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Terrestrial consequences of hypervelocity impact – Shock metamorphism, shock barometry, and newly discovered impact structures

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University of Freiburg

Cover picture: Thin section photomicrograph of bedrock sample from the Siljan impact structure with quartz crystal displaying multiple sets of planar deformation features (crossed polars). The width of the photo is 520 μm. Photography and design: Sanna Alwmark and Mimmi Nilsson.

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Abstract

Impact cratering was once considered a rare geological process of no, or little, importance to the evolution of the Solar System and planet Earth. After more than 50 years of space exploration and the discovery of numerous (~190 as of October 2016) impact structures on Earth, this view has changed, and it is now clear that impact craters are in fact one of the most common morphological features on solid bodies in the Solar System.

The formation of a (hypervelocity) impact crater involves extreme conditions that cannot be compared with any other natural geological process, with extreme pressures and temperatures causing melting and/or vaporization of both projectile and portions of the target rocks. Upon impact, shock waves are generated at the projectile-target interface, which pass through the target rocks at supersonic velocity. The passage of the shock waves induce irreversible changes, so called shock metamorphic effects in the target rocks, including the formation of high pressure mineral polymorphs, diaplectic glasses, and microdeformation features in minerals. The most investigated of these microstructures are planar deformation features (PDFs) in quartz. These are straight, parallel, closely spaced (2-10 µm apart), sets of (when fresh) glass lamellae only naturally formed by impact cratering. PDFs are oriented parallel to specific crystallographic planes, with the most frequently reported orientations being parallel to low Miller-Bravais index planes (e.g., $\{10\bar{1}3\}$, $\{10\bar{1}2\}$). The orientation pattern of a PDF population differ depending on the pressure that the host quartz grain was subjected to, meaning that the orientations of PDFs can be used as a shock barometer, allowing e.g., production of shock barometry profiles that illustrate shock attenuation at impact structures.

The research presented in this thesis focuses on impact craters, and the process by which they form, impact cratering, with special emphasis on shock metamorphic features in target rocks at the Siljan impact structure (Sweden). The results and discussion highlight the importance of the way datasets of PDF statistics are obtained and processed, using manual and/or automated methods of indexing. The interpretation of the dataset can influence the shock barometry models, and the need for a unified method is discussed.

With regards to the Siljan impact structure, the pre-erosional rim-to-rim diameter of the crater was estimated to be on the order of 60 km, based on a combination of shock barometry and numerical simulation, produced by a collision between a ~5 km diameter projectile and Earth. Results of the numerical modeling are consistent with a sedimentary thickness overlying the crystalline basement at the time of impact of ~2.5 km, and post-impact erosion of the crater on the order of 3 to 3.5 km.

The thesis also encompasses studies of two other, newly confirmed, Swedish impact structures, Målingen and Hummeln. The possible means of formation for both Målingen and Hummeln had been discussed for many years before the first bona fide evidence for the impact origin of the two structures was presented in papers included in this thesis.

Furthermore, terrestrial impact structures with reliable ages (i.e., errors on age of less than 2 %) are discussed in the context of possible variations in the impactor flux to Earth over time. According to the results, there is presently no evidence for the existence of a periodic contribution to the terrestrial impact population.

Key words: Impact cratering; impact structure; shock metamorphism; shock barometry; quartz; planar deformation features; Siljan; Målingen; Hummeln

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Till mina fantastiska barn

Contents

List of papers

This thesis is based on the six papers listed below, which have been appended to the thesis. Papers I and II are reprinted under permission of John Wiley and Sons, Inc. Paper III is reprinted under permission of the Geologic Society of America. Paper IV has been submitted to the journal Monthly Notices of the Royal Astronomical Society for consideration. Papers V and VI are manuscripts to be submitted.

Note that the last name of the author of this thesis, Alwmark, is a married name, and thus early publications of the author are under the maiden name, Holm. In order to connect the early work with recent/future work, a combination of the maiden name and the married name is used.

Paper I

Holm S., Alwmark C., Alvarez W., and Schmitz B. 2011. Shock barometry of the Siljan impact structure, Sweden. Meteoritics & Planetary Science 46:1888–1909. DOI: 10.1111/j.1945-5100.2011.01303.x.

Paper II

Alwmark C., Holm-Alwmark S., Ormö J., and Sturkell E. 2014. Shocked quartz grains from the Målingen structure, Sweden - Evidence for a twin crater of the Lockne impact structure. Meteoritics & Planetary Science 49:1076–1082. DOI: 10.1111/maps.12314.

Paper III

Alwmark C., Ferrière L., Holm-Alwmark S., Ormö J., Leroux H., and Sturkell E. 2015. Impact origin for the Hummeln structure (Sweden) and its link to the Ordovician disruption of the L chondrite parent body. Geology 43:279–282. DOI: 10.1130/G36429.1.

Paper IV

Meier M. M. M., and Holm-Alwmark S. A tale of clusters: No resolvable periodicity in the terrestrial impact cratering record. Submitted to Monthly Notices of the Royal Astronomical Society, manuscript.

Paper V

Holm-Alwmark S., Rae A.S.P., Ferrière L., Alwmark C., and Collins G.S. Combining shock barometry with numerical modeling: insights into complex crater formation – The example of the Siljan impact structure (Sweden), manuscript.

Paper VI

Holm-Alwmark S., Ferrière L., Alwmark C., Poelchau M. H. Investigation of shocked quartz grains using the universal stage – What can be done and how to do it in an appropriate way: The case study of the Siljan impact structure (Sweden), manuscript.

Basic definitions and abbreviations

Here are definitions and abbreviations of the most important terms used in this thesis.

Hypervelocity impact crater –	Morphological structure formed by an extraterrestrial body that is large enough and coherent enough to enter and pass through the Earth's atmosphere and strike the surface at virtually its original cosmic velocity (>11 km/s; i.e., hypervelocity impact).
Impact structure –	Non-pristine impact crater e.g., lacking original morphology due to erosion.
Shock metamorphism –	"All changes in rocks and minerals resulting from the passage of transient, high-pressure shock waves" (French 1968, p.2).

PFs – Planar fractures

FFs – Feather features

PDFs – Planar deformation features

1. Introduction

In this thesis, impact craters, and the process by which they form, impact cratering, is explored through several methods, including field observations, mineralogical investigations, and numerical modeling.

The primary aims of the thesis are to investigate and to characterize the distribution of shock metamorphic features in impactites, to examine the specific features of the Siljan impact structure, Sweden, in order to establish the original size and morphology of it, and also to use this information for improving the understanding of shock metamorphism, the crater forming process in general, and to explore possible large scale questions related to this field of research, e.g., the variations in impactor flux to Earth through time.

Three papers and three manuscripts form the basis of this thesis. They are re/pre-printed here as appendices, and summarized in section 6. Additional peer-reviewed papers and extended abstracts produced during my PhD-studies, not included in this thesis, are listed in Appendix A.

The research presented in this thesis has partly been funded by generous contributions from The Royal Physiographic Society in Lund, Johan Christian Mobergs resestipendiefond: Lunds Geologiska Fältklubb (The Geological Field Club of Lund). Also the Barringer Family Fund for Meteorite Impact Research is acknowledged for their financial support.

2. Impact cratering – A major geologic process

After more than 50 years of space exploration and studies of a growing number of confirmed impact structures on Earth, impact cratering has evolved from being considered a peripheral geological process into a fundamental part of the history of both Earth and the Solar System. Indeed, impact craters are one of the most common landforms on all celestial bodies in the inner Solar System (except for Earth), and on most satellites of the gas giants and on the icy bodies of the Kuiper belt (Fig. 1).

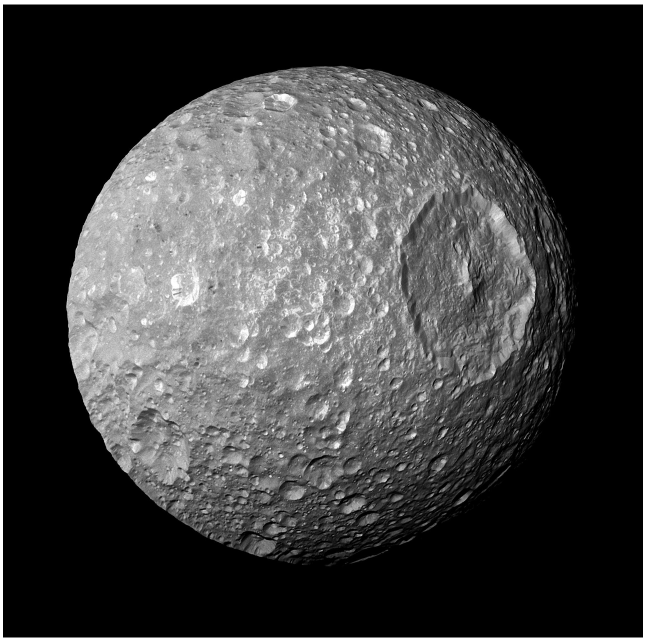
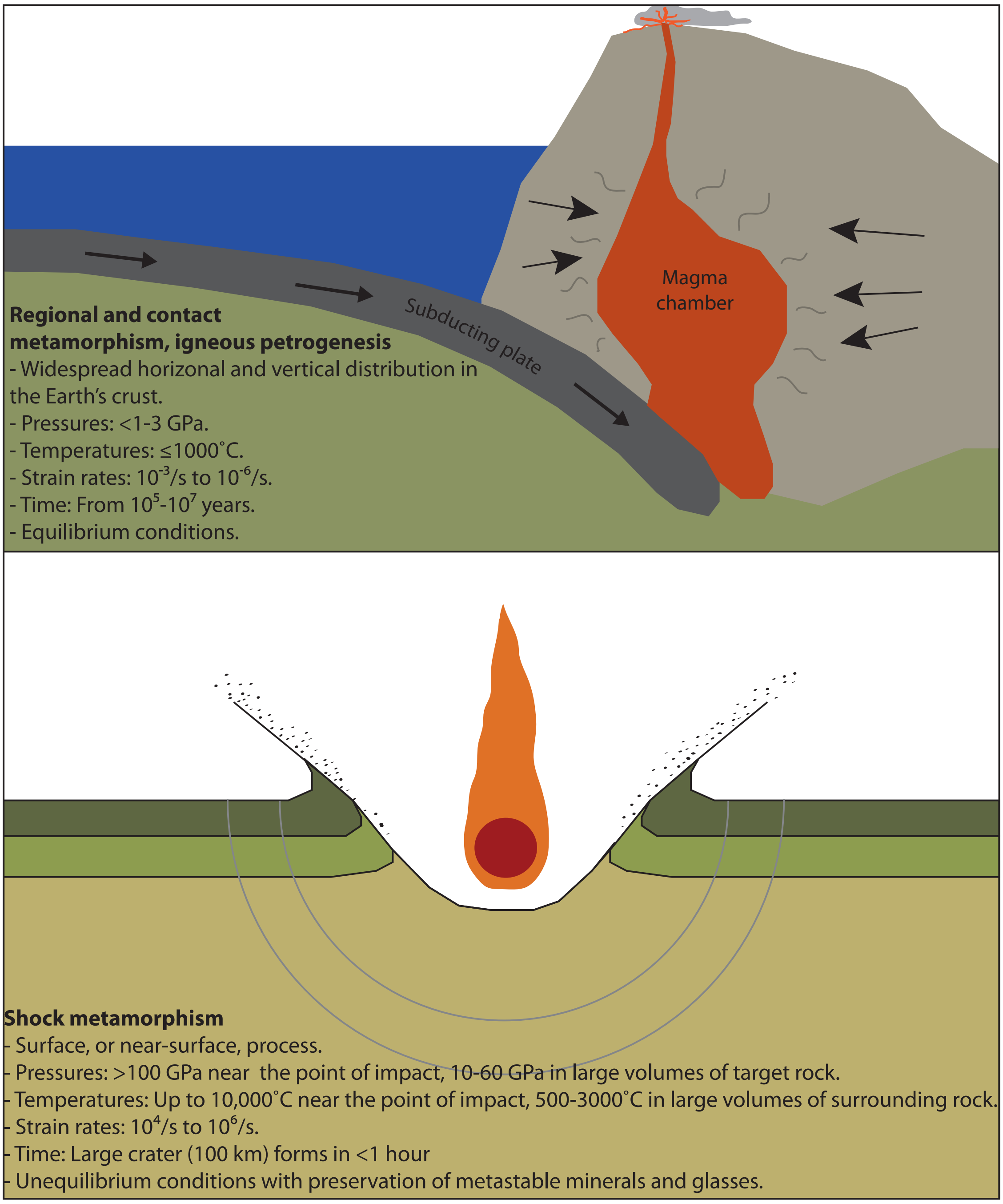


Fig. 1. This is not a space station… Landscape dominated by impact craters on Saturn satellite Mimas, captured by the NASA Cassini spacecraft. The large impact crater (~130 km in diameter) is called Herschel (Photograph credit NASA/JPL-Caltech/Space Science Institute).

