Meteorite impact structures – geotourism in the central Baltic

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METEORITE IMPACT STRUCTURES –
GEOTOURISM IN THE CENTRAL BALTIC

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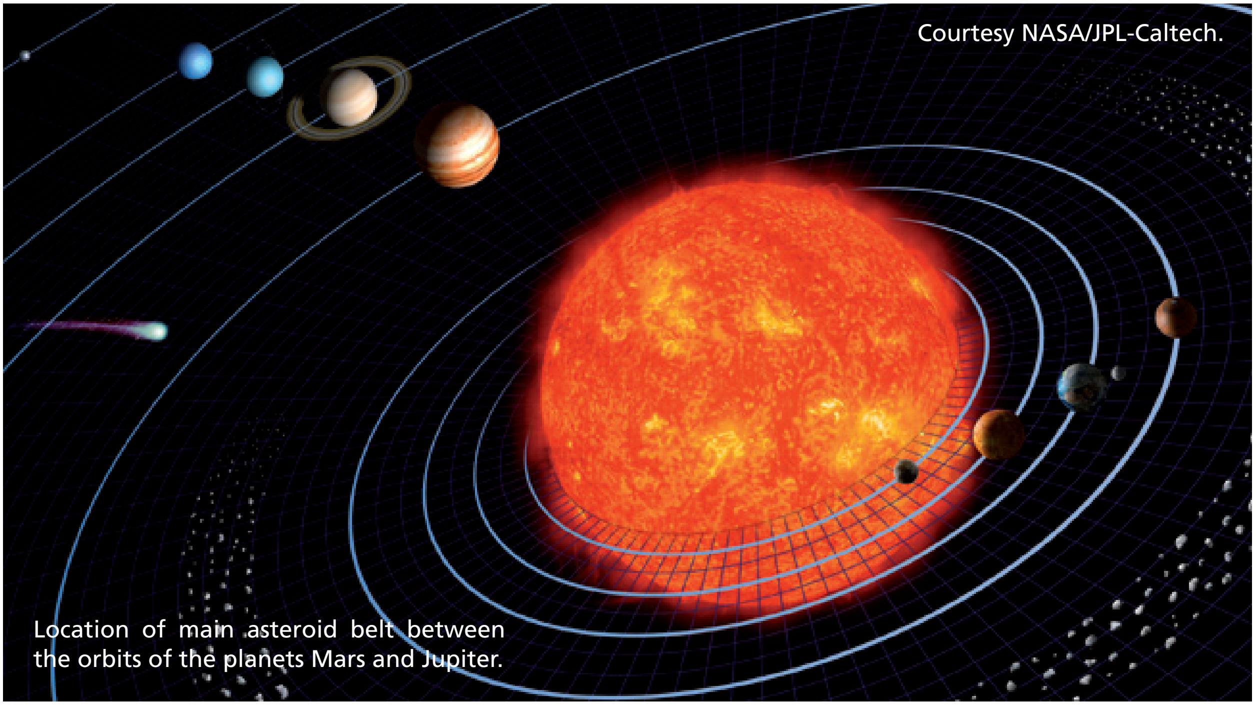
Imagine for a moment that you are standing on the Estonian seacoast, looking northeast in the evening twilight. You are completely alone – the nearest person is far, far away. Suddenly, your attention is caught by a bright light above the dark horizon. At first just a spark, it quickly brightens and splits into several individual streaks. Within seconds it has become a searing flash. The bright objects pass silently over your head, followed a moment later by a deafening crack. The ground heaves, and a blast wave flings you backwards. Sheets of fire erupt into the evening sky. Pieces of rock crash into the surrounding soil, others are engulfed by fire. A fiery mushroom cloud drifts over the landscape covering everything in dust; the solid rocks you were standing on have disintegrated. This is what you might have seen if you where standing on the island of Saaremaa a few thousand years ago when the Kaali meteorite struck.

This is the second book in a six-volume series called *Fostering Geotourism on Central Baltic Islands*. In this contribution you will learn about the meteorites that have impacted the central Baltic area – such as the Kaali meteorite; what meteorite craters look like and how they differ from each other. You will understand how meteorites may have influenced life on Earth – on a local and global scale. You will learn how scientists use fragments of evidence to piece together the history of meteorite impacts and how they can identify meteorite craters that are several hundred million years old. Finally you will read about some of the meteorite impacts that have occurred in the central Baltic area since the beginning of Earth history millions of years ago.

Before we go into the details about the central Baltic craters we need to start at the beginning and answer basic questions such as; what is a meteorite and what is a crater?

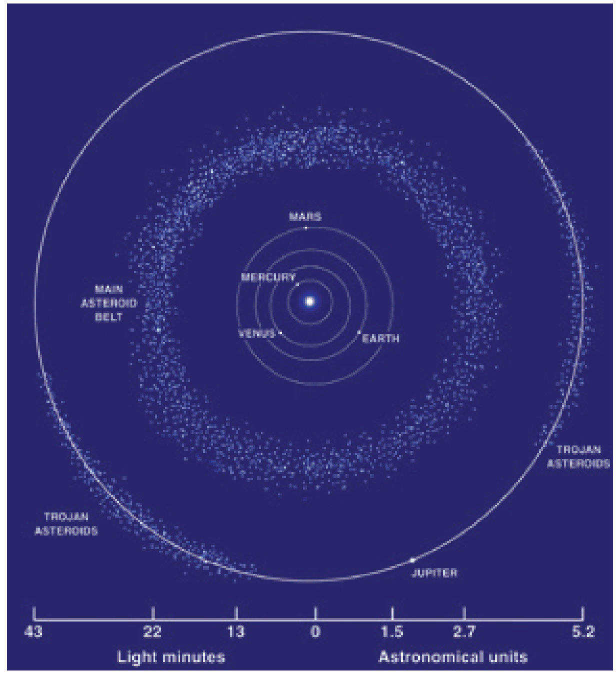

Courtesy NASA/JPL-Caltech.

Location of main asteroid belt between the orbits of the planets Mars and Jupiter.

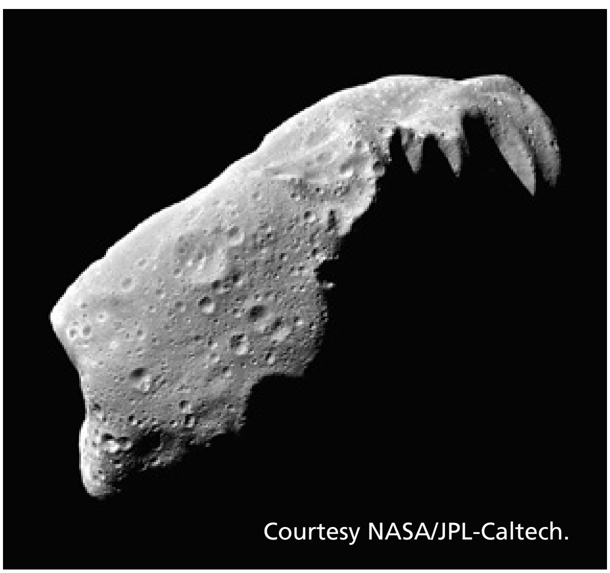
2. What are asteroids, meteoroids and comets?

We tend to think of the Solar System as just the planets in orbit around the Sun; but it actually contains many other objects as well. These objects have different names depending on for example the size and appearance of the object.

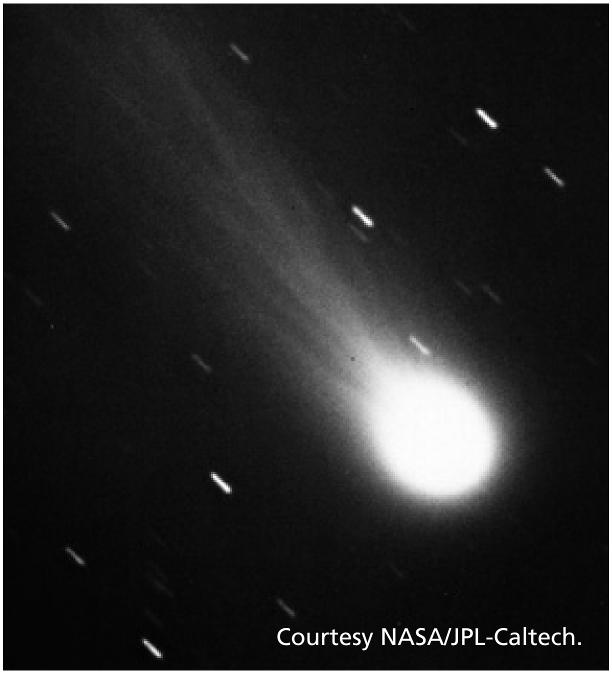
Asteroids are rocky bodies that are largely confined to the asteroid belt between Mars and Jupiter in the inner Solar System. They are the ″building blocks″ that never collected to form into a full-sized terrestrial planet, such as Earth, when the Solar System was formed about 4600 million years (hereafter Ma) ago. They behave like tiny planets and travel around the Sun in close to circular elliptical orbits in the plane of the ecliptic, much like our own planet. This means that an asteroid is always located roughly the same distance from the Sun. A *meteoroid* is a piece of rock travelling in space, much like an asteroid. Although there is no official distinction between the two, the term asteroid typically refers to objects that are larger than a few hundred metres across. Consequently a meteoroid is essentially a small asteroid. A *comet* is basically a dusty chunk of ice (they are sometimes referred to as "dirty snowballs"). In contrast to the asteroids, a comet travels around the Sun along highly elliptical orbits inclined at random angles to the ecliptic, which means that they are sometimes closer to the Sun and sometimes further away. As long as the comet is in the outer Solar System it remains frozen and dark, and therefore very difficult to detect. However, at times when a comet is closer to the Sun,



Asteroids are material left over from the formation of the Solar System. The main asteroid belt lies in the region between Mars and Jupiter. The Trojan asteroids lie in Jupiter's orbit, in two distinct regions in front of and behind the planet. Courtesy of Lunar and Planetary Institute.



This view of the asteroid 243 Ida was taken by Galileo spacecraft on August 28, 1993. Ida is the second asteroid ever encountered by a spacecraft. It appears to be about 52 kilometres in length, more than twice as large as Gaspra, the first asteroid observed by Galileo in October 1991. Ida is an irregularly shaped asteroid placed by scientists in the S class (believed to be like stony or stony iron meteorites). This view shows numerous craters, including many degraded craters larger than any seen on Gaspra.



This photograph of Halley's Comet was taken January 13, 1986, by James W. Young, resident astronomer of JPL's Table Mountain Observatory in the San Bernardino Mountains, using the 24-inch reflective telescope. In the photo you can see the coma of gases and about 725 000 kilometres of the charged ion tail.

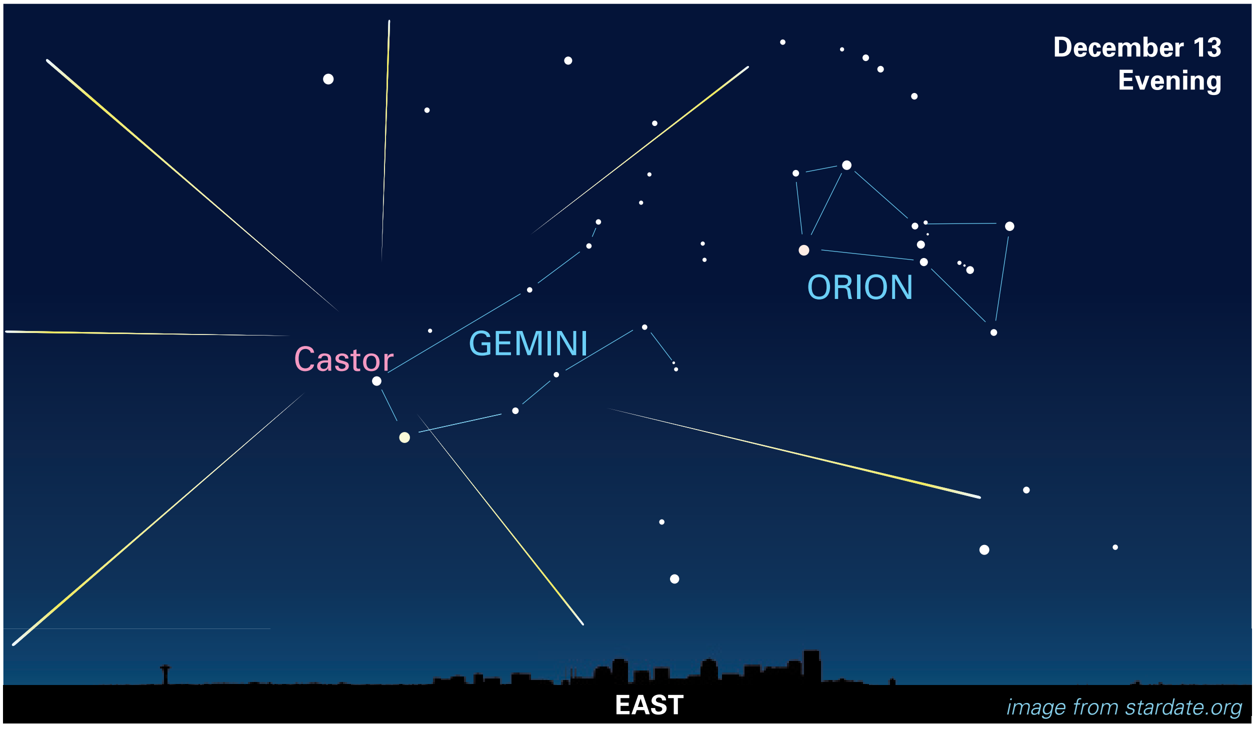
the solar radiation causes the comet to heat up and vaporise. The gases that are liberated begin to glow, producing a fuzzy, luminous ball called a coma. The solar winds blow these glowing gases outward, away from the Sun, into a tail that can be as long as 150 million km. This phenomenon produces one of the most amazing sights that can be seen in the night sky. The distances in space are almost impossible to grasp but, to give you an idea 150 million km is the distance between the Earth and the Sun (a distance that is also called one Astronomical Unit, AU), and it takes approximately 8 minutes for light to travel the distance.

Comets have very different orbital periods, ranging from a few years, to hundreds of thousands of years. A comet is always named after the person who discovered it and the most famous comet is perhaps Halley´s Comet. The English astronomer Edmond Halley published in 1705 his ideas about comets that had been sighted in the years 1456, 1531, 1607 and 1682. He suggested that it was the same comet that returned on a regular basis and he calculated its orbital period to be 75-76 years, predicting that the comet would return in 1758. Unfortunately, Halley did not live until then, as he died in 1742, but the comet appeared just as he said. When it did, the comet became generally known as Halley's Comet. Halley's Comet last entered the inner Solar System in 1986, and we can expect to see it again sometime in the year 2061. Scientists know where it is presently located as well, but it is too faint to be seen even when using the best telescopes and probably it will not be seen even by astronomers until after 2050.

3. What are meteors and meteorites?

Our Earth is on constant collision course with the objects that are travelling through space and small objects collide with our planet on a regular basis. In fact, the mass of the Earth is increasing day by day because of this extraterrestrial input. It is estimated that the total mass of objects that strike the Earth is about 10^7-10^9 kg every year – the weight of six million cars. Most of this extra mass is in the form of dust-sized particles that slowly settle to the surface.

When a meteoroid enters the Earth´s atmosphere, it becomes known as a *meteor*. As it plunges through the atmosphere it slows down, and frictional heat is generated, resulting in a visible streak of light. This is a very common phenomenon and is sometimes called a falling, or shooting star. Under excellent conditions, you might see about eight meteors per hour. How-

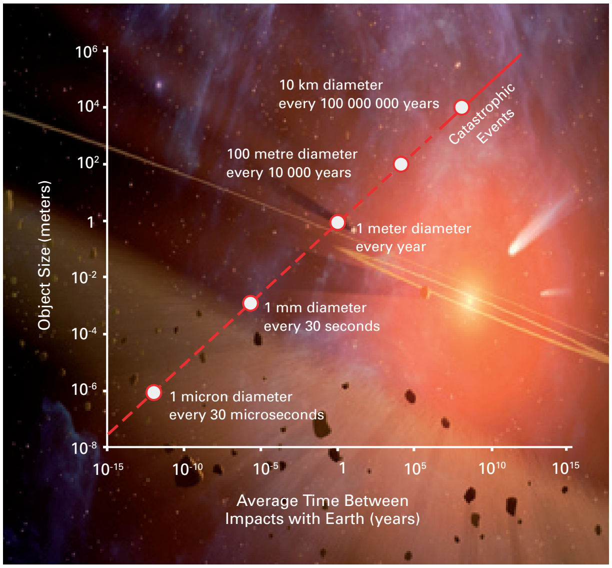


ever, at certain times falling stars are more common than usual and if you are lucky you may see a great number of meteors in a short period of time. Such an occasion is called a meteor shower and occurs when the Earth passes through the trail of dust and debris left behind by comets on their orbits around the Sun. At least ten notable meteor showers occur every year and they are given names based on the constellations from which the meteors appear to originate. In order to see a fine meteor display you need a clear night sky, preferably without a moon because the brightness of the moon may significantly obscure the faint meteors. To give you an example, under perfect conditions in the early morning hours (roughly from 2 at night to dawn) on December 13 every year you may see up to 100 meteors each hour as the Earth passes through the Geminids meteor shower. Do not forget to make a wish when you see a falling star.

Geminid meteors appear to fall from near the star Castor, one of the "heads" of the constellation Gemini, the twins. The meteors are not actually related to Castor; they are debris from an asteroid called Phaethon. The shower recurs each year when Earth passes through this debris strung along Phaethon's orbit around the Sun. The Geminid shower was the first to be linked to an asteroid. Most meteor showers occur when Earth crosses the orbit of a comet. Though the Geminid shower was discovered in the 1860s, it was only in 1983 that astronomers identified Phaeton as the source of the shower.

This book is about meteorite impact craters, but we still haven't defined what a meteorite is. There is, however, a simple answer to that. If any of the pieces of rock discussed above survives its descent through the atmosphere and reaches the ground, it is called a *meteorite*. Most meteorites that fall onto Earth's surface are believed to have originated from the asteroid belt from which, as the result of either the Sun's gravitational attraction or through collision with other objects, they have been knocked or pulled out of their orbit. A handful of meteorites discovered on Earth appear to come from the Moon and Mars. These meteorites must have broken off when other objects collided with the Moon or Mars with enough force to launch debris away from the planet and into orbit around the Sun. Eventually these rocks, originally from another planet would collide with Earth and end up in a desert for example – or someone´s back yard. The age and composition of the primary matter of the Solar System's planets, their satellites, asteroids and meteoroids are similar, making it easy to distinguish between a rock that has fallen to Earth from space and a rock that has been formed on Earth.

The frequency at which meteorites strike the Earth depends on the size of the objects: the bigger they are, the rarer the impact. Tiny objects, with diameters of about 1 mm, strike the Earth about once every 30 seconds. Larger objects, that are greater than 1 km in diameter, are fortunately much less frequent, but still strike the Earth once in a million years – and 10 km sized objects impact once every 100 million years – on average. When large meteorites impact the Earth they can cause enormous environmental catastrophes, big enough to alter the course of evolution.



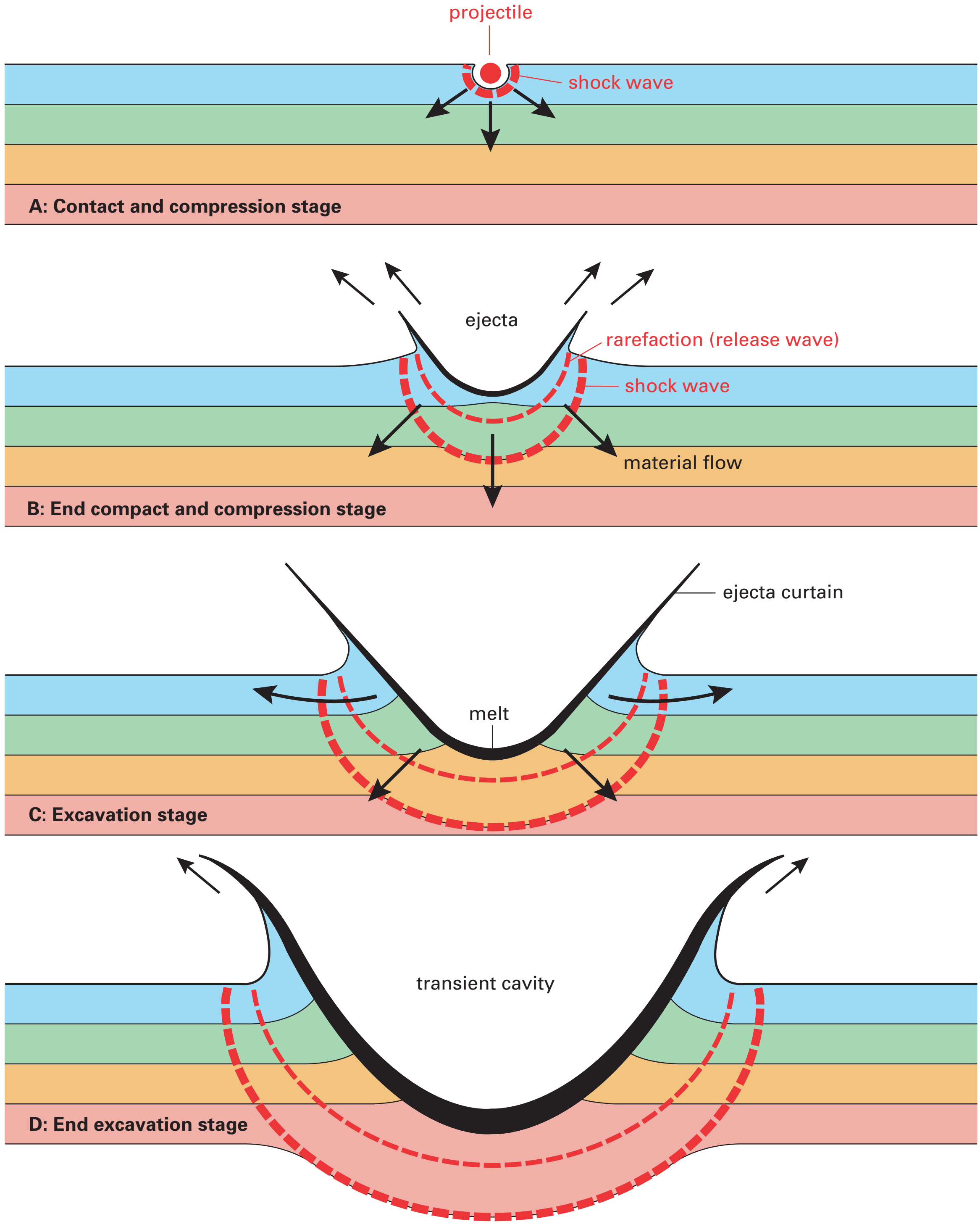
Graph showing the frequency at which meteorites of a certain size impact with Earth. Background image courtesy of NASA/JPL-Caltech.

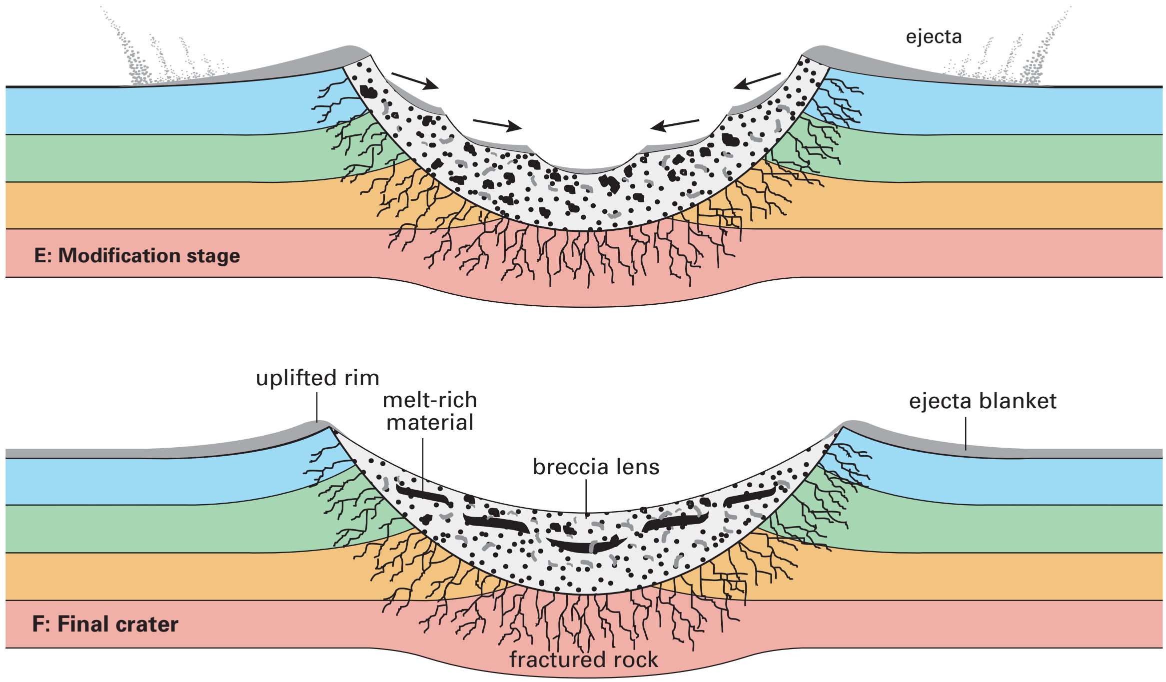
4. The biological and geological consequences of a meteorite impact

Fortunately, our civilization has not experienced any devastating impacts; in fact it is several million years since the last meteorite impact of any evolutionary significance. However, things could have turned out very differently for life on Earth if a large meteorite had impacted more recently: the result would have been devastating. A large meteorite impact would wipe out most of the human population and it is possible that other animals would replace us. Consequently it is of interest to discuss how meteorites may play a significant role in shaping not only the geology but also the biology of our Earth.

Impacts involving potentially devastating meteorites occur on a time scale of about every 50 million years. That much time has passed since the last giant meteorite punched a huge hole in the ocean floor close to Nova Scotia, Canada. Travelling at a speed of 20 000 km per hour, the object, 2 km in diameter, slammed into the Atlantic and created a crater 40 km across. With this in mind, and if you believe the statistics, the Earth may experience another major impact in the not so distant future. But how is Earth affected by a meteorite impact?

