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GEOCHEMICAL STUDIES OF IMPACT BRECCIAS AND COUNTRY ROCKS FROM THE EL'GYGYTGYN IMPACT STRUCTURE, RUSSIA

Ulli RASCHKE[1,2*], Ralf Thomas SCHMITT[1], Iain MCDONALD[3], Wolf Uwe REIMOLD[1,4], Dieter MADER[5], and Christian KOEBERL[5,6]

[1]Museum für Naturkunde Berlin, Leibniz Institute for Evolution and Biodiversity Science, Invalidenstraße 43, 10115 Berlin, Germany

[2]Freie Universität Berlin, Institut für Geologische Wissenschaften, Malteser Str. 74-100, 12249 Berlin

[3]School of Earth & Ocean Sciences, Cardiff University, Cardiff CF10 3YE, UK

[4]Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany

[5] Department of Lithospheric Research, Center for Earth Sciences, University of Vienna, Althanstrasse 14, 1090 Vienna, Austria

[6] Natural History Museum, Burgring 7, 1010 Vienna, Austria

*Corresponding author. E-mail: ulli.raschke@outlook.com

Abstract

The complex impact structure El'gygytgyn in northeastern Russia (age 3.6 Ma, diameter 18 km) was formed in ~88 Ma old volcanic target rocks of the Ochotsk-Chukotsky Volcanic Belt (OCVB). In 2009, El'gygytgyn was the target of a drilling project of the International Continental Scientific Drilling Program (ICDP), and in summer 2011 it was investigated further by a Russian-German expedition. Drill core material and surface samples, including volcanic target rocks and impactites, have been investigated by various geochemical techniques in order to improve the record of trace element characteristics for these lithologies and to attempt to detect and constrain a possible meteoritic component. The bedrock units of the ICDP drill core reflect the felsic volcanics that are predominant in the crater vicinity. The overlying suevites comprise a mixture of all currently known target lithologies, dominated by felsic rocks but lacking a discernable meteoritic component based on platinum group element (PGE) abundances. The reworked suevite, directly overlain by lake sediments, is not only comparatively enriched in shocked minerals and impact glass spherules, but also contains the highest concentrations of Os, Ir, Ru, and Rh compared to other El'gygytgyn impactites. This is - to a lesser extent - the result of admixture of a mafic component, but more likely the signature of a chondritic meteoritic component. However, the highly siderophile element contribution from target material akin to the mafic blocks of the ICDP drill core to the impactites remains poorly constrained.

INTRODUCTION AND GEOLOGICAL BACKGROUND

The El'gygytgyn impact structure is located on the Chukotka Peninsula of far northeast Russia; it is centered at 67°30´N and 172°34´E (Fig. 1). The 18 km diameter, near-circular depression is largely filled by the 12 km wide Lake El'gygytgyn. The impact age was determined at 3.58 ± 0.04 Ma (Layer 2000). The volcanic target rocks belong to the Late Cretaceous Ochotsk-Chukotsky Volcanic Belt (OCVB) that is of Albian to Campanian/Maastrichtian (86-106 Ma) age (Belyi and Belaya 1998; Raschke et al. 2014 and references therein). The target lithologies are generally known from the work of Belyi (1994), Belyi and Belaya (1998), and from Gurov and co-workers (Gurov et al. 1978, 2005, 2007; Gurov and Gurova 1983). These authors described the OCVB rocks as a suite comprising (from top to bottom): ignimbrites (mainly felsic, 250 m); tuffs and rhyolitic lavas (200 m); tuffs and andesitic lava (70 m, occurring especially to the southwest of the crater); and finally ash and welded tuffs of rhyolitic and dacitic compositions (100 m). Above this sequence a ca. 110 m thick basalt sill occurs as a plateau at the northeastern crater rim (Gurov et al. 2004). Additionally, there are previously unknown lithologies at the southeastern crater rim that were defined for the first time by Raschke et al. (2014). Mount Otvevergin, on the northeastern lakeshore, is composed of reddish and greenish ignimbrites. In the southeastern sector of the lake several mini-plateaus occur that are made up of (sub)horizontal basalt or andesite layers; they are, on aggregate, ~2 km^2 in area extent. To the south of the lake, a suite of gray to reddish, basaltic-andesitic tuffs is present (see Fig.1).

Figure 1

The crater rim is well preserved, except for the southeastern part that has been eroded by the Enmyvaam River, a periodic outflow from the lake. Previous studies have shown that rocks of the crater rim did not reveal any characteristic shock metamorphic effects (Gurov et al. 2007; Raschke et al. 2014). The originally in situ ejecta deposits (comprising a mélange of unshocked and shocked rocks, and fragments of impact melt breccia) around the impact crater have been nearly completely eroded by arctic weathering. Only a few allochthonous remnants have been found, embedded in the lacustrine and fluvial terraces inside and outside of the crater rim. These include rounded cobbles (2-15 cm in size), and larger, meter-sized blocks of dark impact melt breccia (Raschke et al. 2014; Pittarello et al., 2013; and references therein). Aerodynamically shaped glass bombs occur together with shock metamorphosed rocks in the lacustrine terraces inside the crater and also in terraces along some streams (e.g., along the Enmyvaam river) in the environs of the crater. All recorded types of impactites from the wider crater area are generally fresh and most of the samples described do not display significant post-impact hydrothermal alteration and weathering (Gurov and Koeberl 2004; Raschke et al. 2014). The impact origin was confirmed by Gurov and co-workers, who found evidence for shock metamorphism in some samples from the crater region (Gurov et al. 1978, 1979, 2005). That includes planar deformation features in quartz, diaplectic quartz glass, coesite and stishovite, and planar fractures in quartz (which by themselves are not shock diagnostic).

In spring 2009 an International Continental Scientific Drilling Program (ICDP) drilling campaign (summarized in Koeberl et al. 2013) recovered a ~520 m long drill core, comprising ~318 m of lacustrine sediments and ~200 m of impactites (drilling location shown in the cross-section of Fig. 2). The drilled impactites can be stratigraphically divided (from top to bottom, see Fig. 3) into ~12 m of reworked suevite (316.77 – 328.00 m below lake floor [mblf]), ~63 m of suevite (328.00 – 390.74 mblf), and ~30 m of upper (390.74 – 420.89 mblf) and ~96 m of lower bedrock (420.89 – 517.00 mblf) (Raschke et al. 2013a). The lower bedrock is interpreted as (parautochthonous) crater basement. It is crosscut by a single, thin polymict impact breccia dike at 471.42 – 471.96 mblf depth. The upper bedrock unit contains different ignimbrites, and three meter-sized mafic blocks (at ~391, 420, and 422 mblf depth). The bedrock units are mainly unshocked but intensely fractured. The suevitic units contain shocked minerals and relatively rare impact melt particles. Only in the reworked suevite, at the top of the drilled sequence, stronger shocked lithic clasts, melt particles and impact-produced glass spherules are abundant (cf. also Wittmann et al. 2013). All drilled rocks are moderately to strongly weathered (for detailed petrographic information, see Raschke et al. 2013b, Pittarello et al. 2013).

Figures 2, 3

In addition, one of us (UR) participated in a 2011 Russian-German expedition to El'gygytgyn to supplement the existing surface geological data base with new mapping results and to obtain surface samples of country rocks and impactites for comparison with drill core lithologies. Based on the 2011 surface exploration, an upgraded geological map of the El'gygytgyn area was compiled (Raschke et al. 2014). The Zr/TiO_2 vs. Nb/Y diagram of Fig. 4 (data from Raschke et al. 2013b, 2014) illustrates the variability of the compositions of the drill core and surface samples. Both sample sets cover the same range of compositions. Obviously, the predominance of target rocks in the basaltic or andesitic-basaltic field of Fig. 4 is based on the proportionally higher number of samples analyzed from these lithologies.

Figure 4

Impact and volcanic melt rocks in the crater area and in the drill core

The distinction between the volcanic and impact melt rocks has proven to be a complex task in the study of the El'gygytgyn crater (cf. Pittarello and Koeberl 2013a). In contrast to the majority of other impact craters on Earth, the classification of melt particles is a basic requirement for the distinction between impact-generated and volcanic melt particles. Furthermore, the determination of a meteoritic component in impact produced melt particles can help to confirm the type of projectile and its role as well as its dissipation in the impact process.

Volcanic melt particles occur in the ignimbritic rocks of the upper and lower bedrock. They are generally recrystallized and similar in their composition to the rhyolitic or rhyodacitic host rocks. Alkali feldspar and mafic minerals (biotite and amphibole) occur as phenocrysts in the fine-grained melt. Altered glassy fragments are found inside the pumice fragments of the rhyolitic or rhyodacitic ignimbrite. A detailed description of these volcanic melt particles was given by Raschke et al. (2013b, 2014).

Impact melt occurs in four different settings: i) blocks of impact melt breccia and glass bombs in the lake terraces; ii) tiny (0.5 - 1.5 mm) glass spherules on the lake terrace and along the Enmyvaam River (Glushkova and Smirnoff 2007); iii) similar spherules in the reworked suevite section of the ICDP drill core (Wittmann et al. 2013; Goderis et al. 2013); and iv) small (altered) melt particles in the drilled suevite section (Pittarello et al. 2013; Raschke et al. 2013b).

i) Impact melt breccia sampled on the surface (Gurov and Koeberl 2004) outside the crater structure occurs as a fresh, heterogeneous mélange of glassy, mostly blackish but also translucent "schlieren", which may be rich in vesicles, but relatively poor in mineral or lithic inclusions. Other melt breccia resembles a volcanic scoria with larger clasts of unmelted or only partially molten rock fragments. The composition of such breccia depends on the host rock material and can include pieces of, e.g., pumice, ignimbrite, andesite, or basalt. The minerals in these clasts often show shock features, for example planar fractures, planar deformation features, and diaplectic glass (see Raschke et al. 2013b; Pittarello and Koeberl 2013b).

ii) Up to 1.5 mm size glass spherules found in lacustrine sediments to the south of the crater (during the Quaternary, lake El'gygytgyn covered a larger surface area and had a higher lake level) and in fluvial terraces along the Enmyvaam River (Gurov 1979; Glushkova and Smirnov 2007) were analyzed by Adolph and Deutsch (2010), Smirnov et al. (2011), and Wittmann et al. (2013). All these authors concluded, on the basis of geochemical data, that the spherules were impact-produced melt droplets that had been deposited from the collapsing ejecta plume (with lithic debris) in a thin layer on the juvenile post-impact surface. Overall, the spherules are strongly heterogeneous, ranging in composition from basaltic to rhyolitic, and are probably derived from the different volcanic lithologies in the target area, which requires, in turn, that the spherules did not undergo homogenization in the ejecta plume (see Wittmann et al. 2013).

iii) An accumulation of spherules occurs on top of the reworked suevite section between 317 and 322 mblf. The spherules are very heterogeneous and occur in different types. First, there are hollow spherules with a glassy margin and may contain a few crystal inclusions or microfragments of different minerals (e.g. feldspar, quartz and zeolite). Another type of spherule is filled by aluminosilicate glassy melt, which contains microlites of feldspar or of mafic composition (Raschke et al. 2013b and references therein).

iv) Impact melt was identified in the matrix of the suevite section of the drill core between 328 and 391 mblf (Raschke et al. 2013b). This comprises very small melt particles, ~1 mm in size, which are generally altered to secondary phyllosilicates (e.g., smectites and chlorites). These particles amount to much less than 1 vol% of the whole suevite package.