Impact cratering as a process involves collisions between celestial bodies of various sizes, e.g., planets and asteroids or comets. In the early Solar System, collisions between primitive objects led to the formation of planetesimals, and later planets (Wetherill 1980 and references therein). The most widely accepted theory for the formation of Earth's Moon is that it was formed by the collision of a Mars-sized object with Earth at the end of its accretion (Canup and Asphaug 2001). For the evolution of the early Earth, impact cratering has played a major role (see discussions in e.g., Grieve et al. 2006; Koberl 2006), e.g. in shaping the early terrestrial crust. Later in Earth history impacts have resulted in major perturbations of the ecosystem, and at least on one occasion has the collision with a celestial body caused global mass extinction, at the Cretaceous-Paleogene boundary (Alvarez et al. 1980; Hildebrand 1991). Today, we reap the riches produced by impact cratering in the form of hydrocarbon deposits and some of the world's largest ore resources (for a review see Grieve 2013).

After the early catastrophic period of Earth history and the resurfacing event commonly called the Late Heavy Bombardment (e.g., Hartmann et al. 2000; Ryder et al. 2000; Hartmann et al. 2007 and references therein), defined by a dramatically increased cratering rate in the inner Solar System at



Regional and contact metamorphism, igneous petrogenesis

- Widespread horizonal and vertical distribution in the Earth's crust.
- Pressures: <1-3 GPa.
- Temperatures: ≤1000°C.
- Strain rates: 10^{-3}/s to 10^{-6}/s.
- Time: From 10^{5}-10^{7} years.
- Equilibrium conditions.

Shock metamorphism

- Surface, or near-surface, process.
- Pressures: >100 GPa near the point of impact, 10-60 GPa in large volumes of target rock.
- Temperatures: Up to 10,000°C near the point of impact, 500-3000°C in large volumes of surrounding rock.
- Strain rates: 10^{4}/s to 10^{6}/s.
- Time: Large crater (100 km) forms in <1 hour
- Unequilibrium conditions with preservation of metastable minerals and glasses.

Fig. 2. Cartoon comparing characteristic conditions of shock metamorphism with those of other, more "conventional", geological processes. Data from French 1998, Table 4.1.

about 3.9 Ga, impact cratering as a process became subordinate to more gradualistic geological processes such as volcanism and continental collisions on Earth, but it has nevertheless remained effective up until today (e.g., the collision of comet Shoemaker-Levy 9 into Jupiter in July 1994), and will remain so in the future.

The study of impact craters on Earth is hindered by the destructive forces of volcanic resurfacing, continental collisions, sedimentary burial and erosion, which leads to poor preservation of the impact craters themselves, and other associated products such as ejecta layers. The formation, on Earth, of a large crater resulting from a hypervelocity impact event has never been documented by humans, and the process itself is vastly different from other geological processes such as volcanic eruptions and earthquakes, in that it involves extreme physical conditions (Fig. 2), and, compared to conventional geological processes, an extremely short time-frame. This means that although many aspects of impact cratering are well understood, fundamental parts of the cratering process, and associated deformations, transformations, and products, are still poorly understood.

3. The formation of an impact crater

A stony body >50 m in diameter, or an iron body >20 m in diameter (e.g., French 1998; Osinski and Pierazzo 2013; see also Bland and Artemieva 2003), has the potential to penetrate the Earth's atmosphere with little or no deceleration, and thus hit the surface at cosmic velocities (>11 km/s). The moment that the leading edge of this extraterrestrial body makes contact with the surface of the Earth, a hypervelocity impact crater starts to form. The crater-forming process is traditionally (e.g., Gault et al. 1968; Melosh 1989; French 1998; Osinski and Pierazzo 2013, and references therein) divided into three stages, summarized below, each dominated by different physical processes; the contact and compression stage, the excavation stage, and the modification stage.

3.1. The contact and compression stage

When the projectile makes contact with the ground surface it is stopped in a fraction of a second, penetrating only 1-2 times its own diameter (if the target is solid rock; Kieffer and Simonds 1980; O'Keefe and Ahrens 1982; Fig. 3). Shock waves that travel at supersonic velocities are generated at the point of impact, and transfer the immense kinetic energy of the projectile into the target rocks. A complementary shock wave also travels back into the projectile, and when this reaches the rear side of the body, it is reflected back as a rarefaction wave which, on its passage back through the projectile, unloads it from extreme pressures, causing it to melt and/or vaporize completely (Melosh 1989).

The shock waves travel through the target rock in a hemispherical pattern (Fig. 3) and lose energy as they travel away from the point of impact due to energy density loss as the shock front is dispersed over an increasingly larger area. Additional energy is lost due to heating, deformation, and acceleration of target rocks. This means that the peak pressures of the shock waves decrease rapidly, forming a series of concentric shock zones, or envelopes, around the point of impact (e.g., Melosh 1989). Shock pressures far exceed 100 GPa at the point of impact (Melosh 1989; Melosh 2013), causing melting and vaporization of target material. Further away (up to several km depending on the magnitude of the impact), shock pressures typically range between 10-50 GPa (e.g., French 1998), resulting in unique shock metamorphic effects in a large portion of the target rocks.

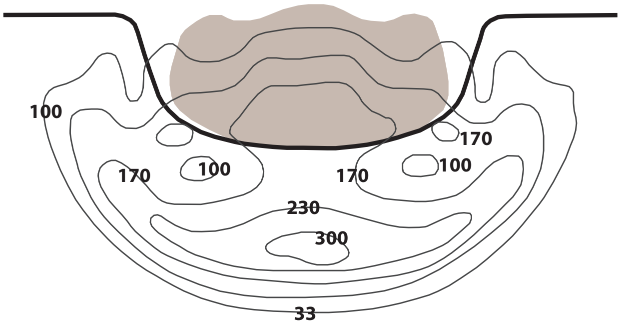


Fig. 3. Cartoon showing conditions one second after the impact of an originally spherical 46-km-diameter projectile onto the Moon (similar conditions apply to terrestrial impacts, and also for smaller impacts) based on original model by O'Keefe and Ahrens (1975). This figure illustrates how the projectile has become compressed after penetrating about half its diameter into the target, and shock waves (pressures in GPa) radiate outwards from the projectile-target interface, and also back into the projectile. Figure modified from Melosh (1989) and French (1998).

The contact and compression stage grades into the excavation stage at the moment that the projectile is unloaded by the rarefaction wave, and the whole process does not take more than a few seconds, even in cases where very large extraterrestrial objects collide with Earth (Melosh 1989). As an example, Melosh (2013) calculates that the contact and compression stage during the impact event that caused the Cretaceous-Paleogene mass extinction, 66 million years ago, lasted only 0.5 seconds (in this case, the projectile was ~10(14) km in diameter).

3.2 The excavation stage

During this second stage of crater formation, the actual impact crater is opened up through complex interactions between the shock waves and the target rocks. Since the projectile is vaporized and melted at this point, it plays no further role in forming the crater. Instead, an excavation flow is initiated around the impact point due to target material being left with a residual velocity after first the compression, and then the release, of the high pressures as the shock wave passes through the material (Melosh 1989). This excavation flow drives material away from the point of impact but also interacts with rarefaction waves, resulting in an upward component in the movement of material (Turtle et al. 2005). Material is thus ejected out from the forming crater on ballistic trajectories, and the combination of these movements opens up the so called transient cavity. The transient cavity is defined as “the opening, or collapsing, crater at any given instant during the impact event” (Turtle et al. 2005, p. 4). The same authors provide a definition for the related term “transient crater” as “an idealized [crater] shape defined by the maximum extent to which excavation proceeds in every direction” (Turtle et al. 2005, p. 4). The different directions of moving material in the transient cavity results in an upper excavated zone, and a lower displaced zone (Fig. 4). When the energy carried by the shock and release waves is insufficient to drive material out from the crater, excavation ceases, and so also the excavation stage. Although lasting longer than the contact and compression stage, even in large collisional events, this stage lasts no more than a few minutes (Melosh 1989).

Part of the process of impact crater formation is also the melting and vaporization of target material, at a volume about equal to the one of the projectile (in the case of a typical large impact on Earth; Melosh 2013). This material expands out from the forming crater, becoming a vapor that violently mixes with condensing melt droplets, small ejected fragments, and the atmosphere, together forming the so called vapor plume (Melosh 1989). The plume continues to expand from the site of impact until it has equilibrated with the surrounding atmosphere and/or extended into space. The material will eventually rain down on Earth, at distances covering the entire planet in the case of large impacts (Melosh 1989; Johnson and Melosh 2012).

3.3 The modification stage

This stage is defined by the modification of the transient cavity by more conventional geological processes like gravity and rock mechanics, and does not involve the shock waves, which are now low-pressure elastic, or seismic, waves. The degree of modification is mainly controlled by the size of the transient cavity and the target rock properties, resulting in either a so-called “simple”, or “complex”, final crater (Dence 1965; Melosh and Ivanov 1999; Fig. 5). On Earth, the transition from craters classified as simple, whose morphologies differ little from the original transient crater, to complex craters that are formed by collapse of the transient crater, occurs at about 2 km for impacts into sedimentary targets, and at about 4 km for

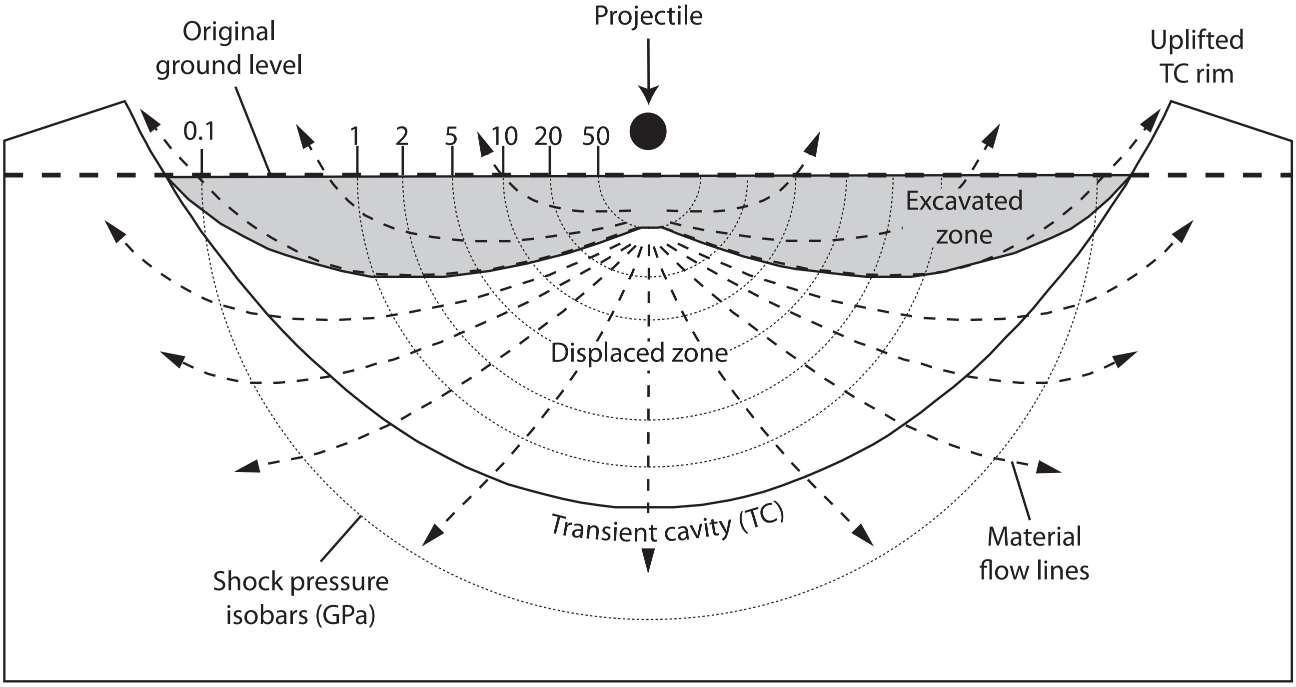


Fig. 4. Illustration of the formation of the transient crater during the excavation stage. Dashed arrows represent the excavation flow that opens up the crater. The gray area defines the excavated zone, where material is driven out from the crater and deposits as ejecta surrounding the final structure. In the displaced zone, material is driven downward and outward, and does not leave the crater. Original peak shock pressure contours (units in GPa) indicate that the ejected material is going to reflect a plethora of shock conditions ranging from molten (vaporized) material to the simplest of shock deformation effects such as fracturing, indistinguishable from fracturing produced by “normal” geologic processes. Figure modified from French (1998).

