The glasses from Mesozoic sediments of Anabar region (Arctic Siberia, Russia)

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Abstract. The glasses were found in the tuffisites of Orto-Yiarginskoe field (Anabar region, Arctic Siberia). The composition of the glasses is comparable with the composition of the glasses from the Popigai impact structure and the gneisses of the Archean basement of the Anabar folded system. The age of the studied glasses is comparable with the age of the glasses of the Popigai impact structure. Mineralogical studies were carried out using scanning electron microscopy (MIRA 3 LMU, Tescan Ltd) with the INCA Energy 450+ XMax 80 microanalysis system (Oxford Instruments Ltd). The age of the glasses is determined by the 40Ar-39Ar method in the Collective Use Center of the IGM SB RAS.

1. Introduction

Rich quaternary alluvial diamond placers (with admixtures of gold and platinum group minerals), as well as placer deposits of relict Pliocene erosion-karst valleys have been discovered, developed, and these are successfully mined in the Anabar diamondiferous area (ADA). Motherlodes of diamond and noble metals so far have not reliably established on this territory. The revealed bodies of the Kuonam kimberlite complex of the Triassic age are non-diamondiferous or poorly diamond-bearing.

After discovery of the largest placer of the Ebelyakh River, in the course of exploration and prospecting works for diamonds, it has been established in the ADA the widespread occurrence of karst among dolomites of the Anabar suite of the Upper Cambrian and diamond potential of some horizons of sediments filling karst. As a whole, low productive for diamonds sandy and loamy sediments dominate in the Cretaceous sediments of funnel sinks.

At the same time, in the carbonate base, a part of cape-shaped and funnel-shaped depressions (oval in plane view in cross-section) are filled with specific red clays with intense limonitization and green sideritized clays. It is these rocks in which diamonds finds are known. When prospecting and evaluation works were performed, such rocks were often related to karst sediments of the Cretaceous age. At the same time, a number of researchers proved that these sediments were crusts of weathering of endogenous rocks: tuffs of alkaline basalts and lamproites and these crusts could be a source of diamonds in the Cenozoic placers. The chemical composition of the rocks is characterized by high contents of iron and aluminum oxides, until appearance of free alumina.

In core-samples of certain core holes in the Anabar region on the Orto-Yiarginskoe field, fragments of fresh glasses were found (Figure 1). According to the data of sporo-pollen analysis, the age of rocks...
with inclusions of glasses corresponds to the Later Cretaceous. We carried out a complex mineralogical and geochemical study of glasses and determined their age using the 40Ar-39Ar method. The research results are presented in this work.

Figure 1. Fragments of glasses in tuffisite of Orto-Yiarginskoe field, Anabar district (borehole 810, depth 16.8 m). a - the general plan; b - detail.

2. Geological setting
The Orto-Yiarginskoe field field is confined to the eastern flank of a large tectonic structure of the Siberian platform (Anabar anticlise). Within the scope of the antecilce, two structural stages are distinguished: the lower Archean stage, which is the platform basement, and the upper one corresponding to the sedimentary cover. The basement depth in the region of the Yiarginsky field is 1-2 km [1]. The platform basement was formed over a long period from 3.5 billion years onwards and ending with 1.9 billion years [2, 3]. The upper structural stage is composed of Cambrian carbonate series and overlying Late Cretaceous terrigenous sediments.

Fragments (rock debris) of fresh glasses were found in cores of some core holes in the Late Cretaceous (Post-Cretaceous) sediments of the Anabar region (Orto-Yiarginsky field) dated early by a sporo-pollen method. The most large-scale manifestation of this complex is established in the locality in the upper reaches of the Otordur stream. Within the bounds of the studied site, rocks of the Mesozoic age are located among carbonate sediments of the Lower and Middle Cambrian. From the surface, these rocks are overlapped only by thin (0-9 m, in the average, 4.1 m) quaternary poorly consolidated sediments.

