The Meteoritical Society

Meteoritics & Planetary Science 54, Nr 10, 2532–2540 (2019)
doi: 10.1111/maps.13241

Remnants of paleoflora in impact melt rocks of the El'gygytgyn crater (Chukotka, Russia)

E. P. GUROV[1], V. V. PERMIAKOV[1], and C. KOEBERL[2,3*]

[1]Institute of Geological Sciences, National Academy of Sciences of Ukraine, Gontchara Str., 55b, Kiev, Ukraine
[2]Department of Lithospheric Research, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria
[3]Natural History Museum, Burgring, A-1010 Vienna, Austria
[*]Corresponding author. E-mail: christian.koeberl@univie.ac.at

(Received 19 August 2018; revision accepted 07 December 2018)

Abstract–Remnants of paleoflora were discovered in impact melt rocks from the El'gygytgyn crater, Chukotka, Russia. El'gygytgyn is a 3.58 Ma, 18 km diameter impact structure in Chukotka, northeastern Russia. A circular crater basin is surrounded by an uplifted rim. The crater floor is occupied by the El'gygytgyn Lake, 12 km in diameter, surrounded by lacustrine terraces up to 80 m in height. Impactites found at the El'gygytgyn crater include impact melt rocks, glass bombs, and shock metamorphosed volcanic rocks. Most impact melt rocks occur only in redeposited state in the terrace lake deposits. Floral remnants were discovered in impact melt rocks from various locations in the terrace deposits. The floral remnants include fragments of leaves, cell tissue, and undetermined organic matter that occur in vesicles within glassy melt rocks and impact melt breccias. After the discovery of floral remnants in impact melt breccias from upper Miocene strata in Argentina, and the description of floral imprints in the Dakhleh Glass of proposed impact origin in Egypt, the detection of paleoflora remnants in impact melt rocks of the El'gygytgyn structure is the first such occurrence in a confirmed impact crater on Earth.

INTRODUCTION

The discovery of plant fossils in impact melt rocks was first reported in impact breccias from Cenozoic sediments of Argentina (Schultz and Harris 2005; Harris and Schultz 2007), who discussed the possibilities of survival and long-term preservation of organic remnants after an impact event. A detailed description of fossilized flora in impact rocks of Argentina was made later by Schultz et al. (2014a). Impact melt breccias occur in seven layers in loessoid sediments deposited in the age interval between 9.21 ± 0.08 Ma and 6 ± 2 ka, and glasses in these layers, from as yet unknown sources, contain numerous floral remains with preserved morphological and chemical signatures of herbaceous plants (Harris and Schultz 2007; Schultz et al. 2014a; Harris 2015). These authors suggested that their discovery provides a new strategy of study of impact melt rocks for the search and possible identification of traces of possible early life on ancient Mars and other planets (Harris and Schultz 2007; Schultz et al. 2014a).

At about the same time, floral imprints were determined in Dakhleh Glass of assumed impact origin in the Western Desert of Egypt (Osinski et al. 2007). While the source of this material is not yet known, the Dakhleh Glasses were considered by these authors as proximal ejecta of some still unidentified impact structure (Osinski et al. 2007).

Another discovery of organic matter was made in studies of impact glasses from the Darwin crater in Tasmania (Howard 2008; Howard et al. 2013). Cellulose, lignin, and aliphatic biomarkers of plant species trapped in porous carbon spheres were discovered in some types of Darwin glass (Howard et al. 2013). These data have shown that organic materials can survive capture and transportation by impact melt at impact processes. An experimental confirmation of the survival of biogenic material during impact was published by Burchell et al. (2014, 2017).

The interest in these discoveries increased after investigations of the Martian meteorite Tissint, which fell in Morocco in 2011. Tissint, an olivine-phyric shergottite, experienced several impact events and contains veins of impact melt. Carbonaceous spheroids and plates were described in a fragment of Tissint, which were suggested to represent a possible biomarker (Wallis et al. 2014).

A further investigation of carbonaceous material in the Tissint meteorite was made by Lin et al. (2014), who described kerogen-like carbonaceous components from open cracks in shock-melt veins of Tissint. The carbon isotopic composition of these components provides "a tantalizing hint" for their biogenic origin on Mars (Lin et al. 2014), although it is possible that these are just terrestrial contaminations.

Our investigations of the El'gygytgyn crater in Chukotka led to the discovery of plant remnants preserved in impact melt rocks from that structure. The impact melt rocks on the modern surface of the El'gygytgyn have been redeposited and occur in lacustrine terraces, as a result of sloughing and slipping of impact melt flows from the rim and inner slopes of the crater. The floral remnants were found in fragments and blocks of impact melt rocks from locations in the eastern, southern, and western parts of the crater. Floral remnants in impact melt rocks occur in vesicles in glass. They are predominantly dense aggregates of fragments of (herbaceous) plants, rarely particles of cell tissue and some other forms.