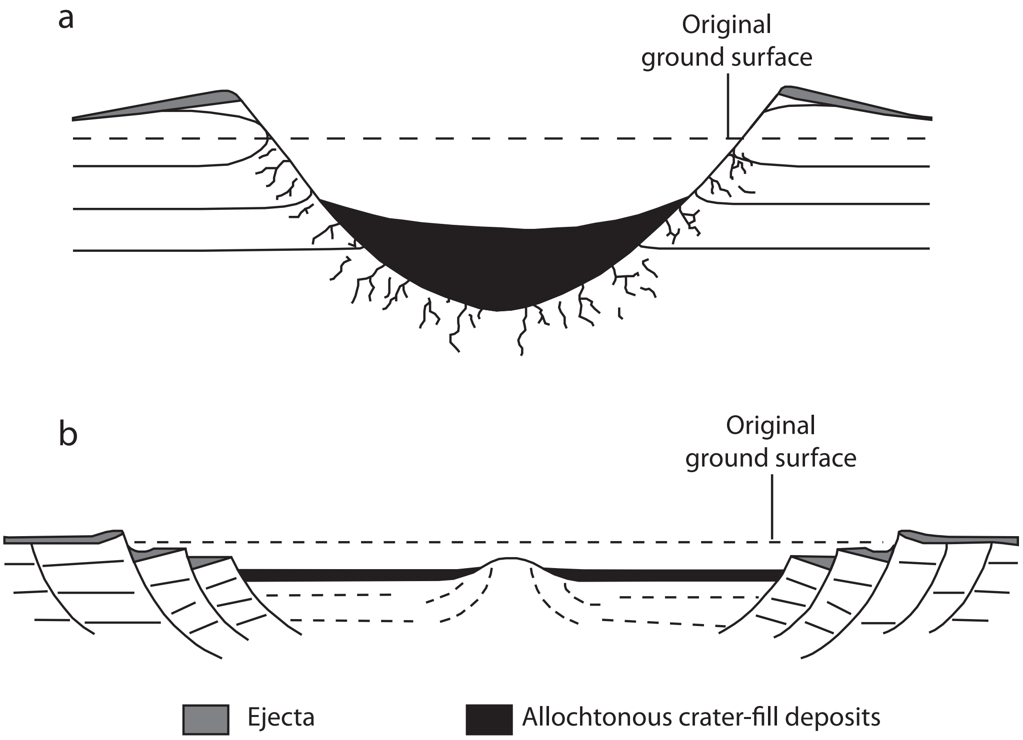


Fig 5. Schematic cross section of a) pristine simple crater and b) pristine complex crater. Figure modified from Turtle et al. (2005).

impacts into crystalline targets (Grieve 1987; Melosh and Ivanov 1999).

There is no well-defined end to the modification stage (French 1998), but rather a gradual transition from impact-related uplift and collapse of the transient cavity to normal geological mass movement processes, isostatic uplift, erosion, and sedimentation.

3.4 The morphology of impact craters

A bowl-shaped depression into the Earth (i.e., the transient crater) is not stable, and alters quickly during the modification stage. In small structures, this alteration is dominated by the collapse of the upper crater walls, forming circular depressions (Fig. 6) filled with an allochtonous breccia lens, and an uplifted rim (Fig. 5a; e.g., Grieve 1987). In larger structures major structural changes to the transient cavity take place as the central part of the crater floor is uplifted and the peripheral area around the rim collapses (Figs. 5b and 7; Kenkmann et al. 2013 and references therein). Observations from the Moon and other celestial bodies in the Solar System have allowed the recognition of different types of complex craters, depending on crater size. These are (with increasing size) central peak, central peak basin, and

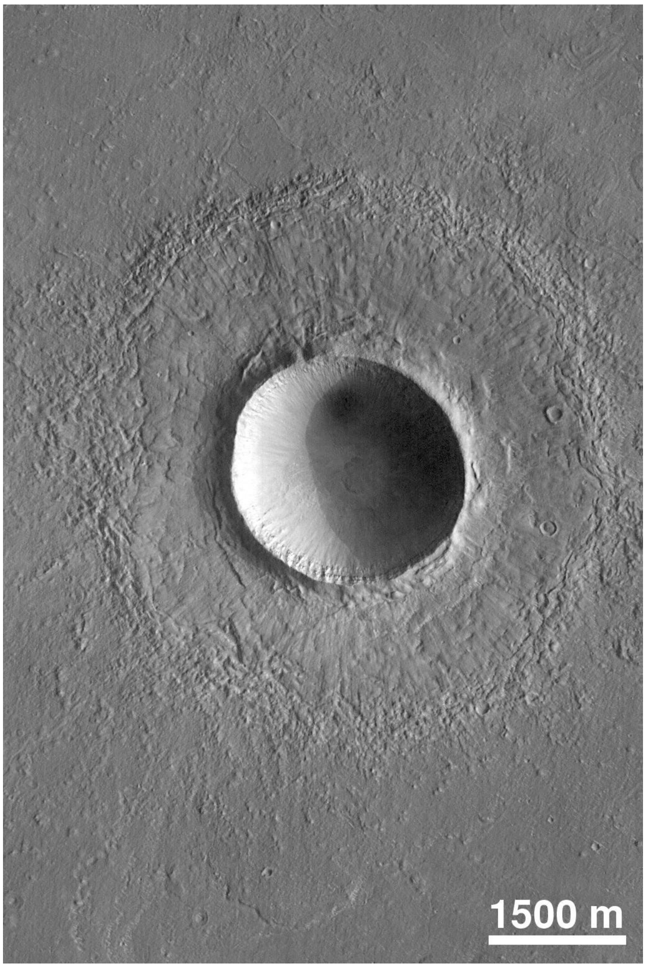


Fig. 6. Photograph, taken by Mars Global Surveyor, of a simple crater on Mars (Photograph credit NASA/JPL/MSSS).

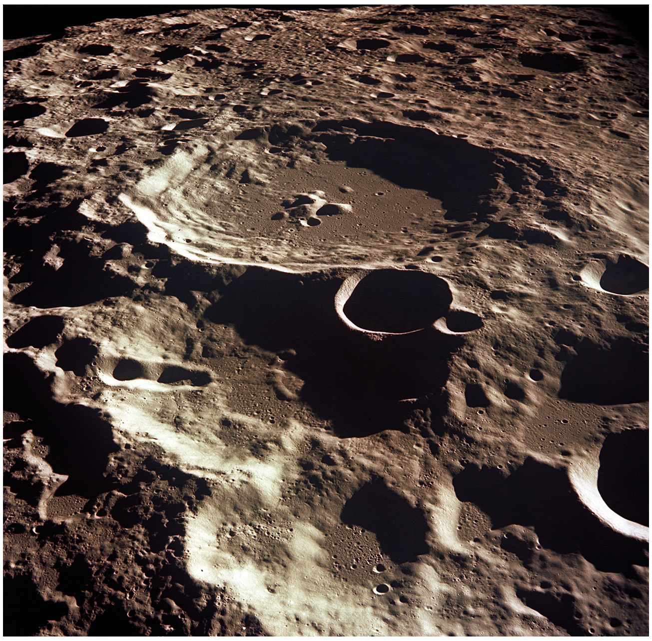


Fig. 7. Photograph of the farside of the Moon (as seen from the Apollo 11 spacecraft in lunar orbit) showing a densely cratered landscape. The complex crater, roughly in the middle of the photograph, is called Daedalus (formerly referred to as Crater No. 308) and has a diameter of about 80 km (Photograph credit NASA).

peak ring basin type complex craters (Osinski and Pierazzo 2013). On Earth, it is typically not possible to determine which type a complex crater belongs to due to erosion.

The largest impact structures in the Solar System are referred to as multi-ring basins, which (as indicated by the name) are surrounded by multiple observable rings. The formation of these types of craters is poorly understood (Melosh 1989; Head 2010; see also discussion in Osinski and Pierazzo 2013), partly due to them being present on some celestial bodies (e.g., the Moon and Jovian satellite Callisto), but not on others (e.g., Mars or Venus; Osinski and Pierazzo 2013). The largest terrestrial impact structures Vredefort (South Africa) and Sudbury (Canada) are deeply eroded and morphological details are difficult to interpret. The third largest, Chicxulub, is much younger and covered by sediments, and thus better preserved. Geophysical data from this structure has been interpreted to suggest a multi-ring basin morphology (Morgan et al. 1997; Grieve et al. 2008).

4. Impactites and shock metamorphism

The formation of an impact crater involves physical conditions that are extreme in terms of energy release, pressures, temperatures, and strain rates (Figs. 2 and 8). Shock waves travel through the target rock at speeds of several km per second, passing individual mineral grains and even whole rock samples in nano- to microseconds. The onset and release of pressure is therefore highly transient, and in addition post-shock temperature increase results from the deposition of energy into the target material by the shock waves (French 1998). The temperature increases with shock wave pressures, reaching levels which cause melting and/or vaporization of target material. The impact process is thus vastly different from the processes that control conventional metamorphism and igneous petrogenesis (Fig. 8). Peak shock pressures during the impact event range from ≥2 GPa in the final crater rim region, to >100 GPa near the point of impact, which can be compared with pressures of <1-3 GPa during the "normal" geologic processes exemplified above. Even the formation of a relatively small crater, e.g., Meteor Crater (Arizona; diameter ~1.2 km), formed by a projectile ~55 meters in diameter, releases energies corresponding to the blasts during the biggest recorded volcanic eruptions. Such amounts of energies far exceed those released during a hydrogen bomb explosion (French 1998).

Along with the formation of a new morphological surface feature, new rock types are also produced by impact metamorphism of target rocks, and these are called impactites. Impactites range from fractured autochtonous target rocks to completely new rock types, such as melt-bearing breccias and impact melt rocks. An IUGS-recommended classification scheme for impactites was presented by Stöffler and Grieve (2007), where both terms and ways of classification of these rock types are described in detail.

4.1 Shock metamorphic effects

Shock metamorphic effects (Table 1, Fig. 8) are irreversible changes to rocks and minerals formed by subjection to shock pressures induced by impact. Minerals and rocks in a large portion of target rock

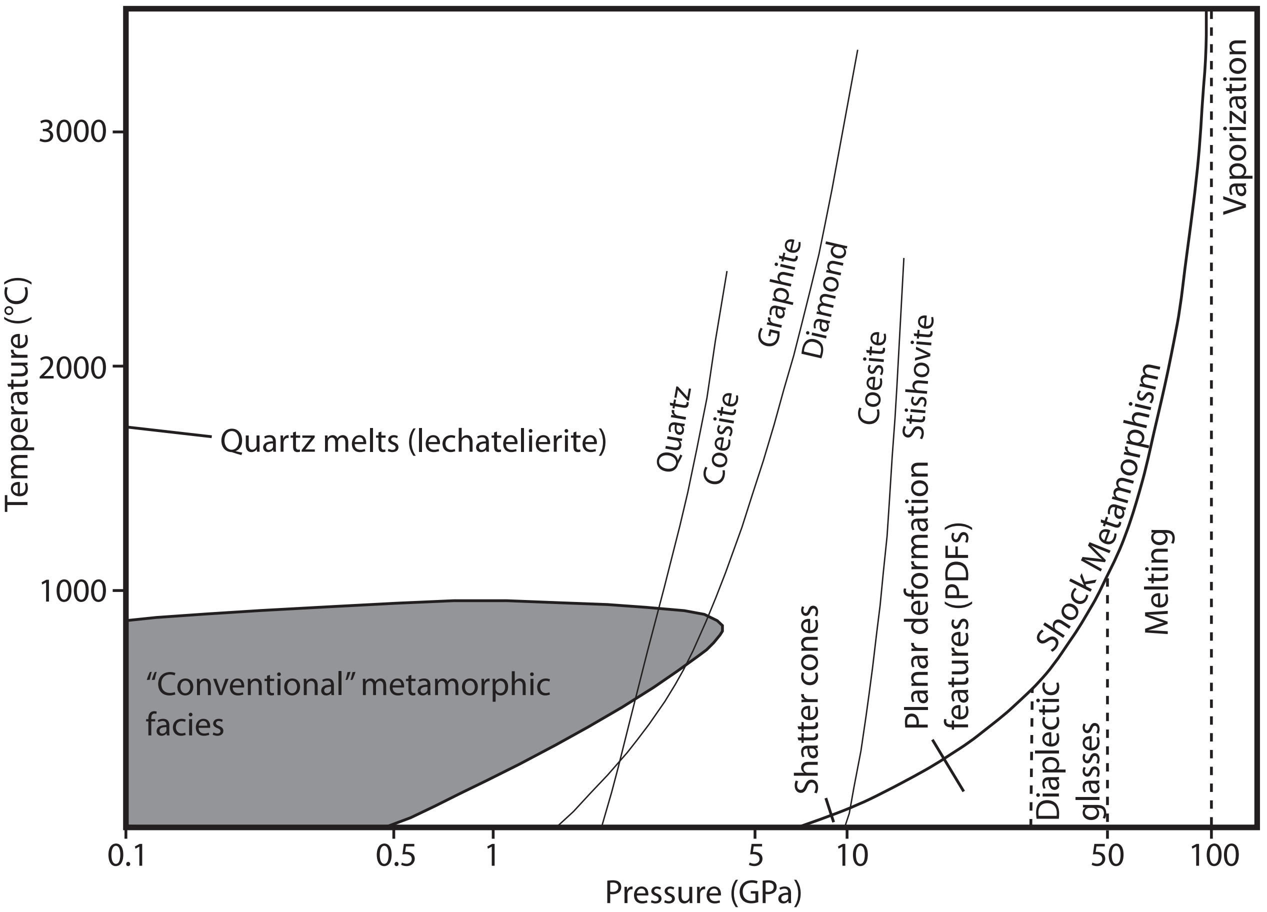


Fig. 8. The extreme physical conditions of impact cratering compared to conventional crustal metamorphism. Vertical dashed lines indicate approximate formation conditions for exemplified shock effects. The curve labeled "shock metamorphism" indicates post-shock temperatures produced by specific shock pressures (in granitic crystalline rocks). The formation conditions for high pressure mineral polymorphs (coesite, diamond, and stishovite) varies under shock conditions, the solid lines in this diagram indicates formational conditions under static equilibrium conditions. Note that the x-axis is logarithmic. Figure modified from French 1998.