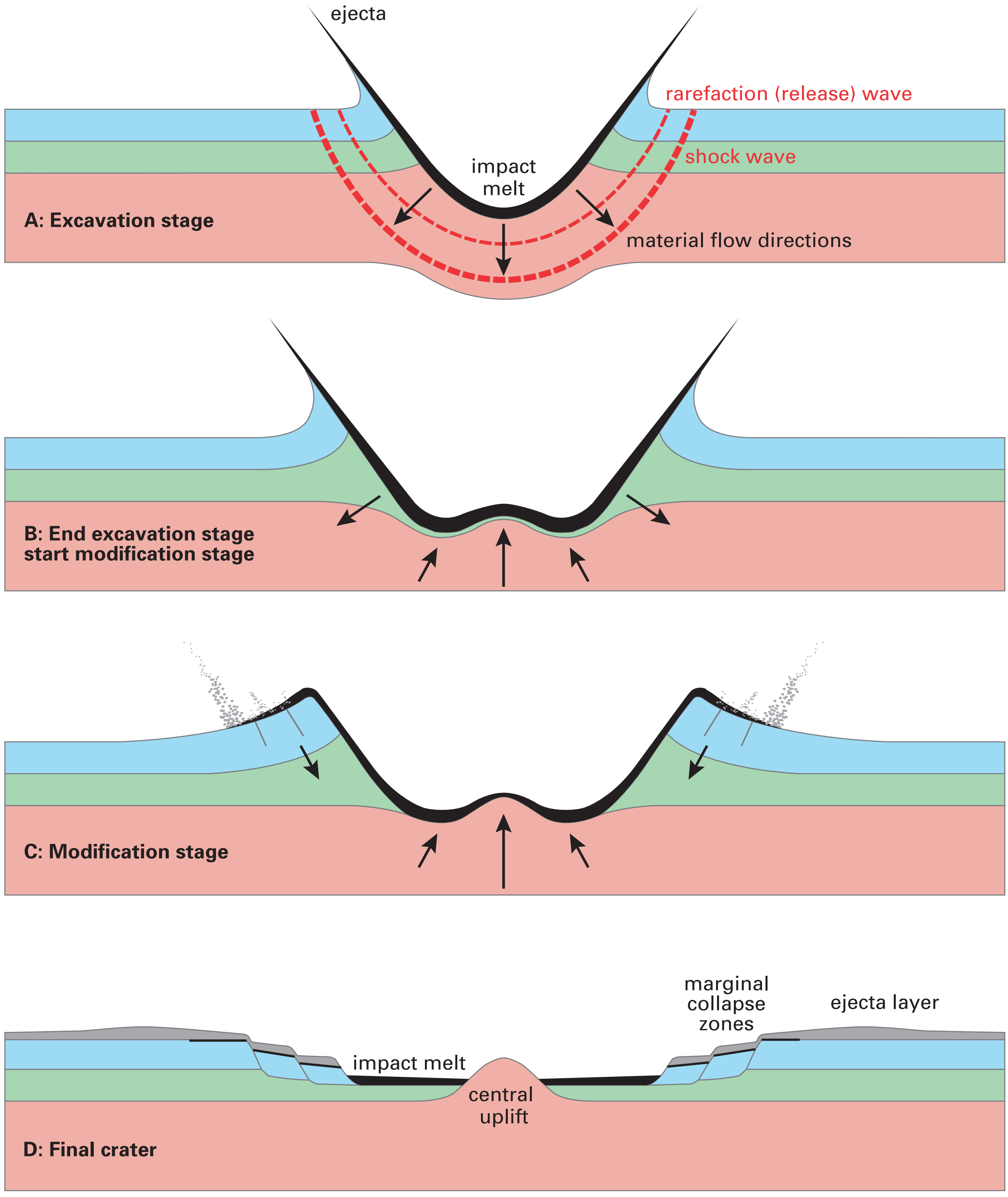
When a large meteorite crashes to the ground at high speed, it results in a massive explosion. The impact releases huge amounts of energy and extreme physical conditions of pressure, temperature, and strain are reached in the blink of an eye, creating features


projectile
shock wave
A: Contact and compression stage
ejecta
rarefaction (release wave)
shock wave
material flow
B: End compact and compression stage
ejecta curtain
melt
C: Excavation stage
transient cavity
D: End excavation stage



Formation and development of a simple impact structure:
Simple craters are the smallest type of craters and occur as bowl-shaped depressions less than a few (2-4) kilometres across. As a smaller meteorite hits the Earth a simple crater is formed in a series of steps; (A) initial penetration of the meteorite creates a shockwave that is directed outward during the contact and compression stage; (B) the shock waves continues to expand and excavate the target rocks and a secondary wave (rarefaction or release wave) directs near-surface material upward and outward; (C) both the shock wave and the rarefaction wave continue to expand, melted rocks line the expanding cavity and well developed ejecta (ejecta layer, or curtain) is transported outward from the opening crater; (D) the transient cavity is completely lined with melted rocks and reaches its maximum extent and an uplifted crater rim forms; (E) right after the crater has formed it starts to become modified, the walls of the crater collapse and fall back into the crater and mixes with the ejecta curtain to form a deposit of mixed breccia; (F) the final stage of the crater is a simple bowl shaped depression partially filled with breccias and impact melt. The first steps (A)-(D) takes a few seconds whereas the final structure (E)-(F) takes minutes to hours to form (redrawn from Fig 3.3 in French, 1998).

in the rocks that show unique deformation patterns that are only produced during a meteorite impact. Because the meteorite suffers extreme shock during the moment of impact (the first stage of the formation of a crater is called the contact and compression stage) it almost completely melts and vaporises. This means that an impact crater usually does not host any leftover pieces of the body that produced the crater. The impact creates strong shock waves that pierce through the rocks creating a crater that looks like a deep bowl-shaped depression on the surface. The size of this, so-called *transient* crater depends very much on the amount of energy released during the impact and to a lesser extent on the properties of the target rocks. After the initial shock has passed, the transient crater immediately begins to be modified by more conventional factors like gravity, water and wind.


ejecta
rarefaction (release) wave
shock wave
impact
melt
A: Excavation stage
material flow directions
B: End excavation stage
start modification stage
C: Modification stage
marginal
collapse
zones
ejecta layer
impact melt
central
uplift
D: Final crater

Based on what the impact crater looks like, scientists have described three different types of crater: *simple* and *complex craters*, and *multiring basins*. Simple craters are the smallest types and occur as bowl-shaped depressions less than a few (2-4) kilometres across. Complex craters are more than 2-4 kilometres in diameter and characterized by a central area that is elevated and often occur as a central topographic peak and/or ring in the middle of the crater. This uplifted area is in turn surrounded by a circular depression which is filled with rubble from the impact (a type of rock called breccia that consists of angular rock fragments) and rocks formed from melt; and a complex rim area cut through with geological faults. Complex craters have shallower depth-diameter ratios than simple craters. At even larger crater diameters of over several tens of km, the resulting structures, and especially the centrally uplifted area, become even more complicated. As the crater size increases, the character of the central uplift changes, and the single central peak is progressively replaced by a more complex series of concentric rings and basins (multiring basins).

The final crater structure, whether simple or complex, consists of deformed and fractured rocks covered by ejected material outside the crater and with crater-fill deposits such as impact breccias and impact melts within it. These near-surface lithologies are immediately subject to geological processes: erosion, burial or tectonic deformation. If the crater forms on land, erosion will quickly remove the ejecta and destroy the rim. If the crater forms in a site covered by water, it will immediately begin to fill with sediments, potentially protecting the crater from subsequent erosion.

The far side of the Moon is rough and full of craters. This large impact basin is Crater 308 which spans about 30 kilometers. It was photographed by the crew of Apollo 11 as they circled the Moon in 1969. Courtesy of NASA / Apollo 11 crew.

When compared to other terrestrial planets and the Moon, Earth seems to have a low number of impact craters. The reason for this is the activity of geological processes on Earth such as erosion and sediment transport. Topographic highs are thus eroded, and topographic lows filled with sediments. In other words these processes relatively quickly even out the surface of the Earth, in the process destroying or hiding impact craters. This is reflected in a bias in the ages of

Formation and development of a complex impact structure:
As a larger meteorite hits the Earth a complex crater is formed in a series of steps; (A) formation of a large hollow as part of the excavation process; (B) a central uplift begins to form during the subsequent modification stage; (C) the walls of the crater start to collapse, the central uplift continues to develop and the melted rocks drape over the uplifted rocks; (D) the final structure consists of a central uplift surrounded by a relatively flat plain and by a terraced rim (redrawn from Fig 3.10 in French, 1998).

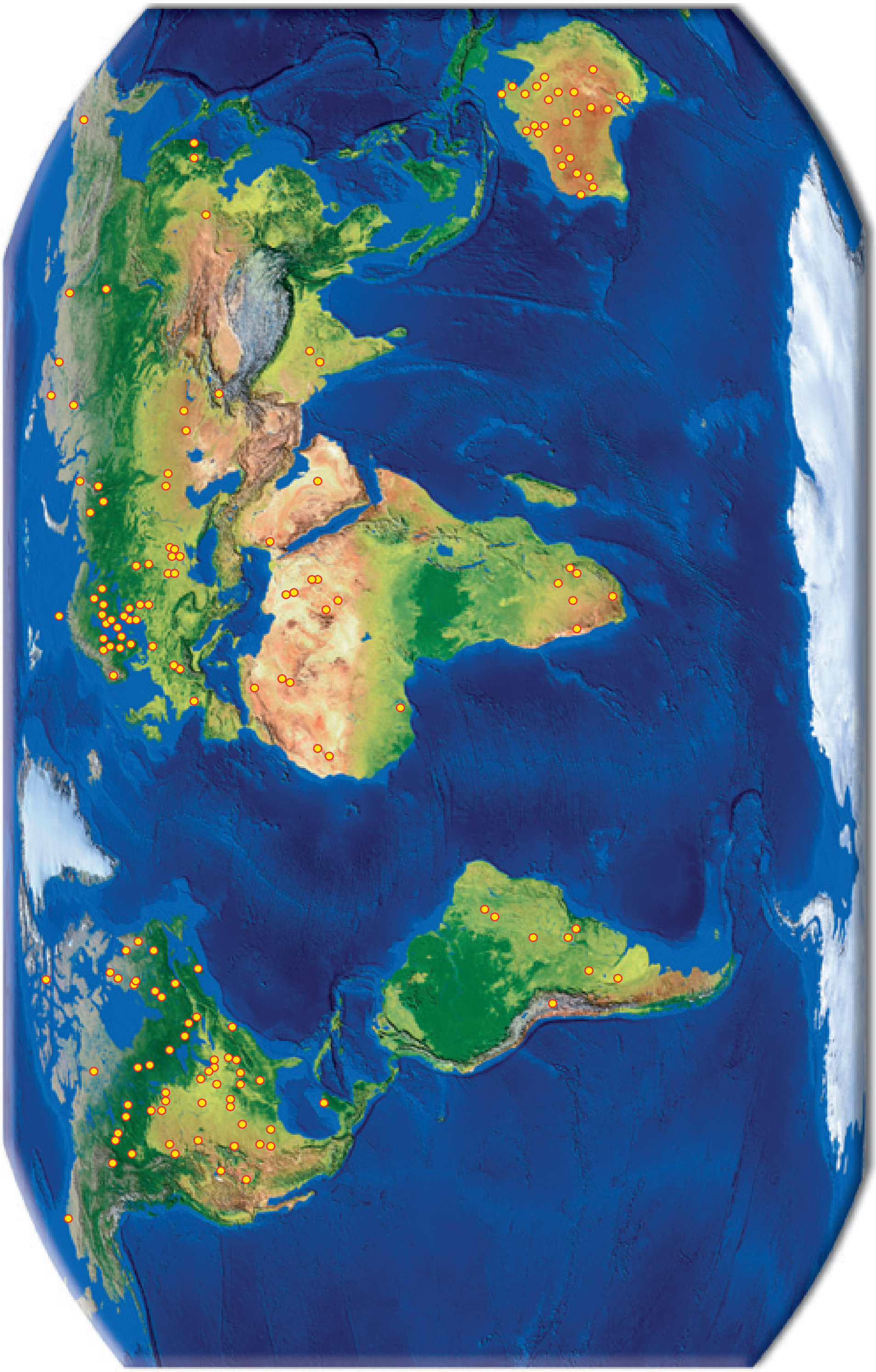
terrestrial craters – over half of the known craters are 200 Ma or younger. Concentrations of known craters occur on the ancient continental, or cratonic, areas of North America, Australia, South Africa and Europe. These are geologically stable areas with relatively low rates of erosion and low levels of tectonic activity. They are also areas where there have been active programs for search and study of impact craters. As we will see in the following chapter, a meteorite impact may have wide-spread influence on the organisms living on Earth. When a large meteorite crashes into the Earth, much of life is affected to an equally large degree. In the wake of a large impact, toxic gases are released from the ground and strong acid rains fall on the Earth. The impact might well also spread large quantities of dust into the atmosphere and soot from burning forests may clog the skies causing darkening. Sunlight would not be able to penetrate the atmosphere leading to cooling of the planet, and organisms that rely on photosynthesis for their metabolism such as plants and algae would perish. If the meteorite landed in the ocean it would instantly vaporise enormous quantities of water that would saturate the atmosphere with steam, and tsunamis would sweep away all the forests and drown all animal life along continental coasts. Whole ecosystems would be devastated, and their collapse might even lead to a mass extinction – something that has happened many times during Earth´s long history.

5. Impacts through time – and some Earth history

5.1 Archean impacts

When the Earth was formed, alongside the rest of the Solar System approximately 4600 Ma ago, internal heat production was much higher than today and the Earth consisted of hot, molten rocks – instead of oceans of waters as today, there were oceans of magma. Early in the history of the Solar System rocks were abundant in space and therefore more meteorites bombarded the Earth. Heavy meteoritic and volcanic activities destroyed all traces of rock and therefore rocks of this age are missing from the geological record. Any solid rock that had formed on the early Earth had a short life span before it melted again. About 500 million years after its formation, the Earth had cooled down sufficiently to form continents, and liquid water was probably also found on the surface. This period that followed the initial, chaotic time is called the Archean eon (circa 3800-2500 Ma ago). Despite the fact that solid rocks existed, rocks of this age are very rare on Earth. The reasons for the lack of rocks from this time lie in the basic way in which the surface of the Earth changes through time, a process called plate tectonics. The Earth’s surface is divided into about a dozen large, mostly rigid plates that slowly move relative to each other. When plates collide, older rock is destroyed; and when they move apart, new rocks are formed by molten magma moving up from below to fill the space. Although these processes largely affect rocks forming the ocean floors rather than the continents, the continents are also affected. Very ancient rocks such as those from Archean times are more likely to have gone through this cycle of destruction. That is why rocks that are as old as the Archean only are preserved in a few places on Earth, whereas the rest have been destroyed due to the plate tectonic movements. Consequently, most rocks on Earth are younger than 3800 Ma and the oldest rocks known are from Greenland, Canada, South Africa and Australia; quite ancient rocks are also known in Scandinavia as well.

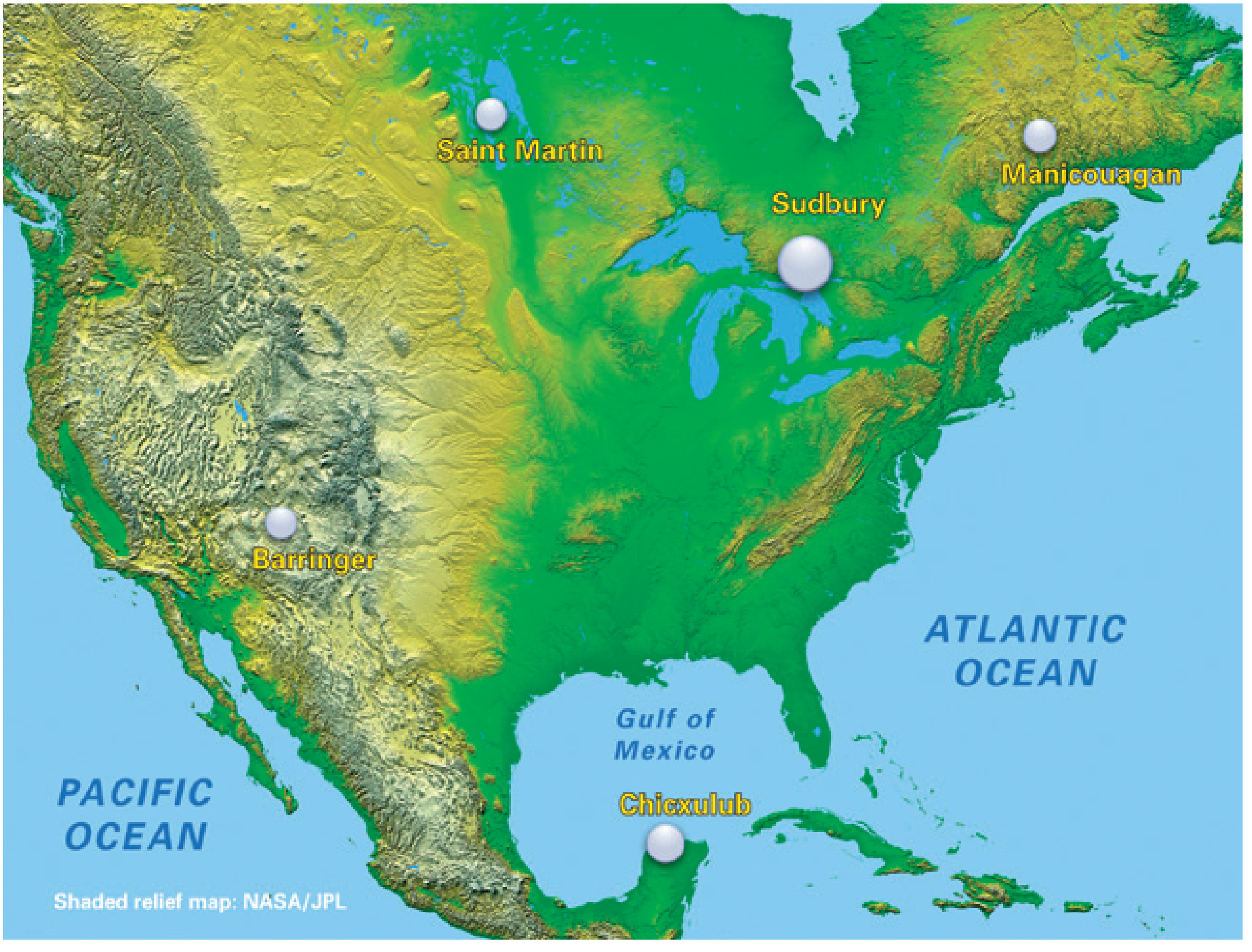
Even though Archean rocks are rare, we do find traces of meteorite impacts in them. Some of the old-



Map of known impact sites on Earth (data from Earth Impact Database).

est rocks in South Africa and Australia contain layers of small spherical silicate grains that are interpreted as debris from some of the oldest known meteorite impacts. These sand-sized spherules are 3500 Ma old and occur in layers up to 30 cm thick in the Barberton area in South Africa but also in the Pilbara area in Australia. The extremely high temperatures generated by the force of the impact melts and then fuse the sediment into these tiny glass-like spherules. Additional evidence for a meteoritic origin of these spherule layers is the high iridium content, a metal that is naturally rare on Earth (see more below).

Major impact sites in North America.



5.2 Proterozoic impacts

The Proterozoic eon marks a shift from an unstable Earth to one with more stable geological conditions. The start of the Proterozoic is defined at 2500 Ma ago and it ended 542 Ma ago with the famous *Cambrian explosion* (referring to the sudden appearance of complex shell-bearing organisms in the fossil record). About 1000 Ma ago nearly 80 % of the continental crust had already formed and all the landmasses were connected in a single large supercontinent called Rodinia. Towards the end of the eon Rodinia broke into several individual pieces that each formed their own continent. The climate was much cooler in the Proterozoic compared with the Archean and life was common but small – mainly bacteria and single celled algae. However these tiny organisms used sunlight as their energy source and produced oxygen as a bi-product in the process that is called photosynthesis. The oxygen released by these organisms and which eventually accumulated in the atmosphere was one of the most important controls on the evolution of life on Earth. The extra energy oxygen makes available to organisms is one reason why they grow large and complex.

The Earth experienced several major glaciations throughout the Proterozoic, some of them so severe that they covered the whole Earth in ice, from the poles to the equator. The glaciations culminated towards the end of the Proterozoic with several pulses of global ice ages, a period referred to as the Snowball Earth. How did the Earth return to more normal conditions from being completely locked in ice? Perhaps a truly catastrophic event such as a massive meteorite impact could release the Earth from the deadlock caused by the ice? There is evidence of a meteorite impact that coincides with the first major glaciations about 2200 Ma ago. The Vredefort impact structure in South Africa is now virtually eroded away but the original structure is estimated to have had an original diameter of more than 160 km and the impact could well have been large enough to melt crustal rocks – and the ice of course. Slightly younger is the meteorite that crashed into the Ontario area in Canada 1850 Ma ago.

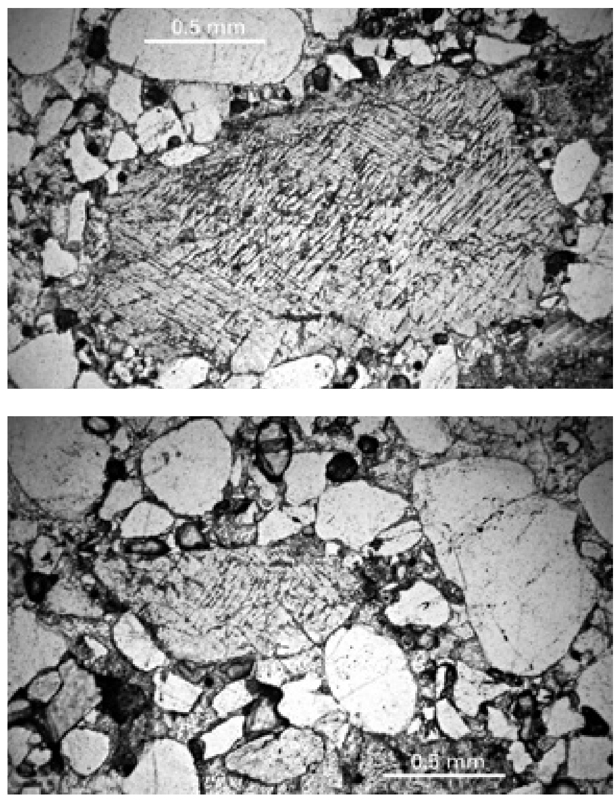
5.3 Phanerozoic impacts

As we have already discussed, the older the rocks are the more likely it is that they have experienced severe erosion – or complete destruction. Consequently the likelihood that we find preserved meteorite craters decreases with age. Still, there are at least 150 large and many smaller craters known from the last 500 million years. This period of time is of particular significance, because it broadly coincides with the fossil record of animals. Since the Cambrian (beginning circa 542 Ma ago), the evolution of animals has completely altered the Earth. The history of life has been highly eventful, and many of the evolving species have suffered or become extinct due to meteorite impacts. The most well-known of these is of course the meteorite that caused the extinction of the dinosaurs but there are many other examples, some of which are described below. Another important event in terms of animal evolution takes place during the Ordovician (circa 489-444 Ma ago). Following an extinction event at the end of the Cambrian, the beginning of the Ordovician was marked by a diversification of animal life, probably with several causes. Changes in the configuration of the continental plates, tectonic activity or added nutrient supply may have acted as triggers for this evolution. Interestingly, an increased frequency of meteorite impacts may also have amplified ecological escalation. It has been argued that the major phase of organism diversification took place about 470 Ma ago and coincided with a disturbance in the asteroid belt. The break-up in the asteroid belt resulted in increased delivery of extraterrestrial material towards the Earth, some meteorites being kilometre-sized. In Baltoscandia especially, this event is well documented and several of the craters formed at the time, such as Kärdla, Tvären and Lockne will be examined in more detail this book.

Let us return to our brief history of meteorites through times with a mention of a major extinction at the end of the Devonian (circa 360 Ma ago). During the Devonian the continents drifted towards each other, closing the oceans between them, a process that would eventually culminate in the formation of another large supercontinent about 250 Ma ago, this time called Pangaea (meaning *all land*). Pangaea was surrounded by an enormous ocean known as Panthalassa. Volcanic eruptions and meteorite impacts were frequent on Pangaea. Although little is known about the extinction, it has been suggested that it was also at least partly caused by a meteorite impact. Evidence for Devonian meteorite impacts comes in the form of deposits of glassy beads, called *microtektites*, in Belgium and China. Microtektites form when large meteorite impacts throw molten rocks into the atmosphere where they cool and turn into a sort of glass that is distinct from other kinds of glass formed, for example, by volcanism. A potential source of the microtektites is the Siljan impact in Sweden (estimated impact 377 Ma ago). In the American states of Illinois, Missouri and Kansas a series of strange structures has been dated to be 310-330 Ma old. Eight large depressions 3-16 km in diameter are spread along a straight line at an average distance of about 100 km. First considered to be the remnants of volcanic eruptions, the structures have now been reinterpreted as being the eroded traces of impact craters created as an asteroid broke up into small pieces that slammed into the Earth. Objects travelling through the Solar System frequently break apart, and if an asteroid fragmented close to our planet the impact that followed could produce craters in such a linear pattern (similar structures can also be seen on the Moon). It is not only the lack of volcanic rocks at these sites that made the scientists reinterpret the structures: there are many other features that support an impact cause. For example, the rocks in the depressions are folded along circular fractures – typical for meteorite impacts. Crystals of shocked quartz, the result of instantaneous, extreme

Well-developed shatter cone from the Siljan impact structure. The black quadrangle in the lower right corner is 1 cm wide. Courtesy of H. Stehlik.

Quartz grains with two-directional set of planar deformation features from the ejecta layer of the Kärdla impact crater. Photo: G. Baranov, courtesy of A. Kleesment (Institute of Geology at Tallinn University of Technology).

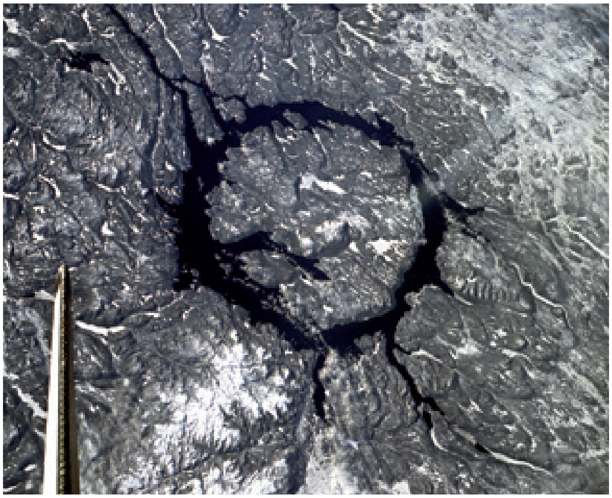


pressure, are found at several sites, and shatter cones are common at two other sites. *Shocked quartz* forms when the quartz crystals undergo a sudden pulse of great pressure, but do not melt. The shock forms an unusual set of microstructures in the mineral, making it possible to identify an impact as the source of the structures. *Shatter cones* form when the shock wave caused by the impact compress the rock into distinctively conical shapes that can be microscopic to several metres in size.

