

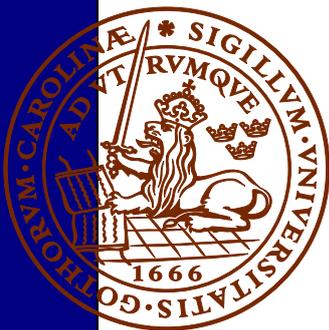
# Microscopic shock-metamorphic features in crystalline bedrock:

## A comparison between shocked and unshocked granite from the Siljan impact structure

***Robert Mroczek***

Dissertations in Geology at Lund University,  
Bachelor's thesis, no 418  
(15 hp/ECTS credits)

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Department of Geology  
Lund University  
2014



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**Front Page: heavily shocked sample from Siljan. Photo taken by Robert Mroczek.**

# Microscopic Shock-metamorphic Features in crystalline bed rock: A comparison between shocked and unshocked granite from the Siljan impact structure

ROBERT MROCZEK

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**Abstract:** During the Devonian, 377 Ma ago, the Earth was impacted by a large celestial body, striking ground in the Siljan area in Dalarna, Sweden. The impact created what is today the largest confirmed impact structure in western Europe. Since its formation, the structure has however been heavily eroded, leaving no trace of the original crater. Today, it is instead recognizable due to the central plateau and a partly lake-filled annular depression. The central plateau presents a chance to see what has happened to the bedrock which, at the time of impact, was situated hundreds to thousands of meters beneath the crater floor.

As the majority of shock-features created when an impact event occurs are on the microscopic scale, using a microscope is a necessity when studying them.

This study has focused on 14 thin sections, taken from granites in the Siljan area. They have been analyzed using a polarization microscope. Site 11 showed by far the most signs of being shocked, with PDFs in the quartz showing in almost all (95-100%) of the grains, while site 67 showed very little (5-10%) signs despite being located at roughly the same distance from the center of the structure. PDFs were also observed in the K-feldspars of site 11. The low percentage of quartz-grains in site 67 which displayed PDFs can however be explained by large grain size and the fact that a U-stage was not used.

PDFs are the only type of shock-metamorphic effect which was definitively identified, however other effects which are not directly accredited to the shock-waves, but rather to long-term secondary effects (due to the cracking of the bedrock) were also found. The bedrock in the area has been heavily chloritized, with about 90% of the biotite in the shocked samples having been converted to chlorite, while the estimate for the non-shocked samples is set to about 60% conversion. This is probably an effect from the impact (although not a direct one), which would have given rise to cracks, potentially speeding up the process of chloritization considerably, and increasing the amounts of recrystallized clay minerals, which seem to be slightly more abundant in the shocked samples.

**Keywords:** Impact structure, Siljan, Planar deformation features.

**Supervisors:** Carl Alwmark, Sanna Alwmark.

**Subject:** Bedrock Geology.

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# Mikroskopiska chock-metamorfa effekter i kristallin berggrund: En jämförelse mellan chockad och ochockad granit från impaktstrukturen i Siljansområdet

ROBERT MROCZEK

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**Abstrakt:** Under tidsperioden devon, för ca 377 miljoner år sedan, träffades Jorden av en stor himlakropp, vilken slog ned i Siljansområdet i nuvarande Dalarna. Nedslaget gav upphov till vad som idag är den största bekräftade nedslagskratern i västra Europa. Sedan tiden för nedslaget, har strukturen blivit kraftigt eroderad, och idag så finns det inga synliga delar av kratern kvar. Strukturen är dock igenkännbar, på grund av sin centrala upphöjning, vilken fortfarande reser sig som en reaktion på det stora tryck som komprimerade marken vid nedslaget. Upphöjningen är även omringad utav en delvis vattenfylld sänka. Den centrala upphöjningen innebär en möjlighet att se vad som har hänt med den berggrund, vilken befann sig hundratals till tusentals meter under kraterbotten direkt efter att området träffats av himlakroppen, och som idag utgör markytan.

Eftersom majoriteten av så kallade chockmetamorfa effekter återfinns i mikroskopiska mineral, så är det nödvändigt att använda ett mikroskop för att undersöka vad som hänt med marken. Denna studie fokuserar på 14 tunnslip, från graniten i Siljansområdet, vilka har analyserats med hjälp av polarisationsmikroskop. Proven från provplats 11 uppvisade överlagset mest tecken på att ha utsatts för höga tryck och därmed blivit chockade. Nästan alla (95-100%) av kvartskornen uppvisade PDFer (Planar deformation features) på denna plats, medan bergarterna från provplats 67, vilken bör ha uppvisat samma mängd eller mer tecken på chock (på grund av att båda platserna befann sig på ungefär samma avstånd från den fastställda nedslagsplatsen), visade mycket få (5-10% av kornen uppvisade PDFer) tecken på att ha blivit chockade. I proverna från plats 11 återfanns även PDFer i Kalifältspaterna.

Den låga andelen kvartskorn från provplats 67 som uppvisade PDFer kan dock hänföras till en kombination av att kvartskornen i proverna var mycket stora, och att ett universalbord inte använts.

PDFer är den enda typen av chockmetamorfa effekter som kunde identifieras i proverna. Däremot finns det tecken på sekundära effekter från nedslaget i form av en ökad kloritisering av de chockade proverna. Detta på grund av att nedslaget orsakat sprickor i berggrunden som därmed snabbat på omvandlingen till klorit. De chockade proverna uppvisade en omvandlingsgrad på ca 90 %, medan de ochockade proverna visade en klart lägre grad (ca 60 %). Den högre sprickfrekvensen kan även ha snabbat på processen som omvandlat primära mineral till de andra lermineral som nu återfinns i proverna. Dessa syns som mörkröda, amorfa aggregat. Dessa aggregat har hittats i alla proverna, men verkar finnas i större mängd i de chockade proverna.

**Nyckelord:** Impakt struktur, Siljan, chock-metamorfism.

**Handledare:** Carl Alwmark, Sanna Alwmark.

**Ämne:** Berggrundsgeologi

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# 1. Introduction

Impact structures are one of the most common geological features in the solar system (Ormö et al. 2014). They cover the faces of our neighboring planets and their moons, and span thousands of kilometers in diameter. Most impact structures on Earth however, are invisible or have been fully removed because of erosion and tectonics. While it is only recently that we have understood that large impact events can have deep-going effects, affecting large-scale tectonics (French 1998), it should come as no surprise that large impacts played a big role in the formation of our own planet's crust.

