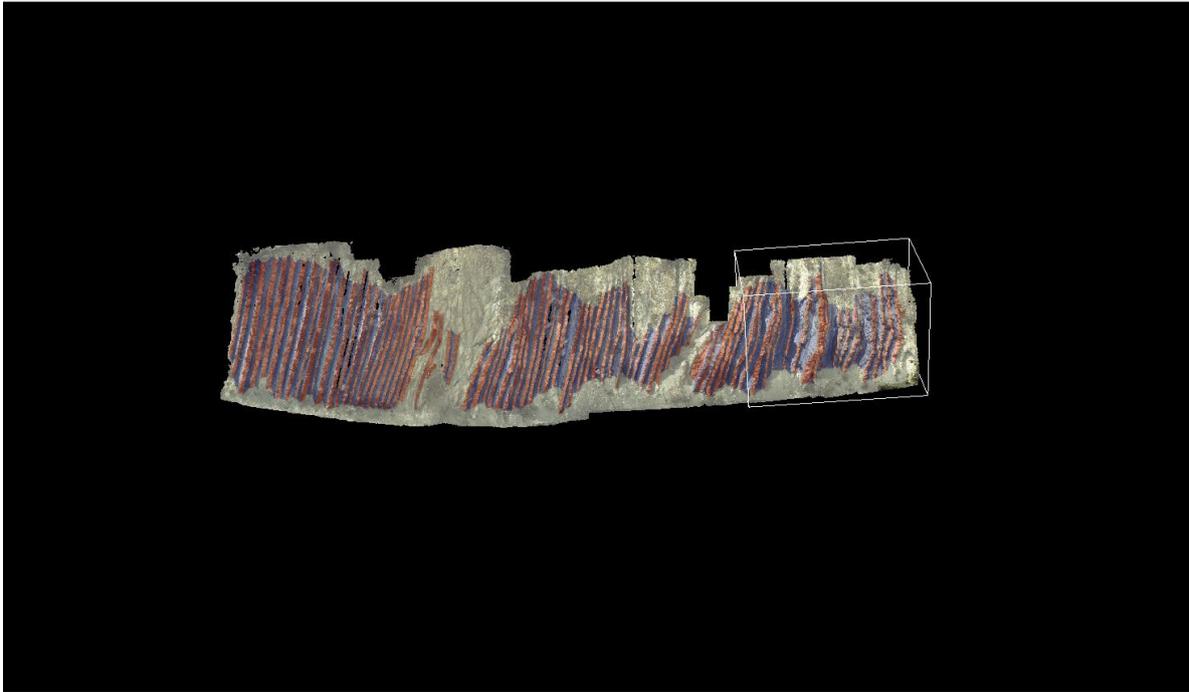


Virtual Outcrop Analysis using Lime



Bachelor Thesis

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23-10-2017

Abstract

With laser scanning or photogrammetry techniques 3D models of rock outcrops can be made. For analysis and visualisation of such models the software Lime was created by the Virtual Outcrop Geology group.

The aim of this thesis is to examine what functions Lime includes and how they can be used to visualise, interpret and measure the geologic features of an outcrop. To do this, a laser scan model of an outcrop containing limestone-marlstone alternations deposited during the Hauterivian age was used. The outcrop is located near the town of La Charce, France.

A method was developed to process raw laser scan data into a configuration that can be imported into Lime. This includes registration in the Leica Cyclone software, georeferencing and meshing in the free point cloud software CloudCompare and texturing in the free mesh software Meshlab. Functionalities that were examined in Lime include the use of texture functions, visualising the stratigraphic layers, measuring dip and dip direction of the formation, measuring layer thickness and importing a digital elevation model to show the location of the outcrop.

Contents

Abstract	1
1. Introduction	4
1.1 Research Questions	4
2. Geology	5
3. 3D data acquisition and processing	9
3.1 Photogrammetry	9
3.2 Lidar	11
3.2.1 Principle	11
3.2.2 Processing Data	11
Registration.....	11
Georeferencing	12
Creating a mesh	13
4. Processing the La Charge data	16
4.1 Description of data	16
4.2 Registration	16
4.3 Georeferencing	17
4.4 Creating a Mesh	18
4.5 Creating a texture file with MeshLab	21
5. Lime Methodology	22
5.1 Importing models	22
5.2 Texture Functions	22
5.3 Tracing the stratigraphy	24
5.4 Projecting the stratigraphy	25
5.5 Determining dip of layers	26
5.6 Using planes to show the layers	28
5.7 Determining layer thickness	29
5.8 Incorporating other data	29
DEM	29
6. Lime Results	32
6.1 Layer visualisation	32
6.2 Dip and dip direction	34
6.3 Layer Thickness	38
6.4 DEM	41
7. Conclusion/Discussion	43
7.1 Research questions	43

7.2 Programme speed	44
7.3 Comparison with other software	45
References	46
Appendix	48
Matlab code to calculate dip and dip direction of polyline	48
Matlab code to create layer thickness diagrams	49

1. Introduction

The use of laser scanning and photogrammetry techniques to create 3D models of outcrops has become widespread in recent years. An outcrop is a location where the rock that normally lies under the surface is exposed, so they are useful sources of information for geologists. A 3D model of an outcrop can be created with a laser scanner, which sends out a beam of light to the object and measure the time it takes for the light to return. Another method is photogrammetry, which uses a number of overlapping photographs taken from different locations to create a 3d model. Using 3D models of outcrops allows to take more measurements in more places than with fieldwork, and the data can be used by many people without having to visit the specific location.

As a result there has been a growing need for software for visualisation and analysis of virtual outcrops. The program LIME has been developed for this purpose by the Virtual Outcrop Geology Group, a collaboration between CIPR Bergen and the University of Aberdeen. It was released in September 2016.

This thesis aims to explore the extent to which LIME can be used to visualise, interpret and measure 3d outcrop models, and the processes needed to achieve this. Features that are examined specifically are the thickness of the layers, the dip and orientation. The possibilities to include information from different sources are also examined, in particular incorporating a digital elevation model.

To do this, data created by laser scanning of an outcrop is used. The data was originally created by E. F. Prentice using the laser scanner Leica ScanStation C10. The outcrop that is described in this thesis is located near the commune of La Charce, Drôme, Rhône-Alpes in south eastern France. It is a sedimentary outcrop that consists of layers of limestone and marlstone.

The processing of photogrammetry data will only be described in theory. The entire process that was used to convert the laser scan data will be described.

1.1 Research Questions

- 1. What processes are necessary to convert laser scan or photogrammetry data into a usable configuration in LIME?**
- 2. To what extent can Lime be used for interpretation and visualisation of geological features?**
- 3. Can Lime be used to measure geological features?**

2. Geology

The La Charce outcrop was originally deposited in an area called the Vocontian basin, as carbonate sedimentary rock. (1) During the Jurassic and Cretaceous periods the Vocontian basin was a shallow sea between the continents of Laurasia to the north and Gondwana to the south, opening to the Tethys ocean to the east. It was formed as a result of the breaking up of Pangea. In figure 1a it can be spotted just north of what is called the Alpine Ocean.

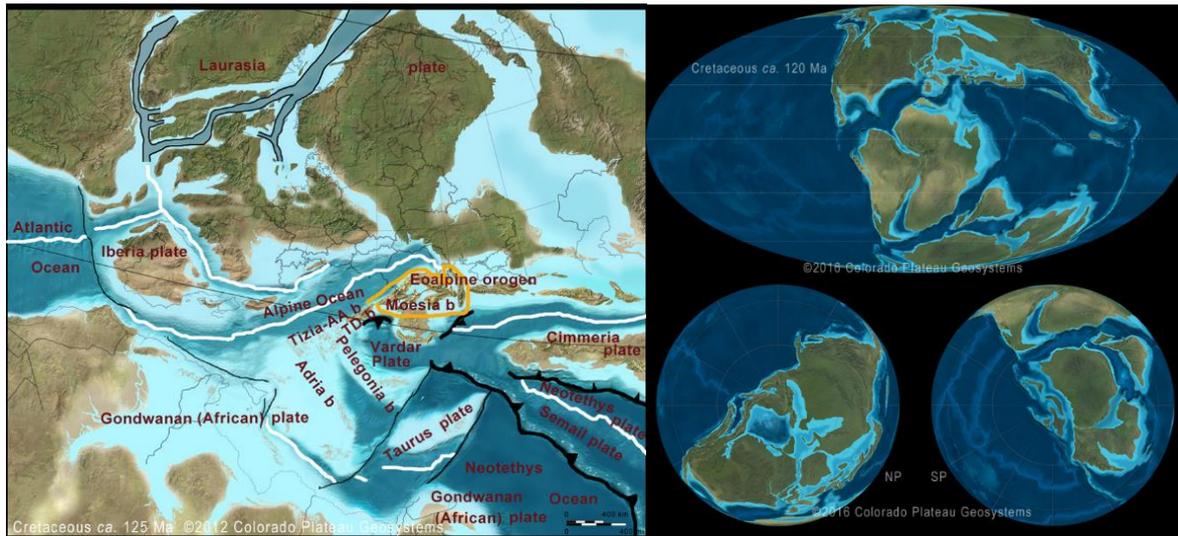


Figure 1:(a) Europe during the early Cretaceous (125 Ma) (b) World map during the Cretaceous (120 Ma)[2]

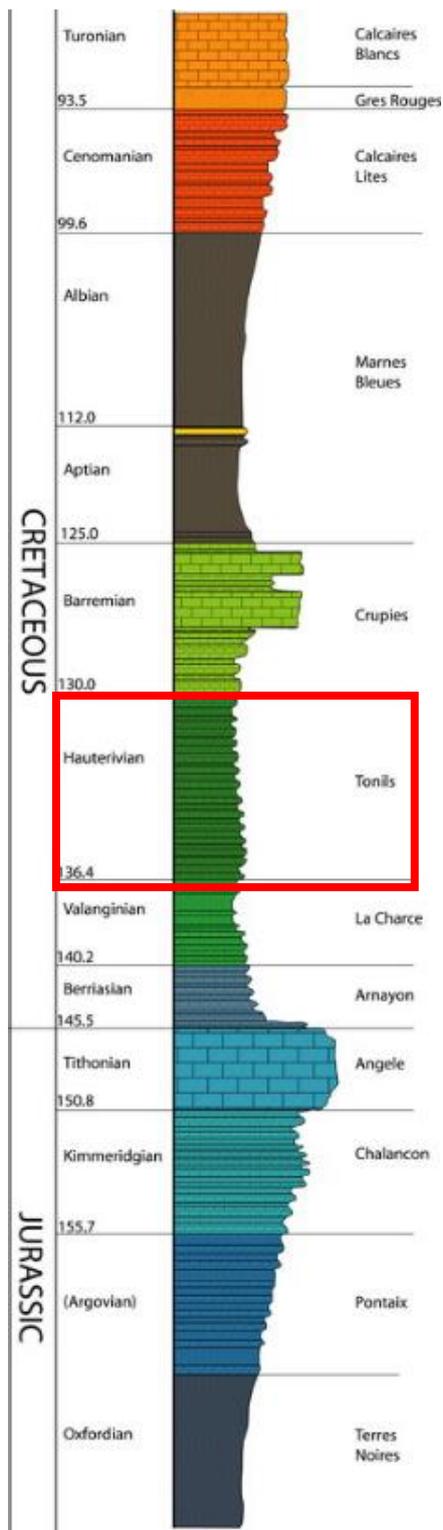


Figure 2: Stratigraphy found in the Vocontian Basin (Jan Kees Blom). The outlined age (Hauterivian) is when the La Charce outcrop sediments were deposited.

The formations that are found in this area are from the upper Jurassic to the Upper Cretaceous period, more specifically the Oxfordian age to the Turonian age (163.5-89.8 Ma). They contain almost exclusively limestone-marl alternations. This indicates a relatively shallow marine carbonate shelf, with carbonate formed in situ by biological processes, and limited supply of material that was transported from the continent. Specifically, it can be described as an epicontinental or epeiric shelf, meaning it was located on the continental shelf during a time of high sea levels. The water level in such an environment would be highly variable. As a result the rocks could be deposited in very different circumstances, which could explain the alternation of the layers. (3)

The limestone and marl layers can be easily distinguished in the field by their vastly different weathering. In limestone-marl alterations the much stronger limestone layers seem to protrude from the outcrop as the brittle marlstone is weathered away. Formations containing exclusively limestone form steep cliffs of massive rock, where the thick beds can be recognized. Formations containing mostly marlstone have a much more gradual slope due to higher erosion, and consist of loose sediment which can be removed by hand.

The origin of the rhythmic limestone-marlstone alternations is somewhat controversial, and can be described by two different possible origins, or a combination of the two. The classic explanation involves cyclical changes in climate and sea level, influenced by Milankovitch cycles (also called orbital forcing). Milankovitch cycles are rhythmic patterns in the way the earth orbits around the sun. Possible cycles that have an influence on the climate include eccentricity (100 thousand years cycle), tilt (41 thousand years) and precession (22 thousand years). (3) Changes in climate and sea level can have an influence on the biological production of carbonates, the transport of carbonates to other areas of the basin, the transport of clastic clay sediments from the continent, the saturation of calcium carbonate in sea water, and oxygen levels in the sea. (4)

The cycle times of the Milankovitch cycles are of the same order of magnitude as the alternations of the layers.

The second explanation involves differential diagenesis of the sediments. Diagenesis means the changes in a rock by pressure and/or temperature after it has been buried. Differential diagenesis means that rocks with different properties will react differently to diagenesis. As the sediments are buried, the pressure causes calcium carbonate to dissolve from some of the layers. This is then migrated to the adjacent layers, where it forms cement. As this process continues, the marlstone layers are depleted of calcium, whereas the limestone layers are cemented with it. This could explain the sharp layer boundaries and large lithological differences in terms of strength and calcium content. The presence of small fossils in the marlstone layers points to the dissolution of only aragonite, whereas calcite remains intact. In this theory, the sharp alternations are a result of differential diagenesis, caused by small differences between the original layers. The influence of environmental fluctuations could therefore be overestimated. (5) However, there are a number of issues with this explanation. Firstly, the layers in these alternations are very constant in size, often varying only lightly over the distance of hundreds of meters. If differential diagenesis was the main cause, it should be expected that it has a large influence on the shape of the layers, and it would result in lens-like shapes, not very regular layers. (6) Secondly, a substantial amount of aragonite would be required in the original sediment to cause so much calcium to be migrated from one layer to the next. The presence of so much aragonite in this environment is questioned. (4)



Figure 3: The author at the La Charce outcrop

The specific outcrop that is described in this thesis is known as le Serre de l'Ane. This outcrop was selected as candidate GPPS for the Hauterivian stage in 1995, and is so far the only candidate. (7) A GSSP (Global Boundary Stratotype Section and Point) is a standard reference point for the lower boundary of a stratigraphic stage, defined by the International Commission of Stratigraphy. The site was selected for candidacy because of its large area of exposure, small amount of deformation, and abundance of fossils. Especially the ammonites *Acanthodiscus radiates* are of importance, since their appearance is the correlation event that defines the start of the Hauterivian stage. (8) For its geological significance it was selected as a Espace Naturel Sensible in 2014.

The Hauterivian stage (132.9-129.4 Ma) in the Vocontian basin can be recognized by its very regular alternations of limestone and marlstone, and layers of comparable thickness. The layers are between 20cm

and 60cm in size. The Valanginian stage below it has much thicker packs of marlstone, and the occurrence of limestone layers is more irregular. The Barremian stage above contains much more limestone, with only thin layers of marlstone.



Figure 4: Google street view image of the outcrop

3. 3D data acquisition and processing

3.1 Photogrammetry

Photogrammetry refers to any measurements that are done based on photographs. In this report, it specifically refers to the use of pictures to generate a three-dimensional model, also called stereophotogrammetry.

