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REMAINS OF PALEOFLORA IN THE BRECCIAS OF THE ONAPING FORMATION, SUDBURY IMPACT STRUCTURE, ONTARIO, CANADA

Electron microscopic investigations of four breccia samples of the Onaping Formation, Sudbury impact structure, Canada, have been carried out for the search of possible remains of paleoflora and identification of the nature of organic matter and their composition. Two forms of plant remains were discovered in the breccias. The first form is represented by single plant particles scattered in the matrix of breccias and included in gas vesicles in devitrified glasses. These particles are leaf-shaped, stem-shaped, tubular, and spherical objects, ranging from 5-10 to 200-300 μm in size. It is supposed that algal flora inhabiting the sea basin before the Sudbury impact was the source of this form of plant residues in breccias.

The second form of plant remains in breccias is represented by plant detritus in carbon-bearing fragments of mudstones included in the breccia matrix. These fragments, reaching a size to 1000-1200 μm , have irregular shapes and complicated rugged contacts with the host breccia. Plant residues in mudstones are mainly ribbon-like scraps from 3-5 to 200-300 μm long, some while rare particles have a more complex shape. The matrix of the mudstones is a heterogeneous fine-grained clay-like substance with a network of micron-wide open joint fissures. The carbon content in mudstone matrix ranges from 7-10 to 20-25 wt%. Muddy bottom sediments of the pre-impact sea basin are supposed to be a source of mudstone fragments in breccias, while the algal flora inhabited the sea during their sedimentation served as a source of plant detritus in mudstones. Fragments of mudstones and floral residues are an important source of organic carbon in breccias of the Onaping Formation. The discovery of paleofloral remains in the breccias indicates the existence of a previously unknown complex algal flora that inhabited the pre-impact sea before the impact event 1.85 billion years ago at the very end of the Paleoproterozoic.

The Sudbury impact structure is comparable in size to the Chicxulub impact structure, the formation of which caused the Cretaceous-Paleogene mass extinction. We assume that the formation of the Sudbury structure had a catastrophic impact on the paleoflora of the late Paleoproterozoic, the remnants of which were preserved in the breccias of the Onaping Formation.

Keywords: impact structure; breccia; paleoflora; plant remains; bottom sediment.

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Introduction and geological setting

Remains of plant microfossils were discovered in breccias of the Onaping Formation, Sudbury impact structure, Canada. The Sudbury structure, 1.85 billion years old (Krogh et al., 1984; Corfu, Lightfoot, 1997), is a deeply eroded multi-ring impact structure with an original diameter of approximately 200-250 km (Dickin et al., 1996; Mungall et al., 2004). The structure is located on the Canadian Shield at the border of the Archean Superior Province, consisted of Archean gneisses, meta-volcanic and meta-sedimentary rocks, and the Southern Province, which comprises Proterozoic formations of the Huronian Supergroup of meta-volcanic and meta-sedimentary rock complex of about 10-12 km thickness. A shallow foreland sea basin covered the surface of the basement on the eve of the impact event (Peredery, 1972; Beals, Lozej, 1975; Grieve et al., 2010).

Currently, the surviving part of the Sudbury structure consists of the Sudbury Igneous Complex (SIC) with Ni-Cu-PGE mineralization, brecciated footwall rocks, and the Sudbury Basin of 60×27 km size, occupied by an overlying crater-fill series of the Whitewater Group (Fig. 1) (Ames et al., 2002; Muir and Peredery, 1984; Pye et al., 1984).

The SIC is represented by a canoe-shaped body (Heymann et al., 1999) of impact melt rocks of predominant noritic and gabbroic composition. Both the modern elliptical shape of the structure, elongated from southwest to northeast, and the complex shape of the SIC body, were formed in the Penocean Orogeny at approximately 1.85 Ga, the Yavapai Orogeny at approximately 1.75 Ga (Piercey et al., 2007) and later by the Granville Orogeny (Szabo, Halls, 2006).

The crater-fill Whitewater Group consists of four formations: (oldest to the youngest): the Onaping, Vermillon, Onwatin, and Chelmsford Formations (French, 1968; Beales, Lozej, 1975; Muir, Peredery, 1984).

The Onaping Formation, 1.4-1.6 km thick, is the lowermost member of the Whitewater Group (French, 1967; 1968; Beales, Lozej, 1975; Muir, Peredery, 1984; Ames et al., 2002). The Onaping Formation is represented by a complex of breccias and impact melt rocks formed as a result of deposition of fall-back ejecta, sea water intrusions into

the crater basin and its interaction with the SIC surface, and transportation of fall-out ejecta into the crater basin from the surrounding shelf by resurge waves (Peredery, 1972; Peredery, Morrison, 1984; Grieve et al., 2010). Three main divisions were distinguished in the Onaping Formation: Garson, Sandcherry, and Dowling members (Peredery, Morrison, 1984; Ames et al., 2002, 2006; Grieve et al., 2010).

The Garson member, distributed in the southeastern part of the Sudbury basin, is represented by breccia and megabreccia of 100 (500) m thickness, consisting of blocks and clasts of basement rocks. Formation of these deposits occurred immediately after the impact event and collapse of the annular uplift (Ames et al., 2002, 2006).

The Sandcherry member overlaps deposits of the Garson member. The Sandcherry member is formed by breccias of a total thickness of 50-500 m, containing ~65 vol% of glass fragments and ~15 vol% of clasts of basement rocks in a fine-grained matrix. When the surface of impact melt interacted with the sea water, the fall-back breccia sequence was intruded by impact melt of andesite composition, forming concordant and cross-cutting fluid-breccia bodies (Ames et al., 2006; Grieve et al., 2010).

The Dowling member, more 1000 m thick, lies on the surface of the Sandcherry member. Distinctive features of the breccia are a high content of matrix of ~60 vol%, the predominance of small (less than 5 mm) fragments of chloritized glass comprising ~25-40 vol%, and the presence of ~0.4 wt% carbon in these rocks. Thus, an important feature of the composition of the Onaping Formation is high content of organic carbon in breccias of the Dowling member, what remained difficult to explain for many decades (Beales, Lozej, 1975; French, 1968; Naldrett, 1999). To date, many various sources of carbon in the Onaping Formation were proposed.

At an early stage in studying the Sudbury structure, it was proposed to divide of the Onaping Formation into two parts: the lower Gray Onaping, formed as a result of the deposition of fall-back ejecta, and the upper Black Onaping with a high carbon content, formed as a result of mixing of fall-back material with washed-in fall-out ejecta from the surface of the surrounding shelf (Peredery, 1972; Beales, Lozej, 1975). It was assumed that algal flora inhabited the illuminated shelf zone on

the eve of the impact event was a probable source of organic matter in breccias of the Black Onaping (Beales, Lozej, 1975).

Avermann (1994) subdivided the Onaping Formation into the Basal Member (0-300 m thick), Grey Member (300-500 m thick), Green Member (5-70 m thick), Lower Black Member (100-200 m thick), and Upper Black Member (800-900 m thick). The remains of small algae were also briefly described in breccia of the Black Member (Avermann, 1994). The carbon isotopic composition ($\delta^{13}\text{C} = -30.10$ – -31.06‰) of the breccias of the Black Member show its biogenic origin according to the data by Schidlovski (1987). Biological activity in Precambrian has been suggested, according to which the formation of biogenic material was originated during slow sedimentation in a local euxinic crater basin (Avermann, 1994). This author excluded non-organic and extraterrestrial sources of carbon in breccias of the Onaping Formation.

A detailed study of organic matter in the Onaping Formation was carried out by Heymann and coauthors (1999). The isotopic composition of carbon in 17 breccia samples of the Black Member and one sample of the Gray Member confirmed its biogenic origin. These authors concluded that organic matter in deposits of the Onaping Formation is a result of the biological activity and high fecundity of prokaryotes (archaea and bacteria) over several million years of sedimentation in the Sudbury basin, what determined the high content of organic carbon in the Black Member (Heymann et al., 1999). These authors excluded carbonaceous target rocks, atmospheric CO_2 , and the impacting projectile as likely carbon sources.