In the case of the Earth, our thick atmosphere protects us from the small centimeter-meter sized projectiles which bombard our planet every day. The majority of small projectiles are incinerated trying to penetrate the atmosphere, but larger projectiles, with diameters upwards of several meters, can penetrate it. The vast majority does not do any significant damage, or form craters larger than a few meters in size (Ocampo et al. 2006). But every once in a while a larger object can potentially lay waste to areas thousands of kilometers in diameter and cause global effects which can devastate the ecosystem of the entire planet. Even on geological timescales, an impact of this magnitude is rare, and has never been experienced by humanity (French 1998). Only one such event has been confirmed.

The mass extinction at the Cretaceous-Paleogene (K-Pg) boundary is the event that most confidently been linked to an extraterrestrial cause, an asteroid impact in Mexico 66 Ma (Vajda et al. 2003; Schulte et al. 2011; ). The crater has since been buried, but thick ejecta deposits prevail proximal to the impact site (Ocampo et al. 2006; Wigforss-Lange et al. 2007) and these have been linked to the so called boundary clay that can be identified globally as the division between the Mesozoic and the Cenozoic (Farrow et al. 2011; Schulte et al. 2011).

When looking with a microscope onto rocks which have been affected by an impact, one can see that these events create features and minerals exclusive to these events (French 1998). The reason for this is that the temperatures and pressures created by an impact have no other equal on Earth. Nowhere else on Earth can temperatures of this magnitude be reached in such a short amount of time or pressure waves of such magnitude develop. The pres-

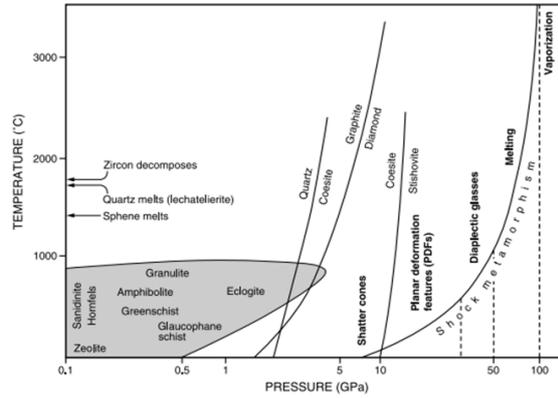


Figure 1: Picture showing the T-P conditions required for certain shock-metamorphic effects (in bold text) to appear. The grey area shows the conditions under which "normal" metamorphic rocks form. Picture is taken from French(1998).

ures created by a large projectile colliding with the Earth are beyond what any rock created under lithostatic pressures ever experience (Fig. 1). This gives rise to unique features which can be used to identify both recent and relict impact structures (French 1998). Most of these features are microscopic. Only one of these unique features can be clearly seen by a naked eye. These are shatter cones, which can be found in sizes of several meters in length. This study focuses on describing how the bedrock in the Siljan area, Sweden, reacted to the extreme conditions created by the impact of a large extraterrestrial body. The aim is to further the understanding of how such an impact event affects the bedrock both chemically, and texturally. This is done by examining shocked and unshocked granites in thin sections from Siljan under a polarization microscope.

## 2. Materials & methods

### 2.1 Thin section microscopy

Most of the analysis in this study has been performed using a polarization microscope. In total, 14 thin sections retrieved from four different locales in the Siljan area have been analyzed. All of the thin sections were borrowed from S. Holm of Lund University, and previously used in her publication (Holm et al 2011). Two of these locales (No. 11 and No. 67) are located in the central parts of the Siljan impact structure, and contain shock-metamorphosed minerals. The other two locales (No. 1 and No. 18) are also from the Siljan area, but from parts which

are further from the center, and which has not been shocked. All of them are part of the same geological unit, which is the Järna granite (see fig 3, page 5).

From each locale, three to four thin sections were analyzed. All 14 thin-sections were analyzed in both cross-polarized light (XPL) and plane-polarized light (PPL). First, all of the non-shocked samples were examined to get an idea of how the bedrock normally looks. This was followed up by identifying as many of the minerals in the thin-sections as possible, and continuously marking points of interest on a “map” which had been made beforehand by scanning the samples and printing them out on a piece of paper (A4 size). Minerals which could not be definitively identified were marked on these maps and verified by analyzing using SEM-EDS later on. Lastly, the texture of the samples was noted. This process was then repeated for the shocked samples. Again all of the minerals were noted. interesting features/unidentifiable minerals were marked on the maps, and the textures of the samples was noted.

When all of the samples had been analyzed, differences in texture and mineral composition between the shocked and non-shocked samples were noted. Once this comparison had been made, the samples were all analyzed once again. This time, searching for shock-metamorphic effects specifically, in order to determine which effects could be found. The effects were noted, and in some cases, photographed.

## 2.2 SEM-analysis

After all of the samples were examined, and points of interest had been marked on the “maps”, the most interesting samples were chosen (samples 1a and 67a) and examined in a SEM (model Hitachi 3400N) in order to identify the minerals which could not be distinguished with the polarization microscope alone.

## 3. The formation of an Impact structure

Every year, the Earth is bombarded by an

average of 40 000 tons of extraterrestrial material. The vast majority of this is on the millimeter-scale. Small projectiles are destroyed in the atmosphere as a result of frictional heating. Large projectiles, measuring hundreds or even thousands of meters in diameter, pass through the atmosphere unaffected and deliver their full force upon the surface of the Earth. They carry kinetic energies equaling thousands of nuclear bombs, and hit Earth at speeds of tens of km/s (French 1998). Such speeds would make even the smallest pebble deadly if we didn't have our atmosphere protecting us.

A collision with another body means that all of the kinetic energy carried by the projectile will almost instantaneously be converted into shockwaves which in turn is converted into heat energy as it passes through the medium. The projectile is entirely vaporized upon impact. The shockwaves give rise to a series of so-called shock- metamorphic features which are unique to impact structures. These features range from macroscopic ones such as shatter cones, which can be clearly seen by the naked eye, to microscopic features in individual mineral grains, to new mineral assemblages due to changes in pressure and temperature. These features will be covered further on.

The events of an impact are usually divided into three stages (French 1998). These stages are as follows, in chronological order:

### **Contact and compression stage:**

This constitutes the first moments where the projectile hits the ground and generates shock-waves, which travel at supersonic velocities. The shock-waves originate from the projectile and travel outward into the ground, expanding like ripples would in water. This shock-wave is accompanied by a release wave, which immediately follows the shock-wave and relieves the rock of the pressures added by the shock-wave, producing heat and kinetic energy. Once the release wave has traveled throughout the projectile, it will be vaporized. This marks

the end of the contact and compression stage.