In photogrammetry, a 3D model is created by using photographs taken from different locations of the same object. It is based on the concepts of parallax and foreshortening. Parallax refers to how the position of an object in the observer's field of view changes depending on the observer's location. Figure 5 shows that on the left image the object point is to the right of the y axis, while on the right image the object point is to the left of the y axis. Foreshortening means that there is less parallax for objects that are further away from the observer. In figure 5 the difference would be smaller if the object point was further away. If the positions and orientations of the images are known the location of the object can be determined using these principles. The process of determining the position of an object from two other known positions is called intersection. The opposite process is resection. Resection is determining the position of the observer from the locations of other known points. (12)

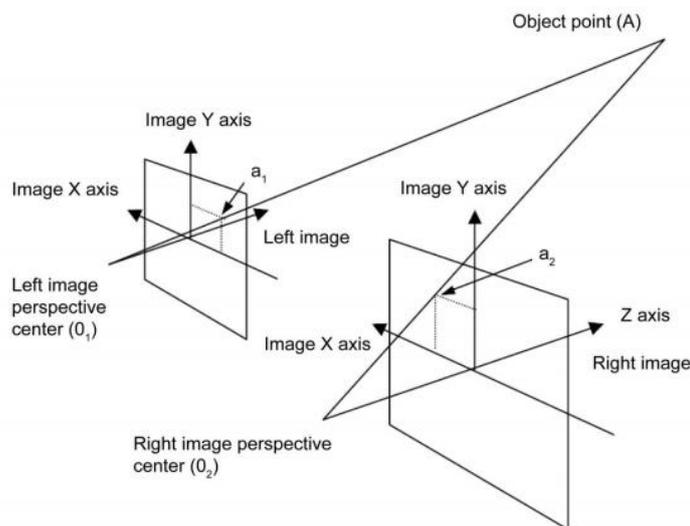


Figure 5: Principle of intersection (12)

Photogrammetry has some practical advantages for outcrop geology compared to laser scanning. One of these is mobility. Whereas laser scanning often requires large tripods to be placed on a level surface, photographs can be taken from any place that the maker can reach. Drones are available for both technologies. Another major advantage for outcrop geology is that the technology is widely available. Specialized cameras and drones for photogrammetry exist, but it can also be done with any smartphone that has a camera, if some sacrifices in quality are permitted.

Software that can be used to create 3D models from photogrammetry data include 3DM analyst by Adam Technology, Sirovision and Agisoft PhotoScan. A common approach to modelling from photogrammetry is structure from motion. With this technique it is not necessary to collect the exact coordinates and orientation of the photographs.

The approach is to first determine key feature points in the photographs. These features can be corners, edges or blobs. Many different algorithms for feature detection exist. The next step is feature extraction or feature description. Here the feature that has been found is characterized so it can be matched to other photographs. Again, there are a multiple algorithms to do this. (13) If one feature is found on multiple photographs it is matched. The matched points are then used to construct the model through a process called bundle adjustment. In bundle adjustment, both the location of the object and the position and orientation of the cameras are placed and altered in such a way that they fit together best.

For an overview of methods for feature detection and extraction, see Hassaballah (2016) (13). For an extensive review of the bundle adjustment problem, see Triggs (2000) (14).

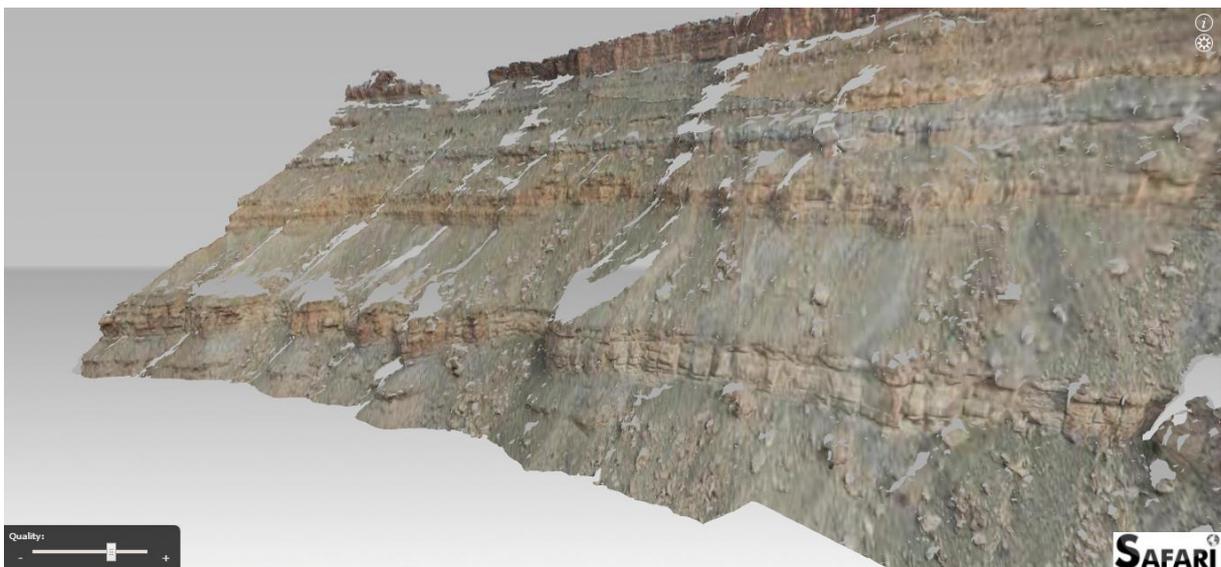


Figure 6: Example of 3d model from photogrammetry. (23)

3.2 Lidar

3.2.1 Principle

Lidar is an acronym standing for light detection and ranging system. The basic principle of lidar is to emit a narrow beam of light, which is reflected on the object that is to be measured. The travel time of the beam is measured, which allows the range of the object to be calculated. This is done by simply dividing the travel time by two and multiplying by the speed of light. In combination with the emitter's location and direction of the light beam the location of the reflected surface is acquired. Intensity and colour of the returned signal are also commonly measured, which can be used to determine lithology or for more realistic visualisation. Intensity is a measure of the amount of light that is returned. Factors that influence the intensity include distance, the reflectance of the object and environmental factors, as well as a range of influences relating to the scanner. (20)

For the application of outcrop geology the distinction is made between terrestrial lidar and airborne lidar (on a plane or drone). Terrestrial laser scanning is the most widely used of the two for outcrop geology, while airborne laser scanning is mostly used for remote or inaccessible outcrops. The working principles of the two are similar, but airborne lidar can introduce issues relating to cost, availability, accuracy and data density. (9) Advantages include the ability to scan inaccessible outcrops or very large outcrops. A third option that has become available is mobile laser scanning. Here the laser scan is fitted on a backpack.

When scanning using laser technology, the scanners field of view should be taken into consideration, an outcrop could be partly out of view. For this reason, it is common to use multiple scanning locations for a single outcrop to account for its size or geometry. Scanning is usually done from a relatively low position, which is why creating complete models of relatively high outcrops can be difficult when using terrestrial scanning, since parts of the outcrop can be completely out of view.

The output of laser scans is in the form of point cloud data. This means that the data is just a large set of individual points that have xyz coordinates. Because there is a very large amount of data points the cloud looks like a solid surface, as can be seen in figure 11 or 14.

3.2.2 Processing Data

Registration

To combine the numerous scans of a single outcrop into a coherent model they have to be fitted together through a process called registration. With registration, the point clouds are transformed and rotated until the correct configuration is found, without manipulating the individual forms of the clouds. An important requirement for registration is sufficient overlap between scans.

A common approach is feature-based registration. Feature-based methods look for easily identifiable points or features in both clouds, and fit the clouds together at these points. The features can be manually placed targets on the outcrop or clear geometric points such as corners, which can be identified manually or automatically. (10)

Georeferencing

The coordinates of the pointcloud are relative from the scanner location. It can be useful to convert to global coordinates for a number of reasons. Firstly, for determining the orientation of the layers in the outcrop the model should be oriented with the correct side north. Secondly, if the model needs to be accurately placed on a satellite image or digital elevation model it should be in global coordinates. In addition, this would allow to see multiple outcrop models relative to each other in one digital environment.

The coordinates of a number of easily identifiable targets can be measured for georeferencing. These targets can then be located in the point cloud. The entire point cloud can then be translated, rotated and scaled so that the locations of the targets match the coordinates which were measured.

For this thesis UTM coordinates are used. UTM (Universal Transverse Mercator) is a coordinate system that divides the earth into 60 bands of longitude. Each band is then projected onto a flat surface using a transverse Mercator projection. A Mercator projection is done by projecting every part of a sphere onto a cylinder which fits around the sphere (see figure 7). With transverse Mercator, the part which is projected is where the sphere almost touches the cylinder. Because the difference in longitude in each zone is small the distortion when it is projected is relatively small as well. (16)

The advantage of using UTM coordinates is that they use Cartesian coordinates (x and y coordinates). For each UTM zone the Cartesian coordinates are in meters. So if the 3D model is converted to UTM coordinates, it is in global coordinates and it can still be used for measurements in meters. Google Earth can be used to easily convert latitude/longitude coordinates into UTM coordinates.

A disadvantage is that near the edges of a UTM zone the +y direction becomes different from the actual north direction. This needs to be kept in mind when determining the dip direction of the layers.

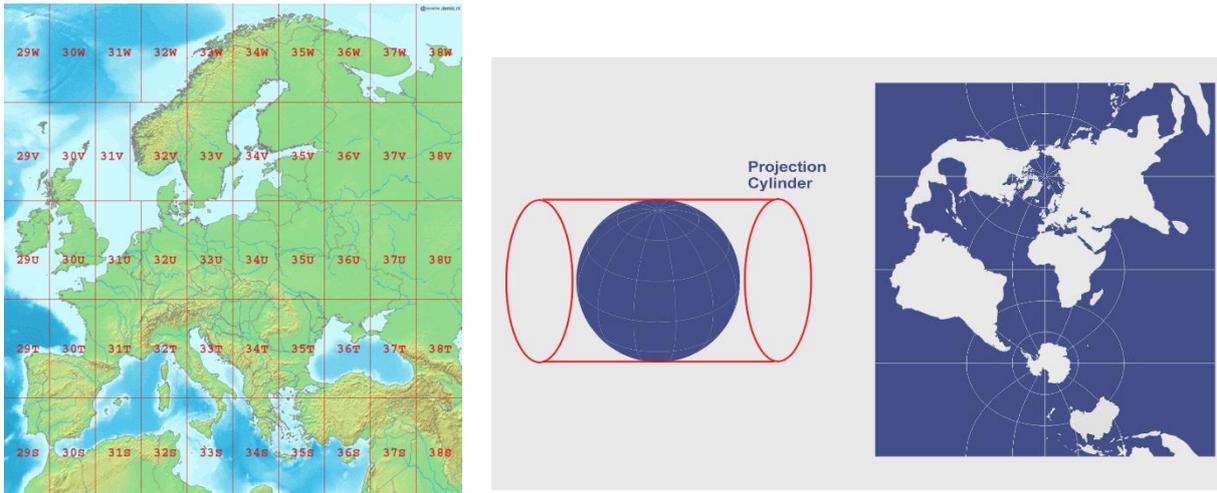


Figure 7: (a) UTM zones in Europe (15) (b) Transverse Mercator projection (16)

Creating a mesh

It is possible to perform interpretation and visualisation on the point cloud data alone, but to use the data in Lime it needs to be converted into a mesh. A mesh is a surface that consists of triangles with the points of the cloud as vertices.

Many different mathematical approaches for mesh creation exist. For this thesis the data was processed using the free pointcloud software CloudCompare. (21) The background of the two methods that are available in CloudCompare are therefore discussed here.

The first method is called Delaunay 2.5D. This method projects the points in the cloud on a 2D surface. The triangulation is then done in 2D. The objective of the triangulation is that only the three vertices of the triangle fall within the circle that is formed by the vertices of the triangle. The resulting triangles are then applied to the 3D pointcloud. (11)

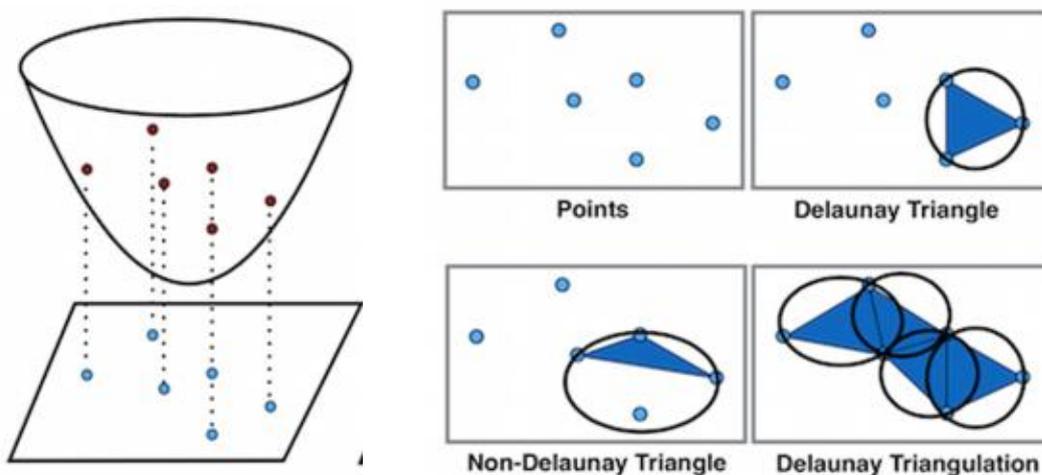


Figure 8: (a) projection on a 2d plane (b) Delaunay triangulation (22)

Because the Delaunay method does the actual triangulation in 2D, it can only be used on objects that can be represented by a single projection. For example, a sphere cannot be triangulated this way, because the top and the bottom would be projected on the same place. Therefore this method is mostly fit for clouds that are oriented in one direction such as digital elevation models. The Delaunay function could in theory be used for outcrops that are very flat.

The second function that can be used is Poisson surface reconstruction. This function was developed by Misha Kazhdan of Johns Hopkins University. Before this method is used the normals of the cloud have to be calculated. Normals are vectors that are at 90 degree angles to the surface that is formed by the cloud.

Poisson surface reconstruction uses the normals to calculate the indicator function. The indicator function simply gives a value of 0 for any point that lies outside the surface of the model and a value of 1 for any point inside the surface.

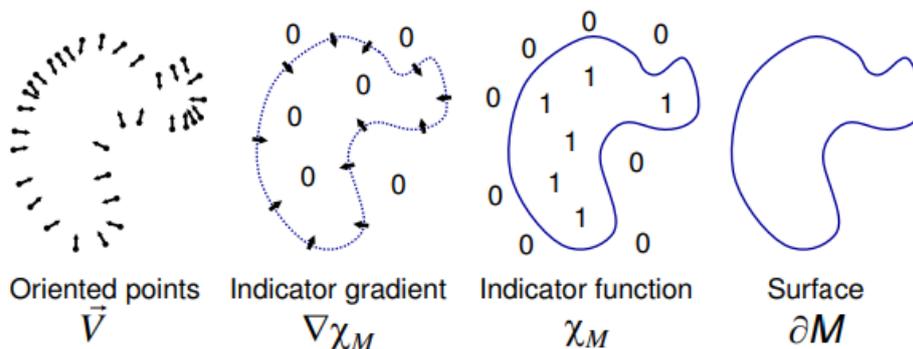


Figure 9: Poisson reconstruction in 2D (18)

As a result, the gradient of the indicator function is 0 everywhere inside the surface, since the value of the indicator function is 1 for every point inside. The same goes for every point outside the surface, where every value is 0. Only at the surface itself does the gradient of the indicator function have a value. The normals that already have been calculated are essentially the same: they only have a value at the surface of the model. The divergence can be used to describe the vector field of normals. As a result, the divergence of the normals is equal to the divergence of the gradient of the indicator function. The divergence of the gradient is also known as the Laplace operator. This equation is written as $\Delta\chi = \nabla\vec{V}$, Δ is the Laplace operator, χ is the indicator function, ∇ is the gradient and \vec{V} is the vector field of normals. This equation has the form of a Poisson equation. \vec{V} is known at a limited number of points, so χ is determined so it most closely satisfies the Poisson equation.

For a detailed explanation of the function, see reference (18)

Many more different mathematical approaches to mesh generation exist, such as Advancing Front Technique, Ruppert's algorithm, Stretched grid method and 3D Delaunay methods. In addition a wide variety of software for meshes is available, because 3D modelling is used in

many different fields. Examples of programs are MeshLab, CUBIT and Pointwise. CloudCompare is not made specifically for mesh generation, but for the purpose of this thesis it is acceptable.

