Natural History Museum

”The Gardnos structure; the impactites, sedimentary deposits and post-impact history”

by

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Preface

This dissertation is the result of a four-year research fellowship at the Natural History Museum and Department of Geosciences at the University of Oslo. Starting in 2004, the period has been extended due to child-birth and maternity leave. Apart from scientific research, the position as a research fellow also included half a year of compulsory courses and one full year of departmental duties like contribution to exhibitions, public lectures, student teaching and field assistance, organizing excursions and preparing field guides both for the public and geological community, and presenting geology in general for school classes and the public. In relation to my research I have been able to participate in several conferences, workshops, field trips and courses during these years. This has given me the opportunity to visit several impact structures: the Ritland structure in Norway, the Siljan and Lockne structures in Sweden, the Nördlinger Ries and Steinheim structures in Germany, the Wetumpka structure in Alabama, and the Decaturville and Crooked Creek structures in Missouri. The list of impact craters on Earth, however, is long and increasing every year (presently 176; Earth impact Database visited March 2009; http://www.unb.ca/passc/ImpactDatabase), so I guess I have just started!

The main objective of the research has been the Gardnos impact structure, which was recognized as an impact structure in the early 1990s by Johannes Dons and Johan Naterstad at the Natural History Museum, University of Oslo. Field work was carried out in the area of the Gardnos impact structure, whereas the main analytical part of the work was conducted mainly at the University of Oslo, at the Natural History Museum and the Department of Geosciences, and during two visits to the Planetary and Space Sciences Research Institute at The Open University, Milton Keynes. The scientific results of the research are presented as four papers and manuscripts for publication in international scientific journals. This thesis is divided into eight chapters, with an introduction to impact cratering (chapter 1), geological background (chapter 2), methodology (chapter 3), an outline of the background of the thesis and the papers (chapter 4), and at last it presents the individual papers/manuscripts (chapter 5-8).

Primary supervisor on this Ph.D. project has been Prof. Henning Dypvik (Department of Geosciences, University of Oslo) and supplementary supervisors have been Dr. Johan Naterstad (retired from Natural History Museum, University of Oslo), Prof. Elen Roaldset (Natural History Museum, University of Oslo), Prof. Iain Gilmour (Planetary and Space Sciences Research Institute, The Open University, Milton Keynes), Prof. Bevan French

(Department of Paleobiology, Smithsonian Institution, Washington) and Prof. Christian Koeberl (Department of Lithospheric Research, University of Vienna).

Acknowledgements

First I would like to thank my supervisor Henning Dypvik for introducing me to the field of impact research, for sharing his knowledge, experience and contact network in the impact field, for always being ready for a discussion and for inspiring me to carry on with the thesis. Then equally many thanks go to my family for their support, to my common-law husband Ola Nilsen for inspiration and good advice, to my parents for extensive babysitting and help on the daily logistics, and finally especially thanks to my two girls Tina and Mari for constantly reminding me that there are other things in life than this thesis!

I also wish to thank all the rest of my supervising committee; Johan Naterstad for valuable guiding in the field introducing me to the geology, botany and cultural history of the Gardnos area, Bevan French especially for help on the curious microstructures in the suevite, Christian Koeberl for help with manuscripts, Elen Roaldset for general support and for the opportunity to work with various and interesting tasks at the Natural History Museum, and, not the least, Iain Gilmour, for cooperation on the carbon studies and for great hospitality during my stays at the Open University. I felt most welcome there, and was able to do a lot of work in short time due to good facilities and also all help from Mabs Gilmour, who guided me through all the laboratory work. Thanks!

I owe Fernando Corfu a great many thanks for introducing me to the U-Pb dating by ID-TIMS method. Odd Nilsen shared his experience on the use of U-stage to measure planar deformation features (PDFs) in quartz grains. Steven Goderis from the Vrije University of Brussel visited Gardnos in autumn 2005 and I was happy for the company in field, and for the opportunity to be a little involved in his following research on finding the type of projectile in the Gardnos impact.

Lots of thanks goes to the Nes county, Tom Jahren and the people at Gardnos tourist visitor centre for logistical aid, company, useful discussions and coffee at the visitor centre during my field work! The land-owners, Gulsvik and Rømcke families, have been generous to let me access their private roads by car during field work, and even let bus-loads of geologists in as part of guided excursions to the Gardnos crater structure. I would also like to thank people at the Natural History Museum and at the Department of Geosciences for making the social framework for my working days, and sometimes useful conversations on impact-related topics as well. Most important has been Svein Olav Krøgli as the third member of our little "impact-group". An important extension of our impact network is the Nordforsk-funded

Network on Impact Research (NIR), and I am grateful for the chance to attend short courses, workshops and meetings on impact topics arranged by this network. Even more important, I would like to thank everyone within and associated with the network for making these happenings so interesting and instructive.

Additionally I got valuable technical support during the various analyses at the University of Oslo. Salah Akahvan provided more than two hundred high quality thin sections, Hans Jørgen Berg was always there to assist with the SEM, Gunborg Bye Fjeld helped with heavy mineral separation, and Turid Vinje, Berit Løken Berg and Mufak Naoroz helped with XRF, XRD and some SEM/CL investigations.

Abstract

The Gardnos structure in Hallingdal, Norway is an eroded impact crater, presently consisting of impactites and crater infill sediments exposed within a roughly circular area of about five km diameter. Investigations in the early 1990s confirmed its impact origin, however a number of issues regarding the crater formation and post-impact history were still unresolved. The time of impact was poorly constrained to between 900 and 400 Ma, the geological setting uncertain and the source of organic carbon within the impactites unknown. These obviously inter-related questions touch different fields within geology (involving radiometric dating, sedimentology and organic chemistry) thus a multi-disciplinary approach was required. Another premise at Gardnos is the availability of outcrops. Erosion has erased some of the original crater shape; however, it has also exposed impact-related lithologies from breccias and fractured basement deep underneath the crater floor, to the allochthonous melt-bearing breccias and post-impact sediments. Whereas previous works were based on samples from a few central localities, this study aims to describe the entire structure and the impact-related lithologies based on detailed mapping and much broader sampling. The stratigraphic and lateral variations within each lithology are key information to understand the crater formation and post-impact process. During this study the structure has been mapped in detail with special emphasis on the crater suevite and sedimentary infill lithologies. Tentative reconstruction of the fresh crater indicates a central peak in the centre, surrounded by a relatively flat plain and crater walls, making the original crater diameter likely about six kilometers.

Melt-bearing breccias (dominated by suevite) directly overlies the original crater floor which consists of shattered basement rocks constituting the (par)autochthonous Gardnos Breccia. The suevite contains a mix of shocked and unshocked material, melt and lithic fragments of various sizes. Orientations of planar deformation features (PDFs) in quartz grains indicate maximum shock pressures above 20 GPa. The distribution of lithic fragments originating from large parts of the crater demonstrates the extreme forces responsible for the formation of this unit. Melt generally occurs as individual fragments, amounting from zero to 40 vol% of the bulk rock. Minor amounts of a clast-rich impact melt rock occur, where melt constitutes the matrix (up to 85 vol% of bulk rock). Volume calculations of the original melt content within the crater are in fairly good agreement with previous estimates and with general models for melt volumes in craters of this size. The melt fragments within the suevite

appear with a variety of shapes, textures and chemical composition, depending on the original target rock composition and degree of melting. This indicates that most melting during impact took place locally before mixing with clastic impact debris, and there never existed a large homogeneous melt sheet during crater formation. Most chemical variations within the suevite unit can be explained by incorporation of mafic rocks into a dominant mix of granitic, gneissic and quartzitic target rocks. The variations in lithic clast content in the suevite indicate mixing of material from large part of the crater. Melt fragments often appear stretched in one direction, in accordance with deposition by flow. Other melt fragments are apparently rotated and deformed, and we speculate if the mark the boundaries between successive pulses of suevite flows. In the Branden core from the central parts of the Gardnos crater a one meter thick fine-grained layer occurs between the suevite and the main sequence of post-impact sediments. This layer is lacking shocked mineral grains, lapilli and other evidence for deposition from the impact plume, and thus should probably be assigned to the post-impact succession. This indicates a brief (?) period of relative quiet conditions in the crater between deposition of the suevite and the coarse post-impact sediments.

The main sequence of post-impact sediments filling in the crater depression comprises a wide range of siliciclastics: sedimentary breccias, coarse conglomerates, conglomeratic sandstones, sandstones, and interbedded fine sandstones, siltstones, and shales reflecting the shifting depositional environment. The impact probably happened in a shallow marine environment and rock avalanches and debris flows probably initiated as the crater rim was broken at its weakest parts and water entered the crater depression shortly after impact. The overlying conglomeratic and sandy sequences show significant local thickness variation, consistent with coalescing fan-shaped deposits along the lower crater wall, as well as on the crater floor. Sand-enriched density flows dominated in the water-filled crater. Above fine-grained sandstones, siltstones and shales were deposited, representing the re-establishment of quiet conditions, maybe comparable to the pre-impact depositional conditions.

Zircon and titanite grains have been dated by U-Pb isotope dilution - thermo-ionization mass spectrometry (ID-TIMS). Some zircon grains appear almost unaffected by later events, retaining close to original (>1000 Ma) ages. Concordant ages of 995-999 Ma for titanite represent late Sveconorwegian metamorphism, and concordant titanite and zircon ~380 Ma ages likely recorded the Caledonian orogeny. A large group of zircon grains have U-Pb ages reflecting the influence of the Caledonian orogeny and recent Pb-loss. A minor group of zircon grains yielding data with relatively high discordance for moderate U contents, including a grain with proven granular, probably impact-related, texture. Most likely the zircon subject to impact-induced deformation suffered contemporary extensive lead-loss or complete resetting. This group of zircon grains fits a discordia line with an upper intercept of 546 ± 5 Ma, suggested to be the approximate time of impact.

Rocks within the Gardnos impact structure have elevated concentrations of organic carbon relative to rocks outside the structure. The carbon content and stable C-isotope values in the different impact-related lithologies (impactites and post-impact sediments) have been studied in order to establish the origin of carbon and its mobilization. The carbon probably was derived from carbon-bearing sediments overlying the crystalline basement at the time of impact. Though the carbon entered the structure during impact, the akkumulation of carbon in the overlying coarse-grained post-impact sediments indicate that re-distribution of carbon during post-impact cooling may have been significant. Later mobilization by Caledonian metamorphism probably had local limited effects.

List of papers

Paper I: Kalleson, E., Dypvik, H., and Naterstad, J. (2008) Post-impact sediments in the Gardnos impact structure, Norway, *in* Evans, K., Horton Jr., J.W., King Jr. D.T., and Morrow, J.R. (eds.) The Sedimentary Record of Meterorite Impacts, Geological Society of America Special Paper 437, 19-41.

Paper II: Kalleson, E., Corfu, F. and Dypvik, H. (in press) U-Pb systematics of zircon and titanite from the Gardnos impact structure, Norway: evidence for impact at 546 Ma? Geochimica et Geochimica Acta 73, 3077-3092.

Paper III: Kalleson, E., Dypvik, H., and Gilmour, I. (in prep.) Distribution of carbon in different impact-related lithologies from the Gardnos structure. 37 p.

Paper IV: Kalleson, E., Dypvik, H., and Nilsen, O. (in prep.) Melt-bearing impact breccias within the Gardnos structure. 51 p.

Contents

1. INTRODUCTION TO IMPACT CRATERING

1.1. The importance of impact cratering

During the last part of the twentieth century geology to some extent has changed from an Earth to a planetary science. More about this trend and the main contributions to its progress has been summarized by French (2004), Pati and Reimold (2007) and in an essay by Marvin (2002). Before the Apollo missions some geologists still believed the craters on the Moon were of volcanic origin. New insights from the space missions were important for recognizing impact cratering as a geological process both on the Earth and other planetary bodies.

It is now generally accepted that through the Earth's history impacts have influenced the geological and biological evolution. Early in the history of our solar system when the planets formed, the Earth was under continuous bombardment. The Earth – Moon system most likely formed by a collision 4.5 billion years ago between the proto-Earth and a Mars-sized impactor, and the Moon subsequently accreted from the impact debris. Organic molecules have been (and still are) delivered to Earth through interplanetary dust particles, asteroid airburst, comets and meteorites, and Chyba and Sagan (1992) suggested that this may have been important for the evolution of life. Comets have also been suggested to have brought water to the Earth's oceans (Mumma et al., 2001). The relevance of impacts in the evolution of the Earth's crust was outlined by Grieve (2006). More about the role of impact processes on the early Earth is presented in a review by Koeberl (2006).