Life on Earth has experienced many extinctions but nothing compares to what happened 250 Ma ago, the Permian-Triassic extinction event – or, *Mother of Mass Extinctions* or simply *the Great Dying*. Only five percent of all marine species living at the time and 30 % of the terrestrial vertebrate species survived this catastrophic event, the rest were lost forever. The *Murder on the Orient Express* hypothesis has been put forward for the extinction; this means that many factors, all acting together probably led to the extinctions. The extinction was rapid, probably taking place in less than a million years, and although marine organisms suffered severely terrestrial ecosystems were also badly affected. For example, plants that thrived in the southern hemisphere produced thick and extensive coal beds that completely disappear at the boundary. No coal was laid down anywhere in the world for at least 6 Ma after the mass extinction. The extinction also coincided with the largest known volcanic eruptions in Earth history.

Sporadically, an event at the boundary between the Earth´s core and mantle sets a giant pulse of heat in motion. This magma rises towards the surface as a plume that, as it reaches the surface of the Earth, melts the crust. As the massive plume penetrates the crust it causes volcanic eruptions that pour thousands of cubic kilometres of basalts (called flood basalts) over the surface. Flood basalts poured over what is now western Siberia exactly at the P-T boundary. The resulting *Siberian traps* completely cover an area that is 4 million km^2 in area and approximately 2-3 million km^3 in volume. Such an event would of course be devastating for life. But as mentioned before there were probably several different causes that each contributed to the extinction. In Antarctica, right at the P-T boundary, pieces of a meteorite together with shocked quartz (but no iridium anomaly) have been found. Unusual metal fragments that are almost pure iron as well as grains rich in nickel and silica that may have been created during an impact have been found in China, Japan and Australia. These features indicate a meteoritic origin; but no crater that matches the findings has been discovered to date. It is of course possible that the crater has been eroded and no trace of it will ever be found. The reason for this argument has already been touched upon but one reason is the fact that water covers some 70 % of the Earth’s surface. Through plate tectonics the rocks in the oceans are recycled, and no ocean rocks are older than about 200 Ma. The likelihood that the meteorite impacted the ocean is thus much higher than it impacted a continent; and if it impacted an ocean it is likely that the crater was destroyed in the process of sea-floor spreading and subduction. Even so, an impact structure called the Wilkes Land crater in Antarctica has been suggested to be the remains of a meteorite impact at the P-T boundary.

Since younger craters are much more likely to have been preserved there are quite a large number of craters preserved in the last 200 Ma. One of the more well-known is the Manicouagan structure in Quebec, Canada. An almost perfectly circular ring of water is seen at the impact site today. Almost 100 km in diameter, it was formed when sections of the crater were



The Manicouagan impact structure in central Quebec, Canada is one of the largest impact craters still preserved on the surface of the Earth. This space shuttle view shows the prominent 70 kilometre wide annular lake that fills a ring where impact-brecciated rock has been eroded by glaciation. The lake surrounds the more erosion-resistant melt sheet created by impact into metamorphic and igneous rock types. Courtesy of NASA / LPI.

flooded around the raised centre of the impact structure. The structure was formed 210 Ma ago, roughly the same time as the Saint Martin structure (40 km in diameter) in Winnipeg, Canada, the Rochechouart (26 km in diameter) in France and impact structures in Ukraine and USA (15 and 10 km in diameter, respectively). Once again, the timing of the impacts coincides with a mass extinction at the end of the Triassic.

Around the beginning of the Cretaceous period (roughly 130 Ma ago) a large meteorite struck our Baltoscandian parts of the world. Off northern Norway in the Barents Sea lies the 40 km wide Mjølnir crater. It was identified as a crater through high concentrations of iridium in the surrounding sediments in addition to the presence of shocked quartz. Because the meteorite that created Mjølnir impacted a seabed it has retained many of its original features and the crater itself as well as the surrounding debris is among the best preserved in the world.

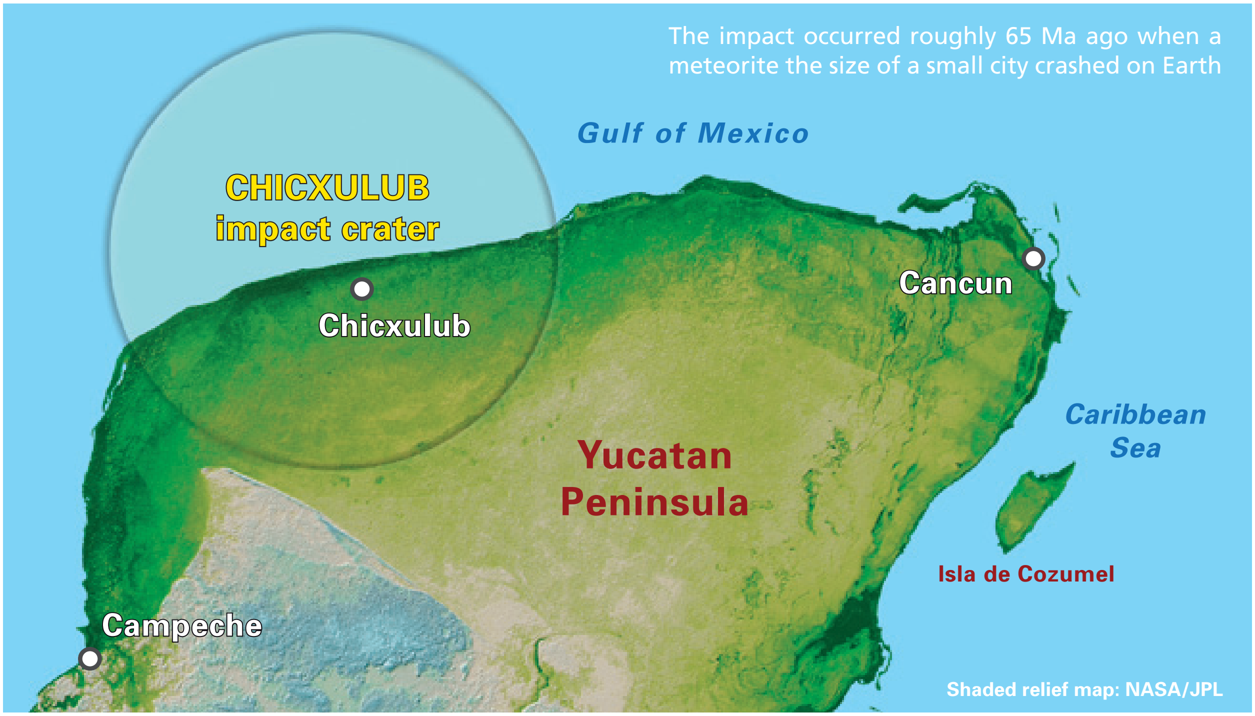
One of the scenically most impressive craters is the so-called Meteor Crater, also known as Barrington Crater or Canyon Diablo crater. It is located close to the city of Winslow in the northern Arizona desert, USA. It was formed about 50 000 years ago when a nickel-iron meteorite measuring around 50 m across impacted the area that at the time was not a desert but open grassland with woodlands: woolly mammoths and giant ground sloths were some of the animals present. On impact the meteorite ejected 200 million tons of rock and excavated a crater measuring 1.2 km across and 170 m deep. The actual meteorite was mostly vaporised and very little of it remained within the crater it had created. The crater itself is surrounded by a steep rim of upraised sedimentary layers that rises 45 metres above the surrounding desert floor. The centre of the crater is filled with over 200 metres of rock debris. Because it lies in the desert and therefore in a fairly stable climate it has escaped much of the erosion that has destroyed most other impact structures in the world, and Meteor Crater is the best-preserved impact structure of its size anywhere in the world.

5.3.1 Did a meteorite cause the extinction of the dinosaurs?

Possibly the most widely-known impact is the meteorite that may have finally wiped the dinosaurs off the face of the Earth. Sixty five million years ago almost all large vertebrates (dinosaurs, plesiosaurs, mosasaurs and pterosaurs) on land, at sea, and in the air suddenly became extinct and most plankton and many groups of tropical invertebrates, especially reef-builders, and many land plants were severely

View of the chalk and limestone cliffs at Stevns klint in Denmark, one of the best places in the world showing the Cretaceous-Tertiary boundary (65 million years ago). Photo: S. Willman.

affected. There are a number of hypotheses about what the causes of this extinction were, but the most popular is that it was caused by a meteorite impact. The evidence for an impact lies in the unusual composition of the rocks of that age. Rocks deposited in the Pacific Ocean, the Caribbean, Europe (Stevns klint in Denmark being the best example) and much of North America contain extraordinarily high amounts of the metal iridium, regardless of whether or not the rocks were deposited in land or at sea. Iridium is rarer than gold on Earth, and the amount of iridium in these rocks is so high that there must be an extraterrestrial source – a meteorite. However, the amount of iridium is not the only source of evidence. Other well-known meteorite impact structures often have fragments of shocked quartz, and tiny glass spheres are also present. All over North America, rocks of K-T boundary age contain these glass spherules, and just above the contact is a thin layer of clay that contains iridium along with fragments of shocked quartz. The impact crater itself has also been found – it goes by the name Chicxulub and is a roughly oval structure deeply buried under the sediments of the Yucatán peninsula in Mexico.



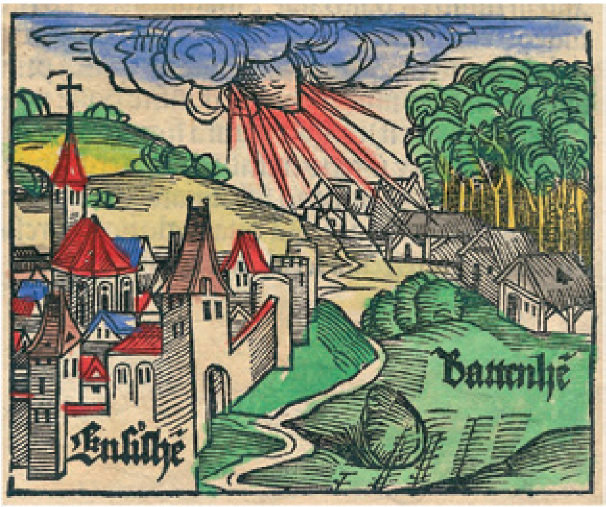
Barringer impact crater. Photo: Gordon Osinski, University of Western Ontario, Canada.

6. Fact and Fiction

Although we now know much about meteorites and other space objects this has not always been the case. Even just a few centuries ago, it was unthinkable that rocks could fall from the sky, and bright meteors caused wonder and bewilderment among people all over the world. In general, researchers of natural sciences had difficulties getting their message across if the results opposed religious ideas.

Accounts of meteorite falls have been recorded throughout human history but after the Middle Ages the idea that stones could fall from the skies were considered absurd. Thomas Jefferson, the third President of the United States (1743-1826, president 1801-1809) was a man with expertise in a significant number of subjects, for example in architecture, palaeontology, and archaeology, but he was also an ingenious inventor. When he was told that two Yale University professors had reported the fall of meteorites over Weston, Connecticut in December of 1807, his response was typical of the attitude at the time. He said: *"I could more easily believe that two Yankee professors would lie than that stones would fall from heaven"*.

Nevertheless, the body of evidence was steadily growing, and the first meteorite to be analysed by modern methods fell at Luce in France in 1768. The meteorite was studied by three chemists at the most prestigious scientific body at the time – Institut de France, sent there by Abbot Bachelay. Several witnesses testified that the rock did indeed fall from the sky and the chemical analyses concluded that the rock consisted of 55 % vitrifiable earth, 6 % iron and 8.5 % sulphur in addition to other compounds. However the chemists concluded that the rock did not fall from the sky but that it was transformed from a rock that had been struck by lightning. *"We believe we can therefore conclude...that the stone presented by M. Bachelay did not originate in thunder; that it did not fall from the sky..., that this stone is nothing other than pyrite-bearing sandstone...which was perhaps covered by a thin layer of soil or grass that was struck by lightning, and the heat was great enough to melt the surface of the part struck; but it did not continue long enough to penetrate the interior*".



Hand-coloured woodcut showing the fall of the Ensisheim meteorite in 1492 (from H. Schedel *Liber Chronicarum*, 1493).

Andreas Xavier Stütz, a priest and mineralogist but also Assistant Director of the Imperial Natural History Collection in Vienna, published a paper in 1790 entitled *On some stones allegedly fallen from heaven*. The purpose of his paper was to discredit the idea that stones may fall from the sky and so he wrote about the Hraschina iron meteorite that fell in Croatia in 1751 *"It may have been possible for even the most enlightened minds in Germany to have believed such things in 1751, due to the terrible ignorance then prevailing of natural history and practical physics; but in our time it would be unpardonable to regard such fairy tales as likely*". The Hraschina iron meteorite was investigated by the Bishop of Agram at the request of the Emperor Franz I who sent a report together with a 40 kg specimen to Vienna. The bishop's report contained sworn statements of seven witnesses who said that at six o'clock in the evening on May 26, 1751 they saw a brilliant ball of fire split into two balls linked by fiery chains. Some witnesses also saw a large rock plunge into a newly-ploughed field, making the ground shake, as in an earthquake.

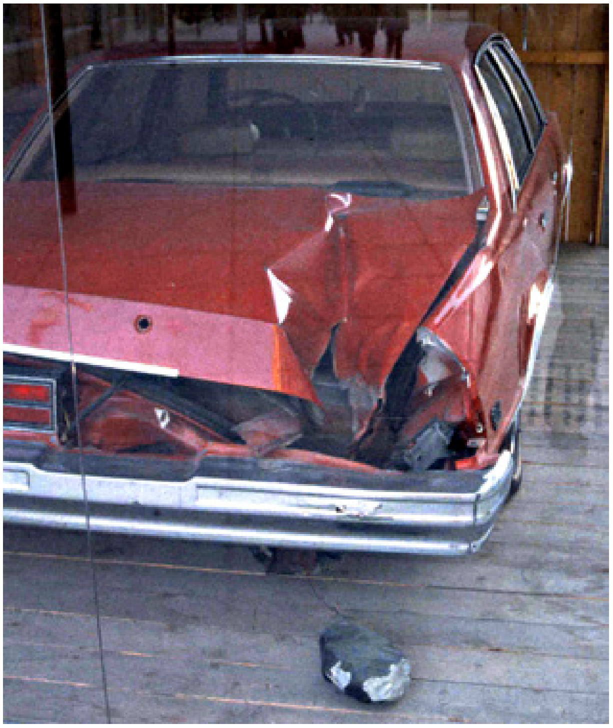
The same year, at 9:30 in the evening on July 24, a brilliant fireball travelling over southern France was witnessed by numerous people. The meteor broke up into several shining fragments and pieces of what was to be called the Barbotan stone meteorite were showered down near the villages Barbotan and Agen. Although an official testimony was signed by the mayor of Barbotan and his deputies and meteorite fragments were exhibited, this did not prevent Pierre Bertholon, editor of the *Journal des Sciences Utiles*, from dismissing the meteorite impact as groundless and physically impossible.

During the following centuries the number of witness reports and collected rock samples reached such proportions that scientists could no longer deny that meteorites must come from space. Not without reluctance, the idea became more accepted.

As we now know, thousands of meteorites fall down on Earth each year. On April 26, 1803 in a serene spring sky, numerous stones fell over L'Aigle, a small city in Normandie, France. It is estimated that between 2000-3000 fragments fell from the sky and 37 kg of meteoritic material were collected, the largest individual piece weighed 9 kg. On June 9 1866, a stone meteorite shower of over 1000 stones hit Knyahinya, Ukraine. The total weight of recovered specimens is about 500 kg, the largest weighing about 293 kg. The largest recorded meteorite shower however occurred over a 127 km^2 area in the vicinity of the town Pultusk, close to Warsaw in Poland, in the evening of January 30, 1868. The estimated total mass of recovered meteorites reached 8.863 kg and the number of fragments counted exceeded 68 000. Most of the fragments called *Pultusk peas* had a mass of few grams with the largest specimen found weighing 9.095 grams.

Of course, if you would find yourself in the middle of such a meteorite shower you would be in serious danger. There are, however, only a few known occurrences when people have been hit by meteorites. The first well-documented extraterrestrial object to have

The 39 kg iron meteorite Hraschina in the meteorite collection of the Natural History Museum in Vienna, Austria.



The Peekskill meteorite, which appeared brighter than full Moon, was witnessed by thousands across the East Coast of the USA on October 9, 1992. The 12.4 kg stony meteorite fell in Peekskill, New York, smashing the trunk of a parked 1980 Chevy Malibu car. Photo: Pierre Thomas.

injured a human being concerns the famous Sylacauga (Hodges) meteorite that fell on November 30, 1954 on the town of Sylacauga in Alabama, USA. A fragment of the Sylacauga meteorite weighing almost 4 kg crashed through the roof of the house, bounced off a large wooden console radio and hit Ann Elizabeth Hodges who was napping on a couch. The meteorite was donated to the University of Alabama Museum of Natural History in Tuscaloosa where it is now exhibited.

Another documented case of a meteorite hitting a person occurred on August 12, 1992 when a young Ugandan boy was struck on the head by a small fragment (3 grams) of the Mbale meteorite after it hit a banana tree first. A total of 863 fragments (ca 150 kg) of the Mbale meteorite in Uganda were recovered.

Much more common are records of meteorites hitting cars and houses. The most famous example is the Peekskill meteorite. Travelling across the east coast of USA a large fireball was seen by thousands of people on the evening October 9, 1992. The meteorite broke into smaller pieces of which one, weighing 12 kg, punched through the trunk of a Chevrolet Malibu parked in Peekskill, New York to the good fortune of Michelle Knapp, the owner of the car. She was able to sell the 12-year-old car that she bought for only 100 dollars as a collector's item for tens of thousands of dollars. The car, and the meteorite that hit it, today travel the world as an excellent example of a meteorite impact, albeit on a small scale.

One of the most recent meteorite strikes on a building was recorded on January 2, 2007 when an iron meteorite weighing 377 grams fell through the roof of a New Jersey home and landed in the second-floor bathroom. On June 13, 2004 a grapefruit-sized meteorite weighing 1.3 kg smashed through the house roof in Auckland, New Zealand. After plummeting through the tiled roof, it hit a leather couch and bounced back up to the ceiling before rolling under the computer where it was discovered.

7. History of Baltic meteorite impacts

7.1. The history of discovering impact craters in Baltic area

Geoscientific studies in the countries around the Baltic Sea have a long and fruitful history. Research had already started here in the 17th century, and soon it reached international standards, primarily by works in chemistry, mineralogy and palaeontology. The breakthrough for geology as a science took place in the 19th century when geological surveys, societies and university departments were established in the Baltic countries. The first geological maps, the results of a scientific approach to the surface and subsurface geology, were drawn in the middle of the 19th century. However, the conspicuous impact craters, especially when they occurred in the surface as exotic hollows, must have attracted people much earlier. The youngest cratering event described in the following chapters, Kaali, was first mentioned in 1794 by a German naturalist J.E. Rauch. It took more than 140 years to the moment when geological science had developed enough to acknowledge its impact origin. Meanwhile, the impact hypothesis for Kaali was advanced in 1919 by Estonian schoolteacher Julius Kalkun-Kaljuvee in a textbook on general geology. In 1937, when scientists found the remnants of the iron meteorite responsible for the event, Kaali became the first confirmed impact structure in northern Europe.

However, as early as in the late 18th century and early 19th century, several of the presently recognized Nordic craters were suggested to be of impact origin. At the meeting of the Geological Society of Stockholm in 1910, the Swedish professor of mineralogy and geology Arvid Gustaf Högbom (1857-1940) suggested, while reporting on Meteor Crater in Arizona, that the Mien and Dellen lakes could be impact craters because of the presence of peculiar melt rocks. Unfortunately, this suggestion was not taken seriously and went unrecognized for some 50 years until the paradigm in Fennoscandia shifted drastically. This was especially due to the engagement of the Swedish geologists Frans E. Wickman, Nils-Bertil Svensson and Kurt Fredriksson. In the wake of the establishment of diagnostic shock metamorphic alterations, like high-pressure variants of minerals (for example coesite and stishovite) and high-pressure structures (shatter cones, planar quartz, etc), Lappajärvi, Mien and Dellen were reinvestigated and their impact origin proved in the 1960s. The next two decades, 1970s and 1980s, resulted in the discovery and confirmation of Kärdla, Söderfjärden and Lumparn, mainly by the application of indirect study methods like geophysical mapping and imaging from satellites.

Nordic participation in meteorite impact research has increased through the years. Intensive studies and interdisciplinary scientific networks during the last decades have resulted in several new discoveries, making the area around the Baltic Sea the world's most cratered region per area, with about 30 confirmed cases. The next chapters describe the structures close to the coastline of the Baltic Sea, and some other larger and well-studied crater sites nearby.

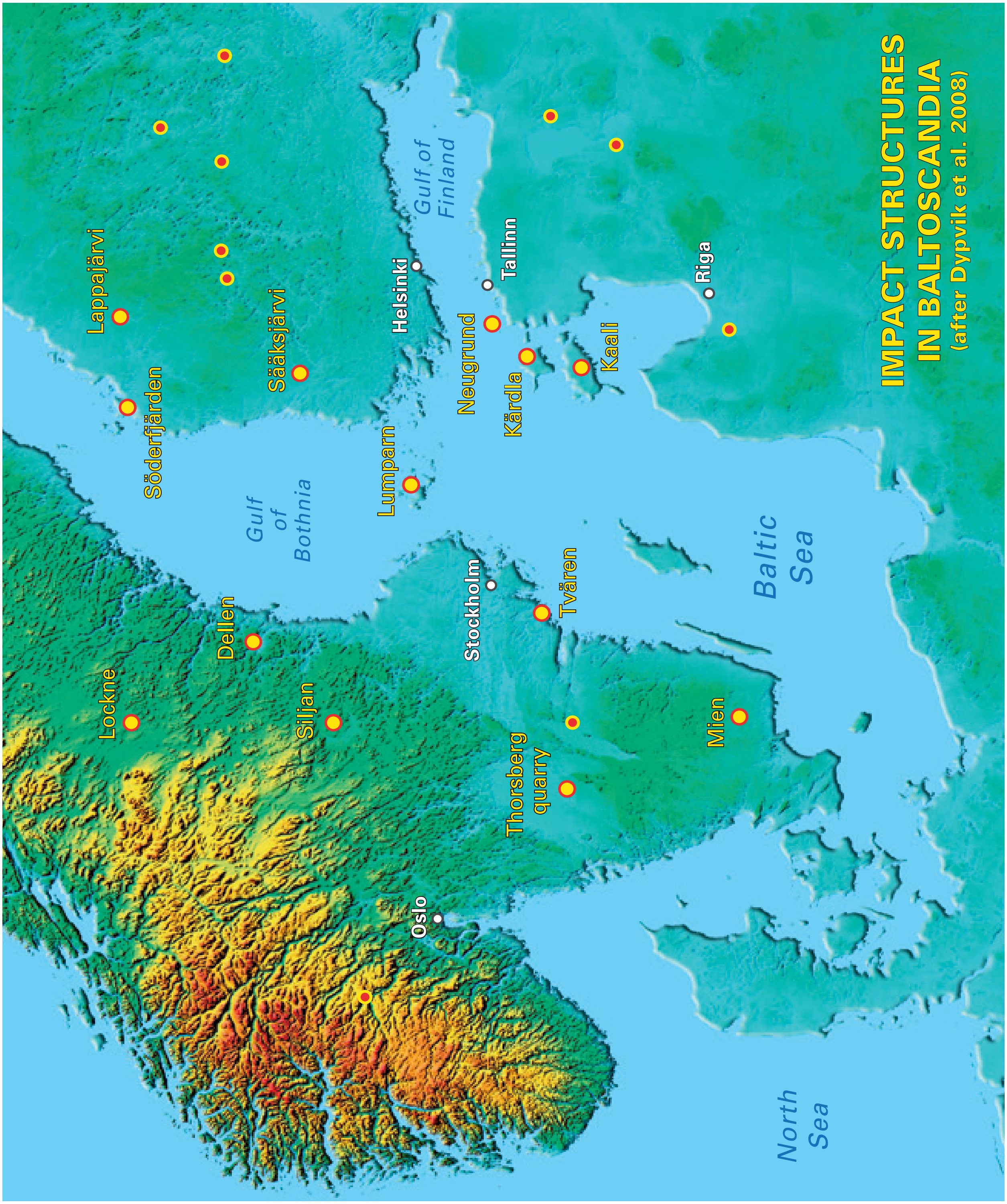
7.2. Exploring Baltic area meteorite craters

Ages and diameters of the impact craters in the Baltic area vary considerably, but many are relatively small (less than 10 km) and most were formed 535-377 Ma ago. There are two principal reasons for this bias. First, owing to the effects of regional geological evolution, shallow epicontinental seas covered most of the Baltic area during the early and middle Palaeozoic, causing immediate burial and good preservation of the freshly formed craters. Second, about 470

Ma ago (in the Middle Ordovician) a huge cosmic event occurred in the asteroid belt, the region of the Solar System located between the orbits of the planets Mars and Jupiter. Nowadays the event is referred to as the breakup of the L-chondrite parent body, and it was followed by a major meteorite shower during the Phanerozoic eon. The best empirical evidence for the shower comes from the finds of a two to three orders-of-magnitude enrichment of fossil L-chondrite meteorites and micrometeorites in Middle Ordovician marine limestones in Thorsberg marine limestone quarry, southern Sweden (see chapter 7.2.10). In a search project, pursued together with quarry workers since 1993, a total of 87 fossil meteorites with diameters up to 21 cm have been found (data as of January, 2010). In addition, abundant sediment-dispersed L-chondritic chromite grains have been recovered from Middle Ordovician limestones worldwide. Four craters in our region, namely Lockne, Tvären and Kärdla, were formed between 470 and 455 Ma ago indicating that they may have been related to the meteorite shower. Also, the Middle Ordovician (466 Ma ago) Osmussaar breccias, situated along the northwestern coast of Estonia, are rich in L-chondritic chromite grains of extraterrestrial origin, and shocked quartz. The breccias are exposed on Osmussaar island (coordinates 59°18´N, 23°28´E) and seen as strongly cemented brecciated limey sandstones that intrude into the surrounding limestone sequence. The chromite grains within the breccias are highly angular, suggesting short transportation from a still unknown impact event/crater.

Next we will describe some of the best-known meteorite craters in Baltoscandia, starting with the youngest.

Brecciated sandstones at the waterfront on Osmussaar.

