GIMA
Geographical Information Management and Applications

Capturing Sedimentary Outcrops in 3D

Putting the Geologists' Needs into Practice

Thesis report

Reinder N. Reindersma

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Wageningen UR

Colophon

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Responsible Professor:
Prof.dr. Steven de Jong – Utrecht University

Supervisors:
Drs. Maarten Zeylmans Van Emmichoven – Utrecht University
Drs. Tamara van de Ven – TNO Geological Survey of the Netherlands

Contact information:
R.N. (Reinder) Reindersma
Reinder.Reindersma@tno.nl / Reindersma@gmail.com

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Preface

After a full year of work, I am proud to present my Master's Thesis on Capturing Sedimentary Outcrop is 3D. It has been written as part of the master's degree of Geographical Information Management and Applications (GIMA), offered by Utrecht University, Delft University of Technology, University of Twente, and Wageningen University.

The decision to perform a geology-related research was made quickly since I'm part of team geomodelling at the Geological Survey of the Netherlands for the last ten years. When I first heard about capturing outcrops in 3D with Structure from Motion, I immediately knew I found my ideal thesis topic. It has the perfect mix of geology, geo-informatics, and 3D visualizations I was looking for, and the results of my study can directly be implemented at TNO-GDN. And I got to play with drones!

I would like to take the opportunity to thank all the people who helped and supported me. First and foremost, my supervisors Maarten Zeylmans van Emmickhoven[1], Steven de Jong[1], and Tamara van de Ven[2], whose guidance and supervision was extremely beneficial. The discussions I held with them provided me with new ideas and a proper direction for my research. I would also like to thank Michiel van der Meulen[2] for the opportunity to earn my master's degree at GIMA. Freek Busschers[2] and Renaud Bouroullec[2] for trusting me with their innovative ideas on DOMs, SfM, and sedimentary outcrops, and their willingness to advise when requested. Armin Menkovic[2] for organizing the fieldtrips and the geological backgrounds of the spectacular quarry Hendrik. For all their help, advice, and guidance through all phases of my research, I would like to thank Arno Bovens[3], Pierre Swelsen[3], Pieter van der Klugt[2], Wim Booltink[2], Ronald Harting[2], Willem Dabekaussen[2], Rob van Ede[2], Jeroen Schokker[2], Patrick Kiden[2], Denise Maljers[2], Vincent Vandeweijer[2], Ronald van Balen[4], Marcel van Maarsseveen[1], and Marijn Bovée[5]. I would also like to thank the 15 anonymous participants of the needs assessment for their time and excellent input (you know who you are!). It was a great experience interacting with them and exchanging ideas. Last, but certainly not least, I want to thank Ron Beers for all his support and care during the last 3 amazing years I spent at GIMA.

I have fully enjoyed my time, I hope you will enjoy my thesis.

Reinder Reindersma,

Utrecht, November 2019

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[1] Utrecht University, [2] TNO-GDN, [3] Hendrik Bedrijven Brunssum B.V., [4] VU Amsterdam, [5] HAS Hogeschool.

List of Abbreviations & Acronyms

1D/2D/2.5D/3D/4D	One/two/two and half/three/four-dimensional
AI	Artificial Intelligence
AHN2	Actueel Hoogtebestand Nederland
AR	Augmented reality
CPT	Cone Penetration Test
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DINO	Data en Informatie van de Nederlandse Ondergrond
DOM	Digital Outcrop Model
EPSG	Registry of spatial reference systems
ESRI	Environmental Systems Research Institute
GB	Gigabyte
GCG	Ground Control Point
GDN	Geological Survey of the Netherlands
GIMA	Geographical Information Management and Applications
GIS	Geographic Information System
GPS	Global Positioning System
LiDAR	Light Detection and Ranging
LxWxH	Length x Width x Height
MB	Megabyte
NAP	Normaal Amsterdams Peil
NIR	Near-infrared
OBJ	Wavefront geometry definition file
RD	Rijksdriehoekscoördinaten
REGIS	Regionaal Geohydrologisch Informatie Systeem
RGB	Red, Green, Blue
SBB	Standard Boorbeschrijvingsmethode
SfM	Structure from Motion
SLPK	Scene Layer Package
STL	Surface Tessellation Language
TIN	Triangular Irregular Network
TLS	Tiled model data format
TNO	Dutch Organisation for Applied Scientific Research
UAV	Unmanned Aerial Vehicle
UTM	Universal Transverse Mercator coordinate system
UU	Utrecht University
VR	Virtual reality
UTM	Universal Transverse Mercator
WGS84	World Geodetic System 1984

Summary

Outcrops of unconsolidated sediments provide very valuable information about Dutch geology, but are vulnerable to erosion and destruction by man. By digitally preserving them in 3D, these outcrops can be visualized, analyzed and revisited in the office. An effective way to digitally capture outcrops is to create a Digital Outcrop Model (DOM) by using Structure from Motion, a low-cost, user-friendly photogrammetric technique.

The intended use of a DOM will determine the minimum needed requirements in terms of detail, precision, and accuracy. In its turn, the requirements will determine the methods that are used during data collection. This study will answer the question of how sedimentary outcrops can effectively be captured as DOMs, to be applied in geology as usable 3D models.

To define the usability of a DOM, a needs assessment was performed among 15 specialized earth scientists. They were asked about their current fieldwork practices, the potential use of DOMs in their work, and the minimum needed requirements. The information was used to create three DOMs on different scale levels of an active clay and sand quarry, in Brunssum, the Netherlands. The data acquisition was performed using a high-end digital camera and a UAV (drone) to capture data from inaccessible and invisible areas.

The study shows that DOMs are seen as powerful communication tools by a large majority of interviewed geologists, for example, to discuss with colleagues, to present results, or to introduce a new audience to geology. The most striking result is that the need for less-detailed overview models exceeds the need for the high-resolution models of outcrop sections. Overview models of large outcrops offer the ability to create virtual viewpoints, swap between scales, and collect data from areas that are physically unreachable, which will all help to see the larger geological perspective of an area. Even though the high-resolution detail models can provide geologists with information on sediment grain sizes and colors, it is generally believed that geological interpretations should not be made solely based on information derived from DOMs. However, if the models are accurately georeferenced and combined with other geo-data in a GIS, it will be a very valuable new addition to geological research. Finally, regardless of the use of the model in the short term, creating DOMs offers the opportunity to secure and archive sedimentary outcrops for feature research, even after their destruction.

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1 Introduction

1.1 Research context

The Netherlands is among the most densely populated countries in the world, and its subsurface is also used intensively. It is used for cables, pipes, tunnels, and seasonal thermal energy storage installations. Groundwater is extracted for drinking purposes, and resources such as gravel, sand, and clay are mined at the surface (Figure 1.1). To safely use the subsurface, it is key to know its geological structure and properties. For the past 100 years, the Geological Survey of the Netherlands (TNO-GDN) collects, stores, and manages available data and uses it to geologically map the subsurface. In the last decades, this is done by creating three-dimensional (3D) layer and voxel models that are published as open data to the public.

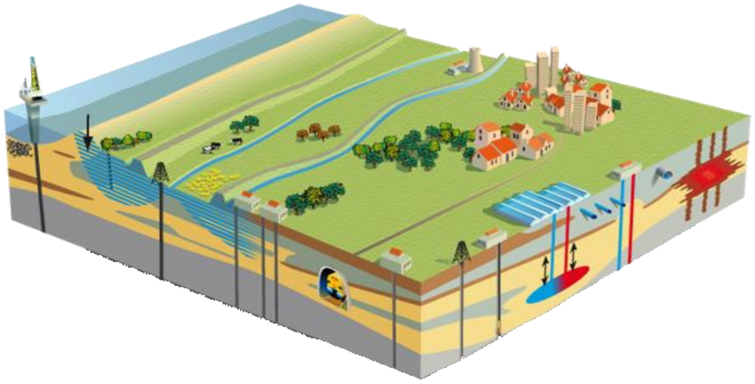


Figure 1.1: Overview of potential use of the shallow subsurface in the Netherlands. (Source: TNO-GDN, 2018)

What makes the Netherlands unique is the predominantly flat landscape, created by the accumulation of large amounts of sediments over the last millions of years. The landscape itself gives very little information about the structure and sediments in the subsurface, so most knowledge must come from boreholes, cone penetration tests (CPTs), and seismic data that are used to collect subsurface data. However, in a few places, older sediment layers that are normally buried, are locally exposed to the surface, or ‘crop out’. These outcrops allow for direct observation of the subsurface in 3D and are therefore extremely important for earth scientists for understanding the geological processes that have formed the subsurface.

Although outcrops provide very valuable information about Dutch geology, they are currently not systematically captured and analyzed. In the previous century, capturing outcrops was done with drawings (Figure 1.2) which is a very time-consuming method. Later, this was replaced by taking photographs, but this often results in a low-quality, unreferenced and incomplete dataset that is not suitable for further analysis. It is even more unfortunate when is considered that most sedimentary outcrops in the Netherlands are temporally exposed, since they are usually very vulnerable to erosion and destruction by man. In particular man-made outcrops in active quarries and outcrops created during infrastructural works are only visible for a short period of time, ranging from a few days to just a couple of hours.

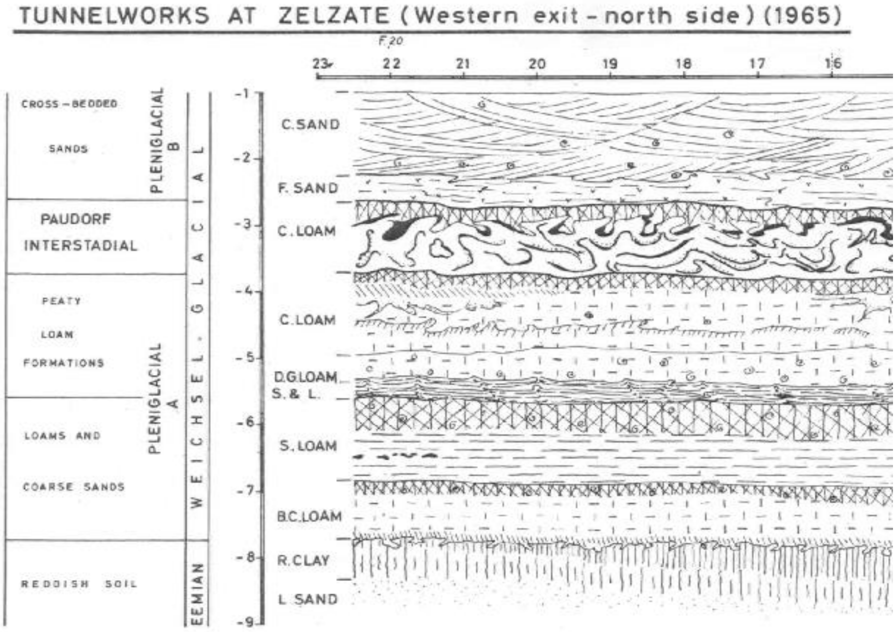


Figure 1.2: Example of a drawing of an outcrop at Zelzate, Belgium. After: Paepe *et al.* (1967).

1.2 Objectives and research questions

Because of their vulnerability and scientific relevance, more attention should be paid to the possibilities of digital preservation of outcrops. A relatively new and effective way is to create a three-dimensional Digital Outcrop Model or DOM. Wilkinson *et al.* (2016) define a DOM as “a digital representation of an outcrop with sufficient detail, precision, and accuracy such that it forms a usable duplication of its real-world counterpart, most commonly presented as a 3D model”. They allow us to visualize, analyse, and revisit geological outcrops, even after their destruction. The models can be used for data presentation, discussion, and sharing of geological features (García-Selles *et al.*, 2014), they can help to create geological overview and to train geologists (Hodgetts, 2013), and possibly to make geological interpretations (McCaffrey *et al.*, 2005), and measurements (Fleming, 2018). Outcrops can be efficiently captured by using digital photography, and can later be modelled into a point cloud, usually the starting point for a 3D model.

Creating 3D point clouds from photographs can be achieved by using Structure from Motion (SfM), a close-range photogrammetry technique, used to obtain dense point clouds of a space or an object (Assali *et al.*, 2014). SfM is considered to be a cheap and user-friendly alternative for LiDAR (Westoby *et al.*,2012). According to Cawood *et al.* (2017), assessments of LiDAR and SfM methodologies suggest that results of SfM can be compared to high data-density LiDAR. SfM has already successfully been used in a wide range of geoscience applications, for example in studies on soil erosion (Heng *et al.*, 2010), paleontology (Petti *et al.*, 2018), speleology (Triantafyllou *et al.*, 2019), glacial research (Kraaijenbrink *et al.*, 2016, Immerzeel *et al.*, 2014), coastal dune dynamics (Ruessink *et al.*, 2018), river bank erosion (Hemmelder *et al.*, 2018), and landslide dynamics (Turner *et al.*,2015, Lucieer *et al.*, 2014, Niethammer *et al.*, 2012). However, few studies are available in literature on creating DOMs of sedimentary outcrops using SfM. It is expected that they will require different levels of detail than hard-rock outcrops, to analyse its key properties.

TNO-GDN is interested in developing a protocol to systematically and efficiently capture sedimentary outcrops in the Netherlands as DOMs with Structure from Motion. However, the requirements of a DOM should result from the intended use of the model and should be researched first. This leads to objective of this study:

How can Digital Outcrop Models of sedimentary outcrops, created with Structure from Motion, and having sufficient detail, precision, and accuracy be a valuable addition to geological research?

Various research questions are formulated on the basis of this objective.

1. *What are the types of sedimentary outcrops that can be found in the Netherlands, and what are their main characteristics?*
2. *What are the reasons to perform fieldwork on sedimentary outcrops, and which types of outcrops are visited the most?*
3. *How can DOMs of sedimentary outcrops be used in geological research, and could they serve as a replacement for fieldwork?*
4. *What are the requirements of a DOM in terms of detail, precision and accuracy to be a valuable addition to geological research?*
5. *How should data be collected in the field to meet the requirements with SfM?*

1.3 Scope

The Netherlands is part of a large subsidence basin where sediments have accumulated for the last 400 million years (Stouthamer *et al.*, 2015). These sedimentation processes created stacked layers of unconsolidated materials, such as gravel, sand, loam, clay, and peat. Since 95% of the material at the surface in the Netherlands consists of unconsolidated sediments (Figure 1.3), this will be the focus of this study.

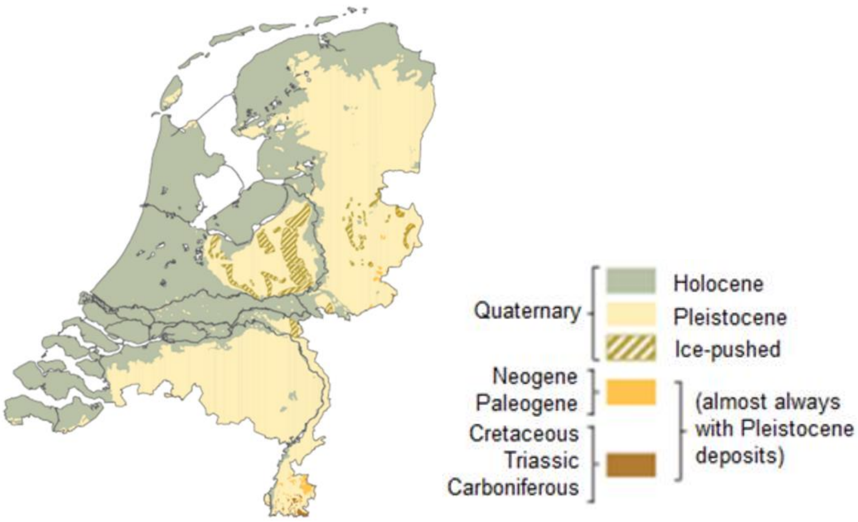


Figure 1.3: Sediments at the surface in the Netherlands, classified by era of deposition. Only the last category (dark brown color) consist of consolidated material (source: TNO-GDN, 2004)

The research was performed in close collaboration with TNO-GDN, and used the institution's available fieldwork equipment. By using TNO-GDN's own resources, it will be more likely that the results of this study will be put into practice in the near future. The field equipment includes a high-end digital camera with the ability to manually change settings, such as zoom level and ISO value, and a quad-copter drone (UAV), that can shoot high-resolution airborne RGB images of outcrops. The specifications of the used equipment are described in more detail in Appendix I.