Fullerenes have been described as one of the carbon carriers in the Onaping Formation (Becker et al., 1994; Mossman et al., 2003). Determination of several grains of impact diamond in breccias (Masaitis et al., 1999) indicated pre-impact origin of some part of the carbonaceous matter in the Onaping Formation.

Thus, the carbon source in the Onaping Formation remained a difficult problem for a long time (Dressler, Sharpton, 1999; Naldrett, 1999). Based on a review of studies of carbon and its sources in the Onaping Formation, Grieve and coauthors (2010) stated that “the source of carbon is not known unequivocally”, and concluded that “an extensive study of carbon origin and distribu-

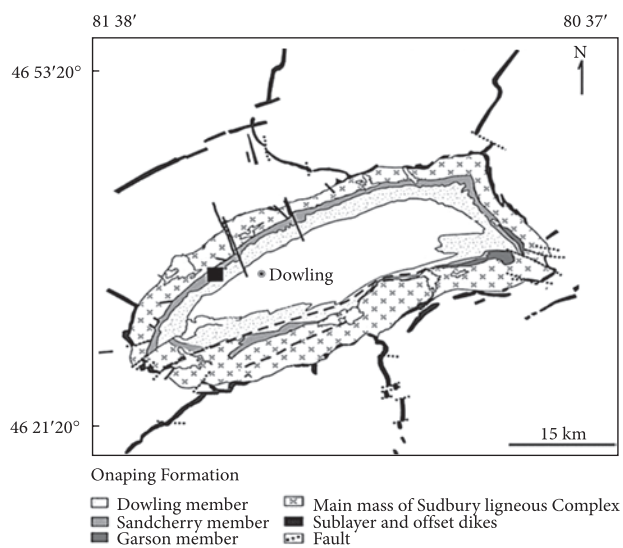


Fig. 1. Simplified geologic map of the Sudbury impact structure (modified from Grieve et al., 2010). The area of sampling (Dowling Township, west side of Onaping River) is indicated by the black square. The white area inside the elliptical basin indicates the occurrence of upper Whitewater Series units (Onwatin and Chelmsford Formations). White areas outside basin designate pre-impact target rocks: Archean crystalline rocks (North) and Huronian metasediments (South). (For details, see (Rousell, Brown, 2009))

tion in the Onaping could be a fruitful area for future research”.

Howard et al. (2013) first described biomarkers of plant species in the impact melt ejecta from the Darwin crater, Tasmania, Australia. Harris and Schultz (2007) and Schulz et al. (2014) described floral remnants in impact melt rocks and impact melt breccias forming 7 horizons of clasts in loess depositions of the Argentinean Pampa, and proposed a strategy for searching of traces of ancient life in impact melt rocks on Mars. Later, paleofloral residues were discovered in impact melt rocks of the El'gygytgyn crater in Chukotka, Russia (Gurov et al., 2019). The high content of biogenic carbon in the Onaping Formation, on one hand, and the strategy proposed by Schultz et al. (2014) for searching for traces of ancient life in impact melt rocks and breccias, on another hand, served as the basis for our electron microscopic studies of breccias of the Onaping Formation for search of possible traces of organic life. These investigations have led to the discovery of microfossil remains in the rocks of the Sandcherry member and have also confirmed the high potential of impact processes for preserving traces of

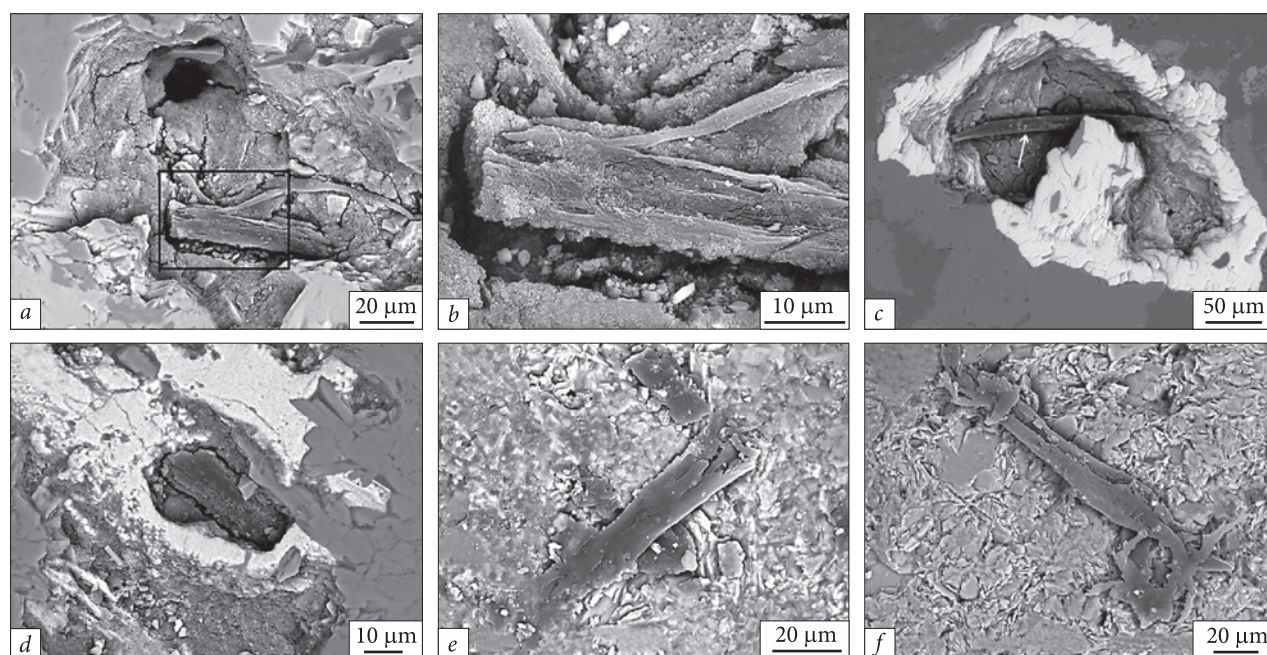


Fig. 2. BSE images of carbonaceous microparticles in breccias of the Onaping Formation: *a* — fragmentary elongate carbonaceous microparticle in mineralized vesicle in altered glass. The rectangle outlines the enlarged image shown in Fig. 2, *b*; *b* — close-up image of the same particle shown in Fig. 2, *a*. The surface of the particle has a silicate cover (upper Sandcherry Member, sample SUD-99-13-B-G-6); *c* — fragment of a carbonaceous particle (shown by a white arrow) in vesicle in glass. Inner surface of vesicle is covered with pyrite (white) (upper Sandcherry Member, sample SUD-99-13-A-G-21); *d* — carbonaceous particle in a gas vesicle lined with pyrite (upper Sandcherry Member, sample SUD-99-13-A-G-22); *e* — split elongate carbonaceous particle in fine-grained matrix (upper Sandcherry Member, sample SUD-99-B-G-5); *f* — complex elongated carbonaceous particle with apparently twisted “root-like” end in altered glass (lower Sandcherry Member, sample SUD-99-12-B-3-31)

ancient life for almost two billion years on the Earth and other planets (Gurov et al., 2020).

