The Ritland impact structure:

Characteristics and distribution of the ejecta layer and associated Lower Paleozoic sedimentary succession

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Master Thesis in Geosciences
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UNIVERSITY OF OSLO
June 1st, 2011
Abstract

The newly discovered Ritland impact structure is located in Hjelmeland Municipality in Rogaland County, Western Norway. The structure is 2.7 km in diameter, about 350 meters deep and probably of Early/Middle Cambrian age. In this study, parts of the Lower Paleozoic succession, which include a layer of material ejected during impact, has been mapped and logged east of the impact structure. The depositional environment has been interpreted based on the combined sedimentary field data, including sedimentological logs and general mapping, as well as petrographical and mineralogical studies including thin sections, XRD, SEM and CL analysis. In addition to discuss the depositional environment of the Early Cambrian succession overlying the sub-Cambrian peneplain, special emphasis has been on the ejecta layer which is observed some meters above the basement.

During the Cambrian transgression, the Ritland area became a part of an extensive sea which at the time covered most of Scandinavia, as well as the Baltic. The stratigraphy reveals that the environment was quite calm and in periods stagnant, although bioturbation frequently occurred. Although the overall development seems to be transgressive, a shorter period of regression seems to have occurred as well. A layer found up to a few meters below the ejecta layer is characterized by calcite precipitation and stromatolites, suggesting minor water depth.

The term “ejecta” describes the debris expelled from the crater during impact and crater formation. The ejecta layer is matrix-supported, consisting of clasts of basement rocks of various sizes; from blocks and boulders down to sand and silt-sized fragments in shale. The average clast size decreases both away from the crater centre as well as upwards within the ejecta bed. For most impacts, ejecta are emplaced ballistically. The fact that the ejecta layer is found within marine deposits some meters above the sub-Cambrian peneplain strongly suggest that the Ritland area was covered by a shallow sea at the time of impact. The presence of water at the time of impact probably increased the extent of the ejecta distribution. In addition, the presence of water may have caused early post-impact reworking of the ejecta layer by wave action, tsunamis, currents or resurge flows.

The ejecta layer has been observed as far as 4.9 km (3.6 crater radii) from the crater centre. Originally it most likely extended much farther out when comparing the ejecta distribution at Ritland with other craters of similar configuration and size.

Both microscopic and macroscopic evidences of shock metamorphism have been found within the ejecta layer. Several samples collected in the area revealed planar deformation features (PDFs) in quartz grains, while a cluster of shatter cones were observed at another locality. Such features only form by shock pressures of several GPa, and are considered evidence of meteorite impact.

The Silurian-Devonian Caledonian Orogen thrust nappes altered the stratigraphic column overlying the peneplain. Thus, there is an uncertainty regarding the presently observed height of the ejecta layer above the basement, as well as its original thickness. The Lower Paleozoic successions overlying the sub-Cambrian peneplain were in addition further exposed to later uplift, erosion and glaciation compared to the sediments found within the crater. Consequently the ejecta layer is only partly preserved and the field observations have been restricted to locations east of the crater.
Contents

1. Introduction ........................................................................................................... 8

2. Impact Geology ....................................................................................................... 9
   2.1 Historical background ....................................................................................... 9
   2.2 The formation and characteristics of impact structures .................................. 10
   2.3 Shock metamorphism ...................................................................................... 13
      2.3.1 Shatter cones .......................................................................................... 13
      2.3.2 Planar deformation features (PDFs) ......................................................... 14
      2.3.3 Other shock metamorphism features ....................................................... 15
   2.4 Ejecta formation and mechanisms .................................................................. 15
      2.4.1 Vapor and dust plume ............................................................................. 15
      2.4.2 Ejecta curtain ......................................................................................... 17
      2.4.3 Ballistic sedimentation ............................................................................ 17
      2.4.4 Ejecta distribution ................................................................................... 18
      2.4.5 Fluidization of ejecta ............................................................................... 20
      2.4.6 The presence of water ............................................................................. 21

3. Geological setting .................................................................................................. 22
   3.1 Target rocks ..................................................................................................... 22
      3.1.1 The crystalline basement rocks ................................................................. 22
      3.1.2 The Early Cambrian sedimentary sequence ............................................. 23
   3.2 Post impact events – The Caledonian Orogeny ................................................. 24

4. Methods ................................................................................................................ 25
   4.1 Field logging, mapping and sampling ............................................................... 25
   4.2 Petrographical analysis ................................................................................... 28
      4.2.1 Thin section ............................................................................................. 28
      4.2.2 Scanning Electron Microscopy (SEM) ...................................................... 28
      4.2.3 Cathodoluminescence (CL) ..................................................................... 30
   4.3 X-ray diffraction (XRD) ................................................................................ 30

5. Sedimentological description ................................................................................. 32
   5.1 Stratigraphical logs ......................................................................................... 32
   5.2 Lithological facies description ....................................................................... 41
   5.3 Facies associations ......................................................................................... 47
   5.4 Ejecta layer thickness distribution .................................................................. 48

6. Petrography and mineralogy .................................................................................. 49
   6.1 Thin section description .................................................................................. 49
      6.1.1 Facies association 1 ................................................................................ 49
      6.1.2 Facies association 2 ................................................................................ 50
      6.1.3 Facies association 3 ................................................................................ 52
   6.2 XRD description .............................................................................................. 53
      6.2.1 Facies association 1 ................................................................................ 55
      6.2.2 Facies association 2 ................................................................................ 55
      6.2.3 Facies association 3 ................................................................................ 56
      6.2.4 Facies association 4 ................................................................................ 57
      6.2.5 General trends ......................................................................................... 57
   6.3 SEM description ............................................................................................... 61
      6.3.1 Facies association 2 ................................................................................ 61
1. Introduction

The Ritland impact structure is located in Hjelmeland municipality in Rogaland county, southwestern Norway (Figure 1.1A and B). It represents the eroded remnants of an early Cambrian impact crater, 2.7 km in diameter and approximately 350 meters deep. This master thesis is based on field mapping and sedimentological and petrographical analysis of the Lower Paleozoic sedimentary deposits overlying the sub-Cambrian peneplain east of the Ritland impact structure. Within these deposits ejecta material are preserved.

The thesis is a part of a project funded by the Research Council of Norway (2009-2012). The project, which is lead by professor Henning Dypvik (UiO) and Fridtjof Riis (NPD), includes one post-doc, one Ph.D. and several master students. Detailed field work and laboratory analyses within the project have been carried out in the years 2009 - 2011 in order to characterize the crater structure and understand the processes behind. Particularly in focus are the configuration of the sedimentary infills, the melt-bearing impactites, the structural development and the ejecta layer, all in order to better understand the mechanisms of formation.

Geological studies in the Ritland area have been carried out over several decades. Henningsmoen (1952) and Bruton and Harper (2000) described the fossiliferous Middle Cambrian shales, while Sigmond (1978) was the first to identify and map the brecciated rocks in the area. Later, Spjeldnaes (1985) noted the depression in the sub-Cambrian peneplain occurring in the crater. It was first in 2001 that Fridtjof Riis suggested the impact origin of the breccias and the palaeo-relief in the peneplain (Riis et al., 2011). The finding of planar deformation features (“PDFs”) in quartz grains in 2007 proved this theory right. The ongoing study aims to further document the evidence of an impact and investigate all perspectives of it.

This master thesis will describe and discuss the sedimentary succession found overlying the sub-Cambrian peneplain and the ejecta layer within. The objective is to interpret the pre-, syn- and post-impact depositional environment as well as the ejecta layer which is exposed at several localities east of the impact structure. The likely presence of a shallow sea at the time of impact probably had a great influence on the characteristics and deposition of the ejecta layer. The evidences found in the field may provide valuable information regarding the processes behind the ejecta formation and distribution, as well as the general crater formation, and will be discussed and compared with ejecta surrounding other craters.

Figure 1.1: A) Geological map of the Ritland area. B) Location of the Ritland impact structure. The black dots represent known Fennoscandian impact structures. Figures modified from Riis et al. (2011).
2. Impact Geology

2.1 Historical background

Impact cratering has certainly played an important role in the geological history of our solar system, including the Earth. The present Earth and Moon is the result of a large collision between the proto-Earth and Theia, a hypothetical object the size of Mars, almost 4.5 billion years ago (Hartmann and Davis, 1975). During the entire Earth's history, interplanetary dust, meteorites and comets have supplied the Earth with organic matter, which according to Chyba and Sagan (1992) may have played a role in the evolution of life. It is also likely that much of the water found in the oceans today have been brought to Earth by comets (Mumma et al., 2001). Meteorite impacts is thought to have caused at least one mass extinction (Alvarez et al., 1980; French, 2004). Another aspect of the importance of impact cratering, is an economic one. Some of the world's largest impact craters contain e.g. large ore and hydrocarbon resources.

Craters are formed by a variety of processes, including volcanism, impact cratering, subsidence, secondary cratering and collapse (Montanari and Koeberl, 2000). The lunar craters, first observed by Galileo Galilei in the beginning of the 17th century, were until at least the 1950's thought to be of volcanic origin (Melosh, 1989). Impact cratering was long ignored as an important geological and planetary process. It is just in the recent decades that attention has been paid to impact craters.

The “revolution”, according to French (2004), started in the 1960s with the space exploration and particularly the Apollo program which soon established that impact craters were common geological features in the solar system. However, the results were not immediately recognized by most scientists, nor was it applied to the field of terrestrial geology. At this time, only meteorites themselves were considered evidence of an impact crater. However, during the course of the years, shock metamorphic features such as planar deformation features (PDFs) and shatter cones became considered evidences of impact as well. This lead to a rapid increase in the number of known impact structures on the planet, from 15 in 1960 to 50 in 1968 (French, 2004).

An important milestone in impact geology came with a paper by Alvarez et al. (1980), suggesting that the major biological extinction at the K-P (Cretaceous - Paleogene) boundary was connected with an impact. The boundary was characterized by pronounced global iridium anomalies, a typical signature related to impacts (French and Koeberl, 2010). Later, the Chicxulub structure on the Yucatán Peninsula was found to be the site of impact (Melosh, 1989; Sharpton et al., 1992).

Today, 178 impact craters are confirmed (Figure 2.1.1; Earth Impact Database, 2011), and the number has been growing by 3-4 per annum (French, 2004). Most impact scientists believe there are still many impact craters yet to be discovered (Grieve, 1987; French, 2004), especially in the marine realm (Dypvik and Jansa, 2003; Dypvik et al., 2004) since oceans cover more than 70% of the Earth's surface.
2.2 The formation and characteristics of impact structures

Craters can generally be described as depressions in the topography, with circular shape and locally intensely structural disturbance and brecciation. Two main crater types are recognized; simple and complex. Simple craters are described as bowl-shaped (see Figure 2.2.1A and B), one example being the Barringer (or Meteor) Crater (Melosh, 1989). Simple craters are generally smaller than the complex ones. The upper size limit of simple craters is controlled by the target rocks. On Earth, the largest simple craters are about 4 km in diameter if the target rocks are crystalline, and 2 km if the target rocks are sedimentary (Grieve, 1987).

Complex craters may have central peaks and/or rings surrounded by one or several peripheral depressions and a faulted rim (Figure 2.2.1C and D). Examples of complex multiring craters are the 40 km diameter Mjølnir structure in the Barents Sea (Gudlaugsson, 1993) and the 300 km diameter Vredefort structure in South Africa (Therriault et al., 1993). As craters on the Earth are exposed to weathering and erosion, the best examples are found on the Moon and on Mars, which lack both tectonism and an atmosphere (Mars inhibit a very thin atmosphere).
Although crater formation is a continuous process, three stages are generally recognized (Melosh, 1989; French, 1998):

1) Contact and compression
2) Excavation
3) Modification

The development of a simple crater is illustrated in Figure 2.2.2. In addition, Suuroja et al. (2002) has suggested that a fourth stage, the resurge stage, ought to be added when discussing marine impacts.

The contact and compression stage starts as the projectile hits the target surface (Melosh, 1989). It is a very brief stage, lasting less than a second for most craters. The projectile compresses and accelerates the target mass. Shock waves originate at the point or points of contact, and these areas may experience pressures up to hundreds of GPa. Simultaneously, the target mass decelerates the projectile by its resistance to move. The contact and compression stage ends when the projectile has unloaded the high pressure and the result is that the kinetic energy is transferred to the target rocks. During this short period, the projectile may reach a depth of 1 – 2 times its own diameter (French, 1998).

The excavation stage which follows the contact and compression stage involves an almost hemispherical down- and outward movement of the shock wave through the target rocks. The shock wave gradually loses its momentum as it expands and engulfs more material.
The shock wave and the following rarefaction wave fracture and accelerates material. This will drive the target rock outward from the point of impact, producing a symmetric excavation flow around the center of the structure. The uppermost target rocks will get an upward and outward movement leading to ejection of material out of the crater. At lower levels, target rocks will move downward and outward. The result of these movements is a bowl-shaped depression in the target rocks, the transient crater, as well as an ejecta curtain outside the crater. Only the material in the upper one third of the excavated crater is ever ejected. The excavation stage lasts relatively much longer than the contact and compression stage, from seconds to minutes.

Figure 2.2.2: Development of a simple impact structure. Series of cross-section diagrams showing progressive development of a small, bowl-shaped simple impact structure in a horizontally layered target: (a) contact/compression stage: initial penetration of projectile, outward radiation of shock waves; (b) start of excavation stage: continued expansion of shock wave into target; development of tensile wave (rarefaction or release wave) behind shock wave as the near-surface part of original shock wave is reflected downward from ground surface; interaction of rarefaction wave with ground surface to accelerate near-surface material upward and outward; (c) middle of excavation stage: continued expansion of shock wave and rarefaction wave; development of melt lining in expanding transient cavity; well-developed outward ejecta flow (ejecta curtain) from the opening crater; (d) end of excavation stage: transient cavity reaches maximum extent to form melt-lined transient crater; near-surface ejecta curtain reaches maximum extent, and uplifted crater rim develops; (e) start of modification stage: over steepened walls of transient crater collapse back into cavity, accompanied by near-crater ejecta, to form deposit of mixed breccia (breccia lens) within crater; (f) final simple crater: a bowl-shaped depression, partially filled with complex breccias and bodies of impact melt. Times involved are a few seconds to form the transient crater (a)–(d), and minutes to hours for the final crater (e)–(f). Subsequent changes reflect the normal geological processes of erosion and infilling. Figures and figure text after French (1998).
The modification stage is the time where the transient crater reaches its maximum size. At this point, the crater is unstable. Loose debris from the rim and walls slide down and accumulates on the crater floor, making the apparent crater less deep and somewhat wider (Figure 2.2.2e). In large craters, slump terraces may form, and a central peak may develop in the interior. This stage lasts less than a minute for small structures, and up to several minutes for large structures.

2.3 Shock metamorphism

During the contact and compression stage, the projectile transfers its kinetic energy onto the target rocks. Typical terrestrial impact velocities may be 15 – 25 km/s (Grieve, 1987), giving rise to peak pressures up to several hundred GPa and temperatures up to several thousand °C. In contrast, normal endogenic metamorphism may reach temperatures of up to 1200 °C and pressures up to 2 GPa (Montanari and Koeberl, 2000). The energy radiates from the point of contact through a hemispherical shock wave, which decays exponentially as it expands outwards and downwards. This high pressure and temperature regime, although very short-lived, leads to a series of changes in the target minerals and rocks called shock metamorphism (Figure 2.3.1). Shock metamorphism give rise to several unique features, some of which are only found in association with impacts.

![Temperature and pressure fields for endogenic and shock metamorphism](French, 1998).

2.3.1 Shatter cones

Shatter cones are multiple sets of striated conical features developed at relatively low shock pressures found in the rocks of terrestrial impact structures (French and Koeberl, 2010). These features are the only shock effects visible in megascopic scale (outcrop and hand-specimen,
see example in Figure 2.3.2A). Shatter cones are complete or partial cones forming in all rock types. They are best developed in fine-grained, structurally isotropic rocks, especially carbonates (Grieve, 1987). Sizes range from less than a centimeter to several meters. Shatter cones occur mostly in the central uplift and in lower and outer parts of a crater (Montanari and Koeberl, 2000), as well as within the ejected material. Experimental and geological studies suggest that shatter cones form under shock pressures of 2 – 20 GPa.

2.3.2 Planar deformation features (PDFs)

Planar deformation features (PDFs) are multiple sets of thin, parallel and closely spaced planes of deformation found in minerals, mainly quartz (Figure 2.3.2B; French and Koeberl, 2010). The sets remain within one grain without crossing the grain boundary and the individual planes are typically less than 1 µm thick and only a few µm apart. PDFs are always oriented parallel to specific crystallographic planes within the quartz grain.

Although the detailed generation of planar deformation features is not clear, they have been reproduced in experimental studies at pressures of ~10-30 GPa. Such high levels of pressure rule out the possibility of the features being produced by endogenic processes in crustal rocks. Thus, PDFs remain one of the strongest and most widely used evidence of an impact (French and Koeberl, 2010).

Any given quartz grain that has been exposed to shock pressures, will develop PDFs with specific crystallographic orientations relative to the c-axis, reflecting the degree of shock (Ferrière et al., 2009). These specific crystallographic orientations of PDFs are formed at different levels of shock pressure. Thus, they can be statistically analyzed (see section 4.2 and Figure 4.2) and used as “shock barometers”.

Figure 2.3.2: A) Group of shatter cones in fine-grained carbonate rock from the Steinheim structure, Germany. B) Two sets of intersecting PDFs in a quartz grain from the Bosumtwi impact structure, Ghana. Figures by French and Koeberl (2010).
2.3.3 Other shock metamorphism features

Planar fractures (PFs) are multiple sets of parallel open planar fractures produced mainly in quartz grains at shock pressures of <10 GPa. They are distinguished from PDFs by having thicker fractures (<2-3µm) and wider spaces (>15 µm) between the fractures (Montanari and Koeberl, 2000). As similar features also may form in normal endogenic processes, PFs cannot be used uniquely in identifying an impact structure (French and Koeberl, 2010).

Diaplectic glass occur mainly in quartz and feldspar at high shock pressure levels (30 – 50 GPa). It is an isotropic phase with the original crystal texture and fabric preserved (Montanari and Koeberl, 2000). Diaplectic glasses are according to French and Koeberl (2010) just as good indicators of an impact as PDFs. They are however more rare, as the higher shock pressure required to form them occur within a smaller volume of target rocks during impact.

High-pressure polymorphs, are phases not produced in the Earths crust, but may be found in an impact structure. Certain minerals transform from one phase to another at a given pressure and temperature (Montanari and Koeberl, 2000). During an impact, graphite may be converted to diamonds, while quartz may transform into stishovite and coesite (French and Koeberl, 2010). French (1998) urges caution using these as evidences of an impact, since some of these minerals may also be produced by deeper endogenic forces.

Mineral melts may form in small volumes of the the target rock which experience extremely high pressures (>50 GPa) and inhibit post-impact temperatures of 1 500 °C (French and Koeberl, 2010). These temperatures are sufficient to melt the rock and homogenize the chemical composition. Depending on how fast the melted rocks cool, glass (rapid cooling) or fine-grained melt rocks (slow cooling) forms. Mineral melts may serve as an independent evidence of impact, and the melt may also be used for dating the impact event as the isotopic system used in radiometric age measurements are reset (French and Koeberl, 2010).

2.4 Ejecta formation and mechanisms

Ejecta reflect debris that has been excavated from an impact crater. This material falls back to the ground forming ejecta deposits, mainly outside the crater. The morphology of these deposits depends upon several factors. These include distance from the site of impact, the size of the projectile and the crater, the target rock composition and the presence or absence of an atmosphere and water (Melosh, 1989).

2.4.1 Vapor and dust plume

The earliest and fastest material to leave the site of impact is a plume of vapor from the meteorite and the target rocks (Melosh, 1989). The vapor and dust plume expansion begins during the contact and compression stage as soon as the rarefaction wave reaches the rear of the projectile (see illustration in Figure 2.4.1 A). The expanding gas starts out as an heterogeneous mixture of components with different composition, temperature and directions. After some time, it becomes more homogenous, forming a nearly hemispherical plume with high outward and upward velocity components. The plume will continue to expand as long as
there is a pressure gradient to the ambient atmosphere.

