Petrology of impactites from El’gygytgyn crater: Breccias in ICDP-drill core 1C, glassy impact melt rocks and spherules

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(Received 15 February 2012; revision accepted 09 October 2012)

Abstract—El’gygytgyn is a 18 km diameter, 3.6 Ma old impact crater in NE Siberia. International Continental Scientific Drilling Program—El’gygytgyn hole 1C was drilled on the frozen crater lake, 2.3 km from the crater center to a final depth of 517 m below the lake floor. Petrographic and geochemical analyses of 26 drill core samples, three impact melt rocks from the surface, and seven glass spherules from surface deposits outside the crater are used to characterize the impactite inventory at El’gygytgyn. The bottom 98 m of hole 1C intersected monomict brecciated, unshocked, rhyolitic ignimbrite with minor intercalations of polymict breccia and mafic inclusions. These lithologies are overlain by 89 m of polymict breccia whose components occasionally exhibit scarce, low-degree shock metamorphic features. This unit is succeeded by 10 m of suevite that contains about 1 vol% glassy impact melt shards < 1 cm in size and a low amount of shock metamorphosed lithic clasts. The suevite is capped by a reworked fallout deposit that constitutes a transition over 4 m into lacustrine sedimentation. A higher abundance of shock metamorphosed lithic clasts, and glass spherules, some with Ni-rich spinel and admixture of an ultramafic component, characterize this unit. We tentatively interpret this impactite section as allochthonous breccia in the vicinity of El’gygytgyn’s central ring uplift. The geochemical compositions of seven glass spherules from terrace deposits 2 km outside the crater and eight spherules from the reworked fallout deposit in hole 1C show far greater variability than the composition of impact melt shards and impact melt rocks. Some of these spherules also show strong enrichments in siderophile elements.

INTRODUCTION

El’gygytgyn is a 18 km diameter, 3.58 ± 0.04 Ma old impact crater on the NE Siberian Chukotka peninsula (Gurov et al. 1978; Layer 2000; Gurov and Koeberl 2004). An asymmetrically offset 12 km diameter and up to 170 m deep lake fills the interior of the structure. The lacustrine deposits are studied for their paleoclimatic record (e.g., Nowaczyk et al. 2002; Melles et al. 2005, 2011, 2012). According to the interpretation of seismic data by Gebhardt et al. (2006), El’gygytgyn’s central uplift collapsed to a 7–7.5 km diameter and 2 km wide central ring. In contrast, earlier gravity modeling suggested only a small, 2 km diameter central uplift (Dabizha and Feldman 1982). A generalized preimpact upper target stratigraphy of 83.2–91.1 Ma old volcanics (Belyi 1998; Layer 2000; Gurov et al. 2007; Stone et al. 2009) was established by Gurov and Gurova (1991) from exposures at the crater and comprises from top to bottom 250 m rhyolitic ignimbrites, 200 m of rhyolitic tuffs and
lavas, 70 m of andesitic tuffs and lavas, and 100 m of rhyolitic and dacitic ash tuffs and welded tuffs. Paleocene age basaltic intrusions modified this target assemblage (e.g., Glushkova and Smirnov 2005).

Petrographic studies of rocks that occur on lake terraces and in glacial deposits around the crater found variously shock metamorphosed lithologies that exhibit planar deformation features (PDF) in quartz and feldspar, diaplectic quartz glass, coesite, stishovite, and diamond (Gurov et al. 1978, 1979, 2005; Feldman et al. 1981; Dabizha and Feldman 1982; Kapustkina et al. 1985; Gurov and Koeberl 2004). In addition, glassy impact melts occur in outcrops in and around the crater, and impact glass spherules were discovered in surficial deposits inside and outside the crater (Adolph and Deutsch 2009, 2010; Smirnov et al. 2011). On the basis of analysis of siderophile elements in glassy melt bombs from El’gygytgyn, Va’lter et al. (1982) proposed an ureilitic impactor.

In spring 2009, the International Continental Scientific Drilling Program (ICDP); the Austrian Federal Ministry of Science and Research; the Federal Ministry of Education and Research, Germany; the German Science Foundation DFG; the Russian Academy of Sciences; and the U.S. National Science Foundation cosponsored the drilling of three core holes (Site 5011-1) on the frozen crater lake of El’gygytgyn. The deepest, hole 1C, was drilled at 67°30′/172°4′59″, about 2.3 km east of the crater center. It penetrated 225.3 m of lacustrine sediments and 207.5 m of impactites, of which only 157.4 m (76%) were recovered, to a final depth of 517.3 m below the lake floor (mblf) (Melles et al. 2011; Koeberl et al. Forthcoming) (Fig. 1).

We present petrographic and geochemical data for samples characteristic for the rock types recovered in the impactite core section, and related impactites from surface outcrops. These data are used to derive formation and emplacement conditions for these materials, which are among the best preserved impactites known from a large terrestrial crater.

SAMPLES AND METHODS

Altogether 26 samples with typical lengths of 5 cm were taken from the 6.6 cm diameter ICDP drill cores in the depth interval from 316.8 to 517.3 mblf and studied petrographically and geochemically (Table 1; Figs. 2 and 3; A1–A5). The cores are documented by drill core scans (http://www.icdp-online.org/front_content.php?idcat = 512 &client = 29&lang = 28; last accessed May 31, 2012). In addition, 3 glassy melt clasts from the W’ crater rim (67°30′57″N/171°51′36″E) were studied (Table 1; Figs. 3d; A5c–e) as well as 7 glassy spherules collected in terrace deposits of the Enmyvaam River about 2 km beyond its effluence at the SE crater rim (Fig. A6) (Adolph and Deutsch 2009). A total of 39 petrographic thin sections, 7 from single spherules, 2 from each of the three melt clasts, and 26 from the core samples, were studied by optical and electron optical microscopy and electron microprobe analysis (EMPA).

Bulk geochemical data for impact melt rock samples, impact melt particles, one partly remelted tuff clast, and seven spherules (Table 1) were produced with EMPA on
Table 1. Sample list.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Top (mblf)</th>
<th>Unit</th>
<th>Length (mm)</th>
<th>Sample type(^a)</th>
<th>Analyses(^b)</th>
<th>Sample description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM8</td>
<td>n.a.</td>
<td>Impact melt rock, surface</td>
<td>28</td>
<td>hs</td>
<td>TS, EMPA</td>
<td>Fragments of dark brown, glassy melt rock with layered inclusions of fine debris.</td>
</tr>
<tr>
<td>TM12</td>
<td>n.a.</td>
<td>Impact melt rock, surface</td>
<td>47</td>
<td>hs</td>
<td>TS, EMPA, RAMAN</td>
<td>Dark brown, glassy melt rock with layered inclusions of fine debris.</td>
</tr>
<tr>
<td>TM17</td>
<td>n.a.</td>
<td>Impact melt rock, surface</td>
<td>34</td>
<td>hs</td>
<td>TS, EMPA</td>
<td>Dark brown, glassy melt rock with layered inclusions of fine debris.</td>
</tr>
<tr>
<td>316.7</td>
<td>316.77</td>
<td>Reworked fallout deposit, hosts spherules Sph1–3</td>
<td>225</td>
<td>qc</td>
<td>TS, EMPA</td>
<td>Well-consolidated, matrix-dominated, polymict breccia with size-sorted intercalations; it contains up to 5 mm long, glassy melt shards, spherules Sph1–3, and one spherule-shaped void.</td>
</tr>
<tr>
<td>317.6</td>
<td>317.66</td>
<td>Reworked fallout deposit, hosts spherules Sph4–8</td>
<td>50</td>
<td>hc</td>
<td>TS, EMPA, RAMAN, LA-ICP-MS</td>
<td>Polymict breccia/coarse sand; bottom half is dominated by 1–2 cm size, subangular, variegated clasts, top half is size-sorted coarse sand with components smaller than 2 mm, some dark components have rounded and shard shapes. Contains spherules Sph4–8 and one spherule-shaped void.</td>
</tr>
<tr>
<td>318.9</td>
<td>318.92</td>
<td>Reworked fallout deposit, hosts spherule SphY</td>
<td>40</td>
<td>hc</td>
<td>TS, EMPA</td>
<td>Reworked, fine sediments, laminated and cross-bedded. Contains spherule SphY and 8 spherule-shaped voids.</td>
</tr>
<tr>
<td>321.5</td>
<td>321.56</td>
<td>Suevite</td>
<td>50</td>
<td>hc</td>
<td>TS, EMPA</td>
<td>Polymict impact breccia with white, contorted clast and a tuff clast.</td>
</tr>
<tr>
<td>323.9</td>
<td>323.9</td>
<td>Suevite</td>
<td>50</td>
<td>hc</td>
<td>TS</td>
<td>Polymict impact breccia, size-sorted, largest clast 0.5 cm.</td>
</tr>
<tr>
<td>325.7</td>
<td>325.7</td>
<td>Suevite</td>
<td>50</td>
<td>hc</td>
<td>TS</td>
<td>Polymict impact breccia with dark, contorted lava clast and tuff clast.</td>
</tr>
<tr>
<td>326.1</td>
<td>326.1</td>
<td>Suevite</td>
<td>50</td>
<td>hc</td>
<td>TS, EMPA</td>
<td>Polymict impact breccia, contains mantled clasts.</td>
</tr>
<tr>
<td>327.8</td>
<td>327.8</td>
<td>Suevite</td>
<td>50</td>
<td>hc</td>
<td>TS</td>
<td>Polymict impact breccia, dominated by light green, vesicular, flow-textured volcanic clasts.</td>
</tr>
<tr>
<td>328.1</td>
<td>328.13</td>
<td>Suevite</td>
<td>50</td>
<td>hc</td>
<td>TS</td>
<td>Polymict impact breccia, clast-dominated.</td>
</tr>
<tr>
<td>330.9</td>
<td>330.95</td>
<td>Upper polymict impact breccia</td>
<td>50</td>
<td>hc</td>
<td>TS</td>
<td>Polymict breccia with secondary clay deposits in fractures.</td>
</tr>
<tr>
<td>345.6</td>
<td>345.6</td>
<td>Upper polymict impact breccia</td>
<td>50</td>
<td>hc</td>
<td>TS</td>
<td>Polymict breccia, soil-like, contains dark volcanic clast.</td>
</tr>
<tr>
<td>347.3</td>
<td>347.3</td>
<td>Upper polymict impact breccia</td>
<td>50</td>
<td>hc</td>
<td>TS</td>
<td>Polymict breccia, with altered ignimbrite clast.</td>
</tr>
<tr>
<td>348.1</td>
<td>348.12</td>
<td>Upper polymict impact breccia</td>
<td>50</td>
<td>fc</td>
<td>TS</td>
<td>Polymict breccia, with larger volcanic clasts.</td>
</tr>
<tr>
<td>349.6</td>
<td>349.61</td>
<td>Upper polymict impact breccia</td>
<td>50</td>
<td>qc</td>
<td>TS</td>
<td>Polymict breccia, crumby with variegated volcanic clasts.</td>
</tr>
<tr>
<td>351.8</td>
<td>351.84</td>
<td>Upper polymict impact breccia</td>
<td>50</td>
<td>qc</td>
<td>TS</td>
<td>Altered volcanic clast with gabbroic texture.</td>
</tr>
<tr>
<td>368.8</td>
<td>368.78</td>
<td>Upper polymict impact breccia</td>
<td>50</td>
<td>hc</td>
<td>TS</td>
<td>Solid ignimbrite clast surrounded by fine debris.</td>
</tr>
<tr>
<td>372.7</td>
<td>372.78</td>
<td>Upper polymict impact breccia</td>
<td>50</td>
<td>hc</td>
<td>TS</td>
<td>Crumby polymict breccia, with green and gray pebbles of volcanic clasts.</td>
</tr>
<tr>
<td>374.4</td>
<td>374.4</td>
<td>Upper polymict impact breccia</td>
<td>50</td>
<td>hc</td>
<td>TS</td>
<td>Polymict breccia of felsic volcanic clasts and brown melt.</td>
</tr>
<tr>
<td>381.8</td>
<td>381.84</td>
<td>Upper polymict impact breccia</td>
<td>50</td>
<td>fc</td>
<td>TS</td>
<td>Altered ignimbrite clast with light brown melt streaks.</td>
</tr>
<tr>
<td>382.3</td>
<td>382.3</td>
<td>Upper polymict impact breccia</td>
<td>50</td>
<td>hc</td>
<td>TS</td>
<td>Polymict breccia, contains larger angular clasts of green ignimbrite.</td>
</tr>
<tr>
<td>Sample name</td>
<td>Top (mblf)</td>
<td>Unit</td>
<td>Length (mm)</td>
<td>Sample type&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Analyses&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Sample description</td>
</tr>
<tr>
<td>------------</td>
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<td>-----------------------------</td>
<td>-------------</td>
<td>--------------------------</td>
<td>----------------------</td>
<td>------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>386.1</td>
<td>386.17</td>
<td>Upper polymict impact breccia</td>
<td>50</td>
<td>he</td>
<td>TS</td>
<td>Crumbly polymict breccia with dark and gray-green pebbles in pink matrix.</td>
</tr>
<tr>
<td>390.1</td>
<td>390.15</td>
<td>Upper polymict impact breccia</td>
<td>50</td>
<td>he</td>
<td>TS</td>
<td>Polymict breccia, soil-like, with contorted green ignimbrite clasts.</td>
</tr>
<tr>
<td>391.6</td>
<td>391.65</td>
<td>Upper polymict impact breccia</td>
<td>50</td>
<td>he</td>
<td>TS</td>
<td>Mafic intrusion of very fine-grained, brittle melt into ignimbrite breccia.</td>
</tr>
<tr>
<td>435.4</td>
<td>435.42</td>
<td>Upper ignimbrite</td>
<td>50</td>
<td>he</td>
<td>TS</td>
<td>Solid ignimbrite clast with abundant melt streaks.</td>
</tr>
<tr>
<td>471.4</td>
<td>471.46</td>
<td>Lower polymict impact breccia</td>
<td>50</td>
<td>he</td>
<td>TS</td>
<td>Poorly consolidated polymict breccia, with crumbly matrix and dark pebbles.</td>
</tr>
<tr>
<td>517</td>
<td>517.04</td>
<td>Lower ignimbrite</td>
<td>50</td>
<td>he</td>
<td>TS</td>
<td>Brittly deformed green-gray ignimbrite.</td>
</tr>
<tr>
<td>E-1</td>
<td>n.a.</td>
<td>Single spherule</td>
<td>0.7</td>
<td>sp</td>
<td>TS, EMPA, LA-ICP-MS</td>
<td>Black, elongated-ellipsoid spherule fragment, surface shows mechanical corrosion features of abundant, 20 µm long, scaly abrasion pits; material contains several bubbles and round inclusions of crystalline debris.</td>
</tr>
<tr>
<td>E-2</td>
<td>n.a.</td>
<td>Single spherule</td>
<td>0.5</td>
<td>sp</td>
<td>TS, EMPA, LA-ICP-MS</td>
<td>Dark brown to black fragment of an ellipsoid spherule with mild mechanical corrosion of surface and few bubbles, contains schlieren of assimilated inclusions.</td>
</tr>
<tr>
<td>E-3</td>
<td>n.a.</td>
<td>Single spherule</td>
<td>0.3</td>
<td>sp</td>
<td>TS, EMPA, LA-ICP-MS</td>
<td>Dark brown, ellipsoid with intense mechanically corroded surface, contains round, polymineralic inclusions.</td>
</tr>
<tr>
<td>E-4</td>
<td>n.a.</td>
<td>Single spherule</td>
<td>0.4</td>
<td>sp</td>
<td>TS, EMPA, LA-ICP-MS</td>
<td>Black, with teardrop-shaped, mildly corroded surface and contains few bubbles and round, polymineralic inclusions.</td>
</tr>
<tr>
<td>E-7</td>
<td>n.a.</td>
<td>Single spherule</td>
<td>0.3</td>
<td>sp</td>
<td>TS, EMPA, LA-ICP-MS</td>
<td>Black, round, homogeneous with bubbles.</td>
</tr>
<tr>
<td>E-8</td>
<td>n.a.</td>
<td>Single spherule</td>
<td>0.2</td>
<td>sp</td>
<td>TS, EMPA, LA-ICP-MS</td>
<td>Yellow, round, without inclusions of debris and few bubbles.</td>
</tr>
<tr>
<td>E-9</td>
<td>N.a.</td>
<td>Single spherule</td>
<td>0.2</td>
<td>sp</td>
<td>TS, EMPA, LA-ICP-MS</td>
<td>Black, round, without inclusions of debris.</td>
</tr>
</tbody>
</table>