Samples and methods

Four breccia samples of the Onaping Formation (from the collection of B.M. French) were studied for search of the paleofloral remains. All samples were collected from the road-cuts of the Highway 144 in the Dowling Township (Fig. 1). Samples SUD-99-12-B-3 and SUD-99-12-3-2 represent the breccia of the lower Sandcherry member. Petrographic study of thin sections had shown that the breccias are composed of fragments of target rocks and minerals in microcrystalline and glassy matrix. These fragments, up to 10 mm in size, compose ~60% breccia. They are represented by meta-sedimentary basement rocks, mainly quartzites, rare crystalline basement rocks and devitrified glasses. Mineral clasts are mainly represented by quartz and feldspars. Samples SUD-99-13-A-G and SUD-99-13-B-G are the breccias of the upper Sandcherry member. Clasts up to 10 mm in size

compose ~40% breccia, while dark opaque non-transparent matrix has predominant distribution. Clasts are mainly represented by acute-angled particles and shards of devitrified and chloritized glass. Some particles are vesicular. Sulfidization occurs in glass shards and sometimes covers the inner surface of the gas vesicles.

Six polished sections, four ground surface sections and four chips with fresh surfaces were prepared for electron microscopic investigation for the search and study of paleofloral remains in the breccias. Our studies were performed using a scanning electron microscope (SEM) JEOL JSM-6490LV and an INCA Energy + X-ray spectrometry system (Oxford Instruments). The system included an energy dispersive spectrometer (EDS) INCAx-act with an analytical silicon drift detector (ADD). In addition, backscattered electron (BSE) images were obtained with the SEM instrument. The accelerate voltage of the EDS analysis was 20 kV, and the beam current was 1-1.5 nA. The resolution of the EDS was 133 eV, and the detection limit 0.2 wt%. 210 BSE images and 220

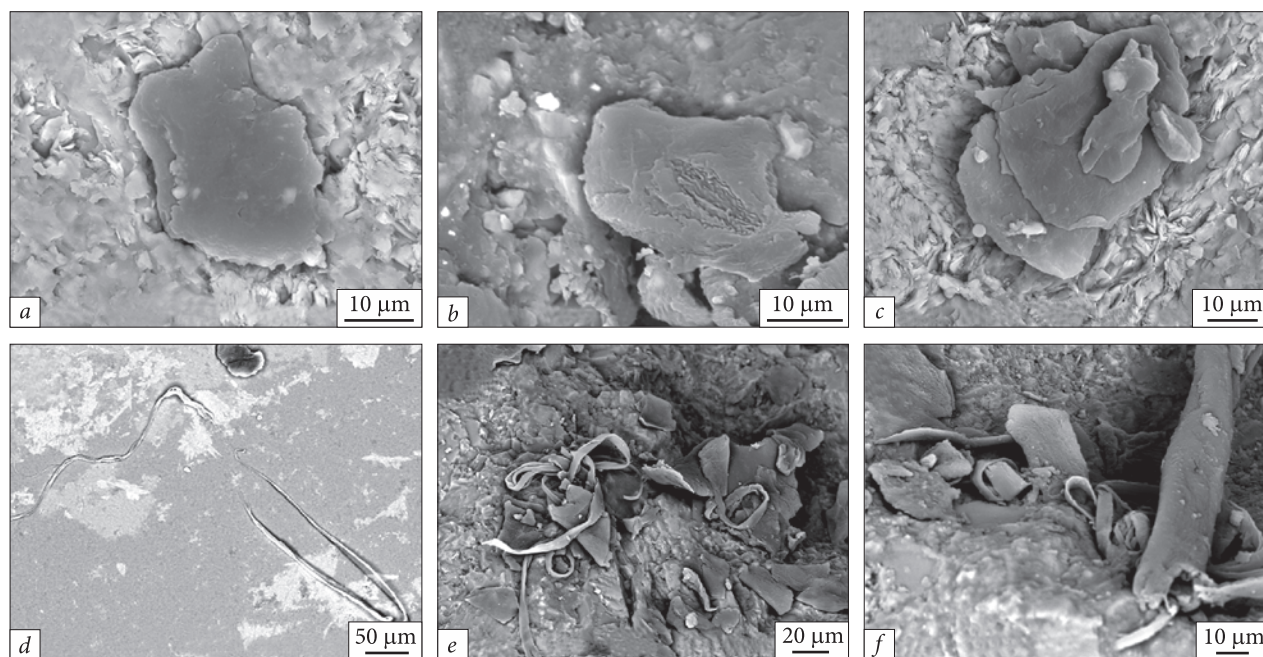


Fig. 3. Backscattered electron (BSE) images of carbonaceous microfossils in breccias of the Onaping Formation: *a* — irregular flat leaf-like particle in recrystallized glass (lower Sandcherry Member, SUD-99-12- B-3-28); *b* — leaf-like particle with ornamented surface (lower Sandcherry Member, sample SUD-99-12-B-3-1); *c* — aggregation or of leaf-shaped particles in breccia (lower Sandcherry member, sample SUD-99-12-B-G-25); *d* — ribbon-like particle in devitrified and chloritized glass (upper Sandcherry Member, sample SUD-99-13-B-G-7P); *e* — accumulation of ribbon-like and leaf-shaped particles in devitrified glass (upper Sandcherry member, sample SUD-99-13-B-G-5); *f* — Accumulation of plant particles in breccia. Tubular particle with unfilled (?) channel on the right part of the image (lower Sandcherry Member, sample SUD-99-12-B-G-36)

EDS analyzes of plant remains were obtained in these studies, the most typical of which are presented in this paper. All investigations were performed in the Institute of Geological Sciences, National Academy of Sciences of Ukraine, in Kyiv, Ukraine.

Results

Numerous plant microfossils have been found by electron microscopic examination of all studied breccia samples of the Sandcherry member. Separate plant particles are distributed in matrix of breccias and in gas vesicles in glassy shards. These particles are from 5-10 to 200-300 μm size and have a diverse shape and structure. The most common are elongated stem-shaped particles up to ~300 μm long which often have broken and split ends and represent parts of larger plants (Fig. 2, *a-f*). Stem-shaped particles sometimes discover traces of layered and fibrous structure (Fig. 2, *b* and 2, *e*). The surface of floral particles located in gas vesicles is sometimes coated with a thin silicate cover (Fig. 2, *b*), while the inner surface

of some vesicles is covered with pyrite (Fig. 2, *c* and 2, *d*).

Leaf-shaped particles are a common form of plant remains in the Onaping breccias (Fig. 3, *a-c*). These particles are mainly 15 to 40 micrometers in size and about 1-2 micrometers thick. Some particles exhibit a weakly expressed layered structure. Leaf-shaped particles with a smooth surface predominate, although their forms with an ornamented surface are rarely observed (Fig. 3, *b*). Accumulations (accretions?) of several sub-parallel oriented leaf-shaped particles were occasionally observed in breccias (Fig. 3, *c*). Ribbon-like particles have curved and twisted shapes reaching 300-400 μm in length and 3-6 μm in thickness (Fig. 3, *d-e*). Tubular particles, to 100-150 μm in length and 5-20 μm in thickness, have unfilled (?) central channel (Fig. 3, *f*). In addition to single plant particles, clusters of 3-10 particles of different morphology were rarely observed (Fig. 3, *e-f*).