Condensation of the vaporized material starts in the center of the vapor cloud and spread outwards as the plume expands. This give rise to unique particles of different sizes. Nickel-iron spherules 100 – 200 µm in size has been reported around the Meteor Crater (Nininger, 1949 in Melosh, 1989). Similar observations has also been done around the 22 km diameter Ries impact structure, Germany (French and Koeberl, 2010). See example of spherules in Figure 2.4.1 C. While spherules are formed by the condensation of vapor, tektites, which are small glassy blobs, are formed by the solidification of impact melt (Melosh, 1989). Tektites have been found among other places around the 10,5 km diameter Bosumtwi Crater in Ghana (Figure 2.4.1 B).

According to Oberbeck (1975), the material derived from the vapor cloud is deposited as a base surge. Base surge deposition is associated with nuclear and explosion experiments, but Shoemaker (1963, in Oberbeck, 1975) suggested that the process would also be valid for impact crating. As the material in the vapor cloud starts to condense and the temperature falls, it starts falling back to the ground. As this happens, the potential energy is converted to kinetic energy, and as the material reaches the ground, it gets pushed radially outwards by its own weight.

It is unclear how much material the ground-hugging base-surge may carry. Some explosion experiments has shown that it only deposits a marginal layer of dust. The distribution of this thin layer is strongly controlled by wind and may not be recognized in the sedimentary record. Still, the discovery of spherules and tektites is important as they may be used as stratigraphic markers and indicators of an impact structure, as well as providing some insight into the impact angle and the distribution of the ejecta. There are reported cases where the findings of spherules and/or tektites has lead to the discovery of new impact structures (Montanari and Koeberl, 2000; French and Koeberl, 2010).

![Figure 2.4.1: A) Initial stage of the vapor plume expansion. The plume is expanding fast and the flow pattern is complex. Modified from Melosh (1989). B) Microtektites sourced from the Bosumtwi impact structure showing both spherical and elongate droplet-shaped forms (French and Koeberl, 2010). C) Impact-melt spherule layer from the Wittenoom Formation, Australia (French and Koeberl, 2010).](image)
2.4.2 Ejecta curtain

While some material is ejected from the crater during the contact and compression stage in a vapor plume, most ejecta is transported out of the crater by excavation. The excavation process is outlined in chapter 2.2. The rarefaction wave, which immediately follows the shock wave traveling through the target rocks, give rise to an upward and outward directed pressure gradient (Melosh, 1989). It is this pressure gradient that produces the upward and outward directional excavation flow. The maximum excavation velocity is typically between one-sixth to one-tenth of the impact velocity, which would equal 1.5 – 4.2 km/s based on the typical terrestrial impact velocities given by Grieve (1987).

Material excavated from the crater is considered to be ejecta only if it surpasses the original target surface. At this point, the moving debris become individual projectiles moving in ballistic trajectories. They form the ejecta curtain, an outward expanding inverted cone, due to an coincidence of alignments (Melosh, 1989). The ejecta curtain shape is dependent of the angle, velocity and time of ejection. Still, it maintains a characteristic inverted cone-shape whose sides form an angle of about 45 degrees with the target surface.

2.4.3 Ballistic sedimentation

Oberbeck (1965) first coined the term “ballistic sedimentation” in an article on the emplacement of ejecta around lunar craters. He suggested that ejected debris, following different ballistic trajectories, could crater the surface on which it impacted. This could lead to the incorporation of locally derived material into the primary ejecta and also create an outward high speed debris flow (Figure 2.4.2). It has later been accepted that this process is also occurring on our planet. For instance, significant amounts of local material have been mixed with the primary ejecta in the ejecta layer around the Ries structure, see appendix 5 (Dennis, 1971; von Engelhardt, 1990; Osinski, 2006).

The ejecta cone-shaped curtain developed during impact consist of material of different sizes with different velocities and angles relative to the target surface (Melosh, 1989). Oberbeck (1975) suggested that the ejecta curtain observed in laboratory and explosion (i.e. nuclear or TNT) experiments are most likely similar to larger scale ejecta curtains associated with impacts. Several conclusions were then drawn regarding emplacement of ejecta. Firstly, most of the material excavated from the crater would follow relatively low-angle trajectories relative to the target surface. Very little material would be thrown out of the crater at angles higher than 45 degrees relative to the target surface. Secondly, the largest fragments originating from the deepest part of the stratigraphy would have the lowest velocity and be emplaced closest to the crater rim. The smallest fragments would be transported highest in the curtain and have the highest velocities. Thus, the ejecta found farthest away from the crater would be material derived from the shallowest part of the target rocks. It also mean that at greater distances from the crater, the material can strike down with higher velocities. This is illustrated in Figure 2.4.2.

Oberbeck (1975) further stated that when the velocity of the ejecta striking the ground reaches a certain value, the material will erode and mix with the surface material. The horizontal velocity will be transferred onto this mix of primary ejecta and local material which will
continue the motion outwards. This mixture moves rapidly outwards as a ground-hugging debris flow similar to the flow of rock avalanches.

Melosh (1989) points out that ballistic sedimentation will in most cases cause an underestimation of ejecta layer thicknesses based on formulas by amongst others McGetchin et al. (1973), see section 2.4.4. He states, however, that these equations still provide a good insight to the proportion of primary ejecta even if the local material is not considered.

2.4.4 Ejecta distribution

Essentially all impact craters are surrounded by ejected material derived from the interior of the crater. Ejecta deposits are generally thickest close to the crater and thinning outwards. The recognizable continuous part of the ejecta material is called the ejecta blanket which often extend about one crater radii (crater center to crater rim) from the crater rim (Melosh, 1989).

The distribution of ejecta may be classified as proximal or distal ejecta (Montanari and Koeberl, 2000). Proximal ejecta is defined by being deposited within five crater radii of the rim and comprises about 90 % of all the ejected material. Distal ejecta accounts for the last 10
% of the ejected material and occur beyond five crater radii from the crater rim. About 50 % of the ejecta will be deposited within one crater radii from the rim.

For impacts on an airless body such as the Moon, the excavated ejecta moves outward from the crater in purely ballistic, or free flight, trajectories (Carr et al., 1977). For planets that are possessing an atmosphere (e.g. the Earth), the atmosphere may somewhat alter the ejecta distribution. The general decrease in ejecta layer thickness outward from a crater rim is however valid for most craters. Several authors have described this relationship by an empirically derived formula. One of the most commonly used is a formula by McGetchin et al. (1973) derived from observations on small terrestrial craters:

\[ t = 0.04 \pm 0.01 R(r/R)^{-3.0} \]

where \( t \) is the thickness of the ejecta layer at a distance \( r \) from the rim. \( R \) is the radius of the transient crater. All dimensions are in meters.

Since most of the ejecta is emplaced in a very short distance from the crater, much of it is expected to be found on or near the crater rim. Pike (1977, in Melosh, 1989) found that small lunar craters had rim heights equal to about 4 % of the crater diameter following the formula:

\[ h_R = 0.036D^{1.014} \]

where \( h_R \) is the rim height and \( D \) is the diameter of the crater (both in meters). Given a diameter of approximately 2700 meter for the original Ritland crater, the calculated rim height would equal 109 meters.

The rim height is not entirely made up of ejecta. Approximately half of the height is owed to the structural uplift of the underlying pre-impact surface. This uplift is created by plastic deformation of the rocks which dies off rapidly away from the crater. Another contribution to the rim height are breccia filled dikes in the crater walls. These are formed by injection of crushed basement caused by horizontal pressure differences during crater formation.

The ejecta at the top of the rim is thrown out of the crater at very low velocities and the original stratigraphy may be preserved in the ejecta layer. However, as the material in the lowest part of the excavated crater is thrown out last, the ejecta stratigraphy on the rim is expected to be inverted. If little or no collapse of the crater rim occur, an overturned fold may also be present.

Another feature associated with the rims are giant blocks of rock, representing the last material to leave the crater. The blocks on the rims are usually the largest of all the ejected material. A study by Moore (1971, in Melosh, 1989) on blocks on lunar craters has shown a relationship between the maximum block size and the diameter of the crater:

\[ l_b \sim (0.1 \text{ to } 0.3)D^{2/3} \]

where \( l_b \) is the maximum size of the block and \( D \) is the crater diameter (both in meters). Melosh (1989) points out, however, that this relationship is quite crude and that observed block sizes may differ from this relationship by a factor of two, depending on parameters such as rock strength. In the circumference of the Ries crater rim, mega-blocks up to 2 km in size have been reported (Dennis, 1971; von Engelhardt, 1990). These are almost ten times larger than predicted by the relationship above.

Ejecta fragments are found in all sizes, ranging from blocks tens to hundreds of meters in size down to micron-sized particles. According to Melosh (1989), fragment sizes are expected to decrease away from the crater, which is supported by observations outside the Meteor crater.
and the Ries structure. He further points out that distal ejecta on average is more shocked (or even melted) than proximal ejecta as ejecta transported farther out originates from the shallowest and more shocked part of the excavated crater.

Impact angles have a great influence on the distribution of ejecta, whereas the crater shape remains the same for most oblique impacts with the exception of very low angle impacts (Melosh, 1989). According to Gault and Wedekind (1978), the ejecta deposits display axial symmetries for impact angles down to at least 45°. For impact angles lower than 45°, ejecta deposits become asymmetric, and for angles lower than 30°, “forbidden zones” without ejecta develop. The shape of the ejecta deposits around craters may be used as a diagnostic feature for recognizing oblique craters and determining the direction of impact (Pierazzo and Melosh, 2000).

2.4.5 Fluidization of ejecta

Ballistic sedimentation explains how ejected material may move farther out from the crater as a ground-hugging debris flow after striking the ground. The magnitude of movement, however, seems to be marginal on bodies such as the Moon and Mercury. On Mars, on the other hand, indications of flow has been reported by many workers (Carr et al, 1977; Mouginis-Mark, 1981; Barlow, 2006). Such features with a fluidized appearance include:

- A flow pattern of ejecta around obstacles such as hills and older craters
- “Shadow zones” behind obstacles essentially free of ejecta
- Lack of ejecta on top of many obstacles
- Strong radial pattern of ejecta deposits
- Thickening outward ejecta deposit
- Buildup of ejecta at the end of ejecta blankets (“ramparts”)
- Larger radial extent of continuous ejecta blanket

which all supports the theory first suggested by Carr et al. (1977) that the ejecta configuration was produced by flow. They characterized it as a thin, dense ground-hugging flow based on these observations.

The more fluidized appearance of ejecta blankets on Mars compared to other bodies can be explained by the presence of subsurface volatiles (water, CO₂ and methane) in the target rocks and a thin atmosphere. The volatiles, especially water, are thought to greatly enhance the mobility of the ejected debris making it comparable to terrestrial mudflows (Melosh, 1989). The ejecta blanket may thus extend farther than a “dry” ejecta blanket would. The terrestrial mudflow analog also explains the terminal ridge or rampart at the end of the ejecta blankets found on Mars. It should be noted that craters on Mars smaller than about 5 km in diameter often do not exhibit this morphology. This can be explained by the fact that the volatile-rich zones in target rocks on Mars often are found a few hundred meters below the surface. Craters shallower than this would not penetrate this zone and thus the ejecta is expected to be “dry”.

The presence of a thin atmosphere is also considered to control the ejecta distribution around
craters on Mars (Melosh, 1989; Komatsu et al., 2007; Barlow, 2009). An impact-induced turbulence may affect the finer-grained ejecta material, making it either fall short of their ballistic range or be transported farther out by a base-surge-type density current. The low pressure found behind the ejecta curtain will eventually be filled by an inward-directed wind that may transport some of the fines back towards the crater. Schultz and Gault (1979 in Melosh, 1989) suggests that the turbulence also may explain the terminal ridges. They believe that the presence of volatiles still plays a key role in the Martian ejecta blanket deposition.

Fluidized ejecta blankets have also been reported around impact craters on Earth. The Lonar crater, India, described in appendix 5, has an ejecta configuration affected by the presence of volatiles. The ejecta distribution diverge from the expected ballistic model and ends in a terminal rampart, clearly showing the ejected debris were fluidized at the time of emplacement.

### 2.4.6 The presence of water

The presence of a water layer at the site of impact, such as a shallow sea, is likely to influence the distribution of ejecta. The water column can be recognized as a part of the impact target. The bolide will then penetrate deeper compared to a land target impact as the uppermost water column is less dense and has less strength than the underlying rocks. Disregarding the water column, the target rocks beneath will get less penetrated compared to a land target impact. As the ejecta is mainly derived from the upper third of the transient crater (Melosh, 1989), a larger fraction of the ejecta from a marine-target impact would be water, and a lesser amount of the ejecta would be rocks compared to a land target impact.

The availability and incorporation of water within the ejecta curtain most likely leads to fluidization of the ejecta. Ormø and Lindström (2000) suggested that this could explain the greater extent of ejecta deposits for the Lockne crater, Sweden compared to most land-target craters.

Shuvalov and Dypvik (2004) argued that for a water depth comparable to or larger than the size of the impacting bolide, the ejecta expansion would be restricted by both the wall of the transient water cavity as well as the water surge. In this case, no distal ejecta would be expected to be found. They noted that for impacts into very shallow seas (water depth less than the diameter of the impacting bolide), the solid ejecta may have higher escape velocity than for land-target impacts. This is caused by the expected presence of volatile-rich (wet) sediments which is more susceptible to vaporization and expansion.

As the modification stage of the crater formation begins, debris-loaded water starts to rush back into the dry, excavated crater (Ormø and Lindström, 2000). The collapse of the water mass starts near the base, and forms a centripetally moving bottom current, which may even affect distal ejecta (Dypvik and Jansa, 2003). Other reworking processes outlined by Dypvik and Jansa (2003) in association with marine-target impacts are the formation of mega-tsunamis, strong currents and high waves. The bolide striking the sea-floor may also generate earthquakes leading to fluidization of sediments, slope instability, slumping, slides, turbidite generation, debris-flows etc. Consequently, ejecta deposits may be quite complex and heterogeneous units.
3. Geological setting

The Ritland impact structure originally formed a circular depression in the sub-Cambrian peneplain. It is 2.7 km in diameter and about 350 meters deep, located in a mountainous area in Hjelmeland municipality, Rogaland county in south-western Norway (Figure 1.1B and Figure 4.1.1A). The crater has been filled in by sediments during Cambrian, and later covered by Caledonian thrust nappes (Riis et al., 2011). Several episodes of glacial erosion have later removed part of the thrust nappes and the infill sediments. The result is a well exposed three dimensional impact structure. Within the structure, brecciated rocks, sedimentary crater infill and melt-bearing rocks are exposed. Although the age of the crater is not certain, crater-filling shales contain fossils dated to the Middle Cambrian, thus providing a minimum age of the impact event. Ejected material has been found in a layer outside the impact structure measuring up to more than 3 meters in thickness. The ejecta layer originally surrounded the crater, but due to erosion it seems to be restricted to some localities east of the present day structure.

3.1 Target rocks

3.1.1 The crystalline basement rocks

The flat to slightly undulating sub-Cambrian peneplain is today well exposed many places in the mountainous areas of southern Norway (Ramberg et al., 2006). The peneplain can be observed a few kilometers east of the impact structure as a distinctively flat morphological surface (Figure 3.1.1.1 and marked with a light grey color in the geological map in Figure 1.1A).

![Figure 3.1.1.1: The exposed, flat sub-Cambrian peneplain in the Melands Grønahei area east of the Ritland structure. The Rekkjebrotet hills are shown in the background.](image)

In the southern part of Norway, Precambrian rocks originate from the Fennoscandian shield and are composed mainly of granitic gneisses (Nordgulen and Andresen, 2006). These rocks were formed between 1800 and 900 Ma during periods of volcanism, deformation and orogenies, with alternating periods of erosion and sedimentation.

In the Middle Proterozoic (1130 – 900 Ma), the Fennoscandian shield became a part of the
supercontinent Rodinia during the Sveconorwegian orogeny (Bingen et al., 2008). As the break-up of Rodinia started toward the end of Precambrian, the Fennoscandian shield was eroded and became the continent of Baltica.

The basement rocks of Baltica were exposed to extensive erosion and weathering during Neoproterozoic (Nielsen and Schovsbo, 2010), an era characterized by vast climatic changes. Global ice ages in Cryogerian caused erosion on Baltica, while the following tropical Ediacaran is characterized by severe weathering of the basement rocks (Nystuen, 2006). The result was an extensively peneplained surface known as the sub-Cambrian peneplain which marks a hiatus between the igneous and metamorphic Proterozoic rocks below and the overlying Cambro-Silurian sedimentary deposits.

3.1.2 The Early Cambrian sedimentary sequence

Figure 3.1.1.2 display the general appearance of the stratigraphy in the region. The stratigraphic column is based on work by Andresen (1982), Riis et al. (2011) and field observations by the author. The ejecta layer is marked in orange and is observed a few meters above the sub-Cambrian peneplain.

At the end of Precambrian (Neoproterozoic), rifting gave rise to continental break-up. The Scandinavian part of Baltica was earlier thought to have faced the Iapetus Ocean and the continent of Laurentia. New research (Torsvik and Cocks, 2005 in Nielsen and Schovsbo, 2010), suggests that the present-day western margin were facing the Siberian continent, separated by the Ægir Ocean.

The split up led to drowning of vast areas of the continent, known as the Cambrian transgression. The coastline retreated tens and hundreds of kilometers landward in the low relief landscape. This resulted in the creation of a very wide marginal epicontinental setting, called the Baltoscandic margin (Bjørlykke and Englund, 1979; Andresen, 1982; Nielsen and Schovsbo, 2010). It is suggested by Thickpenny (1984) to have extended at least 800 km in the present east-west direction, covering large areas of Scandinavia.

The transgression created a wave-dominated sea with deposition controlled largely by storms (Nielsen and Schovsbo, 2010). The oxygen content at the sea bottom was relatively low during this period, especially from Mid-Cambrian and onwards. The transgression is thought to have occurred in pulses, and followed by a short, but significant progradation. In the late Early Cambrian, extensive flooding greatly reduced the clastic supply, characterized by a condensed deposition of shales with authigenic minerals being more dominant.

A basal conglomerate unit is found widespread in Scandinavia and the Baltic region overlying the sub-Cambrian basement (Figure 3.1.1.2; Nielsen and Schovsbo, 2010). This layer is also present in the Hardangervidda region, south-western Norway where it reaches a thickness of 0,5 meters (Andresen, 1982; Haremo, 1987), consisting of reworked, locally derived material. Andresen (1982) suggested it to be remnant material due to weathering of the basement rocks which underwent little or no transportation before deposition. The quartzitic, feldspatic and sometimes gneissic clasts are 1 – 20 mm in size and poorly sorted. The conglomerate is matrix-supported and the matrix consist mostly of silt or clay. Haremo (1987) found generally phosphorite as a part of the matrix in some localities. At Ritland, this conglomerate
A sandstone bed with a thickness of up to a few meters overlying the basal conglomerate marks the onset of the Cambrian transgression on the Baltoscandic margin (Figure 3.1.1.2). In the Hardangervidda area, Haremo (1987) described this unit as a 2 meter thick quartzite bed, blueish in color. East of the Ritland impact structure, the sand bed is thinner and contains more silt. Some meters of clayey and sandy siltstone is observed overlying this bed (this paper).

In the late Early Cambrian, the clastic supply greatly diminished, and by the Middle Cambrian, the Alum Shale Formation was deposited. The late Early and Middle Cambrian depositional environment is characterized by high organic production, very low clastic supply and restricted water circulation (Bjørlykke and Englund, 1979; Thickpenny, 1984; Gee et al., 2008; Nielsen and Schovsbo, 2010). Black shales starts to dominate the stratigraphy at Ritland just above the ejecta layer, see figure 3.1.1.2.

The palaeogeographic position of the Baltoscandic margin can apply to the modern shallow marine areas positioned west of continents at high latitudes such as SW Africa and Peru and Chile (Brasier, 1980) as an analogue. Phosphorite deposition was also widespread on the Baltoscandic platform in the Cambrian, and phosphorite is found through most of the Cambrian deposits at Ritland.

### 3.2 Post impact events – The Caledonian Orogeny

The Caledonian Orogeny was a result of the closure of the Iapetus Ocean and the following collision between Baltica and Laurentia in the mid Silurian to early Devonian (Gee et al., 2008). The deformation during the orogeny includes three major episodes of regional folding and thrusting (Andresen 1982; Andresen and Færseth, 1982; Haremo, 1987). During these events, allochthonous structural units originating from the Baltoscandian margin and platform were transported up to several 100 kilometers toward southeast. These nappe units were emplaced onto Precambrian basement and the Lower Paleozoic sedimentary cover rocks (Figure 3.1.1.2). The soft clay-rich lower Paleozoic sedimentary deposits at Ritland acted as a thrust plane and have been severely altered and/or removed in many areas. Luckily, much of the ejecta layer around the crater were preserved, and later, the nappe units partly protected the impact structure and the ejecta layer against erosion.