**Excavation stage:**

As the release wave passes through the ground, some of it melts or vaporizes (the ground which is closest to the projectile), while the kinetic energy developed upon the release, will give rise to mass movements (fig. 3, page 4) and the creation of cracks throughout the bedrock. Ejecta and impact melt is thrown outwards from the impact location, blanketing the area around the crater. This stage ends when the shockwaves have completely dissipated, and the crater has been formed. The entire process occurs very quickly. A crater with a diameter of 100 km is fully formed within 15 minutes after impact (French 1998).

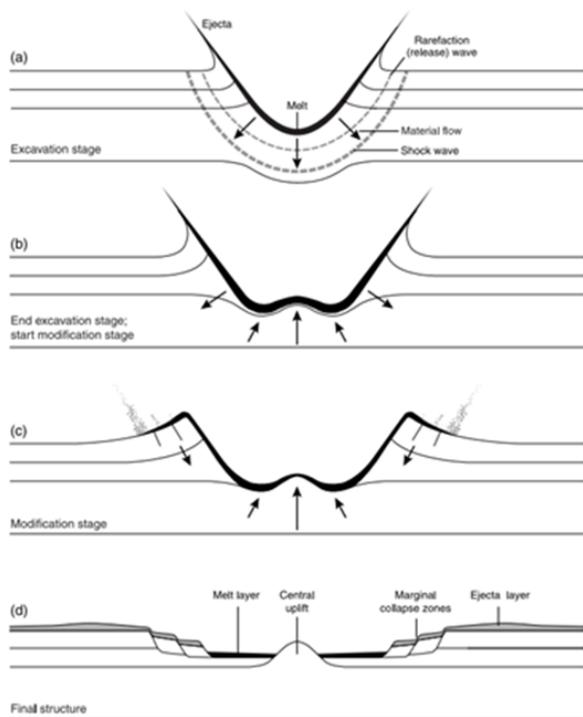


Figure 3: Illustration showing the stages of an impact event. The first picture shows the start of the excavation stage, moments after the projectile hits and subsequently is vaporized as a result of the immense heat. The following pictures show mass movement in and around the crater. Taken from French (1998).

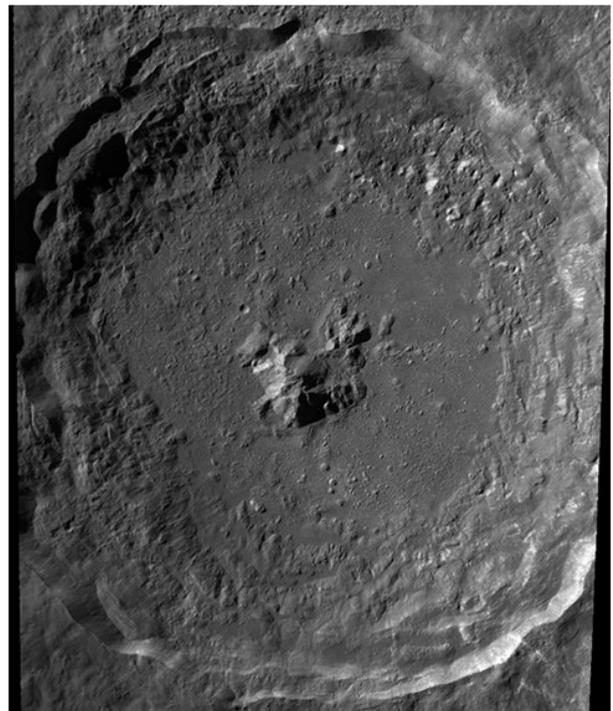


Figure 2: Photograph showing the moon crater Copernicus. With its diameter of 85 km, a central peak and a meltsheet surrounding it, this relatively young crater would be similar to what the Siljan impact structure, Sweden, which has been examined in this study, would have looked like shortly after its impact, 377 MA.

**Modification stage:**

Starting after the shockwaves has dissipated; the modification stage includes mechanical and gravitational processes which determine the final shape of the crater. This happens as a reaction to the large pressure which was put onto the ground directly beneath the impact. The ground which was compressed by the impact slowly expands (over millions of years). There is however no well-defined end of this stage as it is tied to these long-term processes of decompression uplift and erosion which continually changes the appearance of the crater.

#### 4. Shock-metamorphic effects in crystalline bedrock

##### 4.1 Macroscopic features (Shatter cones)

Large features which are visible to the eye are limited to shattercones (fig 4). These can range from just a few centimeters in size, to tens of meters. Shattercones start to form under relatively low shock- pressures ( $>2$  GPa) and continue to form until about 30GPa. They are commonly observed in the central uplift of craters, and are only known from impact structures (French 1998). They appear as series of striae originating from a single point (the apex) and curve in an oblate pattern resulting in a cone-like structure (French 1998). They often appear in groups like the one in figure 4. These structures are also fractal in nature, meaning that each cone most often consists of smaller cones. It was previously thought that the apexes always pointed toward the direction from which the shock-wave originated, but recent studies show that this is not necessarily the case (Ferriere 2010). It is unknown how exactly the process resulting in this capturing of the strain in the rock works.



Figure 4: Well-developed shattercones in limestone, showing how the striae diverge from the cone apexes. Picture taken from French (1998).

##### 4.2 Microscopic features

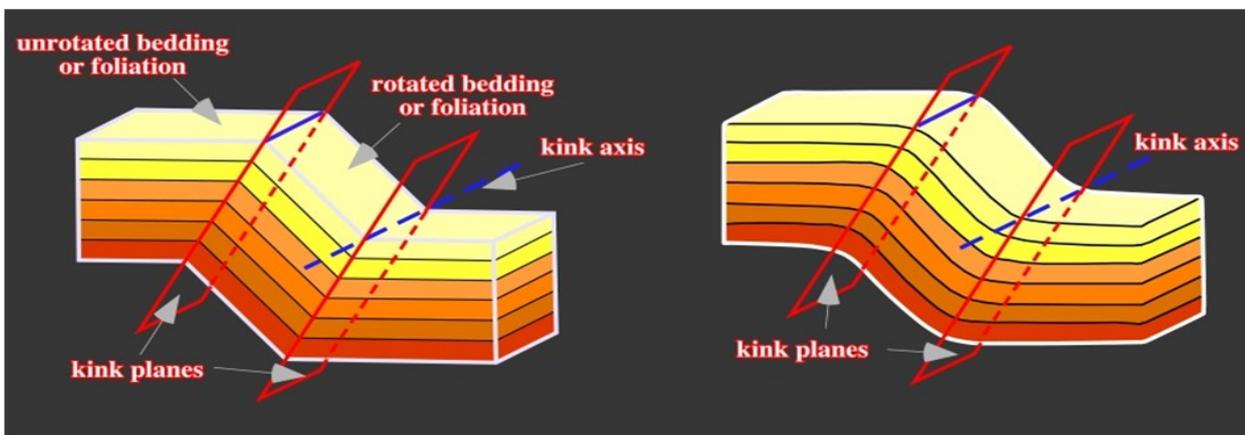


Figure 5: Illustration showing the principle of how a kink band is formed. The rotated bedding has a different angle of distinction because of its angular displacement to the other planes. Taken from Faill (1969).

