

Structural and petrographic characterization of the Mien impact structure, Sweden

Lara Schönherr

Dissertations in Geology at Lund University,
Master's thesis, no 728
(45 hp/ECTS credits)



Department of Geology
Lund University
2026

Structural and petrographic characterization of the Mien impact structure, Sweden

Master's thesis
Lara Schönherr

Department of Geology
Lund University
2026

Contents

1. Introduction.....	7
2. Background.....	7
2.1. Impact craters	
2.1.1. Formation	
2.1.2. Simple and complex craters	
2.1.3. Impactites	
2.1.4. Shock metamorphism	
2.2.5. Geophysical mapping of impact structures	
2.2. Geological setting	
3. Material and Methods.....	13
4. Results.....	15
4.1. Petrographic descriptions	
4.1.1. Lithic breccia	
4.1.2. Suevitic breccia	
4.1.3. Impact melt rocks	
4.2. SEM-analysis	
4.3. Mapping	
5. Discussion.....	18
5.1. Where is the crater located?	
5.2. How large could the crater be?	
5.3. What is Ramsö?	
6. Conclusion.....	24
9. Acknowledgments.....	25
10. References.....	25
Appendix.....	28

Structural and petrographic characterization of the Mien impact structure, Sweden

Lara Schönherr

Schönherr, L., 2026: Structural and petrographic characterization of the Mien impact structure, Sweden. *Dissertations in Geology at Lund University*, No. 728, 26 pp. 45 hp (45 ECTS credits).

Abstract: The Mien structure, a partly lake-filled depression in southern Sweden, was confirmed to be an impact structure in the 1960s. The structure formed about 120 Myr ago. Poor exposure of outcropping bedrock in and around the lake, due to a thick cover of glacial sediments, has made morphological mapping and impactite classification challenging. Constrains on crater diameter and morphological features such as the central uplift of the structure are solely based on geophysical measurements from the 1980s and 1990s. Impactites have been found as glacial boulders along the southern shore of Lake Mien and in drill cores retrieved from the island Ramsö in the central part of the lake. The latter are the only findings of in situ impactites. This study combines field mapping with a review of geophysical measurements, as well as petrographic and petrological analysis of sampled impactites and pre-existing thin sections from earlier studies on Mien. This has led to an allocation of the impact structure's centre and central uplift, constrains on the distribution of impact melt rock and the identification of Ramsö as a likely crater fill remnant. In this thesis two types of lithic breccia, two types of suevitic breccia and five types of impact melt rock have been identified. Findings of larger structural features, such as rim faults and radial fractures, that could assist the assignment of crater diameter and overall morphology, proved unsuccessful due to the advanced erosion of the impact structure and the poor access and quality of outcropping bedrock.

Keywords: Impact structure, Mien, impactites, structural morphology, shock metamorphism

Supervisor: Sanna Alwmark

Subject: Bedrock Geology

Lara Schönherr, Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden. E-mail: la8215sc-s@student.lu.se

Strukturell och petrografisk karaktärisering av astroblemet Mien, Sverige

Lara Schönherr

Schönherr, L., 2026: Strukturell och petrografisk karaktärisering av astroblemet Mien, Sverige. Avhandlingar i geologi vid Lunds universitet, nr. 728, 26 sid. 45 hp (45 ECTS).

Sammanfattning: Mienstrukturen, en delvis vattenfylld sänka i södra Sverige, bekräftades vara ett astroblem på 1960-talet. Strukturen bildades runt 120 miljoner år sedan. Dålig exponering av berggrunden i och runt sjön, på grund av tjocka lager glaciala sediment, har gjort geomorfologisk kartering och klassificering av impaktbergarter till en utmaning. Data angående kraterdiameter och morfologiska särdrag som exempelvis central uplift är enbart baserade på geofysiska mätningar från 1980- och 90-talet. Impaktiter har hittats i form av flyttblock längs sjön Miens södra strand, samt i borrhälsar från ön Ramsö som ligger i den centrala delen av sjön. De senare är de enda fynden av *in situ* impaktiter. Denna studie kombinerar kartering i fält med en granskning av geofysiska mätningar, samt petrografiska och petrologiska analyser av bergartsprover och redan existerande tunnklip från tidigare studier av Mien. Detta ledde till en lokalisering av kraterstrukturens centrum och central uplift, fördelning av impaktsmälta samt karaktäriseringen av Ramsö som sannolika rester av kraterfyllnad. Detta arbetet beskriver två typer av litisk breccia, två typer av suevitisk breccia samt fem typer av impaktsmälta. Storskaliga särdrag, som exempelvis förkastningar och radiella sprickor i berggrunden, kunde inte identifieras på grund av den fortskridna erosionen av astroblemet samt den svårtillgängliga och sig i dåligt skick befinnande berggrunden.

Nyckelord: Astroblem, Mien, impaktiter, geomorfologi, chockmetamorfos

Handledare: Sanna Alwmark

Ämnesinriktning: Berggrundsgeologi

Lara Schönherr, Geologiska institutionen, Lunds Universitet, Sölvegatan 12, 223 62 Lund, Sverige. E-post: la8215sc-s@student.lu.se

1. Introduction

Looking at the Moon, our closest object in space, its surface is heavily scarred from craters of all sizes (Fig. 1). The presence of an atmosphere only plays a minor part in the absence of the same abundance of crater structures on Earth, since it only obliterates the small projectiles. Far more important players are the presence of tectonics, erosion and vegetation on Earth that make the identification of impact structures challenging, if not impossible. However, the rising interest in this subject has generated extensive research, marking more and more craters on the map (e.g., Osinski *et al.*, 2022). The bias to geographical location of confirmed craters is large, since accessibility can differ immensely for different regions, both in terms of environmental factors, where oceans, ice sheets, dense forest and mountainous regions act as natural barriers for investigations, but also the human factors of infrastructure, conflicts and national interest (French, 1998; Osinski *et al.*, 2022). There are two major factors that contribute to the importance of studying impact events: 1) meteorites and asteroids carry valuable information on the formation of the solar system and the early history of our planet, since their chemistry and rock composition mirror those of the undifferentiated and primary bodies of the early solar system, and 2) the undeniable significance these events had on life throughout time, the most well-known case being the impact event that is credited for the extinction of the dinosaurs 65 million years ago (Alvarez *et al.*, 1980). However, meteorites are not just regarded as a destroying factor but also as a possible origin of life, one of the major theories on that matter being the bombardment of the young planet Earth with extraterrestrial bodies carrying organic molecules (e.g. Glavin *et al.*, 2009). The extent of our society and infrastructure mostly generates an interest in the factor of a possible catastrophe and its potential prevention.

The unusual nature of the rock types found around Lake Mien in southernmost Sweden (Fig. 2) had sparked interest already at the end of the 19th century but were labelled as volcanic and the almost circular lake was believed to be the rather recent remains of a caldera until the mid-20th century (Holst, 1890; Eskola, 1931; Asklund, 1931). The bedrock in the area originates from the Blekinge-Bornholm Orogeny, ~1.8 Ga, as part of the Transscandinavian Igneous Belt (TIB) (Wik *et al.*, 2009), and consists of different granitoids, such as granite, monzodiorite and granodiorite, as well as rhyolite in the northern part of the lake (Wik *et al.*, 2009). Breccia, both lithic and suevitic, as well as impact melt rocks can be found among glacially deposited rocks and boulders on the southern shore of the lake and were first confirmed as such when findings of coesite and shocked quartz proved the impact origin of the Mien structure in 1965 (Svensson & Wickman, Engelhardt & Stöffler, 1965). A detailed study of the Mien impact structure was performed by Stanfors (1973), who, despite the confirmed presence of shock metamorphism and typical impactites, did not take a clear stand on the formation of the structure. Stanfors (1973) and other older works refer to the impactites as “Mien-rhyolite”,



Figure 1. The surface of the Moon, paved with impact craters of all sizes. Photo: NASA

which should not be confused with the actual rhyolite that covers a large area at the northern shore of the Mien Lake. In 1978 the first age estimate of the Mien structure was presented (Bottomley *et al.* 1978), which indicated an age around 121 Ma. Geophysical measurements (magnetic, gravimetric and seismic) of the Mien structure were conducted in the 1980s and 1990s (Henkel, 1982; Åström, 1996 & 1998). The presence of reidite and FRIGN (‘former reidite in granular neoblastic’) zircon in the Mien impactites was confirmed by Martell *et al.* (2021) and a study aiming to obtain a U/Pb age from shocked zircon at Mien was published in 2024 (Herrmann *et al.*, 2024).

This MSc project aims to combine old and new knowledge on the Mien structure and review its morphology and petrology, with the background of 50 years of intense research and new insights on impact crater formation. This included fieldwork for characterization of the bedrock around the lake and to collect samples for petrographic description in addition to the existing ones from former studies. The main questions this study aims to answer is the exact location of the original crater, its extent and the identification of the confirmed remnants within the impact structure.

2. Background

2.1. Impact craters

Impact craters on Earth are formed when a projectile passing through the atmosphere without a decrease in original cosmic velocity (i.e., hypervelocity impact; e.g., French, 1998; Osinski *et al.*, 2022) collides with the surface. This requires a certain size and material coherency, since smaller projectiles are slowed down by the friction caused by the air resistance in the atmosphere (French, 1998). The energies transmitted into the target through shock waves by a hypervelocity impact are immense and even small impacts exceed those of thermonuclear weapons significantly (French, 1998). Within an exceptionally small timeframe, sec-

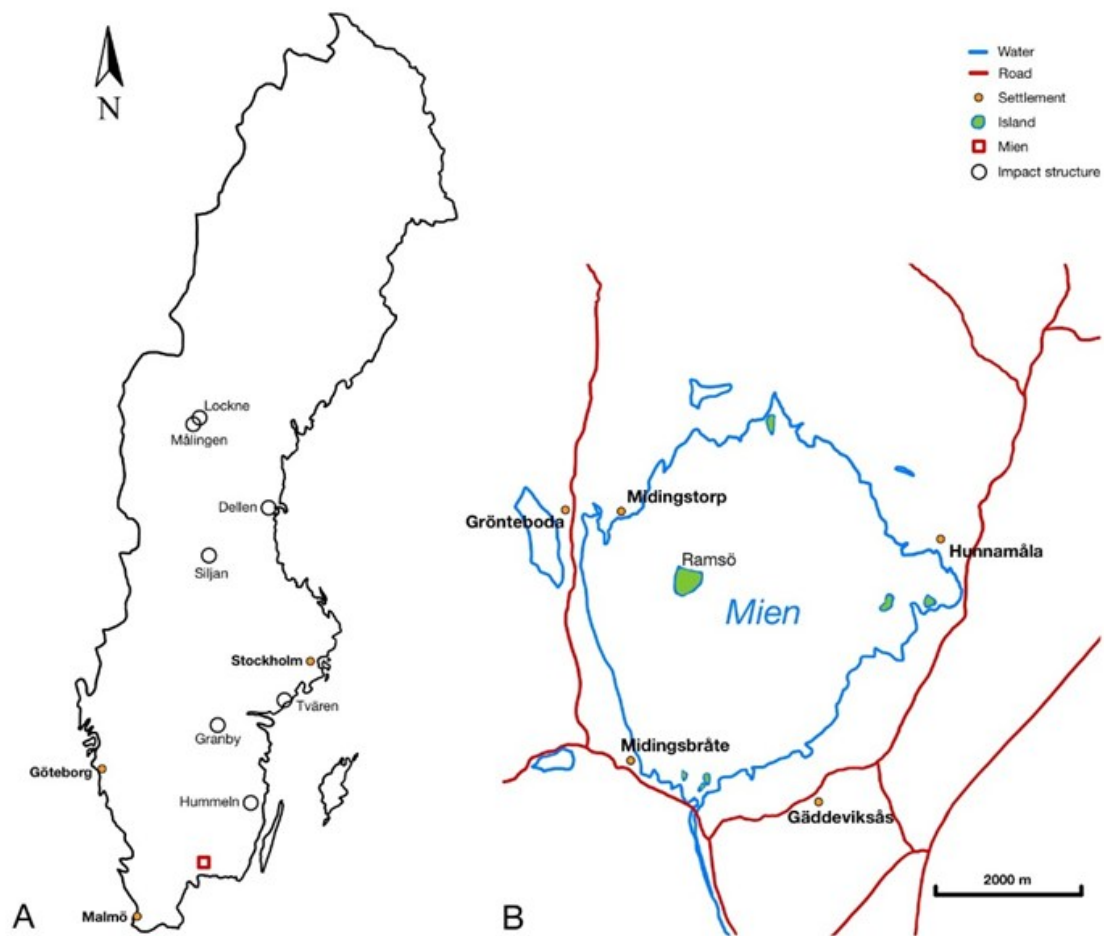


Figure 2. Map of Sweden and all its confirmed impact structures (A) as well as a close-up map of the Mien Lake and its location in Sweden (B). Data from Lantmäteriet and Holm-Alwmark (2021).

onds at most, the underlying bedrock is exposed to extremely high pressures, up to several 100 GPa, which yields a unique type of metamorphism referred to as *shock metamorphism*. Products of shock metamorphism include shatter cones, high pressure polymorphs of already existing minerals in the bedrock, amorphous phases and shock features within mineral grains, such as planar deformation features (PDFs). Such structures are crucial for the correct identification of impact craters. Larger features include extensive brecciation of the surrounding rocks. The heat generated by the shock waves results in extensive melting during pressure release, leading to metamorphic features such as flow textures, partial melting, decomposition of mineral grains and recrystallization (French & Koeberl, 2010; Stöffler *et al.*, 2018).

2.1.1. Formation

A hypervelocity impact requires a projectile with cosmic velocity, also referred to as escape velocity, meaning >11 km/s for Earth. This demands a minimum diameter of >20 m for metal projectiles and >50 m for stony projectiles in order for the object not to lose speed to the air resistance in the Earth's atmosphere (French, 1998). The moment it hits the Earth's surface

the energy of the object is transferred into the target by a shock wave. Another shock wave will travel back into the projectile. When this reaches the back end of the object it transforms into a so-called release wave that unloads the projectile, which leads to its complete melting or vaporization. The target rock is likewise released of the high shock pressures and consequently large rock masses will melt and/or vaporize. The process also leads to fracturing and brecciation. The shock wave that is transmitted into the ground by the impact expands hemispherical in all directions, which, together with deformation and heating of the target rocks, causes it to lose energy exponentially with increased distance to the source. While pressures at the point of impact can peak at several 100 GPa the intensity is reduced to eventually correspond to seismic waves. Therefore, the surrounding rocks exhibit hemispherical shock zones with different grades of deformation according to the peak pressures the shock wave had when passing through (French, 1998; Kenkmann *et al.*, 2014). The extent of these zones depends on many aspects, including the size of the projectile and the target rock characteristics. Unequivocal shock metamorphic features are found within a more limited radius from the target point, since this process requires minimum pressures at 2 GPa (French, 1998; French &

Koeberl, 2010). Brecciation, fracturing and faulting of the bedrock can extend far beyond the zone of shock metamorphism (French, 1998). Fracturing and faulting can be the product of simple seismic waves, which for the largest impact events can extend notably around the entire planet (French, 1998). However, these processes are in retrospect difficult to connect to impact events rather than normal tectonics. Shock wave decay can be reconstructed to form a hemispherical pattern around the point of impact, not only covering a large surface area but also reaching deep into the lithosphere (French, 1998; Kenkmann *et al.*, 2014). The deepest lying rocks of an impact structure can become exposed after long-time weathering and make even very old craters identifiable, one example being the Yarrabubba impact structure in western Australia with an age of 2,2 billion years (Erickson *et al.*, 2020).