Mblf = meters below lake floor.

<sup>a</sup>Sample types: hs = hand specimen, qc = quarter drill core, hc = half drill core, fc = full drill core, sp = spherule.

<sup>b</sup>TS = thin section microscopy; EMPA = electron microprobe analysis; RAMAN = Raman micro-spectroscopy; LA-ICP-MS = laser ablation-inductively coupled mass-spectrometry.
a Cameca SX-100 at the NASA-Johnson Space Center (JSC) in Houston. Silicate glass and minerals were analyzed using 15 keV accelerating voltage, a beam current of 15 nA, and beam diameters of 5 and 20 μm to avoid volatilization. To further minimize possible volatilization, counting times for the measurements were 10 s for Na and K, but 20 s for Si, Fe, Mg, Ca, Cr, Al, Ti, Mn, Ni, S, and P. Two additional spherules (Sph7 and Sph8, Table 1) were analyzed with a very similar set-up on a JEOL JXA-8200 Electron Microprobe at the Department of Earth and Planetary Sciences, Washington University in Saint Louis; measurements on two spherules that were also analyzed in Houston replicated the previous results. The seven spherules E1–4 and E7–9 from outside the crater were analyzed with the JEOL JXA 8900 Superprobe at the Institut für Mineralogie, Westfälische Wilhelms Universität (WWU) Münster, with an acceleration voltage of 15 kV, a 15 nA beam current, and a beam diameter of 10 μm. Typical detection limits for microprobe analyses were 0.02 wt% for MgO, Al₂O₃, K₂O, P₂O₅, and SO₃; 0.03 wt% for SiO₂; 0.04 wt.% for Na₂O; MnO, and FeO; 0.05 wt% for CaO and NiO; 0.06 for Cr₂O₃; and 0.07 for TiO₂. Replicate analyses of standards as unknowns confirmed
the typical accuracy of the electron microprobe analyses to better than 2% relative error for major and 5% for minor element concentrations, but they were between 10 and 30% for concentrations close to the detection limit.

Backscattered electron images were taken with a JEOL JXA-8200 Electron Microprobe at the Department of Earth and Planetary Sciences, Washington University in Saint Louis and on a JEOL 6610-LV scanning electron microscope at the Institut für Planetologie in Münster.

Micro-Raman spectroscopy was performed on a notch-filter-based Dilor LabRam spectrometer, with a He-Ne laser of 632.8 nm wavelength and a spot size of approximately 1 μm, at NASA-JSC on two thin sections (Table 1). Spectra were recorded with a thermoelectrically cooled CCD detector operated with a 1800 grooves mm\(^{-1}\) grating and a wave number accuracy of 1 cm\(^{-1}\). Background reduction was attained by Gauss-Lorentz fitting using the LabSpec v.2.08 software by Dilor SA and the Université de Reims.

Concentrations of 31 trace elements in spherules E1–4 and E7–9 were determined by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) (Element...
2, Thermo-Scientific sector field ICP—mass spectrometer), using a 193 nm ArF excimer laser (UP193HE, New Wave Research) at the Institut für Mineralogie, WWU. The laser was focused to a diameter of 60 μm and operated at a repetition rate of 5 Hz with a uniform energy density rate of 8–9 J cm⁻² during the analysis of 2–3 spots on each spherule. The concentration data were processed with the LA-ICP-MS data reduction software Glitter (Access Macquarie Ltd.), using Si as internal, and National Institute of Standards and Technology (NIST) SRM-612 multi-element glass as external standards. The reproducibility of multiple standard analyses was generally much better than 5% relative standard deviation (RSD) with exception of the data for W (<6% RSD) and Ta (<7% RSD). For a full description of the analytical technique, see Berndt et al. (2011).

A similar set-up was used for spherules Sph5–8 at Ghent University, where a New Wave Research UP193HE ArF excimer-based laser ablation system is coupled to an Element XR (Thermo Scientific) double-focusing sector field ICP—mass spectrometer, focusing sector field ICP-MS instrument. Analysis was performed via single spot (55 μm) ablation at a repetition rate of 10 Hz and a monitored energy density of 10 J cm⁻² on the sample surface. Using ²⁹Si as internal standard, quantification was performed via external calibration versus several glass reference materials (NISTSRM612, USGS natural and synthetic glasses BHVO-2G, GSD-1G, and GSE-1G). Based on the standards and settings described, reproducibilities for the elements measured are typically between 5 and 10% RSD.

RESULTS

Petrography

Lower Ignimbrite, 517.3–474.0 mbflf

This basal section of core 1C (Fig. 1) recovered green, matrix-supported ignimbrite with light colored, mm long phenocrysts (Fig. 2a) and brown, several cm thick, aphanitic melt particles embedded in a green groundmass. These melt particles are generally elongated and aligned in a uniform direction with dips of 45–60° relative to the drill core axis, which is considerably steeper than the original dip of 6–10° that was reported by Gurov et al. (2007) for the volcanic target rocks in the vicinity of the crater. Also, typically mm long, angular, shard-shaped particles with a bright emerald color are components of this rock. Veins and vugs are commonly filled with secondary pink zeolite that form bladed crystals and rims white to beige carbonate; green phyllosilicates form the last secondary alteration product of this assemblage. Frequently, the ignimbrite is brittle deformed, which also affected the brown melt particles and secondary alteration products. The longest coherent core piece in this subunit is 40 cm long from 490.6 to 491 mbflf.

A thin section of sample 517.0 mbflf (Fig. A1a) shows a well-consolidated, pervasively altered porphyritic rock with 2 mm long, ameboid melt particles that are elongated to a common orientation. Millimeter sized, shard-shaped melt particles occur as well. All melt is pervasively altered to yellowish-brown, cryptocrystalline masses. Opaques with rusty haloes are finely dispersed in darker brownish melt. Mineral inclusions in the altered matrix comprise euhedral to subhedral, clear quartz, rare mica, euhedral, mottled and partly sericitized plagioclase, euhedral, mottled sandine, and skeletal apatite. Mafic mineral inclusions with a typical size of 0.3 mm commonly have euhedral to subhedral shapes and are pervasively altered to chlorite and hematite. Mafic minerals and plagioclase are in part replaced by carbonate that displays intense mechanical twinning. Voids in the matrix and melt are filled with zeolite. No indicators of a shock metamorphic overprint were observed in this thin section.

Lower Polymict Impact Breccia, 472.1–473.3 mbflf

This matrix supported, polymict breccia (Figs. 1 and 2b) is unsorted, and composed of a fine-grained, pink-brown clastic matrix with up to 3 mm long, dark, subrounded clasts, and cm long, angular clasts of ignimbrite. The longest clast, at 471.65 to 471.7 mbflf, is an ignimbrite that is similar to the surrounding host lithology. This polymict breccia is associated with core loss at its bottom part from 474.02 to 472.06 mbflf, and above its upper contact with a 25 cm thick ignimbrite breccia, where core loss occurred between 471.02 and 470.37 mbflf.

Under the microscope, sample 471.4 mbflf (Fig. A1b) displays a matrix and unshocked components similar to the surrounding ignimbrite. However, it is unconsolidated, contains exotic clasts, and does not show shape-preferred orientation of melt components. Mineral fragments comprise mica and quartz that occasionally display subplanar fractures and slight undulose extinction. Some anhedral carbonate grains show extensive mechanical twinning. An angular, altered, 2.6 mm long melt fragment with flow texture hosts inclusions of chloritized mafic minerals, carbonate, chaledony, and zeolite. Exotic clasts include a 2 mm long felsic, igneous rock fragment that contains mottled, partly sericitized and zeolitized plagioclase, angular, chloritized (greenschist?) clasts with zeolitized plagioclase, felsic (granitoid?) clasts with euhedral, chloritized biotite, and other, altered mafic components.

Upper Ignimbrite, 470.4–419.3 mbflf

Above 470.37 mbflf, green ignimbrite occurs (Fig. 1) that is macroscopically similar to the section from 517.1
to 474.0 mblf. It also displays monomict brecciation, with the longest coherent core piece being 40 cm long between 467.4 and 467.0 mblf.

In thin section, sample 435.4 mblf (Fig. A1c) displays a 0.5 cm thick brown, ameboid melt vein and exhibits unshocked mineral inclusions that are similar in both melt and host matrix to the sample of the lower ignimbrite at 517.0 mblf. However, shard-shaped melt particles are lacking in this thin section and its mineral assemblage contains up to 1.5 mm long, brown, pleochroic kaersuite. The rims of these kaersuite crystals are occasionally replaced by mechanically twinned carbonate.

