outcrop. In part 2, this is much less the case, but another phenomenon can be noticed. The fractures from set B form, in contrast to part 1, a very clear conjugate pattern. The fractures from set A form only a very small conjugate pattern, not nearly as obvious as in the western part of the outcrop.

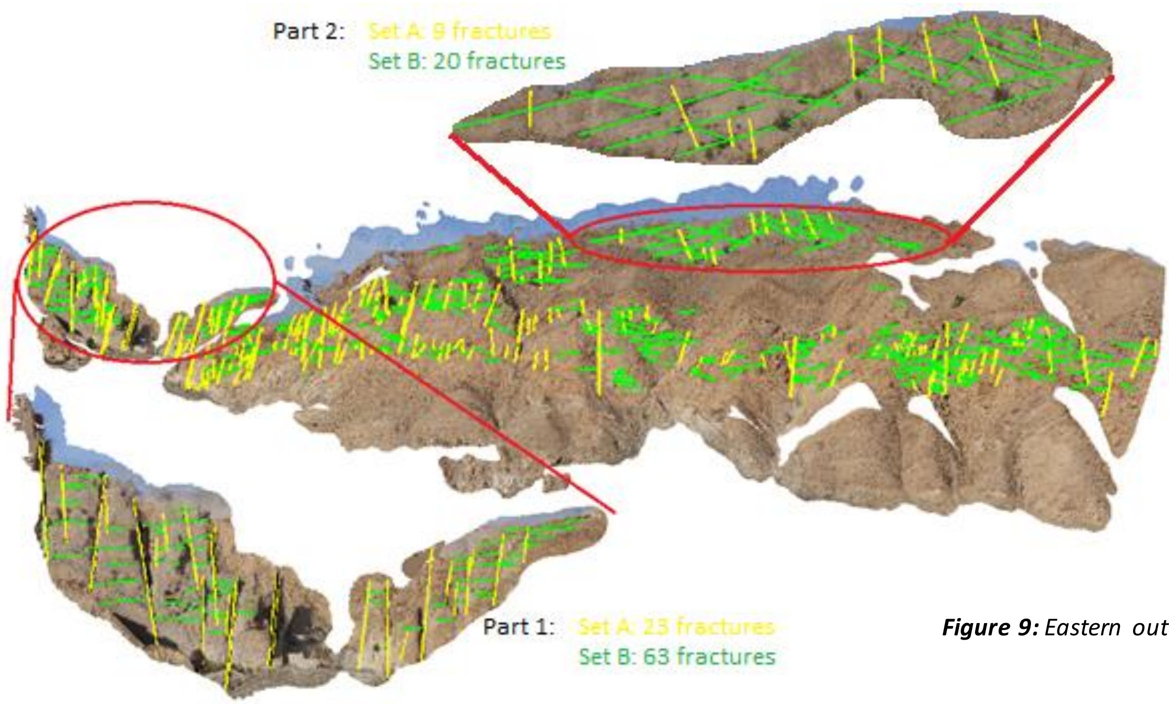
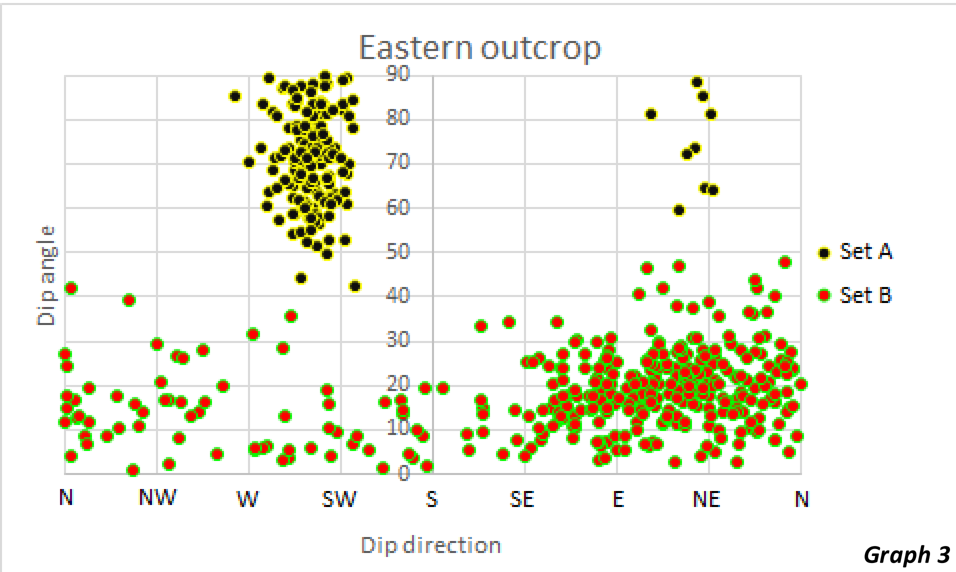
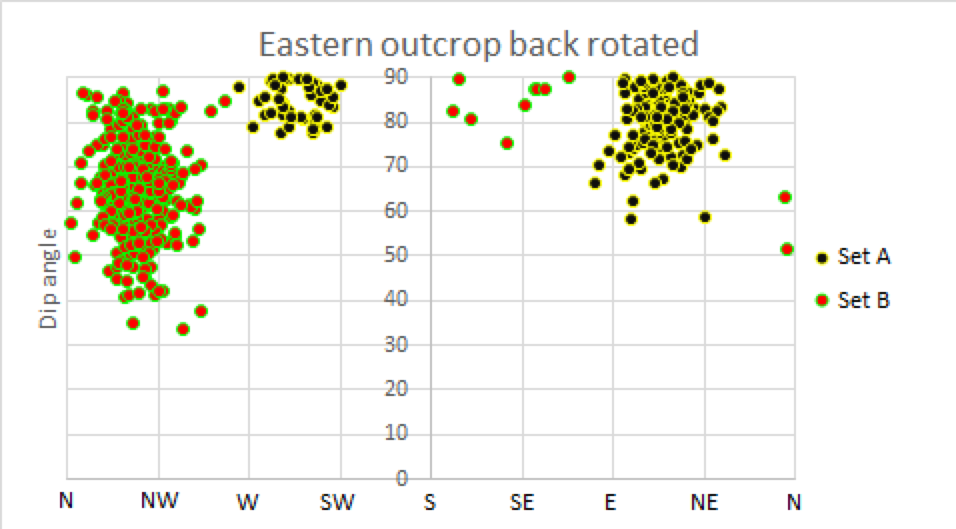


