ГЕОЛОГИЯ, ПОИСКИ И РАЗВЕДКА ТВЁРДЫХ ПОЛЕЗНЫХ ИСКОПАЕМЫХ, МИНЕРАГЕНИЯ

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Placer Gold Composition and Provenance Studies in the Kuznetskiy Alatau and Western Sayan, South-East Siberia: Results of Field Trip, Summer 2014

G. J. G. Paxman[a], B. S. Gregory[a], S. J. Payne[a], J. B. Forshaw[a], M. P. Brady[a], M. D. Khan[a], D. Avadanii[a], G. Wardle[a], J. J. Wills[b], O. N. Kovin[c], O. B. Naumova[c], B. M. Osovetskiy[c], and V. A. Naumov[d]

[a]Department of Earth Sciences, University of Oxford, South Parks Road, Oxford OX1 3AN, UK. E-mail: guyp@earth.ox.ac.uk
[b]Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK
[c]Geological Faculty, Perm State University, 15 Bukireva Str., Perm 614990, Russia
[d]Natural Sciences Institute of Perm State University, 4 Genkelya Str., Perm 614990, Russia

This article presents the results of a study of gold samples obtained by students during a practical field trip in the summer of 2014. Placer gold samples retrieved from four rivers in southeast Siberia (Khakassia and Tyva territories) by panning and sluicing were described and analyzed compositionally by Scanning Electron Microscopy. There is evidence from grain flattening and morphology for significant variations in gold transport distance, both within and between sample locations. The composition and texture of gold is compared to similar studies in the Yukon, and it is inferred that most of the placer gold in the region originated from orogenic lode sources. This orogenic gold is of Devonian to Carboniferous age. There is also evidence for a contribution from igneous intrusion-related bedrock gold, which is supported by the presence of granite, granodiorite and sienite intrusions of Devonian age. There is scope for further study, since relatively few grains were analyzed here. In addition, if compositional data of the prospective primary gold deposits can be obtained, there would be potential for more precise determination of provenance.

Keywords: *placer gold; Kuznetskiy Alatau; West Sayan; Siberia; sampling; panning; composition; grain morphology.*

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Introduction

Previous studies of the texture and composition of placer gold samples from the Western Yukon [3]; [7] have allowed the authors to draw preliminary conclusions regarding the origin and depositional history of the grains. In this study, we employ the same methods on four river locations in southeast Siberia. The study was carried out in order to develop an understanding of the evolution of the gold deposits that are found in the alluvium of these rivers. After recovering the placer gold from the locations, the samples were taken to Perm State University, Russia. Here, the gold grains were separated from the concentrate, and their chemical composition was analyzed. In addition, the morphology of the gold was described. The data were integrated, and some conclusions regarding the provenance of the grains are presented here. From the compositional data, we attempt to match placer gold particles to possible sources, while the textural information provides an insight into the transportation history of the gold.

Geographical settings

The area of study is located within the southern part of Siberia and encompasses territories of the Khakassia, and Tyva (Tuva) Republics (figure 1). The Republic of Khakassia, whose capital city is Abakan, is located northwest from Tyva Republic. Krasnoyarsk Kray, Kemerovskaya Oblast, Tyva Republic, and Altay Republic border Khakassia. The Kuznetskiy Alatau Mountains serve as the geographical border to the west, with the Western Sayan ranges stretching along the southern border. Eastern boundary of Khakassia is formed by the Dzhebashsky Range and Yenisey River [11].

In Khakassia, there are two rivers of interest, at which samples were collected - the Abakan and Beliy Ius (figure 2). The Abakan River rises in the Altay Mountains and flows northeast through the Minusinsk Depression, joining the Yenisey River at the confluence in Abakan. The Beliy Ius, a tributary of the Chulym River, has its sources in the Kuznetskiy Alatau.

Figure 1. *Location of the study area*

Khakassia is rich in mineral resources (e.g. coal, iron ore, and nonferrous metal ore, including gold).

The Tyva Republic is situated in the far south of Siberia (figure 1). It borders Khakassia to the northwest, Krasnoyarsk Krai to the north, Altay to the southwest, Irkutskaya Oblast to the northeast, Buryatia to the east, and Mongolia to the south. Its capital city, Kyzyl, is located near the geographic centre of Asia.

Two major rivers of Tyva, Bia Khem and Kaa Khem (with its tributary Bai Syut), are tributaries of the Yenisey River (Ulug-Khem), which flows west through Tyva and then passes through the Western Sayan Mountains in a gorge containing the Sayano-Shushenskaya Dam.

The river then flows through the Minusinsk Hollow to the east of the Kuznetskiy Alatau. The Minusinsk Hollow also contains a famous deposit of coal: The Minusinsk Coal Basin. Natural mineral resources of Tyva include iron ore, gold, cobalt, coal and asbestos. Gold samples were taken from two localities in Tyva: Bia (Bii, Biy) Khem (Upper Yenisey River) and Bai Syut (figure 2).