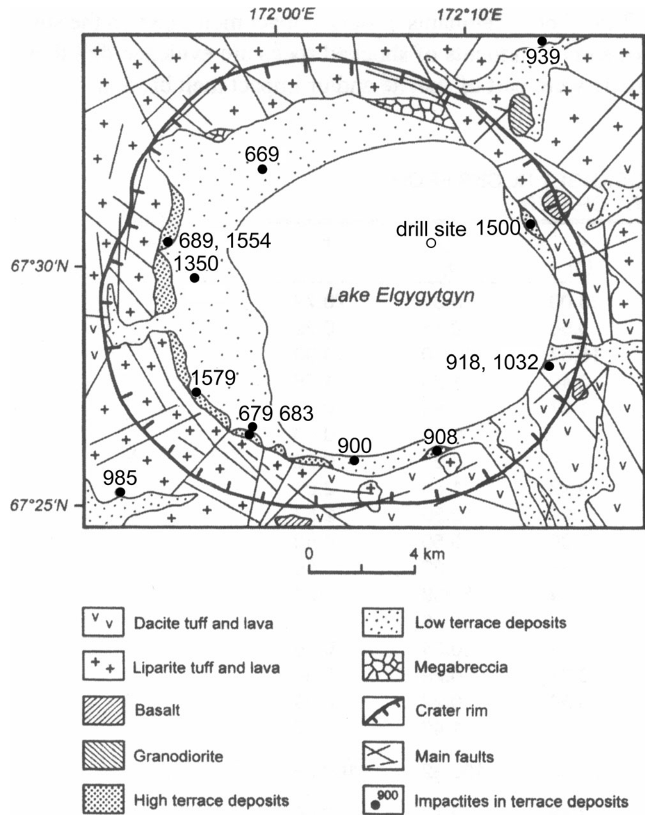

Fig. 1. Schematic geological map of the El'gygytgyn impact crater (modified after Gurov and Koeberl 2004; Gurov et al. 2005). The location of the drill site of the ICDP project is shown by the open circle. Sample locations of samples discussed in this manuscript are indicated.

GEOLOGICAL BACKGROUND

The El'gygytgyn impact structure is located in the central area of the Chukotka Peninsula in the far northeastern part of Russia (Fig. 1) (Gurov et al. 1978). The 18 km diameter crater is a well-preserved flat-floored circular basin, surrounded by an uplifted rim. The crater floor, about 14 km in diameter, is filled by nearly circular Lake El'gygytgyn, which is 12 km in diameter and up to 170 m deep in its central part. A complex system of lacustrine terraces surrounds the lake. The two highest terraces are elevated ~80 and 60 m above the lake level (Gurov and Koeberl 2004; Gurov et al. 2007). A central peak is not exposed on the recent surface of the crater floor, but the presence of an ~2 km wide central peak was suggested by Dabizha and Feldman (1982) from gravity measurements. Seismic investigations confirmed the presence of a central peak of approximately 2 km in diameter, centered with respect to the crater rim, and buried underneath the lake sediments (Gebhardt et al. 2006). The crater is surrounded by an uplifted rim that rises up to ~180 m above the lake level and 140 m above the surrounding area (Gurov et al. 2005, 2007).

The El'gygytgyn crater is located in the outer zone of the Late Cretaceous Ochotsk-Chukotka Volcanic Belt (OCVB) in a complex of volcanic rocks described mainly as the Pykarvaam and Koekvun Formations (Feldman et al. 1981; Stone et al. 2009). ^{40}Ar-^{39}Ar dating of the unshocked volcanic rocks within the crater area gave ages from 89.3 to 83.2 Ma (Layer 2000). The age of the Pykarvaam Formation was determined as 88.5 ± 1.7 Ma (Stone et al. 2009).

The crater was formed in a monoclinal sequence of volcanic rocks dipping 6° to 10° to the east. The pre-impact stratigraphy was compiled from numerous sections of volcanic rocks and tuffs exposed along the inner and outer slopes of the rim. It includes (from the top to the bottom): approximately 250 m of rhyolitic ignimbrites, 200 m of rhyolitic lavas and tuffs, approximately 70 m of andesitic tuffs and lavas, and approximately 100 m of rhyolitic to dacitic ash and welded tuffs. Thus, the complete thickness of the observed sequence is more than 600 m (Gurov and

Gurova 1991; Gurov and Koeberl 2004; Gurov et al. 2005). This sequence belongs to the Pykarvaam Formation that predominates in most of the southern, western, and northern parts of the crater rim, while dacitic and andesitic lavas and tuffs of the Koekvun Formation dominate in its southeastern part. A basalt plateau, about 110 m thick, occurs on the surface of rhyolitic and dacitic lavas and ignimbrites (Gurov and Koeberl 2004; Koeberl et al. 2013; Raschke et al. 2013).

Ignimbrites and tuffs of rhyolites and dacites are the most abundant rock types of the crater target. Mineral clasts and phenocrysts of these rocks are quartz, orthoclase, and plagioclase, and mafic minerals are biotite and amphibole. Fine-grained matrices of lavas and ignimbrites are composed of quartz and feldspars. Andesites and andesite tuffs contain phenocrysts of andesine, amphibole, and clinopyroxene in fine-grained matrix. Volcanic rocks of the crater rim do not show any shock metamorphic effects (Gurov et al. 1978; Gurov and Koeberl 2004).

Shock metamorphosed rocks and impact melt rocks in the El'gygytgyn crater occur on the modern erosional surface, having been redeposited in lake terrace deposits. Impact rocks include shock metamorphosed volcanic rocks, glassy bombs, and impact melt rocks (e.g., Gurov and Koeberl 2004). Shocked target rocks and glassy bombs are widely distributed in the lacustrine terraces inside the structure and rarely occur in terraces of small streams on the outer slopes of the crater rim. Their source was the ejecta layer of suevites and lithic breccias that has been completely eroded.

Impact melt rocks occur only in several localities in lacustrine terraces inside the crater basin. These localities were probably derived from solidified flows and pools of impact melt on the crater rim and wall (Gurov and Koeberl 2004), similar to the distribution of impact melt flows in some lunar craters (Hawke and Head 1977). The parameters of such flows are unknown. At various locations where impact melt rocks are found, they consist of several fragments and blocks of impact melt rocks and impact melt breccias. While the largest blocks of impact melt rocks reach up to 1 m in size, the initial thickness of these flows was ≥1 m. The impact material is thought to have been transported to its final location in the terraces due to slumping off the rim along short distances; thus, there was not enough distance for all fragments to have been rounded. All types of impact rocks are fresh and do not contain any traces of hydrothermal alteration and weathering (Gurov et al. 2005; Pittarello et al. 2013).