Figure 9: *Eastern outcrop*

The eastern outcrop consists of the same two fracture sets as the western outcrop. The dip direction-dip angle plot in graph 3 also gives a similar result as the western part of the outcrop. The only difference is that much more of the fractures from set A are dipping towards the east. The horizontal fractures have a dip of about 0 to 40 degrees and a very wide range of strike values. After back rotating, the big range in dip angles stays, but the strike values concentrate around a value of about 60 degrees, this is plotted in graph 4. The vertical back rotated fractures have a dip angle of about 70 to 90 degrees and a dip direction towards the W – SW and another group towards the E – NE. After back rotation the two different groups with an opposite dip direction are much clearer than before back rotating. This could be caused by the large differences in the dip angle of the bedding in the eastern outcrop, the western bedding has almost the same orientation in the entire outcrop. The difference in dip angle between part 1 and part 2 is about 25 degrees, so some fractures will be rotated a little bit too much. To solve this problem, in the next paragraph we will look at smaller datasets.



Graph 3



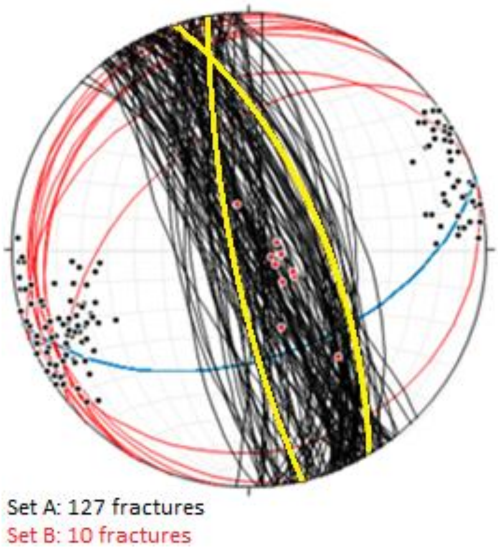
Graph 4

5.3 Smaller datasets

In the previous graphs, we looked at the entire dataset of the eastern and western outcrops. These big datasets contain all the fractures, so also the fractures that are not very clear. For a better and cleaner result, it is better to just look at a few small parts of the dataset. These small parts contain only the fractures for which it can be said with big certainty that they have the right orientation. We will look at the results in stereonet. In figures 10 is the stereonet with only the fractures from the western outcrop digitized with high certainty. The black lines and black poles are fractures from set A and the red lines and red poles are fractures from set B, this is the same in all the following stereonets. The blue line is the orientation of the bedding. The left picture shows the fractures as they are originally digitized. The right picture shows the back rotated fractures, the bedding in this stereonet is completely horizontal. The fractures from set B in the western outcrop are very hard to model. Mostly it is almost impossible to determine the dip angle of the fracture plane s. This is why there are so little red fractures left in figure 13. The fractures from set A have much more relief, so it can be said with certainty that the orientation they have in the stereonet figures is the right orientation.

The results in figures 10, 11 and 12 show some differences. The fractures from set B in part 2 of the eastern outcrop show really convincing proof of conjugate fractures. After back rotating, one system has a strike of about 30 degrees and the other system has a strike of about 75 degrees. This is shown in figure 12. There is an angle of 45 degrees between the two conjugate fracture systems. The intersections between the two systems are nearly vertical. Part 1 of the eastern outcrop does not show conjugate fractures at all (figure 11). It is possible that at some places of the outcrop only one of the two systems of the conjugate fractures is developed. In the back rotated stereonet in figure 11, the fractures from set B have a strike of about 70 degrees. This corresponds to one of the conjugate systems in part 2, so maybe the other system is not developed in part 1 of the eastern outcrop. The back rotated stereonet from the western outcrop shows a set with a strike of about 65 degrees (figure 10). There are only a few fractures from set B in this stereonet, so the error will be much bigger, but it looks like an orientation close to one of the conjugate fracture systems in the eastern outcrop. It proves that the fractures from set B are actually conjugate fractures, but that both sets are not developed everywhere in the formation.