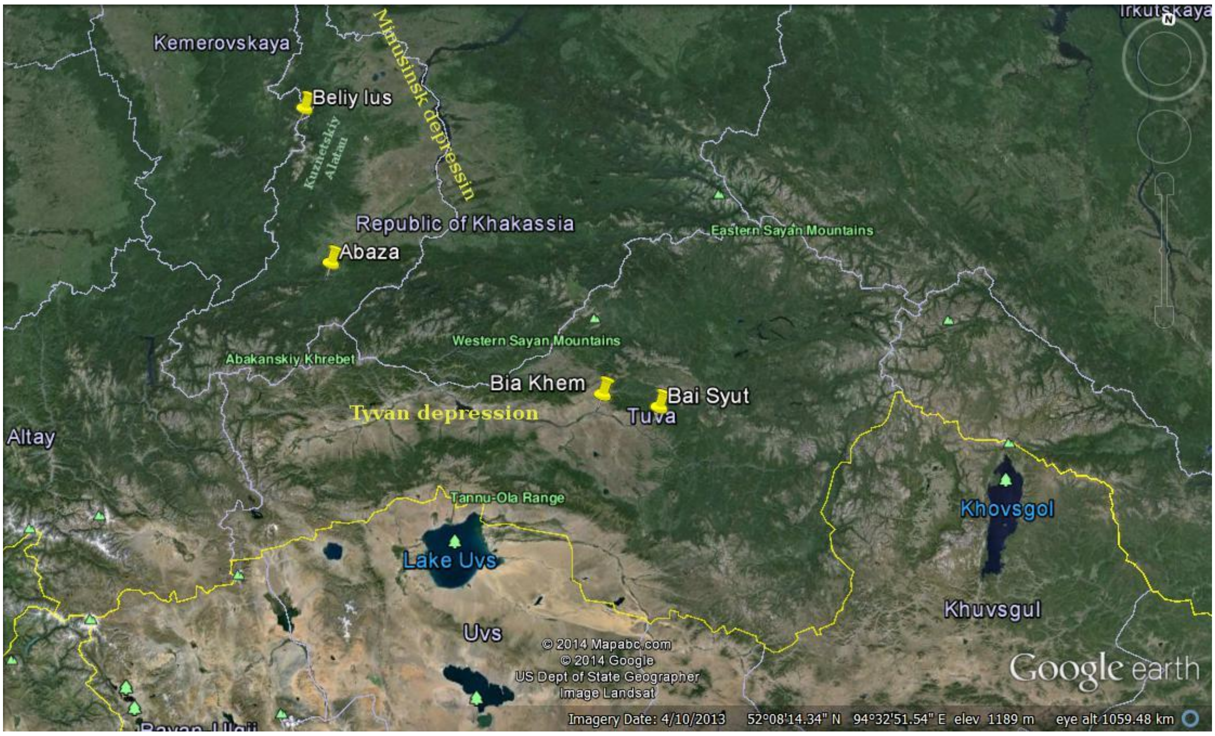

Figure 2. *Sampling sites location. The yellow pins accompanied by white labels mark the four geographic locations (rivers) at which gold samples were collected (modified from Google [5])*

A wide range of lithologies outcrops within the Khakassia and Tyva Republics. In general, a bimodal distribution of the geology is reflected in the landscape (figure 3).

Figure 3. *Geography of the south-central Siberia area (modified from Wikipedia [17]). The area of study is shown by the orange box*

Geology and tectonics of the area

Precambrian to Upper Palaeozoic sedimentary and igneous rocks form the elevated regions of the Kuznetskiy Alatau and Western Sayan Mountains [10]. These rocks are juxtaposed against Devonian–Permian sediments, which comprise the Minusinsk Depression [14]. The action of approximately north–south-trending normal faults caused subsidence of the South Minusinsk Depression in the Devonian while the regions to the north (Kuznetskiy Alatau) and south (Western Sayan Mountains) were contemporaneously uplifted. Denudation of these uplifted Precambrian–Silurian rocks provided a sediment supply, which filled the accommodation space. Sedimentation also occurred in the North Minusinsk Depression to the northeast of the Kuznetskiy Alatau.

The basement rocks are Rifean (Neoproterozoic) to Cambrian in age [9]. They comprise a large sequence of meta-sedimentary rocks metamorphosed during the Salair (Kuznetskiy Alatau) and Caledonian Orogenies (Western Sayan). An ophiolite sequence is exposed, with ultramafic and gabbroic rocks at the base. The overlying pillow basalts are succeeded by metapelites, black quartzites, and marbles. Typical metamorphic conditions peaked in the amphibolite facies, although retrogression to greenschist facies is common. Chlorite schists are exposed in the Western Sayan Mountains. These rocks are folded into large-scale anticlinal and synclinal structures, which make up the Kuznetskiy Alatau and Western Sayan Mountains.

In the Ordovician and Early Silurian, large-scale igneous intrusive activity occurred in the Kuznetskiy Alatau. Granites, sienites and diorites were intruded into the pre-existing Cambrian and Rifean rocks. Contemporaneously, in Tyva, the Hemchikskaya Basin (east of the Western Sayan Mountains) began to accumulate sediment. A wide variety of lithology is recorded, including sandstones, conglomerates, clays, limestones and marls, as well as tuffs and basalts.

At the start of the Devonian, extension resulted in the formation of the North and South Minusinsk basins and the Central Tyva Depression. Denudation of the local uplands formed a sediment source, and a large sequence of Devonian to Permian sediments was formed. The early fill was coarse clastic material. In the Carboniferous, the depositional environment was deltaic. Silts and clays are widespread, and coal deposits were also formed. Bentonites are found within the coal-bearing basins, containing smectite clays and glassy fragments of volcanic ash. The youngest fill in these basins is Permian sandstones and siltstones (aleurolites).

The last igneous activity of importance occurred in the Devonian, and affected the Kuznetskiy Alatau and Western Sayan Mountains. This effusive and intrusive activity was responsible for mineralization, including formation of intrusion-related gold deposits. These bedrock gold formations are a source of placer gold found in the present-day and paleo-rivers in the region.

The tectonic processes of this region in simple terms can be linked to the disintegration of Rodinia and formation of Pangaea [13].

There are four significant orogenic events in this region. The first occurred during the Early Palaeozoic; its products are commonly referred to as the Salairides. The event led to the formation of the basement of the Minusinsk Depression, and the Eastern Sayan mountain range, which strikes southeast–northwest for 1000 km from Lake Baikal to the Yenisey River.

The next event, the Caledonian Orogeny, occurred from the mid-Cambrian to the Early Devonian and resulted in the formation of the West Sayan and Altay mountain ranges. Variscan folding in the Carboniferous and Permian followed this event.

The Early Palaeozoic structures of the Salairides and Caledonides are believed to be a result of the accretion of numerous Paleo-Asiatic islands to the Siberian continent [1]. This was the collision event between the Siberian continent and the Tyva-Mongolian massif that caused the Salair Orogeny and produced the associated batholiths and granite-gneiss domes [13]. It also resulted in the Devonian collision with the Altay microplate; this led to the formation of the Caledonian fold belt. Subsequently, the combined Siberian-Altay-Sayan landmass passed over a hot spot, initiating intraplate magmatism, crustal extension and faulting [12].

The collision of Kazakhstan and Siberia after the mid-Devonian produced subduction zones between the two paleo-continents. During the Early Carboniferous, the development of the Kazakh-Siberian subduction zone resulted in the thrusting of the Salair block over the Siberian margin. This culminated in the mid-Carboniferous with the main sequence of mountain-building activity [4].