3. Sample description
Maximum thickness of sediments (more than 200 m) dated back to the Cretaceous period are defined in karst cavities of funnel-shaped and tabular-shaped. Intervals of rocks with glasses are not large in the thickness: these are the first tens of centimeters along boreholes. Material of these rocks was obtained by specialists of OJSC Almazy Anabara in the process of performing exploratory drilling works on the verification of geophysical anomalies in the territory of the Orto-Yiarginsky field. Macroscopically, the rock containing glasses is a fine detrital (2-30 mm) breccia (Figure. 2), the amount of fragments being about 20-40%. The relative share of fragments of bubbly and foamy glasses is no more than 60%. The rock also contains fragments of biotite-feldspathic crystalline rocks, quartz sandstone, Cambrian carbonate rocks, and carbonized vegetable remains. The binder mass is fine-grained, ash-grey in colour. with the massive texture and specific macro porosity.

The glasses are heterogeneous: from opaque, foamy, pumice-like, to transparent greenish-yellow and brown in colour. Almost black glasses with variegated tarnish on walls of bubbles are less common.
Figure 2. Fragments of the core from the borehole 708s-1, the depth – 27.7 m; a - contact (transition) of ash-gray psammitic tuffsite and small-clastic breccia with fragments of bubbly and foamed glass; b - glasses of the first and second varieties in a single fragment.

Glasses include relics of quartz, in some cases with planar elements. The viscous-plastic flow textures are peculiar to glasses. The lithological characteristic of these sediments in the section obtained as a result of drilling is listed in Table 1. Two samples of glasses for isotopic probing were taken from samples 708с-1.3 and 708с-1.4. The samples were taken from core hole (№ 708с-1) at depths 27.7m and 29.7m, respectively.

Table 1. The lithological section of the Orto-Yiarginsky field deposits (from borehole 708s-1, top to bottom).

| Interval (m) | Description of the rocks                                                                 | Age            |
|-------------|------------------------------------------------------------------------------------------|----------------|
| 0-0.3       | Soil layer                                                                               | Quaternary s.  |
| 0.3-4.0     | Permafrost zone with ice (40%): aleurites, grayish, brownish-gray sandy loam with gravel and small fragments of dolomite |                |
| 4.0-4.5     | Brown sandy loam                                                                         | MC*            |
| 4.5-7.2     | Dolomite is fissured, altered (from light gray to brown-gray)                            |                |
| 7.2-23.5    | Tuffisites are ash gray psammitic. In the interval of 11.2-11.4 m - brecciated sideritized dolomite. The amount of coarse siderite up to 40% | E-O (?)        |
| 23.5-24.3   | Dolomite is light gray, massive, sugar-like, very strong                                 | MC (?)         |
| 24.3-27.7   | Ash-gray psammitic tuffisites                                                            | E-O**          |
| 27.7-31.0   | Fluidized-explosive breccias with the vitrocrystallolastic structure of the groundmass and the prevalence of foamed glass in the fragments | E-O           |
| 31.0-41.7   | Ash gray psammitic tuffisites                                                            | E-O (?)        |
| 41.7-48.3   | Light gray, massive, fine-grained, weakly fissured dolomites                              | MC             |
| 48.3-71.0   | Interstratification of light gray dolomites and gray limestones                           | MC             |
| 71.0-74.1   | Green limestones strong fine-grained, massive                                            | MC             |

*MC – Middle Cambrian; **E-O - Eocene-Oligocene (this study).

Rocks enclosing “layers” with glasses are represented by very peculiar, mainly sandy, and to a lesser extent, breccia-like sediments. Based on the enormous volumes of geological prospecting and exploration performed by geologists of many organizations, it has been established that rocks of the complex are uniquely associated with rocks repeatedly described within Popigai ring (or impact) structure as allogenic breccia and psammitic-aleuritic coptoclastites by reference to geological,
petrographic, and mineralogical-geochemical peculiarities. The overwhelming majority of geologists who have studied these rocks are beyond any doubt that the rocks were formed due to invasion of mobile fluid-saturated mixture into upper horizons of the Lower Paleozoic carbonate cover and weakly bound Cretaceous terrigenous sediments overlying this cover. Intervals of such rocks are contrast with Mesozoic sediments by their structure, composition, porosity of rocks, the presence of large number of inclusions (xenoliths and xenoblocks) of rocks of different ages, inconsistency of age dating obtained by different methods (from Cretaceous to Eocene-Oligocene), and by the presence of glass inclusions (Figures 2, 3, 4). But these rocks are especially contrastively distinguished by their forms of occurrence with specific bodies represented by zones crosscutting rocks of the older age (from Proterozoic to Cretaceous), and also in the form of conical bodies facing by their wide part the earth’s surface with the tilt angles of walls from of 15 to 45о.Most of geologists studied these rocks (especially from a practical point of view as sources of high-quality diamonds as well as, to a certain extent, gold and platinum group metals) consider that these rocks should be attributed to fluidizates and tuffisites.