Western outcrop **Western outcrop back rotated**



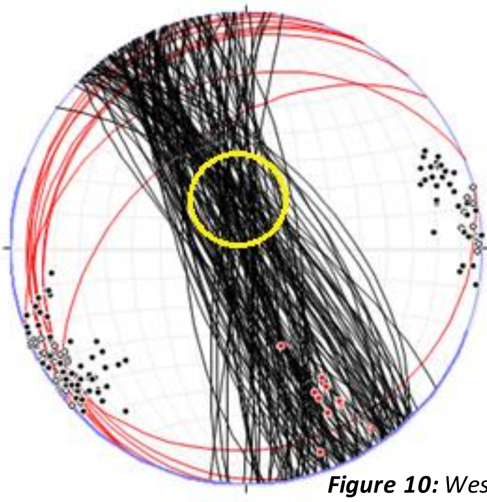
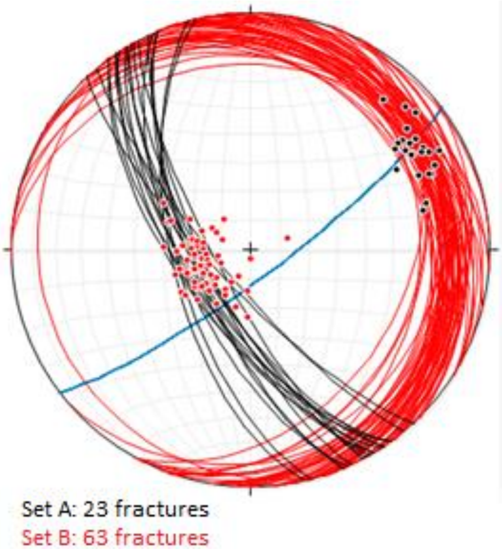


Figure 10: *Western outcrop*

Eastern part 1 **Eastern part 1 back rotated**



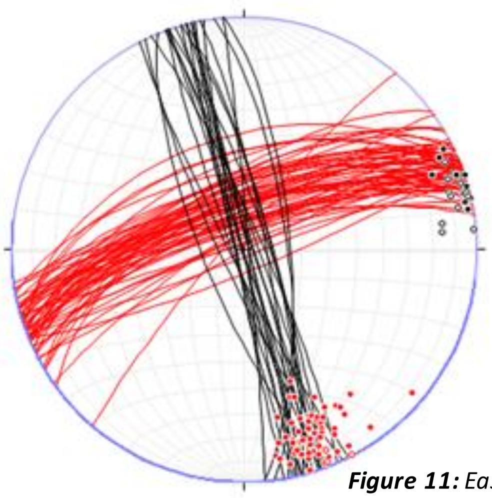
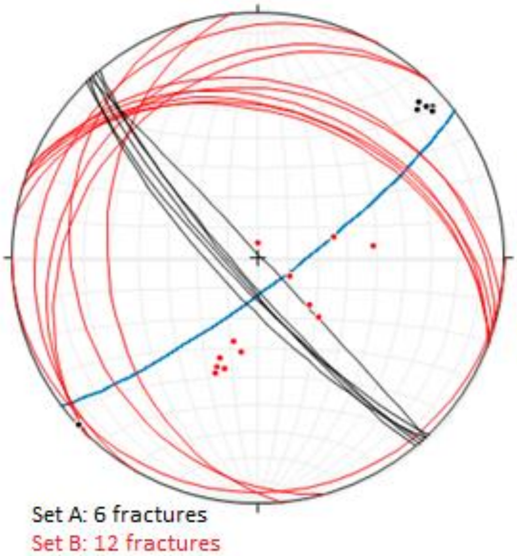