Towards the end of the Variscan Orogeny, nappes were formed and shearing occurred along fault planes. Orogenic activity was absent during the Mesozoic, but resumed in the Oligocene. By this time, most of Altay-Sayan orogenic belt had been eroded.

This region is marked by evidence of intense faulting associated with the numerous orogenies, strike-slip plate tectonics and magmatism that have occurred over the Phanerozoic. Active tectonics still exist today, the most prominent of which is the Baikal Rift Zone to the east, which spans 2000km, and is extending at a rate of about 4mm/yr southeast–northwest.

Methodology of sampling and sample analysis

Field procedures. In the field, we collected samples of valley alluvium from the four geographic locations described above (figure 2). Unconsolidated fluvial sediment is a common source of placer mineral deposits, which form by gravitational separation during the sedimentary processes taking place in the river. Gold and other heavy minerals are concentrated along the insides of bends – away from the Thalweg – where current velocities are insufficient to transport the particles further, providing the optimum conditions for deposition. A gold-bearing fraction was obtained from the auriferous gravel by panning and/or sluicing.

Panning uses the principle of gravitational settling in a fluid medium (water), whereby heavy minerals sink to the base of the sediment pile, allowing the lighter siliciclastic grains to be removed. Occasionally, sluicing was used to separate heavy and light fractions of finer-grained (sub-2mm) material. The silts and clays were sluiced using a spiral concentrator (figure 4), which causes the material to separate into two streams at the bottom.

Denser material moves to the inside; lighter material finishes on the outside [7]. The less dense fraction (containing clastic material such as clay) was collected and resluiced multiple times. This was to ensure that all the heavy minerals had ample chance to separate into the heavy fraction. Both fractions were ultimately collected for laboratory analysis.

Figure 4. *Dr. Vladimir Naumov is demonstrating the sluicing apparatus used to separate the heavy mineral and clay fractions in the field (Beliy Ius River). The principle behind the technique is that grains are separated in the sluice owing to their density*

Laboratory methods. Before analysis, the gold pan samples were dried thoroughly. For larger samples, it was necessary to first separate an ultra-heavy fraction from the main fraction of sediment. This was achieved by small-scale panning with water and, where necessary, further gravitational sorting in a heavy liquid (tribromoethane) with high specific gravity (3g/cm^3). The samples were dried using a heater to prepare them for examination. The ultra-heavy fraction was commonly rich in magnetite, and so a magnet was passed over the sample in order to remove the majority of Fe_3O_4 mineral grains, leaving non-magnetic minerals, including gold. Typically, the samples comprised around 50% magnetite.

To inspect the remaining material, we used the Leica ES2 and Meiji Techno EMF binocular microscopes (figure 5). Each grain was examined manually to uncover gold particles and flakes, which were systematically described and separated.

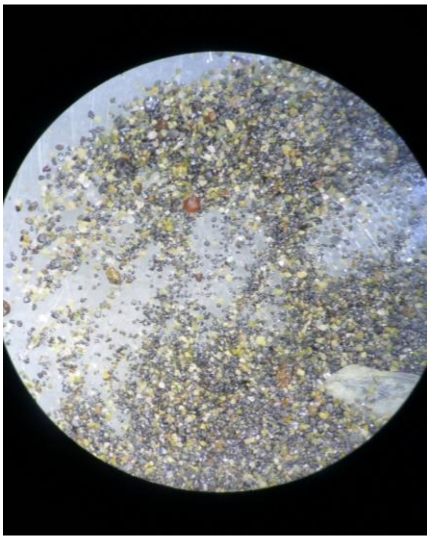

Figure 5. *Sample 39, seen through a binocular microscope; a variety of minerals can be seen. The field of view is 20mm*

Minerals in the samples at this stage included felsic minerals (quartz and feldspars); iron minerals (magnetite and hematite); sulphide minerals (pyrite and chalcopyrite); epidote; gold; garnet; and rock fragments.

The features of the gold particles documented were: grain size (x- and y-axes), grain morphology, surface texture, colour, and grain outline. Eighty-five gold grains were recovered altogether; forty-four of the smallest were placed on an adhesive carbon tab attached to an aluminium cylinder specimen mount for use in a Scanning Electron Microscope (SEM).

Two SEMs were used in the laboratory studies in the Department of Mineralogy and Petrology at Perm State University. We used a JEOL JSM-6390LV SEM to determine the elemental composition of each of the 44 gold flakes. The distance between the electron gun and the sample was set to 9mm. Compositional percentages of *Au, Ag, Cu, Co, Ni, As, Sb, Bi, Se, Pt, Hg, Al* and *Fe* were recorded, as well as any other elements, such as *Si*, that occurred in percentages of more than 2.5%. The weight percentages of detected elements were then normalized, such that they summed to 100%.

We subsequently used a JEOL JSM-7500F Field Emission SEM (figure 6), in order to examine each grain more closely and capture images of them. Details noted include the presence of silicate inclusions and clay films, pits, scratches, and various nanostructures.

Results and discussion

This section presents the results of the morphological and geochemical analyses for the four sample sites. Owing to their close proximity and common source, the Bai Syut and Bia Khem localities are presented together. The results for each locality are discussed within each subsection, and then all localities are compared. For each site, the gold is described in terms of location, size (dimensions and area), flattening, outline, surface texture, and composition (including gold fineness). Those descriptors whose meaning is not immediately apparent are de tailed here.

Figure 6. *The JEOL JSM-7500 Field Emission Scanning Electron Microscope at Perm State University used to examine and image gold particles*

The flattening index is a quantitative measure of the extent to which a grain of gold is elongated from a circular shape. The index is calculated as [6]: *Flattening=(x-y)/x*, where *x* is the length of the *x*-axis and *y* is the length of the *y*-axis. A circular grain (whose *x*-axis and *y*-axis are the same length) has a flattening of zero. A very elongate grain (whose *x*-axis is much longer than the *y*-axis) has a flattening close to one. The *x*-axis is always defined as the longer of the two dimensions, with the *y*-axis perpendicular. Higgins [6] suggests that flattening is a useful indicator of transportation distance between 5 and 15 km. At shorter distances, the source morphology dominates, whereas at larger distances, most grains have become well flattened.