There are four types of shock-metamorphic effects in crystalline bedrock at the microscopic scale:

- Kink Banding
- Planar deformation features & Planar fractures (PDFs and PFs)
- High-pressure mineral polymorphs (in quartz)
- Diaplectic/thetomorphic glass

### **Kink banding**

Kink bands are linear features which are found mainly in micas, but may also occur in other minerals. They appear in impact events, but may also occur in tectonic deformation environments, as they appear in relatively low-pressure settings of below 5 GPa (French 1998). Kink bands in single mineral grains appear as zones which has a different angle of distinction. This happens because the crystallographic planes have been displaced (see figure 5).

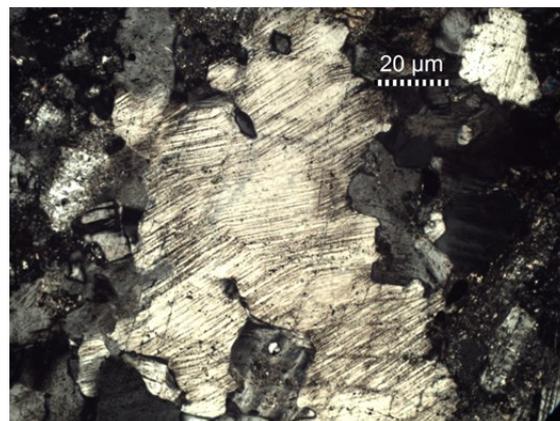
### **Planar fractures & Planar deformation features (PFs and PDFs)**

Two distinctively different features are visible mainly in quartz, but also in some feldspars. These are the PFs and the PDFs. Planar fractures are cracks which occur along the crystallographic planes of the crystal, creating a small void in the crystal and appearing in a microscope as a straight black line in affected crystals. They basically act as new grain boundaries with respect to the much thinner and more closely spaced PDFs, which form at higher pressures, and as such never transect PF's. PFs start forming at comparably low shock-pressures (3.5-15 GPa) depending on the orientation of the crystal and they are not very good indicators of impact structures on their own, as they may form from "normal" elastic shocks below

### **High-pressure mineral polymorphs (in quartz)**

If shock-pressures reach >12 GPa, quartz may start to break down, and form stishovite. This is somewhat peculiar, as

5 GPa. PDF's are considered diagnostic of impact structures, and exist in a variety of minerals. They form at pressures between 8-25 GPa (French 1998) and appear as thin black lines in a microscope (fig. 6; fig. 7). The reason for these black lines is that the shockwaves travelling through the crystal strain it, producing heat. This makes certain crystallographic planes at different temperatures melt into an amorphous phase which turns that particular part of the crystal isotropic. This means that it is possible to discern approximately how much pressure each grain was exposed to by judging the number of crystallographic planes which has formed lamellae. In time, the PDFs start to break down, and often release water into the crys-



*Figure 6: Photograph of A heavily shocked quartz grain from sample site 11 from Siljan, Sweden. PDFs are clearly visible throughout the grain as thin black lines. Taken in XPL.*



*Figure 7: Photo showing PDF's in quartz, illustrating how thin PDF's are. Taken from Stöffler and Langenhorst (1994).*

stishovite is normally only stable at lithostatic pressures >40GPa. Normally, one would expect to see coesite form long before stishovite, however in conditions found during impact events, these boundaries are interchanged, and coesite is formed at shock-pressures >30 GPa.

### **Diaplectic glasses**

Formed in the higher ranges of the shock pressures (35-45 GPa) these glasses are formed from quartz and feldspar crystals which no longer can retain their ordered crystal structure. At these pressures, PDF's stop forming, and instead they turn isotropic by reshaping their crystal structure entirely, turning parts of it, or even the entire crystal into an amorphous phase, called diaplectic or thetomorphic glass. Despite it being called (French 1998), its structure is not completely amorphous. The crystals retain much of its former structure, as the process is not a complete melting one. Grains which are diaplectic often retain their shape (Stöffler 1974), and as such they may be hard to distinguish in a microscope.

## **5. The Siljan impact structure**

### **5.1 Location**

The Siljan impact structure is located in Dalarna, central Sweden (coordinates of the center of the structure: N61°02.196'; E014°54.467'; fig. 8.)

### **5.2 Geological setting**

At the time of the impact (during the Devonian, 377 million years ago; Reimold et al 2005), the crystalline bedrock in the Siljan area was covered by sediments. Some publications state that the cover was 400-500m thick (Rondot 1975; Lindström 1991;). A few recent publications state that it could have been as thick as 2-4km, based on conodont alteration indices and fission track data (Tullborg et al 1995; Larson et al 1999; Cederbom et al 2001;).

The Siljan impact structure is defined by a central area, surrounded by an annular partly lake-filled depression (Holm et al 2011).

(Åberg & Bollmark 1985; Persson & Ripa 1993;). The differences between the two granites of the area are largely as follows; the Siljan granite is coarse-grained with cm-sized crystals and is reddish in color, containing a large fraction of feldspars. Portions of it also contain large amounts of cm-sized titanite crystals. The Järna granite is very rich in quartz, and portions of it contain a lot of biotite and/or chlorite (Hammergren P. & Fors K. 1983). It is far more fine-grained than the Siljan granite with few grains reaching sizes above a centimeter.