Figure 11: *Easterm outcrop part 1*

Eastern part 2 **Eastern part 2 back rotated**



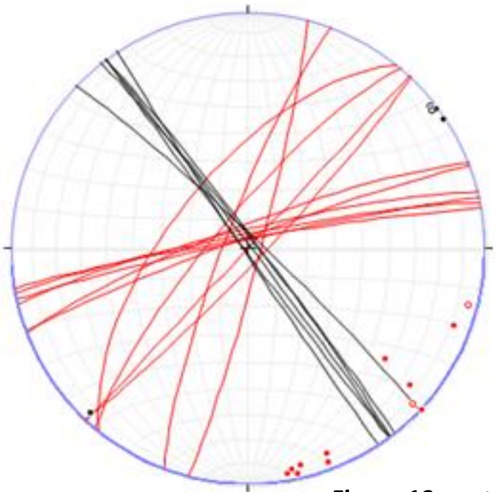


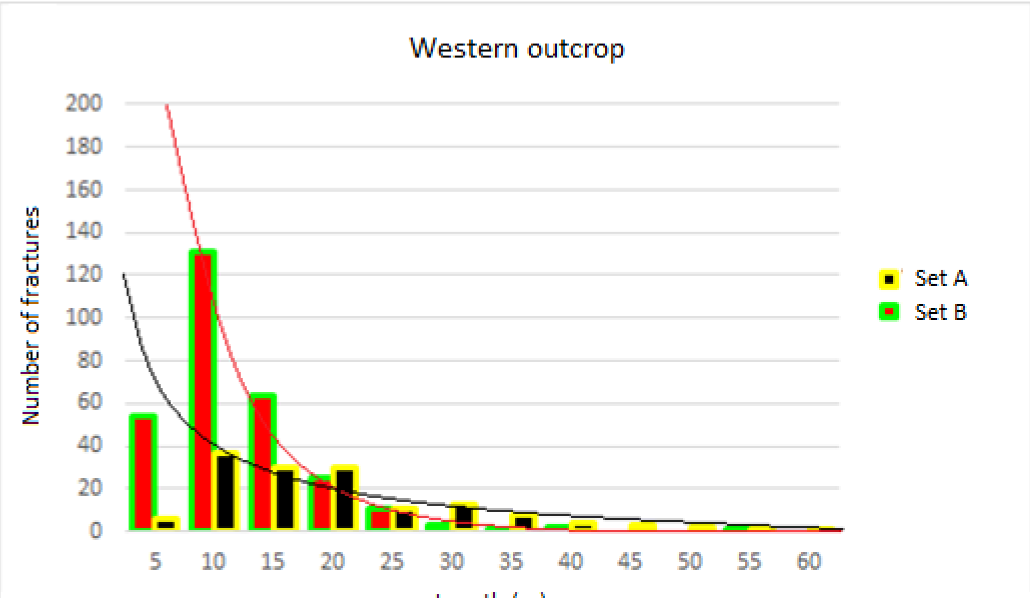
Figure 12: *eastern outcrop part 2*

In set A, it is harder to find evidence for conjugate fractures. As mentioned before, there are conjugate fractures visible in the left side of the western outcrop, this can be seen in figure 7. Figure 10 shows the stereonet from this area. The fractures from set A contain some noise but it is clear that some fractures dip a little bit to the east and others dip to the west. There is certainly evidence of conjugate fractures in the data. The yellow lines show the average orientation of the two conjugate systems. After back rotating, the intersections between these two systems should be vertical, but on average they have an intersection line with an orientation of about 350/70, it is displayed in the yellow circle in figure 10. The eastern outcrop contains much less reliable vertical fractures from set A, so it is harder to get reliable information from them. Just like the fractures from set B, it could be possible that only one of the two sets is developed in this specific area of the outcrop. There is only not much prove for this, but we can say that in the western outcrop the vertical fractures do show a conjugate system.

5.4 Fracture lengths

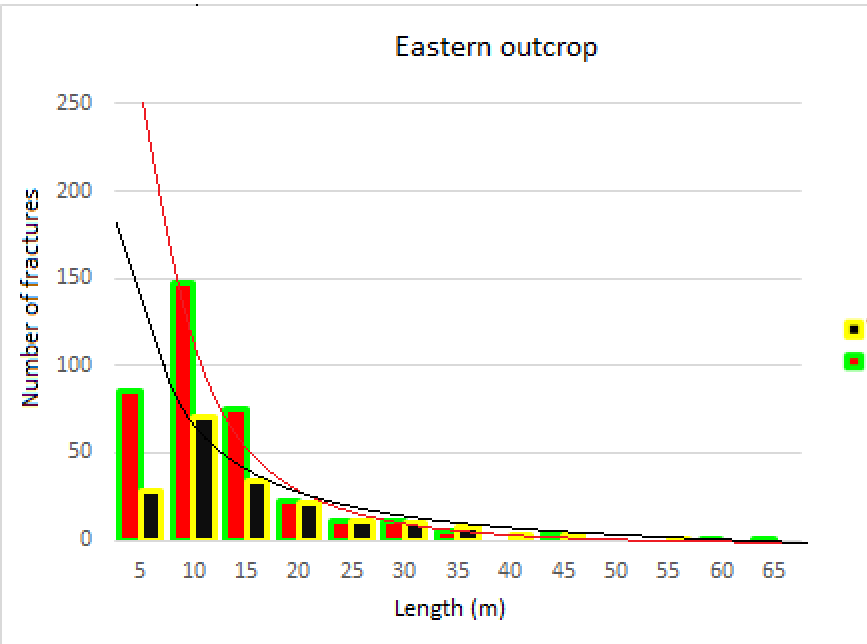
There are two main properties that describe the position and size of the fracture. We looked at the orientation, so the length is the next important property. A histogram of the length of the fractures of the western outcrop is displayed in graph 5. Set A has an average fracture length of 17,4 m. Set B has an average length of 9,8 m. It is clear that set A is longer than set B, this can be confirmed by graph 5, because there are more fractures longer than 25 meter in set A than in set B. many people have found that fracture size distributions follow power-law relations [*Bonnet, 2001*]. The power-law relation corresponding to the fracture sets are drawn in graph 5. Set A has no constrictions to fracture size, so we expect the power-law relation. Set B is limited by the vertical system, so the power-law relation may be more complex. Following this relation, there should be much more small fractures in the outcrop than digitized. These fractures probably are not opened or the resolution of the pictures is too low to see them. We can conclude that the fracture larger than 5 meter are properly digitized, because they follow the power-law relation perfectly.