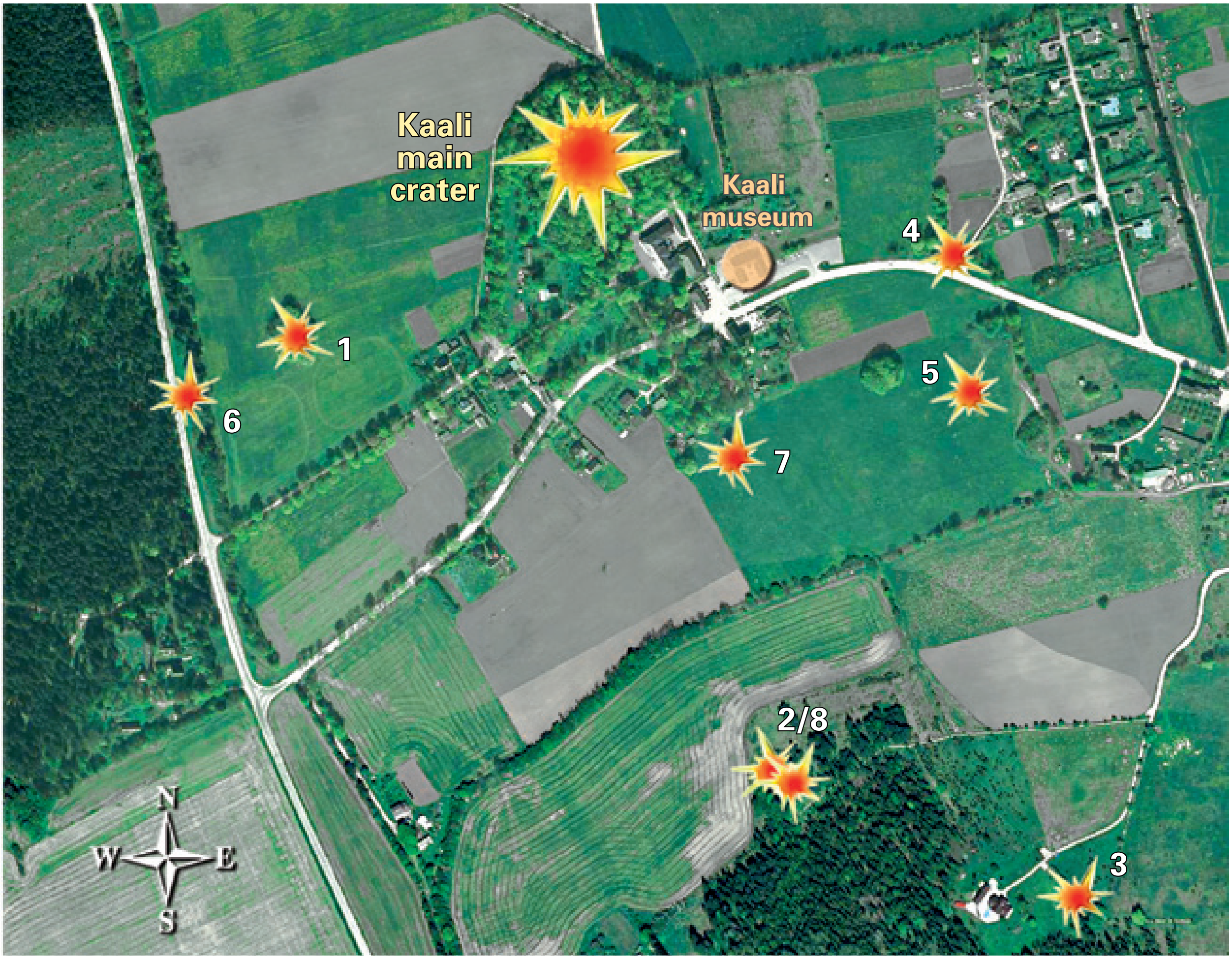

IMPACT STRUCTURES
IN BALTOSCANDIA
(after Dypvik et al. 2008)
Lappajärvi
Söderfjärden
Sääksjärvi
Helsinki
Gulf of
Finland
Tallinn
Neugrund
Kärdla
Kaali
Riga
Lumparn
Gulf
of
Bothnia
Dellen
Lockne
Siljan
Stockholm
Tvären
Baltic
Sea
Thorsberg
quarry
Mien
Oslo
North
Sea

7.2.1. Kaali, Estonia

Location: On the island of Saaremaa, Estonia, 19 km northeast of Kuressaare town; coordinates 58°22´N, 22°40´E.

Age: The age of the Kaali impact is uncertain but is estimated to be between 1750 and 6500 years B.C. The age has been the subject of extensive discussion during the last decade, but it is definitely post-glacial. Material from three different localities (and different ages) has been considered to reflect the event, and has been dated by various methods. First, evidence in the form of organic matter (such as pieces of charcoal, wood and peat) and pollen and diatom remains within the post-impact sediments (at different depths) of Kaali and its satellite structures have revealed a wide range of ages, but the deepest (and presumably oldest) material started to accumulate at about 1750 B.C. Second, glassy spherules in three mires in Saaremaa and one in Hiiumaa were found in mid-1990. The peat layer containing these particles rich in silicon, calcium, iron and nickel was dated to 6270-6500 B.C.

Location of the Kaali main crater and satellite craters (1-8) in the Kaali crater field.



Kaali satellite crater no. 1

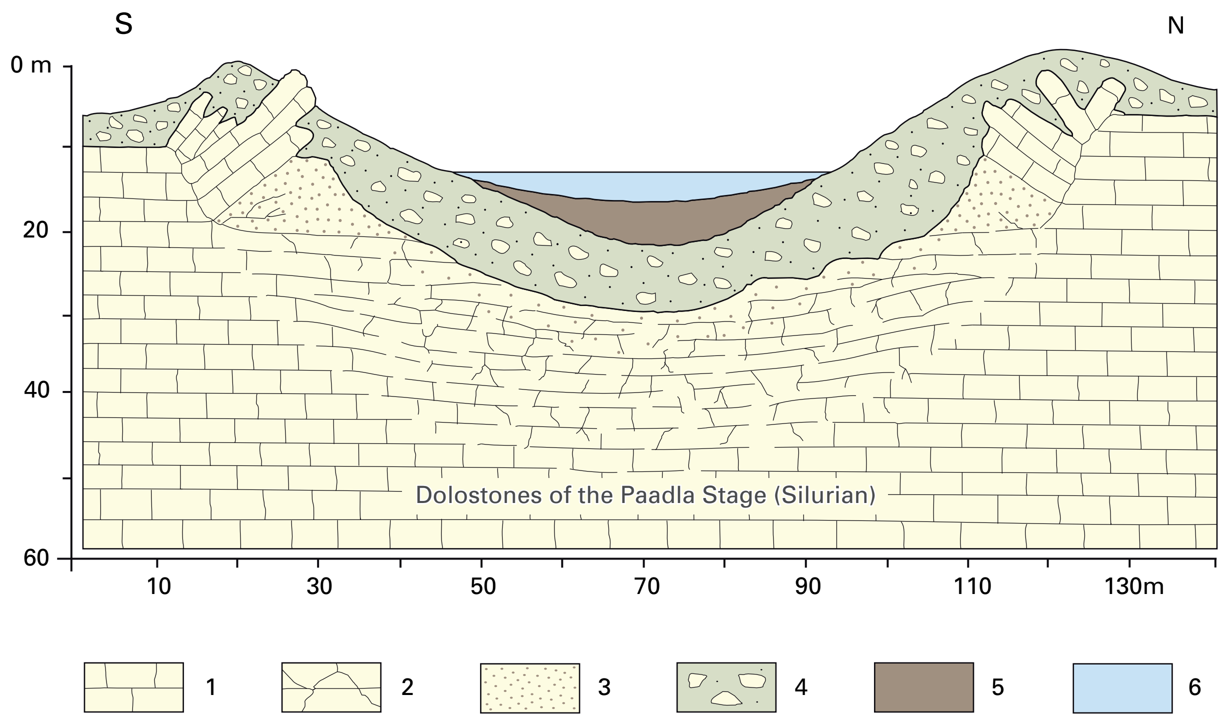
Kaali satellite crater no. 3

Kaali main crater

Description of the crater area: The Kaali crater field – a main 110 m diameter crater flanked by eight smaller secondary structures (1-4 m deep and 12-40 m in diameter) – was formed as the result of a meteorite shower. The crater field is an easily accessible and popular tourist attraction. The Kaali meteorite shower is important for our understanding of meteorite impacts because cosmic catastrophes of this magnitude taking place in a populated area in historical time are very rare. The craters formed in a layered target of Quaternary till overlying the horizontally bedded Silurian dolostones, a type of hard carbonate rock. Only the main structure is deep enough to include a body of water as is reflected in the name *Kaalijärv* (*järv* means lake in the Estonian language).

The energy released by the impact can be seen today as outward tilted blocks of dolostones exposed on the inner slope of the uplifted rim surrounding the deep depression.

Based on the sizes of the Kaali craters, the composition of the target rocks and the meteorite composition, the initial mass of the meteorite has been estimated at 400-10 000 tonnes travelling with a velocity of 15-45 km/s. Upon entering the atmosphere this was reduced to a weight of 20-80 tonnes and 10-20 km/s at the moment of impact. The relative distribution of the structures in the field favours the interpretation that the meteor came from the south-southeast direction, as the largest crater is normally located at, or near, the downrange boundary of the crater field.



Schematic geological cross section of the Kaali main impact crater. 1 - intact dolostones of the Paadla Stage (Silurian), 2 - fractured dolostones, 3 - powdered dolostone, 4 - ejecta in glacial till, 5 - lake sediments (gyttja and peat), 6 - water.

Kaali satellite crater no. 4

If the impacting meteorite penetrated through the overlying quaternary sediments into the Silurian dolostone below, the enormous energy of the impact would have both vaporised the dolostone and the water contained within it to form a set of superheated gases. A dense set of impact-related cracks would have allowed the gases to penetrate deep into the rocks below, altering the rocks as they did so. At the same time, the intense pressure generated by the instantaneous formation of these gases within the rocks would have caused an enormous explosion, shattering the surrounding rocks into powder, and throwing it upwards out of the impact site. The focus of the explosion was presumably situated in the place of the greatest pressure, which is to say directly under the solid body.

Altogether 2.5 kg of iron meteorite pieces have (officially) been collected in Kaali and most of them are stored at the meteoritical collection of the Institute of Geology, Tallinn Technical University. Polished surfaces of pieces of the meteorites display typical *Widmanstätten* patterns – characteristic cross-hatched patterns consisting of bands of two different iron-nickel minerals called kamacite and taenite. In addition to iron, the meteorites contain 7.25 % nickel, but are also rich in rare elements like iridium, gallium, germanium, rhenium, platinum and gold. Soils within the Kaali craters and nearest surroundings are known to contain some (less than 10 grams per 1 m^3) microscopic magnetite- and/or silicate-rich material.

The first investigator of Kaali main crater was Rauch who in 1794 suggested that the depression was the remnant of an extinct volcano. However, it is obvious that islanders were aware of this exotic hollow much earlier. The morphology of the crater and the uplifted dolostones gave rise to several legends and tales. It was believed that the lake had no bottom and its waters were hiding an entrance to hell. This belief was partially triggered by statements of some lake researchers. For instance, Johann Wilhelm Ludwig von Luce wrote in his work of 1827: "*The water in the lake is always clear and fresh and it is very deep.*

The largest iron meteorite chip ever found from Kaali weighs 28.4 gr. Width is 28 mm. Both specimens are from the collections of the Institute of Geology at Tallinn University of Techonology. Photos: T. Bauert

Most Kaali iron meteorite chips are covered with a rusty coat and range from a few millimeters to 8 mm in size.

When I fifty years ago exerting all my strength threw an about-4-m-long pole into the lake, and it flew out of the water in a few seconds, and I grabbed it, I couldn't find any sign suggesting that the tip of the pole had touched the mud on the lake bottom". In reality, the water depth in the lake is 5-6 metres during high-water periods. During low-water periods the basin is almost dry. The most rapid lake-level rise was recorded in September 1927 when the water rose by nearly 2 m as a result of heavy rainfall for eight days straight.

Hofman was the first to properly describe the structure of the Kaali main crater in 1837. He noted that the Kaali depression showed an astonishing resemblance to maars – volcanic funnels on the Eifel plateau – and the tilt of the uplifted dolostones on the crater slopes indicated an explosion, the force of which had been directed from the bottom and upwards. Hofman suggested an abrupt eruption of water, steam, gas and mud in the Kaali crater area, and his theory was supported by Wangenheim von Quelen in 1849, who presented a visual plan and possible cross-section of the Kaali main crater.

In the autumn of 1927, following an order from the Mining Department of Estonia, Ivan Reinwald went to explore the solid bed in the craters by digging and boring. Reinwald established that the bottom of the crater is approximately horizontal and has a somewhat curved form. A funnel-shaped depression with a drawn out form was discovered in the hard bottom rocks. Later investigations showed that the main crater is slightly asymmetric, being about 0.4 m deeper at the northwestern margin than in the central part. As another peculiarity of the crater, Reinwald mentioned huge dolostone blocks tilted upwards at an angle of 30-40 degrees. After clearing the slope on the north side of the crater, it became evident that the general thickness of the tilted rocks was 8 m, and that they were absolutely identical with the upper part of the strata at the exterior base of the crater. In the centre of the lake bottom large stones had been heaped up as a monument to a deceased owner of the estate. The stones originated partly from the interior of the crater itself, and partly from elsewhere. Based on the above facts, Reinwald reached the conclusion that the craters were of meteoritic origin. In September 1927, Meyer and Kraus from Riga visited the Kaali area. They were accompanied by Reinwald and Alfred Lothar Wegener, founder of the theory of continental drift. As a result of a short five-day period of fieldwork Kraus, Meyer and Wegener earlier than Reinwald published the idea of a meteoritic origin of the Kaali craters. Several scientists later expressed the same opinion, but any remaining doubts about a meteoritic origin of the Kaali craters were removed in 1937 when Reinwald discovered meteoritic iron. At that time the Kaali craters were the first landforms described from Europe of proven extraterrestrial origin, previously only known from the Diablo/Barringer crater in the USA. After a decision of the Nature Conservation Council of Estonia, the Kaali craters became protected already as early as November 1937. The State geological reserve was established in 1959 and in 1978 the area was enlarged and presently covers 50 hectares. Regretfully, human activities have caused great changes to the Kaali craters. These include farming, road-building and scientific excavations combined with great numbers of visitors – tens of thousands of people annually.

Beginning in 1976, archaeologists have subsequently investigated the Kaali crater field. The archaeological excavations on the outer slope of the main crater's eastern rim revealed silver objects, probably sacrifices or hidden property, as well as the remains of a stone fence that once bordered the crater in the west. It is possible that this fence once protected the stronghold and Lake Kaali, a prominent cult location. From ancient times the name of Kaali was *Pühha Järv,* which means the sacred lake.

The Roman historian Tacitus is widely known for his description of the German tribes, that is, those Europeans living north and east of the Roman frontier, called the Limes. In his work *Germanica*, Tacitus wrote in A.D. 98 that *"On the right (Eastern) side of the Swedish Ocean live the Estonians, their habits and clothing are similar to Swedes, but their language is nearer to English. They worship the mother of gods ("matrem deum venerantur")"*. In Greek and Roman mythology, the mother of gods is usually identified with the Phrygian goddess Cybele. The Cybele cult at Pessinus in Asia Minor was renowned for the transfer of a meteorite to Rome in 204 (or 205) B.C. So the mother of gods to Tacitus was associated with meteorites, probably with the Kaali meteorite.

Historian and writer Lennart Meri (1929-2006, President of Estonia 1992-2001) combined the existing data and his own imaginings about the Kaali catastrophe in his books *Hõbevalge* (1976) and *Hõbevalgem* (1983). Meri studied the voyage of the Greek explorer Pytheas of Massilia (present day Marseille), who between 350-325 B.C. visited Britain and possibly also the island of Saaremaa (Ultima Thule) when searching for information on the Baltic Sea and its amber. Pytheas wrote in his book on the *Earth Sea* – *"The barbarian showed me the grave where the Sun fell dead. The Sun was obscured until the smoke from the burning forests and the dust from the explosion had dissipated."* Traces of this event are preserved in Finnish-Estonian, Latvian and Germanic mythology, but have also extended into Celtic, Greek and even Christian mythology. For example, in the Greek epic *Argonautica* by Appolonius of Rhodes (295-215 B.C.), a sailor claimed to have found *"a deep lake in the far north – the burial of the Sun, from which still fog rose as from the glowing wound"*. This gave Meri reason to suggest that Lake Kaali and the meteorite catastrophe were known among the geographers and philosophers long before it was scientifically accepted.

Kaali Visitor Centre includes a museum of local geology and meteoritics in the light of Kaali craters, and a hotel with conference facilities and was established in 2005 by a local non-profit company. Here, the visitors can study the geology and hear from guides the story of the Phaethon, the son of the Sun, who fell down like a star with his flaming hair on an island in the distant northern lands in the Gulf of Eridanos, leaving behind a grave resembling a small but deep lake.

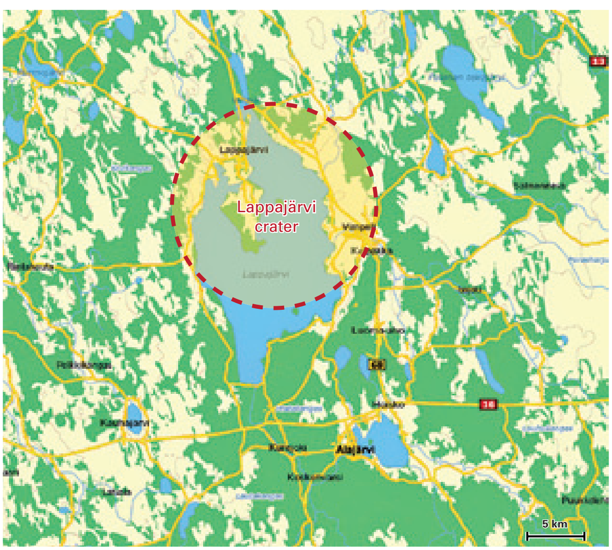
How to get here: An airport is located in Kuressaare but most visitors probably come from Tallinn from where you can take a bus to Kuressaare. Once on Saaremaa there are busses from Kuressaare to Kaali.

Kaali Visitor Centre

7.2.2. Lappajärvi, Finland

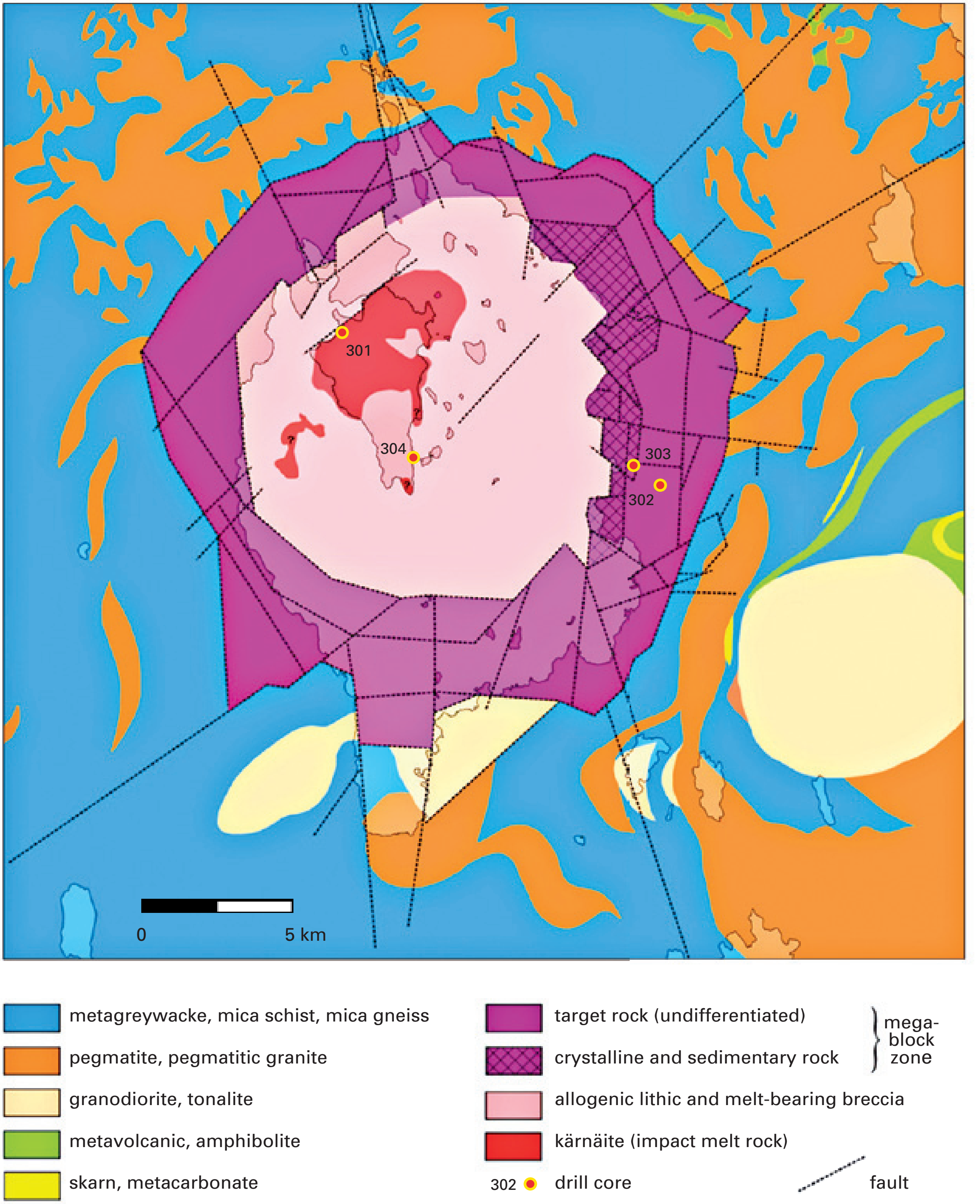
Location: The Lappajärvi impact structure is located in western Finland, about 350 km north of Helsinki and 190 km from Tampere; coordinates 63°10´N, 23°40´E.

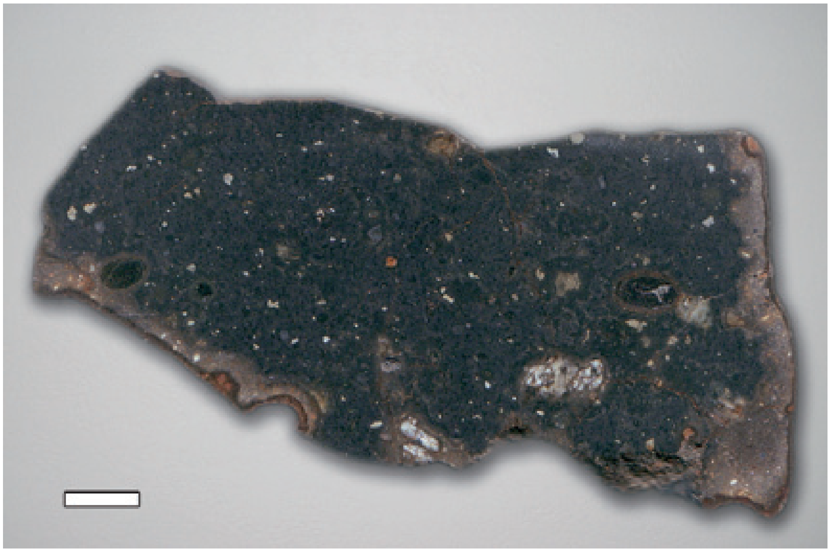
Age: The age of the structure is 77-78 Ma old (Upper Cretaceous).



Description of the crater area: An elliptical lake that is 23 km long in the north-south direction and 12 km wide occupies the structure. Because of its large size, which is unusual for the region, the lake offers great scenic views and recreational value. It also serves as a reservoir for drinking water and hydro-power production. A spa hotel at the northern side of the lake includes a thematic meteorite exhibition. The northern part of the lake hosts a large island, called Kärnänsaari, where the dark dense impact melt rocks are exposed and have been quarried for building stone. In 1921, these melt rocks were described as dark porphyres and called *kärnäite* by the Finnish geologist Hugo Berghell. In the 1950s the possibility of a meteoritic origin for Lappajärvi was suggested, and confirmed in 1968 through the discovery of shocked quartz in bedrock fragments enclosed in the kärnäite boulders. The Lappajärvi impact crater is 22-23 km wide but the structural disturbances formed by the

Opposite page; Geological map of the Lappajärvi impact structure. Lakes are indicated by shore contours and slightly lighter colouring (redrawn after Abels, 2003).


301
304
303
302
0
5 km
metagreywacke, mica schist, mica gneiss
pegmatite, pegmatitic granite
granodiorite, tonalite
metavolcanic, amphibolite
skarn, metacarbonate
target rock (undifferentiated)
crystalline and sedimentary rock
mega-block zone
allogenic lithic and melt-bearing breccia
kärnäite (impact melt rock)
302 drill core
fault



Lappajärvi impact melt rock. Scale bar equals 1 cm. Courtesy of K. Ernstson.

Kärnänsaari hosts two drill holes, and the western coast of the lake two more, drilled for scientific purposes to compare Lappajärvi to other complex, high velocity impact formations. It was found that melted and brecciated rocks fill the more than 200 m deep depression whereas the impact melt rock forms a homogeneous lens-like body. The target rocks, the Palaeoproterozoic Svecofennian crystalline and metasedimentary rocks (granites, granodiorites, pegmatites and amphibolites) were found fractured and intersected by dikes of breccia. At the time of impact the basement was most likely thinly covered (less than 200 m) by Mesoproterozoic (circa 1200 Ma old) silt- and sandstones and Cambrian age (circa 500 Ma old) sandstones and limestones. The sedimentary rocks are found as inclusions in the impact melt and occur in the inner slopes of the structure, the so-called megablock zone.

impact are observed beyond this limit. The topography around Lappajärvi reveals a slightly elevated crater rim that is about 55 m above the lake level on the northern and western sides but as much as 106 m on the southern side. The lake is deepest along the two north-northwest-oriented troughs on the eastern and western side reaching maximum depths slightly greater than 35 m. Outside these troughs the lake is much shallower.

The composition of a dense impact melt rock called kärnäite present in the area reveals that the type of meteorite that formed Lappajärvi was an H-chondrite that was about a kilometre in diameter. Numerous boulders of kärnäites and suevites may be observed on the shores of the southern parts of the lake and can be traced in the Quaternary deposits for considerable distances to the southeast. Suevites are found in Quaternary deposits, especially in the esker and glacial tills, although only as up to 50 cm large boulders and pebbles, as well as different kinds of shocked crystalline rocks. The main source of these rocks is the bot-

Meteorite exhibition at the Spa Kivitippu, Lappajärvi.

tom of the lake Lappajärvi. Suevites are reported to include tiny (circa 0.1 mm across) white, yellowish-white, grey and black impact-produced diamonds.

How to get here: The closest airport is in Vaasa, the nearest train-station is Kauhava and buses run from Seinäjoki, Lapua and Alajärvi.