While the ejecta layer was completely eroded, fragmental impact breccias and suevites underneath the lacustrine sediments in the central part of the crater were encountered in borehole 5011-1 by an International Continental Scientific Drilling Program (ICDP) drilling project in 2009 (e.g., Koeberl et al. 2013). The borehole 5011-1 was centered on the outer flanks of the central uplift (Koeberl et al. 2013). Impact rocks were discovered under the lake sediments at 316.8 m to the bottom of the hole at 517 m (e.g., Koeberl et al. 2013; Raschke et al. 2013; Wittmann et al. 2013). Impact rocks in the core include three main types, i.e., (1) suevite and polymict impact breccia (316.7–390.7 mblf), (2) highly altered volcanic rocks of rhyolitic to basaltic composition (390.7–421.8 mblf), and (3) fractured and welded rhyolitic–dacitic ignimbrites (421.8–517.09 mblf) (Koeberl et al. 2013; Pittarello et al. 2013; Raschke et al. 2013).

MATERIALS AND METHODS

Samples of impact melt rocks for this study were collected by E. P. Gurov and E. P. Gurova during field work at the El'gygytgyn crater from 1977 to 1980. The floral remnants were discovered in the samples from several locations of impact melt rocks from the terrace deposits of the western, southern, and eastern parts of the crater. It is assumed that these accumulations represent rocks from separate flows of impact melt.

Twenty-eight samples of impact melt rocks were selected for investigations. Fifty thin sections for optical microscopy and 25 polished sections for electron microscopy were prepared for search of floral remnants and petrographic studies. Thin sections were investigated by optical microscopy to determine the mineralogical composition and texture of the impact melt rocks, to search for floral remnants, and to select representative points for electron microscopy.

Electron microscopic investigations included the search and study of floral remnants, conditions of their localization in impact melt rock, morphology, and chemical composition. The investigations of the impact melt rocks included a study of the structures and composition of the matrix. Floral residues were preserved within the vesicles, and the morphology and the inner surface mineralization of these vesicles was also studied. Impact melt rocks contain numerous clasts; thus, the composition of clast-free areas of matrix was considered as a probable composition of the initial impact melt. A scanning electron microscope (SEM) JEOL JSM-6490LV and an INCA Energy+ X-ray spectrometry system (Oxford Instruments) were used for the study of the floral remnants. The system includes an energy dispersive spectrometer (EDS) INCAx-act with an analytical silicon drift detector (ADD). In addition, backscattered electron images (BSE) were obtained with this SEM instrument. The acceleration 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%. The universal collection of 55 elements for X-ray microanalysis (Micro-Analysis Consultants Ltd., Cambridge PE27 3LF UK) was used for the calibration of the analytical program Oxford INCA Energy^{+}.

RESULTS

Impact Melt Rocks

Black and dark gray impact melt rocks containing the floral remnants consist of highly vesicular glass with clasts of shocked volcanic rocks, minerals, and glasses (Figs. 2A–C). A brick-red crust of burned sandy clay, with a thickness from 1 to 3 mm, occurs on the surface of one fragment of impact melt rock from the western part of the crater (Fig. 2B). Some floral remnants were discovered in a fragment of melted sedimentary rock from the eastern part of the crater. Trough-shaped unfilled channels are visible on the cut surface of that fragment (Fig. 2D). A thin core of dark gray vesicular clast-rich melt is preserved on one side of the fragment, indicating its initial occurrence (formation) within impact melt. Its composition (Table 1, analysis 5) shows a high content of silica, suggesting that the initial rock was probably a fine-grained quartz sandstone with minor admixture of an aluminosilicate-rich clayey material.

Impact melt rocks contain vesicular colorless to light brown fluidal glass with microlites of hypersthene, $En_{(56–64)}Fs_{(33–41)}Wo_{(2–3)}$, and clasts of shocked volcanic rocks, glasses, and minerals (Fig. 3A). Clasts, from micrometers to millimeters in size, form about 10 to 20–25 vol% of the rock. Clasts of shocked volcanic rocks and particles of brown, dark green, and black glass have sharp contacts with glassy matrix. The most abundant minerals in the clasts are diaplectic quartz with coesite