The length histogram of the eastern outcrop is plotted in graph 6. In this part of the outcrop, set A has an average length of 13,0 meter and set B has an average length of 10,1 meter. The value for set B is comparable to the western outcrop, but the value for set A is much lower. This is probably



Graph 5

caused by the fact that the long vertical fractures from set A extend beyond the outcrop. In part 1 of the eastern outcrop almost all the vertical fractures go through the entire outcrop from top to bottom. This means they are digitized as smaller fractures than they really are. This might have given a distorted image of the length histogram. Also in this histogram, it is convincing that the fractures larger than 5 meter are properly digitized, because the histogram follows the power-law relation.



Graph 6

5.5 Fracture intensity

The western and eastern outcrop are both divided in three areas to be able to see the difference in fracture intensity in the outcrop itself. In each of these three areas the fracture intensity is calculated. Figure 13 is a picture from Gocad where all the fracture intersection are visible as white lines. The outcrop surface has been omitted and only the fracture lines where the fractures intersect with the outcrop are visible. The yellow areas are the chosen areas wherein the fracture i ntensity is calculated. These areas are chosen because the resolution is high and there is not much obstructing the outcrop from our view. This means we most likely have interpreted practically all fractures that are there. We can say that these areas give reliable information of the fracture intensity in the formation. When the entire outcrop is taken into account when calculating the fracture intensity, the result will be a too low value. Figure 14 shows the fracture intersections with the outcrop of the eastern outcrop. This outcrop is also separated in three areas. The areas left and right of the gorge are from part 1, so this part of the outcrop is split in two areas. The yellow enclosed area on the right is part 2 (part 1 and 2 are visualized in figure 9).

The results are given in table 1. The surface in square meters of the area is given and the length of all the fractures of that fracture set in the area is given. The two values are divided to get the fracture intensity of that area of the outcrop. The western part of the outcrop has a fracture intensity of about 0,30 m^{-1} for set B and about 0,15 m^{-1} for set A. The fracture intensity does not change much throughout the outcrop. The values are very similar, the fracture intensity for set A has a value of 0,15 m^{-1} for all three areas. The eastern outcrop has a fracture intensity of about 0,22 m^{-1} for set B and about 0,20 m^{-1} for set A. There is one area with a much smaller fracture intensity than the other areas. This is part 2 of the eastern outcrop. It has very little fractures from set A, this is no error or mistake, because also on the pictures it can be confirmed that there really are very little fractures from set A in this area. This means that there actually are some places in the outcrop with a much lower fracture intensity than the rest of the formation. This is only observed in the fractures from set A. The fracture intensity of set B is slightly lower in the eastern part, but the total fracture intensity counts up to comparable values with the western part. So there are relatively more fractures from set A in the eastern outcrop than fractures from set B compared to the western part. The only exception is part 2 of the eastern outcrop. Due to the low amount of fractures from set A, the total fracture intensity is much lower than everywhere else in the investigated outcrop.

Figure 13: *Gocad, western outcrop*

Figure 14: *Gocad, eastern outcrop*

Western outcrop	Western part set B			Western part set A			Total
	Surface (m^2)	Length (m)	P21 (m^{-1})	Surface (m^2)	Length (m)	P21 (m^{-1})	P21 Total (m^{-1})
Right	1904,5	485,6	0,25	3536,5	525,3	0,15	0,40
Middle	1196,9	420,2	0,35	3782,8	573,4	0,15	0,50
Left	1378,0	456,4	0,33	4261,8	641,9	0,15	0,48

Eastern outcrop	Eastern part set B			Eastern part set A			Total
	Surface (m^2)	Length (m)	P21 (m^{-1})	Surface (m^2)	Length (m)	P21 (m^{-1})	P21 Total (m^{-1})
Part 2	3406,2	637,1	0,19	2010,6	131,6	0,065	0,25
Part 1 left of gorge	552,8	144,5	0,26	946,4	202,3	0,21	0,48
Part 1 right of gorge	1269,5	253,1	0,20	1990,3	400,2	0,20	0,40

Table 1: *fracture intensity*

5.6 Total results

A summary of the results and the total results is given in table 2. For both outcrops, the number of fractures, the average length, the dip angle, the dip direction and the fracture intensity is given. There is no single number for the dip direction of set A, because of the conjugate system, so set A has two dip directions opposite to each other. Set B also contains conjugate fractures, but they are not visible in the data before back rotating. After back rotating the fractures from set B are also split into two systems.

