Petrographic and Petrochemical Characteristics of Suevite Matrix, Western Part of the Kara Astrobleme (Russia)

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Abstract. The Kara Astrobleme is a unique geological object located in the northwestern part of the Arctic zone of Russia. Impactites from the Kara crater are diamondiferous to various degrees. At present the Kara suevites are relatively poorly studied. Until now the petrographic features of the matrix have been described in general terms, and petrochemically the cementing mass of the suevites has not yet been studied. In 2015 suevite breccias of the southern part of the Kara Astrobleme were subdivided into three different types. It was later suggested that the suevites of the western part of the impact crater, located at the Pu'yu and Sayakha rivers, could be type II suevites, but at the same time they had a number of distinctive features which might be associated with different formation conditions of these rocks. Hence it is relevant to study the matrix of the suevites of the mentioned areas to clarify their facies and formation features. The paper presents results of a comprehensive study with a detailed description of the suevite matrix at Pu'yu and Sayakha rivers conducted for the first time for the suevites of the Kara Astrobleme. Through optical and microprobe studies we described petrographic and petrochemical features of the cementing mass of the suevites. We discovered that the matrix of the studied rocks was characterized by the similarity of the mineralogical composition, but differing in structural and content features. We found that all the studied rocks belonged to the aerodynamic ejection facies, within which they differed in the temperature conditions of formation which might be associated with the different initial position of the suevite material in the impact cloud. The research results clarify the type and facies of suevites in other areas of the impact structure that will allow defining facies variability and detail characteristics of suevite breccias of the Kara Astrobleme. The obtained data demonstrate genetic regularities of impactites and allow predict the diamond content of the Astrobleme as a whole.

1. Introduction
The Kara Astrobleme is a unique geological object located in the northwestern part of the Arctic zone of Russia. Impactites of the Kara Astrobleme, suevites and melt rocks, are diamondiferous to various degrees [1, 2]. Suevites are impact polymict breccias. The main components of suevites are lithoclasts — fragments of target rocks, vitroclasts — fragments of impact melt, and a finely dispersed cementing material of the same composition — matrix or ground mass [3, 4]. During the active study of the Kara impactites, the geomorphological, structural-textural, petrographic and petrochemical features of the suevites were studied [5-8]. At the same time, the petrographic features of the matrix were described in general terms, and petrochemically the cementing mass of suevites was not studied so far.
Meanwhile, it is known that the formation conditions of impact breccias are best reflected in the matrix of these rocks [7]. The study of the character, degree of lithification and sintering of the ground mass, its relationship with the clastogenic and melt components of suevitic breccias is very informative for explaining the suevites facies setting, formation and restoring the lithological sequence of the rocks distribution in the coptogenic complex. The study of the matrix is especially valuable when analyzing facies features and geological position of impactites under conditions of intense erosion, sodding, or in the core of wells.

In 2015, the suevites from the southern part of the Kara Astrobleme were subdivided into three types, presumably formed according to different dominating proto-rocks and differing by the set of features [9-11]. In the course of further researches we revealed that varieties of suevites differed by structural and content features of the matrix which allowed confirming facies differences of the identified types [12, 13].

Later, studying the clastogenic component of impactites of the western (Put'yu River) and northwestern (Sayakha River) parts of the Kara Astrobleme, it was found that they could belong to the type II suevites, presumably formed from essentially carbonate rocks of the target [14, 15]. At the same time, it was noted that the suevites of these regions had a number of distinctive features associated with differences in the formation conditions of these rocks.

Hence it is now relevant to study the matrix of the suevites of the indicated regions to clarify their facies and formation features to define the suevite facies variability of the Kara Astrobleme as a whole. This paper presents results of the study and comparative analysis of petrographic and material features of the suevite matrix at the Put'yu and Sayakha rivers.

2. Materials and methods
For our study we sampled impactites in natural outcrops on the Sayakha River (Sampling point 38) and the Put'yu River (s.p. 49, 54). From the Sayakha River we studied samples of lapilli suevites, which differed by the amount of detrital components – clast-rich from the upper part of the outcrop and clast-poor from the lower part (s.p. 38). At the Put'yu River we studied coarse-grained (s.p. 49) and blocky-agglomeratic suevites (Figure 1).

Figure 1. Location of the Kara Astrobleme on the Google map (A) and position of the studied rocks within the crater (B): lapilli suevites on the Sayakha River (s.p. 38); coarse-grained (s.p. 49) and blocky-agglomeratic (s.p. 54) suevites on the Put'yu River [16].
The matrix of suevites consists of fragments of mineral clasts and melt particles less than 0.1 mm in size [4]. In the course of our present study, the matrix was subdivided into three types by its nature – clastogenic, filled by well-separated mineral grains, debris and particles; partially sintered, composed of partially fused fragments with clearly distinguishable outlines and intensely sintered into a single homogeneous mass with relict outlines of particles.