Shock waves interacting with the target bedrock results in a complicated excavation flow that results in the opening of the bowl-shaped crater structure. While the projectile initiates the cratering process by penetrating the ground around two times its own diameter, the shock waves interact with the target rocks in such a way that these are shattered and kinetic energy obtained from the conversion of shock waves throws the remnants outwards (French, 1998). Melted and brecciated rock is heavily mixed and moved, some of which even outside of the crater, and some can be lifted into the air as ejecta and deposited inside and beyond the crater structure.

The diameter of an impact crater is generally 20-30 times the diameter of the original projectile, while the maximum depth is approximately one third of its diameter for simple craters and 1/10 for complex craters (French, 1998; Kenkmann *et al.*, 2014). The bowl-shaped depression that forms after impact is called the transient crater and refers to the unstable structure prior to collapse of the rim and other gravity-driven modification. When shock waves can no longer continue to grow the transient crater, gravity takes over and causes further modification of the structure (French, 1998). Together, these processes require a maximum time of a few minutes. The final crater structure is of course modified by erosion throughout its existence but the time frame from the moment of impact to final crater is a mere instant from a geological perspective.

2.1.2 Simple and complex craters

Impact structures have different morphologies, mainly governed by gravity, size of projectile, and target characteristics. The smallest hypervelocity impact craters, at most a few kilometres in diameter and formed by projectiles not larger than 200 m across (French, 1998), create bowl-shaped depressions in the ground, which are known as simple craters (Fig. 3). Meteor (or Barringer) Crater in Arizona is a schoolbook example of a simple crater (Kenkmann *et al.*, 2014). As the crater diameter increases, however, the degree of structural collapse and gravitational rebound increases, and thus larger structures are known as complex craters (Fig. 3) (French, 1998). The simple to complex crater transition on Earth happens at about 2 km and 4 km respectively for loose

sediments and crystalline bedrock (Grieve, 1987). These numbers are based on calculations and observed craters, however, exceptions such as Goat Paddock Crater in Australia, a ~5 km crater structure in sandstone that is neither typically simple nor complex (Milton & Macdonald, 2005), do exist. The essential difference to simple craters is the complex movement of the sub-crater rocks induced by a large enough amount of energy, which in interaction with gravity, surpasses the strength of the target rocks (French, 1998). A complex crater displays less of a bowl-shape and more of a flat plain bordered by an elevated, highly faulted rim. A characteristic feature of a complex crater is the central uplift, a result of the bedrock underneath the point of impact rebounding after excavation of the transient crater, in a sort of elastic response (Ferrière *et al.*, 2008; Koeberl, 2009). These types of impact craters therefore often exhibit a peak in their centre, their distinctiveness naturally varying with the level of erosion that has occurred. With growing diameter, the central peak will display a small basin in its centre and for even larger structures it will transform completely into a so-called peak ring structure (French, 1998). The largest structures, >100 km in diameter on Earth, exhibit complex sets of rings, and are called multi-ring basins (French, 1998). The formation of a complex crater is often illustrated with a droplet or solid object penetrating a liquid surface, since the resulting cavity, followed by an upwards splash of liquid, as the result of rebound, and the spherical waves radiating outwards from the point of impact can be applied to the ground movements during an impact event (Melosh, 1989; French, 1998). The difference is the material; hence the bedrock does not realign with the original flat surface when all the energy has been distributed but stays frozen in the excavated position. The mechanisms behind this process, especially the formation of a central uplift, have yet to be fully described (e.g. Kenkmann *et al.*, 2005; Koeberl, 2009). Detailed studies of the fracturing and deformation of central uplifts have introduced several theories connected to strength reduction of the target rocks, including frictional melt and acoustic fluidization, where rock debris acts like a liquid due to very strong ground vibrations (Melosh, 2015). The main difficulty in establishing a general theory behind cratering processes is the uniqueness of each case, where projectile size, target location and rock properties play an important role during the crater formation and for the morphology of the final crater (Kenkmann *et al.*, 2014). Faulting connected to impact, in all parts of the crater, has been proven to be quite different in sedimentary rocks compared to crystalline basement rocks (Kenkmann *et al.*, 2014). The same goes for the morphology of the crater at different sizes and for the morphology of the central uplift (Kenkmann *et al.*, 2014). Mechanisms behind the formation of a central uplift may also vary with size of the projectile. Melt formation may play an important role in the strength reduction and central uplift formation in larger structures while it's not sufficient in smaller complex craters (Melosh, 2015). In contrast there are also structures large enough to exhibit a central uplift yet have none. The Ries structure in Germany is one such example (McCall,

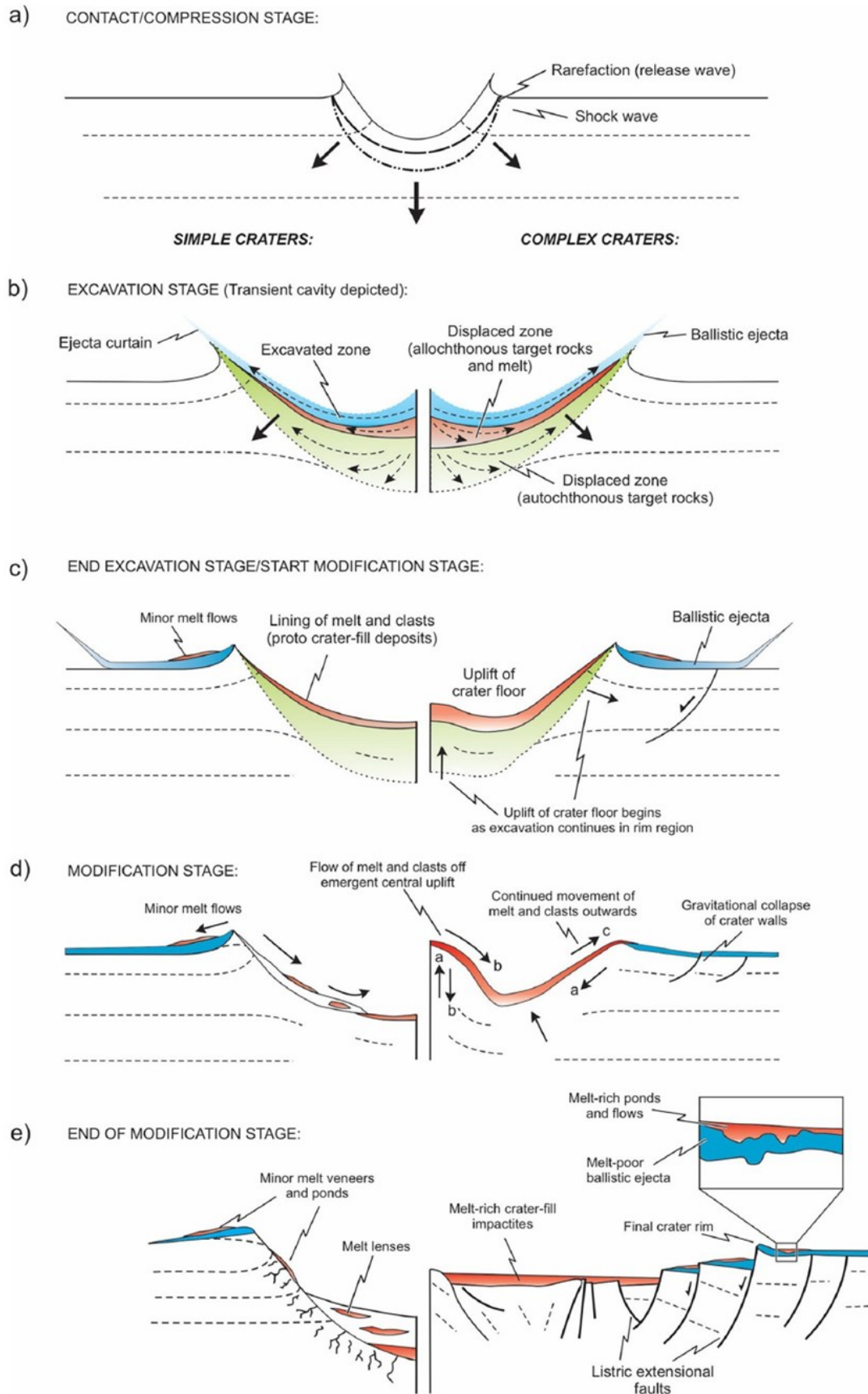


Figure 3: The different stages of the formation of an impact crater, simple crater to the left and complex crater to the right. The figures show both the differences in morphology and impactite distribution (stratigraphy) of the two types. From Osinski *et al.* (2022).

2023). A possible explanation is that the size of the Ries crater is in a transition zone between a central peak and a peak ring structure, which has led to the collapse of the peak, but the dynamic outward movement did not exhibit forces strong enough to create an uplifted ring structure (McCall, 2023).

Multi-ring basins can be over a 1000 km in diameter and most date back to the early stages of the solar system when collisions between large objects were more common. There are three possible terrestrial impact structures that are large enough to candidate as multi-ring basins: Vredefort in South Africa, Chicxulub in Mexico and Sudbury in Canada. Several studies imply each of these to exhibit multi-ring features (e.g. Deutsch *et al.*, 1995; Morgan & Warner, 1999; Grieve & Theriault, 2000). The major problem with both Vredefort and Sudbury is the deep erosion both structures have experienced due to their age of 2020 and 1850 Ma respectively (Grieve & Theriault, 2000). Chicxulub on the other hand is in relation a very young (65 Ma (Jourdan *et al.*, 2009) and well-preserved, although buried, structure and has been the subject of several in-depth seismic studies and 3D mapping projects (e.g. Morgan & Warner, 1999; Gúzman-Hidalgo *et al.* 2021). These studies favour a multi-ring structure but show reluctance in comparing it to extraterrestrial, such as lunar, multi-ring basins (Morgan & Warner, 1999). Morphological studies of multi-ring basins are entirely based on planets and moons of our solar system, where the lack of running water, strong winds and drastic temperature changes as well as the lack of an atmosphere entirely leave surfaces almost untouched and structures visible over vast periods of time. Venus and the Moon are such examples. However, significant gravitational differences as well as the inner structure of planets and moons must be considered when applying these measures to Earth (French, 1998; Morgan & Warner, 1999).

All these processes and the different resulting structures naturally raise the question of how to determine the size of a crater. The term crater diameter is neither easily definable in the field nor as a theoretical concept (Turtle *et al.*, 2005). Terms like transient crater diameter, rim diameter, true crater diameter and apparent crater diameter make crater descriptions rather hard to navigate through. The same goes for central peak diameter, central uplift diameter, true depth, apparent depth and rim height. Most of these are connected to different stages of erosion (Turtle *et al.*, 2005). Transient crater diameter is the size of the bowl-shaped depression that collapses to form the final impact crater, in other words, one that is unknown in most cases. Rim diameter is the rim-to-rim diameter of the crater at any stage of erosion. True crater diameter is mostly referred to as the border between deformed and undeformed rock around a crater structure (Turtle *et al.*, 2005). In contrast there is the apparent crater, the crater size according to features visible at the surface, for example the outermost continuous concentric faults (Turtle *et al.*, 2005). These features change significantly with time and ongoing erosion and can be hard to correlate with the original rim. As for the true depth and apparent depth the difference is that true depth is measured

from the original, pre-impact ground surface and down to the surface underneath infill, ejecta and plume deposits. Apparent depth is from the original ground surface to the visible bottom of the crater. Central peak diameter is the diameter of the visible uplifted peak structure in the centre of a complex crater (Turtle *et al.*, 2005). Once this peak is eroded and only a general uplift of bedrock in relation to the surroundings can be determined, the surface diameter of this uplift is referred to as central uplift diameter.

2.1.3 Impactites

Impactites, all rocks produced or deformed by impact events (French, 1998), can be difficult to identify as such despite their unique formation conditions. Breccia, melt-bearing rocks and pseudotachylitic breccia all more or less have counterparts among the rock types formed via endogenic processes on Earth and a definite identification requires evident shock metamorphic features in order to exclude other means of formation (French & Koeberl, 2010). However, not all impactites show definite signs of shock deformation and their identification relies on larger structures related to impacts or proximal rocks featuring evident shock metamorphism (Stöffler *et al.*, 2018). The nature of impactites varies with location of formation within the crater, size of the projectile and target rock properties (Stöffler *et al.*, 2018). The latter plays an important role in the inconsistency of impactite classification (Stöffler *et al.*, 2018). The combination of unique projectile size and unique target rock properties for every crater has continuously sparked debates when generalizing impactite formation mechanisms and properties (Stöffler *et al.*, 2018). Overall, impactites include breccia, melt rocks, massive bedrock, ejecta and vapour plume deposits, and are classified depending on place of origin, extent of transport before deposition, melt/glass content and if they are shocked or unshocked (Stöffler *et al.*, 2018). Impactites within the crater structure are divided into parautochthonous, referring to the subcrater rocks experiencing minimum displacement, possibly moved as larger blocks, and allochthonous, which occur as dikes, crater-fill and ejecta and have been broken up and excavated (Stöffler *et al.*, 2018). Distal ejecta deposits found outside the crater structure comprise highly shocked clasts of melt and glass (Stöffler *et al.*, 2018). Melt content in impactites classifies the rock as either a lithic breccia, suevitic breccia (also referred to as melt-bearing breccia), or impact melt rock (from least to most amount of melt).

Breccia are classified based on melt proportion, fragment lithology and matrix character. Lithic breccia contain only rock- and mineral fragments within a clastic matrix (Stöffler *et al.*, 2018). These are common among the parautochthonous sub-crater rocks (monomict) and in the allochthonous outer parts of the crater (often polymict, depending on the local lithology) (Stöffler *et al.*, 2018). Melt-bearing breccia are differentiated depending on if the melt appears solely as fragments or if it acts as a matrix. If the melt appears as fragments the rock type is referred to as suevitic breccia, a polymict lithic breccia containing fragments of melt and/or glass, with varying degrees of shock metamorphic components (Stöffler *et al.*, 2013).