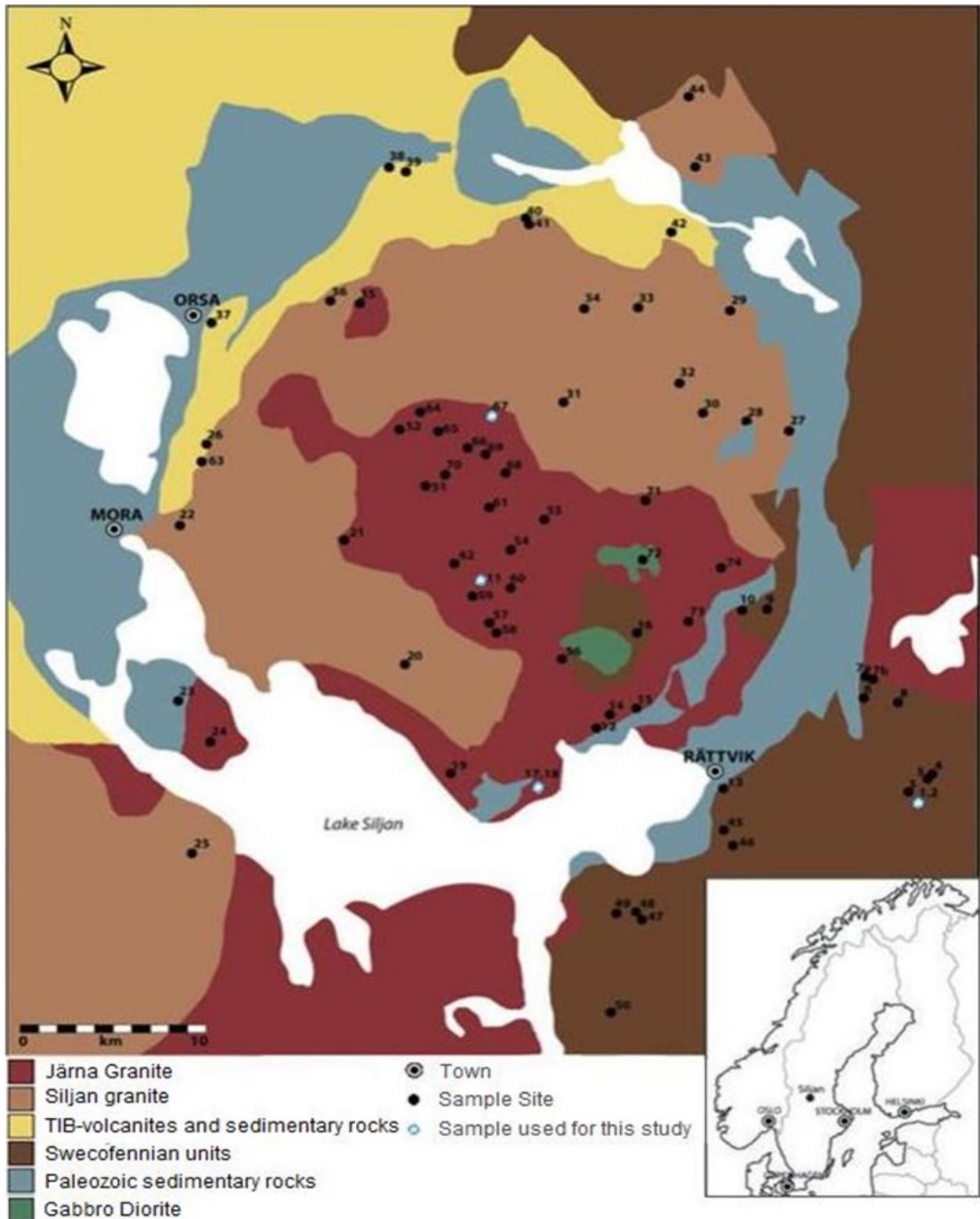


Figure 8: A map of the bedrock in and around the Siljan impact structure (after Kresten & Aaro 1987; Holm et al 2011), indicating the types of rock in the area and where the samples used for this study were taken from (No 1, 11, 18 and 67). The map in the lower right shows the location of Siljan along with a few landmarks. Samples used are borrowed from S. Holm (Lund University) and the samples were previously used in her publication (Holm et al 2011). Modified by Robert Mroczek.

The diameter of the structure has been debated and the most commonly quoted size of the structure is 52 km (Grieve 1982; 1988;). Another study utilizing structural geology puts the diameter to 65 km (Kenkmann & von Dalgwig 2000). The central plateau, which is partly surrounded by lakes, has a diameter of roughly 30 km. The structure has however been greatly modified since its formation, and is estimated to have experienced a minimum of 1 km of erosion since it was formed because it lacks features such as a melt sheet, which would otherwise be present in such a large structure (Grieve et al 1988). There is however PTB (pseudotachylite breccia) veins scattered in the more highly shocked parts of the Siljan area. The extensive erosion of the structure means that the currently exposed bedrock was originally situated underneath the crater floor.

The inner part of the structure can be characterized by two main types of rock; Dala granites of Siljan type and Järna type. The Siljan granite has been dated to 1.7 GA (Lee et al 1988; Juhlin et al 1991; Ahl et al 1999;), and the Järna granite to 1.8 GA

## 6. Results

### 6.1 Non-shocked samples:

#### Mineral composition:

The samples contain low amounts of K-feldspar, but are rich in quartz. The non-K-feldspar throughout the samples has been heavily sericitized, while the K-feldspar is in good shape, showing no signs of being broken down. There are abundant pseudomorphs of biotite which have been replaced by chlorite throughout the samples. There are a lot of small opaque grains scattered throughout the samples (one of which was analyzed using SEM-EDS, showing that it was an iron oxide (Fig. 9)). They are almost always (>90%) surrounded by a series of coronas consisting of (innermost to outermost, respectively) an aluminum silicate which could not be identified, biotite, chlorite and possibly rutile, judging from SEM- analysis. Also, small amounts of red-brown recrystallized clay minerals are present in all of the samples.

Sample site no. 1.	
Geological setting:	Järna granite
Number of thinsections:	4
Minerals found:	Quartz, feldspar, biotite, chlorite, muscovite, aluminum silicate, epidote and iron oxide.

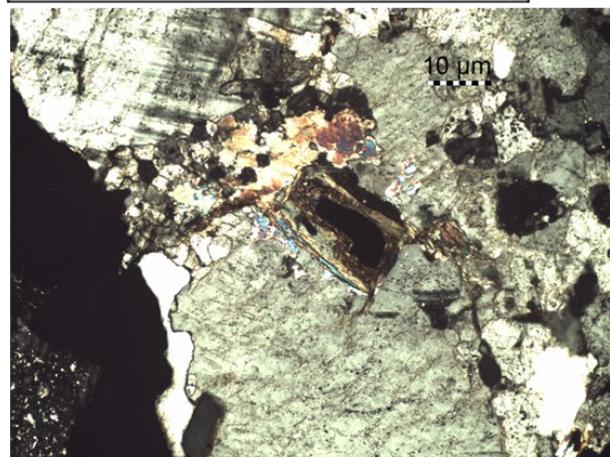


Figure 9: Photograph of site 1, showing the opaque with its coronas, which was examined with the SEM. Above the central grain is a group of epidote grains. The grey-green dusty looking mineral is plagioclase. In the top left there is a grain of k-feldspar, and scattered throughout the sample are clear-looking quartz grains. Taken in XPL.