*Figure 3.1.1.2: The regional stratigraphic column based on Andresen (1982), Riis et al. (2011) and field observations by the author.*
4. Methods

4.1 Field logging, mapping and sampling

The field logging, mapping and sampling took place at Ritland (Figure 4.1.1A and B) during two trips in the summer of 2010. The first field trip was performed from the 11th to the 17th of June, and the second from the 3rd to the 12th of August. The field work was conducted at the Melands Grønahei (Locality reference: “MGH”), Raudkleiv (“RAU”) and Rekkjebroten (“REK”) localities. These localities are all relatively close to the Melands Grønahei tourist cabin owned by Den Norske Turistforeningen (“DNT”). The cabin, situated directly on the sub-Cambrian peneplain, was used for accommodation most of the days in field.

Figure 4.1.1: A) Map of the area east of the Ritland impact structure. The red circle marks the approximate extent of the crater. The green square display the study areas shown in B), and the small blue circle marks the location of the DNT tourist cabin. The DNT tourist paths are marked by red dashed lines. B) Overview of the study areas east of the Ritland impact structure. The logged sections is marked by the yellow circles. The ejecta layer visible in outcrops is marked in orange (exaggerated width). The red area is the approximate extent of the Melands Grønahei study area. The RAU 2 site is about 1,45 kilometers from the crater rim.
Figure 4.1.1B shows the working areas with all logged localities marked by yellow circles. The ejecta layer observed in outcrops is marked in orange. The size of the ejecta layer is exaggerated in this map for clearance. The approximate extent of the Melands Grønahei working area is marked in red. Overview photos from the working areas are also presented in Figure 4.1.2.

The MGH area is generally very flat (see i.e. Figure 3.1.1.1), exposing the sub-Cambrian peneplain. The degree of exposure is very good with little vegetation. In some places, the basal conglomerates were found overlying the peneplain. Descriptions and samples from the MGH area are mostly related to the conglomerates. In addition, some sandy silt benches were found overlying the conglomerates. All of the MGH localities were situated within an area measuring about 1.7 km x 0.3 km (Figure 4.1.1A and 4.1.2B).

The REK area is found on a north-south directed hillside facing eastwards with partial exposure of the stratigraphy (see Figure 4.1.2B). The hill stretches up to about 10 - 15 meters above the peneplain, the uppermost part is often completely covered by marsh which restricted logging and sampling possibilities. Two localities, REK-1 (south) and REK-2 (north), were logged and sampled from this area. In addition, a small exposure of the ejecta layer (sample REK-3-1-10) were found close to REK-1.

The RAU area is a terraced east-west directed hillside facing towards south (Figure 4.1.2A). The terraces represent different lithologies; the base of the lowermost bench was often found to represent the top of the peneplain whereas its top in many cases conveniently represented the top of the ejecta layer. Four localities in this area were logged and sampled; RAU-1, RAU-2, RAU-3 and RAU-4. In addition, shales found close to RAU-1 were sampled as RAU-5. The distance between RAU-1 (farthest to the east) and RAU-2 (farthest to the west is about 2 km with RAU-3 and RAU-4 positioned in between. The exposures in this area are generally good, although the boundary between the basement rocks and the overlying sedimentary rocks was only observed in RAU-3.

The localities were logged on sedimentological logging sheets with a 1:50 scale. Hammer was used for sampling and for preparing fresh exposures. Hand specimens were studied by hand-lens for sedimentological structures, as well as grain sizes which were classified according to the Wentworth grain size scale (“φ scale”; Wentworth, 1922). Orientation of bedding and sedimentological structures were measured by compass. All sections were in addition documented by photos. GPS was used to determine the exact position of each locality (Table 4.1.1).

<table>
<thead>
<tr>
<th>Locality</th>
<th>GPS coordinates</th>
<th>Distance from crater centre (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raudkleiv 2</td>
<td>32V N354766 E6569462</td>
<td>2695</td>
</tr>
<tr>
<td>Raudkleiv 3</td>
<td>32V N356307 E6567954</td>
<td>3373</td>
</tr>
<tr>
<td>Raudkleiv 4</td>
<td>32V N356854 E6568182</td>
<td>3842</td>
</tr>
<tr>
<td>Raudkleiv 1</td>
<td>32V N357365 E6568068</td>
<td>4366</td>
</tr>
<tr>
<td>Rekkjebroten 1</td>
<td>32V N357953 E6568853</td>
<td>4855</td>
</tr>
<tr>
<td>Rekkjebroten 2</td>
<td>32V N358227 E6569644</td>
<td>5167</td>
</tr>
</tbody>
</table>

Table 4.1.1: GPS coordinates and distance from the crater centre for each of the logged localities.
Samples were collected from all localities. There was no fixed interval between the samples, partially governed by the degree of exposure and partially to get representative lithologies. Prioritized sampling was done where lithologies were changing and where the ejecta layer were found. The samples were given unique names providing information starting with area, then locality, sample number and year. As an example, sample RAU-1-5-10 is collected from the Raudkleiv area at locality number one. The sample is the fifth sample from this locality and it was collected in the field season of 2010.

The author logged under supervision of Professor Henning Dypvik with assistance by Fridtjof Riis and Elin Kalleson both in June and August. Additional field assistance was provided by Lotta Kagg during the August field trip.

Figure 4.1.2: A) Overview of the Raudkleiv area. B) Overview of the Rekkjebrotet area in the background and parts of the Melands Grønahei area in the front. Logged sections are marked in yellow, the basement in red and the ejecta layer in orange. The orientations of the pictures are marked in the upper right corners.
4.2 Petrographical analysis

The petrographical analysis has been performed using thin sections, XRD, SEM and CL.

4.2.1 Thin section

Thin sections were prepared by Lars Kirkesæther in Petro-Sec at the Institute for Energy Technology (Institutt for energiteknikk). Small epoxy impregnated rock slabs polished down to a thickness of 30 µm were glued to a 2,7 cm x 4,7 cm glass slide.

Out of a total of 29 prepared thin sections, 23 were studied in detail under a petrographic microscope in order to support data from logging, improve the descriptions of the lithologies and to look for PDFs and other shock metamorphic features in the ejecta layer. The following attributes from the thin sections were noted: lithology, grain contact/framework configuration, structures, average and maximum grain size, sorting, grain shape and other notable features. Sorting were determined after Longiaru (1984), and roundness after Powers (1953). Grain sizes were determined based on the Wentworth grain size scale (Wentworth, 1922):

- Clay: < 0,004 mm.
- Silt: 0,004 – 0,063 mm.
- Very fine sand: 0,063 – 0,125 mm.
- Fine sand: 0,125 – 0,25 mm.
- Medium sand: 0,25 – 0,5 mm.
- Coarse sand: 0,5 – 1 mm.
- Very coarse sand: 1-2 mm.
- Granule: 2 – 4 mm.
- Pebble: 4 – 64 mm.
- Cobble: 64 – 256 mm.
- Boulder: > 256 mm.

The results from the thin section investigation are summarized in Table iii in appendix 3.

Universal stage (“U-stage”) microscope analysis was performed in order to investigate the crystallographic orientations of the PDFs. Only four of a total of nine PDFs were investigated due to the position of some of the PDFs, with the latter five being located at the edge of the thin section glass slides. The procedure of investigation followed the standard technique delineated by Ferrière et al. (2009). Figure 4.2 represent the new stereographic template (NSPT) used in this study. Each circle has a 5° envelope of error, marking the position of the most common poles to PDF planes. The results from this study are presented in section 6.1.3.
4.2.2 Scanning Electron Microscopy (SEM)

The scanning electron microscope (SEM) lets the user acquire highly magnified images of the surface of a sample (Goldstein, 2003). An electron beam is created by heating a wolfram filament and accelerating the produced electrons. The beam is then focused onto the sample in a rectangular (raster) pattern. The electrons interact with atoms in the sample which produce X-rays, back-scattered electrons (BSE), secondary electrons (SE), cathodoluminescence (CL) and heat.

By registrating the back-scattered electrons, an image can be created, revealing the texture, topography and composition of the scanned sample surface. Heavy elements reflects a higher share of electrons than lighter ones (about 50% of the electrons directed to uranium is back-scattered vs. 10% for carbon). Minerals with heavy elements thus appear brighter on the image created. BSE is the most commonly used mode for imaging.

CL is the emission of light from excited atoms in the sample returning to their ground state. This can for instance be used to study the interior texture of a mineral such as fractures and zoning. It may also be used to identify certain mineral groups such as phosphates and carbonates. See section 4.2.3 for a more detailed description.

SE are electrons sourced from the outermost shell of the atoms in the sample. They have a relatively low energy and comes from only the surface of the sample. SE can thus be used for topographic (three-dimensional) imaging and have higher resolution than BSE.

The different wavelengths and wave energies of the emitted X-rays are specific for each element. By using electron dispersive X-ray spectroscopy (EDS), it is possible to immediately identify the chemical composition and abundance of for instance a mineral. This method is called “point&ID” and is an integrated part of the SEM software.

Before analyzing, the thin sections were carbon-coated to improve the quality of the image.
Non-conductive samples may accumulate a charge when scanned by the electron microscope which may cause errors and disturbances on the image.

4.2.3 Cathodoluminescence (CL)

Cathodoluminescence analysis was performed at the Department of Geosciences, University of Oslo using a Nikon optical microscope with a mounted CITL (Cambridge Image Technology Limited) electron gun and vacuum pump. A total of 12 samples from facies associations 1, 2 and 3 were investigated using the instrument. The electron gun was set at approximately 10 – 12 kV and 500µA.

Material bombarded by a stream of electrons from an electron gun will emit material and energy (see the description of SEM analysis). Amongst those are photons, “packets of light”, which is a phenomenon called cathodoluminescence (“CL”; Boggs and Krinsley, 2006). Luminescence has its origin in molecular distortions of crystallized material, such as minerals (Nickel, 1978). Although luminescence may occur in many minerals, the voltage and current may be tuned in order to only investigate certain minerals. In this work, the focus was on the carbonate and apatite in the samples. Depending on factors such as host rock, degree of metamorphism and trace elements within a mineral, the minerals will luminesce with characteristic colours. In this analysis, the carbonates were found to be reddish, while the apatite was yellow. The results from the analysis are presented in section 6.4.

4.3 X-ray diffraction (XRD)

X-ray diffraction (XRD) analysis were used to identify the mineralogical composition of the samples. This is possible as the structure of each mineral inhibit specific crystallographic orientations which give rise to characteristic peak positions on the XRD diagram (Morris et al., 2008). The peaks can be interpreted both visually and with the use of special software, for instance MacDiff (Petschick, 2011). The mineral content may be semi-quantified based on the intensity of the different peaks, but this is a complicated method which only provides a rough estimation of the percentages of the different minerals. Thus, the results are referred to as XRD percentages.

A total of 27 samples collected in the field were prepared for XRD analysis as followed:

- The samples were crushed using a mortar and pestle.
- The crushed material (about 8-10 grams) of each sample then underwent powderization in a steel slinging mill for approximately 2 minutes. Some of the quartz-rich and coarse-grained samples required several minutes.
- Finally, about 2 grams of the powder were packed into XRD sample holders, ready for the analysis.
- The XRD analysis were conducted at the Department of Geosciences, University of Oslo using a Phillips X’Pert MPD.

23 of the samples were investigated further, see Table 4.2.1. The samples from the ejecta layer
are marked in bold. The results from the XRD analysis are summarized in Table iv in appendix 4.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Height above basement</th>
<th>Sample</th>
<th>Height above basement</th>
<th>Sample</th>
<th>Height above basement</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGH-2-1-10</td>
<td>0 - 0,3 m</td>
<td>RAU-1-2-10</td>
<td>3,0 m</td>
<td>RAU-1-4-10</td>
<td>8,5 m</td>
</tr>
<tr>
<td>MGH-10-3-10</td>
<td>0 – 0,3 m</td>
<td>REK-2-4-10</td>
<td>3,8 m</td>
<td>RAU-2-6-10</td>
<td>8,9 m</td>
</tr>
<tr>
<td>RAU-3-1-10</td>
<td>0,5 m</td>
<td>RAU-1-3-10</td>
<td>4,0 m</td>
<td>REK-1-9-10</td>
<td>9,0 m</td>
</tr>
<tr>
<td>RAU-1-1-10</td>
<td>1,0 m</td>
<td>RAU-3-3-10</td>
<td>5,0 m</td>
<td>RAU-1-7-10</td>
<td>10,7 m</td>
</tr>
<tr>
<td>RAU-2-5-10</td>
<td>1,5 m</td>
<td>REK-1-5-10</td>
<td>6,2 m</td>
<td>RAU-4-3-10</td>
<td>12,0 m</td>
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<td>RAU-3-2-10</td>
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<td>REK-1-8-10</td>
<td>8,0 m</td>
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<td></td>
</tr>
</tbody>
</table>

Table 4.2.1: Samples prepared for XRD analyses and their stratigraphical position above the basement following the general stratigraphical log in Figure 5.1.7.

The semi-quantification of the mineral content in the samples was carried out by digital processing of the XRD data using the MacDiff software (Petschick, 2011). This program was used for establishing a baseline of intensity in each of the samples, followed by identifying the target peaks (see Table 4.2.2). The peak areas were then calculated by multiplying the peak top to baseline with the width at half the peak height. The results are shown in Table iv in appendix 4 containing the XRD percentage of the different minerals for all the samples.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>d – value (Å)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hematite</td>
<td>2,70</td>
<td>0,02</td>
</tr>
<tr>
<td>Pyrite</td>
<td>2,71</td>
<td>0,025</td>
</tr>
<tr>
<td>Apatite</td>
<td>2,77</td>
<td>0,025</td>
</tr>
<tr>
<td>Ankerite</td>
<td>2,90</td>
<td>0,025</td>
</tr>
<tr>
<td>Calcite</td>
<td>3,03</td>
<td>0,02</td>
</tr>
<tr>
<td>Jarosite</td>
<td>3,09</td>
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</tr>
<tr>
<td>Albite</td>
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<td>Microcline</td>
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<td>Goethite</td>
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<tr>
<td>Quartz</td>
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</tr>
<tr>
<td>Gypsum</td>
<td>7,56</td>
<td>0,025</td>
</tr>
<tr>
<td>Muscovite / biotite</td>
<td>10,0</td>
<td>0,1</td>
</tr>
</tbody>
</table>

Table 4.2.2: The peak value (d-value) and range of the targeted minerals. The hematite, jarosite, goethite and gypsum are considered products formed by weathering.
5. Sedimentological description

The sedimentological description is mainly based on field logs and supported by petrographical analysis (thin section, XRD, SEM and CL) as well as photographs and other field observations. Six sections were logged in detail in the Rekkjebrotet and Raudkleiv areas east of the crater (Figure 4.1.1). Some outcrops close to the logged sections were also studied to fill out blank spots in the logs. In addition, the basal conglomerate and the overlying sandy siltstone were studied in the Melands Grønahei area. Figure 4.1.2 presents partial overviews of the working areas with some of the logged sections marked in yellow (RAU1, RAU3, RAU4 and REK2) and the ejecta layer in orange. The basement is marked by a red color.

According to the International Commission of Stratigraphy (2011), a stratigraphic unit is defined as “A body of rock established as a distinct entity in the classification of the Earth's rocks, based on any of the properties or attributes or combinations thereof that rocks possess.” Following this definition, four stratigraphic units have been proposed in this work; Unit A is suggested to represent the basal conglomerates, unit B the overlying sandy and clayey siltstones, unit C the ejecta bed and unit D the overlying silty shales. These units are mainly classified based on their lithological properties.

5.1 Stratigraphical logs

In this section, the logged sections are presented. The legend in Figure 5.1.1 is applicable for all the logs. A correlation between the logs has been attempted and is presented in Figure 5.1.7. In addition, a general stratigraphy (Figure 5.1.8) is presented at the end of this section to illustrate common features which are repeatedly observed in field and / or in the logs and to classify the stratigraphy into stratigraphical units and facies associations. The ejecta layer, where present, is marked on the logs with thick lines.
Figure 5.1.1: The sedimentological log of Raudkleiv 1 section and legend. The samples gathered from this locality are listed to the right of the log. Numbers given in italic show samples studied in thin section, bold show samples studied by XRD, while bold italic indicate samples studied both in thin section and by XRD.
Figure 5.1.2: The sedimentological log of Raudkleiv 2. The samples gathered from this locality are listed to the right of the log. Numbers given in italic show samples studied in thin section, bold shows samples studied by XRD, while bold italic indicate samples studied both in thin section and by XRD. Note that the exact position of sample RAU-2-1-10 is not accounted for, but it was collected from the ejecta layer.
Raudkleiv 3 (RAU-3)

Figure 5.1.3: The sedimentological log of Raudkleiv 3. The samples gathered from this locality are listed to the right of the log. Numbers given in italic show samples studied in thin section, bold show samples studied by XRD, while bold italic indicate samples studied both in thin section and by XRD.
Figure 5.1.4: The sedimentological log of Raudkleiv 4. The samples gathered from this locality are listed to the right of the log. Numbers given in italic show samples studied in thin section, bold show samples studied by XRD, while bold italic indicate samples studied both in thin section and by XRD.
Figure 5.1.5: The sedimentological log of Rekkjebrotet 1. The samples gathered from this locality are listed to the right of the log. Numbers given in italic show samples studied in thin section, bold show samples studied by XRD, while bold italic indicate samples studied both in thin section and by XRD.
Figure 5.1.6: The sedimentological log of Rekkjebrotet 2. The samples gathered from this locality are listed to the right of the log. Numbers given in italic show samples studied in thin section, bold show samples studied by XRD, while bold italic indicate samples studied both in thin section and by XRD.
Figure 5.1.7: Correlation between the logs. The ejecta layer (red), calcite-rich layer (blue) and basal conglomerates (green) have been correlated. Missing elements are marked by a question mark. The distance between the sections are marked between the locality names in the headline.
General stratigraphical expression

Figure 5.1.8: A simplified composite log expressing the general stratigraphy in the area. It is based on all available logs, thin sections and field observations. The log reflects the thickest exposure of the ejecta layer as observed in locality Raudkleiv 3. The position of the different facies associations (see section 5.3) is marked on the right side of the log.
5.2 Lithological facies description

Facies is a distinct body of rock that has formed under a certain depositional setting within a restricted area (Boggs, 2006). Moreover, Moore (1949, in Boggs, 2006) described facies as “any areally restricted part of a designated stratigraphical unit which exhibits characters significantly different from those of other parts of the unit.” In this work, nine facies have been recognized by their distinct texture, lithology and/or structures using field logs and thin sections information. Boundaries between the respective facies have been set based on abrupt changes in their characteristics reflecting shifts in the depositional environment. These facies have then been categorized into five facies associations. The facies with their respective characteristics and their presence within the simplified stratigraphical column (Figure 5.1.7) are listed in Table 5.2.1, and further described in the text. The facies may however be found at different heights in the different localities. The exact position of the various facies in each of the localities is presented in Table i in appendix 2.

Lithological classification of the different facies is done based on the classification schemes of Folk (1974, see Figure 5.2.1), as well as on the mineralogical and structural characteristics. The thickness of both the facies and the facies associations are determined based on all the logged sections.