Such types of rocks can occur both inside the crater structure and outside, and are classified accordingly (Stöffler *et al.*, 2013). The type locality for suevitic breccia or “suevite” is the Ries impact structure in Germany, although the application of the term “suevite”, as defined by the rocks found at Ries, to general impact melt-bearing breccia is debated (Stöffler *et al.*, 2013) and the term “suevitic breccia” is therefore used. Suevitic breccia (melt-bearing breccia) have consistently been found in most impact structures present within crystalline silicate bedrock, where lasting bodies of melt and glass are able to form. Impactites that consist of mainly melt and/or glass and only contain few lithic fragments are classified as impact melt rocks.

Impact melt forms during two processes: (1) pressure unload of the projectile and target rocks when the energy of the shock waves is converted into heat and (2) frictional melting during the displacement and faulting of target rocks (Kenkmann *et al.*, 2014). Temperatures naturally vary with projectile size and shock pressures and the amount of melt produced is dependent on temperature as well as target rock type (Stöffler *et al.*, 2018). Sedimentary rocks generally experience whole-rock melting at significantly lower temperatures than crystalline rocks, both felsic and mafic, due to their porous nature (Stöffler *et al.*, 2018). The porosity, however, also favours the production of highly vesicular melt portions that are easily ejected to the outer parts of the crater or dispersed in the vapour plume and sedimentary targets therefore do not necessarily yield more melt (Kieffer & Simonds, 1980; French, 1998; Stöffler *et al.*, 2018). Impacts into hard crystalline bedrock usually form more or less coherent impact melt sheets, even in smaller craters, although significantly less melt is produced in simple craters than complex craters and much of it is ejected (Osinski *et al.*, 2022). For larger impacts, melt sheets with a thickness of several kilometres can form (Kring, 1995; Osinski *et al.*, 2022), including the melt flowing beyond the rim of the crater. Since the melt forms instantaneously after impact the volume is immediately dislocated by the shock waves and driven outwards and upwards. When moved across the floor, while cooling, lithic fragments are incorporated, forming separate units of impact melt rock and melt-bearing breccia. Impact melt rocks are in many cases similar to volcanic rocks, both on the smaller scale and in larger features like columnar jointing of thick melt sheets (Kenkmann *et al.*, 2014; Osinski *et al.*, 2022). The distinctively different formation processes are however evident as impact melt rocks include shock-metamorphosed minerals, exhibit chemical disequilibrium as well as rare chemical compositions and element signatures from the projectile. They also lack typical volcanic features, such as feldspar and quartz phenocrysts as well as mantle xenoliths. Instead, the rocks mirror the lithology of the surface rocks at the impact site (French, 1998).

2.1.4 Shock metamorphism

Definitive indicators of shock metamorphism are the most important identification factors concerning the existence of an impact structure. These form as a response to the extreme conditions induced by the colli-

sion (French, 1998). As a comparison, normal pressures during rock formation and metamorphism within the Earth usually do not exceed 3 GPa, while impact pressures can reach several 100 GPa (French, 1998). The first unique shock-metamorphic features form at around 2 GPa, so called shatter cones, which are also the only macroscopic attributes (French & Koeberl, 2010). Increasing shock pressures lead to the formation of planar fractures, planar deformation features in quartz and feldspar, diaplectic glass, high pressure polymorphs, partial and complete melting of mineral grains and eventually complete vaporization at more than 100 GPa (Kenkmann *et al.*, 2014). Shatter cones are conically fractured pieces of rock, ranging from a few centimetres to several meters in size (French, 1998). There is no bias to the type of rock in which they form but the distinct striations radiating from the top of the cone are more pronounced in fine-grained rocks (French & Koeberl, 2010). The first microscopic unequivocal evidence of impact to form are planar fractures (PFs), parallel fractures in silicates such as quartz, feldspar and zircon that form around 5-8 GPa (French & Koeberl, 2010; Osinski *et al.*, 2022). Planar deformation features (PDFs) start to form in quartz grains at about 10 GPa (French & Koeberl, 2010) and are parallel sets of thin amorphous planes in the crystal lattice that are oriented along rational crystallographic planes (French, 1998; French & Koeberl, 2010). At higher pressures, from around 30 GPa (French & Koeberl, 2010; Osinski *et al.*, 2022), the entire mineral grain is transformed into an amorphous state, so-called diaplectic glass. In contrast to glass formed from temperature-induced melting the original texture and fabric of the grain is kept, however, making it optically isotropic when examined through a microscope. Once the shock pressures reach ~45-60 GPa (French & Koeberl, 2010; Kenkmann *et al.*, 2014) the heat induced is more than 900°C, which is beyond the melting point of several minerals, such as quartz and feldspar. At these shock pressures, selective melting starts to happen (French, 1998; French & Koeberl, 2010). This process is significantly different from the partial melting happening at equilibrium conditions within the Earth. Because of the immediate induction of heat the entire mineral grain will melt instantaneously, together with all grains of the same kind, and produce melting textures at respective spots in the rock while other minerals are undisturbed (French, 1998). At shock pressures high enough to retain elevated temperatures for a longer period of time, normal eutectic melting at the rims of mineral grains may occur. Above 60 GPa the temperatures reach beyond 1500°C in crystalline rocks (significantly lower shock pressures are required to reach these temperatures in porous sedimentary rocks and sediments) (French & Koeberl, 2010) and complete melting takes place. Above 80-100 GPa the rocks are vaporised and result in glasses formed through condensation of the vapor plume (French, 1998).

Except for shock-induced textures and fabrics, high-pressure polymorphs can act as indicators for impact-induced pressure conditions. Some high-pressure mineral polymorphs are unique for impact events due to extremely high pressures required for formation, while others also can be found in deep-mantle rocks and

need to be more carefully considered (French & Koeberl, 2010). Common polymorphs used as indicators are the two SiO₂-polymorphs coesite and stishovite, as well as diamond (French & Koeberl, 2010). Out of these three, stishovite is the most reliable indicator, and almost all findings are related to impact events, with only a few findings in ultra high-pressure mantle rocks (French & Koeberl, 2010). Coesite and diamond require less pressure and are found in naturally occurring rocks formed in high P-T environments (French & Koeberl, 2010). The shock pressures at which specific high-pressure polymorphs are formed differ with target rock type, induced heat and melt formation (Stöffler *et al.*, 2018). Over the years a wide range of different minerals have been found to produce distinctive high pressure polymorphs during impact events, among them zircon (reidite), rutile (riesite) and other oxides, feldspars and garnet (Miyahara *et al.*, 2021).

2.1.4 Geophysical mapping of impact structures

Apart from impactites and shock-metamorphic features in minerals, the structural and petrological features of impact structures can be detected through geophysical analysis (Pilkington & Grieve, 1992). Geophysical anomalies do not apply to all impact structures, but a significant number showcase either one or several of gravimetric, magnetic and seismic anomalies (Pilkington & Grieve, 1992). Impact craters usually feature a negative gravimetric anomaly, due to the brecciation and fracturing of the bedrock as well as the later sediment infill of the bowl-shaped structure, since these have lower density than the surrounding rocks (Pilkington & Grieve, 1992). Magnetic anomalies are significantly less consistent because they depend on several different factors, such as the lithology of the target rocks, melt generation and the ability to obtain remanent magnetization (Pilkington & Grieve, 1992; Cowan & Cooper, 2005). Central uplifts in complex crater structures may generate magnetic anomalies when exposing magnetic rocks at the surface (Pilkington & Grieve, 1992). Impact melt sheets often show high magnetic anomalies through processes like shock de- and remagnetization as well as thermal and chemical induced remanent magnetization (Cowan & Cooper, 2005). Seismic studies have an important role in the subsurface mapping of impact structures, as they repeatedly show specific patterns depending on the location within the structure, such as incoherence of reflectors in heavily fractured terrain, regular faulting at the edges of the crater and continuous reflectors determining the unaffected bedrock outside of the structure (Pilkington & Grieve, 1992). The mapping of shocked bedrock may also be obtained through resistivity measurements, with lower resistivity in fractured areas (Pilkington & Grieve, 1992).

2.2 Geological setting

The Mien impact structure is located in the region of Småland, approximately 30 km north of Karlshamn, in southern Sweden (Fig. 2). A circular lake fills up parts of the estimated crater depression, between 4,5 and 5 km in diameter (Åström, 1996), the island Ramsö is

situated in the western, central part. The original size of the crater is calculated to be around 9 km in diameter (Åström, 1996). Any extensive mapping of the impact structure has been proven difficult due to the rather thick layers of till, between 5-30 m, around the lake and 3-10 m on Ramsö (Stanfors, 1973; SGU, 2025), a maximum lake depth of 39 m (SMHI, 2025) as well as a significant amount of lake sediments. The material retrieved for previous studies originates from five cores drilled on Ramsö and from a trail of glacially deposited boulders just south of the southern shore of the lake (Stanfors, 1973). Glacially deposited impactites have only been found around the southern part of the lake, likely due to the north-to-south ice movement during the last glacial maximum (Stanfors, 1973; SGU, 2025d).

There is an incoherent circular, positive magnetic anomaly underneath the lake, the strongest signal being located underneath the island Ramsö (Wedmark, 2012). The Mien structure also exhibits a negative gravimetric anomaly, its centre coinciding with the centre of the lake (Henkel, 1982). Seismics have measured disruptions in the bedrock within an area of 15-17 km in diameter around the centre of the structure. Based on these measurements, the diameter of the original crater has been estimated at 9 km (Åström, 1996, 1998).

A drilling campaign was performed on Ramsö between 1963 and 1967, producing five cores between 8 m and 74 m in length (Stanfors, 1973). The two cores drilled in 1964 penetrate through the between 30 and 40 m thick layers of impactites and breccia down to the heavily weathered and crushed granitic basement rocks. Stanfors' (1973) description of the rocks from the cores indicate, in ascending order, a stratigraphy of lithic breccia, suevitic breccia and impact melt rock, which would suggest the rock types being in situ, since they follow the expected stratigraphy of an impact structure deposit (cf. Stöffler *et al.*, 2018, Osinski *et al.*, 2022). Stanfors (1973) reported five different varieties of impact melt rock and two varieties of suevitic breccia from the drill cores. The variations are determined by different amounts of melt, rock fragments, glass and the fabric and texture of each sample. Previous studies of the Mien structure have identified PDFs (Planar Deformation Features) in quartz and zircon as well as high-pressure polymorphs of both minerals (coesite and reidite) (Engelhard & Stöffler, 1965; Martell *et al.*, 2021). Several attempts of obtaining an age of the Mien impact structure have been made, ranging from 121 to 92 Ma (Storzer 1971; Welin, 1978, Bottomly *et al.* 1978; Schmieder & Kring, 2020; Herrmann *et al.*, 2023). According to Jourdan *et al.* (2009) the best age estimation for Mien is 121 ± 2.3 Ma (~Barremian-Aptian boundary), obtained through ⁴⁰Ar/³⁹Ar dating by Bottomley *et al.* (1978). U/Pb dating of shocked zircon by Herrmann *et al.* (2024) yielded a similar age, 120.0 ± 1.0 Ma. However, all attempts to date the impactites at Mien have confirmed large uncertainties, both in age and concerning the applied methods.

3. Materials and methods

Two days of field work were conducted at Lake Mien, one for collecting samples of impactites and one for

mapping and classifying the outcropping bedrock around the lake. Fieldwork and sampling was facilitated by SGU maps for bedrock and Quaternary deposits (Wik *et al.*, 2009; Malmberg Persson, 2010). The bedrock map displays expected rock type and thus facilitates the identification of any deviations, and the

map of Quaternary deposits shows the location of outcropping in situ bedrock. All outcrops within 1 km of the lake were visited, including a few additional locations within 2 km where no closer option was available, in total ten locations (Fig. 4). 10-15 samples of impactites were collected at the southern shore of

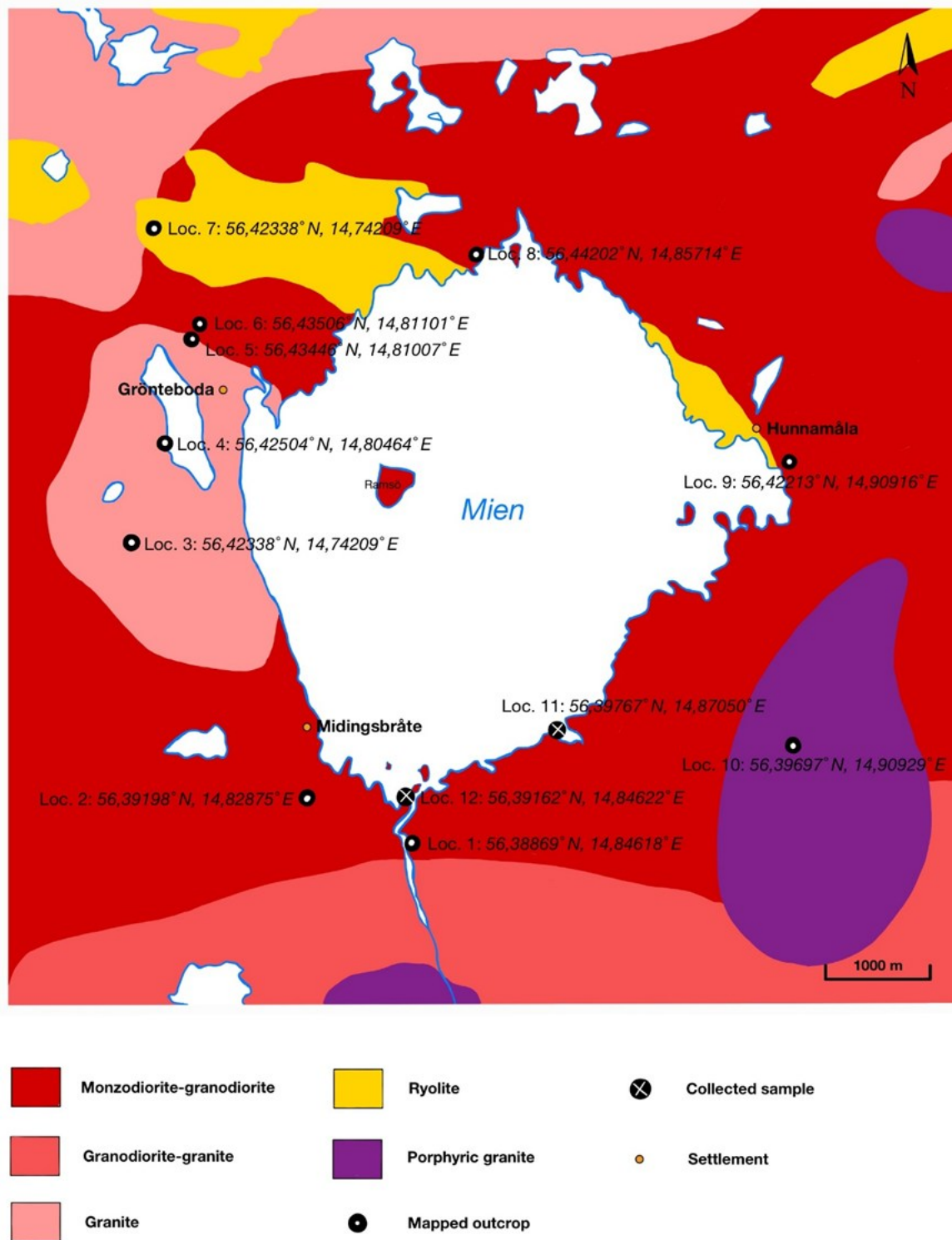


Figure 4: Bedrock map with marked locations and coordinates of visited outcrops around the lake, as part of the attempted mapping of the impactites within this project. Map data from SGU (Wik *et al.*, 2009) and Lantmäteriet.