**Lower and Upper Mafic Inclusions, 422.7–422.4 and 420.9–420.3 mblf**

The lower mafic inclusion is 26 cm thick, dark green and highly fractured (Fig. 1). Its luster and schistose foliation is reminiscent of highly altered, ultramafic rocks. Below and above the mafic inclusion, the host ignimbrite is intensely fragmented to, on average, 2 cm long clasts over core lengths of 20 and 40 cm, respectively. From 422.05 to 421.48 mblf, the ignimbrite is less intensely fragmented, but the intense fracturing resumes between 421.48 and 420.9 mblf, where cm-long ignimbrite fragments were recovered. Another mafic inclusion that is less fractured but similar in color and texture occurs between 420.9 and 420.27 mblf. It shows mm wide fractures that are filled with white crystalline material (probably carbonate) that dip at 80° to the core axis. Above this inclusion, 60 cm of core was lost before 40 cm of ignimbrite debris that consists of 2 cm long clasts was recovered.

**Upper Polymict Impact Breccia, 419.3–330.8 mblf**

The character of this subunit (Fig. 1) varies from clastic matrix-supported with cm-size, suspended clasts (Fig. 2c), to sections composed of boulders of volcanic rocks. From 391.75 to 390.7 mblf, a relatively coherent boulder of monomictly brecciated ignimbrite occurs that contains a green, mafic intrusion from 391.72 to 391.66 mblf. The ignimbrite boulder with the mafic intrusion is succeeded by a core section that contains a pink-colored, very fine-grained matrix from 389.9 to 390.1 mblf, which appears to be a size-sorted layer in between larger ignimbrite boulders. Possibly the largest, more or less coherent, pinkish-gray ignimbrite boulder in this subunit is 2.3 m thick between 385.9 and 383.6 mblf. It contains up to 2 cm thick, highly altered, green melt domains. The lithological character changes via a strongly brecciated section and about 1 m of core loss to a matrix-supported breccia. This matrix-supported breccia is clearly polymict with felsic volcanic clasts that can reach a few dm in length, and dark clasts that are typically smaller than 1 cm. Intriguingly, some of these 1 cm long dark clasts, e.g., at 374.75, 374.77, 375.02, and 349.86 mblf, are subrounded, have glassy luster, and are reminiscent of the glassy impact melt clasts from the surface. Other dark clasts appear to be gabbroic or basaltic, e.g., a fragmented, dark green-brown clast with a network of shear fractures between 352.2 and 351.5 mblf, and a 4 cm long, dark green clast with 0.3 cm long, white phenocrysts at 345.45 mblf.

From 364.44 to 364.37 mblf, in a run where only 7% core recovery was attained, a core piece occurs that consists of coarse sandstone. At 351.35 to 351.45 mblf, the core section contains a clast of a possible welded tuff that has horizontal, 0.5 cm thick, elongated domains (fiamme?) in a fine matrix.

At 345.8 mblf, a 4 cm thick, gray-green melt vein occurs in a section of coarse matrix. It has an igneous contact with the breccia matrix and contains several mm sized, bronze-colored inclusions, similar to altered phenocrysts in basalt fragments, and does not seem to include undigested clasts. The matrix in this polymict breccia section varies in color from dark to light gray, pink, and brownish. It is generally composed of poorly sorted, coarse-to-fine sand that has occasionally been washed out, leaving behind rounded clasts of volcanic rocks. Between 331.09 and 331.19 mblf, a section of brecciated, light green volcanic rock is associated with a network of silty mud that is likely a secondary product linked to drilling operations or fluid circulation in the breccia section. Sample 330.9 mblf (Fig. A3e) displays poor consolidation and secondary clay deposition in fractures.

In thin section, a sample of the mafic intrusion in an ignimbrite boulder at 391.66 mblf captures green melt rock that engulfs a tan to gray-colored inclusion of brecciated ignimbrite (Fig. A1d). The green melt is pervasively chloritized and contains well-preserved, flow-aligned, approximately 0.4 mm long and 0.05 mm thick, euhedral plagioclase laths. These phenocrysts are aligned parallel to the contact plane with the brecciated ignimbrite. Skeletal, mottled plagioclase crystals occur as inclusions and are associated with carbonate. Carbonate also occurs as mechanically twinned crystals that fill cracks and amygdules. Mafic phenocrysts are pervasively chloritized. The felsic melt breccia in this sample exhibits a mineral assemblage and texture similar to the ignimbrite at 517.0 mblf. Melt particles in it are angular and altered to phyllosilicates, and melt shards are welded. Contact relationships with the mafic melt suggest that the mafic melt intruded the felsic volcanic breccia because fragments of the felsic material were drawn into the mafic melt. Also, few mm thick contact zones are developed that exhibit darker colors than usual in both the mafic melt and the felsic breccia. Plagioclase laths in the mafic melt in these contact zones have a reduced size compared with the main
region of the intrusion. No diagnostic shock metamorphic features were found in this thin section.

The thin section of sample 390.1 mblf (Fig. A3e) shows a polymict impact breccia of cm long, felsic volcanic rocks in a finely comminuted matrix. One 4 × 3 mm long clast has a matrix with dark schlieren (compare the description of a similar impactite lithology from the Chicxulub crater in Kenkmann et al. [2004]) and contains quartz clasts with planar fractures and feather features that indicate a minimum shock metamorphic overprint <10 GPa (Poelchau and Kenkmann 2011; Figs. 4a and 4b), next to mineral clasts that are unshocked. Another quartz grain with planar fractures and possible feather features occurs in the matrix of this sample, outside the darkened domain. Potassium feldspar clasts occasionally exhibit intense undulose extinction and subplanar fracturing but unshocked, clear quartz clasts with sharp extinction occur as well. Biotite is altered to epidote and/or chlorite. Melt fragments are pervasively altered to phyllosilicates. A few, small, mafic clasts that are altered to chlorite and zoisite are possibly relics of greenschist. Late stage alteration cemented this rock incompletely with zeolite, which also partly fills late fractures that cut across the rock.

A thin section from a sample at 386.1 mblf (Fig. A1f) displays a breccia that is dominantly composed of fragments of up to 1 cm long felsic volcanic rock and brown melt without diagnostic shock metamorphic features. Thin sections of samples from depths of 381.8, 368.8, 351.8, 348.1, and 347.3 mblf (Figs. A2b,e,f, A3b,c) mostly show unshocked ignimbrite clasts. Similar lithologies at 382.3 and 374.4 mblf (Figs. A2a and c) depth contain one clast of quartz each with possible planar fracturing and associated feather features. Three samples from depths of 372.8, 349.6, and 345.6 mblf (Figs. A2d A3a, A3d) are unshocked, yet contain variable proportions of mafic volcanic clasts mixed with ignimbrite debris. Thin section 345.6 mblf (Fig. A3d) captures a >3 cm long basalt clast that crystallized 10 μm long, tabular plagioclase crystals and stubby, 5–8 μm long pyroxene crystals in an aphanitic matrix. Moreover, extensively altered, porphyritic olivine and clinopyroxene complement this basaltic assemblage.

**Suevite, 329.1–319.1 mblf**

Between 331 and 328 mblf, a very poorly consolidated and intensely disaggregated portion of drill core occurs, which includes core loss of 1.7 m between 329.1 and 330.8 mblf. Above this depth, the lithology changes to a polymict breccia (suevite, cf. Horton et al. 2009) (Figs. 1, 2d, 3a, and 3b) that is dominated by tuff clasts that are highly vesicular and vary in color from light to dark gray. Still, diameter sized, bleached ignimbrite clasts are frequently present. A few dark, angular clasts with glassy luster and sharp boundaries with the host matrix, e.g., 0.5 cm long at 327.24 and 327.4 mblf, 1.5 cm long at 320.11 mblf, resemble the impact melt rock specimens that were collected on the surface.

The thickest target rock fragment measures almost 1 m at 323.95 to 323 mblf. It is a fractured, highly vesicular, reddish-brown tuff with white vesicle fills (zeolite?). Typical sizes of tuff clasts are 5–20 cm. The medium-gray clastic matrix is generally unsorted, sandy, and frequently contains variegated, angular clasts. In-between clast-supported sections, the matrix can be silty and appears to be secondary or redeposited because it exhibits flow textures and lamination. Similar to sections in the upper polymict impact breccia unit below, the
matrix is washed out or eroded in places, which might be due to its unconsolidated nature, drilling operations, or cleaning of the cores. Three dark, mm to 2 cm thick veins occur at 325.06 to 325.18 mblf, 327.39 to 327.43 mblf, and 325.95 to 325.97 mblf. They show a sharp contrast to the matrix, but no reaction corona that may be expected if they were impact melt.

In thin section, sample 328.1 mblf (Fig. A3f) is the only suevite sample that shows size sorting, layering, alignment, and rounding of clasts together with enhanced porosity. This thin section furthermore contains abundant basaltic fragments (aphyric types and one pyroxene-phric type with 1 mm long clinopyroxene phenocrysts) that are mixed with felsic volcanic clasts, including a relatively fresh tuff clast. Two tentative isotropic impact melt particles justify the classification as suevite: One is a 0.5 mm long, shard-shaped melt particle and the other is a 0.2 mm diameter, oval bead with tiny vesicles (compare Fig. 5a). Apart from these two glass particles, no shocked components were identified in this sample.

Angular, isotropic impact melt particles that are devoid of liquidus-phase phenocrysts were found in all five polymict samples from the suevite unit. Some of these melt particles contain almost round vesicles, while others display flattened vesicles, layering, and fluidal textured glass (Figs. 5b–e). Several isotropic, vesicular impact melt particles are up to 3.6 mm in size (thin section 325.7 mblf), but more typical are isotropic impact melt shards with sizes of 0.1 mm that are suspended in the clastic breccia matrix. One impact melt particle in thin section 326.1 mblf and one in thin section 327.43 mblf show a sharp contrast to the matrix, but no reaction corona that may be expected if they were impact melt.

Fig. 5. Impact melt particles in ICDP-El’gygytgyn hole 1C core samples. a) Microtektite-like glass bead in suevite sample 326.1 mblf, back-scattered electron (BSE) image, note small bubbles near rim and triangular inclusion (arrow) that is associated with bubbles; b) three shard-shaped translucent impact melt particles in suevite sample 321.5 mblf, ppl; c) large, layered impact melt particle in sample 321.5 mblf with d) inclusion of F-Cl apatite with vesicular texture that suggests incipient decomposition, back-scattered electron (BSE) image; e) fluidal, translucent impact melt particle, sample 325.1 mblf; f) shard-shaped impact melt particle has inclusion of quartz clast with three sets of PDF (arrows) in reworked fallout deposit sample 317.6 mblf, ppl.
323.9 mblf are 130–150 \( \mu m \) diameter, subrounded, isotropic glass beads with tiny vesicles near their rims (Fig. 5a). All these impact melt particles exhibit sharp contacts with the suevite matrix, which suggests rapid quenching below the glass transition temperature and subsequent fragmentation before deposition. In thin section 323.9 mblf, glassy impact melt particles are slightly yellowish-brown and partly birefringent, suggesting a higher degree of hydration than what is observed for the more pristine impact melt particles in the other suevite samples. An apatite clast in one of these glassy melt fragments exhibits a vesicular texture that suggests incipient decomposition (Figs. 5c–d) due to reheating to about 800 to 1200°C (Barralet et al. 2002).

Thin section 327.8 mblf shows a low-density, light gray, vesicular tuff clast (Fig. A4a). It displays dark, aphanitic domains in a medium gray, speckled matrix of <10 \( \mu m \) crystals with high relief suspended in poorly crystallized, low-relief material. The flattened vesicles are sometimes filled with poorly crystallized carbonate in the center that is surrounded by stubby zeolites. No crystalline clast inclusions could be identified. Similar clasts, some of which may contain scarce crystalline clast inclusions, occur in all other samples from the suevite unit and are frequently >1 cm long. One tuff clast in thin section 326.1 mblf is shocked and displays an isotropized, 1 cm long domain that has a much higher density of bubbles than the “unshocked” portion of this clast (Fig. A4b; Fig. 3a). Other target rock clasts are felsic and mafic volcanics. All volcanic target rock clasts sustained pervasive alteration to phyllosilicates, and are in part replaced with carbonate and/or zeolites. Voids in the matrix are partly filled with 20 \( \mu m \) long, stubby, euhedral zeolite crystals.