Particles of a spherical, globular and toroidal shape, 15-30 μm in diameter, have been observed in breccias (Fig. 4, *a-d*). Their initial surface is smooth, and a characteristic radial system of

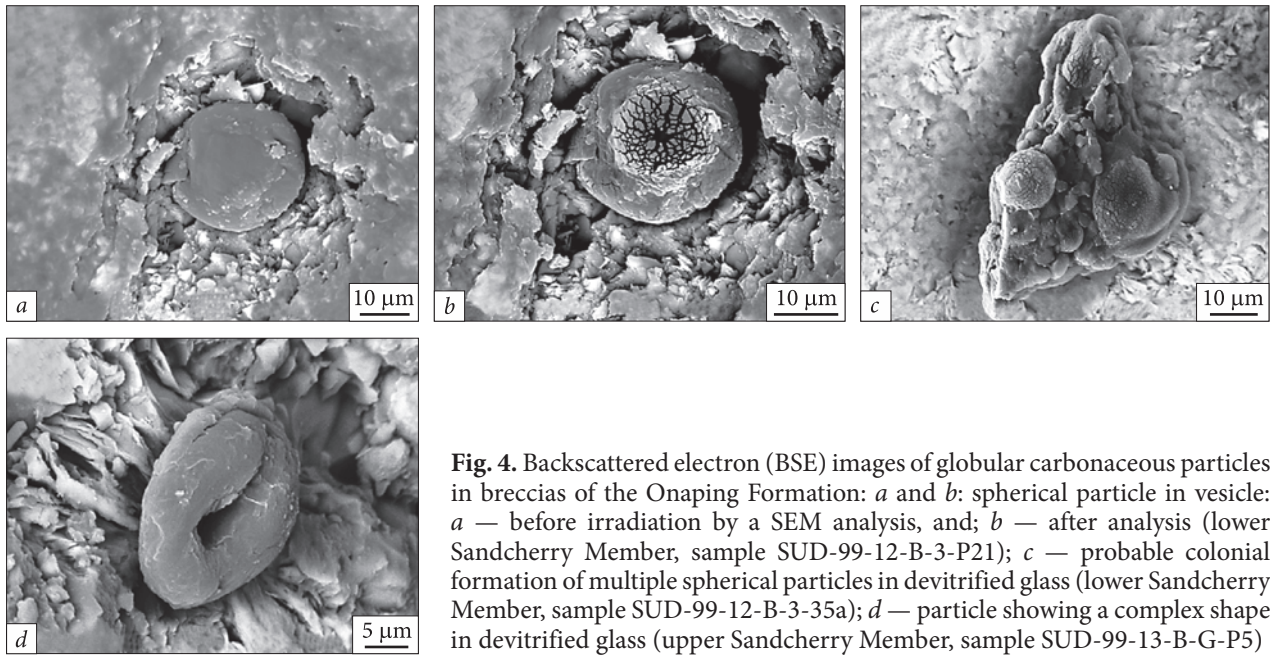


Fig. 4. Backscattered electron (BSE) images of globular carbonaceous particles in breccias of the Onaping Formation: *a* and *b*: spherical particle in vesicle: *a* — before irradiation by a SEM analysis, and; *b* — after analysis (lower Sandcherry Member, sample SUD-99-12-B-3-P21); *c* — probable colonial formation of multiple spherical particles in devitrified glass (lower Sandcherry Member, sample SUD-99-12-B-3-35a); *d* — particle showing a complex shape in devitrified glass (upper Sandcherry Member, sample SUD-99-13-B-G-P5)

Table 1. Chemical composition (EDS data) for carbonaceous particles in the breccias of the Onaping Formation (analyses 1-7a) and the El'gygytyn crater (analyses 8 and 9) (in wt%)

Element	1	2	3	4	5	6	7	7a	8	9
C	24.2	36.2	59.5	32.6	59.1	35.1	46.9	57.4	56.0	63.6
O	64.4	54.1	34.4	54.7	33.6	43.1	50.2	40.4	37.3	26.7
Si	1.9	2.4	2.2	3.9	2.1	16.8	0.1	0.4	4.5	1.9
Al	2.7	3.9	1.0	1.3	1.6	1.5	b.d.	b.d.	1.3	b.d.
Fe	2.8	0.8	1.7	3.2	2.4	1.4	b.d.	b.d.	b.d.	b.d.
Mg	b.d.	b.d.	1.1	1.0	1.7	0.5	b.d.	b.d.	b.d.	b.d.
Ca	b.d.	b.d.	b.d.	1.3	b.d.	1.4	0.2	0.1	0.9	b.d.
Na	b.d.	b.d.	b.d.	1.2	b.d.	b.d.	1.1	1.2	b.d.	0.9
K	b.d.	b.d.	d.d.	b.d.	b.d.	b.d.	0.2	b.d.	b.d.	1.5
Cl	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.5	0.5	b.d.	5.4
S	b.d.	b.d.	b.d.	b.d.	0.4	b.d.	b.d.	b.d.	b.d.	b.d.
<i>Total</i>	96.0	97.4	99.9	99.2	100.5	99.8	99.2	100.0	100.0	100.0

Notes: b.d — below detection limit. Sample details: Sudbury impact structure: 1 — lamellar particle size $3 \times 20 \mu\text{m}$ (sample SUD-99-13-A-G-8); 2 — lamellar particle size $20 \times 57 \mu\text{m}$ (sample SUD-99-13-A-G-6); 3 — complicated stem-shaped particle size $30 \times 110 \mu\text{m}$ (sample SUD-99-12-B-3-25); 4 — lamellar particle size $20 \times 35 \mu\text{m}$ (sample SUD-99-12-D-3-3); 5 — lamellar particle size $3 \times 20 \mu\text{m}$ (sample SUD-99-B-3-5); 6 — spherical particle with a diameter of $25 \mu\text{m}$ (sample SUD-99-12-3-2-3). 7, 7a Toroidal body size $17 \times 25 \mu\text{m}$ (sample SUD-99-13-B-G-5); 7 — the first, and (7a) the sixth point analyzes. El'gygytyn impact crater; 8 — leaf-shaped particle (sample El-1032-2-6); 9 — globular particle (sample El-1032-3-7).

branching fissures appears under the action of an electron beam during investigations (Fig. 4, *a, b*). These variations are accompanied by a change in the particle composition (Table 1, analyses 7 and 7a). A probable colonial formation of globular bodies, covered with a carbonaceous shell, was observed in breccia (Fig. 4, *c*). Particles of a complex toroidal shape are rare in the breccias (Fig. 4, *d*).

The composition of plant particles from breccias of the Onaping Formation is shown in Table 1. The main elements are carbon and oxygen. The carbon content varies widely from ~12 to 60 wt% with a typical content of 30 to 45 wt%. The oxygen content ranges from 30 to 65 wt%, most typically 40-55 wt%. High contents of Si, Al, and other elements in some particles are due to their