Previous studies of siderophile elements, Platinum Group Elements, and Rare Earth Elements

Pittarello et al. (2013) analyzed rare earth element (REE) concentrations of drill core rocks and compared these with volcanic rocks from the regional geological setting. With the exception of data for the mafic blocks from the drill core, all other impactite samples, including the suevites, plot in the same space as the volcanic target rocks. Raschke et al.'s (2014) chemical comparison between impactites of the drill core and regionally occurring lithologies revealed very similar chemical compositions of upper and lower bedrock and the suevitic units, as well as the surface rocks from the crater rim that are dominated by the rhyolitic or rhyodacitic ignimbrites.

The enrichment of siderophile elements in microtektites (or microkrystites) is generally a very useful tool for the determination of a projectile signature (Koeberl 2014; Koeberl et al. 2012). According to Wittmann et al. (2013), the siderophile element contents in the spherules of the reworked suevite are highly variable. The El'gygytgyn glass spherules show a wide range of compositions, reflecting the geochemical signature of the target lithology assemblage composed of both mafic and felsic rocks (Raschke et al. 2013b; Wittmann et al., 2013). The siderophile element contents of the spherules in the reworked suevite are highly variable (Ni ~30 to 1400 ppm), similar to the spherules from outside of the crater (Ni ~300 to 1100 ppm), and are probably related to projectile contamination (see also Wittmann et al. 2013).

Foriel et al. (2013) found that some impact glass samples from the surface of the El'gygytgyn area have a chromium isotopic anomaly that agrees best with an ureilite source. They suggested that the impactor could have had a composition similar to that of the Almahata Sitta meteorite from Sudan, which is an ureilite with clasts of ordinary chondrite (Jenniskens et al. 2009).

Platinum group element (PGE) analyses were undertaken by Goderis et al. (2013) on the spherule-bearing deposits, as well as on a few hand specimens of impact melt recovered from the crater rim. Together with their Os isotope and Ir concentration analysis, these authors concluded that rather than an achrondritic (ureilitic) impactor composition, an ordinary chondrite type was probable.

Based on these previous studies, especially the instrumental neutron activation analysis (INAA) data of Pittarello et al. (2013), as well as work done on drill core and country rock samples by Raschke et al. (2013b, 2014), we decided to try to derive more information about the geochemical character of the impactites and their target rocks, including the comparison with impact melt breccia that was collected on the lake terraces within the crater. Another goal has been the identification of a meteoritic component using siderophile element abundances in impactites from the El'gygytgyn crater.

SAMPLES AND ANALYTICAL METHODS

A suite of 17 samples from the ICDP drill core (impactites, including suevite and bedrock lithologies) was selected for INAA. A second suite of samples (7 ICDP drill core and 10 surface specimens) was used for PGE analysis. Some petrographic and chemical details about the surface samples have previously been presented in Raschke et al. (2014). Sampled drill core depths (this work and from Pittarello et al. 2013) are given in Table 1.

Table 1

The measurements by INAA were carried out at the Department of Lithospheric Research, University of Vienna. The contents of some major (Na, K, and Fe) and many trace elements (including the REE) were determined using this method. In general, about 130 mg of powdered sample was sealed in a polyethylene capsule and irradiated in the 250 kW Triga Mark-II reactor of the Atomic Institute in Vienna. For calibration three international rock standards were used: (i) Allende carbonaceous chondrite (Smithsonian Institution, Washington DC, see Jarosewich et al. 1987); (ii) Ailsa Craig Granite AC-E (Centre de Recherche Petrographique et Geochimique, Nancy, France, see Govindaraju 1989); and (iii) Devonian Ohio Shale SDO-1 (USGS, see Govindaraju 1994). Further details about the method, technique, and accuracy on results is given by Koeberl (1993) and Mader and Koeberl (2009). The INAA data for the various lithologies of the ICDP drill core are reported in Table 2.

Table 2

The contents of the PGE and Au were determined in Cardiff by inductively coupled plasma-mass spectrometry (ICP-MS) after pre-concentration by Ni-sulfide fire assay with co-precipitation, using external calibration. Ffor each sample 15 grams of material was used. Two low level concentrations of powdered reference material were used for the validation of PGE analysis: i) WITS-1 (a silicified komatiite and ultramafic rock from the Barberton area, South Africa), and ii) TDB-1, a basaltic (diabase) rock sample from Canada (Tredoux and McDonald 1996). More details regarding the analytical technique and the related precision and accuracy values have been published in Huber et al. (2001) and McDonald and Viljoen (2006). For drill core and surface samples the PGE and Au abundance data are reported in Table 3.

Table 3

In addition, we used the datasets of siderophile elements from petrographic and geochemical studies, which we have already published for the drill core material (Raschke et al. 2013b) and for the surface samples of the wider crater region (Raschke et al. 2014). Additional trace element data for the ICDP drill core from Pittarello et al. (2013) measured by INAA in the same laboratory as our samples were used to extend the data set, especially for scarce lithologies such as the mafic blocks. All samples are listed in Table 1 and Fig. 3. Using this large dataset we tried to discriminate special characteristics of the reworked suevite (including layers of impact produced glass spherules) and the other impactites from the drill core in contrast to the target rocks from the crater vicinity, inclusive of impact melt breccia from the lake terrace. Furthermore, we compared our results with respect to the data of Goderis et al. (2013), Wittmann et al. (2013), Foriel et al. (2013), and Pittarello et al. (2013).

RESULTS

Composition of the drill core material and target rocks

The El'gygytgyn drill core material and the surface samples mainly comprise felsic volcanic rocks. Rhyolitic or rhyodacitic ignimbrites are the predominant rock types in the drill core (lower bedrock unit, ~50 % of the impactite section) as well as regarding the country rocks. In the vicinity of the crater more than 90 % of the country rocks are SiO_2-rich volcanics (Raschke et al. 2014). The mafic rocks, i.e., basalts, andesitic basalts, and their eruptive equivalents (phreatomagmatic tuffs), form a minor contribution in the area and are only found in the southeastern sector of the crater environs.

In this work, we focus on four types of lithologies for chemical discrimination and interpretation: i) the reworked suevite with accumulated impact glass spherules in the groundmass (see Raschke et al. 2013b and Wittmann et al. 2013, as well as references therein); ii) the impact melt breccia from the lake terrace that might carry a possible meteoritic component; iii) the suevite, a mélange of all possible target lithologies and impact melt particles; and iv) the mafic blocks from the drill core between upper and lower bedrock unit. These blocks are possibly derived from basaltic intrusions (sills) and are highly altered and fractured. These altered samples are characterized by a high loss on ignition (LOI) as well as an extraordinary chemical signature in comparison to all other target rocks; they are enriched in a wide range of metal oxides and easily recognizable in the compositional discrimination diagrams.

Rare Earth Elements

The average REE contents of the different lithologies of the ICDP drill core from this and previous studies are summarized in Table 4. The CI chondrite normalized REE patterns for sampled lithologies are shown in Figs. 5a-c. The patterns of the average upper and lower bedrock of the ICDP drill core (Fig. 5a) are very similar. They indicate enrichments for the average upper and lower bedrock by factors of 75 to 89 for La, and 10 to 8 for Yb, respectively, compared to CI chondrite composition. The light REE (LREE) are enriched compared to the heavy REE (HREE) (average La_N/Yb_N 8-10), and a negative Eu anomaly (average Eu/Eu* ~ 0.6 to 0.7; $Eu/Eu^* = Eu_N/(Sm_N \times Gd_N)^{0.5}$) is characteristic for these rocks. Another prominent feature of the upper and lower bedrock is a flat pattern of HREE. In comparison to the rocks of the Ochotsk-Chukotsky Volcanic Belt (OCVB), the upper and lower bedrock show less fractionation and slightly lower REE ratios, namely La_N/Yb_N ratios of 7.9 and 10.8 for the upper and lower bedrock, respectively, compared to ~ 8 to 18 for the OCVB, and La/Sm ratios of 3.7 and 4.9, respectively, compared to 5 to 8 for the OCVB (Tikhomirov et al. 2008).

In contrast to the felsic target rocks, the mafic blocks of the ICDP drill core display different REE patterns **(Fig. 5b)**. The CI chondrite-normalized REE patterns of the mafic block samples show comparable signatures characterized by an enrichment of the LREE compared to the HREE and a slightly fractionated profile for the HREE. The REE patterns show different enrichments for the mafic blocks at 391, 420 and 422 mblf by factors of 134, 50, and 143 for La, and 9, 9, and 15 for Yb, respectively, compared to CI chondrite composition. The enrichment of the LREE is more prominent in the blocks at 391 and 422 mblf with La_N/Yb_N ratios of 14 and 9.5, respectively, compared to the block at 420 mblf with a La_N/Yb_N ratio of 5.9. The REE patterns for the mafic blocks at 391 and 422 mblf do not show distinct Eu anomalies, whereas the block at 420 mblf displays - in contrast to all other lithologies - a slightly positive Eu anomaly with a Eu/Eu* ratio of 1.15. However, these blocks are very heterogeneous, and it is difficult to compare these with each other or with other lithologies from the drill core, crater, and the OCVB.

The average signatures for suevite, the polymict impact breccia dike, and the reworked suevite of the ICDP drill core display similar REE patterns (Fig. 5c). All lithologies show an enrichment of the REE compared to the CI chondrite composition by factors of 90, 79, and 90 for La, and 8, 8, and 10 for Yb for the suevite, polymict impact breccia dike, and reworked suevite, respectively. The LREE are enriched compared to the HREE in these lithologies with La_N/Yb_N ratios of 10.6, 9.4, and 9.4, respectively, and negative Eu anomalies are present, with Eu/Eu* ratios of 0.60, 0.69, and 0.58 for the suevite, polymict impact breccia dike, and reworked suevite, respectively. The REE patterns of the suevite and polymict impact breccia dike show strong similarities to those of the upper and lower bedrock, and indicate that the suevite mainly formed from these target lithologies. This is also visible in the Yb vs. Gd diagram (Fig. 5d). The reworked suevite indicates some slight differences in the REE patterns from those for the suevite. The absolute concentrations of the REE and the enrichments of the REE compared to CI chondrite composition are slightly higher, and the negative Eu anomaly is lower in the reworked suevite in comparison to the suevite and the lower and upper bedrock. This behavior could be explained by an additional admixture of mafic material in the reworked suevite compared to the suevite, as suggested in the Yb vs. Gd diagram (Fig. 5d).