**Reworked Fallout Deposit, 319.1–315.4 mblf**

The suevite unit ends with a 3 cm thick clast at 319.14 mblf and is succeeded above by a breccia unit that occasionally has a conglomeratic character (Fig. 1). Interestingly, there is a noticeable change toward a more sorted and finer sandy matrix in the core section from 319.4 to 319.14 mblf, which still contains tuff clasts up to 10 cm in length; in contrast, the unsorted core section below displays a coarse sand matrix with abundant cm size angular clasts. Between 319.14 and 318.8 mblf, a distinctly size-sorted, sandy section is present. It includes a flaser-textured intercalation between 318.9 and 319 mblf that shows convoluted bedding of fine sand interfingered with coarse sand and subtle upward fining of medium-to-coarse sand from 318.9 to 318.8 mblf.

In the following decimeters above 318.9 mblf, clasts larger than 1 cm are typically subangular to round. Also, a finest fraction of sediment (< medium sand) is mostly missing in the matrix, suggesting a sorting process. Between 318.72 and 318.67 mblf, a poorly sorted, coarse sand deposit is cut by a horizontal layer of medium-grained sand that shows upward coarsening over about 5 cm. Above, larger components and clasts of about 1 cm in size occur that appear more angular. This section contains another sorted portion between 318.3 and 318.4 mblf, where 3 mm long clasts are embedded in a coarse sand to gravel layer, which is capped by a 3.5 cm long, green volcanic clast. Above this clast, at 318.25 mblf, the matrix changes toward an unsorted, polymict breccia. A size-sorted, coarse sand layer from 317.65 to 317.69 mblf is cut by the deposition of about 9 cm unsorted breccia before an upward coarsening sand to gravel was deposited (Fig. 3c) that gradually changes into an unconsolidated breccia with a maximum clast size of 4 cm at 317.4 mblf. The section unil 316.8 mblf is intensely deformed, apparently due to disking from drilling operations. Larger, light gray volcanic clasts are dismembered, but appear to have had maximum lengths of 6 cm up until 317.2 mblf. Then, a size-sorted section of coarse sand with up to 2 cm sized pebbles occurs. Above 317 m to 316.8 mblf, coarse, gray sand with polymict clasts up to 0.5 cm in size is present. This sorted section...
coordinates of their long axes. One of the felsic volcanic particulate matrix. Most clasts display a horizontal captures an unsorted polymict breccia that is mainly formed due to plucking during preparation of the thin sections.

Eight 0.15 mm diameter spherules (SphY) are the dominant clast type in the polymict domains. Unshocked felsic volcanics with sizes up to 4 mm matrix. Unshocked felsic volcanics with sizes up to 4 mm are the dominant clast type in the polymict domains. Mafic clasts are mostly chloritized. No features diagnostic of shock metamorphism in mineral clasts or angular, isotropic (impact) melt particles were found in this thin section.

A medium-to-coarse gray sand with occasional inclusions of angular to rounded clasts and intercalations of gravely material then probably represents true lacustrine sedimentation, in which several cm long pebbles are embedded in a laminated to cross-bedded, well-sorted sand layer that exhibits alternating light to dark gray colors.

In thin section, sample 318.9 mblf (Fig A4f) displays 1 cm long clasts of polymict microbreccia that are imbricated subhorizontally and embedded in a sand matrix. Unshocked felsic volcanics with sizes up to 4 mm are the dominant clast type in the polymict domains. Mafic clasts are mostly chloritized. No features diagnostic of shock metamorphism in mineral clasts or angular, isotropic (impact) melt particles were found in this thin section. One 0.15 mm diameter spherule (SphY) is present that is pervasively altered to cryptocrystalline feldspathic material and some 10 µm long, euhedral Ca-Na-aluminosilicate crystals. Along parts of its rim and as single, submicrometer grainlets, this glass spherule hosts particles with high mass-contrast in back-scattered electron images (i.e., they contain elements that exhibit higher atomic numbers on average than surrounding components). Energy-dispersive spectrometry reveals that these grainlets are rich in Fe, Cr, and Ni, facilitating their tentative identification as Ni-rich spinels. Eight rounded to oval, 0.1–0.23 mm voids occur exclusively in the breccia slivers of this thin section. They occasionally have 10 µm euhedral, tabular K-Na-Ca-aluminosilicate crystals lining the rims. It appears likely that these voids formed due to plucking during preparation of the thin sections.

The thin section of sample 317.6 mblf (Fig. A5a) captures an unsorted polymict breccia that is mainly composed of up to 7 mm long felsic, volcanic clasts in a particulate matrix. Most clasts display a horizontal alignment of their long axes. One of the felsic volcanic clasts may record a faint shock metamorphic overprint of <10 GPa manifested by abundant short fractures; a sanidine inclusion that exhibits one set of possible undecorated PDF, and plagioclase inclusions that display planar fractures. Diagnostic shock metamorphic features are present in the form of a quartz crystal with at least three sets of undecorated PDF that is an inclusion in a 0.25 mm long, isotropic, transparent, angular, highly vesicular melt particle (Fig. 5f). This particle cannot simply represent a shocked volcanic melt fragment that contained a quartz phenocryst because the >10 GPa shock pressure required to produce three sets of PDF in quartz would have crushed all pre-existing vesiocularity in the rhyolitic melt (e.g., Kieffer 1971; Stöffler and Grieve 2007). It follows that the glass and vesicles must stem from remelting and that the shocked quartz grain must be a clast that became entrained in this melt. Consequently, this assemblage confirms that the glassy, angular melt particles are fragments of rapidly quenched impact melts, fully consistent with stage IV shock metamorphism of the acid volcanic rocks at El’gygytgyn according to Gurov and Koeberl (2004).

Moreover, three 0.7 to 1.5 mm long diaplectic quartz glass clasts with intergrowths of coesite in this thin section (Figs. 6a and 6b) yield unambiguous evidence for shock metamorphic pressures between 35–50 GPa (e.g., Fritz et al. 2011; Langenhorst and Deutsch 2012). The largest impact melt particle in this thin section is approximately 1 mm long. Similar particles may have a slight yellowish color and/or elongated or shard shapes. Five round to oval, 0.1–0.4 mm diameter glass spherules were found in this thin section. One spherule (Sph5) is transparent and clear. Spherule Sph4 is hollow and consists of a fragmented rim that exhibits an alteration front, which consumed parts of the relict glass. Near the center, two domains of serrated K-Ca-Na-aluminosilicate (glass?) occur that are similar to material that is present in one of the spherule-outline-voids in thin section 318.9 mblf. Oval spherule Sph6 is concentrically zoned with a lower mass-contrast rim and a higher mass-contrast core. It also contains submicrometer, high mass-contrast crystals that protrude beyond its outer rim. Energy-dispersive spectrometry indicates that these crystals are enriched in Fe, Ni, and Cr relative to their host glass, suggesting that they could be Ni-rich spinels. Dumbbell-shaped, 0.21 mm long particle Sph7 consists of at least 3 fused droplets, 130, 80, and 6 µm in apparent diameter, that have different compositions. Sph8 is a round spherule, 0.13 mm in apparent diameter. It shows a disturbed, partly concentric zonation with a higher mass-contrast core and a lower mass-contrast rim. Putative Ni-rich spinels similar to the ones in Sph6 occur at its rim and as half-circular traces of inclusions. Four, up to 20 µm long, acicular ferro-magnesian silicate crystals are present near the rim
as well. A 0.1 mm diameter, round void is present in this thin section, likely where a spherule was plucked.

The thin section of a sample from 316.7 mblf (Fig. A5b) captures a size-sorted, clast-supported breccia of angular to subrounded clasts of felsic and mafic volcanics. These clasts have similar sizes of 1 to 3 mm and exhibit an upward-fining trend indicative of sorting. The largest clast is a 4 mm long, brownish, welded ash tuff clast. A 1 mm long quartz grain that is an inclusion in a volcanic clast displays planar fractures and associated feather features. One single, much smaller quartz clast shows one set of undecorated PDF as well as planar fractures, and a highly undulous, 0.8 mm long feldspar clast exhibits planar fractures and several sets of short PDF. Several small, transparent, glassy impact melt shards occur in the thin section along with three spherules. Spherule Sph2 is transparent, oval, and 0.3 mm in apparent diameter (Figs. 7a and 7b). Spherule Sph1 is transparent, oval, 0.25 mm in apparent diameter, and has a brown rim that is 8 μm wide around a homogeneous core (Figs. 7c and 7d). The brown material is a 5 μm thick alteration front that dissolved the spherule glass toward the core. Submicrometer silicate crystals remain along the trace of the outer rim. This spherule is also concentrically zoned with a higher mass-contrast core and an outer core that contains some dusting with cryptocrystalline material. Spherule Sph3 is round, 0.23 mm in apparent diameter, and hollow. Relics of a 6 μm wide, light brown rim remain that contain skeletal crystals of Mg-rich pyroxene and tiny inclusions of high mass-contrast that is Ni- and Fe-rich (Figs. 7e and 7f). A 0.49 mm diameter, round void in the
thin section mimics the outline of a spherule; it contains a few grains of debris and a mass of feldspathic material with serrated edges that resembles the relict hydrated, high-silica glass in the core of Sph4. This is likely the relict outline of a plucked spherule.

Impact Melt Rocks

To allow comparison with literature data, we analyzed three coherent impact melt rocks, TM8, TM12, and TM17, that were collected near the western crater rim. These rocks have dark olive-brown to black colors, sizes between 4.7 and 2.8 cm, and weigh between 27.6 and 11.6 g (Table 1). They are composed of flow-textured, glassy, isotropic melt that entrained unmelted, polymineralic debris (Figs. A5c–e). Shock metamorphic features were identified in a few quartz inclusions in TM12 and TM17, which confirm that these samples are impact melt rocks. Although the third sample did not yield indicators for shock metamorphosed quartz, it contains single grains of entrained zircons that exhibit granular textures (Fig. 8a), which record recovery from partial decomposition due to their residence in super-heated impact melt (Wittmann et al. 2006, 2009a). In contrast to the much smaller impact melt particles in the drill core samples, liquidus phase phenocrysts are present in two of the three impact melt rock samples in the form of pyroxene trichites (Figs. 8a and 8b). Pyroxene trichites have previously been recognized in impact melts from the El’gygytgyn and Ries craters (Gurov et al. 1979a; Von Engelhardt et al. 1995). Such crystal shapes are also common occurrences in silicic volcanic glasses and were interpreted to indicate static quench crystallization after emplacement (Ross 1962).

Spherules from the SE Crater Rim

Of the seven 0.2–0.7 mm diameter glass spherules E1–4 and E7–9 that were collected outside the crater rim (Adolph and Deutsch 2009; Table 1; Figs. A5a–g), three are fragments of teardrop-shaped particles (E1, E2, E4), and four are oval to round and unfragmented, apart from minor mechanical abrasion of their surfaces. Their colors range from black to dark brown and one is yellow. Only two, E7 and E9, do not exhibit vesicles; of the five spherules with vesicles, four (E1, E2, E3, E4) contain associated relics of variably assimilated debris (Figs. 9a–d). In spherule E4, late accreted, incompletely assimilated material protrudes beyond the round rim. No inclusions of high mass-contrast phases were found in these spherules.

Raman Spectroscopy

Coesite forms characteristic, 1–10 μm thick, vermicular to globular intergrowths with clear diaplectic quartz glass in three clasts in sample 317.6 mblf (Fig. 6a). According to three EMPA measurement spots, the diaplectic quartz glass is rather pure silica (Na2O, MgO, Al2O3, P2O5, SO2, K2O, CaO, TiO2, Cr2O3, NiO, FeO, and MnO ≤ 0.05 wt%) and its Raman spectrum shows the characteristic shape and broad bands of diaplectic quartz glass (Fig. 6b; Fritz et al. 2011). Coesite was likewise identified by its characteristic Raman bands (Fig. 6b; e.g., Wittmann et al. 2006).

Inclusions in impact melt rock samples TM8 and TM12 yielded Raman spectra of rutile, with the characteristic bands at 440 and 612 cm−1 (Liu and Mernagh 1992), and five zircon crystals, with their characteristic bands near 975 and 1007 cm−1. No decomposition products or high-pressure polymorphs were found in these grains (compare Wittmann et al. 2006).

Geochemical Composition

Impact Melts

EMPA of 11 translucent impact melt particles in three thin sections from the reworked fallout deposits
and suevite units are reported in Table 2. Analytical totals between 96 and 100 wt% suggest that some of these particles underwent hydration, incorporating up to 4 wt% volatiles. In the total-alkali-silica diagram (Fig. 10), their average compositions are subalkaline rhyolitic to rhyo-dacitic.

In contrast, EMPA of the three glassy impact melt rocks TM8, TM12, and TM17 yielded analytical totals that suggest no significant hydration (Table 3), confirming their pristine nature. Their similar geochemical character is reflected by small variations in the major and minor elements and a high degree of homogeneity indicated by small standard deviations. The overall geochemical composition is subalkaline rhyolitic; hence, they are similar to the impact melt particles from the ICDP drill core samples (Fig. 10).