**Figure 3.** a - sandy tuffisite with rare small xenoliths and characteristic matrix porosity. Borehole 708y-1, 16.2 m. B - “Exploded” xenolith of pink quartz-sand sandstone of the lower Riphean Mukun series in tuffizite. The marginal part of the xenolith is partially disintegrated with the linear “pulling away” of the fragments. The chains of large flattened voids in the tuffisitic matrix are oriented along the direction of “pulling apart” xenolith fragments. Borehole 608s-2, 51 m.

The average thickness of fluidizates within the explored acreage (150 hectares) is 37.9 m (according to the data from 28 boreholes). Based on the results of the study, two petrographic varieties of rocks have been distinguished: sandy tuffisites and fluidizate breccias. In a quantitative terms, sandy tuffizites are sharply dominant. These are massive rocks with a psammitic texture. The rocks are characterized by marvelous consistency of the material composition and textural-structural features just as in plane, so in section. The deposits are represented by massive fine-grained rocks ash-grey in colour containing scattered fragments (xenoliths) of various rocks ranging in size from the first millimeters to 20 cm (Figures. 1, 2, 3). Xenoblocks up to 10 cm in size are also recognized. The volume fraction of debris, as a rule, is not large (2-15%).

The presence of macropores in the ground mass, which occupy 1-5%, in some places up to 10% of the rock volume. Pores (voids) have the form of a sphere of a triaxial ellipsoid up to 10 mm in size, which sometimes line up in chains.

**4. Analytical techniques**

Fragments of glass samples (708c-1.3 and 708c-1.4) were extracted from tuffisites, placed in checkers and covered with epoxy resin. After the resin hardened, the samples were opened and leveled by
grinding, and then coated with Super Cement glue, followed by polishing with diamond pastes. Polished glasses were studied by ore microscopy using an AxioSkop A1 microscope and SEM methods. The composition and morphology of the glasses grains were investigated using a MIRA 3 LMU (Tescan Orsay Holding) scanning electron microscope with an attached INCA Energy 450 XMax 80 (Oxford Instruments Nanoanalysis) microanalysis energy-dispersive system at the X-ray Laboratory of the Institute of Geology and Mineralogy, Siberian Branch RAS (analysts N.S. Karmanov, M.V. Khlestov). We employed an accelerating voltage of 20 kV, a beam current of 1600 pA, an energy resolution (MIRA) of 126-127 eV at the Mn Kα line, and a region (3-5 μm), depending on the average atomic number of the sample and the wavelength of analytical line.

$^{40}$Ar/$^{39}$Ar measurements were performed at the Analytical Centre of Multi elemental and Isotope Investigations at IGM SB RAS. Samples and biotite MCA-11 (K/Ar standard OSO no. 129-88), which was used as the mineral monitor, were wrapped in Al foil and vacuum-sealed in quartz vials. Biotite MCA-11 was certified as an $^{40}$Ar/$^{39}$Ar monitor with use of the muscovite Bern 4m and biotite LP-6 internationally certified standards [4]. The quartz ampoules with samples were irradiated in the Cd-coated channel of a research reactor (VVR-K type) at the Tomsk Polytechnic University, Tomsk, Russia. The neutron gradient did not exceed 0.5 % at the sample size. $^{40}$Ar/$^{39}$Ar step heating experiments were undertaken using a quartz vial heated by external furnace. Released argon was purified by exposure to Zr-Al SAES-getters. The isotopic composition of Ar was measured on a Noble Gas 5400 mass spectrometer. The $^{40}$Ar blank at 1200°C, measured over a period of 10 min, did not exceed $5 \times 10^{-10}$ ncm$^3$. The reported analytical errors are ± 1σ.

Figure 4. Microstructure of the main matrix of tuffisites. Micrograph, thin section, a - nicsls //, b – with analyzer. Borehole 708y-1, 16.2 m.