Figure 5, Table 4

Siderophile elements

The concentrations of the siderophile elements Co, Ni, and Cr, and the Ni/Cr, Ni/Co, and Cr/Co ratios are summarized for the different lithologies of the ICDP drill core in Table 5. Our results show that, in general, the siderophile element concentrations are low in the felsic (lower and upper bedrock) and distinctly higher in the mafic target lithologies (mafic blocks), with the highest concentrations of siderophile elements having been measured for the mafic block at ~420 mblf. The concentrations of the siderophile elements and their ratios within the suevite are quite similar to the respective concentrations and ratios in the lower and upper bedrock. The concentrations of siderophile elements reported for impact melt rocks and glass bombs collected at the surface around the crater are also in this range, with concentrations of <50 ppm Cr, <7 ppm Co, and <21 ppm Ni (Gurov and Koeberl 2004; Gurov et al. 2005). Therefore, a contamination of the suevite and the impact melt rocks by a meteoritic component is not obvious in these siderophile element abundances.

Slightly higher concentrations of siderophile elements together with lower Ni/Cr and higher Ni/Co and Cr/Co ratios in comparison to the suevite unit are observed in the reworked suevite and within a polymict impact breccia dike occurring in the lower bedrock at ~471 mblf. For the impact spherules (Wittmann et al. 2013) the contents of siderophile elements (measured by LA-ICP-MS) are much higher in comparison to all other target lithologies (Table 5), e.g. the Ni data for some samples (sph6 at 317.60 mblf) show high values up to 1400 ppm (Wittmann et al. 2013). Regarding to the moderately siderophile element budget of the reworked suevite (Table 5), these spherules are negligible. These observations agree with the results of Pittarello et al. (2013) and Goderis et al. (2013). Therefore, the higher concentrations of siderophile elements in the reworked suevite and polymict impact breccia dike, and their different ratios in comparison to the suevite, are most likely the result of a higher amount of mafic material within these impactites. Overall, the observed siderophile element ratios for the suevite, reworked suevite, and polymict impact breccia dike do not match meteoritic ratios (e.g., Tagle and Berlin 2008; Koeberl 2014).

Table 5

Platinum Element Group analysis – the presence of a meteoritic component

Results of the PGE and Au analysis are given in Table 3 and plotted in Figs. 6 and 7. The Ir contents of the target rocks vary between < 0.03 and 0.52 ppb (Table 3). The Ir concentrations of the felsic lithologies are generally low (< 0.10 ppb), whereas higher Ir contents (0.52 ppb) were measured for the basaltic target lithologies, especially for the highly altered and metal oxide enriched mafic blocks at ~420 and 422 mblf in the drill core. The high Ir concentrations in the mafic blocks are associated with high Os concentrations, but also with elevated concentrations of Pt, Pd, and Au that are typical of many mafic lavas (e.g., Barnes et al. 1985; Tredoux et al. 1995; McDonald 1998; Crocket 2002).

The Ir contents of the suevite, impact melt breccia and polymict impact breccia dike samples are in the range of 0.04 to 0.09 ppb, and in good agreement with data previously presented by Goderis et al. (2013), who determined a range from 0.05 to 0.20 ppb for similar samples. Gurov and Koeberl (2004) reported Ir concentrations of 0.02 to 0.11 ppb for impact melt rocks and glass bombs from El'gygytgyn, which also corresponds well with our new measurements.

Notably part of the reworked suevite has a significantly higher PGE concentration in comparison to the suevite, impact melt breccia, and polymict impact breccia dike, as well as most of the felsic and mafic target lithologies (Table 3), in terms of Os (0.40 ppb), Ir (0.42 ppb), Ru (0.64 ppb), and Rh (0.19 ppb) (Fig. 6c). Additionally, these values are very similar to those for the mafic block at ~420 mblf, but also considerably increased in comparison with the mafic blocks at ~391 and 422 mblf. The Os/Ir ratio of the reworked suevite is higher (~1) compared to the values for the mafic blocks at ~420 and 422 mblf (~0.8; an Os/Ir-ratio < 1 is typical for mafic magmas (Barnes et al. 1985).

Figure 6, 7

DISCUSSION

Goderis et al. (2013) analysed a wide range of siderophile element contents in the mafic block at ~391 mblf, in the dike of polymict impact breccia (471 mblf), and in the reworked suevite at 318.9 mblf (named by these authors as "bottom of reworked fallout deposit") of the ICDP drill core. Raschke et al. (2013b) also reported high concentrations of Ni, Cr, and Co for the mafic blocks from the drill core (423 to 391 mblf). Goderis et al. (2013) reported that the $^{187}Os/^{188}Os$ isotopic signal of the mafic block at 391.6 mblf is much more radiogenic (2.8 +/- 0.1) than the reworked suevite (0.148 +/- 0.001 - 0.239 +/- 0.006). This suggests the Os in the reworked suevite cannot be derived from the mafic component. Consequently, the mafic blocks and similar lithologies cannot be the only contributors to the moderate siderophile elements budget of the drilled impactites. The Ni/Cr and Cr/Co abundance for some samples are between the values of chondritic and primitive achondritic (ureilitic) meteoritic components, especially for impact glass spherules from outside of the crater. The Ni/Co ratios fall between values for ureilites, branchinites, and chondrites (Warren et al. 2006).

The distribution of spherules in the reworked suevite section is reminiscent of similar impact spherules found in the ICDP drill core LB-5 from the Bosumtwi crater in Ghana (Koeberl et al. 2007). Bosumtwi is a 10.5-km diameter complex impact structure in the same size range as El'gygytgyn. These spherules were preserved in what has been interpreted as the youngest fallback deposit (Koeberl et al. 2007). At Bosumtwi, despite the presence of a high indigenous component linked to ultramafic target rocks, the spherule-bearing deposit shows a slightly elevated and distinct (i.e., unfractionated) PGE signature (Goderis et al. 2007).

Quantitative chemical analysis by EMPA-EDX has indicated that the glasses in these spherules are compositionally heterogeneous (Koeberl et al. 2007a). The detection of the projectile component is a difficult and complicated task, because some of the target lithologies with high PGE contents mask the presence of an extraterrestrial component. For the El'gygytgyn impact crater, Goderis et al. (2013) determined generally very low PGE contents in the impactites (> 50 % under quantification limit) with the result that Ir, Ru, Pt, and Rh are slightly enriched in the reworked suevite and the impact melt breccia, while Pd and Au are not equally elevated. In general, the PGE and Au plots show that the El'gygytgyn samples are generally comparable to chondritic patterns. Based on the slight Ir enrichment with flat, nonfractionated CI-normalized PGE patterns for the reworked suevite, Os isotope ratios for the spherule-bearing deposit that are inconsistent with the target rock composition, and mixing models for the major and Cr, Co, and Ni composition of the spherules characterized by LA-ICP-MS, Goderis et al. (2013) favored an ordinary chondrite (possible LL-type) as the most likely type of projectile for El'gygytgyn.

Foriel et al. (2013) compiled analytical data from Pittarello et al. (2013) of the ICDP drill core and a glass bomb, which was collected at the crater surface. Additionally, these authors used data by Val´ter et al. (1982) and Gurov and Koeberl (2004). Similar to Goderis et al. (2013), Foriel et al. (2013) found an enrichment of siderophile elements (Cr, Co, and Ni) for the suevite of the drill core, but could not substantiate a meteoritic component, because it was not possible to constrain the influence of mafic target rocks (indigenous component). Nonetheless, they found in one of their impact glass samples non-terrestrial Cr isotopic values. Such values are close to those of ureilitic meteorites, but also within analytical error of the range determined for eucrites and ordinary chondrites. These authors concluded that the ratios for siderophile elements did match neither chondritic nor achondritic meteorite compositions. Based on the Cr isotope data, Foriel et al. (2013) favored a ureilite type impactor, although an ordinary chondrite could not be excluded. Other types of meteorites were considered unlikely though.

Here, we present new results on trace element compositions, including siderophile elements, especially the PGE, of the impactites and target rocks from the El'gygytgyn impact crater (Tables 2-5). The concentrations of the siderophile elements (Cr, Co, and Ni) are typically very low in the felsic volcanics/ignimbrites, but slightly enriched in the mafic target lithologies and extraordinarily high in the three mafic blocks of the drill core (Raschke et al. 2013b, 2014; Pittarello et al. 2013). The siderophile element, as well as the REE abundances and patterns, for the upper and lower bedrock of the drill core correspond to those for suevite samples (Figs. 5a-c, Tables 4, 5). These observations are in agreement with those of Goderis et al. (2013). Therefore, the suevite represents mixtures of all target lithologies in accordance with their regional proportions. The contribution of the mafic target lithologies (~ 7 % based on surface geology, Raschke et al. 2014) to the trace element budget of the suevite is negligible.

Generally, the PGE concentrations (Table 3), their ratios (Fig. 6), and the CI-normalized PGE patterns (Fig. 7) for the suevite are also in the same range as the data for the felsic to intermediate target lithologies. The PGE data confirm the observations based on siderophile element abundances, and, therefore, a meteoritic component could not be detected in the suevite based on trace element data alone. The parautochthonous origin of the lower bedrock drilled in the crater basement, as discussed in Raschke et al. (2013b), could be confirmed by these trace element data. The chemical characteristics of the felsic surface rocks and the lower bedrock are similar and represent the same lithology, namely rhyodacitic ignimbrite.

The reworked suevite at the top of the impactite section of the drill core contains a larger amount of strongly shocked lithoclasts, impact melt particles, and impact glass spherules, and is chemically characterized by an enrichment of Fe-, Al-, and Mg-oxides compared with all other impactites (Raschke et al. 2013b). Also, the REE concentrations and patterns (Fig. 5, Table 4) display a slight difference to the suevites and the felsic target lithologies. A comparatively higher proportion of a mafic component in the reworked suevite could provide an explanation for these differences. For this process two different scenarios, or a combination of these, can be imagined: (i) First, suevite is formed as a ground surge inside the inner crater. This is followed by addition of highly shocked clasts from all target rock types, and intercalation of mafic and intermediate rocks especially at the top of the suevite sequence due to debris coming off the collapsing crater rim - besides mixing in of some material from the ejecta plume. (ii) Second, the pre-impact geology of the target volume could have contained a higher proportion of mafic and intermediate rocks than indicated by the crater environs today. This could be supported by the actual stratigraphy of the crater rim (Raschke et al. 2014). The older rocks (felsic ignimbrites of the Pykarvaam Formation) are partly covered in the SE and E of the crater by sub-horizontal layers of younger (Voron'in and Koekvun' formations) basalts and andesites. In addition, phreatomagmatic tuffs of basaltic-andesitic composition occur to the south of the crater (Raschke et al. 2014).