Whereas a possible extraterrestrial origin for carbon and water as pre-requisites for life on Earth is still debated, there is more agreement that impact events can influence the course of evolution by extinctions. Most famous is the Cretaceous-Tertiary (K-T) boundary extinction which was found to be associated with pronounced geochemical anomalies of for instance Iridium (Ir), caused by extraterrestrial input from a large meteorite impact (Alvarez et al., 1980). Later the about 200 km diameter Chicxulub impact structure in Mexico was identified as the impact site (Hildebrand et al., 1991; Sharpton et al.,1992).

"The importance of being cratered" was further outlined by French (2004) summing up the knowledge acquired from previous impact studies. Additionally French (2004) identified new scientific challenges for future investigations: to determine the full range of impact effects preserved on Earth, to apply the knowledge obtained from impact phenomena to more general geological problems, and continue the merger of the once exotic field of impact geology with mainstream geosciences.

Currently 176 impact craters are recognized on Earth (Earth Impact Database visited March 2009; http://www.unb.ca/passc/rpif/index.html). The problem (or maybe we should say fortunate circumstances?) is that no really large impacts have been observed on Earth in historical time. However, the collision of the comet Shoemaker-Levy 9 on the surface of Jupiter in 1994 (Spencer and Mitton, 1995) demonstrated the tremendous forces released by hypervelocity impacts. Small-scale laboratory hypervelocity impact experiments may provide constraints on the physics of small impacts. Numerical simulation models also increase our understanding of the impact process and its effects, both on small impacts and through scaling also on large impacts (Melosh 1989). However, in order to understand the physics and chemistry associated with large impacts it is necessary to look at the existing impact structures.

Compared to many other planetary bodies, impact craters on Earth are often poorly preserved. The Earth's active geological environment with plate tectonics, volcanism, weathering and erosion may mask and finally totally erase impact structures. Still, extensive sampling of impact-produced rocks is presently only feasible on Earth. These rocks, called "impactites", may record the extreme pressures and temperatures released during impact as various mineralogical modifications, and are one of the main data sources for impact studies.

1.2. The risk of impact

The Earth is bombarded by hundred tons of extraterrestrial material every day! Mostly the dust or sand-sized particles burn up in the atmosphere and never reach the ground. Larger pieces may survive the travel through the atmosphere, hit the ground and may be picked up as meteorites. Recovered meteorites ranges from pebble-size to the largest one ever found, the Hoba meteorite of 60 tons! The larger objects may fracture due to the aerodynamic stresses on the way through the atmosphere. The Barringer Crater in Arizona (1.2 km diameter, 50 000 years old) was formed by the collision of an iron meteorite of about 50 m diameter. A probably equally large object disrupted in the sky above Tunguska in Siberia in 1908, creating a big air-blast that knocked down trees over an area of more than 2000 km^2 (Vasilyev, 1998). It never reached the ground, and no crater formed. Objects of this size statistically hit the Earth about every thousand years (Atkinson et al., 2000). The really large objects (> 100 m diameter) are not much retarded in speed when passing through the atmosphere and will hit the ground close to their original cosmic velocity (between 11 and 72 km/s, on average ~ 20 km/s). There is a strong correlation between the size and frequency of objects colliding with Earth (Fig. 1.1), as a consequence of a specific size-frequency distribution in the Asteroid belt where most of the objects originate from. Consequently the risk of a large impact is relatively small.

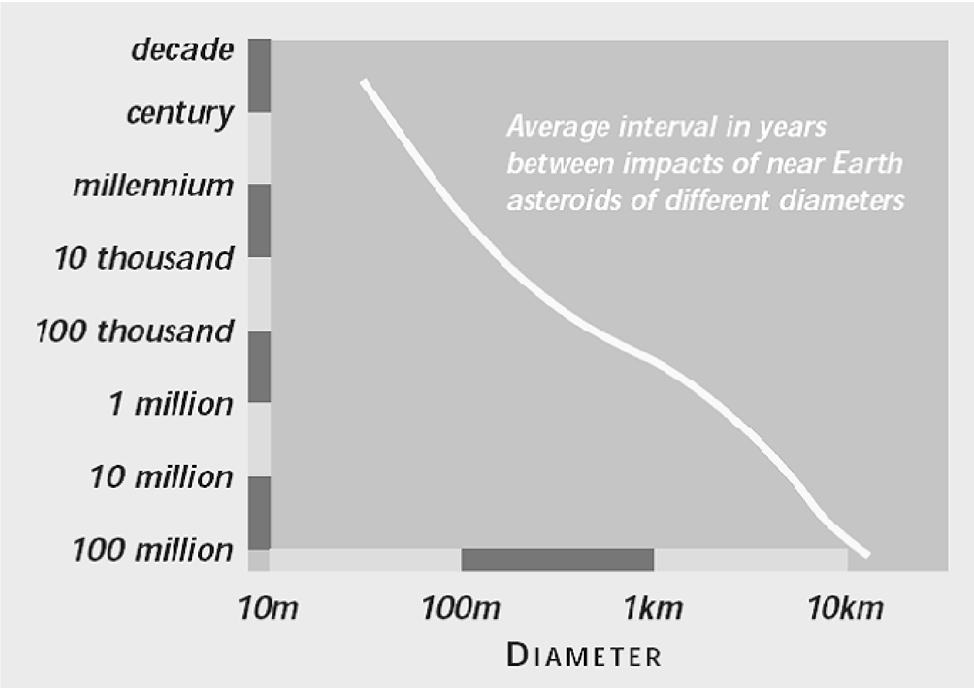

Fig. 1.1. Risk of impact: The average interval in years between impacts of objects of different diameter, illustrating the relatively frequent collisions by smaller objects and the expected long time-span between larger-magnitude impacts (Atkinson et al., 2000).

1.3. Impact crater formation

The term "impact" or "hypervelocity impact" is defined as the collision of two (planetary) bodies at or near cosmic velocity, which causes the propagation of a shock wave in both the impactor and the target body (Melosh, 1989). The formation of an impact crater is a complicated and dynamic process (Melosh, 1989; Melosh and Ivanov, 1999; Collins et al., 2005; Turtle et al., 2005). The website http://www.lpl.arizona.edu/impacteffects/ presents a program based on Collins et al. (2005) and offers an opportunity to calculate the effects of an impact based on input of impactor diameter, impactor density, impact velocity before atmospheric entry, impact angle, the distance from the impact at which the environmental effects are to be calculated, and the target type (sedimentary rock, crystalline rock, or a water layer above rock).

By convention three stages of an impact event are distinguished (Gault et al., 1968; Melosh, 1989); 1) contact and shock compression, 2) transient crater growth by crater material ejection, and 3) transient cavity modification (slumping or collapse). The crater formation is quick, in the order of seconds to minutes for most craters. The stages mentioned above have no strict boundaries, but emphasize the dominant mechanism acting at any given time during the crater formation. The crater formation process is illustrated in Fig. 1.2.

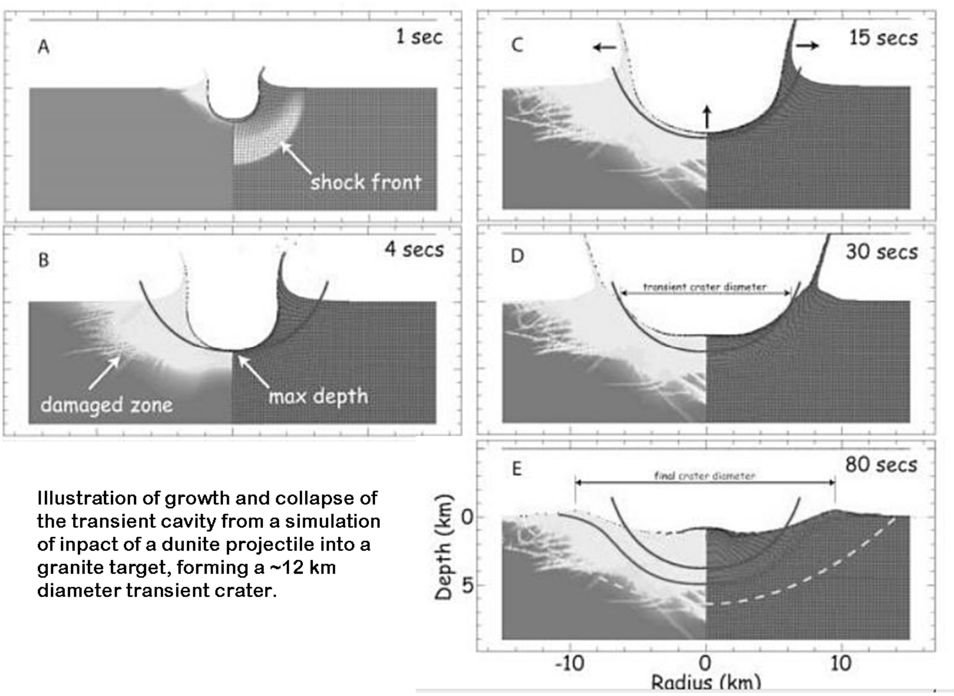

Fig. 1.2. Crater formation (from Turtle et al., 2005). (A) Early hemispherical growth of transient crater. B) Maximum of hemispherical growth reached. Upper solid curve marks the outline of the idealized transient crater. C) The transient crater continues to increase in diameter, until a maximum is reached in D). E) The final crater after modification. The lower solid curve marks the predicted extent of a highly disturbed region. Below is a damaged zone and the dashed curve marks the boundary between fractured and unfractured target material.

1.3.1. Contact and compression stage

The first stage of contact and compression only lasts for a very short time, less than a second for most craters (Melosh, 1989). When the projectile hits the ground it pushes target material out of its path, compressing and accelerating it. At the same time the target's resistance to penetration decelerates the projectile. Shock waves are created at the boundary between the compressed and uncompressed material. At the impact point, peak shock wave pressures may exceed 100 GPa. As the projectile penetrates into the target (not more than two times its diameter) the shock front spreads and propagates into both projectile and target. When the shock wave that was reflected back into the projectile reaches the back end of the projectile, it is reflected forward into the projectile as a rarefaction wave, also called release wave. As the release wave passes through the projectile back to its front again, the projectile is unloaded from the shock pressures and may melt or vaporize upon unloading. At this point where the whole projectile is unloaded, the release wave continues forward into the target and begins to decompress it as well and starts the next stage of excavation.

1.3.2. Excavation stage

During the excavation stage a more-or-less hemispherical shock wave propagates into the target. It decays in strength because its energy is spread over a greater volume of material and because of irreversible energy losses in the shock-compressed material. The rapid passage of the shock wave leaves the material behind in motion, in a direction radially away from the impact site. The shock waves that travel upward and intersect with the original ground surface are reflected downwards as rarefaction waves. These downward moving rarefaction waves create an upward-directed pressure gradient behind the shock. This adds an upward component to the radially directed velocity of the target material behind the shock wave, and produces the upward and outward excavation flow that opens the transient cavity. About equal volumes of material are either ejected out of the crater or displaced by plastic flow downward into the target. Initially the transient crater is shaped like a hemisphere. In non-ductile targets, however, the resistance increases downwards, and the crater stops increasing in depth while it may continue to grow outwards, increasing the crater radius. The maximum depth and diameter of the transient crater are mainly determined by the projectile diameter and velocity, with target properties (density and strength) of second order importance. The depth-to-diameter ratio, however, is between 1:4 and 1:3, almost independently of size and other parameters.

1.3.3. Modification stage

Modification of the transient crater is mainly driven by gravity. The collapse results in shallower and more stable crater geometry. In smaller craters slumping of the crater walls dominate, whereas in large craters stepped terraces may form along the walls, and the crater floor may be subject to uplift and central peak formation. The inward (and in larger craters upward) motion during the modification stage results in mixing of clastic breccia and melt inside the crater depression.

1.4. Crater morphology

Nearly all fresh craters can be described as “circular rimmed depressions”. Looking at the crater morphology in more detail there are many variations. The basic division of crater shapes is set between simple and complex craters (Fig. 1.3). In general small craters (< 4 km diameter for craters in crystalline target on Earth, Grieve, 1987) are simple and the larger craters are complex. Simple craters are described as bowl-shaped depressions, with a structurally uplifted rim. The typical example is Barringer Crater, Arizona (Fig. 1.4). The complex craters may be further divided into craters with just a central peak and craters with internal peak ring(s). Examples of complex, multiring craters on Earth are the Vredefort structure in South Africa and the Mjølnir structure in the Barents Sea (Fig. 1.5a and b). The 2 ga old, 300 km diameter Vredefort structure was a result of impact into crystalline target, whereas the 142 Ma old, 40 km diameter, Mjølnir structure was formed in softer sedimentary strata on the bottom of a shallow sea. This illustrates how the final crater shape depends on both the size of impact and the target properties. As most craters on Earth are more or less buried or eroded, the best geomorphological examples are from the Moon and other planets where craters are much better preserved (Fig. 1.5c and d). The craters generally show a systematic change in morphology from small bowl-shaped simple craters, to slump-walled complex craters, to terrace-walled complex craters to impact basins. Some large craters are so-called multi-ring craters.