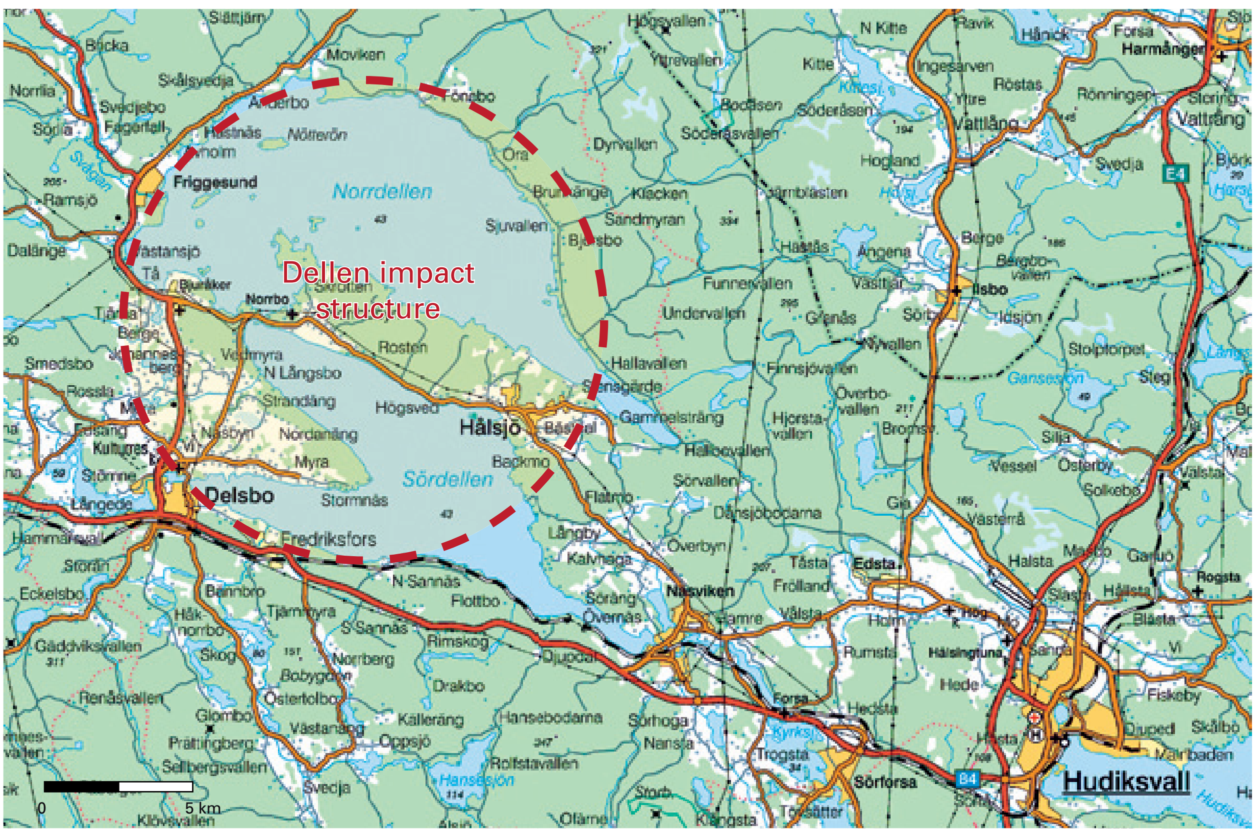
7.2.3. Dellen, Sweden

Location: The Dellen meteorite impact structure is located close to the town Delsbo in central Sweden (Hälsingland County) some 300 km north-northwest of Stockholm; coordinates 61°51´N,16°41´E.

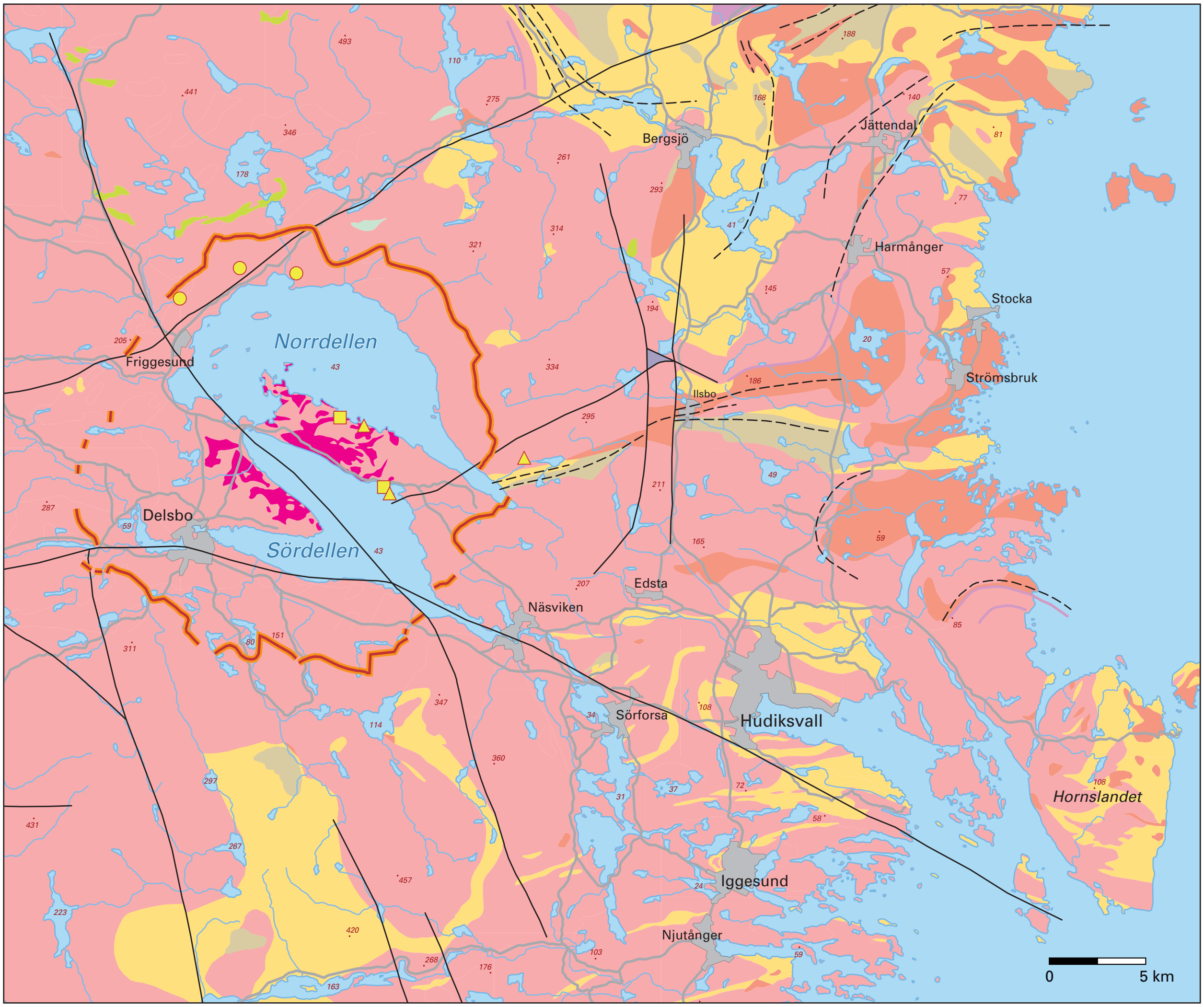
Age: The age of the crater is estimated at 89 Ma (Upper Cretaceous).

Description of the crater area: The Dellen impact structure is a rounded depression, with a rim-to-rim diameter of 19 km, hosting two large, partly curved and elongated lakes (Norra Dellen and Södra Dellen) separated by an approximately two kilometre wide isthmus called Norrbonäset. The maximum depth of the lakes is slightly over 60 m whereas the crater rim rises 50-200 m above the lake level, being higher in the northern, north-eastern, and eastern sides. The rim hosts numerous impact-associated radial and transverse fractures.

The structure was first (Svenonius in 1888) described as the remnant of a Tertiary volcano by findings of exposures and boulders of *dellenite* that, at that time,



Location of the Dellen impact structure near Hudiksvall, central Sweden. Background map from Lantmäteriet.



Mesozoic 250 – 66 Ma

89 Ma impact melt rock

Mesoproterozoic 1600 – 1000 Ma

diabase

sedimentary rock (sandstone, greywacke, shale etc.)

Paleoproterozoic ca 1870 – 1660 Ma

basic intrusive rock (gabbro, diorite etc.)

basic volcanic rock (basalt etc.)

acid to intermediate intrusive rock (granite etc.)

basic metavolcanic rock

acid to intermediate intrusive rock (granite etc.)

Paleoproterozoic ca 1960 – 1860 Ma

sedimentary rock (sandstone, greywacke etc.)

metamorphosed rock (gneiss, schist etc.)

ductile shear zone

brittle deformation (fault, fracture, fracture zone)

Dellen crater data (after Henkel, 1992)

topographic rim of the crater

dellenite outcrop

boulders of glass

pseudotachylite

View from Avholmsberget over the Dellen Lake. Photo: H. Stehlik

were interpreted as tuff breccias, devitrified lavas, and glassy lavas. An impact origin for Dellen was first suggested in 1910. Later, in 1963, Fredriksson and Wickman drew attention to the similarity of boulders found in Dellen to corresponding samples from the Ries Basin in Germany and Lake Mien in Sweden. In 1968, Svensson proved the impact origin of Dellen by the discovery of planar elements in shocked quartz from Precambrian fragments in a boulder of impact breccia.

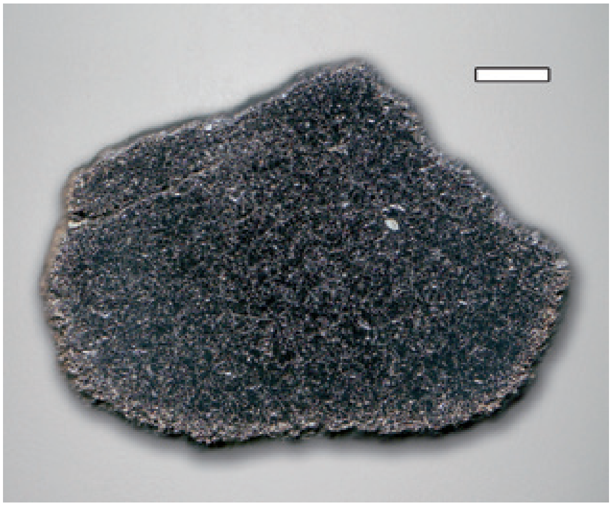
The Dellen structure was formed in granitic rocks, with an estimated age of 1800 Ma, that cover much of the area. The rock is called the Ljusdal granite which in a pre- to early stage of the Svecofennian mountain building intruded into the circa 1880 Ma old turbiditic metagreywackes and has subsequently been affected by Svecokarelian regional metamorphism and deformation. The granodioritic granite at the impact site is fairly homogeneous, consisting mainly of quartz, potassium feldspar, and biotite. The area was subjected to erosion, but, most likely, was also covered by sediments for short time periods.

Dellen crater elements projected on a simplified bedrock map from the Geological Survey of Sweden.

Because no sedimentary fragments are reported in the crater-fill breccias, a dominantly crystalline target for the Dellen impact is suggested. Most of the transported sedimentary infill (breccias, suevites and impact melt rocks) is buried under water or Quaternary sediments. The central part of the structure is occupied by an almost circular impact melt sheet of considerable thickness – estimated to be up to 500 m thick. The melt sheet is mostly buried as there are only two exposures of melt rocks on the northern side of the Norrbonäset isthmus, which continue under the water. So far, boulders of polymict breccias and melt rocks are found in a few stone heaps, collected from the surrounding arable land by farmers, in one location only west of Södra Dellen. Brecciated and melted rocks are also found on the shores of the small islands in Norra Dellen. During the Pleistocene glaciations, Dellen suffered from selective erosion, in other words the glacier shaped the landscape differently according to the mechanical strength of the underlying rocks. Transported breccias were more easily eroded, especially in the direction of the glacier movement (which during the latest glaciation was northwest-southeast), whereas the harder impact melt rocks were less affected.

A small town called Delsbo is located in the south-western quarter of the crater. The best view over the Dellen lakes and crater can be obtained from the inner slope of the crater rim at the northwestern side, from a place called Avholmsberget (the mountain of Avholm).

How to get here: The closest airports are in Östersund and Stockholm from where you can take a train to Hudiksvall and then a local bus from Hudiksvall to Delsbo. However, the localities are spread out over a large area and you need your own transport in order to get a proper overview of the crater area.



Dellenite – impact melt rock. Scale bar equals 1 cm. Courtesy of K. Ernstson.

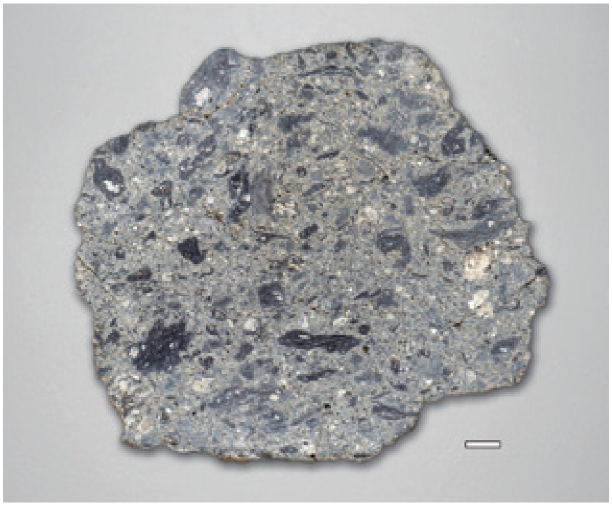
7.2.4. Mien, Sweden

Location: Lake Mien is situated 30 km north of the town of Karlshamn in southern Sweden; coordinates 56°25´N, 14°52´E.

Age: The age of the crater is estimated at 121 Ma (Lower Cretaceous).

Description of the crater area: The crater lake has a more rhombic than circular form and is about 5 km in diameter, has a maximum depth of almost 40 m on the northern side, and has a small island (Ramsö) in its north-western part. The lake fills a depression in the Precambrian basement rocks consisting mainly of granites and gneisses. According to drilling data from

Panoramic view of Lake Mien with Ramsö island. Photo: T. Bauert



Suevite from Lake Mien impact structure.
Scale bar equals 1 cm. Courtesy of K. Ernstson.

Location of the Mien impact structure in Skåne, southern Sweden. Background map from Lantmäteriet.

1968, the depression is filled with impact-associated melt rocks and breccias that are overlaid by later glacial deposits. Prior to the drillings, impactites were found along the southern and south-eastern shores of Lake Mien (described first by Holst in 1890 as rhyolites). The rhyolitic and breccia boulders that consist of the same crystalline material as the bedrock in the near vicinity of the lake have thus been transported by the ice from the area that is today occupied by the lake.

The very first suggestion for an impact origin of Lake Mien was made in 1910. Unfortunately, other explanations, such that it was the remnant of a volcano or a maar structure were used until 1965, when Svensson and Wickman identified coesite (a type of quartz

that is formed at high pressure) in material originating from Lake Mien. This discovery was immediately supported by findings of multiple sets of deformation lamellae in quartz grains in the breccia boulders. Impact melt rocks from Mien are reported as being marginally enriched in iridium but also in chromium, indicating a stony meteorite as the impacting projectile.

How to get here: The closest airport is Ronneby-Kallinge near Karlskrona and the closest train station is Karlshamn. Mien is located close to road 29.

7.2.5. Lumparn, Finland

Location: Lumparn is a bay surrounded by land on Åland, Finland; coordinates 60°09′N, 20°08′E.

Age: 360-1250 Ma old (Carboniferous-Mesoproterozoic).

Description of the crater area: The Åland islands form an archipelago that extends from Finland and continues almost all the way across to Sweden. The archipelago consists of almost 300 habitable islands of which the main island is called Åland. A large (circa 85 km²) rhomb-shaped bay in the middle of Åland, bordered by the municipalities of Sund to the north, Lumparland to the east, Lemland to the south and Jomala to the west, hosts the deeply excavated Lumparn crater. The crater is about 6.8 km wide and was formed by a meteorite that was about half a kilometre in diameter. The bay is rather shallow, being less than 20 m deep, making the waves choppy and dangerous for boats.

Unusual geological features such as frequent limestone boulders on the southern shore, an in-place 500 m long limestone shoal called *Kalkhällen* in the northern part of the bay (exposed at low water only), and breccia occurrences near the village Önningby already attracted geologists a century ago. The curiosity among the scientists had a simple explanation;

Heavily fractured and brecciated rapakivi granite at Tällnäs. Photo: T. Bauert.

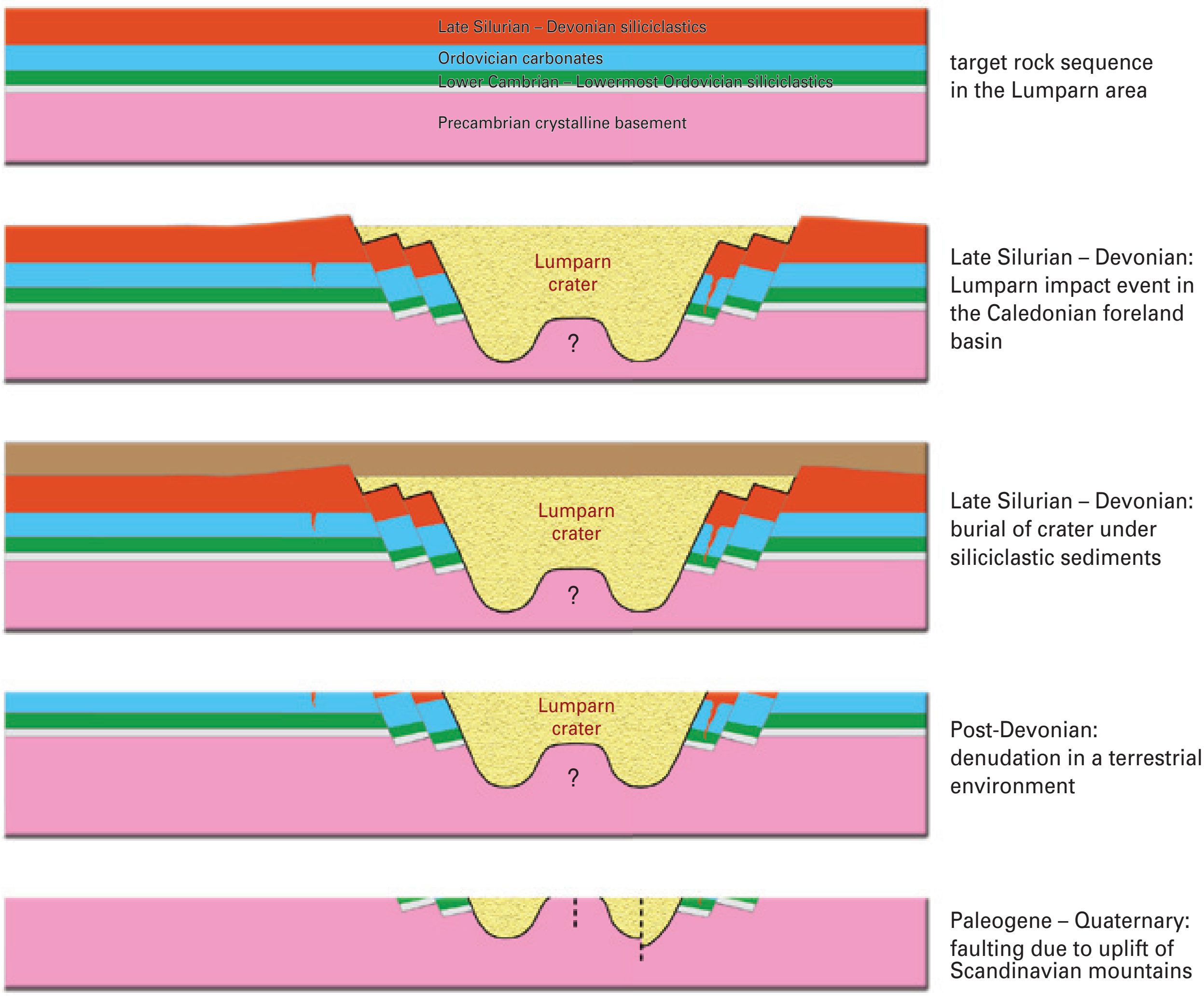
Location of the Lumparn impact structure on Åland islands.

Geology around Lumparn Bay. The Kalkhällen shoal close to northern shore is marked with "x" (adapted from Fig. 5.5 in Abels, 2003).


Tosarby
Smedsbole
Bomarsund
Stornäset
Tranvik
Norrskogen
Näsudden
Mickelsö
x
Kalkhällen
Lumpo udd
Röda kon
Lumparn Bay
Norrboda
Österkalmare
Nordanberg
Långnäs udd
Vindar-
berget
Tullen
Tällnäs
Önningby
Segelgrundet
Klockars
Kungsnäs
Rödhäll
Krokstad
Holmsudden
Önningby-
fjärden
Bock-
holm
Skag
Bastvik
Norrby
Pellas
Knutsboda
Rörstorp
Söderby
0
2 km
quartz-porphyritic hornblende rapakivi
hornblende rapakivi
normal rapakivi (wiborgite)
even-grained rapakivi
impact-related
disturbance

the closest limestone occurrence is reported in the Gävle Bay in Sweden as far away as 165 km from Åland – so where did the limestone come from? For a long time, the commonly accepted explanation for the Lumparn structure was that it was a down-faulted basin overridden by Pleistocene glaciations. In 1979, Glen Merrill (at that time professor at the College of Charleston, USA) studied the limestones by palaeontological means and suggested for the first time an impact origin for Lumparn. In 1992, Svensson succeeded in confirming the impact origin on the basis of shock features in brecciated material from drill-core in the central part of the bay.

The Lumparn structure hosts several drill-holes, some of which have revealed Cambrian sands, allogenic impact breccias and some traces of suevite within the crater under the Lumparn Bay. A central uplift is indicated by a central drillcore that encountered strongly shocked granites below Pleistocene drift. The age relationship between the Ordovician Kalkhällen



Possible sequence of events affecting the Lumparn area (based on Fig 5.72 in Abels, 2003).

limestones and the impact is still not clarified: did sedimentation take place before or after the impact? The upper age is limited to the Mesozoic because a Lumparn-sized crater with preserved allogenic breccias would have been completely eroded without protective burial under molasse in a Caledonian foreland basin in Late Silurian to Devonian. As no Jotnian rocks were encountered in the drillings, the impact event is younger than 1250 Ma.

How to get here: The closest airport is in Mariehamn but there are frequent cruise ferries arriving from Stockholm, Helsinki and Tallinn and also other ports.

Subhorizontally exposed rapakivi breccia at Rödhäll (below). Close-up of breccia sill is shown on upper right. The large, subangular granite clast in the centre is about 20x10 cm in size. Photos: T. Bauert.

7.2.6. Siljan, Sweden

Location: The Siljan ring impact structure is located in Dalarna county, in central Sweden; coordinates 61º05′N, 15º00′E.

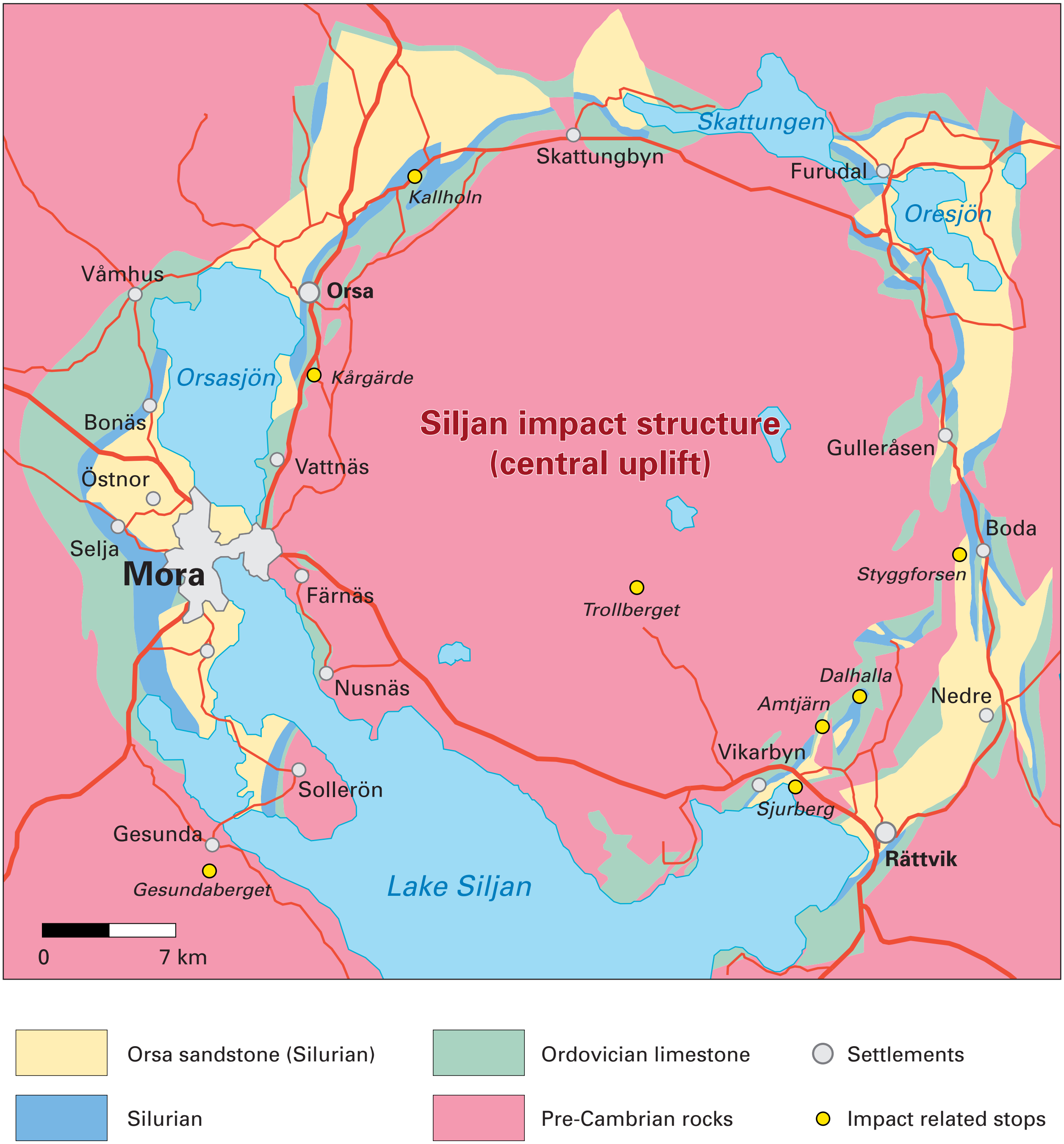
Age: The most recent dating of the impact gives an age of 377 Ma (Upper Devonian).

Description of the crater area: Siljan is the largest impact structure in Western Europe. This well-known circular impact structure is sufficiently big to be notable already at first glance of a geological map of Sweden. Impact events of comparable magnitude to the Siljan impact take place at a rate of about one impact every 10-20 million years. The central topographic high (the 28-30 km diameter central uplift of the complex impact structure) of the present structure is composed mainly of Proterozoic granites. It is surrounded by a relatively depressed circular (up to a diameter of about 44 km) zone where Palaeozoic (Ordovician and Silurian) pre-impact sediments are exposed. The depression, also called the ring basin, is dominated by a series of lakes that are wider in the southern part (Lake Siljan, is Sweden's sixth largest lake) and narrower in the north (Lake Skattungen). Because the structure itself is eroded (it is estimated that between 400 m and 4 km of overlying material has been removed) the original rim diameter of the structure is difficult to estimate. The estimates of the original size range from 52 km (just including the ring basin) to 75 km (based on the highest topography of the hills surrounding the basin). Looking towards the south along the northwestern slope provides the best view over the generally flat inner structure with the southern margin forming the horizon.