However, the siderophile elements and PGE are significantly enriched in the reworked suevite in comparison to all other impactites and most of the target lithologies (Figs. 6, 7, Tables 3, 5). The idea of admixture of a mafic component to form the package of reworked suevite, as mentioned before, cannot explain the high values of Os, Ir, Ru, and Rh found for this unit, in comparison to the composition of the mafic target lithologies (Table 3). Only the mafic blocks drilled in the ICDP core, especially the mafic block at ~420 mblf, have significantly enriched PGE values, which are in the range of the PGE values of the reworked suevite. Nevertheless, it is not plausible that a very strong mafic contamination similar to the composition of the mafic blocks would alone be responsible for the high PGE concentrations in the reworked suevite based on mass balance for the major and other trace elements, including the REE and iron (see Figs. 5-7). However, a hitherto undiscovered, additional ultramafic lithology is possible but so far remains hypothetical. Therefore, a contamination by a meteoritic component in this uppermost reworked suevite seems plausible. A combination of the two scenarios described above, a mixing during the crater collapse with an additional input from meteoritic components and a proportion of basaltic target rocks, would probably be the best-fit hypothesis. This is similar to the findings of Goderis et al. (2013), who also suggested the likely admixture of a meteoritic component to the reworked suevite.

The average PGE concentrations of the El'gygytgyn target (Table 6) were calculated using the surface area proportions of the target lithologies from Raschke et al. (2014), and the PGE concentrations of these lithologies from Table 3. Based on these data, we attempt to reproduce the PGE content of the reworked suevite, especially the Os, Ir, and Ru concentrations, by mixing the average El'gygytgyn target with different proportions of average ureilite (Warren et al. 2006), LL and CI chondrite (Tagle and Berlin 2008). The best fits for these mixtures, based on a fixed Os concentration according to the content of the reworked suevite, were achieved with an admixture of 0.12 % ureilite, 0.10 % LL chondrite, and 0.07 % CI chondrite component, respectively (see Table 6). A comparison between these three meteoritic components shows that the best match could be achieved with admixture of both chondritic components. A better calculation including major and siderophile elements is currently not possible, because the majority of data were measured by XRF and not by INAA or LA-ICP-MS.

A similar finding is revealed by comparison of the Os/Ir and Os/Ru ratios, which are 0.95 and 0.63, 1.23 and 0.82, 1.08 and 0.70, and 1.06 and 0.70, for the reworked suevite, average ureilite, LL, and CI chondrite, respectively (data for ureilites from Warren et al. 2006, and for chondrites from Tagle and Berlin 2008). These results suggest the possible admixture of a chondritic component to the reworked suevite similar to the findings of Goderis et al. (2013). Taking into account the moderately siderophile element ratios reported by these authors for the spherules in the reworked suevite section, an ordinary chondrite component seems to provide the best option as a possible impactor for the El'gygytgyn impact, based on the PGE data.

The method used by Foriel et al. (2013) to determine the nature of projectile component by Cr isotopic measurements would be difficult to use on the reworked suevite samples, because the Cr isotope method is generally capable of detecting only ≥ 1 % extraterrestrial component, whereas PGE abundances allow to determine somewhat lower meteoritic admixtures (in rare cases to about 0.2 %) (cf. Koeberl 2014; Koeberl et al. 2002). Nevertheless, the uncertainties about the role of the mafic blocks with their relatively high PGE concentrations and their possible contribution to the reworked suevite prevent the unambiguous detection of a meteoritic component. The nature of these impactites requires further investigation.

CONCLUSIONS

1. Impact melt breccia found at the surface is obviously a mélange of mainly rhyo(dacitic) ignimbrite and rare basaltic andesite, based on major and trace element compositions. Compared with the drilled rocks, the composition of the suevite and the upper bedrock unit closely matches the impact melt breccia. The PGE content of the impact melt breccia is also similar to that of the suevite sequence between 328 and 391 mblf of the ICDP drill core.
2. Based on PGE analyses, the suevite in the drill core does not show evidence of any unambiguous meteoritic contamination.
3. The mafic blocks of the drill core (between suevite and lower bedrock) at ~420 and 422 mblf are very unusual in their composition, compared to all other drill core and surface lithologies. Their siderophile and PGE concentrations are much higher than the respective concentrations of investigated basaltic rocks at the surface. The probable enrichment with metal oxides (TiO_2, Al_2O_3, Fe_2O_3, MgO) and trace elements (Sc, V, Cr, Co, Ni, Cu, Zn), as well as the PGE, during a hydrothermal alteration process seems plausible as indicated by a high loss on ignition (LOI) and the strongly altered state of these blocks.
4. The concentrations of PGE in the reworked suevite are much higher compared to all other impactites. These elevated PGE contents are most likely the result of an admixture of a meteoritic component, probably of chondritic composition – in good agreement with the previous work of Goderis et al. (2013) and Gurov and Koeberl (2004).
5. Nevertheless, the reworked suevite contains also a higher proportion of a mafic component, as indicated by the REE content, in comparison to the suevite. The composition of this mafic component and its PGE content cannot clearly be determined because of the possible contribution of the chemically unusual mafic blocks to the element budget. Therefore, it is not possible at this stage to unambiguously determine the nature of the meteoritic projectile from the new results of this study either.

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Figure captions

Fig. 1: Geological map of the El'gygytgyn impact crater with drill core location. Small inset indicating the geographic location of this impact structure in NE Siberia (Raschke et al. 2014)

Fig. 2: Simplified NW-SE cross-section through the El'gygytgyn impact structure, showing the drill core location and drilled lithologies. For more detail see Raschke et al. (2013a) and Koeberl et al. (2013). Based on a diagram by Melles et al. 2011.

Fig. 3: Stratigraphic column of the ICDP drill core (modified after Raschke et al. 2013a). The stratigraphic positions of samples used for INAA and PGE analyses are indicated, as well as those of samples analyzed by INAA from Pittarello et al. (2013) used in this work.

Fig. 4: Zr/TiO_2 vs. Nb/Y diagram for classification of volcanic rocks after Winchester and Floyd (1977). Note: The suevitic units (incl. reworked suevite) plot in the same field as the upper and lower bedrock of the drill core as well as the rhyolitic and rhyodacitic ignimbrites from the crater rim. These lithologies are illustrated by differently shaded fields that each include a larger number of data. The

symbols for mafic units represent a single analysis per sample. Data from Raschke et al. (2013b, 2014).

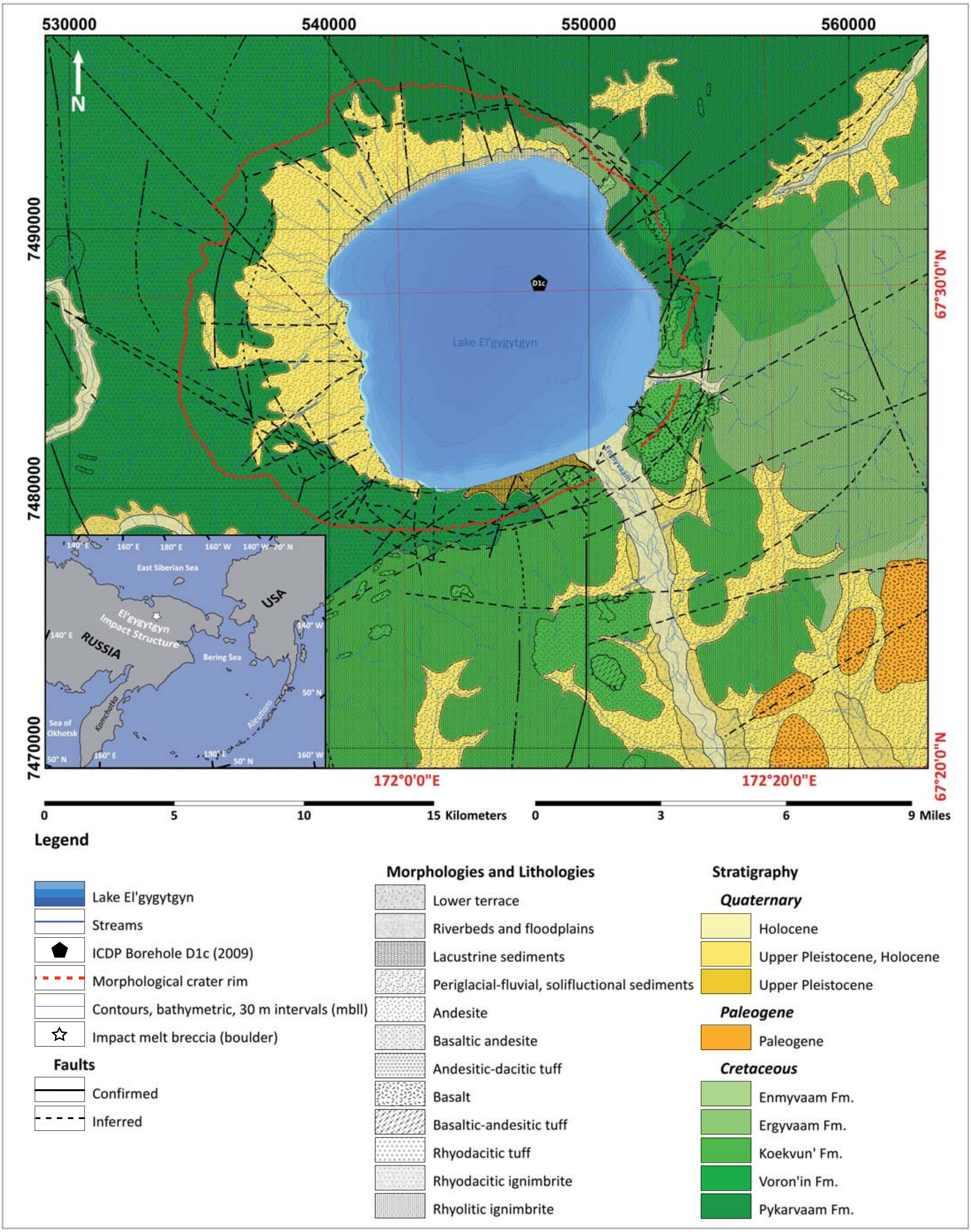
Fig. 5: CI chondrite normalized REE plots (normalization values from Taylor and McLennan 1985) for samples of the ICDP drill core: **(a)** upper and lower bedrock; **(b)** three mafic blocks at depths of 391, 420, and 422 mblf; **(c)** reworked suevite, suevite, and polymict impact breccia dike. (**d)** Yb vs. Gd-diagram displaying the distinctly increased concentrations of Gd and Yb in the mafic blocks at 391 and 422 mblf, and the admixture of such a mafic component to the reworked suevite. Note that surface volcanic target lithologies and impact melt breccia are not plotted in this figure.

Fig. 6: **(a)** Os vs. Ir, **(b)** Rh vs. Ir, and **(c)** Ru vs. Ir abundance plots. Note the high concentrations of these elements in the mafic block at 420 mblf and the reworked suevite.

Fig. 7: CI-normalized PGE plots (normalization values from Lodders 2003) of **(a)** surface volcanic rocks including rhyolitic ignimbrite, rhydodacitic ignimbrite, andesite, andesitic-dacitic tuff, basalt, and basaltic-andesitic tuff, **(b)** the three mafic blocks in the ICDP drill core at 391, 420, and 422 mblf depths, and **(c)** reworked suevite, suevite, impact melt breccia, and polymict impact breccia dike. Note the significantly higher concentrations of Os, Ir, Ru, and Rh in the reworked suevite.