Petrographic studies were carried out in double-sided polished thin sections under an optical microscope in transmitted and reflected light. For further detail studies by microprobe analysis (MPA) and scanning electron microscopy (SEM) we prepared polished sections covered with carbon sputtering.

The content detail and structural-textural features of the matrix were studied by SEM and MPA using an electron microscope in the mode of back-reflected (BSE) and secondary electrons (SE), the material composition was determined by local and square microprobe analyzes. The square analyzes were carried out for several homogeneous areas of the matrix, the areas of the scanned regions ranged from 2500 μm² to 1 mm², depending on the representativeness and homogeneity of the selected area. Interpretation of the results of MPA was made by variational diagrams of petrochemical components.

3. Petrographic characteristics

3.1. Put'yu suevites

During optical and SEM studies of the Put'yu suevites we determined that the matrix has up to 45 % of the rock volume. It is a heterogeneous, finely dispersed, sintered in areas, having from light gray to brownish gray clastic material. The nature of the association between the sintered and clastic matrix determines the patchy texture of the rocks at the micro-level. The average size of the particles composing the matrix in thin sections is 30–50 μm.

3.1.1. Clastic matrix. The clastic matrix is dominated by micrograined calcite (up to half of the volume of the ground mass), particles of quartz, potassium feldspar, plagioclase are less found, accumulations of carbonaceous particles are ubiquitous, pyrite and occasionally titanite are present as accessories (Figure 2). Mineral clasts are generally intensely corroded and have ragged, indistinct outlines. Secondary micas (muscovite, sericite), hydromicas, and chlorite are well developed in the binding mass. Sometimes quartz fragments contain systems of planar deformation elements (up to three directions); diaplectical glasses on quartz and feldspars are occasionally found. The cementing mass of the suevites contains small (~20 μm, rarely up to 100 μm) brownish and light gray isometric particles and accumulations of finely dispersed melt matter with indistinct outlines.

3.1.2. Partially sintered matrix is about 15–20 % (occasionally up to 30–40 %) of the total volume of the ground mass of the suevites. It is more homogeneous, opaque, partially isotropic, has a darker brownish color, forms randomly located areas, as though impregnating the rocks. The areas of partially sintered matrix are characterized by irregular indistinct outlines, often form accretionary margins along the clast periphery. The mineral composition of the components in such areas is similar to that in the clastic matrix, however, in comparison to the latter, the fragments of minerals here are very poorly preserved and generally occur in minor amounts (Figure 2).

3.2. Sayakha suevites

The matrix of the Sayakha suevites is rather homogeneous, predominantly sintered, brownish-brown in color, composes up to 50-60 % of the rock volume. On average, the size of the debris component in the matrix ranges from 30 to 100 μm.

3.2.1. Partially sintered matrix. The content of partially sintered matrix in rare cases reaches 15–20 % of the total matrix volume. Such areas are observed in the form of bizarre extended vein-like
structures, as though penetrating the intensely sintered matrix, sometimes forming larger blot-like areas. The partially sintered matrix is characterized by a light gray color and variegated appearance. It contains fragments of calcite, quartz, feldspars, tiny particles of carbon matter, secondary muscovite, chlorite, hydromica, glauconite, pyrite, and occasionally apatite. The presence of numerous organic residues is characteristic (Figure 2). Partially sintered matrix is noted only in suevites from the upper part of the outcrop and is practically absent in the rocks of the lower part of the section.

**Figure 2.** SEM images of the matrix of the Sayakha (A, B) and Put'yu suevites (C, D), BSE mode. A – partially sintered matrix of lapilli suevite enriched in fragments; B – intensely sintered matrix of lapilli clast-poor suevite; C – clastic matrix of coarse-grained suevite; D – clastic partially sintered matrix of blocky-agglomeratic suevite. Ab – albite, Ap – apatite, Cal – calcite, Chl – chlorite, CM – carbon matter, F – fossils, Ms – muscovite, Py – pyrite, Qz – quartz.

3.2.2. Intensively sintered matrix is an aggregate of sintered mineral particles of pelitic size (1–10 µm). Due to intensive sintering, the particles are combined into a continuous dense mass, where the particles have gradual transitions into each other, not clear boundaries, and can be defined only by
relict outlines. Such a matrix is dark, brownish, partially isotropic, in terms of the mineral composition of the constituent components, in general, is similar to the clastogenic one, however, it is characterized by a lower content of micas and carbonaceous particles and a larger fragment size (on average 80–100 μm) (Figure 2). Sometimes it contains clasts of feldspars, less often quartz with large deformation cracks and systems of planar elements (up to 4 directions), as well as dialectic glasses for these minerals. Large fragments of minerals (mainly quartz) are characterized by clear, regular outlines. The dependence of the clasts shape on their size is noted: the larger ones are generally angular, the smaller ones are rounded, elliptical.