will be subjected to pressures above their Hugoniot elastic limit (HEL), i.e., the yield strength of the material (Melosh 1989; Stöffler and Langenhorst 1994; Langenhorst 2002). For most geologic materials, the HEL lies between roughly 1-10 GPa (see e.g., Melosh 1989, and references therein), and for quartz specifically, it ranges between 5-8 GPa (Ferrière and Osinski 2013). The specific changes are a function of having to adapt to the extreme temperature and pressure conditions at high strain rates and short shock pulse durations, leaving rocks and minerals no time to deform by equilibrium reactions.

Although shock metamorphic effects have been described in many minerals (e.g., quartz, potassium feldspar, plagioclase feldspar, zircon, olivine), quartz is by far the best-studied of all minerals with respect to shock metamorphism (see e.g., papers in French and Short 1968; von Engelhardt and Bertsch 1969; Stöffler 1972; Stöffler and Langenhorst 1994; Grieve et al. 1996; French 1998; French and Koeberl 2010). This is because it is abundant in terrestrial

Table 1. Shock pressures, post-shock temperatures, and effects (dense, non-porous rocks).

Approximate shock pressure (Gpa)	Estimated postshock temperature (°C)	Effects
2–6	<100	Rock fracturing, formation of breccia Shatter cones
5–7	100	Mineral fracturing: (0001) and $\{10\bar{1}1\}$ in quartz
8–10	100	Basal Brazil twins in quartz
10	100	Quartz with PDFs: $\{10\bar{1}3\}$
12–15	150	Quartz -> stishovite
13	150	Graphite -> cubic diamond
20	170	Quartz with PDFs: $\{10\bar{1}2\}$ etc. Quartz & feldspar with reduced refractive indexes, lowered birefringence
>30	275	Quartz -> coesite
35	300	Diaplectic quartz & feldspar glasses
45	900	Normal (melted) feldspar glass
60	>1500	Rock glasses, crystallized melt rocks (quenched from liquids)
80–100	>2500	Rock glasses (condensed from vapor)

Table modified from French (1998), and based on data from Stöffler (1984), Melosh (1989), and Stöffler and Langenhorst (1994).

crustal rocks, it is resistant to weathering, it has simple optical features, and it develops shock metamorphic features over a wide pressure range. Studies of shock metamorphic features have dominantly been focused at non-porous acidic igneous and metamorphic rocks (e.g., granite), while other rock types such as basaltic rocks and sedimentary rocks are far less studied (e.g., French 1998; Grieve et al. 1996), with the only exception being sandstones (Kieffer 1971, 1975; Kieffer et al. 1976), which have been investigated mainly due to the target rocks of the Meteor Crater being sandstone.

Studies of shock metamorphosed rocks and laboratory experiments have showed that different shock pressures produce a different set of shock metamorphic features in the target rocks (Hörz 1968; Müller and Défourneaux 1968; Engelhardt and Bertsch 1969; Stöffler 1972; Robertson 1975; Grieve and Robertson 1976; Stöffler and Langenhorst 1994; Grieve et al. 1996; Huffman and Reimold 1996; French 1998). Therefore, it is possible to define different stages of shock metamorphism, and to use specific features as shock pressure barometers. The description of shock metamorphic features that follows below is compiled from studies of dense, crystalline, quartz-bearing, rocks.

In the low pressure range (~2-10 GPa), the only distinctive shock metamorphic feature detectable with the naked eye, shatter cones, develop (Fig. 9). Shatter cones are “distinctive curved, striated fractures that typically form partial to complete cones” (French 1998, p. 36), or as recently defined, in a little bit more detail: “rounded and diverging striations appearing on curved and spaced fracture surfaces of variable orientations distributed within the volume of rock” (Baratoux and Reimold 2016, p. 1395). Shatter cones are best developed in fine-grained lithologies, but they also occur in medium- to coarse-grained rocks, where they are often poorly developed (Fig. 9). Along with shatter cones in the low pressure range is the formation of microscopic deformation features including planar fractures (PFs), mechanical brazil-twin lamellae in quartz (Kieffer et al. 1976; Goltrant et al. 1991; hereafter referred to as basal PDFs, because they are oriented parallel to the basal plane of the crystal in which they are found), and feather features (FFs; e.g., Poelchau and Kenkmann 2011). These features are discussed in more detail in section 4.1.1.

In the ~>10-45 GPa pressure range high pressure mineral polymorphs (e.g., diamond, coesite) and microscopic deformation features in individual crystals are produced (see below for a description of these features in quartz). At higher pressures (≥50 GPa), partial to complete melting of the target rocks takes place. The highest pressure regime (≥100 GPa) results in vaporization of large volumes of target rocks near the point of impact.

In the following sections, shock metamorphism of quartz (in crystalline target rocks) will be discussed in more detail. For corresponding information on how other minerals respond to the passing shock wave during impact events, the reader is referred to e.g., papers in French and Short (1968), Stöffler (1972), Bischoff and Stöffler (1992), French (1998), and Ferrière and Osinski (2013).

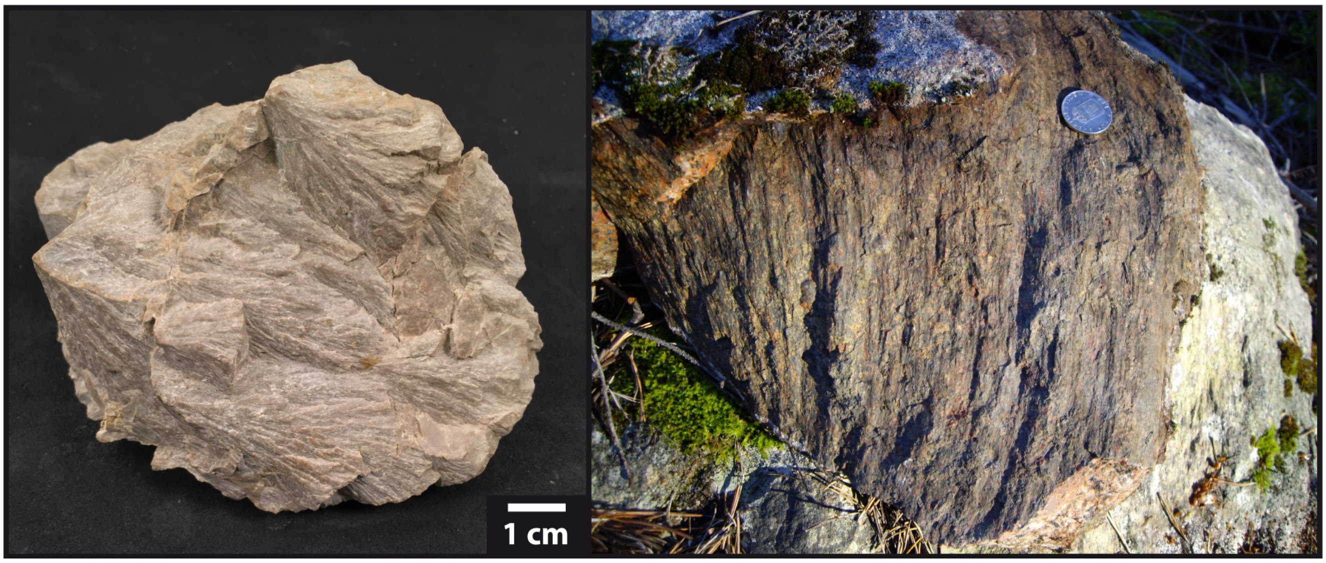


Fig. 9. Left: Photograph of well-developed shatter cones in sample from the Wells Creek impact structure (Tennessee, USA). Right: Photograph of typically poorly developed shatter cone in coarse-grained granite from the Siljan impact structure (Sweden).

4.1.1 Shocked quartz – PFs, FFs, PDFs, and more

Quartz displaying evidence of shock metamorphism, called “shocked quartz” for short, is one of the most extensively studied products of impact cratering (e.g., von Engelhardt and Bertsch 1969; Stöffler 1972; Alexopoulos et al. 1988; Stöffler and Langenhorst 1994; Grieve et al. 1996; French 1998; Ferrière et al. 2009a). As a response to being compressed by the passing shock wave, quartz behaves in a number of ways, depending on the shock pressure. At lower shock pressures, it responds by developing irregular fractures, which are not diagnostic shock effects, and planar microstructures. Planar microstructures (PFs, FFs, and PDFs), are crystallographically controlled and thus their orientations are described using Miller-Bravais indices. The four (*hkil*) indices describe how the plane (or any of the parallel planes) intersects the main crystallographic axes of the crystal (the a_1, a_2, a_3, and c axes; Fig. 10). Some of the crystallographic planes where PFs and PDFs occur have correlative right hand or left hand (or positive/negative) forms, e.g., positive and negative rhombohedra $\{10\bar{1}3\}$ and $\{01\bar{1}3\}$, each with three sets of symmetrically equivalent planes. Because of the symmetry class of α-quartz, and limitations of the microscope technique used to determine crystallographic orientations of PFs and PDFs, wavy brackets are used to describe forms of planes, because it is not possible to determine which symmetrically equivalent plane is in question (Stöffler and Langenhorst 1994).

At higher pressures, the crystal may e.g., be transformed into diaplectic glass, high-pressure polymorphs, or even melt (see below).

4.1.1.1 Planar fractures (PFs)

PFs are straight, thin, open fractures that occur as single, or multiple parallel sets in the host quartz crystal (Fig. 11a). The individual fractures are generally 3-10 µm thick, and spaced more than 15-20 µm apart, i.e., both thicker than, and positioned at greater distance apart, than individual PDF lamellae (see below; Stöffler and Langenhorst 1994; Grieve et al. 1996; French 1998; French and Koeberl 2010 and references therein). PFs require a minimum of 5-8 GPa for their formation (French 1998) and are most frequently oriented along the (0001) and $\{10\bar{1}1\}$-orientations (Ferrière and Osinski 2013).

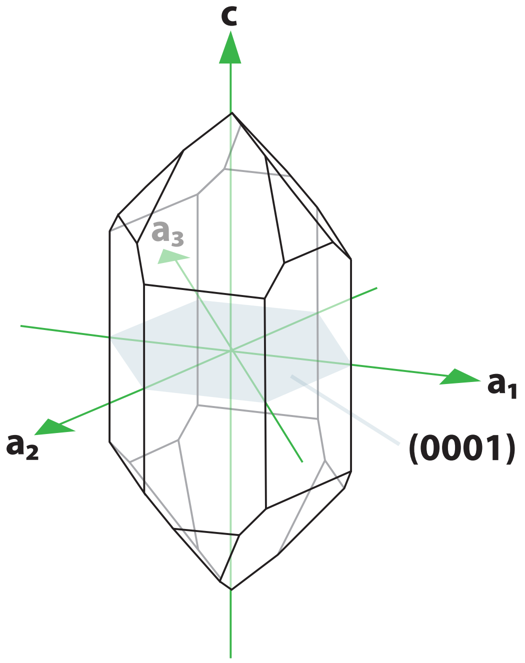


Fig. 10. Figure of an idealized quartz crystal showing the c-, a_1-, a_2-, and a_3-axes. A plane (which could be a PDF lamellae) oriented along the basal plane of the crystal is also displayed. Modified from Fig. 4 on www.quartzpage.de/crs_intro.html.

