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Notes on some impact rocks from the Janisjarvi structure, Karelia, Russia

Abstract: The Janisjarvi impact structure is located on the northern edge of Ladoga Lake, in Karelia, Russia. This research was carried out to study the biotite-quartz-feldspar-garnet-staurolite schist and several impact-metamorphosed rocks. In schist, biotite inclusions in garnet, pleochroic fields in biotite and asymmetry in the staurolite-biotite contact were observed. These characteristics were related to regional metamorphism of the target rock, and impact-induced features were not detected. No 'kinky' bands were observed in biotite. Fluidal structures and undulose extinction were rare in the analysed specimens. Injections of the tagamite melt into the clasts of cataclased recrystallising glass were noted. Fine-grained grey impact rock was cemented by a glassy micro-net with specimens of recrystallising quartz paramorphosis. In most of the analysed impactites, isotropic spherules and 'ballen quartz' structures, as well as sets of PDF (planar deformation features) and PF (planar fractures) in tagamite and quartz paramorphosis specimens were recognised. Except in schist, dynamic recrystallisation by 'boundary migration' was common. Secondary mineralisations were found for iron oxides, chlorite and calcite.

Keywords: ballen structure, impactites, Janisjarvi astrobleme, PDF, quartz paramorphosis, secondary minerallisation, spherules

Introduction

The Janisjarvi impact structure and a lake in it are located at latitude 61°58'N and longitude 30°55'E, about 219 km north of Saint Petersburg and to the north of Ladoga Lake in Karelia, Russia, (Fig. 1; Jourdan et al. 2008). The structure has a diameter of about 14 km and is considered as the oldest in Russia (Masaitis 1999). Its shape was also described as oval with dimensions of approximately 13 17 km (Larionova et al 2006). Various radioisotopic and palaeomagnetic records indicate an age of 700 Ma for the structure (Müller et al. 1990; Salminen et al. 2006; Jourdan et al. 2008). The structure was created in the target schists which contact the Karelian craton from the northeast. Proterozoic andalusite-

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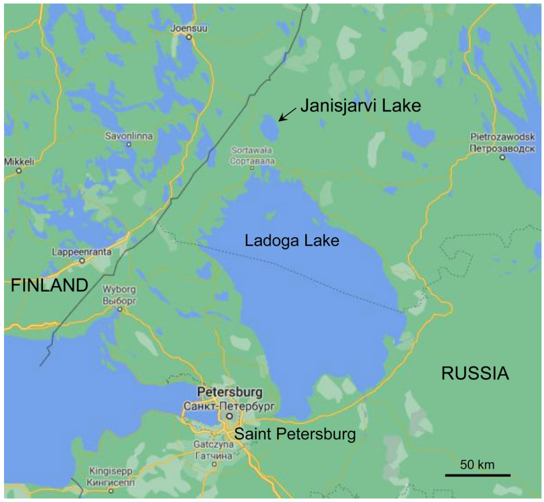

Fig. 1. Location of the Janisjarvi Lake to the north of Saint Petersburg and Ladoga Lake. Source: GoogleMaps (modified).

-staurolite schists were observed to the west of the Janisjarvi Lake, and around the lake they were fractured by impact (Salminen et al. 2006; Kotova et al. 2009). Biotite, muscovite, quartz, garnet, staurolite, andalusite and cordierite were detected in the target schists (Feldman et al. 1979). The structure was distinctly eroded during the glaciation period. The only outcrops of the impact rocks are preserved on three islands in the centre of the lake, which are considered as the remains of the central uplift. Impactites were also collected on the peninsula, on the south-western shore (Masaitis 1999; Fig. 2).

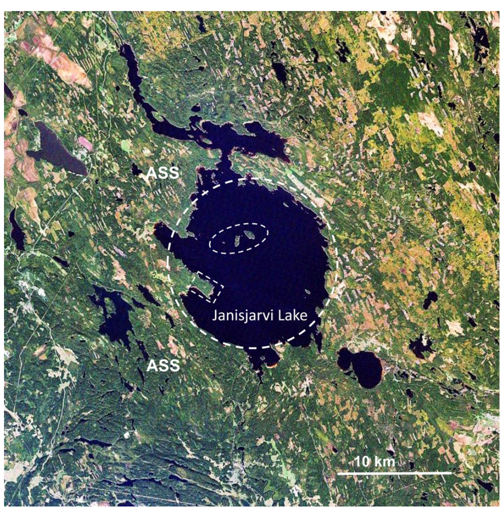

Fig. 2. Estimated size of the Janisjarvi structure (circle) and the locations of impactite sampling: peninsula (rectangle) and three islands (ellipse); ASS – andalusite and staurolite bearing schists. Source: https://en.wikipedia.org/wiki/Lake%20Yanisyarvi?uselang=zh-CN [modified after Jourdan et al. (2008) and Kotova et al. (2009)].

The Janisjarvi impactites are represented by impact melt rocks (tagamites), agglomeratic suevites, breccias and shatter cones (Masaitis 1999; Salminen et al. 2006). Tagamites were recognised as a dark, microcrystalline rock, which is differentiated by the high or low cooling temperature regime. Suevites and breccias were cemented by fine-grained matrices. It was proved that the minerals of impactites originated from quite homogeneous target rocks (Koljonen and Rosenberg 1976; Larionova et al. 2006; Salminen et al. 2006; Sergienko et al. 2017).