Exposure is extremely poor in much of the Siljan structure. Consequently, little material that could be used to obtain a reliable age for impact has been produced. Impact melt breccias within the central uplift are however found in few localities.

Location of the Siljan impact structure in Dalarna, central Sweden. Background map from Lantmäteriet.

The idea that this easily seen, peculiar structure was formed by an impact was first formulated in 1963. The final evidence for interpreting the Siljan ring as a meteorite impact structure came in the form of shocked quartz and was presented by Svensson in 1971, who already suggested a post-Silurian (less than 416 Ma old) age for the impact event. Also, as evidence for an impact, shatter cones and small melt veinlets have been observed throughout the uplifted central part of the structure and some peripheral locations. Re-appraisal of the impact idea came with the launching of the Deep Gas Project by a consortium in 1982. It was initiated in order to investigate the controversial hypothesis that hydrocarbons might seep from the mantle into near-surface impact-deformed basement along the deep fractures in the case where the impact has been sufficiently large to have penetrated the entire crust. The project resulted in large quantities of data collected from several shallow (down to almost 800 m depth) and two deeper drillholes (the 6.8 km deep Gravberg-1 drillhole near



Siljan geological map. Distribution of the main rock types in the Siljan impact structure. The central uplift consists of mainly granites with some volcanic and sedimentary rocks. The central uplift is 25-30 km in diameter and is surrounded by a ring shaped depression that is 5-10 km wide and contains sedimentary rocks of Ordovician and Silurian age (adapted after Fig. 6 in Lindström et al., 2008).

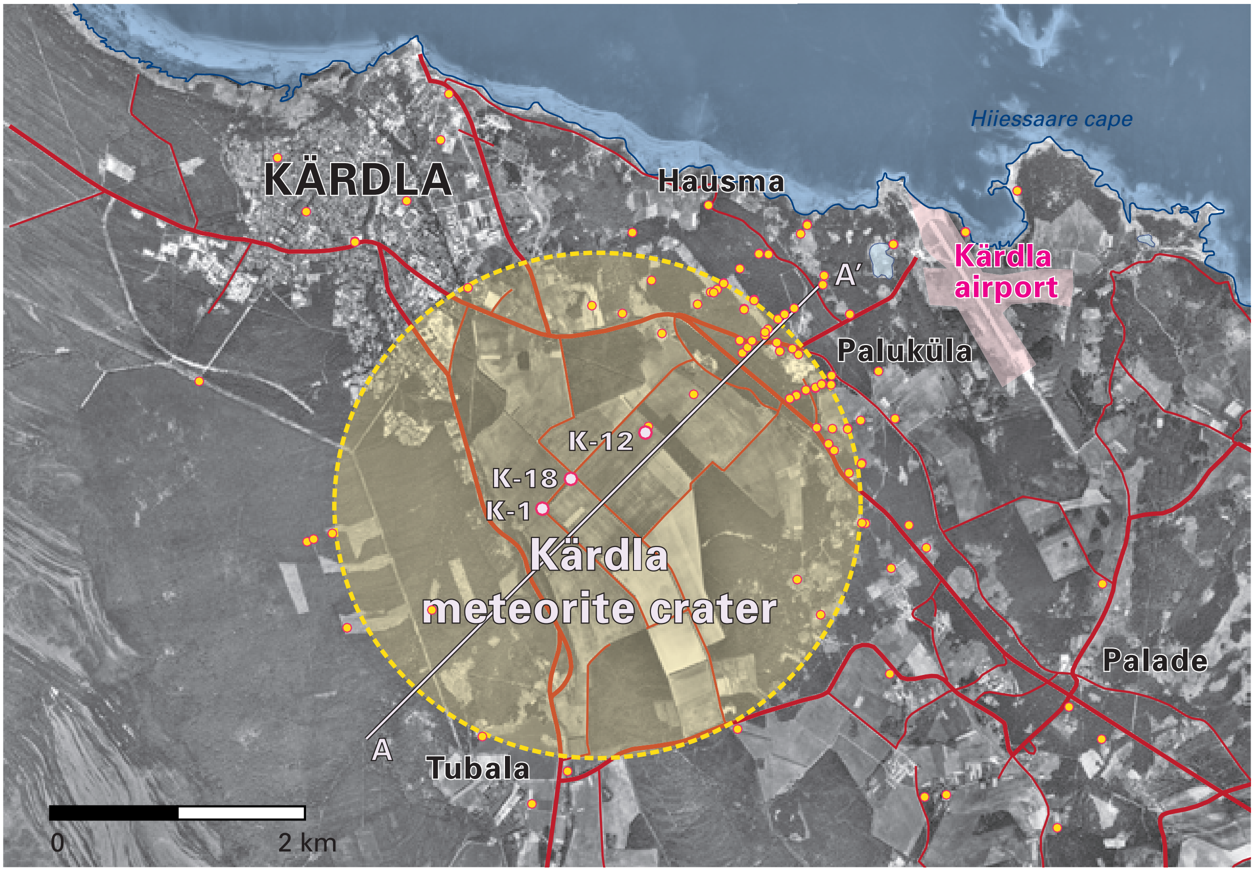
The tilted bedding in Osmundsberget quarry is a result of the Siljan meteorite impact.

the depression and the 6.5 km deep Stenberg-1 drill-hole in the central peak). The project did not result in discovery of enough hydrocarbons to be of any economic interest and was abandoned. Some impact-related hydrothermal lead and zinc mineralization does, however, occur at the outer margin, and has been mined locally about 15 km southeast from the Siljan ring in localities called Mårtanberg and Slättberg.

Siljan, as the largest impact structure in the region, has recently become of interest for studies focused on impact tectonics and geothermal energy resources. The key features of the structure such as original size, extent of impact features, and lack of impact melt rocks and prominent geophysical anomalies still remain to be fully understood. A question about a connection between the Siljan impact and a mass extinction observed at 374.5 Ma ago has been raised. However, it seems the Siljan impact is somewhat older than this age and still too small to generate a global catastrophe.

How to get here: The closest airport is Mora-Siljan and train stations are in Rättvik and Mora. The roads E45 and 70 run on either side of Lake Siljan.

Location of the Kärdla impact structure. Yellow dots denote locations of boreholes. The dashed line delineates the crater rim. A – A′ refers to the location of the impact structure cross section (adapted from Fig. 1 in Jõeleht et al., 2005).



7.2.7. Kärdla, Estonia

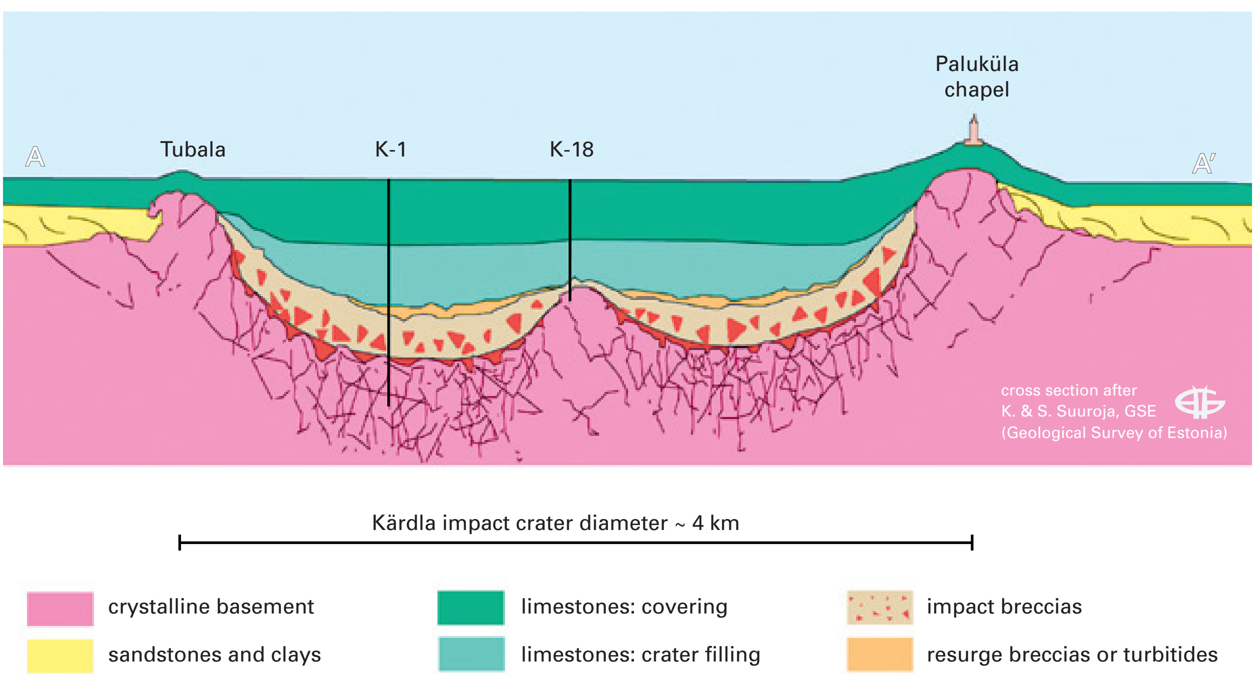
Location: The Kärdla impact crater is located on the island of Hiiumaa in western Estonia; coordinates 58°59′N, 22°48′E.

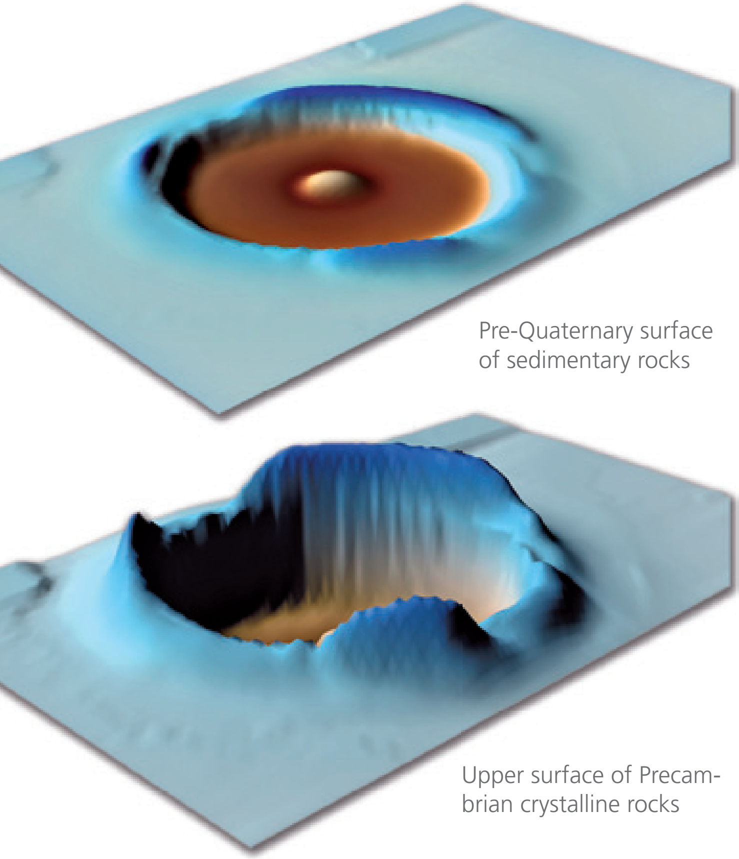
Age: The age is estimated at about 455 Ma old (Upper Ordovician).

Description of the crater area: The very first clues that the Kärdla impact crater existed were discovered by Eichwald (1843) and Schrenk (1854) who described abnormally tilted limestones in a quarry in Paluküla, a village at the northeastern rim of the Kärdla crater. They drew attention to the 20 degree tilt of the rocks in the quarry, the normal tilt of Estonian sedimentary rocks being less than 1 degree. At the beginning of 1967 crystalline rocks were discovered in Paluküla while drilling a well for ground-water. The crystalline rocks occur at a very shallow depth of 22 m in a region where crystalline rocks are typically located at a depth of 200 m. As is now known this well penetrated the rim of the crater under the very thin post-impact cover of Ordovician limestone. However, at that time the geological feature was interpreted in connection with tectonic movements connected to the Caledonian mountain building 400-500 Ma ago. The discovery initiated a search for crystalline rocks that could be used for building stone. This included an intensive drilling programme, and gravity and ground magnetic mapping that, in 1972, revealed a crater structure 4 km in diameter. In 1980 the meteorite impact origin of Kärdla was proved by the discovery of shocked quartz from the impact breccia.

The Kärdla impact took place in an epicontinental sea and penetrated the Precambrian crystalline basement to a depth of 280 m, after piercing the 140 m thick Ordovician and Cambrian sedimentary cover. The event took place about 455 Ma ago (dated using the fossil graptolite *Diplograptus multidens*) and the cra-

The Kärdla impact structure cross section.



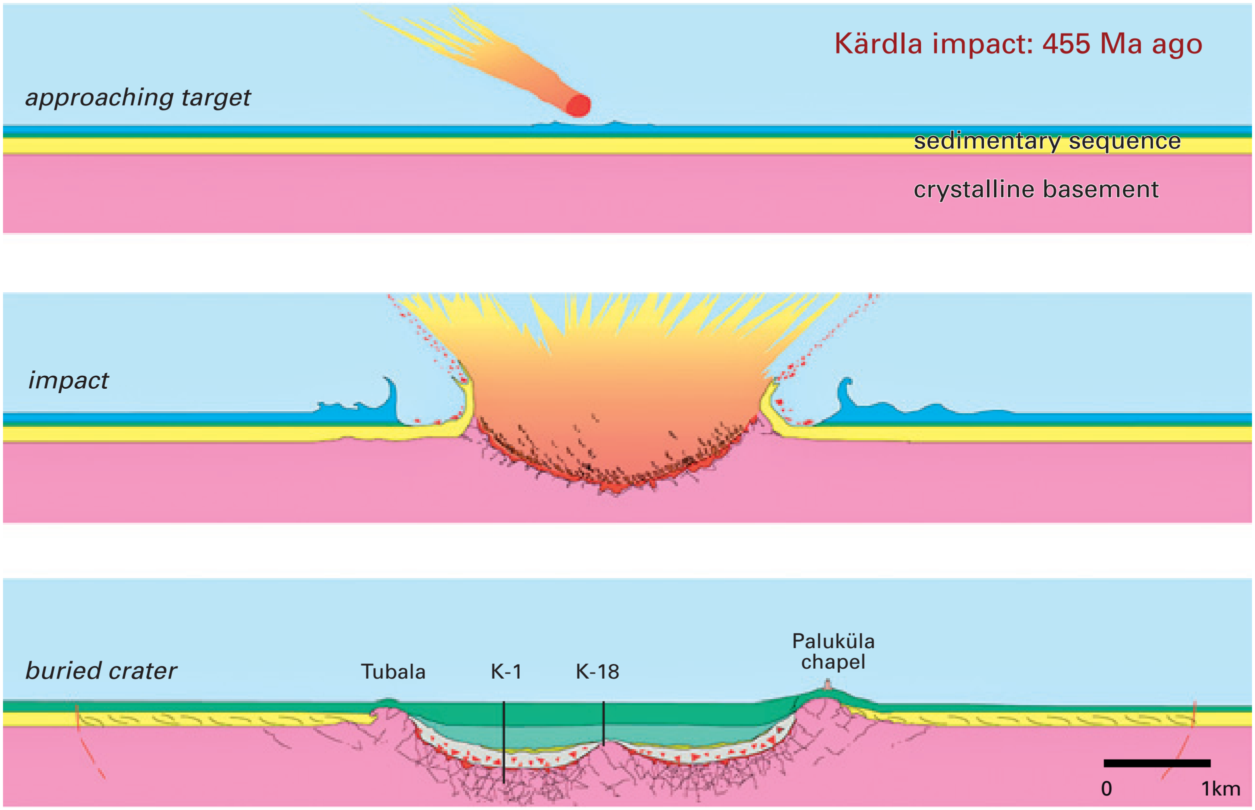


Digital elevation models of the Kärdla crater (courtesy of K. & S. Suuroja, Geological Survey of Estonia)

ter therefore belongs to the series of impact structures that formed during the Middle to Late Ordovician enhanced flux of L-chondrites. The impact sculptured the crystalline basement topography: in some places, up to 250 m high. A one kilometre wide rim with a wavy top surrounds the crater, 3.5 km in diameter and 400-500 m deep. The depression is filled with allochthonous fragmental breccias, covered by resurge conglomerates, conglomeratic turbitides and sands that were eroded from the uplifted walls prior to burial. As the seawater returned to the crater minutes after the impact the water formed at least two gullies through the crystalline rim, however different extents of rim uplift and collapse seem to be the initial cause for the formation of gullies. Marine sedimentation resumed immediately after the impact and the structure was filled with sediments and the crystalline rims were completely covered after about 7 Ma. In spite of a long regional predominantly continental period from the Carboniferous to the Paleogene, Kärdla was never subjected to erosion and has preserved its inner structure perfectly. The ejecta blanket formed during the impact is also well preserved, except at the crater rim where it was eroded prior to formation of the protective sedimentary cover. The ejecta layer lies in a succession of Upper Ordovician carbonate rocks as a 1 cm to 10 m thick bed of fragmented and disintegrated Cambrian and Lower Ordovician sand, silt and clay, with a minor component of fragments from all the other lithological units of the target rocks. The thickness and grain size of the ejecta layer decreases with distance whereas the most distant occurrence was discovered in a drillcore 42 km from the crater centre.

Nowadays, owing to extensive drilling programmes during the Soviet era, Kärdla is penetrated by more than 100 drillholes that have provided scientists with a lot of data. The uplift is not recognizable from ground or from geophysical maps because of its considerable depth and lack of sufficient petrophysical contrast between the uplift and surroundings. Based on space and aerial photographs, and marine seismic reflection profiles Kärdla seems to be surrounded by an elliptical (southwest-northeast elongated) feature (a possible ring fault). The 2-8 km wide zone between the rim and ring feature is reported to be strongly disturbed, including fractured, folded and disturbed blocks.

Several natural resources are related to the Kärdla structure: crystalline building stone, chemically pure limestone and dolomitized limestone, galena and sphalerite mineralization in the crater rim, glaciolacustrine clays, sand and gravel, and high quality mineral water. Mineral water was extracted from the deeper layers in the central part of the crater, and



Sequence of cross sections showing possible formation of the Kärdla impact crater (after K. & S. Suuroja, Geological Survey of Estonia).

was for many years bottled and marketed under the trade mark *Kärdla*. Unfortunately, production ceased in 1990 for economic reasons. Limestones were quarried in Paluküla some time ago and used for building purposes.

The Kärdla crater is buried by post-impact Ordovician and Quaternary sediments and therefore it is well preserved but most of the crater is under ground and its outlines are only barely visible in the present topography. Despite the fact that the crater itself is almost completely hidden in topography, the results of four decades of research have made Kärdla known worldwide as one of the most thoroughly investigated meteorite impact structures. In order to provide the public with knowledge and information about the impact and formation of the crater, a walking trail (geotrail) with 12 stops was organised and a colour-printed booklet was published by the Geological Survey of Estonia. At the more interesting sites of the geotrail introductory posters were erected. Some bedrock exposures were cleaned up to demonstrate visible structures of the buried structure. Paluküla Hill hosts a small wooden tower presenting a view towards the fields occupying the central plain of the crater.

How to get here: A very small airport is located in Kärdla; the alternative way to travel here is by bus from Tallinn.

7.2.8. Tvären, Sweden

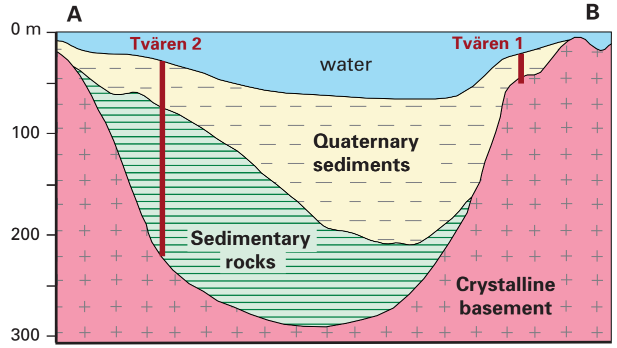
Location: The Tvären bay is located 72 km south-southwest of Stockholm; coordinates 58°46′N, 17°25′E

Age: The age is estimated at 455 Ma (Upper Ordovician) and known from biostratigraphic dating of fossil chitinozoans and conodonts.

Description of the crater area: Tvären bay constitutes an unusual morphological feature at the Swedish coast-line. The bay is almost circular (3.5 km across) but hosts an unexposed 80 m deep central circular depression, 2 km in diameter. The first impact interpretation for this unusually deep bay was made in 1963 but most of our knowledge about the structure comes from 1991, when a core (Tvären-2) was drilled near the centre of the structure. The crater is thought to have been formed by a meteorite impacting an ocean, as it hosts a lens of impact breccias formed by the resurge of water into the crater immediately after the impact. The sea must have been rather deep,

Location of the Tvären impact structure in the Tvären Bay, south of Stockholm. Background map from Lantmäteriet.

as the newly-formed crater rim did not prevent the water rushing back into the impact depression. The resurge breccias are composed of fragments of the crystalline bedrock and pieces of sedimentary rocks. The sedimentary rocks are composed of lower to middle Ordovician limestone that together with poorly lithified Cambrian sandstones occupied the sea bottom at the time of impact. The sequence of resurge deposits starts (from below) with a calcareous breccia grading upwards into finer turbiditic sandstones and mudstones. The resurge deposits contain many signs of shock metamorphism: quartz, feldspars and basement rock clasts host frequent deformation features, and minerals possibly altered by melting into clay minerals have been reported. Below the resurge breccias lies shocked crystalline bedrock and above them they are covered by post-impact marine sedimentary rocks.



Tvären crater cross section based on drillings and seismic profiles (redrawn from Fig. 2b in Frisk & Ormö, 2007). For location of Tvären 1 and Tvären 2 drill sites, see Tvären area map on next page.

How to get here: The closest airports are Arlanda and Skavsta, and the closest train station is Nyköping, close to road 219.

View to the southeast over the Tvären bay from Studsvik.
Photo: T. Bauert

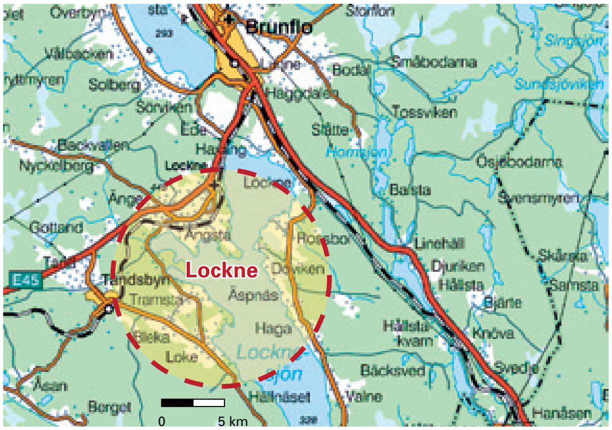
Map of the Tvären crater showing the location of the two drill cores in the structure as well as the fan of glacial erratic Dalby Limestone boulders found on the islands south of the crater (Tvären impact structure related elements are after Fig. 2a in Frisk & Ormö, 2007).

7.2.9. Lockne, Sweden

Location: The Lockne crater is situated about 20 km south of the town of Östersund, Jämtland, central Sweden; coordinates 63°00′N, 14°49′E

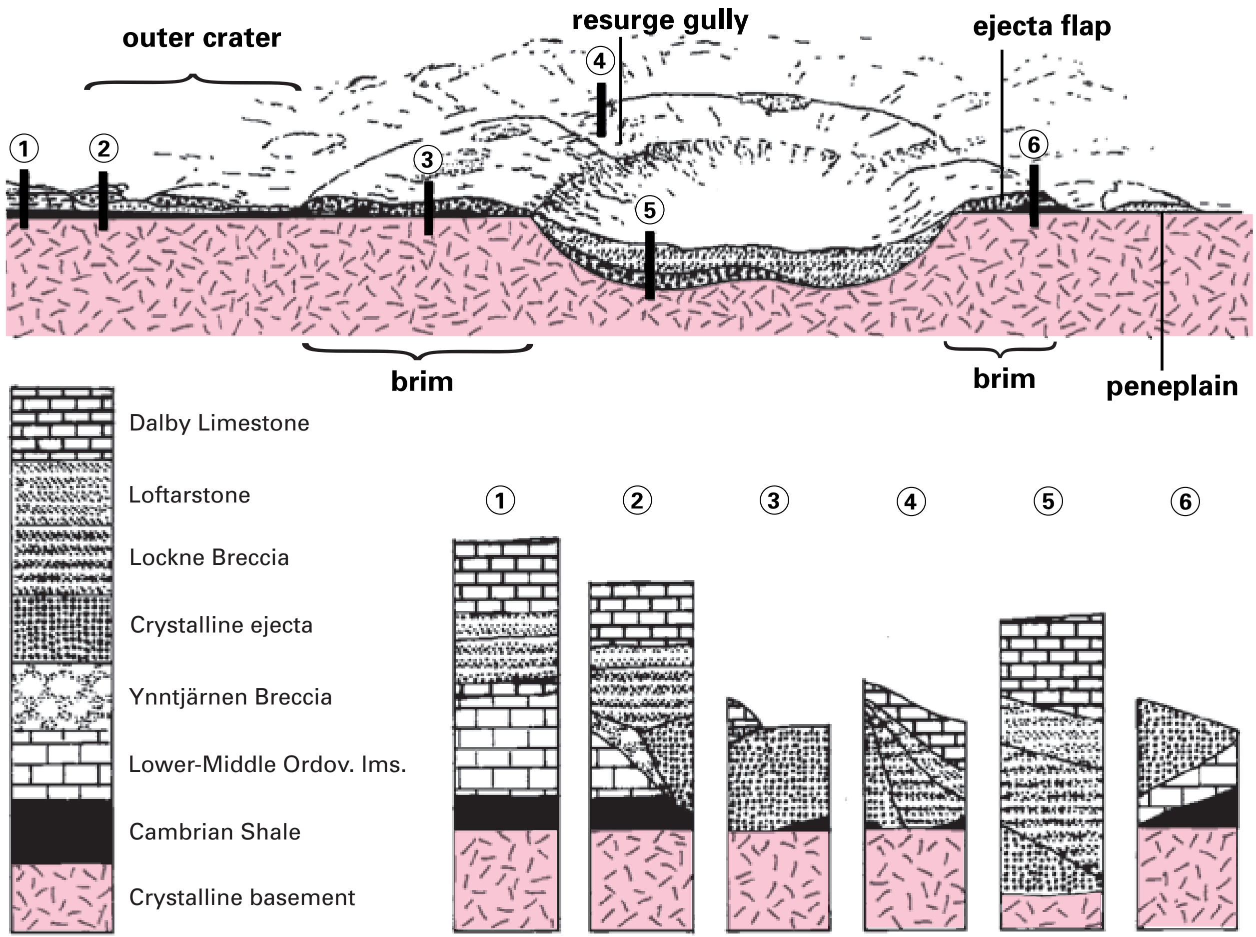
Age: The age is estimated at 458 Ma (Upper Ordovician).