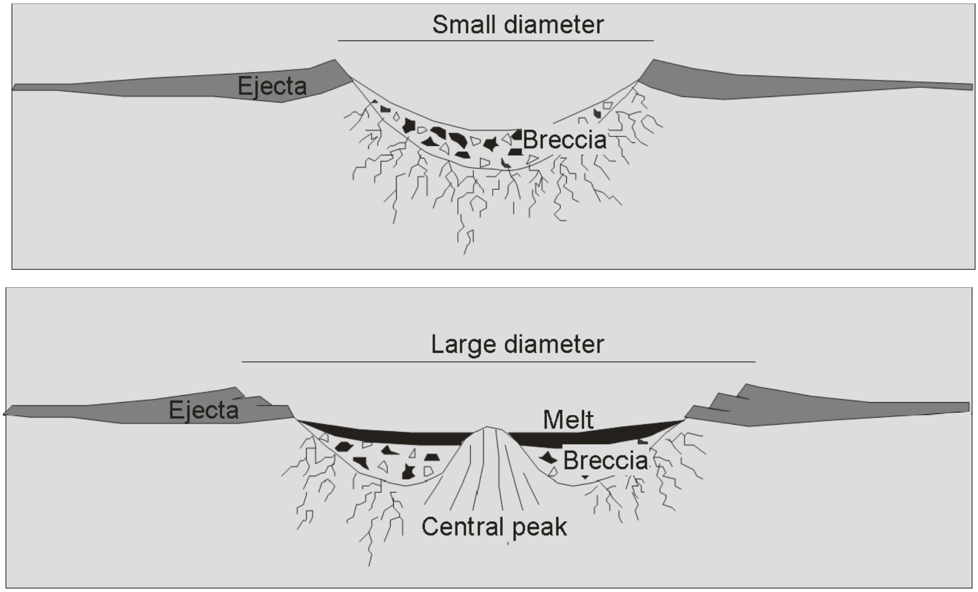

Fig. 1.3: Schematic drawing illustrating simple and complex crater shapes (after Melosh, 1989).

Fig. 1.4: Aerial photo of the approximately 50 000 years old, 1.2 km diameter Barringer (Meteor) Crater, Arizona. Image credit: NASA.

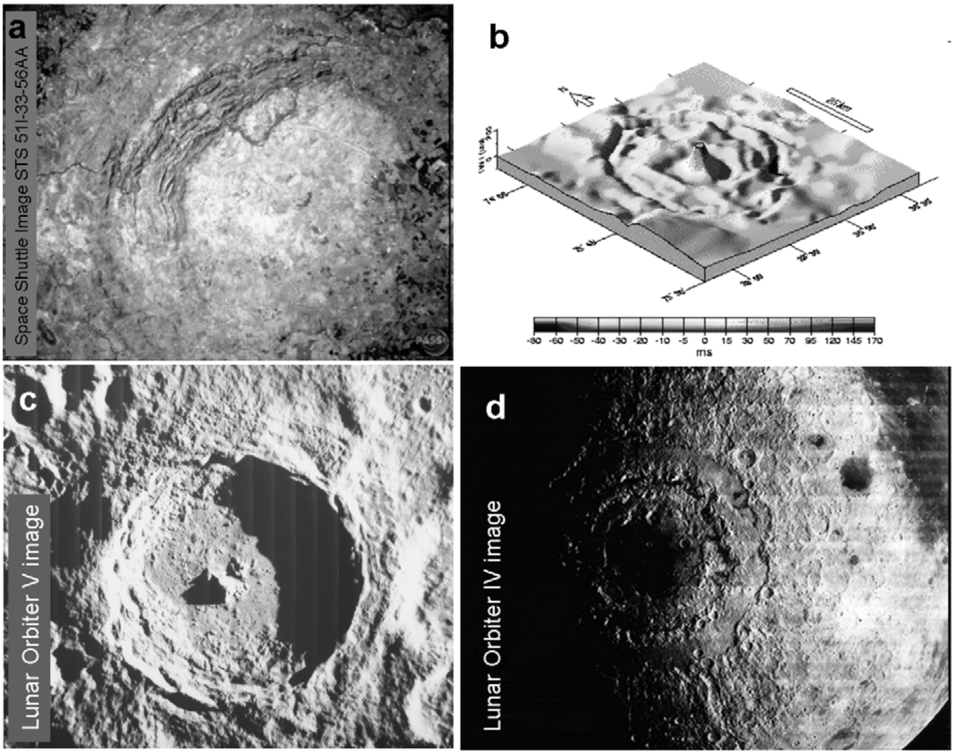

Fig. 1.5: Examples of complex craters. a) The Vredefort structure, South Africa (300 km diameter) is about 2 Ga old and deeply eroded (Image from Earth impact Database). b) Illuminated perspective image of the residual two-way traveltime surface of the Mjølnir structure (40 km diameter) buried below the present seafloor of the Barents Sea (Image from Tsikalas et al., 1998).
The complex Tycho crater, 85 km diameter. Right: The multi-ring Mare Orientale, 900 km diameter. Image credit: NASA.

1.5. Impact rocks (impactites)

A variety of impactites are formed during the complex but very short sequence of processes during impact. Target rocks may be fractured, shocked, melted and even vaporized. Definitions and classification of impactites are outlined by Stöffler and Grieve (2007), and their formation further discussed in a review by French (1998). Only a very brief description of the major types is presented here.

Impactites formed within or close to the crater are called “proximal”, whereas the material deposited further away is called “distal”. The proximal impactites comprise various breccias and melt rocks. The target rocks of the crater floor may be shattered and brecciated more or less in place, whereas other rock debris and melt are transported during the excavation stage, and may be deposited upon ballistic transport or from the central ejecta plume and upon collapse of the transient cavity during the modification stage. As a consequence of the crater formation process, shocked rocks and impact melt may mix with unshocked lithic and mineral fragments forming polymict breccias in and around the crater.

The material thrown out of the crater is generally called **ejecta** and commonly forms continuous deposits extending some two – three crater radii away. **Suevite** is a melt-bearing impactite with essentially clastic matrix. Suevites are commonly polymict breccias, except in the cases of single lithology targets. The minerals in the rock fragments within suevites (also called suevitic breccias) commonly display shock-metamorphic effects. Suevite was named after a rock found at Ries crater in southern Germany. Breccias without any melt particles are called **lithic impact breccias**. The autochthonous lithic breccias are generally monomict, whereas allochthonous lithic breccias commonly are polymict. The amount of melt generated (relative to clastic material) increases with the size of impact. In small craters none or very little melt is formed. Impact melt lithologies occur as 1) allochthonous coherent melt sheets, 2) inclusions in polymict impact breccias (suevite), and 3) dykes and veins in the autochthonous crater basement or in displaced rock fragments. **Melt rocks** may be subdivided into clast-rich-, clast-poor-, and clast-free, according to the content / absence of lithic fragments.

The distal impactites comprise tektites and airfall beds. The **airfall beds** are generally discontinuous and consist of the finest material. The iridium-anomaly at the K-T boundary occurs world-wide, indicating that the finest material from the Chicxulub impact in Mexico went high up to the atmosphere and spread all around the Earth. **Tektites** are natural glasses originated as melt from surface-near target rocks ejected during impact, and may be found far away from the impact site. There are several tektite strewn fields in part linked to craters around the world. In Europe the famous green moldavites (tektites) found in the Czech Republic have been suggested to originate from the Nördlinger Ries crater (Germany) a few hundred kilometres away based on coinciding age estimates (Gentner, 1971) and more recent simulations of an oblique impact at Ries make it probable that such a relation exists (Artemieva et al., 2002).

1.6. Recognizing impact structures

Impact structures are often discovered as features of roughly circular shape. Some relative young structures may have preserved a morphological rim and maybe a central uplift. The characteristic shape of the impact structures may have to serve as a solitary criterion for recognition at other planetary bodies where other data are not available. However, there is a risk of confusing with circular volcanic features. Remote sensing techniques, digital elevation models and geophysical data sets may be useful with regard to first indications of the existence of potential impact structures or add supplementing information of proven ones (Koeberl, 2007). The use of models for automatic detection of circular structures may provide an efficient way to screen large geographic areas for previously unknown structures (Krøgli et al., 2007). However, on Earth the highly active geological environment (sea-floor spreading, volcanism, weathering and erosion) serves to remove, modify and mask the terrestrial impact record (absolutely the case with Gardnos!). This often makes it hard to recognize impact structures on the Earth by their shape. On the other hand, on Earth often ground-truth information on possible impact structures is available. The presence of breccias that can not be explained by known volcanism or tectonic events may hint at potential impact structures. Impact structures may be characterized by geophysical anomalies, like gravity, magnetics and resistivity. Interpretation of these geophysical anomalies may aid in understanding a geological structure, and when several methods are used together, the mutual constraints set by each method can lead to significantly less ambiguity in the interpretation. Still, the most commonly used impact markers are elevated contents of siderophile elements (especially iridium and other platinum group elements (PGEs), and the presence of shock metamorphic effects in minerals (especially planar deformation features in quartz) (Koeberl, 2007).

1.6.1. Geophysical anomalies in impact structures

An impact may disturb the original distribution of physical rock properties. At Chixculub rocks were disturbed all the way down to Moho (Melosh, 2001). The great advantage of geophysical methods is that they give subsurface data and covers large volumes of rocks. Twenty % of the Earth's known craters are buried beneath post-impact sediments, and the major tool for investigation of these is geophysics (Pilkington and Grieve, 1992). Of the main geophysical methods are gravimetry, magnetometry, seismic (reflection/refraction), electromagnetic and electric. In addition there are a suite tools available for bore hole logging.

The most common and conspicuous geophysical signature in small impact structures is a circular **gravity** low. In simple craters this anomaly is related to the presence of an allochthonous breccia lens of increased porosity. Large complex structures may exhibit a relative gravity high in the crater centre caused by an upheaval of denser rocks from greater depths related to the central uplift. However, when interpreting gravity anomalies, local factors like target rock and the erosional level, must always be considered. The precision of the data vary considerably, from very precise surface measurements, to more regional studies, to large-scale data acquisition from airplane and even to satellite information.

Seismic techniques provide information of the subsurface structure. Brecciation and fracturing will lower the density of the rocks, and thereby reduce the seismic velocities. The extensive faulting and brecciation will usually lead to incoherent seismic reflections within the impact structure (see also Stewart, 2003).

Electrical properties are very much related to fracturing and circulation of water within fractures. It is thus a method for mapping the degree and extent of brecciation, particularly in impact structures in crystalline basement (Henkel, 1992).

The **magnetic** properties of the target rock can be changed by an impact, by shock, thermal and geochemical effects. Shock pressure can remove existing remanent magnetization, and at high pressures magnetic susceptibility may be reduced (Pilkington and Grieve, 1992). Magnetic minerals like magnetite may acquire a thermo-remanent magnetization according to the Earth's magnetic field at the time of impact. Comparing with the known apparent polar wander path for the respective continent, paleomagnetic studies may shed light on the timing of impacts (see for instance Carporzen and Gilder, 2006).

1.6.2. Shock metamorphic features

Shock metamorphism is indeed mineralogy at the extremes. Fig. 1.6 illustrates the pressure and temperature fields for endogenous and shock metamorphism. The threshold for onset of characteristic shock metamorphism varies according to mineralogy and porosity of the rock, but is about 5 GPa for a common rock-forming mineral as quartz (Stöffler and Langenhorst, 1994). This is well above the pressure fields associated with endogenous shock metamorphism (Fig. 1.6). The shock-wave pressures also differ from other "normal" geological processes because they are very sudden and brief. It passes through the rock minerals in microseconds, and shock deformation effects therefore reflect transient stress conditions, high strain rates and possibly rapid quenching. This may result in unique features, which in nature are only found related to hypervelocity impacts (though some can be created by shock experiments in laboratories). Shock metamorphic effects in rocks and minerals have been reviewed by French (1998) and will only be very briefly described here. The most common/acknowledged shock deformation features are listed in Table 1.1.