Materials and methods

The objects of this study were flat fragments of the following impact rocks: biotite-quartz-feldspar-garnet-staurolite schist, impact melt rock (tagamite), suevite, diaplectic glass, quartz paramorphosis specimen, and adjacent to it, small fragments of fine-grained grey rock cemented by glass. The specimens had polished surfaces, while the opposite surfaces were exposed as cut or fractured. They were analysed macroscopically using a stereomicroscope, and the micro--fragments were studied with an Amplival polarisation microscope (Carl Zeiss Jena). Images were collected using Konica Minolta Dimage-Z6 and Nikon Coolpix A10 cameras. For spherules and 'ballen' subunits, the range of the diameter and arithmetic averages were calculated.

Results

Macro- and microscopic description

A target rock – biotite-quartz-feldspar-garnet-staurolite schist

The analysed schist (Fig. 3A) contained biotite, colourless translucent feldspar, quartz, porphyroblasts of almandine-spessartine garnet, fragments of staurolite crystals and rare, tiny pieces of probably magnetite-ilmenite exhibiting weak magnetism.

Biotite inclusions were observed in the garnet crystals (Fig. 4A) as arranged linearly in some porphyroblasts corresponding to the arrangement of the biotite plates in schist. Close to the large fragment of the staurolite porphyroblast, the arrangement of biotite plates was linear in the lower part of the porphyroblast and irregular in the upper part, indicating the disappearance of schistosity (Figs. 3A, 4B). The porphyroblast was surrounded by numerous biotite plates on one side (Fig. 4B), which indicates the movement of the porphyroblast, occurring during schist petrogenesis. A smaller staurolite porphyroblast was observed in the lower part of the specimen where the linear pattern of the biotite plates and the bright vein were slightly bent. In cracks, the bright veins were filled with rock-forming minerals, involving biotite having a haphazard arrangement of the plates. In the specimen a black domain was also noted with a dominant biotite (not visible in Fig. 3A; lower left part of the specimen). Its surface was weathered, where garnet

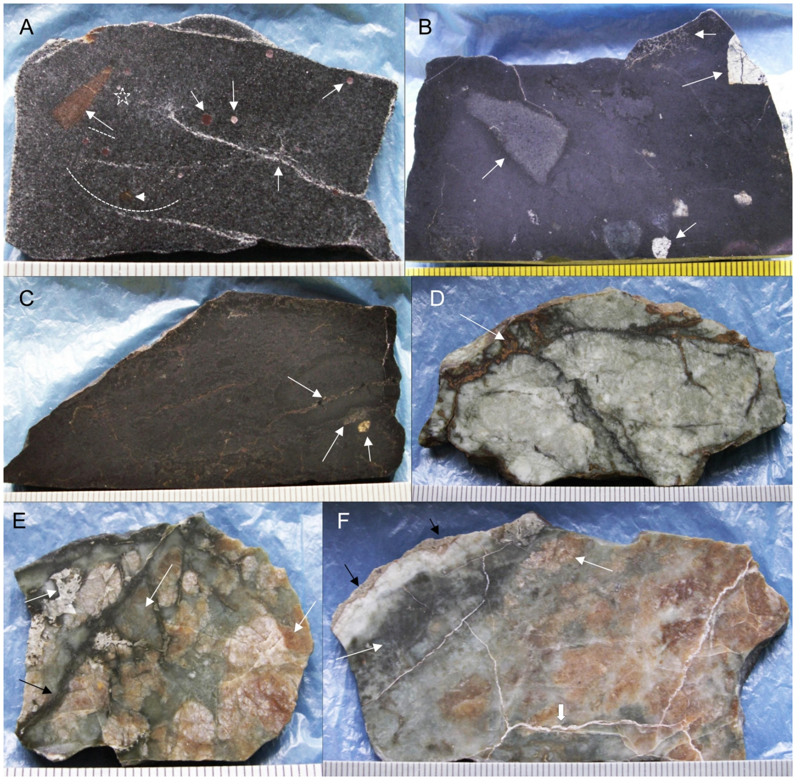

Fig. 3. Macroscopic characteristics of the Janisjarvi impactites. The studied specimens are shown from the polished side. A – the metamorphosed biotite-quartz-feldspar-garnet-staurolite schist; white dashed lines indicate the linear arrangement of the biotite plates, a small staurolite porphyroblast (lower small arrow) and a large porphyroblast (left arrow), garnet porphyroblasts (right arrows), a domain with the distorted arrangement of the biotite plates (white star); B – fragment of the impact melt rock (tagamite) with various clasts (white arrows) and a spotted black-and-white domain (upper arrow); C – black suevite with some clasts (lower arrows) and a vein with the brecciated material (upper arrow); D – the grey-green diaplectic glass with veins filled with secondary minerals (arrow); E – quartz paramorphosis showing different domains (arrows) and a light melt (upper left arrow); F – quartz paramorphosis with greenish and reddish domains (white thin arrows) and fragments of a fine-grained rock closely adjacent to quartz (upper black arrows) and white veins with secondary minerals (bold arrow). Scale in mm.

crystals were removed out and numerous pleochroic fields were present in the biotite plates (Fig. 6A), with biotite observed to be partially chloritised. The examined slate specimen showed traits of regional metamorphism but no changes induced by the impact.