Western outcrop		**Set A**	**Set A back rotated**	**Set B**	**Set B back rotated**
	Number of fractures	146		292	
	Average length (m)	17,4		9,8	
	Dip angle (degrees)	78,9	79,0	22,3	66,1
	Dip direction (degrees)	247,5/67,5	235,0/70,0	307,8	344,9/155,0
	Fracture intensity (m^{-1})	0,15		0,31	
Eastern outcrop					
	Number of fractures	188		364	
	Average length (m)	13,0		10,1	
	Dip angle (degrees)	71,3	81,1	18,3	64,9
	Dip direction (degrees)	239,0/52,0	244,0/67,0	72,9	323,1/138,0
	Fracture intensity (m^{-1})	0,16		0,22	
Total					
	Number of fractures	334		656	
	Average length (m)	14,9		10,0	
	Dip angle (degrees)	74,6	80,2	20,1	65,4
	Dip direction (degrees)	242,7/58,8	240,1/68,3	177,4	332,8
	Fracture intensity (m^{-1})	0,15		0,27	

Table 2: *total results*

6. Conclusion

The investigated outcrop contains two main fracture sets, separated as set A and set B. set A consists of almost vertical fractures in the outcrop and set B consists of more horizontal fractures. They are perpendicular to each other. After unfolding both sets, the fractures from set A have a dip angle of about 90 degrees and the fractures from set B have a dip angle of about 60 degrees. The vertical fractures are longer with a total average length of 14,9 meter. Actually the average length is probably longer than this value because a lot of vertical fractures extend beyond the outcrop. The fractures from set B often stop when they meet a vertical fracture, so they are probably formed later. Set B has an average length of 10,1 meter. Both sets show evidence of conjugate fractures, but the conjugate fractures are not developed through the entire outcrop. The vertical conjugate fractures can best be found in the left part of the western outcrop. In the eastern outcrop there is only very little evidence of vertical conjugate fractures. On the other hand, the horizontal conjugate fractures can most be found in part 2 of the eastern outcrop. The western outcrop also has some horizontal conjugate fractures, but they are less clear and cannot be seen in the stereonet data. This probably means that the formation consists of conjugate fractures, but that on some places only one of the two sets is developed.

The fracture intensity of both sets is calculated in three places in both outcrops. It is striking to see that the fracture intensity is not the same throughout the outcrop. Part 2 of the eastern outcrop has a very low fracture intensity for the fractures from set A. This is no error, because it is a very clean area with a high enough resolution to distinguish all the fractures present. It means that the formation does not have a very evenly distributed fracture system, but there are some places with a much lower intensity. In all the other investigated areas the total fracture intensity was very comparable.

This outcrop has a large recognizable fracture pattern, but this pattern is not as predictable as it appears to be after a first look at the outcrop. There are big differences in orientation and fracture intensity in just a few hundred meters of the outcrop, which can be important for further investigation in fluid flow in the Kef Eddour formation.

7. Recommendations

The software used during this project can be very helpful and it makes it possible to collect a lot of data about the fractures, but there are some disadvantages that may cause some errors or uncertainties in the data. It is important to know what the problems are and what they can cause. In this chapter, a few of the problems will be explained so that when the software is used again, the same mistakes are not made again.

7.1 Disadvantages of the software

The idea of using the program OpenPlot was to be able to determine the orientation of the fractures. Something that could not be done on the conventional way when using only pictures of the outcrop. However there are some disadvantages that can make it a lot harder than it seems at the start of the project. There were some problems with the orientation of the long vertical fractures. The large amount of relief seemed like an advantage, because the orientation is easy to determine. However, sometimes it caused wrong results. Two big vertical fractures are displayed in figure 15. On the top, a sketch of a horizontal intersection is drawn. The red lines are the fractures as they would be interpreted in the software. The left trench has sharp corners and it is clear that the fracture planes are fairly perpendicular to the outcrop surface. In the right picture, the corners of the trench are much gentler. This can have two different causes. The edge can be eroded away, leaving the gentle curve. The other reason can be that the software smoothens the edge, because it interpolates between points on the outcrop surface. This can be noticed when pictures are compared to the outcrop model. Some of the edges are much sharper in real than in the outcrop model. These two reasons cause that the fractures seem to have an angle with the outcrop, where they are probably perpendicular. This is shown in the top right sketch in figure 15. Judging from field data, the left and right fractures are probably both perpendicular to the outcrop unless the smooth edges of the trench.

Figure 15: *errors in fractures*

An example of the just described problem occurred in this project. In figure 16 on the left are some of the longest fractures in the outcrop modelled in a stereonet. On the right, the same fractures are back rotated. The left picture should show two sets of fractures dipping in the opposite direction, because they are conjugate fractures. After back rotating they should be vertical and have vertical intersection lines. Actually the result gives the exact opposite. This is due to the problems explained in figure 15. The fractures got a too small angle to the outcrop surface, where they should probably be perpendicular to the outcrop. This problem was dealt with and the right results were given earlier.