Description of the crater area: The Lockne crater has a more than 7 km wide central depression that surrounds the northern part of the lake Lockne (Locknesjön). At the time of impact, a crystalline basement consisting of granitic rocks of mid- to late Proterozoic age (1800-1200 Ma) was covered by Cambrian and Ordovician sedimentary rocks about 80 m thick and relatively deep (500-800 m) sea water. The area of impact was on the continental margin of the palaeocontinent Baltica next to the Iapetus Ocean – an ocean that was later eliminated during the Caledo-



Location of the Lockne impact structure near Östersund, northern Sweden. Background map from Lantmäteriet.

M. Lindström introducing the Lockne impact structure in 2007.



Principal stratigraphy and terminology used for the Lockne crater. The sketch of the crater leaves out any tectonic complications and is intended to show only very generalized features, such as the relation of the principal structures to the sub-Cambrian peneplain (after Lindström et al., 2005).

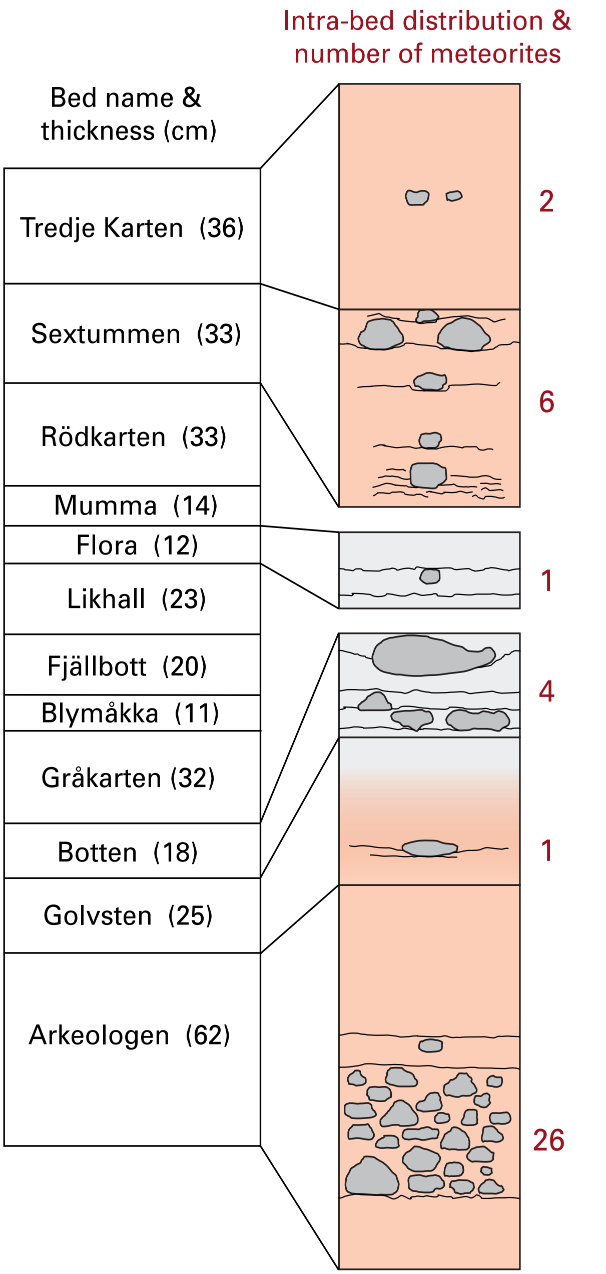
nian orogeny. Because of the deep water, the oblique impact by a several hundred meter wide chondritic meteorite created a huge tsunami wave that soon resurged back into the newly-formed crater. The fast-flowing water eroded the rocks it travelled across and created radial furrows (resurge gullies) through the crater rim. The resurge currents created a distinct marker bed (called Lockne Breccia and Loftarsten) in the surroundings of the crater, and this bed can be seen today in several exposures and limestone quarries in the area. Below the resurge breccias the Tandsbyn Breccia that consists of intensely fractured local Proterozoic rocks, and shattered basement rocks are found. After its formation the crater was covered by further marine sedimentation.

In the Silurian, the orogenic Caledonian movements reached the Lockne area and the crater was covered by rocks transported from other areas (nappes). The emplacement of nappes on top of the Lockne structure helped to preserve it from erosion, thus the preservation of the crater is excellent and the exposure

is reasonable. Nowadays, the Lockne impact site is located at the boundary between the Caledonides and the exposed crystalline basement of the Baltic Shield, and most of the nappes are eroded away. However, a remnant of a nappe is still situated in the central part of Lockne. The centre of the crater can be placed in the vicinity of Tramsta farm, northwestern coast of Locknesjön. The eastern part of the crater is situated in the lake and on its eastern shore. The structure is topographically pronounced as a three-quarter-circle with the northern, western and southern margins forming the crater wall that rises up to 140 m above the lake.

Ynntjärnen Breccia resting on autochthonous Middle Ordovician Limestone. Road section near Kajan, Tandsbyn. Photo: J. Ormö.

How to get here: The closest airport and train-stop is in Östersund, train also stops in Tandsbyn. Regional buses run from Östersund to Ångsta where a crater museum is established. The museum introduces the geology of the area, the Lockne crater, and its bedrock. The impact process is illustrated by modern advanced animation.



In total, 40 fossil meteorites weighing 7.7 kg of have been recovered from the Thorsberg quarry, most of them from the bed referred to as Arkeologen. The distribution of the meteorites within the rock succession show that there have been at least 12 different falls over a period of less than 1.75 Ma (after Fig. 2 in Schmitz et al., 2001).

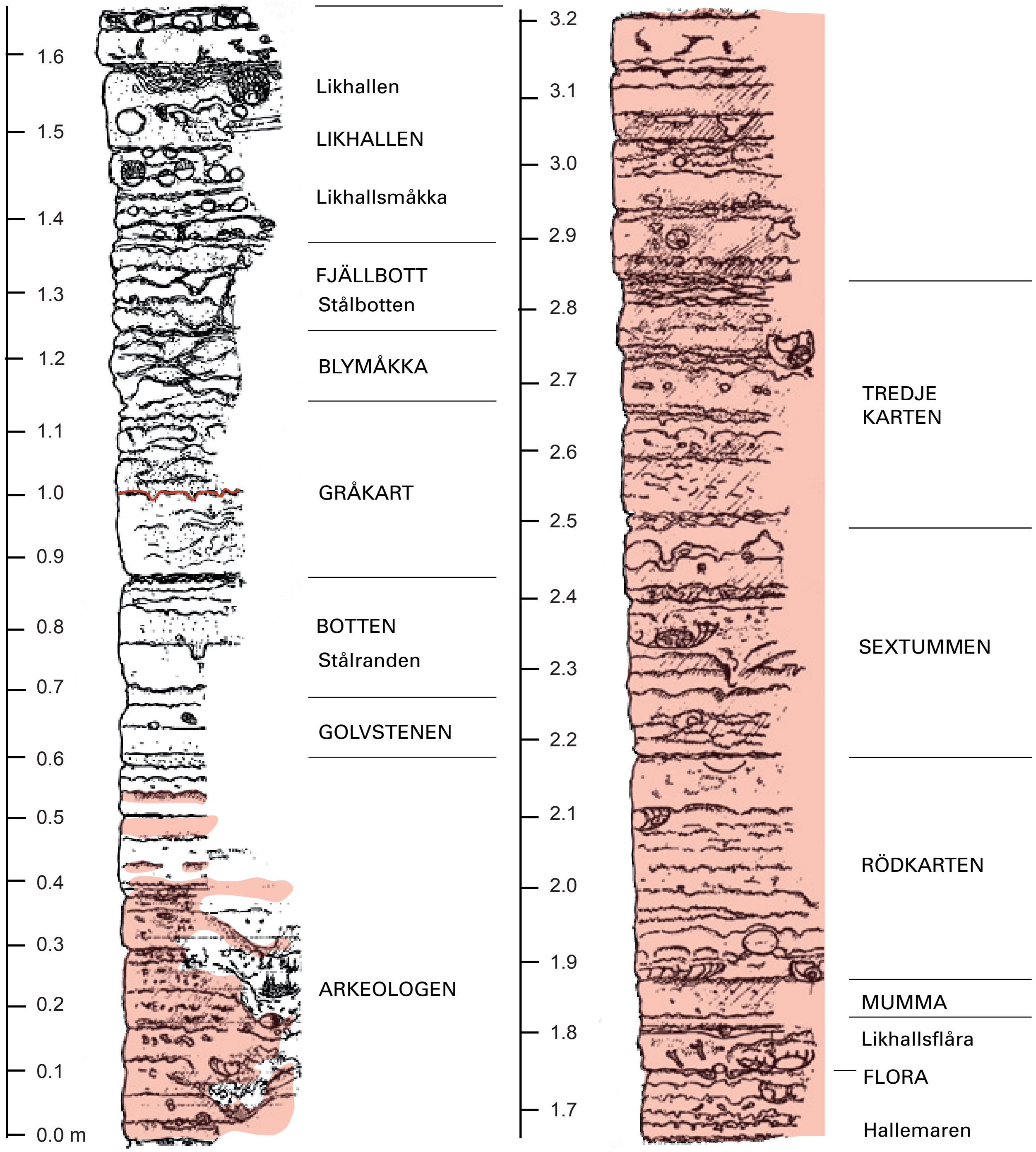
7.2.10. Thorsberg quarry, Sweden

Location: Kinnekulle, Götene Municipality, Southern Sweden; 130 km northeast of Göteborg; coordinates 58°35′N, 13°26′E.

Age: The fossil meteorites in the quarry impacted Earth during a period of a few million years about 470 Ma ago (Middle Ordovician).

Description: The Thorsberg quarry is actually not a crater but a rather unusual place where fossil meteorites are found embedded in Middle Ordovician limestone. The quarry is attached to one of many stonemasons that used to be active in the area but is the only one that is still operating today. It produces mainly polished limestone slabs used for indoor decoration. The first fossil meteorite was discovered in the Thorsberg quarry in 1988. The meteorite is called the Österplana meteorite and was found among the limestone plates that had been discarded because they were blemished and therefore not wanted for building stones. Since 1993, when a project of identifying the meteorites within the limestone was started, tens of fossil meteorites up to 21cm in diameter have been discovered. Nowadays, the workers and own-

Location of the Thorsberg quarry in Kinnekulle area, southern Sweden. Background map from Lantmäteriet.



The sedimentary succession in the Thorsberg quarry. The names are those used by the local stone-mason. Colour shows the distribution of mostly grey (lower) and red (upper) limestone in the area (after Fig. 6 in Lindström et al., 2008).

ers of the quarry and sawing factory are trained to look out for meteorites, which are usually found during sawing but occasionally discovered on exposed surfaces in the quarry.

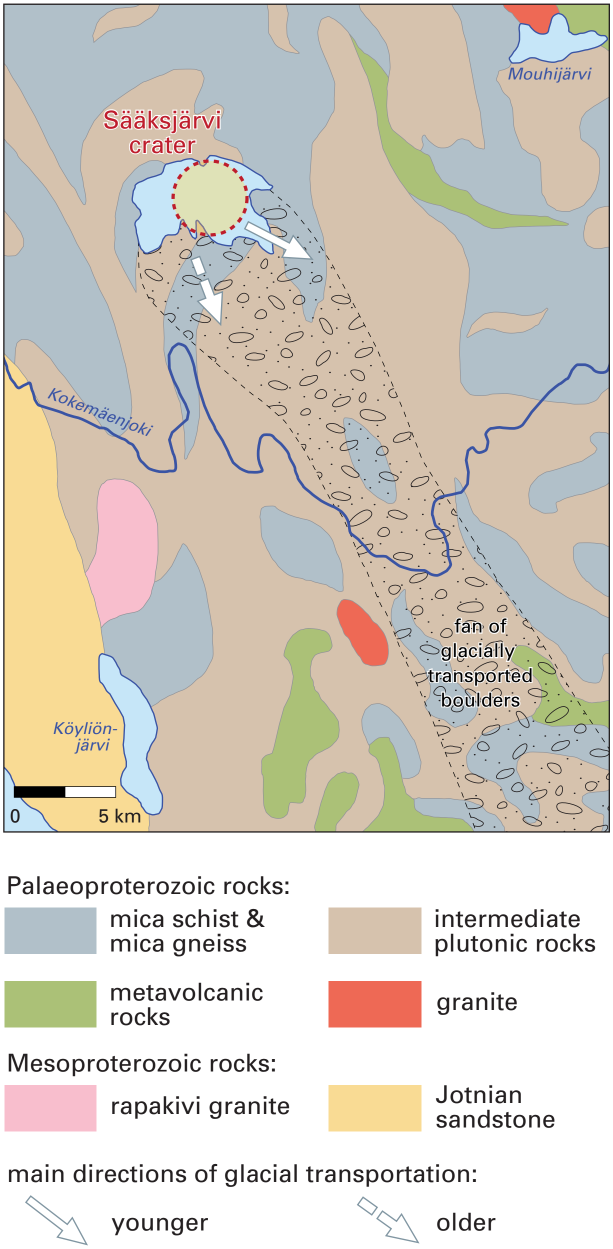
The quarried Orthoceratite Limestone was deposited in an epicontinental sea that covered most of the region in the Ordovician Period. This condensed limestone formed at a very slow rate of one to a few mm per 1000 years; thus, the actively quarried 3.2 m vertical sequence of rock represents a time span of about 1.75 Ma. Meteorites are typically found on hard grounds, where they accumulated together with abundant nautiloid shells. Fragile nautiloid shells are commonly well-preserved, ruling out the possibility that the meteorites were transported to this area, for example by bottom currents. Geochemical studies of the Thorsberg meteorites indicate that most of them are L-chondrites representing a large number of individual falls, thus hinting at the disruption of a larger parent asteroid body about 470 Ma ago with a subsequent high meteorite influx. The limestone is also reported to contain abundant microscopic L-chondritic chromite grains that originate primarily from micrometeorites decomposing on the seafloor. Such findings from rock sequences younger than 470 Ma are not limited to Thorsberg but are present worldwide, suggesting at a process that influenced the whole globe.

Fossil stony meteorites (L-chondrites) from the Thorsberg quarry: **above** – Gla-003 (17x23 mm in size) from the Glaskarten bed; **right** – Österplana 018 / Ark-018 (40x33 mm in size) from the Arkeologen bed. Courtesy of M. Tassinari. Photos: T. Bauert.

How to get here: The closest airport is Göteborg whereas the closest towns with train connection are Mariestad and Lidköping.

7.2.11. Sääksjärvi, Finland

Location: The Sääksjärvi impact structure is located in south-western Finland about 200 km northwest from Helsinki and 75 km from Tampere; coordinates 61°24′N, 22°24′E.

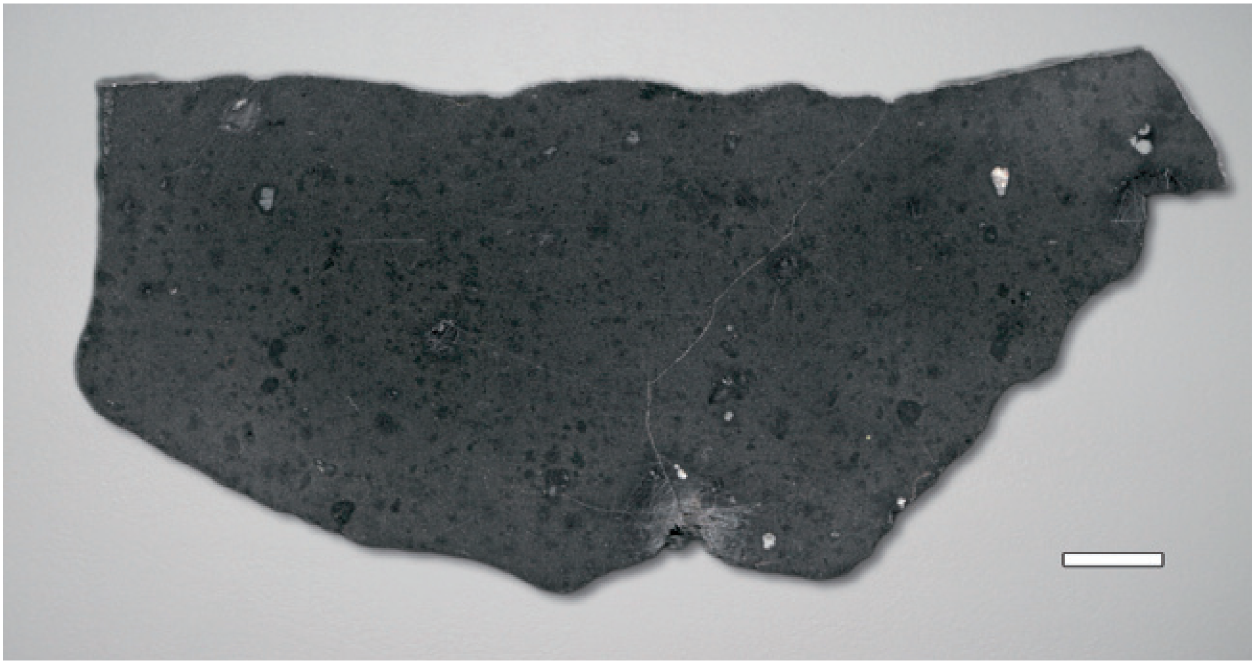


Location of the Sääksjärvi impact structure east of Pori town, southwestern Finland.

Age: Around 500-520 Ma old (Lower Cambrian).

Description of the crater area: The Sääksjärvi structure consists of a crater that is 5 km in diameter according to geophysical data. A meteorite impact origin was proved by Finnish geologist Heikki Papunen in 1969. The interpretation was based on the discovery of impact-produced agate pebbles occurring in glaciofluvial material, traceable for at least 50 km southwest from the crater. Nowadays, this old crater hosts a lake and is somewhat eroded. However, the crater depression that was formed in the Svecofennian 1900 Ma old crystalline bedrock is filled with a variety of impactites: breccias, suevites and melt rocks. These impact-associated rocks can only be seen in drillcores and are not exposed anywhere in the area, but boulders of breccias and melt-containing rocks are found in great numbers along the

Geological map of the Sääksjärvi impact crater area (based on Fig. 1 in Kinnunen & Lindqvist, 1998).



Impact melt rock from the Sääksjärvi structure area. Scale bar equals 1 cm. Courtesy of K. Ernstson.

shore line of Lake Sääksjärvi, particularly southeast of the lake. Geochemical studies of metal elements from impact melt rocks suggest that the Sääksjärvi projectile was most likely a chondritic stony meteorite.

How to get here: The closest airport and train-stop is in Pori; the crater is located south of highway 11.

7.2.12. Söderfjärden, Finland

Location: Söderfjärden is located in southern Ostrobothnia, central-west Finland close to Vaasa; coordinates 63°01′N, 21°36′E.

Age: Approximately 530 Ma old (Lower Cambrian).

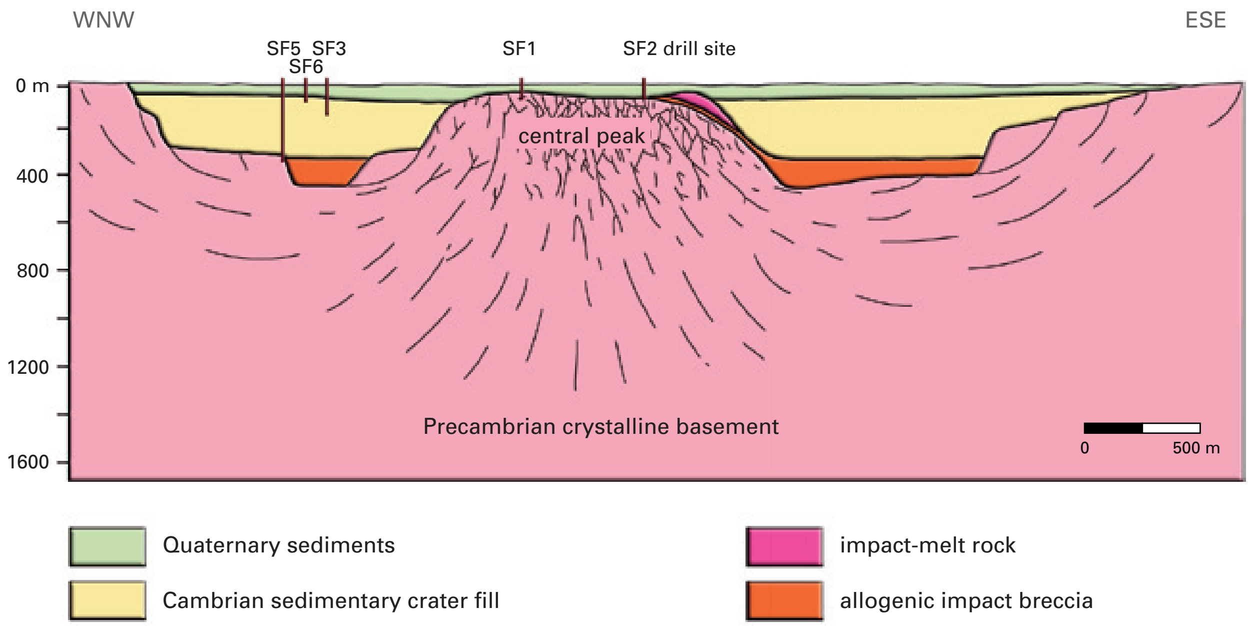
Description of the crater area: Söderfjärden (which means southern bay in Swedish) is a complex impact crater that is 6.6 km wide. The northern part of this structure belongs to the town of Vaasa and the southern part belongs to the municipality of Korsholm. The structure is unusual when compared to the other

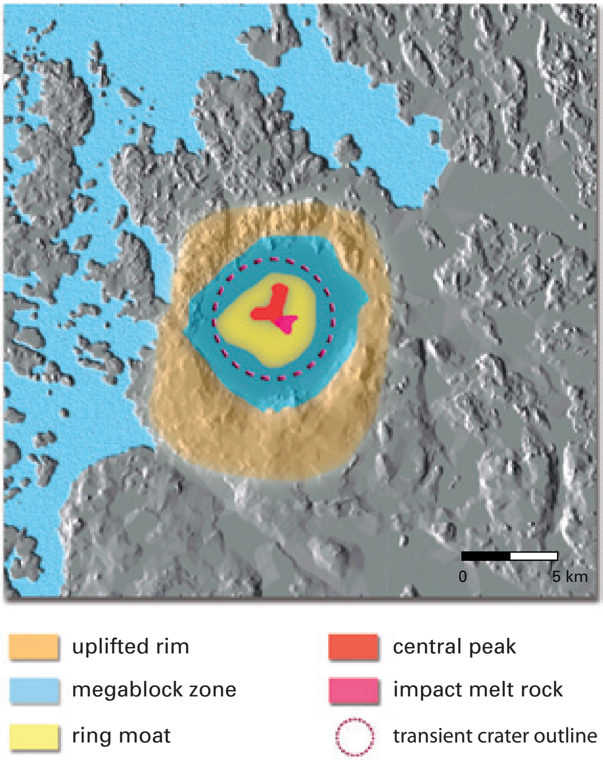
Location of the Söderfjärden and Lappajärvi impact structures close to Vaasa town, western Finland.

ten Finnish impact structures that are all associated with a water body. However, because of the land uplift (which is circa 7.6 mm per year in the area) and the proximity to the Bothnian Sea, Söderfjärden was a bay until it recently dried up in the beginning

Aerial view of Söderfjärden impact crater area (above) showing a nice pattern of radially distributed arable fields. Courtesy of Lentokuva Vallas OY / Hannu Vallas.

Schematic cross section through the Söderfjärden impact crater (based on Fig. 4.54 in Abels, 2003).



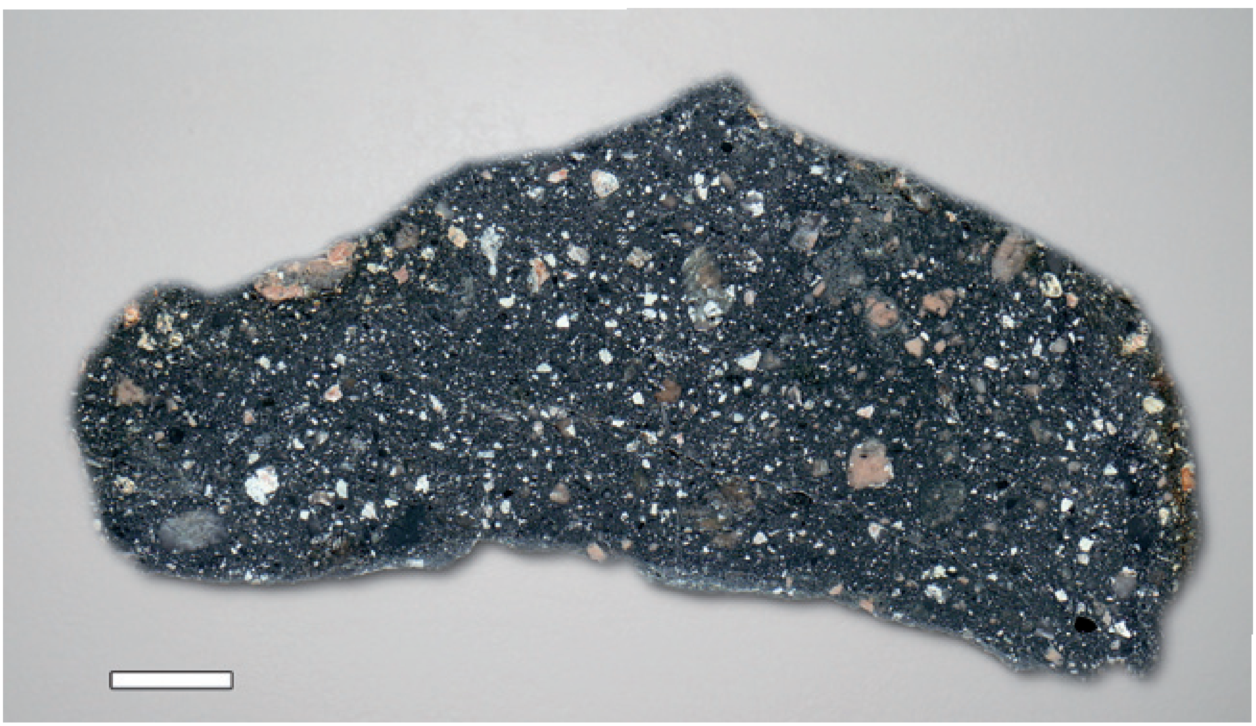


Söderfjärden crater elements on a shaded area map (based on Figs 4.34 and 4.53 in Abels, 2003).

of the 20th century. Nowadays it serves as farmland and provides a beautiful aerial view of radially distributed fields occupying a circular plain surrounded by forests.