Abstract

The complex impact structure El'gygytgyn in northeastern Russia (age 3.6 Ma, diameter 18 km) was formed in ~88 Ma old volcanic target rocks of the Ochotsk-Chukotsky Volcanic Belt (OCVB). In 2009, El'gygytgyn was the target of a drilling project of the International Continental Scientific Drilling Program (ICDP), and in summer 2011 it was investigated further by a Russian-German expedition. Drill core material and surface samples, including volcanic target rocks and impactites, have been investigated by various geochemical techniques in order to improve the record of trace element characteristics for these lithologies and to attempt to detect and constrain a possible meteoritic component. The bedrock units of the ICDP drill core reflect the felsic volcanics that are predominant in the crater vicinity. The overlying suevites comprise a mixture of all currently known target lithologies, dominated by felsic rocks but lacking a discernable meteoritic component based on platinum group element (PGE) abundances. The reworked suevite, directly overlain by lake sediments, is not only comparatively enriched in shocked minerals and impact glass spherules, but also contains the highest concentrations of Os, Ir, Ru, and Rh compared to other El'gygytgyn impactites. This is - to a lesser extent - the result of admixture of a mafic component, but more likely the signature of a chondritic meteoritic component. However, the highly siderophile element contribution from target material akin to the mafic blocks of the ICDP drill core to the impactites remains poorly constrained.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560000
7490000
7480000
7470000
N
D1c
Lake El'gygytgyn
Enmyvaam
67°30'0"N
67°20'0"N
172°0'0"E
172°20'0"E
East Siberian Sea
USA
El'gygytgyn Impact Structure
RUSSIA
Bering Sea
Sea of Okhotsk
Kamchatka
Aleutians
140° E
160° E
180° E
160° W
140° W
70° N
50° N
0
5
10
15 Kilometers
0
3
6
9 Miles
Legend
Lake El'gygytgyn
Streams
ICDP Borehole D1c (2009)
Morphological crater rim
Contours, bathymetric, 30 m intervals (mbll)
Impact melt breccia (boulder)
Faults
Confirmed
Inferred
Morphologies and Lithologies
Lower terrace
Riverbeds and floodplains
Lacustrine sediments
Periglacial-fluvial, soliflunctional sediments
Andesite
Basaltic andesite
Andesitic-dacitic tuff
Basalt
Basaltic-andesitic tuff
Rhyodacitic tuff
Rhyodacitic ignimbrite
Rhyolitic ignimbrite
Stratigraphy
Quaternary
Holocene
Upper Pleistocene, Holocene
Upper Pleistocene
Paleogene
Paleogene
Cretaceous
Enmyvaam Fm.
Ergyvaam Fm.
Koekvun' Fm.
Voron'in Fm.
Pykarvaam Fm.

Fig. 1

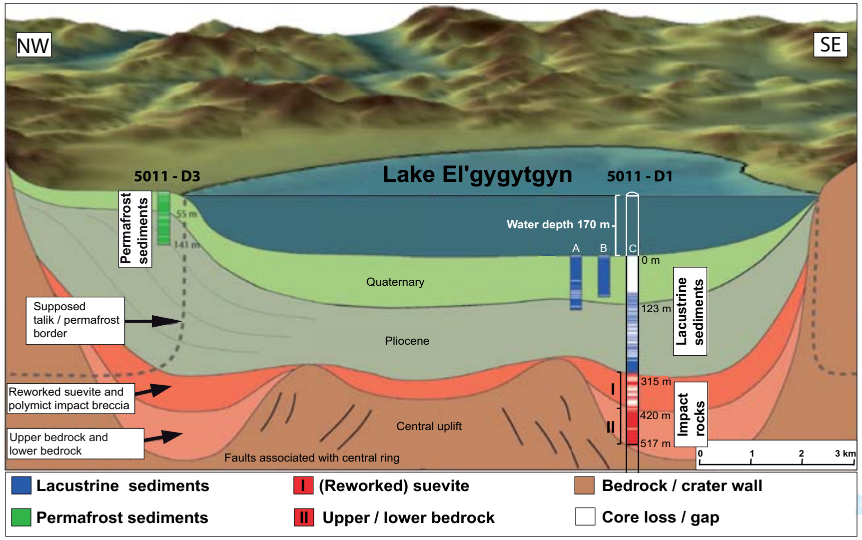
NW
SE
Lake El'gygytgyn
5011 - D3
5011 - D1
Permafrost sediments
55 m
141 m
Water depth 170 m
A
B
C
0 m
123 m
315 m
420 m
517 m
Quaternary
Pliocene
Central uplift
Faults associated with central ring
Lacustrine sediments
Impact rocks
I
II
Supposed talik / permafrost border
Reworked suevite and polymict impact breccia
Upper bedrock and lower bedrock
0
1
2
3 km
Lacustrine sediments
Permafrost sediments
(Reworked) suevite
Upper / lower bedrock
Bedrock / crater wall
Core loss / gap

Fig. 2

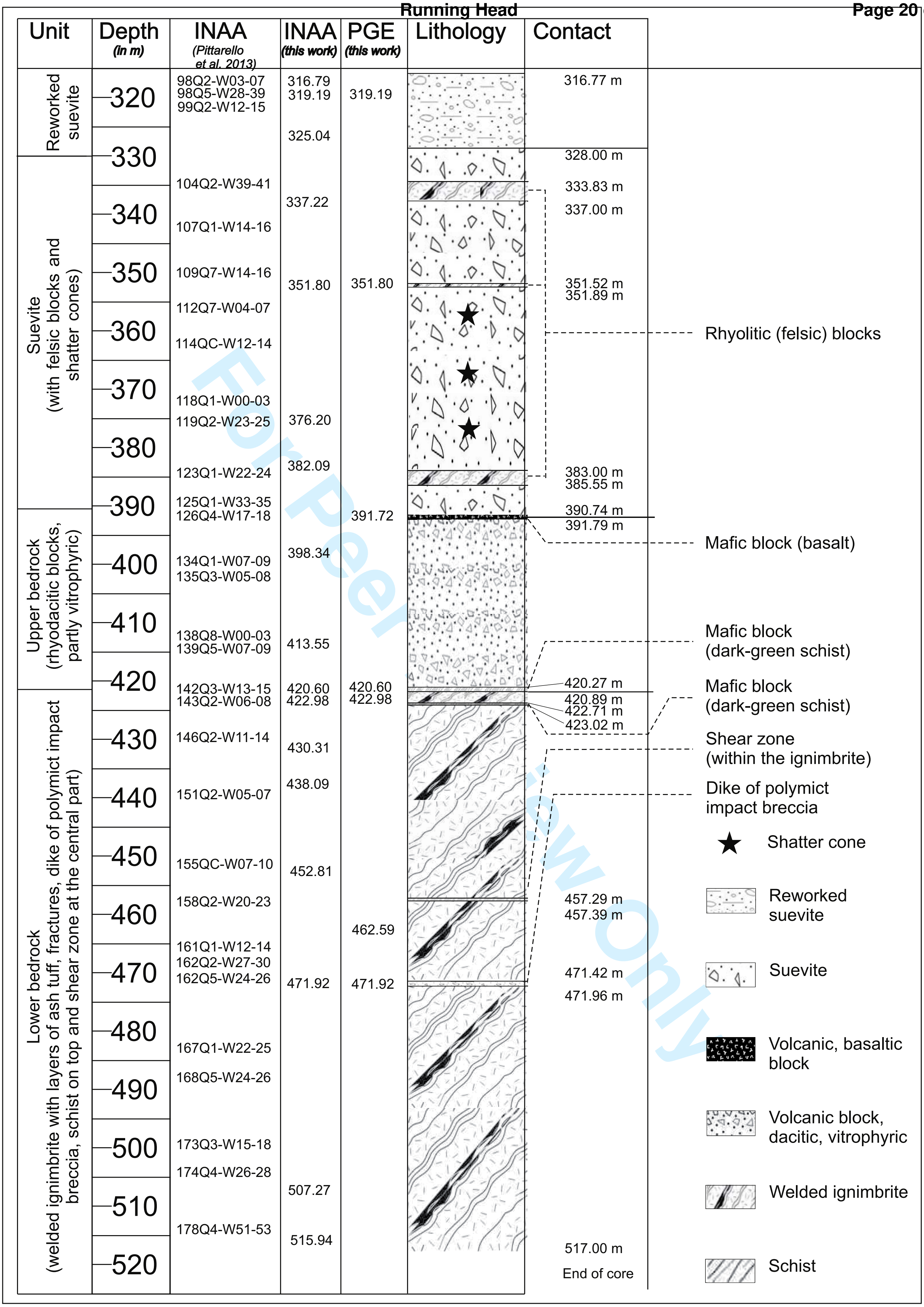
Unit
Depth (in m)
INAA (Pittarello et al. 2013)
INAA (this work)
PGE (this work)
Lithology
Contact
Reworked suevite
Suevite (with felsic blocks and shatter cones)
Upper bedrock (rhyodacitic blocks, partly vitrophyric)
Lower bedrock (welded ignimbrite with layers of ash tuff, fractures, dike of polymict impact breccia, schist on top and shear zone at the central part)
320
330
340
350
360
370
380
390
400
410
420
430
440
450
460
470
480
490
500
510
520
98Q2-W03-07
98Q5-W28-39
99Q2-W12-15
104Q2-W39-41
107Q1-W14-16
109Q7-W14-16
112Q7-W04-07
114QC-W12-14
118Q1-W00-03
119Q2-W23-25
123Q1-W22-24
125Q1-W33-35
126Q4-W17-18
134Q1-W07-09
135Q3-W05-08
138Q8-W00-03
139Q5-W07-09
142Q3-W13-15
143Q2-W06-08
146Q2-W11-14
151Q2-W05-07
155QC-W07-10
158Q2-W20-23
161Q1-W12-14
162Q2-W27-30
162Q5-W24-26
167Q1-W22-25
168Q5-W24-26
173Q3-W15-18
174Q4-W26-28
178Q4-W51-53
316.79
319.19
325.04
337.22
351.80
376.20
382.09
398.34
413.55
420.60
422.98
430.31
438.09
452.81
471.92
507.27
515.94
319.19
351.80
391.72
420.60
422.98
462.59
471.92
316.77 m
328.00 m
333.83 m
337.00 m
351.52 m
351.89 m
383.00 m
385.55 m
390.74 m
391.79 m
420.27 m
420.89 m
422.71 m
423.02 m
457.29 m
457.39 m
471.42 m
471.96 m
517.00 m
End of core
Rhyolitic (felsic) blocks
Mafic block (basalt)
Mafic block (dark-green schist)
Mafic block (dark-green schist)
Shear zone (within the ignimbrite)
Dike of polymict impact breccia
Shatter cone
Reworked suevite
Suevite
Volcanic, basaltic block
Volcanic block, dacitic, vitrophyric
Welded ignimbrite
Schist