4.1.1.2 Feather features (FFs)

FFs are sets of parallel, straight/slightly curved lamellae that branch off of PFs, and that to some degree are crystallographically controlled (Fig. 11a; French et al. 2004; Poelchau and Kenkmann 2011). These features have been quite poorly studied but Poelchau and Kenkmann (2011) suggests that they are formed by shearing of PFs during shock wave passage, meaning that they could be indicative of shock deformation. Poelchau and Kenkmann (2011) suggested these features to be indicative of the lower pressure regime of shock metamorphism (~7-10 GPa), but further studies are needed to understand their formation better.

4.1.1.3 Planar deformation features (PDFs)

PDFs are sets of straight, parallel, crystallographically controlled amorphous lamellae formed naturally only in the case of impact (Fig. 11b-d; French and Short 1968; von Engelhardt and Bertsch 1969; Stöffler 1972; Alexopoulos et al. 1988; Stöffler and Langenhorst 1994; Grieve et al. 1996; French 1998). The individual lamellae are closely spaced, typically 2-10 µm apart, and thin, less than 2 µm. PDFs often occur in multiple sets in a quartz crystal, oriented along specific rational crystallographic planes. Most frequently they are oriented along the (0001), $\{10\bar{1}3\}$, and $\{10\bar{1}2\}$ orientations, and in lower amounts parallel to the $\{10\bar{1}4\}$, $\{10\bar{1}1\}$, $\{10\bar{1}0\}$, $\{11\bar{2}2\}$, $\{11\bar{2}1\}$, $\{21\bar{3}1\}$, $\{51\bar{6}1\}$, $\{11\bar{2}0\}$, $\{22\bar{4}1\}$, $\{31\bar{4}1\}$, $\{40\bar{4}1\}$, and $\{51\bar{6}0\}$ orientations (Table 2; e.g., Stöffler and

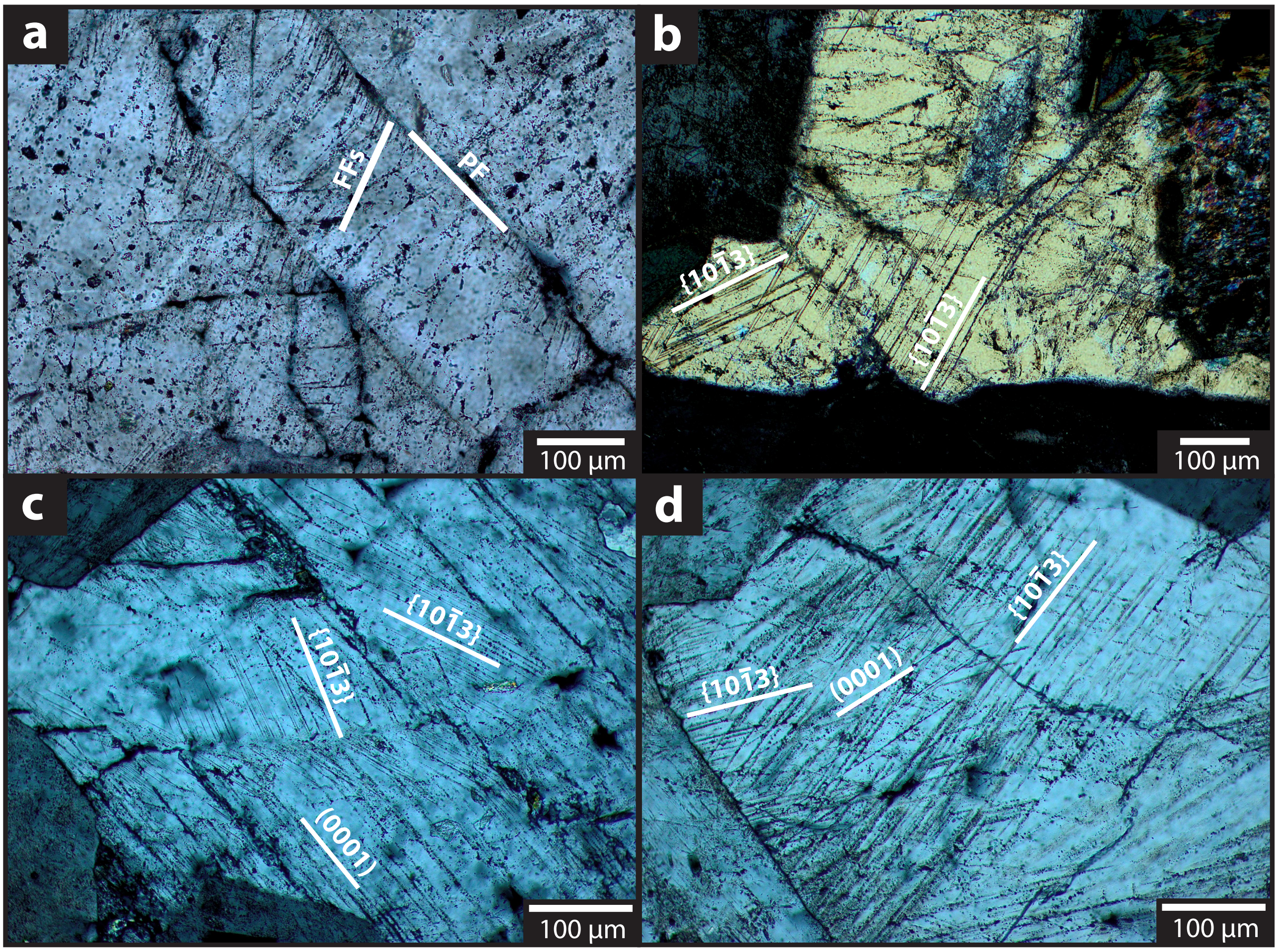


Fig. 11. Thin section photomicrographs of quartz grains from drill core samples from the Siljan impact structure (Sweden; Cross-polarized light). a) Quartz grain with two PFs oriented parallel to the (0001) orientation, with FFs emanating from both of them. b) Quartz grain with two sets of {10$\bar{1}$3}-equivalent orientations. c) Quartz grain with two PDFs sets with {10$\bar{1}$3}-equivalent orientations and one set oriented parallel to the basal plane of the crystal. d) Quartz grain with two PDFs sets with {10$\bar{1}$3}-equivalent orientations and one set oriented parallel to the basal plane of the crystal.

Langenhorst 1994; French 1998; Ferrière et al. 2009a). The most frequent method for determining the crystallographic orientations of PDFs is by the use of a universal stage (U-stage) or a spindle stage, and then manually indexing the lamellae using a stereographic projection template (see von Engelhardt and Bertsch (1969), Langenhorst (2002), or Ferrière et al. (2009a) for a detailed description of the procedure). Modern techniques such as transmission electron microscopy (TEM) and scanning electron microscope electron backscatter diffraction (SEM-EBSD) can also be used to investigate properties of PDFs (including crystallographic properties) at the micro- to nanometer scale.

The details concerning the formation of PDFs are not completely resolved, but it is clear that the process involves an interaction between the passing shock wave and specific directions in the crystal lattice, causing transformation into a dense amorphous phase, without the involvement of shear deformation (Goltrant et al. 1992; Stöffler and Langenhorst 1994; Trepmann and Spray 2006; Trepmann 2008; French and Koeberl 2010). Basal PDFs (mechanical Brazil twins) form by shock-induced shear deformation, and are thus in fact not true PDFs (e.g., McLaren et al. 1967; Trepmann 2008).

PDFs are remarkably long-lived, and persist in sub-crater target rocks even if the surface morphology of the crater has been removed by erosion. With time however, the originally glassy lamellae transform into so called decorated PDFs (e.g., Goltrant et al. 1992; Trepmann and Spray 2006). This transformation involves the recrystallization of the glassy material back to quartz, and exsolution of fluids previously dissolved in the glass. Thus, even if the lamellae themselves are missing, the trails of fluid inclusions remain, still recording the original orientations of the PDFs.

Presence of PDFs in quartz in a rock sample represents unequivocal evidence for impact, because

Table 2. The most common crystallographic orientations of PDFs in quartz.

#	Symbol	Miller-Bravais indices {*hkil*}	Polar angle (°)*	Azimuthal angle (°)	Crystallographic form	No. of symmetrically equivalent planes
1	c	(0001)	0.00	—	Basal pinacoid	1
2	ω, ω'	$\{10\bar{1}3\}$, $\{01\bar{1}3\}$	22.95	30	Rhombohedron	3
3	π, π'	$\{10\bar{1}2\}$, $\{01\bar{1}2\}$	32.42	30	Rhombohedron	3
4	r, z	$\{10\bar{1}1\}$, $\{01\bar{1}1\}$	51.79	30	Rhombohedron	3
5	m	$\{10\bar{1}0\}$	90.00	30	Hexagonal prism	3
6	ξ	$\{11\bar{2}2\}$, $\{2\bar{1}\bar{1}2\}$	47.73	60	Trigonal dipyramid	3
7	s	$\{11\bar{2}1\}$, $\{2\bar{1}\bar{1}1\}$	65.56	60	Trigonal dipyramid	3
8	—	$\{21\bar{3}1\}$, $\{3\bar{2}\bar{1}1\}$, $\{3\bar{1}\bar{2}1\}$, $\{12\bar{3}1\}$	73.71	50	Trigonal trapezohedron	6
9	x	$\{51\bar{6}1\}$, $\{6\bar{5}\bar{1}1\}$, $\{6\bar{1}\bar{5}1\}$, $\{15\bar{6}1\}$	82.07	40	Trigonal trapezohedron	6
10	a	$\{11\bar{2}0\}$, $\{2\bar{1}\bar{1}0\}$	90.00	60	Trigonal prism	3
11	—	$\{22\bar{4}1\}$, $\{4\bar{2}\bar{2}1\}$	77.20	60	Trigonal dipyramid	3
12	—	$\{31\bar{4}1\}$, $\{4\bar{3}\bar{1}1\}$, $\{4\bar{1}\bar{3}1\}$, $\{13\bar{4}1\}$	77.91	45	Trigonal trapezohedron	6
13	t	$\{40\bar{4}1\}$, $\{04\bar{4}1\}$	78.87	30	Rhombohedron	3
14	k	$\{51\bar{6}0\}$, $\{6\bar{1}\bar{5}0\}$	90.00	40	Ditrigonal prism	6
e	—	$\{10\bar{1}4\}$, $\{01\bar{1}4\}$	17.62	30	Rhombohedron	3

Table modified from Ferrière et al. (2009a), based on data from Stöffler and Langenhorst (1994).

*Angle between poles to PDFs and the c-axis of the host quartz grain.

their formation requires at least 10-15 GPa (basal PDFs are formed from >5 GPa; Hörz 1968; Müller and Défourneaux 1968; Gratz et al. 1992; Stöffler and Langenhorst 1994; Grieve et al. 1996; Huffman and Reimold 1996), and because quartz is so common in the crust of the Earth, these features often represent the first bona fide evidence for the impact origin of a geological structure (e.g., French 1968; Short and Bunch 1968 and references therein; Ferrière et al. 2010; Ferrière et al. 2011; Alwmark et al. 2014, paper II; Alwmark et al. 2015, paper III; Kenkmann et al. 2015).

4.1.1.4 Other shock metamorphic effects in quartz

Aside from planar microstructures, the passing shock wave may also cause distortion of the quartz crystal lattice into domains leading to development of mosaicism (Trepmann 2008). Mosaicism is characterized by an irregular extinction pattern (each domain has an extinction angle different by a few degrees from the adjacent domains) under cross polarized light. It should not be confused with undulatory extinction, which forms due to the (plastic) deformation of the crystal structure and is common in rocks that were tectonically deformed. Mosaicism is not recognized as unique to impact environments.

With increasing shock pressure, the optical properties of quartz (refractivity index and birefringence) decrease until the crystals transform to diaplectic glass, which happens around 35 GPa (for dense, non-porous rocks; e.g., Stöffler 1972; Stöffler and Langenhorst 1994 and references therein). The density of the quartz crystal is also affected by the shock wave (Langenhorst 1994; Langenhorst and Deutsch 1994), reflecting the presence of glass in the crystal.