the lake (Fig. 4). The collected hand specimens consist of transported glacial boulders. Six thin sections were cut from two of the samples; three from a suevitic breccia and three from an impact melt rock. The thin sections were cut to include as large of a variety of features incorporated in the different rock types as possible, such as different types of clasts as well as the finer ground mass. Cutting was limited by the brittle nature of the rocks, especially the suevitic breccia. A fraction of each hand specimen was crushed and panned for extraction of zircons and other heavy minerals of interest, for a survey aimed at investigating possible features indicating shock metamorphism. After panning, the grains were hand-picked, based on shape and colour, with the help of a compound microscope and tweezers and mounted on carbon tape for SEM/EDS-analysis (scanning electron microscopy/energy dispersive x-ray spectroscopy). The SEM/EDS-analysis had the purpose of analysing the surface, inner structure, mineral type and chemical composition of the grains, using the Tescan Mira3 High Resolution Schottky FE-SEM at the Department of Geology, Lund University. The secondary (SE) and backscatter electron detectors (BSE) as well as the Oxford energy dispersive spectroscopy (EDS) system were used. The energy of the electron beam (the HV-value) during analysis was set at 15,0 kV. EDS and the produced chemical spectra were used to confirm the mineral type of each grain as well as the chemical composition of shock alterations and secondary mineral growth. Grains with potential shock metamorphic features were cast in epoxy, polished to mid-plane and re-examined with SEM to analyse the inner structure of the grains. Grains of interest, both polished and unpolished, were photographed. Two of the thin sections (MIE-M07-4 and MIE-M09-2, Appendix 1), one from the suevitic breccia (MIE-M07-4) and one from the impact melt rock (MIE-M09-2), were also analysed with SEM/EDS to obtain detailed data on both texture and mineral- and amorphous composition. Shock metamorphic features were photographed. EDS-analysis was repeatedly used for the identification of mineral grains as well as for the chemical composition of the amorphous phases of the melt-bearing rocks. Settings and detectors were the same as for the analysis of the heavy mineral grains, previously described in this section. A selection of around 30 thin sections from previous studies on the Mien structure were examined with a compound microscope to classify the different impactites. The impactite classification is made according to the system proposed by Stöffler *et al.* (2018).

4. Results

4.1 Petrographic descriptions

Based on the examined thin sections, both those from previous studies and those from the collected samples within this project, the rocks can be classified as two types of lithic breccia, two types of suevitic breccia, and five types of impact melt rock (Table 1).

4.1.3 Lithic breccia

The lithic breccia consists of granitic lithic clasts, up to several centimetres in size, set in a matrix composed

of fragmented and crushed bedrock. The fragments of the matrix are angular, while the granitic clasts are occasionally more rounded. The division into two types of lithic breccia (Table 1) is based on the absence of a matrix in type 1 as well as a wider distribution of clast sizes in type 2. Type 2 also exhibits a “dirty” texture in several places, obtained from secondary alteration.

4.1.2 Suevitic breccia

The suevitic breccia is fine-grained with a few larger clasts consisting of both mineral grains, pieces of granitic bedrock and fragments of melt/glass, of varying sizes up to several centimeters. Similar to the lithic breccia, smaller fragments are angular while larger clasts are angular to sub-rounded. Two different types of suevitic breccia were identified in this study (Table 1). Again, the subdivision is based on the texture of the different samples. While one consists of more or less homogenous lithic fragments in between the larger clasts of bedrock and melt, the other one additionally displays a very fine-grained matrix of crushed rock and isotropic elements. PDFs and ballen texture in quartz are common features in both types. The suevitic breccia from the sampled impactites (Appendix 1) corresponds to type 2 in Table 1.

4.1.1 Impact melt rocks

The impact melt rock samples show two major differences in texture, but can further be subdivided into five different types (Table 1). Impact melt rock type 1, 2 and 3 constitute larger melt and glass veins, exhibiting flow texture but no clear crystallisation pattern. The veins rather exhibit the amorphous texture of glass, making a clear distinction between melt and glass difficult. The veins flow in between intact, but recrystallized and broken up, pieces of granitic bedrock and mineral grains. The majority of the recrystallized melt/glass has a spherulitic texture (Fig. 5D). A few spherules were found within the melt/glass veins (Fig. 5C). Type 4 and 5 exhibit a fine-grained crystallized matrix, resembling an igneous texture, with a few larger intact single-crystal grains sporadically distributed within the rock, many of which show signs of shock-metamorphism, such as PDFs and ballen texture in quartz (Fig. 5A, B, F and H), as well as partial melting at the rims. The crystals of the matrix are mainly lath-shaped, which in some parts has developed into a spinifex-like texture (Fig. 5E). On a more detailed basis these impact melt rocks can be divided into five different types depending on the number of lithic clasts, the distribution of the melt/glass and the size of the spherulite crystals (Table 1). The sampled and cut impact melt rock (Appendix 2) corresponds to type 3 in Table 1.

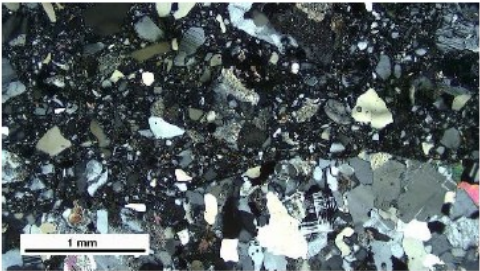
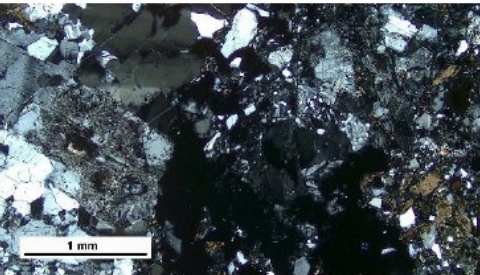
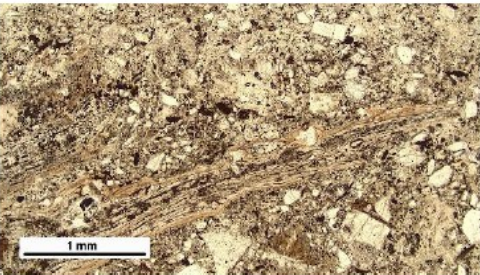
4.2 SEM-analysis

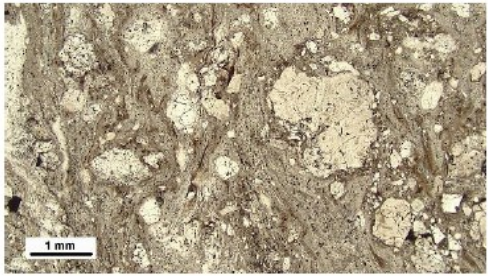
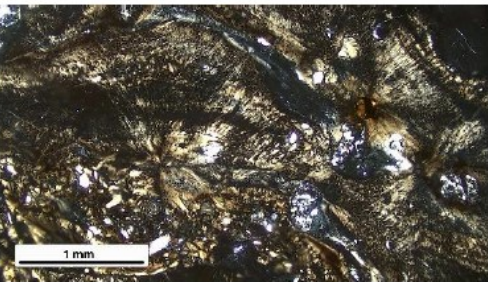
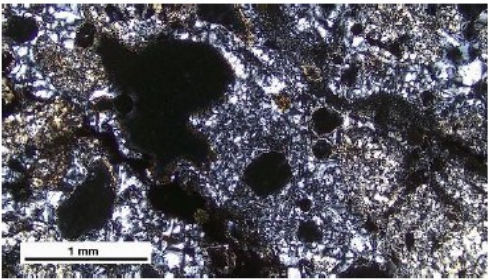
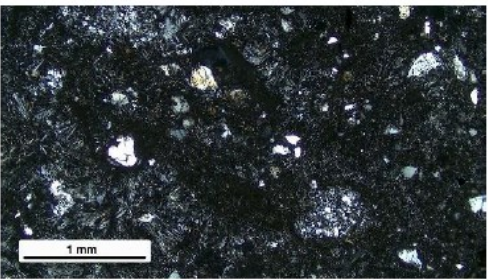
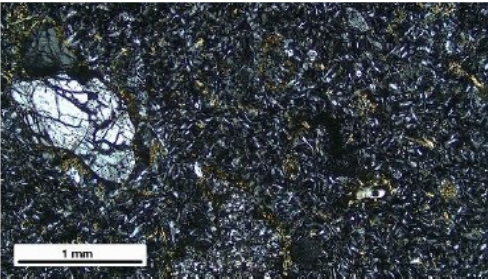
Mineral grains exhibiting shock metamorphic features found within the crushed rock samples were mainly zircon, apatite, monazite, FeTi-oxide as well as Fe- and Ti-bearing silicates. The zircon grains displayed various types of textures: fracturing, sets of parallel planar features, potentially planar fractures (PFs) (French & Koeberl, 2010) and granular texture were

the common ones (Fig. 6). A large number of zircons also exhibited varying degrees of porosity throughout the crystals (Fig. 6E). The nature of the fractures differed from grain to grain, some displaying more or less random fracturing, other following a distinct pattern. One general pattern that could be observed in several grains was the fractures forming perpendicular

to each other, in a net-like structure (Fig. 5G). Essentially all zircon grains showed at least minor fracturing. In some grains the core was left unaltered while fractures followed the zoning of the crystal outward from the core (Fig. 6D and E). PFs were issued as straight, parallel linear fractures (Fig. 6F), similar to PDFs, except different in thickness but not

Table 1. Classification and description of the different types of impactites found at Mien. Classification according to Stöffler *et al.* (2017). The thin sections are from previous studies of Mien (e.g. Martell (2018) and Martell *et al.* (2021) and the exact location is not known for all the samples. All samples are from glacial boulders collected around the southern and eastern shores of the Mien Lake.

Image of thin section	Sample name, location and classification	Description
	8569, Exact location unknown, Lithic breccia type 1	Fragmented bedrock and granitic clasts of varying sizes. The fragments in between the larger granitic pieces of rock are more homogenous in size. No clear matrix is visible.
	Ö9A, Exact location unknown, Lithic breccia type 2	Fragmented bedrock and granitic clasts of varying sizes. Fragments vary in size and lie in a matrix of crushed rock and isotropic elements (glass?). "Dirty" textures due to secondary alteration are common.
	Ö5, Exact location unknown, Suevitic breccia type 1	Fragmented bedrock with minor matrix, clasts of granitic bedrock and melt. PDFs, ballen quartz and checkerboard texture in feldspar grains.
	17.07, 56.368815°N 14.856186°E, Suevitic breccia type 2	Fragmented bedrock with a partly isotropic matrix of finely crushed bedrock and melt. Abundant PDFs in quartz.

	17.03, 56.368815°N 14.856186°E, Impact melt rock type 1	Clast rich impact melt rock with dominating melt/glass exhibiting flow texture. Traces of partial melting at the rim of some grains. Shock features such as PDFs and ballen texture in quartz are common. Recrystallization of mineral grains and smaller parts of the melt/glass are visible.
	8564, Exact location unknown, Impact melt rock type 2	Melt/glass veins with large spherulitic recrystallization. Clast rich, breccia-like patches and larger, broken up mineral grains. PDFs and ballen texture in quartz.
	15-03L, Exact location unknown, Impact melt rock type 3	Holohyaline texture, dominating melt/glass veins with complete spherulitic recrystallization. Mineral grains display recrystallization, rims and “dirty” surfaces of secondary alteration. Lots of ballen quartz and minor PDFs. The black spots in the picture are vesicles.
	Ö3B, Exact location unknown, Impact melt rock type 4	Finely crystallized impact melt rock with aphanitic texture. At some places displaying spinifex texture. Medium amount of clasts. Spherulitic texture at places as well as recrystallized grains showing checkerboard texture. “Dirty” surface from secondary alteration. PDFs and ballen texture in quartz.
	Ö1A, Exact location unknown, Impact melt rock type 5	Clast poor impact melt rock with aphanitic texture. The laths are larger than the above-described aphanitic impact melt rock. Fractured grains, ballen texture in quartz, PDFs and checkerboard recrystallization. Spinifex texture at places.

always possible to tell apart. The most common alteration in zircons were microscopic pores displayed throughout the grain (Fig. 6E). The pores were found both randomly distributed and arranged in parallel,

straight lines. Granular texture, entire grains or parts of a grain transformed into small granules (Fig. 6A and B), was found in apatite, monazite and Fe-silicates apart from zircon. Apatite additionally exhibited pores

and a parallel linear pattern, however, not sufficient to classify them as PFs or PDFs (Fig. 6C). The Fe- and Ti-bearing oxides from the crushed samples showed the least amount of alteration. However, SEM-analysis of a thin section from one of the suevitic breccia showed both PDFs and granular fracturing in FeTi-oxides (Fig. 5H).

4.3 Mapping

Mapping of the in situ bedrock around Lake Mien (Fig. 4) confirms earlier surveys (e.g. Stanfors, 1973) that no exposed impactites are available for study. The bedrock is granitic, ranging from granite to granodiorite. Fabric defined by preferred orientation of mineral grains, assemblages of dark minerals and assemblages of varying grain size were observed in the outcrops. The majority of the rocks were medium-coarse-grained. However, everything from fine- to very coarse-grained rocks were found. All rocks featured minor or major weathering. Fresh cuts were

scarce to non-existent, partly due to the very limited extent of the outcrops as well as the lush vegetation and thick layer of mosses covering most of the rocks. Impact melt rock and suevitic breccia were found as loose boulders along the southern and south-eastern shore of the lake.