4. Processing the La Charce data

4.1 Description of data

The data that is used in this thesis was originally collected by E. F. Prentice in 2016. (19) The Leica ScanStation C10 was used. The scanner has an accuracy of 6 mm according to its datasheet. The outcrop was scanned from four different stations to give enough coverage. 7 point clouds were collected, station 1 has two scans, station 2 has three scans and stations 3 and 4 both have one scan. This data consists of xyz coordinates, and in this case combined with intensity and RGB values. The xyz coordinates are in meters, and are relative from the scanning locations. The intensity value is between 0 and 1, while the RGB values are between 0 and 255.



Figure 10: Leica ScanStation c10

4.2 Registration

To register the pointclouds of the La Charce outcrop the program Leica Cyclone was used. A feature-based registration was used as the approach by E.F. Prentice, so the data already included the location of several targets that were manually placed near the outcrop. Registration can then be done automatically in Cyclone.

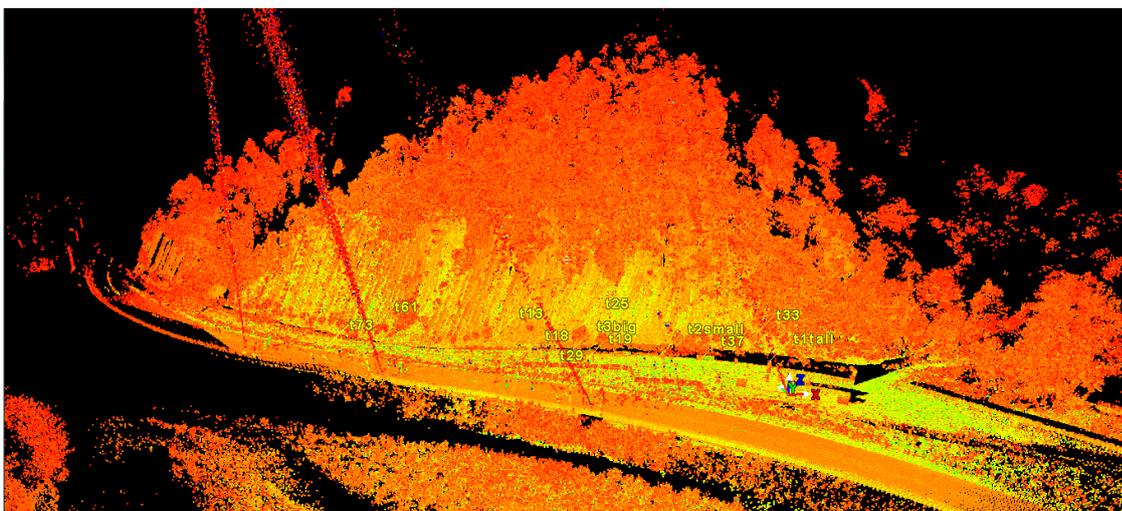


Figure 11: The complete scan after registration in Cyclone. The colour represents intensity.

Further processing of the data was done in the free pointcloud software CloudCompare. (21) The data can be exported from Cyclone as a ptx file. It can then be directly opened in CloudCompare.

4.3 Georeferencing

GNSS (Global Navigation Satellite System) data was collected in combination with the scans. This was done with Post-Processed Kinematic surveying using the Trimble R8 system. The system collects the latitude and longitude of its location. Its horizontal accuracy is approximately 1 cm. At targets that would be easily recognisable in the scan a large number of GNSS points was made. The data is shown in Google Earth in figure 12.



Figure 12: GNSS data in Google Earth

The coordinates were converted into UTM. The outcrop is located near the east border of the 31T UTM zone, so an error in the north direction of the UTM coordinates can be expected. The difference between the north direction in UTM and the true north can be measured in Google Earth by drawing a line with a constant easting (or x) value and checking the direction in degrees of the line. The UTM north is 1.72 degrees east of the true north at La Charce. The error in distance measurements was also looked at in Google Earth, but was too small to measure this way (certainly smaller than 0.05%) so this can be neglected.

After opening the model in CloudCompare six targets of which the coordinates are known were located. A text file containing the UTM coordinates of these points was created and also opened in CloudCompare. The pointcloud of the outcrop can then be converted to UTM coordinates by selecting both clouds and using `Tools/Registration/Align (point pairs picking)`. In this function the six points with correct coordinates are first selected, and then the six corresponding points on the outcrop model are selected. CloudCompare then aligns the two clouds. The error in aligning ranges from approximately 20 cm to 2 meters.

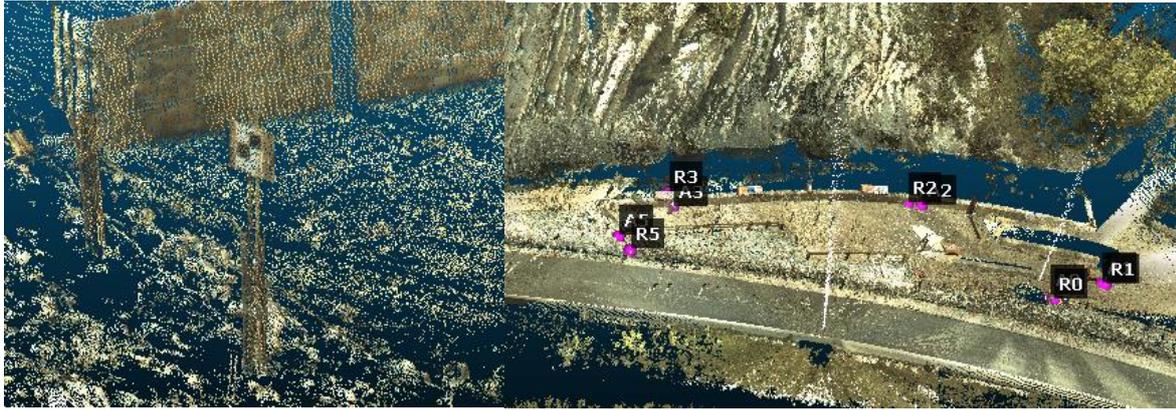


Figure 13: (a) an example of a target in CloudCompare (b) the target points after aligning

4.4 Creating a Mesh

To be able to import the model into Lime it needs to be converted into a mesh. However, the entire file has 72.5 million points. In order to make it easier to work with, both for the computer and for the user, several things can be done. Firstly, the seven individual clouds are merged into a single cloud by selecting them and using `Edit/Merge`. Secondly, there are large parts of the cloud that are not relevant for the outcrop model, such as the road, foliage, and parts of the outcrop that are very low in detail. The relevant part of the cloud can be cut out by using `Edit/segment`. Finally, if the pointcloud is still too large to work with it can be subsampled by using `Edit/Subsample` and choosing a maximum distance between points. This will remove points from regions where the density is high. This will obviously reduce resolution. After the La Charge cloud was merged and cropped it was running smoothly, so subsampling was not done.

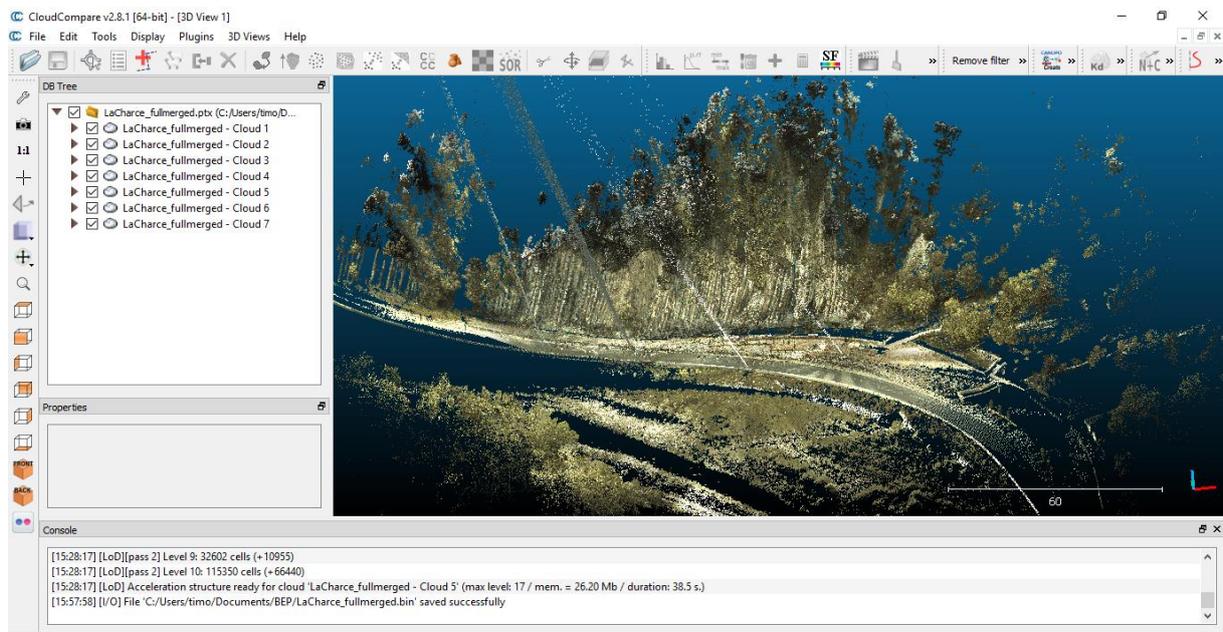


Figure 14: Outcrop model in CloudCompare

The easiest and fastest way to create a mesh in CloudCompare is to use Delaunay triangulation, `Edit/Mesh/Delaunay 2.5D` (best fit plane).

Applying this method to the La Charce model results in a mesh that looks good from some perspectives, but some parts of the model are distorted, especially the difference between limestone and marlstone layers. This is because the wrong points are connected when projecting the cloud to a flat surface, as described in chapter 3. The limestone layers protrude from the outcrop and the marlstone layers are more shallow between them, which makes it difficult to make an accurate mesh using this method.

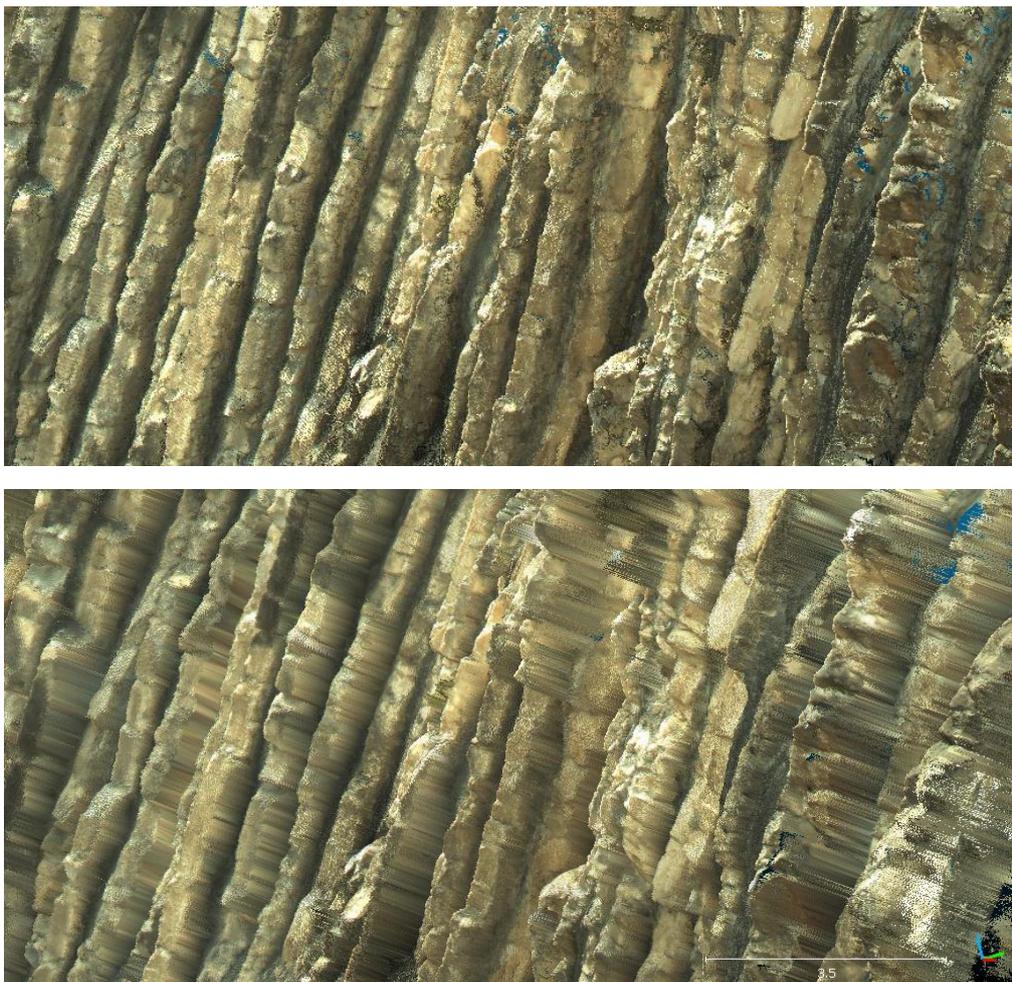


Figure 15: (a) Original point cloud (b) Result of Delaunay triangulation

The second mesh function in CloudCompare is the Poisson Surface Reconstruction. Before this is used, the normals of the surface have to be computed. In CloudCompare this is done by using `Edit/Normal/Compute`. The plugin for Poisson surface reconstruction can be found under `Plugins/Poisson surface reconstruction`.

The plugin uses octrees to work with the pointcloud. An octree is basically a division of space in cubes. Every cube can be divided into 8 smaller cubes. This way a model can be divided into small and large cubes depending on the amount of detail of that region.

As can be seen in figure 16a, the general structure is more clear than when using the Delaunay method. However, the surface of the model has a strange texture. Especially the plants on the outcrop appear strange. To get rid of erroneous parts, a density model was created at the same time that the triangulation was done. This model displays the density of points for any part of the mesh. A minimum point density can be chosen, so that the parts of the outcrop with low point density get cut out. As can be seen in figure 16b the worst parts of the model are removed, but this does not make the surface of the other parts look better, and there are now a number of holes in the model.