Diaplectic quartz glass is a type of glass that does not form by melting, but by solid-state transformation (De Carli and Jamieson 1959). This means that the glass is amorphous, but there is no change in crystal morphology or texture, and the grains lack other signs of melting such as flow texture or vesicles (French 1998 and references therein). Lechatelierite, on the other hand, a silica glass, forms at pressures ~50 GPa (again, for dense, non-porous rocks; Stöffler and Langenhorst 1994 and references therein), where post-shock temperatures are high enough to cause melting (for lechatelierite specifically temperatures above 1713 °C (French 1998). Lechatelierite is not indicative of the impact environment because it also occurs naturally in fulgurites (glass produced by lightning strikes).

The high pressure mineral polymorphs of quartz, stishovite and coesite, are produced by shock compression between 12-45 GPa and 30-60 GPa, respectively (these numbers are valid for dense, non-porous crystalline rocks; Stöffler and Langenhorst 1994 and references therein). Coesite is formed under normal geological, static equilibrium, at pressures of about 2 GPa, and therefore it occurs naturally in kimberlites and ultra-high-pressure metamorphic rocks (Ferrière and Osinski 2013 and references therein).

4.1.1.5 Toasted quartz and ballen silica – post-shock features

Toasted quartz (cover picture of the thesis), characterized by a brownish appearance, results, according to Whitehead et al. (2002), from presence of frequent tiny fluid inclusions principally located along decorated PDFs, or by vesiculation after pressure release at high post-shock temperatures (Ferrière et al. 2009b).

Ballen silica either has an α-quartz or α-cristobalite structure and consists of individual "ballen", which are spheroidal, or to some degree elongated, bodies that form a scale-like pattern (Fig. 12; Ferrière et al. 2009c and references therein). The most recent theories about the formational mechanisms for ballen quartz in the impact environment are given by Ferrière et al. (2009c), and consist of two models. The first one is a solid-solid transition from α-quartz to diaplectic glass, which is followed by formation of ballen of β-cristobalite and/or β-quartz at high temperature, and later back-transformation to α-cristobalite and/or α-quartz. The second model is a solid-liquid transition of quartz from lechatelierite that is followed by crystallization of ballen at high temperature.

4.2. Orientations of PDFs as a shock barometer

Laboratory experiments have showed that the orientations of PDFs in quartz are controlled by the shock pressure that the grains experienced (e.g., Hörz 1968; Müller and Défourneaux 1968; Gratz et al. 1992; Stöffler and Langenhorst 1994; Grieve et al. 1996; Huffman and Reimold 1996; French 1998). Lower pressures (5-10 GPa) are characterized only by the presence of basal PDFs (Grieve et al. 1996; French 1998). When pressures exceed ~10 GPa, also rhombohedral PDFs oriented parallel to the $\{10\bar{1}3\}$ orientation starts to develop (Hörz 1968; Gratz 1992; Stöffler and Langenhorst 1994; Huffman and Reimold 1996; French 1998). At approximately 20 GPa, the first PDFs parallel to $\{10\bar{1}2\}$ start to appear. These become more frequent than the ones oriented parallel to $\{10\bar{1}3\}$ at about 25 GPa, and continue to be the dominating PDF orientation until about 35 GPa, when the quartz grain is transformed to diaplectic glass (Hörz 1968; Müller and Défourneaux 1968; Langenhorst and Deutsch 1994; Huffman and Reimold 1996; French 1998). It is less well known how PDFs oriented along planes of higher Miller-Bravais indices (e.g., $\{10\bar{1}1\}$, $\{11\bar{2}2\}$, $\{22\bar{4}1\}$, $\{21\bar{3}1\}$, and $\{31\bar{4}1\}$) fit into the shock pressure equation, but some experimental studies have reported these sets in their results (e.g., Hörz 1968), and thus pressures of about ~15 GPa are suggested to be required for their formation. Above these shock pressures, it is possible to use the presence of diaplectic glass and high pressure polymorphs (e.g., coesite) for shock pressure estimations. This experimental information has been used to estimate shock pressures at impact structures, and allowed the presentation of shock barometric reconstructions across impact structures (e.g., Robertson 1975; Grieve and Robertson 1976; Robertson and Grieve 1977; Holm et al. 2011), or to show the vertical shock attenuation in drill cores from impact structures (e.g., Masaitis and Pevzner 1999; Ferrière et al. 2008).

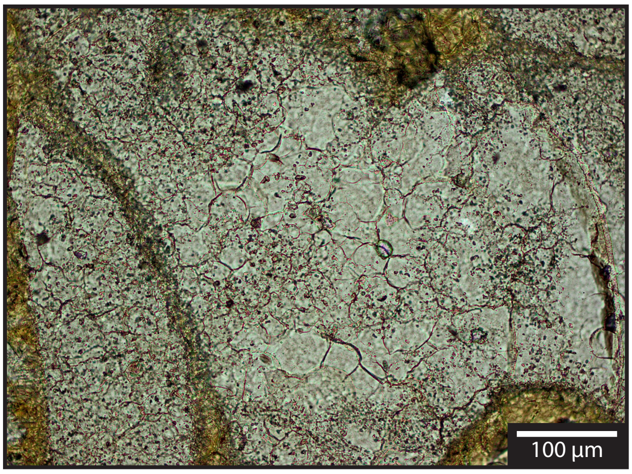


Fig. 12. Thin section photomicrograph of ballen silica from the Mien impact structure, Sweden (plane polarized light).

The number of PDF sets per grain can also be used to display shock attenuation, as suggested by Huffman and Reimold (1996), and also illustrated in PDF data sets from impactite samples (e.g., Robertson 1975; Ferrière et al. 2008; Holm et al. 2011, Paper I). Despite reflecting different pressure conditions, most shock barometry methods have in the past not properly considered this fact (see discussion in Ferrière et al. 2008; Holm et al. 2011, Paper I; Holm-Alwmark et al. in prep., Paper VI).

5. The terrestrial impact crater record

To date (October, 2016), ~190 impact structures have been discovered on Earth according to the online Earth impact database (EIDB). As can be seen in Fig. 13, these are not evenly distributed over the planet. This is a consequence of a variety of factors, including the varied ages of the Earth's crust (an older crust has been subjected to impact cratering over a longer period of time), and cover of rocks by dense forests, ice, and water. Another important factor is the proximity to an establishment where there is a tradition for studying impact craters, which is part of the reason for why a lot of structures have been discovered in e.g., North America.

The terrestrial cratering record reflects an influx of crater-forming projectiles to Earth over a period of ~3.5 Ga (including the oldest spherule layers interpreted to be ejecta layers; Lowe 2003; Simonson et al. 2004; Simonson and Glass 2004; Koeberl 2006). The crater record includes structures with maximum sizes of ~150-300 km (Vredefort, South Africa; depending on the considered definition of diameter; Therriault et al. 1997) and has been analyzed/discussed for the presence of peaks and periodicity and/or cyclicity on a number of occasions, along with suggestions for possible causes for such variations (e.g., Alvarez and Muller 1984; Grieve et al. 1985; Bailer-Jones 2011). Recent research indicates that, based on the terrestrial impact crater record (structures with precise ages determined), there is no discernible periodicity in the influx of crater-forming projectiles to Earth (Meier and Holm-Alwmark 2016, Paper IV). There is more convincing evidence for the presence of age peaks in the crater record, e.g., indicated by the large number of impact structures of mid-Ordovician age (e.g., Ormö et al. 2014; Alwmark et al. 2015, Paper III) and the possible pairing of Chicxulub and Boltysh (Jolley et al. 2010). The causes for a possible increased flux of impactors to Earth during certain periods could be attributed to asteroid break-up events in the main belt and cometary showers (see discussion in Meier and Holm-Alwmark, submitted, Paper IV).

Fig. 13. Map of the world showing the locations of ~190 (as of October 2016; EIDB) impact structures (stars) spread across the planet.

6. Summary of papers

The statement of author's contributions to each paper is given in Table 3.

6.1. Paper I

Holm S., Alwmark C., Alvarez W., and Schmitz B. 2011. Shock barometry of the Siljan impact structure, Sweden. Meteoritics & Planetary Science 46:1888–1909. DOI: 10.1111/j.1945-5100.2011.01303.x.

In this paper we present, for the first time, a detailed characterization of shock-metamorphic features in quartz at the Siljan impact structure, Sweden. Siljan is Europe's largest impact structure, with a commonly quoted diameter of 52 km (Grieve 1982, 1988), and an age of 380.9 ± 4.6 Ma (Reimold et al. 2005; Jourdan et al. 2012). The impact structure is located in the Dalarna province of south-central Sweden (Fig. 14), and consists of a central plateau surrounded by an annular depression that is partly filled by lakes, in particular lake Siljan. The main focus of this paper was the characterization of shocked quartz across the presently exposed Siljan structure. More than 70 bedrock exposures were sampled across the structure, both within the annular depression and outside, and in 21 of these we found evidence of shock metamorphism in the form of PFs and PDFs in quartz. In these samples, 2851 PDF sets in 1179 quartz grains were measured and indexed. The grains average between 1.0 and 3.8 PDF sets/grain, with samples located close to the center of the structure recording higher average number of sets per grain. The majority of the PDF sets (53.2 %) are oriented parallel to the $\{10\bar{1}3\}$-orientation. The second most abundant orientation is (0001), 30.3 % of all PDFs are oriented parallel to the basal plane. PDFs parallel to the $\{10\bar{1}4\}$, $\{10\bar{1}2\}$, $\{10\bar{1}1\}$, $\{10\bar{1}0\}$, $\{11\bar{2}2\}$, $\{11\bar{2}1\}$, $\{21\bar{3}1\}$, $\{51\bar{6}1\}$, $\{11\bar{2}0\}$, $\{22\bar{4}1\}$, $\{31\bar{4}1\}$, and $\{40\bar{4}1\}$ orientations occur in minor amounts.

Based on the PDF orientation pattern in the samples we were able to determine that recorded shock pressures are highest (~20 GPa) near the geographical center of the structure, and that it decreases to <2 GPa at 15 km radial distance, forming circular "shock pressure envelopes".

We used the radial distribution of shocked quartz to estimate the size of the transient cavity to 32-38 km in diameter (34-46 km if erosion is taken into account) using scaling relationships presented by Dence (1972) and Robertson and Grieve (1977). Further scaling relationships from Grieve et al. (1981), Croft (1985), Lakomy (1990), and Therriault et al. (1997) allowed us to calculate diameter

Table 3. Author's contributions to papers.

Activity	**PAPER I**	**PAPER II**	**PAPER III**	**PAPER IV**	**PAPER V**	**PAPER VI**
General project idea and design	X	X	X	X	X	X
Literature study	X	X	X	X	X	X
Field work	X	X	X	N.A.	X	N.A.
Sample preparation	X	–	–	N.A.	X	N.A.
Petrography	X	X	X	N.A.	X	X
Universal stage work*	X	X	X	N.A.	X	X
Numerical Modeling (iSALE)	N.A.	N.A.	N.A.	N.A.	–	N.A.
CSA	N.A.	N.A.	N.A.	–	N.A.	N.A.
Photography	X	–	–	N.A.	X	X
Artwork	X	X	X	–	X	X
Data interpretation and discussion	X	X	X	–	X	X
Manuscript writing	X	–	–	–	X	X
Manuscript corrections	X	X	X	X	X	X

X = The author of this thesis has solely performed, or contributed to, the specified activity.
– = The author of this thesis has not performed the specified activity.
N.A. = Not applicable
*Including indexing of planar deformation features

Fig. 14. Map of Sweden showing the locations of the Målingen, Siljan, and Hummeln impact structures.

estimates of 47-89 km of the present Siljan impact structure (maximum 91 km if erosion is taken into account). For comparison, other diameter estimates for Siljan have been made by Kenkmann and von Dalwigk (2000), who estimated, based on structural investigation concerning fracture pattern, the diameter to 65 km, and Henkel and Aaro (2005), who suggested a present day diameter of 75 km based on topographic features surrounding the structure, and a maximum diameter of 85 km for the pre-erosional crater.

6.2. Paper II

Alwmark C., Holm-Alwmark S., Ormö J., and Sturkell E. 2014. Shocked quartz grains from the Målingen structure, Sweden - Evidence for a twin crater of the Lockne impact structure. Meteoritics & Planetary Science 49:1076–1082. DOI: 10.1111/maps.12314.

In this paper we confirm the impact origin for the, according to previous authors (Thorslund 1940; Gee and Kumpulainen 1980; Karis and Larsson 1982; Simon 1987), peculiar Målingen structure, located in the Jämtland province of northern Sweden (Fig. 14). The structure is circular and bowl-shaped, approximately 700 meters in diameter, presently filled with breccia and sediments and partly covered by a banana-shaped bay of the larger lake Näckten. The infill material is in many ways similar, according also to age determination, to the infill breccias of the nearby 7.5 km-in-diameter Lockne impact structure (Sturkell et al. 1994; Grahn 1997; Ormö et al. 2014), suggesting a marine target impact, just like at Lockne (Lindström et al. 2005). By determining the orientations of PDFs in quartz grains in drill core samples from the central part of the structure, we present unambiguous evidence for the hypervelocity impact origin of the structure. PDFs were measured in 32 quartz grains from three levels in the core, and the resulting dataset show that 74 % of PDFs are parallel to the basal plane of the crystal. The other indexed sets were oriented parallel to the $\{10\bar{1}3\}$ and $\{10\bar{1}4\}$-orientations.