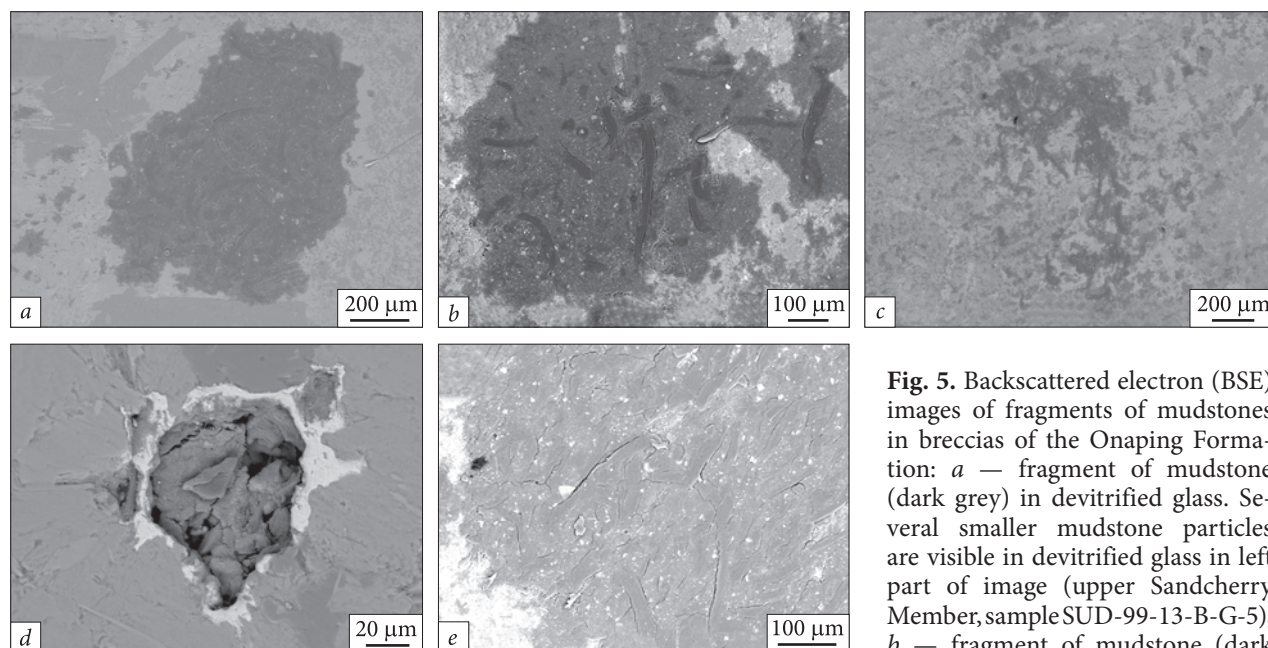


Fig. 5. Backscattered electron (BSE) images of fragments of mudstones in breccias of the Onaping Formation: *a* — fragment of mudstone (dark grey) in devitrified glass. Several smaller mudstone particles are visible in devitrified glass in left part of image (upper Sandcherry Member, sample SUD-99-13-B-G-5); *b* — fragment of mudstone (dark

grey) in devitrified glass. Elongated detrital particles (black in image) and mineral particles (white) occur in mudstone (lower Sandcherry Member, sample SUD-99-12-3-2-11); *c* — accumulation of angular mudstone clasts in devitrified glass (upper Sandcherry Member, sample SUD-99-13-B-G-1); *d* — vacuole in devitrified glass filled by lumpy and clastic mudstone masses. The vacuole is covered with a rim of pyrite (white in image) (upper Sandcherry Member, sample SUD-99-13-A-G-1); *e* — subparallel orientation of detrital particles in mudstone fragment (upper Sandcherry Member, sample SUD-99-13-B-G-2)

silicate coating. Changes in the composition of spherical and toroidal particles by the repeated point EDS analyses as a result of the influence of the electron beam are expressed in a decrease in the oxygen content and a corresponding increase in the content of carbon and other elements possibly indicating the loss of water (Table 1, analyzes 7 and 7a). Two typical analyses of plant particles from impact melt rocks of the Elgygytyn crater are given for comparison (Table 1, analyzes 8 and 9).

Fragments of mudstones containing plant detritus have been found by electron microscopic study of the breccias of the Sandcherry member. These fragments are dark gray in color on the BSE images due to their high carbon content, and clearly stand out against the background of a lightly colored silicate breccia matrix (Fig. 5, *a*, *5*, *c*). Mudstone fragments have a complex shape with rounded to rugged outlines, and are occasionally accompanied by their smaller particles in the matrix of the host breccia (Fig. 5, *a*, *5*, *b*). Mudstone fragments ranging from several tens to many hundred microns in size are present in breccias of the lower Sandcherry member, while their angular clasts ranging from 3-5 μm to 40-50 μm are most common in the upper Sandcherry breccias (Fig. 5, *c*).

A lumpy and clastic structure of the mudstone masses is observed within vacuoles in devitrified glass (Fig. 5, *d*). Mudstones are composed of a fine-grained matrix containing plant detritus, as well as mineral clasts mainly less than 5 μm in size. Content of plant detritus varies from 5-10 to 30-35 vol%, and content of mineral clasts reaches to 5-10 vol%. While irregular orientation of elongated plant particles in mudstones predominates, a subparallel arrangement is observed in some cases (Fig. 5, *e*).

Plant detritus in mudstone fragments is represented mainly by elongated rectilinear or curved particles that are several to 200-300 μm long and 20-40 μm thick, and which are supposedly scraps of ribbon-like algae (Fig. 6, *a* and 6, *b*). More complicated branched (?) particles were rarely observed (Fig. 6, *c*). Tubular particle surrounded by a wide open fissure occurred in mudstone matrix (Fig. 6, *d*). Surface of some elongated particles is weakly ornamented (Fig. 6, *e*). Radial fissures and swelling of the surface of detrital particles appear at each point of the EDS analysis by influence of an electron beam (Fig. 6, *f*). These phenomena are accompanied by changes in the particle composition at the points of the analyses (Table 2).

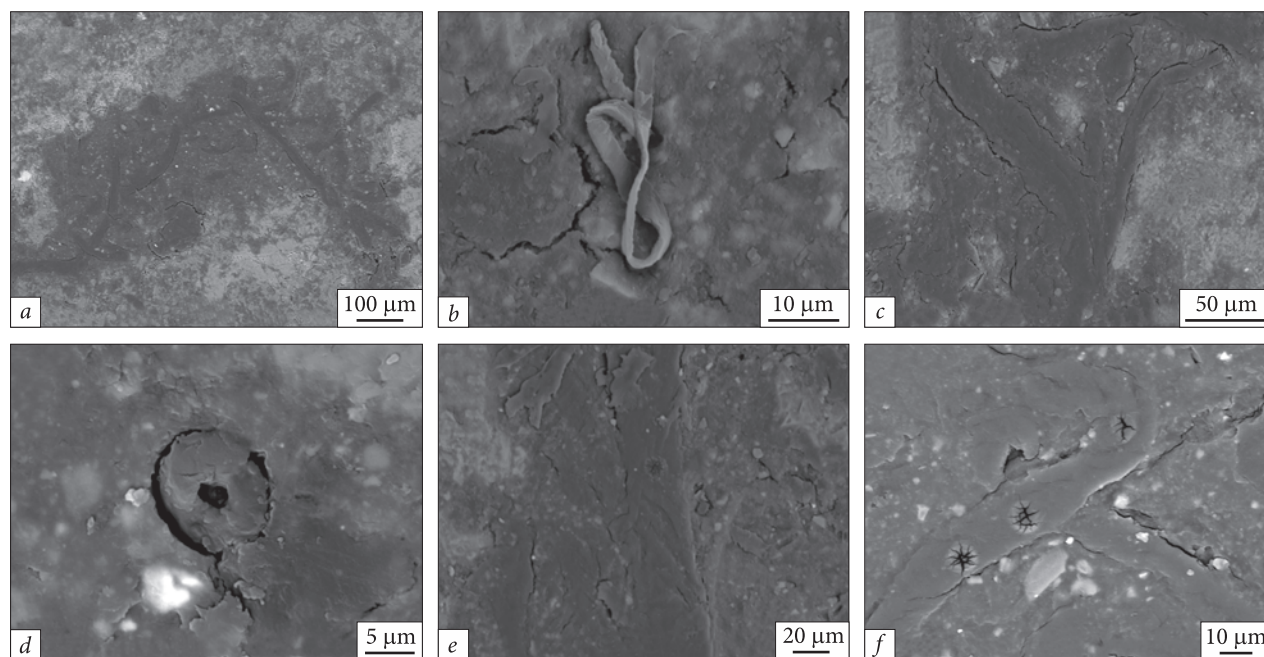


Fig. 6. Backscattered electron (BSE) images of detrital particles in fragments of mudstones in breccias of the Onaping Formation: *a* — elongated detrital particles (dark grey) in the mudstone fragment (lower Sandcherry Member, sample SUD-99-12-3-2-3); *b* — twisted ribbon-like particle in mudstone with open fissures (lower Sandcherry Member, sample SUD-99-12-B-G-1); *c* — complex, apparently branching, detrital particle at the margin of mudstone fragment (dark grey) and devitrified glass clast (light grey) (upper Sandcherry Member, sample SUD-99-13-B-G-4); *d* — tubular detrital particle in a heterogeneous matrix of mudstone, surrounded by an open annular fissure (lower Sandcherry Member, sample SUD-99-12-B-3-11); *e* — detrital particle with ornamented surface. A circular pit from the SEM electron beam is located just above the center of the image (upper Sandcherry Member, sample SUD-99-13-B-G-1); *f* — curved detrital particle displaying three small pits produced by the electron beam during SEM analyses (upper Sandcherry Member, sample SUD-99-13-B-G-5)

The composition of detrital particles is given in Table 2. Carbon content varies from 10-15 to 35-40 wt%, and most often is from 20 to 35 wt%. The carbon/oxygen ratios vary widely. Repeated two- to six-fold EDS analyses of the individual points of detrital particles caused a decrease in the oxygen content and a corresponding increase in the content of carbon and other elements in proportion to their initial content (Table 2, analyses 4, 4a and 6, 6a). The composition of the test point stabilizes after three- to six-fold repetitions of analyses. These changes are due to the evaporation of volatile components from detrital particles under influence of an electron beam. While this process is expressed by the loss of oxygen only, we suppose that it indicates evaporation of water.