Fig. 3

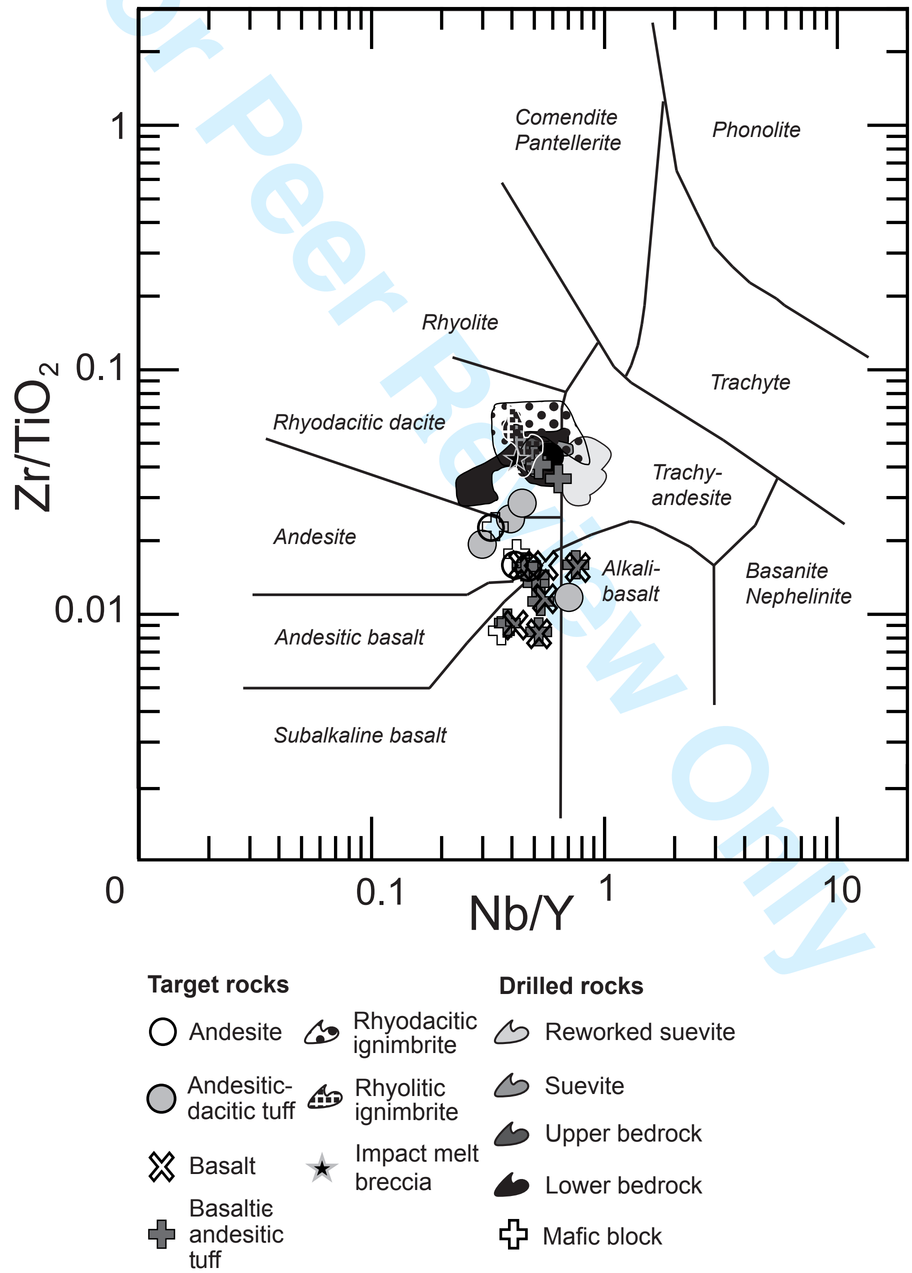
Comendite
Pantellerite
Phonolite
Rhyolite
Trachyte
Rhyodacitic dacite
Trachy-
andesite
Andesite
Alkali-
basalt
Basanite
Nephelinite
Andesitic basalt
Subalkaline basalt
Zr/TiO2
1
0.1
0.01
0
0.1
1
10
Nb/Y
Target rocks
Andesite
Andesitic-
dacitic tuff
Basalt
Basaltie
andesitic
tuff
Rhyodacitic
ignimbrite
Rhyolitic
ignimbrite
Impact melt
breccia
Drilled rocks
Reworked suevite
Suevite
Upper bedrock
Lower bedrock
Mafic block

Fig. 4

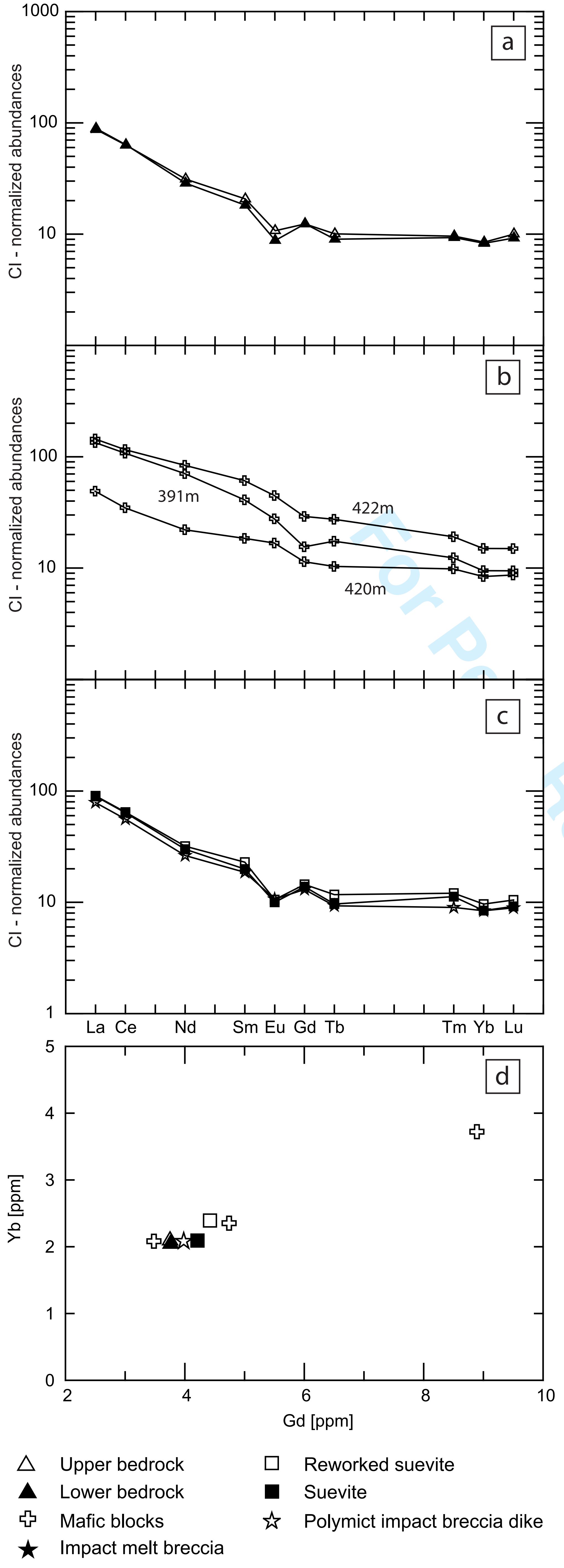
a
b
c
d
1000
100
10
1
CI - normalized abundances
391m
422m
420m
La
Ce
Nd
Sm
Eu
Gd
Tb
Tm
Yb
Lu
Yb [ppm]
Gd [ppm]
0
1
2
3
4
5
2
4
6
8
10
Upper bedrock
Lower bedrock
Mafic blocks
Impact melt breccia
Reworked suevite
Suevite
Polymict impact breccia dike

Fig. 5

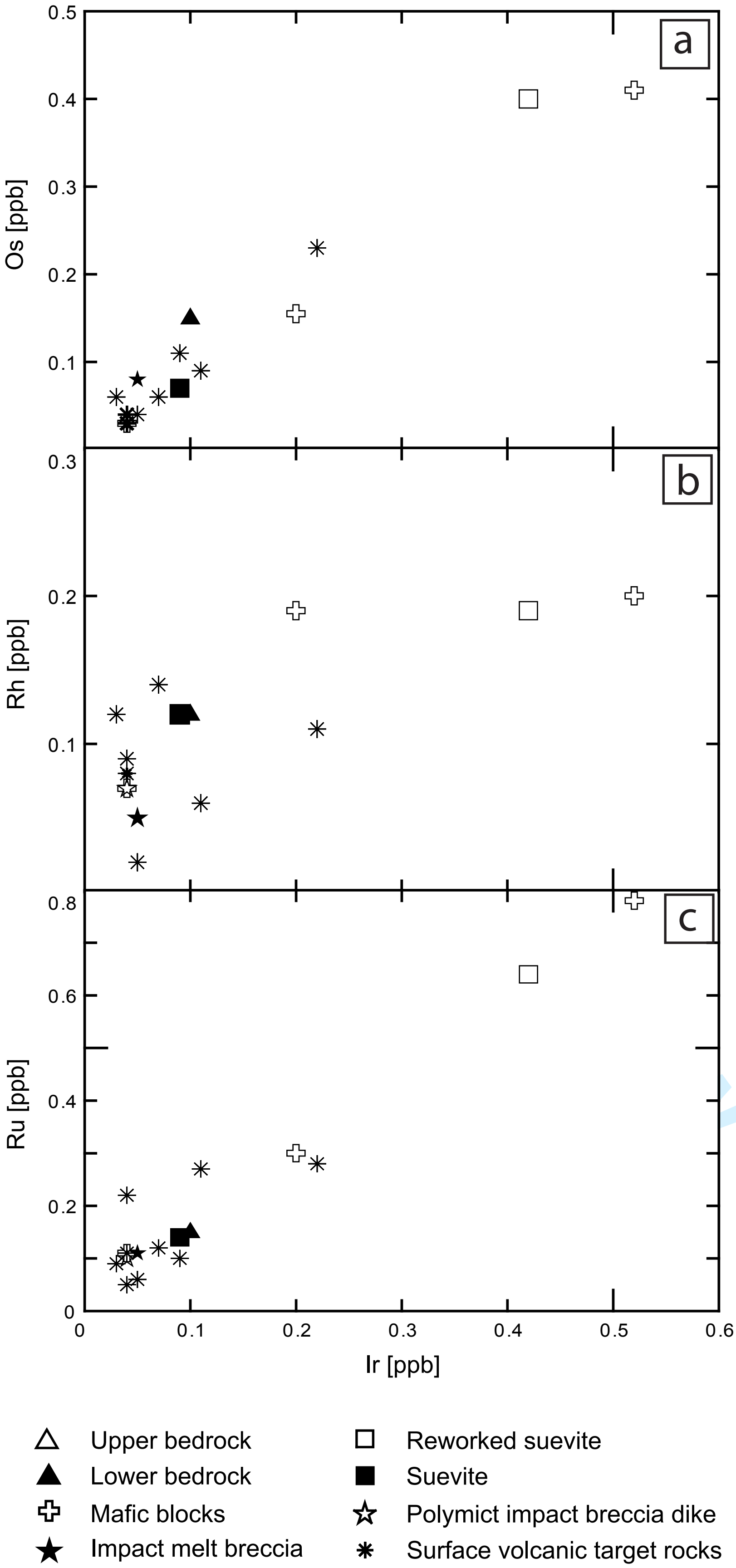
a
b
c
Os [ppb]
Rh [ppb]
Ru [ppb]
Ir [ppb]
0 0.1 0.2 0.3 0.4 0.5 0.6
0.1 0.2 0.3 0.4 0.5
0.1 0.2 0.3
0 0.2 0.4 0.6 0.8
Upper bedrock
Lower bedrock
Mafic blocks
Impact melt breccia
Reworked suevite
Suevite
Polymict impact breccia dike
Surface volcanic target rocks