5. Results
5.1. Mineralogical, geochemical and petrochemical features of glass from sample 708c-1.3.
Fragment of glass more than 2 cm in size along the long axis was studied. In the marginal parts of a grain, the glass is opaque, light grey to white, foamed (froth-like) pumiceous. The central part of the sample has the fluidal texture, tobacco colour with round pores (bubbles) up to 1 mm in size. The results of petrographic and electron microscopic study are shown in Figure. 5 (a, b, c) and are listed in Table 2.

The rock consists of glass having a fluidal texture and structure, which is emphasized by jets and and oriented stripes of bubbly glasses of different composition, often curved with signs of flow. In addition, areas with flow and dissolution structures are in evidence. Glass contains subangular quartz grains, mostly fractured, cataclised, with numerous fluid and mineral inclusions, less often plagioclase, potassium feldspar is hardly found, although local areas of glass enriched in potassium are recognized. Most of not completely melted grains are represented by quartz with zonal rims of glasses of the different composition, which also penetrate trough cracks. Small pores in the glass are round,
while large ones are elongated, which also indicates substance flow. Often there are areas near melted quartz grains saturated with gas-liquid and mineral inclusions with sulfide globules, which on the ground of these characteristics can be attributed to lechatelierite. Sulfide globules ranging in size from several microns to tens ones are presented by a monosulfide solid solution containing iron, sulfur, nickel, and copper. Expressed in terms of 100% sulfide, the contents are as follow: 53.5-62% Fe, 34.3-40.1% S, 0.6-9.6% Ni, and 0.5-2.56% Cu. Sphene, zircon, pyrrhotite are less common in the glass, and monazite, barite, and sulfides of iron, zinc, and copper are found in gas cavities. Albite and two hypersthene grains were found on one microsite of the sample, which may indicate involvement of hypersthene-containing gneisses as a substrate in the process of glass formation. It is known that the complexes of the Archean Anabar folded system are represented, in particular, by rocks of the Khapchansky series: garnet-hypersthene, graphite-biotite-hypersthene, and biotite-hypersthene gneisses [5]. In this case, it is not surprising that not only hypersthene, but also graphite are present in the gneisses.

**Figure 5.** a - lechatelierite and minerals with planar elements in homogeneous glass (xenolith of gneiss) in tuffisites. micrograph of thin section, nicols //. In the center of the picture is a quartz grain with planar elements. At the bottom of the picture is the inclusion of lechatelierite with a clear dispersion effect along the interface between lechatelierite - homogeneous glass. Borehole 408Y-1, 23.7 m; b - micrograph of thin section, nicols //. Fragment of glass with distinct fluidization in the tuffisite. In the glass are rounded voids up to 0.05 mm in the size, made so fine-grained matrix of tuffisites. Borehole 708s-1, 27.7 m; c, d - brownish glass in tuffisite, saturated with fragments of gneiss minerals (quartz, feldspar, biotite). Micrograph of thin section, (c –nicols //; d – with analyzer). Borehole 708s-1, depth 29.7 m.
Table 2. The chemical composition (average values) of glasses from the Mesozoic deposits of the Orto-Yiarginskoe field and the Popigai impact structure (PIS) in comparison with the chemical composition of the gneiss from the PIS.