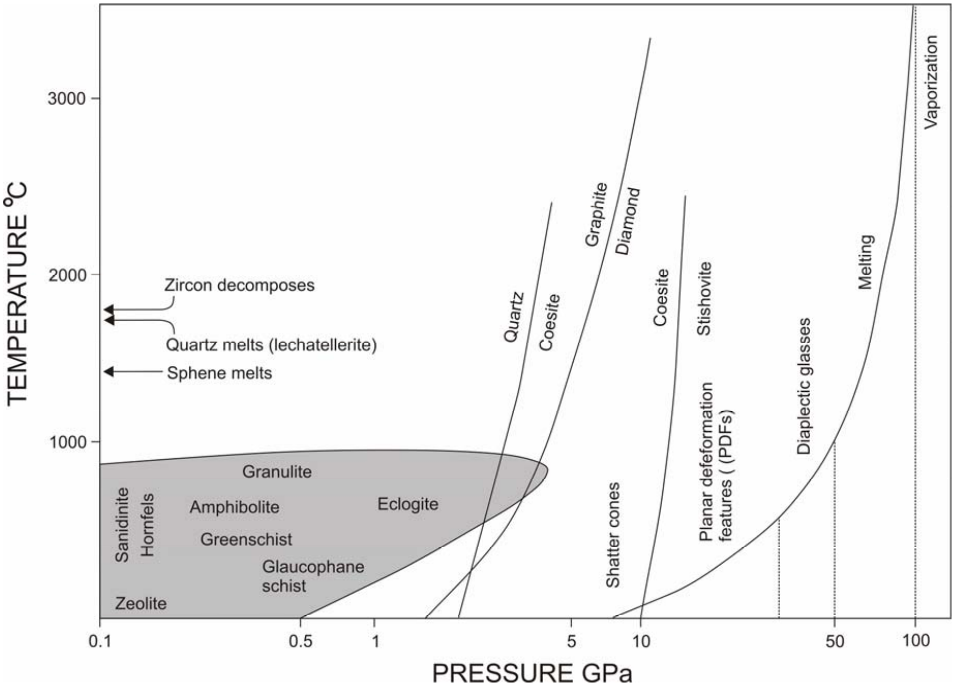

Fig 1.6: Pressure and temperature fields for endogenous metamorphism and shock metamorphism (French, 1998).

Table 1.1: Characteristics and formation pressures of various shock deformation features (from Koeberl, 2002).

Pressure (GPa)	Features	Target characteristics	Feature characteristics
2 -45	Shatter cones	Best developed in homogenous, fine-grained, massive rocks.	Conical fracture surfaces with subordinate striations radiating from a focal point.
5 – 45	Planar fractures and planar deformation features (PDFs)	Highest abundance in crystalline rocks; found in many rock-forming minerals; e.g. quartz, feldspar, olivine and zircon.	PDFs: Sets of closely spaced (1-5 µm) extremely straight, sharply defined parallel lamellae; may occur in multiple sets with specific crystallographic orientations.
30 – 40	Diaplectic glass	Most important in quartz and feldspar (e.g. maskelynite from plagioclase).	Isotropization through solid-state transformation under preservation crystal habit as well as primary defects and sometimes planar features. Index of refraction lower than in crystal but higher than in fusion glass.
15 – 50	High-pressure polymorphs	Quartz polymorphs most common: coesite, stishovite but also ringwoodite form olivine, and others.	Recognizable by crystal parameters, confirmed usually with XRD or NMR; abundance influenced by post-shock temperature and shock duration; stishovite is temperature-labile.
> 15	Impact diamond	From carbon (graphite) present in target rocks; rare.	Cubic (hexagonal?) form; usually very small, but occasionally up to mm-scale; inherit graphite crystal shape.
45 – 70	Mineral melts	Rock-forming minerals (e.g. lechatelierite from quartz).	Impact melts are either glassy (fusion glasses) or crystalline; of macroscopically homogenous but microscopically often heterogeneous composition.

Shatter cones are the only macro-scale feature diagnostic of impact (French, 1998 and references therein). They may be seen with the naked eye as curved, striated fracture surfaces forming partial to complete cones of sizes from 1 cm to 1 m. Shatter cones mostly occur at the central uplift and in the outer and lower parts of a crater. They form at relatively low pressures, but the mechanism of formation is still not well understood. Commonly they are best developed in fine-grained lithologies such as limestone, but can occur also in coarser rocks such as granites (see example from Siljan impact structure in Fig. 1.7a).

Planar fractures (PFs) may develop at 5-8 GPa pressures and form parallel, thin open fractures spaced 15-20 µm or more apart in individual quartz grains (French, 1998). Similar cleavage may also (rarely) occur in quartz from non-impact settings, and consequently PFs are not considered an independent criterion for meteorite impact.

Planar deformation features (PDFs) are not open cracks, but occur as multiple sets of closely spaced (< 10 µm), extremely narrow, parallel regions (Fig. 1.7b). They are distinct from deformation features produced by non-impact processes. PDFs are therefore widely accepted as evidence of meteorite impact and are probably the most famous and intensively studied of the shock metamorphic microstructures (examples of literature is Stöffler and Langenhorst (1994); French (1998) and references therein). The abundance of the PDFs and their orientations relative to the crystallographic axes may be indicative of maximum shock pressure (Stöffler and Langenhorst, 1994), though details in the process of their formation is still topic of research (Goltrant et al, 1992; Leroux et al, 1994; Trepmann, 2008). Planar microstructures may also occur in feldspar, zircon and other minerals.

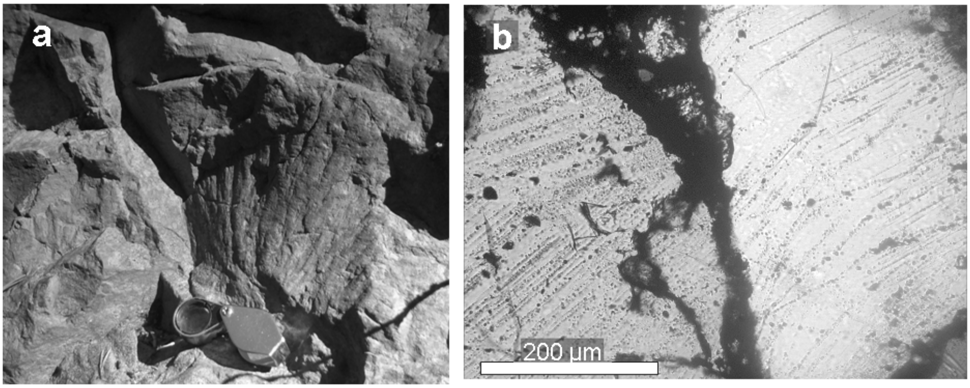

Fig. 1.7. a) Shatter cone in Siljan Granite at Trollberget, central in the Siljan impact structure. The Swedish Siljan structure is 377 Ma old (Reimold et al., 2005) and ~52 km in diameter (Earth impact database, accessed at March 2009). b) Planar deformation features (PDFs) in quartz grains from the Gardnos Breccia.

Diaplectic glass produced by shock shows no evidence of melting and flowing, but preserves the original crystal texture and fabric of a mineral (French, 1998).

High-pressure polymorphs may form when some minerals are subjected to the impact-produced shock waves. Graphite can be converted to diamond, and quartz to stishovite at shock pressures of >12–15 GPa and to coesite at >30 GPa (Stöffler and Langenhorst, 1994). Diamond and coesite also occur naturally in deep-seated rocks, and may be carried to the Earths surface; diamonds by kimberlite volcanic eruptions, and coesite by tectonic processes (French, 1998). Impact diamonds are rare, mainly because their formation requires carbon present in the target rocks prior to impact. Examples of impact diamond are found in the 36 Ma, 100 km diameter Popigai structure in Siberia (Masaitis, 1998), the 14 Ma, 24 km diameter Nördlinger Ries crater in Germany (Schmitt et al., 2005), the 73 Ma, 23 km diameter Lappajärvi structure in Finland (Langenhorst et al., 1999), the 1850 Ma, 250 km diameter Sudbury structure in Canada (Masaitis et al., 1999).

Impact melts are formed by bulk melting as a result of shock heating followed by adiabatic decompression. Temperatures usually exceed magma temperatures by far. Depending on the composition of the melt, the initial temperature and speed of cooling, impact melts may result in either impact glass (if cooled quickly) or fine-grained melt rocks (if cooled slowly).

Pseudotachylitic breccias were first reported from the Vredefort structure by Shand (1916), describing dark, glassy rocks in veins and dykes. The term "psudotachylite" has since then been used/abused for a variety of melt occurrences, from mm-thick veins to thick, up to one km thick bodies, like the "Frood" in the Sudbury impact structure, Canada (Scott et al., 1996). A distinction between shock-type and endogenic-type pseudotachylites based on formation processes was suggested by Spray (1998). However, according to conventional geological terminology pseudotachylite is friction melt, and it may also form by tectonic processes unrelated to meteorite impacts (see for example Lin, 2008). These structures are undoubtedly important to understand the impact process, but the term pseudotachylite should be used very cautiously as there are several problems related to use of the present terminology (Reimold and Gibson, 2005).

1.6.3. Geochemical anomalies

Traces of meteoritic material are also regarded as proofs of an impact. Only in small impacts (projectile < ~50-100 m diameter) pieces of the meteoritic material may be routinely found. In larger impacts most of the projectile is instantly vaporized, and only traces of it (commonly less than 1 %) may be incorporated in the impactites within the crater or the corresponding ejecta outside. However, a meteorite found in sediments from the K-T boundary in the North Pacific Ocean may be a piece of the projectile responsible for Chicxulub impact (Kyte, 1998) and in the 70 km diameter Morokweng in South Africa (Maier et al., 2006). In most cases the contribution of meteoritic matter to the impact lithologies is very small (< 1%), leading to only slight geochemical anomalies. Only elements with high abundances in extraterrestrial objects and low in terrestrial crustal rocks can be used to detect such a meteoritic component. Due to magmatic segregation processes early in the Earth's history, iron and nickel are concentrated in the Earth's core. Along with the iron and nickel went other siderophile elements which thus became depleted in the crust. The platinum group elements (PGEs) comprise ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt) and are, in particular, rare in the Earth's crust. Elevated contents of PGEs together with nickel (Ni), chromium (Cr) and cobalt (Co) are often used to indicate an extraterrestrial component in impactites. This method may reveal a chondritic or iron meteoritic component. However, achondritic impactors (stony meteorites that underwent magmatic differentiation) are more difficult to discern, because they have much lower abundances of these key siderophile elements (Koeberl, 2007).

Enrichment of **iridium** is maybe the most famous geochemical signal indicating an extraterrestrial impact. Ir was found at the K-T-boundary in concentrations several hundreds times the background level (Alvarez, 1980), and later linked to the Chicxulub impact (Hildebrand et al., 1991; Sharpton et al., 1992).

The **rhenium-osmium** (Re-Os) isotopic system also allows distinguishing the isotopic signatures of meteoritic and terrestrial rocks (Koeberl, 1998). Meteorites have relative high contents of Os compared to crustal rocks. The abundance of Re in meteorites are lower than Os, resulting in Re/Os ratios about 0.1 or less. In terrestrial crustal rocks the Re/Os ratio is usually no less than 10. Correspondingly the $^{187}Os/^{188}Os$ ratios are relatively higher in crustal rocks than in meteorites. Addition of meteoritic material thus will cause an increase in Os-content coupled to a decrease in the $^{187}Os/^{188}Os$ ratio.

Chromium isotopes may not only provide evidence of the presence of a meteoritic component, but also help determining the meteorite type. The method is based on the relative abundance of ^{53}Cr (the daughter product of the radionucleide ^{53}Mn). Because Earth homogenized long after ^{53}Mn had fully decayed, there is no variation of $^{53}Cr/^{52}Cr$ ratios in terrestrial samples. In contrast, some meteorite classes are characterized by a variable excess of ^{53}Cr relative to terrestrial samples reflecting a heterogeneous distribution of ^{53}Mn in the early solar system.

Inter-element ratios of the PGEs in the impactites can be derived from the slope of the mixing line obtained by plotting the different PGE abundances in the impactite samples against each other. By combining the different PGE, it becomes possible to obtain the element ratios of the projectile without having to subtract the indigenous target-rock component (McDonald, 2002; Tagle and Hecht, 2006).

2. GEOLOGICAL BACKGROUND

2.1. Regional geology

The Gardnos impact structure is situated in Hallingdal, 150 km north-west of Oslo (Fig. 2.1). The Precambrian basement consists mostly of quartzites and banded micaceous quartzitic gneisses of the Seljord Group (Telemark Supracrustals), granitic gneisses and some mafic rocks (Nordgulen et al., 1997). The rocks were tilted almost to a vertical position during the Sveconorwegian orogeny (1140 - 900 Ma (Bingen et al., 2008)), with the orogen today striking in an approximately north-south direction. At the time of impact, suggested to be 546 Ma ago by Kalleson et al. (2009), the crystalline basement in the area was likely covered by a thin sequence of sedimentary rocks. After impact and following infill of the crater structure the area was subject to deformation and buried beneath several kilometres of nappes/thrust sheets in the Devonian during the Caledonian orogeny. The timing of the impact, however, has been poorly constrained. The youngest known target rock (~ 900 Ma) that were crushed by the impact obviously pre-dates the event and the Caledonian metamorphic event affected the impactites at Gardnos and thus must post-date it. Through Tertiary uplift and subsequent weathering and erosion most of these overlying rocks were removed. During Quaternary time the area was repeatedly glaciated and eroded, re-exposing the impact structure.