The Digital Outcrop Models in this study were all created with Structure from Motion, defined by Westoby *et al.* (2012) as a low-cost, user-friendly photogrammetric technique for obtaining high-resolution datasets at a range of scales. According to Micheletti *et al.* (2015), the development of SfM methods provides the opportunity for very low-cost 3D data acquisition with strongly reduced user supervision and required expertise. Cawood *et al.* (2017) agrees to Micheletti *et al.* by stating that the technique provides the ability to generate a 3D reconstruction, easily and without the expense and specialist knowledge required for LiDAR acquisition and processing. Since field time is often limited and expensive, SfM is a very interesting technique for TNO-GDN to explore. Although SfM is not part of the GIMA curriculum, it has a strong relationship with many other GIMA subjects, such as photogrammetry, point clouds, spatial referencing, and GIS.

The choice of software is Agisoft Metashape Professional, a cost-effective all-in-one Structure from Motion software application. It was based on both expert judgment at TNO-GDN and literature, such as from Niederheiser *et al.* (2016). He states that (after comparing several software packages) Agisoft Metashape offers the user-friendliest workflow and creates the most appealing point-clouds, even though it is giving only little insight into its processing. It can create 3D models with relative ease, using input data from a full range of image sensors, such as NIR, RGB, thermal, and multi-spectral. Also, the ability to create tiled models, use video-import, the geo-referencing options, the possibility to semi-automate the workflow with python, and support of the most widely used 3D data formats, makes Agisoft Metashape a very suitable software application for this study.

2 Theoretical Framework

This Chapter describes the concepts, definitions, and scholarly literature that are relevant for this study. It starts with a general introduction to sedimentology and sedimentary outcrops in the Netherlands. Next, a literature review on the advantages and disadvantages of Digital Outcrop Models will be presented. The last section starts with a short introduction to Structure from Motion, in order to give structure to the literature review on the SfM data collection parameters.

2.1 Sedimentology

Sedimentology is the study of the formation, transport, and deposition of material that accumulates as sediments in continental and marine environments, and eventually can form sedimentary rocks (Nichols, 1999). Sediments are formed by weathering, the physical disintegration and chemical decomposition of older rock and its transport can take place under a variety of conditions: by wind, glaciers, or sub-aqueously in rivers, lakes, and oceans. When the transportation of sediments comes to a halt, the sediments will deposit. Sediment layers usually appear layered and are stacked in a particular way. As a rule of the thumb, the oldest layers are positioned below the younger ones, and all layers are different in composition and shape. (de Mulder *et al.*, 2003).

2.1.1 Outcrops

Places where older sediment layers are exposed to the surface are called outcrops, and two main types can be found in the Netherlands: natural outcrops and man-made outcrops. Natural exposures of older sediment layers occur in areas with erosion, such as on hillsides and river banks (Figure 2.1). Man-made outcrops are usually the result of human actions, such as for quarrying, infrastructural works or scientific research (Figures 2.2 and 2.3). A special category of outcrops consists of outcrops that are labeled as geological heritage (Figure 2.4). They can either be natural or man-made, but they have in common that they are recognized as geologically unique features, that need to be protected and preserved for the future.

Outcrops have long served as the principal source of information for sedimentary and stratigraphic studies. Depending on the size of the outcrop, the scale of the information can range from small (millimeters to meter), intermediate (meter to a hundred meters), to large (hundreds of meters to kilometers). In practice, it is difficult to create a geological overview, and to make observations across multiple scales, or continuously over larger distances (Chesley *et al.*, 2017). According to Hodgetts (2013), outcrop analog data can improve reservoir characterization, and the understanding of their geostatistical properties is essential, as they are the basis for current stochastic reservoir modeling approaches. Howell *et al.* (2014) state that outcrops have played a central role in improving understanding of subsurface reservoir architectures, as they provide important information on geobody size, geometry, and potential connectivity.

Figure 2.1: Natural sedimentary outcrop created by the river Dinkel, the Netherlands. (Source: W.Nelemans, 2007. Extracted from https://www.flickr.com, March 30th, 2019)

Figure 2.2: Rupel or ‘Boom’ clay in an active clay quarry, Rumst, Belgium. (Source: P. Kiden, TNO, 2015)

Figure 2.3: Man-made sedimentary outcrop for geological research on fault structures at Uden, the Netherlands. (Source: P. van der Klugt, TNO, 2016)

Figure 2.4: Geological monument, Meester van der Heijden Groeve at Nieuw-Namen, the Netherlands. (Extracted from www.fossiel.net, March 15th, 2019)

Outcrops are by definition three-dimensional (3D) and therefore provide geologists with more information boreholes or cone-penetration tests (CPTs), that could be considered as two-dimensional (2D) data. This will be explained in Figure 2.5:

Figure 2.5: Information that could be obtained from a borehole (left), versus outcrop information (right). (Source: R.Reindersma, TNO, 2019)

The left image shows the amount of information that could be obtained from a single borehole or CPT. This will provide a geologist mainly with textural sediment properties that apply to the individual sediment grains (e.g. size, shape, color). The outcrop on the right side also provides information about structural sediment properties, that are formed by aggregates of grains (e.g. bedding, faults, ice wedges, cryoturbation). An outcrop can also provide valuable information about the characteristics of the individual sediment layers (e.g. heterogeneity, continuity, regularity). These sediment properties form the basis of geological interpretations, where sediments are classified in a structured system.

Fig. 2.6 & 2.7: Examples of bedding structures in sand layers (left) and an ice wedge (right). (Source: TNO-GDN, 2019)

2.1.2 *Geological interpretations*

A geological interpretation is a compilation and synthesis of all available geological information, in order to get an as precise as possible model of the stratigraphy or depositional environment. Stratigraphy is the science of large-scale layering (stratification) of subsurface layers (strata). By interpreting and classifying strata, geologists can produce a better view of the subsurface, which is fundamental for studies on groundwater, mining locations, or subsidence issues.

There are several ways to classify strata, and which classification is used, depends on the objectives of the study. Examples of stratigraphic classifications are lithostratigraphy (rock type), biostratigraphy (fossils) and chrono-stratigraphy (time). The stratigraphic system that is widely used in the Netherlands is based on lithostratigraphy and is documented in the Nomenclature of the Dutch Geological Survey (TNO-GDN, 2013). The fundamental unit in lithostratigraphy is a formation that can be divided into members and subdivided into beds. Another way of classifying sediments is by their depositional environment or facies. In every depositional environment, sediments will deposit with a characteristic grain size distribution, fossil content, and sedimentary bedding. Examples of facies types are: sands that are deposited in river channels, or thick layers of clay that have accumulated in the adjacent flood basins.

2.2 Digital Outcrop Models

According to Cawood *et al.* (2017), virtual representations of real-file outcrops can be an important source of information, from which a wide variety of geological data can be derived. They can be high-resolution, photo-realistic 3D models, providing an unprecedented capability for geometric analysis (Fleming, 2018). DOMs are used for visualization, analysis and revisiting geological outcrops and for data presentation, discussion, and sharing of geological features (Garcia-Selles, 2014). According to Hodgetts (2013), virtual exposures could even be interpreted in the office. Also, McCaffrey *et al.* (2005) state that DOMs can make field time more efficient by offsetting some data interpretation back in the office. Hodgetts (2013) summarizes more advantages of DOMs, such as:

- Collection of data from otherwise inaccessible areas: During fieldwork access to outcrops is often limited, either due to topography or safety-related issues. In a DOM measurements can be made without having to physically access them directly.
- Virtual viewpoints: In a DOM the data can be viewed from many angles, as well as being able to swap rapidly between different scales. It allows geometries and features not visible from a land-based viewpoint to be seen.
- Generation of new attributes: Data in digital help with interpretation and provide the basis for automated mapping approaches.
- Training: Field time can be very expensive. To make the best use of field time the use of digital outcrop models as an introduction to an area to be visited, or as a chance to re-visit an outcrop once back from the field is of great importance.

Limitations of the DOMs could be texture loss on the rock surface, features hidden by vegetation, and features filtered out of the DOM, because of choices in resolution. García-Selles *et al.* (2014).

2.3 Structure from Motion

A fundamental stage in SfM is the automatic camera alignment, which is performed by specialized software. The accuracy and precision of the camera alignment will directly influence the quality of the final model and will depend highly on the quality of the input data. This data quality is, in turn, a result of the used data collection techniques.

2.3.1 Camera alignment

Alignment in SfM is the use of multiple overlapping images and an image-based terrain extraction algorithm to reconstruct the location of individual points in the photographs in 3D space (Snavely *et al.*, 2008). The camera pose and scene geometry are reconstructed simultaneously by the SfM software. This is done by the automatic identification of features in different images, and by tracking matching features from image to image, the initial camera positions can be estimated (Figure 2.8). The feature coordinates are calculated iteratively using a non-linear least-squares minimization (Snavely *et al.*, 2008).

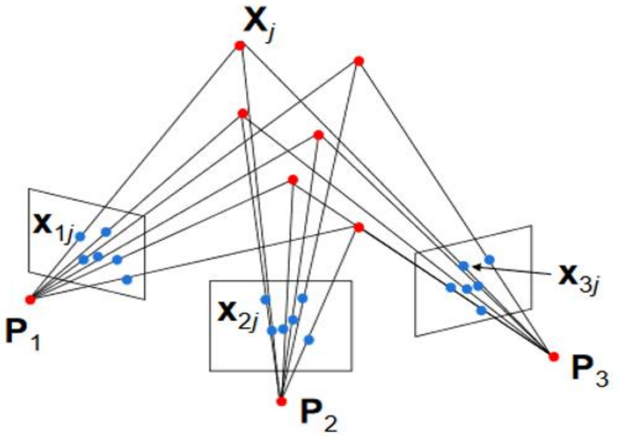


Figure 2.8: Data alignment and point cloud calculation. The coordinates of feature X are calculated by the automatic identification of the feature (X1, X2, X3) on different images P1, P2, and P3. (Extracted from dovkatz.wordpress.com, Oct 31st, 2019)

Unlike traditional photogrammetry, the camera positions in SfM can be derived without a preset scale and orientation. This means that the resulting sparse 3D point cloud is generated in a relative ‘image-space’ coordinate system. If needed, it can afterward be aligned to a real-world, ‘object-space’ coordinate system, by a number of known GCPs with known object-space coordinates. The final quality of the camera calibration and of the point-cloud relies on the images which have varying degrees of error that are hidden from the user and are a function of image properties (Fonstad *et al.*, 2012)

2.3.2 Data collection techniques

Capturing data for SfM can, in theory, be done by using any digital camera. However, as stated above, the data collection techniques and equipment will have a major influence on the quality of the final DOM. The Metashape user manual (Agisoft, 2018) advises using only digital cameras with a reasonably high resolution (5MPix or more) and use the maximum available resolution. Also, ultra-wide-angle and fisheye lenses should be avoided, and the lowest ISO-values should be used, as high ISO-values can induce additional noise to images. Niederheiser *et al.* (2016) advise disabling all automatic options in the cameras themselves, such as the auto-focus, image stabilization, and the good sensor qualities, e.g. sensor sizes and pixel counts, therefore reducing the degrees of freedom during self-calibration. Micheletti *et al.* (2015) advice to avoid overexposed, underexposed and blurred images. It could be concluded that turning off all automatic settings should only be done when the fieldworker is very well acquainted with photography and the used camera equipment. In all cases, data should be collected under consistent lighting conditions, and moving objects and unwanted objects in the foreground should be avoided, as also advised by Micheletti *et al.* (2015). According to Assali *et al.* (2014), the internal camera parameters, such as focal distance and lens distortion, should be determined by calibrating the camera before commencing a survey.

Another key element for successful camera alignment is the coverage of the object of interest. The basic principle is that every point on the object must appear on at least three images gained from spatially different locations. Micheletti *et al.* (2015) describe to capture the whole subject first, and then the detail, ensuring that occlusions are captured adequately. Chesley *et al.* (2017) state, on the other hand, that an excessive number of photos can result in prolonged processing times and unnecessarily large files that can be difficult to manipulate during post-processing. However, Chesley *et al.* also recommend taking more photos than fewer, as SfM processing software typically allows for selective use of images.

According to the Metashape user manual (Agisoft, 2018), an overlap of ~60% between adjacent photos is typically sufficient, but areas with less contrast may need a higher overlap to produce optimal results. Fleming (2018) describes that significant model errors were brought about by the lack of different camera positions. Relatively 2D outcrops imaged by a relatively 1D image array are subject to rotation errors that are difficult to remove without high-resolution ground control. Also, the Metashape user manual (Agisoft, 2018) and Micheletti *et al.* (2015), strongly advise shooting images from as many locations as possible, in both horizontal and vertical direction (Figure 2.9).

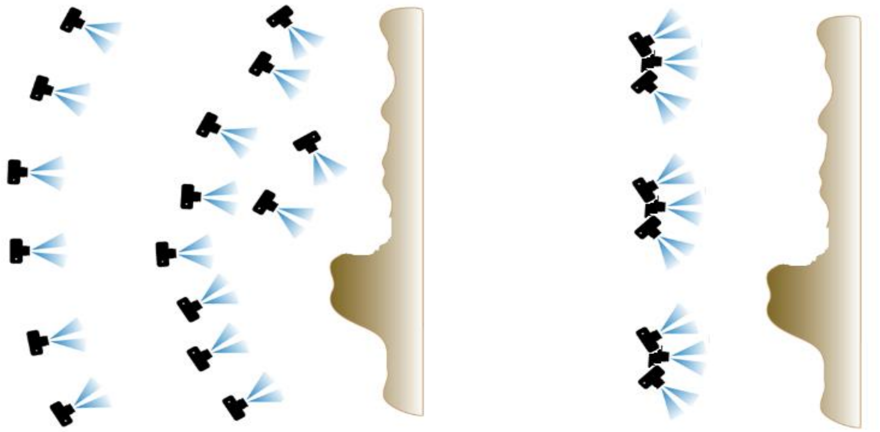


Figure 2.9: Examples of correct and incorrect imagery acquisition. SfM requires multiple images with large overlap from many different positions and directions (left). Collecting images from fixed positions by moving the camera around its axis (right) can lead to insufficient overlap and incomplete coverage of the object of interest. (After Micheletti *et al.*, 2015)

Photogrammetry is a scale-independent measurement technique, which is what gives it its flexibility. However, if the user wants to combine the model with spatial data from other sources, it needs to be georeferenced and scaled. Scaling requires the photogrammetric model to contain at least a known base length, a known 3D distance between two points, or a network of known targets or natural points on the surface of the rock face being digitized (e.g. Assali *et al.*, 2014). As mentioned before, Wilkinson *et al.* (2016) state that a DOM is only usable if it has sufficient detail, precision, and accuracy. Accuracy can be defined as the closeness of measurements to a specific value, while precision is related to the closeness of the measurements to each other (Figure 2.10). In the case of a DOM, the accuracy would tell us something about the quality of georeferencing or positioning of the model, while precision is an indication of the internal consistency or deformation of a model.