| № (n) | SiO₂ | TiO₂ | Al₂O₃ | FeO₄ref | MgO | CaO | Na₂O | K₂O | Сумма |
|-------|------|------|-------|---------|-----|-----|------|-----|-------|
| 1-1   | 61.4 | 0.95 | 16.8  | 7.08    | 3.18| 2.7 | 2.41 | 3.28| 97.8  |
| 1-2   | 60.39| 0.82 | 15.99 | 6.61    | 2.95| 2.45| 2.4  | 3.25| 94.86 |
| 1-3   | 59.47| 0.9  | 16.84 | 7.82    | 3.43| 2.8 | 2.26 | 2.98| 96.5  |
| 1-4   | 57.29| 0.75 | 16.95 | 8.59    | 4.06| 2.56| 2.17 | 2.96| 95.34 |
| 3-1   | 60.89| 0.8  | 16.33 | 7.37    | 3  | 2.59| 2.37 | 3.2 | 96.85 |
| 3-2   | 58.47| 0.83 | 16.87 | 8.4     | 3.66| 2.76| 2.17 | 2.96| 96.13 |
| 3-3   | 59.24| 0.8  | 16.7  | 7.56    | 3.45| 2.71| 2.26 | 3.04| 95.77 |
| 4     | 58.36| 0.83 | 16.59 | 7.28    | 3.38| 2.62| 2.44 | 2.99| 94.49 |
| 5     | 58.83| 0.85 | 15.85 | 7.22    | 3.27| 2.92| 2.12 | 2.94| 94    |
| 6-1   | 60.54| 0.93 | 17.16 | 7.71    | 3.15| 2.62| 2.47 | 3.18| 97.75 |
| 6-2   | 53.78| 0.72 | 15    | 7.62    | 3  | 2.62| 2    | 2.57| 87.6  |
| 6-3   | 61.38| 0.83 | 16.4  | 6.56    | 2.87| 2.94| 2.47 | 3.28| 97.02 |
| 6-4   | 59.71| 0.9  | 17.35 | 7.9     | 3.33| 2.62| 2.37 | 3.1| 97.52 |
| 6-5   | 61.1 | 0.77 | 16.57 | 7.22    | 3.15| 2.46| 2.51 | 3  | 97    |

**C₄v(15)** 59.38 | 0.83 | 16.49 | 7.44 | 3.29 | 2.65 | 2.31 | 3.04 | 95.47

**C₄v(24)** 60.17 | 0.99 | 15.70 | 6.52 | 3.64 | 3.43 | 2.03 | 2.90 | 95.39

The composition of the glass Popigai impact structure (Whieheade et al., 2002)

| **C₄v(25)** | 63.43 | 0.73 | 14.12 | 7.39 | 3.5 | 3.81 | 2.27 | 2.72 | 100.5 |

The composition of gneisses at the base of the Popigai impact structure (Masaitis et al., 1998)

| **C₄v(45)** | 63.44 | 0.77 | 15.45 | 7.67 | 3.2 | 3 | 2.57 | 2.47 | 99.81 |

Notes: № - the number of the analyzed area in glass grain; (n) - the quantity of analyses. From 1-1 to 9 - sample No. 708-1.3, from 11-1 to 22 - sample No. 708-1.4; C₄v – Average content.
Based on the local analysis of sample 708c-1.3, two types of glasses are distinguished, which differ in the composition. The first type is characterized by the concentrations: 50-66% SiO$_2$, 17% Al$_2$O$_3$, 7.0% FeO, 0.9-1.0% TiO$_2$, 3.3-3.5% K$_2$O, 2.5% Na$_2$O, and 3.3-3.3% MgO; concentrations of the second type are as follows: 60-61.9% SiO$_2$, 17.5-17.8% Al$_2$O$_3$, 8-9 FeO, 0.8-0.9% TiO$_2$, 3.0-3.3% K$_2$O, 2.3-2.4% Na$_2$O, and 3.5-4.3% MgO. Thus, as a whole, the glass correspond to andesite in the composition with variations of alkalies, silicic acid, and iron. The analysis data of the glass structure indicate its occurrence as a result of melting of rocks of the medium-acid composition given that preferentially quartz remained in “relic” minerals in glass.

5.2. Mineralogical, geochemical and petrochemical features of glass from sample 708c-1.4.

A fragment of porous glass (sample size was about 10 mm) is transparent, relatively homogeneous, tobacco (brown green) in colour has been studied. The results of petrographic and electron microscopic studies are given in Figures 5, 6 (d, e, f)) and in Table 2. The rock consists of glass (to a large extent, it is close to that described above) of the fluidal texture and structure, which are emphasized by jets and oriented strips of bubbly glasses of different compositions often curved and with signs of flow. In addition, there are areas with flow and dissolution structures, as well as with porphyritic texture. Subangular quartz grains are enclosed in glass mostly fractured, cataclased, with numerous fluid and mineral inclusions, more rarely plagioclase, and potassium feldspar is hardly found, although local areas of glass enriched in potassium are recognized. Most of not completely melted grains are represented by quartz with zonal rims of glasses of the different composition. Small pores in the glass are rounded, while large ones are slightly elongated, which also indicates substance flow. Often there are glass areas near fritted quartz grains saturated with gas-liquid and mineral inclusions with sulfide globules, which, on the ground of these characteristics, can be attributed to lechatelierite.