#### Texture:

The samples are large-grained, well-crystallized, with no signs of disequilibrium other than the coronas around the opaque grains. There are a few cracks in the samples, but most of them have been filled by epidote, while a few have been filled by biotite.

## 6.2 Shocked Samples:

Sample site no. 18.
Geological setting: Järna granite
Number of thinsections: 3
Minerals found:
Quartz, feldspar, biotite, chlorite, epidote and iron oxide

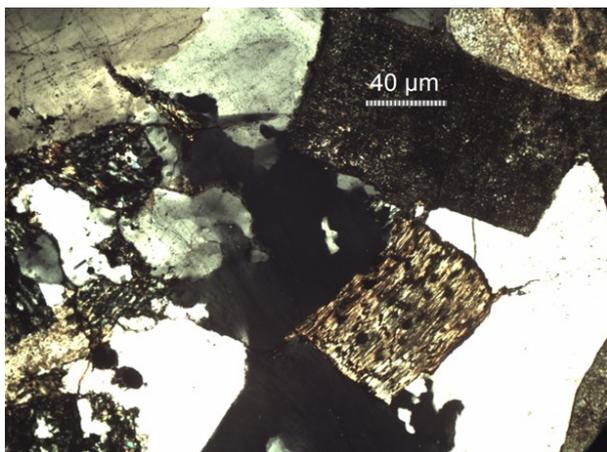


Figure 10: Photograph from sample site 18. Large grains of biotite, quartz and feldspar which has been heavily broken down. A few domains in the lower left portion of the picture look to be aggregates of fine-grained epidote. Taken in XPL.

### Mineral composition:

The composition of the minerals at Sample site no. 18 is very similar to the other sites, with the exception being that there are very low amounts of epidote present. The opaques in these samples seem to be surrounded by the same series of coronas as in the previous samples, leading to the conclusion that they are all iron oxide. The biotite in these samples is also heavily chloritized, albeit to a lesser degree than any of the other sample sites (50-60%).

### Texture

The sample site is very large-grained (cm-sized grains), well-crystallized, and seem to be in almost complete chemical and textural equilibrium (see fig 10). The amount of cracks in these samples is very low, and only small cracks have been observed. The cracks which were seen, were all filled by biotite.

Sample site no. 11.
Geological setting: Järna granite
Number of thinsections: 4
Minerals found:
Quartz, feldspar, biotite, chlorite, hornblende, iron oxide and sillimanite (unconfirmed).

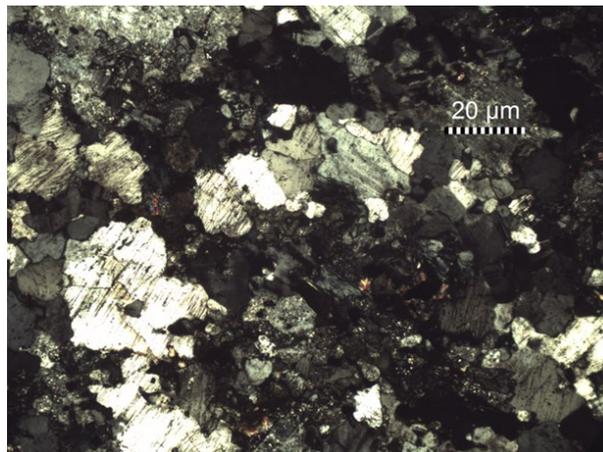


Figure 11: Picture of a sample from site 11. The bright white crystals with black lines in them are heavily shocked quartz grains. Small opaques with coronas around them are scattered through the sample. The dusty-looking minerals are plagioclase. Near the center of the picture is a former biotite crystal which has been chloritized. Small epidote crystals are also scattered throughout. Taken in XPL.

### Mineral composition:

Quartz and k-feldspar heavily dominate, with small amounts of opaques, biotite and chlorite. The chlorite seems to exist exclusively as pseudomorphs, replacing biotite crystals. The quartz in all of the samples is shocked (~100%). Site 11 differs from all of the other sites in that the K-feldspar also displays plenty of PDFs (~70%). All of the samples contain small amounts of red-brown recrystallized clay minerals occurring in amorphous aggregates.

### Texture:

The texture can be described as fine-grained

and often rounded shapes (Fig. 11) when compared to the non-shocked samples. This appears to be the case for all of the mineral phases. While all minerals appear somewhat rounded in shape, this is especially true in the case of the quartz grains, which are very fine-grained and rounded in relation to the other minerals. Also, some of the quartz grains display blue edges. The opaques in these samples are also surrounded by the same series of coronas found in the previous sites throughout the samples. The amount of cracks is close to non-existent.

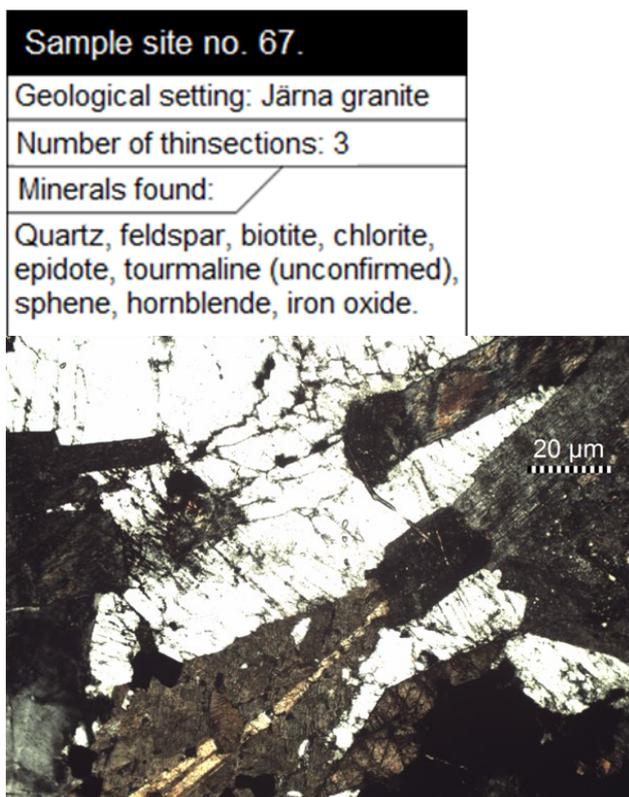


Figure 12. Photo taken from a sample of site 67. In the lower portion of the picture, a large grain with a bright set of twins is visible. It has been interpreted to be hornblende which has been chloritized. To the right of it, there is an extremely well-crystallized sphene crystal. In the upper right hand, a couple of large, dark blue-green biotite grains have been heavily chloritized. The white crystals are quartz-grains, in some of which PDFs are visible (lower right hand crystal). Taken in XPL.