The matrix of the mudstones is fine-grained heterogeneous clay-like matter with abundant plant detritus and clastic mineral grains. Open gaping fissures are often distributed along the boundaries of mudstone fragments with host breccias (Fig. 7, *a*), and also surround some detrital partic-

les (7, *b*). The length of fissures is from some tens to some hundreds micrometers, and width is from <1 μm to ~10 μm, mainly 2-3 μm. Expansion of the network of fissures and increases in their width was observed on the monitor screen during electron scanning of the mudstone fragments (Fig. 7, *c-d*).

This process is accompanied by changes in the composition of the mudstone matrix (Table 3, analyses 3, 3a, 6, 6a). The formation and expansion of open-joint fissures in mudstone fragments and the loss of oxygen indicate the evaporation of volatile components, most likely water, from their composition. The complex form of the fragments of mudstones, their rounded and rugged contacts with the breccia matrix and formation of open fissures testify to their weak consolidated state and probable water content.

The composition of the mudstone matrix is presented in Table 3. The content of carbon in matrix varies from 5 to 30 wt%, and is mainly 12-15 wt%. Changes in the composition of mudstone

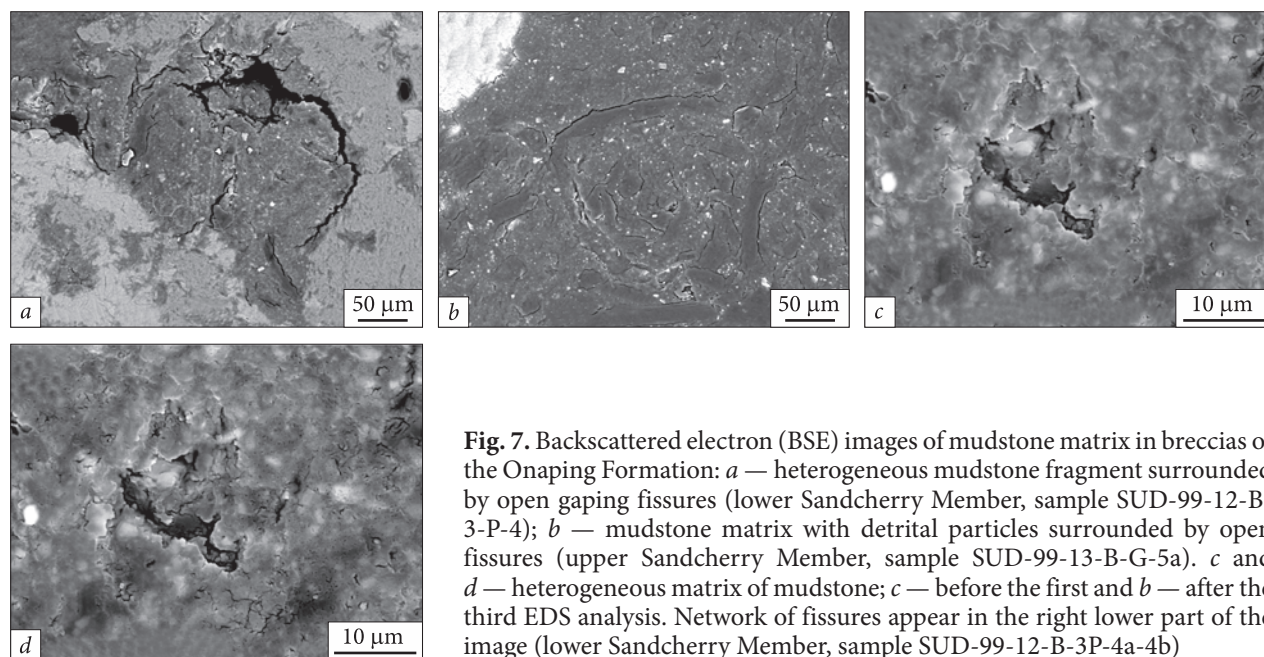


Fig. 7. Backscattered electron (BSE) images of mudstone matrix in breccias of the Onaping Formation: *a* — heterogeneous mudstone fragment surrounded by open gaping fissures (lower Sandcherry Member, sample SUD-99-12-B-3-P-4); *b* — mudstone matrix with detrital particles surrounded by open fissures (upper Sandcherry Member, sample SUD-99-13-B-G-5a). *c* and *d* — heterogeneous matrix of mudstone; *c* — before the first and *b* — after the third EDS analysis. Network of fissures appear in the right lower part of the image (lower Sandcherry Member, sample SUD-99-12-B-3P-4a-4b)

Table 2. Chemical composition (EDS data) for detrital particles from mudstone fragments in breccias of the Onaping Formation (analyses 1-6a) and in impact melt rocks of the El'gygytyn crater (analyses 7 and 8) (in wt%)

Element	1	2	3	4	4a	5	6	6a	7	8
C	14.0	22.8	35.1	36.9	42.7	12.4	34.6	41.4	36.8	49.3
O	47.8	53.8	59.4	58.5	51.6	46.0	62.8	55.5	52.7	42.2
Si	22.0	11.4	4.3	2.2	2.2	24.1	1.2	1.4	6.8	1.7
Al	3.9	1.7	0.5	0.4	0.6	4.7	b.d.	b.d.	1.1	0.9
Fe	4.2	3.6	b.d.	0.5	0.6	3.7	b.d.	b.d.	b.d.	b.d.
Mg	b.d.	1.5	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca	7.5	4.2	0.4	b.d.	b.d.	3.3	0.4	0.5	0.7	1.3
Na	b.d.	b.d.	b.d.	1.0	1.5	2.5	1.0	1.2	b.d.	1.6
K	b.d.	b.d.	b.d.	b.d.	b.d.	1.7	b.d.	b.d.	0.9	b.d.
Cl	b.d.	b.d.	b.d.	b.d.	b.d.	1.6	b.d.	b.d.	0.6	2.1
S	0.7	0.5	0.3	0.5	0.8	b.d.	b.d.	b.d.	b.d.	1.4
<i>Total</i>	100.1	99.5	100.0	100.0	100.0	100.0	100.0	100.0	99.6	100.5

Notes: b.d. — below detection limit. Sample details: 1-4 — Sudbury impact structure. Mudstones of the lower Sandcherry Member: 1 — lamellar particle size $20 \times 95 \mu\text{m}$ (sample SUD-99-12-B-3-2-2); 2 — lamellar particle size $30 \times 220 \mu\text{m}$ (sample SUD-99-12-3-2-11); 3 — curved particle size $30 \times 90 \mu\text{m}$ (sample SUD-99-12-B-3-3P); 4, 4a — roundish particle size $25 \times 30 \mu\text{m}$; 4 — the first (4), and the second (4a) analyses (sample SUD-99-12-B-3-6); 5-6a — mudstones of the upper Sandcherry Member; 5 — lamellar elongated particle $25 \mu\text{m}$ thick (sample SUD-99-13-B-G-3-1); 6, 6a — roundish particle $\sim 25 \mu\text{m}$ diameter; 6 — the first (6) and the second (6a) point analyses (sample SUD-99-13-B-G-5); 7-9 — el'gygytyn impact crater; 7 — Stem-like particle size $30 \times 120 \mu\text{m}$ (sample El-1032-32-4); 8 — particle of irregular shape size $50 \times 70 \mu\text{m}$ (sample 1032-1-8); 9 — lamellar particle size $25 \times 35 \mu\text{m}$ (sample El-900-6-1).

matrix by the repeated EDS analyses caused loss in oxygen and corresponding increase in the content of carbon and other elements in proportion to their initial content that testifies evaporation of volatiles from the matrix (Table 3, analyses 3, 3a and 6, 6a). The composition of the mudstone matrix from the Onaping Formation breccias is close

to the composition of mudstones from impact melt rocks of the El'gygytyn crater (Table 3, analyses 7 and 8).