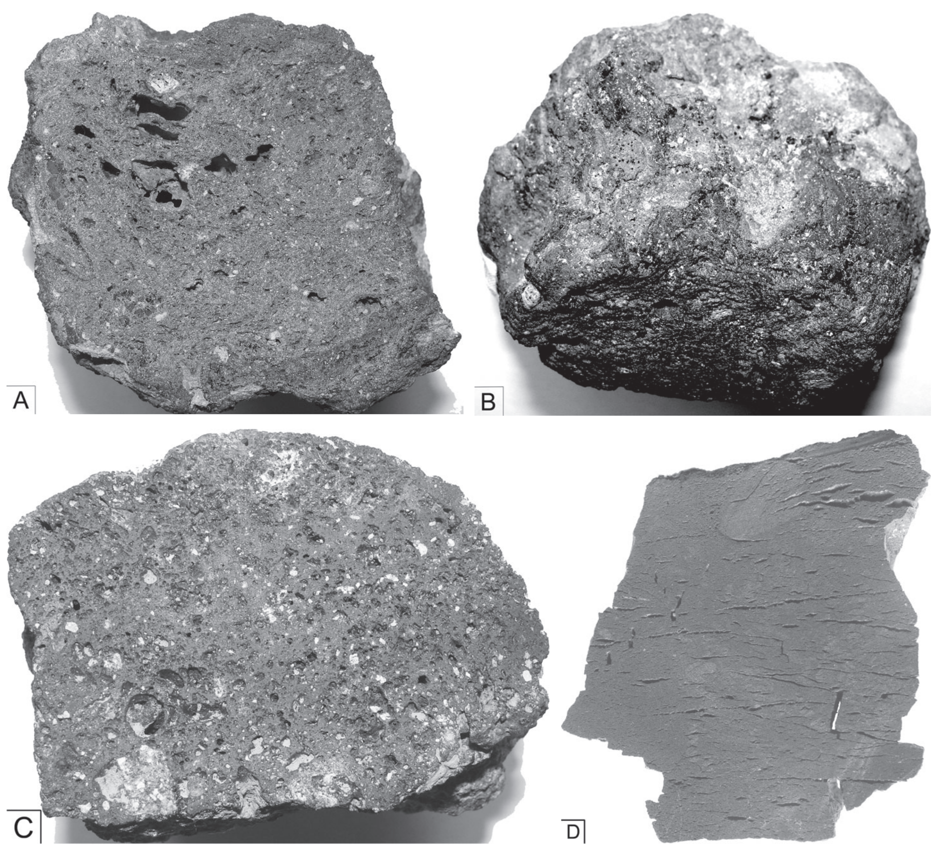

Fig. 2. Photographs of samples of impact melt rocks of the El'gygytgyn crater. A) Cut surface 9 × 7.8 cm of vesicular melt rock with clasts of shocked minerals, and (B) surface of the same sample with welded crust of burned sandy clay (white and light gray in upper part of the photograph) (sample E-1554); (C) Cut surface 10 × 6.5 cm of impact melt rock with clasts of shocked volcanic rocks and minerals (sample E-918); (D) Cut surface 5.5 × 4.2 cm of melted sedimentary rock. Strongly flattened vesicles undergo the layered texture of the rock. Open through channels to 5 cm long are visible in the bottom right corner of the photograph (sample E-1032-3).

segregations, lechatelierite, and ballen quartz. Rare resorbed grains of zircon display traces of softening before complete melting. Softened plastically deformed zircon was observed by SEM study of sample E-900-1. It was plastically twisted, and thin cracks appeared in the most deformed parts of the grain. Numerous vesicles have variable shapes, ranging from spherical and oval to irregular ones. The vesicles often contain opaque particles (Figs. 3B and 3C). The composition of the glassy matrices of the impact melt rocks from four locations are given in Table 1.

Remnants of Flora in Impact Melt Rocks of the El'gygytgyn Crater

An important feature of the glassy impact melt rocks with floral remnants is the high content of vesicles. Some of the vesicles in impact melt rocks from locations in the eastern, southern, and western parts of the crater contain floral remnants. The size of these vesicles ranges from 50 to 500 μm. Their shapes vary from isometric and oval to elongated, and are strongly dependent on the shape of the encapsulated floral remains. The predominant forms of the floral remnants are intertwined elongated fragments and particles of herbaceous (?) plants (Fig. 4A). Rare floral particles are fragments of cellular tissue (Fig. 4B). Some rare objects (Fig. 4C) were determined preliminarily to be spores of yeast mushrooms (Gladun, personal communication). Some vesicles contain single contorted and tubular particles of herbaceous flora, and particles probably of woody vegetation (Fig. 4D). Most other remnants cannot be assigned a particular plant type.

Table 1. Electron microprobe data for glassy matrices of impact melt rocks from the El'gygytgyn crater (in wt%).

Sample	1	2	3	4	5
SiO_2	63.25	64.20	60.53	65.57	90.23
TiO_2	0.14	b.d.	b.d.	b.d.	b.d.
Al_2O_3	19.74	19.84	21.81	21.18	5.80
Fe_2O_3[a]	3.83	3.35	4.27	2.50	0.93
MgO	1.99	1.36	1.75	b.d.	0.17
CaO	2.11	2.55	4.72	4.16	0.25
Na_2O	3.24	3.38	3.97	3.47	0.66
K_2O	5.22	4.81	2.56	2.97	1.16
Total	99.52	99.49	99.61	99.85	99.20

[a]Total iron as Fe_2O_3, b.d. = below detection limit.

Sample details: (1) Average of 16 partially devitrified glassy matrices with hypersthene microlites, sample 918, eastern part of the crater. (2) Average of 12 glassy matrices, sample 1032-1, eastern part of the crater. (3) Average of eight glassy matrices, sample 1554, western part of the crater. (4) Average of eight glassy matrices, sample 900, southern part of the crater. (5) Average of eight analyses of homogeneous glass of (impact) melted sedimentary rock, sample 1032-3, eastern part of the crater. Sample locations see Fig. 1.

The composition of the floral particles is presented in Table 2. The content of C varies in a wide range from 30 to 70 wt%. The main other components are Si, Al, Ca, and Cl in some of the samples.

Spherical and oval globules of organic matter were discovered in a single fragment of glassy impact-melted sedimentary rock from the eastern part of the crater (Fig. 2D). The fragment is composed of homogeneous glass with abundant flattened vesicles. The subparallel orientation of the vesicles accentuates layered texture of the fragment (Fig. 5A). Remains of flora in it probably are particles of woody vegetation (Fig. 5B) and undetermined fragments of leaves encapsulated in elongated vesicles, the shapes of which are determined by the shapes of the floral fragments.

The globules of organic material within this rock fragment have diameters that range from 15 to 30 μm and the largest globule is 45 × 55 μm in size. The surfaces of some of the globules are smooth (Fig. 6A), and a system of radial cracks appears after they are hit with the electron beam (Fig. 6B), maybe because of heating of volatile components. Another type of globules has their surface covered with slightly pyramidal protrusions (Fig. 6C). The scaly structure of cover zones forms under the influence of electron beam (Fig. 6D). The inner structure of the globules was not determined. The composition of some of the globules is shown in Table 2. The content of C ranges from 50 to 70 wt%. The presence of Cl was noted in the composition of most globules.