2.2. The Gardnos structure

Presently the Gardnos structure is represented by outcrops of impactites within a roughly circular area of about 5 km diameter. The structure has been eroded below the level of the once existing crater rim (Fig. 2.2) and estimates of the original crater size indicate a rim-to-rim diameter of 6 km (Kalleson et al., 2008). In the centre of the structure a topographic high consisting of basement rocks rise above the suevite deposits, representing the remnants of a central uplifted peak. Surrounding the central peak once was a relatively flat-floored annular moat about 1 km wide, filled with allochthonous breccias (dominantly suevite) and later post-impact sediments. Parts of this sedimentary infill were removed during the last glaciation (ended about 10 000 years ago). Being softer than the surrounding crystalline basement rocks much of the suevite and over-lying post-impact sediments were eroded as the glacier carved out a small valley in the wall of the main valley of Hallingdalen. The eastern side of the original crater is thus completely erased, and impact breccias from the crater floor and below exposed. The rest of the crater structure is better preserved and in the northern part suevite of about 50 m thickness and up to 150 m post-impact succession can be found. The area is partly covered by moraine, but good exposures are found at steep hillsides and along river beds. In addition the Gardnos structure was cored in 1993, resulting in a 400 m long vertical drill core constituting a reference section for the crater stratigraphy (French et al., 1997).

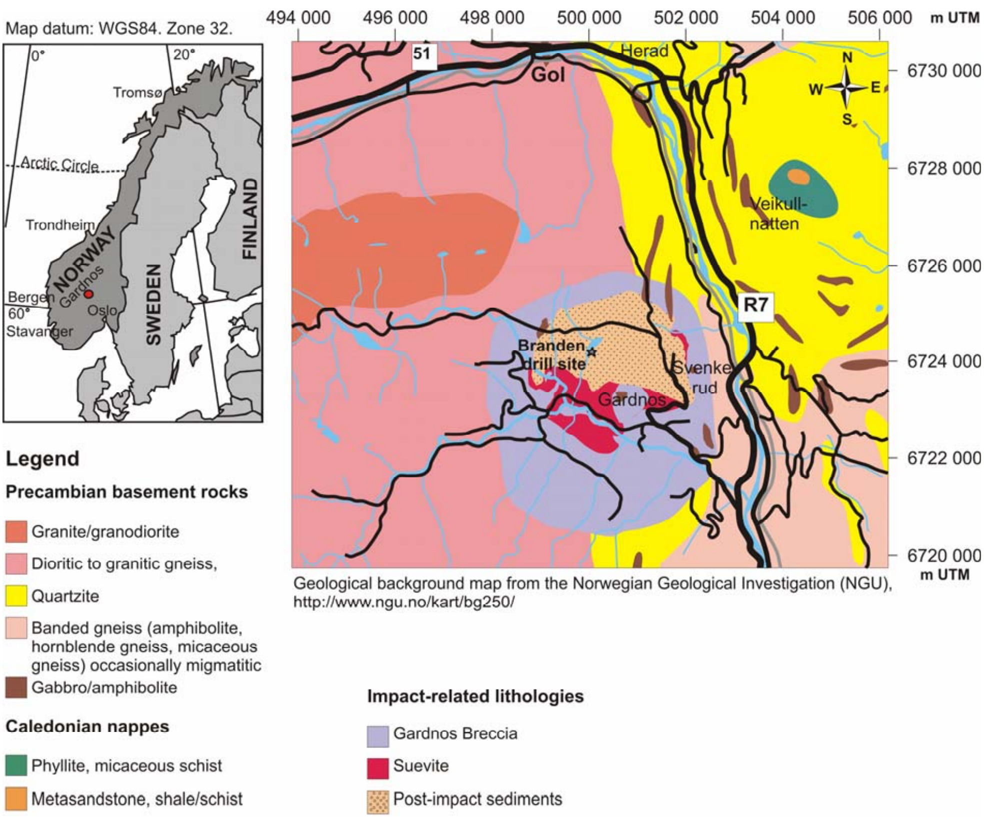

Fig. 2.1. Geological map of the Gardnos area.

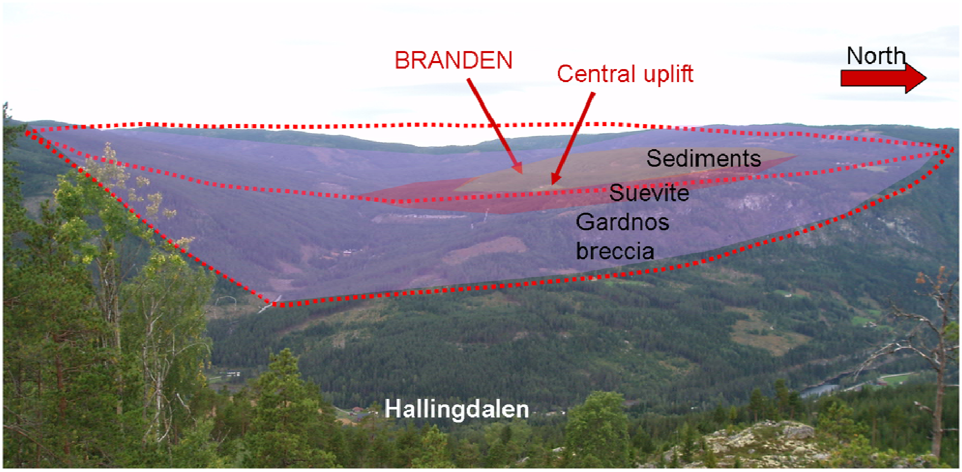

Fig. 2.2. View from the east towards Gardnos. Areas of Gardnos Breccia, suevite and sediments are indicated. The Branden hill is the site of the drill core. The central uplift is recognized by basement rocks rising above the suevite deposits.

2.3. The Gardnos impactites

Lithic (par)autochthonous breccias of at maximum a couple of hundred meters thickness make up most of the crater floor. They were produced by shock and release waves during impact and reflect the local basement lithologies comprising mostly fractured/shattered granitic gneisses in the western part of the crater structure, quartzites and banded gneisses in the eastern part, together with smaller bodies of amphibolitic rocks (Fig. 2.1). Commonly these (par)autochthonous breccias are referred to as **Gardnos Breccia**. Though there are variations in the appearance of the Gardnos Breccia due to local target lithology and degree of fracturing, a Gardnos Breccia sample typically consists of angular light colored granitic or quartzitic clasts embedded in a dark grey, clastic matrix of mineral and rock fragments, with a minor amount of carbon ~1 % TOC (French et al., 1997; Gilmour et al., 2003). Matrix content may vary from minor, mm-thick fillings dividing separate fragments, to matrix-dominated breccias where the clasts are few and small, floating in the matrix (Fig. 2.3 and 2.4a). PDFs in quartz grains are observed in some samples. A unique black quartzite is exposed in only one outcrop, and was described as a separate lithology by French et al. (1997). This quartzite is, as the more common Gardnos Breccia, part of the (par)autochthonous lithic breccias of the crater floor. The black color is due to heavy fracturing at a microscopic level and the presence of carbon within most of the fractures. The amphibolitic basement rocks were brecciated only at a small scale and lack the characteristic black matrix. Being more resistant to erosion they often are found in small topographic highs, like the exposures at the central uplift of the Gardnos structure.

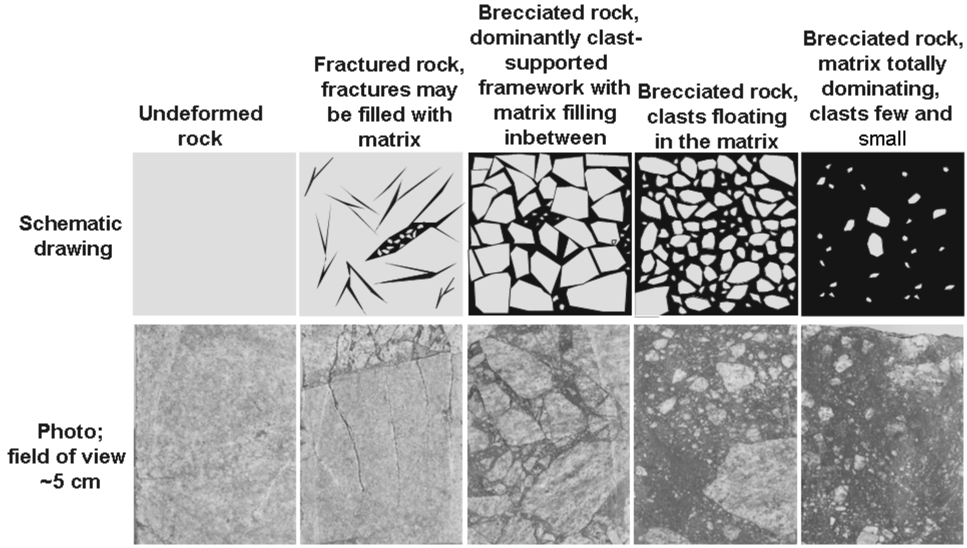

Fig. 2.3. Variations with respect to degree of fracturing and matrix content in Gardnos Breccia.

In central parts of the crater, allochthonous breccias may be found above the Gardnos Breccia. The allochthonous breccias are dominated by **suevite**, "a polymict impact breccia with clastic matrix and mineral clasts in various stages of shock metamorphism including cogenetic impact melt particles which are in a glassy or crystallized state" according to the recent definition by Stöffler and Grieve (2007). The suevite consists of angular rock fragments of different sizes and lithologies and melt fragments of various sizes and compositions floating in a fine-grained, dominantly clastic matrix. In hand specimen it can be distinguished by cm-sized dark fragments of melt, which are best seen on weathered surfaces (Fig. 2.4b). In the clast-rich impact melt rock crystallized melt forms the matrix for rock and mineral clasts. This rock was named "melt-matrix breccia" by French et al. (1997) and described from one outcrop (10 – 20 m wide, maximum 5 m in thickness) found near the centre of the crater.

Due to glacial erosion much of the suevite and post-impact sediments were removed. Today suevite of about 50 m thickness and up to 150 m of post-impact sediments are preserved in the northern part of the structure. In the southern part only Gardnos Breccia are present. The post-impact sediments consist mainly of impact-generated debris from the rim and nearby areas eroded and transported back into the crater depression by debris flows and density flows and deposited (Kalleson et al., 2008). The lowest post-impact sedimentary units immediately succeeding the impactites consist of coarse sedimentary breccias and conglomerates followed by various sandstones. In the upper part there is a generally fining-upwards development towards interbedded fine-grained sandstones and shales.

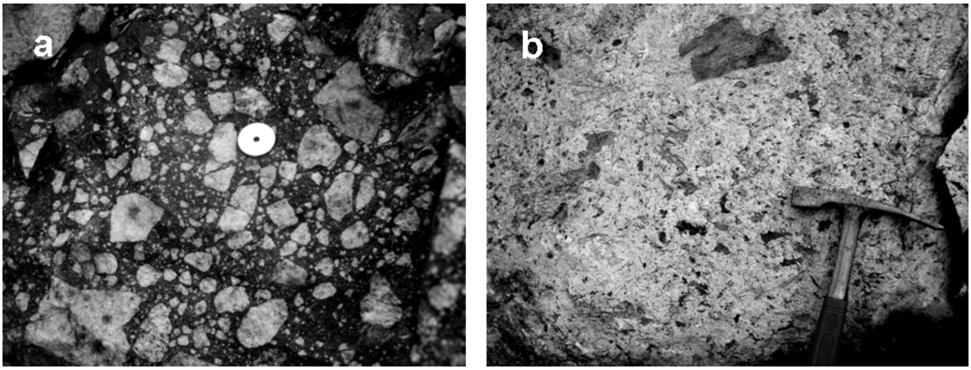

Fig. 2.4. Typical Gardnos impactites. a) Fresh cut surface of Gardnos Breccia. Coin is approx. 2.5 cm diameter. b) Rock surface of weathered suevite.