**Spherules**

EMPA of 8 spherules in two thin sections of the reworked fallout unit and seven spherules that were collected near the SE crater rim are reported in Table 4. These spherules exhibit distinct variations in average
compositions compared with those of the glassy impact melt rocks and particles. This is illustrated by the spread of average compositions in the TAS-diagram (Fig. 10) that range from rhyolitic to dacitic, trachydacitic, trachytic, andesitic, and basaltic-andesitic. All but one compositions display subalkaline affinities. Most of these spherules have analytical totals close to 100 wt%, indicating absence of hydration. However, one (Sph 6) shows compositional zonation between rim and core (Fig. 11a and 11b) that includes significantly lower totals in the rim, which appears to be more mafic than the core. FeO, MgO, and CaO correlate moderately negatively with SiO2 ($R^2$ of 0.54, 0.59, and 0.59, respectively). Concentration ranges for major and minor elements overlap between the Enmyvaam river terrace spherules and those from the ICDP drill core except for TiO2 (Tables 4 and 5).

Table 2. Electron microprobe data for El’gygytgyn impact melt particles.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Na2O (wt%)</th>
<th>MgO (wt%)</th>
<th>Al2O3 (wt%)</th>
<th>SiO2 (wt%)</th>
<th>P2O5 (wt%)</th>
<th>K2O (wt%)</th>
<th>CaO (wt%)</th>
<th>TiO2 (wt%)</th>
<th>FeOa (wt%)</th>
<th>MnO (wt%)</th>
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<tr>
<td>317.6, MP1, n=6</td>
<td>Avg 3.23</td>
<td>0.52</td>
<td>13.7</td>
<td>70.2</td>
<td>0.06</td>
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<td>0.25</td>
<td>1.93</td>
<td>0.05</td>
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<td></td>
<td>σ 0.23</td>
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<td>0.9</td>
<td>1.8</td>
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<td>0.12</td>
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<td>0.03</td>
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<tr>
<td>317.6, MP2, n=5</td>
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<td>0.31</td>
<td>13.8</td>
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<td>0.04</td>
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</tr>
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<td></td>
<td>σ 0.09</td>
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<td>0.15</td>
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<td>0.01</td>
<td>0.08</td>
<td>0.03</td>
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</table>

All melt particle analyses, n = 60

| Avg 3.21 | 0.62 | 14 | 70 | 0.07 | 4.48 | 1.97 | 0.27 | 2.16 | 0.05 | 96.8 |
| σ 0.34 | 0.25 | 0.8 | 1.8 | 0.04 | 0.51 | 0.68 | 0.07 | 0.45 | 0.03 | 0.66 |

*aAll iron as FeO.

n.d. = not detected; n = the numbers of analyses (20 µm beam diameter) that were used to calculate the average (avg), and standard deviation (σ) of oxide concentrations in the respective samples; concentrations of SO2 were up to 0.05 wt%, Cr2O3 were up to 0.06 wt%, and NiO were up to 0.08 wt%; MP1: 0.8 × 0.5 mm long, has deformed vesicles with inclusions of lower mass-contrast materials that are not stable under the beam; MP2: 0.3 × 0.25 mm long, streaky glass that has an inclusion of a shock metamorphosed quartz grain with PDF; MP4: 0.2 × 0.1 mm long with shard shape; MP5: 0.7 × 0.3 mm long, is very vesicular with ilmenite inclusion; MP6: 1.2 × 0.6 mm long, glass with flow-deformed vesicles; MP7: 0.5 × 0.2 mm long, no vesicles, compact, angular; MP8: 3 × 1.8 mm long, layered and streaky, inclusion of apatite with a vesicular texture that suggests incipient decomposition; MP9: 0.7 × 0.6 mm, small vesicles, partly streaky; MP10: 1 × 0.8 mm long with large flow-aligned and deformed vesicles; MP11: 2.5 × 2 mm long with large vesicles that are flow-aligned and deformed into a layer texture; MP12: 0.13 mm long, oval, subrounded bead with tiny gas bubbles."
Assimilated debris in two of the spherules (E2 and E4, Figs. 9a, 9c, and 9d) is SiO₂-rich and one of these domains shows a P₂O₅ and FeO enrichment relative to the homogeneous glass composition (Table 4).

Trace element compositions for the seven Enmyvaam River terrace spherules and 5 spherules in sample 317.6 mblf were analyzed by LA-ICP-MS (Table 5). The CI chondrite-normalized rare earth element (REE) abundances show a strong enrichment between 30 and 200 times CI for the light REE, and a flat pattern of heavy REE enriched by 8 to 30 times CI. Spherules Sph5, Sph7, Sph8, E1, E2, E3, E4, and E8 exhibit small negative Eu anomalies, while spherules Sph6, E7, and E9 do not display a Eu anomaly. Overall, the REE patterns of these spherules mimic the REE patterns of shocked, felsic volcanic target rocks (Gurov et al. 2005). In all but one spherule (Sph5), the siderophile elements Co and Ni are strongly enriched on the order of 10- to 100-fold compared with most known target rocks (Gurov et al. 2005; Goderis et al. 2013). Chromium abundances in these spherules (Table 5) show excellent correlation with Ni ($R^2 = 0.995$, $n = 6$; compare Goderis et al. 2013). The concentration pattern indicates negative Cr/Ni in Sph6, the small droplet of

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**Fig. 10.** Total alkali–silica diagram after Rollinson (1993). Compositions of 15 El’gygytgyn spherules, 3 glassy impact melt rocks, 11 glassy impact melt particles, and 1 partly impact melted tuff clast compared with whole rock data for the upper target rock sequence and three impact melts at El’gygytgyn after Gurov et al. (2005). Data normalized to volatile-free compositions. Dotted line, redrawn after Irvine and Baragar (1971), distinguishes alkaline rocks (above) from subalkaline rocks (below). The average composition of the rim domain in Sph4 plots into the dactitic, the high-silica glass fragments in its core into the andesitic field; the average composition of zoned spherule Sph6 plots in the trachyandesitic field; the compositions of the main, the smaller, and the mini droplets in dumbbell spherule Sph7 plot in the rhyolitic, the dacitic, and andesitic fields, respectively.
Sph7, and Sph8, which have the highest siderophile contents. In contrast, Sph5 and the main droplet of Sph7 (Fig. 12a) have lower siderophile contents and show positive Cr/Ni.

**Secondary Phases**

Defocused beam electron microprobe analyses were performed on (1) a porous, low mass-contrast alteration phase in the hollow core of spherule Sph4; (2) drop-shaped inclusions or vesicle fills of lower mass than the surrounding impact glass in impact melt particles MP1 and MP5; (3) stubby crystals, 30–50 μm long that grew in pores of the breccia matrix in sample 317.6 mblf; and (4) 0.1 × 0.3 mm long, fibrous, rosette-forming crystals, that grew in pores of the breccia matrix in sample 326.1 mblf. These volatile-bearing phases yielded average totals between 83.9 and 89.3 wt% and were damaged by the defocused electron beam. They are sodium-potassium-calcium aluminosilicates, most likely phillipsite and/or chabazite (Chipera and Apps 2001). Phillipsite and chabazite parageneses are typical for low temperature (20–70°C) secondary mineralization in volcanic rocks (Chipera and Apps 2001).

Domains of low mass-contrast replacing the impact glass in the rim of spherule Sph4 appear to be strongly hydrated (totals average about 80 wt%); they are mainly composed of SiO2 (73.5 wt%) and Al2O3 (5 wt%) and minor Na2O, K2O, CaO and FeO (< 1 wt %), and traces of MgO and TiO2 (0.1 wt%).

**DISCUSSION**

**Crater Dimensions and Abundance of Impact Melt in El’gygytgyn Crater**

Scaling relationships (Melosh 1989) suggest a 9–11.7 km diameter transient crater collapsed to the final

![Fig. 11. Chemical zonation in spherule Sph6 from reworked fallout deposit sample 317.6 mblf. a) BSE image, note subtle zonation from core to rim, and the very small high mass-contrast phases in outer few μm of the rim (arrows) that are enriched in Fe, Cr, and Ni; b) concentration variations of selected minor and trace elements, spot numbers correspond to circles in (a).](image-url)
Table 4. Electron microprobe data for 15 El’gygytgyn impact spherules.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Na$_2$O (wt%)</th>
<th>MgO (wt%)</th>
<th>Al$_2$O$_3$ (wt%)</th>
<th>SiO$_2$ (wt%)</th>
<th>P$_2$O$_5$ (wt%)</th>
<th>K$_2$O (wt%)</th>
<th>CaO (wt%)</th>
<th>TiO$_2$ (wt%)</th>
<th>Cr$_2$O$_3$ (wt%)</th>
<th>NiO (wt%)</th>
<th>FeO$^\text{a}$ (wt%)</th>
<th>MnO (wt%)</th>
<th>Total (wt%)</th>
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<td>316.7, Sph1, n = 10</td>
<td>Avg 5.97</td>
<td>4.15</td>
<td>14.1</td>
<td>63.4</td>
<td>&lt;0.02</td>
<td>5.76</td>
<td>2.14</td>
<td>0.41</td>
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<tr>
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<td>3.71</td>
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<td>5.62</td>
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<td>0.16</td>
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<td>0.8</td>
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<td>0.2</td>
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<td>0.03</td>
<td>0.39</td>
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<td>86.4</td>
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<td>0.89</td>
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<td></td>
<td>n = 11</td>
<td>Avg 0.86</td>
<td>1.58</td>
<td>14</td>
<td>71.3</td>
<td>1.01</td>
<td>3.42</td>
<td>1.56</td>
<td>0.73</td>
<td>n.m.</td>
<td>n.m.</td>
<td>5.35</td>
<td>n.d.</td>
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</table>
18 km diameter crater at El'gygytgyn. This transient cavity would have had a maximum depth of 3–3.9 km (Dence et al. 1977), with a volume of impact melt on the order of 2.9–8 km³ (Grieve and Cintala 1992). Maximum depth of excavation would have been approximately 1.2 km (Melosh 1989) and melting could have taken place down to 1.5–2.6 km (Grieve and Cintala 1992). Assuming that half the produced impact melt had been retained in the crater, 1.5–4 km³ of impact melt spread out over the area of the transient cavity would amount to an average thickness of 44–53 m (Grieve and Cintala 1992). Yet, the volume of impact melt this study could identify in the ICDP drill core is smaller than 1 cm. Similar observations were discussed for the Bosumtwi impact crater (e.g., Artemieva 2007; Deutsch et al. 2010; Coney et al. 2010).

Reasons for this apparent lack of impact melt could be numerous:

1. A low impact velocity, and/or a very low angle of impact would yield a smaller volume of impact melt (e.g., Pierazzo and Melosh 2000); the circular shape of the crater, however, is at odds with a very low-angle impact.

2. If the highly vesicular and porous lavas, tuffs, and ignimbrites in the target rock sequence behaved like water-saturated sediments, a coherent impact melt sheet could have been dispersed and much of the melt ejected (Kieffer and Simonds 1980). This may explain the eroded fragments of impact melt that occur with sizes up to approximately 1 m in terrace outcrops of the crater (e.g., Gurov et al. 2005), whereas the largest confirmed impact melt fragment in the drill core is smaller than 1 cm. Similar observations were discussed for the Bosumtwi impact crater (e.g., Artemieva 2007; Deutsch et al. 2007; Coney et al. 2010).