#### Mineral composition:

The composition of minerals at Sample site no. 67 differs from the other sites, with the additions of sphene, hornblende and what may be tourmaline. These samples also have a high fraction of epidote when compared to the other sites. The K-feldspar crystals of site 67 seem to have reacted differently from the K-feldspar of other sites. In site 67, the K-feldspar has been sericitized (30-40%) along with the non-K-feldspar. As was the case with the other sites, this one also contains small amounts of red-brown recrystallized clay minerals scattered throughout the samples, and likewise the biotite has also been heavily (80-90%) sericitized.

#### Texture:

The texture can be described as near-idioblastic. Well-developed and large (cm-sized) crystals of feldspar, epidote, tourmaline (possibly), and sphene dominate the samples (fig. 12). The sphene stands out with its euhedral crystals throughout the samples, along with some minor amounts of what may be tourmaline. PDFs shine with their absence, as the site is located close to the place of impact. They were found exclusively in quartz, and only in small amounts (~5-10%). Very few cracks were present in the samples, but the few which were found, are filled by either biotite or epidote.

## 7. Discussion

### 7.1 Differences in texture

The sites vary greatly from each other. Sites 1, 18, and 67 are all coarse-grained, while site 11 is fine-grained. The differences in grain size is not accredited to the impact, but rather to differences in conditions during the formation of these rocks 1,8 GA ago (Åberg & Bollmark 1985; Persson & Ripa 1993;).

The quartz looks clear with few inclusions, and is abundant in all of the samples. The non-K-feldspars are generally in poor shape, having been sericitized greatly. The K-feldspars have endured and are generally in fine shape other than being shocked in some cases. The exception is the K-feldspars from site 67, which have also been sericitized.

The differences in appearance as far as shock-

metamorphic effects go are in contention with the results put forward by S. Holm (2011). According to her, site 67 is the site which is most heavily shocked, and the reason these effects are not visible under a polarization microscope, is due to the combination of large grain sizes and a very limited number of grains resulting in unfavorable conditions for PDF visibility. Since the analysis was not performed using a U-stage, this means that one is stuck with a two-dimensional view, which skews the results, and make the samples appear far less affected by the shock-wave than they actually are. The fine-grained fabric of the samples from site 11 is far more favorable to the usage of a microscope without a U-stage due to a higher number of grains, and the results are thus more reliable.

The shock-metamorphic effects which are present in these samples are mostly confined to PDFs in quartz and feldspar. In the most shocked samples, there are small amounts of recrystallized clay minerals, which look amorphous and dark red in color.

The high amount of chloritization in the samples can most probably be accredited to the extremely bad shape of the rocks which have been sampled due to the extremely poor exposure of the bedrock in the area.

One can assume that the chloritization is less prominent further below ground, and is mostly not caused by the immediate effects of the impact, although cracks in the bedrock caused by the impact may certainly have sped up the process by exposing the rock to the elements.

## 7.2 Differences in Mineral assemblage

The rocks from sites 1, 11, and 18 show similar assemblages. They all contain quartz, feldspar, biotite, chlorite, some epidote and opaques which all look to be the same considering their surrounding coronas.

Site 67 however has a few differences when compared to these other sites. It also has sphene, possibly tourmaline and a higher fraction of epidote than the others. It would seem that the site 67 samples have been taken from a part of the Siljan type granite, which reportedly should contain sphene (even though, according to the geological map, the area should consist of Järna granite).

## 8. Conclusions

The bedrock impacted in the Siljan area was clearly affected by the impact. The findings from the studied samples amount to the following:

In site 11, the quartz and feldspar have been heavily shocked, and all grains seem to have PDFs to some degree (~95-100%). The grain size of these samples is very fine when compared to the samples from all the other localities.

In site 67, the grain size is considerably larger than in the samples from site 11. All of the mineral grains appear far less shocked (~5-10%) than was expected, considering their central positioning within the structure. Not using a U-stage proved to pose some problems when looking for PDFs in site 67. The large grain size and small number of grains hindered PDF study as the c-axis orientation of the available grains were unfavorable, resulting in a low amount of visible lamellae. This shows the limitations of not using a U-stage for this type of analysis.

The biotite from all samples have been chloritized to some degree. The shocked samples seem to have been chloritized to a higher degree (~90%), compared to the non-shocked samples (~50-60%). This is accredited to impact related cracks in the bedrock, exposing the bedrock to the elements, speeding up the process of chloritization.

All of the shocked samples contain a red-brown phase which is recrystallized clay minerals (personal communication S. Holm, Lund University).

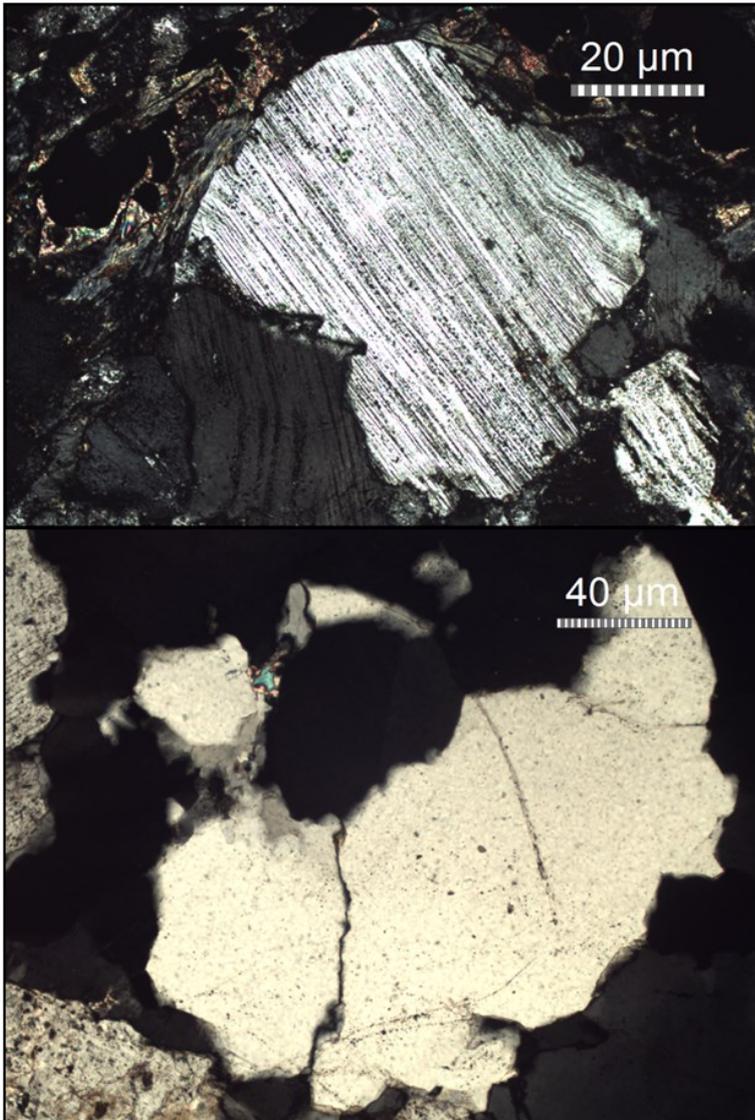
Site 67 has a different mineral assemblage than the other three localities, containing titanite, and a higher fraction of epidote and hornblende than the other locales. This points to it being part of the Siljan type granite, rather than the Järna type granite which is indicated by the map.