The complicated, partly rounded, form of the mudstone fragments, their contorted contacts with the breccia matrix, and the formation of open gaping fissures indicates their weak consolidated

Table 3. Chemical composition (EDS data) for matrix of the mudstone fragments in the breccias of the Onaping Formation (analyses 1-6a) and the El'gygytgyn crater (analyses 7 and 8) (in wt%)

	1	2	3	3a	4	5	6	6a	7	8
C	7.2	13.9	16.3	18.8	22.9	24.6	26.6	30.9	31.3	45.5
O	58.7	50.1	48.0	43.8	53.8	44.8	56.8	47.3	31.8	34.9
Si	20.0	20.1	17.7	17.9	11.4	15.1	8.2	10.7	21.4	8.5
Al	4.7	3.7	3.8	3.7	1.7	4.8	1.7	2.1	4.9	3.7
Fe	1.0	2.3	4.3	4.7	3.6	4.1	1.6	1.9	0.8	0.9
Mg	0.7	1.8	2.5	2.9	1.5	b.d.	0.6	1.0	0.5	b.d.
Ca	1.9	3.3	4.6	5.2	4.2	1.9	2.8	3.5	3.7	3.6
Na	4.0	1.8	1.0	2.0	b.d.	2.4	1.0	1.6	2.7	0.9
K	1.3	0.5	0.9	1.0	b.d.	b.d.	0.7	1.0	2.2	0.8
Cl	b.d.	b.d.	b.d.	b.d.	0.5	b.d.	b.d.	b.d.	0.6	b.d.
S	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
<i>Total</i>	99.5	97.5	99.1	100.0	99.6	97.7	100.0	100.0	99.9	98.8

Notes: b.d. — below detection limit. Sample details: 1-6a — sudbury impact structure: 1 — homogeneous clayey matrix (sample SUD-99-12-3-2-11); 2 — heterogeneous patchy fine-grained matrix (sample SUD-99-12-B-3-2-2). 3, 3a — Homogeneous matrix (sample SUD-99-13-B-G-M2); 3 — the first and 3a the fifth point analyzes; 4 — heterogeneous fine-grained matrix (sample SUD-99-12-3-2-1-3); 5 — heterogeneous patchy fine-grained matrix (sample SUD-99-13-A-G-4); 6, 6a) heterogeneous fine-grained matrix (sample SUD-99-13-B-G-M5); 6 — the first and (6a) the fifth point analyzes; 7, 8 — el'gygytgyn impact crater; 7 — homogeneous clayey matter in a gas vesicle in the glassy impact melt rock (sample El-1032-1-5); 8 — clayey cover of the inner surface of a vesicle in impact melt rock (El-1554-1-15).

state and probable water content. High carbon content and abundant plant detritus are characteristic features of mudstone composition. The bottom sediments of the pre-impact marine basin are assumed to be the source of the mudstone fragments, while plant detritus represents the remains of algal paleoflora that inhabited the sea during their deposition. Subparallel orientation of elongated detrital particles in some mudstone fragments presumably reflects the sedimentation process of the bottom sediments.

Discussion and conclusions

Remains of paleoflora were discovered in breccias of the Onaping Formation, at the Sudbury impact structure. Plant particles, ranging in size from several micrometers to several hundreds of micrometers, have diverse and complex shapes. The diversity of morphology of plant particles suggests that they represent the remains of the complex algae flora that inhabited the marine basin on the eve of the Sudbury impact event 1.85 billion years ago (Gurov et al., 2020). Thus, this discovery confirms the supposition of Beales and Lozej (1975) about the existence of algal flora in the pre-impact marine basin, which served as a source of organic carbon in breccias of the Onaping Formation.

At the same time, the discovery of a single complex of paleoflora in breccias of the Sandcherry member casts on the assumptions about the rapid colonization of the Sudbury basin by algal flora or prokaryotes during the late stages of accumulation of the Black Member, which lasted thousands of years, as suggested by Avermann (1994), or several million years, as was assumed by Heymann et al., (1999). Earlier, Bunch and coauthors (1999) refuted the possibility of colonization of the Onaping breccias during their formation, and characterized the deposition of the flooding complex as a result of “convulsive events”, some of which immediately accompanied the impact: landslides from the crater wall, avalanches, giant tsunamis and earthquakes that accompanied this large-scale impact event.

The second form of paleofloral remains in the Onaping Formation is represented by plant detritus in the fragments of mudstones enclosed in breccias. Mudstone fragments have complex forms and complicated contacts with the host breccia. The content of plant detritus in mudstones reaches 30-35 vol%. Detritus is represented mainly by elongated lamellar rectilinear or curved particles from several to 200-300 µm long, which are likely scraps of ribbon algae.

The matrix of the mudstones is a fine-grained clay-like water-containing heterogeneous substan-

ce with open fissures of up several micrometers wide. The number of the fissures and their width increase during the electron microscopic examination of each sample. While the first fissures are visible at the very beginning of the sample study, it is supposed that their appearance begins when cutting of the sample, continues in a vacuum chamber when powdering, and later continues in an electron microscope chamber under the influence of the electron beam. While this process is accompanied by the loss of oxygen, we suppose that it indicates the evaporation of water from mudstones.

The fragments of mudstones are composed of weakly consolidated clayey C-rich water-bearing matter, containing abundant plant detritus and rare mineral clasts. Bottom sediments of the pre-impact marine basin are assumed as the source of the mudstone fragments, while detritus in their composition represents the remains of algal flora inhabited the sea during mudstone deposition. It is important to note that the structure and composition of mudstones are similar to these properties of some modern sapropelic bottom sediments of the Black Sea as described by Shnyukov and co-authors (2010). The carbon content in the mudstone matrix is mainly 12-15 wt%, and its content in detrital particles is ~20-30 wt%. Thus, the fragments of mudstones are probably an important, if not the main, source of carbon in the breccias of the Onaping Formation. Probably, similar fragments of mudstones were described earlier as the main carrier of organic carbon in the Onaping Formation and were considered as the probable sediments of the underlying Huronian Supergroup, or “unknown pre-impact deposits” (Bunch et al., 1999). It is assumed that the high content of organic carbon in the Dowling Member can be explained by the washout of bottom sediments from a large territory around the impact site, and their transfer to the crater basin by the resurge waves. This distant transportation of weak consolidated bottom sediments caused their fine crushing followed by the formation of a carbon-rich suspension, and its intensive mixing with a predominant material of ejecta in the crater basin.

We propose that the main events and circumstances that determined the accumulation and preservation of floral remains in the breccias of the Onaping Formation by the Sudbury impact are:

1. Deposition of sapropel-like bottom sediments in the marine basin inhabited by algal flora before the impact event 1.85 billion years ago.

2. Asteroid impact. Crater excavation, ejection of target materials, including bottom sediments, from the impact zone. Melting of target rocks and formation of the SIC. Tsunamis.