Grain outline is a qualitative measure of the two-dimensional shape of the grain. In this report, we adopt the nomenclature shown in Higgins [6], and classify grain outline into four categories – branched, complex, equant, and elongate. These are given in order of maturity. A typical gold grain is expected to progress from an initially branched or complex morphology to a more equant and then elongate form. This is due to mechanical abrasion in the hydraulic environment. A caveat is attached to this classification in that the assumption that grains are released from their source with a branched morphology is unlikely to hold in all cases. Some grains may be equant or elongate from the outset.

Surface texture is a measure of the ‘evenness’ of the gold grain surface. Grains were assigned to one of five categories based on a qualitative inspection under the binocular microscope: nodular, uneven, fairly uneven, fairly smooth, and smooth.

Chemical composition refers to the percentage by weight of the major chemical elements contained within the gold sample, as measured using the SEM. Bulk gold fineness is a quantitative measure of the ratio of gold relative to silver in the sample:

$$Bulk\ gold\ fineness = Au/(Au+Ag)\times 1000,$$

where *Au* is the normalized wt. % gold and *Ag* is the normalized wt. % silver. Under this metric, a sample of pure gold has a fineness of 1000, while a sample of pure silver has a fineness of 0. We can also count the fineness incorporating all other metal impurities. In this instance, *Ag* in the formula above is replaced by the sum wt. % of all impurities being considered.

Beliy Ius. We collected nine grains from Beliy Ius (figure 7), four of which were analyzed using the SEM. In terms of surface texture, three of the grains were nodular, three were smooth, two were uneven and one was uneven. For all the samples, the flattening index and surface area were calculated, with the shapes approximated as ellipses. Three of the samples analyzed with the SEM had roughly the same value of the flattening index (approximately 0.40), while grain 5-5 was anomalous with a value of 0.07. The area of the grains varies from approximately 0.067 to 0.59 mm^2. The morphology and general shape of the grains can be observed in the SEM photos (figure 8). Four out of nine grains were classified as complex, two as equant, and three as elongate.

Figure 7. *Sampling site on the bank of Beliy Ius River*

The bulk gold fineness ranges from 958 to 994. The values for fineness with metal impurities are smaller because other metals are taken into account. These values range from 951 to 990. Overall, for this site, the average gold composition is 96.17% and the average silver composition is 2.32%. Of the four grains analyzed by the SEM, none contained less than 94% gold by weight.

There are no notable variations in the general chemical composition of the samples, except in values for *Ag* and *Cu*. *Ag* concentration varies between 0.63% and 4.13%, while *Cu* varies between 0.20% and 0.74%. Grains with high *Ag* concentrations correlate with low concentrations of *Cu*. Conversely, grains with high *Cu* concentrations are associated with lower than average *Ag* concentrations. Some grains contained detectable concentrations of *Hg* and *As*.

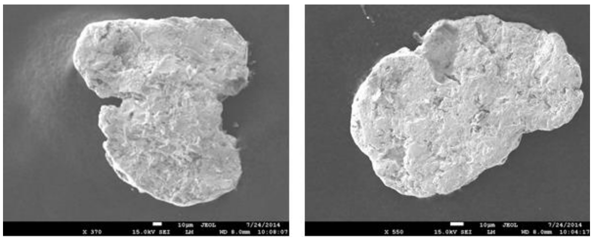

Figure 8. *Representative gold grains collected from the Beliy Ius as seen under the SEM. The grain on the right exhibits micro-scratches oriented top left–bottom right. These are the product of fluvial abrasion and reveal the direction of scouring by other particles, which is evidence of current direction during transport. The magnification is x370 on the left; x550 on the right*

Given the generally high concentrations of *Ag* and low flattening index, the transport distance is likely to be low. Therefore, the grains could have been sampled relatively close to the source. Sample 5-5 has the highest concentration of *Ag* (indicator of low travelling distance) and the lowest flattening index (indicator of high travelling distance). This could be due to the differences in the distribution of elements within the source rock. This suggests the grains may originate from different areas of the same deposit or from different deposits entirely. However, due to the small sample size these data are not sufficient to draw strong conclusions.

We identified three possible sources for the placer gold collected in the Beliy Ius River (figure 9). However, the large gold deposit to southeast of the Beliy Ius can be ruled out as a major contributory source, owing to the presence of the major drainage divide existing between this primary gold and the placer location. The gold is unlikely to be from either of the large sources, 70–100km away. If the grains had been carried this far, evidence for high textural maturity would be observed, which is not the case. The source is most likely to be the small deposit of gold at Kommunar, around 20km to the southwest of the sample location.

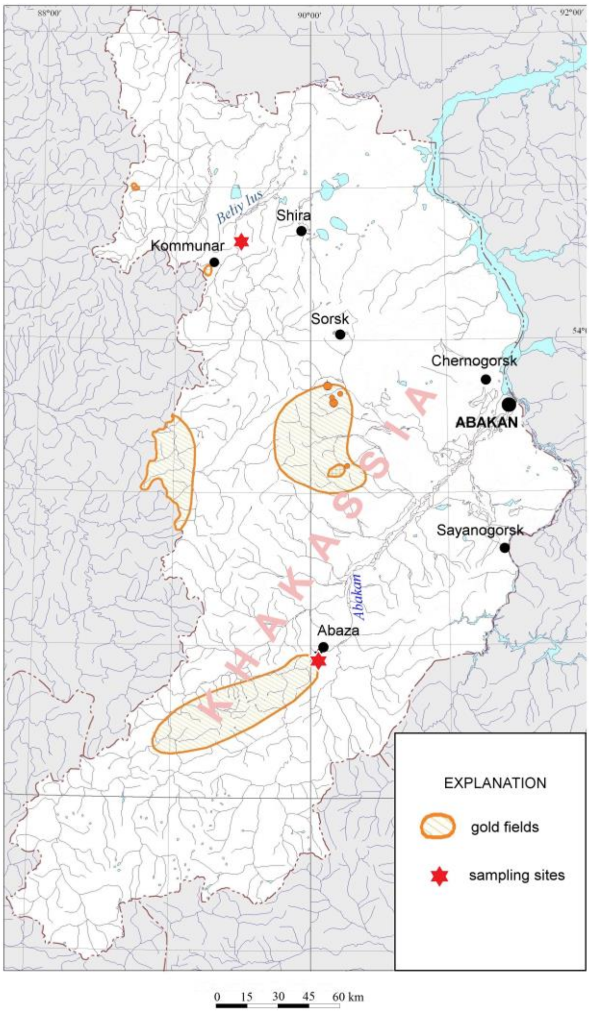

Figure 9. *Map of northern Khakassia, showing prospective and explored gold sources/mines (modified from VSEGEI [15]). The known gold fields are shown by the dashed orange areas. The red stars denote the sample locations on the Beliy Ius and Abakan Rivers*

Abakan River. Forty-one gold grains were collected from the Abakan River near Abaza (figure 9, 10). The size range for the grains is quite small, with all grains falling between 0.1 and 1.0 mm.