Impact melt rock (tagamite)

The tagamite specimen (Fig. 3B) was composed of a black hard melt, in which the lighter heavily altered clasts could be distinctly identified (Figs. 4C–F, 5A). Injection of the black melt into some clasts in the form of numerous branched black veins was visible, as shown in Fig. 4C, D. In the fragment, the clast with numerous tiny veins revealed a fluidal texture (Fig. 4D), while the other clasts showed perlitic-like (Fig. 4E) or spotted (Fig. 5A) textures. In both cases, the

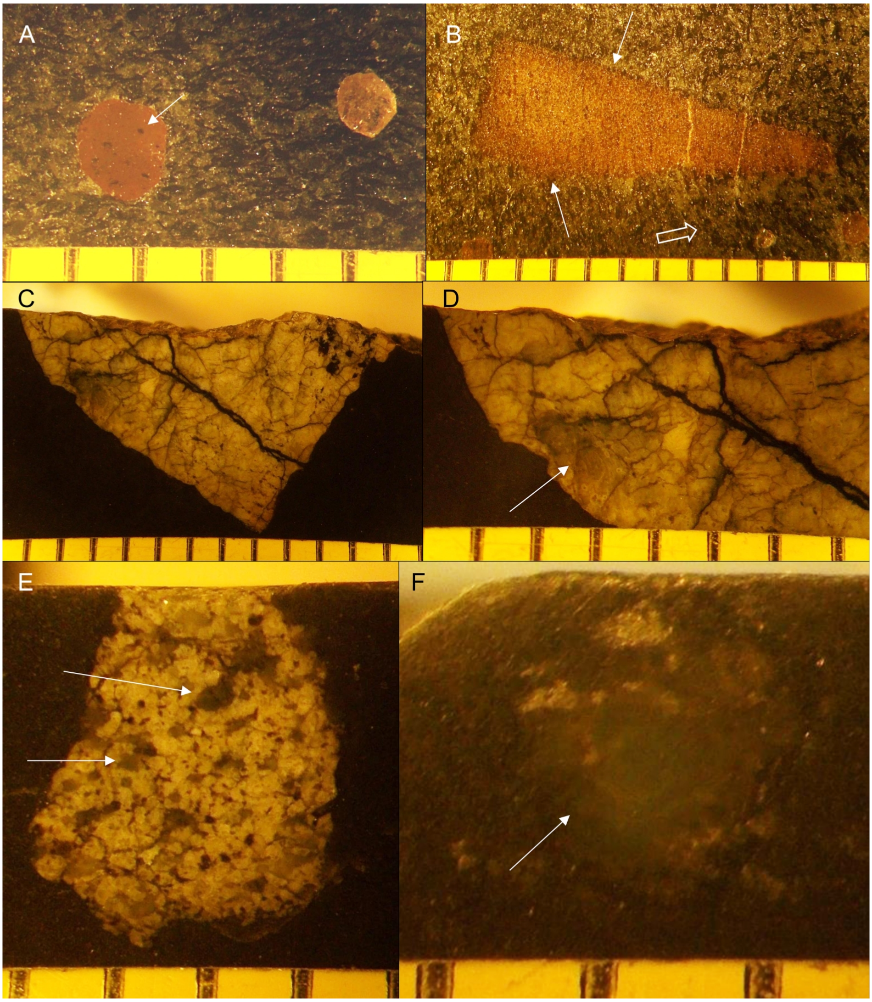

Fig. 4. Details of the Janisjarvi impactites structure. A, B – schist specimen (Fig. 3A); C-F – tagamite specimen (Fig. 3B); A – a garnet porphyroblast with biotite inclusions (arrow), the linearity of biotite plates visible in the right part of the picture; B – a staurolite porphyroblast showing the asymmetry of biotite accumulation (arrows), the linearity of biotite plates (lower arrow), a domain with the distorted linearity of biotite (bold arrow); C – a fragment of the recrystallised quartz glass injected by tiny veins of the black tagamite melt; D – the same specimen as in C with a rare fluidal texture (arrow); E – a light clast with pieces of dark green recrystallised quartz glass (arrows) and white spherical bodies showing perlitic texture; F – a green glass domain (arrow) in the black melt of tagamite. Scale in mm.

observed textures were the result of variation in micro-crystallisation. The tagamite specimen exhibited slightly stronger magnetism compared to the schist specimen. In all parts of the tagamite – black melt, veined clasts and spotted clasts – isotropic glass fragments with visible partial recrystallisation, numerous spherules and very well-developed 'ballen quartz' structures were observed (Fig. 6B–F). The diameter of spherules varied from 20 to 57 μm, while the arithmetic average was 30 μm. The diameter of the 'ballen' subunits was in range of 8–34 μm, while the arithmetic average was 21.7 μm.