2.4. Discovery of the Gardnos impact structure

The characteristic breccias and sedimentary rocks in the Gardnos area deviate from the surrounding basement rocks, indicating the presence of a special geological structure. Its origin was discussed for some time. In the first published paper (Broch, 1945) Gardnos was interpreted as a crypto-volcanic structure, though the lack of true volcanic material was pointed out. This conclusion was not very surprising, seen in the context of the prevailing scientific beliefs at time. It was not until several years later that impacts became a “hot topic”. The Gardnos structure was eventually identified as an impact structure when “shocked” quartz grains were discovered (Dons and Naterstad, 1992).

The discovery of a meteorite crater caused some enthusiasm among scientists as well as the public. A journalist from a Norwegian newspaper promptly hired a helicopter to picture the crater from above. He returned, rather disappointed, stating that the place was all covered by forest so he couldn’t see the crater. Obviously, after some hundred million years, the crater was far from having the “fresh” crater look!

More important, the crater discovery resulted in funding from the Norwegian Research Council to drill a 400 m long vertical core. The drill site was strategically located on a small hill called Branden, and penetrated about 150 m of post-impact sediments, 50 m suevite and 200 m of Gardnos Breccia (Fig. 2.1).

2.5. Previous work

The recognition of Gardnos as an impact structure (Dons and Naterstad, 1992) triggered some new research activity. The main work was presented in a paper by French et al. (1997) describing petrology and geochemistry of the target rocks, impact and post-impact lithologies. They also disclosed some mixing calculations to evaluate target source rocks for the suevite. French et al. (1997) in addition noted the elevated content of organic carbon in the impactites relative to the surrounding basement rocks (~1 % TOC) and presented the first result of stable carbon isotope analysis, indicating a terrestrial origin of the carbon. The Biri Shale and Alum Shale were tested as possible target source rocks, but none matched completely and no conclusion could be drawn. The age of impact was constrained to be between 400 and 900 Ma.

Two topics caught special interest in the scientific environment; the presence of carbon and the unknown age of impact. Gardnos is one of only two globally known impact structures where the impactites contain significantly higher amounts of carbon than the corresponding target rocks, Sudbury in Canada is the other (French, 1968; Bunch et al., 1999; Heymann et al., 1999). Gilmour et al. (2003) presented a detailed study on carbon based on geochemistry, Raman spectroscopy, stable isotope analysis and transmission electron microscopy, extending the previous work by French et al. (1997). The main fraction of the carbon turned out to be poorly ordered to moderately crystalline graphite. In addition impact-generated diamond was identified, proving that at least some of the carbon indeed was present at the time of impact and subject to shock. The variations in ordering of the carbon in the Gardnos impactites led Gilmour et al. (2003) to suggest at least two episodes of carbon emplacement at Gardnos, an initial impact-related incorporation and shock transformation of graphitic material from target rocks followed by later mobilization of carbon.

Most other studies of Gardnos have been rather “fragmented”, based on limited/arbitrary sampling, looking into small details. Anderson and Burke (1996) studied methane fluid inclusions in quartz. The homogenization temperatures for methane corresponding to isochore pressures (1 – 2.5 kbar) are compatible with Caledonian metamorphism, and not with the extreme pressures during impact (Andersen and Burke 1996). They concluded that the methane likely formed in-situ by reactions between solid carbonaceous material and aqueous metamorphic fluid in a post-impact setting. Parnell and Lindgren (2006) studied selected melt fragments from suevite samples. Their findings supported incorporation of carbon in the impact melt, and subsequent precipitation at the boundaries between two immiscible silicate phases now represented stilpnomelane and chlorite, which reflect later alteration. Based on the amount of carbon in the melt Parnell and Lindgren (2006) concluded on Alum Shale as the carbon source rock. They further stated that the impactites formed during extreme conditions, and the Gardnos samples offer an opportunity to draw some general conclusions on the behaviour of carbon during impact-melting. One is that the degree of structural order in the carbonaceous material may not be used as a geothermometer in the cases of impact, because the carbon precipitated from impact melt did not experience the gradual development of structural order found in progressively heated samples. Another point stated by Parnell and Lindgren (2006) regarding impacts on the early Earth is that substantial proportions of carbon processed through impact melts may survive for further processing in prebiotic chemistry or by primitive life. The last contribution in the field of organic chemistry of the Gardnos impactites is the observation of fullerenes. These were detected in samples from Gardnos as part of a study by Elsila et al. (2005). This study, however, was more about sample preparation and analysing techniques for identifying fullerenes, and does not contribute significantly to the understanding of the Gardnos impact.

Dating of the impact event was attempted by ^{40}Ar-^{39}Ar dating on impact melt (Grier et al., 1999). However, the measured ages around 385 Ma were interpreted to show a metamorphic overprint representing the end of the Caledonian orogeny.

A separate study on the geochemistry of the impactites (in which I was happy to take a minor part) was conducted to evaluate the possible impactor responsible for the impact (Goderis et al., 2009). Based on the abundances and inter-element ratios of PGEs, an IA or IIIC non-magmatic iron meteorite was proposed as the most plausible impactor.

2.6. Further work

After the main previous work (chapter 2.5) many questions were still unresolved. The age of the impact was poorly constrained (illustrated in Fig. 2.5), the structure had not been mapped in detail, and consequently all calculations on original crater size and impactite volumes were preliminary estimations. The impactites were well described by French et al. (1997) but sampling was limited to parts of the crater, possibly not 100 % representative or not fully illustrating the internal variations within the lithologies. The origin of the carbon in the impactites was still a topic of discussion and the post-impact history poorly known. The post-impact sedimentary column had so far only been very briefly described, and no interpretation existed.

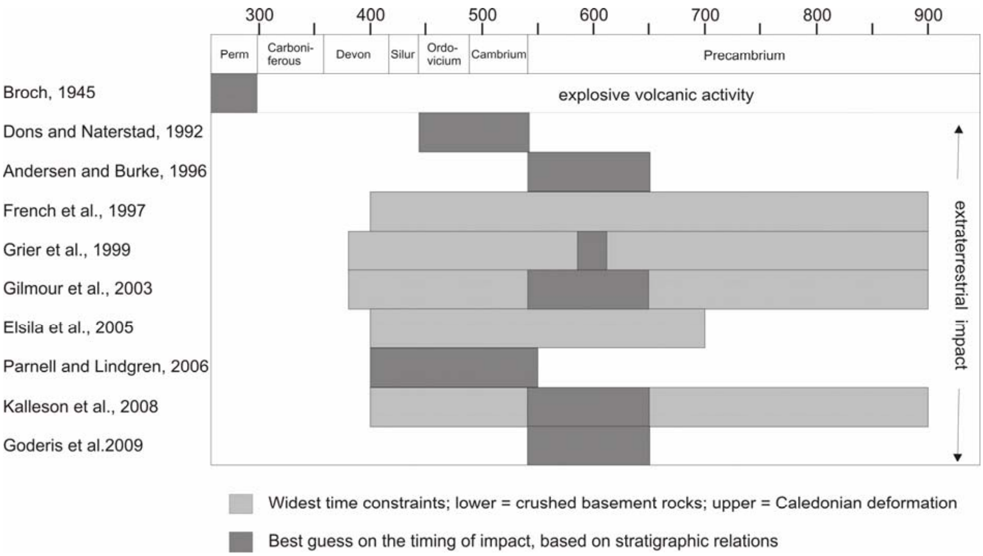

Fig. 2.5. Proposed timing of the Gardnos impact in different publications.

3. METHODOLOGY

This study of the Gardnos impact structure relies on extensive field mapping, detailed field observations and sampling and intensive studies of the 400 m long Branden drill core constituting the reference section for the crater stratigraphy. The rather broad range of sub-topics in this study required approaches through a large number of techniques. Samples from field and core were studied by optical microscopy, universal stage (U-stage), scanning electron microscope (SEM), cathode-luminescence (CL), X-ray fluorescence (XRF), X-ray diffraction (XRD), and mass spectrometry (MS) methods. All instruments are at the University of Oslo (Natural History Museum and Department of Geosciences) except the MS at the Open University, Milton Keynes.

The following sections provide a more detailed and compound outline of the field work and core description along with a brief overview of sample preparation techniques. The analyzing techniques employed in this study are only presented as very short introductions to the main principles of the methods and the reason for applying them to the Gardnos material. Details on the analytical procedures are described in the relevant papers / manuscripts.

3.1. Field and core observations

During the geological mapping, sampling and detailed studies in the field, all observations were registered by GPS and imported to the geographical information system (GIS) package ArcGIS 9.2. These field observations combined with a topographical map and a digital elevation model (DEM) of the area were the base for the geological map and modeling of the lithologies.

The post-impact sandstones and shales are exposed in several steep cliffs in the field, and in the drill core (Figs. 3.1a and 3.2). They were described by detailed sedimentological logging. Another approach was used to describe the crater-fill breccias/conglomerates and the suevite in an efficient but as systematical as possible way that would allow us to compare observations from different outcrops. For the breccias/conglomerates the emphasis was on the clast content, and the main parameters chosen to describe them were rock type, size, and shape (roundness). The main parameters for describing the suevite were the relative proportions of matrix, melt and lithic fragments. Additionally we recorded original rock type and size of the lithic fragments, and shape and size of the melt fragments.

These lithologies were commonly exposed on bare rock surfaces polished by glaciers or rivers. The outcrops were largely (sub-)parallel to bedding planes, and not suitable for conventional sedimentological section logging. In field squares of 0.5 m x 0.5 m were studied on the rock surfaces (Fig. 3.1b). Within these squares all lithic or melt fragments equal to or larger than 1 cm were counted and registered by the chosen parameters. The very best vertical section through the crater-fill breccias/conglomerates and the suevite is represented by the drill core, and the corresponding parameters were used for description on vertical intervals of 0.5 m. In the field, the smallest and darkest grains (amphibolites and some clasts of meta-sediments) were, in spite of intensive cleaning operations to remove organic matter, often very difficult to observe. Efforts were taken to find good exposures, and minimize this and related observational difficulties. The numbers of counted clasts in the core and in the field are not directly comparable, as field sections were cut almost parallel to bedding, and the core represents a vertical section (e.g. almost normal to bedding). The cylindrical shape and limited surface area present in the core may have influenced the textural interpretation of larger clasts which appeared too well rounded. In some core porions the supporting mechanism (clast-supported vs. matrix-supported) of the conglomerates is poorly documented, due to lack of contact observations between larger clasts.

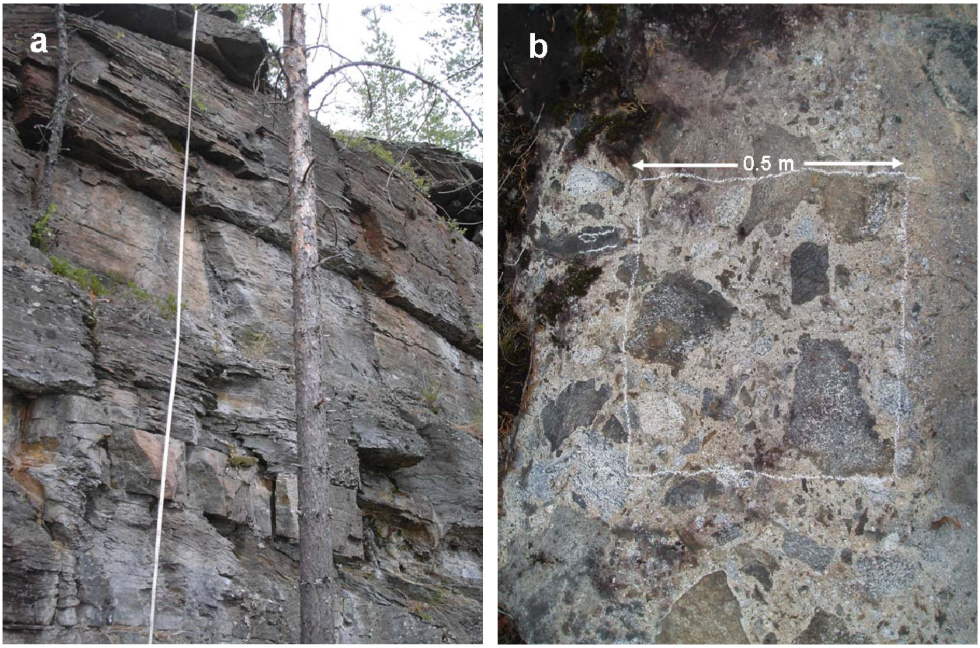

Fig. 3.1. a) Steep cliff at Branden hill, exposing the upper, fine-grained, part of the post-impact sedimentary succession. Cliff is ~5 m high. b) Picture of almost horizontal rock surface of suevite. White rectangle drawn with chalk is 0.5 m x 0.5 m and marks area of closer study.

Fig.3.2. Core box no. 32, containing approximately five meters of core, including the transition from suevite to crater infill sediments. The fine-grained interval is between the arrows.