Fig. 6

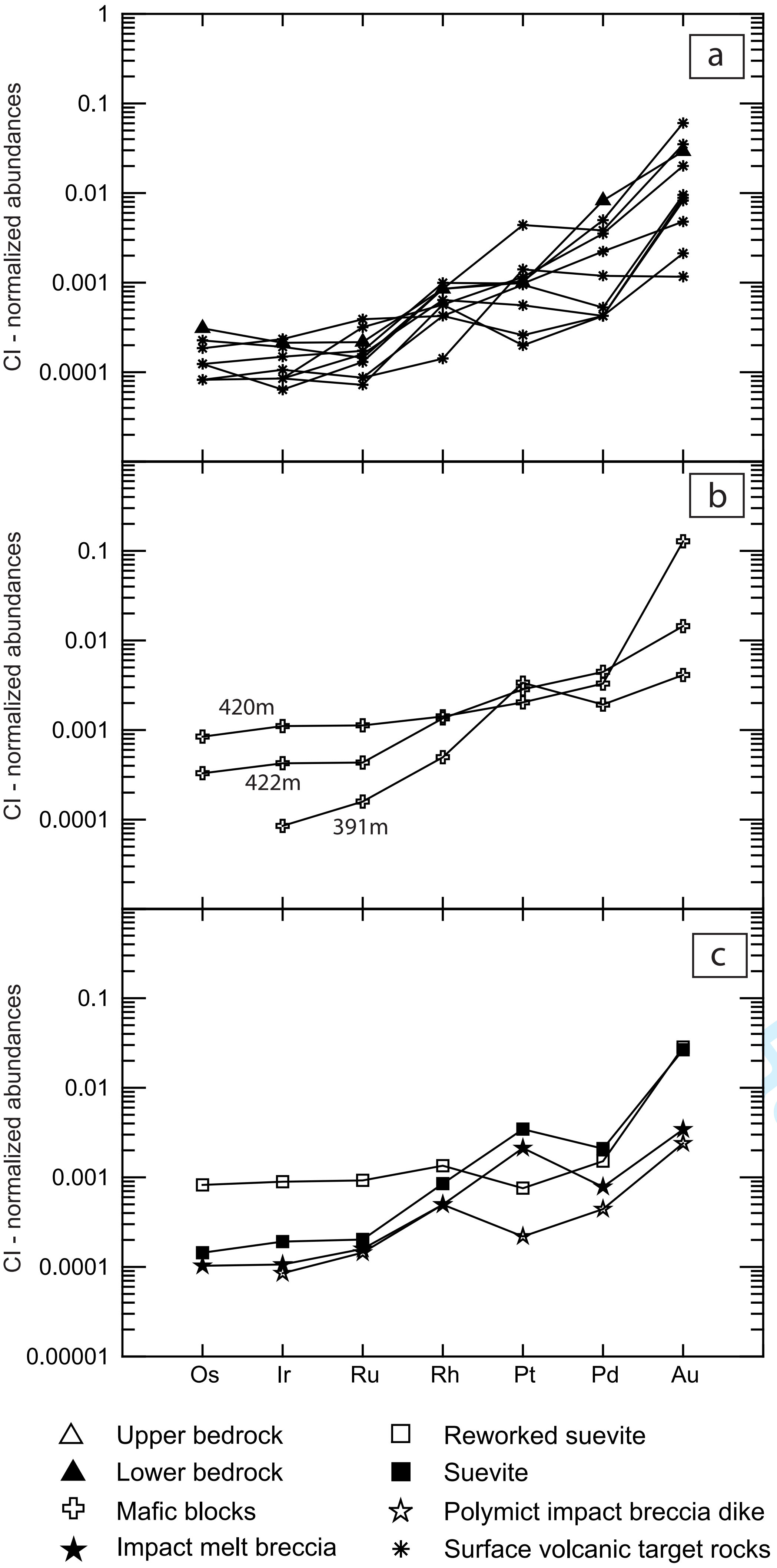
a
b
c
CI - normalized abundances
1
0.1
0.01
0.001
0.0001
0.00001
420m
422m
391m
Os
Ir
Ru
Rh
Pt
Pd
Au
Upper bedrock
Lower bedrock
Mafic blocks
Impact melt breccia
Reworked suevite
Suevite
Polymict impact breccia dike
Surface volcanic target rocks

Fig. 7

Table 1. List of ICDP drill core samples for analytical studies.

Sample	ID	Lithology*
(this work)	*(by Pittarello et al. 2013)*	
UR-ELG_316.79	98Q2-W03-07 (316.80)	rsv
UR-ELG_319.19	98Q5-W28-31 (318.20)	rsv
UR-ELG_325.04	99Q2-W12-15 (319.50)	rsv
UR-ELG_337.22		rsv
UR-ELG_351.80	104Q2-W39-41 (334.70)	sv
UR-ELG_376.20	107Q1-W14-16 (342.70)	sv
UR-ELG_382.09	109Q7-W14-16 (351.40)	sv
	112Q7-W04-07 (355.40)	sv
	114QCC-W02-05 (361.70)	sv
	118Q1-W00-03 (371.30)	sv
	119Q2-W23-25 (374.90)	sv
	123Q1-W22-24 (383.90)	sv
UR-ELG_398.34	125Q1-W33-35 (390.20)	ub
UR-ELG_413.55	134Q1-W07-09 (399.60)	ub
	135Q3-W05-08 (401.80)	ub
	138Q8-W00-03 (412.20)	ub
	139Q5-W07-09 (414.50)	ub
UR-ELG_391.72	126Q4-W17-18 (391.70)	mb
UR-ELG_420.60	142Q3-W13-15 (420.90)	mb
UR-ELG_422.98	143Q2-W06-08 (422.90)	mb
UR-ELG_422.98	146Q2-W11-14 (429.70)	lb
UR-ELG_430.31	151Q2-W05-07 (440.40)	lb
UR-ELG_438.01	155QCC-W07-10(451.40)	lb
UR-ELG_452.81	158Q2-W20-23 (456.90)	lb
UR-ELG_462.59	161Q1-W12-14 (465.10)	lb
	162Q2-W27-30 (468.30)	lb
	162Q5-W24-26 (470.20)	lb
	167Q1-W22-25 (483.10)	lb
	168Q5- W24-26 (487.40)	lb
UR-ELG_507.27	173Q3-W15-18 (500.00)	lb
UR-ELG_515.94	174Q4-W26-28 (503.90)	lb
	178Q4W51-53 (514.30)	lb
UR-ELG_471.92		pibd

*Abbrevations: rsv = reworked suevite, sv = suevite, ub = upper bedrock; lb = lower bedrock; mb = mafic block; pibd = polymict impact breccia dike.

Table 2. Selected major and trace element abundances of samples from the ICDP drill core D1c of the El´gygytgyn impact structure, as determined by INAA.

Sample	UR-ELG	UR-ELG	UR-ELG	UR-ELG	UR-ELG	UR-ELG	UR-ELG	UR-ELG	UR-ELG	UR-ELG	UR-ELG	UR-ELG	UR-ELG	UR-ELG	UR-ELG	UR-ELG	UR-ELG
Depth (mblf)	316.79	319.19	325.04	337.22	351.8	376.2	382.09	398.34	413.55	420.6	422.98	430.31	438.09	452.81	471.92	507.27	515.94
Lithology*	rsv	rsv	rsv	sv	sv	sv	sv	ub	ub	mb	mb	lb	lb	lb	pibd	lb	lb
ppm																	
Na (wt%)	2.48	2.02	2.00	2.21	2.57	2.22	2.41	2.81	2.09	1.25	0.53	2.76	3.03	2.52	1.89	3.19	1.28
K (wt%)	3.09	3.09	2.88	3.00	3.26	3.17	3.03	2.99	2.50	<0.7	0.91	2.94	3.36	3.30	2.66	4.07	2.04
Fe (wt%)	2.41	2.87	2.26	1.51	1.90	1.78	1.91	1.99	2.01	7.97	7.16	1.75	1.70	1.62	2.42	1.72	2.27
Sc	9.17	11.1	7.95	4.48	6.09	5.38	6.07	6.45	6.14	36.9	42.0	5.46	5.59	4.22	9.04	4.65	2.1
Cr	43.2	92.7	26.1	10.7	11.8	19.8	12.4	18.7	13.6	544	872	13.7	10.2	10	58.6	10.5	11.6
Co	6.03	8.38	5.45	2.92	3.52	3.23	3.54	3.69	3.30	30.8	42.7	3.44	3.23	2.71	6.99	3.24	1.01
Ni	28	41	<26	<20	12	4	11	17	3	98	276	6	<24	<21	24	<22	<20
Zn	67	66	56	49	53	47	56	56	57	348	121	50	50	46	58	51	13
Ga	4.9	3.6	6.9	3.4	5.2	4.1	2.8	4.8	6.1	232	19	3.2	<3.7	5.5	5.3	4.5	3.1
As	15.4	16.2	11.4	4.42	9.57	5.96	7.87	8.96	5.72	42.2	91.5	34.9	19.1	8.91	18.3	14.3	47.8
Se	0.03	<1.7	<1.5	<1.3	<1.4	<1.3	<1.4	<1.4	<1.4	<2.8	7.72	<1.4	<1.5	<1.3	<1.6	<1.4	<1.3
Rb	146	118	115	131	132	138	128	136	107	9.51	75.6	115	129	137	121	174	119
Sr	171	318	153	122	283	122	161	196	165	401	172	178	518	217	235	169	76
Zr	241	241	172	193	218	208	222	234	217	166	678	220	229	187	237	221	127
Sb	1.57	1.55	0.98	0.92	1.39	1.17	1.46	1.69	1.54	1.01	4.09	1.55	1.61	0.97	1.84	1.15	2.37
Cs	9.84	7.64	9.22	8.67	4.55	10.3	8.26	6.64	6.85	3.54	30.1	3.83	4.17	4.94	9.18	5.21	5.76
Ba	464	596	299	431	469	417	439	495	481	65	260	481	569	493	419	592	235
La	34.3	28.3	35.7	30.8	30.1	31.5	31.4	30.4	27.8	19.2	51.1	31.7	34.3	41.6	28.9	37.3	24.6
Ce	64.8	56.1	64.7	57.6	56.7	58.9	60.8	58	53.3	34	111	58.8	64.5	72.9	53.5	68.5	39.8
Nd	25	22.6	22.9	19	20.5	20.4	21.9	20.8	19.2	15.6	59	18.7	21.5	22.2	18.7	22.1	13.1
Sm	5.79	5.08	5.03	3.79	4.3	4.06	4.25	4.2	4.13	4.39	13.7	4.05	4.68	4.43	4.3	4.8	3.05
Eu	0.98	0.89	0.84	0.75	0.88	0.77	0.9	0.93	0.77	1.70	3.84	0.81	0.86	0.76	0.93	0.80	0.44
Gd	5.03	4.54	3.86	3.8	4.26	3.25	3.54	3.67	2.99	4.66	10.2	3.11	4.55	4	3.99	4.67	2.61
Tb	0.78	0.71	0.63	0.46	0.55	0.49	0.56	0.52	0.54	0.7	1.59	0.50	0.59	0.5	0.54	0.57	0.48
Tm	0.4	0.34	0.3	0.27	0.3	0.27	0.27	0.29	0.3	0.34	0.61	0.31	0.33	0.26	0.32	0.34	0.38
Yb	2.54	2.35	2.27	1.78	2.04	1.94	2.10	1.98	1.98	2.17	3.65	1.98	2.13	2.01	2.08	2.13	3.19
Lu	0.43	0.41	0.38	0.3	0.34	0.34	0.35	0.33	0.34	0.32	0.56	0.33	0.34	0.33	0.34	0.38	0.57
Hf	5.28	4.71	4.14	4.17	4.59	4.48	4.57	4.74	4.89	2.04	12.3	4.55	4.46	4.11	4.5	4.88	2.17
Ta	0.89	0.67	0.64	0.69	0.65	0.70	0.64	0.66	0.66	0.33	1.1	0.68	0.79	0.73	0.65	0.93	0.63
Au (ppb)	13	<1.3	0.6	0.6	<1.3	<1.1	<1.5	<1.4	<1.2	<1.5	1.7	<1.5	<1.7	<1.3	<0.9	<1.6	<1.3
Th	15.8	11.9	11.8	15.1	13.3	15.1	13.9	13.3	13.1	1.51	5.32	14.9	16.5	17.8	12.7	19.4	12.6
U	4.69	3.33	3.38	3.55	3.69	3.40	3.16	3.49	3.25	0.36	5.98	3.77	5.15	4.00	3.66	5.04	4.81