Suevite

The suevite specimen (Fig. 3C) was composed of a black matrix and a few small clasts delineated from the matrix by distinct envelopes. Glass and a lighter melt (probably quartz-feldspar) were found to be the main components of the clasts. The suevite matrix appeared to be polymineral (Fig. 7A), partly formed by isotropic glass (Fig. 7B), with fragments of the rutile sagenite net (Fig. 7C). The latter was probably formed by changes of ilmenite during the oxidation of iron (Sazonova 1988). Multiple isotropic spherules were also observed (Fig. 7D). The presence of spherules in groups (Fig. 7B) indicated the recrystallisation of quartz through the 'ballen' structures. The diameter of spherules varied between 25 and 88 µm, while the arithmetic average was 61 µm. The diameter of the 'ballen' subunits was in range of 20–53 µm, while the arithmetic average was 38 µm. In the micro-veins of the suevite, brecciated pieces of black melt were noticed. Suevite showed an intermediate degree of magnetism between tagamite and schist.

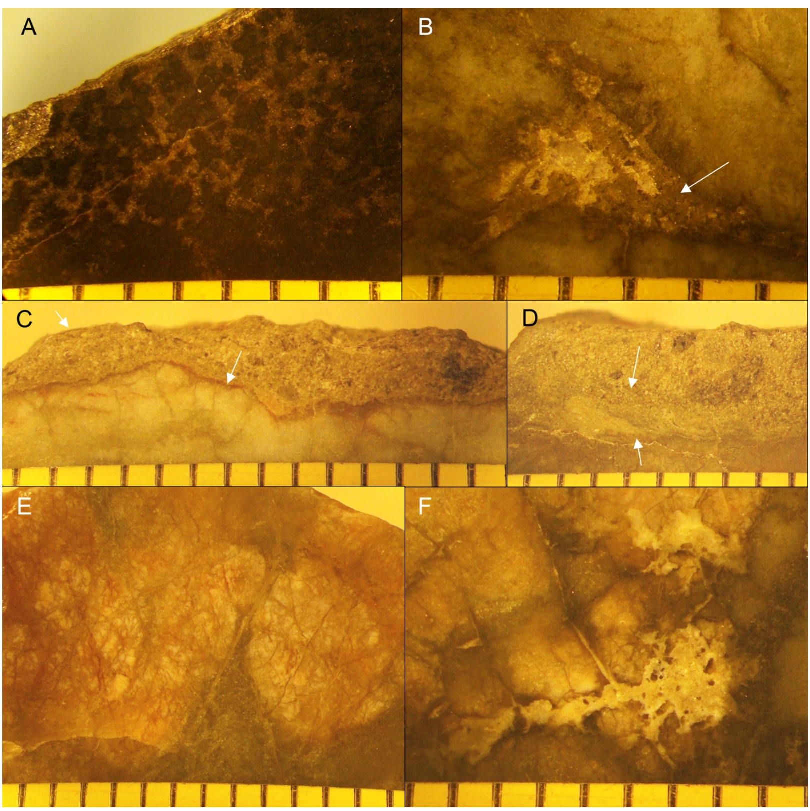

Fig. 5. Details of impactites of the Janisjarvi structure. A – a light-dark spotted domain in the black melt of tagamite; B – a void in diaplectic glass filled by a fine-grained, grey matrix (arrow) and lighter melt; C – the fine-grained grey rock (limited by arrows) closely cemented with a quartz paramorphosis specimen by a tiny glass net; D – the same rock as in C showing a fluidal texture (arrows); E – a fragment of the quartz paramorphosis specimen with reddish domains fractured by a net of tiny veins; F – a fragment of the quartz paramorphosis specimen with a light grey melt penetrating domains of recrystallizing quartz glass. Scale in mm.

Diaplectic glass

The diaplectic glass plate displayed a grey-green colour. It was fractured and secondary mineralisation had occurred in the veins between its fragments (Fig. 3D), and the voids were filled with a fine-grained grey matrix (Fig. 5B). The glass was largely recrystallised. The lobate or amoeboid contacts found between the recrystallising grains indicate a process of high-temperature grain boundary migration (Fig. 8B). Spherules were also observed, with a diameter ranging between 20 µm and 100 µm and an arithmetic average of 55 µm.