5. Discussion

5.1 Where is the crater located?

There are several reasons why the exact location of the original crater is hard to determine: 1) in situ impactites have only been encountered through drillings on Ramsö. Hence, these drillings were performed rather close to each other and do not provide any regional picture of varying impactite distribution, 2) the outcrops that exist around the lake are both scarce, weathered and covered by vegetation, making it hard to recognize any large-scale signs of impact, such as rim faulting and radial fractures, 3)

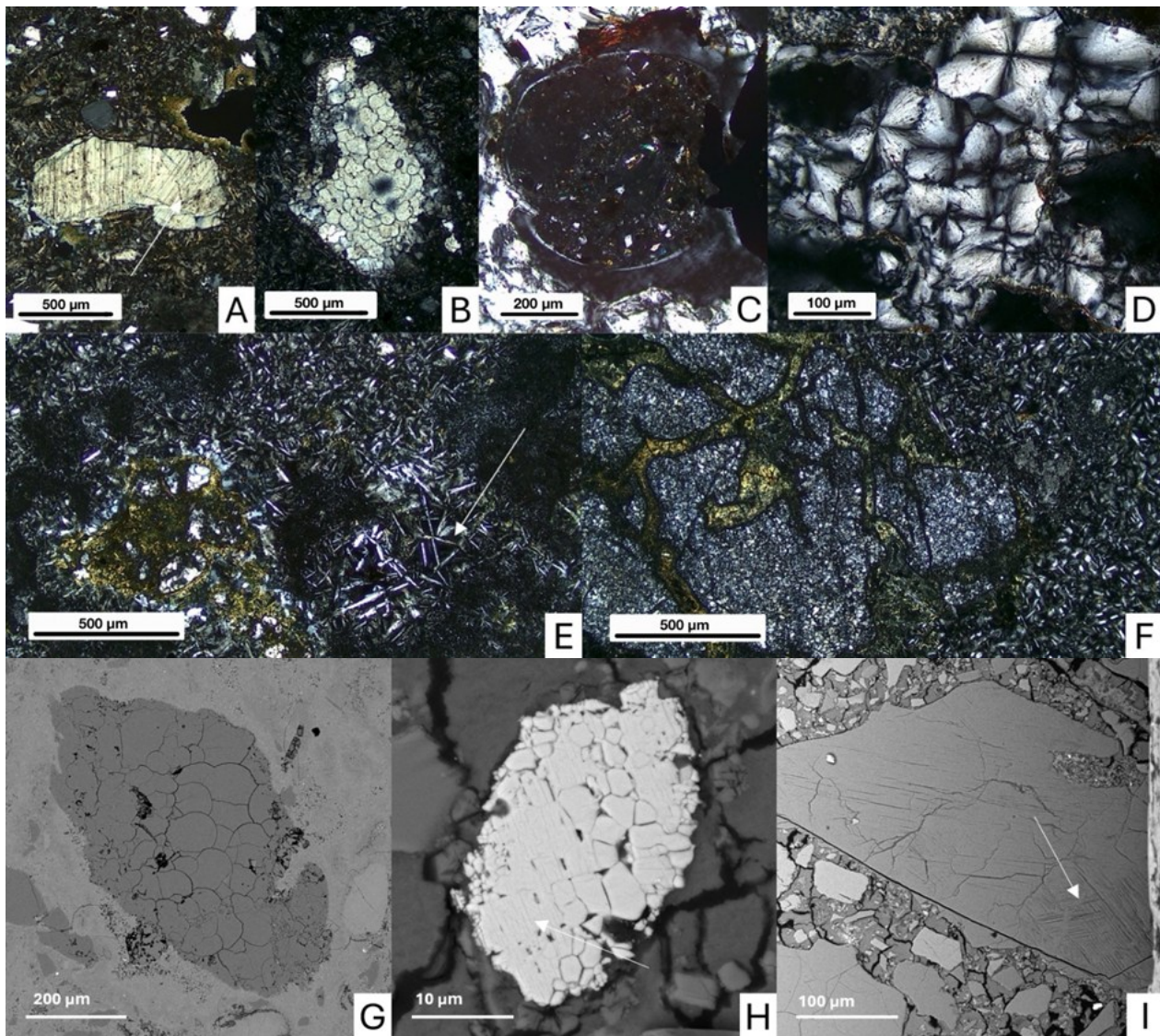


Figure 5. Shock metamorphic features within the impactites at Mien. A: PDFs, B: ballen texture in quartz grains, C: spherule, D: spherulitic recrystallization of glass, E: spinifex-like crystals in impact melt rocks, F: mosaic recrystallization of quartz and feldspar, G: ballen texture, H: PFs (arrow) and net-like fracturing in FeTi-oxide, also observed in other minerals, such as zircon, apatite and monazite, I: PDFs.

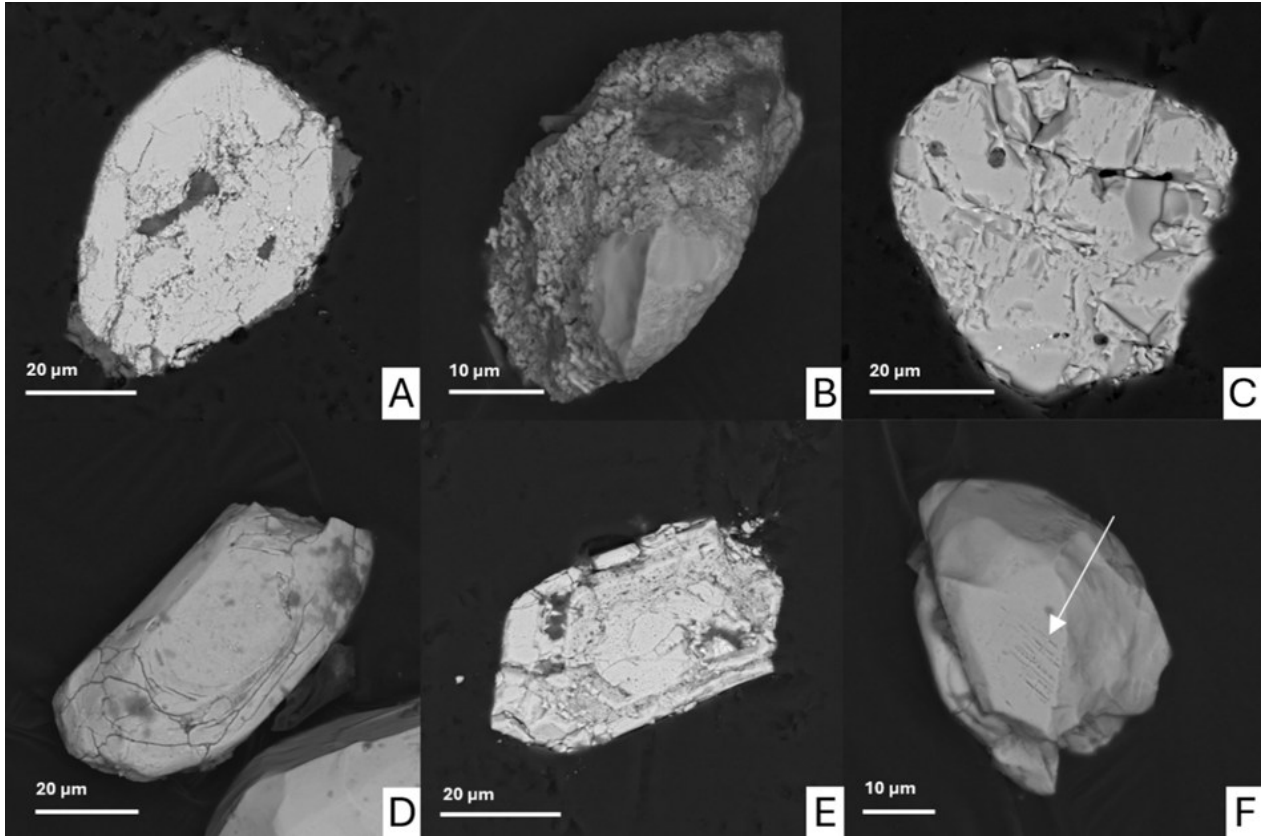


Figure 6. Grains extracted from the crushed sample of an impact melt rock. A: granular zircon, polished to mid-plane, B: granular zircon, C: apatite with small linear features, D, E: zircon with fractures following the zoning of the crystal, E is polished to mid-plane and shows the high porosity of the inner crystal, F: PDFs or PFs in zircon. All grains are from sample MIE-M09, collected at Loc. 11: 56,39767°N; 14,87050°E (Fig.6).

local deformation zones around the lake disturb the geophysical signature and offer alternative explanations to the present anomalies. Because of its rounded shape, Lake Mien was originally thought to fill up the crater cavity. However, the lacking signs of impact at the shores together with two local deformation zones following the western and northeastern shore of the lake (Fig. 7) (Wik *et al.*, 2009) suggest that other processes are, at least partly, responsible for its shape. Since the bedrock alone is a poor indicator when it comes to the impact structure morphology of Mien, geophysical measurements still provide essential evidence for this matter. A gravimetric low coincides with the lake (Fig. 7 and 8), featuring a rise towards the east-northeast and almost no change towards the west (Fig. 7). The combination of the Mien basin and the deformation zone in the northeast of the lake most probably generates the difference. The change in gravimetry is limited and smaller low points like the one at Mien exist at other locations in the region (SGU, 2025c). Alone it would not be sufficient to confirm the crater cavity but accompanied by the magnetic field data and the seismic ‘disruption zone’ described by Åström (1996, 1998), it should be taken into consideration. The seismic disruption zone includes low shear velocities in a certain radius around the estimated original crater rim as well as notably low values of the ratio of P- and S-waves within the crater rim (Åström, 1998). A discontinuous circular positive magnetic anomaly is

present in the central parts of the lake with the strongest output underneath Ramsö, partly coinciding with the lowest measured gravity (Fig. 7). The residual crater cavity features a generally negative magnetic anomaly. Considering the reason for positive magnetic anomalies in other impact structures in combination with the rocks found in the drill cores retrieved from Ramsö and the seismic measurements (Åström & Lund, 1993), the circular anomaly at Mien is most likely connected to either the distribution of melt rock, the central uplift or both. The only other impact structure in Sweden that shows a clear magnetic anomaly related to the structure is Dellen, where the magnetic high is connected to the remanent magnetization of the impact melt rocks, which are well distributed in the centre of the impact structure (Henkel, 1992; SGU, 2025b). Henkel (1982) also reports strong remanent magnetization of the impactites at Mien. Mien and Dellen are similar in age and by far the youngest known impact structures in Sweden (Holm-Alwmark, 2021), which may explain the lack of a magnetic anomaly in the other structures, where the majority of the impact melt rocks, if originally present, have been eroded. The only drillings performed at the lake are from Ramsö, where 20-30 m thick layers of impact melt rock were confirmed. The remaining magnetic anomaly was measured where the depth of the lake is between 20 and 24 m (SMHI, 2025), with no data on the thickness of the lake sediments. The thickness of the melt rocks

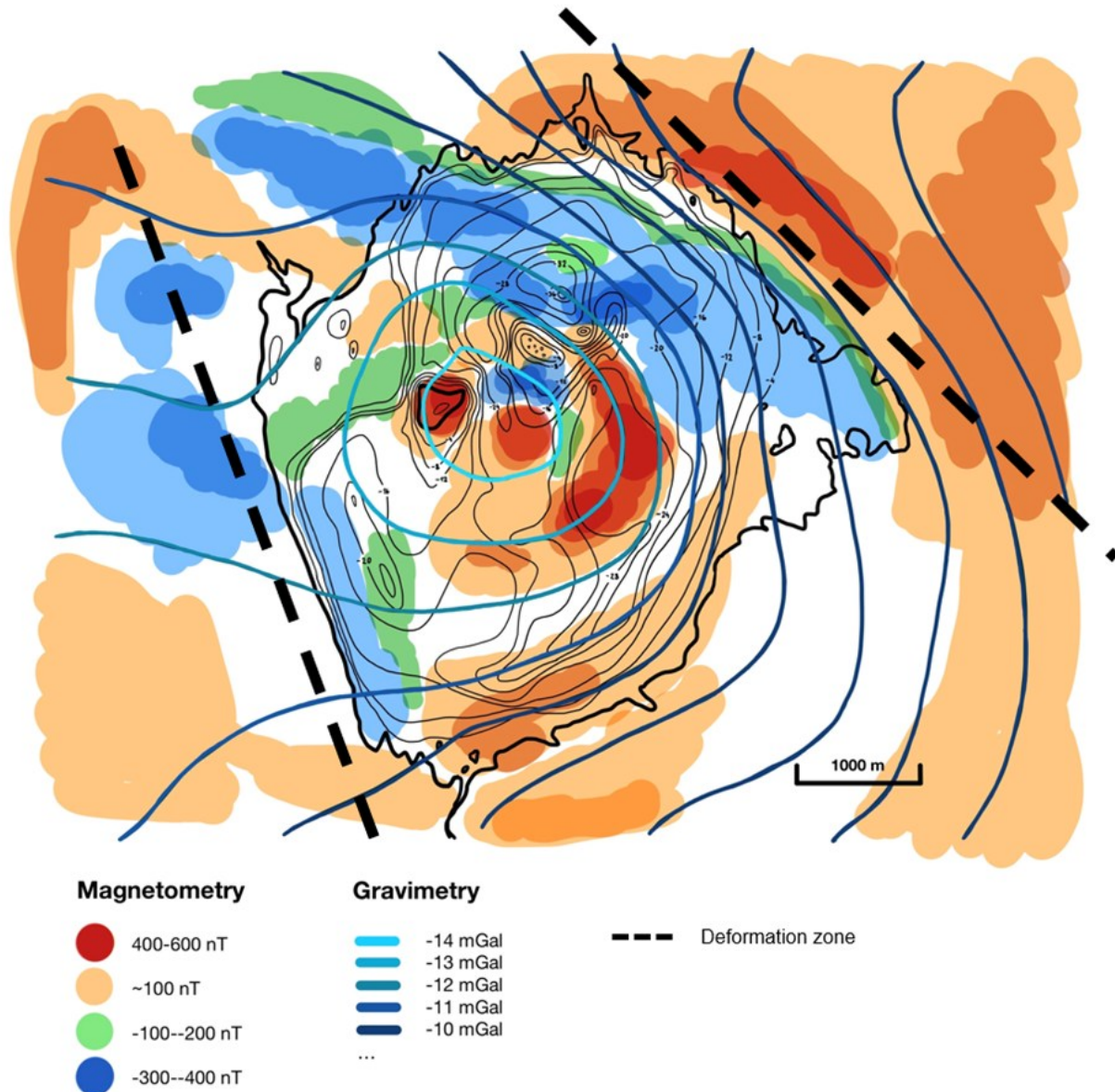


Figure 7. Map combining lakebed topography, magnetometry (colouring) and gravimetry (bouguer anomaly lines). Red represents a magnetic high, blue a magnetic low. Only the anomalies are marked, the white parts of the map have magnetic signals of around 0 nT. Bouguer anomaly lines are coloured light to dark, where lighter lines represent lower values and darker lines represent higher gravimetric values. Each line is a change in gravity of 1 mGal. The dashed lines mark deformation zones. Magnetic and gravimetry data from SGU (2025b, c), lake map and lakebed topography from SMHI (2025), map data for deformation zones from the bedrock map of Kronobergs län (Wik *et al.*, 2009).

should therefore be significantly less pronounced at this location, if the melt sheet was somewhat consistent. However, the magnetic anomaly is similar to the one at Ramsö (SGU, 2025b). Within the inconsistent circular shape of the anomaly there is a shallow area northeast of Ramsö with just a few meters water depth but completely lacking a magnetic high. Impact melt rock and the accompanying remanent magnetization is, however, seldom consistently present on crater floors and a patchy distribution is to be expected (e.g. Cowan & Cooper, 2005; SGU, 2025b). According to Åström (1996, 1998) the low P- to S-wave ratios of the seismic measurements within the crater rim favour the theory of secondary mineral deposition within the fractured

crater floor due to enhanced water circulation induced by thermal effects of a hot blanket, i.e. a layer of melt mixed with breccia and rock fragments that covers parts of the crater floor and where complete cooling can take hundreds to thousands of years. Åström (1996, 1998) suggests that the alteration of existing minerals together with erosion have removed the original remanent magnetization and created magnetic lows in the crater cavity.

