



Observing Digitally

The use of Image-Based 3D Modelling Techniques
for the documentation and study of Rune Stones

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Abstract

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This thesis aims to test and evaluate the use of image-based 3D modelling techniques on rune stones. To test the method a well-documented rune stone was chosen, Hyby stone 1. The stone has been dated to the Viking Age and contains 37 runes, whereof 29 are still visible, two crosses and a stag. These carvings have been detected by other scholars with the use of non-digital methods. In order to evaluate the efficiency of this method it was compared with *Danmarks Runeindskrifter* from 1941-42, which is the standard source for Danish rune stones. The authors used electric light and cameras to document the stone. The thesis combines the commercial software Agisoft Photoscan and the open source software Meshlab. The former was used to create the model with Structure from Motion (SfM) and multi-view reconstruction and the latter for analysing the geometry by applying different types of shaders and then draw the visible carvings. The chosen shaders were two kinds of radiance scaling called lambertian radiance scaling and grey descriptor. By using this method it was possible to reach almost the same result as *Danmarks Runeindskrifter*. The method has proved its efficiency and allows for the definition of a workflow which provides a low cost efficient addition for the means of studying rune stones.

Keywords: Rune Stone, Image Based Modelling, Low cost, Documentation, Viking Age, Agisoft Photoscan, Meshlab, Radiance scaling, 3D.

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1 Introduction

The industrialization was a great boon to humanity but also a great danger to the material remnants of the past. With increasing pollution in the air monuments started to weather away even faster than before. Rune stones were in use from the fourth and fifth century and onwards (Snædal 1994, p. 10). They have become one of the strongest national symbols for the Nordic people and are especially associated with the Viking Age. If the runes disappear future generations will not be able to see these important symbols and unique sources of information about socio-cultural and political developments in Viking Age Scandinavia.

There are ways of preserving the stones, for example by using different chemical means and by monitoring them. The problem is that at the moment there is no way to properly conserve the stones, only means of slowing down the deterioration. One way to preserve the information on monuments is to document them. Documentation is important in archaeology since it allows information that is being excavated or is weathering away to be preserved. With a good documentation method it is possible to reevaluate one's conclusions. The documentation also makes it possible to compare the result with other objects documented in similar ways. In this way it is also possible to spread the information created by the documentation to others. The simplest method of documentation is annotating or sketching the studied objects with the use of pen and paper. During this process the archaeologist needs to make an interpretation which will be visible in the image. With the exponential growth in technology many new methods are tested and incorporated into documentation.

The use of digital instruments for the documentation and analysis of archaeological sites and monuments provide archaeologists and specialists with a more accurate description of the materials retrieved. One tool that can be used is a laser scanner. A laser scanner is a device that can measure objects using lasers, lights or x-rays and generates dense point clouds. With the use of laser scanners it is possible to capture the geometry of physical objects with high accuracy and precision. However, laser scanners are expensive and are not always portable (3D Systems 2015). Another digital method used on rune stones is Reflective Transformation Imaging (RTI). RTI is a computational photographic based method which produces 2D images of objects. The 2D object created with this method keeps the surface shape and is able to enhance the geometrical characteristics of the surface (Cultural Heritage Imaging CHI 2015a). The use of this technique increases the possibilities of scholars and researchers to

study the surface. The method is very light sensitive and requires specific light conditions in order to work.

For this thesis a third option was chosen, image-based 3D modelling. Through the use of this technique it is possible to generate accurate digital replicas of a scene using resolute digital pictures.

1.1 Purpose

The aim of this project is to test and evaluate a low cost approach based on the combination of image-based 3D modelling techniques (for the generation of an accurate and resolute model for the 3D documentation of the rune stone) together with the use of Meshlab, an open source software for the processing and editing of unstructured 3D triangular meshes (for the analysis of the surfaces previously generated). This method will also be able to simulate with high accuracy the geometrical characteristics of the rune stone providing archaeologists with the opportunity to notice elements not visible without the technical aid. The development of such project will allow for the defining of a robust workflow which can eventually be used for the systematic acquisition and analysis of other rune stones. However, this work does not aim to translate any runes since the author does not have sufficient knowledge of runology.

1.2 Research Aim

- Evaluate the use of image-based 3D modelling techniques to document rune stones and using system for the processing and editing of unstructured 3D triangular meshes, such as Meshlab, in order to detect new archaeological information.

1.3 Material

The material chosen for this thesis are rune stones and particularly Hyby rune stone 1, also referred to as Vismarlövstenen or DR 264 (based on its number in *Danmarks Runeindskrifter*). This rune stone is dated to the Viking Age. According to *Danmarks Runeindskrifter* it contains 37 runes, whereof 8 are not visible, two crosses and one stag (Jacobsen & Moltke 1941-42 text, p. 320). The rune stone was discovered and first documented during the 1600s and since then it has been documented five times. Hyby rune stone was also part of a study done by Riksantikvarieämbetet, RAÄ, about weathering, which showed how the stone has deteriorated over time (Löfvendahl 2001, p. 17). The stone was chosen because it is well documented and the deterioration of it is already known. Knowing

these factors makes the evaluation of the effectiveness and limitations of image-based 3D modelling on rune stones more secure.

Runes were the written letters used by the Germanic people in northern Europe. The name of the alphabet comes from its first six letters, which forms the word Futhark. The use of the Futhark started during the first centuries A.D. The runes were carved on different kinds of materials, like bone, stone, metal and wood. The oldest finds of runes were carved on weapons (Snædal 1994, p. 9f). The alphabet has changed over the years since it was first created. The oldest versions of runes were called the older Futhark (Findell 2014, p. 16). This version consisted of 24 runes. The alphabet was divided into three groups with eight runes in each. The second variation of the Futhark came around the turn of the 8th and 9th century (Benneth et al 1994, p. 8). The newer Futhark was a shorter version of the older, consisting of only 16 runes. This newer alphabet was divided into two versions, one with normal runes and one with shorter variations of the same runes. The normal runes are those that can be seen on rune stones. The other version with shorter runes was properly used for carving on wood. The shorter runes are also thought to have been used for personal messages (Sawyer 2003, p. 8ff). The new Futhark was created to better suit the changes which had occurred to the language over time (Benneth et al 1994, p. 8). The runic alphabet underwent a third change during the medieval period when Latin letters were translated into runic characters (Benneth et al 1994, p. 8). The two older Futhark alphabets were not used in the same way as Latin since the Futhark was only for carvings (Enoksen 1999, p. 9).

Rune stones are stones which have had runes carved on them. In Scandinavia there are more than 3000 known rune stones and most of them were carved during the late Viking age, in the 10th and 11th centuries. Most of the Swedish rune stones can be found in the eastern parts of the country, for example the county of Uppland have more than 1000 known rune stones (Sawyer 2003, p. 7). The rune stones in Scania (which in the Viking Age and Middle Ages was a part of Denmark) number 60 monuments (Enoksen 1999, p. 7f). The tradition of raising rune stones is believed to have started in northern parts of Scandinavia and reached southern Sweden some time during the 7th century. The custom of commemorating highborns in rune stones increased after the Jelling stone was made (Sawyer 2010, p. 10). The stones were raised for a number of different reasons but most of them had the same structure of text, where someone carved the runes in memory of a deceased person or an important event (Sawyer 2003, p. 10). The stones were typically commemorating deceased members of the

family or community who died at home or abroad (during the Viking raids, trade or voyaging) (Sawyer 2003, p. 16f). As many rune stones were raised in the period of religious transition from pre-Christian tradition to Christianity, the inscription and symbols carved on the stones inform about religious beliefs of the deceased and their close ones. Another reason to raise a rune stone could have been to show and claim one's property and inheritance. Most of the rune stones were raised by people who had a close relationship to the deceased (Sawyer 2003, p. 48f). The rune stones were often raised in areas where people could see them such as graveyards or near roads and thingsteads (Snædal 1994, p. 20).

1.4 Research History

Rune stones have been studied for centuries and continue to attract scholarly interest. All known stones have been documented by many different scholars. They are the only written sources from before medieval times left by Scandinavians. This gives them an enormous value for understanding language, culture and social interactions. As explained and showed in the following texts the research focus changed over time from documenting the stones to translating the inscriptions and evaluating their stylistic features, and then to connect the customs of raising rune stones and the information they contain to the socio-cultural and political processes taking place in the Viking Age. Another direction taken by the research concerns the effects of weathering on the stones and the development of adequate conservation procedures. Scholars are trying to find chemical solutions which can halt and prevent these effects and to develop documentation methods that do not harm the objects and allow detailed reconstruction of their surface.

The history of systematic research on rune stones can be traced back to Johannes Bureus. Bureus lived during the 1500s and his work and interest in rune stones led to the establishment of the Runverket (Department of runes), which later resulted in the founding of Riksantikvarieämbetet and further research about rune stones (Kaliff 2011, p. 12). The first work published by Bureus on the subject of rune stones was *Runakänslanes läroplan* (1599). It included drawings as well as the author's thoughts on how runes were pronounced and how the grammar was used. This translation was later used by many scholars, including Ole Worm, but it was not the first one. Johannes and Olaus Magnus created a translation of the runes into Latin letters in 1555 (Enokson 1999, p. 11f). Worm was active in the same time as Bureus but in Denmark. On orders from the Danish king Worm set out to document all the Danish rune stones. At this time the counties of Blekinge, Halland and Scania were Danish.

He himself visited some of the rune stones but also hired people to help with the documentation. One of the helpers, Jonas Skonvig, made the drawings of most of the Scanian rune stones (Jacobsen & Moltke 1941-42 text, p. V). All drawings of the Danish rune stones later became woodcuts and published in his work *Monoumenteum Danicorium libri sex* in the year 1643 (Moltke 1932. p. 322). However, the translations provided by Worm were in many cases incorrect (Enoksen 1999, p. 14f).

After the era of Bureus and Worm it would take time before bigger revelations were made within the study of runes. The surveying of runes and runes stones went on, and a work covering all the Swedish rune stones was the biggest focus in Sweden. Johan Hadorph (1630-1693) and Johan Peringsköld (1654-1720) held high offices within the antiquary world in Sweden. During their time they managed to gather over 1000 wooden imprints of Swedish rune stones. In the year 1660 the counties Blekinge, Halland and Scania became Swedish through a peace deal. This meant that the rune stones in these counties now counted as Swedish as well and needed to be included in the work. The one who finally completed this work was Johan Göransson (1712-1769) in *Bautil*, published in 1750 (Enoksen 1999, p. 22).

Sophus Bugge and Ludwig Wimmer reintroduced the runes into modern research. Both scholars managed to understand the system and sounds of the oldest runes on their own during the same time (Enoksen 1999, p. 27). Bugge wrote *Norges Indskrifter med de aeldre runer I-III* (1891-1924) which covered all the Norwegian rune stones (Jacobsen & Moltke 1941-42 text, p. VI). In Denmark Wimmer was asked to write a new collective book about the Danish rune stones. This work was called *De danske Runemindesmærker I-III* (1893-1908), and contained both the stones that Worm had gathered and those which had been found after Worm's time. Wimmer also changed how the stones were documented. Before Wimmer scholars did not visit every rune stone themselves but sent out people to document them or used older documentation. However, Wimmer argued that the scholars should see the stone with their own eyes. He and Magnus Pedersen visited every stone in order to document them. While visiting the stones he noticed that most of the rune stones were not taken care of and that they needed to clean most of the stones in order to read them (Enoksen 1999, p. 27). The reason to update the collective rune stone work was that the knowledge about runes had improved and it was possible to make better translations than Worm's. However, Wimmer's work was not perfect and often contained mistakes. The selection of rune stones was also more limited than that used in Worm's work, as Wimmer only used rune stones from Viking

Age and pre Middle Ages. Unlike Worm, Wimmer did not include the stones in Blekinge and Halland. This was the reason Lis Jacobsen and Erik Moltke decided to make a new book, *Danmarks Runeindskrifter*, which was completed in 1942. The study introduced more modern documentation methods, like the use of electrical light, and did not only use natural light and photographs. Their work included all the rune stones that were not covered by Wimmer (Jacobsen & Moltke 1941-42 text, p. VIf).

During the 20th and 21th century the study of rune stones was divided into two different areas. The first one focuses on the socio-cultural aspects of the runes stones and studies them in a bigger perspective. The research questions addressed are for example spatial locations of rune stones (Wijkander 1983; Wilson 1994; Johansen 1997; Larsson 1997; Zachrisson 1998; Sawyer 2000), chronology and regional differences in ornamental styles (Gräslund 1991; 1992; 1994), regional differences in commemoration (Palm 1992), travels (Larsson 1990; Zilmer 2010), inheritance (Sawyer 1988), social structure (Sawyer 1991), identity (Gräslund 2009), the role of women (Kyhllberg 1983; Gräslund 1989; 1996; Jesch 1991) and religious aspects such as Christianity (Elgh 1987; Herschend 1994; Zilmer 2011) and paganism (Grønvik 1985).

The second area, which this thesis is connected to, explores new ways of documentation provided by the advancement of technology. Laila Kitzler Åhfeldt's study of picture- and rune stones was conducted with a laser scanner. It focuses on the carvers and examines whether it was an individual or a collaboration of carvers belonging to a workshop who made the engravings. By using a laser scanner she was able to study the precise shape of the carvings in order to estimate the tools used for carving the rune stones, and compare the different picture stones. In her studies she contacted modern day rune stone carvers to see how they carved and what tools they choose to work with. The results of her research indicated a possibility to distinguish individual styles even despite the fact that the carving tools changed during the Viking Age. In her work she demonstrated how this specific analysis makes it possible to detect rune stones created by several carvers (Kitzler Åhfeldt 2002).

Alexander Andreff and Rich Potter did a comparison of two different methods: frottage and Reflective Transformation Imaging (RTI). The aim was to evaluate the use of the latter for documenting blind picture stones. A blind picture stone is a stone where either all the carvings have disappear because of weathering or there never were carvings at all. The tests show that

in most cases RTI provides a more conclusive result than frottage. However, RTI needs a more controlled environment in order to provide a good result. RTI is very light sensitive and the sunlight can create an issue with the result. Therefore this method needs to be performed in a tent. This is just preliminary results since it is part of an ongoing research project in the form of Andreeff's doctoral studies. Both scholars argue that neither of the methods are better than the other since the results complimented each other (Andreeff & Potter 2014, p. 687). During an excavation in 2007 near Stenkyrka on Gotland a new rune stone was encountered. While preparing the stone for laser scanning, Kitzler Åhfeldt found a rune on the stone which was previously believed not to contain any runes. Added to the prior focus of the project the scholars wanted to examine whether there were more hidden runes. The test was complemented by RTI performed by Magnus Mårtensson. The result was that RTI worked better in some areas of the stone since the laser scanner could not take the necessary points. The laser scanner was only able to record points every 0,2 millimeter. The conclusion was that both methods are necessary in order to get a better understanding, but no additional runes were found (Kitzler Åhfeldt 2013b).