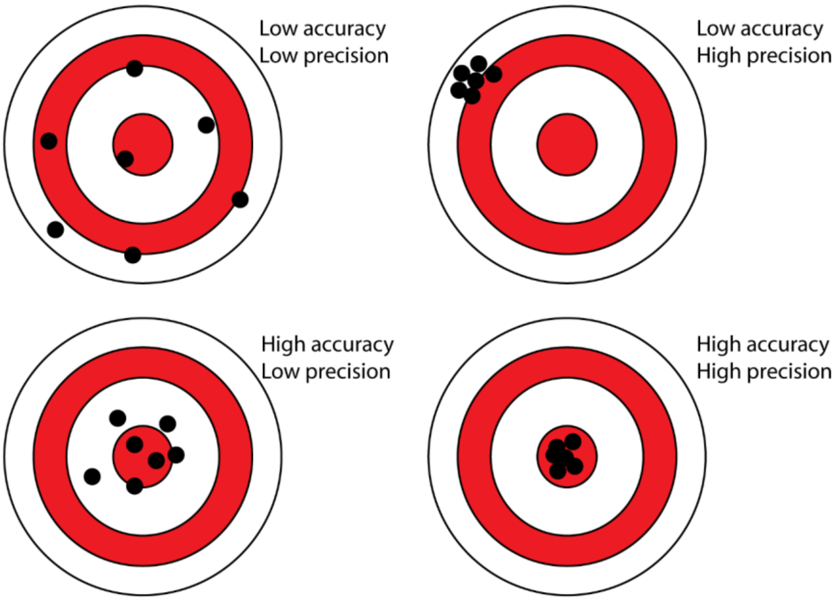


Figure 2.10: The difference between precision and accuracy. (Source: https://sites.google.com, retrieved 19th Oct 2019)

Geotagging the images during the data acquisition phase can increase the accuracy and decrease the time and effort required during processing. (Chesley *et al.*, 2017). However, care must be taken, since Fleming (2018) states that several studies underscore the influence of GPS error in georeferencing SfM-models. Cameras without geotagging capabilities can still be used but require constraints from ground control points (GCPs) in the processing stage (Chesley *et al.*, 2017). A study by Akturk (2018) showed that GCPs had a 6 cm reducing effect on the overall error margin at z values. Although the difference doesn't seem like much, it can have critical importance for sensitivity demanding projects.

3 Methodology & Data

The research was performed in the form of a case study in active quarry Hendrik, Brunssum, the Netherlands. The main steps that can be identified in this study are:

1. Experimental phase
2. Needs assessment
3. Fieldwork at quarry Hendrik
4. Modeling of the final DOMs

3.1 Experimental data and modeling

At the start of the research, an orientating field trip was organized to the selected outcrop (described in Section 3.3), to get better acquainted with the area and with the TNO-GDN equipment. It offered the opportunity to collect experimental datasets that were used to create three DOMs on different scale levels. Since many geologists are not yet familiar with DOMs, the experimental models proved to be very useful during the needs assessment. The used methodology of capturing data and modeling is very similar to steps 3 and 4, it will therefore only be discussed in Sections 3.3 and 3.4, respectively.

3.2 Needs assessment

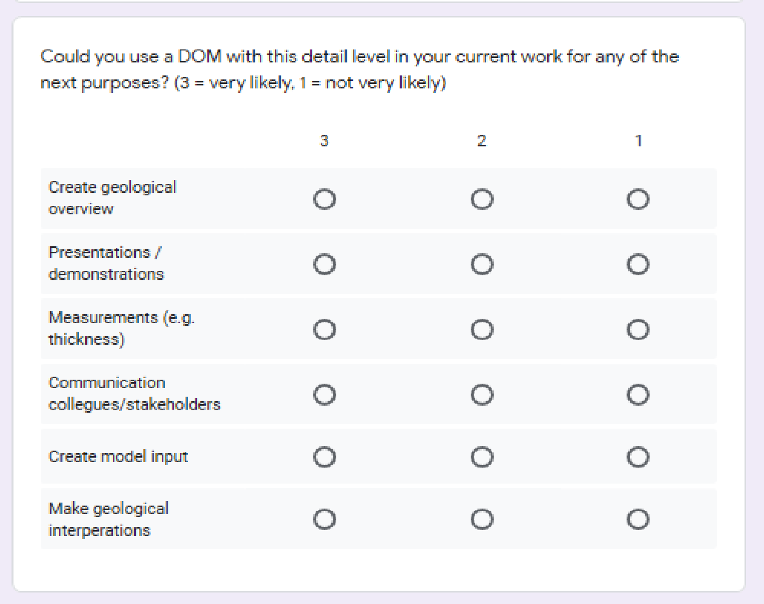
The requirements of a DOM should be a result of the intended use of the model. Most importantly, there needs to be a good balance between the level of detail and size of the model, which are more or less inversely proportional. Very detailed models can easily become too large in file size, which might cause slow loading and navigation, and will highly frustrate the users of the model. On the other hand, models with too little detail could be considered unsuitable for further use. Although it might be tempting to create a DOM with the highest level of detail possible, it would be wiser to first determine whether there is really a need for it. In order to close this gap, a needs assessment was conducted among potential users of DOMs.

A group of 15 Earth Scientists was asked to share their opinions and thoughts on DOMs and how they might be used in their work. To create a diverse and non-biased group as possible, the members were selected on a range of criteria, such as their specializations in earth sciences, work experience, organization, and age category. All selected participants were asked a series of standardized questions and could rate how strongly they agreed with some statements. The questionnaire ended with two open-ended survey questions that asked participants about the expected future developments and possibilities of DOMs for sedimentary geology.

The needs assessment was performed in the form of a personal interview, which gave both the interviewer and the participant the possibility to elaborate on the questions and answers, if needed. The interview started with a short presentation about the general research objectives of this study, SfM, and the experimental DOMs that were created after the first field visit to the quarry. These three experimental DOMs all have a specific scale and detail level, and will be referred to as DOM level 1 to 3. In general, they are comparable to the final models that are presented in Appendix IV.

- **DOM level 1**: An overview model of quarry Hendrik in Brunssum. The modelled area is around 300 x 150 x 60 meters (length x width x depth) and provides the least amount of detail of the three models. The main geological layers can be identified by colour. Lithologies, such as sand, clay, and gravel cannot be distinguished on this scale.
- **DOM level 2**: A medium-scale model of a section of the quarry, with a size of approximately 15 x 10 meters. When zoomed in, the viewer can get an indication of the main lithology. Gravel, sand and clay can be distinguished in the models, and texture, bedding, and structures on a centimetre scale become visible.
- **DOM level 3**: A model of a section of approximately 1 x1.5 meters with a very realistic feel. The smallest visible features are a few millimetres in size.

The first questions were designed to identify the outcrop types that they visit, the annual frequency and the main purposes of the field trips. Next, they were presented with the three experimental DOMs, and were questioned about the potential use of each of the three models, keeping the specific scale levels in mind. To identify the need for georeferenced models, several questions were asked about the accuracy of positioning the models in a real-life reference system, such as WGS84/UTM zone 31N or RD/NAP. In geology, the horizontal dimensions are usually much larger than in the vertical direction. To tackle this issue, the participants were asked to determine two accuracy levels, one for the horizontal and one for the vertical direction. The precision of the models was addressed by asking about the relative importance of accuracy versus precision. In other words, the participants were asked if they preferred a poorly georeferenced but consistent model, or with a well-positioned but internally deformed model. Obviously, a model that is both accurate and precise is always preferred, but the question was designed to determine which of the two should be focused on during modeling if the input data doesn't allow for both. The questionnaire was developed and performed by using the free online application Google Forms (Figure 3.1) and the full set of questions of the used questionnaire is included in Appendix II.



Could you use a DOM with this detail level in your current work for any of the next purposes? (3 = very likely, 1 = not very likely)

	3	2	1
Create geological overview	○	○	○
Presentations / demonstrations	○	○	○
Measurements (e.g. thickness)	○	○	○
Communication collegues/stakeholders	○	○	○
Create model input	○	○	○
Make geological interperations	○	○	○

Figure 3.1: Example of the questionnaire in Google Forms

3.3 Fieldwork and data collection

The outcrop for the case study was selected after consultation with senior geologists of TNO-GDN. The main criteria for selecting were: the presence of a wide variety of different sediments that are representative of the Netherlands, a large scientific relevance for geology, and a temporal character. A site that matches all these criteria is quarry Hendrik, near the city of Brunssum in the region of South-Limburg (Figure 3.2).

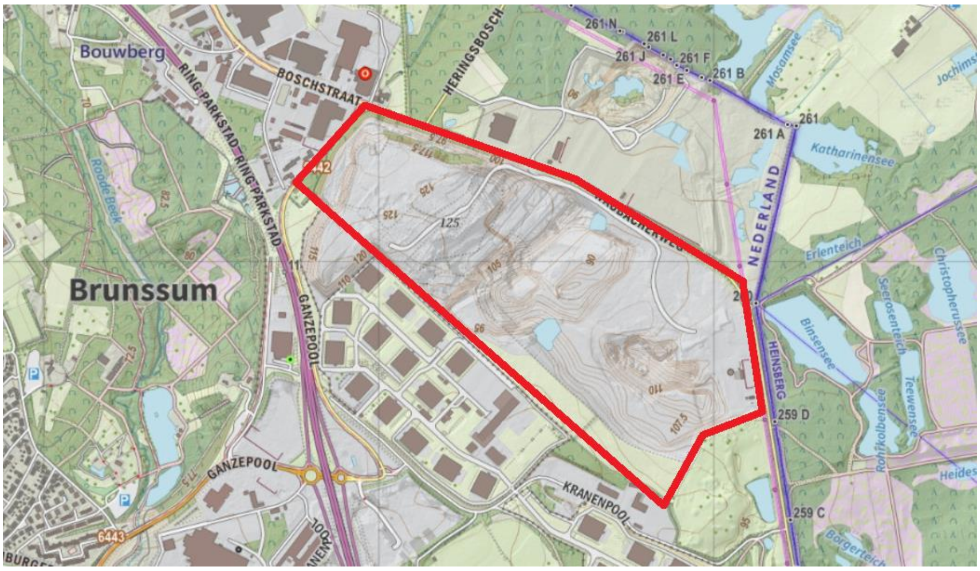


Figure 3.2: Quarry Hendrik near Brunssum, the Netherlands. (Source: opentopo.nl, extracted on June 5th, 2019)

3.3.1 Project area

The site was originally a mine waste dump (tailing) from the coal mine Hendrik that opened in 1915, with tailings over 30 meters high. In 1997 the building company Mourik purchased a part of the tailing area, to extract the large quantities of clay, sand, and gravel that can be found beneath the hills of mine waste material. When the mining concession expires in 2022, the quarry must be completely be re-filled with material, and be covered with a clean layer of new soil material of at least two meters thick, so the area may be used for other purposes (e.g. housing). Large parts of the quarry have already been excavated and re-filled with material, so this means that after 2022 the site can no longer be visited and all the outcrops will be destroyed.

The valuable grey-coloured clay in quarry Hendrik is called “Brunssum clay” and is used in the brick industry (Figure 3.3). The clay can also be found in other parts of the Netherlands, but only in very few places, it is so close to the surface as in quarry Hendrik, making it a valuable location for both mining companies and geologists. The less valuable light-coloured sands and gravels that can be found above the clay are mainly used in the concrete and road construction industries.

Figure 3.3 Outcrop of Brunssum clay layers (lower dark layers) and sand layers (light layers in the middle) below a hill of mine waste (upper dark material) in quarry Hendrik. (Source: J.Stafleu, TNO, 2007)

3.3.2 Data collection

In order to georeference DOMs as accurate as possible, a Differential Global Positioning System (DGPS) was used to measure ground control points (GCP). A DGPS can reduce the error in positioning measurements from meters to centimeters by calculating the difference between the positions indicated by the satellite system and the known fixed positions of fixed ground-based reference stations (Figure 3.4). Markers that were strategically placed in the outcrop can act as GCPs, as long as they are visible in the final model and accurately measured in both vertical and horizontal direction.

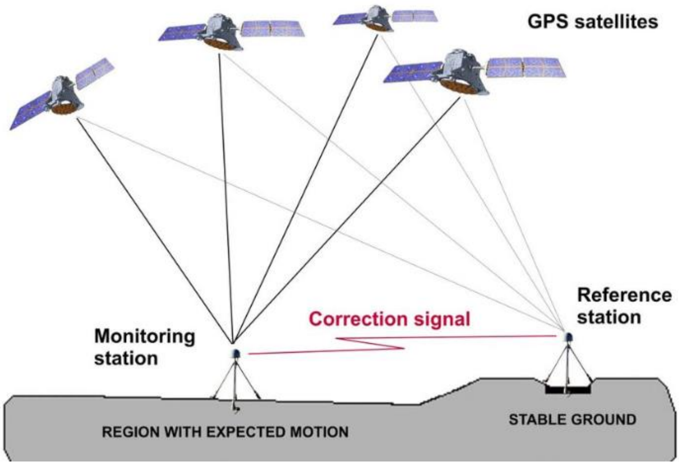


Figure 3.4: Basics of a DGPS. A correction signal from a reference station is used to reduce errors at the monitoring station. (source: www.researchgate.net, extracted Oct 28th, 2019)

An UAV was used to create overview shots by flying above the quarry and to capture areas that could not be physically reached. In order to assure enough overlap, the UAV was mainly used in combination with high-resolution video (4K). Agisoft Metashape has the ability to extract video frames at a regular interval that can be used as input data for SfM. The flying speed was kept as constant as possible during a single take to assure a constant overlap when extracting the frames from the video. Since these derived frames are not geotagged, several additional photos were shot with the UAV as well, to help to align the data in Agisoft Metashape. The data was collected from as many positions as possible, and from different heights in the quarry. To avoid moving objects on the images, the overview shots of the quarry were mainly shot during lunch-time, when the otherwise moving trucks and excavators were not in use. The rest of the dataset was captured by taking photographs with the hand-held camera, also from as many angles and distances as possible. The hand-held camera has geo-tagging possibilities, but this functionality proved to be very unreliable, so several additional geotagged photos were taken with a smartphone, to be combined in Agisoft Metashape later.

3.4 Modeling

The basic workflow of Agisoft Metashape consists of the following steps:

1. Camera alignment
2. Dense point cloud calculation
3. Creating a surface or mesh
4. Creating a model texture

3.4.1 Camera alignment

The collected data was imported and aligned in Agisoft Metashape in an iterative process, resulting in a coarse point cloud (Figure 3.5). By starting with a subset of only the highest quality data, both the calculation time and the risk of errors were strongly reduced. The aligned cameras and resulting coarse point cloud were visually inspected, and images that caused an error were identified and removed from the dataset. In the case of insufficient data coverage, Agisoft Metashape offers the possibility to add more data to the already aligned datasets. During alignment, the metadata that holds the location information is used to position the coarse point cloud directly in a known reference system. Since the geotagging is done in WGS84 and Agisoft Metashape doesn’t support the Dutch national reference system RD/NAP (EPSG:7415) yet, the models were created in WGS84 (EPSG:4326), with the WGS84 ellipsoid as vertical reference. The camera alignment is a fundamental step in SfM and has a direct influence on the end result, so the highest available aligning settings were used.