Zircon, magnetite, and pyrrhotite are rarely found in glass, and in gas cavities, apatite, barite, titanium magnetite, chromite, calcium carbonate (with magnesium admixture), monazite barite, and sulfides of iron, zinc and copper are met. Sulfide globules ranging in size from several microns to tens ones are represented by a monosulfide solid solution (mss) containing iron, sulfur, nickel, and copper (rare cobalt) expressed in terms of 100% sulfide, the contents are as follow: 55.3-74.1% Fe, 11.7-36.2% S, 1.4-7.8% Ni, and 1.35-10.1% Cu.

Based on the local analysis of sample 708c-1.4, two types of glasses differing in composition are distinguished. The first type is characterized by the concentrations: 64-66% SiO$_2$, 15.5-16.0% Al$_2$O$_3$, 7% FeO, 0.8-0.9% TiO$_2$, 3.0-3.2% K$_2$O, 2.0-2.3% Na$_2$O, 3.0-3.7% MgO; The concentrations of the second type are as follows: 59-61% SiO$_2$, 14.5-17.0% Al$_2$O$_3$, 8-9% FeO, 0/6-0.9% TiO$_2$, 1.8-2.2% K$_2$O, 1.5-2.0% Na$_2$O, and 4.7-7.4% MgO. The presented data were obtained as a result of calculation for 100% of glass (carbon was not taken into account). Thus, glasses in sample 708c-1.4 are represented mainly by two types: andesitic and dacitic compositions. But at several points, the analytical data show the concentrations corresponding to andesite-basalt and even basalt occurring also due to melting of rocks of the medium-acid composition taking into consideration that mainly quartz remained in glass in “relic” minerals in glass.
Figure 6. SEM photographs of a glass grains No. 708c-1.3 (a, b, c) and No. 708c-1.4 (d, e, f).

a - at the point 14 is quartz, with a large number of globules and relics of planar elements, through which preferential melting takes place. At point 9 is monazite spherule located in a cavity filled with...
graphite?; 7- titanite with no signs of change. An elongated spherule with a reaction border is composed of carbonaceous matter (graphite?). Points 10, 11 are glass (lechatelierite?) with fluid and mineral micro and nano-sized inclusions.

b - Glass with vortex fluid structure. At points 1, 2, 6 are quartz; 3, 4, 7 - glass of feldspar composition; 5 - monosulfide solid solution (mss) globule contains 53.5% Fe, 34.3% S, 9.6% Ni, 2.56% Cu (in terms of 100% sulfide).

c - Glass with vortex fluid structure. At points 1, 2, 3 are carbonaceous matter (graphite?) with chlorine from 0.22 to 0.24% Cl; at point 10 is graphite mixed with CaO and FeO. At points 4, 7, 8 - quartz; at point 6 - a relic of undemelted quartz with an admixture of K2O and FeO; at point 5 - glass; at point 9 - the sulfide globule which contains 58.8% Fe, 40.1% S, 0.6% Ni, 0.5% Cu (in terms of 100% sulfide.)

d - general view of the sample glass No. 708c-1.4. The spherules are composed of carbonaceous matter. Partially fused gray fragments - quartz; light gray - glass.

e - spherules and black areas (points 3, 11) are made of carbonaceous matter (graphite?). Point 4 is a cataclysed, partially melted grain of quartz, probably represented on the periphery of lechatelierite?. Mss at point 2 contains 74.1% of Fe; 11.7% S; 4.1% Ni; 10.1% Cu (in terms of 100%.)

f - sulfides of iron, nickel and copper are concentrated at the boundary of the melt - quartz. The spherules are made of carbonaceous matter (graphite?) (point 7). Lechatelierite is possible inside a quartz grain near a large crack. 1 – melted from the edges, broken-down quartz grain; 2, 6 silicate glass; 3, 4, 5 - monosulfide solid solution consisting of iron, nickel and copper sulfides; at point 8, a grain was found similar to grain at point 14, which contains barium, zinc, iron and sulfur.