A study of the effects of weathering was carried out by Riksantikvarieämbetet during the 1990s. The result showed that weathering has affected the stones since they were risen, but during the last couple of centuries the effects have increased because there are more chemicals in the air. It was not the first time this was speculated between scholars; Bureus had a similar theory (Löfvendahl et al 2001, p. 1ff). Many different methods have been tested in order to protect rune stones and carvings. These have included a wide variation of approaches, from scrubbing to the use of chemicals. The different scrubbing methods harm the stone and the microorganisms grow back fast. The pressure washers and steam cleaners remove unwanted organisms fast, but they grow back and increases the effects of weathering. Another method that has been tested covers the stone from light. The advantages of it is that the stone is not hurt physically or chemically, but it can take up to three years until the microorganisms die and the stone is clean. Ethanol have been used to clean stones in Norway. It seems to have the desired effect but works slow. Acids and bases have been used too, they have a fast effects but damages the stone. Enzymes could be used as well since they are effective and does not hurt the stone but they do not work well in the field. Quaternary ammonium compounds are used in Sweden. They are effective, not very toxic and do not damage the stone. Some studies have shown that the use of this method has increased the amount of microorganisms that grow back and have made them more resistant. The conclusion of the report was that more research

is necessary about the methods that are good for the environment, are efficient and do not damage the stone further. In the present the most effective way of protecting the stones is to place them in controlled environments (Ernfridsson 2010).

RAÄ and Länsantikvarieämbetet wanted to move Hyby rune stone inside a building nearby Hyby church. The reason for this was that the stone had already been damaged by weathering. According to the law (SFS 1988:950, Chapter 2, §12-13) it was within their right to move the rune stone since it was likely to be further damaged if it remained at its current location. However, the village community did not want the stone to be moved and in the end the stone remained in Vismarlöv. The law also stresses the importance of keeping cultural landscapes intact for the purposes of understanding and maintaining the past so that both present and future people can enjoy and learn from it. RAÄ:s conclusion was that a roof should be added in order to protect the rune stone. However, this would not be necessary if the rune stone was under continual observation (Lövfendahl et al 2001, p. 17f).

1.5 Documentation Methods

The oldest method used to document rune stones and other epigraphic material is drawing by hand. This method was used by the earliest scholars like Johannes Bureus and Ole Worm. Worm normally used a piece of chalk and filled in the runes in order to see them better. He then proceeded with copying them down on paper (Moltke 1932. p. 322).

Frottage (or rubbing method) is a simple method. The user puts a paper on the object (such as rock carvings) and then starts to rub a piece of charcoal on the paper. The carvings will be shown on the paper as lighter and darker patches. The problems with frottage are that repeated use can damage the surface and the result does not always show the difference between carvings and natural features (González-Aguilera et al 2009, p. 1110).

Another way of studying rune stones was to make copies of the stone using the flong method. This was used by Erik Moltke and Lis Jacobsen, the authors of *Danmarks Runeindskrifter* from 1941-42. The two scholars used stereo flong paper in order to create copies of the runes and parts of the rune stones. The paper was first dipped into water for 15 seconds and then placed on the object. It was then knocked into the carvings. The paper became porous so that the water went through it. This process was repeated until the carving was as wet as it needed to be. The next step was to take the piece of paper and knock it into the carving again. This

time the user needed to be sure that the carving was completely covered by the paper. When the paper was completely covering the carvings another material was placed over the paper in order to suck the water out of it. The paper was then removed and left to dry, and this imprint could be taken home to be studied (Moltke 1932, p. 327f).

One important addition to the documentation process was the camera, and later on the digital camera. The ability to photograph excavations and monuments revolutionized documentation. It made it possible to document the object more realistically by providing the ability to document damages of the monuments or findings on excavations. This procedure is quicker than drawing by hand and does not force an interpretation of the user. The latter is a disadvantage since information is not provided solely by an image but by the interpretation made by the archaeologist while drawing. The pictures only show how the objects look when the user takes them.

Another method for the study of rune stones relies on the use of artificial lights and a camera. It was described by Moltke as one of a few new modern methods in 1932. Instead of using the natural sunlight, which had been used before, it was now possible to use strong electric lights. By moving the light source around the rune stone it was possible to spot carvings that could not be seen otherwise. This could be documented by either a photograph or a drawing (Moltke 1932, p. 327f).

An even more modern version of the technique described by Moltke is Reflective Transformation Imaging, RTI. The method was presented by Dan Gelb and Tom Malzbender in 2001. RTI is a computational photographic method which produces a bi dimensional visualization. The produced visualization has the same geometry as the object and allows the user to enhance it. In order to perform a RTI acquisition a camera, artificial lights, black or red glossy balls and the two free softwares RTI builder and RTI viewer is needed. For a deeper explanation of how RTI works I recommend the reader to take a look at CHI's website (CHI 2015a) and the instructions about how to perform it (CHI 2015b).

Laser scanners are instruments that create an accurate and resolute three dimensional description of objects. These tools use laser beams to measure objects and are used in archaeology to document artefacts, buildings and landscapes. The measurements are stored in dense point clouds. There are three general types of laser scanners which are deployed for

different objects. The first one is triangulation laser scanner. It sends out laser beams through a rotating mirror which spreads them across the object. The beam is then reflected back to the laser scanner and detected by the sensor. The scanner creates a point cloud by triangulating the angle of the mirror, the known distance between the sensor and the mirror and the position on the sensor that the beam hits (Jones 2011, p. 7f). The triangulation scanner have high accuracy but a low range. Therefore it is often used for small objects, for instance artefacts (Cooper 2011, p. 26) or carvings (Davies 2011, p. 31). Time of Flight (ToF) laser scanner is based on the known speed of light. The scanner starts a clock when the beam is sent out and stops it when the beam returns. Based on the time and the known angle of the mirror it can create a point cloud. The third scanner is called phase-comparison and is similar to the ToF. It sends out beams but instead of time it uses the strength of the returning beam (Jones 2011, p. 8). These types of laser scanner are used for larger objects such as buildings (Bennet 2011, p. 21; Russell 2011, p. 37). To document landscapes airborne laser scanners are used which are based on ToF. They are often called Light Detection And Ranging (LiDAR). In archaeology LiDAR data is used to see subtle differences in the landscape (Shaw 2011, p.32). A fourth kind of scanner is the structured light laser scanner. The scanning is performed using a projector, a scanner and a camera. During the first step the projector sends out light in the form of vertical stripes in black and white. The scanner then measures the deformation of these patterns, which makes it possible to calculate XYZ coordinates for each pixel recorded by the camera. The second step is to flood the object with the projector lamp or external lights in order to capture a colour image. The collected data is then transferred to a computer and pre-processed (McPherron et al 2009, p. 20).

Laila Kitzler Åhfeldt, who works at Runverket (Department of runes within RAÄ), used laser scanners in order to analyse and document picture- and rune stones. The scanner used during this research activity was an ATOS II, which is a light structured laser scanner. The scanner was bought in 2005 from GOM Optical Measuring Techniques (Kitzler Åhfeldt 2013a, p. 59) and has been used to record 68 picture stones on Gotland, Sweden (Kitzler Åhfeldt 2013a). The result can be seen on Riksantikvarieämbetets website (RAÄ). The main aim of the projects was to make the 3D models public in order to encourage more detailed studies. In this project Kitzler Åhfeldt also found evidence of templates being used for rune carvings, and the repeated use of the same templates strengthen her earlier theory that carvers worked together in workshops.

Image-based 3D modelling is used within archaeology and cultural heritage for many different purposes which portrays its strength and the various uses of this method. The method has been used to document excavations and trenches (Calleri et al 2011, De Reu et al 2013, Dell'Unto 2014). Landscapes can be documented and studied with this method by sending the camera up in the air on a hellkite to take pictures (Verhoeven 2011). Image-based 3D modelling has also been used on rock art in Russia (Plets et al. 2012). This experiment will be discussed in chapter 2.2.

There are some differences in acquisition and result between scanning and image-based 3D modelling. Moving around while taking pictures allows for a more versatile acquisition compared to moving the scanner (Jones 2011, p. 7). However, the result is more dependent on the user's ability to take pictures. The time of acquisition with a camera is faster than with the scanner, but the post-processing usually takes more time than the scanning (Fassi et al 2013, p. 79f). The scanner provides more accurate measurements than image-based 3D modelling. However, this is currently improving in image-based 3D modelling, making the result closer to that of the scanners (Skarlatos & Kiparissi 2012, p. 304).

1.6 Source Criticism

There are a few different variables which need to be considered during the acquisition. The first is that despite the capacity of the software to generate an accurate and resolute 3D surface model, the outcome of the model is strictly connected to the capacity of the user acquiring good pictures. For this reason it is important to analyse the pictures before creating the model. If certain parts of the object is missing or covered the software will not be able to reconstruct that area. The quality of the pictures directly affect the model and the better pictures taken the better the model becomes.

Another important aspect to take into consideration when taking pictures is the weather. In order to get the best result the acquisition should be carried out during a cloudy day. If the wind is too strong it is hard to hold the camera steady, which applies to both humans and some tripods. The wind may also move objects, like grass or leaves, which might make them blow in front of the camera or be in different positions between pictures. This could cause problems for the software when trying to create the model. Rain can destroy the camera if it is not protected or capable of resisting water. The rain pouring down on the object can trick the

software into creating a false model where it tries to align the pictures after the colour. The sun often dries the material which can make it change colour. This leads to a different perception of the object and could confuse the software.

One aspect which might have affected the result of the investigation is the fact that the rune stone had not been cleaned in some time. As can be seen in the pictures there were lichen and other microorganisms growing on the rune stone. These usually grow in shadows and under trees. In order to avoid the sun they grow into the carvings which might have caused the software not to apprehend how deep the carvings were or how they were shaped.

1.7 Theory

“Computers not only change the way we do things, but more importantly they change the way we think about what we do and why we do it.” – Gary Lock (2003, p. xiii).

The use of digital archaeology has been approached in two different ways (Zubrow 2006, p. 11). The first view sees digital archaeology as a tool, or rather as a method. If digital archaeology is only a methodology it makes it possible to apply it to different theoretical thinking within archaeology, such as processual and post-processual currents. The reason behind this argument is that the result of digital investigation are as theory-biased as carbon dating since they will all yield the same result (Zubrow 2006, p. 11). Approaching digital archaeology with this mindset allows for a tool which creates data that can be applied to most research questions since only technological understanding is needed. There are also scholars who argue that digital archaeology can and should be seen as a new or at least the foundation of a new theory (Conolly & Lake 2006, p. 8). Seeing digital archaeology as a new theory changes the way archaeologists have to address their work. This forces the archaeologists to approach problems differently and ask other questions. In the end it changes the way interpretations are made (Zubrow 2006, p. 9). The reason behind this is that digital archaeology and the post-processual way of thinking are very different. The main reason behind this is that digital archaeology is analytic, reconstructive and measurable while post-processual is deconstructive, interpretive and narrative (Zubrow 2006, p. 17).

In the frame of this work the digital workflow was used as a tool in support of the author's interpretations. However the product of this tool, the 3D model, is not particularly useful on its own unless it is put into a theoretical frame. For the model to provide new knowledge and

be informative it needs to play an active role instead of just being a visualization tool. “3D information can be regarded as the core of the knowledge process, because it creates feedback, then cybernetic differences, among the interactor, the scientist and the ecosystem” (Forte 2010, p. 11).

Having a tool or a method capable to simulate with high accuracy the geometrical characteristics of a monument, such as the carvings on a rune stone, provides a robust base for the interpretation that has to be done by a scholar. It is important to note that the digital methods do not replace the traditional ones but should be used complementary (Campana 2014, p. 8). Even if the 3D models can convey certain aspect of objects better, for instance texture, colours and effects of illumination, the creation of hand-rendered images of objects better expose the interpretative nature of recording. The naturalistic realism achieved in rendering digital images can be deceiving since many layers of inference is involved in their production (Hodder 2013, p. 519f). Therefore it is as important in digital archaeology as it is in all research to have a transparency in everything that has been done to reach one’s conclusion.

2 Methods

The first idea of this project was to make a comparative study between image-based 3D modelling, laser scanners and RTI for the use on rune stones. However, only one of these methods could be tested within the time frame. The chosen method was image-based 3D modelling and the reason for this is two-folded. Firstly, it was the only one of the three methods that had not previously been used on rune stones. Secondly it was the method the author was most familiar with.

In order to evaluate the efficiency of the method two approaches were employed, bottom-up and top-down. The bottom-up approach was used in the form of field acquisition and the study of the created 3D models. This approach was used to estimate the level of visibility of the features detected on the 3D model compared with the real monument. The top-down approach was used to become familiar with the rune stone, previous interpretations and the methodology normally used for this kind of studies. The advantage of this for the evaluation of the method was invaluable. The combining of the top-down and the bottom-up approaches allows for a deeper understanding of the result and the method.

In order to test and evaluate the method two models were made for the thesis. This was done by making two acquisitions using two different cameras and by doing two post processions using two different computers and two different sets of settings in two different editions of the commercial software Agisoft Photoscan.

The following sub-chapter provide an explanation of the workflow employed to document and analyse the rune stone of this study.

2.1 Pictures

For this thesis two different sets of cameras and lenses were used. The first camera was a Canon EOS 350D with a Canon EFS 18-55 lens. For the second set of pictures a Canon EOS 550D with a Canon EFS 18-55 lens was used. The pictures were taken in JPG and RAW image format. Pictures in JPG format are compressed in order to reduce the size of the file. This format allows for the generation of a larger number of pictures which saves the memory of the camera. On the other side the JPG format decreases the quality of the pictures and thereby produces less qualitative 3D models. Moreover, JPG files can be used in different softwares, like Photoscan, to calculate the 3D scene. RAW files are pictures which are unprocessed and uncompressed in grayscale by the camera. These images keep all their

metadata which makes the pictures larger than the JPG. Since they are not compressed the images contain a higher quality which can be seen in the colours for instance (Adobe 2014, p. 346). The advantage of the RAW images is that since all the metadata are kept Photoscan has more information to work with. However, the RAW images needs to be converted to a file format that can be read by the software. In order to convert the files a software for image processing is necessary, for example Adobe Lightroom (Adobe 2015a) or Adobe Photoshop CC (Adobe 2015b). Adobe Lightroom is a software that can be used for the storing, editing and developing of images, while Adobe Photoshop is one of the most common softwares used for image processing. Adobe Photoshop CC was chosen for the thesis since it has a script that can convert several files from one file format to another at the same time. Once the pictures had been acquired they were converted from RAW to TIF. TIF is a file format that does not compress the images and therefore maintain the quality. The time required for the conversion process differs depending on the amount of images.