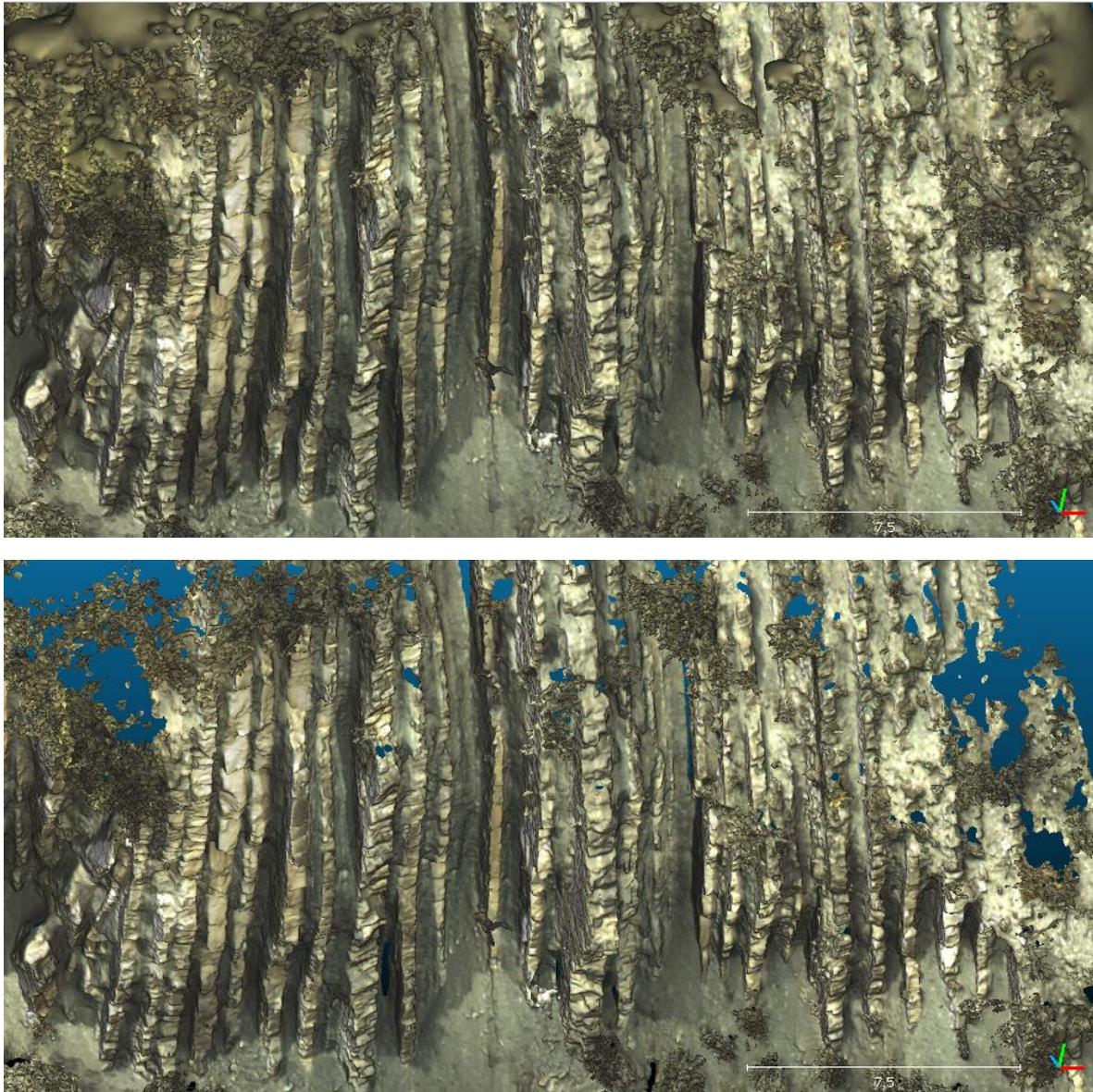


Figure 16: (a) Mesh after Poisson surface reconstruction (b) after density range was applied

A number of options were tried out to see the effect on the mesh. Changing the sample per node for the octree, calculating the normals with a different function or changing the boundary conditions for the Poisson function all had little visual effect on the mesh.

4.5 Creating a texture file with MeshLab

When transferring the mesh from CloudCompare to Lime, it was found that the colours of the model were lost, no matter what format the file was in. The problem seems to be that CloudCompare uses per vertex colours, meaning it stores the RGB values on the points of the triangles of the mesh. Lime uses textures which are saved separately from the 3D model. This has the advantage that multiple textures can be used on top of each other, and they can be individually manipulated.

Unfortunately CloudCompare does not have a function to convert the colours to a texture (since it is a program mainly for point clouds, not for meshes). In order to do this the free software MeshLab was used. After opening the mesh in MeshLab, use `Filters/Texture/Parametrization: Trivial Per-Triangle`. Next, use `Filters/Texture/Transfer: Vertex Color to Texture`. This creates a texture file. Finally, save the mesh (.obj was used). A .mtl file is automatically saved as well, which links the mesh file with the texture.

As a result of this process the texture consists of coloured triangles. They are small enough so that the mesh looks practically the same as with per vertex colour.

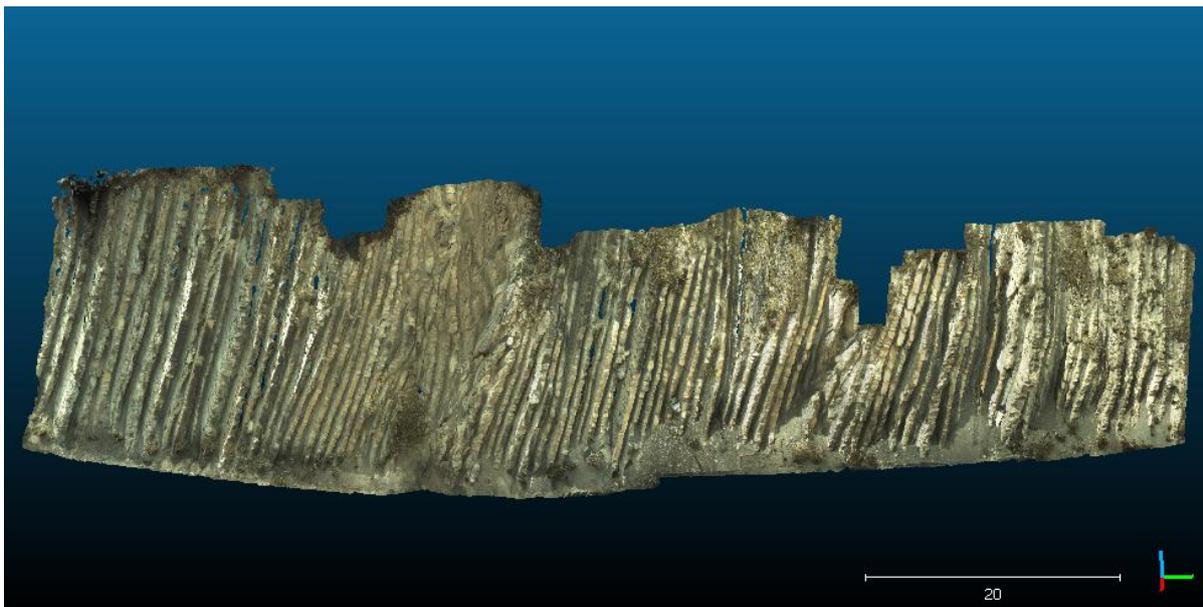


Figure 17: The resulting model

5. Lime Methodology

5.1 Importing models

In lime, the mesh model can be imported by using `File/Import 3D Model`. The table below shows the file types that are supported. Note that these file types can be used by other programs than just the source program for which they were initially intended.

File Extension	Source Program	Created by
.ply	general 3D modelling software	Greg Turk, Stanford University
.obj	The Advanced Visualizer	Wavefront Technologies
.ive, .osg, .osga	OpenSceneGraph	(open source)
.stl	stereolithography programs	3D Systems
.3ds	Autodesk 3ds Max	Autodesk
.dxf	AutoCAD	Autodesk
.shp	GIS software	Environmental Systems Research Institute
.dae	general 3D graphics software	Khronos Group

As described in the previous chapter, the colour of the model should be in a texture file, not in per vertex colour. Lime uses textures that are projected on the 3D models. Textures can be placed on top of each other, and the opacity of each can be adjusted so that multiple textures are visible at the same time on the model.

When the model was imported into Lime, the texture looked gritty. To solve this the minification filter needs to be changed to 'nearest' or 'linear'. The minification filter can be found by right clicking on the model and choosing `Display Settings`, under the properties tab.

5.2 Texture Functions

In Lime a number of properties can be shown as a texture on the model. These can be found by right clicking on the model and going to `Display Settings`. Clicking on add layer gives the following options.

1. Elevation (Z)

This function simply colours the model by height. After adding the layer, go to the colour tab and click on Calculate Range. This gives a useful indication of the size of the outcrop.

2. Dip/Slope

This layer shows how steep the model is at every point. Note that it does not show the dip of the stratigraphy but only the slope of the landscape.

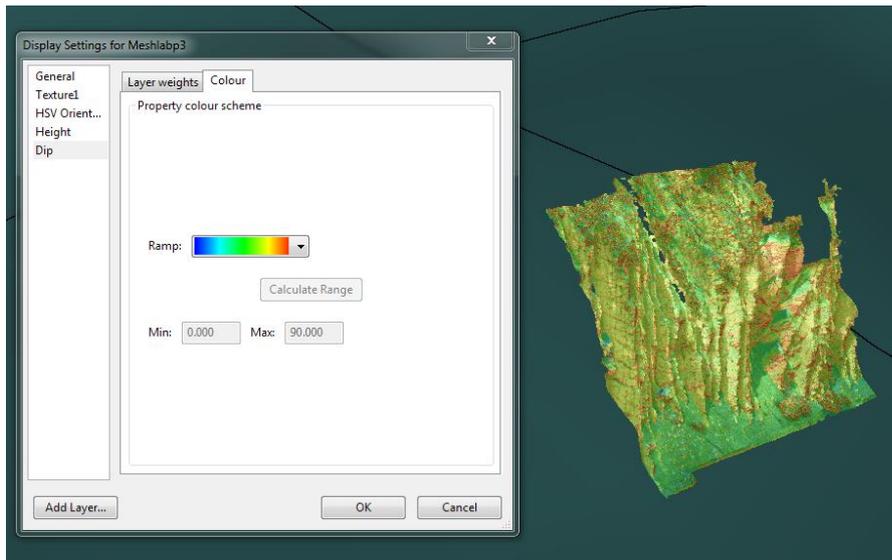


Figure 18: Example of dip shown as a texture

3. Dip direction/aspect

Shows the direction of the slope of the model. The range is from 0 degrees to 360 degrees. As a result, directions that are slightly west of north (slightly less than 360 degrees) get a very different colour than directions slightly east of north (slightly more than 0 degrees) even though they are similar.

4. Strike

In principle the same as Dip direction/aspect, but shows the orientation of the strike, which is perpendicular to the dip direction.

5. Dip*Dip direction

Calculates the dip multiplied by the dip direction. Values are between 0 and 1. The purpose is to display information on both dip and dip direction in one image. However, it is ambiguous because a single value can be the result of multiple combinations of dip and dip direction.

6. HSV Orientation

HSV stands for hue saturation value. In this function, the dip direction is coloured by hue, and the dip is coloured by saturation. This means that gradual slopes are coloured almost white and that steep slopes are coloured brightly. This allows both parameters to be displayed in one image.

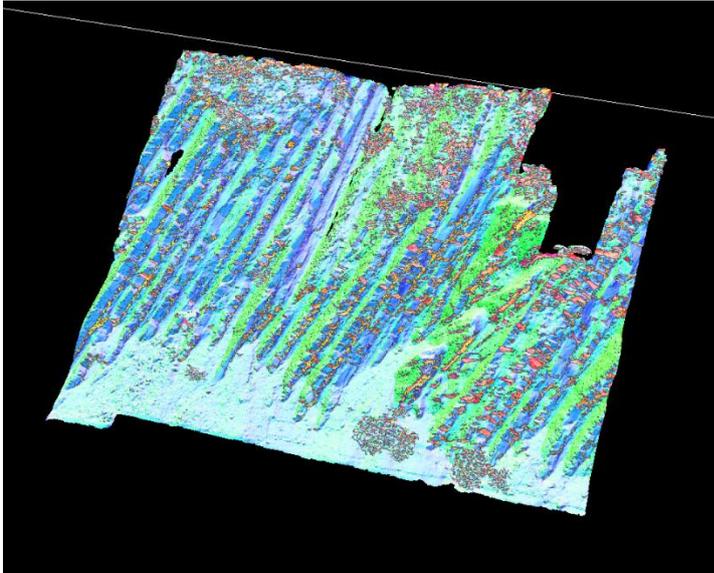


Figure 19: Orientation and dip in one image. The bottom of the slope is gradual, so it is coloured white.

7. Contours

Creates contour lines on the model. The interval, colour and line width can be changed in the properties tab.

8. Grid

Projects a top down grid on the model. This is useful to do on the DEM, because it accentuates the shape of the landscape, and it gives a useful scale to see the size of objects on the DEM. The interval, colour and line width can be changed in the properties tab.

9. Datum line

Creates a single line that follows the contour of the model at a chosen height. The height, colour and line width can be changed in the properties tab.

5.3 Tracing the stratigraphy

One of Lime's main features is the ability to highlight the different stratigraphic layers. This can be done by tracing a three dimensional polyline on the model. The function can be found under `Measure/Create Line`. The line is created by holding the shift button and clicking on the model to create the points.

It is possible that one of the two layers at a boundary protrudes from the other (see figure 20). Different approaches can be used to trace such layer boundaries. The user can choose to draw the points of the line on the top layer, the bottom layer, or alternate between them. Only drawing on either the top or bottom layer (figure 20a) will result in the clearest visualisation. Alternating between picking points on the top layer and the bottom layer (figure 20b) will look much messier. However, it could be useful for determining the dip of the layers, since the points are chosen on the plane of the layer (see chapter Determining dip of layers).

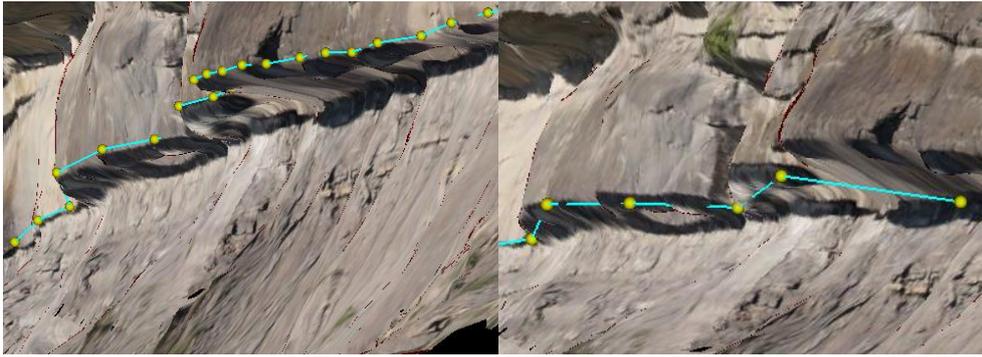


Figure 20: (a) Drawing a polyline on the top layer of the boundary (b) alternating between top and bottom layer. Image is of the Ainsa test data in Lime.

In some places it can be difficult to see the layer boundaries, so it can be helpful to use a texture function (chapter 4.2) to highlight these. It was found that using the HSV orientation texture with an opacity of 20% is useful.

The lines can be exported as .obj file or as ASCII file to be used in other programs. However, it is not possible to import a line in Lime, so they cannot be used in another project file as the one they were created in.

5.4 Projecting the stratigraphy

After all the relevant boundaries have been traced, it is possible to project the stratigraphy on a 2D panel. This can be useful to capture the whole sequence of layers in one image, and to project the image back on the model.

A panel is created by right clicking on the panels map and selecting create panel. The panel is created from 2 points and the XY helper plane should be selected. The panel is created by clicking on two points in front of the outcrop, in such a way that the panel stretches across the part of the outcrop that is of interest. It is also best to orient the panel so that it is perpendicular to the layers. This prevents the lines from overlapping, and results in the most accurate section. To help do this, planes can be created that correspond to the layers, by going to `measure/Structural Data from 3 Points`, and clicking on 3 points of the layer. Doing this multiple times along the length of the outcrop can help to orient the panel perpendicular to the layers, see figure 21.

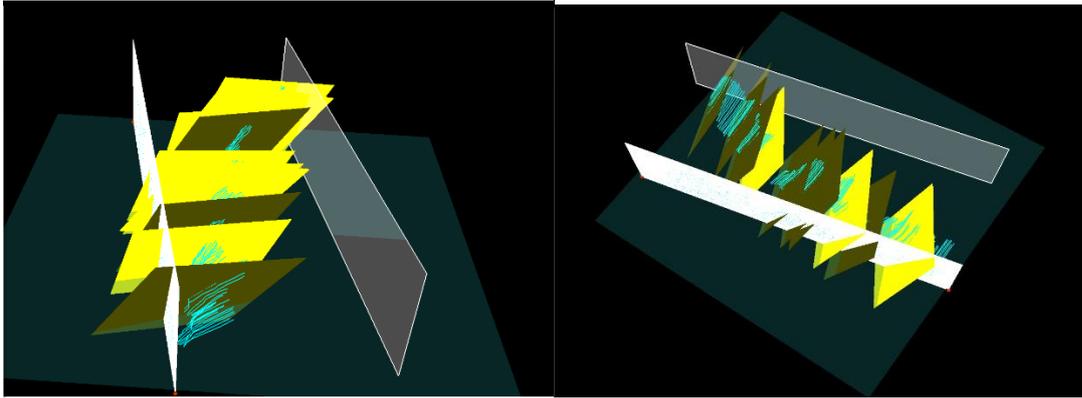


Figure 21: The blue lines are projected on the white panel. The yellow planes correspond to the orientation of the layers. The grey panel shows the range of projection.