5.3. The $^{40}$Ar-$^{39}$Ar age of glass

For glass sample No 708-1.3, an age spectrum was obtained in which a plateau is distinguished consisting of three stages characterized by 63.4% of evolved $^{39}$Ar and the age value 35.3 ± 1.0 Ma old (Figure 7). On the isochronous diagram, points form a regression with age value of 34.5 ± 1.1 Ma, which is consistent with the plateau age. Thus, it is logical to assume the age calculated by the plateau method to be commensurate with the sample formation time.

For the glass sample No 708-1.4, an age spectrum of the saddle-shaped form (Figure 7) was obtained, which is often interpreted as a sign of the presence of radiogenic $^{40}$Ar. In this case, the sample age should not be older than the minimum value in the middle part of the spectrum. Consequently, the sample was formed not earlier than 40.0 ± 1.3 Ma back.

On the other hand, in the isochronous diagram, three point form a linear regression characterized by the value 66.3 ± 1.7 Ma with MSWD = 4. Based on the data set, it seems unlikely that the isochronous age for this glass sample has any geological meaning.

As a result of $^{40}$Ar/$^{39}$Ar dating of glasses from the Orto-Yiarginskoe field (Anabar region, Arctic Siberia), the following age values for sample 708c-1.3 were obtained: 35.3±1.0 Ma (plateau age), 32.5±0.7 Ma (integral age), and 34.5±1.1 Ma (isochronous age). For sample 708c-1.4, the results of $^{40}$Ar/$^{39}$Ar determination are as follows: 40.0±1.3 Ma (plateau age) and 44.1±0.8 Ma (integral age). The plateau age values for sample 708c-1.4 are more preferred.
Figure 7. $^{40}$Ar / $^{39}$Ar age spectra with stepwise annealing of glasses samples No 708c - 1.3 (top row) and No 708c - 1.4 (bottom row).

6. Discussion and conclusions

The age of glasses from tuffisites of the Orto-Yiarginskoe field (Anabar region, Arctic Siberia) is compared, to the full extent, with glasses from the Popigai structure [6, 7, 8, 9]. In the first publication [6], the average age of glasses from the Popigai structure is given as 35.7±0.2 Ma. The subsequent revision of these data allowed the authors [7] to recommend the value of 36.42±0.81 million years with the scatter of data from 33.67±0.02 to 38.29±1.25 million years. Earlier definitions also correspond to the Eocene-Oligocene boundary, it is reasonable that with exception of not completely melted Archean gneisses, the age of which is more than a billion years old (see references in [6]). Thus, fragments of glasses of the Eocene-Oligocene were found among the sediments of the Cretaceous age. Glasses are molten (partially molten) rocks, presumably gneisses of the Khapchansky series. The composition of glasses corresponds to the andesite (708c-1.3) and andesite-dacite (708c-1.4) compositions. Sulfide globules abundant in glasses of samples 708c-1.3 and 708c-1.4 are represented by a monosulfide solid solution containing iron, sulfur, nickel, and copper in their composition: iron (53-74%), nickel (0.6-9.6%), copper (0.5-10.1%) and sulfur. Cobalt (up to 0.5%) was revealed in singular globules. Comparison of the chemical composition of studied glasses from Orto-Yiarginskoe field with glasses from the Popigai ring (impact) structure and gneisses from the basement of the Archean Anabar folded system indicates just as their proximity, so differences (Table 2, Figure 8). On the diagram SiO$_2$ – Na$_2$O+K$_2$O, the most part of compositional points of the Popigai structure fall into fields of andesite and dacite. Wide variations in the compositions of tuffisites from the Orto-Yiarginsky field may be attributed to incomplete melting of quartz as evidenced by its fritted relics (remains). At the same time, as judged by the ratios TiO$_2$, Al$_2$O$_3$, FeO, K$_2$O with SiO$_2$, it is possible to assume different compositions of rocks for which glasses of the Popigai structure and Orto-Yiarginskoe field were formed.
The reasons for appearance of glasses of the Eocene-Oligocene age can be explained by formation of the large Popigai structure located 250-300 km to the west – north-west of the territory under consideration. However, it is not entirely clear the occurrence of rocks with Eocene-Oligocene glasses among Cretaceous sediments.