The images used to generate the 3D model were converted from RAW to TIF. To make a fair assessment of the differences between TIF and JPG the RAW files were converted to both formats. The comparison shows that the JPG images (Figure 1) are slightly greener than the TIF files (Figure 2). The fact that the pictures were taken in RAW format extended the acquisition time since the memory card had to be emptied. The final result of the model would probably not have changed much if JPG images had been used instead, except for the colours on the texture. However, it is just a speculation which needs to be confirmed since no test of this was done in this thesis.



Figure 1. Image taken in RAW during the second acquisition and converted to JPG (Friberg 2015).



Figure 2. Image taken in RAW during the second acquisition and converted to TIF (Friberg 2015).

2.2 Structure from Motion and multi-view reconstruction

Image-based 3D modelling is divided into two main steps, Structure from Motion (SfM) and multi-view stereo reconstruction. While using SfM the software calculates the camera parameters for each image. Then it compares similar geometrical features of the object from every image and calculates the corresponding position in a virtual space. When the software has estimated the camera's position the second step has been reached. The software uses the pre-estimated camera parameters and image pixels to create a dense point cloud. The cloud is then processed into a 3D model (Verhoeven 2012; De Reu 2013 et al; Dell'Unto 2014).

As mentioned earlier the method has been tested on rock carvings in the mountains of Altai, Russia. The rock carvings were in danger of deteriorate from weathering. In order to document all the carvings in a low cost way image-based 3D modelling was attempted. The model was created in Agisoft Photoscan professional and then imported into Meshlab, where the texture was turned off and the lights were moved to highlight different areas. In their conclusion they stated that the result of the experiment was beyond their expectations but further fine-tuning of the workflow was needed (Plets et al 2012). A similar workflow is used in this thesis but the radiance scaling shader provided by Meshlab has been added. The reason behind this is that it allows for a better visualization of the geometry.

The software chosen for the development of the 3D models in the frame of this thesis is Agisoft Photoscan (<http://www.agisoft.com/>). Photoscan is a software created by the Russian company Agisoft LLC in 2010. There are two different variants of Photoscan, standard and professional. The cost differences between these are rather steep (Agisoft LLC 2015A). The standard edition is enough to create a model, but the professional contains extra features such as georeferencing and 4D processing (Agisoft LLC 2015B). These functions are not necessary for this thesis but it is possible to mimic them using other softwares, such as Meshlab or GIS. The Photoscan version used in this work is 1.1.3.2018. The reason Photoscan was chosen is that it allows for the workflow, SfM and multi-view reconstruction, to be processed offline and allows the user to change the settings during the production. It also allows for a projection of textures. There are other softwares which can be used for image-based 3D modelling; Autodesk 123D Catch (Autodesk 2015), Bundler (Snavely 2015), PhotoModeler scanner (Eos Systems Inc, 2014), Photosynth (Microsoft Corporation, 2015) and VisualSFM (Wu 2015). However, they do not provide everything in the same user-friendly package or with the same control over the modelling.

2.3 Meshlab

Since Photoscan standard edition does not offer any tools for analysing the models another software was needed. The software chosen for this thesis was Meshlab, which is an open-source software developed at the Visual Computing Lab of the ISTI-CNR. The software was designed to be a general 3D mesh processing system tool. The user should be able to visualize 3D models created elsewhere as well as point clouds created by laser scanners. While using Meshlab the user should also be able to align, edit, repair, clean, heal, render and convert meshes (Cignoni et al. 2008).

The tools used in Meshlab to analyse and annotate were *shaders* (rendered on the mesh) and *Z-painting*. Shaders are inbuilt programs that work with any model (Meshlab 2014). The shaders are applied temporarily to the geometry of the model. When the shaders are activated they change the visualization of the geometry in a wide variation of ways. These variations can be used to study the model from different perspectives. The shader used for this thesis is radiance scaling. This shader enhances the surface of the geometry by changing the reflected light intensities of the model based on surface curvature and material characteristics. It enhances the surface concavities and convexities (Vergne et al 2010, p. 143) which makes the carvings easier to see on the model of the rune stone. In this thesis two variants of the radiance scaling was used: lambertian radiance scaling (Figure 3) and grey descriptor (Figure 4). Lambertian radiance scaling produces a light grey visualization of the mesh whereas the carved areas are shown in a darker grey. The grey descriptor also changes the visualization to grey but uses darker colour tones. The main differences between these shaders are that the lambertian allows the user to move the light around whereas the second one does not. This allows the user to highlight the model from different perspectives. However, since the radiance scaling is based on the light the features not highlighted becomes darker and not possible to spot. In order to look at different parts both the light and the model need to be moved. The grey descriptor uses a static light. When the model is turned around all carvings are still visible. This makes it easier to get an overall perspective of the carvings. Both shaders allow the user to notice and then annotate (using the painting tool) the features as result of the analysis. It is possible to see one's drawings while using the lambertian radiance scaling, but not while using the grey descriptor. Using both variants on their own would make it possible to spot all the carvings. In this thesis the grey descriptor was used to create an overview painting and the lambertian radiance scaling was used to make smaller changes.

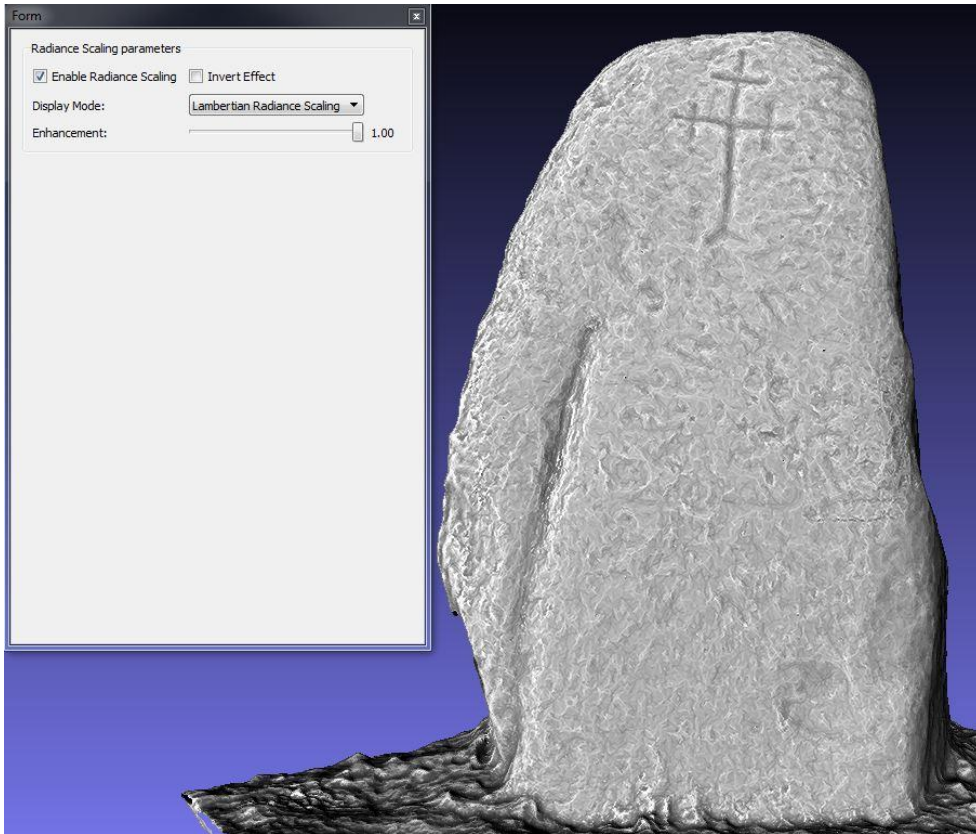


Figure 3. A visualization of the front of the first model in Meshlab with the Lambertian Radiance Scaling activated.

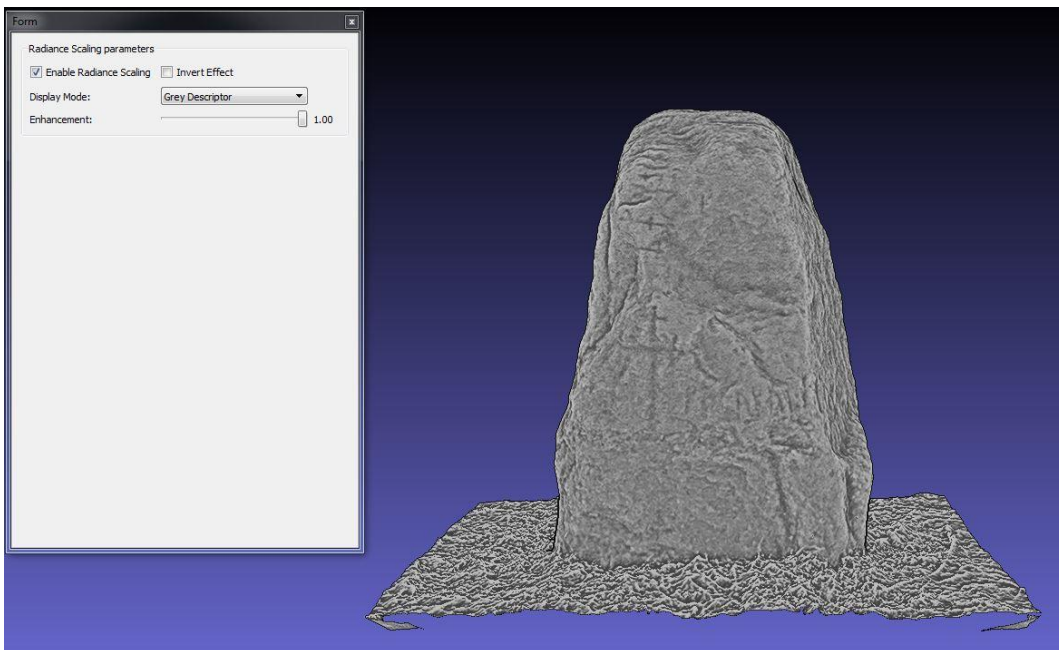


Figure 4. A visualization of the back of the second model in Meshlab with the Grey Descriptor activated.

3 Case study

This section will be divided into four parts. The first part covers the research history of Hyby rune stone. The second part describes the acquisitions of the images of the rune stone. The third part addresses the post processing and explains all the settings. The fourth covers the use of Meshlab and the shaders used on the models. In this part the results of the models are shown.

3.1 Hyby rune stone

The Hyby stone (DR 264), also known as Vismarlöv rune stone, is located in Vismarlöv in Scania, Sweden. It has been dated to the Viking age. The stone was found in 1624 in a stone wall located south of the westernmost farm in Vismarlöv. The Hyby rune stone was relocated outside a school in Vismarlöv, where it remained until 1966. It was then placed in a field south of Vismarlöv. During the years 1985-86 it was taken in for cleaning, conservation and some repairs. In 1987 it was moved to the location where it stands today, at Vismarlövs bygata (village street) (Löfvendahl et al 2001, p. 17).

This stone was first documented by the scholar Ole Worm and drawn by Jonas Skonvig in 1627 (Figure 5). Worm's interpretation of the rune stone shows that there were 42 runes. On the rune stone there were also two crosses and a stag. A later scholar, Wimmer, visited and documented the stone in 1876. He found there to be 37 runes. However, it was no longer possible to see the stag's feet. Moltke studied the runes in 1931 and he found 37 runes of which eight were not visible because of weathering. Riksantikvarieämbetet's documentation, performed during the conservation of the rune stone and the study of weathering during 1990s, found that one more rune had weathered away. Moreover it was now only possible to see the upper half of the stag and both crosses were damaged (Löfvendahl et al 2001, p. 17). Today it is still possible to see most of the runes. The cross on the front is very well preserved but only the horns and part of the head of the stag are visible. On the back of the stone a couple of runes can be seen but only parts of the cross.

The stone inscription can be translated as following:

A: Thord carved these runes....

B: Folkvi owns Hög(by)?

(Jacobsen & Moltke 1941-42 text, p. 320)

There have been different interpretations of the stag. According to a local source whom Worm

spoke to the stag was supposed to be a sign of the king's hunting ground (RAÄ 1985). A later theory connected the symbolism of the stag with a person who recently became converted to Christianity. The argument for this theory comes from hymn 42 "Like as a hart panteth after a water brooks, so panteth my soul after you, O God" according to RAÄ's sign by the rune stone. The crosses are thought to be signs of Christianity but according to Worm's source they were a sign for Dalby kloster (RAÄ 1985). No sources supporting Worm's theory have not been found. However, the fact that there is an area close to the rune stone called Kungsmark (The king's land) could support the idea of it being the king's hunting ground.



Figure 5. A drawing of Hyby rune stone made by Jonas Skonvig in 1627 (Worm 1643, p. 205).

3.1.1 Acquisition

The first acquisition was performed 2015-02-03. During the first acquisition a Canon EOS 350D camera was used. The acquisition took 40 minutes and about 200 pictures were taken. These pictures were taken in JPG format with resolution of 3456 x 2304 (Figure 6).



Figure 6. Photo taken in JPG format during the first acquisition (Friberg 2015).

The second acquisition was performed 2015-02-25. The camera used this time was the Canon EOS 550D. It was used together with a tripod in order to acquire sharper images. The tripod could not be used for the pictures taken from the ground level because it could not be lowered that far. Instead two boxes with the measurement 40x26x12 centimeters and six smaller boxes with the measurements 14x13,5x1 centimeters were used in order to stabilize and angle the camera. The acquisition started in the morning and took about 6 hours. The total amount of pictures taken was around 1100. These pictures were then divided into two categories, one for tripod and one for handheld. All pictures were converted in Photoshop from RAW to TIF so that they could be read properly by Photoscan. The resolution of these pictures was 5184 x 3456 (Figure 2).

3.1.2 Post processing

The first model was created in Agisoft Photoscan standard. For this model 207 pictures were used. The pictures cover all sides of the rune stone (Figure 7). The alignment created 13,612 points (Figure 8). The dense cloud created from this alignment consisted of 5,090,966 points (Figure 9). A portion of these points are of the surrounding ground. The final model consisted of 340,989 faces and 172,057 vertices (Figure 10). Then a texture with the resolution 4096x4096 was created and applied to the model (Figure 11). The settings in Photoscan were in most cases on medium except for the accuracy, which was set on high. The differences in the settings are reflected in the resolution and time consumption. High keeps the resolution of the picture while medium reduces the resolution with a factor of four and low by another four (Agisoft LLC 2013, p. 9f). One change that was made was setting depth filtering on mild instead of aggressive. During the dense point cloud generation reconstruction the software calculates the depth maps on every image. Depending on the images the software creates outliers among the points. During this stage the setting depth filtering was set to mild instead of aggressive. If aggressive had been used the software would not have recognized small details on the model. This could have caused the carvings to become invisible. This setting is better for objects with less small details such as buildings. The mild setting is the opposite. While it is activated the software does a more precise calculation and recognize all small details such as carvings (Agisoft LLC 2013, p. 11).