The investigated quartz grains were derived from parautochtonous breccia underneath the sediment infill, and thus transportation of the shocked material from Lockne can be excluded. We propose, considering the sedimentological and biostratigraphical aspects of the crater infill, that the Målingen structure is coeval with Lockne and thus the pair represents the first marine target doublet craters on Earth.

6.3. Paper III

Alwmark C., Ferrière L., Holm-Alwmark S., Ormö J., Leroux H., and Sturkell E. 2015. Impact origin for the Hummeln structure (Sweden) and its link to the Ordovician disruption of the L chondrite parent body. Geology 43:279–282. DOI: 10.1130/G36429.1.

In this paper we present the first ever evidence for the hypervelocity impact origin for the Hummeln structure, located in the Småland province of southern Sweden (Fig. 14). The origin of the structure has been debated for over 200 years (e.g., Hisinger 1826; Nordenskjöld 1937, 1944; Fredriksson and Wickman 1963), and this paper finally settles the discussion by showing evidence of shock metamorphism in the form of PDFs in quartz grains from parautochtonous breccia from the crater walls. Hummeln is believed to have formed during the Middle Ordovician (Grahn et al. 1996), and thus another impact structure is added to the list of known such structures from this period. Since there seems to be an anomalously high number of impact structures formed during the Middle Ordovician (e.g., Ormö and Lindström 2000; Ormö et al. 2014), the discovery of Hummeln furthers the hypothesis of an increased bombardment by asteroidal fragments on Earth following the L-chondrite parent body breakup event in the main asteroid belt.

Also of great importance with the confirmation of the Hummeln structure is the remarkably well preserved nature of the structure, contradicting the general opinion that small impact structures (Hummeln is 1.2 km in diameter) cannot survive on Earth for long periods of time.

6.4. Paper IV

Meier M.M.M., and Holm-Alwmark S. A tale of clusters: No resolvable periodicity in the terrestrial impact cratering record. Submitted to MNRAS, moderate revisions are in order.

A possible cyclic, or periodic, component to the terrestrial crater record has been discussed for decades, including also speculations regarding what might be the cause of such possible variations (e.g., Alvarez and Muller 1984; Grieve et al. 1985). In 2015, Rampino and Caldeira reported the results of a circular spectral analysis (CSA) of the terrestrial impact record over the past 260 million years. The authors suggest a cyclical occurrence of both impact and extinction events with a period of 26 Ma. Many of the impact structures used as a basis for the CSA in the Rampino and Caldeira (2015) paper have recently been precisely dated using the ^{40}Ar/^{39}Ar method (uncertainties <2 %), with different resulting ages than those used in their analysis (in some cases far outside the previously stated uncertainties, e.g., for the Puchezh-Katunki impact structure; Holm-Alwmark et al. in prep). This suggests that the results of the CSA performed by Rampino and Caldeira (2015) cannot be considered reliable. In this paper, we perform a CSA based on a list of reliable and precise impact ages compiled by Jourdan et al. (2009), Jourdan (2012), and Jourdan et al. (2012), a list also updated by us, for the last 260 and 500 Ma, and find no significant periodicity. A periodic contribution of >65 % of the total impactor flux over the last 500 Ma can currently be excluded at the 95% confidence level, if our list is indeed representative of the true impact crater population. The reason for our results differing from those of Rampino and Caldeira (2015) is mainly the presence of "clustered" ages (i.e., coeval within mutual age uncertainties) in their data set, which are less frequent in ours. We also show that the 26 Ma periodic signal that was carried by these clustered impacts is not significant if tested against artificially clustered impact series. This means that we can conclude that there is presently no convincing evidence for a periodic component in the terrestrial impact crater record, and that caution should be applied when using a list of impact structures with variable quality of age data for interpretations on possible cyclicity or periodicity in the impactor flux to Earth.

6.5. Paper V

Holm-Alwmark S., Rae A.S.P., Ferrière L., Alwmark C., and Collins G.S. Combining shock barometry with numerical modeling: insights into complex crater formation – The example of the Siljan impact structure (Sweden), manuscript.

In paper V we present a vertical shock barometry profile of the Siljan impact structure based on PDFs in shocked quartz in samples from the ~600 meter deep Hättberg drill core, and from the ~100 meter deep Vålarna drill core. The results are combined with the surface shock barometry profile presented in Holm et al. (2011, Paper I), and numerical modeling using the iSALE shock physics code (see paper for full list of references relating to this method) in order to reconstruct the pre-erosional Siljan crater.

The vertical shock attenuation at Siljan, according to PDF orientations in samples from the Hättberg drill core, is characterized by a smooth decrease in recorded shock pressure from the two top-most samples (estimated pressures 15-20 GPa), to the deeper samples (estimated pressures 10-15 GPa), with shock attenuation also further displayed using the average number of PDF sets/grain in the samples.

In the numerical modeling, we fixed the parameters relating to the angle of incidence, the velocity of the impactor, the impactor material, and the target material (both granitic and sedimentary). Since the impact occurred into a mixed target sequence (crystalline basement overlain by Paleozoic sediments) that is poorly understood due to complete erosion of these sediments in the area outside of the annular depression (see discussion on this in e.g., Larson et al. 1999; Cederbom et al. 2000; Hendriks & Redfield 2005), we varied the thickness of the sediments in the models. We also varied the size of the impactor and the acoustic fluidization parameters.

Observational constraints set up by the presence of Paleozoic sediments at ~15 km radial distance in the impact structure and a minimum ~50 km final crater (i.e., the approximate size of the present-day structure), in combination with shock barometric observations allowed us to select a best-fit model of the total models run. This model produces a transient cavity of ~25 km in diameter, and a final crater with a rim-rim diameter of ~60 km, reproducing the observed shock attenuation pattern across both the surface of the structure, and the drill cores, and is consistent with structural observations. Our new estimation of the original size of Siljan, with a rim-to-rim diameter of 60 km, is not easily directly comparable to those made in previous studies, such as in Kenkmann and von Dalwigk (2000) and Holm et al. (2011, Paper I). The reason for that is that, compared to the structural deformation in the target rocks and the spatial distribution of these deformations, it is not exactly known how the rim-to-rim diameter of an impact crater can be compared with the apparent crater diameter, which takes erosion into account (see definitions in Turtle et al. 2005).

The present-day shock attenuation pattern is consistent with a level of erosion of the crater corresponding to ~3-3.5 km (according to the best-fit model). Furthermore, the impactor size in this model is 5 km in diameter, and the thickness of the pre-impact sedimentary sequence is 2.5 km. The model predicts the present-day sedimentary sequence to preserve ~1 km where it is the thickest, and to be ~7 km wide. This model also predicts the uppermost sedimentary sequence at the time of impact (i.e., the youngest sediments) to have been removed by erosion at present. Finally, our numerical models suggest that the original morphology of the Siljan structure was a transitional central peak - peak-ring crater.

6.6. Paper VI

Holm-Alwmark S., Ferrière L., Alwmark C., and Poelchau M. H. Investigation of shocked quartz grains using the universal stage – What can be done and how to do it in an appropriate way: The case study of the Siljan impact structure (Sweden), manuscript.

In this paper, we present a detailed statistical analysis of PDF populations in samples from the Siljan impact structure (Sweden). We report on some observations and address some problems that we have encountered while performing detailed U-stage measurements and indexing studies of shocked quartz grains. Since the process of indexing PDFs is somewhat tedious and very time-consuming, two automated indexing programs have recently been presented. One is an algorithm designed for use in Microsoft Excel, the so-called ANIE (Automated Numerical Index Executor, Huber et al. 2011), and the other one a web-based program, the so-called WIP (Web-based program for Indexing PDFs, Losiak et al. 2016), that allow to take the weight off researchers by automatically performing the indexing of PDFs. In this paper we discuss the significant differences obtained when indexing our measurements using the manual graphical method and the two different indexing programs from Huber et al. (2011) and Losiak et al. (2016). We also discuss the new stereographic projection template (NSPT) and the addition of the $\{10\bar{1}4\}$-orientation, indexing of endogenic (planar to non-planar) features that are misinterpreted as being PDFs, spatial distribution of PDFs, with focus on the occurrence of PDFs oriented parallel to positive and negative low-angle rhombohedral forms ($\{10\bar{1}4\}$, $\{10\bar{1}3\}$, and $\{10\bar{1}2\}$), and PDF orientation statistics as a function of c-axis attitude. We further discuss the potential implications on shock barometry studies based on these problems/observations associated with PDF statistics.

We show that the currently used stereographic projection template for indexing PDFs overindexes low angle Miller-Bravais index rhombohedral planes, but that this is not a problem when dealing with PDFs. However, when measuring endogenic features (thinking that they are or could be PDFs) we show that it is possible to index most of them to somewhat the same proportions as if they would be PDFs. This illustrates that proper and detailed documentation of the investigated features, not just the measurements, are critical for identifying PDFs in quartz.

We suggest that a unified means of assigning shock pressures to samples based on PDFs in quartz is necessary to allow comparisons of datasets and that this method takes into account not only the number of PDF sets/grain, but also the number of high Miller-Bravais index planes.

7. Impact cratering and the future

What was once considered a "science-fiction theme" (French 1968, p. 1), is now considered a major geological process, both for the Earth and the Solar System. Today impact cratering not only attracts attention from the scientific community but also from the general public and media. The interest, especially in presenting evidence for new impacts, perhaps even in combination with a biosphere event, has on several occasions resulted in presentation of studies where the "evidence" of impact is, at best, controversial (e.g., Becker et al. 2004; Firestone et al. 2007). More extensive discussions on this subject are presented in French and Koeberl (2010), Jourdan et al. (2012), and Racki (2012). The data presented in such studies can be misleading for people without expert knowledge, in particular if it is published in the most prestigious journals (e.g., Becker et al. 2004; Firestone et al. 2007). With regards to shock metamorphic features in quartz, it remains as important as ever, that published information on PDFs is detailed, thorough, and that information on the full data set of PDFs is reported (see e.g., Ferrière et al. 2009a, Holm-Alwmark et al. in prep., paper VI). The frequencies of all measured PDF sets (including unindexed) should be reported, with information also on the average number of sets/grain, and preferentially also the angular relationships between PDF poles and the c-axes of the host quartz grains, e.g., in so called binned histograms, where it is evident also where the unindexed sets are located (see Fig. 15 for an example). This is especially important considering that more and more of the structures which can be considered "easy targets" for confirmation as impact structures, have now been confirmed as such, leaving us with the trickier sample sets, e.g., those where PDFs in quartz are rare, or difficult to detect due to poor development or state of preservation.

The positive connection between a structure and impact cratering can also be hindered by lack of the traditional evidence (i.e., the shock metamorphic features that are best studied), e.g., in target rocks that are lacking quartz such as basalts or carbonate rocks. One important step into the future is to focus attention towards the understanding of shock metamorphism of target rocks lacking these evidences better, and to evaluate whether these rocks contain minerals that can be easily and undoubtedly recognized as unique to an impact environment. In extraterrestrial rocks, this is a known problem, since the material lack quartz, and for this reason silicate minerals such as olivine or pyroxene are used. Hopefully, in the future, we will collect samples from more/new extraterrestrial bodies, and the evaluation of shock metamorphic features in that material will be one of the key areas of study.

Although we now know of about 190 impact structures on Earth (EIDB), and a few of those are particularly well studied, e.g., Meteor crater (e.g., Shoemaker 1960; Kieffer 1971; Melosh and Collins 2005; Poelchau et al. 2009; see also Kring 2007 and references therein), and the Ries (e.g., Stöffler 1966; von Engelhardt and Stöffler 1968; von Engelhardt and Bertsch 1969; Chao and Minkin 1977; Collins et al. 2008), many structures are associated with just the so called "discovery paper", where the first evidence of impact is presented (e.g., the Alwmark et al. 2014, Paper II, and Alwmark et al. 2015, Paper III, are the discovery papers for the Målingen and the Hummeln impact structures, respectively), which can be regarded as the most "spectacular" part of doing impact crater research. This means that there are a lot of observations that remain to be made from impact structures, in particular those from subsurface rocks, since drilling is expensive. For example, Alwmark et al. (2015, paper III) discusses the potentials of drilling into the Hummeln structure for the retrieval of a full impactite sequence, the results of which for example could aid the understanding of the formation of small impacts into a shallow sea.