The panel is oriented vertically. In the render to texture settings, change the min range and max range so that the outcrop falls within the range. The panel can also be inverted so it faces the right way. Select the Lines option so the polylines are projected on the panel. The pixel size generally needs to be decreased so the section is increased in detail. When the settings are correct click OK to create the panel.

This results in a panel to which all the polylines that are displayed are projected. The panel can be exported as an image file by going to the display settings of the panel, right click on the texture and choose Export layer texture. In an image processing program details can be added to the section, such as coloured layers, names of layers or any other notes. It is possible to project the new section back on the outcrop model. To do this, right click on the name of the panel that was used to create the section, and select Add Overlay Texture. Select Image File as the overlay type, and choose the image of the modified section. It is important that the size of the section was not changed as it was modified. Click OK, the section should now be visible on the projection panel. Now right click on the outcrop model name and select Add Overlay Texture. The overlay type is now Project Object Texture. Select the panel of the section as object and click OK.

5.5 Determining dip of layers

Since sedimentary layers are planar, they can be described by two values: the dip and the dip direction. The dip is the steepest angle of the plane with the horizontal, measured in degrees. The dip direction is the direction the dip points towards. It is measured in degrees starting from north and going clockwise.

In Lime it is possible to determine the dip of layers by creating a plane. This is done by choosing `Structural Data from 3 Points` in the Measure menu. As the name suggests, the user can choose 3 points anywhere on the model and a plane is fitted through these points. The dip and dip direction are then displayed, and the plane can be saved. This is a very quick method, but it is possible that the dip and orientation are different depending on what part of the layer is used. It is not possible to fit a plane to more than 3 points in Lime.

Therefore it could be difficult to determine the dip that represents the formation most accurately. One possibility is to use the plane function many times, but this is time consuming.

Another possibility is to use the polylines that are drawn previously on the stratigraphy. These lines can be exported in an ASCII format, as a list of xyz coordinates. A script was made in Matlab to calculate the dip using these files. The entire script can be found in the appendix.

After the coordinates are loaded in Matlab, a for-loop is created that does the calculations for every possible combination of three points. Firstly, the coordinates of point A are subtracted from point B, and from point C, resulting in two vectors. The cross product of these vectors is then calculated. The resulting vector is perpendicular to the plane. The dip and dip direction of the plane are calculated from this vector. 1.72 is subtracted from the dip direction to compensate for the difference between the UTM north and true north. After this calculation is done for every combination of three points, the results are plotted in two histograms.

This script can be used for a single layer, or it can be used on all the lines that were drawn in Lime. This shows whether the layers all have a similar or different orientation.

If the three points are too much in line with each other, they could give an erroneous dip and orientation. In this case the plane that is formed by the points only gives an apparent dip. These errors can be spotted by a lower dip than average, and a different dip direction than usual.

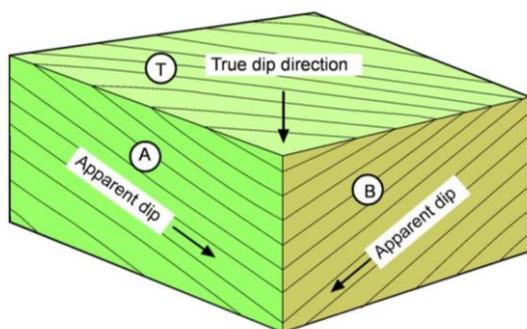


Figure 22: Apparent dip and true dip (3)

Another error that can occur is that the three points are chosen in such a way that they form a plane with the orientation of a joint or of the front of the layer (see figure 23). This is usually when the three points are close together. These errors can be easily spotted by their very different dip direction, often 180 degrees opposite to the true dip direction. The dip can also be very different, but this depends on the orientation of the layer.



Figure 23: Three points resulting in a wrong dip. The yellow plane illustrates the dip that was calculated by the three points. It is perpendicular to the layers.

5.6 Using planes to show the layers

In addition to using the projection method previously described, planes can be created to show the stratigraphy of the outcrop (figure 24). This is done by choosing `Structural Data` from `3 Points` in the `Measure` menu. This has as an advantage that the plane size can be adjusted, so the layers are extrapolated. However, it is difficult to use with layers that are not completely flat, and if there is a large number of layers in the outcrop it becomes visually confusing.



Figure 24: Planes visualising the layers (25)

5.7 Determining layer thickness

To measure the layer thicknesses in Lime the polyline function has to be used again. Two points can be drawn on the layer boundaries and the length of the line is displayed. One polyline can be drawn through all layer boundaries to collect the thicknesses in one file. This can then be exported and opened in Matlab, where the data can be analysed. The script that was used to create diagrams from the Lime data in Matlab can be found in the appendix.

5.8 Incorporating other data

DEM

A digital elevation model is a 3d model of a terrain with the purpose of showing the elevation. DEM's are often made with similar techniques as previously described (Lidar and photogrammetry) but usually with airbourne or satellite technology.

A DEM can be imported into Lime just like a 3D model of an outcrop. This also creates the option to import multiple outcrop models and see their locations relative to each other. This is potentially very useful, since geologists often use multiple outcrops to interpolate and predict the presence of certain rock formations in areas between outcrops. If the outcrop models can be captured in one model it is possible to examine how they fit together.

For this project ASTER GDEM was used. This stands for Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model. ASTER is a device on NASA's Terra satellite created by the Ministry of Economy, Trade and Industry of Japan. It is used to create images of earth for a variety of purposes, including digital elevation models. It has an accuracy of approximately 17 meters with a confidence level of 95%. (17)

To incorporate a DEM into Lime it needs to be turned into a mesh just like the laser scan model. ASTER GDEM was opened in CloudCompare as a TIF file. It is already in UTM coordinates. At this point it is basically an image file with one colour value for every point, which corresponds to the elevation at that point. To turn it from a 2D image into a 3D pointcloud use Edit/Scalar Fields/Set SF as coordinate(s), and select z. The cloud is then made into a mesh using Edit/Mesh/Delaunay 2.5D (XY plane). It can be exported from CloudCompare as a PLY file and then imported as a 3D model in Lime.

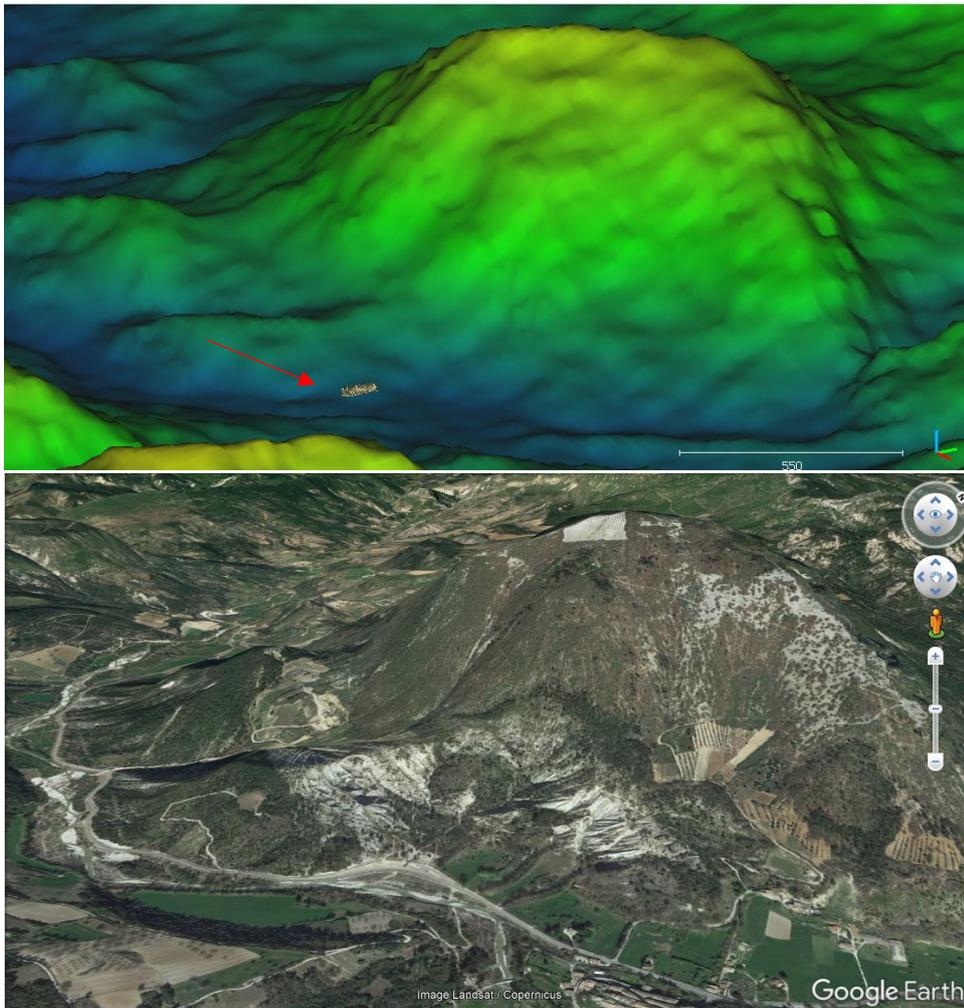


Figure 25:(a) The La Charce model on the DEM in CloudCompare (b) the same location in Google Earth

Images

Images can be loaded into Lime by creating a panel and selecting the image file option. The panels can be located so they intersect the model. This allows geophysical images from different sources to be incorporated, such as electrical resistivity, ground penetrating radar or reflection seismology. Photographs from the fieldwork could also be shown, for example fossils or details of faults and folds. Another option is to add logs that show the stratigraphy found in the area, taken from literature. Georeferenced images can also be imported with their coordinates, for example a satellite image of the surroundings.

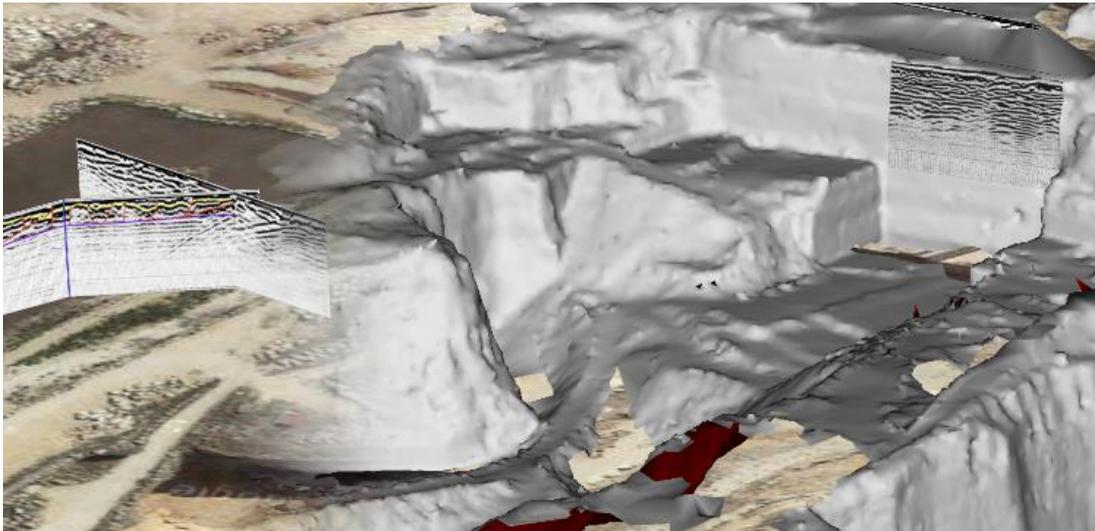


Figure 26: Ground Penetrating Radar (GPR) images in Lime (24)

6. Lime Results

6.1 Layer visualisation

Figure 27 shows the lines that were drawn on the model model to show the stratigraphy. The area between the lines was coloured red for limestone and blue for marlstone, and projected back on the model as seen in figure 28. There is one place where there is a gap in between the lines (figure 28 where there is no colour), this is because there is a lot of deformation here so interpretation is difficult.

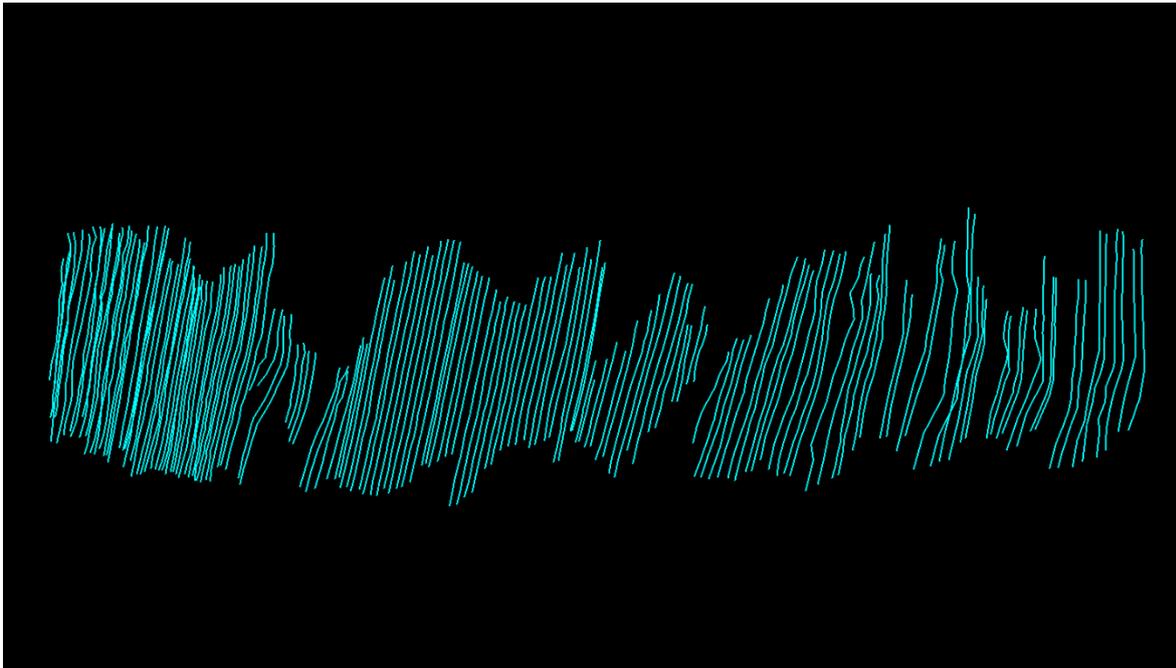


Figure 27: Lines drawn on the layer boundaries

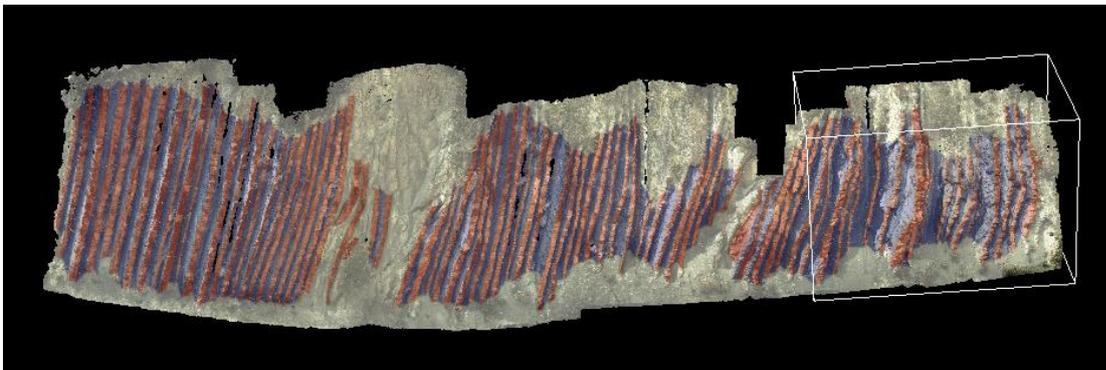
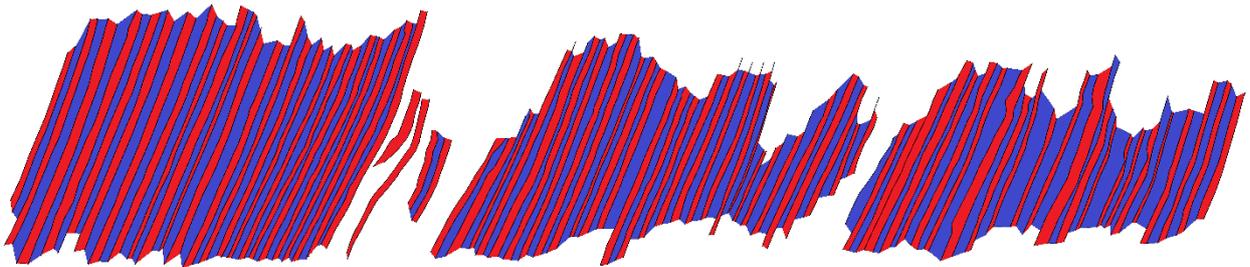