<table>
<thead>
<tr>
<th>Facies No.</th>
<th>Facies</th>
<th>Grain size</th>
<th>Physical/biological structures</th>
<th>Facies association / height above basement</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Conglomerate</td>
<td>Silt to pebble</td>
<td>Matrix-supported, mostly rounded clasts.</td>
<td>FA1 / 0.0 - 0.3 m</td>
</tr>
<tr>
<td>II</td>
<td>Laminated siltstone / sandstone</td>
<td>Silt to medium sand</td>
<td>Good sorting and laminated</td>
<td>FA2 / 0.3 – 1.0 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FA2 / 3.0 – 3.7 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FA2 / 4.7 – 5.1 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FA2 / 6.0 – 6.4 m</td>
</tr>
<tr>
<td>III</td>
<td>Slightly bioturbated siltstone with lamination and lenses</td>
<td>Clay to silt</td>
<td>Clayey, laminated siltstone showing some evidence of bioturbation and water escape</td>
<td>FA2 / 1.0 - 1.5 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FA2 / 1.5 – 3.0 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FA2 / 3.7 – 4.7 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FA2 / 5.1 – 6.0 m</td>
</tr>
<tr>
<td>IV</td>
<td>Highly bioturbated siltstone</td>
<td>Clay to very fine sand</td>
<td>Moderate to poor sorting, faint laminae and lenses</td>
<td>FA2 / 6.5 – 7.2 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FA2 / 9.2 – 9.8 m</td>
</tr>
<tr>
<td>V</td>
<td>Soft sediment deformed siltstone</td>
<td>Clay to very fine sand</td>
<td>Syn-sedimentary fold, flame structures</td>
<td>FA2 / 7.2 – 7.6 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FA2 / 8.3 – 9.2 m</td>
</tr>
<tr>
<td>VI</td>
<td>Calcite-rich siltstone</td>
<td>Clay to very fine sand</td>
<td>Heavily bioturbated, faint laminae and lenses</td>
<td>FA2 / 7.6 – 8.2 m</td>
</tr>
<tr>
<td>VII</td>
<td>Silty sandstone</td>
<td>Silt to very fine sand</td>
<td>Upward coarsening</td>
<td>FA2 / 8.2 – 8.3 m</td>
</tr>
<tr>
<td>VIII</td>
<td>Ejecta layer: conglomerate with clayey to sandy matrix</td>
<td>Clay to boulder</td>
<td>Matrix-supported, undulating base, clast size decrease upward, sand content increase upward. Slightly folded in top.</td>
<td>FA3 / 9.8 – 13.1 m</td>
</tr>
<tr>
<td>IX</td>
<td>Silty shale</td>
<td>Clay to silt</td>
<td>Fissile shale, pyrite-rich</td>
<td>FA4 / 14.0 – 14.5 m</td>
</tr>
</tbody>
</table>

Table 5.2.1: Nine facies recognized in the stratigraphy with their respective characteristics, facies association and height above the basement.
I  

**Conglomerate** – this facies occur in logs RAU-3, REK-1 and REK-2. In addition, this basal conglomerate has been observed multiple places in Melands Grønaheii (Figure 5.2.2). It forms a layer up to 30 cm in thickness overlying the basement rocks. It is patchy, occurring in low relief “pockets” on the peneplain. The conglomerate consist mainly of gneiss, feldspar and dark quartz clasts in a silty to sandy matrix. The conglomerate is matrix-supported. Most clasts are rounded and quartz clasts are usually more rounded than the gneiss clasts which may be sub-angular. Most clasts are 0.5 – 5 cm in size. Smaller and larger clasts are however also observed. They represent about 5-30 % of the total volume of the conglomerate.

![Conglomerate overlying the basement. The largest clasts are generally rounded and consist of dark quartz.](image)

II  

**Laminated siltstone / sandstone** – this facies occur in four different levels in the stratigraphical column from the localities RAU-1, RAU-2, RAU-3, REK-1 and REK-2: 0,3 – 1,0 m (upwards fining; Figure 5.2.3); 3,0 – 3,7 m (upwards coarsening); 4,7 –
5.1 m (no grading) and 6.0 – 6.4 m (no grading). The grain size range from silt to medium sand.

Figure 5.2.3: Laminated normally graded silty sandstone overlying the basal conglomerates at the Melands Grønahei area.

### III  Slightly bioturbated siltstone with lamination and lenses
This facies is recognized at three levels in the stratigraphy in all of the logs; 1.5 – 3.0 m (upwards coarsening); 3.7 – 4.7 m (upwards coarsening) and 5.1 – 6.0 m (no grading). The two lowermost levels have a relatively high clay content in the bottom, about 30 – 55 %. There are also observed slickensides at these levels. The third level contains very little clay. The grain size range from clay to silt with silt generally being the most dominant size. All the units show some evidence of bioturbation and possible water escape structures, however, the lamination is still visible.

### IV  Highly bioturbated siltstone
This facies represents two levels in the stratigraphical column from all localities except RAU-4; 6.5 – 7.2 m and 9.2 – 9.8 m. The lowermost level is faintly upwards coarsening whereas the second level shows no grading. The second level contains more clay than the lowermost. The grain size range from clay to very fine sand. The sorting is moderate to poor, and only faint laminae and/or lenses are visible.

### V  Soft sediment deformed siltstone
This facies is observed at two levels in the stratigraphy at locality RAU-2; 7.2 – 7.6 m and 8.3 – 9.2 m. Structures observed at these two levels include syn-sedimentary fold, convolute lamination and flame structures (Figure 6.1.2.1 and 6.1.2.2). Both levels display lamination and well sorting, the uppermost level is however slightly bioturbated. The grain size range from clay to very fine sand.

### VI  Calcite-rich siltstone
This facies is found at one level in the stratigraphical column in logs RAU-3, REK-1 and REK-2 (Figure 6.1.2.3); 7.6 – 8.2 m. The calcite content is estimated to be 10-20 %. The grain size vary from clay to very fine sand, and silt is
dominating. The sorting is moderate to poor. The rock unit is heavily bioturbated with only faint lamination.

VII  **Silty sandstone** – this facies is represented in the stratigraphy by one thin silty sandstone unit found 8.2 – 8.3 meters above the basement rocks in localities RAU-1, RAU-2, RAU-4 and REK-1. The grain size range from silt to very fine sand, with very fine sand being the dominant grain size. No clay is apparent within the sandstone bed. The unit is upwards coarsening.

VIII  **Ejecta layer: conglomerate with clayey to sandy matrix** – this facies represent the ejecta layer found about 10 meters above the basement in all localities except REK-2. The grain size range from clay to boulder and it is matrix-supported. The base of the layer is undulating, governed by the presence of the lowermost boulders. Generally the largest boulders are found in the lowest part of the ejecta layer and the clast size decrease upwards whereas the sand content increases upwards. The clayey to sandy matrix seems to be somewhat folded around the largest boulders. In field, the observed clasts consist of gneiss, whereas smaller clasts found in thin section consist also of quartz and feldspar. The largest clasts in the lowermost part are ranging from 110 cm up to 280 cm in diameter (Figure 5.2.5E) whereas typical clast sizes range from 10 – 40 cm (Figure 5.2.4).

![Image](image_url)

**Figure 5.2.4**: Outcrop of the entire ejecta layer at locality RAU-1. A) Picture is taken from the lowermost part facing upwards. See hammer in the middle left for scale. B) A sketch of the same outcrop illustrating some of the largest exposed clasts within the ejecta layer.
Figure 5.2.5: Overview of the logged localities. The pictures are showing some of the characteristics of the ejecta layer. A) Uppermost part of ejecta layer at RAU-2 showing a jumbled ejecta deposit and a slightly folded upper part. B) Gneiss clast in matrix at RAU-4. C) Shatter cone found within the ejecta layer observed at RAU-1. D) The ejecta layer from RAU-2 as seen from above. E) The largest block observed within the ejecta layer was found at RAU-3. The block is about 2.8 meters in diameter and consist of gneiss. See hammer in the middle of the picture for scale.
At the RAU-1 locality, an ensemble of calcitic shatter cones (Figure 5.2.6A and B) was observed. In the top of the ejecta layer (Figure 5.2.5D), the largest clast measured was 25 cm in diameter. Typical clast sizes were found to be 1 – 10 cm as well as sand-sized fragments. The ejecta layer exhibits some degree of folding in the uppermost 10-20 cm (Figure 5.2.5A), and the clasts in this part are possibly imbricated.

*Figure 5.2.6A and B: Two of the shatter cones observed in the assemblage of shatter cones within the ejecta layer at RAU-1.*

**IX Silty shale** – this facies was observed close to the RAU-1 locality less than 1 meter above the observed ejecta layer. The rock unit has a minimum thickness of about 0.5 meters. Grain size vary from clay to silt with clay being dominant. The shale is fissile, rusty in color and has a high pyrite content. Slickensides and precipitated quartz were observed within the unit.
5.3 Facies associations

The facies are grouped together into facies associations based on similarities in characteristics and possible depositional environment:

- **FA1:** Basal conglomerates and breccias (0,0 – 0,3 m):
  - *Conglomerate (I)*

- **FA2:** Silt- and sandstones (0,3 – 9,8 m):
  - *Laminated siltstone / sandstone (II), Slightly bioturbated siltstone with lamination and lenses (III), Highly bioturbated siltstone (IV), Soft sediment deformed siltstone (V), Calcite-rich siltstone (VI) and Silty sandstone (VII)*

- **FA3:** Ejecta layer (9,8 – 13,1 m):
  - *Ejecta layer: conglomerate with clayey to sandy matrix (VIII)*

- **FA4:** Shales (14,0 – 14,5 m):
  - *Silty shale (IX)*

The position of the different facies in the stratigraphical column is presented in Table i in appendix 2.

FA1 consists of basal conglomerates found at several localities in the Rekkjebrotet, Raudkleiv and Melands Grønahei area. The conglomerate facies (Figure 5.2.2) was found overlying the basement rocks. The thickness of the conglomerates vary from 0 to 30 cm.

FA2 consists mainly of silt- and sandstones with minor amounts of clay. There seems to be at least two coarsening upwards units, the first from approximately 1,5 to 4,0 meters, and the second from approximately 4,0 to 6,0 meters (Figure 5.1.8). At the base of the upwards...
coarsening units, the clay content is quite high (30-50%). These parts are associated with slickensides. Most beds still exhibit lamination, but moderate bioturbation have altered some of them and in a few beds, lamination is no longer visible. Calcite were observed in field in one unit in this facies association; 7.6 – 8.2 meters above the basement rocks.

FA3 represents the ejecta layer which is included in five of the logs. In addition, it has been observed almost continuously between the Raudkleiv and the Rekkjebroet area. The ejecta layer is a clayey and silty layer with the presence of small and large clasts of mainly gneiss as well as quartz, feldspar and at least one occurrence of calcite. In locality RAU-1, an assemblage of shatter cones was found with sizes ranging from approximately 3-10 cm.

FA4 represents the silty shales facies found at one locality close to RAU-1 about 0.75 meters above the ejecta layer (Figure 5.2.7). Slickensides were observed within the 0.5 meters thick exposure.

In terms of stratigraphic units, unit A contains facies association 1, unit B contains facies association 2, units C contains facies association 3 and unit D contains facies association 4.

5.4 Ejecta layer thickness distribution

The thickness of the ejecta layer was measured in five localities. All of the observed thicknesses are minimum thicknesses, as vegetation to a variable degree, cover the layer. The results are presented in Figure 5.4.1 and plotted together with the ballistic model by McGetchin et al. (1973) using a crater diameter of 2.7 km. The ballistic model provide expected thicknesses given a ballistic mode of ejecta emplacement. The thickness observations of the ejecta layer at Ritland seems to diverge from the ballistic model.

Figure 5.4.1: The observed ejecta layer thickness distribution compared to the ballistic model by McGetchin et al. (1973). The observed thicknesses are considered minimum thicknesses, as vegetation partly covers the layer, especially in the locality farthest away from the crater.
6. Petrography and mineralogy

6.1 Thin section description

This section will present the results from the thin section analysis. A complete thin section sample list with lithological and petrographical characteristics is presented in Table iii in appendix 3.

6.1.1 Facies association 1

Three thin sections (MGH-1-2-10, MGH-14-1-10 and MGH-6-1-10) from this facies association have been studied in detail. The samples are characterized by the clasts consisting of quartz, feldspar and gneiss. The quartz clasts are generally more rounded than clasts of other lithologies, and large clasts are generally more rounded than smaller clasts. The most common grain shape is sub-rounded. The matrix consist mostly of silt and sand, although clay is also present. The most common grain contact seems to be floating grains and tangential contact, however, in MGH-14-1-10 which is more dominated by sand, both concavo-convex, tangential and sutured contacts are observed. Figure 6.1.1 shows a representative part of the conglomerate in sample MGH-6-1-10.

Figure 6.1.1: Sample MGH-6-1-10 seen in microscope. There are both quartz and feldspar clasts present, with feldspar being dominant. The rounding is clearly variable, however, rounded clasts are dominant in the sample. The matrix consist mainly of silt and sand, mostly of feldspatic composition, but also quartz and small amounts of mica. See scale in the lower right part.
6.1.2 Facies association 2

From this facies association, ten thin sections have been studied (sorted by increasing height above basement; MGH-6-2-10, REK-1-2-10, RAU-2-5-10, REK-2-3-10, REK-1-7-10, RAU-2-9-10, REK-2-7-10, RAU-2-6-10, REK-2-6-10 and RAU-4-1-10). The dominant grain size is silt, although very fine sand and clay are also present. The average sorting is moderate, and the grain shapes mostly angular to sub-angular. Most of the samples show lamination. However, the lamination is clearly disturbed by bioturbation and/or other syn-sedimentary deformations in most of the samples. Syn-sedimentary deformation structures such as syn-sedimentary fold (Figure 6.1.2.2), convolute lamination (Figure 6.1.2.1) and flame structures are especially apparent in sample REK-2-3-10 at about 3.0 meters and RAU-2-9-10 and RAU-2-6-10 at 7.5 – 8.5 meters.

There are two exceptions showing no apparent signs of bioturbation. The first exception is found in the lowermost sample (MGH-6-2-10, 0.5 meters above basement). It is collected from a silty sandstone with good lamination/bedding. The average grain size is fine sand, the sorting is well and there is no apparent bioturbation. The common grain shape is sub-angular to sub-rounded. Common grain contacts are concavo-convex and sutured.

The second exception is found in sample RAU-2-9-10 7.5 meters above the basement. This sample exhibit alternating laminae of silt and clay, and very fine sand. A syn-sedimentary fold and flame structures are present (Figure 6.1.2.2). The dominant grain size is silt, and the sorting is well to very well. The common grain shapes are sub-angular to sub-rounded and grain contacts are both long, concavo-convex and sutured. There is no visible bioturbation.

Sample REK-1-7-10 is found at 7.0 meters above the basement. Silt is the dominant grain size and the sorting is moderately well to well. Grain shapes are angular to sub-angular. The grains are mostly floating. Framboidal pyrite is found right beneath a clay-rich laminae. This lamina is fractured, and the fracture fill is parallel with bedding and consist of iron oxides. The sample is slightly laminated, and at least five coarsening upward units were identified within
the thin section.

Figure 6.1.2.2: The thin section of sample RAU-2-9-10. The syn-sedimentary fold is marked by a red rectangle, whereas some of the best developed flame structures are marked by red arrows. The size of the thin section is about 2.7 x 4.7 cm.

Sample REK-2-7-10 is the only thin section with considerable amounts of calcite present (Figure 6.1.2.3, about 10-20% of total sample). Calcite is dominating in one area of the sample, otherwise, silt-sized quartz and feldspar is dominating. Laminae and lenses are faint, the sorting is moderate to poor and the most common grain shape is sub-angular. The grains are mostly floating. Bioturbation is moderate to heavy. Two stromatolitic fragments consisting of banded layers of quartz and apatite were observed. The largest fragment was about 2 mm in length, the second 0.5 mm long. These are also described in sections 6.3 and 6.4.

Figure 6.1.2.3: This picture represents the calcite-rich part of sample REK-2-7-10. The calcite has a light green to pink color. See scale in the middle right of the picture.
6.1.3 Facies association 3

Ten thin sections from FA3, the ejecta layer, have been studied (from the lowest part and upward: RAU-3-4-10, RAU-3-5-10, RAU-1-7-10, RAU-4-2-10, RAU-2-8-10, REK-3-1-10, RAU-4-3-10, RAU-4-4-10, RAU-1-8-10. The exact position of sample RAU-2-1-10 was not accounted for). Although clasts are present in these thin sections, they primarily represent the matrix. The matrix consist of almost equal amounts of clay, silt and sand. Silt is however slightly more common, especially in the lower part of the ejecta layer. The clay and sand content seems to be increasing upwards. The average sorting is overall poor, although a couple of samples (RAU-1-7-10 and RAU-2-1-10) have moderately well to well sorting. The grain shapes are mostly angular, larger grains are often sub-angular to sub-rounded. The grains are generally floating in all of the thin sections. The dominant mineral is feldspar, followed by quartz and smaller amounts of mica, and possibly calcite.

The sample REK-3-1-10 (about 11.6 meters above the basement) thin section is represented by a gneiss clast with some matrix around and within. The matrix consist mostly of silt and the sorting is poor. The grains are mostly angular. The larger clasts are mostly gneissic, whereas smaller clasts and sand- and silt-sized grains are feldspatic and quartzitic. Some mica grains were also observed. Microcrystalline quartz is observed as rims around minerals which are missing from the sample (holes). It is also present as fracture filling.

Microcrystalline quartz is also observed scattered in samples RAU-3-4-10, RAU-4-4-10 and RAU-1-8-10. RAU-3-4-10 was collected about 10.3 meters above the basement. The most common grain size in the sample is silt and the sorting is moderate to poor. Grains are mostly angular. A stromatolitic fragment similar to those found in sample REK-2-7-10 was observed.

Figure 6.1.3.1: A quartz grain within a rock fragment from RAU-2 showing three sets of PDFs.
PDFs have been encountered in quartz grains in four of the samples; one in RAU-1-7-10, one in RAU-3-4-10, one in RAU-4-4-10, whereas four were found in sample RAU-2-1-10. Three of these four were found within a gneissic rock fragment, whereas the fourth was found in a quartz grain in the matrix. A photograph of one of the PDF containing quartz grains is presented in Figure 6.1.3.1. The PDFs found in the thin section from sample RAU-2-1-10 were measured performing U-stage analysis. One of the grains inhibited one crystallographic plane, in another grain, two planes were measured. In the latter two grains, three planes were found, giving a combined nine planes within the four grains containing PDFs. These planes were plotted in a NSPT (see section 4.2.1), and the results are given in Figure 6.1.3.2.

![Crystallographic PDF orientations](image)

**Figure 6.1.3.2:** A histogram showing the combined planes found in four PDF grains in sample RAU-2-1-10. The numbers of the crystallographic planes (CP) correspond to the template in Figure 4.2. The crystallographic planes correspond to the following Miller indices: CP2 = \{10-13\}, CP3 = \{10-12\}, CP6 = \{11-22\} and CP9 =\{51-61\}.

### 6.2 XRD description

28 samples were analyzed using XRD and 23 of these were investigated further. The results are summarized in Figure 6.2.1 and Table iv in appendix 4. Metamorphic minerals (goethite, hematite, jarosite and gypsum) were excluded from the figure and the following descriptions in order to investigate the primary composition of the samples.
Figure 6.2.1: Results from the XRD analysis. The samples are presented according to their facies associations. The metamorphic minerals are excluded from this figure which thus represents the primary mineralogical composition.
6.2.1 Facies association 1

This FA consist of the basal conglomerate found widespread on the sub-Cambrian peneplain and is represented by two XRD samples; MGH-2-1-10 and MGH-10-3-10. It should be noted that the samples primarily represent the matrix, although some small clasts were present. Both of the samples are relatively poor in quartz, with an average quartz content of 13 XRD%. Feldspar dominates the basal conglomerate, the average total feldspar content for the two samples is 80 XRD%. Albite make up 22 XRD%, microcline 58 XRD% and orthoclase 1 XRD% (only observed in MGH-2-1-10). The resulting quartz/feldspar ratio is low, 0,2, meaning the amount of feldspar by far exceeds the amount of quartz.

The mica content is quite low with an average of 1 XRD%. The average calcite and apatite content is minor, providing 1 XRD% and 1 XRD%. The average ankerite content is 3 XRD%, and pyrite contribute with 1 XRD% (only found in MGH-2-1-10).

6.2.2 Facies association 2

This FA consist of sandy and clayey siltstones and is represented by 17 samples collected from five localities (in stratigraphic order); RAU-3-1-10, RAU-1-1-10, RAU-2-5-10, RAU-3-2-10, REK-1-2-10, REK-2-3-10, RAU-1-2-10, REK-2-4-10, RAU-1-3-10, RAU-3-3-10, REK-1-5-10, REK-1-7-10, REK-2-5-10, REK-1-8-10, RAU-1-4-10, RAU-2-6-10 and REK-1-9-10.

The quartz content in the samples belonging to FA2 ranges from 20 XRD% up to 51 XRD%. The average quartz content is 35 XRD%. There are two clear trends regarding quartz through FA2. From 0,3 m and up to about 5 m (sample RAU-1-3-10), the quartz content is generally increasing. Above 5 m, the content is generally decreasing with an increase close to the top of the FA2.

The feldspar content ranges from 27 XRD% (sample REK-1-9-10) to 52 XRD% (sample RAU-3-1-10). The average feldspar content is 43 XRD%, slightly higher than the average quartz content. Albite contributes with 20 XRD%, microcline 20 XRD% and orthoclase 3 XRD%.