3.2. Sample preparation

Polished thin sections for optical microscopy, scanning electron microscopy (SEM) and cathode luminescence were prepared at the Natural History Museum, University of Oslo.

Most of the thin sections are standard type without any impregnation or cover glass. However, a few more fragile/brittle samples had to be impregnated in epoxy before preparation.

Several analysing techniques, like XRF, XRD and the stable C-isotope MS, are based on bulk rock powder. Samples were cut to small chips at the diamond saw, and then crushed in a sling mill at the Natural History Museum, University of Oslo. The XRD analyses were performed directly on the bulk rock powder, whereas for the XRF further preparation took place at the Department of Geosciences, University of Oslo. For trace element analysis beads of bulk rock powder were pressed, and beads for major elements were made by melting a mix of rock powder and borax ($Li_2B_4O_7$ Spectroflux 100) in the proportions 1:9).

The samples for stable C-isotope MS were treated by HCl prior to analysis to remove any carbonate. This was done partly at the Department of Geosciences, University of Oslo and partly at the Open University, Milton Keynes.

Sample preparation for zircon and titanite studies was performed at the Department of Geosciences, University of Oslo. Rock samples were crushed in a jaw crusher and pulverized with a mill. The heavy mineral fractions were separated in several steps: At the Wilfley table running water acted as the sorting agent, then after drying, sieving at 250 μm was applied to the heaviest fraction, the material that passed the sieve was subjected to magnetic separation to remove most iron particles, and at last heavy liquid flotation further enhanced the separation process. The remaining heavy mineral fraction was studied under a binocular microscope, and grains for analysis were picked. Most selected zircon and titanite grains were abraded and analysed by the ID-TIMS method, but some zircons were picked and glued to thin section slides before polishing and analysing by SEM/CL.

3.3. Optical microscopy

Thin sections were examined with an optical microscope in transmitted light. Thin section observations have been important to describe and understand the impactites. Special attention has been paid to melt particles in the suevite, micro-fractures and brecciation patterns, and the occurrence of carbon. Selected thin sections were analyzed for modal composition (grain counts), and a few for U-stage microscope analysis for determining the crystallographical orientations of PDFs in quartz.

In the modal composition analysis a minimum of 400 grains on each thin section were counted and assigned to a mineral (quartz, K-feldspar, plagioclase, chlorite, etc.) or rock fragment. Thin section observations were used to describe mineralogical variations in the crater infill sediments, to look for trends and evaluate possible shifts in source rocks.

The use of U-stage to determine the orientations of PDF planes in impact-shocked quartz grains was first applied by Engelhardt and Bertsch (1969). A detailed description of the method is presented by Ferrière et al. (submitted). The U-stage analysis was executed on selected thin sections from the suevite and Gardnos Breccia. It required the installation of special U-stage objectives and the U-stage assemblage (Fig. 3.3a). The U-stage allows measurements of c-axis and of poles perpendicular to planes of all PDFs. These data were plotted on a stereographic Wulff net, and then indexed by a stereographic projection template displaying the possible pole orientations of common PDF planes within a 5° envelope of measurement error (Fig. 3.3b) (Engelhardt and Bertsch, 1969). Statistically the orientations of PDFs reflect the shock pressures the minerals have been subject to during impact.

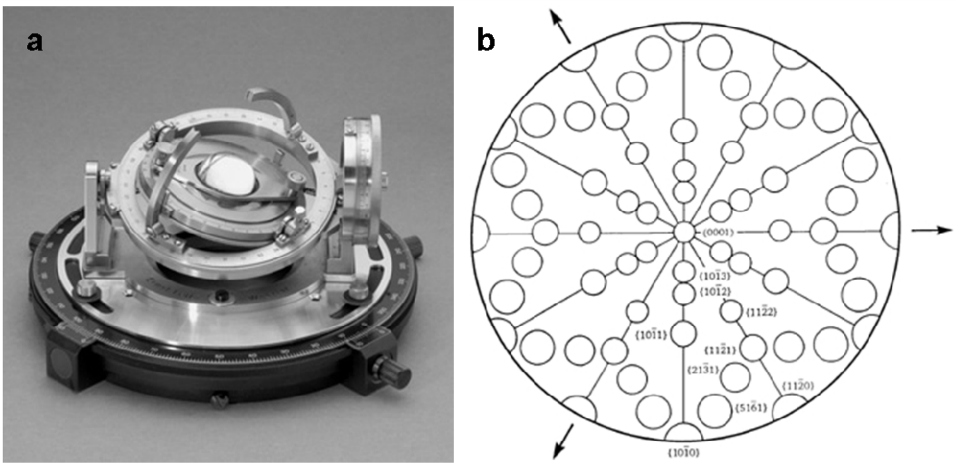

Fig. 3.3. a) An U-stage assemblage (photo from modernmicroscopy.com, 2007). b) Stereographic projection of quartz with the c-axis plotted in center (from Engelhardt and Bertsch, 1969).

3.4. Scanning electron microscopy (SEM)

Scanning electron microscopy (SEM) is mainly used for acquisition of high magnification images. For more details on the technique see for example Goldstein (2003). The SEM images the sample surface by scanning it with a high-energy beam of electrons in a raster pattern. The electrons interact with the atoms in the sample producing backscattered electrons, secondary electrons, X-rays, cathodoluminescence and other radiation.

Backscattered electron (BSE) mode is commonly used for imaging. BSE are beam electrons that are reflected from the sample by elastic scattering. Heavy elements (high atomic number) backscatter electrons more strongly than light elements (low atomic number), and thus appear brighter in the image. This method was particularly useful in our case for the detailed study of Gardnos suevite samples, to distinguish the various features and minerals not recognized in the optical microscope.

Secondary electrons (low energy electrons, < 50 eV) are ejected in an ionized state from atoms at the surface layer of the sample. Secondary electron imaging (SEI) or environmental secondary electron detector (ESED) images yield a three-dimensional appearance useful for understanding the surface structure of a sample. In the study of Gardnos samples this gave important information on, for example, micro-fracture patterns in some lithologies.

X-rays may also be detected and analyzed in an SEM equipped for energy-dispersive X-ray spectroscopy (EDS). The emitted wavelengths and energies are specific for each element and may be used to identify the abundance of elements in the sample. This was extensively used in the present study as a complement to the optical microscopy to identify or confirm the presence of minerals by their elemental composition. The low vacuum mode allowed for analysis without carbon coating of the thin sections, and the occurrence of carbon in the impactites could be confirmed and studied in detail.

Cathodoluminescence (CL) is the emission of light when atoms excited by high-energy electrons return to their ground state. In the SEM, CL detectors either collect all light emitted by the specimen, or can analyze the wavelengths emitted by the specimen and display an emission spectrum or an image of the distribution of CL emitted by the specimen in real color. In the present study this technique was applied to slides with zircons, and revealed their interior texture (zoning, fratures etc.).

3.5. X-ray fluorescence (XRF) spectrometry

The concentrations of major and some trace elements may be determined by X-ray fluorescence (XRF) spectrometry, a standard technique widely used for bulk chemical analysis (see for example Williams, 1987). When the sample is exposed to short-wavelength x-ray radiation with energy greater than its ionization potential, ejection of one or more electrons from the atom take place. X-rays can be energetic enough to expel strongly bonded electrons from the inner orbitals of the atom. Such removal of electrons makes the structure of the atom unstable, and electrons in higher orbitals "fall" into the lower orbital to fill the holes, releasing energy in the form of photons. These energies are equal to the energy differences of the two orbitals involved, and are characteristic for each element. The concentrations of the different elements may be quantified by comparing the emitted wavelengths and intensities to reference standards.

The elemental composition of bulk rock samples of Gardnos suevite has been used to describe variations within this lithology. Trace element data may record geochemical anomalies possibly indicating post-impact mobilization of certain elements.

3.6. X-ray diffraction

X-ray diffraction (XRD) analysis is used to identify minerals. Mineral crystals are regular arrays of atoms, and X-rays can be considered waves of electromagnetic radiation. When the X-rays strike the electrons in the crystal lattice, secondary spherical waves are produced. These waves cancel one another out in most directions through destructive interference, but they add constructively in a few specific directions, determined by Bragg's law:

$$2d \sin \theta = n \lambda,$$

where d is the spacing between diffracting planes, θ is the incident angle, n is any integer, and λ is the wavelength of the beam (in this case X-ray). These specific directions are called reflections and are characteristic for different minerals. To produce significant diffraction patterns, the spacing between the scatterers (electrons) and the wavelength of the impinging wave should be roughly similar in size. X-rays are very useful because they have wavelengths (λ) typically of the same order of magnitude (1-100 Ångströms) as the spacing (d) between planes in most mineral crystals.

In this study the XRD technique was used for identifying minerals of some bulk rock samples and as complement to the thin section modal analysis. Additionally one zircon grain was analysed by single crystal XRD to search for the existence of other mineral phases and to evaluate the interior structure of the grain (turned out to be equivalent to powder rather than a single crystal).

3.7. Mass spectrometry (MS)

Mass spectrometry (MS) is an analytical technique for the determination of the elemental (and isotopic) composition of a sample. Typically a sample is ionized by the impact of an electron beam, resulting in the formation of charged particles (ions). These ions then pass through a magnetic field and are dispersed into separate beams on the basis of the ion masses to charge ratios. These mass-resolved beams are then directed into collectors where the intensity of the ion beam is recorded. Comparison of intensities of signals from selected mass-to-charge ratios yields precise isotope ratios.

In the present study MS techniques were used both to determine the stable carbon isotopes (^{12}C and ^{13}C) and to measure U and Pb isotopes for dating zircon and titanite.

3.7.1. Isotope ratio mass spectrometry (IRMS)

The isotope ratio mass spectrometer (IRMS) allows the precise measurement of mixtures of stable isotopes. One application is to measure isotopic variations arising from mass-dependent isotopic fractionation in natural systems. In the present work at Gardnos the ^{12}C and ^{13}C isotopes were determined. Stable isotope measurements of light elements are usually made in an instrument with a gas source supplying continuous streams of the reference and sample gases, which are sequentially switched by a changeover valve (Fig. 3.4). The samples are combusted prior to measuring to produce the gases. The IRMS's collector may consist of an array of Faraday cups (conductive metal vessels which neutralise ions that hit them whilst themselves becoming charged). The detected isotopic ratios are compared to a measured standard for an accurate determination of the isotopic composition. The carbon isotope ratio standard for CO_2 is based on a fossil belemnite found in the Pee Dee Formation, a limestone formed in the Cretaceous period in South Carolina, U.S.A. with a ^{13}C / ^{12}C ratio of 0.0112372.

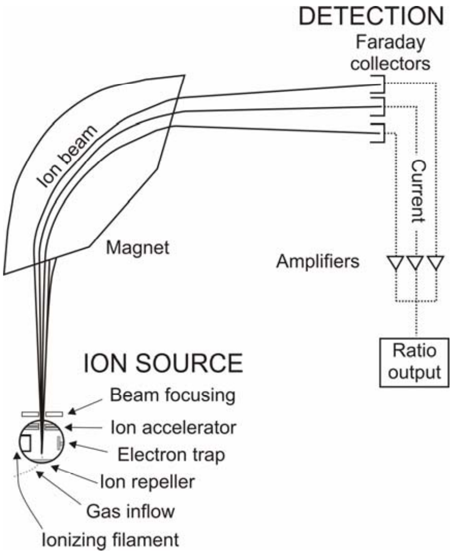

Fig. 3.4. Schematics of a simple mass spectrometer with sector type mass analyzer. (Image from http://en.wikipedia.org/wiki/Isotope_ratio_mass_spectrometry, accessed March 2009).

3.7.2. Isotope dilution – thermal ionization isotopes mass spectrometry (ID-TIMS)

In a thermal ionization mass spectrometer (TIMS) the elements are ionized thermally, usually by passing a current through a thin metal ribbon(s) under vacuum.

The isotope dilution technique increases the precision and accuracy of the analysis. The sample containing an element of natural isotopic composition is mixed with a “spike” solution, which contains a known concentration of the element, artificially enriched in one of its isotopes. By measuring (by mass spectrometry) each isotope in this known mix of sample and spike solutions, the concentration of the isotopes in the sample may be calculated.