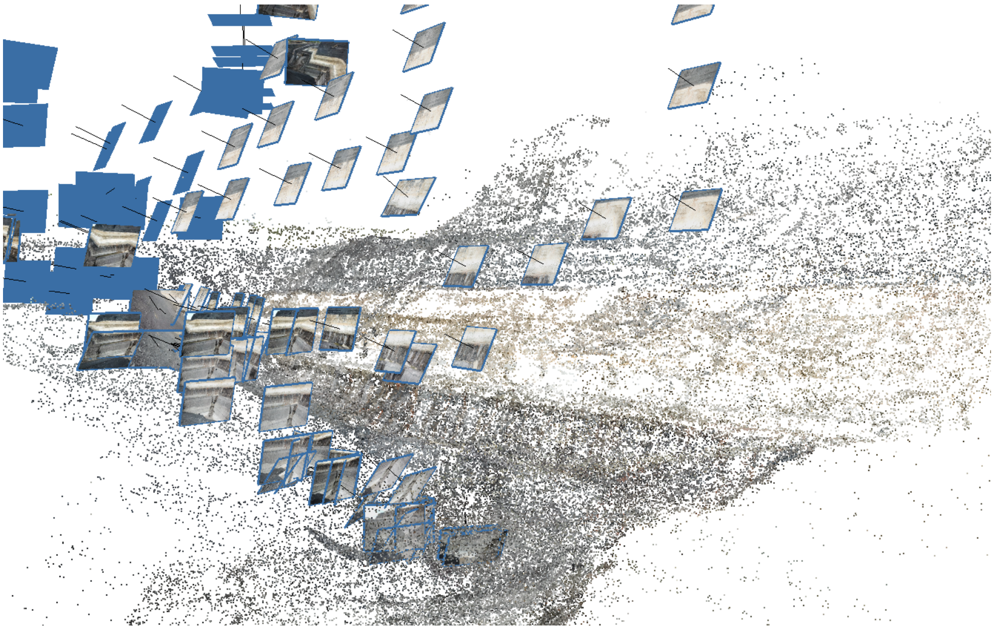


Figure 3.5: Photo alignment and a sparse point cloud of matching tie-points.

3.4.2 *Dense point cloud calculation*

After visually inspecting the coarse point cloud, a densified point cloud was constructed. The input files are the same images as used for the coarse point cloud, but this time the software tries to match all possible tie-points it can find. Calculating the dense point cloud is the most time-consuming step in SfM, and will largely determine the final file size of the final model. The Agisoft Metashape user manual (2018) only recommends the highest settings in the case of ultra-high-resolution models, so medium settings were used in this step. Depth filtering algorithms can be used to automatically reduce the number of outliers in the point cloud, however, this was used with the greatest care, to avoid the removal of points that were accidentally mistaken for outliers.

3.4.3 *Surface*

The next step is to create a surface or mesh from the dense point cloud, a triangulated surface, and can be a full 3D arbitrary surface or a 2.5D height field (Figure 3.7). An 3D arbitrary surface can be used for the modeling of any kind of object and could be selected for closed 3D objects, such as statues and buildings. A height field surface type is optimized for the modeling of planar surfaces, such as terrains and walls, and it requires a lower amount of memory and thus allows for larger data sets to be processed. However, objects in the foreground will not be modeled separately but will become part of the outcrop in the background. If the input data doesn’t cover the complete area of the model, there is often an option to fill holes in the model by using different interpolation techniques, but this should also be used with the greatest care, since the final model will appear to be more detailed than it actually is. Agisoft Metashape offers the option to build a tiled model where the data is stored in a hierarchical tile format, allowing for responsive visualization of large-area 3D models in high resolution (Figure 3.6)

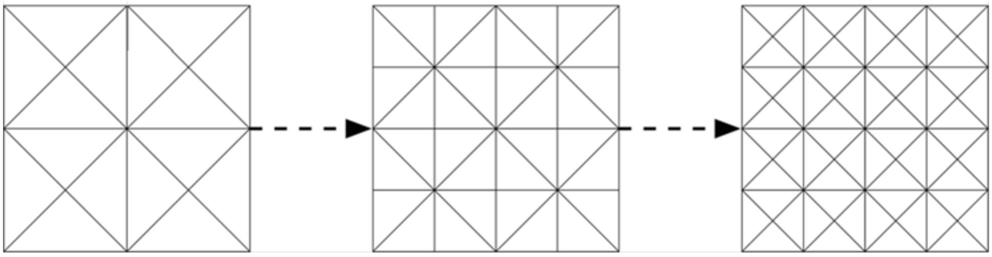


Figure 3.6: Multi-resolution tiled models, more detail appears when zooming. After: Puppo (2018).

For the created DOMs it was chosen to create 2.5D height fields, without interpolation, and use a tiled model structure, which results in shorter calculation times and better performance of the final models, without a major loss in quality.

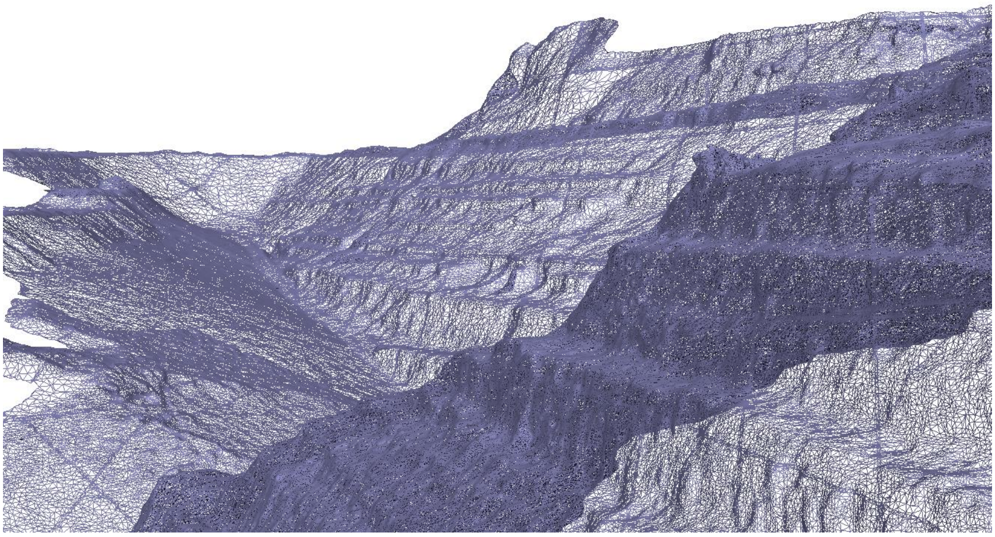


Figure 3.7: Mesh or surface. The tiled structure can be recognized as blue crossing lines.

3.4.4 *Texture*

Based on the aligned images, an orthophoto or texture can be created. This texture is draped over the calculated surface, giving the model a more realistic look. In areas of the model with less surface texture, it can potentially add some detail to the model, but this extra detail is only optical and will not increase the actual resolution of the 3D model. The texture is also created as a tiled service, so different levels of orthophotos match the level of detail of the corresponding surface levels. Figure 3.8 summarizes the different processing steps of a model created with SfM.

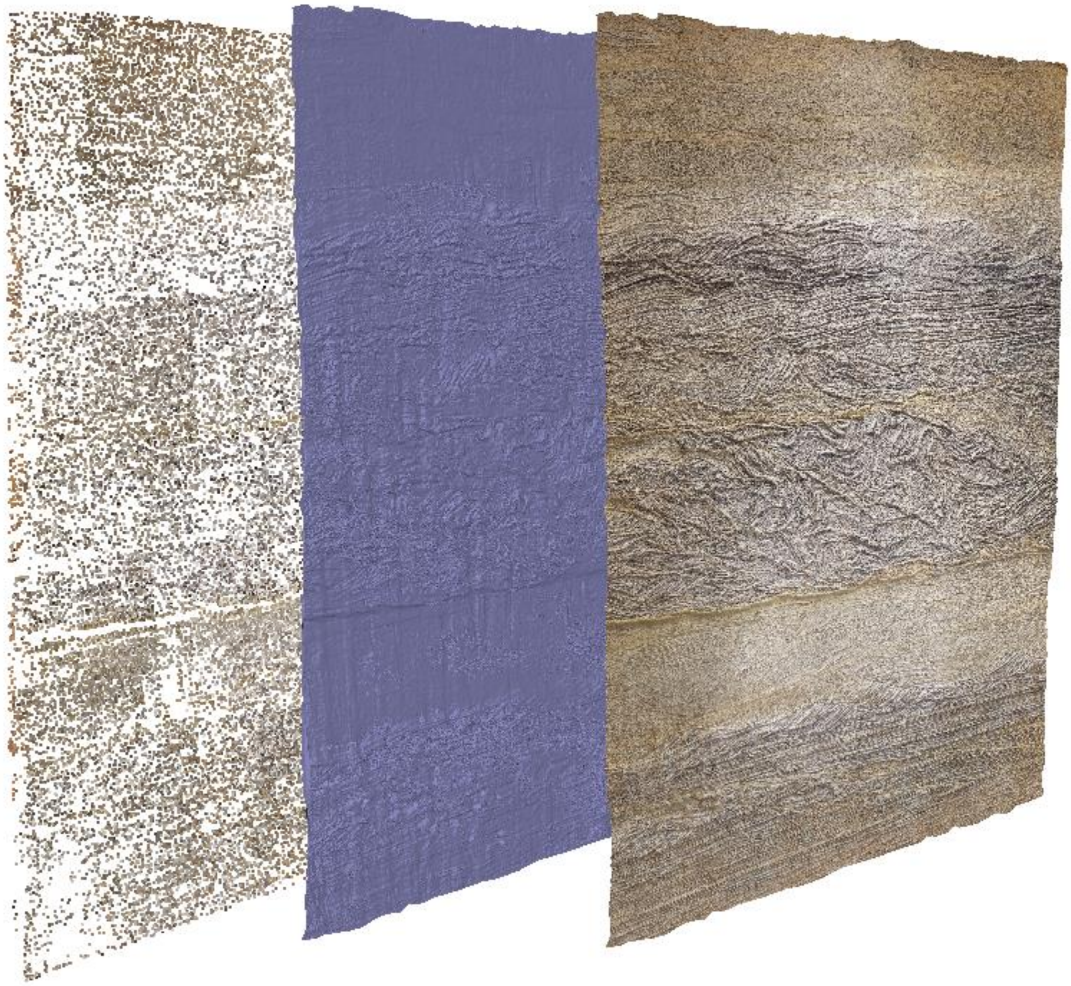


Figure 3.8: Examples of a sparse point cloud (left), a surface (middle) and a textured model (right) of a geological lacquer profile.

4 Results

The results of the needs assessment, fieldwork, and the modeling phase will be presented in this Chapter. Only the most relevant findings of the needs assessment will be discussed, followed by a summary of the conclusions, but the original dataset of the needs assessment was anonymized and is included in Appendix III. Next, the datasets collected during the fieldwork will be described, and the Chapter will end with a description of the final DOMs, some examples of what geological features can be identified, and of the possibilities of a DOM when imported in a GIS.

4.1 Needs assessment

4.1.1 Group diversity

The interviewed specialists are earth scientists from TNO-GDN, Utrecht University and Vrije Universiteit Amsterdam, and have a wide range of specializations. As shown in Figure 4.2, over two-thirds of the group members characterize themselves as a geologist, however, many of them have over one specialization, such as sedimentology, stratigraphy, and hydrology. About half of the group has over 20 years of relevant work experience in earth sciences (Figure 4.1).

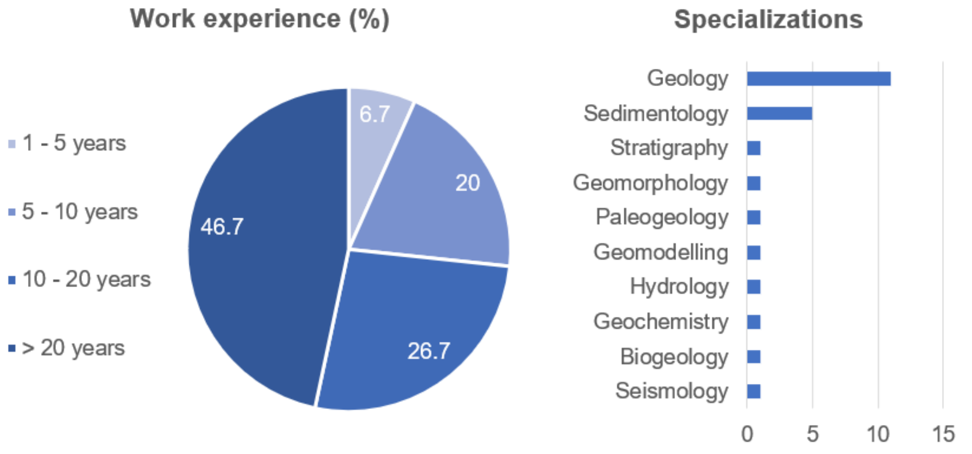


Figure 4.1 & 4.2: Relevant work experience in earth sciences (left) and specializations (right)

4.1.2 Current fieldwork practices

The most visited types of outcrops in the Netherlands are active and abandoned quarries, closely followed by temporal outcrops during infrastructural works. (Figure 4.3), natural outcrops and outcrops for scientific research are the least visited, mostly because they are less abundant in the Netherlands. On average, the group members visit around five outcrops per year, but this differs significantly from person to person.

The main reason to make field trips is for educational purposes and training, followed by creating geological overview and data collection (Figure 4.4). Although during most field trips some measurements are performed, only 17% of the field trips making measurements is the main reason for the visit.

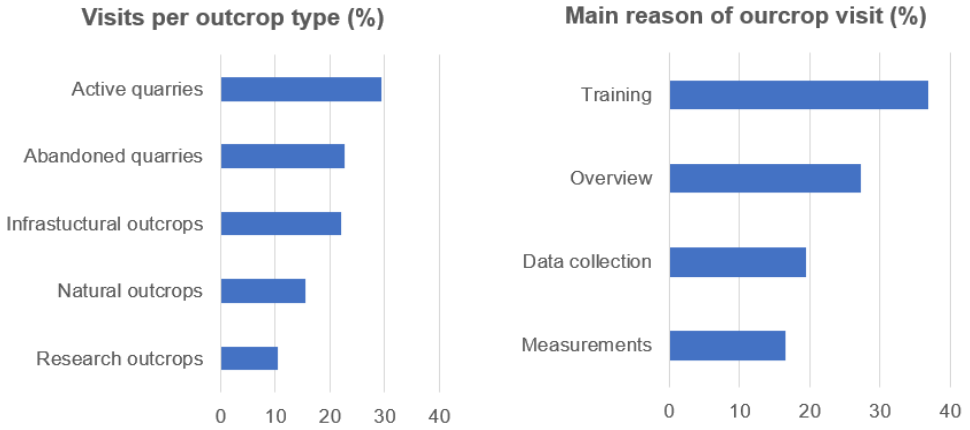


Figure 4.3 & 4.4: Number of visits per outcrop type (left) and reasons for visiting an outcrop (right)

4.1.3 The potential use of DOMs

All participants were asked about the potential use of DOMs in their work for each of the three created experimental models. They have different scales and detail levels and are referred to as DOM level 1 (overview model), DOM level 2 (quarry section), and DOM level 3 (most detailed model). The experimental models strongly resemble the final models, which are described in more detail in Chapter 4: Results. For each of the statements, the participants could choose between *very likely*, *likely*, and *not likely* to be used in their work. The response was used to add weight to the answers by multiplying them with a factor 3, 1, and 0 respectively (Figure 4.5).