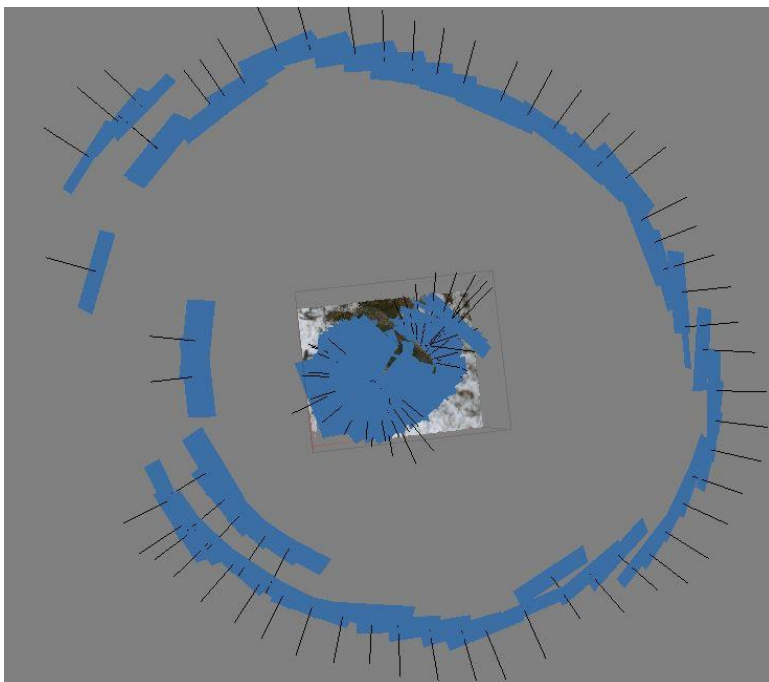


Figure 7. Print screen of the camera positions of the first model recreated by Agisoft Photoscan.

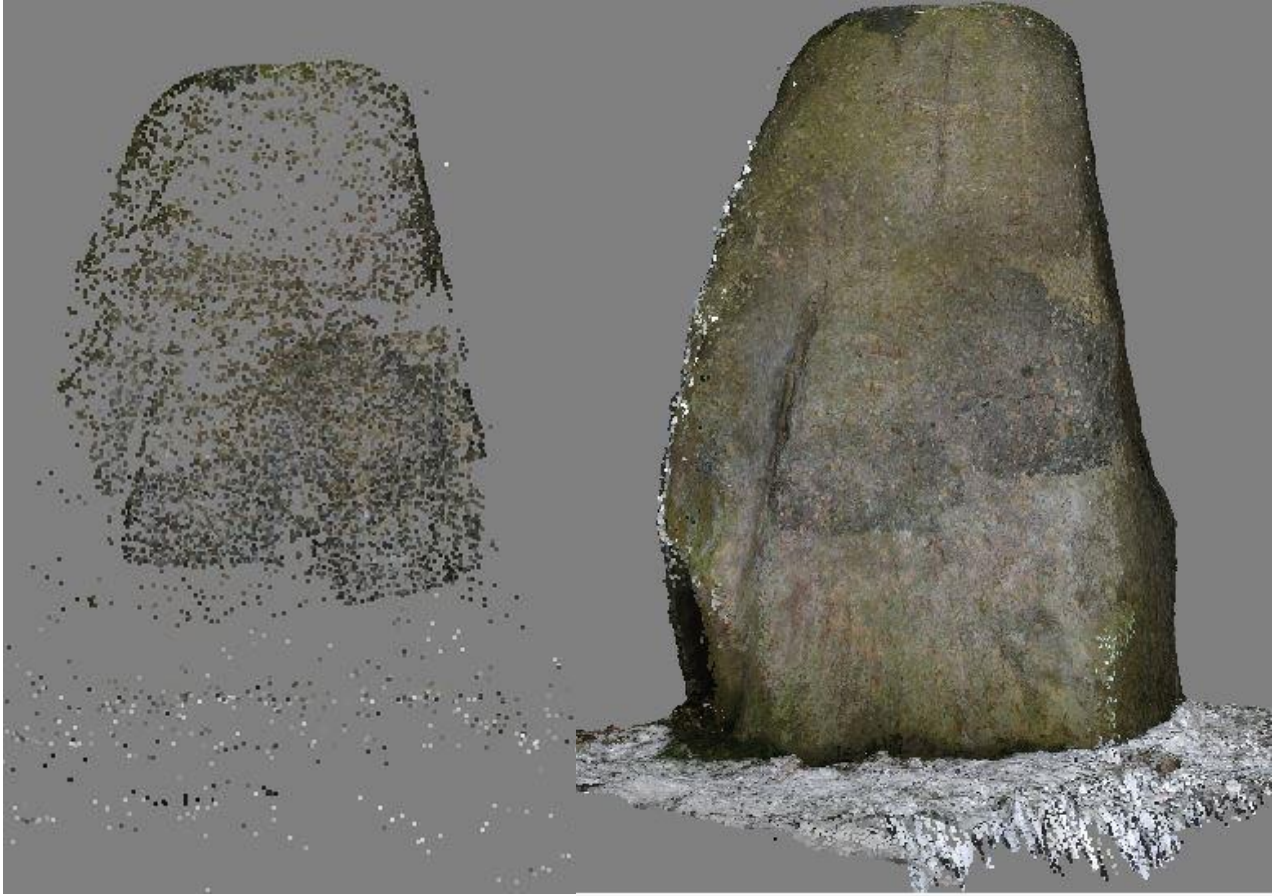


Figure 8. Print screen of the result of the alignment and optimize alignment of the first model in Agisoft Photoscan.

Figure 9. Print screen of the dense cloud of the first model in Agisoft Photoscan.



Figure 10. Print screen of the mesh created of the first model in Agisoft Photoscan.



Figure 11. Print screen of the textured mesh of the first model in Agisoft Photoscan.

The second model was created in Agisoft Photoscan professional. For this model 591 pictures were used. These pictures covered the rune stone in a spiral looking route (Figure 12). The spiral movement was necessary because the terrain did not allow the tripod to be moved in a complete circle. As can be seen on the pictures they were taken very close to the rune stone from all angles. This was done in order to try to capture all the angles of the carvings. The alignment created 16,254 points (Figure 13). The dense cloud created from this alignment consisted of 16,970,228 points (Figure 14). The finished mesh consisted of two million faces and one million vertices (Figure 15). Then a texture with the resolution 4096x4096 was created and applied to the model (Figure 16). Alignment was set to high and many of the settings was kept as they were. One change was made and it was to put depth from aggressive to mild.

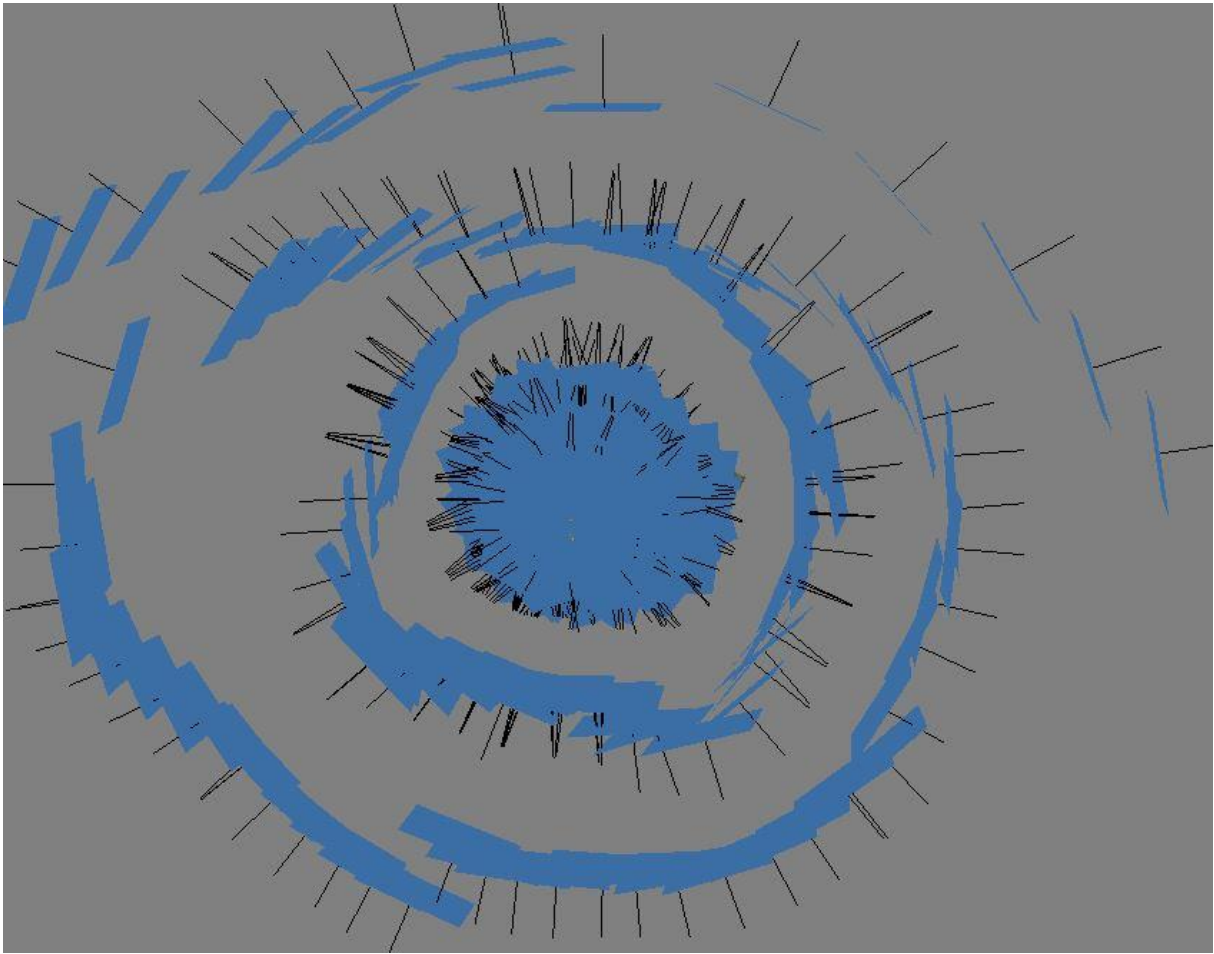


Figure 12. Print screen of the camera positions of the second model recreated by Agisoft Photoscan.

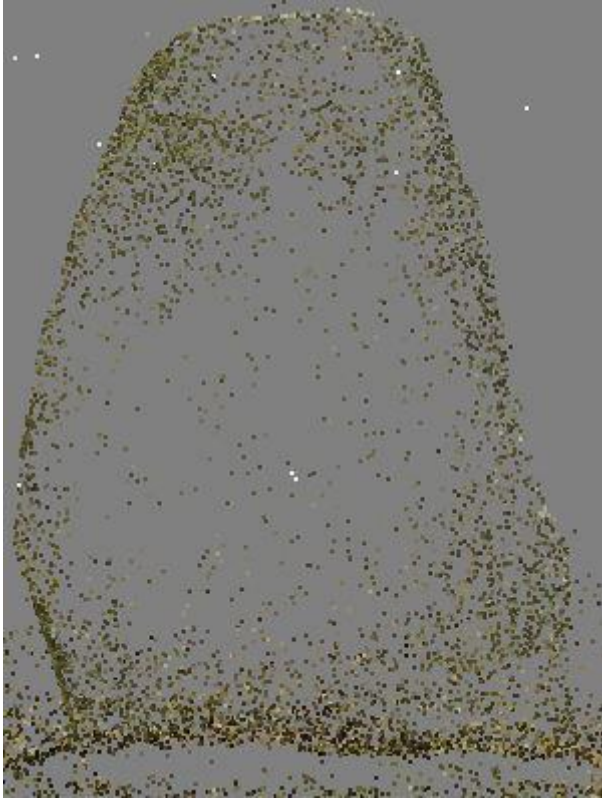


Figure 13. Print screen of the result of the alignment and optimize alignment of the second mode in Agisoft Photoscan.



Figure 14. Print screen of the dense cloud of the second model in Agisoft Photoscan.



Figure 15. Print screen of the mesh created of the second model in Agisoft Photoscan.



Figure 16. Print screen of the textured mesh of the second model in Agisoft Photoscan.



Figure 19. Picture of the back of Hyby rune stone from the second acquisition (Friberg 2015).



Figure 20. Picture of the back of Hyby rune stone taken by Bengt A. Lundberg 1989-05-23 (RAÄ c).

demonstrated more properly further down in this chapter.

The back is not as well preserved as the front. Most of the paint is gone and the carvings are hard to spot (Figure 19). The cross on the first picture is not visible but can be seen when looked at in a particular angle. However, some of the runes, *ŋʀ.!, still got colour and it is still possible to see some of the carvings on the back if studied closely with the naked eye. As seen on the older picture (Figure 20) there are supposed to be 15 runes in one line. There are also carvings from the top going down. The first one is an R <ŕ> rune and the others could be something called house marks, which will be discussed further in chapter 4.3.

The models made for this thesis will be presented here. When the models had been produced by Photoscan they were imported into Meshlab. The following pages contain the textured models displayed from three different angles (Figure 21-26).