Figure 10. *Sampling site on the bank of Abakan River*

The majority have a smooth surface texture, and very few are nodular. Instead, many had a platy shape. The modal grain outline was equant (23 grains), while the rest were complex (12 grains) or elongate (6 grains). No grains were branched (figure 11). Grain flattening index varied between 0 and 0.80, although the average was only 0.25, suggesting that most grains had a flattening index significantly lower than the median (0.40).

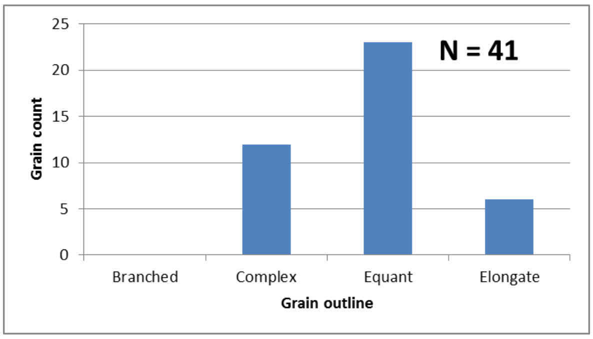

Figure 11. *A histogram showing the distribution of grain outlines from the Abakan River. 41 grains were described in total*

SEM images of typical gold grains from this locality are shown in figure 12. Microstructures are also well developed in several grains, with micro-scratches (figure 13) representing the action of mechanical abrasion in the fluvial environment.

Compositionally, gold contents of almost all grains were exceptionally high. Of the 20 grains analyzed by the SEM, only four were found to contain less than 95% *Au* by weight.

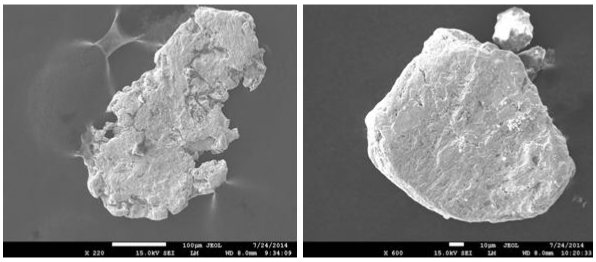

Figure 12. *Representative gold grains collected from the Abakan River as seen under the SEM. A grain with complex outline and high flattening index is shown on the left, and an equant grain with lower flattening index is shown on the right. The sample on the left is photographed with a magnification of x220, and on the right x600*

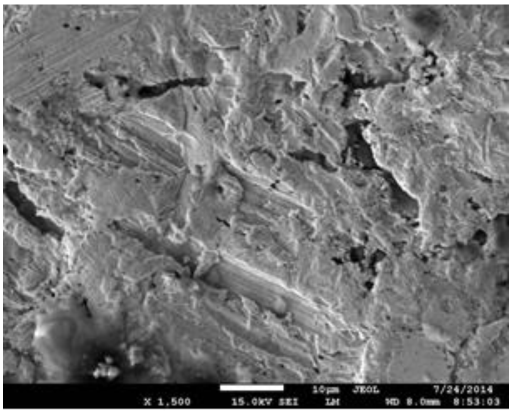

Figure 13. *A highly magnified SEM image of a gold grain from the Abakan River showing micro-scratches on its surface. This provides evidence that this grain was transported in an alluvial environment in at least two directions over its transport history. The image is of x1500 magnification*

The highest gold concentration was 99.18% and the average was 97.66%. Only one of the grains had a bulk gold fineness value lower than 970, indicating exceptionally pure samples. Of the elements present other than *Au*, the most significant were *Ag* and *Cu*. *Ag* concentrations reached 4.3% in one sample. The other metals, which were detected when conducting SEM analysis, were *Co, Ni, As, Se, Pd, Sb, Pt* and *Hg*. This variety of heavy metals may be an indicator of the source of the gold. It was observed that when neither *Cu* nor *Ag* were present, it was common for two other heavy metals to be found as impurities.

It can be inferred from the data collected that the gold panned from the Abakan River is likely to have only one source. Geochemical analysis of the grains under SEM would support this hypothesis, due to the consistently high concentration of gold and abundance of heavy metals. The low concentrations of *Ag* and *Cu* also suggest a relatively mature gold deposit, as leaching could have occurred largely; the high proportion of equant grains in the sample supports this claim. However, the large number of complex grains and the high variation in flattening index may support a different hypothesis. Figure 9 shows that the sample location is within a major gold source area in Khakassia. The Abakan River is located at the edge of a large gold-bearing area, around 80km x 20km. This means that there is potential for significant variation in the textural and compositional maturity of the placer gold depending on its distance from the source.

Bai Syut and Bia Khem. Thirty-five gold grains in total were collected from the Bai Syut and Bia Khem sample localities. Thirty-two of them were collected near the Tardan gold deposit at Bai Syut. The remaining three were collected 60 km westward at the Bia Khem River (figure 2, 14).

Figure 14. *Location of sampling sites in Tyva Republic. From left to right: panning at Bia Syut River; Bia Khem River bank*

The grains range in size from 0.1 to 3.0 mm, although only one quarter of the grains are greater than 1.0 mm. The majority have a relatively uneven surface texture and many are nodular. The modal grain outline was complex. Half of the grains were categorised into this descriptor, while most others were described as equant. Only five grains were elongate, and none of them were branched (figure 15). Grain flattening index varied between 0 and 0.61, with an average of 0.36. Interestingly, the three grains from Bia Khem all had flattening indices of close to 0.15, significantly lower than the overall average.