3. If the drill site is located on top or on the flank of the central uplift (Gebhardt et al. 2006), most

---

**Table 4. Continued.** Electron microprobe data for 15 El'gygytgyn impact spherules.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Na₂O (wt%)</th>
<th>MgO (wt%)</th>
<th>Al₂O₃ (wt%)</th>
<th>SiO₂ (wt%)</th>
<th>P₂O₅ (wt%)</th>
<th>K₂O (wt%)</th>
<th>CaO (wt%)</th>
<th>TiO₂ (wt%)</th>
<th>Cr₂O₃ (wt%)</th>
<th>NiO (wt%)</th>
<th>FeO⁺ (wt%)</th>
<th>MnO (wt%)</th>
<th>Total (wt%)</th>
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<tr>
<td>E7, n = 9</td>
<td>2.4</td>
<td>5.61</td>
<td>15.7</td>
<td>58.4</td>
<td>n.m.</td>
<td>1.82</td>
<td>5.13</td>
<td>0.87</td>
<td>n.m.</td>
<td>n.m.</td>
<td>9.69</td>
<td>0.17</td>
<td>99.8</td>
</tr>
<tr>
<td>σ</td>
<td>0.21</td>
<td>0.23</td>
<td>0.8</td>
<td>0.6</td>
<td>n.m.</td>
<td>0.16</td>
<td>0.21</td>
<td>0.14</td>
<td>n.m.</td>
<td>n.m.</td>
<td>0.28</td>
<td>0.07</td>
<td>0.64</td>
</tr>
<tr>
<td>E8, n = 8</td>
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<td>2.08</td>
<td>17.1</td>
<td>67.3</td>
<td>n.m.</td>
<td>3.47</td>
<td>1.92</td>
<td>0.71</td>
<td>n.m.</td>
<td>n.m.</td>
<td>5.28</td>
<td>0.06</td>
<td>99.8</td>
</tr>
<tr>
<td>σ</td>
<td>0.13</td>
<td>0.22</td>
<td>0.5</td>
<td>1</td>
<td>n.m.</td>
<td>0.2</td>
<td>0.23</td>
<td>0.09</td>
<td>n.m.</td>
<td>n.m.</td>
<td>0.2</td>
<td>0.05</td>
<td>0.5</td>
</tr>
<tr>
<td>E9, n = 5</td>
<td>1.12</td>
<td>9.14</td>
<td>18</td>
<td>52.9</td>
<td>n.m.</td>
<td>0.63</td>
<td>7.67</td>
<td>0.94</td>
<td>n.m.</td>
<td>n.m.</td>
<td>9.07</td>
<td>0.16</td>
<td>99.6</td>
</tr>
</tbody>
</table>

*All iron as FeO; see Fig. 9a; see Fig. 9c; n.d. = not detected; n.m. = not measured; n = the numbers of analyses (20 µm beam diameter, unless noted otherwise) that were used to calculate the average (avg), and standard deviation (σ) of oxide concentrations in the respective samples; all SO₂ analyses were <0.06 wt%; Sph1: complete, oval, apparent Ø of 0.2 × 0.14 mm, has a 5 µm rim of crystals and is concentrically zoned; Sph2: complete, oval, apparent Ø of 0.3 × 0.25 mm, homogeneous; Sph3: hollow, round, apparent Ø of 0.23 mm, has 5 µm rim of skeletal pyroxene and few blebs of Ni-Fe rich material, some glass remains, 5 µm beam Ø; Sph4: hollow, oval, apparent Ø of 0.3 × 0.24 mm; 5 µm rim of low mass-contrast alteration phase and corrosion, some glass remains as angular domains in rim, core retains fragments of hydrated, high SiO₂ glass; 5 µm beam Ø; Sph5: complete, oval, apparent Ø of 0.21 × 0.18 mm, homogeneous; Sph6: complete, oval/egg-shaped, apparent Ø of 0.09 × 0.06 mm, very thin 3 µm thick outer rim with Ni-rich spinel crystals, spherule is zoned with lower mass-contrast core and higher mass-contrast rim; Sph7: complete, dumbbell-shaped, 210 µm long particle consisting of at least three fused droplets, 130, 80, and 6 µm in apparent diameters, Sph8: complete, round apparent Ø of 0.13 mm, complex zonation, traces of Ni-rich spinels and acicular Mg-Fe-silicates; E1–E4 and E7–E9 are spherules collected near the SW rim of El'gygytgyn crater and were analyzed with a 10 µm Ø beam; E1: broken, 0.74 × 0.45 mm long sliver contains up to 40 µm Ø round vesicles and assimilated debris of lower mass-contrast near the rim that is associated with small vesicles; E2: oval, 0.51 × 0.36 mm fragment with schlieren of assimilated lower mass-contrast material that are associated with <10 µm Ø particles, one measurement (x) captured a high-SiO₂ domain that corresponded to reduced concentrations in all other elements except Na₂O; E3: an oval, 0.31 × 0.27 mm spherule with an intensely chipped outer surface—it has several domains of assimilated lower mass-contrast matter that form ameboid shapes, which are associated with small vesicles throughout the particle, the largest vesicle is 35 µm in Ø; E4: oval, 0.38 × 0.24 mm Ø, with a high-SiO₂-debris-filled, 40 µm Ø, round indentation—it also contains two 100 and 80 µm long inclusions of assimilated lower mass-contrast material at its rim, the larger of which protrudes beyond the trace of the round rim—spot analyses on this debris indicates relative SiO₂ and K₂O enrichments compared to the bulk composition and a P₂O₅ and FeO enrichment in one of the spots (c); E7: a round, 0.24 mm Ø homogeneous spherule with little surface abrasion; E8: a round, 0.27 mm Ø homogeneous spherule with a round, 20 µm Ø vesicle near its center and moderate surface abrasion; E9: a round, 0.2 mm Ø homogeneous spherule with strong abrasion of its surface.
<table>
<thead>
<tr>
<th>Sample</th>
<th>E1 (n = 3)</th>
<th>E2 (n = 3)</th>
<th>E3 (n = 2)</th>
<th>E4 (n = 3)</th>
<th>E7 (n = 3)</th>
<th>E8 (n = 2)</th>
<th>Sph5 (n = 7)</th>
<th>Sph6 (n = 2)</th>
<th>Sph7–small droplet (n = 1)</th>
<th>Sph7–main droplet (n = 3)</th>
<th>Sph8 rim with matrix (n = 1)</th>
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</table>

[The article was corrected on 17 June 2013. In table 5, headers which were erroneously identifying Average compositional values as standard deviation (σ) and vice versa were corrected.]
impact melt could have pooled in topographically lower regions of the ring syncline during the crater modification stage.

**Melt-Mixing**

Using least squares mixing calculations (Bryan et al. 1969; Korotev et al. 1995), the composition of impact melt particles was modeled from mixtures of target rock components occurring at El’gygytgyn. We used literature data from Gurov et al. (2005, their Table 1, normalized to volatile-free compositions) for the compositions of target rocks. Our calculations indicate that the average composition of the impact melt particles can be produced from $77 \pm 11.4\%$ “rhyolitic ignimbrite” and $24.7 \pm 11.3\%$ “rhyolite” within analytical variation (Table 6). This means that the average composition of melt particles could have been derived from impact melting and mixing of the upper 450 m of the target rock sequence with an approximate ratio of $\frac{3}{4}$ of rhyolitic ignimbrite and $\frac{1}{4}$ of rhyolite. It follows that the uppermost 250 m of the target sequence could have contributed a dominant proportion to the analyzed impact melt particles.

The three impact melt rocks TM8, TM12, and TM17 can be modeled as predominantly derived from the uppermost “rhyolitic ignimbrite” target component of Gurov et al. (2005) plus an addition of up to 6% “andesite, andesitic tuff” (Table 6). The major and minor element average composition of all three impact
Table 6. Results of least squares mixing calculations of target rock compositions.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rhyolitic ignimbrite&lt;sup&gt;a&lt;/sup&gt; (%)</th>
<th>Rhyolite&lt;sup&gt;a&lt;/sup&gt; (%)</th>
<th>Andesite, andesitic tuff&lt;sup&gt;a&lt;/sup&gt; (%)</th>
<th>SiO&lt;sub&gt;2&lt;/sub&gt; (wt%)</th>
<th>TiO&lt;sub&gt;2&lt;/sub&gt; (wt%)</th>
<th>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt; (wt%)</th>
<th>FeO (wt%)</th>
<th>MnO (wt%)</th>
<th>MgO (wt%)</th>
<th>CaO (wt%)</th>
<th>Na&lt;sub&gt;2&lt;/sub&gt;O (wt%)</th>
<th>K&lt;sub&gt;2&lt;/sub&gt;O (wt%)</th>
<th>P&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt; (wt%)</th>
<th>Sum oxides (wt%)</th>
<th>(\chi^2)</th>
<th>(\chi^2/\nu)</th>
</tr>
</thead>
<tbody>
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<td>MP Avg.</td>
<td>77.0 ± 11.4</td>
<td>24.7 ± 11.3</td>
<td>n.a.</td>
<td>72.29</td>
<td>0.28</td>
<td>14.46</td>
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<td>0.64</td>
<td>2.03</td>
<td>3.32</td>
<td>4.63</td>
<td>0.07</td>
<td>100</td>
<td>3.4</td>
<td>0.4</td>
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<tr>
<td>All TM</td>
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<td>3.7 ± 2.9</td>
<td>n.a.</td>
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<td>0.34</td>
<td>14.96</td>
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<td>0.08</td>
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<td>2.97</td>
<td>4.13</td>
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<td>1.6</td>
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<td>Avg.</td>
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<td>TM12</td>
<td>99.8 ± 2.7</td>
<td>1.9 ± 2.5</td>
<td>n.a.</td>
<td>71.02</td>
<td>0.34</td>
<td>14.99</td>
<td>2.7</td>
<td>0.07</td>
<td>0.94</td>
<td>2.7</td>
<td>3.07</td>
<td>4.11</td>
<td>0.07</td>
<td>100</td>
<td>11.2</td>
<td>1.4</td>
</tr>
<tr>
<td>TM17</td>
<td>95.5 ± 4.0</td>
<td>6.2 ± 3.8</td>
<td>n.a.</td>
<td>71.13</td>
<td>0.33</td>
<td>14.96</td>
<td>2.78</td>
<td>0.08</td>
<td>1.01</td>
<td>2.67</td>
<td>2.93</td>
<td>4.04</td>
<td>0.06</td>
<td>100</td>
<td>39.7</td>
<td>5.0</td>
</tr>
</tbody>
</table>

<sup>a</sup>Volcanic target rocks from the El'gygytgyn impact crater after Gurov et al. (2005), normalized to volatile-free compositions; \(\chi^2\) is the sum of least squares, and \(\nu\) the number of major, minor, and trace elements minus the number of components, i.e., rock compositions used for the mixing calculation (Korotev et al. 1995). Standard deviations of the impact melt particle average composition (MP avg.) and impact melt rock samples (TM8, TM12, TM17 and the average of these analyses all TM avg.) from Tables 2 and 3, normalized to 100 wt%. Relative standard deviations in % of these data were used as weighting factors for the mixing calculations. Note that the goodness of fit of these calculations is reflected by \(\chi^2/\nu\) approaching 1 (Korotev et al. 1995).
melt rocks (Table 3) is actually very similar to the average composition of the “rhyolitic ignimbrite,” the target rock that composed the upper 250 m of the target sequence according to Gurov et al. (2005). Unfortunately, these authors do not provide standard deviations in their data; however, the differences being so minor, it can be assumed that the impact melt rocks TM8, TM12, and TM17 could have been derived from the “rhyolitic ignimbrite” target member alone. Thus, even if scaling relationships of Grieve and Cintala (1992) suggest the depth of the melt zone at El’gygytgyn could have been down to 2.6 km, the glassy impact melt rocks and the glassy melt particles appear to have been produced dominantly from rhyolitic ignimbrite that constituted the upper 250 m of the target rock sequence.

These results confirm the conclusion of Gurov and Koeberl (2004) that “the composition of impact glasses is very similar to the composition of volcanic rocks of the upper, 250 m-thick, layer of the crater basement; the closest similarity is observed for ignimbrites.”

In contrast, major and minor element concentration patterns of the spherules could not be modeled in good approximation as mixtures of the 5 main target rock components reported by Gurov et al. (2005). This is mainly because the MgO, CaO, and FeO abundances, and high concentrations of Na₂O and Al₂O₃ in individual spherules exceed the ranges reported for the major target rock components (Gurov et al. 2005; Table 4). These results are surprising, yet they seem to mirror a relative larger compositional variation of target lithologies, and/or a significant contribution of an impactor component to these spherules. Goderis et al. (2013) present a more elaborate melt-mixing approach for the spherules to identify a likely projectile.

Spherules

Impact spherules occur in ancient ejecta layers (Simonson and Glass 2004), globally distributed Phanerozoic strewn fields (e.g., Smit 1999; Whitehead et al. 2000), and occasionally in proximal impactite deposits (Graup 1981). Their occurrence is not restricted to Earth as spherules characterize lunar regolith breccias (e.g., Symes et al. 1998; Ruzicka et al. 2000), and also occur in howardite meteorites (Olsen et al. 1990; Barrat et al. 2009). Following laboratory experiments for constraining crystallization conditions recorded in crystallized lunar spherules, Symes et al. (1998) suggested that these particles probably formed in basin-forming impact events during their residence in large ejecta plumes.