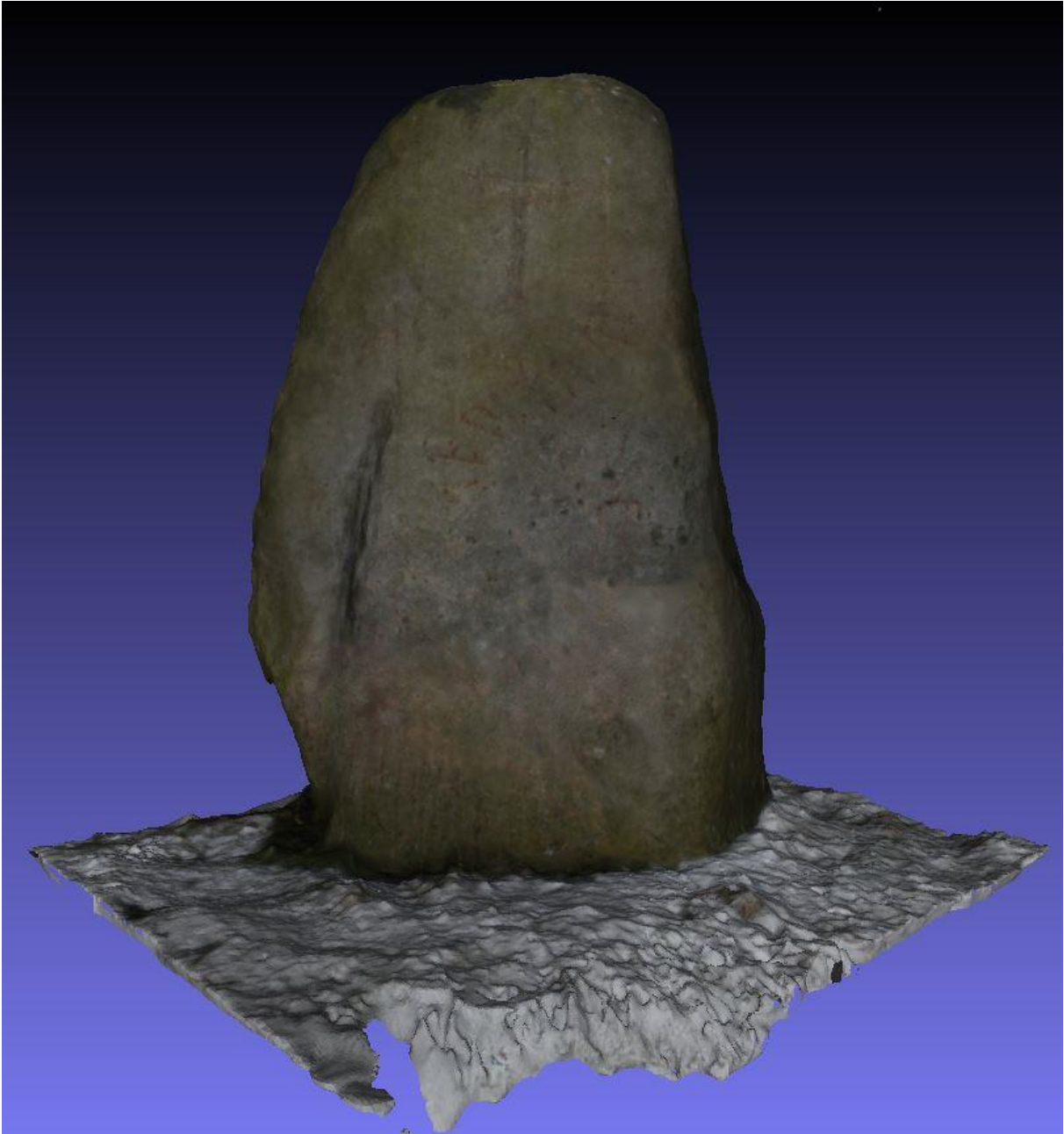


Figure 21. A visualization of the front of the first model, with texture created in Agisoft Photoscan, imported to Meshlab.



Figure 22. A visualization of the back of the first model, with texture created in Agisoft Photoscan, imported to Meshlab.



Figure 23. A visualization of the side of the first model, with texture created in Agisoft Photoscan, imported to Meshlab.



Figure 24. A visualization of the front of the second model, with texture created in Agisoft Photoscan, imported to Meshlab.



Figure 25. A visualization of the back of the second model, with texture created in Agisoft Photoscan, imported to Meshlab.



Figure 26. A visualization of the side of the second model, with texture created in Agisoft Photoscan, imported to Meshlab.

The first step was to analyze the model in order to test how many carvings that could be detected without the visual aid of the tools in Meshlab. This was done in order to test the differences in camera and picture quality after the model was completed. The red colour was used since it is similar to how rune stones are coloured in reality. In the first model five runes were visible on the front (Figure 27). These were in the middle of the rune stone between the cross and upper part of the stag, which both could be seen and identified. It was also possible to see parts of other runes. Six runes were visible on the front of the second model with texture on. On the second model the carvings were easier to spot since the model was brighter (Figure 28). The following pictures will show the differences between the models generated using different settings.

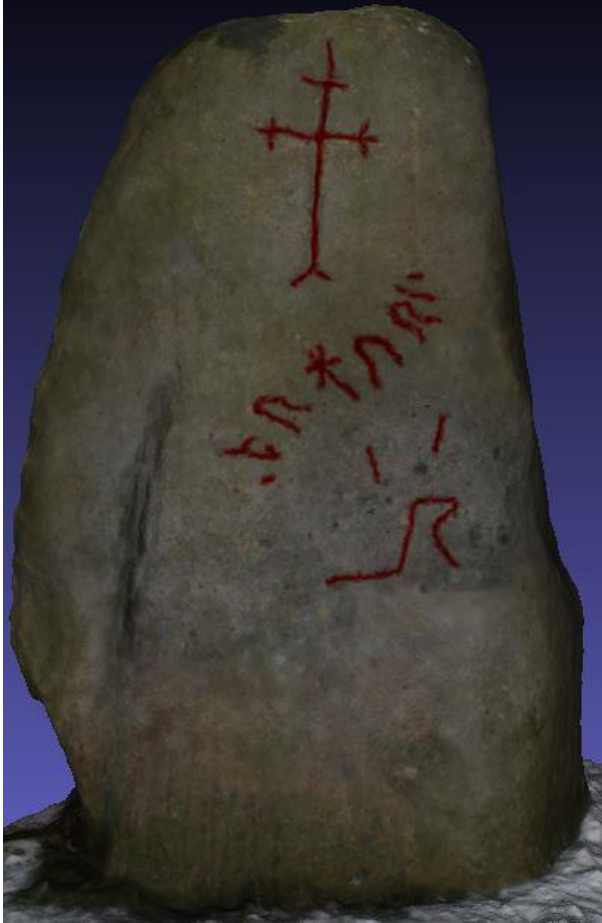


Figure 27. A visualization of the front of the first model with the carvings visible on the texture marked. The model was created in Agisoft Photoscan and imported to Meshlab.

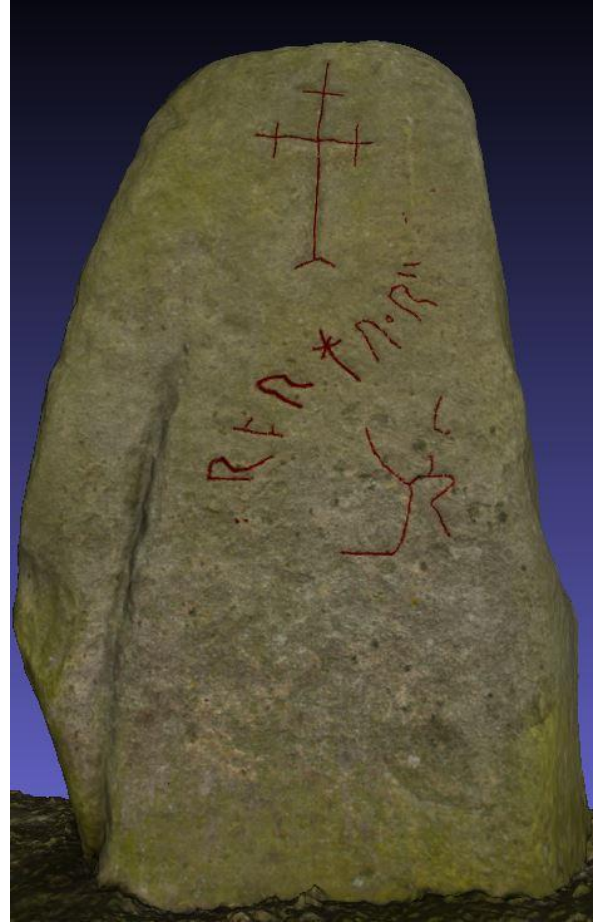


Figure 28. A visualization of the front of the second model with the carvings visible on the texture marked. The model was created in Agisoft Photoscan and imported to Meshlab.



Figure 29. A visualization of the back and side of the first model with the carvings visible on the texture marked. The model was created in Agisoft Photoscan and imported to Meshlab.

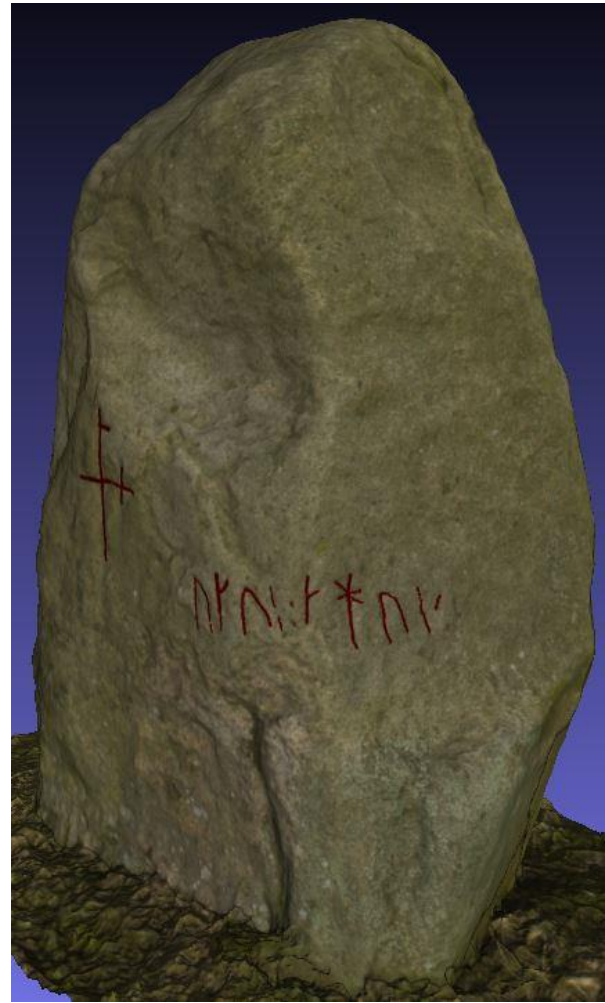


Figure 30. A visualization of the back and side of the second model with the carvings visible on the texture marked. The model was created in Agisoft Photoscan and imported to Meshlab.

On the back of the first model a part of the cross could be seen from certain angles. It was also possible to see four runes and parts of others (Figure 29). On the second model it was possible to see the cross as well (Figure 30). However, unlike on the first one it was possible to see up to eight runes. Once again the brightness of the second model makes the carvings easier to spot.

The second step of the work in Meshlab was to study the geometry of the different models. In order to do this the texture was turned off (Figure 31 & 32) and shaders were activated. The chosen shaders were two kinds of radiance scaling, lambertian radiance scaling (Figure 33 & 34) and grey descriptor (Figure 35 & 36). The only change in the parameters, except for toggling the different modes on and off, was to improve the enhancement from 0.5 to 1. By increasing the enhancement the effects of the radiance scaling are improved which makes the

carvings easier to see. As can be seen below the carvings on the models are easier to spot compared to their textured counterparts.

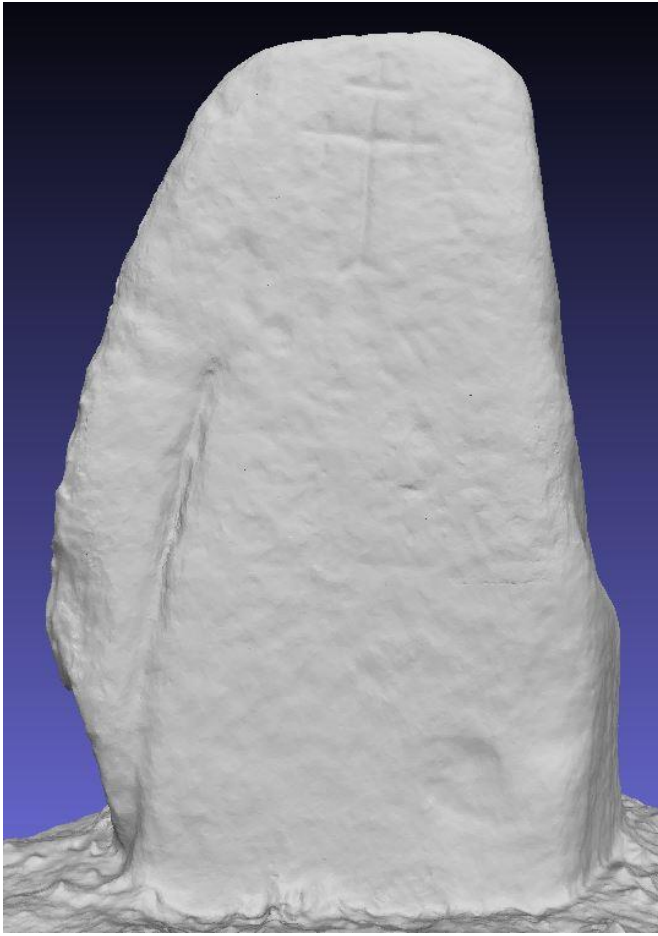


Figure 31. A visualization of the front of the first model without texture. The model was created in Agisoft Photoscan and imported to Meshlab.

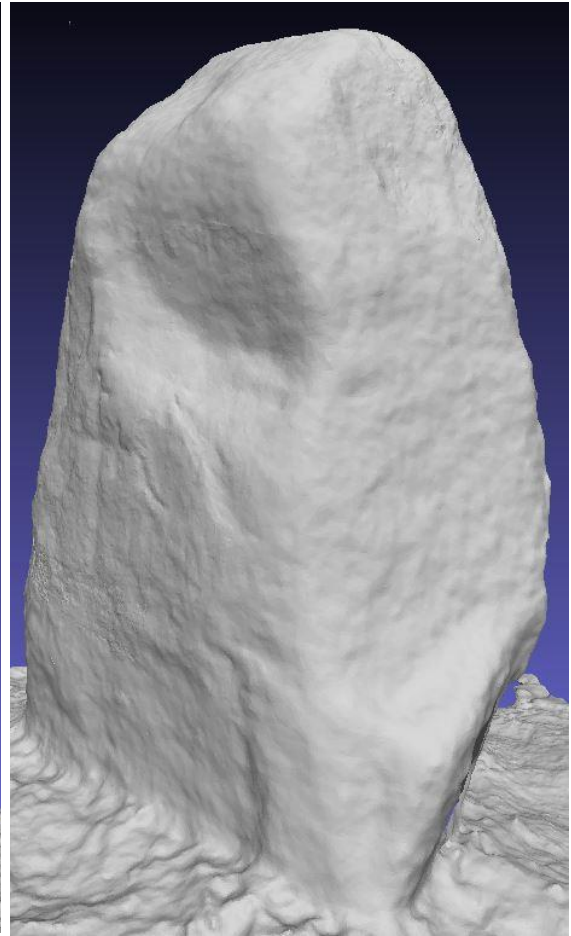


Figure 32. A visualization of the back of the first model without texture. The model was created in Agisoft Photoscan and imported to Meshlab.



Figure 33. A visualization of the front of the first model with the shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The model was created in Agisoft Photoscan and imported to Meshlab.



Figure 34. A visualization of the back and side of the first model with the shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The model was created in Agisoft Photoscan and imported to Meshlab.