DISCUSSION AND CONCLUSIONS

The El'gygytgyn impact structure is located in the central mountainous region of the Chukotka Peninsula. The crater occupies the territory of the axial part and southeastern slopes of the Academician Obruchev Ridge, and lowland at its southeastern foothill.

Redeposited impact melt rocks and impact melt breccias occur in the El'gygytgyn crater in lacustrine terraces, at various locations all around the lake. Here we report the finding of impact melt rocks with plant remnants at several locations in the eastern, southern, and western parts of the crater basin.

Vesicular textures of impact melt rocks and their enrichment by herbaceous floral remnants testify to the probable precipitation of impact melt onto the swampy areas with a predominance of herbaceous flora. We suggest that the brick-red crust on the surface of one fragment of impact melt rock represents the remnant of an unconsolidated water-bearing sedimentary substratum, particles of which were welded to the

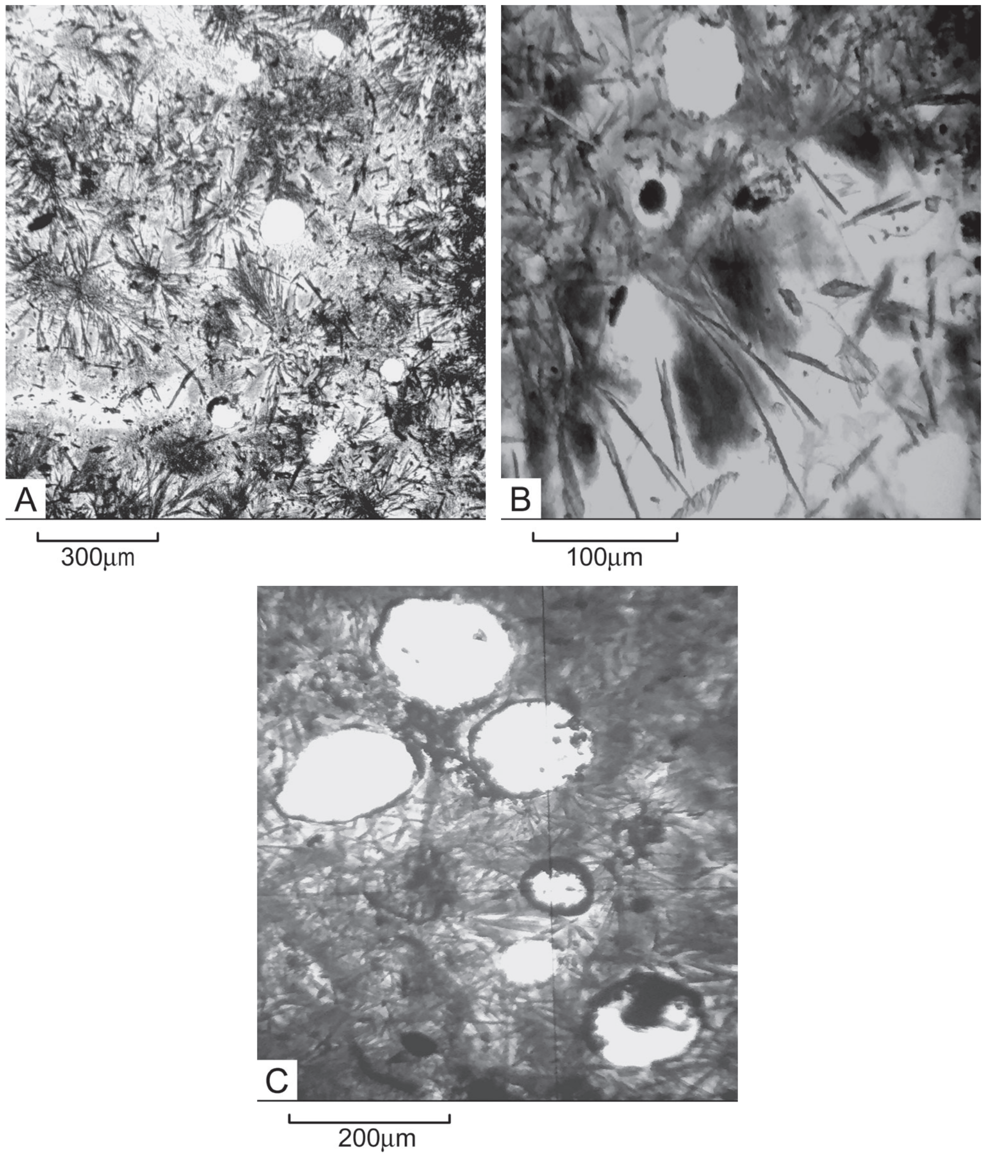

Fig. 3. Microphotographs of impact melt rocks of the El'gygytgyn crater. A) Glassy matrix melt rock with rare vesicles and microliths of pyroxene (sample E-900-11, parallel polars). B) Dark organic matter occupies the central part of vesicle near the center of image. Glassy matrix contains long-prismatic microlites of pyroxene and dark devitrified areas (sample E-1554, parallel polars). C) Vesicles with relics of organic matter in impact melt rock with microlites of pyroxene. Dark opaque organic matter partially fills some vesicles or preserves on their interface (sample 918, parallel polars).

surface of impact melt rock. The preservation of organic matter in impact melt rocks from Argentina happened due to the melt falling into a swamp, but mostly the plant matter was entrained in the melts as they were being formed and ejected (Schultz et al. 2014a, 2014b), or an area of humid wooden vegetation and swamps in Tasmania (Howard et al. 2013); in some cases, it appears possible that the organic remains are from the pre-impact target.