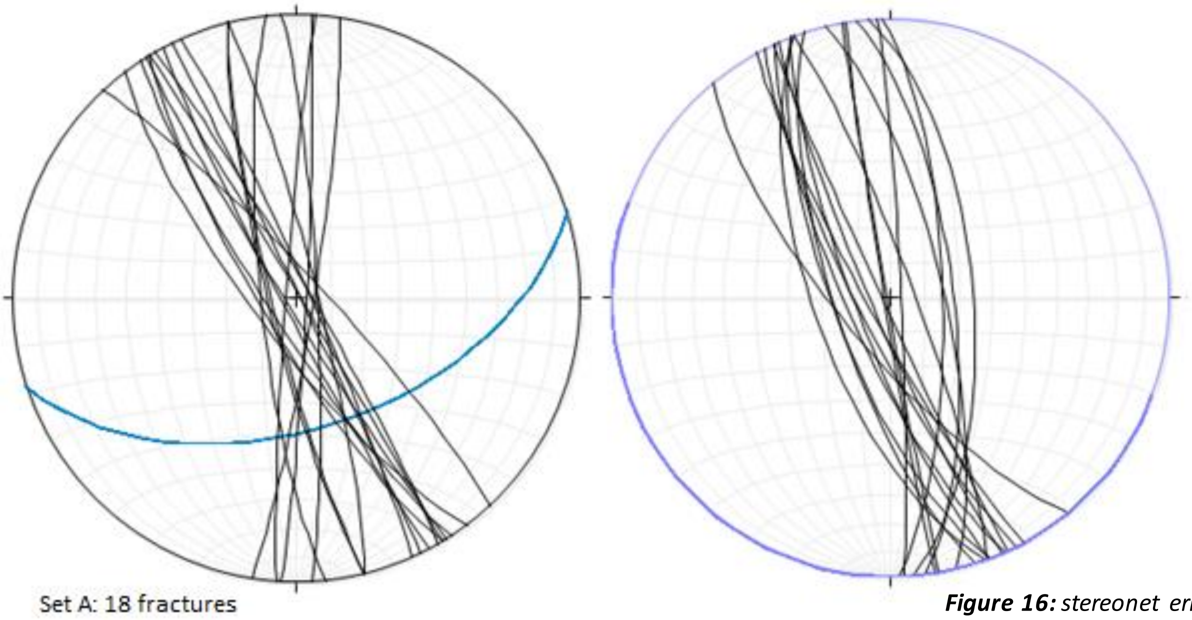


Figure 16: *stereonet error*

7.2 Horizontal fractures

The horizontal fractures in this outcrop mostly do not have much relief. It can be very difficult to give the fracture planes the right orientation. When a fracture intersects with the outcrop at a very flat part, the fracture line is actually almost a straight line and it is very hard to put the third point of the polyline exactly in this line. Usually the first and second point are placed at the two ends of the fracture and the other points somewhere in the middle to determine the third dimension. When all these points are on one straight line, the orientation in the third direction deviates very easy. It can be a big challenge to put that third point exactly between the first two points. When the third point is just a small distance off, the orientation can be up to 90 degrees from what it should be. When it is not taken into account, it may cause errors in the data. Sometimes fracture planes that are placed wrong must be deleted and placed again with more precision.

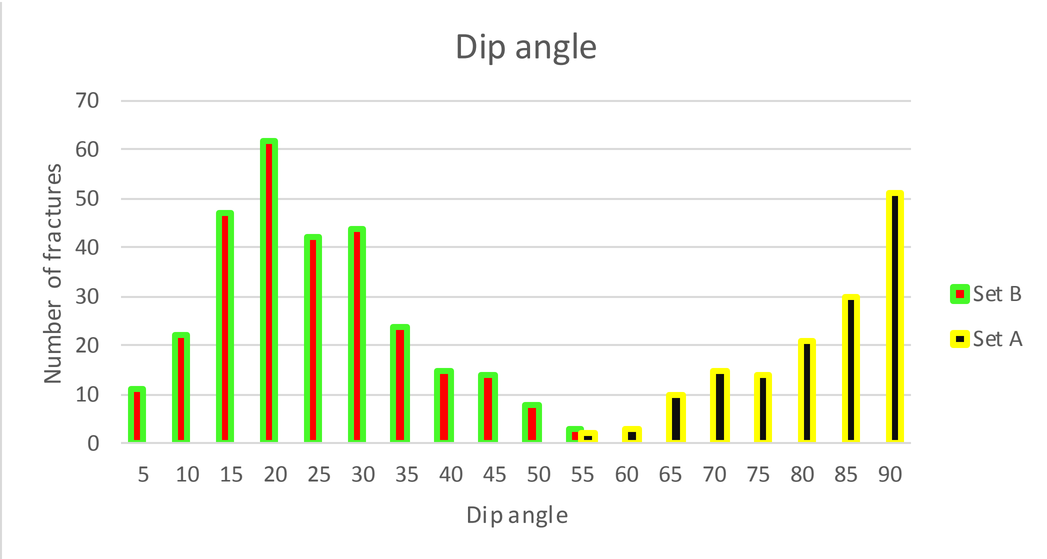
Another disadvantage of OpenPlot software is the stretching of the pictures on the outcrop surface. In Photoscan, the 3D outcrop model is made from the pictures of the outcrop. On some places the photos are taken from below of the outcrop where the outcrop is tilted away from the photographer. To fit the picture on the outcrop, Photoscan has to stretch the pictures in the direction where the photographer points the camera. This causes some distortions of the outcrop surface. Some fractures seem to have a different orientation than they have in reality. Fractures that are actually horizontal and perpendicular may seem to have a lower dip angle because of this distortion. Some cross fractures may seem to be much more vertical than in reality. These distortions can be very significant, up to 20 – 30 degrees in dip angle. It is best to look at picture taken in the field to confirm an orientation when the presumption is made that the orientation is wrong.