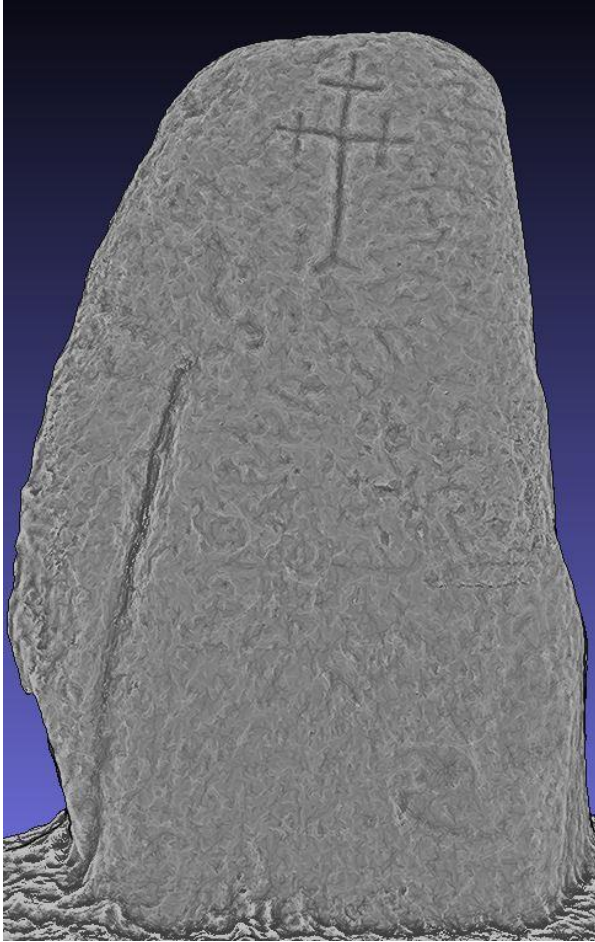


Figure 35. A visualization of the front of the first model with the shader radiance scaling setting grey descriptor turned on and enhancement turned to 1. The model was created in Agisoft Photoscan and imported to Meshlab.

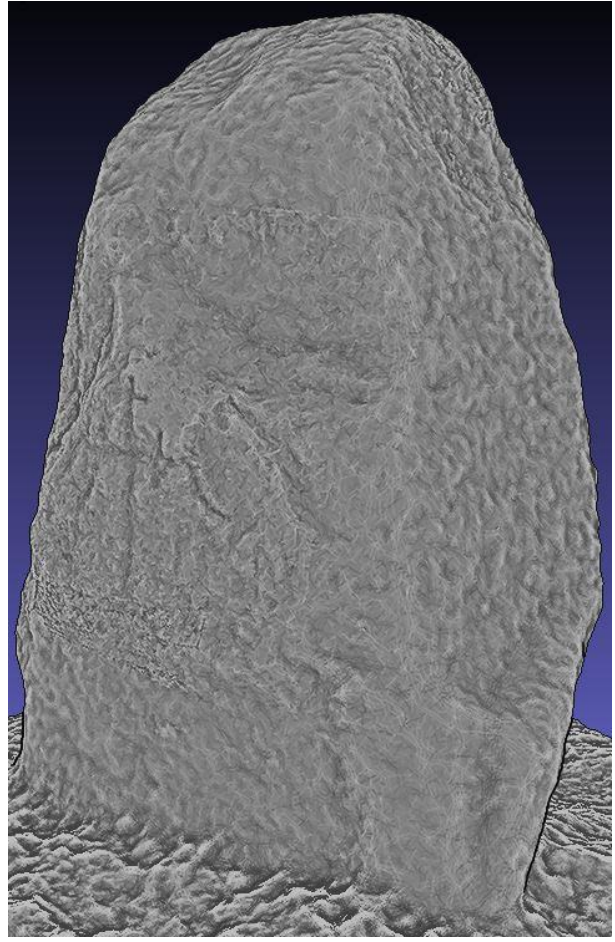


Figure 36. A visualization of the back and side of the first model with the shader radiance scaling setting grey descriptor turned on and enhancement turned to 1. The model was created in Agisoft Photoscan and imported to Meshlab.



Figure 37. A visualization of the stag carving on the front of the rune stone on the first model, with the shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The model was created in Agisoft Photoscan and imported to Meshlab.

This gives the opportunity to study the geometry of the models. As can be seen above the carvings on the rune stone become more visible. However, it is possible to spot some problems with the first model. The geometry could have been better. There are lines on the model which do not exist on the second model (Figure 37) or in the picture taken by RAÄ. For instance, there is a line going from the base of the throat of the stag which is heading right. Below the first one there is a similar second line.

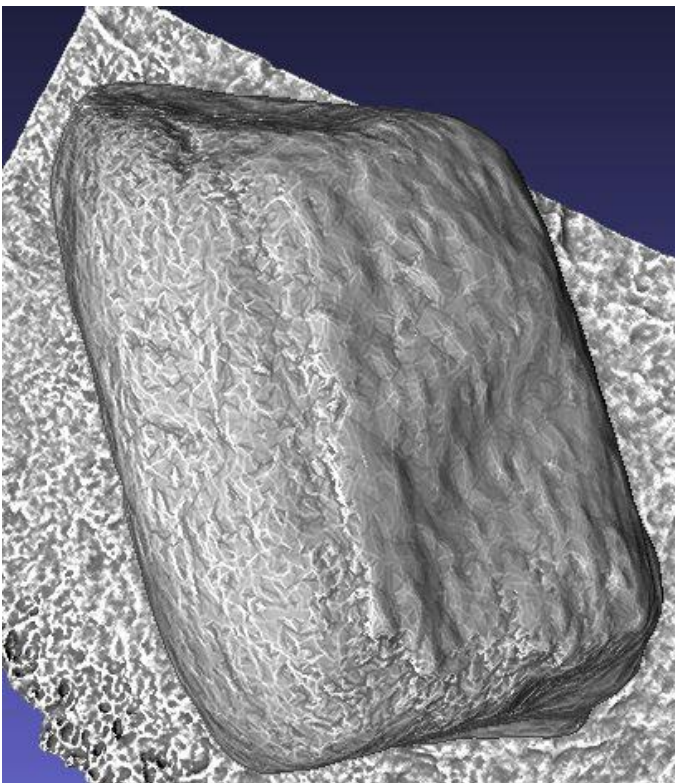


Figure 38. A visualization of the top of the rune stone on the first model with the shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The model was created in Agisoft Photoscan and imported to Meshlab.

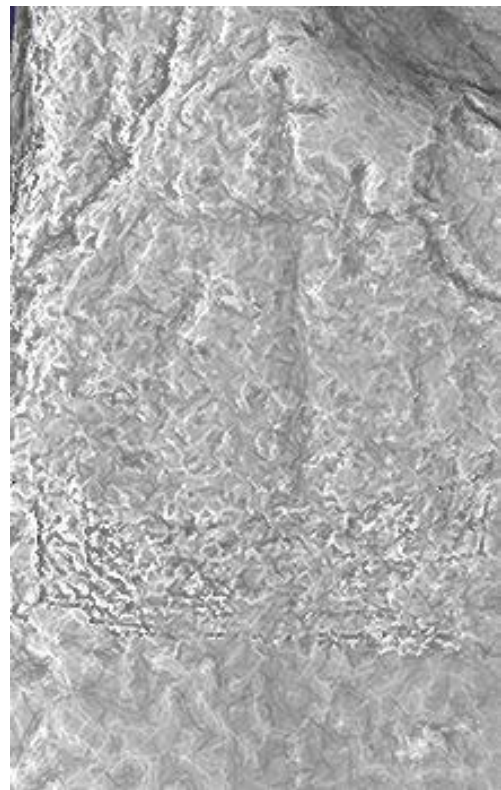


Figure 39. A visualization of the cross on the back of the rune stone on the first model with the shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The model was created in Agisoft Photoscan and imported to Meshlab.

Except for the lines near the stag there are other problems with the model. As can be seen on the images above there are noise on the model. The geometry changes quite rapidly from clear carvings into a blurry grey. On the top of the rune stone (Figure 38) and below the cross on the back there are some noise as well (Figure 39). The noise was created by Photoscan when it was trying to create the geometry of these parts of the model. It was caused either by lacking coverage or the quality of the pictures covering these parts. If the pictures had been of better quality these problems would have been averted. One solution would be to take more pictures than what is necessary and only use the good ones for the creation of the model.

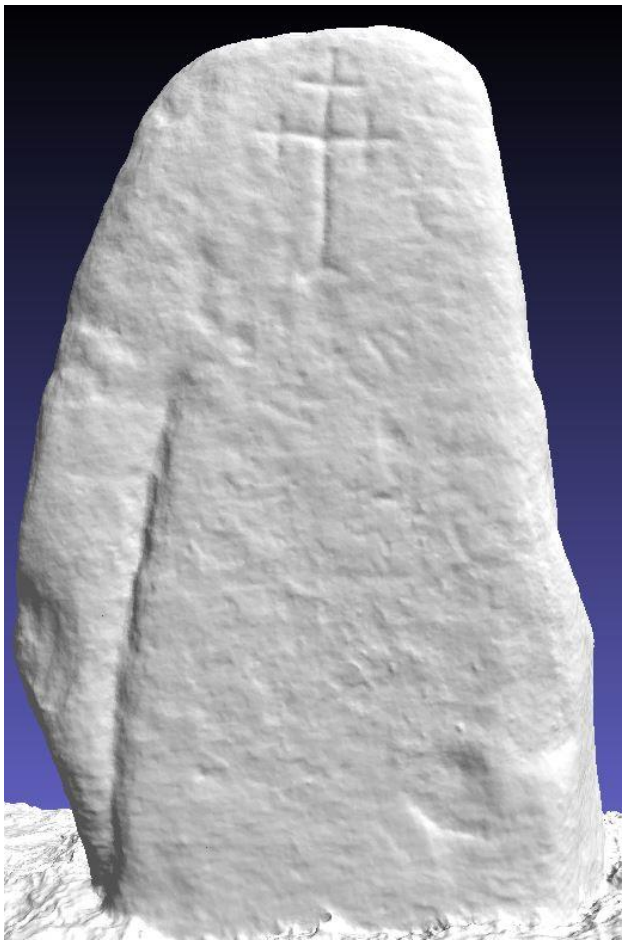


Figure 40. A visualization of the front of the second model without texture. The model was created in Agisoft Photoscan and imported to Meshlab.

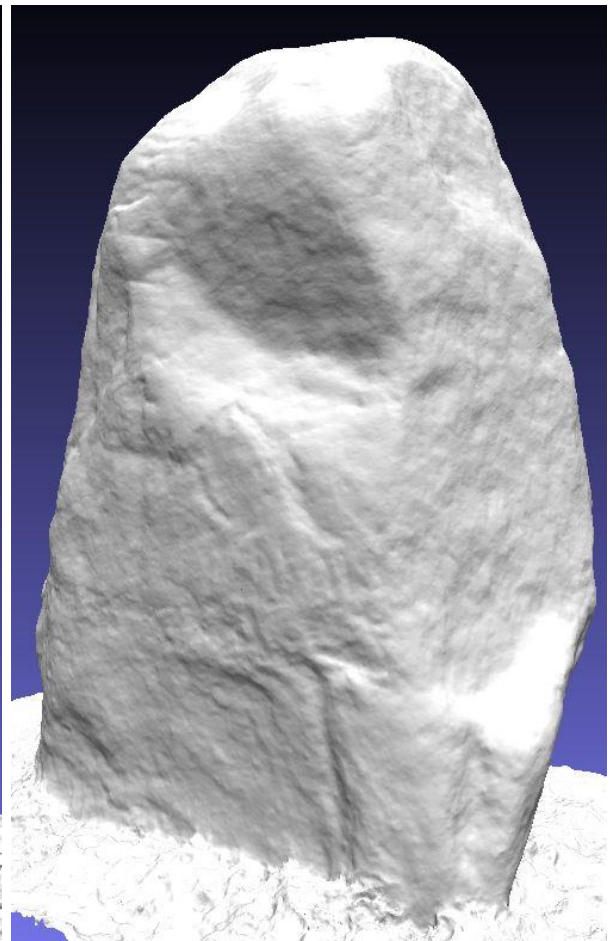


Figure 41. A visualization of the back and side of the second model without texture. The model was created in Agisoft Photoscan and imported to Meshlab.



Figure 42. A visualization of the front of the second model with the shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The model was created in Agisoft Photoscan and imported to Meshlab.

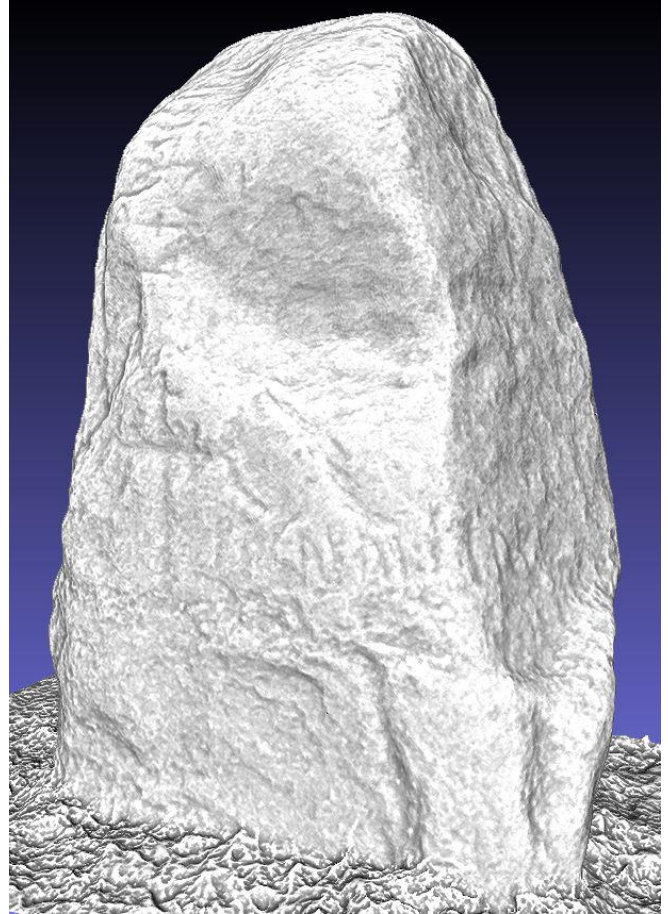


Figure 43. A visualization of the back and side of the second model with the shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The model was created in Agisoft Photoscan and imported to Meshlab.



Figure 44. A visualization of the front of the second model with the shader radiance scaling setting grey descriptor turned on and enhancement turned to 1. The model was created in Agisoft Photoscan and imported to Meshlab.