Impact spherules are thought to result from the condensation of vaporized target rock and impactor (“microkrystites,” e.g., Glass and Burns 1988) or as ballistically emplaced impact melt droplets (“microtektites,” Smit 1999; Simonson and Glass 2004). Microkrystites are round, contain crystallites of pyroxene and/or Ni-rich spinel and are most abundant in distal ejecta deposits. Microtektites are variable in shape, glassy, may contain relict target rock debris, and are most abundant in more proximal ejecta layers (Smit 1999); hence, our dumbbell-shaped spherule Sph7 and the teardrop-shaped spherules E1, E2, E3, and E4 resemble microtektites. The round-to-oval spherules that crystallized pyroxene and/or Ni-rich spinel (Sph 1, Sph3, Sph6, Sph8, SphY), in contrast, could represent microkrystites.

Although the 7 spherules E1–E4 and E7–E9 were collected from reworked deposits outside the crater, their impact origin is inferred from three main arguments:

First, they are composed of pristine glass, while target rock clasts in the ICDP drilling indicate pervasive alteration that predates the impact.

Second, they exhibit variable compositions from rhyolitic to basaltic-andesitic (Fig. 10) that are grossly similar and in part overlap with the compositions of glassy spherules in samples 316.7 and 317.6 mblf (Tables 4 and 5; Fig. 10). A volcanic origin would imply that they formed during subsequent eruptions of chemically different lavas. However, Heiken (1972) showed that only low-viscosity basaltic lavas form volcanic spherules. Implications from the compositional difference between the spherules from the ICDP drill core samples and those collected outside the SE crater rim are discussed below. Furthermore, accreted lithic debris, which occurs in 4 of these spherules, has long been regarded as an indication for the impact origin of lunar spherules (Heiken et al. 1974). The apparent lack of Ni-Cr-rich crystals near the rims of spherules E1–E4 and E7–E9 may be due to abrasion of their surfaces (Fig. A6).

Third, assuming that these spherules formed as volcanic melt droplets, their high siderophile contents have no match in the known target rock sequence (Goderis et al. 2013; Raschke et al., Forthcoming), which strongly implies an impact origin.

Similar reasoning negates the notion that the spherules that occur in the reworked fallout deposit could represent reworked volcanic melt products.

Petrographic Contexts of Spherules

The relatively spherule-rich reworked fallout deposits in El’gygytgyn crater, to our knowledge, is only the second such known deposit within a complex crater after the excellently preserved fallback layer in the Bosumtwi crater (Koeberl et al. 2007). In contrast to Bosumtwi, the reworked fallout deposit appears to be traceable in the proximity of the El’gygytgyn crater to a distance of at least 17 km south of the crater rim (corresponding to “20 km south of the crater lake” according to Glushkova...
discovered a very low abundance of 0.06 cm

differently in these craters. For example, Graup (1981)
Alternatively, spherules may have been deposited
in El’gygytgyn drill core samples (Figs. 7c–f).

spherules. This could be due in part to dissolution of
projectile (Pernicka et al. 1987), but appear to lack impact
Rochechouart (Lambert 2010), may contain traces of the
large craters, e.g., Ries (Jankowski 1977) and

matrices were deposited (Glushkova et al. 2005).

Kohered deposits that overlie suevites in other
large craters, e.g., Ries (Jankowski 1977) and
Rochechouart (Lambert 2010), may contain traces of the
projectile (Pernicka et al. 1987), but appear to lack impact
spherules. This could be due in part to dissolution of
spherule glass, a process that also affected some spherules in
El’gygytgyn drill core samples (Figs. 7c–f).

Alternatively, spherules may have been deposited
differently in these craters. For example, Graup (1981)
discovered a very low abundance of 0.06 cm$^{-2}$ glass
spherules in fallback suevite of the Ries crater. This
suggests entrainment of spherules in the bulk ejecta plume
at the Ries crater. Likewise, a few possible microtektite-like
glass beads (Fig. 5a) occur in the suevite unit in
El’gygytgyn crater.


Compositional Variation of the El’gygytgyn Spherules

A striking property of the spherules is their
compositional variation (Fig. 10). Mixing calculations
generally fail to reproduce their compositions from the
major lithologies of the presumed upper 620 m of target
rocks (Gurov and Gurova 1991; Gurov et al. 2005).
Thus, the glass spherules appear to record formation from
discrete portions of the target rock sequence and/or
variable admixtures of an ultramafic projectile (Goderis
et al. 2013). Possibly, a pronounced mafic component in
spherules E1–4 and E7–9 collected beyond the SE crater
rim could record the presence of a basaltic target member
in this region of the crater. This can be inferred from
impact melt compositions in the southern part of the
 crater reported by Gurov et al. (2005) that differ from
impact melt rock compositions from the SW, W, NW, N,
and NE of the crater, and the outcrops of mafic tuffs
occurring toward the SE of the crater (Stone et al. 2009).

Projectile Component

Nickel abundances between 300 and 1400 ppm in
El’gygytgyn spherules (Table 5) probably relate to
projectile contamination because they exceed Ni
abundances in most target rocks and impact melt rocks
by up to two orders of magnitude (compare Goderis
et al. [2013]; and references therein). The Ni-enrichment

does not correlate with FeO concentrations or chemical
homogeneity, and no correlation of Ni concentrations
with spherule shapes was observed (Tables 4 and 5).
It is also noteworthy that the spherule that exhibits one of
the highest concentrations of NiO, Sph6 (Fig. 11), is oval,
compositionally zoned, and has fine, Ni-rich spinel
crystals at its rim. Overall, this indicates that spherules,
both melt droplets and possible condensation products,
did not undergo homogenization in El’gygytgyn’s ejecta
plume. A similar, variable abundance of siderophile
elements was found among the microtektite-like
spherules from the Bosumtwi crater (Koeberl et al.
2007). This is also true for the late Eocene microkrystites
that are thought to have originated from the Popigai

Popigai microkrystites record a possible impactor
signature in their siderophile element enrichments (Glass
and Koeberl 1999; Kyte et al. 2011), similar to
microkrystites from the Chicxulub impact (e.g., Smit
[1999] and references therein). Numerical modeling of
Artemieva and Morgan (2009) found that distal
Chicxulub spherules/microkrystites may contain up to
1/3 vaporized/melted projectile material. Goderis et al.
(2013) report melt-mixing calculations that show the
proximal El’gygytgyn spherules may contain up to 18% of
an ordinary chondrite impactor, most likely type LL.

Implications for the Ejecta Plume

Melt droplets have been found at bomb test sites,
associated with terrestrial impacts, and in lunar Apollo
samples (e.g., Heiken and Lofgren 1971; Margolis et al.
1991). Heiken and Lofgren (1971) pointed out that such
particles probably form from the melting and accretion
debris in an impact or explosion fireball. Kyte et al.
(2010) point out that spherules from the oceanic Eltanin
impact grew through accretion. These authors concluded
that such accretionary spherules are more abundant in
small impacts at localities closest to the impact site. The
glass spherules at Bosumtwi (Koeberl et al. 2007) and
El’gygytgyn were among the last impactites deposited in
the crater, and would thus have to be linked to the
earliest, fast ejected material (compare Kyte and
Bostwick 1995). Accretion and assimilation of Si-rich
debris in spherules E1, E2, and E3 (Figs. 9a and 9b) and
E4 (Figs. 9c and 9d) indicate that they are unlikely to
have condensed from a vapor cloud, but instead
represent droplets engulfed in a plume laden with lithic
debris. In this regard, these spherules are similar to a
glass spherule from a suevite deposit of the Ries crater
that bears inclusions of diaplectic quartz glass (Graup
1981). In contrast, at least three of our El’gygytgyn
spherules bear evidence for growth through accretion of
smaller melt droplets. Dumbbell-shaped aggregate Sph7
(Figs. 12a and 12b) is composed of at least three melt
droplets of different compositions that were fused together while they were viscous. Traces of accreted melt droplets in Sph8 are the two semicircular inclusion trails of Ni-rich spinels (Figs. 12c and 12d; cf. Kyte et al. 2007), which occur in a similar manner in altered spherule SphY. The Ni-rich spinel in spherules Sph6, Sph8, and SphY must have formed on the surface of Ni-rich melt droplets under high oxygen fugacity conditions (Kyte and Bostwick 1995). Nonetheless, the alkali element-rich compositions of these spherules along with refractive components in relatively unfractonated proportions that can be described as mixtures between acid volcanic target rocks and ordinary chondrite impactor (Goderis et al. 2013) negate formation due to condensation from a vapor cloud (Ebel and Grossman 2005). In summary, Ni-spinel bearing spherules in the El'gygytgyn crater record formation as melt droplets that grew by accretion. Other microtektite-like spherules probably record residence in cooler regions of the ejecta plume that was laden with solid debris and melt droplets.

**Emplacement Reconstruction**

**The Lower 98 m (517.3–419.3 mbf)**

The lower and upper ignimbrite units are likely allochthonous material that was transported to its present, relatively subdued location, from a stratigraphically higher allochthonous material that was transported to its present, relatively submerged location toward the top of the upper target rock sequence would have escaped severe shock metamorphism. Considering the drill site is 2.3 km off the crater center (Melles et al. 2011), it may be on top or the upper flank of a central uplift. Gebhardt et al. (2006) concluded from geophysical data that this central uplift collapsed to a ring structure. Scaling relationships infer that the central uplift at El'gygytgyn would have had a maximum diameter of 5.9 km (Therriault et al. 1997) and could contain target rocks that were uplifted from a maximum stratigraphic depth on the order of 1.4–1.7 km (Grieve et al. 1981). Furthermore, numerical modeling of the El'gygytgyn impact by Collins et al. (2008) infers that at a radial distance of 2.3 km from the center, the parautochthonous basement experienced peak shock pressures of approximately 16 GPa. According to this model, this parautochthonous basement is overlain by unshocked, slumped allochthonous material mixed with highly shocked ejecta. Possibly, the movement of these decimeter-sized blocks could have been accomplished during the crater modification phase. Then, the collapse of the transient cavity and the formation of the central ring caused inward and downward mass movements (e.g., Kenkmann et al. 2004).

Geophysical modeling of Gebhardt et al. (2006) inferred thicknesses of allochthonous breccia of approximately 100 m on top of the collapsed central uplift and gradual thickening to 400 m in the annular moat. This allochthonous breccia is thought to be overlain by brecciated bedrock. If the drilling is located in the vicinity of the central ring, and the allochthonous breccia sequence contains the upper and lower ignimbrite blocks, then the drilling site is more likely located on the flank of the central ring structure or in the annular moat of the crater. This suggests that the drilled section may be overlain by pooled melt that overlies the brecciated crater floor. However, the presence of such pooled impact melt was not resolved from geophysical data (Gebhardt et al. 2006), and therefore seems implausible.

The polymict breccia sliver between the ignimbrite blocks may be debris that was picked up during the approximately 2–4 km relative radial transport distance that can be inferred, if the ignimbrite blocks moved from near the upper wall of the transient cavity to their final location. Alternatively, it may represent a breccia dike injection into the ignimbrite blocks (cf. Raschke et al., Forthcoming). It is puzzling that in this breccia lithology, slightly elevated siderophile element
concentrations (including those of platinum group elements) have been measured, which may represent a diluted meteoritic component (Goderis et al. 2013). Raschke et al. (2013) report shock metamorphosed components in this unit. A similar impact stratigraphy was reported by Kenkmann et al. (2004) from the Yaxcopoil-1 drilling through the Chicxulub impact structure. There, blocks of displaced sedimentary rocks are variably brecciated and intercalated with polymict breccia that contains rare shock metamorphosed quartz.

**Upper Polymict Impact Breccia (330.8–419.3 mblf)**

This unit varies from blocky debris mostly derived from felsic volcanics to matrix-supported materials that are mixtures of felsic and mafic volcanics, indicating an origin in the upper few hundred meters of the target rock sequence. The unit contains scarce shock metamorphic features and generally seems to lack impact melt. This and the unsorted nature and low contents of shock metamorphosed material may indicate that this material is debris from locations near the outer and upper transient cavity that also engulfed the underlying ignimbrite blocks. Blocky, polymict breccias that contain components with limited shock metamorphic overprint form the bottom of the crater fill in complex impact structures. Such assemblages are known from the Chesapeake Bay (Horton et al. 2009; Wittmann et al. 2009b) and Ries crater (Von Engelhardt and Graup 1977); however, the blocky debris in these craters is clearly derived from relative greater depths in the respective target rock sequences.

**Suevite (319.4–329.1 mblf)**

This approximately 10 m thick section contains approximately 1 vol% of rapidly quenched, glassy impact melt. The chemical composition of these angular particles (Fig. 10) indicates that they are a product of localized impact melting of the uppermost target rocks. This could mean that this study failed to identify impact melt lithologies that were derived from intermediate to mafic target rocks. Such melt lithologies could exhibit an alteration behavior that makes them hard to distinguish from the altered volcanic target rocks. Detailed petrographic studies of thermally decomposed mineral clasts could be helpful to identify further types of impact melts (cf. Chao 1968; Wittmann et al. 2009).