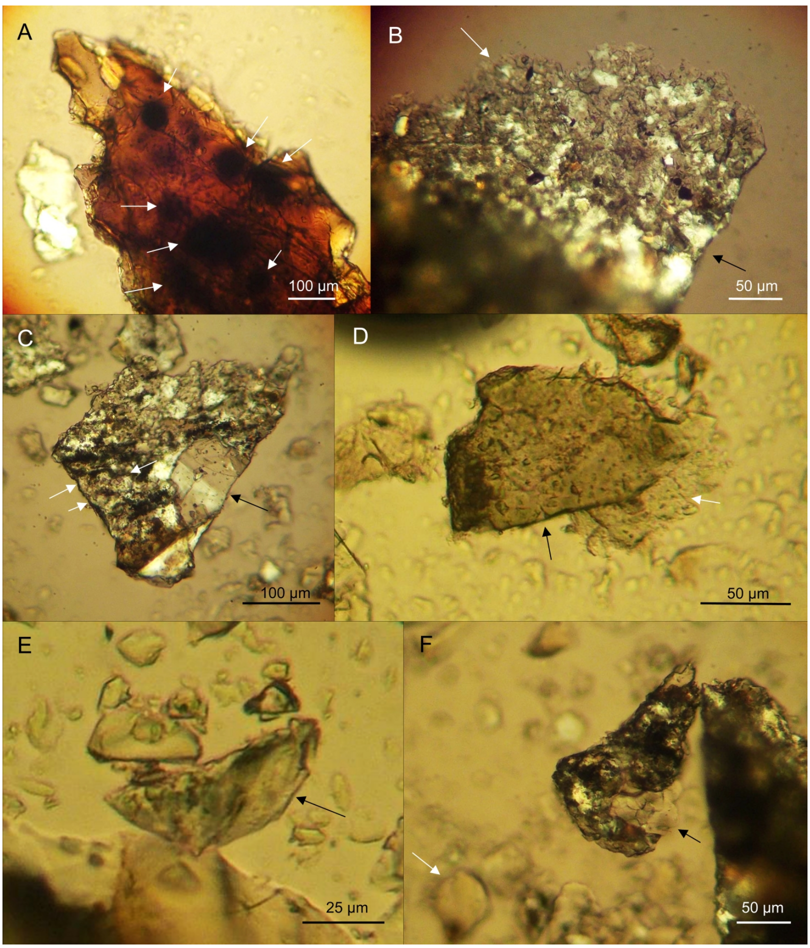

Fig. 6. Microstructures of the Janisjarvi impactites. A – biotite plates from the metamorphosed schist showing dark pleochroic fields (arrows); B – a fragment of the black tagamite melt with isotropic (dark) and recrystallised (light) parts shown by arrows; C – a fragment of the light-dark spotted domain in tagamite with the 'ballen quartz' fragment (white arrows) and a piece of recrystallising glass showing 'undulose extinction' (black arrow); D – a fragment of the light green clast from tagamite (Fig. 4C) showing a weak anisotropy in the left dark part (black arrow) and isotropy in the right lighter part (white arrow); E – half of the glassy spherule (arrow) from the light-dark spotted domain in tagamite; F – a droplet-shaped 'ballen quartz' structure from the black melt of tagamite with partially exposed light spherical 'ballen' subunits (black arrow) and a spherule (white arrow). Nicols partially crossed.

Quartz paramorphoses

Two specimens of recrystallising quartz were analysed (Fig. 3E, F). One of them was closely connected to a fragment of the fine-grained, grey rock cemented by a tiny net of glass (Fig. 3F). In the specimen shown in Fig. 3E, reddish strongly veined domains, solid glass domains ranging in colour from black, green to grey-green and a few fragments of the light melt (probably quartz-feldspar) penetrating between the domains mentioned above were observed. Secondary mineralisation had taken place in the voids. In the specimen shown in Fig. 3F, the grey fine-grained rock adhered tightly to the quartz paramorphosis specimen due to the fine veins of quartz glass penetrating between them. The veins formed a micro-net in the rock. The quartz paramorphosis specimen was fractured, with secondary mineralisation observed between the fragments. The green domains showed recrystallisation, and spherules (Fig. 8A) as well as 'ballen quartz' structures were visible in them. The diameter of the spherules varied with a range of 32–34 µm, while arithmetic average is 33 µm. The diameter of the 'ballen' subunits was in a range of 12–24 µm, while the arithmetic average was 17.4 µm. Numerous quartz fragments with planar deformation features (PDFs) and planar fractures (PFs) were observed in the reddish domains (Fig. 8D). PDFs occurred as one, two or three sets of lamellae per quartz fragment. The lamellae were spaced 1.8 µm apart, per average. PFs were less frequently observed, and their fractures were spaced 5.6 µm apart, per average. For instance, two PFs, shown by an upper white arrow in Fig. 8D, are spaced 5.9 µm apart. The bright, irregular melt consisted of anisotropic and isotropic fragments optically showing a rough microstructure (Fig. 8C). This structure appeared as a pattern of micro-recrystallisation as shown in Fig. 8B (high-temperature dynamic recrystallisation by grain boundary migration), indicating an earlier growth stage of recrystallising quartz grains.

Fine-grained rock

Fragments of this rock were tightly adhered to a plate of recrystallising quartz (Fig. 3F), and it is likely that a bomb-shaped quartz glass was embedded in this rock. The rock matrix was to be found fine-grained, cemented with a micro-net of glass which was visible on the polished surface. This net was connected to the glass of the quartz bomb by numerous strands. The rock contained numerous spherules of various sizes and their 'ballen quartz'-type clusters. It seems that, this type of rock, together with the quartz glass bomb, may be a component of suevite.

Secondary minerallisations

These mineralisations were mainly observed in the cracks and veins of the specimens of the diaplectic glass and paramorphoses of quartz. They were mostly composed of Fe compounds, chlorite (Fig. 9A, B) and calcite (Fig. 9C). The calcite veins contained clasts of cataclased and/or brecciated glass arranged parallel to the vein or in a disorganised manner (Fig. 9C). In the black veins of a specimen