Figure 28: Layers projected on the model

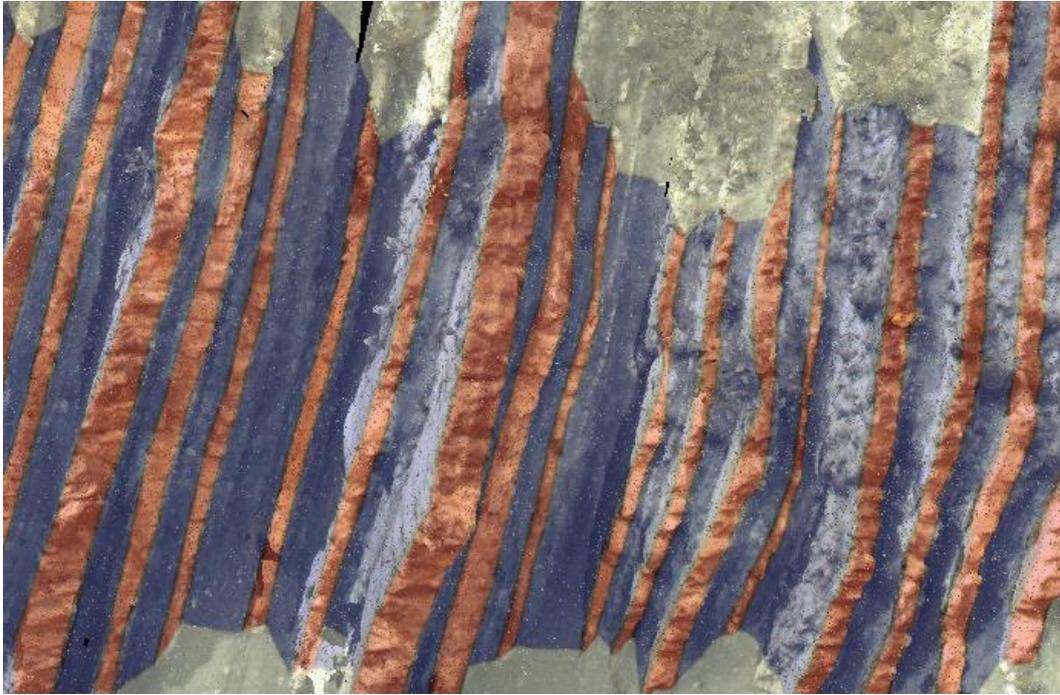


Figure 29: Layer visualisation in more detail

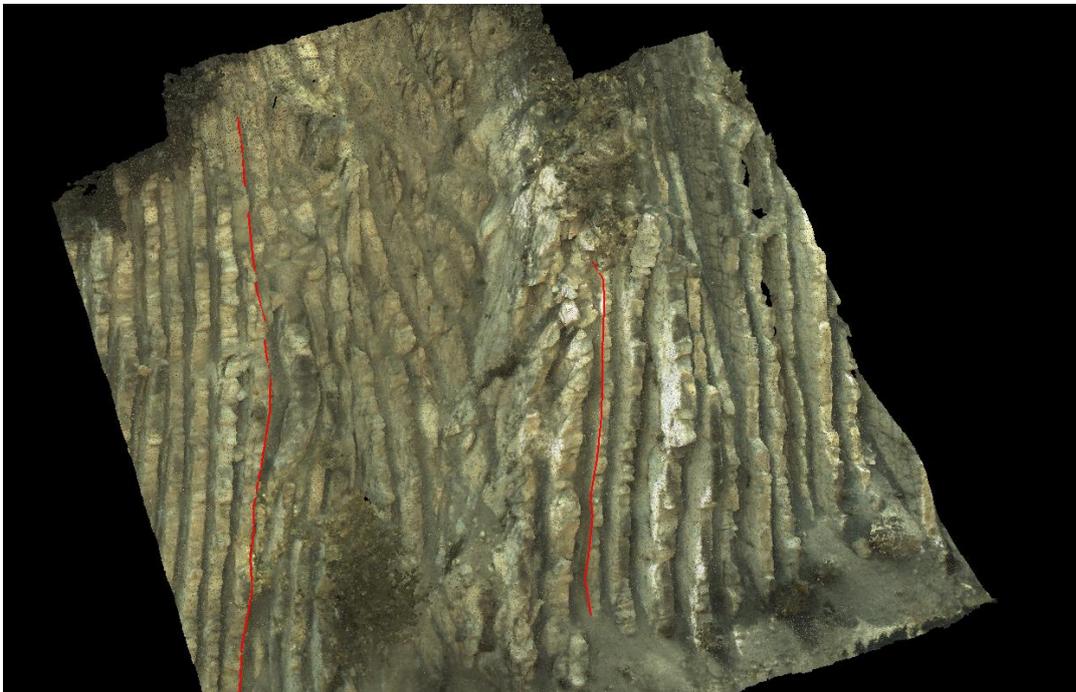


Figure 30: Closer look at the part with deformation

6.2 Dip and dip direction

The lines were exported to matlab as ASCII files to calculate dip and dip direction. Some of the lines that were drawn on the layers were in regions with deformation, so their points were uncertain or did not lie on a plane. The red lines in figure 31 were separated before calculating the dip and dip direction.

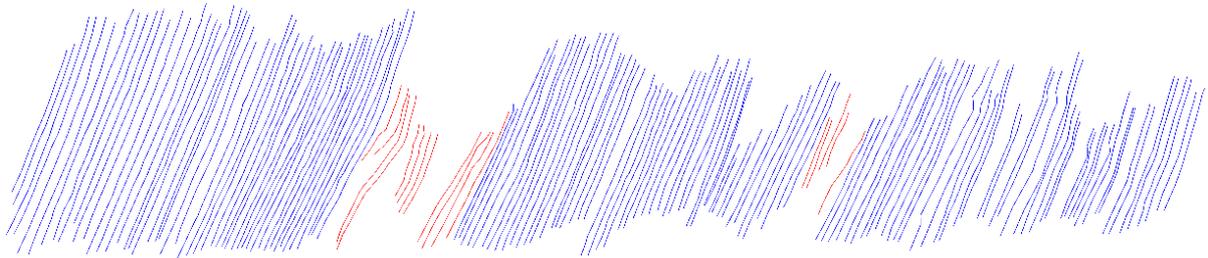


Figure 31: Red lines are in deformed regions

In total 143 blue lines were used to calculate the overall orientation, consisting of 2023 points on the model. For every line every combination of 3 points was used, resulting in 73907 combinations of dip and dip direction. The results are plotted in the following histograms.

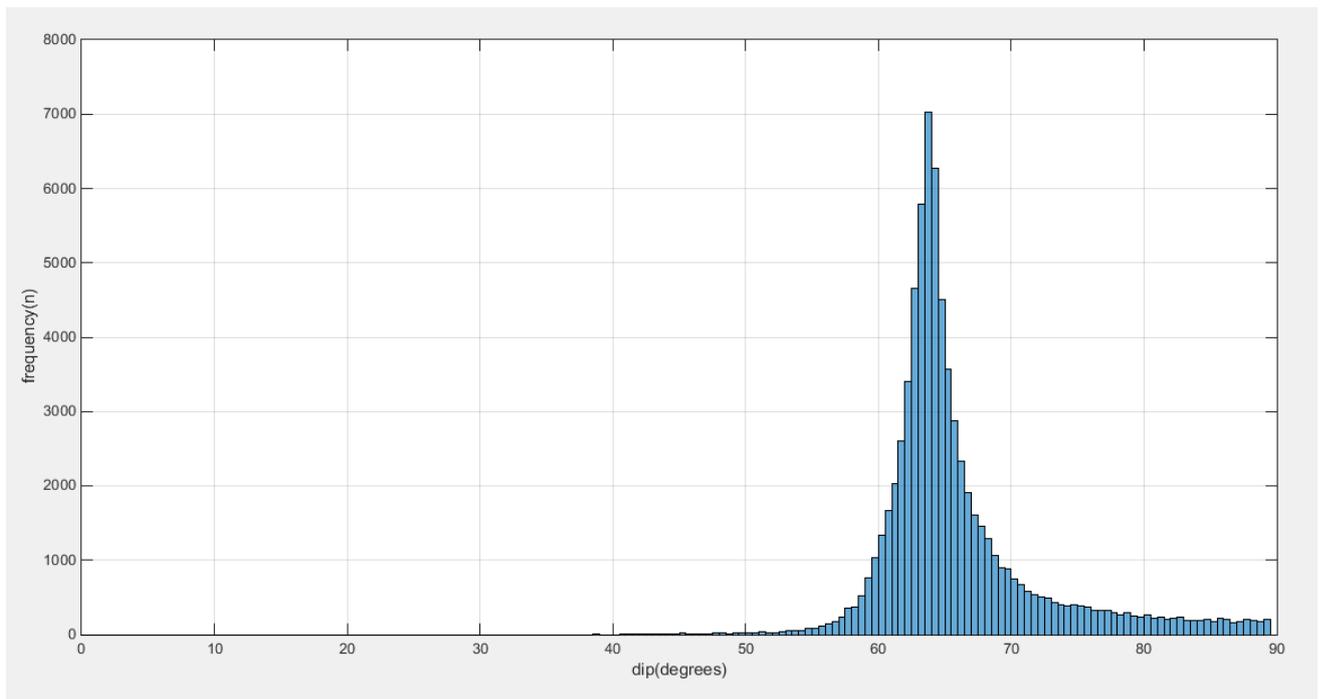


Figure 32: Histogram of the dip of the the complete outcrop (Matlab)

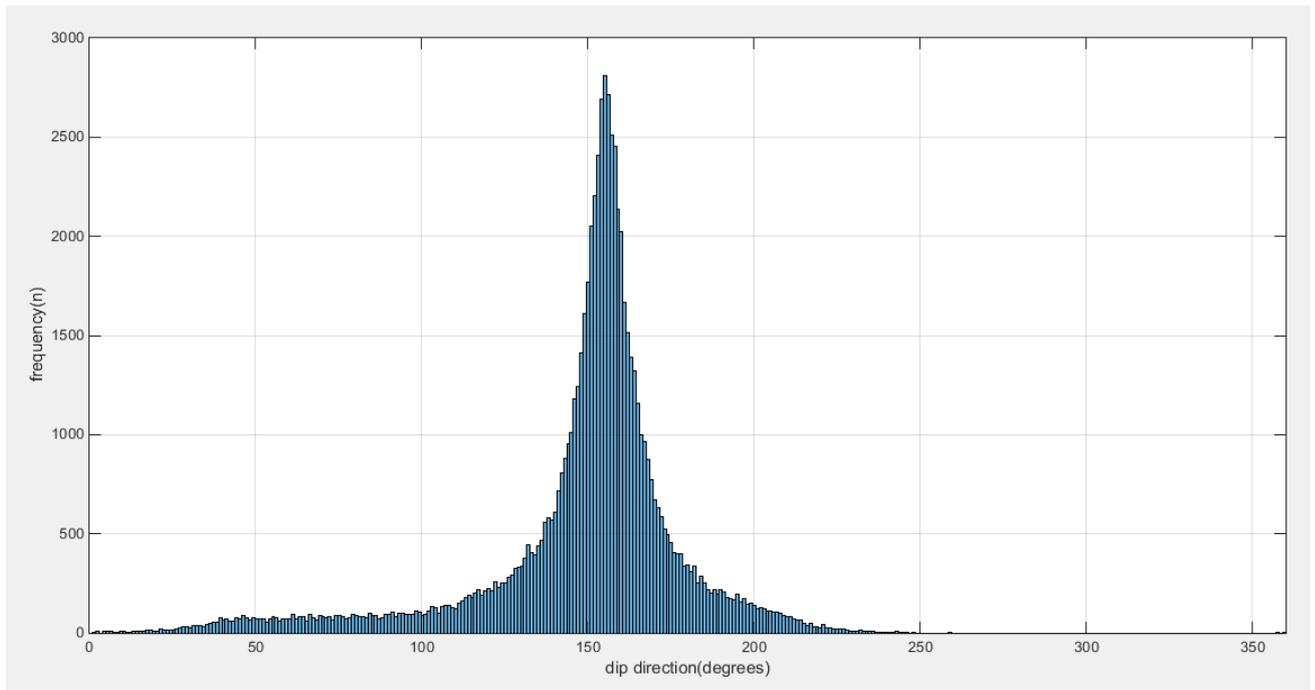


Figure 33: Histogram of the dip direction of the complete outcrop (Matlab)

With bins of 0.5 degrees width the most frequent dip is 63 degrees and the most frequent dip direction is 155 degrees. Most of the data is centred around these values, but in addition there are some orientations with a dip of 75-90 degrees and direction of around 40-80 degrees. These probably correspond to the orientation of the front of the layer (as depicted in figure 23 in chapter 5.5) because they have a very steep dip and a direction that is approximately perpendicular to the real dip direction.

The mean dip is 66.08 degrees. The standard deviation is 6.25 degrees.

The mean dip direction is 149.01 degrees. The standard deviation is 30.69 degrees.

E. Prentice determined an average dip of 64 degrees and an average dip direction of 157 degrees.
(19)

It is possible that as a result of some geologic process the orientation is different depending on what part of the outcrop is looked at. It can be interesting to look at the layer orientation of the layers to the left of the deformation and the layers to the right, to see if they are different as a result of the deformation.

Comparing the two sets of layers in figures 34 and 35 shows that they are very similar. The dominant dip and dip direction are still 63 and 155 degrees. The distribution is slightly different, for example the dip direction to the left of the deformation has more outliers. However, this is probably a result of other factors, such as detail of the model, length of the layers or distance between the points that form the lines.