Save this caveat, no coherent bodies of impact melt are present in this suevite section that is characterized by dm-long clasts of lava and tuff lithologies. Such lithologies may correspond to the intermediate to lower levels in the known target rock sequence down to 620 m depth. A change in depositional dynamics with the collapse of the ejecta plume may have created rheologic properties that caused core loss toward the bottom of the suevite unit. Lateral ground-surfing may have interfered with vertical movements induced from the fall-back of lofted ejecta or the development of the central uplift. These processes probably occurred simultaneously, with ejecta plume components collapsing into chaotically surging debris (compare Wittmann et al. 2009b), which diluted the highly shocked fallback material. Scarce mantled clasts (Figs. 3a, A4d), the rapidly quenched melt shards (Figs. 5b,f), and microtektite-like glass beads (Fig. 5a) may indicate that these components record transport in El’gygytgyn’s ejecta plume. A projectile component, if present, is too diluted to be identified by trace element analysis of lithologies from the suevite unit (Goderis et al. 2013). The low abundance of shock features and impact melt in this suevite unit is remarkable. This is more typically a characteristic of crater deposits that are interpreted as ground surge-related, to account for the high dilution with unshocked lithic components (cf. Stöffler et al. 1977; Wittmann et al. 2009b). Nonetheless, late fallback material from the ejecta plume contains more concentrated shocked target rock and projectile components (Goderis et al. 2013) in the reworked fallout deposit above the suevite unit.

**Reworked Fallout Deposits (319.4–315.4 mblf)**

The overall situation at El’gygytgyn-ICDP hole 1C appears similar to the one at Bosumtwi crater, where little melt was captured in the ICDP drill holes near the center of the structure, whilst melt-rich suevite crops out near and beyond the crater rim (e.g., Artemieva 2007; Deutsch et al. 2007; Coney et al. 2010). The apparent lack of impact melt in hole 1C may indicate that most of the impact melt at El’gygytgyn was ejected and later eroded (Melles et al. 2011). In the Bosumtwi crater, a size-sorted unit on top of the impactite deposits contains microtektite-like spherules, accretionary lapilli, and shocked quartz in its uppermost 10 cm (Koeberl et al. 2007). At El’gygytgyn, a similar fallout deposit was reworked. However, its reworking and erosion were probably minor before sediments of the crater-lake sealed the depositional sequence of impactites. The reworked fallout deposit contains up to 7 fining upward cycles in the section that is covered by our samples from 319.14 to 316.77 m. From 316.77 to 315.35 m, about four more such cycles occur, probably recording debris flows of eroded material from the uplifted central ring or the more distal crater rim. The strongest impactor signature occurs in the flaser-textured sand sample at 318.9 mblf (Goderis et al. 2013) collected in close proximity to the boundary between suevite and reworked fallout deposits at 319.1 mblf. This sample also contains the highest abundance of spherules (approximately 1.4 cm⁻²). Thus, even if reworking affected the deposits of ejecta plume materials, a significant portion of fallback ejecta is recorded at the base of these reworked fallout deposits. For comparison, the highest concentration of spherules...
and other glass particles in Bosumtwi’s exquisitely preserved fallout deposit layer is approximately 5 wt%, but it is not clear if it records an impactor signature (Goderis et al. 2007; Koeberl et al. 2007).

In estimating the thickness of the spherule bed in the 1C drill core, we assume a mean diameter of 0.3 mm for the spherules and count the relict imprints where spherules were plucked from the thin sections. This yields an abundance of 150 to 310 spherules in a 2 cm wide and 2.2 m thick section that is covered by the spherule-bearing samples 318.9, 317.6, and 316.7 mblf, which would have constituted a 5.3–9.4 mm thick spherule layer. If the lowest abundance in the three samples of 0.8 spherules per cm² is extrapolated over the thickness of the reworked fallout deposits, a 10 mm thick layer of spherules results. This layer could have formed within hours to days after the spherules settled through the reestablished, undisturbed atmosphere above El’gygytgyn crater along with similar size debris from heights of 85–100 km (Kring and Durda 2002; Stößler et al. 2004).

CONCLUSIONS

1. ICDP-El’gygytgyn hole 1C provides a 1-D sample through the complex El’gygytgyn impact crater, of which 26 samples were analyzed in this study. Although the limits of this level of observation have to be appreciated, the core appears to capture a remarkably complete lithological section of very well-preserved, almost pristine impactites.
2. Very little shock metamorphosed components could be identified in the drill core samples studied here. Only about 3% of an impact melt volume calculated for a crater that size can be accounted for in the drilled section; possibly, larger quantities of impact melt lithologies are located at depth.
3. Alternatively, the apparent lack of impact melt at El’gygytgyn may suggest that the dominantly felsic volcanic sequence behaved similarly to sedimentary target rocks, and unlike crystalline lithologies, suggesting that porous, possibly water-saturated target rocks such as carbonates, evaporites, clastic sediments, lavas, and tuffs have a strong effect on the nature and distribution of impactite lithologies, as inferred by Kieffer and Simonds (1980) and Poelchau et al. (2012).
4. Impact melt particles in the suevite are modeled as mixtures of a dominant rhyolitic ignimbrite component. Three rapidly quenched, glassy impact melt rocks collected at the crater surface indicate the presence of an intermediate mafic, probably andesitic component along with rhyolitic ignimbrite; this suggests that these impact melts could have been generated from the upper 0.5 km of the target.
5. Glassy impact spherules from El’gygytgyn are petrographically and compositionally variable; they record lateral variation of preimpact target rocks on a regional scale (Gurov et al. 2005; Stone et al. 2009), and contain a pronounced impactor component; microtektilike spherules record accretion and assimilation of polymineralic debris in a cooler region of the ejecta plume or growth through accretion of melt droplets in a much hotter portion of the ejecta plume. Our estimate for the original thickness of this spherule layer is on the order of 5–10 mm.
6. Geophysical data suggest that the drill site is located on the collapsed central uplift; the lower 98 m of the sequence is mostly composed of unshocked blocks, probably derived from surficial target rocks. This conclusion is supported by:
   a. The depositional sequence recorded in the lithological units, which, at its bottom, suggests that decameter-thick blocks of surficial ignimbrite slumped inward and downward from a location outside the 5–10 GPa isobar during crater modification. A thin sliver of polymict impact breccia separates two of these blocks and the upper ignimbrite block contains brecciated mafic inclusions near its top that are likely remnants of Paleocene basaltic intrusives;
   b. On top of these blocks, the 89 m thick polymict impact breccia containing very few components that record low shock metamorphic overprints is likely disaggregated debris that collapsed back into the crater along with the ignimbrite blocks from a location at the outer and upper wall of the transient cavity;
   c. This ground-surge debris is capped by 10 m thick, impact-melt-poor suevite containing angular, shard-shaped melt particles, microtektilike glass beads, and a few mantled particles. These particles may indicate the presence of an airborne ejecta plume component, which became entrained and diluted in the ground surge;
   d. The suevite unit grades into what appears to be a unit of aquatically reworked fallout deposits composed of 7–11 fining-upward sequences of breccias, gravels, and sands topped by lacustrine background sedimentation. Reworking and dilution must have been limited, though, as impact spherules (abundance up to 1.4 cm⁻²) and an impactor component (Goderis et al. 2013) were retained. A “chaotic horizon” that contains impact spherules occurs at least as far as 17 km south of the crater rim (Glushkova et al. 2005; Smirnov et al. 2011).

Acknowledgments—We thank O. Glushkova and G. Fedorov for providing spherule samples; T. Martin (Greensboro Day School, PolarTREC) for providing the
impact melt rock samples; U. Heitmann, U. Raschke for drill core sample handling, initial petrographic overview, and sharing drafts of his manuscripts; the El'gygytgyn Scientific Party for drilling operations and procurement of drill core samples; sponsors of the drilling campaign (ICDP, Austrian Federal Ministry of Science and Research, Federal Ministry of Education and Research, Germany, German Science Foundation, Russian Academy of Sciences, U.S. National Science Foundation); J. Brigham-Grette for discussions and sampling support; D. A. Kring for sampling support at the Lunar and Planetary Institute, Houston; L. Le (NASA-JSC) for Raman spectroscopy support; A. Peslier (NASA-JSC) for EMPA support, M. Roden (University of Georgia) for optical microscopy support; J. Berndt-Gerdes (WWU) for advice with LA-ICP-MS analysis; ICDP-core scan documentation by the GfZ Potsdam; R. Korotev and P. Carpenter (Washington University in St. Louis) for probe and melt mixing support. S. G. is a postdoctoral fellow of the FWO projects G.A078.11 and G.0021.11. We appreciate the constructive reviews and comments by C. Koeberl, B. Simonson, and W. U. Reimold. This is LPI Contribution #1700.

Editorial Handling—Dr. Christian Koeberl

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Fig. A1. Scans of thin sections of samples from the lower core section of ICDP El’gygytgyn hole 1C. a) Lower ignimbrite 517.0 mblf, note light green, volcanic melt shards (arrows); b) lower polymict impact breccia 474.4 mblf, note possible greenschist clast (white arrow) and granitic clast (black arrow); c) upper ignimbrite 435.4 mblf, note brown melt vein (arrows); d) basaltic intrusion 391.6 mblf, note basalt domains (white arrows) that contain felsic breccia clasts (black arrows); e) upper polymict impact breccia 390.1 mblf, note dark clast that contains shocked quartz (arrow); f) upper polymict impact breccia 386.1 mblf. Thin sections are typically 4 cm long.
Fig. A2. Scans of thin sections of upper polymict impact breccia samples of ICDP-El'gygytgyn hole 1C. 

a) 382.3 mblf; b) 381.8 m, note ignimbrite clast (white arrow) that is surrounded by breccia of volcanic rocks (black arrows); c) 374.4 mblf; d) 372.7 mblf; e) 368.8 mblf, note large felsic volcanic clast at bottom 2/3 of the thin section; f) 351.8 mblf is an ignimbrite clast.
Fig. A3. Scans of thin sections of upper polymict impact breccia and suevite transition samples of ICDP El'gygytgyn hole 1C.

a) Upper polymict impact breccia 349.6 mblf; note various types of felsic volcanic clasts (black arrows) and altered mafic clast (gray arrow);
b) 348.1 mblf, ignimbrite clast with sizable brown melt domain (white arrow) and green kaersutite crystals (black arrows);
c) 347.3 mblf is an ignimbrite clast, note common alignment of elongated brown melt particles;
d) 345.6 mblf, note large basalt clast (arrow) with altered orange olivine phenocrysts;
e) 330.9 mblf, note fractured secondary phyllosilicate fillings (arrows);
f) suevite to upper polymict impact breccia transition sample 328.1 mblf, note abundant basalt clasts (gray arrows), small tuff clast (black arrow), and layering in clast-supported upper portion of the thin section. Thin sections are typically 4 cm long.
Fig. A4. Scans of thin sections of suevite and reworked fallout deposits samples of ICDP-El'gygytgyn hole 1C drill cores. 

a) Tuff clast at 327.8 mblf; b) suevite 326.1 mblf, note partly impact melted tuff clast (black arrow) and translucent impact melt clast (gray arrow); c) suevite 325.7 mblf, note large lava clast (black arrow), translucent impact melt clast (gray arrow) and secondary phyllosilicate filling (white arrow); d) suevite 323.9 mblf, note possible mantled clasts (arrows); e) suevite 321.5 mblf, note large tuff clasts (black arrows) and translucent, vesicular impact melt clast (gray arrow); f) reworked fallout deposit 318.9 mblf, note sand matrix that embeds slivers of coarser grained breccia. Thin sections are typically 4 cm long.
Fig. A5. Thin section scans.

a) Reworked fallout deposit sample 317.6 mblf, note poor sorting; b) reworked fallout deposit sample 316.7 mblf, top is toward the right side, note upward-fining; d)–e) Glassy impact melt rocks TM8, TM12, and TM17 collected near the western crater rim; note translucent glassy impact melt that is mixed with dark, unmelted debris. Thin sections are typically 4 cm long.
Fig. A6. Thin section micrograph pairs (plane polarized at the top and reflected light at the bottom) of single spherules E1–E9 that were collected near the SE’ crater rim.

a) Spherule E1; b) spherule E2; c) spherule E3, note high density of vesicles; d) spherule E4, note accreted polymineralic debris (arrow); e) spherule E7; f) spherule E8; g) spherule E9.