The second possible explanation for the magnetic anomaly is the presence of a central uplift and magnetic rocks that have been pushed to the surface, something that would explain its evenly circular shape. Bedrock featuring strong magnetic fields are common in the area, both in association with magmatic

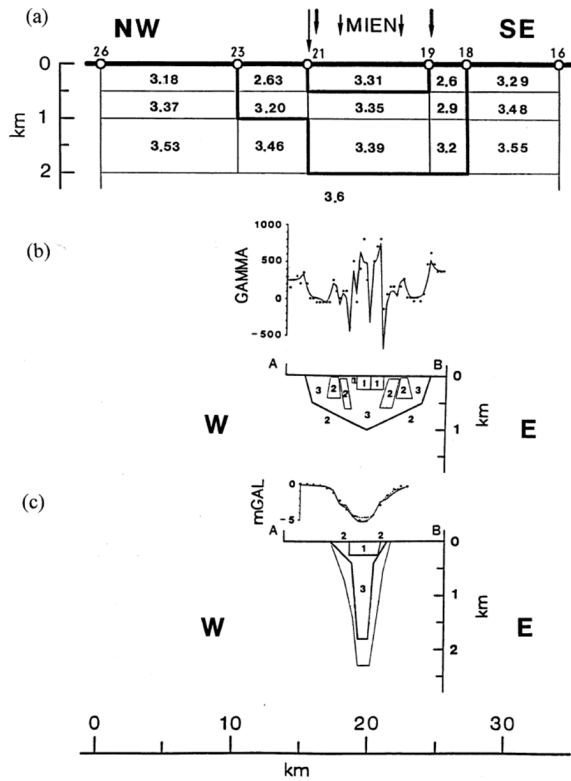


Figure 8: Seismic measurements and interpretation (a), from Åström (1996), thick arrows marking the former crater rim and the arrows on both sides of “MIEN” mark the shores of the lake. The shear velocity is measured in kms-1. Magnetic (b) and gravimetric (c) measurements and interpretations are from Henkel (1982) along a different profile W to E over the lake. The numbers in the magnetic interpretation A-B in (b) indicate 1) impactites, 2) “less altered target rocks” and 3) “low magnetic target rocks”. The numbers in the gravimetric interpretation A-B in (c) indicate 1) impactites, 2) water and 3) fractured target rocks.

intrusions and deformation zones. The closest is a deformation zone at the northeastern shore of the lake featuring an anomaly of around 300-400 nT and a second deformation zone 2-3 km north and northwest of the lake featuring a strong anomaly of up to 1400 nT (SGU, 2025b). Displacement of deeper lying rocks towards the surface is therefore a reasonable explanation for the positive magnetic signature at the centre of the lake. Regardless of the origin of the anomaly, being melt distribution or central uplift, it most likely marks the centre of the crater, since impact melt is most widely distributed closest to the point of impact (Kenkmann *et al.*, 2014; Osinski *et al.*, 2022). It should also be pointed out that one of the proposed origins for the magnetic anomaly does not exclude the other, since the central uplift may be partially covered by impact melt rocks (Kenkmann *et al.*, 2014; Osinski *et al.*, 2022), which after erosion of the central peak may appear as a ring feature. Backed up by the aligning gravimetric and seismic data, the centre of the impact structure can be assigned to this part of the lake.

The remaining morphology of the impact structure is more difficult to interpret since magnetic and gravimetric data are disturbed by nearby tectonic

features and because erosion has removed large parts of the original crater structure. As discussed above, field mapping of bedrock and large-scale structures, such as radial fractures and faults, did not reveal any relevant information because of the poor distribution of outcrops around the lake and the lack of any clear type of impact-related features, leading on to the next question.

5.2 How large could the crater be?

The gravimetric low at the lake, assuming it to only reflect the lost density of the bedrock due to brecciation and fracturing during the impact event, will have been affected significantly by erosion and is not a reliable source when determining the size of the crater. Surrounding factors, such as the deformation zones northeast and west of the lake also contribute to distorting the gravimetric signature of the impact structure. The gravimetry should therefore only be used as a rough indicator and complementary evidence of where the crater cavity is located. Since visible large-scale structures are missing, seismic measurements from Åström & Lund (1993) together with the magnetic data from Henkel (1982) and available impactites, provide the most relevant data for the evaluation of the size of the impact structure (Fig. 8). The seismic measurements have already been used to estimate the original crater diameter to 9 km, based on the disruption diameter of 15-17 km (Åström, 1996, 1998). This is challenged by the absence of any indicators of impact beyond the shore of the lake, considering its 120 Ma age and the preservation of other structures with similar ages. Osinski *et al.* (2022, p. 17) categorises the erosional level at Mien to 5 out of 7, meaning exposure of the crater floor and only remnants of the crater fill remaining (Fig. 9B). The exposure of the impact structure and later glacial erosion followed by infill and coverage by glacial deposits may have led to the poor preservation of the structure. It is possible that larger structures, such as rim faults and large-scale radial fractures exist but vegetation and Quaternary deposits prevent the mapping of such features.

The impactites collected in the area may be compiled to represent an almost complete stratigraphy (Fig. 10). Because some of the rocks were not collected in situ this cannot, however, be confirmed, and the samples may originate from different parts of the impact structure. First, the drill cores from Ramsö display a typical complex crater stratigraphy, where impact melt rock overlays suevitic and lithic breccia and lastly the fractured basement rocks (Stöffler *et al.*, 2018; Osinski *et al.*, 2022). The layer of breccia, both lithic and suevitic, is very thin, a maximum of a few metres in thickness, suggesting the location being close to the central uplift, where impact melt rocks dominate relative breccia. A complex crater in crystalline bedrock requires a minimum size of 4 km in diameter (Grieve, 1987). From expected pressure and temperature gradients, and based on previous studies (e.g. Osinski *et al.*, 2012), the impactites can be arranged in the following order (from bottom to top): lithic breccia overlays the fractured but mostly unaltered granitic basement rocks, followed by the suevitic breccia and the clast-rich impact melt rock

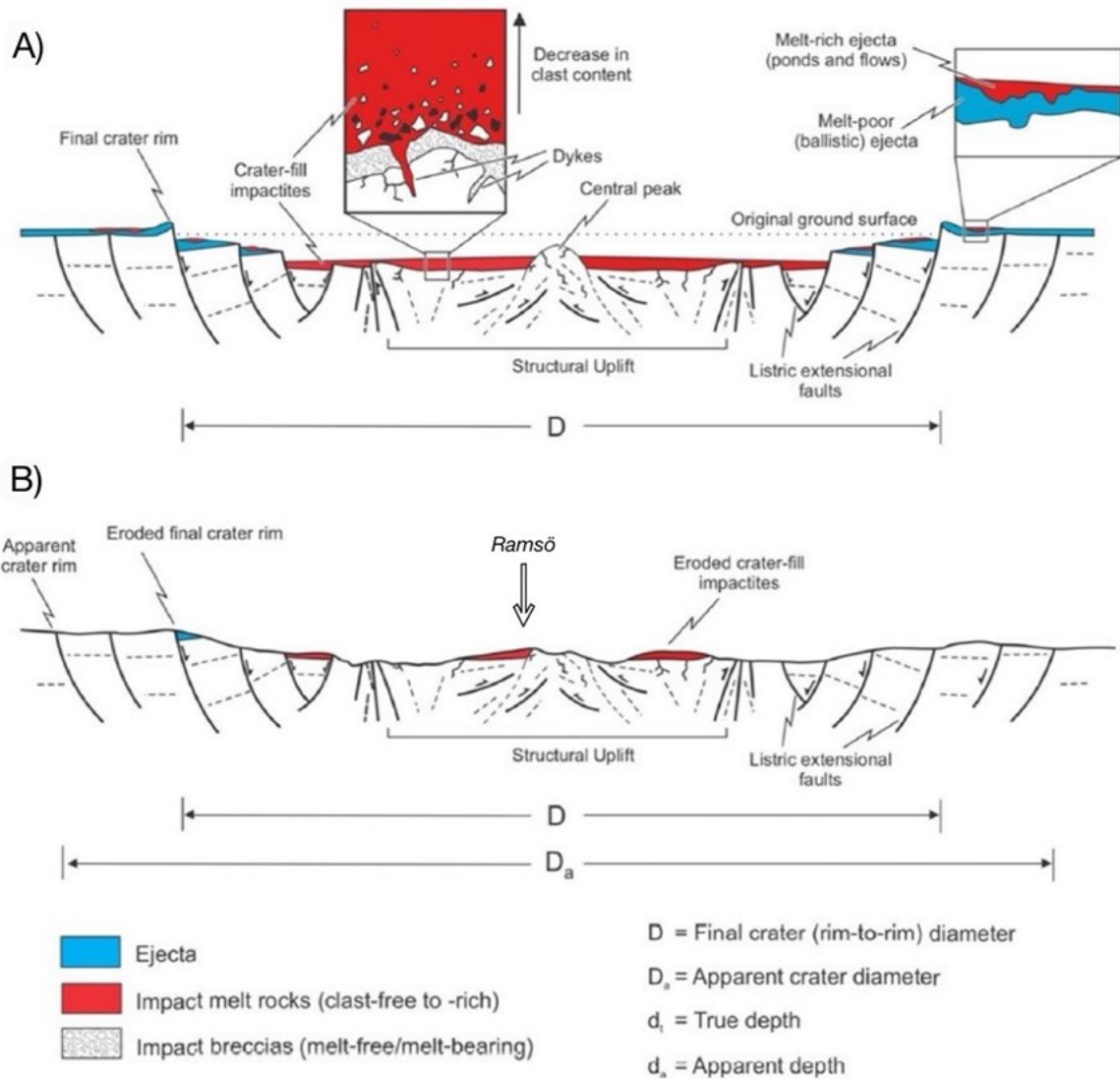


Figure 9. Structural morphology and general impactite distribution of a complex crater in crystalline bedrock, pre-erosion (A) and post-erosion (B). The assumed location of Ramsö in relation to the Mien crater structure is marked with an arrow in B. Modified from Osinski *et al.* (2011).

containing melt/glass swirls. The top consists of the crystallised melt rock (igneous texture), finer grains and more lithic fragments in the bottom and larger crystals with fewer clasts on top. There is a general pattern of decrease in lithic fragments from the lowermost part of the proposed stratigraphy to the uppermost, due to increased mixing with the fractured bedrock towards the bottom of the crater. The amount of mixing also reflects the cooling rate in the different rock types, where the suevitic breccia, containing mostly glass, displays evidence of very fast cooling of melt, and the crystallized impact melt rock exhibits larger crystals the less lithic fragments are incorporated in the melt. Another general pattern is the increase of shock metamorphic features from bottom to top, the lithic breccia only containing a few minor shock features while the impact melt rocks contain large numbers of mainly ballen quartz, PFs and PDFs. It should be noted that the different rock types, except for the igneous textured impact melt rocks that are to be expected in the central parts of the crater where the

generated heat is sufficient to slow down the cooling rate, can be found elsewhere in the structure and thus may represent distance from the crater centre instead of the level in the stratigraphy, e.g. the suevitic breccia also exists as ejecta. The drill cores retrieved from Ramsö and their description provided by Stanfors (1973), however, largely mirror the described stratigraphy. Although this confirms a complex crater structure, the constraints in size are not particularly valuable, since these types of rocks form in both smaller and larger craters. However, the shock features found can provide some insight into peak shock pressures, both ballen quartz and FRIGN zircon requiring high shock pressures and temperatures to form. Ballen quartz, which was abundant in both the impact melt rocks and the suevitic breccia, forms at minimum 1200 °C and 30-35 GPa (Ferrière *et al.*, 2010) and FRIGN zircon forming at minimum 1670 °C and 30 GPa (Cavosie *et al.*, 2018; Osinski *et al.*, 2022).