*Abbrevations: rsv = reworked suevite, sv = suevite, ub = upper bedrock; lb = lower bedrock; mb = mafic block; pibd = polymict impact breccia dike.

Table 3. Concentrations of platinum group elements and Au in impactites and target lithologies from the ICDP drill core D1c and surface outcrops.

Sample	Lithology	Os ppb	Ir ppb	Ru ppb	Rh ppb	Pt ppb	Pd ppb	Au ppb
ICDP drill core								
UR-ELG 319.19 mblf	reworked suevite	0.40	0.42	0.64	0.19	0.76	0.89	4.15
UR-ELG 351.8 mblf	suevite	0.07	0.09	0.14	0.12	3.46	1.23	3.87
UR-ELG 391.72 mblf	mafic block	<0.03	0.04	0.11	0.07	3.38	1.13	0.60
UR-ELG 420.6 mblf	mafic block	0.41	0.52	0.78	0.20	2.04	1.94	18.65
UR-ELG 422.8 mblf	mafic block	0.16	0.20	0.30	0.19	2.86	2.62	2.11
UR-ELG 462.59 mblf	lower bedrock	0.15	0.10	0.15	0.12	1.00	4.84	4.26
UR-ELG 471.92 mblf	polym. impact breccia dike	<0.03	0.04	0.10	0.07	0.22	0.26	0.35
Surface outcrops								
UR-2011_1.1	andesitic-dacitic tuff	<0.03	<0.03	0.06	0.06	0.26	0.25	1.20
UR-2011_3.7	basalt	0.06	0.07	0.12	0.14	0.98	1.31	0.70
UR-2011_4.4	basaltic andesite	0.09	0.11	0.27	0.06	0.95	0.31	1.39
UR-2011_4.5	rhyodacitic tuff	0.11	0.09	0.10	0.12	4.41	2.25	5.10
UR-2011_5.3	rhyolitic ignimbrite	0.04	0.05	0.06	0.02	1.41	0.70	0.17
UR-2011_7.2	andesite	0.04	0.04	0.11	0.09	0.56	0.25	1.29
UR-2011_9.2	basaltic-andesitic tuff	0.06	0.03	0.09	0.12	1.04	2.93	8.82
UR-2011_9.11b	impact melt	0.05	0.05	0.11	0.07	2.13	0.46	0.50
UR-2011_9.12a	rhyodacitic ignimbrite	<0.03	0.04	0.22	0.08	0.20	0.25	0.31
UR-2011_10.1a	rhyodacitic ignimbrite	<0.03	0.04	0.05	0.08	1.16	2.07	2.93

Table 4. Compilation of the average REE contents, their standard deviations, and the Eu/Eu* and La_N/Yb_N ratios of the ICDP El'gygytgyn drill core lithologies.*

ppm	Reworked suevite avg. n = 6	Suevite avg. n = 12	Polymict impact breccia dike ~471 mblf n = 1	Upper bedrock avg. n = 7	Lower bedrock avg. n = 17	Mafic block ~391 mblf n = 1	Mafic block ~420 mblf avg. n = 2	Mafic block ~422 mblf avg. n = 2
La	33.2 ± 3.5	32.9 ± 2.3	28.9	31.8 ± 3.0	32.5 ± 4.1	49.2	18.0 ± 1.4	53.0 ± 1.9
Ce	61.8 ± 5.8	61.0 ± 3.9	53.5	60.0 ± 5.6	60.5 ± 7.7	103.0	33.3 ± 1.0	111 ± 1
Nd	22.7 ± 1.6	21.3 ± 1.9	18.7	22.1 ± 2.9	20.3 ± 2.2	50.2	15.7 ± 0.1	59.6 ± 0.8
Sm	5.30 ± 0.66	4.50 ± 0.56	4.30	4.76 ± 0.72	4.18 ± 0.47	9.47	4.27 ± 0.18	14.1 ± 0.6
Eu	0.92 ± 0.08	0.87 ± 0.13	0.93	0.93 ± 0.18	0.76 ± 0.11	2.41	1.46 ± 0.35	3.90 ± 0.09
Gd	4.43 ± 0.59	4.22 ± 0.66	3.99	3.76 ± 0.67	3.77 ± 0.66	4.75	3.49 ± 1.67	8.90 ± 1.90
Tb	0.68 ± 0.11	0.56 ± 0.08	0.54	0.58 ± 0.09	0.52 ± 0.05	1.01	0.60 ± 0.14	1.59 ± 0.00
Tm	0.43 ± 0.11	0.40 ± 0.10	0.32	0.34 ± 0.05	0.33 ± 0.03	0.44	0.35 ± 0.01	0.68 ± 0.01
Yb	2.39 ± 0.26	2.09 ± 0.22	2.08	2.09 ± 0.20	2.04 ± 0.33	2.35	2.08 ± 0.13	3.72 ± 0.10
Lu	0.40 ± 0.04	0.35 ± 0.03	0.34	0.38 ± 0.04	0.35 ± 0.06	0.36	0.33 ± 0.01	0.57 ± 0.01
Eu_{avg}/Eu_{avg}*	0.58	0.61	0.69	0.67	0.59	1.10	1.16	1.06
La_{avgN}/Yb_{avgN}	9.39	10.64	9.39	10.28	10.77	14.15	5.85	9.63

*Based on data of this work and from Pittarello et al. (2013); n = number of samples, normalization values from Taylor and McLennan, 1985.

Table 5. Compilation of the average Cr, Co, and Ni contents, their standard deviations, and their ratios for the ICDP El'gygytgyn drill core lithologies*; for comparison data for impact spherules from the El'gygytgyn crater are also reported**.

ppm	Reworked suevite avg. n = 6	Suevite avg. n = 12	Polymict impact breccia dike ~471 mblf n = 1	Upper bedrock avg. n = 7	Lower bedrock avg. n = 17	Mafic block ~391 mblf n = 1	Mafic block ~420 mblf avg. n = 2	Mafic block ~422 mblf avg. n = 2	Impact spherules** n = 13
Cr	34.8 ± 31.4	12.3 ± 13.8	58.6	13.2 ± 7.4	8.1 ± 4.0	95.1	499 ± 64	1061 ± 267	329 ± 267
Co	5.89 ± 1.48	3.97 ± 1.52	6.99	4.49 ± 1.62	3.10 ± 0.60	29.2	32.4 ± 2.2	54.6 ± 16.7	44.4 ± 26.2
Ni	24.9 ± 13.7	10.7 ± 5.2	24	11.8 ± 6.4	10.7 ± 3.4	76.9	100 ± 3	331 ± 77	564 ± 467
Ni_{avg}/Cr_{avg}	0.72	0.87	0.40	0.89	1.32	0.81	0.20	0.31	1.71
Ni_{avg}/Co_{avg}	4.22	2.70	3.43	2.63	3.45	2.63	3.09	6.06	12.70
Cr_{avg}/Co_{avg}	5.91	3.10	8.38	4.00	2.61	3.26	15.40	19.43	7.41

*Based on data of this work and from Pittarello et al. (2013); **based on data from Wittmann et al. (2013); these impact spherules originate from the reworked suevite of the ICDP El'gygytgyn drill core and from outside of the crater; n = number of samples.

Table 6. Calculated average PGE composition of the El'gygytgyn target in comparison to the reworked suevite and calculated impactites.*

PGE	Average El'gygytgyn target	Reworked suevite (319 mblf)	Average target + 0.12 % ureilite	Average target + 0.10 % LL chondrite	Average target + 0.07 % CI chondrite
ppb					
Os	0.04	0.40	0.40	0.40	0.39
Ir	0.05	0.42	0.34	0.39	0.38
Ru	0.07	0.64	0.51	0.59	0.57
Rh	0.03	0.19	n.a.**	0.14	0.12
Pt	1.38	0.76	1.87	2.09	2.05
Pd	0.72	0.89	0.79	1.22	1.11
Au	0.27	4.15	0.30	0.39	0.37

*Data based on the average El'gygytgyn target with an admixture of 0.12 % average ureilite, 0.10 % average LL chondrite and 0.07 % average CI chondrite, respectively. Data for ureilite (based on 24 samples) by Warren et al. (2006) and for LL and CI chondrites by Tagle and Berlin (2008). **n.a. = not available.