3.3. Comparative analysis
According to the results of petrographic studies, we determined that the clastic components of the matrix of the suevites from the Put’yu River and suevites from the Sayakha River, in general, had a similar mineral composition. In this case, the matrix of the Put’yu suevites, in contrast to the Sayakha rocks, contained significantly more carbon matter, with worse preservation of mineral components which were characterized by intensely corroded, indistinct outlines. In the Sayakha suevites, in comparison to the Put’yu suevites, a higher content of the cementing mass is noted, changing from bottom to top along the section from intensely sintered to partially sintered with rare areas of the clastogenic matrix. The ground mass of the Put’yu suevites is predominantly clastic and only partly sintered.

4. Petrochemical characteristics
The studies of the rocks by SEM and MPA specified and supplemented the data of the petrographic study of rocks.

4.1. Put’yu suevites
Studying the Put’yu suevites by electron microscopy we revealed that at the micro-level, the matrix of these rocks was loose and heterogeneous, porous to varying degrees, consisted of irregular accumulations of sintered particles, which gave the rocks a porous and clotted texture. In general, the matrix of rocks was characterized mainly by an aluminosilicate composition with a variable proportion of carbonate matter, a relatively high content of iron, magnesium and alkalis (mainly potassium).

The microprobe analyzes confirmed the mineral composition of the cementing mass, which was established by the petrographic study of the suevites; in addition, particles of apatite, pyrite, titanite, and rutile were identified (Figure 2). We found that plagioclase fragments in the matrix generally had an acidic composition corresponding to albite; calcite mainly contained impurities of manganese (up to 1.2 wt. %), iron and magnesium (0.2–0.6 wt. %). It was noted that calcite in the matrix occurred as irregular crystalline-granular aggregates, less often as angular fragments.

4.1.1. The clastic matrix is predominantly porous, with sparse areas of partially sintered material. The content of pore space reaches 8–10 % of the total volume of the ground mass (Figure 2). The clastic matrix contains (wt. %) CaO in the range of 2.5–6.1 %, SiO₂ 46.2–54.7 %, Al₂O₃ 8.7–12.1 %, FeO 3.2–5.1 %, MgO 2.5–4.4 %, K₂O 1.2–2.9 % и Na₂O 1–2.2 %, TiO₂ 0.5–1.6 %, rare P₂O₅ and MnO (~ 0.7 and 0.3 %, respectively) (Figure 3).

4.1.2. The partially sintered matrix, in comparison to the clastogenic matrix, is less porous and has a significantly denser structure (Figure 2). In such a matrix, the content (wt. %) of CaO from 0.8 to 2.3 %, SiO₂ 53.7–57.6 %, Al₂O₃ 11.4–11.9 %, FeO 3.9–4.8 %, MgO 2.9–3.6 %, K₂O 2.8–3.3 %, Na₂O 1.2–2.1 %, TiO₂ ~0.5–0.7 % (Figure 3). We determined that wide variations in the content of carbon matter and silicic acid in the cementing mass of the Put’yu suevites depended on the nature of the matrix: partially sintered areas showed a higher content of SiO₂ and a lower content of CaO.
Figure 3. Variational diagrams of main petrogenic components of suevite matrix from the Sayakha and Put'yu rivers according to square microprobe analyzes (wt. %).
When studying coarse-grained and blocky-agglomeratic suevites we found that the matrix of the rocks was characterized by some petrochemical discrepancies (Figure 3). The matrix of blocky-agglomeratic suevites, in comparison to the coarse-grained ones, was distinguished by a higher content of potassium oxide, alumina, a slightly higher content of sodium oxide and a low content of magnesium, as well as a large discrepancy between the values of CaO and SiO₂.

4.2. Sayakha suevites

Microprobe studies with square analyzes presented that the Sayakha suevites were characterized by a fairly homogeneous matrix of predominantly aluminosilicate composition with a relatively high content of carbonate matter, iron and magnesium. Microprobe analyzes of the constituent components of the matrix confirmed the mineral composition of the binder mass established earlier in the study of rocks under an optical microscope (Figure 2). We determined that the fragments of feldspars in the matrix were represented by acidic plagioclase (albite), calcite contained impurities of magnesium (up to 2.5 wt. %), manganese and iron (0.2–0.8 wt. %).

We found that the matrix was characterized by some discrepancies in material composition. The suevites in the lower part of the section differed from the rocks in the upper part by a higher SO₃ content and absence of MnO; otherwise, they had similar values of the contents of the main petrogenic components.