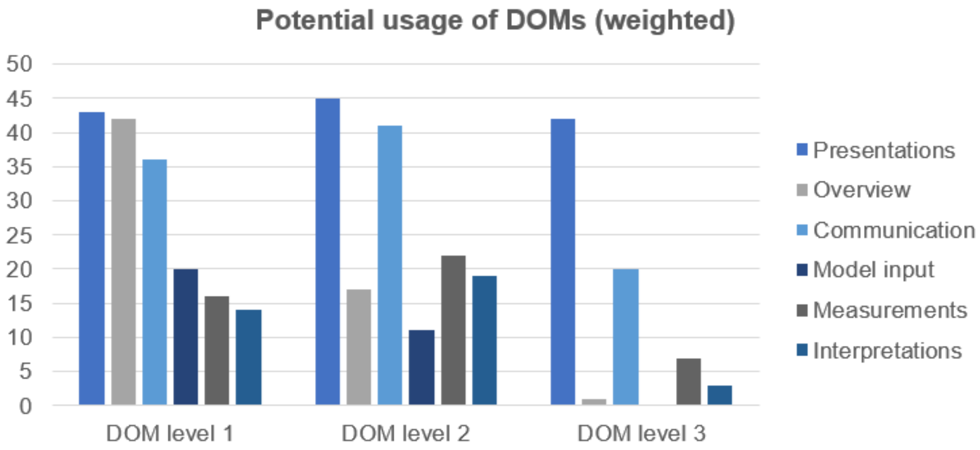


Figure 4.5: The potential usage of DOMs, per scale level.

What can be noticed from Figure 4.5 is that all three DOMs are seen as powerful tools for presentations and as a valuable communication tool in projects. What stands out is that DOM level 1 and 2 have the widest range of potential applications, while the DOM level 3 (the most detailed) is mostly seen as a presentation tool.

The participants think that especially DOM level 1 will help to create a better geological overview, one of the main reasons for outcrop visits (Figure 4.4). Both DOM levels 1 and 2 might serve as input data for 3D geological subsurface models, or act as a validation set for existing models. DOM level 2 has the most potential to be used to make measurements in the office, such as the average thickness of layers.

According to all 15 interviewed specialists, geological interpretations cannot be made solely based on information of a DOM. However, some existing interpretations could be improved, and new interpretations could be made, if the models are georeferenced and combined with other available geo-data, especially on DOM level 1 and 2.

When asked about the preference which DOMs to use in their work, 11 out of 15 geologists chose a combination of different scales, in the form of a nested model. By placing detailed models inside an overview model, a geologist can create overview, but also zoom in to the most interesting parts of a quarry. The most interesting option is a combination of DOM level 1 and 2. None of the participants would use the more detailed models DOM level 2 and 3 without the combination of any of the other models.

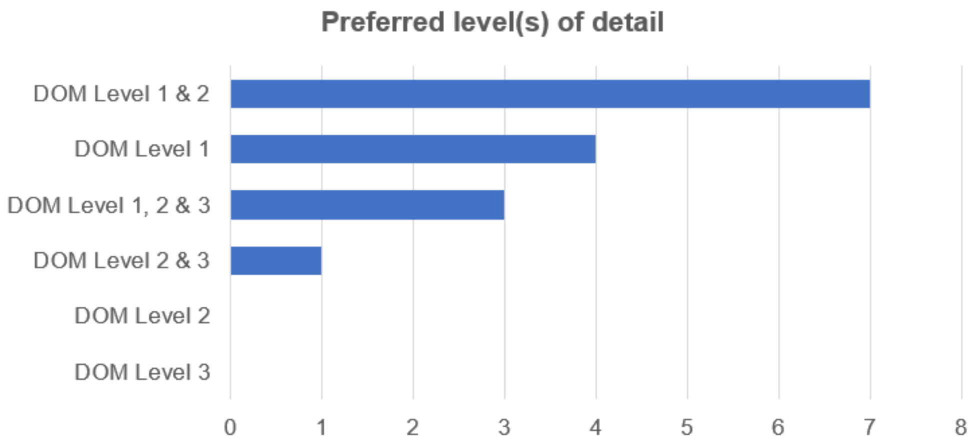
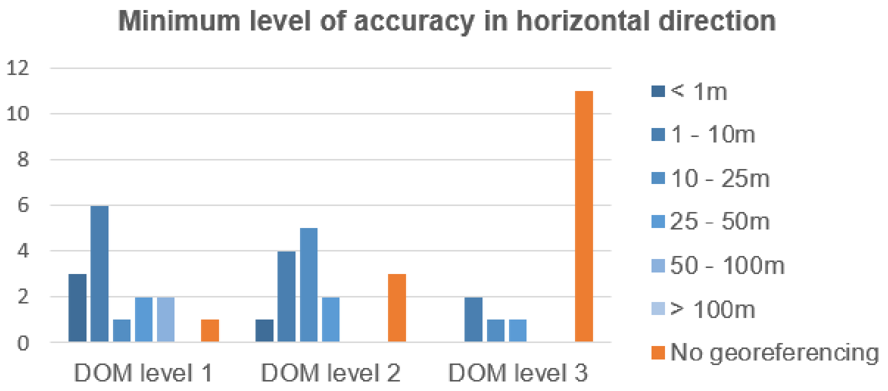


Figure 4.6: Preferred level(s) of detail.

4.1.4 *Precision and accuracy*

The demonstrated overview model was automatically georeferenced in Agisoft Metashape, by using the information from the geotagged images. When asked about the importance of georeferencing, 14 out of 15 geologists indicated that DOMs should be positioned in a known coordinate system, such as WGS84/UTM zone 31N or RD/NAP. All members of the group agree that an accurate positioning in the vertical direction (height) is more important than in horizontal direction. Surprisingly, the majority of the participants see no need in georeferencing the most detailed model, DOM level 3. This can be explained by the fact that it is mainly seen as a showcase, without many practical applications in geological research. Several of the participants mentioned that the accuracy of positioning of the individual models is less important than the consistency between the nested models, meaning that the detailed models should be placed very accurate inside the overview models.



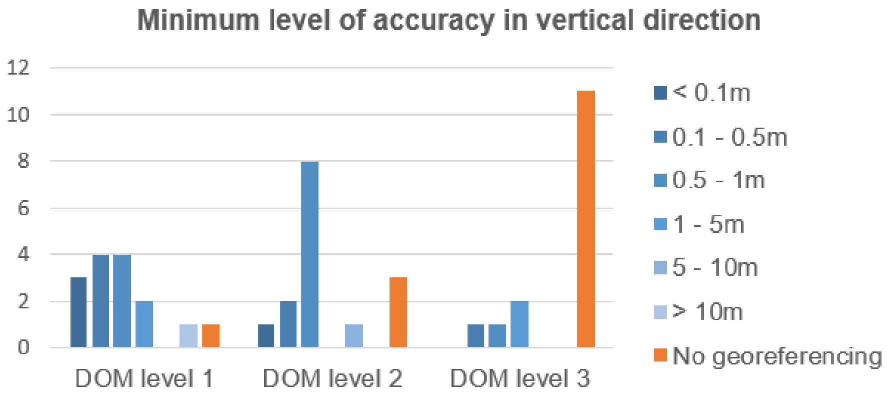


Figure 4.7: The minimum needed horizontal and vertical accuracy per scale level.

A large majority (13 out of 15) prefer a poorly referenced but consistent model, over a model that is deformed but accurately positioned in space. The main reason is that undeformed models can still be used to make internal measurements, such as on layer thickness and dip, while deformed models are considered too unreliable to work with.

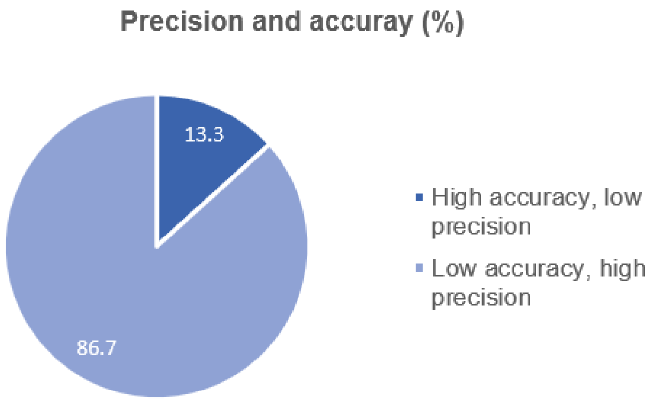
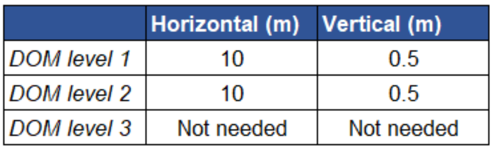


Figure 4.8: The importance of precision versus accuracy

4.1.5 *Conclusions and future developments*

By analysing the questionnaire results, several conclusions can be drawn.
Over 60% of the outcrops that are visited in the Netherlands are very likely to be destroyed in the short term. The main reasons for visiting outcrops are training and creating geological overview of an area, for which especially DOM levels 1 and 2 are regarded as useful. Most interestingly is that all the participants preferred overview models over the detail models. They are also very interested in the combination of nested DOM on multiple scale levels, where several detail models of the most interesting locations are placed in a larger overview model, which allows geologists to continuously zoom in and out, and navigate areas to develop new geological theories. All DOMs (with exception of the most detailed models), should be georeferenced in a real-world coordinate system. Although the answers about the minimum requirements on accuracy differed widely, a guideline for the minimum accuracy in both directions was determined (Table 3). However, most participants mentioned to prefer more accurate geopositioned models. These values should therefore be seen as the absolute minimum needed accuracy.



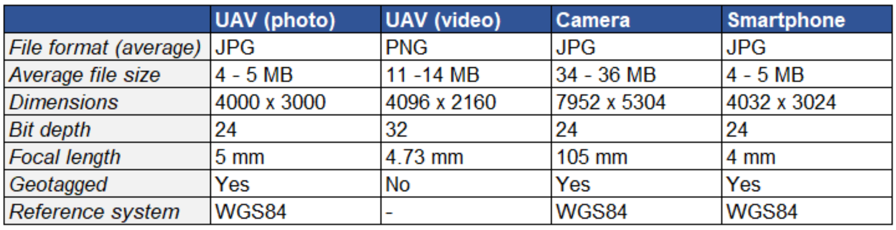
	Horizontal (m)	**Vertical (m)**
DOM level 1	10	0.5
DOM level 2	10	0.5
DOM level 3	Not needed	Not needed

Table 4.1: Guideline for the absolute minimum level of accuracy of georeferencing

The open questions about expected future developments of DOMs and their usage in sedimentary geology produced a large variety of answers. However, one development was mentioned by all geologists, which is using DOMs to create time series in active changing environments. When an outcrop is visited multiple times through time, the individual georeferenced models could be analysed in one single view in a GIS. This would enable to trace geological structures (e.g. ancient river beddings, fault lines) in all three dimensions, or calculate the speed and volumes of natural erosion. Other potential developments were: Automatic interpretations based on artificial intelligence (AI) and neural networks, DOMs in virtual and augmented reality (VR/AR), the development of a system to archive DOMs in combination with a portal for online dissemination, and the possibility to make annotations or to create hyperlinks to additional information on the web. It has to be noticed that these future developments might require other levels of detail, precision, and accuracy.

4.2 Fieldwork

The dataset collected during the final field trip consists of photographs and videos from the UAV, the handheld camera, and a smartphone. The total file size exceeds over 30GB, however, only a selection of the input data was used to create the DOMs. The general specifications of the dataset are summarized in table 4.2.



	UAV (photo)	UAV (video)	Camera	Smartphone
File format (average)	JPG	PNG	JPG	JPG
Average file size	4 - 5 MB	11 -14 MB	34 - 36 MB	4 - 5 MB
Dimensions	4000 x 3000	4096 x 2160	7952 x 5304	4032 x 3024
Bit depth	24	32	24	24
Focal length	5 mm	4.73 mm	105 mm	4 mm
Geotagged	Yes	No	Yes	Yes
Reference system	WGS84	-	WGS84	WGS84

Table 4.2: Specifications of the SfM input data from different sources.

4.3 3D Models

4.3.1 DOM level 1

The first model is an overview model of the south-western part of quarry Hendrik, with a real-life dimension of approximately 240 x 130 x 80 meters (LxWxH). The model offers unprecedented new viewpoints of the quarry, especially when zooming out to a birds-eye view (Figure 4.9). The whole outcrop can be seen in a single glance, providing the necessary overview that geologist can't obtain in the field, and the largest geological features can clearly be seen and traced over the full length of the quarry. In the middle, a light band of sands and gravel (A) can clearly be distinguished from the darker coloured Brunssum clay below (B), the dark material above the sandy layers is waste material from the former coal mine Hendrik (C). The dark material D is also mine waste material that was used to re-fill the quarry after excavating.

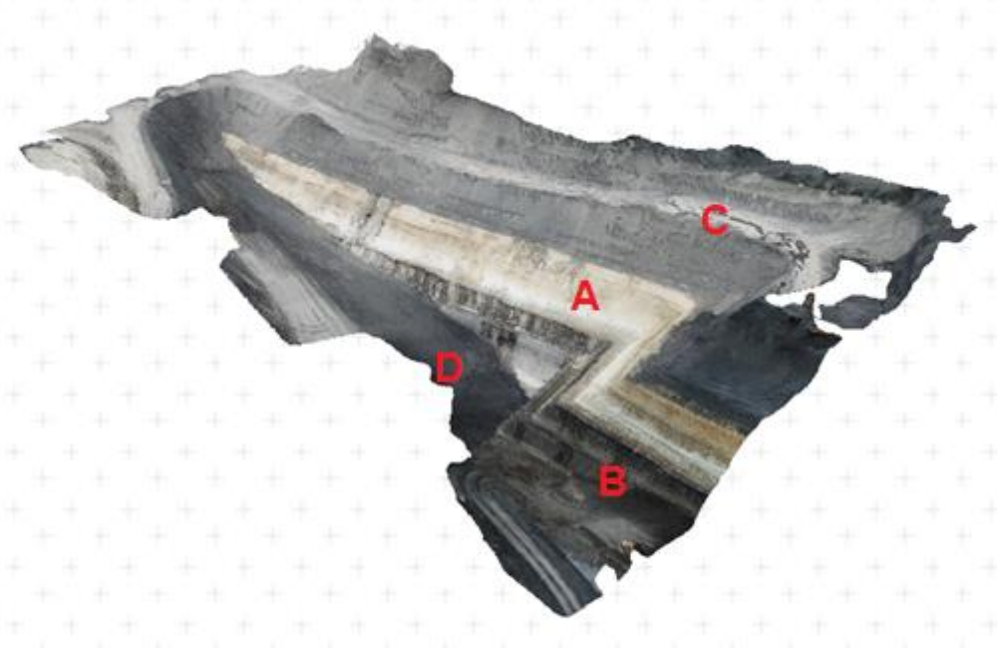


Figure 4.9: DOM level 1 overview model of quarry Hendrik in a birds-eye view.

When zoomed in, the model reveals more detail, because of the tiled structure of the model (Figure 4.10). Inside the bright-colored band, different sediment layers can better be distinguished from one another. Some very striking vertical structures appear in the model which are the result from the excavators mining the clay and sand layers. These structures appear to be more clearly in the upper part of the light-colored band (A) than in the lower part (B). This might be a sign for a geologist that the upper part contains more clay than the lower part, which holds its structure better than loose sand. However, this could never be determined with certainty, without performing additional field measurements.