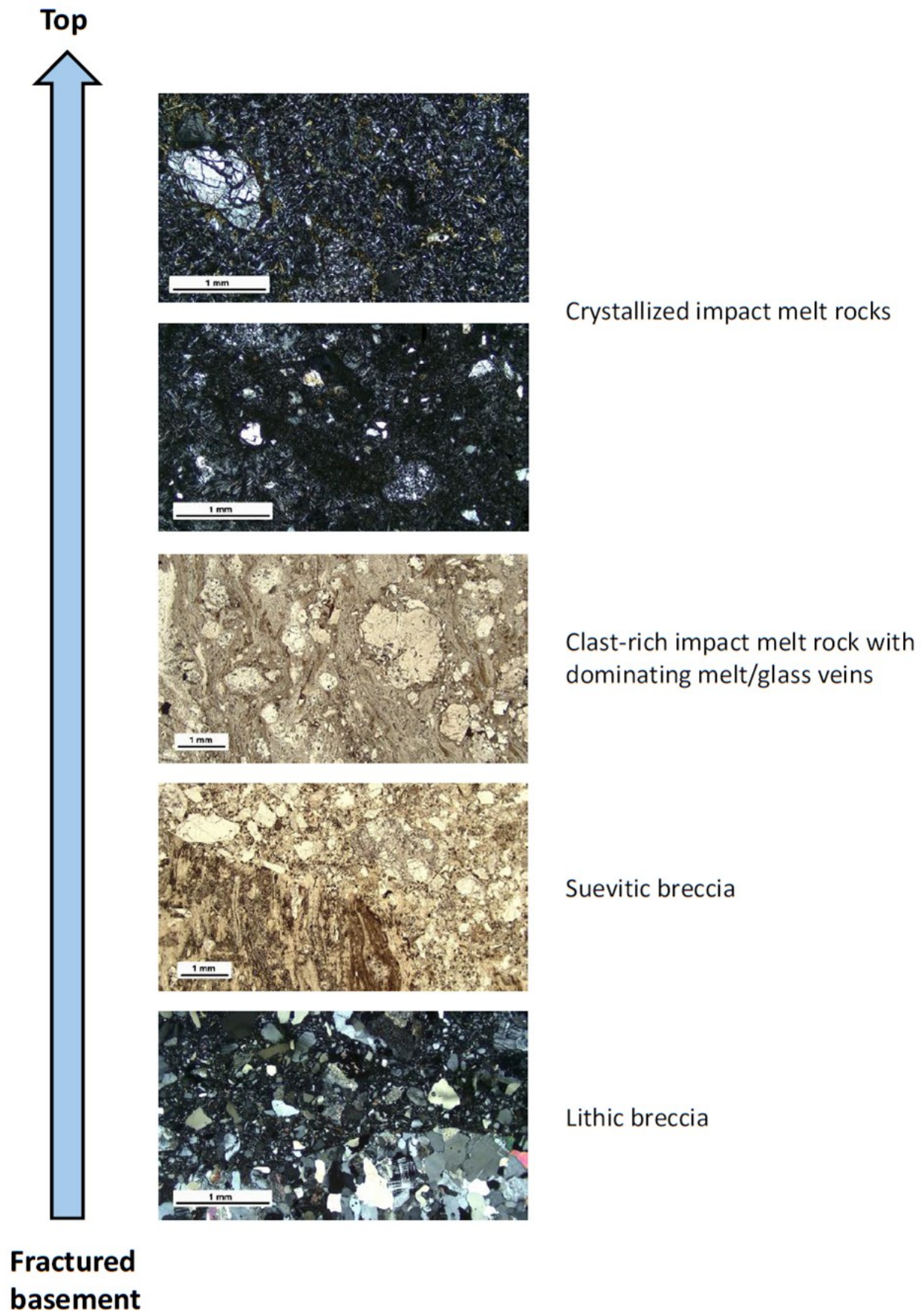


Figure 10. Proposed stratigraphy of the impactites at Mien, based on the drill cores and the knowledge on impactite stratigraphy of complex crater fill in other craters (e.g. Osinski *et al.*, 2012).

5.3 What is Ramsö?

A structure that has been central in the investigation of the Mien impact structure is Ramsö, the island towards the centre of the lake where the only available cores confirming in situ impactites have been retrieved and where the magnetic signature is at its strongest. So, what is the island, and why did this part withstand erosion better than the rest of the impact structure? The drill cores reveal rather thick layers of impact melt rock on the island, a rock that is more resistant to erosion than breccia, especially to glacial and fluvial erosion (Osinski *et al.*, 2022). Ramsö could be a remnant of the crater fill that for some reason withstood the erosion better than other parts and now represents an example of inverted topography. A point that was made in the previous paragraph was the expected close relation between Ramsö and the central uplift (Fig. 9), due to very thin layers of breccia compared to the impact melt rock. If the area forming the present island was located on the northwestern slope of the original central uplift (assuming that the location of the central uplift is reflected by the geophysical measurements and lakebed topography (Fig. 7)), the uplift may have acted as a protection from glacial erosion. The uneven lakebed and Ramsö being the only larger remnant can be explained by complex erosional mechanisms acting throughout the 120 Ma, including several glacial periods, and differences in the composition of the surface rock. The island being the remnant of the original central peak is rather unlikely for several reasons. First, the picture that the geophysical data provides does not place Ramsö at the centre of the impact structure. Further, the impactites on the island suggest that no erosion of the elevated basement rocks of the central peak occurred, however, the basement shows no increased elevation compared to the surrounding rocks and the shore, based on the drill cores and the lake depth. Lastly, considering the level of erosion and the estimated size of the original crater the central uplift should be expected to have a larger area than the one represented by only Ramsö. Instead, Ramsö is a remnant of the crater infill, likely in direct connection to the central uplift and the circular magnetic anomaly possibly traces melt remnants around the rim of the central uplift, similar to the illustration in Fig. 9B.

6. Conclusion

This study confirms the challenges met in earlier studies with mapping of the Mien impact structure due to poor access to outcrops and in situ impactites as well as large-scale structures that constrain its dimensions and structural properties. Geophysical measurements of the area need to be interpreted cautiously, since several deformation zones around the lake may distort a potential signature linked with impact processes. However, combining the available geophysical data with impactites from both the drill cores and glacially transported samples provides sufficient information to estimate the centre of the impact structure (the point of impact) to coincide with the centre of the lake, confirm Mien to be a complex crater and estimate its size to 9 km in diameter (Fig. 11). The claim of Mien being a complex structure is

backed by both the geophysical measurements, the lakebed topography and the stratigraphy of the drill cores at Ramsö, where impact melt rocks overlie breccia. Estimates of the size are solely based on the geophysical measurements, especially the seismic data, measuring the disruption diameter of the fractured bedrock originating from the impact. The rounded shape of the Mien Lake is most likely not, or at least only partly, due to the impact structure and rather a result of two deformation zones following the western and northeastern shore. It is, however, possible that the impact structure played a role in providing the basin that enables the presence of a modern-day lake in the area. The island Ramsö is a remnant of the crater infill, preserved through the cover of more erosion resistant impact melt rock in combination with a favoured location and connection to the central uplift. For further constraints on the morphology of the impact structure, detailed geophysical mapping of the lake and its surroundings should be included in future studies. A drill core from another shallow part of the lake would be useful for mapping the distribution of the impactites and to investigate if more remnants of the crater infill exist.

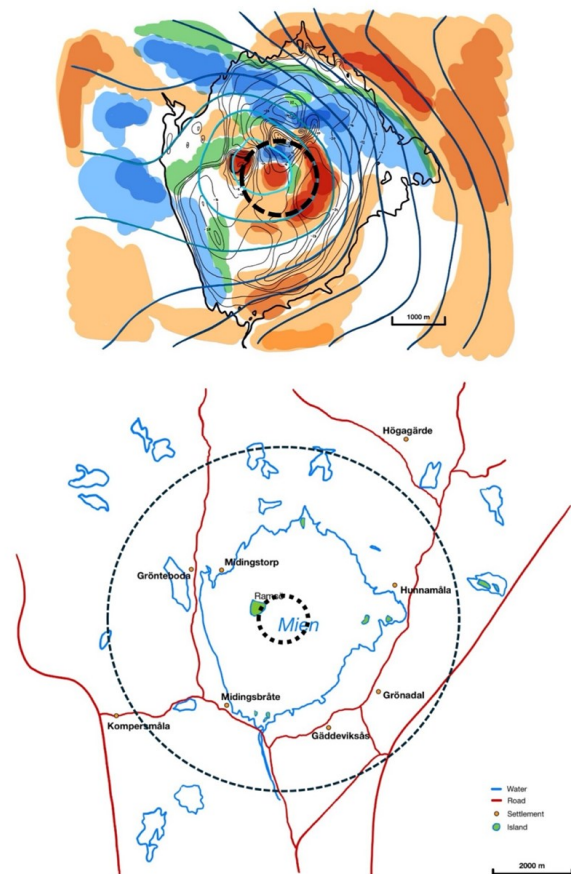


Figure 11. Estimated location of the central uplift and centre of the Mien impact structure (thicker dashed circle in the upper and lower map). The geophysical (upper) map includes the magnetic and gravimetric measurements, which the allocation is mainly based on. The thinner dashed circle in the lower map is the original crater size based on the seismic measurements and calculations made by Åström (1993, 1996).

7. Acknowledgments

First and foremost I'd like to express my gratitude towards my supervisor, Sanna Alwmark, and the Impact Geology Research Team at the Department of Geology in Lund, especially Carl Alwmark, Patrycja Struzynska and William Hyde, for all the help along the way and for making scientific research fun. I'd also like to thank the examination committee, especially Mikael Calner, for the constructive and valuable feedback. Last but not least, a big thank you goes to my fellow classmates and the "Bunker Crew" for making this last year so very enjoyable, as well as to my family for the never-ending love and support they give me every day.

8. References

- Alvarez, L. W., Alvarez, W., Asaro, F., & Michel, H. V. (1980). Extraterrestrial Cause for the Cretaceous-Tertiary Extinction. *Science*, 208(4448), 1095–1108.
- Bottomley, R. J., York, D. & Grieve, R. A. F. (1978). 40Ar/39Ar ages of Scandinavian impact structures: I. Mien and Siljan. *Contributions to Mineralogy and Petrology*, 68, 79–84.
- Cavosie, A.J., Erickson, T.M., Montalvo, P.E., Prado, D.C., Cintron, N.O., Gibbon, R.J. (2018). The Rietputs Formation in South Africa. *Microstructural Geochronology, Geophysical Monograph Series*.
<https://doi.org/10.1002/9781119227250.ch9>.
- Cowan, D.R. & Cooper, G.R.J. (2005). Enhancement of magnetic signatures of impact structures. *Large meteorite impacts III: Geological Society of America Special Paper*, 384, 51–65.
- Deutsch, A., Grieve, R. A. F., Avermann, M., Bischoff, L., Brockmeyer, P., Buhl, D., Lakomy, R., Müller-Mohr, V., Ostermann, M. & Stöfler, D. (1995). The Sudbury Structure (Ontario, Canada): a tectonically deformed multi-ring basin. *Geologische Rundschau*, 84(4), 697–709.
- Engelhardt, W. & Stöfler, D. (1965). Spaltflächen im Quarz als Anzeichen für Einschläge großer Meteoriten. *Naturwissenschaften*, 54, 489–490.
- Erickson, T. M., Kirkland, C. L., Timms, N. E., Cavosie, A. J. & Davison, T. M. (2020). Precise radiometric age establishes Yarrabubba, Western Australia, as Earth's oldest recognised meteorite impact structure. *Nature Communications*, 11(300). <https://doi-org.ludwig.lub.lu.se/10.1038/s41467-019-13985-7>
- Eskola, P. (1931). *Geologins Grunder* I. Holger Schildts Förlag.
- Ferrière, L., Koeberl, C., Ivanov, B. A. & Reimold, W. U. (2008). Shock Metamorphism of Bosumtwi Impact Crater Rocks, Shock Attenuation, and Uplift Formation. *Science*, 322, 1678–1681.
- Ferrière, L., Koeberl, C., Libowitzky, E., Reimold, W. U., Greshake, A., and Brandstätter, F. (2010). Ballen quartz and cristobalite in impactites: New investigations. *Large Meteorite Impacts and Planetary Evolution IV: Geological Society of America Special Paper*, 465, 609–618
- French, B. M. (1998). *Traces of Catastrophe: A Handbook of Shock-Metamorphic Effects in Terrestrial Meteorite Impact Structures*. LPI Contribution No. 954, Lunar and Planetary Institute, Houston.
- Glavin, D. P., Dworkin, J. P. & Szostak, J. W. (2009). Enrichment of the Amino Acid L-Isovaline by Aqueous Alteration on CI and CM Meteorite Parent Bodies. *Proceedings of the National Academy of Sciences of the United States of America*, 106(14), 5487–5492.
- Grieve, R. A. F. (1987). Terrestrial Impact Structures. *Ann. Rev. Earth Planet. Sci.*, 15, 245–270.
- Grieve, R. & Theriault, A. (2000). Vredefort, Sudbury, Chicxulub: Three of a Kind? *Ann. Rev. Earth Planet. Sci.*, 28, 305–338.
- Gúzman-Hidalgo, E., Grajales-Nishimura, J. M., Eberli, G. P., Aguayo-Camargo, J. E., Urrutia-Fucugauchi, J. & Pérez-Cruz, L. (2021). *Marine Geology*, 441.
- Henkel, H. (1982). The Lake Mien structure. *Geological Survey Sweden Geophys. Dep. Rep.*
- Henkel, H. & Pesonen, L. J. (1992). Impact craters and craterform structures in Fennoscandia. *Tectonophysics*, 216, 31–40.
- Herrmann, M., Kenny, G. G., Martell, J., Whitehouse, M. J. & Alwmark, C. (2024). The first U-Pb age for shocked zircon from the Mien impact structure, Sweden, and implications for metamictization-induced zircon texture formed during impact events. *Meteoritics & Planetary Science*, 59(1), 211–241.
- Holm-Alwmark, S. (2021). Impact cratering record of Sweden - A review. *The Geological Society of America Special Paper*, 550, 1–39.
- Holst, N. O. (1890). Ryoliten vid sjön Mien (ser. C, no. 110). *Sveriges Geologiska Undersökning*.
- Hughes, D. W. (2003). The approximate ratios between the diameters of terrestrial impact craters and the causative incident asteroids. *MNRAS*, 338, 999–1003.
- Jourdan, F., Renne, P. R. & Reimold, W. U. (2009). An appraisal of the ages of terrestrial impact structures. *Earth and Planetary Science Letters*, 286, 1–13.
- Kenkmann, T., Jahn, A., Scherler, D., & Ivanov, B.A. (2005). Structure and formation of a central uplift: A case study at the Upheaval Dome impact crater, Utah. *Large meteorite impacts III: Geological Society of America Special Paper*, 384, 85–115.
- Kenkmann, T., Poelchau, M. H. & Wulf, G. (2014). Structural geology of impact craters. *Journal of Structural Geology*, 62, 156–182.
- Kieffer, S. W. & Simonds, C. H. (1980). The role of volatiles and lithology in the impact cratering process. *Rev. Geophys. Space Phys.*, 18, 143–181.
- Kring, D. A. (1995). The dimensions of the Chicxulub impact crater and impact melt sheet. *Journal of Geophysical Research*, 100(E8), 16979–16986.
- Malmberg Persson, K. (2010). *Jordartskartan 4E Tingsryd SO, skala 1:100 000. Sveriges geologiska undersökning*, K 163.
- Martell, J. (2018). Detection of shock metamorphism