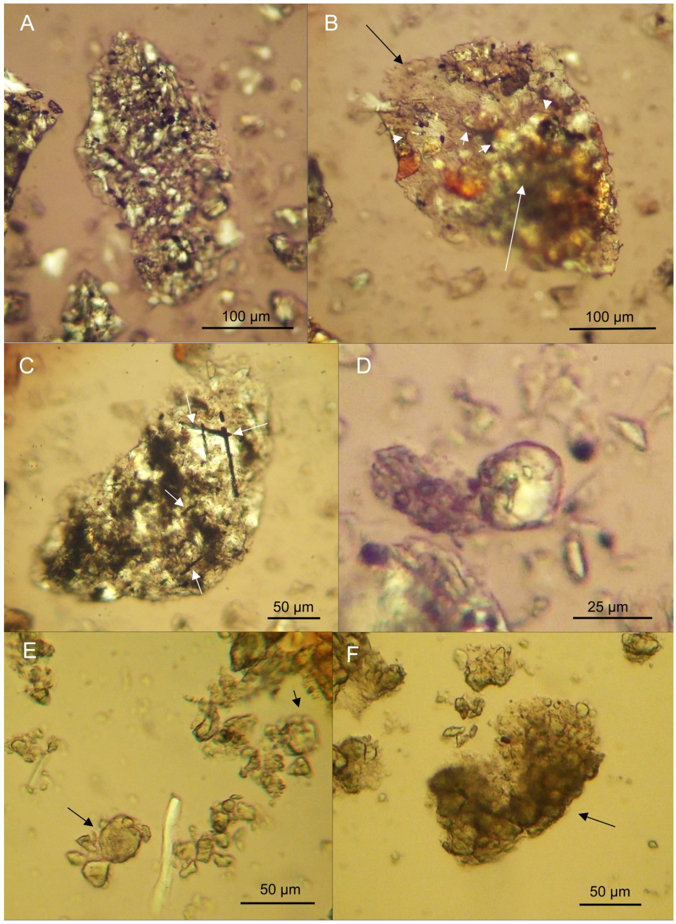

Fig. 7. Microstructures of the Janisjarvi impactites. A – a fragment of the black polymineral matrix of suevite; B – a fragment of the black matrix of suevite with iso- (black arrow) and aniso-tropic (white arrow) parts and spherules or 'ballen' subunits (white short arrows); C – a fragment of sagenite net (probably rutile; also see Sazonova 1988); D – a spherule from the suevite black matrix; E – spherules from the reddish domain in the quartz paramorphosis specimen (arrows); F – a fragment of the 'ballen quartz' structure (arrow) taken from the grey fine-grained rock cemented to the quartz paramorphosis specimen (see Fig. 5C, D). Nicols partially crossed.

of diaplectic glass, sharp-edged microclasts of transparent glass were observed in an amorphous mass of chlorite mineralisation.

Discussion and concluding remarks

The data from the schist specimen of the Janisjarvi structure indicated shifting movements of staurolite porphyroblasts in relation to the biotite-quartz-feldspar layers. Larger accumulation of biotite plates was observed on one side of the staurolite porphyroblast. This was accompanied by the formation of biotite-poor domains with a disturbed linear arrangement of biotite plates. At the sites of schist weathering, garnet porphyroblasts, biotite plates and quartz and feldspar crystals

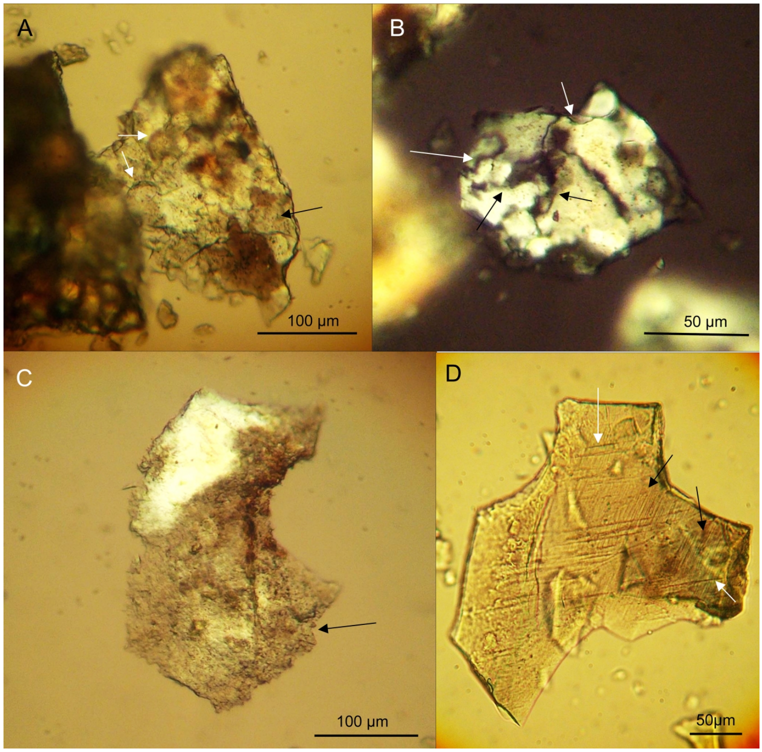

Fig. 8. Microstructures of the Janisjarvi impactites. A – a fragment of green glass with spherules (arrows) taken from the quartz paramorphosis specimen; B – a fragment of diaplectic glass with dynamically recrystallising quartz grains having interlobate and ameboid grain boundaries (arrows); C – a fragment of the light melt taken from the quartz paramorphosis specimen (Fig. 3E) showing iso- and anisotropy as well as recrystallization seen in the form of micrograins that make the surface of the fragment rough (arrow); D – a piece of quartz grain taken from a reddish domain in the quartz paramorphosis specimen with a set of PDF lamellae (black arrows) and planar fractures (PFs; white arrows) which crossed PDF. Nicols partially crossed.