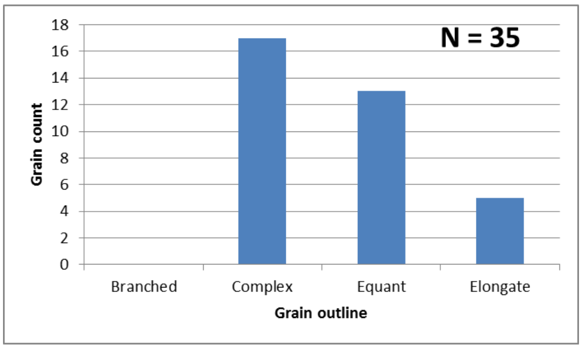

Figure 15. *A histogram showing the distribution of grain outlines from Bai Syut and Bia Khem. Thirty-five grains were described in total*

SEM images of typical gold grains from these localities are shown in figure 16.

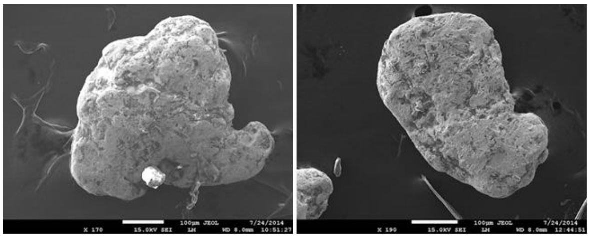

Figure 16. *Representative gold grains collected from Bai Syut as seen under the SEM. A grain with complex outline and low flattening index is shown on the left, and an equant grain with higher flattening index is shown on the right. The magnification is x170 on the left; x190 on the right. Based on the morphologies, we infer that the right grain has been transported further*

Compositionally, gold contents of almost all grains were very high. Of the 20 grains analyzed by the SEM, only six were found to contain less than 95% gold by weight. Only three grains had a bulk gold fineness value lower than 980. However, two of these fineness values were 909 and 919, so their *Ag* content was significantly elevated relative to the other samples (figure 17).

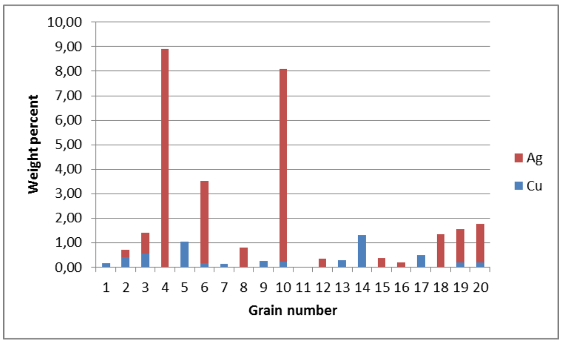

Figure 17. *Graph showing weight percentage Ag (red) and Cu (blue) content of 20 grains from Bai Syut and Bia Khem. Notable is the bimodal distribution of grains with high Ag, low Cu (4; 6; 8; 10; 12; 15; 16; 18; 19; 20) and low Ag, high Cu (1; 2; 5; 7; 9; 13; 14; 17). This may reflect a difference in provenance of these two families of gold grains*

Aside from a few grains containing detectable *Hg* and *As*, the most notable variations in element concentrations were those of *Cu* and *Ag*. Those grains with elevated *Cu* concentrations typically exhibited lower than average or negligible *Ag* concentrations. Conversely, the grains with high *Ag* concentrations commonly contained no or little *Cu*. Several grains contained only *Cu* or only *Ag*.

The relatively low amount of flattening and prevalence of complex and equant grain outlines suggest the transportation distance from the source is relatively low. Examining the map of gold sources in the region (figure 18), it can be seen that the one large source of primary gold is proximal to the Bai Syut and Bia Khem sites. Therefore, we would expect the grains to be texturally immature, owing to the low transport distance, and this is indeed what we see. The low flattening of the grains from the Bia Khem might suggest they were found closer to the source, but figure 18 implies this is not the case. Three grains are insufficient to draw any firm conclusions in this case.

We might infer, from the geochemical analysis, that there are probably two or more sources for the placer gold grains. One distinct population is characterized by high *Cu* and relatively low *Ag*, while the other contains elevated *Ag* but low *Cu*. Although there is only one major bedrock gold source (figure 18), there are many lateral variations in composition. It may be that two or more different gold types within the large source area are contributing to the placers. Another possibility is that there is an input from the small source to the north of Kyzyl (figure 18). It is difficult, however, to envisage how these grains could get into the Bai Syut River, because they belong to different river basins not connected to each other, and they should appear highly texturally mature.

Comparison and discussion. Of the three areas, the Beliy Ius River had the highest average flattening index, with 0.39. From this, we might infer that the grains collected in this river had been transported farther than those in the Bai Syut (0.36) and Abakan (0.25) Rivers. However, the difference is not especially significant. Assessment of the grain outlines suggests the Abakan grains are more mature than those from Bai Syut, which