3. Deposition of fall-back material in the crater basin on the SIC surface and on the surface of the surrounding shelf. Formation of the Sandcherry member breccias in the crater basin.

4. Ongoing deposition of ejecta and their mixing with the material of ejecta and bottom sediments washed away from the surrounding shelf by tsunamis and transferred into the crater basin by the resurge waves. Fine crushing of bottom sediments during transportation to the crater basin and mixing with a fall-back material inside the crater basin (deposition of the Dowling member).

The search and study of flora remains in the breccias of the Onaping Formation led to the discovery of a previously unknown complex paleoflora of the Late Paleoproterozoic.

Fossils of the Late Paleoproterozoic — Early Mesoproterozoic age were previously described in metasedimentary rocks, 2.1-1.6 billion years old, on the Canadian Shield (Han, Runnegar, 1992), on the China Platform (Hofmann, Chen, 1981; Xiao, Dong, 2006), on the Indian Shield (Kumar, 2016; Sharma, Singh, 2019), and in some other regions. These micro- and macroscopic remains are mainly two-dimensional carbonaceous compressions on the bedding surfaces of ancient sediments. Such degree of preservation presents very limited opportunities for studying the shape and structure of organic remains (Patterson, 1999; Knoll, 2014). A notable exception is provided by the well-preserved microbiota in the Huronian Gunflint Formation (Awramik, Barghoorn, 1977), a chert-bearing unit which is overlain, over a wide region, by ejecta deposits from the Sudbury impact itself (Addison et al., 2005; Cannon et al., 2010).

Compared to previously described fossils in meta-sedimentary rocks of the Late Paleoproterozoic — Early Mesoproterozoic age, described here algae remains in breccias of the Onaping Formation are represented by bulk particles, preserving some details of morphology of the original plants. These features of plant remains in breccias of the Onaping Formation present exceptional opportu-

nities for study of the paleoflora of the Late Paleoproterozoic.

The Sudbury impact structure, with an original diameter of approximately 200-250 km (Dickin et al., 1996; Mungall et al., 2004), is comparable to the Chicxulub impact structure with a diameter of about 195-210 km (Gulick et al., 2008, 2017; Morgan et al., 1999) in terms of parameters and formation conditions. Their comparable or close parameters, as well as the formation of both structures under marine conditions, allows to suggest comparable scales of geological and ecological consequences of their formation. While the formation of the Chicxulub impact structure caused the Cretaceous-Paleogene mass extinction (for reviews and bibliography, see (Rampino, Haggerty, 1996; Catastrophic Events and Mass extinction: Impacts and Beyond, 2002; Schulte et al., 2010; Robertson et al., 2013; Gulick et al., 2017; Rampino et al., 2019), we assume that the formation of the Sudbury impact structure caused the mass extinction of the algal flora of the Late Paleoproterozoic and introduced some corrections in its further development. Thus, the microfossils in the breccias of the Onaping Formation represent the remains of a Late Paleoproterozoic paleoflora on the eve of the Sudbury impact event. In such a case, the search and study of microfossils in sediments of the Vermillion and Onwatin Formations and their comparative study with the remains of paleoflora in the breccias of the Onaping Formation can lead to the discovery of traces of the catastrophic influence of the Sudbury event on the organic world of the Late Paleoproterozoic and related radical changes around 1.85 billion years ago.

Earlier, based on the discovery of distal ejecta of the Sudbury structure and its comparison with the ejecta of the Chicxulub impact structure, Addison and coauthors (2005) proposed further comparative study of the Sudbury and Chicxulub ejecta to find out “the consequences of large impacts for life and ocean chemistry at very different times in Earth’s history” (p. 196).

The Sudbury structure had very long and complicated history of post-impact development, therefore, the discovery of floral remains in the Sudbury structure confirmed the extremely favorable conditions for the preserving of traces of ancient life by impact processes and reinforces a strategy of search for traces of ancient life in impact melt rocks on Mars (Harris, Schultz, 2007; Schultz et al., 2014). These ideas have acquired relevance support by the discovery and study of organic matter in the Martian meteorite ALH84001 from Antarctica (McKay et al., 1996), and shergottite Tissint (Morocco) (Lin et al., 2014; Schultz et al., 2020).

The discovery of biomarkers of plant species in the glassy melt ejecta from the Darwin crater in Tasmania (Howard et al. (2013), the discovery of plant remains in fragments of impact melt rocks from the Argentine Pampa (Schultz et al., 2014), and later in impact melt rocks of the Elgygytyn crater (Gurov et al., 2019) confirmed the possibility of preserving remains of paleoflora in impact rocks that have not been exposed to high temperatures and pressures for several million years. The establishment of plant residues in breccias of the Onaping Formation indicates the exceptional potential for the preservation of plant residues for about two billion years in impact rocks that experienced intense thermal and hydrothermal action of the SIC, regional metamorphism and tectonics action during the Penocian, Yavapai, and Grenville Orogeny. Thus, the discovery of the paleofloral remains in one from the most ancient terrestrial impact structures is of particular importance both for search and studying traces of ancient life on Earth and on Mars and other planets.

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ЗАЛИШКИ ПАЛЕОФЛОРИ В БРЕКЧІЯХ ФОРМАЦІЇ ОНАПІНГ, ІМПАКТНА СТРУКТУРА САДБЕРІ, ОНТАРІО, КАНАДА

Проведено електронно-мікроскопічне дослідження зразків брекчій формації Онапінг імпактної структури Садбері (Канада) з метою пошуків залишків палеофлори і визначення природи органічної речовини в їх складі. У брекчіях Онапінг були виявлені дві форми рослинних залишків. Перша форма представлена поодинокими рослинними частинками, поширеними в матриці брекчій і включеними в газові вакуолі в розкриталізованому імпактному склі. Ці частинки розміром від 5—10 до 200—300 мкм є об'єктами у формі листя, стебел, а також часток трубчастої і сферичної форми. Передбачається, що джерелом цієї форми рослинних залишків слугувала водоростева флора, що населяла морський басейн напередодні астероїдного удару Садбері.

Друга форма рослинних залишків у формації Онапінг представлена рослинним детритом в уламках вуглецевміщуючих глинистих порід, що входять до складу брекчій. Детритові частинки, що досягають розмірів 1000—1200 мкм, мають неправильну форму і складні нерівні контакти з вміщуючими брекчіями. Рослинні залишки в складі глинистих уламків представлені головним чином стрічкоподібними частинками довжиною від 3—5 до 200—300 мкм, в той час як більш рідкісні частинки мають складну трубчасту і пластинчасту форму. Матриця глинистих порід представлена неоднорідною тонкозернистою глинистою речовиною з сіткою відкритих тріщин мікронного розміру. Вміст вуглецю в матриці глинистих частинок коливається від 7—10 до 20—25 мас.%. Джерелом цих частинок у брекчіях послужили мулисті донні осади доударного морського басейну, а водоростева флора, яка мешкала в морі під час їхньої седиментації, стала джерелом включеного в них рослинного детриту. Уламки глинистих порід і рослинні залишки є важливим джерелом органічного вуглецю в брекчіях формації Онапінг. Виявлення залишків палеофлори в брекчіях формації Онапінг вказує на існування раніше невідомої складної водоростевої флори, що населяла морський басейн до ударної події 1,85 мільярда років тому в кінці палеопротерозою.

Імпактна структура Садбері за параметрами порівнянна з кратером Чиксулуб, що викликав крейдово-палеогенове масове вимирання біоти. Ми припускаємо, що формування структури Садбері мало катастрофічні наслідки для палеофлори пізнього палеопротерозою, залишки якої збереглися в брекчіях формації Онапінг.

Ключові слова: імпактна структура; брекчія; палеофлора; рослинні залишки; донні відклади.