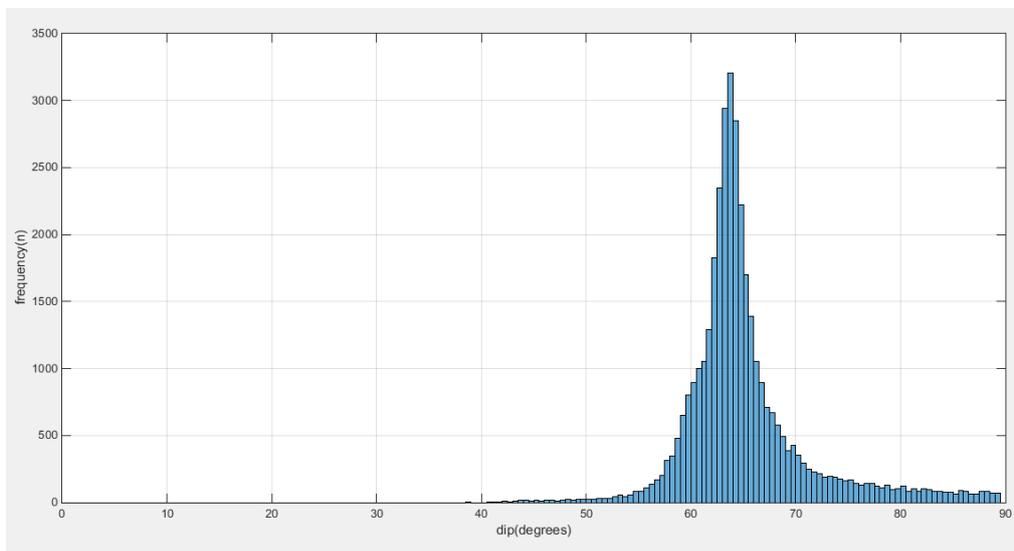
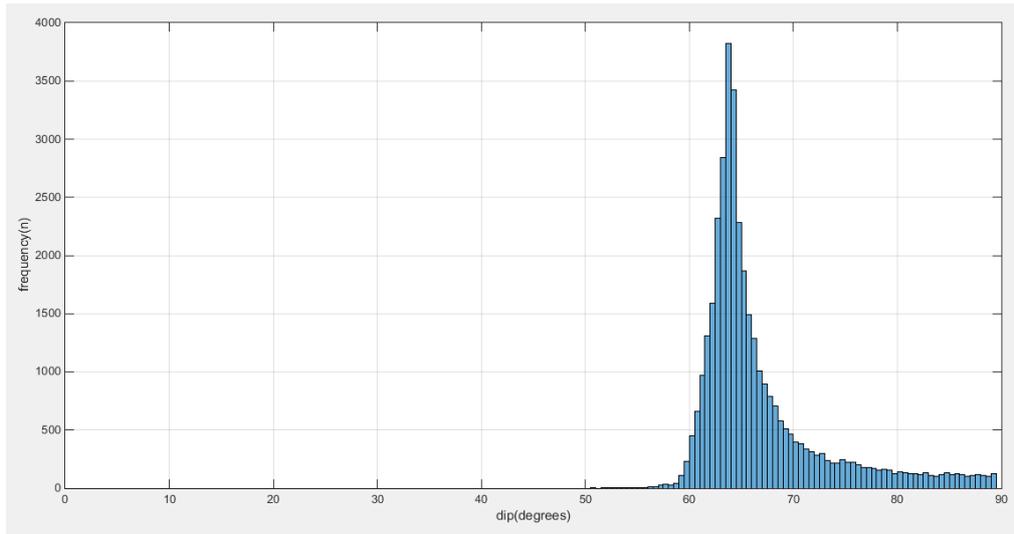


Figure 34: Dip of the layers to the left of the deformation (top) and to the right of the deformation (bottom)

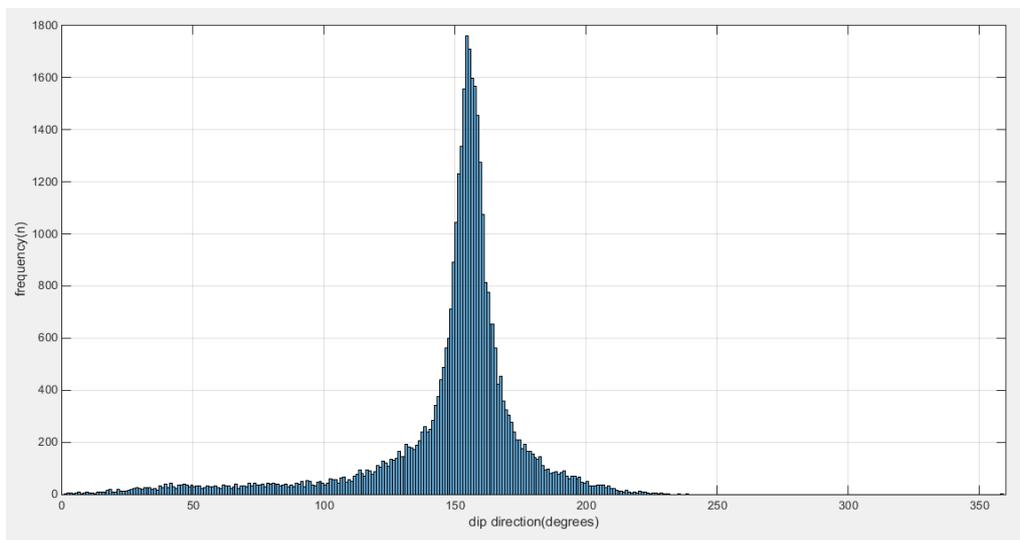
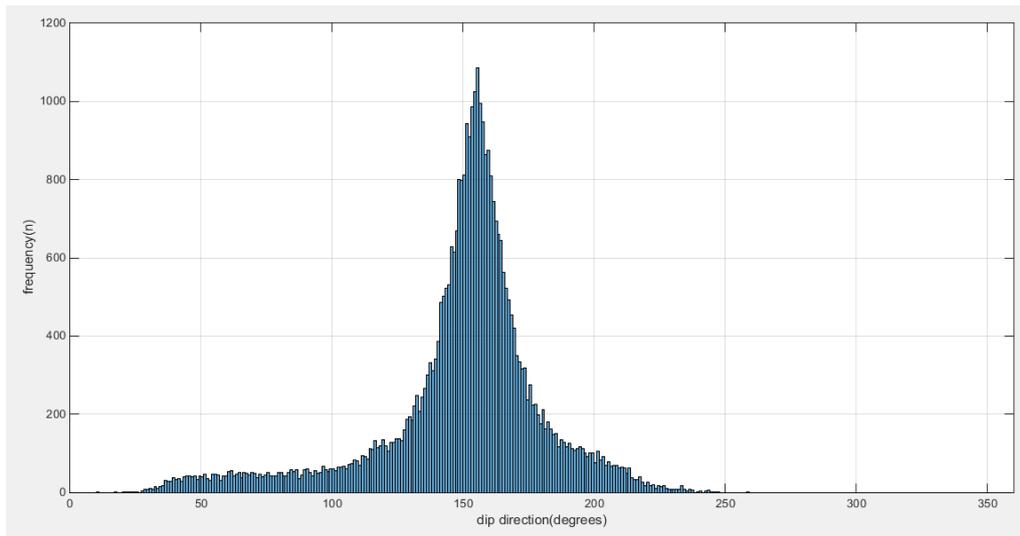


Figure 35: Dip direction of the layers to the left of the deformation (top) and to the right of the deformation (bottom)

6.3 Layer Thickness

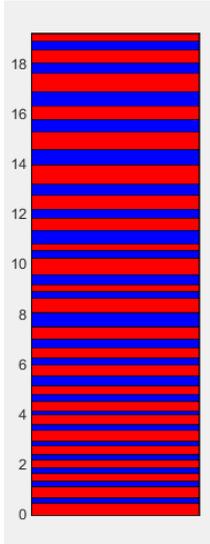


Figure 36 shows the polyline that was used to measure the layer thicknesses. It moves up and down depending on what part of the model showed the clearest layer boundaries, to be able to measure the thickness more precisely. The resulting logs (figure 37) show the thickness of the layers in meters. Red layers are limestone, blue layers are marlstone. The logs are in three parts, since between these were parts with deformation where it was not possible to measure accurate layer thicknesses. The bottom layers in the log are located on the right in the outcrop.

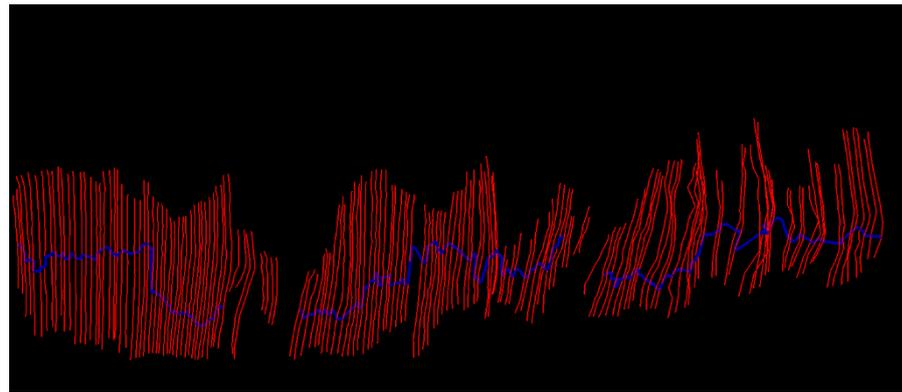
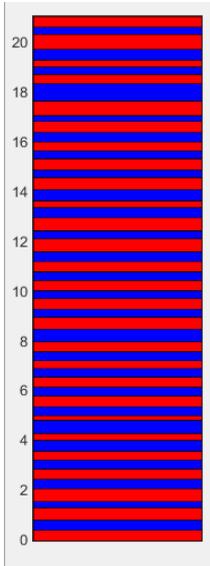


Figure 36: Red lines follow the layer boundaries, blue lines were used to measure the layer thicknesses

Figure 38 shows all layer thicknesses in bar charts, figure 39 shows the histograms of the layer thicknesses.

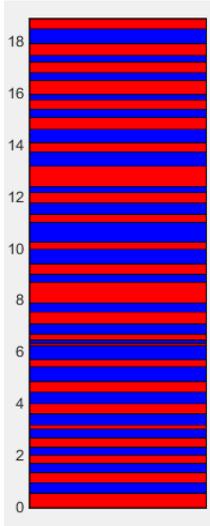


Figure 37: Logs of the outcrop (divided in 3 parts)

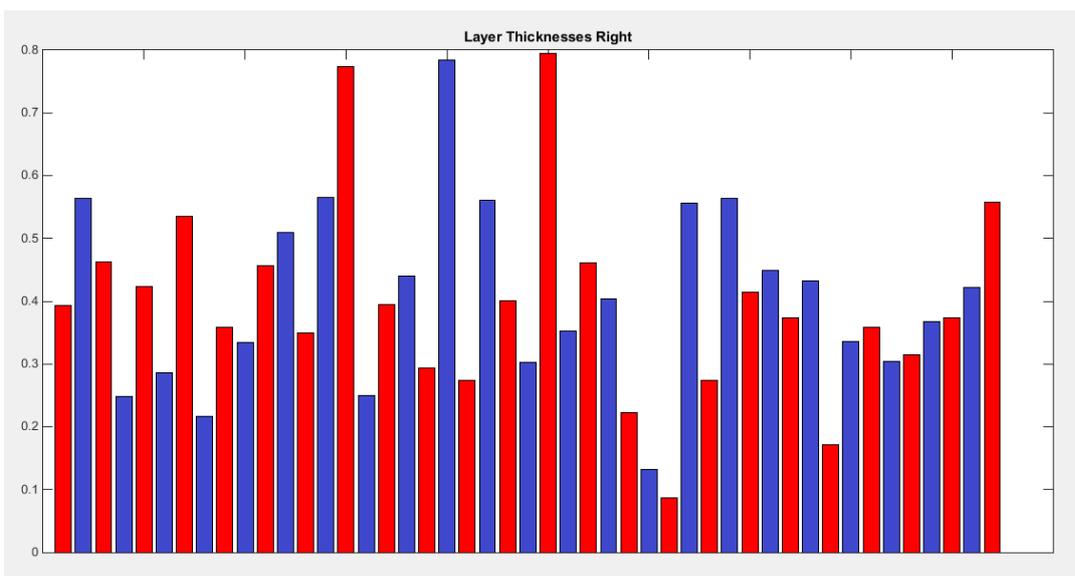
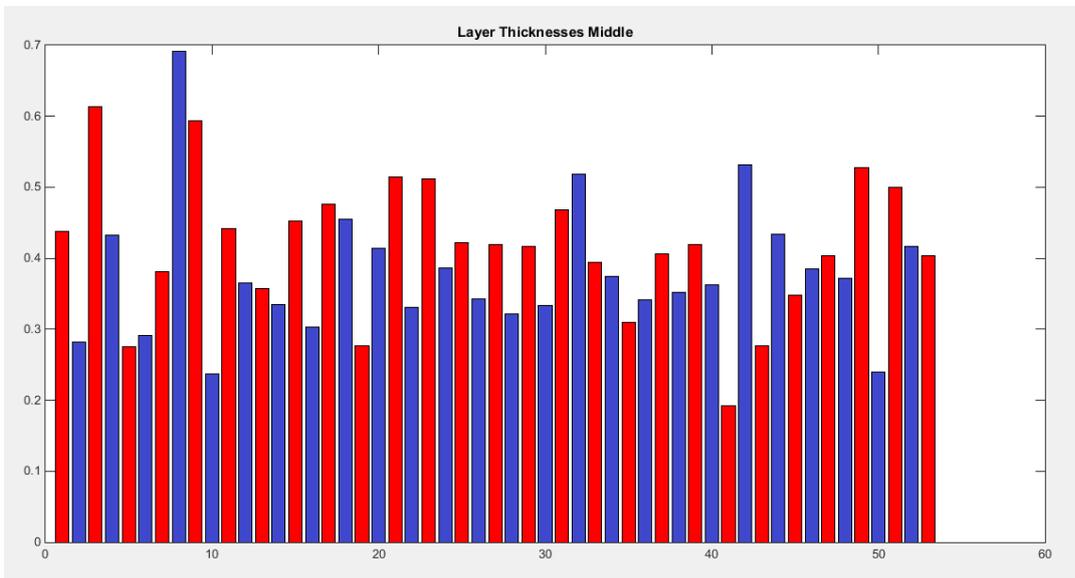
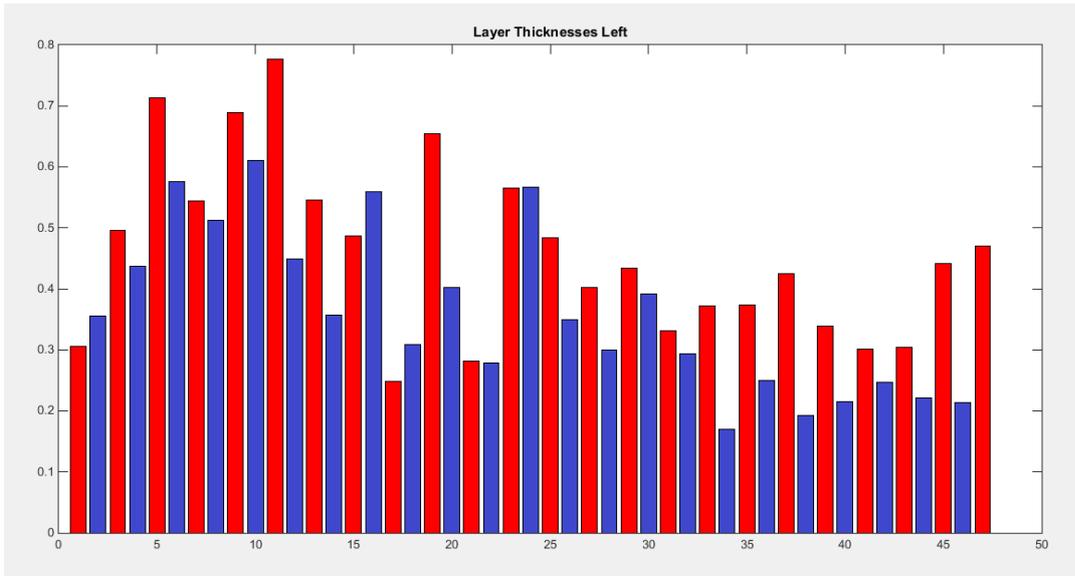


Figure 38: Bar charts showing every layer thickness in meters.

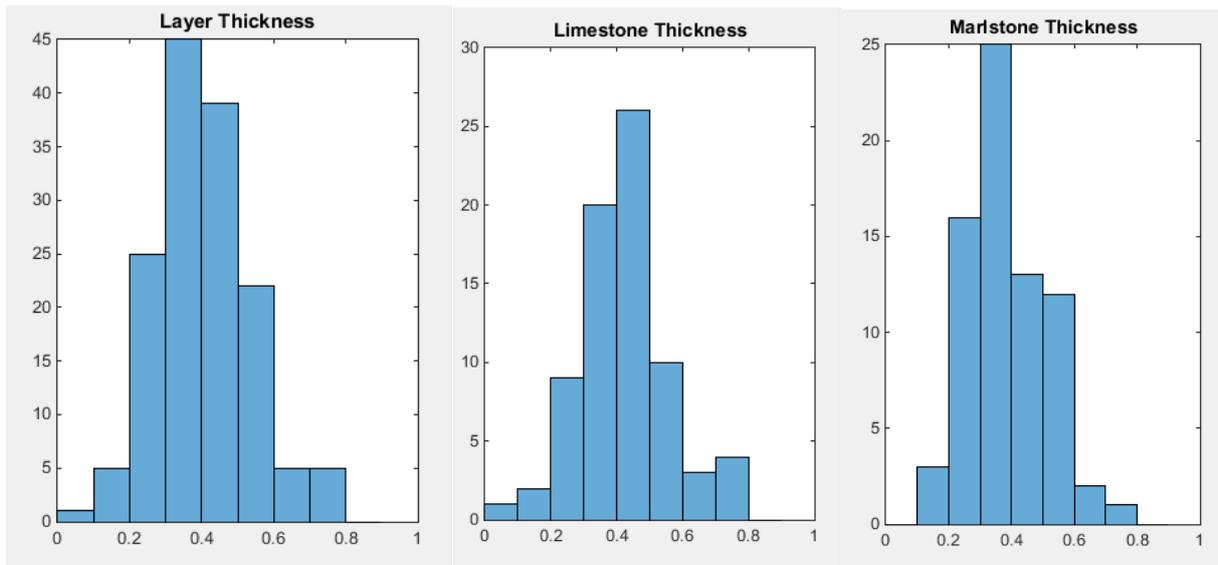


Figure 39: Histograms for layer thicknesses in meters: (a) all layers (b) limestone layers (c) marlstone layers

6.4 DEM

The following images show the model placed on the DEM in Lime. The model is slightly elevated to prevent it from intersecting with the DEM. A grid was added to the DEM with intervals of 50 meters.