Clearly seen on satellite images this circular agricultural plain, 5.3 km wide, has attracted the interest of geoscientists since the early 1970s. A preliminary study by Finnish geologists Jouko Talvitie and Heikki Papunen revealed erratic boulders and breccias at the crater rim. Geophysical (gravity, electric and seismic) studies revealed an unusual structure hidden in the ground. The structure was drilled in the hope of finding economically important deposits of sedimentary limestone. However, no limestones but, rather,

Lithic breccia from the Söderfjärden impact structure area. Scale bar equals 1 cm. Courtesy of K. Ernstson.



siliciclastic sediments of Cambrian age were found to overlie the brecciated Precambrian (1900–1870 Ma old) granitic bedrock within the over 400 m deep crater basin. The crater is covered by an up to 74 m thick lens of Quaternary deposits whereas the crystalline bedrock is exposed occasionally in the rim area that stands 30-35 m above the surrounding surface. Drillings and geophysical studies have revealed the presence of a buried central uplift that is about 1.4 km wide and 300 m high. The age of the crater is about 530 Ma; however, further studies, such as radiometric dating of possible melt, are needed to refine the age. Despite Söderfjärden´s old age it is exceptionally well-preserved due to long-term burial under the post-impact rocks. It was re-exposed presumably not earlier than 60 Ma ago, and suffered only weak glacial erosion in the last 20 000 years.

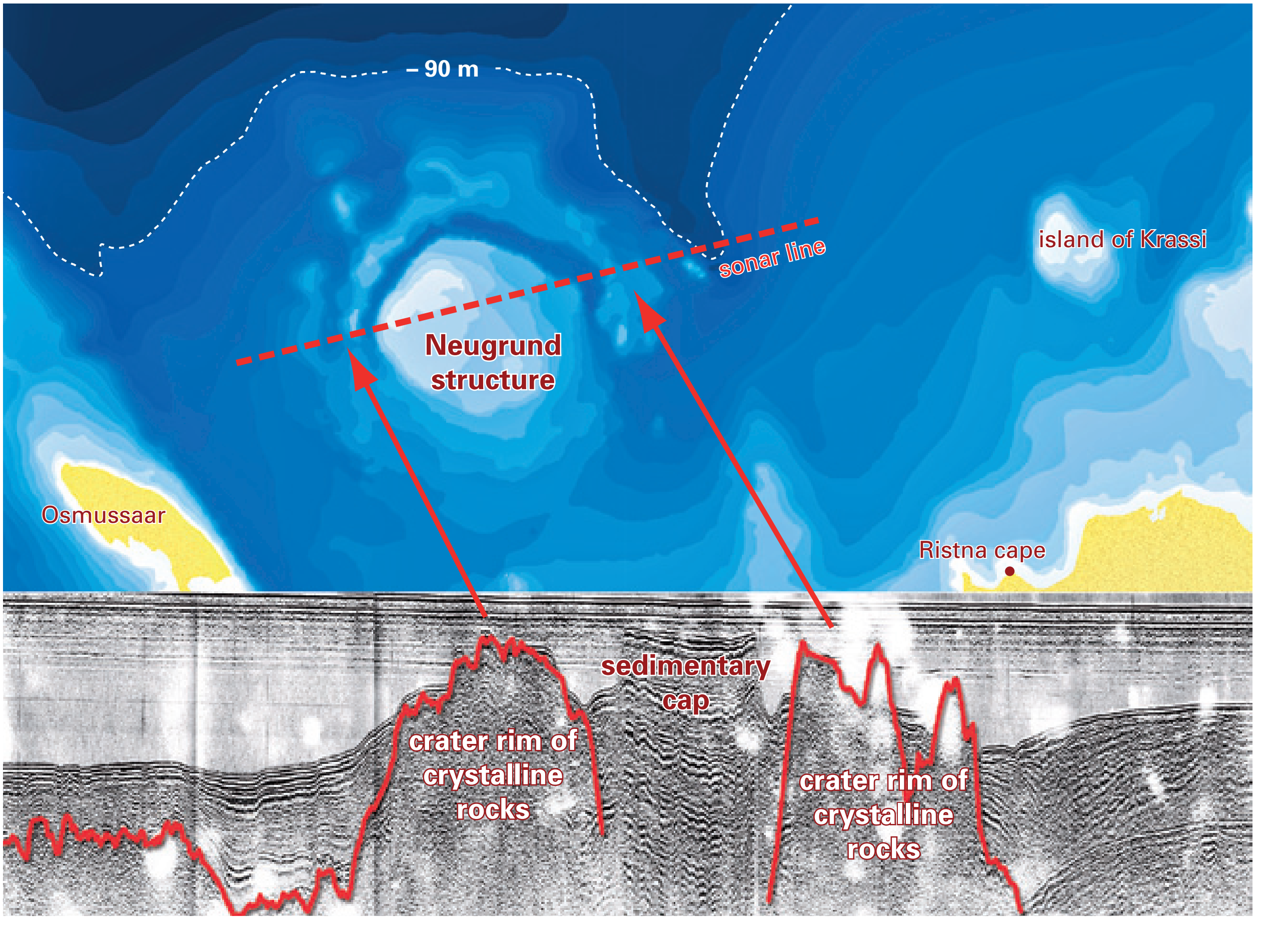
How to get here: The closest airport is in Vaasa and so is the closest train station, highway E12 is also close.

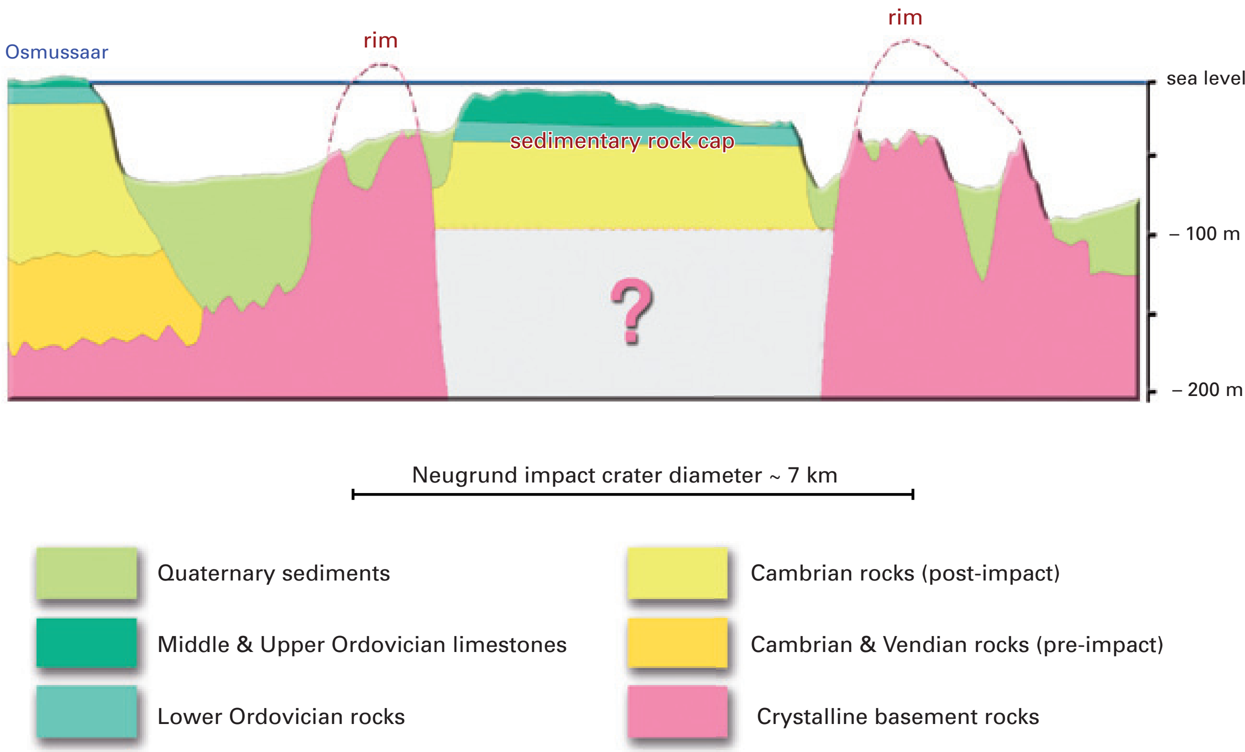
7.2.13. Neugrund, Estonia

Location: In the southwest Gulf of Finland; coordinates 59°20′N, 23°32′E.

Age: Circa 535 Ma old (Lower Cambrian).

Seismic section of the Neugrund impact structure area (after S. Suuroja, Geological Survey of Estonia).





Neugrund impact structure cross section (after S. Suuroja, Geological Survey of Estonia).

Description of the crater area: The Neugrund crater is the latest proven, but oldest structure of impact origin in the area. A shallow circular central plateau (Neugrund Bank) consisting of post-impact infilling sediments, this submerged structure was long known as a hazard among sailors, something that is witnessed by the numerous shipwrecks. Geologically, it was studied as late as in 1980s in the course of a regional geological-geophysical mapping of the seas around the former USSR. However, in Osmussaar island, large brecciated erratic boulders, which, nowadays, are known to represent glacially removed pieces from the crystalline rim of Neugrund, had already been observed and scientifically described in the 1920s. It took almost another 70 years until it was suggested that these boulders might be associated with an impact structure. Extensive geophysical and underwater geological studies were launched on Neugrund Bank and the Neugrund structure, and their surrounding areas were investigated by seismoacoustic sounding in a joint Estonian–Swedish expedition. The drillcores from Osmussaar island and northwestern Estonia were re-examined and new cores were drilled. The impact suggestion was further supported by reinterpretations of the earlier findings of up to 19 m thick strongly deformed and brecciated layer in cores drilled in the course of the small-scale (1:200 000) geological mapping of the basement of the onshore area and Osmussaar island. This layer served as a basis for dating the structure and suggesting a shallow marine origin. The Ring Canyon is as much as 70 m deep and 200-500 m wide and is better developed on the northern side of the structure. It was formed due to glacial erosion that selectively

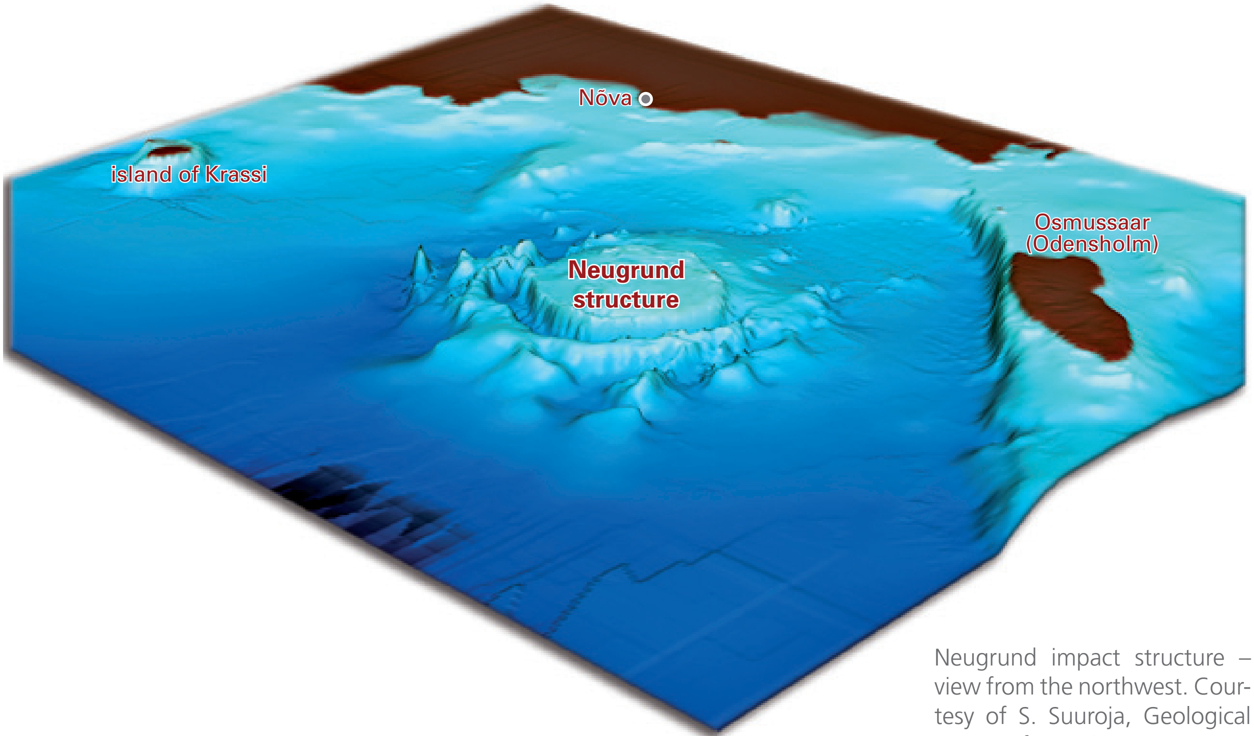
Megabreccia boulders at the Toomanina cape, northwestern Estonia derive from the Neugrund impact structure. The height of individual boulders may reach over 2 metres.

Loose boulder of Neugrund breccia at the Ristna cape, northwestern Estonia. Length of boulder is about 0.9 m.

removed the fractured crystalline rocks at the inner slopes of the rim. The bottom of the canyon is filled with sediments of Quaternary age. At the time of impact the meteorite hit a shallow sea about 50 m deep with a sea bottom consisting of 100 m of clay-, silt- and sandstones of Early Cambrian age lying on top of Svecofennian crystalline basement.

The effects of the impact in the Neugrund crater is seen as shocked quartz grains collected from the rim and distal ejecta, as shatter cones, and as glass made of quartz and feldspar. The Neugrund structure has a rim diameter of about 7 km whereas its depth is unknown. An impact structure of such a size definitely has a central uplift but that is not directly observed in Neugrund because later sediment deposition and transported breccias with unknown thickness fill the depression. The topmost layers of the post-impact sedimentary deposition are composed of Early and Late Ordovician lime- and dolostones that form a 4.5 km wide central plateau over the basin. The Neugrund structure was buried completely under sedimentary rocks for about 530 Ma until erosion revealed the structure. The sediments also protected the structure from erosion by the last continental glaciers that sculptured the rest of the area, eroded the stone and carried different material, including the gneiss breccia blocks off the crater rim to the Estonian mainland. These erratic boulders, that guided geologists to the secrets of the Neugrund structure, are still lying in the coastal and offshore areas of the northwestern and western Estonia.

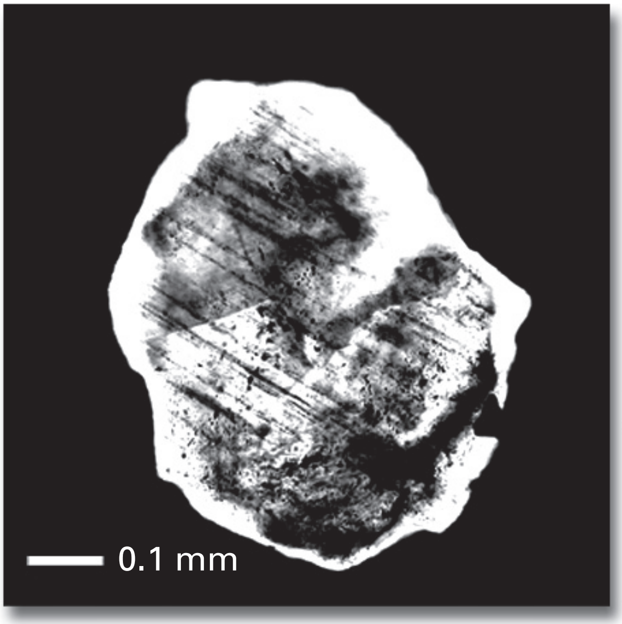
A strongly eroded crater rim composed of crystalline rocks stands 60-120 m above the upper surface of crystalline bedrock and is 2.5-3.0 km wide, whereas on the northwestern side three separate ridges are outlined. Moreover, the existence of an about 20 km wide ring fault (related to 10-60 m high terrace) and a 3-5 km wide area (circular depression) between the rim wall and fault have been outlined. Crystalline bedrock, covered by 10-50 m thick pile of Quaternary sediments, is found to be dislocated within the depression. To refine the exact age and inner structure of Neugrund, drilling from the central plateau is needed.

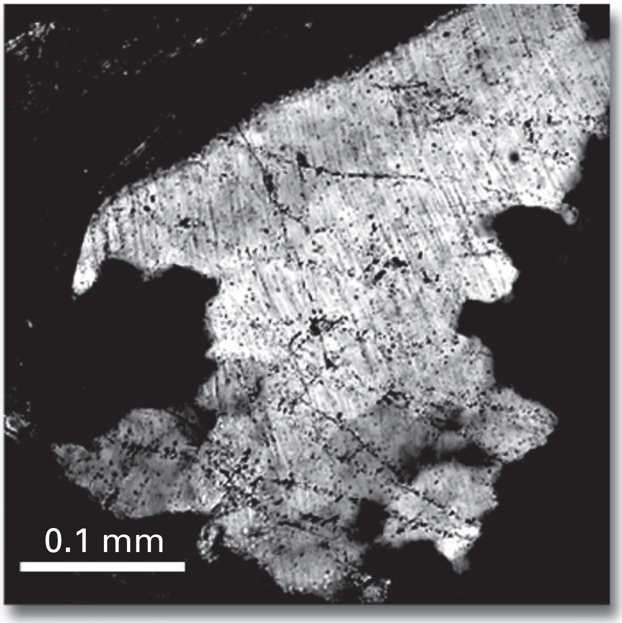


Neugrund impact structure – view from the northwest. Courtesy of S. Suuroja, Geological Survey of Estonia.

How to get here: The closest airport is Tallinn, and the closest towns are Keila and Haapsalu. Impact breccia boulders can be seen at the coastline but a car is needed for that purpose. No crater structure is visible by direct observation.

Quartz grains with planar deformation features from the Neugrund structure impactites. Courtesy of S. Suuroja, Geological Survey of Estonia.





8. Glossary

Agate – a translucent variety of quartz (mainly chalcedony) that can be found in virtually all colours.

Allochthon – a body of rock that has been transported from its original position, usually over a large distance.

Allogenic – a rock that has been formed elsewhere and transported to its present location.

Amphibolite – a rock consisting mainly of the minerals amphibole and plagioclase.

Archean – the period in time between 3800-2500 Ma ago.

Asteroid – one of the many small rocky bodies in orbit around the Sun. Most asteroid orbits are between those of Mars and Jupiter. The largest asteroid is Ceres, nearly 1,000 km in diameter. There are likely 10 million or more 1 km in diameter or larger, of which nearly 100 000 have currently been discovered.

Astronomical Unit – the average distance between the Earth and Sun, equal to 149597870 km, also called AU.

Basalt – a general term for dark-coloured igneous rocks composed chiefly of the minerals plagioclase and clino-pyroxene.

Basement – the part of Earth's crust consisting of igneous and metamorphic rocks, which are overlain by sedimentary cover, also called crystalline basement.

Breccia – a coarse-grained rock, composed of angular broken rock fragments held together by a mineral cement or in a fine-grained matrix.

Caledonian orogeny – a name used for the early Palaeozoic (Late Silurian and Early Devonian) deformation that created a mountain belt, the Caledonides, extending from Ireland and Scotland northeastward through Scandinavia.

Cambrian – a geologic period and system of the Palaeozoic Era spanning from 542-488 Ma ago.

Chitinozoans – a group of flask-shaped, organic-walled, marine microfossils that are good biostratigraphic tools.

Chromite – a brownish-black to iron-black mineral.

Coesite – a variety of quartz that is found in impact craters or in rocks (such as suevite) associated with impact structures.

Coma – the diffuse shell of gas which surrounds the nucleus of a comet and gives it a glowing appearance.

Comet – a dusty chunk of ice that travel around the Sun in a highly elliptical orbit. When the comet is closer to the Sun it heats up and liberates hot glowing gases (see coma).

Conglomerate – a coarse-grained rock, composed of rounded fragments larger than 2 mm in diameter.

Conodonts – small phosphatic fossils, considered as teeth belonging to a fish-like animal.

Craton – the stable part of the Earth's continental areas that have not been pervasively metamorphosed and deformed for at least about one billion years.

Devonian – a geologic period and system of the Palaeozoic Era spanning from 416-359 Ma ago.

Dolomite – both a carbonate rock and a mineral consisting of calcium magnesium carbonate (formula, $CaMg(CO3)_2$).

Dolostone – a sedimentary rock consisting of the mineral dolomite.

Ecliptic – the plane of the orbit of the Earth around the Sun, the orbits of the planets all lie within 3.4 degrees of this plane.

Erratic boulder – a boulder dislocated by a glacier or a continental glacier and deposited in another environment.

Esker – a narrow winding ridge composed of stratified sand and gravel, deposited by glacial meltwater.

Falling star – see meteor

Fennoscandia – a term used to describe Scandinavia, the Kola Peninsula, Karelia and Finland and geologically also underlying Fennoscandian Shield of Norway, Sweden, Finland, and northern Denmark. The Fennoscandian Shield in Scandinavia is over 3.1 Ga old.

Foreland – the exterior area of an orogenic belt where deformation occurs without significant metamorphism.

Galena – a bluish-grey to lead-grey mineral with a shiny metallic lustre. Galena is the most important ore of lead and one of the most important sources of silver.

Gneiss – a metamorphic rock, in which bands of granular minerals alternate with bands in which minerals having flaky or elongate habits predominate. A very common rock in Scandinavia.

Granite – a light coloured, coarse-grained igneous rock consisting largely of quartz, feldspar and mica. A very common rock in Scandinavia.

Granodiorite – an igneous rock consisting largely of quartz, feldspar, similar to granite.

Graptolite – an extinct group of stick-like colonial, marine organisms that commonly occur in black shales, and are good for biostratigraphic dating.

H-chondrite – a stony meteorite with high iron content.

Impactite – a term used for any shock-metamorphosed rock, including breccias and melt rocks.

Jotnian – a stage of the Middle-Upper Proterozoic, from about 1600-65 Ma ago of the, Baltic Sea region.

Kamacite – a metallic grey meteorite mineral consisting of nickel and iron.

L-chondrite – a stony meteorite with low iron content.

Maar – a low-relief, broad crater formed by an explosive volcanic eruption. It is often occupied by a shallow lake and surrounded by a crater ring.

Mesoproterozoic – the middle part of the Proterozoic, lasting from about 1600-1000 Ma ago.

Metamorphism – the process of changing the characteristics of a rock in response to changes in temperature and pressure, usually due to plate tectonic movements.

Meteor – a short-lived, glowing trail of a meteoroid entering the Earth´s atmosphere where all the material burns up before reaching the ground.

Meteoroid – a small, extraterrestrial body within the Solar System that may enter the Earth´s atmosphere if its orbit crosses that of the Earth. If the meteoroid enters the atmosphere it is referred to as a meteor and if it reaches the surface it is called a meteorite.

Meteorite – an extraterrestrial body that enters the Earth´s atmosphere and lands on the surface. Most are small (cm scale) but some can be enormous.

Microtektites – small fragments of silica-rich, translucent black glass, they are often teardrop-shaped indicating rapid cooling and solidification during transport. They are thought to form from meteorite impacts on to silicate-rich rocks. The material melts on impact, is thrown up into the atmosphere where the droplets solidify and spread around the impact area.

Mire – a marshy, swampy, or boggy wetland that accumulates peat.

Molasse – a term used to describe the mainly shallow-marine and non-marine sediments formed from the erosion of a mountain belt during mountain building.

Multiring basin – a large basin formed by a meteorite impact. Several concentric rings of mountains surround the basin and the energy involved in forming such basin is in the order of 10^{27}.

Mosasaur – an extinct group of marine lizards that could grow up to 9 m long with a long, slim body, short neck and long head.

Nappe – a sheetlike, transported rock unit, which has moved on a predominantly horizontal surface.

Nautiloid – a type of cephalopod with straight, curved, or coiled chambered external shell. They reached their peak in the Ordovician and Silurian and the genus *Nautilus* is the only living today.

Ordovician – a geologic period and system of the Palaeozoic Era spanning from 488-444 Ma ago.

Orogeny – the process of mountain building.

Orthoceratite – any nautiloid belonging to the genus *Orthoceras*, characterized by the presence of three longitudinal furrows on the body chamber.

Palaeozoic – the earliest of three geologic eras of the Phanerozoic Eon. The Palaeozoic spanned from roughly 542-251 Ma ago and includes the Cambrian, Ordovician, Silurian, Devonian, Carboniferous and Permian.

Pegmatite – an exceptionally coarse-grained igneous rock, most grains are one cm or more in diameter.

Phanerozoic – the current Eon that started 542 Ma ago until present. Consists of three eras; Palaeozoic, Mesozoic and Cenozoic.

Plesiosaur – an extinct group of aquatic reptiles, that could grow up to 15 m long, some were short-necked and some were swan-necked.

Pleistocene – the time span covering 1.75 Ma and 11.5 ka ago.

Polymict breccia – a brecciated meteorite containing fragments of differing composition and origin.

Porphyry – an igneous rock of any composition that contains large crystals in a fine-grained groundmass.

Proterozoic – the period in time between 2500-542 Ma ago.

Pterosaur – an extinct group of flying reptiles that were particularly common in the Jurassic.

Quaternary – the time span between 1.75 Ma and the present.

Radiocarbon dating method – a radiometric dating method that uses the naturally occurring isotope carbon-14 to determine the age up to ca 50 000 years.

Rhyolite – a fine-grained igneous rock with a sugary texture consisting of quartz, feldspar and one or more ferromagnesian minerals.

Rodinia – the name of a supercontinent which contained most or all of Earth's landmass between 1100-750 Ma years ago.

Till – unsorted sediment laid down by the direct action of glacial ice.

Shatter cone – a geological feature formed during meteorite impact craters, they have a conical structure that repeats to form a cone-in-cone structure, they range in size from microscopic to several metres.

Shocked quartz – a form of quartz formed due to intense pressure, such as a meteorite impact. Shocked quartz have been deformed along the crystal planes forming microscopic lines called planar deformation features (or PDFs), or shock lamellae.

Shooting star – see meteor.

Schreibersite – a silver-white to tin-white, highly magnetic, meteorite mineral that occurs in tables or plates as oriented inclusions in iron meteorites.

Sphalerite – a yellow, brown, or black mineral consisting largely of zinc sulfide.

Stony-iron meteorites –- contain large amounts of both metallic and rocky material. Silicate minerals olivine, pyroxene and plagioclase occur as inclusions.

Stony meteorites – are similar in composition to Earth's mantle rock, primarily of silicate minerals olivine and pyroxene. That makes them difficult to identify, even though they are the most common type of meteorites, accounting for 93% of all known meteorite falls.

Stishovite – a high-pressure, extremely dense variety of quartz.

Suevite – melt fragment breccia with clastic matrix containing rock and mineral clasts in various stages of shock metamorphism.

Svecofennian – a stage of the Lower Proterozoic, from about 2600-2100 Ma ago in the Baltic Shield region.

Taenite – a metallic white meteorite mineral consisting of nickel and iron.

Tertiary – the time span between 65-1.75 Ma.

Turbitide – a sediment or rock deposited from, or inferred to have been deposited from, a marine turbidity current.

Widmanstätten pattern – a characteristic cross-hatched pattern that becomes visible on the polished surface of most iron meteorites.

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