Impact melt with floral remnants reached high temperatures, similar to what has been described from the Argentinean samples. The occurrence in melt rocks of lechatelierite, quartz with ballen structures, and plastically deformed zircon allows us to estimate the temperature of the melt $\geq$1700($-$1900)^{o}C (e.g., El Goresy 1968; Wittmann et al. 2006), which is in agreement with experiments of Schultz et al. (2014a, 2014b) about the preservation of morphological features of floral remnants in siliceous melts at temperatures >1500 °C.

It is interesting to note some similarity of the globules and spherical bodies in impact melt rocks from

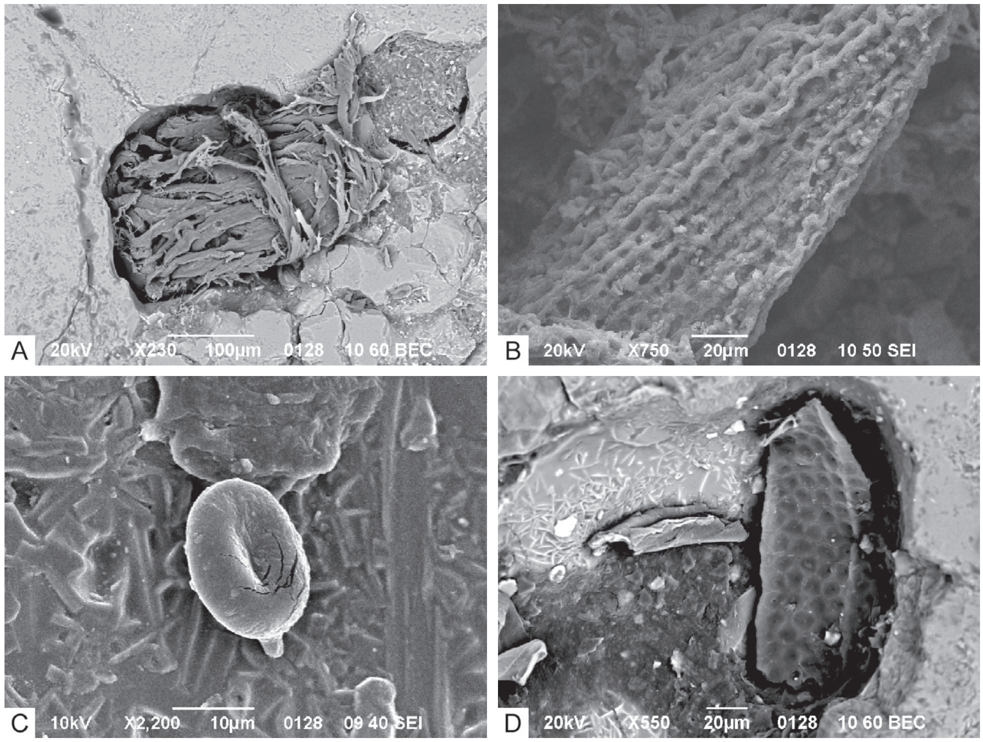

Fig. 4. Backscattered electron (BSE) images of floral remnants in impact melt rocks of the El'gygytgyn crater. A) Floral remnants in glassy matrix (sample E-918). B) Scrap of cell tissue (sample 918). C) Probable spore and plant particle in a vesicle (sample E-1032-2). D) Remains of floral particles in a vesicle. White feldspar crystallites cover parts of interface of vesicle (sample E-1032-2).

Table 2. Electron microprobe data for floral remnants in El'gygytgyn impact melt rocks (in wt%).

Sample	1	2	3	4	5	6	7	8
C	51.64	55.95	62.50	72.07	44.63	52.82	63.59	70.91
O	46.47	37.28	36.03	27.82	50.99	39.74	26.65	28.33
Si	0.71	4.50	0.82	0.04	1.22	1.41	1.93	0.17
Al	0.63	1.31	0.31	0.03	0.73	1.01	–	0.09
Fe	–	–	–	–	1.13	1.37	–	–
Ca	–	0.95	0.35	–	–	–	–	–
Na	–	–	–	–	–	0.61	0.91	–
K	–	–	–	–	0.55	0.93	1.50	–
Cl	–	–	–	–	0.75	2.22	5.42	–
Total	99.45	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Sample details. (1) Cell tissue, sample 918-3-5. (2) Particle of leaf, sample 1032-2-6. (3) Tubular floral particle, sample 1032-2-2. (4) Floral particle, sample 1032-3-14. (5–8) Spherical bodies in impact-melted sedimentary rock: (5) Sample 1032-3-13. (6) Sample 1032-3-11. (7) Sample 1032-3-12. (8) Sample 1032-3-1. Data for 2–8 were normalized to 100 wt%. Sample locations see Fig. 1.

the El'gygytgyn crater with globules of Tissint meteorite (Wallis et al. 2014). Not only the shapes of these objects but also some compositional features (high content of C, presence of Cl) reinforce their similarities. Thus, investigations of floral remnants in impact melt rocks of the El'gygytgyn crater may help us to better understand the behavior of organic matter in Martian meteorites.