The quartz/feldspar ratio ranges from 0,6 (RAU-1-4-10) to 1,4 (RAU-1-3-10) and the average ratio is 0,9, significantly higher than for the basal conglomerate. The quartz/feldspar ratio strongly resembles the quartz trend. It is increasing up to about 5 meters, then overall decreasing through the rest of FA2 (and further up in the stratigraphy). There is however a slight increase in the ratio just below the ejecta layer (FA3).

The mica content in FA2 is ranging from 3 XRD% in sample RAU-3-1-10 up to 40 XRD% in sample REK-2-5-10. The average content is 22,5 XRD%. Although there is no pronounced trend, the mica content is somewhat increasing through the FA2, with generally more consistent high values towards the top of the column.

The calcite content is generally low with 0 XRD% in seven samples and < 1 XRD% in seven more. However, two samples yielded a calcite content of 3 XRD% (REK-1-2-10) and as high as 20 XRD% (REK-1-8-10). For the latter sample, the calcite were also observed in thin section analysis as well as in field. The average calcite content is 2 XRD%, much owing to
The apatite content in FA2 ranges from 0 XRD% (in eight samples) up to 5 XRD% in REK-1-9-10. The average content is 1 XRD%.

The ankerite content varies between 0 XRD% (in four samples) and up to 6 XRD% (sample REK-2-3-10). The average content is 2 XRD%. There is no clear trend in the ankerite content, a slight decrease through FA2 is however visible.

The pyrite content range from 0 XRD% (in eleven samples) up to 3 XRD% in sample RAU-3-2-10. The average pyrite content in FA2 is 0 XRD%.

### 6.2.3 Facies association 3

The ejecta layer is found about 9.8 meters above the sub-Cambrian peneplain, although this height vary between the different localities. The observed (i.e. minimum) thickness also vary between the different localities, ranging from 0.5 meters to more than 3.0 meters. The XRD results obtained from the two ejecta layer samples (RAU-1-7-10 and RAU-4-3-10) provide information about the mineral content of the layer.

It is however important to remember that these results contains information of both the primary deposited sediments (mostly clay and silt) as well as the ejected material excavated from the crater. On the other hand, the two selected samples contains mainly the matrix material and none of the large ejected gneiss clasts. They are therefore not fully representative of the average ejecta layer mineral content.

The quartz content ranges from 14 XRD% in the middle of the ejecta layer (RAU-1-7-10) up to 28 XRD% in the top of the ejecta layer (RAU-4-3-10). The average quartz content is 21 XRD%.

The feldspar content is ranging from 58 XRD% (RAU-4-3-10) to 59 XRD% (RAU-1-7-10), practically the same value and giving an average of 58.5 XRD%. The albite content ranges from 31 XRD% (RAU-1-7-1) up to 41 XRD% (RAU-4-3-10), averaging 36 XRD%. The microcline content ranges from 11 XRD% (RAU-4-3-10) up to 22 XRD% (RAU-1-7-10), averaging 16 XRD%. The orthoclase is ranging from 6 XRD% (RAU-1-7-10) up to 7 XRD% (RAU-4-3-10), averaging 6 XRD%.

The quartz/feldspar ratio ranges from 0.2 (RAU-1-7-10) up to 0.5 (RAU-4-3-10) with an average of 0.4, significantly lower than the ratio found in FA2.

The mica content is ranging from 11 XRD% (RAU-4-3-10) up to 23 XRD% (RAU-1-7-10), averaging 17 XRD%.

The calcite content in the ejecta layer ranges from 0 XRD% (RAU-4-3-10) to 1 XRD% (RAU-1-7-10), averaging 0 XRD%.

The apatite content is approximately 1 XRD%.

The ankerite content ranges from 2 XRD% (RAU-4-3-10) to 3 XRD% (RAU-1-7-10), averaging 2 XRD%.

Pyrite is detected in neither of the samples from the ejecta layer.
6.2.4 Facies association 4

FA4 consist of silty shales found about one meter above the ejecta layer. The amount of vegetation and the nature of the outcrops made it too difficult to collect any samples at the top ejecta layer boundary. Two samples, RAU-5-1-10 and RAU-5-2-10, were collected from the same locality. RAU-5-1-10 were collected some cm's below RAU-5-2-10.

The quartz content in FA4 is quite low, ranging from 9 XRD% in RAU-5-2-10 to 10 XRD% in RAU-5-1-10. This makes an average of 10 XRD%.

The feldspar content ranges from 36 XRD% (RAU-5-1-10) up to 51 XRD% (RAU-5-2-10), averaging 43 XRD%. The albite content is ranging from 22 XRD% (RAU-5-1-10) to 26 XRD% (RAU-5-2-10), averaging 24 XRD%. The microcline content is ranging from 9 XRD% (RAU-5-1-10) up to 21 XRD% (RAU-5-2-10), averaging 15 XRD%. The orthoclase content is approximately 4 XRD% in both samples.

The quartz/feldspar ratio ranges from 0,2 (RAU-5-2-10) to 0,3 (RAU-5-1-10), averaging 0,2. These values are lower than for the underlying ejecta layer, and significantly lower than for FA2, displaying a steady decline in the Q/F ratio starting at RAU-3-3-10 (5 meters above the peneplain).

The mica content is ranging from 21 XRD% (RAU-5-2-10) up to 50 XRD% (RAU-5-1-10), averaging 36 XRD%.

The calcite content is insignificant, well below 1 XRD%.

The apatite content is quite high, ranging from 1 XRD% in RAU-5-1-10, up to 7 XRD% in RAU-5-2-10, the highest value encountered. The average apatite content is 4 XRD%.

The ankerite content is quite low, ranging from 0 XRD% (RAU-5-1-10) to 1 XRD% (RAU-5-2-10), averaging 0 XRD%.

The pyrite content is high in this FA, ranging from 3 XRD% in RAU-5-1-10 up to as much as 11 XRD% in RAU-5-2-10, averaging 7 XRD%.

6.2.5 General trends

Quartz and feldspar

In FA1 and FA2, the quartz/feldspar ratio (Figure 6.2.6.1) is increasing from <0,2 in the basal conglomerates up to >1,4 at about 4 meters above the basement (RAU-1-3-10). The ratio within the first 5 meters is quite variable with three alternating highs and lows in the ratio. Above 5 meters, the quartz/feldspar ratio is generally decreasing, except a minor increase up to a ratio of >1 below the ejecta layer (at about 9 meters). The decrease continues through the ejecta layer and the overlying shales to values of < 0,2.

Mica

The mica content do not show any clear trend. However, there is generally a higher content of mica above the middle part of FA2 and into FA3 and FA4, compared to FA1 and the lower part of FA2.
Figure 6.2.6.1: The quartz-feldspar ratio throughout the stratigraphical column. Although there are some intervals displaying high or upward increasing ratio, the overall trend seems to be decreasing.
Figure 6.2.6.2: The quartz / authigenic minerals (calcite, ankerite, apatite and pyrite) ratio. The gap in the lower part of the stratigraphy represents two samples with no apparent authigenic minerals. Allogenic minerals, represented by quartz, are thus dominant in this part. The ratio is decreasing up to the calcite-rich bed at 8 meters, followed by a rapid increase. This is again followed by a decrease.
Authigenic minerals (Calcite, ankerite, apatite and pyrite)

There are generally only small amounts of calcite present (< 1 XRD%) in the facies associations investigated. Some exceptions do however exist with 3 XRD% at about 2.5 meters, and a very high value (20 XRD%) encountered at about 8 meters. A small percentage of ankerite is found in most of the examined samples. Somewhat lower values are found in FA4 where the ankerite content is averaging 0 XRD%.

The apatite content is unevenly distributed throughout the stratigraphic column. Whereas several samples returned zero values for apatite, others have a content of between 0 - 2 XRD% apatite. A few samples returned relatively high values above 4 XRD% with the highest being 7 XRD% in FA4. There is no clear trend of the content of apatite, but there seems to be somewhat higher values from the middle part of FA2 and upwards.

Pyrite is present in 13 out of the 23 XRD samples in various amounts. Most pyrite seem to be present in the FA4 shales with values of 3 XRD% and 11 XRD%.

Figure 6.2.6.2 shows the ratio between quartz, which is allogenic, and the authigenic minerals calcite, ankerite, apatite and pyrite. The gap in the lower part of the stratigraphy represents two samples which yielded no authigenic minerals. There is then a general decrease up to 7.9 meters where the ratio falls just below 1. This is followed by a sharp increase up to 9.0 meters where the ratio reaches 178. The ratio is again followed by a general decrease, ending at well below 1 in the uppermost sample collected in the FA4 shales. The authigenic minerals in the ejecta layer are not truly authigenic, as they have been emplaced as a part of the ejecta following the impact. Thus, the ratio in the ejecta layer is not a true allogenic vs authigenic ratio.

6.3 SEM description

The SEM analysis was carried out to identify some of the minerals and fragments observed in certain thin section samples. The samples were collected from facies association 2 and 3 and were investigated using BSE (see description in section 4.2.2). Pictures and elemental composition (spectrum) of the samples are presented in appendix 1.

6.3.1 Facies association 2

REK-1-2-10

REK-1-2-10 represents a siltstone found about 2.5 meters above the basement. The point&ID tool was used to identify the minerals present in a small, representative part of the sample (Figure 6.3.1.1 and Figure I in appendix 1). In this sample, quartz, K-feldspar, apatite and pyrite are present. The dark grey matrix is quartz which seems to dominate the sample (spectrum 4). The brighter grey mineral marked spectrum 5 is K-feldspar. The white mineral in the middle of the picture is pyrite.
Figure 6.3.1.1: The BSE picture of a small, representative part of sample REK-1-2-10. Quartz, K-feldspar, apatite and pyrite are present in the sample.

The off-white mineral in the lower right part of the picture (spectrum 6) is apatite which seems to occur as a rim around the quartz grains in this part. The grey to black parts of the sample (spectrum 1) are epoxy, representing holes in the thin section.

**REK-1-7-10**

Two areas within this thin section have been analyzed, A and B. The A area is representative for the lowermost stratigraphic part of the sample (Figure II in appendix 1), whereas the B area is focusing on a fractured, fine-grained laminae (Figure 6.3.1.2 and Figure III in appendix 1).

A) SEM analysis reveals that (at least) quartz, biotite and ilmenite are present in this sample. Quartz (spectrum 6) seems to be dominating, biotite (spectrum 1) is abundant as well. The biotite occur as elongate minerals. Two relatively round bright minerals are identified as ilmenite (spectrum 2 and 5).

B) The fractures are not filled in this area. The stratigraphic up direction is from left to the right. The fracture(s) seems to follow the lamination/bedding in the sample and have formed in the most fine-grained part of the sample which contains mostly clay and silt. Little quartz (spectrum 3) is present in the fine-grained part, but it is found both beneath and above the fine-grained laminae. Rich zones of framboidal pyrite (spectrum 2) have been observed right beneath the fine-grained laminae. Apatite, ilmenite, biotite and K-feldspar is also observed in this part of the sample. Spectrum 1 shows the elemental composition within the pink rectangle. Several of the minerals discussed seems to be found here, with the exception of apatite and ilmenite.
Figure 6.3.1.2: This picture is gathered from the REK-1-7-10B SEM analysis. The stratigraphic up direction is marked by the arrow, and the fractured part in the middle is also the most fine-grained part of the sample. Right beneath the laminae, frambooidal pyrite has been observed. Spectrum 1 represents the elemental composition within the pink rectangle.

REK-2-7-10

Figure 6.3.1.3: A 0.5 mm long stromatolitic fragment found in sample REK-2-7-10. The fragment consist of bands of quartz (dark) and apatite (bright).
In this sample, the analysis were focused on a stromatolitic fragment (Figure 6.3.1.3 and Figure IV in appendix 1). The fragment is about 0.5 mm long and consist of bands of a light and a heavy mineral (black and light grey in BSE picture). The black mineral is found to be quartz (spectrum 2), while the light grey mineral represents apatite.

RAU-4-1-10

This sample was collected in the sandy and silty shales right beneath the ejecta layer. A representative area of the sample was examined (Figure V in appendix 1). Two grains of quartz (spectrum 1) and K-feldspar (spectrum 2) are observed with silt consisting of mostly biotite (spectrum 4) as well as albite (spectrum 6), apatite (spectrum 5 and 8) and K-feldspar (spectrum 7). The apatite observed here contains some cerium.

6.3.2 Facies association 3

RAU-3-4-10

RAU-3-4-10 was collected from the lowermost part of the ejecta layer. The focus in this sample has been on a stromatolitic fragment (Figure 6.3.2.1 and Figure VI in appendix 1) found to be up to 2 mm long. As in sample REK-2-7-10, this fragment consist of bands of quartz and apatite. The apatite contains small amounts of cerium and neodymium. Small grains of pyrite were also found within the fragment.
quartz (spectrum 2) and apatite (spectrum 1). Small grains of pyrite is also found within the fragment. The apatite contains small amounts of the rare earth elements (REE) cerium and neodymium.

**RAU-4-4-10**

This sample was collected from the upper part of the ejecta layer. The small area in focus (Figure VII in appendix 1) was typical for the matrix in the sample, and was investigated to determine the mineral assemblage. Several minerals occurred about equal amounts; biotite, K-feldspar, albite, apatite and quartz. A small, bright (heavy) apatite grain (spectrum 4) contains cerium.

### 6.4 CL description

A total of twelve samples from three facies associations were investigated by CL analysis, mainly to observe and describe the presence (or absence) of apatite and carbonates. Whereas apatite were found in most samples, significant amounts of calcite were only found in sample REK-2-7-10. In addition, a few stromatolitic fragments were observed as they contained apatite. The observations of apatite and calcite in the CL-investigated thin sections are shortly described in the sections 6.4.1 – 6.4.3. The results are summarized in Table 6.4.1.

#### 6.4.1 Facies association 1

**MGH-14-1-10**

One large apatite fragment with many smaller grains within was observed. The smaller grains were angular to rounded in grain shape. The fragment seems to be associated with an adjacent network of fractures. The network consist of many small fractures which are filled with apatite. The fractures are discontinuous, it seems they are all a part of, and restricted to one large fragment.

One slightly smaller apatite fragment was observed as well. This fragment is more rounded and homogenous in appearance, but contains some smaller clasts of a different composition.

Very small grains of apatite are scattered all over the sample. Even though they are widespread, their sizes make them insignificant compared to other minerals.

Apatite rims around some grains in the sample are observed. The rims are thin, and are found both around feldspars and quartz.

Only trace amounts of calcite were observed.
### 6.4.2 Facies association 2

**MGH-6-2-10**

Apatite grains are present mainly in the lower half of the sample. The largest concentration is found right below a less than 1 mm thick clay-rich laminae. Above this laminae, no apatite is observed. The grains are mostly angular, and generally smaller than the average grain size.

**RAU-2-5-10**

Insignificant amounts of apatite in the sample. A few clay/silt-sized apatite grains were observed.

**REK-1-7-10**

Apatite is found scattered throughout the sample. A fractured laminae of clay is associated with a zone of significant amounts of apatite. The zone is found stratigraphically above the clay laminae, and the apatite content is estimated to 20 – 30 %. Another feature observed (also observed in thin section, section 6.1.2) is the frambooidal pyrite associated with the clay laminae. Whereas the highest concentration of apatite is found above the laminae, the pyrite is concentrated below.

**REK-2-7-10**

In this sample, calcite is dominating compared to apatite. Whereas the calcite occur in particular zones, the apatite is scattered throughout the sample. One stromatolitic fragment was observed with certainty in the sample, whereas some smaller fragments were described as possible stromatolitic fragments.

**RAU-2-6-10**

Small amounts of apatite are present as relatively minor grains which are scattered throughout the sample.

**RAU-1-7-10**

Considerably amounts of relatively large, irregular and elongated apatite fragments are found in the coarse-grained parts of the sample.

### 6.4.3 Facies association 3

**REK-3-1-10**

No apatite was observed.
RAU-2-1-10

Minute amounts of apatite present in the sample.

RAU-4-4-10

Moderate amounts of irregular apatite fragments are observed. Two fragments are possibly of stromatolitic origin.

RAU-4-2-10

Some apatite grains present.

RAU-4-3-10

Moderate to relatively high amounts of apatite fragments. Many were found to be irregular or elongate in shape. Some of the elongate fragments were identified as possible stromatolite fragments.

<table>
<thead>
<tr>
<th>Facies association</th>
<th>Sample</th>
<th>Height above basement</th>
<th>Apatite amount</th>
<th>Calcite amount</th>
<th>Stromatolitic fragments observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA1</td>
<td>MGH-14-1-10</td>
<td>0 – 0,3 m</td>
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<td>None</td>
<td>None</td>
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<tr>
<td>FA2</td>
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<td>None</td>
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<tr>
<td></td>
<td>RAU-2-5-10</td>
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<td>Low</td>
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<td>None</td>
</tr>
<tr>
<td></td>
<td>REK-1-7-10</td>
<td>7,0 m</td>
<td>High</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>REK-2-7-10</td>
<td>8,0 m</td>
<td>Moderate</td>
<td>High</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>RAU-2-6-10</td>
<td>8,5 m</td>
<td>Low</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>FA3</td>
<td>RAU-1-7-10</td>
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<td>Moderate</td>
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</tr>
<tr>
<td></td>
<td>RAU-4-2-10</td>
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<td>Low</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>REK-3-1-10</td>
<td>11,6 m</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>RAU-4-3-10</td>
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<td>None</td>
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<td></td>
<td>RAU-4-4-10</td>
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<td>2</td>
</tr>
<tr>
<td></td>
<td>RAU-2-1-10</td>
<td>-</td>
<td>Low</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

Table 6.4.1: The summarized results of the CL analysis. While apatite was found in most samples, significant amounts of calcite were only observed in one sample. Stromatolitic fragments were observed in three of the samples.
7. Discussion

In this section, the data from all the stratigraphic units will be discussed and a possible depositional environment will be suggested. The discussion consists of two parts, the first part will focus on the pre- and post-impact sedimentary stratigraphy, while the second part is focusing on the syn-impact (and early post-impact) ejecta layer.

7.1 The pre- and post-impact sedimentary deposits

7.1.1 Stratigraphic unit A (0,0 – 0,3m)

The stratigraphic unit A consist of FA1, which is conglomerate overlying the sub-Cambrian peneplain. It is up to 30 cm thick, observed in low relief “pockets”. The conglomerate consist mainly of quartz, feldspar and gneiss clasts in a silty to sandy matrix. The clasts are normally 0,5 – 5 cm in size, but smaller and larger clasts are present as well. The clasts represents approximately 5 – 30% of the volume. Most clasts are rounded, but some are more angular. The quartz clasts are generally more rounded than clasts of other lithologies.

The grain sizes, grain shapes, sorting and quartz/feldspar ratios are all maturity controlled factors (Boggs, 2006), and may thus be used as indicators of the degree of reworking and / or transportation.

Considering the low quartz/feldspar ratio (Figure 6.2.6.1) and the degree of sorting (Table iii, appendix 3), the conglomerate seems to be somewhat immature. A similar conglomeratic basal layer has also been observed in comparable stratigraphical units at other places such as the Hardangervidda region (Andresen, 1982; Haremo, 1987). Haremo (1987) described the clasts as being poorly sorted and angular. At Ritland, the distribution is more varied in terms of rounding and sorting. A significant share of the clasts seems to be rounded, and the sorting varies from very poor to well. It is unlikely that the material has been transported very far, as the relief of the peneplained surface is thought to have been very low. However, the observations suggest that there has at least been some reworking, possibly over a longer period and in several episodes. The mechanisms of reworking are probably mainly by waves given the very shallow water depth during the onset of the Cambrian transgression.

Since a long distance transport of the sediments is unlikely, another origin of the clasts could be explained by fault breccias. Some faults were observed at Ritland, and fault breccias were observed in one locality in the Melands Grønahei area. If this was the source of the clasts, however, one would expect to find them mainly in association with faults. The basal conglomerate is observed by other workers, both in the Hardangervidda (Andresen, 1982; Haremo, 1987) and the Oslo region (Nyland and Teigland, 1984) as well as in other places in Scandinavia and the Baltic region (Thickpenny, 1984; Nielsen and Schovsbo, 2010). The widespread of the conglomerate makes it unlikely that the clasts are of fault origin.

It seems more probable that the clasts represents locally derived remnants of the weathered basement, a theory also supported by Andresen (1982). The rounded quartz clasts have possibly been transported farther or more likely been reworked during a longer period (several episodes) than the more angular gneissic and feldspatic clasts. Thus, the angular
clasts are probably younger and more locally derived than the more rounded clasts. The large local variations in lithology could be explained by the undulations in the peneplained surface, giving rise to highs and lows where small-scale erosion, reworking and deposition could transpire.