Relying on experiential data on shock-wave deformation of gold-containing pyrite-quartz compound at P>10–15 GPa and T>1700° (in the central zone), it has been established that a series of structural elements is formed in compacted rocks: 1) axial zone of amorphization, vitrification, and partial melting corresponding to the axial cumulative jet of loading; 2) intersecting (interference) systems of radial impact arc cracks; 3) zone of plastic flow and deformation; 4) compactite outer zone (Figure 9) [12]. In our case, an axial zone of amorphization, vitrification, and melting, and also intersecting (interference) systems of impact (collision) arc cracks associated with the zone is of particular interest. The interrelation of linear dimensions (in plan view) of the axial zone and arc cracks may be represented as 1:10 and even 1:20. If the data obtained correlate with the scale of the Popigai structure (the crater diameter is 100 km), then it is possible to make an assumption about appearance of impact (collision or dislocation) zones for many hundreds of kilometers. As judged by the structure of the river network in the Popigai crater and its surrounding, as well as the data of space observations (Figure 9) [13], it is possible to talk about existence of such zones.

The revealed specific rocks related to tuffisites can apparently be explained by appearance of impact dislocation zones during the process of impactogenesis [14]. It is also well to bear in mind the possibility of origination of tuffisites as a result of “endogenous impactogenesis”, in the course of which specific rocks up to “Tuffisitic Kimberlite” (TK) and “Tuffisitic Kimberlite Breccias” (TKB) may be formed [15 - 20]. It is significant that kimberlite bodies were exposed by drilling in one of “funnel sinks” filled with tuffisites in the Orto-Yiarginsky field (oral report of M.G. Mukhamedyarov). It is not inconceivable that the big event, in particular, Popigai, could simulate endogenous activity in the region.

In any case, relationship between impact events and endogenous activity has been discussed in recent works, in particular, as evidence, data are given on united Cretaceous-Paleogene age of basalts from the Deccan plateau and Chixculub astrolime, and Shiva [21]. It is probably not accidental that the Anabarsky diamondiferous region is located within a ring structure (of undetermined age), revealed by the interpretation of satellite images and confirmed by geophysical data [22, 23] and interpreted as Anabarskaya deep explosive structure (Figure 10) [24].
Figure 8. Variation of SiO₂ versus (Na₂O+K₂O), Na₂O, K₂O, TiO₂, Al₂O₃, FeO₉, MgO, CaO in the glasses of Orto-Yiarginskoe field, and Popigai structure, and in the biotite-garnet gneiss basement Popigai structure.
Figure 9. Digital elevation model (satellite image) of the Popigai impact structure and its immediate environment (a). The outer propagation edge of impact breccia is indicated by a dotted line, the centerline of the inner annular shaft is shown by a solid line (using data from Deutsch et al., 2000). The system of radial shock arc cracks and submeridional discontinuities intersecting radial cracks is clearly visible. b, c, d - photographs of cross-sections of the compacted pyrite-quartz mixture after the shock-wave load. In the center there is a zone of amorphization, vitrification and melting, from which shock arc cracks diverge. c - to the left of the center there is a well-marked fracture crack (subvertical), to the right it is weakly manifested; d - the shear nature of shock arc cracks is clearly visible in the metal shell. The diameter of the central zone of 0.2-0.3 mm; compactite diameter of 20 mm (by Zhmodik et al., 2004).
Figure 10. Geological position of the Popigai diamondiferous ring structure (I, diameter 100km) and deep explosive structures: Anabarskaya (II), Kotuykanskaya (III), Esseyskaya (IV), Dzarayskaya (V), detected by the interpretation of satellite images and confirmed of the geophysical methods (Rosen and others. 1986). The structures are confined to the frame of the Anabarsky shield, composed of Archean granite-gneisses (I), which also form a ring elevation in the Popigai structure (2); 3 - fields of kimberlite pipes: 1-Dalbihinskoe, 2-Tucholanskoe, 3-Kharamaiskoe, 4-Kuranakhskoe, 5-Kuonamskое, 6-Luchakanskое, 7-West-Ukukitskое, 8-East-Ukukitskое, 9-Chomurда, 10-Ogonier Uryakhsky, 11-Merchymensky, 12-Molodinsky, 13-Kuoisky, 14-Toluopsky, 15-Kharbosuonsky.

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