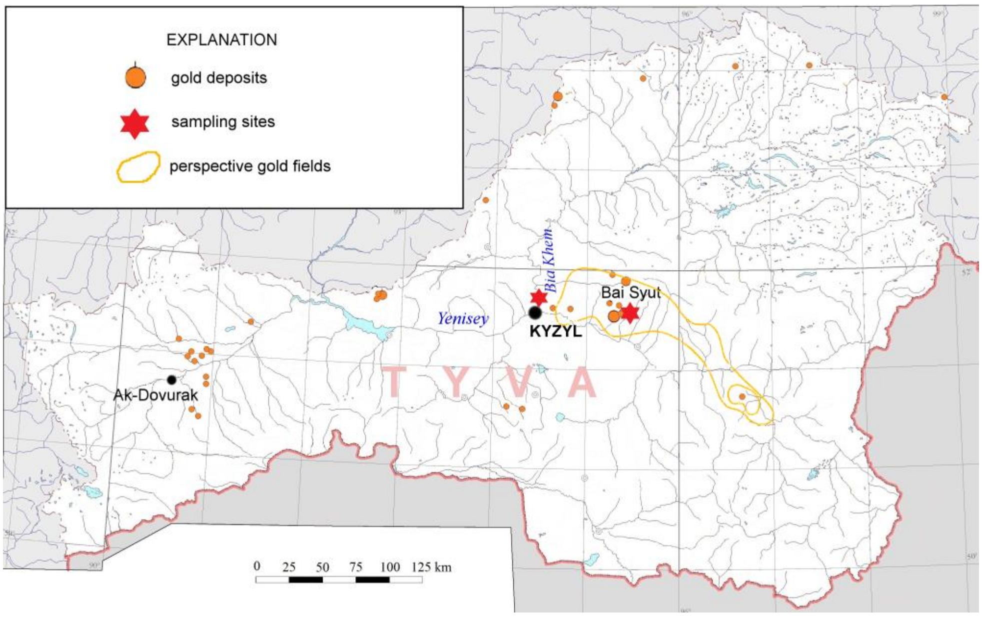

Figure 18. *Map of the Kyzyl region of Tyva showing explored gold sources/mines (modified from VSEGEI [16]). The known gold deposits are shown by the orange areas. Red stars mark the sample locations*

is contradictory to the average flattening indices.

This may be reconciled if we recall that flattening is a reliable indicator of transport distance only between 5 and 15 km [6]. Since the sample locations were commonly much closer to (in some cases the site was superimposed on bedrock gold) or much further from the primary gold source areas, the usefulness of the flattening index as a proxy for transport distance in this study is doubtful. Furthermore, with relatively few grains in each location, there was often quite a large range of flattening values, making the mean value somewhat ambiguous.

Another possible proxy for the time spent in the fluvial environment is the surface texture of the grains. As shown in figure 19, the grains from Bai Syut and Bia Khem were typically nodular and uneven, whereas the Abakan grains tended to be more smooth. This suggests the Abakan grains had been subjected to a greater degree of fluvial abrasion, causing their surface to become smoother. However, surface texture may also reflect differences in the gold source. Moreover, grains transported a similar distance in two different rivers could be subject to significantly different levels of erosion, which is governed by factors such as current velocity, channel profile, and other parameters in the river's hydrological regime.

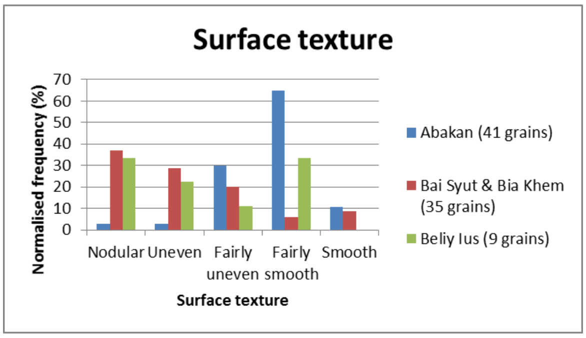

Figure 19. *Histogram showing the normalised frequency of grains with various surface textures in each of the sample locations. The notable comparison to be drawn is the high number of fairly smooth and smooth grains from the Abakan River, whereas most grains from Bai Syut were uneven or nodular*

Compositionally, all the gold had notably high fineness values. However, each site did have notable compositional trends. The Abakan River gold was often remarkably close to being pure, and almost all grains had bulk fineness above 980. The average bulk fineness was 989. Aside from *Ag*, the common impurity was *Cu*, but only in very low quantities. The other metal impurities, which were detectable in only a very few grains, were *Ni*, *As* and *Hg*. The Bai Syut gold was slightly less pure, but the average bulk fineness was still 986 (figure 20). The trace element signature was slightly different, with *Co* and *Se* occasionally present instead of *Ni* and *As*. *Hg* was more common in this location. It was difficult to discern any patterns from the four analysed grains from the Beliy Ius River, although the average bulk fineness was notably lower at 976. *Cu* and *Ag* were always present (with evidence of the bimodality that characterised the Bai Syut and Bia Khem grains), and *Co* and *As* were occasionally observed. *Hg* was entirely absent.

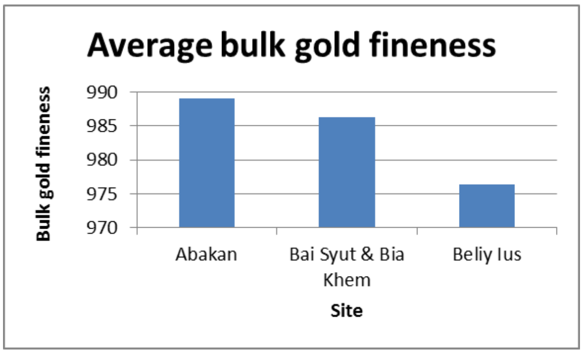

Figure 24. *Average bulk gold fineness values for the three geographical locations in this study*

From the compositional data, we can conclude that there are clear differences in the source of the gold for each placer site, but the broad category of bedrock gold is likely to be the same. We can conclude, therefore, that the primary gold sources involved were likely formed in the same event, but with local variation in chemical conditions controlling the subtle chemistry of the final product.

Gold from the Abakan River had a high percentage weight of *Au*, perhaps meaning that it is softer than samples from other sites, and subsequently more likely to be susceptible to mechanical erosion during transport. Hence, a shorter distance is required to make an initially branched grain become equant, or even elongate. However, this purity could also be due to the leaching of metals such as *Ag* and *Cu* as it is transported, with this argument being supported by the high proportion of equant grains. However, the presence of heavy minerals in almost every grain analyzed contradicts this hypothesis. More detailed study of surface texture should provide us with the answer as to where the source of this Abakan River placer gold is located.

As we have seen, much of the placer gold has relatively low *Ag* and *Hg* concentrations, the latter often undetectable. If we assume the placer gold is a good representation of the primary source, we can make an inference about its origin. Chapman et al. [3] found evidence for three styles of gold mineralisation from their studies in the Yukon. These are orogenic, low sulphidation epithermal, and intrusion-related. The characteristics of these three types from the Yukon are displayed in a Table.

Of these three styles of mineralisation, the placer gold of studied area best matches the orogenic type. *Ag* contents are notably low in the placer gold of this study. An explanation for this may be that the SEM probed only the rim of the grain, which can be subject to leaching in the natural environment, leading to the preferential removal of *Ag*. *Hg* and *Ag* contents were not high nor varied enough to support an epithermal origin. There is also a general lack of sulphide inclusions observed in the grains collected in Siberia, which does not favour an epithermal source [8]. Elevated *Cu*, particularly in the Bai Syut locality, may support an intrusion-related source. Indeed, this may be one of the two proposed origins for this placer gold.