Phosphates are described by many workers in the Cambrian sedimentary deposits on the Baltoscandic margin. The increased levels of phosphate in the oceans at the time, combined with high latitudes and upwelling of cold, nutritious sea water onto the shelf are all factors thought to have contributed to the phosphorite deposition. The precipitation of phosphorite is largely controlled by the pH in the water, much like carbonate precipitation. Chauhan (1979) noted that a pH of about 7.1 is needed in order for phosphorite to precipitate, comparable to 7.8 for carbonates. Ascending waters in association with upwelling onto shelves experience an increase in pH as the temperature increases and the CO$_2$ partial pressure decreases. Thus, phosphate in the sediments may indicate a relatively shallow depositional setting. It is also an indicator of low clastic influx, as it is mostly found in association with hiatuses and drowning (transgressive) surfaces.

Both XRD and CL analysis has shown that phosphorite is present in the basal conglomerates at Ritland in the form of apatite, supporting the notion of a shallow and low clastic influx setting. In the CL analysis, the phosphorite was found as clasts, fracture fillings, rims around clastic grains and as smaller fragments within the conglomerates. Apatite has also been observed in the XRD analysis, see Figure 6.2.1. The apatite rims around other grains and the fracture fills are probably representing recrystallization / early diagenesis, and the rounded apatite clasts probably represents apatite-rich reworked material.

### 7.1.2 Stratigraphic unit B (0.3 – 9.8 m)

The stratigraphic unit B consist of FA2 which is found overlying the basal conglomerates and below the ejecta layer. It is represented mainly by siltstones with significant amounts of sand and clay. A normally graded siltstone is found in several localities right above the basal conglomerates. The layer is less than one meter thick, and thin section study has shown that it is laminated with fine sand being the average grain size. According to Hiscott (2003), graded beds are often the result of short-lived, waning events such as storms on a shallow marine shelf, introducing sediments by downslope transport. It could also indicate a more gradual decrease in bottom water energy and a shift in depositional environment from a very proximal setting to a less proximal setting. This would fit well with the onset of the Cambrian transgression at the time of deposition.

The XRD analysis display increased quartz/feldspar ratios compared to the underlying conglomerates. This suggests the layer to be more mature and reworked. Combined with the lack of bioturbation, one might expect the deposition to have taken place in a high energy environment such as the shore face zone. However, as the layer seems to be mainly laminated, as opposed to having wave action structures such as ripples, dunes or hummocky cross-stratification, the deposition might have taken place below the fair weather wave base. In that case, the lack of bioturbation might be explained by a lag in time before colonization of benthic organisms took place. Alternatively, the lack of bioturbation may have been caused by high energy and intensive reworking of rather thin sediments.
CL analysis has revealed a moderate content of phosphate (apatite) in the layer, comparable to the basal conglomerates. This again suggests a low influx of clastic sediments.

Unit B seems to consist of at least two meter-scale inverse graded units. The first unit is found from approximately 1.5 meters above the basement up to 4.0 meters, and the second from 4.0 meters to approximately 5.0 - 6.0 meters. Both of the sequences have a high clay content (30 – 50%) and are black in color at the base. The clay content suggests that the sedimentation rate was low and the black color that it may contain organic matter which would indicate lack of oxygen (Boggs, 2006). Anoxic bottom conditions are also supported by the presence of a significant amount of pyrite in the XRD analysis in sample RAU-3-2-10 (Berner, 1970). Even though the water depth probably was very shallow at the time of deposition, possible stagnant conditions on the Early Cambrian Baltoscandic shelf may have lead to oxygen deficiency on the bottom (Thickpenny 1984; Nielsen and Schovsbo, 2010)

The upwards coarsening grain sizes may suggest that the clastic supply or the transportation energy was increasing following the initial deposition of clay. It is also evident that the bottom conditions went from anoxic to more oxic, as bioturbation is observed from about 2.0 - 2.5 meters and upwards. The introduction of oxygen at the sea bottom may indicate higher energy on the shelf caused either by more storm activity or a regression lowering the storm wave base. Convolute lamination was encountered in the thin section from sample REK-2-3-10 along with flame structures. According to Middleton (2003), convolute lamination is formed by rapid deposition causing pore pressures higher than hydrostatic pressures and consequently liquefication of the sediment. Liquefaction of sediments may also be caused by processes such as earthquake shocks and breaking waves. As the depositional setting is thought to have been in a tectonically stable area (Bjørlykke and Englund, 1979; Nielsen and Schovsbo, 2010), earthquakes were most likely minor in the area at the time. Differential overloading indicate a rather rapid deposition, whereas breaking waves may reflect a low water depth. Both seems reasonable, given the coarsening upward development.

Flame structures are wavy to flame-shaped tongues of mud projected into the overlying layer. The structures are formed by rapid deposition of sand over unconsolidated mud followed by sinking of the sand into the underlying layer (Middleton, 2003). They are commonly found with convolute lamination or other syn-sedimentary structures. The structures found in sample REK-2-3-10 thus suggest a relatively high clastic influx.

The alternating laminae of sand / silt and clay in samples REK-2-3-10 (and RAU-2-9-10) reflect cyclic variations in the clastic influx at the time of deposition. If the laminae are annual sediment deposits, they are called varves (Gilbert, 2003). Clastic varves are formed by seasonal climatic variations. The fine-grained sediments are deposited in low-energy conditions during low inflow of water and sediments (usually winter), and the coarse-grained sediments reflect deposition during larger inflows and more circulation (usually summer). The climate control both the continental runoff as well as storm activity. It is not clear whether the alternating dark and bright laminae in the samples investigated represent annual cycles or not. Thus, they should be referred to as rhythmites which is a non-temporal term. Goldhammer (2003) describes small scale variations in the sea level and / or storm activity as possible factors forming rhythmites.

At approximately 4.0 meters, above the first upward coarsening unit, black silty shale where encountered, marking the base of the second upward coarsening unit. The sudden introduction of significant amounts of clay and the black color can probably be attributed to a new step in the transgression, leading to a landward movement of the coastline, thus decreasing the clastic
influx. The laminated basal part of the unit points to more stagnant conditions. Sparse bioturbation is observed in the lower part of the unit, suggesting some availability of oxygen. The two coarsening upward units are followed by sandy and clayey siltstones with generally little variation in grain sizes. The interval is characterized by alternating units of lamination and bioturbation. However, even the laminated units generally shows some signs of bioturbation, suggesting the bottom was oxygenized. Exceptions are seen by thin section analyses of samples taken from approximately 7.0 and 7.5 meters above the basement. At 7.0 meters, a clay-rich laminae is observed with a rich zone of frambooidal pyrite right beneath (Figure 6.3.1.2). Right above the laminae, significant amounts of apatite where observed using CL (section 6.2.4). The presence of a clay laminae and the frambooidal pyrite is indicative of both a very low sedimentation rate as well as anoxic bottom conditions. The large amount of apatite above the laminae suggests the elastic input was low at the time, which fits well with the deposition of mainly clay.

Half a meter above, at approximately level 7.5 meters, a laminated siltstone layer was observed in thin section. A syn-sedimentary fold had developed with laminae alternating between silt and clay, and very fine sand (Figure 6.1.2.2). According to Sylvester and Lowe (2003), syn-sedimentary folds are structures formed by sediment liquefaction and water escape, normally consisting of mudstones or sandy shale sediments. They are generally found in units that were deposited rapidly. Thus, the observation indicate an increase in the sedimentation rate at this level. Flame structures were also observed and are regarded to reflect rapid deposition as well. No bioturbation were observed within this layer, indicative of continued anoxic conditions.

About 8.0 meters above the basement, a calcite-rich layer was encountered. It was visible in field as having weathered holes. Calcite were also observed in thin sections, XRD, SEM and CL. Carbonate precipitation can occur organically or inorganically (Boggs, 2006). Inorganic precipitation of carbonates is favored mainly by high water temperatures, low pressures and low salinities. Thus, a shallow water setting is optimal, especially containing brackish or fresh water. Organisms play a huge role in the formation of carbonates. The most important role they play is by direct extraction of CaCO$_3$ from the sea water to form skeletal elements. The process of photosynthesis by organisms within the photic zone is also important, as it removes CO$_2$ from the water, thus increasing the pH. This improves the conditions of inorganic carbonate precipitation. Overall, carbonate precipitation, organic or inorganic, is favored in a shallow water setting with low clastic input, especially within the photic zone. It may thus be suggested that the calcite-rich layer reflects a shallow water setting at the time of deposition.

Although bioturbation is found through most of the stratigraphy, no fossils were encountered with the exception of stromatolitic fragments within the calcite rich layer and the ejecta layer. Stromatolites are formed by algal mats, most commonly cyanobacteria, in the marine realm (Hofmann, 1969). The most fundamental feature of stromatolites is the lamination; each individual laminae being composed of a couplet of lamellae that represent periodic growth. The cyanobacteria represent the organic lamellae which may trap sediments, forming the sedimentary lamellae, often quartz silt (Pomoni-Papaioannou, 1994). The alternating laminae reflect cyclic pulses in intensity of sediment precipitation in the mat environment (Krajewski et al., 2000).

SEM analysis has shown that the lamellae consist of quartz alternating with apatite. The quartz most likely represent the sedimentary lamellae, while the apatite seems to have replaced the organic lamellae. Phosphate replacement have been reported in stromatolites by
several workers, such as Chauhan (1979), Krajewski (1984), Pomoni-Papaioannou (1994) and Álvaro et al. (2010).

Krajewski (1984) has described experiments showing that the decay of organic material by bacteria lead to a release of biologically uptaken phosphorous which could combine with Ca$^{2+}$ ions in the sea water to form apatite. Furthermore, organic material not only acts as a source of phosphate, but also as a substrate on which phosphate preferentially nucleates (Pomoni-Papaioannou, 1994).

According to Hofmann (1969) and Chauhan (1979), stromatolites are best developed in the sub-, inter- and supratidal marginal marine settings. This fits very well with the observed calcite content in the same layer, suggesting the water depth at the time of deposition was very low. However, the stromatolites observed are here referred to as stromatolitic fragments, as they have been transported and were not formed in place. This assumption seems fair, considering the fragmental appearance of the stromatolites and that the laminae in the fragments does not coincide with the bedding plane of the layers. Still, it is reasonable to presume that they were transported only a short distance on the flat shelf. Thus, the water depth at the time of deposition was relatively low, likely within the photic zone.

CL analysis has shown that the apatite content at this stratigraphic level was moderate, supporting the indications of a shallow marine setting. It is also, in combination with the calcite, pointing to a reduced clastic sedimentation.

Moderate bioturbation is found through most of the upper part of the stratigraphic unit B. Some laminated intervals are still preserved in the thin section samples investigated. Overall, the upper part of unit B seems to have been exposed to more bioturbation than the lower part. Brasier (1982, and references therein) described several ways in which transgressions may lead to an increase in biodiversity. Organisms are most abundant in lower-energy areas of the shelf, with the greatest populations to be found on the inner shelf right below the wave base. This could explain the observed increase in bioturbation through FA2, as large areas of the drowned shelf gradually became available and suitable for marine life forms during the transgression. One also need to consider the global scale Cambrian explosion (Brasier, 1982; Brasier, 1992; Ramberg et al., 2006) that took place, in which a rapid evolution of life occurred during a short geological period of time. Taking this into account, the upward increase in bioturbation may reflect the evolution of life in the ocean at the time.

The depositional environment at Ritland in the Early Cambrian most likely was a wave-dominated shelf (Nielsen and Schovsbo, 2010), and storm deposits should be expected within the stratigraphical sequence.

Storm beds, or tempestites, are particularly characteristic of shelf sediments (Myrow, 2003 and references therein). The coarsest material is found in the basal part and may consist of coarse silt, fine sand, skeletal fragments and, in some cases, gravel. They are generally embedded in finer grained muds with erosive bases, hummocky cross-stratification and upwards fining development. Myrow (2003) suggested that the formation of storm beds are commonly due to a combination of near-shore parallel geostrophic flows and onshore-offshore directed storm waves. The net movement of sediments following the combinations of these flows would have an oblique offshore directed direction.

The tempestite structures described above, such as erosive bases and hummocky cross stratification, seems to be lacking in the studied section, suggesting a generally low energy depositional environment. Still, the periodic presence of more sand-rich layers would be
indicative of higher energy intervals associated with lowered wave bases (storms). The lack of structures could be explained by post depositional bioturbation, which according to observations by Nielsen and Schovsbo (2010) both has destroyed sedimentary structures and mixed the storm layers with the fair-weather sediments.

Nielsen and Schovsbo (2010) indicated that at least one regressional phase is found within the overall Cambrian transgression. The regression is thought to have been followed by a significant decrease in clastic influx in late Early Cambrian caused by the continuation of the transgression. There are several observations in the present study supporting this. Firstly, the intervals with highest clay content in this stratigraphic unit are found in the lower part in association with the two upwards coarsening units, while the clay content is generally lower in the middle to upper part of the facies association. Secondly, there is found both stromatolitic fragments as well as a calcite rich zone in the upper part of this unit, suggesting a very shallow water depth. Thirdly, when looking at the quartz / authigenic minerals ratio, the overall trend seems to decrease, except for a spike occurring at about nine meters, signaling a stronger influx of sediments, again followed by a decline. There is also an increase in the quartz / feldspar ratio coinciding with the aforementioned spike, suggesting influx of mature and reworked coastal sediments.

The following period of lower clastic influx to the shelf, as stated by Nielsen and Schovsbo (2010), can also be supported by observations from stratigraphic unit D which clearly shows a depositional environment dominated by more fine-grained sediments. See the description of facies association 4 below.

### 7.1.3 Stratigraphic unit D (14,0 – 14,5 m)

The shales of unit D have been observed a few meters above the ejecta layer in several places. However, they have only been logged in one locality, as vegetation often cover the top of the ejecta layer.

The shales consist of about 70 % clay and 30 % silt, thus representing a substantial shift in the facies and depositional environment. The clay content is the highest encountered in the stratigraphical column. The more fine-grained material, as well as the low quartz / authigenic minerals and quartz / feldspar ratios point to a reduced clastic input of less mature material. This could be explained by a landward displacement of facies caused by the continuation of the transgression, as stated by Nielsen and Schovsbo (2010). The amounts of apatite present suggests deposition under shallow marine conditions. Since the relief of the drowned peneplain was very low, a large landward shift of the coast line need not have lead to a substantial increase in the water depth.

The high content of pyrite suggests an anoxic ocean bottom at the time of deposition or soon after, which indicates stagnant water.
7.2 Stratigraphic unit C (the ejecta layer)

7.2.1 Shock metamorphism

Shatter cones

An assemblage of shatter cones was found within the ejecta layer at RAU-1. These cones consist of almost pure calcite, but they contained a few quartz grain with no visible PDFs. As significant amounts of calcite are found only within one layer (facies VI) in the target stratigraphy, it is reasonable to presume the shatter cones were formed within this layer during the contact and compression stage. They were then expelled from the crater as an assemblage during the excavation stage and emplaced outside the crater at the present day RAU-1 locality. Shatter cones develop when subjected to pressures of 2 – 30 GPa, thus they are expected to form in the higher part of the target rocks (Melosh, 1989; French, 1998). This fits very well with the fact that the calcite-rich layer is found just a few meters below the ejecta layer. Thus, it was probably exposed to sufficiently high pressures for formation of shatter cones. The lack of PDFs within the quartz grains of the shatter cones, indicate pressures probably below 10 GPa.

Occurrences of shatter cones are of great value as strong indicators of an impact. It is possible to mistake other features for being shatter cones. According to French and Koeberl (2010), there are three special features separating shatter cones from other non-impact structures. 1) The striations on shatter cones may resemble slickensides, but slickenside striations are always parallel whereas shatter cone striations diverge. 2) Shatter cones may form in all rock types, and independently of preexisting structures such as bedding. 3) Shatter cones, as opposed to wind-ablated rocks, are penetrating, meaning they extend into the underlying rocks. The first and third feature are evident in the Ritland shatter cones, confirming their origin.

PDFs

PDFs were observed in quartz grains in samples from ejecta beds in localities RAU-1, RAU-2, RAU-3 and RAU-4. Their presence is considered evidence of an impact (French and Koeberl, 2010). In addition, the distribution and degree of shocking can tell us something about the distribution of the ejecta. The most shocked rocks during impact were located in the uppermost part of the target rocks. This is also the material that has the potential to be ejected farthest away from the crater (Oberbeck, 1975; Melosh, 1989; French and Koeberl, 2010). Thus, in distal ejecta, a relatively higher share of the ejected material could potentially contain PDFs.

At Ritland, a total of nine PDFs carrying grains have been found in the ejecta layer in four of the five logged localities. This is too few to be of statistical significance for any interpretation of their distribution. Grain sizes are of great importance for finding PDFs. The sampling at Ritland were mainly done of the matrix within the ejecta layer, resulting in many very fine grained thin sections in which PDFs may be hard to discover. All of the quartz grains in which PDFs were found, were at least silt-sized, but more commonly sand-sized. Thus, more PDFs may be present in the samples, but may have been too small to be observed.

PDFs may be used as indicators of shock pressure, while their internal orientation of planes provide a better estimate of the pressure they have been exposed to. In Grieve and Robertson
(1976), different shock pressure values were assigned for some of the crystallographic planes associated with PDFs. 8,8 GPa indicate grains with orientations parallel to plane 1, 12 GPa for orientations parallel to plane 1 and 2, 15 GPa for grains with orientations parallel to plane 1, 2 and 11. A pressure of 17,5 GPa were assigned to grains with orientations parallel to plane 2, 3 and 11. When applying these values with the results presented in Figure 6.1.3.2, it seems evident that at least one of the grains were subjected to pressures of minimum 17,5 GPa (plane 3). The pressures were likely even higher, as plane 6 and 9 were also observed. Similar and somewhat higher values from PDFs have also been encountered by Elin Kalleson (pers. comm.).

Ferrière et al. (2009) and French and Koeberl (2010) cautioned that in order to reach a minimum level of precision and repeatability, at least 20 and up to 100 PDF sets per sample should be measured. In this paper, only four PDF sets were successfully analyzed in only one sample. Thus, the results presented here at best only provide a slight indication of the possible maximum pressures ejecta from this sample were subjected to.

No other shock metamorphic features were found within the ejecta layer. Given a water depth at the time of impact of about 100 meters, the maximum shock pressures at Ritland is thought to have reached approximately 200 GPa (Shuvalov et al., 2011). Only a very small volume of rock was however subjected to such pressures.

7.2.2 Ejecta configuration and distribution
The ejecta layer was observed in exposures in the Raudkleiv and Rekkjebrotet areas east of the Ritland impact structure (Figure 4.1.1 and 5.2.5). The RAU-2 locality is closest to the crater centre (2,7 km), whereas REK-3 (close to REK-1) represents the most remote ejecta (4,9 km) from the crater centre.

Height above the basement and the thickness of the ejecta layer vary from locality to locality (Figure 5.1.7). This reflects primary thickness of the layer, but could also be affected by later tectonic activity or erroneous observations due to limited exposures. At the RAU-1 locality, the ejecta layer was observed several meters above expected level, compared to other localities (Figure 5.1.7). The height difference is probably associated with fault movements very close to the locality (Figure 4.1.2A). The thickest ejecta layer thickness is about 3,5 meters (RAU-3). Larger thicknesses have been observed closer to the crater rim.

The base of the ejecta layer is defined by a sudden introduction of large gneissic clasts in the fine-grained marine sediments. The base is undulating due to the difference in height in which the clasts first appear. The basal clasts are generally the largest, with the largest being 2,8 meters in diameter at locality RAU-3 (Figure 5.2.5E). There has been observed several boulders larger than one meter in diameter in the lower part of the ejecta layer in other sites close to the crater. Two mechanisms may account for this sorting. Firstly, at the time of impact and ejecta expelling, the sea floor most likely consisted of soft, unconsolidated sediments, primarily silt and clay. When the ejected boulders stroke the sea floor, they may have had sufficient kinetic energy to penetrate the sediment surface. It is also likely that the boulders after deposition gradually sunk down through the unconsolidated mud by their own weight.

Secondly, according to Lindström et al. (2005) larger ejecta clasts will sink to the sea floor
more quickly than smaller clasts in a marine-target impact. Given that a shallow sea was present during ejecta deposition, the settling of the ejecta through the water column acted as a sorting mechanism for the final ejecta deposit, resulting in a general fining upwards succession.