The discovery of floral remnants in impact melt rocks of the El'gygytgyn crater is the third known case of impact fossilization of floral matter either as body fossils (Schultz and Harris 2005), imprints (Osinski et al. 2007), or preserved organic matter (Howard et al. 2013; Schultz et al. 2014a, 2014b) in impact melt rocks. At the same time, El'gygytgyn is the first confirmed

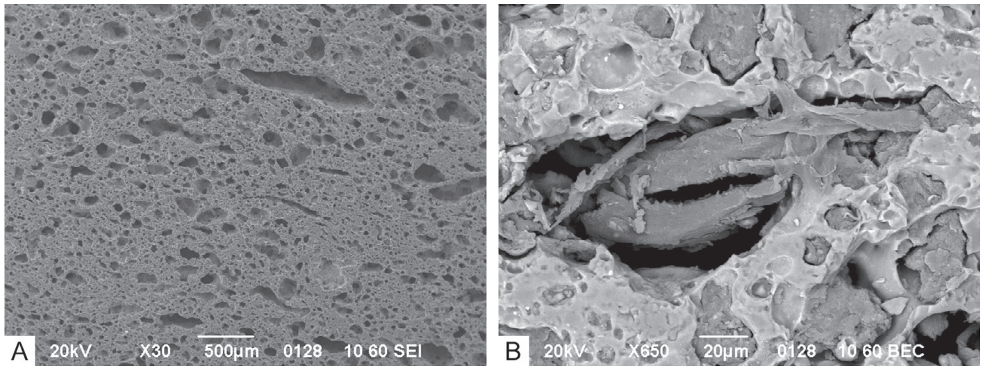

Fig. 5. BSE images of glassy impact-melted sedimentary rock with floral remnants (sample E-1032-3). A) Strongly vesicular glass with subparallel orientation of flattened vesicles. B) Scraps of wooden particles in vesicle.

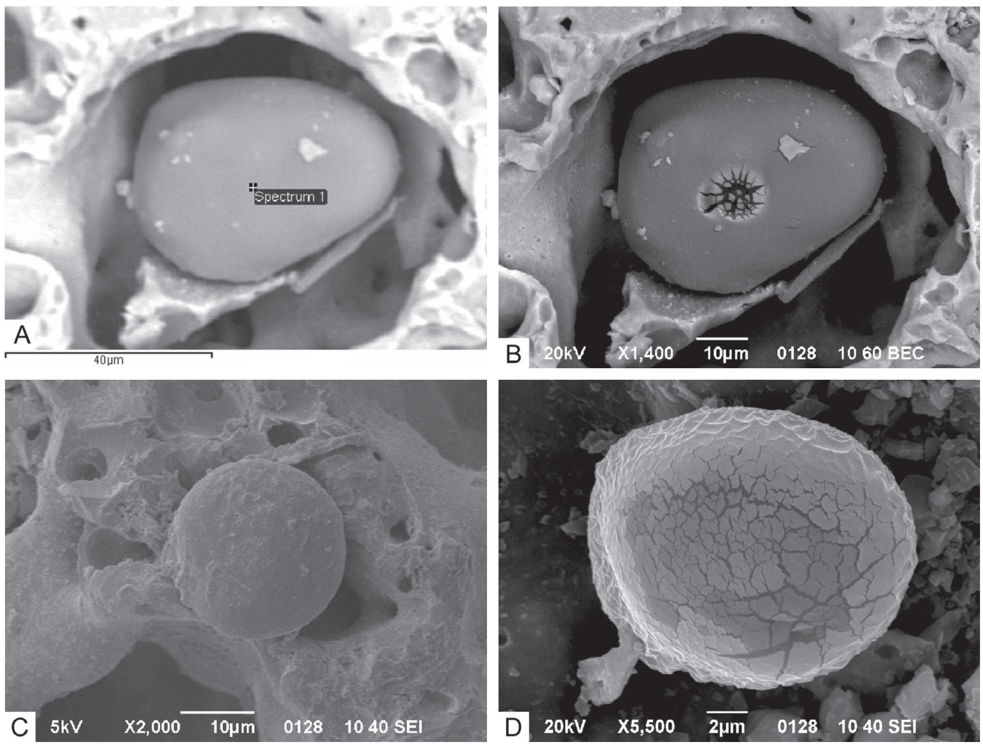

Fig. 6. BSE images of globules in melted sedimentary rock (sample E-1032-3). A) Egg-shaped globule with smooth surface. B) The same globule with trace of electron beam damage. C) Spherical globule with the surface covered with minor pyramidal protrusions. D) Oval spheroid with traces of electron beam damage. The cracked inner surface of the globule appears under a scaly external zone that was preserved at its edges.

terrestrial impact structure with preserved flora in impact melt rocks. Our data further constrain the conditions for the preservation of organic remnants in impact processes.

Acknowledgments—We are grateful to Katerina Tkachenko for help with in writing and preparing of this manuscript and to Dmitro Gladun for advice and interesting discussions. We thank Scott Harris and an anonymous reviewer for constructive comments that helped to improve the manuscript. This manuscript honors our colleague and friend W. Uwe Reimold.

Editorial Handling—Dr. Jeffrey Plescia

REFERENCES

Burchell M. J., McDermott K. H., Price M. C., and Yolland L. J. 2014. Survival of fossils under extreme shocks induced by hypervelocity impacts. *Philosophical*