Looking at a massive dataset with all the fractures in it may cause too big errors. It is better to just look at a small part of the dataset that contains only fractures that can be modelled with a high certainty. The most important thing is to recognize an eroded edge, or a distortion of a fracture. This might be very helpful and save time when the wrongly placed fractures have to be taken out.

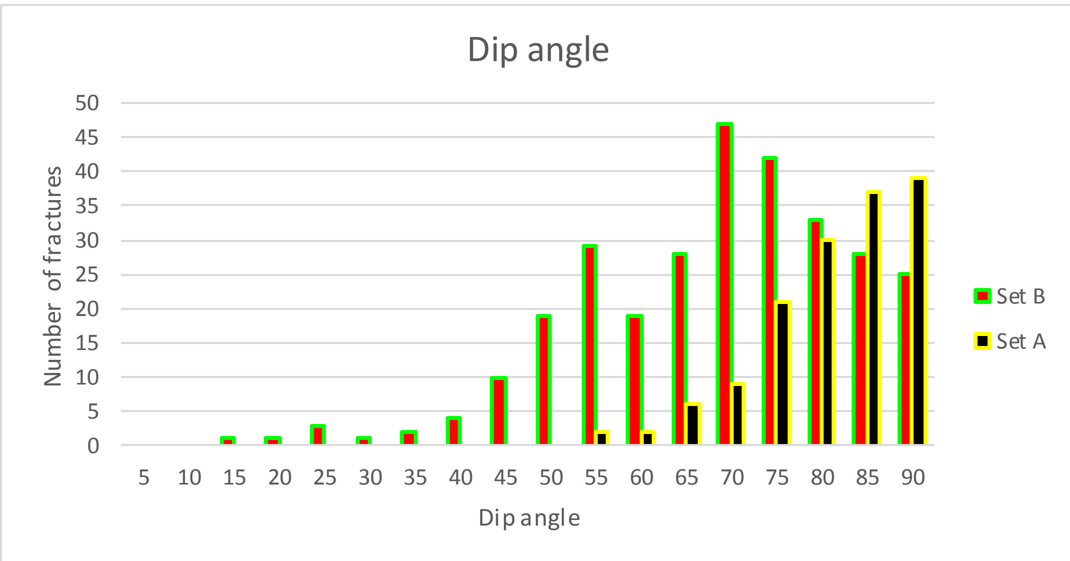
It is best to only do the fracture modelling in OpenPlot software and use other software to process the data further. OpenPlot can be very unhandy when a single fracture has to be changed or an orientation of a fracture has to be decided. The modelling of the fractures has to be done perfect before exporting the data to other software, because going back to OpenPlot later to change anything can cause a lot of work. The fractures aren't numbered so finding one fracture to change is almost impossible when a few hundred fractures are modelled.

8. Appendix

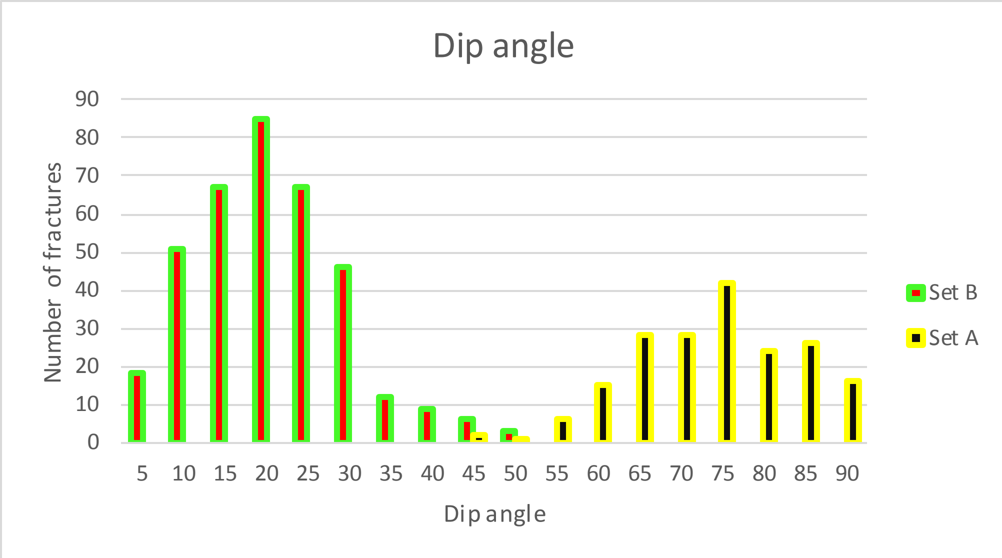
Dip angle histogram of the western outcrop



Dip angle histogram of the western outcrop back rotated



Dip angle histogram of the eastern outcrop



Dip angle histogram of the eastern outcrop back rotated