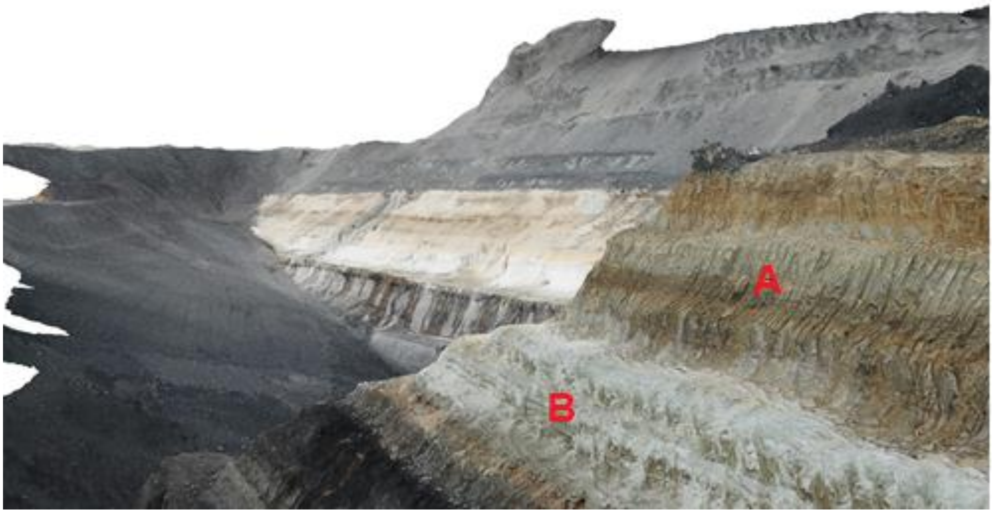


Figure 4.10: Overview model DOM level 1, zoomed in.

A major advantage of DOM level 1, is that physical unreachable or invisible areas can be inspected in the model, for example, the deepest part of the quarry could not be seen from any of the viewpoints in the quarry. By using the UAV, the area could be captured and incorporated in the model, resulting in several new geological findings. In Figure 4.11, an unknown incision of an ancient stream could be detected (A), and the model also proved the presence of a thin dark-colored layer in the quarry, most likely a lignite layer (B). Also, a light-colored layer at the bottom was detected, most likely very fine-grained white sand (C). The presence of this layer was expected, but the exact depth and pattern were not known. Features D result from natural weathering processes by wind and rain after excavation.

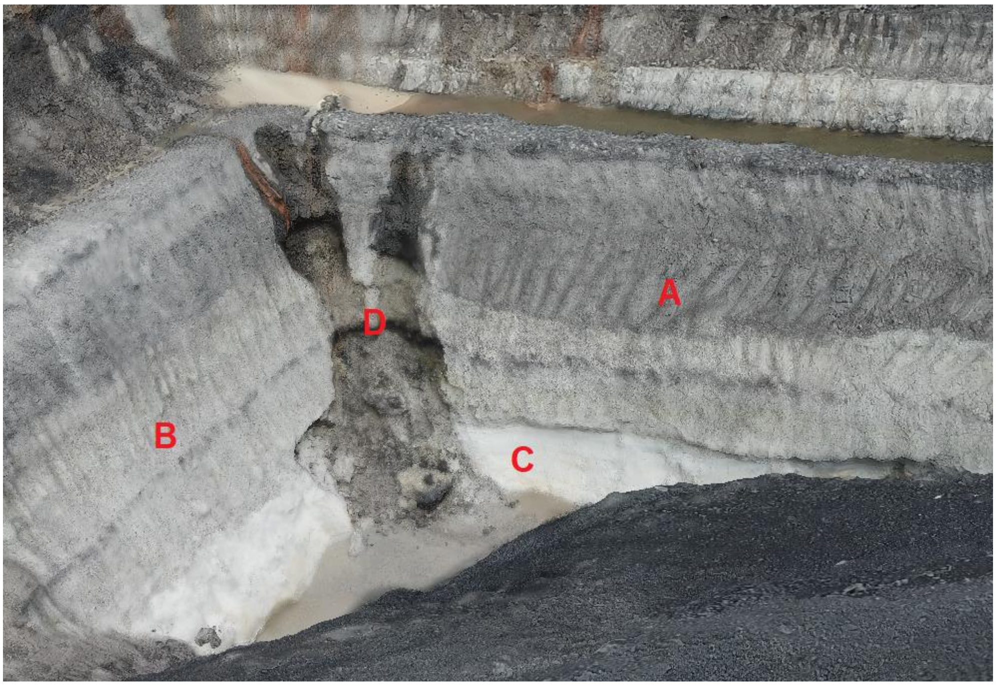


Figure 4.11: Detail of the deepest part of the overview model.

The downside of this model is the loss of detail, because of the choices in scale and resolution. Figure 4.12 shows an example of the difference between the DOM (left), and the original photo (right), seem from the same location. However, according to the results of the needs assessment, the loss of detail on this scale is acceptable for the interviewed specialists.

Figure 4.12: DOM level 1 (left) and photograph (right), showing the loss of detail in the DOM.

An indication of the precision of the model is presented in Figure 4.13. The error estimates of the camera locations are represented in Agisoft Metashape by colored ellipses, plotted on a top view of the model. Error estimates in height are represented by color, the error estimates in horizontal direction are represented by the ellipse shape. It can be seen that the maximum camera position error in vertical direction is around 7 meters, and the maximum horizontal error is estimated around 10 meters. The images with the highest errors proved to be the set of photographs collected with the hand-held camera, that were added to the previously aligned UAV images. Most likely the difference in camera settings, lenses and lighting conditions caused problems during the photo-alignment phase. The ellipses in Figure 4.13 represent the errors of individual images, but the precision of the final model is also a result of the amount of coverage and overlap. The same area was successfully captured by UAV imagery without camera errors, so the model error is expected to be smaller than the 7 to 10 meters in Figure 4.13. Unfortunately, the exact precision throughout the model cannot be determined.

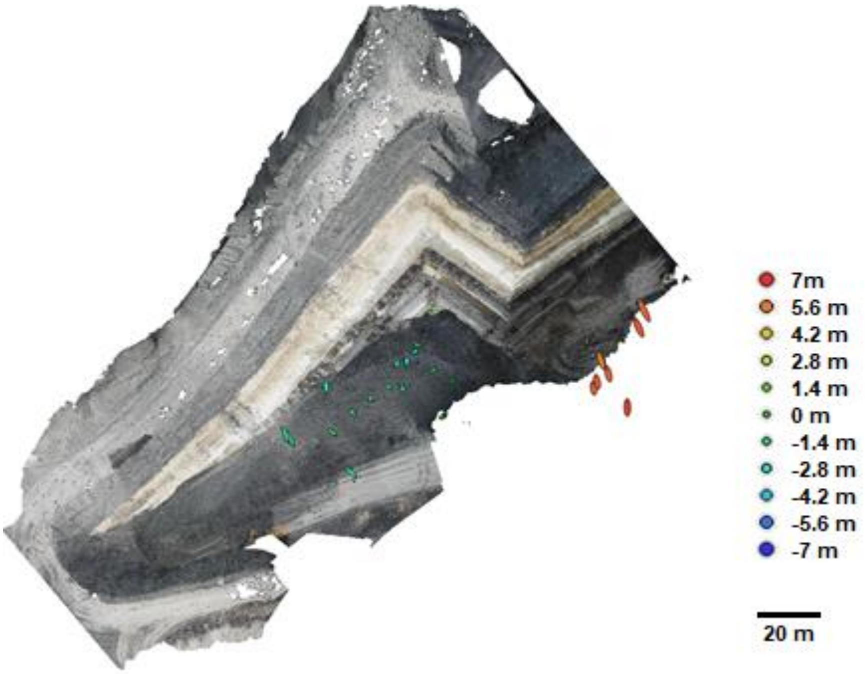


Figure 4.13: Error estimates of camera locations. Errors in vertical direction are represented by color, errors in horizontal direction are represented by ellipse shape.

Georeferencing the model was done by using the GPS information of the geotagged images, since the placed GCP markers proved to be unusable after the fieldwork. The markers were reflectors that were placed for a LiDAR research on the same day, but could not be recognized in the final models, because of their highly reflective surface. The vertical accuracy of the internal GPS of the UAV is claimed to be 0.5 meters in vertical direction and 1.5 meters in horizontal direction by the manufacturer. By importing the model in a GIS and combining it with existing borehole data and a DEM (AHN2), it was estimated that both the horizontal and vertical accuracy are within a few meters. However, this could not be confirmed since the exact accuracy of the reference material also has an uncertainty, and there were no permanent objects (e.g. houses, roads) included in the model. The technical specifications of the model (and the other models) are given in Appendix IV. A low-resolution version of this model can be viewed online in 3D at Sketchfab.

4.3.2 *DOM detail level 2*

The second model is a part of a quarry wall, with a dimension of approximately 12 by 6 meters, that consists mostly of sands and gravel (Figure 4.14) This DOM offers more detail than the overview model, and the brown- and red-colored gravel, enclosed by the lighter-colored sands, can be seen. In this part of the quarry, the wind had time to erode the quarry wall, resulting in even more striking features that resemble a geological lacquer profile. The finer sands were blown out, while the heavier sands and gravel remained in its place, as seen in Figure 4.14. With this model, the user gets a good indication of the main lithologies of the outcrop and besides on color, the gravel grains can also be identified in the model's surface itself (A). Smaller laminae with a thickness of less than a centimeter can be recognized in area B. However, on this detail level, specialists can’t perform reliable measurements on individual grains to determine the main lithology.

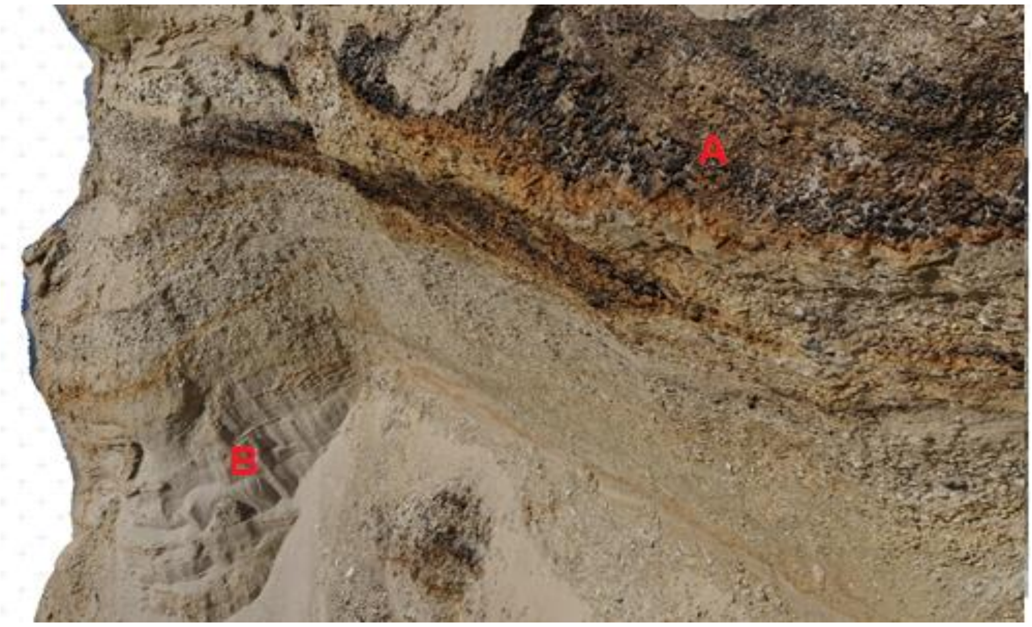


Figure 4.14: Dom level 2, zoomed in. Gravel (A), and small bedding structures (B) can clearly be identified in this model.

4.3.3 *DOM detail level 3*

The last DOM is the most detailed model that was created during this study (Figure 4.15). The section measures about 1 x 1.5 meters and mostly consists of clay, mixed with fine sand. When zoomed in, the model can be visualized in its real-life proportions on bigger computer screens (creating a so-called “wow-effect”, according to the participants). In this DOM, we most likely see the result of groundwater flowing out, possibly caused by a water-resistant layer below. The red colors might indicate that the source material is very rich in iron, while the purple colors might be caused by manganese hydroxides. Also, this can only be determined by collecting and analyzing samples in the field.

Figure 4.15: DOM level 3, a very detailed and realistic looking model of a quarry section.

4.3.4 *DOMs and GIS*

Agisoft offers the possibility to export the textured models to a wide variety of output formats, such as OBJ, STL and TLS. When exported as a georeferenced Scene Layer Package (SLPK), the model can be imported into ESRI ArcGIS. In a GIS the model can be combined with other digital data, such as boreholes, CPTs, and 3D geological models. In Figure 4.16 the georeferenced overview model of quarry Hendrik is visualized with borehole data from the TNO-GDN database DINO, and with a cross-section of the 3D hydrogeological model REGIS II.2, also produced by TNO-GDN. It can be seen that the subsurface at the location of the closest borehole is already excavated. The second borehole sticks out of the model which could mean two things: The model wasn't georeferenced properly, or the location or height of borehole isn't accurate, which is often the case with older boreholes. It can also be noticed that the level of detail of the DOM highly exceeds the level of detail of REGIS II.2, and could add valuable new information for feature models.

Another advantage of georeferenced models is that measurements can be made in physically unreachable areas, as also previously mentioned by Hodgetts (2013). The layers in the deepest part of quarry Hendrik could not only be identified in DOM level 1, but their geometry could also be measured in a GIS (Figure 4.17). The layers can also be easily traced with a 3D polyline drawn on the model surface, and this information could be directly used as input for a new generation of geological models.

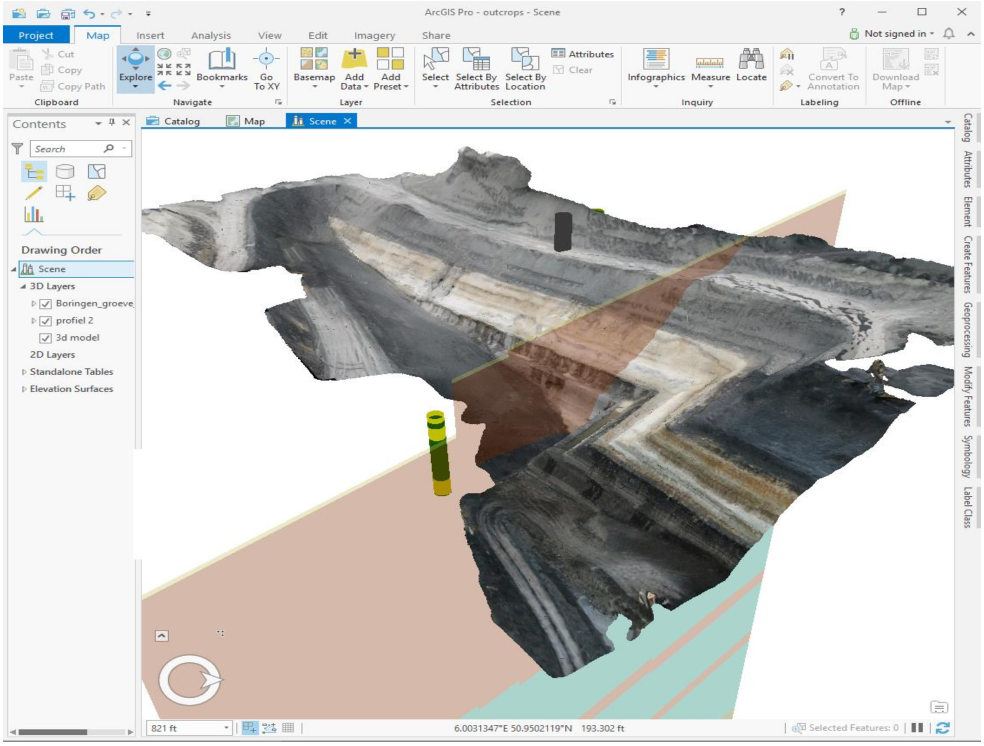


Figure 4.16: DOM in a GIS, with 3D borehole information and model data from TNO-GDN.