were found to be loosened. Pleochroic fields were observed in the biotite plates (Fig. 6A), but without visible zircon crystals, the radioactivity of which could create the fields (Borkowska and Smulikowski 1973). In garnet-mica-schists from Scotland, Dempster et al. (2008) detected very small zircons, with a size of 0.2–3.0 µm. It is probable that such zircons, which are not visible under a light microscope, were active in Janisjarvi schists. Under a shock load of 20–25 GPa, which created the Janisjarvi structure, biotite was changed showing reduced birefringence and pleochroism and staurolite porphyroblasts were pseudomorphosed, but this did not occur in the case of garnet crystals, which were decomposed only below 40 GPa (Feldman 1994). Kozlov et al. (2002) provided experimental data on impact pressure regimes which caused crystal decomposition and the formation of new phases for the Janisjarvi schist dark minerals: biotite (33 GPa), staurolite (36 GPa) and garnet (40 GPa). In the Janisjarvi garnet, chemical but not structural changes occurred under impact. FeO and MgO abundances were noticed to be increased at the edge of crystals (Raitala 1997). No shock structures were

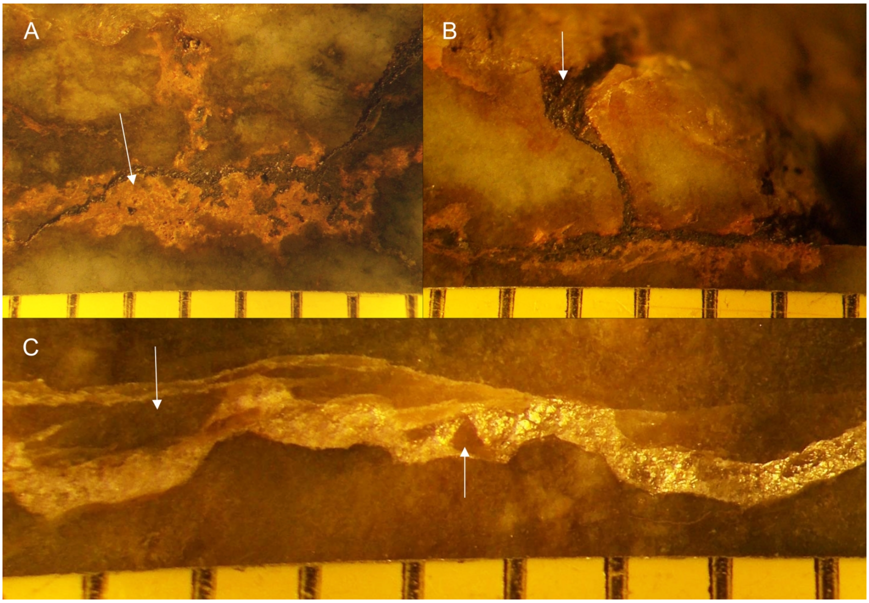

Fig. 9. Secondary mineralisation in the Janisjarvi impactites. A – the brown FeO mineralisation (arrow) in diaplectic glass; B – a vein with dark chlorite (arrow) and brown FeO in diaplectic glass; C – a vein with light calcite and green clasts of brecciated quartz glass in the specimen of quartz paramorphosis. Scale in mm.

observed in the schists at the basement, probably because fine-grained mica-schist reduced the influence of impact (Koljonen and Rosenberg 1976). This suggest that the changes observed in this study might have been caused by regional metamorphism during the petrogenesis of schists.

A characteristic feature of the Janisjarvi impactites was the presence of isotropic spherules, with a diameter of 20–100 μm. The largest spherules were observed in suevite. Up to four times (404 μm) larger spherules have been recorded in suevite from the Ries crater, where five types of them were distinguished (Sears et al. 1996). The fallout deposit from the El'gygytgyn crater on the Chukotka Peninsula contained abundant glass spherules, with diameters similar to those of Ries (Wittmann et al. 2013). In suevites, glass spherules appeared to be a common structure (Kosina 2017a). Spherical subunits of the quartz 'ballen structure' were similar to glass spherules. In the present study, the diameters of the spherules were found to range from 8 to 53 μm, which agrees with the range 25–75 μm provided by Trepman et al. (2020). The ranges of the diameters of glass spherules and 'ballen' subunits partially overlap. Data presented by Jackson et al. (2016) showed that quartz recrystallised first in the centre of the 'ballen structure' and the spherical subunits remained unchanged on its periphery. A similar pattern of recrystallisation was found in the 'ballen structures' in the impactites of the Puchezh-Katunki astrobleme (Kosina 2019). French (1998) presented an opinion that the 'ballen structure' is a characteristic feature of lechatelierite (quartz diaplectic glass). Osinski (2007) cited pressure ranges for the creation of diaplectic glass in porous rocks from 5 to 35 GPa, and in solid rocks from about 32 to 60 GPa. Ferrière et al. (2010a) proved that -quartz and -cristobalite coexisted during quartz recrystallisation in the 'ballen structure'. The 'ballen structures' were detected mainly in tagamites and other melt rocks (Ferrière et al. 2010a), as well as in other types of impactites (Kosina 2017b, 2019; this study). Sometimes, they appeared in the shape of a droplet (Ferrière et al. 2010a; Trepman et al. 2020; this study Fig. 6F). Undulatory extinction of the subunits of the 'ballen structure' (Trepman et al. 2020) was also noted in this research, but rarely. The transformation of amorphous lechatelierite into spherical 'ballen' subunits occurs by three processes: decompression, cooling and dehydration which are similar to those involved in the development of perlitic textures in volcanic rocks (Trepman et al. 2020). The 'ballen structures' showed that recrystallisation of quartz is common in the Janisjarvi impactites. It occurs through the process of dynamic grain boundary migration, which is typical at high temperatures (Passchier and Trouw 2005).