The ejecta layer consist of both ejected material, as well as locally derived, primary sediments mixed with the ejecta. Oberbeck (1975) described the mixing of ejecta and local material as a part of “ballistic sedimentation”. This mechanism causes mixing partly by the primary deposition of ejected material into local background sediments, but also by the following ground-hugging flow caused by high initial horizontal velocity of the ejecta. Ballistic sedimentation is described as a depositional mechanism at the Ries impact structure amongst others, see appendix 5. The “Bunte Breccia” ejecta layer at Ries is a highly heterogeneous mixture which only display minute degree of internal sorting of the clasts. In comparison, the ejecta layer at Ritland seems to be better sorted, with a clear internal trend regarding clast sizes as well as the sand and clay content. This indicates lesser mixing of ejecta and local material at Ritland compared to Ries and that the mixing occurred mainly as primary deposition of ejected material into the local material without any significant outward ground-hugging flow. This can probably be explained by the difference in size between the two craters as well as the presence of a shallow sea at Ritland. At Ries, much more energy was involved in the impact and because of the lack of a water column over the target rocks, a relatively larger amount of ejecta were expelled from the crater. It should be noted however, that the strength of the flow, and thus the degree of mixing, is dependent on the horizontal velocity of the ejecta. This value increases farther away from the crater (Figure 2.4.2, Oberbeck, 1975; Melosh, 1989), thus the degree of mixing of ejecta and local material at Ritland is expected to increase away from the crater.

Increased mixing within the ejecta layer outwards from the crater has not been observed at Ritland. However, this may be explained by the limited lateral exposure of the ejecta layer (only observed up to 2,6 crater radii from the crater rim), as well as the presence of vegetation in each of the localities.

The texture of the unit is matrix-supported, and the matrix in the lower part of the layer consist mainly of silt with some clay and sand. As it is unlikely for smaller sized ejecta to have penetrated and sunken significantly below the sea floor bottom compared to large boulders, the matrix in the lower part of the ejecta may represent primary background sediments. Given that the boulders may have sunken down post-impact, the matrix in the lower ejecta layer is likely older than the impact event.

An upwards decrease in clast size has been observed in well exposed ejecta sections. Thin section analysis and field observations also indicate an increase in sand and clay upwards within the ejecta layer (more matrix and more fine-grained ejecta). This probably reflect the ejecta sedimentation, as postulated by Lindström et al. (2005), with gradual settling of ejecta from the water column and a general fining upwards succession.

The uppermost part of the ejecta layer is generally partly covered by vegetation and it seems to be slightly folded where observed (see Figure 5.2.5A). The presence of vegetation has also prevented the author from finding the boundary between the ejecta layer and overlying rocks. The exposure of the shales in stratigraphic unit D was the closest observation possible and were done approximately one meter above the exposed ejecta layer at RAU-1. There is likely a gradual transition between the ejecta layer and the following unit.
As pointed out by Melosh (1989), the mixing of ejecta within local material will result in an apparent ejecta layer being thicker than expected from ballistic ejecta deposits (e.g. the formula by McGetchin et al., 1973). Based on field observations, it seems that the dominant sediment in the ejecta layer is of local origin. It would be speculative to quantify how much of the ejecta layer is local material and how much is true ejecta, but it seems that local material represent at least 50% of the ejecta layer and probably considerably more. This is supported by the modeled primary ejecta layer thicknesses at Ritland done by Shyvalov et al. (2011) which are considerably thinner than the observed (primary ejecta and local material) ejecta layer thicknesses done by the author.

When comparing the ballistically modeled ejecta layer thickness with the observed thickness (Figure 5.4.1), it seems that the ejecta around the Ritland impact structure has not been purely ballistically emplaced. Considering the apparent thickness is probably at least twice the size of original ejecta expected; the modeled ballistic thicknesses and the observations seems to agree reasonably. The diverging values in locality REK-1 can probably be attributed to more vegetation cover than in the other localities. Vegetation coverage may have influenced (reduced and complicated) the measurements of thicknesses in other localities as well.

Even though the ejecta layer display thicknesses similar to the those yielded by the ballistic model, the overall trend differs some. It seems to be rather thin close to the crater and do not display the same decrease outwards as one would see if the ejecta were emplaced ballistically. Instead, the trend line is quite flat. Similar observations have also been done around other terrestrial craters such as the Lonar Crater in India (Maloof et al., 2010; black line in Figure C, appendix 5) and the Kärdla crater in Estonia (Suuroja and Suuroja, 2006; Figure B, appendix 5). Comparison with other craters is only valid if the thickness close to the crater represents mainly primary ejecta deposition, as opposed to post-impact deposition/erosion or reworking by resurge flows, tsunamis etc.

As the atmosphere and/or fluids on Earth are involved in all impact craters found on this planet, Buchner et al. (2007) has stated that rampart craters on Mars probably are the closest equivalent to impact craters preserved on Earth. The trend line at Ritland seems more related to what has been found around craters with fluidized ejecta such as Martian craters (grey line in Figure C and E, appendix 5), than craters on air- and waterless planetary bodies such as the Moon. Fluidized ejecta beds generally display a homogeneous to outward thickening development as well as thinner than expected ejecta thickness closer to the crater rim.

According to Melosh (1989), the presence of liquid water may greatly enhance the mobility of the excavated debris, converting dry ejecta to a fluid debris flow similar to terrestrial mudflows, resulting in an increase in the extent of the ejecta blanket. In addition, according to Carr et al. (1977) and Komatsu et al. (2007), vaporized volatiles may increase the velocity of the ejecta, which also could result in a wider extent.

The observations at Ritland strongly suggest the ejecta were fluidized during emplacement, likely caused by both the volatiles within the unconsolidated target sediments as well as the body of water which is thought to have been in place at the time of impact. This would imply that the ejecta blanket originally extended farther out than what has been observed. An originally wider extent of the ejecta blanket has also been suggested by numerical modeling by Shuvalov et al. (2011), given that the water depth at the time of impact was considerably less than 200 meters. Furthermore, one would expect to find a terminal ridge (rampart) at a certain distance from the crater. The significantly thinner ejecta deposit at the farthest locality from the crater could be evidence of this. It is uncertain how thick the unit is at this
locality, as vegetation covered up parts of the ejecta layer. A third implication of fluidized ejecta would be a lobe-like configuration of the ejecta blanket around the crater. It is however hard to prove this, as the ejecta layer has only been observed east of the crater.

It should be noted that only five ejecta layer thickness observations has been done at Ritland so far. The erosion of the ejecta layer both laterally, as well as in all other directions than east of the crater, is also constraining. The observations are thus hardly sufficient for providing a complete picture of the distribution, and it only serves as an indication. The lack of a significantly exposed ejecta layer also makes it hard to diagnose whether the impact was oblique or not. The shape of the crater may only be used as a diagnostic feature if the impact was very low-angled (<10°, Melosh, 1989), which is not likely to have been the case at Ritland.

It should also be considered that post-impact events such as impact-induced resurge flows and tsunamis, and non-impact storm waves and currents to some degree may have reworked the original ejecta layer distribution.

The presence of water

The presence of a shallow sea at Ritland at the time of impact seems most probable, as several meters of marine sediments are found deposited on the sub-Cambrian peneplain below, as well as above the ejecta layer. The pre-impact depositional environment has been interpreted as a shallow shelf with low clastic influx and periods of stagnant conditions. The presence of a calcite-rich layer and the observations of stromatolitic fragments suggest the water depth was very shallow, possibly with deposition within the photic zone. Given that the shelf was tectonically stable in Cambrian (Nielsen and Schovsbo, 2010), it is unlikely that the water depth increased significantly until the time of impact.

The calculated original crater rim height for Ritland by the author is approximately 109 meters, see section 2.4.4. This is comparable with calculation of a approximately 100 meter rim height by Shuvalov et al. (2011). According to observations on the sedimentary crater infill by Tomczyk (2010), the crater was most likely partially dry for some time (months, years?) after crater formation. This suggests that the crater rim acted as a barrier against the sea. Thus, is seems possible that the rim height was larger than the water depth at the time of impact.

Shuvalov and Dypvik (2004) suggested that the water depth is of great importance for the maximum extent of the ejecta in marine impacts. It was shown by numerical modeling that if the water depth was equal to, or larger than the impacting bolide, the transient wall of water formed at the crater formation stage would greatly inhibit the extent of the ejecta. If the water depth is much smaller than the diameter of the bolide, the fluidization of the ejecta results in an extended ejecta blanket. Similar factors were also described by Shuvalov et al. (2011) for the Ritland event. This indicate that the water depth was significantly less than the bolide which is thought to have been approximately 115 meters in diameter (Riis et al., 2011).

Based on these facts, as well as environmental interpretations by Nielsen and Schovsbo (2010), it is suggested that the water depth was less than 100 meters at the time of impact. A similar suggestion has also been made by Shuvalov et al. (2011) based on numerical modeling of the crater formation and ejecta distribution at Ritland.

The position of the ejecta layer within the stratigraphical column may serve as an indicator of
the age of the crater. East of the Ritland impact structure, the ejecta layer is found approximately 10 meters above the sub-Cambrian peneplain. In this study, the ejecta layer is categorized as stratigraphic unit C, located above unit B and below unit D. Nielsen and Schovsbo (2010) has suggested that the late Early Cambrian period on the Baltoscandic shelf experienced a period of regression, followed by a decrease in clastic supply due to the continuation of the Cambrian transgression. As discussed in section 6.1.2, these events seems to be present in the upper part of unit B and continuing in unit D. With the ejecta layer located between these stratigraphic units, a late Early Cambrian age of the crater formation is probable. In addition, Henningsmoen (1952) and Bruton and Harper (2000) has described fossils of Middle Cambrian age found within the crater infill sediments. Thus, the crater must be older than these fossils, suggesting an age of the impact of late Early Cambrian to Middle Cambrian. The age is comparable, but probably younger than the approximately 546 Ma old Gardnos impact structure located in Hallingdal, Norway (Kalleson, 2009).

A suggested model of the crater formation and ejecta expulsion of the Ritland impact structure is presented in Figure 7.2.2.1.

Figure 7.2.2.1: The crater formation and ejecta expulsion of the Ritland impact structure. The model is based on Shuvalov et al. (2011), Riis et al. (2011) and field observations by the author. 

A) The pre-impact setting at Ritland. The sub-Cambrian peneplain was most likely covered by a shallow sea and a few meters of marine sediments prior to the impact. B) The basement becomes severely crushed and fractured during impact. Immediately following the impact, target rocks are excavated from the crater together with water. The water forms a wall which slightly inhibits the outward movement of the ejecta. At the same time, the presence of volatiles, basically water, within the target rocks may lead to an increase in the
maximum ejecta velocity as vaporization accelerates ejected material. C) Most of the ejecta breaks through the wall of water and continue to move outward as a part of the ejecta curtain(s). The presence of water may cause fluidization of the ejecta and enhance its extent. Much of the ejecta strikes the ground close to the crater, forming the crater rim together with the partly uplifted basement. The rim build-up is approximately 100 m in height, forming a barrier between the sea and the crater. The crater walls and rim are unstable and rock avalanches form scree deposits within the crater. D) All of the excavated material has settled. Whereas most of the ejecta is found outside the crater, some has also fallen back into the crater. The ejecta layer is thickest close to the crater, and decreases outwards. It is continuous several crater radii from the crater rim and is mixed with the Early Cambrian sediments. Despite the mixing of primary ejecta and secondary locally derived material, the ejecta bed is normally graded with the largest blocks being found in the lowest part. The crater walls and rim continue to produce avalanches into the crater. The rim is somewhat higher than the water column, but unstable, consisting mostly of loose debris. The water is likely to enter the crater not long after impact (days/weeks/months?) both by sieving through the rim and by further collapse of the rim.
8. Conclusion

The ejecta layer from the Ritland impact has been successfully identified at several locations up to 4.9 km from the centre of the crater structure. It occurs within the Lower Paleozoic succession which has been investigated for the palaeo-environmental setting before, at, and after impact.

The Lower Paleozoic sedimentary succession east of Ritland reflect deposition on a shallow marine shelf setting. During the Cambrian transgression, the Ritland area became a part of an extensive epicontinental sea that covered most of Scandinavia and the Baltic region. The shelf was tectonically stable, and the water depth was quite low through most of the Cambrian. This study supports the observations by others in that the bottom conditions was periodically anoxic. However, bioturbation is also quite extensive, suggesting periods of oxic bottom conditions as well. The sedimentary influx was low through most of the period, especially from late Early Cambrian and into Middle Cambrian.

The overall development as envisioned in field observations reveals an overall transgression, although one or several minor periods of regressions also may have occurred. An especially low water level seems probable with the observations of large amounts of calcite and stromatolitic fragments within one layer about 8 meters stratigraphically above the basement. This is accompanied by a generally higher content of silt- and sand-sized grains than clay compared to the lower part of the section. In addition, both the quartz / authigenic minerals ratio and the quartz / feldspar ratio display a higher influx of more mature sediments in this part, weakly suggesting deposition closer to land.

At least 8-10 meters of marine sediments were deposited before impact. Large amounts of debris were expelled during the excavation stage and deposited around the crater. Shatter cones and PDFs found within the ejecta layer serve as evidence of the impact as well as being “shock barometers”. One of the PDF containing quartz grains were subjected to shock pressures of at least 17.5 GPa, as revealed in U-stage microscope analysis. However, even higher pressures were most likely present at the time of impact.

The distribution of the ejecta suggests it was to a large extent fluidized at the time of expulsion and not emplaced in purely ballistic trajectories. This is indicated by the ejecta layer thickness trend, which diverge from the modeled ballistic trend expected for “dry” ejecta layers. Comparable craters with volatiles present such as the Estonian Kärdla crater and typical Martian craters display ejecta layers with fluidized appearance as well.

The ejecta thickness trend in this study is only based on observations from five localities east of the impact structure. Further investigations of the extent of the ejecta layer, if possible, would be of great value in determining the mode of emplacement, as the thickness trend presented here only serves as an indication.

The presence of 8-10 meters of marine sediments below the ejecta layer, as well as the overlying marine sediments, strongly suggest the Ritland area was covered by a shallow sea at the time of impact. Based on the extent of the ejecta layer, the water depth was most likely significantly less than the diameter of the bolide which is thought to have been approximately 115 meters. In this paper, it is suggested that the water depth was less than 100 meters at the time of impact. Similar water depth values are suggested in other studies such as Shuvalov et al. (2011) and Nielsen and Schovsbo (2010).
The position of the ejecta layer within the stratigraphical column indicate the maximum crater age to be approximately late Early Cambrian. The observations of Middle Cambrian fossils in the crater filling sediments provide the minimum age of crater formation. The Ritland impact structure is probably younger than the Gardnos structure (546 Ma), which is the closest known impact structure to Ritland.

The crater was filled by sediments during the Cambrian period and later covered by Caledonian nappe units. While the Caledonian Orogeny probably helped preserving the Ritland impact structure and the ejecta layer by the overlying thrust nappes, but the Caledonian deformation altered and also removed parts of the Lower Paleozoic sedimentary deposits in the area. Several periods of glacial erosion have later removed parts of the nappes and the crater infill, revealing a three-dimensional exposure of the present impact structure. Unfortunately, much of the ejecta layer has been eroded as well, and has presently only been found in an area east of the impact structure.
References


Morris, C., Sieve, B. J. and Bullen, H. A. 2008. *E-Learning Module: Introduction to X-ray Diffraction.* Available at:
http://www.asdlib.org/onlineArticles/ecourseware/Bullen_XRD/XRDModule_ind_ex.htm
(Accessed: 01.03.11)


87


Appendices

Appendix 1 SEM results

Figure 1: The results from the SEM analysis performed on sample REK-1-2-10. The upper figure display a small area within the sample, whereas the lower figure is a legend, representing the mineralogical composition of the selected grains and matrix.
Figure II: The results from the SEM analysis performed on sample REK-1-7-10, area A. The upper figure display a small area within the sample, whereas the lower figure is a legend, representing the mineralogical composition of the selected grains and matrix.
Figure III: The results from the SEM analysis performed on sample REK-1-7-10, area B. The upper figure display a small area within the sample, whereas the lower figure is a legend, representing the mineralogical composition of the selected grains and matrix. Spectrum 1 display the mineralogical composition within the pink rectangle.
Figure IV: The results from the SEM analysis performed on sample REK-2-7-10. The upper figure displays a small area within the sample, whereas the lower figure is a legend, representing the mineralogical composition of the stromatolitic fragment.
Figure V: The results from the SEM analysis performed on sample RAU-4-1-10. The upper figure display a small area within the sample, whereas the lower figure is a legend, representing the mineralogical composition of the selected grains and matrix.
Figure VI: The results from the SEM analysis performed on sample RAU-3-4-10. The upper figure displays a small area within the sample, whereas the lower figure is a legend, representing the mineralogical composition of a stromatolitic fragment and an adjacent grain.
Figure VII: The results from the SEM analysis performed on sample RAU-4-4-10. The upper figure display a small area within the sample, whereas the lower figure is a legend, representing the mineralogical composition of the selected grains and matrix.
## Appendix 2 Facies tables

<table>
<thead>
<tr>
<th>Locality</th>
<th>Facies N°</th>
<th>Height above basement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Raudkleiv 1</strong></td>
<td>II</td>
<td>0,8 – 1,3 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2,8 – 4,3 m</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>1,3 – 2,8 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5,0 – 5,5 m</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>7,5 – 8,2 m</td>
</tr>
<tr>
<td></td>
<td>VII</td>
<td>8,2 – 8,3 m</td>
</tr>
<tr>
<td></td>
<td>VIII</td>
<td>17,5 – 20,4 m</td>
</tr>
<tr>
<td></td>
<td>IX</td>
<td>21,1 – 21,6 m</td>
</tr>
<tr>
<td><strong>Raudkleiv 2</strong></td>
<td>II</td>
<td>1,5 – 2,2 m</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>2,2 – 4,5 m</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>9,9 – 10,8 m</td>
</tr>
<tr>
<td></td>
<td>VII</td>
<td>10,8 – 11,0 m</td>
</tr>
<tr>
<td></td>
<td>VIII</td>
<td>12,0 – 13,2 m</td>
</tr>
<tr>
<td><strong>Raudkleiv 3</strong></td>
<td>I</td>
<td>0,0 – 0,3 m</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>0,3 – 0,9 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,8 – 3,2 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3,8 – 4,6 m</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>0,9 – 1,3 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3,2 – 3,8 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5,1 – 5,5 m</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>4,6 – 5,1 m</td>
</tr>
<tr>
<td></td>
<td>VI</td>
<td>7,6 – 8,3 m</td>
</tr>
<tr>
<td></td>
<td>VIII</td>
<td>9,5 – 13,0 m</td>
</tr>
<tr>
<td><strong>Raudkleiv 4</strong></td>
<td>III</td>
<td>7,5 – 8,3 m</td>
</tr>
<tr>
<td></td>
<td>VII</td>
<td>8,2 – 8,3 m</td>
</tr>
<tr>
<td></td>
<td>VIII</td>
<td>9,2 – 12,0 m</td>
</tr>
<tr>
<td><strong>Rekkjebrotet 1</strong></td>
<td>I</td>
<td>0,0 – 0,3 m</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>0,3 – 0,9 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4,5 – 5,1 m</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>0,9 – 1,5 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2,0 – 3,3 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3,3 – 4,5 m</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>10,5 – 10,8 m</td>
</tr>
<tr>
<td></td>
<td>VI</td>
<td>7,7 – 8,2 m</td>
</tr>
<tr>
<td></td>
<td>VII</td>
<td>8,2 – 8,3 m</td>
</tr>
<tr>
<td></td>
<td>VIII</td>
<td>11,3 – 11,8 m</td>
</tr>
<tr>
<td>Facies No</td>
<td>Facies</td>
<td>Grain size</td>
</tr>
<tr>
<td>-----------</td>
<td>---------------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>I</td>
<td>Conglomerate</td>
<td>Silt to pebble</td>
</tr>
</tbody>
</table>
| II        | Laminated siltstone / sandstone  | Silt to medium sand | Good sorting and laminated                                           | FA2 / 0,3 – 1,0 m  
                  |                                  |                              |                                      | FA2 / 3,0 – 3,7 m  
                  |                                  |                              |                                      | FA2 / 4,7 – 5,1 m  
                  |                                  |                              |                                      | FA2 / 6,0 – 6,4 m  |
| III       | Slightly bioturbated siltstone   | Clay to silt    | Clayey, laminated siltstone showing some evidence of bioturbation and water escape | FA2 / 1,0 - 1,5 m  
                  | with lamination and lenses       |                              |                                      | FA2 / 1,5 – 3,0 m  
                  |                                  |                              |                                      | FA2 / 3,7 – 4,7 m  
                  |                                  |                              |                                      | FA2 / 5,1 – 6,0 m  |
| IV        | Highly bioturbated siltstone     | Clay to very fine sand | Moderate to poor sorting, faint laminae and lenses                      | FA2 / 6,5 – 7,2 m  
                  |                                  |                              |                                      | FA2 / 9,2 – 9,8 m  |
| V         | Soft sediment deformed siltstone | Clay to very fine sand | Syn-sedimentary fold, flame structures                                | FA2 / 7,2 – 7,6 m  
                  |                                  |                              |                                      | FA2 / 8,3 – 9,2 m  |
| VI        | Calcite-rich siltstone           | Clay to very fine sand | Heavily bioturbated, faint laminae and lenses                          | FA2 / 7,6 – 8,2 m  |
| VII       | Silty sandstone                  | Silt to very fine sand | Upward coarsening                                                      | FA2 / 8,2 – 8,3 m  |
| VIII      | Ejecta layer: conglomerate with clayey to sandy matrix | Clay to boulder | Matrix-supported, undulating base, clast size decrease upward, sand content increase upward. Slightly folded in top. | FA3 / 9,8 – 13,1 m  |
| IX        | Silty shale                      | Clay to silt    | Fissile shale, pyrite-rich                                            | FA4 / 14,0 – 14,5 m |

Table i: The exact position of the various facies in each of the localities.