The uranium-lead (U-Pb) method relies on two separate decay systems, from ^{238}U to ^{206}Pb with a half-life of 4.47 billion years, and ^{235}U to ^{207}Pb with a half-life of 704 million years. The term “U-Pb dating” normally implies the coupled use of both decay systems in a concordia diagram (Fig. 3.5) and ideally provides the age of formation of the mineral or may record possible events of isotopic resetting (in the Gardnos case impact and / or metamorphism). The systems are not always completely closed through time, for example samples may suffer Pb-loss and data plot below the concordia curve on the diagram. Sometimes such discordant data may still hold important age information, but may require multiple analyses and involve more interpretation. U-Pb dating is usually performed on the mineral zircon ($ZrSiO_4$), because when zircon forms, U and Pb are strongly fractionate due to differences in charge and ionic radius (Mezger and Krogstad, 1997). The method may also work for some other minerals such as monazite and titanite, and was applied to zircon and titanite from the Gardnos impactites.

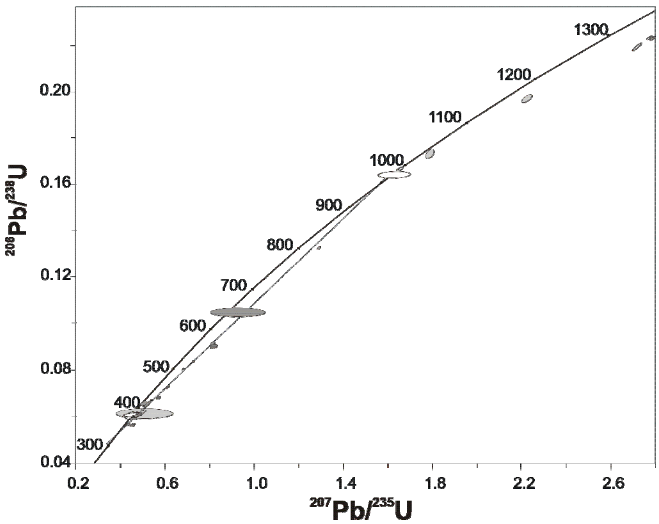

Fig. 3.5. Example of concordia diagram with data from the Gardnos impactites. The data are plotted as ellipses, illustrating the analytical error (2σ). Most of the analyzed grains have suffered Pb-loss during impact or metamorphic events and plot below the concordia curve in the diagram. Exceptions are some titanites formed at ~995 Ma and one at ~380 Ma, plotting concordant on the curve.

4. THE PAPERS

4.1. What is so special about the Gardnos structure?

Each impact structure is a unique geological structure, a result of;
a) the impacting bolide (impactor type, size, speed, incoming angle),
b) the target rocks (crystalline, sedimentary),
c) the geological setting (covered by water and / or soft unconsolidated sediments?) and
d) the post impact history (infilling, post-impact cooling rate, burial, diagenesis, metamorphism, erosion).
The different impact structures offer different opportunities for analysing. Whereas sampling in some structures relies solely on drill cores, the Gardnos structure has the advantage of being easily accessible and due to erosion, exposing a range of impact-related rocks; from deep below crater floor, through lithic breccias, suevite and post-impact crater infill. This makes Gardnos an excellent object for extensive sampling and detailed analysis, offering an opportunity to document the heterogeneities and possible trends within the impact lithologies (missed / over-looked where only drill core information is available).

In the Gardnos structure the presence of carbon in the impactites is a curiosity. Significantly elevated amounts of carbon in the impactites compared to the corresponding target rocks is also known from the Sudbury impact structure (1850 Ma, 250 km diameter) in Canada (French, 1968; Bunch et al., 1999; Heymann et al., 1999). The carbon in Gardnos was identified to be of terrestrial origin (French et al, 1997).

A main challenge at Gardnos has been the poorly defined age of the impact event. Post-impact erosion has removed any ejecta outside the crater, making stratigraphic correlations difficult, the fossil record is very scarce, and post-impact regional metamorphism is complicating radiometric dating. A better characterization of the impact age would in addition increase the scientific value of the information of the post-impact sedimentary succession. Being deposited within the crater-depression, carved out in the hard crystalline basement, these sediments have been sheltered from erosion and may represent a stratigraphic interval poorly (or not at all) preserved known in place anywhere else in Norway.

4.2. Theme of the thesis

Since the start of this thesis the title has been ”The Gardnos structure; the impactites, sedimentary deposits and post-impact history”. The questions needing to be resolved were several, and partly inter-related: like the geological setting, target environment, the presence of organic carbon and the age of impact. A clearly multidisciplinary approach was chosen and the papers thus represent studies in several different areas including: sedimentology, U-Pb dating, mineralogy and geochemistry of impactites, and organic geochemistry. Each paper thus presents new data on different areas, but also complements the others in increasing our general understanding of the Gardnos structure and the impact-related lithologies.

The sedimentary deposits comprise the post-impact succession and are thoroughly presented in Paper I. These sedimentary deposits record the very first part of the post-impact history and are a key to its interpretation. Paper I also includes an updated geological map of the Gardnos structure and a tentative reconstruction of the original crater.

The age of impact event is of great importance for the general understanding of the structure. Paper II presents the results of a study on zircon and titanite from the impactites. Based on interpretation of U-Pb data from ID-TIMS, an age of the impact event is proposed, and the post-impact thermal history discussed.

Paper III concerns the carbon content of the impactites and post-impact succession. The carbon distribution and mode of appearance is described, and the discussion focuses on the geological setting at the time of impact, the post-impact history and possible mobilization of carbon.

Paper IV presents new analysis of the Gardnos suevite. The suevite is the most heterogeneous of the impact lithologies, and through extensive sampling stratigraphical and lateral variations in its composition are revealed. It contains highly impact-shocked material and in particular the distribution of PDFs in quartz and the occurrence and textures of melt fragments has been studied.

Paper I

Kalleson, E., Dypvik, D., and Naterstad, J. (2008) Post-impact sediments in the Gardnos impact structure, Norway, *in* Evans, K., Horton Jr., J.W., King Jr. D.T., and Morrow, J.R. (eds.) The Sedimentary Record of Meterorite Impacts, Geological Society of America Special Paper 437, 19-41.

This paper presents the first results from detailed field work in the Gardnos structure, with a special focus on the post-impact crater fill succession. It presents an updated geological map, and describes the sediments based on field and core observations. The crater structure was excavated in mainly crystalline basement rocks, and after formation filled with sediments. The crater depression both acted as a sediment trap and protected the relatively softer sedimentary deposits against deformation and erosion during later geological events. Probably very few autochthonous sedimentary sequences from this time period exist elsewhere in Norway today, and the crater infill rocks at Gardnos may represent a unique record.

Presently these post-impact sedimentary rocks are preserved mostly in the northern part of the crater structure. The succession has a maximum thickness of about 150 m, and the drill core penetrating this interval constitutes the stratigraphic reference section of the crater. The sediments range from coarse conglomerates and breccias, through sandstones of various grain-sizes, topped by relatively fine-grained deposits of interbedded sandstones and shales. The section has an erosive top.

The deposits reflect different depositional processes acting in the fresh crater. This detailed study aims to improve the understanding of the geological setting at the time of impact, addressing factors influencing the depositional environment and the active processes like crater size, water depth and target rock composition. The original crater was about six kilometres in diameter, with a short-lived crater rim standing up above the shallow sea that likely covered the target area at the time of impact. Sediments were deposited in the crater depression in a complex pattern indicating several depositional events possibly initiated by collapse of the rim and central peak. Most of the sedimentary succession has a mineralogical composition similar to the excavated target rocks and is probably dominated by impact debris. In the uppermost part of the preserved sedimentary column a marked shift in mineralogical composition may represent influx from other sedimentary sources outside the crater.

Paper II

Kalleson, E., Corfu, F. and Dypvik, H. (2009) U-Pb systematics of zircon and titanite from the Gardnos impact structure, Norway: evidence for impact at 546 Ma? Geochimica et Geochimica Acta 73, 3077-3092.

In addition to contributing to the understanding of the regional geology of an area, precise ages of impact structures are important to better estimate the terrestrial cratering rate and to test the hypothesis of periodicity in impact events. Especially for large impact structures it is important with precise dating to link the impact craters with ejecta layers and proposed extinction events. The Gardnos impact event is poorly dated. A lower constraint is set by the youngest age of crushed basement rocks of ~900 Ma which must pre-date the impact. The upper constraint is given by the Caledonian metamorphic event (~400 Ma) which has affected the impactites and thus post-dates it. In the Gardnos case a better age estimate could help with the understanding of the geological setting during impact, and to test the conclusions of paper I (Kalleson et al., 2008). Different methods may be used for dating; Rb-Sr and Sm-Nd isochrones, U-Pb analyses, K-Ar (^{39}Ar-^{40}Ar) on melt rocks, fission track on glassy material, paleomagnetic measurements and stratigraphic relations (fossil record) (Deutsch and Schärer, 1994). Gardnos is a relatively small impact (no coherent melt sheet), it lacks a good fossil record (though some promising structures, still undetermined, have been found in the post-impact succession), and some time after formation the structure underwent Caledonian metamorphism when it was buried beneath several km-thick nappe units. Previous ^{39}Ar-^{40}Ar-dating failed due to this Caledonian overprint (Grier et al., 1999). The U-Pb-systematics of zircon may be more resistant to the metamorphic event, on the other hand it may also have been more difficult to affect by the impact event, and may show nothing at all.

The U-Pb data from the Gardnos impactites was challenging to interpret. The analysed grains originated from a variety of target rocks of different ages, being shocked to different levels and mixed together during impact and crater formation. Probably relying on their state of preservation, they also responded differently to the later Caledonian metamorphism. Despite these complicating factors, there seem to be some zircon grains with impact-related deformation features, and a small group of zircons with high discordance and relatively low U-content line up on a discordia line indicating an event at 546 Ma, suggested to be the age of impact.

Paper III

Kalleson, E., Dypvik, H. and Gilmour, I. (in preparation) Distribution of carbon in different impact-related lithologies from the Gardnos structure.

Coal-like carbon impregnation of breccias within the Gardnos structure was first reported by Broch (1945) and later described by French et al. (1997) and Gilmour et al. (2003). This makes Gardnos one of only two (Sudbury in Canada is the other (French, 1968; Bunch et al., 1999; Heymann et al., 1999)) globally known impact structures with elevated carbon content in the impactites. Depletion of the heavy stable carbon isotope ^{13}C relative to ^{12}C is consistent with biogenically derived carbon, and excludes a carbonaceous meteorite as likely impactor (French et al., 1997; Gilmour et al., 2003). The carbon source may have been carbonaceous shale overlying the basement rocks at time of impact, being mixed into the breccias during the violent impact process. Both the Proterozoic Biri Shale and the Cambrian Alum Shale have earlier been suggested as possible source rocks for the carbon, but neither fit well with models of geochemical mixing calculations (Gilmour et al., 2003). In this Ph.D. study a much broader set of samples from field and drill core were available, and potential stratigraphical and geographical variations in organic carbon content and stable C-isotopes could be studied. Our findings support that the majority of carbon likely was derived from carbon-rich sediments overlying the crystalline basement at the time of impact and introduced to the impactites during the impact event. Stratigraphic differences in the occurrence of carbon and weak trends towards heavy ^{13}C-isotope depletion upwards in the impactite succession and outwards from the crater centre are in accordance with preferential mobilization of the lighter isotopes during circulation related to the post-impact cooling stage. Later mobilization by Caledonian metamorphism was probably limited to local effects.

Paper IV

Kalleson, E., Dypvik, H. and Nilsen, O. (in preparation) Melt-bearing impact breccias within the Gardnos structure.

This paper addresses the melt-bearing, allochthonous impact breccias (dominated by suevite) which are preserved within the central part of the Gardnos structure. This work is based on extensive sampling over wide areas in the field and through the entire suevite interval in the drill core. The interval of allochthonous breccias within Gardnos is surprisingly thin (only ~50 m), dominated by suevite. To get a better understanding of the original suevite volumes and of what remains within the crater today, a simple 3D model of the original crater was constructed. The calculated volumes confirmed the previous conception of relatively small amounts of allochthonous breccias within the crater.

This paper extends previous studies of the suevite in general by attempting to describe potential stratigraphic and lateral variations within this lithology. The formation and deposition of suevite is not well understood, and our intention was to use a sedimentological approach to interpret these deposits. The Gardnos area is particularly suited to study the mixing of material during impact, because the pre-impact target lithology shifts from west to east in the crater. Consequently we described the breccias according to matrix content, melt and lithic fragments as well as bulk geochemistry and demonstrated a thorough mixing of target rock material.

The chemical variations within the suevite unit probably reflect various portions of mafic rocks incorporated into a dominant mix of granitic, gneissic and quartzitic target rocks. The lithic clast content in the suevite varies apparently almost random stratigraphically and geographically, indicating thorough mixing of material from large part of the crater. Melt fragments often appear stretched as expected if deposited by flow. Some apparently rotated and deformed melt fragments occur more frequently at certain stratigraphic levels in the Branden core, possibly marking the boundaries between successive pulses of suevite flows.

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