Figure 4.17: Drawing 3D polylines and measuring layer thickness in a DOM.

5 Discussion

In this Chapter, the results from the literature review, the needs assessment, and the experiences from the case study in quarry Hendrik will be brought together and be discussed. This will be done by systematically addressing each of the research questions from Chapter 1, in order to come to the conclusions that will answer the main objective of this study in the next Chapter.

5.1 Sedimentary outcrops in the Netherlands

"What are the types of sedimentary outcrops that can be found in the Netherlands, and what are their main characteristics?"

At the start of this study, several types of unconsolidated sedimentary outcrops were defined, based on scientific literature and expert judgment from geologists of TNO-GDN: Natural outcrops, outcrops in active and abandoned quarries, outcrops as a result from infrastructural works, outcrops for geological research, and geological monuments. These categories refer to the function of the outcrop, but not to specific properties of the outcrops, such as size, location or sediment type. There is however a property that can divide them into two major groups, and that is the factor time. Active quarries, infrastructural outcrops, and research outcrops have in common that they are exposed for a very short period of time.

In active quarries, an existing outcrop will be destroyed by excavating material, but will create a new outcrop at the same time. Outcrops at infrastructural works and research outcrops, on the other hand, are usually covered up after the work is done, and can most likely never be visited again. When geologists want to study these short-lived outcrop types, they will have to perform all their fieldwork in the time frame that is given. Most likely, only very few geologists will get the chance to visit the outcrop, often without paying attention to systematically capture outcrop data.

What the other outcrop types have in common is that they are all very vulnerable to natural erosion, as they consist of relatively soft, unconsolidated material. Although they can exist for a longer time, they will eventually all become the victim of natural forces. Some of these outcrops are scientifically very valuable, for example, because of a relatively rare sediment content, and these types of outcrops should be protected where possible, and captured in models for feature generations of geologists.

5.2 Fieldwork

"What are the reasons to perform fieldwork on sedimentary outcrops, and which types of outcrops are visited the most?"

According to Hodgetts (2013), and Howell *et al.* (2014), outcrop data can improve the understanding of the structures of the subsurface, as they provide important information on geobody size, geometry, and potential connectivity. Textural properties of sediments (e.g. grain size, colour) can also be obtained from boreholes or CPTs. However, these 2D data sources provide very minimal information about the structural properties of the subsurface, such as faults and bedding structures.

Other 3D aspects of the subsurface, such as continuity, heterogeneity, and regularity of layers, can also be examined in sedimentary outcrops.

All these characteristics form the input for geological interpretations, that help geologists to create a better view of the subsurface. This view is, in its turn, fundamental to other geological studies, such as on groundwater, subsidence, or earthquakes. The need to create overview was reflected in the answers from the interviewed earth scientists and was mentioned as one of the main reasons to visit sedimentary outcrops. In geology, the smaller features and details always have to be placed in a larger geological perspective to be truly meaningful.

To analyse the size and geometry of sediment layers, measurements are performed in the field, for example, on layer thickness and dip. To a lesser extent, field trips are organized to collect sample material for analysis in the office. However, the most important reason to visit outcrops is for training and education purposes. By visiting sedimentary outcrops with a group, the senior geologists can transfer their knowledge to a new generation of earth scientists. The outcrops that mostly used for training are active and abandoned quarries, and outcrops at infrastructural works, and the needs assessment also showed that over 60% of all visits are at short-lived outcrop types. This means that most of the outcrops are visited in groups, within a very short time frame. As a result, these field trips should be very well prepared in advance to make the best the available field time.

5.3 DOM usage

"How can DOMs of sedimentary outcrops be used in geological research, and could they serve as a replacement for fieldwork?"

Many authors describe the large potential of DOMs in geology, for example, to create overview, for training (Hodgetts, 2013), communication, presentations (García-Selles *et al.*, 2014), geological interpretations (McCaffrey *et al.*, 2005), and measurements (Fleming, 2018). We have to take into account that the majority of these researches were performed with a focus on hard-rock outcrops, so the results do not automatically apply to sedimentary outcrops. What is characteristic for sedimentary outcrops is their vulnerability to erosion and destruction by man. While hard-rock outcrops can remain unchanged for hundreds or even thousands of years, many sedimentary outcrops only exist for a very short period of time. If an outcrop is destroyed or can't longer be physically visited for any other reason, a DOM is regarded as the best possible representation of the original outcrop.

5.3.1 Training

The main reason to visit outcrops in the Netherlands is for training and education. These types of visits usually start with an introduction of the area to explain the larger geological settings. This is mostly done at an overview point in the field, with paper maps, and by pointing out features in the distance. Hodgetts (2013) states that, in order to make the best of the available time in the field, a DOM can be used to give the fieldwork introduction in advance, for example, the previous day in the office. The ability to navigate through the DOMs will help to better identify the important features of the outcrop, and valuable field time can be saved on the day of the excursion. Another advantage of giving the introduction inside is that all participants can better hear the field guide, which is often a large problem during field trips in groups.

The downside is that the models of the outcrop have to be made in advance, which might be difficult if the outcrop is in a remote area. In very active changing environments, such as quarries, the DOM should not be made too far in advance, although it is expected that most older DOMs could still serve a tool to explain the larger geological setting of an area. Using only DOMs to train geologists is not an option for the participants of the needs assessment. It is essential for geologists that they get to feel the materials with their own hands and to experience the real-life dimensions of geological structures in the field, for a better understanding of the work they do in the office.

5.3.2 Creating overview

The needs assessment showed that most of the participants want to create a geological overview of the area, to put the details into a larger perspective. This overview is usually difficult to obtain in the field, because of the large dimensions of the main geological structures. Hodgetts (2013) describes the advantages of using virtual viewpoints, and 14 out of 15 specialists agree with Hodgetts, in the sense that they prefer to use an overview model over a highly detailed model, to inspect the entire outcrop from all angles. Especially the ability to zoom out and see an outcrop from a birds-eye perspective is considered being a huge advantage of DOMs, over the traditional fieldwork practices. Specific layers in larger quarries could be traced in a DOM over long distances, and when multiple DOMs are created of nearby outcrops, geological layers might be traced over tens of kilometres, revealing even larger geological structures and patterns of the subsurface. The downside of overview models is that they easily get too big to be handled by the current generation of computers, so choices in scale and detail have to be made in advance, as also stated by García-Selles *et al.* (2014).

Hodgetts (2013) also describes the advantage of swapping between scales to see the larger geological perspective. Most of the participants of the needs assessment indicated that constantly switching between details and overview, is a very effective method to come to new geological insights. Therefore, a majority prefers to use nested models over individual models, which enables swapping between even larger scales than in a single DOM. It can be concluded that especially the overview models will largely contribute to creating geological overview, by providing complete new ways to look at outcrops that were previously impossible.

5.3.3 Communication and presentations

García-Selles *et al.* (2014) suggest that DOMs can be used for data presentation, discussion and sharing of geological features, and all the 15 participants agreed with García-Selles *et al.* that DOMs will be very powerful communication tools. They can be used for internal communication in projects, for example to discuss or point out features to colleagues. For external communication, it can be used in meetings with stakeholders to present results, to give demonstrations at conventions, or as study material at universities and schools.

When presenting the final models of this study to several geologists, they immediately started a geological discussion while navigating through the models and pointing out features to each other. According to the participants, the ability to make annotations, draw, or create hyperlinks in the model would make a DOM an even more effective communication tool. The needs assessment surprisingly showed that the category of models as described by Fleming (2018) as “high-resolution, photo-realistic models that provide a 3D base for unprecedented capabilities for geometric analysis”, were only seen as demonstration material without further practical application in geological research. However, they have the most potential to create a so-called “wow-effect”, that can help to attract and interest a new audience to the science of geology.

5.3.4 Measurements

In general, a measurement in the field will be more reliable than a measurement performed in a DOM, since a model is always a simplified representation of the real world. However, a DOM offers the possibility to also collect data from physical unreachable or even invisible areas (Hodgetts, 2013). This was proven by the fact that the UAV was able to capture data from the deepest part of quarry Hendrik, that was not visible from any of the accessible viewpoints, and the otherwise hidden sediment layers could now be measured and traced. Another advantage is that a DOM also offers the chance to re-visit an outcrop, once back from the field. After a field trip, memories can fade, or geological insights can change. A DOM offers the possibility to re-visit the area and perform measurements in all locations in the outcrop that were not made in the field for some reason. All the 15 participants expected to use a DOM to re-visit outcrops, if a DOM was available. However, the user should always be made aware of the estimated accuracy and precision of a model, when making measurements and using the results in other research.

5.3.5 Interpretations

According to several authors (e.g. McCaffrey *et al.*, 2005), DOMs could be used to make geological interpretations in the office, without visiting the field. Although this might be true for hard-rock outcrops, an interpretation in a DOM of a sedimentary outcrop will have to be solely based on sediment color and the larger visible geological structures. The separate grains of the sediments are generally too small to be captured in the model's texture, and the exact grain sizes of the sediments cannot be measured. Although some larger structures could successfully be identified in the DOMs (e.g. bedding structures and gullies), all the participants of the needs assessment agreed that a geological interpretation of sediment layers, purely based on the information in a DOM, is impossible. However, when the main interpretations are done in the field, a DOM could be a useful asset to refine the interpretations afterwards. When a DOM is accurately georeferenced and imported into a GIS, the possibility to combine it with other data will help geologists to identify specific geological layers, something that cannot easily be done in the field. However, it can be concluded that DOMs cannot fully replace fieldwork for making geological interpretations. On the other hand, when the model is georeferenced and imported in a GIS to be combined with other available data, it will be a valuable addition to geological research of sedimentary outcrops.

5.4 Requirements

“What are the requirements of a DOM in terms of detail, precision and accuracy to be a valuable addition to geological research?”

Because of limits of the current generation of computers, and available data collecting techniques, larger outcrops can’t be completely modelled at the highest level of detail. According to Chesley *et al.* (2017), the excessive number of photos that is needed will cause prolonged processing times and unnecessarily large files that can be difficult to manipulate, something that was also experienced during the experimental phase of this study. The time and total size of the dataset that was used to create the most detailed model (DOM level 3: 1 x 1.5 meters), is comparable to that of the overview model (DOM level 1: 340 x 130 meters). If the entire quarry was to be modelled on the detail level of DOM level 3, just collecting the input data would take several weeks to months, even without taking into account that large parts of the quarry are inaccessible. The choices in scale that have to be made in advance, that will also have a direct influence on the model's detail. However, the final models that were created in this study proved that the loss of detail in the overview model is acceptable for most of the interviewed geologists. A selection of more detailed models, such as DOM level 2 and 3, can be created for the most interesting parts of an outcrop. These detailed models can be placed inside the overview as a nested model which a majority of the needs assessment participants preferred over a stand-alone model. The selection of the actual areas that have to be modelled into more detail, should always be done by an expert, to avoid insufficient coverage.

The needs assessment proved that a georeferenced DOM that is combined with other existing data in a GIS (e.g. boreholes, CPTs), can help to obtain new geological insights and can potentially serve as additional input for existing geological models. Although Cawood *et al.* (2017) and Micheletti *et al.* (2015) state that unreferenced material can be used for Structure from Motion, 14 out 15 interviewed geologists prefer the resulting model to be placed in a known coordinate system, such as WGS84/UTM zone 31N. An accuracy of 10 meters or less in horizontal direction (XY) and 0.5 meters or less in vertical direction (Z) is on average considered to be the absolute minimum for overview models and medium scale models (DOM level 1 and 2). It has to be noticed that most geologist would strongly prefer to work with more accurate georeferenced models, but indicated that they could still use models with this minimum level of accuracy, if needed. The majority of the participants did not see the need to georeference the most detailed model since it is mostly considered as a stand-alone showcase.

Precision can be described as the internal consistency of the model which proved to be even more important than accuracy, according to the needs assessment. While undeformed models can be used to make measurements (e.g. layer thickness and dip), a deformed model is considered being too unreliable for use. Deformations are mostly the result of poor camera alignment in SfM, and since this is a relatively short process in the complete SfM workflow, it is strongly advised to perform the camera alignment with the highest possible settings.

5.5 Data collection

"How should data be collected in the field to meet the requirements with SfM?"

The requirements on detail, accuracy and precision of a DOM should determine the methods that are used to collect data in the field. In general, Micheletti *et al.* (2015) advise planning the camera survey in advance to make the best of the available field time. This is even more important when collecting data in sedimentary outcrops, since there is often no second chance to collect new data in a later stage, in case of a mistake, also proved by the use of the wrong type of GCP markers during the fieldwork.

The level of detail of a DOM is mostly the effect of the predetermined scale but is also influenced by the quality of the used equipment, camera settings, data coverage, amount of overlap, and lighting conditions. Agisoft (2018) advises using digital cameras with a reasonably high resolution, and always use its maximum available settings. However, the fieldwork showed that with high-end cameras and UAVs, the highest settings can result in excessively large datasets. A pixel size of 4000x3000 proved to be sufficient to create usable overview models. The hand-held camera for the more detailed models was set to the roughly 8000x6000 pixels to capture smaller details. Niederheiser *et al.* (2016) recommends disabling all automatic options in the cameras themselves, such as the auto-focus, image stabilization, and the good sensor qualities, e.g. sensor sizes and pixel counts. On the other hand, Micheletti *et al.* (2015) strongly advise to avoid overexposed, underexposed and blurred images. The fieldwork proved that if the data collector is not very well acquainted with the used equipment or photography, it is better to use at least some automatic settings. This will greatly reduce the risk of returning from the field with an unusable dataset.

Another key element for the level of detail is the appropriate data coverage of the outcrop. Micheletti *et al.* (2015) describe to capture the whole subject first, and then the detail, ensuring that occlusions are captured adequately. This method will also assure that data, that is needed for the overview models is collected first.

According to the Metashape user manual (Agisoft, 2018), an overlap of ~60% between adjacent photos is typically sufficient. However, in the field, this proved to be challenging, especially when flying a UAV and taking pictures at the same time. When using video instead of photography, the drone pilot can focus on flying and is assured of sufficient coverage and overlap.

Geotagging the images during the data acquisition phase can increase the accuracy and decrease the time and effort required during processing (Chesley *et al.*, 2017). Although this proved to be true during the modeling phase, the desired level of accuracy could not be reached by using a standard GPS, such as build-in in the hand-held camera and UAV. Also, Fleming (2018) states that several studies underscore the role of GPS error in georeferencing SfM-models, especially in vertical direction. Using a DGPS to measure GCPs will greatly reduce the errors. It has to be noticed that even a DGPS can produce an error if it placed too close to a vertical quarry wall, so sufficient markers should be placed strategically throughout the outcrop. According to Fleming (2018), a set of 5 to 10 markers proved to be sufficient to accurately georeference the model. Unfortunately, the GCPs that were placed for this research could not be used, because the software couldn't recognize their reflective surfaces.

The precision of a model is regarded as even more important than the accuracy, according to the needs assessment. The precision of a DOM as a whole directly results from the precision of the camera alignment phase during SfM. Parameters that influence the success rate of camera alignment are: a lack of vertical relief in camera positions (Fleming, 2018), moving objects and changing lighting conditions during data collection (Micheletti *et al.*, 2015). Using a UAV will help to capture data from many height levels, thus reducing errors. In all cases, data should be collected under consistent lighting conditions. Since the weather in the Netherlands can be unstable, it is recommended collect the data in the shortest possible timeframe.