Table ii: Nine facies recognized in the stratigraphy with their respective characteristics, facies association and height above the basement.
## Appendix 3 Thin section descriptions

<table>
<thead>
<tr>
<th>Facies association</th>
<th>Sample</th>
<th>Height above basement</th>
<th>Lithology</th>
<th>Most common grain contact</th>
<th>Predominant structures</th>
<th>Average grain size</th>
<th>Sorting</th>
<th>Most common grain shape</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA1</td>
<td>MGH-1- 2-10</td>
<td>0 – 0,3 m</td>
<td>Conglomerate</td>
<td>Floating / tangential</td>
<td>Heterogeneous</td>
<td>Silt / very fine sand</td>
<td>Very poor</td>
<td>Sub-angular / sub-rounded</td>
<td>Largest clast ~2,2 cm (quartz) second largest is a gneiss clast, no dominant grain size, however, there is more silt than shale.</td>
</tr>
<tr>
<td></td>
<td>MGH-14-1-10</td>
<td>0 – 0,3 m</td>
<td>Conglomeratic sandstone</td>
<td>Concavo-convex, tangential and sutured</td>
<td>Heterogeneous</td>
<td>Medium sand</td>
<td>Moderate / poor</td>
<td>Sub-rounded</td>
<td>Two pebbles (6 – 7,5 mm, gneissic) floating in sandy matrix. Silt and shale also present. Largest grains most rounded.</td>
</tr>
<tr>
<td></td>
<td>MGH-6- 1-10</td>
<td>0 – 0,3 m</td>
<td>Conglomeratic sandstone</td>
<td>Floating / tangential</td>
<td>Heterogeneous</td>
<td>Medium sand</td>
<td>Well</td>
<td>Sub-rounded</td>
<td>Largest grains ~4 mm. Silty matrix, coarse, medium and fine sand dominate.</td>
</tr>
<tr>
<td>FA2</td>
<td>MGH-6- 2-10</td>
<td>0,5 m</td>
<td>Sandstone</td>
<td>Concavo-convex / saturated</td>
<td>Lamination / beds</td>
<td>Fine sand</td>
<td>Well</td>
<td>Sub-angular / sub-rounded</td>
<td>Laminae / beds of somewhat different mean grain size ranging from very fine to fine sand.</td>
</tr>
<tr>
<td></td>
<td>REK-1- 2-10</td>
<td>2,5 m</td>
<td>Siltstone</td>
<td>Floating</td>
<td>Moderate bioturbation</td>
<td>Silt / very fine sand</td>
<td>Moderately well / well</td>
<td>Angular / sub-angular</td>
<td>Some fractures. Faint lamination / lenses. Moderately bioturbated.</td>
</tr>
<tr>
<td></td>
<td>RAU-2- 5-10</td>
<td>2,7 m</td>
<td>Siltstone</td>
<td>Long</td>
<td>Parallel lamination</td>
<td>Silt</td>
<td>Moderately well</td>
<td>Angular</td>
<td>Lamine of silt and clay. Silt dominate. Clay cuts lamination; water escape structure. Possible bioturbation.</td>
</tr>
<tr>
<td></td>
<td>REK-2- 3-10</td>
<td>3,0 m</td>
<td>Siltstone</td>
<td>Long (some concavo-convex and sutured).</td>
<td>Lamination, fractured and folded. Bioturbation and possible water escape structure.</td>
<td>Silt</td>
<td>Very well</td>
<td>Sub-angular / sub-rounded</td>
<td>Fractured and folded. Bioturbation and possible water escape structures: Convolute lamination and flame structures.</td>
</tr>
<tr>
<td></td>
<td>REK-1- 7-10</td>
<td>7,0 m</td>
<td>Siltstone</td>
<td>Floating</td>
<td>Laminae / lenses</td>
<td>Silt</td>
<td>Moderately well / well</td>
<td>Angular / sub-angular</td>
<td>Framboidal pyrite occur right beneath clay-rich laminae. Chert present throughout sample in small amounts. Fracture fill in clay rich laminae parallel with bedding.</td>
</tr>
<tr>
<td></td>
<td>RAU-2- 9-10</td>
<td>7,5 m</td>
<td>Siltstone</td>
<td>Long / concavo-convex / saturated</td>
<td>Alternating laminae of silt and clay and very fine sand</td>
<td>Silt</td>
<td>Well / very well</td>
<td>Sub-angular / sub-rounded</td>
<td>Syn-sedimentary fold. Flame structures. Preferred orientation of elongated grains.</td>
</tr>
<tr>
<td></td>
<td>REK-2- 7-10</td>
<td>8,0 m</td>
<td>Siltstone</td>
<td>Floating</td>
<td>Bioturbation</td>
<td>Silt</td>
<td>Moderate / poor</td>
<td>Sub-angular</td>
<td>Faint laminae / lenses, moderate / heavy bioturbation</td>
</tr>
<tr>
<td></td>
<td>RAU-2- 6-10</td>
<td>8,5 m</td>
<td>Siltstone</td>
<td>Concavo-convex</td>
<td>Lamination of silt and very fine sand.</td>
<td>Silt</td>
<td>Well sorted</td>
<td>Angular / sub-angular</td>
<td>Load casts, flame structures, moderate bioturbation. Possible vertical burrow.</td>
</tr>
<tr>
<td></td>
<td>REK-2- 6-10</td>
<td>9,0 m</td>
<td>Siltstone</td>
<td>Floating</td>
<td>Bioturbation</td>
<td>Silt</td>
<td>Well / very well</td>
<td>Sub-angular / sub-rounded</td>
<td>Moderate bioturbation</td>
</tr>
<tr>
<td>Sample</td>
<td>Lithology</td>
<td>Position</td>
<td>Floating</td>
<td>Texture</td>
<td>Grain Size</td>
<td>Clay Content</td>
<td>Petrolgraphical Characteristics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-----------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>------------</td>
<td>--------------</td>
<td>-------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAU-4-1-10</td>
<td>9.5 m</td>
<td>Sandy and silty shale</td>
<td>Floating</td>
<td>Slightly laminated</td>
<td>Clay and fine / very fine sand</td>
<td>Moderate</td>
<td>Angular</td>
<td>~35 % clay, ~35% fine / very fine sand, ~30% silt. Largest grain 0.75 mm (feldspar). Laminae disturbed.</td>
<td></td>
</tr>
<tr>
<td>RAU-3-4-10</td>
<td>10.3 m</td>
<td>Conglomerate</td>
<td>Floating</td>
<td>Heterogeneous</td>
<td>Silt</td>
<td>Moderate / poor</td>
<td>Angular</td>
<td>Small amounts of clay throughout the sample. Coarse grains scattered, largest grain ~0.75 mm.</td>
<td></td>
</tr>
<tr>
<td>RAU-3-5-10</td>
<td>10.4 m</td>
<td>Gneiss clast</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAU-1-7-10</td>
<td>11.0 m</td>
<td>Matrix</td>
<td>Floating</td>
<td>Heterogeneous</td>
<td>Silt</td>
<td>Moderately well</td>
<td>Angular</td>
<td>~33% clay, ~33% silt, ~33% very fine sand. Grains show preferred orientation.</td>
<td></td>
</tr>
<tr>
<td>RAU-4-2-10</td>
<td>11.0 m</td>
<td>Clasts in matrix</td>
<td>Floating</td>
<td>Heterogeneous</td>
<td>Pebble</td>
<td>Poor</td>
<td>Sand: sub-angular. Pebbles: sub-rounded. Matrix: 25% very coarse -- very fine sand, 40-45 % silt, clay 25-35%. Matrix supported.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAU-2-8-10</td>
<td>11.0 m</td>
<td>Gneiss clast</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>REK-3-1-10</td>
<td>11.6 m</td>
<td>Gneiss clast with matrix</td>
<td>Floating</td>
<td>Fractured</td>
<td>Silt</td>
<td>Poor</td>
<td>Angular</td>
<td>Some spherical and elongate fragments missing, up to 3.5 mm in size (holes in thin section), rimmed by microcrystalline quartz (chert). Chert also present as fracture fill.</td>
<td></td>
</tr>
<tr>
<td>RAU-2-1-10</td>
<td>-</td>
<td>Gneiss clast in matrix</td>
<td>Floating</td>
<td>Heterogeneous</td>
<td>Silt</td>
<td>Moderately well / well</td>
<td>Sub-angular</td>
<td>~50 % silt, ~30 % clay, ~20% fine sand. Some preferred orientation of grains. A few granules (~2-4 mm) present in matrix.</td>
<td></td>
</tr>
<tr>
<td>RAU-4-3-10</td>
<td>12.0 m</td>
<td>Matrix</td>
<td>Floating</td>
<td>Slight lamination</td>
<td>Silt</td>
<td>Moderate</td>
<td>Sub-angular</td>
<td>Lamination of clay and silt. One zone rich in fine / medium sand. Largest grain is 3.5 mm. It looks to have sunken down and pulled other grains with it.</td>
<td></td>
</tr>
<tr>
<td>RAU-4-4-10</td>
<td>12.0 m</td>
<td>Matrix</td>
<td>Floating</td>
<td>Slight lamination</td>
<td>Silt</td>
<td>Poor</td>
<td>Angular</td>
<td>Largest grain ~2.5 cm (gneiss). Clay occur mostly as matrix, but also as lamination / fracture fill. Some microcrystalline quartz present.</td>
<td></td>
</tr>
<tr>
<td>RAU-1-8-10</td>
<td>12.0 m</td>
<td>Gneiss clast with matrix</td>
<td>Floating</td>
<td>Fractured</td>
<td>Silt</td>
<td>Poor</td>
<td>Angular / sub-angular</td>
<td>Largest grains in matrix are ~0.2mm. Some microcrystalline quartz is present.</td>
<td></td>
</tr>
</tbody>
</table>

Table iii: A complete thin section sample list with lithological and petrographical characteristics.
Appendix 4 XRD results

Table iv: Results from the XRD analysis. The mineralogical components of the samples are given in XRD%.

<table>
<thead>
<tr>
<th>XRD sample</th>
<th>Field sample</th>
<th>Quartz</th>
<th>Orthoclase</th>
<th>Microcline</th>
<th>Albite</th>
<th>Calcite</th>
<th>Apatite</th>
<th>Ankerite</th>
<th>Pyrite</th>
<th>Mica</th>
</tr>
</thead>
<tbody>
<tr>
<td>7073B</td>
<td>MCH-2-1-10</td>
<td>12.6%</td>
<td>1.03%</td>
<td>53.33%</td>
<td>25.52%</td>
<td>0.33%</td>
<td>1.68%</td>
<td>1.88%</td>
<td>1.54%</td>
<td>1.11%</td>
</tr>
<tr>
<td>7075B</td>
<td>MGH-10-3-10</td>
<td>13.92%</td>
<td>0.00%</td>
<td>61.59%</td>
<td>17.59%</td>
<td>0.85%</td>
<td>0.93%</td>
<td>3.04%</td>
<td>0.00%</td>
<td>1.68%</td>
</tr>
<tr>
<td>6758</td>
<td>RAU-3-1-10</td>
<td>38.37%</td>
<td>0.00%</td>
<td>30.81%</td>
<td>21.40%</td>
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Appendix 5 Impact craters

The Kärdla impact crater, Estonia

The Kärdla impact crater is an Ordovician shallow marine impact structure found on Hiiumaa Island, Estonia with a diameter of about 4 km (Suuroja et al., 2002; Suuroja and Suuroja, 2006). It is regarded as a well preserved impact structure. At the time of impact, the water depth is though to have been about 100 meters, while the impacting bolide was about 200 m in diameter. The target rocks consist of a crystalline basement overlain by 142 meters of sedimentary rocks.

The ejecta blanket is found to be continuous up to 15 crater radii (30 km) away from the crater center, see Figure A (Suuroja and Suuroja, 2006). Figure B the ejecta layer distribution together with the ballistically modeled ejecta distribution. The ejecta thickness distribution diverge from the ballistic model, being comparably thinner close to the crater and thicker outwards. This is a typical signature of a fluidized ejecta blanket (Maloof et al., 2010; see also description the Lonar crater below).

The ejecta layer is described as a 0.01 – 3.5 m thick sandy layer within the Ordovician carbonate rocks. The thickest ejecta layer encountered is 14 meters in core K-16 (Suuroja et al., 2002). However, this number includes resurge and turbidite material (S. Suuroja, pers. comm.). Excluding this core, the thickest ejecta deposit were found in core F370, being 6.40 meters thick and located 3 km east of the crater center. In the area around the crater, the ejecta deposits have been removed by resurge waves or short-term post-impact erosion (Figure A). The ejecta blanket is restricted to the north by the erosion escarpment of the Baltic Klint (Tammekann, 1940 in Suuroja and Suuroja, 2006).

Figure A: The Kärdla impact structure. Upper left: Map showing the position of the Hiiumaa Island. Right: Ejecta thickness distribution derived from cores. The white area in the middle is shows where ejecta has been eroded. The dark grey area indicates where the ejecta thickness is more than 1 meter. The lightest grey area indicates where the ejecta thickness is less than 0.1 meter. The dots mark bore holes. Figures modified from Suuroja and Suuroja (2006).
Figure B: The ejecta layer thickness distribution (blue line) around the Kärdla crater, Estonia (Data from Suuroja and Suuroja (2006)). A ballistic model is presented in red line. Note the logarithmic scale on the y-axis.
The Lonar crater, India

Fluidized ejecta blankets have not only been reported around Martian impact craters, but around impact craters on Earth as well. The 50 000 years old Lonar Crater in India is a simple crater, 1.88 km in diameter (Fudali et al., 1980; Maloof et al., 2010). The target rocks are basaltic and belong to the Deccan trap flood basalts. The ejecta distribution is reported to diverge strongly from the expected ballistic model, with a thinner ejecta blanket within 1.2 crater radii and thicker ejecta blanket between 1.5 and 3 crater radii (see Figure C; Maloof et al., 2010). A terminal rampart has also been observed, suggesting that the ejecta has been emplaced by a ground-hugging debris-flow, and thus been fluidized.

![Figure C: Ejecta distribution around Lonar crater, India. The solid black line shows the measured ejecta thickness profile of the continuous ejecta blanket around Lonar compared to the ejecta thickness profile for a typical fresh Martian crater (grey line). The dashed line shows the expected ballistic ejecta thickness formulated by McGetchin et al. It is clear that the ejecta blanket around Lonar is genetically more similar to Martian fluidized ejecta blankets than "dry", ballistic ejecta deposits. Figure by Maloof et al. (2010).](image-url)
The Ries impact structure, Germany

The Ries impact structure is a complex crater, 14.8 Ma old and measuring 22-24 km in diameter. The present crater floor is flat due to crater infill by fallback breccia as well as post-impact lake and alluvial deposits (Dennis, 1971). The target rocks consisted of a crystalline basement overlain by approximately 600 meters of Mesozoic sedimentary rocks.

The ejecta consist of both sedimentary and crystalline breccias which show an inverse stratigraphy, the oldest rocks are found uppermost in the ejecta layer and the youngest in the lowermost part. The ejecta layer averages 20-24 meters in thickness. The ejecta blanket is continuous up to three crater radii from the crater rim (Kenkmann and Ivanov, 2006). It is decreasing in thickness outwards, and the clast size decreases as well. According to Osinski (2006), the ejecta layer consist of 31 % primary ejecta excavated during impact and 69 % locally derived material in which the primary ejecta were incorporated into during deposition and mobilization.

The sedimentary Bunte breccia represents the most dominant ejecta deposit (Figure D; Engelhardt, 1990). Individual clasts some meters in size reside in fine grained matrix. Underneath the Bunte Breccia, striated and polished surfaces reveals that a debris surge have occurred after the ballistic deposition due to the ejecta being fluidized.

Between the inner ring and the crater rim, a “megablock zone” has been observed with the largest blocks being 100 meters or more in diameter.

Figure D: The extent of the present day Bunte Breccia marked in red. It is found to be continuous up to three crater radii from the crater rim. The center of the crater is marked in the middle of the picture. The patchiness of the deposits is mainly due to erosion, which have had greatest effect north of the crater. Figure modified from Engelhardt (1990).
The 2.5 km wide Martian Never crater is primarily investigated by using Google Mars and the JMARS (Java Mission-planning and Analysis for Remote Sensing) program (JMARS, 2011). Google Mars may be used to identify craters on Mars and investigate structures and deposits both within and outside craters. The Never crater is presented in Figure E with the ejecta blanket shaded yellow. JMARS was used to study the topography in and around the crater. A topographic profile from the crater rim and northwards is presented in Figure F. The Never crater is presented here as it is a prime example of a crater displaying fluidized ejecta.

Most of the ejecta around the crater displays a concentric pattern of low ridges and grooves as well as small craters in the distal edges of the ejecta. These features are characteristic of ballistic deposits on airless planetary bodies such as the Moon and Mercury. According to Carr et al. (1977), the ejecta blanket is expected to extend approximately 0.8 crater radii from the crater rim if emplaced ballistically. However, observations using Google Mars shows the average extent of the continuous ejecta from the crater rim is 2.7 km or 2.2 crater radii (Figure D). This suggests emplacement of ejecta by flow.

Furthermore, analysis done by the author with JMARS reveals a thickening outward trend of the ejecta blanket, ending in a rampart (Figure F). Similar profiles can be seen around other craters with volatiles present, see Figure B by Maloof et al. (2010). Such profiles are indicative that the ejecta has been fluidized at the time of emplacement.
The uneven, or lobe-like, extent of the ejecta is yet another signal that the ejecta has been fluidized.

Figure F: Topographic profile of the Never crater from the rim and northwards created by the author using JMARS. The steep rim is marked in blue, while the green line represents the thickening outward ejecta layer, ending in a rampart (red). This trend, found around most craters with volatiles present, is indicative that the ejecta was fluidized and has extended farther out than expected for "free flight" ejecta.
Acknowledgments

First of all I would like to thank my supervisor Professor Henning Dypvik for giving me the opportunity to write this thesis and for always being available for questions and discussions. His support and encouragement both in field and at the Department of Geosciences is very much appreciated. I also appreciate the support given by Elin Kalleson during all stages of this thesis; be it assistance during the field work and in the laboratory, or the many discussions and the feedback regarding both impact geology and geology in general. Her dedication to science is truly inspiring!

A special thanks to Fridtjof Riis for his valuable assistance in the field and for sharing his knowledge with me.

I would like to acknowledge Mufak Naoroz for his help with the preparation of the samples for XRD analysis, and Berit Løken Berg for her support with SEM analysis.

Special thanks go also to PhD student Abdus Samad Azad for his help with the petrographical analysis and for the discussions we have had.

The friendly people at Ritland deserve a thank for their hospitality during the field work.

The many coffee breaks with my fellow students at 217 (Andreas, Julie, Geir, Katrine, Håkon, Martine and Nicolai) are also highly appreciated and will be missed!

Last, but not least, I would like to thank my parents for their support, and a special thanks to Lotta for assisting me in the field and for being understanding and motivating during the entire master thesis year.