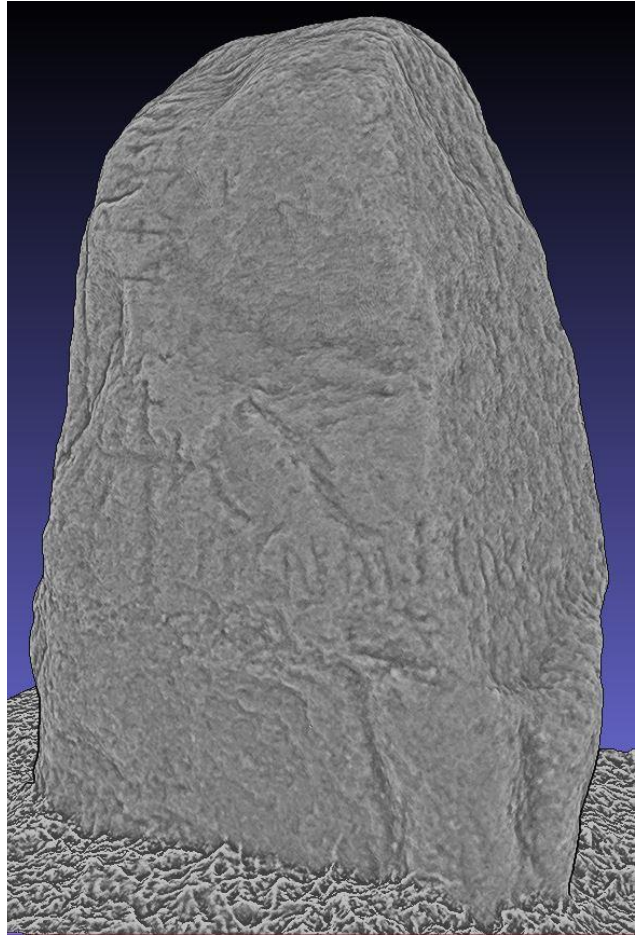


Figure 45. A visualization of the back and side of the second model with the shader radiance scaling setting grey descriptor turned on and enhancement turned to 1. The model was created in Agisoft Photoscan and imported to Meshlab.

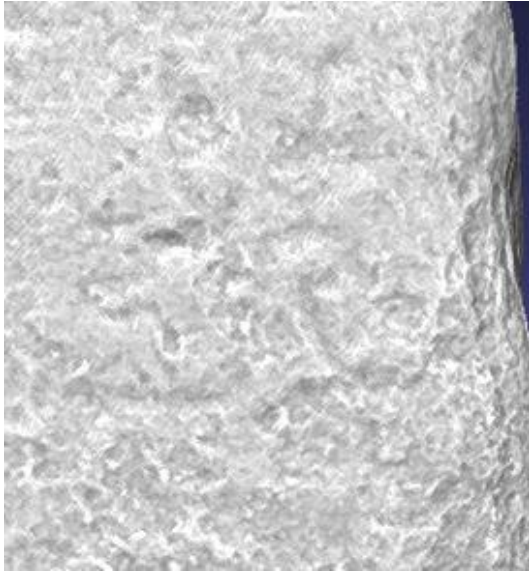


Figure 46. A visualization of the stag carving on the front of the rune stone on the second model, with the shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The model was created in Agisoft Photoscan and imported to Meshlab.

The geometry of the second model was better, as can be seen in the pictures above (Figure 40-45). The problems of the first model do not exist on the second model. If the same areas are studied it is possible to notice differences. The lines by the stag do not exist (Figure 46). The areas on the top (Figure 47) and below the cross are not disturbed (Figure 48), and it is possible to see the carvings on the top of the rune stone.

Despite the problems with the geometry of the first model it was still possible to see carvings without texture. On the front it was possible to spot six runes that were not visible earlier (Figure 49).

However, two runes that were visible in the texture were not visible without it. On the back it was possible to see four runes that were not visible earlier (Figure 51). The runes that were visible with the texture were not visible without it. Instead the model is blurry, which is caused by the problem discussed above. The geometry of the first model was not sufficient to complete a full analysis.

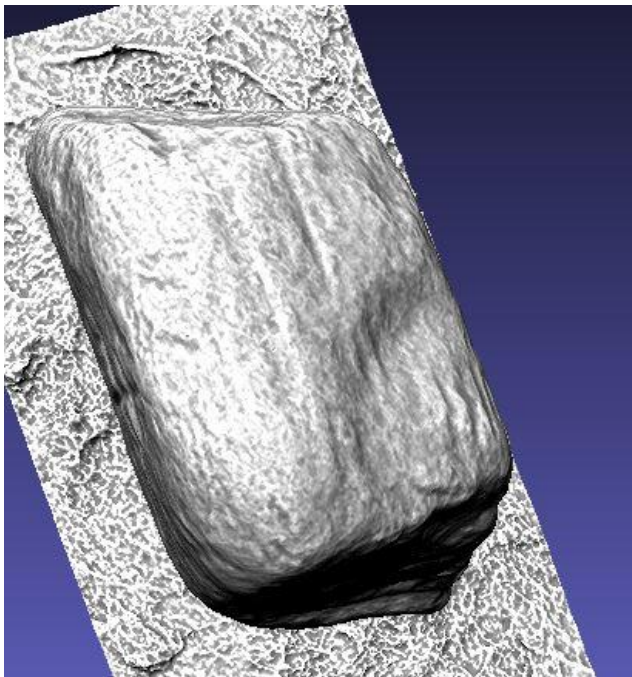


Figure 47. A visualization of the top of the rune stone on the second model with the shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The model was created in Agisoft Photoscan and imported to Meshlab.

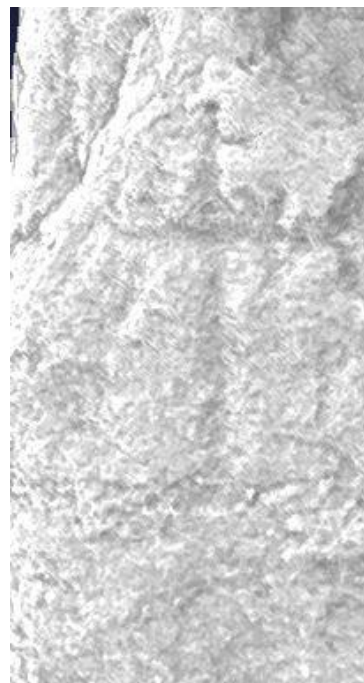


Figure 48. A visualization of the cross on the back of the rune stone on the second model with the shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The model was created in Agisoft Photoscan and imported to Meshlab.



Figure 49. A visualization of the front of the first model with the shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The carvings that were visible while the shader was activated have been marked on the model. The model was created in Agisoft Photoscan and imported to Meshlab.

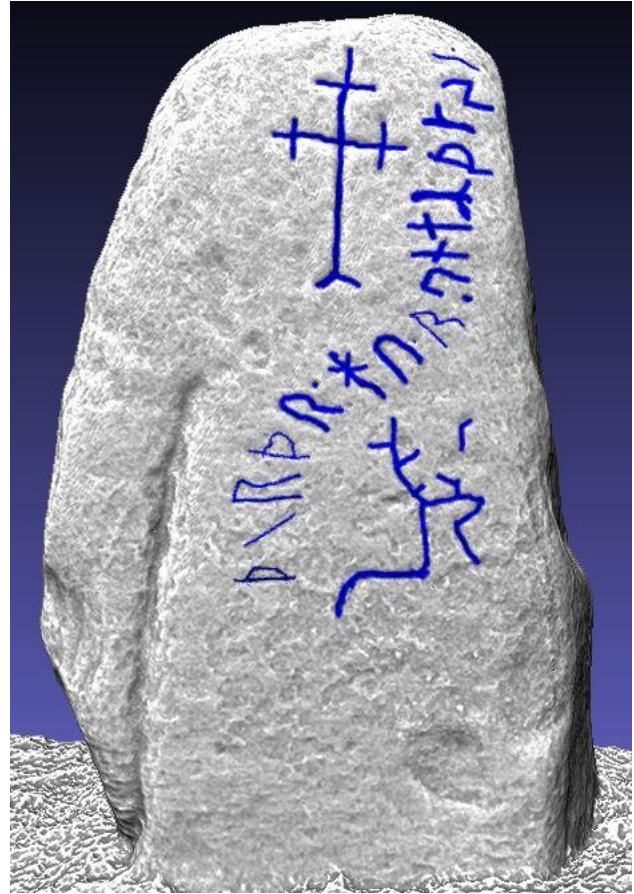


Figure 50. A visualization of the front of the second model with the shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The carvings that were visible while the shader was activated have been marked on the model. The model was created in Agisoft Photoscan and imported to Meshlab.



Figure 51. A visualization of the back and side of the first model with the shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The carvings that were visible while the shader was activated have been marked on the model. The model was created in Agisoft Photoscan and imported to Meshlab.

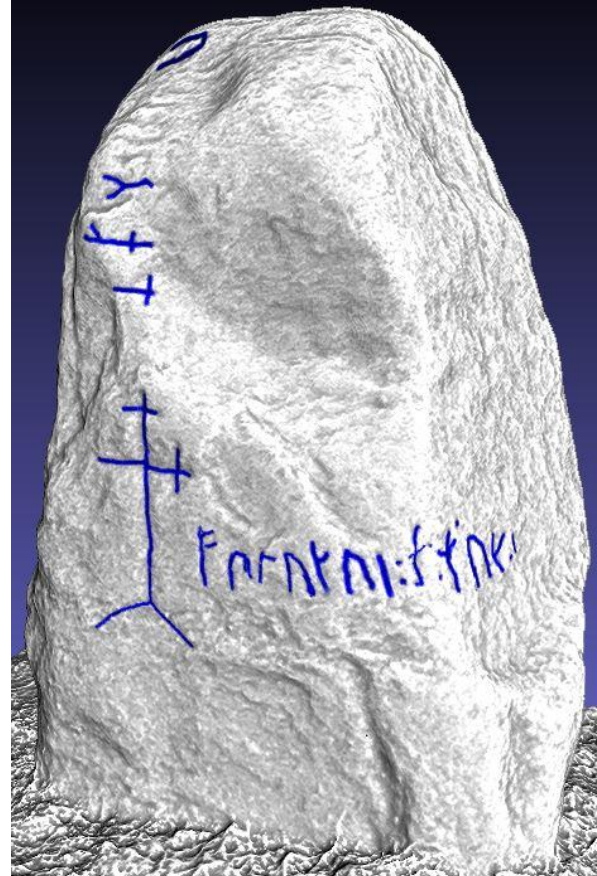


Figure 52. A visualization of the back and side of the second model with the shader radiance scaling setting lambertian radiance scaling turned and enhancement turned to 1. The carvings that were visible while the shader was activated have been marked on the model. The model was created in Agisoft Photoscan and imported to Meshlab.

	Front	þ	ŋ	R	þ	R	* ŋ	R	ŋ	†	†	⋈	þ	†	ŋ	l
First model	12			x	x	x	x	x	x	x			x	x	x	x
Second model	16	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Top	R	Back	þ	ŋ	†	ŋ	†	ŋ	l	†	*	ŋ	þ	†	
First model	0		8	x	x		x	x				x	x	x	x	
Second model	1	x	12	x	x	x	x	x	x	x	x	x	x	x	x	

Table 2. The table shows the runes documented and used for the translation in *Danmarks Runeindskrifter*. The x marks which runes that can be seen on both of the models.

Using the shaders on the second model made it possible to spot all the known carvings (Figure 50 & 52). The crosses and the upper parts of the stag are visible. The house marks were visible on the second model but not on the first. A comparison of the two models shows that the second allows for a clearer understanding the rune stone.

The rune stone is not in perfect condition, as can be seen while studying the images rendered with the different scalings. This leads to it being harder to spot the proper form of the carvings. The first rune is a <þ>. It is a bit damaged but still possible to see. The second rune in the row is a <ŋ> rune. The carving of this rune is severely damaged (Figure 53). As can be seen on the picture there seems to be a part missing. This part has the

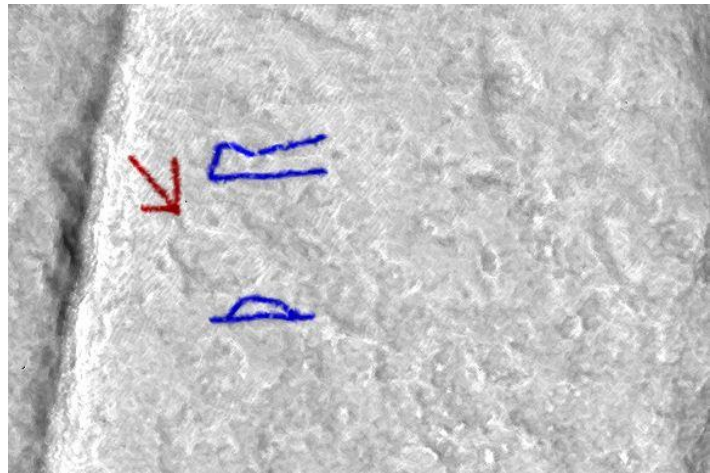


Figure 53. A visualization of the first runes on the front of the second model with shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The carvings that were visible while the shader was activated have been marked on the model. The red arrow shows the damaged rune. The model was created in Agisoft Photoscan and imported to Meshlab.

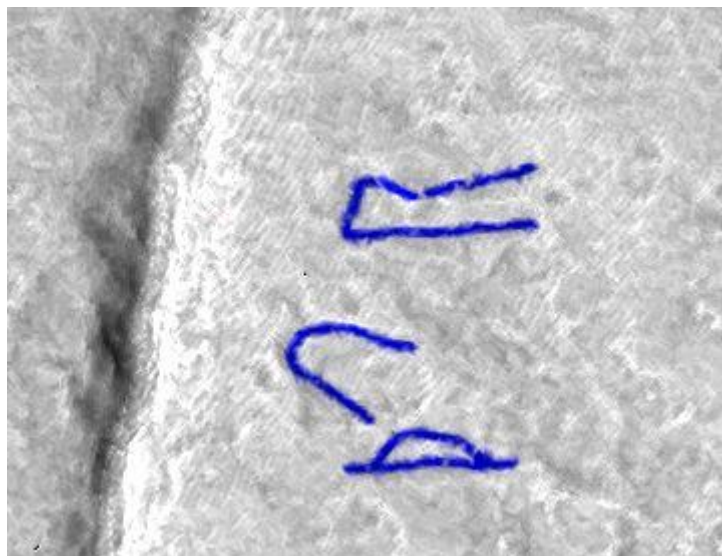


Figure 54. A visualization of the first runes on the front of the second model with shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The carvings that were visible while the shader was activated have been marked on the model. The flake is marked between the runes. The model was created in Agisoft Photoscan and imported to Meshlab.

form of a stone flake (Figure 54). It is possible that the stone has been damaged (Figure 55). In *Danmarks Runeindskrifter* this area seems to be whole. The image taken by RAÄ also shows the area as whole but on their picture only a small part of the rune has been repainted. In the pictures from the second acquisition it seems that this area is covered by lichen and other microorganisms. However, it is possible to see that the area looks damaged. Most of the rest of the runes on the front seem to be intact. The ninth rune, which is an $\langle \mathfrak{N} \rangle$, is partly damaged. The damaged area is in the first part of the rune but it is possible to see the rest of it.