If the gold in the region is mostly orogenic, it likely originated in the Devonian and Carboniferous, during the major mountain-building phase that occurred at the time. Recall from the earlier discussion that there was also widespread igneous activity at this time. Skarn-type mineralization is observed in certain areas (e.g. Tardan gold mine), and this intrusion-related gold may be the source of the high *Cu*-low *Ag* suite in the Bai Syut and Bia Khem Rivers.

Table. *Characteristics of the three types of gold described in the Yukon Territory of Canada (adapted from Chapman et al., [3])*

Ag range (wt. %)	Hg (wt. %)	Cu (wt. %)	Inclusion suite	Style of mineralisation
10–40	0–4.0	Nil	Rare sulphides	Orogenic
10–70	0–11	Nil	Abundant polymetallic sulphides	Low sulphidation epithermal
5–20	Nil	0.05–0.17	Various	Intrusion-related

Conclusion

In this study, we analyzed a total of 85 gold grains collected from four rivers in the South-East Siberia. We have used compositional data and described the morphology of the grains to gain an understanding of the source and transportation history of the placer gold. We can draw the following conclusions:

1. The majority of the placer gold from Beliy Ius has a relatively high flattening index. This suggests that the gold has been transported relatively far from the source. The composition was uniform, although very few grains were available for analysis. Examination of the local geography shows that the small deposit of gold (Kommunar mine) around 20km to the southwest of the sample location is the likely source. These gold grains were transported roughly this distance to the sample location.

2. The gold panned in the Abakan River had very high gold content. The compositions were relatively uniform across all 41 samples. There is one clear source for this gold, and the only likely variation in the history of the gold grains is the transportation distance, since the area of the lode gold source is very wide (80km x 20km). The consistently high fineness values and compositional data suggest the source is uniform across this area, and has very high gold content compared to silver and other metals. The average flattening index of 0.25 suggests low transport distances, but the grain outlines suggest that the gold is quite mature. The reliability of the flattening index at high transportation distances is questionable, and it is likely that the equant and elongate grains have been transported significant distances.

3. Those samples from the Bai Syut and Bia Khem localities have a bimodality in their composition, expressed in the silver and copper concentrations. This is inferred to represent the input from two compositionally distinct areas in a heterogeneous primary gold source. This bedrock gold is located to the east of Kyzyl, and contains orogenic and intrusion-related (skarn) gold.

4. Descriptions of grain outline show that the Bai Syut / Bia Khem grains are more complex in shape than those from the Abakan River, which tend to be more equant or elongate. The geographical maps support the conclusion that the Abakan grains are more mature. This contradicts the flattening data, which suggests Bai Syut grains are more mature, since they have higher flattening index values. This may be reconciled since the flattening index is a reliable indicator of transport distance only between 5 and 15 km. Outline may be viewed as a more accurate measure of maturity, but a firm conclusion is not possible.

5. The four placer sites yielded gold with a distinct chemical composition. Average fineness values are notably different, and certain trace metal signatures are unique to different areas.

6. Most of the placer gold in the South-East Siberia has relatively low silver and mercury concentrations, the latter often undetectable. Assuming the placer gold is a good representation of the primary source, we can infer that most of the gold is of orogenic origin. Epithermal gold is of low sulphidation, and typically has numerous inclusions, wide ranges of silver and detectable mercury [8]. This gold therefore likely originated in the Devonian and Carboniferous, during the major mountain-building phase that occurred at the time. This period was also associated

with widespread igneous activity, which was likely responsible for the concentration of intrusion-related gold which is found locally (e.g. at Tardan gold mine).

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Изучение состава и источников происхождения россыпного золота на Кузнецком Алатау и Западном Саяне, Юго-Восточная Сибирь: результаты полевой практики летом 2014

Г. Дж. Г. Паксман[a], Б. С. Грегори[a], С. Дж. Пэйн[a], Дж. Б. Форшоу[a], М. П. Брэйди[a], М. Д. Хан[a], Д. Авадани[a], Г. Уордл[a], Дж. Дж. Уиллс[b], О. Н. Ковин[c], О.Б. Наумова[c], Б. М. Осовецкий[c], В. А. Наумов[d]

[a]Департамент наук о Земле, Оксфордский университет, South Parks Road, Oxford OX1 3AN, UK. E-mail: guyp@earth.ox.ac.uk
[b]Лаборатория Кларендон, Оксфордский университет, Parks Road, Oxford OX1 3PU, UK
[c]Геологический факультет, Пермский государственный национальный исследовательский университет, 614990, Пермь, ул. Букирева, 15, Россия
[d]Естественнонаучный институт Пермского государственного национального исследовательского университета, 614990, Пермь, ул. Генкеля, 4, Россия

В статье представлены результаты изучения проб россыпного золота, отобранных студентами во время полевой практики летом 2014 г. на четырёх реках Юго-Восточной Сибири с помощью лотков и винтового шлюза, описанных и проанализированных методами электронной микроскопии. Нами установлено, что особенности морфологии зерен золота свидетельствуют о значительном отличии в расстояниях их транспортировки как в пробах с одного места отбора, так и между пробами с разных мест. Состав и текстура золота сравнимы с наблюденными при подобных исследованиях на Юконе. Это позволило предположить, что большая часть россыпного золота в местах отбора проб связана с источниками в коренных золотосодержащих породах эндогенного происхождения девонско-каменноугольного возраста. Присутствие многочисленных интрузий гранитов, гранодиоритов и сиенитов является подтверждением того, что источники россыпного золота могут быть связаны также с коренным золотом интрузивов девонского возраста. Остаются широкие возможности для дальнейших исследований, т. к. в результате работ изучено очень небольшое количество зерен. Следует отметить, что если бы была возможность изучения состава коренного золота территорий, то это позволило бы более точно определить расположение источников россыпного золота из отобранных проб.

Ключевые слова: *россыпное золото, Кузнецкий Алатау, Западный Саян, Сибирь, пробоотбор, промывка на лотке, состав, морфология зерен.*