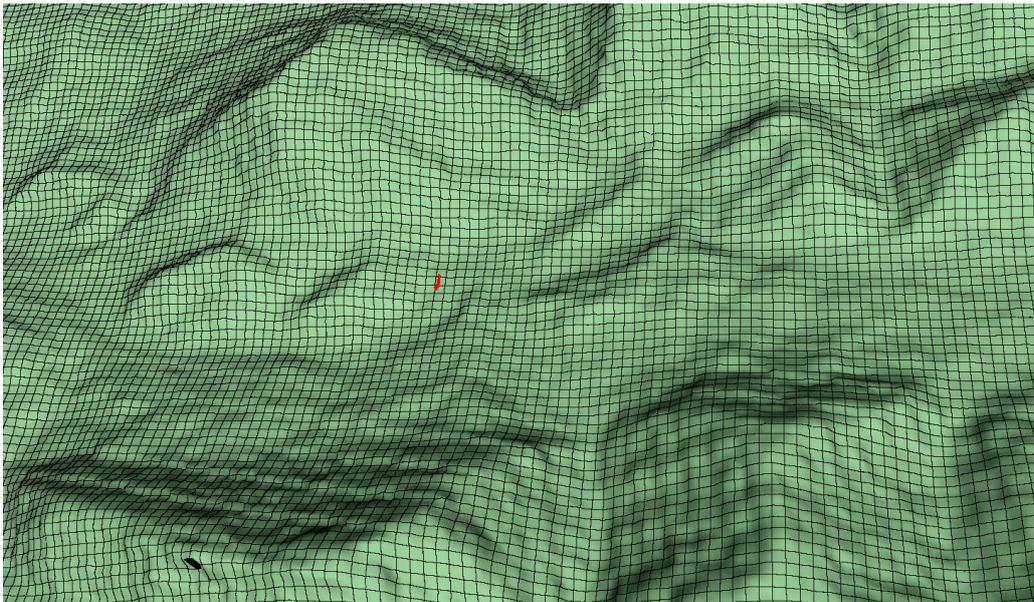
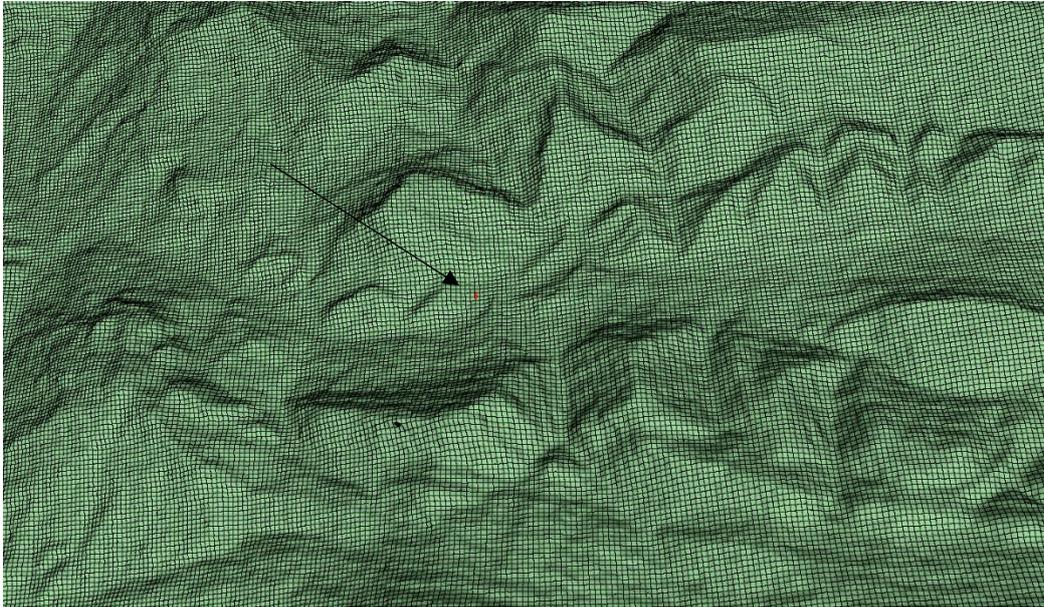


Figure 40: The model in on the DEM in Lime. The model was made red to make it more visible.

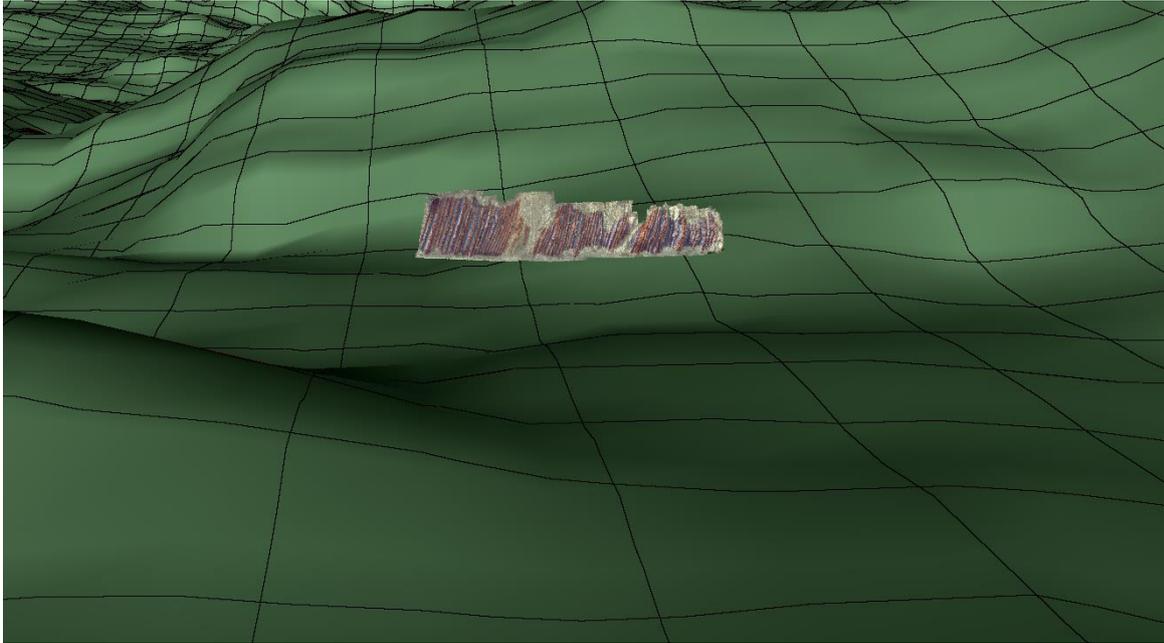


Figure 41: Model on the DEM in Lime, with the layers of the outcrop coloured.

7. Conclusion/Discussion

7.1 Research questions

1. What processes are necessary to convert laser scan or photogrammetry data into a usable configuration in LIME?

The processes to convert the raw laser scan data to Lime consisted of registration, georeferencing, mesh creation and converting to a texture file configuration. Cyclone was used for registration, CloudCompare for georeferencing and mesh creation and Meshlab for creating a texture file.

Registration was quickly and easily done in Cyclone. The errors in registration are between 0.004 and 0.02 meters.

Georeferencing was done using GNSS measurements of targets. The errors in georeferencing were between 0.2 and 1.7 meters, which is much larger than the accuracy of the GNSS device. This is probably because the targets have to be located in the point cloud manually. However, these errors only have an influence on the placement of the model on the DEM and the calculation of the dip direction. In both cases the influence of these errors is expected to be small, since the outcrop itself is approximately 100 meters wide.

Delaunay triangulation and Poisson surface reconstruction were tried for meshing. Poisson surface reconstruction resulted in a better model. The result was satisfactory enough for the purposes of this thesis, but definitely not perfect. Apart from the two that were discussed, many different methods for meshing exist. Software that is more specialized for meshing can be used to create a model with higher quality.

2. To what extent can Lime be used for interpretation and visualisation of geological features?

Lime contains the following functions for visualisation and analysis.

- Using polylines to draw on the outcrop model and extract geometrical data
- Project images on the outcrop model to visualise interpretations
- Create textures on the model that visualise height, slope or direction.
- Create planes that intersect the outcrop, for example at layer boundaries and measure their orientation
- Insert images of geotechnical analyses, literature or field observations as panels
- Import other 3D models, such as different outcrops or digital elevation models
- Import georeferenced images such as satellite images

Geometrical calculations have to be done either one by one or in another program (the dip, dip direction and layer thickness calculations). It is also not possible to import lines or planes unless their parameters are manually filled in in Lime.

Using Lime to visualise multiple outcrop models by placing them on a DEM is in theory possible. However, it is expected this will slow down the program significantly (see chapter 7.2). On a regular computer it is not practical to import multiple models that were created by the process described in this report, but if the file size can be decreased enough it should be possible.

Another practical issue with multiple outcrops is that the zooming in Lime adjusts to the size of the models. When the DEM was loaded together with the outcrop model, it became difficult to look at small details on the outcrop because the camera settings adjusted to the DEM.

3. Can Lime be used to measure geological features?

Exporting the layer boundary lines and using the script that was made in Matlab gave a distribution of dip and dip direction. The method resulted in a large amount of data for what would normally be measured only a few times in the field. Now it is possible to say something about certainty of the measurements, and about variation in these parameters between different parts of the outcrop.

There is a difference between the most frequent values and the mean values, caused by erroneous values with a dip that is too high and orientation that is too low. These can be explained by some planes describing the edge face of the layer rather than the layer itself, see figure 23 in chapter 5. This also contributes to relatively large standard deviations. As a result, the most frequent values are probably more representative of the orientation of the formation than the mean values.

The method for measuring the layer thickness is less reliable than the method for dip and dip direction. This is because only one value was calculated per layer. The line for measuring the thickness also had to be perpendicular to the layer, and on a section that was representative (not partly eroded or deformed). The thickness of the layers is in theory connected to the periods of Milankovitch cycles, so it is an interesting parameter to examine. However there is not a clear pattern visible in the data, except that the thicknesses in the 'middle' section are more constant (see figure 38).

7.2 Programme speed

The laptop became very slow when the La Charce model was loaded. To be able to work with it the model was separated into four parts. Most of the time only one part was made visible to improve the performance, which made the program run ok, even though the framerate was low. When the entire model was visible at the same time it became

practically impossible to move the model around, so this was only done when capturing images.

The virtual outcrop group who created Lime recommend a dedicated GPU for running the 3D graphics and at least 4GB of RAM (but preferably 16GB) for larger datasets. The laptop that was used to run the program has a dedicated GPU, and 4GB of RAM.

The La Charce model that was created has a size of 1.658 GB, which could be the cause of the slowness. A test dataset is available for Lime, called AinsaProject. The laptop was able to run this project in Lime smoothly. The outcrop in this project is of comparable size to La Charce, and the model has sufficient detail. However, the size of the file is only 153 MB. It should therefore be possible to create a model with a much smaller file size. Subsampling can be a way to achieve this quickly, although this will result in a lower resolution.

7.3 Comparison with other software

A large part of the processing was done in CloudCompare, and this programme can also be used for analysis of virtual outcrops. Polylines and planes can be created just like in Lime, but they can also be imported. In addition it includes a lot more functions for geometry and statistics, such as calculating normals and distances, fitting planes and creating cross sections. There is also a plugin that automatically detects facets and fractures which can be used on the layers. Inserting images as planes and projecting images on the model is not possible however. Texture functions are also not possible, equivalent functions can be used on the pointcloud.

A wide variety of other 3D modelling software exists, but most not made specifically with geology in mind. Another programme that is made for virtual outcrop analysis is Virtual Reality Geological Studio, created by D. Hodgetts of the School of Earth and Environmental Sciences, University of Manchester. (26) VRGS works on point clouds and meshes. It has a similar functionality as Lime, using mainly polylines and planes to interpret the model. It also includes more statistical analysis within the program, such as histograms and stereonet.

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Appendix

Matlab code to calculate dip and dip direction of polyline

```
close all
clear all
clc

unit = [0 0 1];
a = 0;
p = zeros(1,3);
dip = 0;
orientation = 0;
nlines = 143;
for line = 1:nlines
Lineplot = dlmread(sprintf('C:\\Users\\Documents\\Line%d.asc',line));

S = size(Lineplot);

for i = 1:S(1)-2
for j = i+1:S(1)-1
    for k = j+1:S(1)
        a = a+1;
        p(a,:) = cross(Lineplot(i,:)-Lineplot(j,:),Lineplot(i,:)-
Lineplot(k,:));
        if p(a,3)<0
            p(a,3)= p(a,3)*-1;
            p(a,:)=p(a,+)/sqrt((p(a,1)^2)+(p(a,2)^2)+(p(a,3)^2));
            dip(a) = acosd(dot(p(a,:),unit));
            p(a,:)=p(a,)*-1;
        else
            p(a,:)=p(a,+)/sqrt((p(a,1)^2)+(p(a,2)^2)+(p(a,3)^2));
            dip(a) = acosd(dot(p(a,:),unit));
        end
        orientation(a) = atan2d(p(a,1),p(a,2));
        orientation(a) = orientation(a)-1.72;
        if orientation(a) < 0
            orientation(a) = 360 + orientation(a);
        end
    end
end
end
end
end
binsdip = 0:0.5:89.5;
figure()
histogram(dip,binsdip)
xlim([0 90])
xlabel('dip(degrees)')
ylabel('frequency(n)')
grid on
binsorientation = 0:359;
figure()
histogram(orientation,binsorientation)
xlim([0 360])
xlabel('dip direction(degrees)')
ylabel('frequency(n)')
grid on
```

Matlab code to create layer thickness diagrams

```
clear all
close all
clc

Lineplot = dlmread('C:\Users\Documents\thickness.asc');
S = size(Lineplot);
a = 0;
for i = 1:4:S(1)
    a = a+1;
    x = abs(Lineplot(i,1)-Lineplot(i+1,1));
    y = abs(Lineplot(i,2)-Lineplot(i+1,2));
    z = abs(Lineplot(i,3)-Lineplot(i+1,3));
    LThickness(a) = sqrt((x^2)+(y^2)+(z^2));
end
a = 0;
for i = 3:4:S(1)
    a = a+1;
    x = abs(Lineplot(i,1)-Lineplot(i+1,1));
    y = abs(Lineplot(i,2)-Lineplot(i+1,2));
    z = abs(Lineplot(i,3)-Lineplot(i+1,3));
    MThickness(a) = sqrt((x^2)+(y^2)+(z^2));
end
a = 0;
for i = 1:2:S(1)
    a = a+1;
    x = abs(Lineplot(i,1)-Lineplot(i+1,1));
    y = abs(Lineplot(i,2)-Lineplot(i+1,2));
    z = abs(Lineplot(i,3)-Lineplot(i+1,3));
    CThickness(a) = sqrt((x^2)+(y^2)+(z^2));
end

N = size(CThickness);
a = -1;
figure()
Thick = zeros(2,N(2));
Thick(1,:) = CThickness(:);
Thick(2,:) = CThickness(:);
h = area(Thick);
set(gca,'XTickLabel',[])
ylim([0 sum(CThickness)])

for i = 1:N(2)
    if a == -1
        h(i).FaceColor = [1 0 0];
    end
    if a == 1
        h(i).FaceColor = [0 0 1];
    end
    a = -a;
end
```