4.2.1. Partially sintered matrix. We determined that partially sintered matrix contained distinct angular fragments embedded in a partially melt mass of fine particles (Figure 2). It was characterized by content (wt. %): CaO 3.7–4.4 %, SiO₂ 51.6–55.4 %, Al₂O₃ 11.1–12.5 %, FeO 5.5–6.2 %, MgO 2.8–3.3 %, K₂O 1.1–1.5 % and Na₂O 0.8–2.6 %, SO₃ 0.6–1.8 %.

4.2.2. Intensively sintered matrix is a single homogeneous mass filled by small melt particles containing larger mineral fragments. The matrix is characterized by a massive texture, in comparison to the partially sintered one, larger mineral fragments are rare and have smoothed outlines, and small particles retain only relict outlines. This matrix contains (wt. %): CaO ~2.4 %, SiO₂ 59.8–64.8 %, Al₂O₃ 10.3–11.4 %, FeO 3.4–5.9 %, MgO 2–2.8 %, K₂O 1.4–1.6 % and Na₂O 0.6–1.1 %, SO₃ 0.7–2.2 %. In contrast to the partially sintered matrix, the intensely sintered matrix has a lower content of calcium oxide and a significantly higher content of silica, it has a slightly lower content of magnesium and sodium oxides, alumina, a slightly higher amount of K₂O, as well as a wider range of values of FeO content (Figure 3).

4.3. Comparative analysis

The matrix of Put'yu and Sayakha suevites is characterized by some discrepancies in the petrochemical composition. In general, all studied suevites have a fairly high CaO content (up to 6 wt. %). The greatest variations (0.8–6 wt. %) are observed in the Put'yu rocks. The matrix of the latter, in comparison to the Sayakha suevites has a lower SiO₂ content, slightly less Al₂O₃ and FeO, a high concentration of alkalis, especially K₂O, and MgO. A characteristic feature of the sintered matrix in all studied rocks is a relatively high content of silica and a low content of CaO (Figure 3).

The data obtained are in a good agreement with the results of the petrographic studies. The aluminosilicate composition of the matrix with an increased content of carbonate matter reflects the composition of the rock-forming minerals of the suevite matrix – quartz, feldspars, and calcite. The significant content of iron and magnesium oxides, apparently, is conditioned by the rapid alteration by secondary micaceous minerals and chlorite along the cementing mass. The relatively high content of potassium oxide in the blocky-agglomeratic Put'yu suevites may be associated with the predominance of muscovite among secondary mineralization (micas and chlorite). The relatively low content of carbon matter and the relatively high content of silica in the heated matrix is generally conditioned by
the predominance of the glass-forming component SiO$_2$, which provides sintering of the material and a lower concentration of calcite and micas.

5. Conclusions
Thus, for the first time, we carried out a comprehensive study with a detailed description of the matrix of the Kara Astrobleme suevites located on the Put'yu and Sayakha rivers. We determined that the matrix of the studied rocks was characterized by the close mineralogical composition, differing in the character of lithification, structural and textural features, and petrochemical composition.

The ground mass of the Put'yu suevites is heterogeneous, mainly clastogenic, loose, with partially sintered areas, characterized by a spotty, lumpy, porous texture. The matrix of the Sayakha suevites is predominantly intensely sintered, with a more uniform dense structure and massive texture.

We revealed a higher content of silica, alumina and iron oxide, a lower content of potassium and magnesium oxides in the matrix of the Sayakha suevites, in contrast to the Put'yu rocks. It was found that the discrepancies in the material composition of the matrix depended on the nature of the lithification of the suevites. The sintered matrix, in comparison to the clastic matrix, had a relatively low CaO content and a high SiO$_2$ content.

The determined features of the matrix of the Sayakha and Put'yu suevites indicate that the rocks belong to the aerodynamic facies and they have different thermal formation conditions conditioned probably by different initial position of the suevite material in the impact cloud. The clastogenic matrix indicates a relatively cold formation environments, partial sintering indicates lithification under conditions of irregular temperature regime. The intensely sintered nature of the matrix of the Sayakha suevites can indicate lithification of the material in a hot condition, presence of residual high temperatures in the deposited material, or a combination of these factors which should be clarified in future. Accordingly, we assumed that the Put'yu suevites represented deposits of the upper part of the impact cloud, and the Sayakha suevites – the lower facie.

The results contribute to determining type and facies affiliation of the suevites in other sectors of the Kara impact structure, allow specifying the suevite facies variability and provide detail characterizing of the suevite breccias of the Kara Astrobleme as a whole. The obtained data can be used to determine suevites genetic features, impact diamonds distribution and to predict the diamond content of this unique Arctic object.

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