In fragments of paramorphosed qartz, sets of PDFs were numerous, especially in the form of a single PDF. Two or three sets were also recorded. Similar numbers of sets, one or two, were noted in the shocked granodiorite from the Keurusselkä structure (central Finland) (Ferrière et al. 2010b). In general, it was reported that in a single quartz grain, their number can reach even 18 (Hamers and Drury 2011). In quartz paramorphoses, lamellae within a set were spaced ca. 2 μm apart. A similar spacing was provided for the Lake Mistastin structure (Alexopoulos et al. 1987). However, in the Keurusselkä structure located westwards the Janisjarvi Lake, PDFs in quartz grains showed lamellar spaces in range of 2–10 μm, and the spacing between PFs was larger than 20 μm (Ferrière et al. 2010b). For PFs in the present study (Fig. 8D), the distance between two fractures was almost four times less (5.9 μm). PFs are created later than PDFs, at a lower postimpact pressure, so they can cross the PDF lamellae (Hamers and Drury 2011). Such a case is presented in Fig. 8D.

Secondary mineralisation is common during post-impact petrogenesis. In this study, it was found to be related to iron oxides, chlorite and calcite. The types of mineralisation depends on the type of the impacted rock and its vertical location (Naumov 1993). Crystallisation of FeO was noted in suevites in many astroblemes, and also in the Ries crater, while chlorite was high in amount near the crater crystalline basement (Osinski 2005). On the islands and peninsula on the western shore of the Janisjarvi Lake, chlorite and carbonate mineralisations were found in the shock-melted rock (Koljonen and Rosenberg 1976). In this study, both minerals were detected in microveins in the diaplectic glass and quartz paramorphosis specimens. They were recognised as bomb-shaped, large clasts in the fine-grained impact rock cemented by a glassy micro-net (Fig. 3D, E, F). Angular microclasts were embedded in the calcite veins after fracturing of these bomb-shaped clasts. It is highly probable that these large clasts (Fig. 3D, E, F) were components of an impact rock cemented by a fine-grained glassy matrix showing fragments with a fluidal texture (Fig. 5C, D). Salminen et al. (2006)

described the matrix of the Janisjarvi suevite as fine-grained (*comminuted*) and composed of fragments of the basement rocks. Such a characteristic relates well to the polymineral matrix in the black, rigid suevite (Fig. 7A) and the fine-grained grey rock (5C, D) observed in this study. Both these are components of suevite.

This research proved that the analysed schist specimen of the target rock was not modified by impact and showed characteristics of regional metamorphism. Dynamic quartz recrystallisation is a common phenomenon in impactites. This was evidenced by the simultaneous occurrence of iso- and anisotropic parts in the analysed impactite fragments. Quartz existed in the form of diaplectic glass and 'ballen structures' as paramorphoses. Impactite structures – clasts in veins – showed that the processes of cataclasis and brecciation also took place at microscale. PDFs were very common in the red domains of quartz paramorphosis specimens; however, PFs were less frequently recorded. Other impactite features, such as fluidal texture, undulose extinction and perlitic-like texture, were not frequently noted.

Streszczenie

Uwagi o niektórych skałach uderzeniowych ze struktury Janisjarvi, Karelia, Rosja

Struktura uderzeniowa Janisjarvi znajduje się na północnym skraju jeziora Ładoga w rosyjskiej Karelii. Analizowano łupek typu biotyt-kwarc-skaleń-granat-staurolit ze skał podłoża struktury oraz kilka skał poddanych metamorfozie uderzeniowej. W łupku odkryto inkluzje biotytowe w granacie, pola pleochroiczne w biotycie i asymetrię kontaktu staurolit-biotyt. W biotycie nie zaobserwowano pasm typu 'kinky'. Struktury fluidalne i faliste wygaszanie światła były rzadkie w analizowanych okazach. Odnotowano injekcje stopu tagamitu w klasty skataklazowanego rekrystalizującego szkliwa. Okaz rekrystalizującej paramorfozy kwarcu był scementowany z drobnoziarnistą skałą impaktową mikrosiecią szkliwa. W większości analizowanych impaktytów rozpoznano izotropowe sferule i struktury 'kwarcu groniastego', a w tagamicie i paramorfozach kwarcu także od jednego do trzech zestawów lameli deformacji planarnych (PDF) oraz spękania planarne (PF). Spękania planarne były znacznie rzadsze niż deformacje i powstawały w stadium postimpaktu. Z wyjątkiem łupku, dynamiczna rekrystalizacja poprzez „migrację falistych granic ziarn" była powszechna. Stwierdzono wtórne mineralizacje tlenków żelaza, chlorytu i kalcytu.

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