- in zircon grains from the Mien impact structure, Sweden. *Dissertations in Geology at Lund University*, No. 542.
- Martell, J., Alwmark, C., Holm-Alwmark, S. & Lindgren, P. (2021). Shock deformation in zircon grains from the Mien impact structure, Sweden. *Meteoritics and Planetary Science*, 56(2), 362-378.
- McCall, N., Gulick, S. P. S., Karro, K., Jöeleht, A., Wilk, J. & Pösges, G. (2024). Understanding the Ries impact structure subsurface from high-resolution seismic data. *Geology*, 52, 39-44. <https://doi.org/10.1130/G51503.1>
- Melosh, H. J. (1989). *Impact Cratering: A Geologic Process*. Oxford University Press.
- Melosh, H. J. (2015). *ACOUSTIC FLUIDIZATION: WHAT IT IS, AND IS NOT*. Bridging the Gap III. *Earth Atmosphere and Planetary Sciences*, Purdue University.
- Milton, D. J. & Macdonald, F. A. (2011). Goat Pad-dock, Western Australia: an impact crater near the simple-complex transition. *Australian Journal of Earth Sciences*, 52, 689-697.
- Morgan, J. & Warner, M. (1999). Morphology of the Chicxulub impact: Peak-ring crater or multi-ring basin? *Geological Society of America Special Paper*, 339, 281-290.
- Miyahara, M., Tomioka, N. & Bindi, L. (2021). Natural and experimental high-pressure, shock-produced terrestrial and extraterrestrial materials. *Progress in Earth and Planetary Science*, 8(1), 1-26.
- Osinski, G. R., Tornabene, L. L. & Grieve, R. A. F. (2011). Impact ejecta emplacement on terrestrial planets. *Earth and Planetary Science Letters*, 310, 167-181.
- Osinski, G. R., Singledon, A. C., Ozaruk, A. & Hansen, J. R. (2012). *NEW INVESTIGATIONS OF THE GOW LAKE IMPACT STRUCTURE, SASKATCHEWAN, CANADA: IMPACT MELT ROCKS, ASTRONAUT TRAINING, AND MORE*. 43rd Lunar and Planetary Science Conference.
- Osinski, G. R., Grieve, R. A. F., Ferrière, L., Losiak, A., Pickersgill, A. E., Cavosie, A. J., Hibbard, S. M., Hill, P. J. A., Bermudez, J. J., Marion, C. L., Newman, J. D., & Simpson, S. L. (2022). Impact Earth: A review of the terrestrial impact record. *Earth-Science Reviews*, 232. <https://doi.org/10.1016/j.earscirev.2022.104112>
- Pilkington, M., and Grieve, R.A.F.. (1992). The geophysical signature of terrestrial impact craters. *Reviews of Geophysics*, 30, 161-181.
- Stöffler, D., Hamann, C. & Metzler, K. (2018). Shock metamorphism of planetary silicate rocks and sediments. Proposal for an updated classification system. *Meteoritics & Planetary Science*, 53(1), 5-49
- Sveriges geologiska undersökning (SGU). (2025a). Jorddjup (Soil depth). [Cartographic material]. SGUs map viewer. <https://apps.sgu.se/kartvisare/kartvisare-jorddjup.html?zoom=481868.94685587916,6247940.139587994,499788.9826959509,6256130.155968026>
- Sveriges geologiska undersökning (SGU). (2025b). Magnetfält (Magnetic field). [Cartographic material]. SGUs map viewer. <https://apps.sgu.se/kartvisare/kartvisare-magnetfalt.html?zoom=483630.78327634226,6247988.461945614,501550.819116414,6256178.478325646>
- Sveriges geologiska undersökning (SGU). (2025c). Tyngdkraft (Gravity). [Cartographic material]. SGUs map viewer. <https://apps.sgu.se/kartvisare/kartvisare-tyngdkraft.html?zoom=483867.3732564929,6248642.49770326,502334.6246511993,6257082.608692247>
- Sveriges geologiska undersökning (SGU). (2025d). Isräfflor (Glacial striations). [Cartographic material]. SGUs map viewer. <https://apps.sgu.se/kartvisare/kartvisare-israfflor.html>
- Sveriges Meteorologiska och Hydrologiska Institutet (SMHI). (2025). Damm- och sjöregister. [Cartographic material]. <https://vattenwebb.smhi.se/svarwebb/>
- Stanfors, R. (1973). *Mienstrukturen - en kryptoexplosiv bildning i Fennoskandias urberg*. PhD-thesis, Department of Geology, Lund University.
- Svensson, N. B. & Wickman, F. E. (1965). Coesite from Lake Mien, southern Sweden. *Nature*, 205, 1202-1203.
- Wedmark, M. (2012). Magnetic anomaly map of Sweden, scale 1:1 million. Sveriges geologiska undersökning, K 424.
- Wik, N.-G., Claeson, D., Bergström, U., Hellström, F., Jelinek, C., Juhojuntti, N., Jönberger, J., Kero, L., Lundqvist, L., Sukotjo, S. & Wikman, H. (2009). *Bedrock map Kronoberg county, scale 1:250 000*. Sveriges geologiska undersökning K 142.
- Turtle, E. P., Perazzo, P., Collins, G. S., Osinski, G. R., Melosh, H. J., Morgan, J. V. & Reimold, W. U. (2005). Impact structures: What does crater diameter mean? Large meteorite impacts III: *Geological Society of America Special Paper*, 384, 1-24.
- Åström, K. & Lund, C-E. (1993). Explosion-generated short-period surface wave dispersion and noise studies along linear seismic arrays in southern Sweden. *Geophys. J. Int.*, 114, 103-115.
- Åström, K. (1996). Geophysical signature of the Lake Mien meteorite crater, southern Sweden. *GFF*, 118(4), 92-93.
- Åström, K. (1998). Seismic signature of the Lake Mien impact structure, southern Sweden. *Geophysical Journal International*, 135(1), 215-231.

Appendix



Appendix 1. One of six thin sections cut from the sampled impactites at Mien, which, besides petrographical studies with a compound microscope, were examined with SEM. MIE-M07-4 is a suevitic breccia type 2.



Appendix 2. One of six thin sections cut from the sampled impactites at Mien, which, besides petrographical studies with a compound microscope, were examined with SEM. MIE-M09-2 is an impact melt rock type 3.

**Tidigare skrifter i serien
”Examensarbeten i Geologi vid Lunds
universitet”:**

673. Barabas, Ricky, 2024: Kan chockmeta-
morfos i okonventionella mineral hjälpa
till att identifiera nedslagskratrar? (15 hp)
674. Nilsson, Sebastian, 2024: The glaciote-
cronic evolution of Ven, Sweden: insights
from a comprehensive structural, sedi-
mentological, and geomorphological anal-
ysis. (45 hp)
675. Brotzen, Olga M., 2024: A new La-
gerstätte-like fossil assemblage from the
early Silurian of Mösseberg, Sweden. (45
hp)
676. Eng, Simon, 2024: Precursors to the
South Atlantic Anomaly - Magnetic field
variations in Lake Eilandvlei, South Afri-
ca. (45 hp)
677. Husén, Simon, 2024: Structural Geologi-
cal Model of the Kaunisvaara Mining
District, Norrbotten, Sweden. (45 hp)
678. Hjalmarsson, Tilda, 2024: Det underkam-
briska problematiska fossilet *Spatan-
gopsis* - Vad är dess verkliga affinitet?
(15 hp)
679. Kuberna, Marcos, 2024: En litteraturstud-
ie om klorparaffiner i grundvattnet och
dess implikationer på hälsa och miljö. (15
hp)
680. Persson, Viktor, 2024: Litteraturstudie:
HIMU ursprung och framtid. (15 hp)
681. Selin, Sigrid, 2024: Hur kan pale-
oekologiska studier hjälpa oss att bättre
förstå hur de ekosystem vi anser
skyddsvärda har formats och hur de bör
vårdas? (15 hp)
682. Rey, August, 2024: Isrörelser och
havstransgressioner speglade i
Kåsebergåsen. (15 hp)
683. von Vultée, Anton, 2024: Babets kvarle-
vor - En morfologisk och sedimentologisk
undersökning av överspolningssediment
vid Tobisvik, Simrishamn. (15 hp)
684. Olsson Roso, Céline, 2024: Fåglarnas
ursprung och tidiga utveckling. (15 hp)
685. Nawrocki, Bartosz, 2024: Karaktärisering
av Cr-spinell i den ordoviciska Loka-
formationen vid Skultorps stenbrott,
Billingen. (15 hp)
686. Rydh, Alexander, 2024: Unraveling Mag-
netic Anomalies: A Study of Earth's Field
Asymmetries during the Laschamps Ex-
cursion. (15 hp)
687. Svensson, Ludvig, 2024: Echoes of im-
pact: A petrographic analysis and classifi-
cation of impact breccias from Hummeln,
Sweden. (15 hp)
688. Pålsson, Malin, 2024: Detektion av
utsläppspolymer med avancerat ekolod –
Undersökning av utsläpp av avloppsvatten
från pappersbruk i havet med EK80, CTD
& filmmaterial. (15hp)
689. Ivanovic, Edwin, 2024: Går det att se
echinodermernas utveckling och diversifi-
ering under ordovicium i tunnslip? (15 hp)
690. Blomvall, Marlene, 2024: Analys av mor-
fologi, beteende och tafonomi hos ett ex-
ceptionellt bevarat fågelfossil från Furfor-
mationen (eocen), Danmark. (15 hp)
691. Elfström, Dari, 2024; Geomorfologisk
studie av Jezerokraterns kant (Mars): Po-
tentiella mekanismer bakom kraterkantens
nuvarande utseende. (15 hp)
692. Andersson, Jacob, 2024: The Cerithium
limestone Member at Stevns Klint reflect-
ing the carbonate production recovery
after the K/Pg mass-extinction. (45 hp)
693. Adler, Linus, 2024: Petrografisk pilotstud-
ie av en högmetamorf epidotrik bergart
från Harbak, västra gnejsregionen i Norge.
(15 hp)
694. Fält, Smilla, 2024: Dateringsmetoder för
terrestriska nedslagskratrar med fokus på
Siljan. (15 hp)
695. Kowal Johnson, Gloria, 2024: Traces of
industrialization in a Baltic Sea sediment
core with particular emphasis on marine
traffic in Bornholmsgattet. (15 hp)
696. Riad, Musa, 2024: Bergkross som filter-
medium i artificiell infiltration. (15 hp)
697. Gleisner, Lovisa, 2024: Unravelling pri-
mary $\delta^{18}\text{O}$ signatures of the 1730-36 Ti-
manfaya parental magmas on Lanzarote.
(45 hp)
698. Johansson, Robin, 2024: Instrumentation
of multilevel systems with transducers to
characterize hydrogeological conditions at
a PCE and TCE contaminated site in
Helsingborg, Sweden. (45 hp)
699. Neumann, Daniel, 2025: Hydrogeological
Dynamics of the Dalköpinge River: Inves-
tigating the Dry Spell Anomaly in a Hyd-
rogeological Context. (45 hp)
700. Durdek, Madeleine, 2025: Risk for water
shortage in Ystad municipality - An
evaluation of aquifer vulnerability to hu-
man impact. (45 hp)
701. Bouhal, Farah, 2025: Evolution of calcar-
eous nannoplankton in the Late Triassic:
Insights at Eiberg Basin (Austria). (45 hp)
702. Barreby, Linn, 2025: Petrographic Analy-
sis of the Loftarstone Resurge Deposit in
the Lockne Impact Structure, Sweden. (45
hp)
703. Dyson, Sarah, 2025: Environmental
change in the Late Weichselian on the
Kullen Peninsula. (45 hp)
704. Kardakos, Nikolaos, 2025: Caprock and
reservoir assessment for CO2 storage in
Lower Palaeozoic Formations of the Bal-

- tic Sea subsurface: Textural, structural and mineralogical characterization using X-ray Computed Tomography, geochemistry and microscopy. (45 hp)
705. Filbå i Serra, Laura, 2025: Weichselian ice dynamics in Jämtland: Lithostratigraphic study of the Köttsjön till deposits. (45 hp)
706. Bäckehag, Kristoffer, 2025: Petrografisk studie av pseudotachylitisk breccia från nedslagskratern Siljan. (15 hp)
707. Zellman, Oskar, 2025: Karaktärisering av laminerade marina sediment under ett globalt utdöende (silur, Gotland). (15 hp)
708. Jögi, Amanda, 2025: En partiell hjärnskål från Åsens krita och dess koppling till den svenska svanödlefauan. (15hp)
709. Rasmusson, Isak, 2025: Behovet av geologisk kunskap inom utbildning och samhälle: En översikt av geologiskt innehåll i gymnasiets ämnesplaner, antagningar till svenska högskole- och universitetsutbildningar inom geovetenskap och arbetsmarknadens behov av personer med geologisk kompetens. (15hp)
710. Brede, Anton, 2025: Integrating Geological Models and Geophysics to Estimate Hydraulic Properties - Providing a Foundation for Hydrogeophysics Research. (15 hp)
711. Zimmermann, Moa, 2025: Utdöda organisters diet: Karaktärisering av en vertebratkoprolit från Skånes kritt. (15hp)
712. Popa, Alexandra, 2025: Aqueous alteration in Martian meteorite Northwest Africa 11013: An analysis of its extent and origin. (15 hp)
713. Jónsdóttir, Svava Kristin, 2025: Grounding zone wedges in the Nyköping area, southeastern Sweden. (45hp)
714. Heim, Emelie, 2025: Den sen- och postglaciala landskapsutvecklingen i Tvååker, Halland. (15 hp)
715. Schiemann, Erik, 2025: Pollen och mikrofossil i en borrhäla från nedslagsstrukturen Hummeln. (15 hp)
716. Blomberg, Hampus, 2025: Vegetationsutvecklingen i Halland och Tvååker: sammanställning av underlag till informationsskyltar vid Naturplats Tvååkers Mosse. (15 hp)
717. Östman, Adrian, 2025: En litteraturstudie om grundvattensdata och modeller som möjliga verktyg inom mineralprospektering. (15 hp)
718. Belcher, Carl Nils, 2025: Systematiska felkällor i deklinationsdata från sedimentära borrhälar. (15 hp)
719. Raas, Valérie, 2025: Cosmogenic Radionuclide Evidence for a Solar Particle Storm at 14,300 BP. (45 hp)
720. Bjarkadóttir, Anna Briet, 2025: Barometry of Clinopyroxene in Xenoliths from the Anaga Region in Tenerife – Constraints on the Magmatic Plumbing System. (45 hp)
721. Grönberg, Joel, 2025: Kan vulkanismen på Kanarieöarna ha uppkommit till följd av en hetfläck?. (15 hp)
722. Cordes, Beatrix, 2025: A review of the contaminant situation of groundwater aquifers in Europe – A historical retrospective and future outlook. (45 hp)
723. Alkasser, Shefaa, 2025: En litteraturstudie om mantelplymhypotesens eventuella tillkortakommanden utifrån ett kanariskt perspektiv. (15 hp)
724. Grönberg, Joel, 2026: Optically stimulated luminescence in Scania: An investigation into its applicability of determining provenance of coastal deposits. (45 hp)
725. Langkjaer, Henrik, 2026: Esker formation during deglaciation of the Scandinavian Ice Sheet, northeast Skåne and Blekinge, Sweden. (45 hp)
726. Corshammar, Johannes, 2026: Petrologisk -petrografisk studie av ankaramitbergarter på Teneriffa. (15 hp)
727. Sonesson, Ville, 2026: BC-koncentrationer i sjösediment: en jämförelse mellan Kina, Schweiz och Finland. (15 hp)
728. Schönherr, Lara, 2026: Structural and petrographic characterization of the Mien impact structure, Sweden. (45 hp)



LUNDS UNIVERSITET

Geologiska institutionen
Lunds universitet
Sölvegatan 12, 223 62 Lund