Transactions of the Royal Society A 372:20130190. https://doi.org/10.1098/rsta.2013.0190, p. 1-14.
Burchell M. J., Harriss K. H., Price M. C., and Yolland L. 2017. Survival of fossilised diatoms and forams in hypervelocity impacts with peak shock pressures in the 1–19 GPa range. *Icarus* 290:81–88.
Dabizha A. I. and Feldman V. I. 1982. Geophysical characteristics of some astroblems of USSR. *Meteoritica* 40:91–101. In Russian.
El Goresy A. 1968. The opaque minerals in impact glasses. In *Shock metamorphism of natural materials*, edited by Short B. M. and French B. M. Baltimore, Maryland: Mono Book Corp. pp. 531–553.
Feldman V. I., Granovsky L. B., Kapustkina I. G., Karoteeva N. N., Sazonova L. V., and Dabija A. I. 1981. Meteorite crater El'gygytgyn. In *Impactites*, edited by Marakhushev A. A. Moscow: Moscow State University Press. pp. 70–92. In Russian.
Gebhardt A. C., Niessen F., and Kopsch C. 2006. Central ring structure identified in one of the world's best- preserved impact craters. *Geology* 34:145–148.
Gurov E. P. and Gurova E. P. 1991. *Geological structure and rock composition of impact structures*. Kiev: Naukova Dumka Press. 160 p. In Russian.
Gurov E. P. and Koeberl C. 2004. Shocked rocks and impact glasses from the El'gygytgyn impact structure, Russia. *Meteoritics & Planetary Science* 39:1495–1508.
Gurov E. P., Valter A. A., Gurova E. P., and Serebrennikov A. I. 1978. Impact meteorite crater El'gygytgyn in Chukotka. *Doklady Academii Nauk USSR* 240:1407–1410. In Russian.
Gurov E. P., Koeberl C., Reimold W. U., Brandstätter F., and Amare K. 2005. Shock metamorphism of siliceous volcanic rocks of the El'gygytgyn impact crater (Chukotka, Russia). In *Large meteorite impacts III*, edited by Kenkmann T., Hörz F. and Deutsch A. *Geological Society of America Special Paper* 384:391–412.
Gurov E. P., Koeberl C., and Yamnichenko A. 2007. El'gygytgyn impact crater, Russia: Structure, tectonics, and morphology. *Meteoritics & Planetary Science* 42:307–319.
Harris R. S. 2015. New observations of Bahia Blanca melt breccias: Narrowing the search for a large Miocene-Pliocene boundary impact crater in Argentina. *Geological Society of America Abstracts with Program* 47:282.
Harris R. S. and Schultz P. H. 2007. Impact amber, popcorn, and pathology: The biology of impact melt breccias and implications for astrobiology (abstract #2306). 38th Lunar and Planetary Science Conference. CD-ROM.
Hawke B. R. and Head J. W. 1977. Impact melt on lunar craters rims. In *Impact and explosion cratering*, edited by Roddy D. J., Pepin R. O., and Merrill R. B. New York: Pergamon Press. pp. 815–841.
Howard K. T. 2008. Geochemistry of Darwin glass and target rocks from Darwin crater, Tasmania, Australia. *Meteoritics & Planetary Science* 43:473–496.
Howard K. T., Bailey M. J., Berhanu D., Bland P. A., Cressey G., Howard L. E., Jeynes C., Matthewman R., Mortins Z., Sephton M. A., Stolojan V., and Verchovsky S. 2013. Biomass preservation in impact melt ejecta. *Nature Geoscience* 6:1018–1022.
Koeberl C., Pittarello L., Reimold W. U., Raschke U., Brigham-Grette J., Melles M., and Minyuk M. 2013. El'gygytgyn impact crater, Chukotka, Arctic Russia: Impact cratering aspects of the 2009 ICDP drilling project. *Meteoritics & Planetary Science* 48:1108–1129.
Layer P. V. 2000. Argon-40/Argon-39 age of the El'gygytyn event, Chukotka, Russia. *Meteoritics & Planetary Science* 35:591–599.
Lin Y., El Goresy A., Hu S., Zhang J., Gillet P., Xu Y., Hao J., Miyahara M., Ouyang Z., Ohtani E., Xu L., Yang W., and Feng L. 2014. NanoSIMS analysis of organic carbon from the Tissint Martian meteorite: Evidence for the past existence of subsurface organic-bearing fluids on Mars. *Meteoritics & Planetary Science* 49:2201–2218.
Osinski G. R., Schwarcz H. P., Smith J. R., Kleindienst M. R., Hendemann M. A., and Churcher C. S. 2007. Evidence for a ~200−100 ka meteorite impact in the Western Desert of Egypt. *Earth and Planetary Science Letters* 253:378–388.
Pittarello L., Schulz T., Koeberl C., Hoffmann J. E., and Münker C. 2013. Petrography, geochemistry, and Hf-Nd isotope evolution of drill core samples and target rocks from the El'gygytgyn impact crater, NE Chukotka, Arctic Russia. *Meteoritics & Planetary Science* 48:1160–1198.
Raschke U., Reimold W. U., Zaag P. T., Pittarello L., and Koeberl C. 2013. Lithostratigraphy of the impactite and bedrock of ICDP drill core D1c from the El'gygytgyn impact crater, Russia. *Meteoritics & Planetary Science* 48:1143–1159.
Schultz P. H. and Harris R. S. 2005. Impact amber: Plant materials captured in impact-generated glasses. 8th NASA Exobiology PI Symposium Program with Abstracts, 94.
Schultz P. H., Harris R. S., Clemett S. J., Thomas-Keprta K. L., and Zárate M. 2014a. Preserved flora and organics in impact melt breccias. *Geology* 42:515–518.
Schultz P. H., Harris R. S., Clemett S. J., Thomas-Keprta K. L., and Zárate M. 2014b. Preserved flora and organics in impact melt breccias (abstract #2002). 48th Lunar and Planetary Science Conference. CD-ROM.
Stone D. V., Layer P. W., and Raikevich M. I. 2009. Age and paleomagnetism of the Okhotsk-Chukotka Volcanic Belt (OCVB) near Lake El'gygytgyn, Chukotka, Russia. *Stephan Müller Special Publication Series* 4:243–260.
Wallis J., Wallis D. H., Wallis M. K., and Wickramasinghe C. 2014. Molecular carbon as a biomarker in the meteorite Tissint. EPSC2014 conference, session TP4.1. Portugal, September 2014.
Wittmann A., Kenkmann T., Schmitt R. T., and Stöffler D. 2006. Shock-metamorphosed zircon in terrestrial craters. *Meteoritics & Planetary Science* 41:433–454.
Wittmann A., Goderis S., Claeys P., Vanhaecke F., Deutsch A., and Adolf L. 2013. Petrology of impactites from the El'gygytgyn crater: Breccias in ICDP-drill core 1C, glassy impact melt rocks and spherules. *Meteoritics & Planetary Science* 48:1199–1235.