Switching focus from the 190 discovered to the yet undiscovered impact structures, Trefil and Raup (1990), Grieve (1991), and Hergarten and Kenkmann (2015) have all discussed the potential for new discoveries of impact structures on Earth. If we can improve the database of discovered structures, while also establishing the ages of newly discovered structures with precision, and more accurately determine the ages of poorly dated known structures

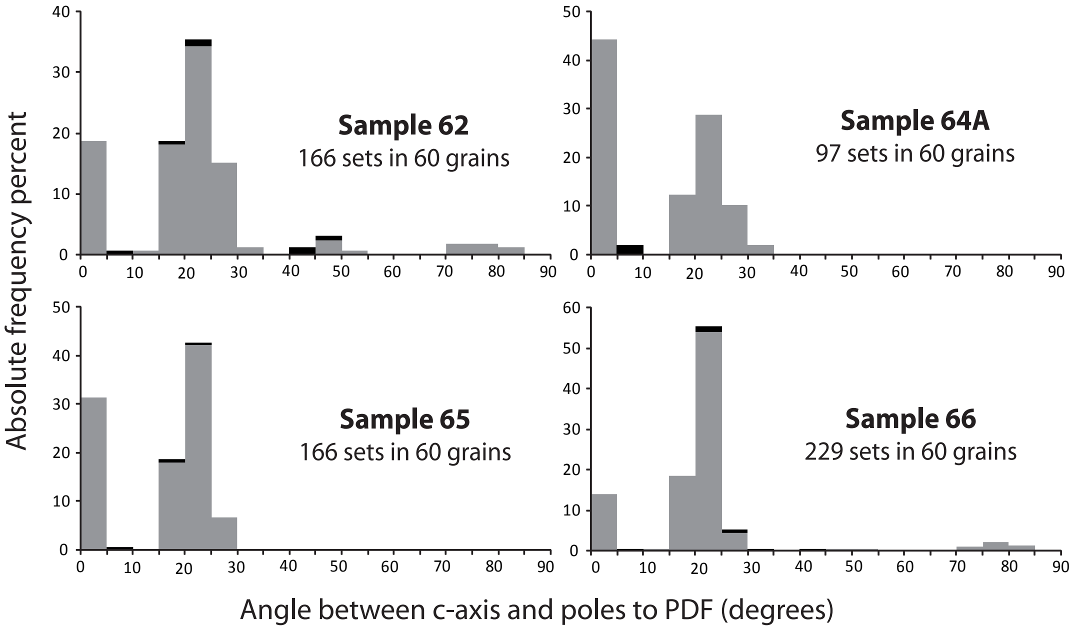


Fig. 15. Histograms of angles between c-axis and poles to PDFs binned by 5°. The PDFs were measured in quartz grains from surface samples from the Siljan impact structure, Sweden. Light gray columns represent PDFs that could be indexed using the new stereographic projection template (Ferrière et al. 2009a). Black columns represent unindexed PDF sets. Figure modified from Holm et al. (2011).

(see discussion in e.g., Jourdan et al. 2012), then we can discuss "big questions" relating to the influx of crater-forming projectiles to Earth. Has the impact cratering rate been constant, and is the influx of material in any way periodic, or cyclic, can any variations be discerned (see discussion in Meier and Holm-Alwmark, submitted, Paper IV)? To me, especially interesting in this topic are discussions about to what extent comets and asteroids form large impact craters on Earth (i.e., ~Chicxulub-sized craters and larger), and if they are equally important in this aspect?

One way to discover new impact structures is to focus on off-shore areas. Since Earth is covered with water to about 70 %, a number of impact structures should be located on the sea floor, even though many of them have been subducted due to plate tectonics. Few impact structures are currently known from partial to complete underwater settings (e.g., Hildebrand et al. 1991; Koeberl et al. 1995; Dypvik et al. 1996; Therriault and Grantz 2005). One specific structure of interest to this subject is the possible impact structure Silverpit (Stewart and Allen 2002), located in the North Sea, recognized by seismic data, but to date not sampled. This means that there are currently no means of saying whether this structure really is the product of impact, until sampling is performed. These types of structures need to be studied by expensive drilling operations, exemplified by the recent drilling into Chicxulub, a campaign likely to yield lots of valuable information, especially regarding the fact that Chicxulub is one of the most well-preserved complex (peak ring) impact structures on Earth.

One part of the database that is especially interesting is that relating to structures formed early in Earth's history. Impact would have been the dominant process at ~>-3.8 Ga, when Grieve (1980) and Grieve et al. (1990) estimate that as many as 200 impact basins with diameters of or bigger than 1000 km formed. What did impacts mean for the early Earth? Was water transported to Earth by extraterrestrial bodies? Did early atmosphere(s) blow away due to large impacts? To what extent did impacts generate large scale volcanic activity and thus early crustal fragments? How could the traces of these very old impacts be recognized?

Many questions have been asked in the above sections, and the way to answer a lot of them is to continue the development of new methods (more advanced numerical simulations and experiments), and to combine the results of those with actual observations made from impact structures, on Earth and on other bodies of our Solar System. This means that now, like in the past, geological observations are ever so important. The key towards a better understanding not only for the processes involved in impact cratering, but in order to understand the evolution of our Solar System, is collaborations between different researchers and research groups with different specific interests and expertise. An example of just this is presented in Holm-Alwmark et al. (in prep., Paper V), where the results of numerical modeling are compared with the results of petrographic observations of rock samples.

Finally, the future brings such great potential for the field of impact cratering with regards to remote sensing of other planetary bodies, and even sample missions to other celestial bodies. New space missions (e.g., Rosetta, New Horizons, Dawn, Hayabusa 2, OSIRIS-Rex, and NASA's upcoming asteroid re-direct mission) are providing new information on e.g., the surface of asteroids, comets, and the morphology of impact craters from e.g., the satellites of Jupiter and Saturn. In light of this, there is great potential to learn more about our fellow companions in the Solar System and to study the morphological complexities of impact craters on different planetary targets. The terrestrial impact structures will not stop to be important though, it is studies of these that will be compared with the "minor glimpses" that presently can be offered from other bodies. Terrestrial impact structures are thus equally important pieces of the puzzle that we are solving in order to understand this fundamental geological process called impact cratering, and ultimately also the history of Earth and the Solar System.

8. Acknowledgments

First of all, I would like to extend my gratitude to Maurits Lindström and Walter Alvarez for showing to me early on in my PhD-studies that being old in the game, and very much considered a legend, does not mean that you cannot be humble, interested in the thoughts of young scientists, and full of enthusiasm and will to share your experience and expertise. It was Maurits and Walter that first really opened up my eyes for the fantastic field of geology called impact cratering.

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Over the past seven years, I have learned a lot about what to expect from a career in academia, and I've met many colleagues in the field of impact cratering. Through interactions with you, I have broadened my knowledge and expertise, and my view of both academia and my field of research, especially while attending conferences. I want to take the opportunity here to specifically address Michael Poelchau. Thanks for generously sharing your expertise and taking the time to answer my questions over the phone, e-mail, and in person. The interactions with you have been more important for me than what you probably realize, thank you so much! I also want to thank Bevan French for showing an interest in me as a young scientist and listening to my views, ideas, and updates of my research.

From the department in Lund I want to thank

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The last person that I want to address is Carl Alwmark. Thank you. My words feel insufficient here, so I'll borrow someone else's:

"Flowers on the hillside blooming crazy
Crickets talking back and forth in rhyme
Blue river running slow and lazy
I could stay with you forever
And never realize the time."

–Bob Dylan (From the song "You're gonna make me lonesome when you go", from the album Blood on the tracks)

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Svensk sammanfattning

Efter mer än 50 år av utforskande av rymden och studier av ett växande antal kända nedslagskratrar på jorden så har bildandet av nedslagskratrar utvecklats från att anses vara en sällsynt geologisk företeelse till en fundamental del av jordens, och solsystemets, historia.

I dag vet vi att nedslagskratrar är en av de vanligaste landformerna på himlakroppar i inre solsystemet, samt på de flesta av gasplaneternas månar och de isiga kropparna i Kuiperbältet. På jorden förstörs nedslagskratrar av destruktiva processer så som plattektonik och erosion, eller döljs av yngre sediment, vegetation eller vattenmassor. Men faktum är att vår jord och de andra kropparna i inre solsystemet till och med bildades genom upprepade kollisioner mellan små partiklar. Dessa växte sig större och större under solsystemets tidiga historia för att bilda protoplaneter. Vår måne bildades sedan genom en enorm kollision mellan den tidiga jorden och en himlakropp stor som planeten Mars. Efter de första dramatiska hundratals miljoner åren i jordens historia som präglades av frekventa kollisioner med andra himlakroppar så stabiliserades inflödet av kraterbildande kroppar till jorden och mer konventionella geologiska processer så som bergskedjeveckning och vulkanism tog över som dominerande landformsbildare. Det här betyder dock inte att nedslagsprocessen har avstannat, den är högst aktiv, något som till exempel kan illustreras av kollisionen mellan kometen Shoemaker-Levy och Jupiter 1994, och den kommer att fortsätta att vara det i framtiden.

Bildandet av en nedslagskrater innefattar extremt höga tryck och temperaturer som inte kan uppnås under någon annan geologisk process, och som inte heller till fullo kan återskapas i experiment. Det här kan illustreras av den enorma förödelsen som nedslaget i slutet på kritperioden resulterade i, då bland annat dinosaurierna dog ut. Eftersom en kollision mellan jorden och en annan himlakropp stor nog att bilda en stor nedslagskrater aldrig någonsin har bevittnats av människan, är vi beroende av studier av kända nedslagskratrar för att förstå den här betydelsefulla, och grundläggande, processen.

Forskningsresultaten som presenteras i den här avhandlingen kretsar kring nedslagskratrar och de processer som råder vid bildandet av dessa strukturer. Genom fältobservationer, mikroskopstudier och numerisk modellering så har Europas största nedslagsstruktur Siljan, belägen i Dalarna, undersökts. I dag är Siljanstrukturen djupt eroderad efter att ha varit exponerad på jordytan under årmiljoner. Trots detta så finns mineralogiska strukturer bevarade i berggrunden i området som vittnar om de extremt höga tryck och temperaturer som rådde när kratern bildades. I avhandlingen undersöks så kallad chockad kvarts för att karakterisera dess utbredning och bestämma de chocktryck som målberggrunden i Siljan utsattes för vid nedslaget. Med hjälp av de uppskattade chocktrycken och numerisk modellering så har vi kunnat rekonstruera den ursprungliga nedslagskratern och bland annat bestämt dess storlek till 60 km i diameter, samt att den bildades av en projektil som var ungefär 5 km i diameter. Vi bedömer också med hjälp av resultaten, att den kristallina berggrunden i nuvarande Siljansområdet vid tidpunkten för nedslaget överlagrades av ungefär 2,5 kilometer sediment, samt att det idag saknas ca. tre kilometer av strukturen på grund av erosion. I avhandlingen presenteras också bevis, i form av chockad kvarts funnen i målberggrund, för att strukturerna Målingen (Jämtland) och Hummeln (Småland) är bildade genom nedslag.

Vidare diskuteras även observationer och problem associerade med inmätningar och presentation av chockad kvartsdata. Dataseten är viktiga både för identifiering av nedslagskratrar samt för bestämning av chocktryck.

Dessutom presenteras också en artikel som diskuterar större frågeställningar rörande inflödet av kraterformande kroppar till jorden under de senaste 500 miljoner åren. Genom analys av väldaterade nedslagskratrar kan vi dra slutsatsen att det i dagsläget saknas bevis för en cyklisk eller periodisk influens i inflödet av projektiler till jorden.

Appendix A

Papers published in refereed journals and extended abstracts not included in this thesis.

Alwmark C., Schmitz B., Holm S., Marone F., and Stampanoni M. 2011. A 3-D study of mineral inclusions in chromite from ordinary chondrites using synchrotron radiation X-ray tomographic microscopy—Method and applications. *Meteoritics & Planetary Science* 46:1071–1081. DOI: 10.1111/j.1945-5100.2011.01214.x.

Gnos E., Hofmann B. A., Halawani M. A., Tarabulsi Y., Hakeem M., Al Shanti M., Greber N. D., Holm S., Alwmark C., Greenwood R. C., and Ramseyer K. 2013. The Wabar impact craters, Saudi Arabia, revisited. *Meteoritics & Planetary Science* 48:2000–2014. DOI: 10.1111/maps.12218.

Alwmark C., Holm S., Meier M. M. M., and Hofmann B. A. 2012. A study of shocked quartz in distal Ries ejecta from eastern Switzerland. 43rd Lunar and Planetary Science Conference. Abstract #1827.