6 Conclusions

Several important conclusions can be drawn, based on the performed research, that help to answer the main objective of this study:

How can Digital Outcrop Models of sedimentary outcrops, created with Structure from Motion, and having sufficient detail, precision, and accuracy be a valuable addition to geological research?

A large part of unconsolidated sedimentary outcrops in the Netherlands are temporally exposed, since they are vulnerable to erosion and destruction by man. They are often visited by geologists, since outcrops can provide them with information about the subsurface that can’t be obtained from other data sources, such as boreholes and CPTs. Capturing these outcrops as a Digital Outcrop Model offers many new opportunities to geological research. Although they will never fully replace the traditional fieldwork, for example to make geological interpretations or training purposes, they proved to be a very valuable addition. However, if an outcrop can’t be physically visited anymore, for example because of destruction, a DOM is regarded among earth scientists as the closest representation of the real outcrop.

DOMs are seen as powerful communication tools for both internal and external communication. They can be used to discuss with colleagues in projects, to present results, for education, and as a showcase at conventions and other presentations. The ability to have virtual viewpoints, and combing georeferenced DOMs with other geo-data in a GIS, will help geologists to see the larger geological perspective, that is difficult to obtain in the field. DOMs also provide the option to re-visit an outcrop, since memories can fade, and new geological insights might ask for new measurements in the outcrop. However, the exact application of a DOM in geological research will highly depend on the level of detail, precision, and accuracy.

At the start of the study, it was expected that sedimentary geologists would prefer the highest level of detail of DOMs, to identify the textural and structural properties of sediments, such as grain sizes and grain size distributions to make geological interpretations. The needs assessment showed that experts make interpretations by first defining the larger geological setting, and that the need for overview models greatly exceeds the need for more detailed DOMs. The most interesting option for geologists proved to be the use of nested models on different scales, where one or more detail models are placed inside an overview model. This enables them to swap continually between different scale levels to come to new geological insights. All interviewed geologists agreed that DOMs always have to be georeferenced, for example in WGS84 or RD/NAP. However, an exception is made for the photo-realistic detail models. They are generally considered as products for demonstrations, but otherwise little practical use for geological research. On average, an absolute minimum accuracy 10 meters or less meters horizontally and 50 cm vertically is considered being acceptable for the other models. The precision of a model is regarded to be more important than its accuracy. A model with a high precision can still be used for internal measurements, even though it might not be positioned well. A deformed model is regarded as too unreliable for further research.

To obtain a dataset to produce DOMs that meet the needed minimum requirements, several things must be taken into account. High-quality equipment is advised, and especially the use of a UAV, to capture physically unreachable areas and improve the precision, proved to be very valuable. To ensure enough coverage and overlap of the images, filming in 4k should be used when using the UAV. To prevent changing lighting conditions, data should be captured as efficiently as possible, preferably starting with overview shots, to more detail later. To accurately georeference the DOMs, ground control points should be used in combination with DGPS measurements.

7 Recommendations

- Collecting data for DOMs created with SfM should become a standard procedure for every field trip to an outcrop. Geologists of the Geological Survey can be trained to collect data, since even smartphone cameras can produce decent 3D models if used in the right way. For longer field trips, it is recommended to develop a protocol to assure the highest quality of input data, consisting of a checklist for fieldwork preparations, and a summary of the most important findings of this research on data collection techniques.

- The archiving and dissemination of DOMs models was not part of this research but needs to be addressed as soon as possible. It is advised to archive DOMs in the DINO database at TNO-GDN, linked to its real location and other available geodata. The DOMs could be made available on the web, for example by using ArcGIS Online or the DINOloket website by TNO-GDN. Another interesting option is to disseminate the calculated dense point clouds as a stand-alone product, for example through the Open Point Cloud Map initiative.

- The most promising feature developments are the correlation of sediment layers between multiple DOMs, and the use of time series in actively changing environments. Creating multiple DOMs trough time offers great new opportunities, such as full 3D modeling of geological features or measuring the volumes of eroded material through time (4D modeling). However, this could mean that new requirements are needed and additional research should be performed.

- Digital LiDAR sensors are expected to become smaller and less expensive in the near future. Scanning outcrops with LiDAR sensors mounted on UAVs, while collecting RGB images for SfM at the same time, could be used to create more detailed and precise DOMs. It is recommended to focus on the opportunities of combining SfM and LiDAR in feature research.

- Spectroscopy is a science that can derive significant information about mineralogy by measuring the emitted, reflected, or scattered light from different rocks and sediments. For certain classes of minerals, spectroscopy is an excellent tool, for example clay mineralogy, iron oxides and hydroxides, carbonates, sulfates, olivines, and pyroxenes. Research on combining SfM, DOMs, and (airborne) spectroscopy measurements could potentially lead to exiting and unprecedented new developments in geology, such as the automatic interpretation of sediment layers.

- The georeferencing of the models in this study wasn’t as successful as expected, since the used markers did not show up in the results. Therefore, it is advised to use large enough and contrasting markers to assure its identification in the model. Round black-and-white discs (as used for photogrammetry techniques with airplanes) with a diagonal of one meter should be sufficient for creating accurate overview models. It is strongly recommended not to use LiDAR reflectors, since their reflective surfaces are not recognized during the photo-alignment phase and will most likely be filtered out.

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Appendix I – Technical specifications resources

Hardware

- Laptop with Intel Core i7-8850H CPU 2.60GHz, 32GB RAM and Intel UHD Graphics 630
- GPS receiver Garmin Oregon® 600
- DGPS (GNSS R8s with Trimble TSC3 field computer)
- Camera Sony α7RIII (24.2 MegaPixel, 4K video, with interchangeable lens)
- Samsung Galaxy A9 Camera (F1.7, 1.4μm pixel)
- SanDisk Extreme micro-SDXC card (128GB 90MB/s)
- Drone DJI Mavic Pro (Quadcopter, 4K video, photo 4Kx3K, gimbal -90° to +30°)

Software

- Agisoft Metashape 1.5.2 Professional Edition
- ESRI ArcGIS Pro 2.2 with 3D Analyst, Spatial Analyst & Data Interoperability
- Python 3 with arcpy and metashape modules
- MeshLab 2016
- DJI GO 4
- Imaging Edge Mobile

Figure I.1: UAV DJI Mavic Pro

Appendix II – Questionnaire questions

This questionnaire starts with a short introduction on Digital Outcrop Models, the research objectives and a demonstration of three DOMs on different scale levels.

- *Level 1: An overview of an active quarry (~300x150 meters)*
- *Level 2: A section of quarry Hoher Stall (~15x10 meters)*
- *Level 3: A detail of quarry Hendrik (~1x1 meter)*

1. **How much experience do you have as an Earth Scientist?**

1 – 5 years	
5 – 10 years	
10 – 20 years	
More than 20 years	

2. **What are your specialties in Earth Sciences? (Multiple answers possible)**

Geology	
Sedimentology	
Seismology	
Biogeology	
Geochemistry	
Hydrology	
Other …	

3. **How often do you visit any of the following outcrops per year?**

	>5 times	1-5 times	< 1 time	Never
Active quarry				
Abandoned quarry				
Natural outcrop				
Scientific outcrop				
Infrastructural outcrop				
Geological monument				

4. **What is the main purpose of your visit? (3 = most important, 1 = least important)**

	3	2	1
Overview/insight			
Data collection			
Making measurements			
Training/education			

5. **Could you use a DOM with this detail level in your current work for any of the next purposes? (3 = very likely, 1 = not very likely)**

	3	2	1
Create overview			
Presentations / demonstrations			
Measurements			
Communication			
Model input			
Interpretations			

6. **With what accuracy (meters) needs a DOM with this detail level to be georeferenced in horizontal (XY) direction?**

7. **With what accuracy (meters) needs a DOM with this detail level to be georeferenced in vertical (z) direction?**

(Questions 5 through 7 were asked for all three detail levels)

14. **What scale level(s) would be the most suited for your work?**

Detail level 1	
Detail level 2	
Detail level 3	
A combination of detail levels 1 & 2	
A combination of detail levels 2 & 3	
A combination of detail levels 1, 2 & 3	

15. **Which of the following do you prefer? A model with …**

High accuracy and low precision	
Low accuracy and high precision	

16. **Do you have any questions or remarks?**

Appendix III – Questionnaire results

The results were anonymized, the gray color represents the most given answer(s) to each question.

Work experience

Participant		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q1	*1-5 years*												x			
	5 -10 years				x			x								x
	10 -20 years	x				x					x				x	
	> 20 years		**x**	**x**			**x**		**x**	**x**		**x**		**x**		**x**

Specializations

Participant		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q2	***Geology***	**x**	**x**	**x**	**x**		**x**	**x**		**x**	**x**	**x**	**x**	**x**	**x**	
	Sedimentology					x	x							x	x	
	Seismology					x										
	Biogeology	x														
	Geochemistry															x
	Hydrology								x							
	Geomodelling								x							
	Paleogeology									x						
	Geomorphology											x				
	Stratigraphy													x		

Outcrop visits per year

Participant			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q3	***Active quarry***	***> 5 times***		**x**				**x**					**x**		**x**		**x**
		1-5 times	**x**		**x**		**x**		**x**	**x**	**x**	**x**		**x**		**x**	
		< 1 time				**x**											
		Never															
	Abandoned quarry	*> 5 times*											x		x		x
		1-5 times	x	x	x			x	x		x	x					
		< 1 time				x	x			x				x		x	
		Never															
	Natural outcrop	*> 5 times*									x	x			x		
		1-5 times					x						x				x
		< 1 time	x		x			x	x								
		Never		x		x				x				x		x	
	Scientific outcrop	*> 5 times*													x		
		1-5 times											x				
		< 1 time	x	x	x	x	x	x	x	x	x					x	x
		Never										x		x			
	Infrastructural outcrop	*> 5 times*	x	x				x					x		x		
		1-5 times			x		x			x							x
		< 1 time				x			x							x	
		Never									x	x		x			
	Geological monument	*> 5 times*											x		x		
		1-5 times															
		< 1 time						x	x								
		Never	x	x	x	x	x			x	x	x		x		x	x

Main purpose of visits

Participant			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q4	Overview	3	x		x			x			x	x	x		x	x	
		2		x			x		x								x
		1				x				x				x			
	Data collection	3		x				x				x	x				x
		2	x		x						x				x	x	
		1				x	x		x	x				x			
	Measurements	3			x							x	x				x
		2		x				x			x				x	x	
		1	x			x	x		x	x				x			
	Training	**3**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**			**x**	**x**	**x**	
		2										**x**					**x**
		1											**x**				

Usability DOM level 1 (overview model)

Participant			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q5	**Overview**	**3**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	
		2															
		1															**x**
	Presentations	**3**	**x**		**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
		2		**x**													
		1															
	Measurements	3		x				x				x					
		2	x			x	x				x				x	x	x
		1			x				x	x			x	x			
	Communication	3	x	x				x		x	x	x	x	x	x	x	x
		2			x		x		x								
		1				x											
	Model input	3	x	x				x		x	x						
		2			x	x			x			x			x		
		1					x						x	x		x	x
	Interpretations	3					x		x								
		2		x	x			x			x	x		x	x	x	
		1	x			x				x			x				x

Minimum horizontal and vertical accuracy of DOM level 1

Participant		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q6	< 1m		x									x				x
	1 - 10m	**x**		**x**	**x**		**x**	**x**			**x**			**x**		
	10 - 25m								x							
	25 - 50m												x		x	
	50 - 100m					x				x						
	> 100m															
	Not needed															

Participant		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q7	< 0.1m										x	x				x
	0.1 - 0.5m			**x**			**x**						**x**	**x**		
	0.5 - 1m	**x**	**x**		**x**			**x**	**x**							
	1 - 5m					x									x	
	5 - 10m															
	> 10m									x						
	Not needed															

Usability DOM level 2

Participant			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q8	Overview	3			x		x										
		2	x			x		x	x		x	x	x	x	x	x	x
		1		x						x							
	Presentations	**3**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
		2															
		1															
	Measurements	3	x				x						x			x	x
		2			x	x		x		x	x			x	x		
		1		x					x			x					
	Communication	**3**	**x**		**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**		**x**
		2		**x**												**x**	
		1															
	Model input	3								x	x						
		2	x				x						x		x		x
		1		x	x	x		x	x			x		x		x	
	Interpretations	3					x		x				x		x		
		2	x			x				x	x			x		x	x
		1		x	x			x				x					

Minimum horizontal and vertical accuracy of DOM level 2

Participant		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q9	**< 1m**	**x**	**x**	**x**	**x**		**x**		**x**				**x**	**x**	**x**	**x**
	1 - 10m					x		x								
	10 - 25m															
	25 - 50m															
	50 - 100m															
	> 100m															
	Not needed									x	x	x				

Participant		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q10	**< 0.1m**			**x**	**x**			**x**						**x**	**x**	**x**
	0.1 - 0.5m	**x**	**x**				**x**		**x**				**x**			
	0.5 - 1m					x										
	1 - 5m															
	5 - 10m															
	> 10m															
	Not needed									x	x	x				

Usability DOM level 3

Participant			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q11	Overview	3															
		2						x									
		1	x	x	x	x	x		x	x	x	x	x	x	x	x	x
	Presentations	**3**	**x**	**x**	**x**		**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
		2															
		1				**x**											
	Measurements	3						x									
		2		x							x					x	x
		1	x		x	x	x		x	x		x	x	x	x		
	Communication	3			x			x	x				x				x
		2		x		x					x	x				x	
		1	x				x			x				x	x		
	Model input	3															
		2															
		1	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Interpretations	3															
		2	x	x							x						
		1			x	x	x	x	x	x		x	x	x	x	x	x

Minimum horizontal and vertical accuracy of DOM level 3

Participant		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q12	*< 1m*	x	x													x
	1 - 10m						x									
	10 - 25m															
	25 - 50m															
	50 - 100m															
	> 100m															
	Not needed			**x**	**x**	**x**		**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	

Participant		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q13	*< 0.1m*		x													x
	0.1 - 0.5m	x					x									
	0.5 - 1m															
	1 - 5m															
	5 - 10m															
	> 10m															
	Not needed			**x**	**x**	**x**		**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	

Preferred DOM level(s)

Participant		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q14	*Level 1*				x	x				x	x					
	Level 2															
	Level 3															
	Level 1& 2	**x**	**x**	**x**				**x**	**x**				**x**	**x**		
	Level 2& 3															x
	Level 1, 2 & 3						x					x			x	

Importance of precision versus accaracy

Participant		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q15	*Acc. > precs.*								x				x			
	Prec. > acc.	**x**	**x**	**x**	**x**	**x**	**x**	**x**		**x**	**x**	**x**		**x**	**x**	**x**

Appendix IV - technical specifications DOMs

DOM level 1 (overview model)

Parameter	Value
Dimensions (LxWxH)	240 x 130 x 80 meters
File type	TLS
File size	345 MB
Number of images used	151
Surface type	Tiled height surface
Alignment accuracy	High
Dense point cloud quality	Medium
Surface face count	High
Texture blending mode	Mosaic

DOM level 2 (medium scale model)

Parameter	Value
Dimensions (LxWxH)	12 x 6 meters
File type	TLS
File size	204 MB
Number of images used	22
Surface type	Tiled height surface
Alignment accuracy	High
Dense point cloud quality	Medium
Surface face count	High
Texture blending mode	Mosaic

DOM level 3 (detail model)

Parameter	Value
Dimensions (LxWxH)	1.5 x 1 meters
File type	TLS
File size	241 MB
Number of images used	34
Surface type	Tiled height surface
Alignment accuracy	High
Dense point cloud quality	Medium
Surface face count	High
Texture blending mode	Mosaic