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## 10. Appendix



*Figure 13: A comparison between quartz of site 11 (top) which has been heavily shocked, and an unshocked grain from site 1. The difference is easily noticeable. What is unusual about the top picture is that there are few angles of lamellae, even though it has so many. In the upper left portion of the top picture, one can see a group of opaques which are surrounded by very colourful coronas, which in previous cases proved to be aluminum silicate. In the right side of the picture a few dark blue chlorite pseudomorphs can be seen. The dusty looking minerals in the bottom picture are feldspars. Both photos are taken in XPL.*

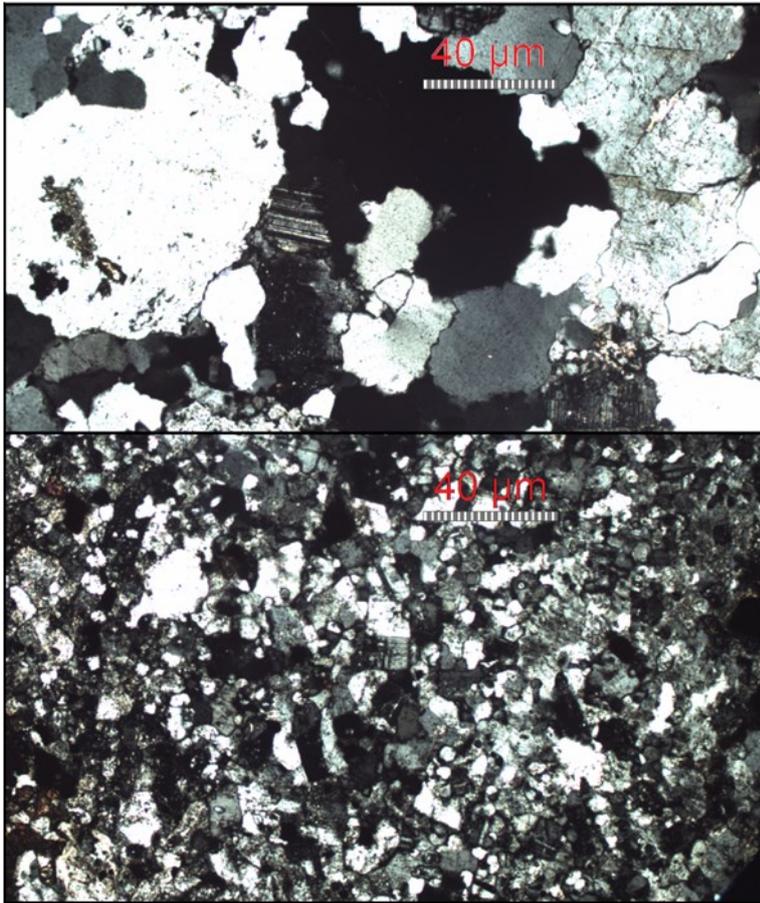


Figure 14: Comparison between textures of the shocked and unshocked samples. The unshocked bedrock (Top) has far larger grain sizes, and the individual grains are also not as rounded as the shocked sample (bottom). The field of view is dominated by quartz in both pictures, but also includes feldspars and micas (bottom left hand of the shocked sample). Top picture is from site 1 (non-shocked), bottom picture is from site 11 (highly shocked). Both photos are taken in XPL.

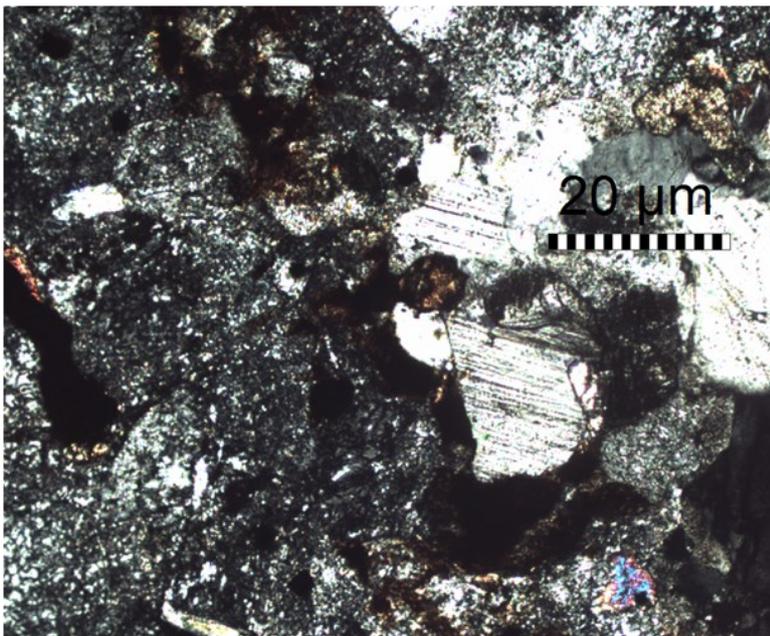


Figure 15: Shocked quartz-grains surrounded by a red-brown phase which is recrystallized clay minerals. The surrounding rocks are sericitized feldspars, and a small grain of epidote in the lower right corner. Taken in XPL.



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