The main differences between the second model and *Danmarks Runeindskrifter* are the damaged parts of the rune stone. Two clear examples of this are the second rune on the front (Figure 56) and a part of the right horn of the stag (Figure 57). It almost looks like someone has cut out a flake from the rune stone. The rune on the back (R) seems to belong to the front row. However, there is no visible traces of carvings in front of it.

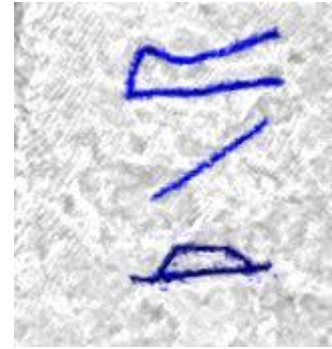


Figure 55. A visualization of the first runes on the front of the second model with shader radiance scaling setting lambertian radiance scaling turned on and enhancement turned to 1. The carvings that were visible while the shader was activated have been marked on the model. What remains of the second rune is marked between the runes. The model was created in Agisoft Photoscan and imported to Meshlab.



Figure 56. A close-up of the second rune on the front. The picture was taken during the second acquisition (Friberg 2015).



Figure 57. A close-up of the right horn of the stag. The picture was taken during the second acquisition (Friberg 2015).

There are some damages on the runes on the back of the stone but most of them are intact. As can be seen on the images (Figure 58 & 59) these were easier to spot than the ones on the front. This could be because these carvings are better preserved in general. The cross on the back seems to be intact and fully visible. The three other carvings will be discussed in a later chapter.

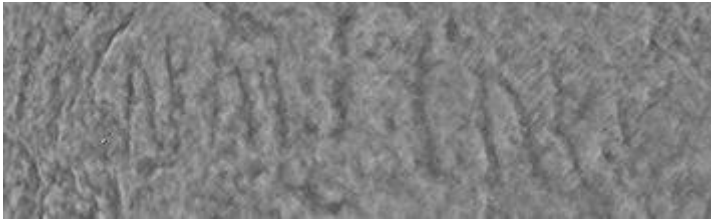


Figure 58. The runes on the back visualized with the grey descriptor on the second model.



Figure 59. The runes on the back visualized with the Lambertian radiance scaling and marked on the second model.

4 Discussion

This part of the thesis begins with a comparison of the two 3D models. The comparison will discuss the differences in the result and the factors that led to them. This will be divided into two subchapters where the first discusses the pictures and acquisition and the second discusses the computers and Photoscan versions. Then the result from the analysis of the second model will be compared with other interpretations of the rune stone, mostly with Jacobsen and Moltke's work *Danmarks Runeindskrifter* since this still is regarded as a standard work. This will be divided into two subchapters, one regarding the runes and the second one regarding other carvings on the rune stone.

4.1 Differences in result

The first model displays a total of 20 runes, two crosses and the upper body, head and horns of the stag. On the second model it was possible to spot 29 runes, three unknown carvings, the two crosses, the upper body, head and horns of the stag but also the front of the body.

4.1.1 Acquisition differences

The main differences between the two models produced for this thesis were the Photoscan versions and the settings during the workflow, the computer used and the set of pictures used. In this specific case the pictures were the biggest reason for the difference in result. There was a big difference between the resolutions of the pictures. The resolution of the first set was much lower which affected the quality of the pictures, and therefore they were not as good as the images from the second acquisition. The pictures were darker and had less colours.

The difference in the chosen file format did not affect the results as much as the camera. As speculated earlier in the thesis the second model would probably not have been much different if JPG images had been used. However, using RAW format on the first set could have changed the result. If the images had been processed, for example by improving the light reducing shadows before they were converted to TIF files, the first model might have been better.

The use of a tripod did improve the quality of the pictures since it kept the camera stable, which led to the obtainment of sharper images. The first set was taken without a tripod which resulted in less sharp images. An example of how this changed the outcome is the grey areas

discussed earlier. These areas were created by Photoscan when trying to recreate non-sharp pictures.

The weather and the time that passed during the acquisition affected the models somewhat. Both days had clouds covering the sun. While taking the first set of images the stone was darker since it had been snowing the day before and the stone had absorbed the water. This affected the colours on the rune stone and partly explains why the first model is darker than the second. The time for the first set was late in the afternoon and the natural sunlight was fading. This led to a quick and hurried acquisition. The advantage of the second acquisition was that it took longer time and started earlier which allowed the photographer to take and retake pictures if necessary. All the mentioned differences can be seen in the pictures in chapter 3.1.1.

4.1.2 Hardware and software differences

The hardware and software choices affected the outcome of the result but not to the same degree. The first model used Photoscan standard while the second used the professional edition. The same settings were used in both editions but the first model had lower settings than the second. This led to that the finished model did not have as good details as the second. Since both models used the same parameters during the creation the choice of edition was irrelevant. If the pictures had been swapped the final result would probably have been the same.

The hardware differences did affect the result. For the first model a computer with AMD FX(tm)-4100 quad-core processor with 8GB of RAM was used. In the Photoscan manual the minimal requirement is 2GB of RAM and an Intel Core 2 Duo processor or equivalent. This is met by the computer but the recommended configuration is not. Agisoft recommends Intel Core i7 processor and 12GB of RAM. To create one model with a photo resolution of 10 megapixels 2GB RAM would be enough for a model of 20 to 30 pictures. 12GB of RAM would allow for up to 200-300 pictures (Agisoft 2013, p. 1). The first computer had no problems creating the first model. However, it had problems trying to create the second model. This led to the computer had to be on for days and eventually overheated and crashed. The second computer met the recommended configuration and had no problem creating the second model. To conclude, with a higher amount of pictures a stronger computer is needed.

4.2 Comparing results

In *Danmark Runeindskrifter* 29 visible runes were detected. This detection was done 83 years ago. They also had the opportunity to clean the rune stone which was not done for this thesis. The second model produced was able to detect 29 runes. The main difference between the results was the stag. In the illustration in *Danmarks Runeindskrifter* more parts of the stag are visible, in particular the lower parts of the body and the legs.

4.3 Uncertain rune carvings

The unknown carvings are those seen on the top of the second model with radiance scaling (Figure 60). These carvings could be runes since they have a shape similar to combinations of different runes. The first one is formed like a Y and could be either an m <ʁ> rune or an r <ʀ> rune but lacks the middle part. The second one could be a combination of the k rune <ʁ> and a <ʀ>. The third one could be a <ʀ> rune or a <ʁ> rune (Figure 61).

Riksantikvarieämbetet filled these carvings with paint during their renovation and repainting but left no explanation why. Enoksen did not show them in his book since he could not with certainty describe them in his illustration. However, he writes about them and calls them bomärken (house marks). They were used to show ownership of one's possessions. The marks were used by everyone from kings to farmers and literate and illiterate alike. The markings could be anything, for example variants of

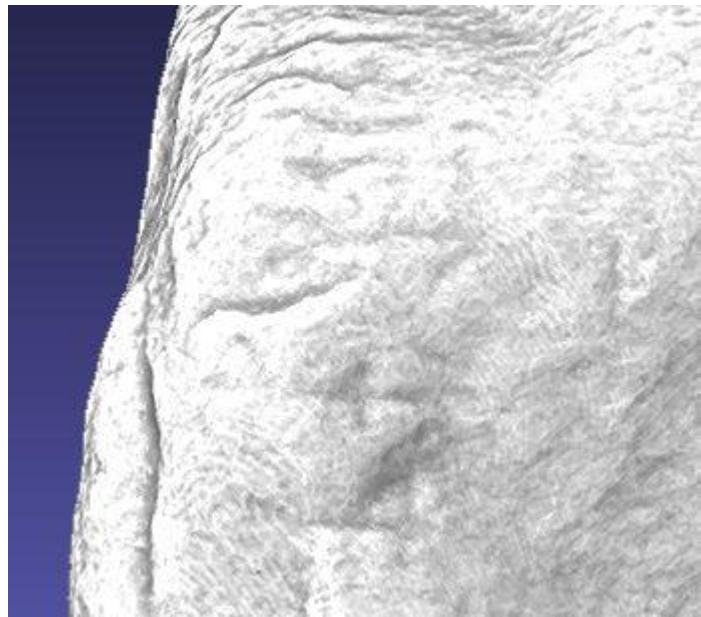


Figure 60. The unknown carvings/house marks visualized with Lambertian radiance scaling on the second model.

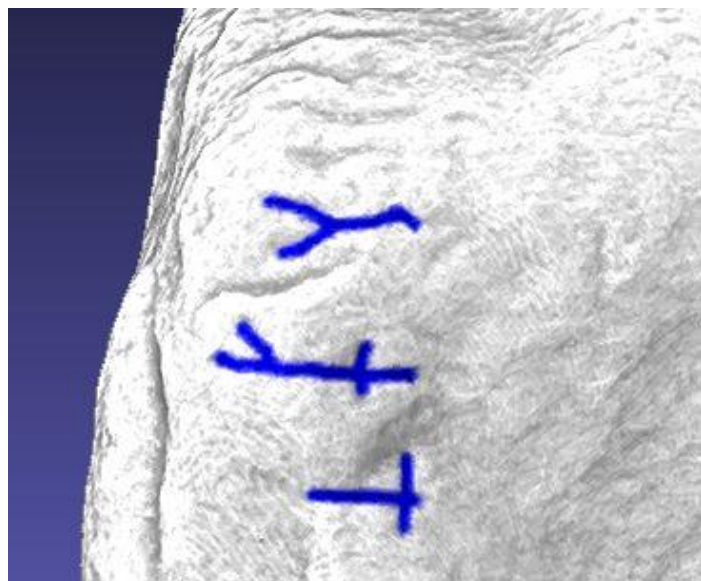


Figure 61. The unknown carvings/house marks visualized with Lambertian radiance scaling and marked on the second model.

crosses, circles, letters or runes (Skånberg 2003, p. 11f). The ones on the Hyby stone are thought to be either a combination of runes or just randomly carved signs (Enoksen 1998, p. 55). According to *Danmarks Runeindskrifter* Wimmer also thought there were runes in a row from the R to the house markings. Jacobsen and Moltke agree about existence of the house marks, but say that they have not been translated yet. However, they disagree that the markings described by Wimmer were actual runes. In their evaluation of these carvings they observe that they seem to follow the structure of the stone and should be seen as grooves (Jacobsen & Moltke 1941-42 text, p. 319).

4.4 Evaluation

The results provided by the method were better than expected. The result illustrated that almost all known carvings could be seen. The model created a view of the rune stone which would not be attainable without it. The radiance scaling allowed for good visualization of the carvings which could be used to create a digital drawing. Moreover, the model can be used for more than a visualization of the carvings. It allows for highlighting different aspects of the geometry and can be used for further studies of the rune stone. The model also makes it possible to spread virtual replicas of the original stone so that more scholars can get a chance to study it. This would make it easier to compare different rune stones with each other in order to look at regional differences. It is possible to use this method to document the rune stones over time by making new models on a set interval. This allows for the possibility to study weathering effects over time. The virtual replica of the monument can also be spread to the public, either through downloadable files published on the internet or by displaying them on monitors in museums.

There are some limitations to the method. The software is user friendly and allow anyone to create a model from a set of overlapping images. However, the quality of the models can differ much depending on the user's experience and the equipment used. In order to create a good model for visualization one has to practice both the acquisition, in order to take good pictures, and the production in the software. Another limitation is the hardware used. The quality of the model does not change depending on the computer but the time of the creation does, and thereby the chance of overheating. Both of these limitations have been shown in this thesis. Another limitation is the drawing function in Meshlab. It does not allow the user to draw on an empty layer but forces one to draw directly on the model. This makes it harder to

compare what has been drawn with a clean model. However, it is possible to have the same model in two different layers. This makes it possible to draw on one model and use one as a reference. The problem with using two models, depending on the size of them, is that it can slow down the software. If the software slows down during the drawing the lines might become crooked or too long and have to be redrawn. This is discussed by Plets et al. (2012), and they state that there is no free or low cost software which allows the user to draw in an empty layer on 3D models. They mention that this operation is possible in the commercial package ArcScene (2012, p. 151). Having the drawings of the carvings in a separate layer also makes it simpler to create a bi dimensional image with only the runes. This image is easier to compare with older interpretations, by placing them side by side, since they are often hand drawn. It is possible to make a rendering with the drawing and the rune stone. By importing this image to a software for image processing, like the commercial software Photoshop or the free software GIMP, it is possible to draw on an empty layer atop of the rendering. However as this is a bi dimensional image created to describe a round object some of the information will be lost since the runes follow the shape of the stone.

There is still room for improvement of this workflow. The geometry created from the images was good and more than sufficient. However, it would probably be possible to have an even better visualization of the rune stone if it had been cleaned before the acquisition. Lichen and microorganisms which grow on the stone and in the carvings can affect the depth calculations during the post-processing. The model might have been improved by further post processing, for example by using a varied amount of pictures and settings. However, this would require more time. As shown by an experiment done by Koutsoudis et al. the model created with the highest amount of pictures is not always the best one (2013, p. 4453ff).

The final result was satisfying for the purpose of this thesis. It was possible to visualize the geometry and to use it as a tool to see the carvings. The accuracy of the method on rune stones has not been tested in this thesis. It would be interesting to compare the model with a laser scanning of the same rune stone. Previous tests of accuracy on image-based 3D modelling and laser scanners have shown it differencing on sub-centimeter levels (Fassi et al. 2013; Thoeni et al 2014).

5 Conclusion

The thesis has shown that image-based 3D modelling is a viable option for the documentation of rune stones. The pipeline, consisting of the acquisition, the creation of the model in Agisoft Photoscan and the analyse in Meshlab, is solid. The addition of the radiance scaling during the analysis improves the visualization. The final result matches almost all earlier observations and the missing parts are caused by damages on the rune stone. The created model allows for a virtual replica in 3D. The study of a three dimensional object in 3D provides more information about it than the study of the object in two dimensional pictures. Unlike an image a model can be studied from different perspectives. The carvings on rune stones and similar monuments follow the shape of the stone, and the advantage of using a model instead of an image while studying these object is that the carvings can be viewed from the correct angle regardless of where they are placed. This virtual replica can be published on the internet and can reach a wider audience than a book or printed report, which makes it available to scholars and the public who might not have a chance to visit it.

The two models show two different qualities. The differences between the models are caused by a number of factors. Both models improve the visualization but the first one is inferior to the second. Images which are sharp and of high resolution are necessary to create a better model. The hardware also changes the outcome. Using an older computer might force the user to either wait for a long time during post-processing or use lower quality settings. The use of Agisoft Photoscan standard or professional is irrelevant for this workflow since all the necessary parameters are available in both editions.

This method is highly encouraged by the author for future documentation of rune stones. It allows for a documentation that is cheap, efficient and does not harm the rune stone. An idea for a future implementation of this method would to apply it to other rune stones.

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