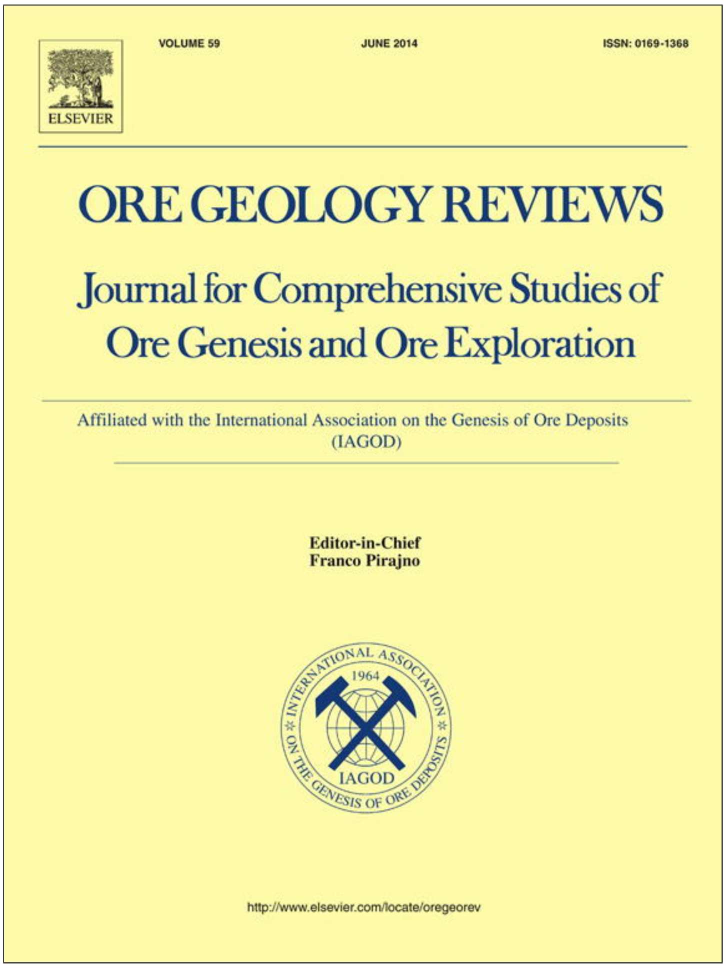
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The Kuranakh epithermal gold deposit (Aldan Shield, East Russia)

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ABSTRACT

The Kuranakh deposit, one of the largest lode gold deposits in Russia, is located within the Central Aldan Ore District on the southern flank of the Siberian craton. The host rocks are flat-lying Jurassic arkose and Lower Cambrian limestone and dolomite overlying a Precambrian metamorphic basement. The hydrothermal mineralizing event is associated with Mesozoic igneous activity. In the mine area, this igneous activity is manifested by three swarms of dikes with a few small plugs and sills of bostonite, microgabbro, and minette. Gold mineralization is spatially related to the dikes, which may be both pre-ore and post-ore in age. The Kuranakh deposit is interpreted as a low-sulfidation epithermal gold deposit with quartz–adularia alteration. Several sub-horizontal, blanket- or ribbon-like orebodies, up to 50 m thick, occur mainly along the karstified contact between Cambrian calcareous footwall rocks and overlaying Jurassic clastic rocks within a narrow, but very long zone of about 25 km. Originally, gold mineralization was associated with pyrite, arsenopyrite, sphalerite, and galena; however, total sulfides constituted only a few percent of the total rock mass. The deposit has been thoroughly oxidized and only traces of arsenopyrite and pyrite are rarely found. Gold occurs primarily as mineral grains, less than 5 μm in size, usually contained within friable grains of porous goethite. Studies of fluid inclusions show a range of homogenization temperatures from 80 °C to 220 °C, but generally ranging from 110 °C to 160 °C. The center of the heat source may have been located in the southern end of the deposit, at its transition to the gold and uranium mineralization hosted in the Precambrian basement of the Siberian craton.

1. Introduction

The Kuranakh gold deposit was discovered in 1947 and modest production began in 1955. Large-scale open pit mining began in 1965 and continues up to Present. The Kuranakh mine was the largest lode gold producer in Russia before 1991 (Benevolskiy, 2002) and has produced 10.6 million oz of gold by end-2012 (Benevolskiy, 2002; Polyus Gold, 2012). Through 1997, the mine has extracted 74.1 million tonnes of ore grading 3.57 g/t gold, reaching its peak of 240,000 to 350,000 oz annual production between 1973 and 1991 (Benevolskiy, 2002), followed by the decline in grade and production afterwards. Current annual output is sustained at 120,000 oz of gold (Polyus Gold, 2012). Gold recovery averages 83% using resin columns. Various estimates suggest that the deposit still contains more than 6.6 million oz of gold in low grade and stockpile material (SRK Consulting, 2006).

Although the Kuranakh deposit is one of the largest and long-lived Russian hard-rock gold mines, the problem of its origin is still under discussion and has been postulated differently by various workers because of its stratabound nature, uncertain relationship between ore and dikes, intensive weathering and karst development, and a close spatial relation of gold mineralization to karst bodies. Our study (Fredericksen, 1998; Fredericksen et al., 1999), accompanied by intensive drilling, assaying, detailed large-scale mapping, structural, mineralogical and fluid inclusion analyses, as well as available mining and published data, proposes a new hypothesis for the origin of Kuranakh deposit.

2. Geological setting

The Kuranakh gold deposit is located within the Central Aldan Ore District (CAD) (Khomich and Boriskina, 2010), situated within the Aldan Shield on the southern flank of Siberian craton (Fig. 1). The Aldan Shield consists predominantly of an Archean rock complex that is metamorphosed to granulite and amphibolite facies. Ancient rocks are folded into a complex system of isoclinal folds. The original rocks are interpreted as mafic volcanic, sedimentary, and volcano-sedimentary rock packages.

Rosen et al. (2006) reported the oldest rocks of the region are mafic schist from the southern part of the shield with an age of ca. 4500 Ma (K–Ar, pyroxene). The gneiss has an age varying from 3960 to 3300 Ma (Rb–Sr, bulk rock samples), and the marble from 3800 Ma (K–Ar, bulk rock samples) to 3150 Ma (Pb–Pb method). Nonconformable Lower Proterozoic calcareous–terrigenous sequences, with minor amount of volcanic material, cover Archean basement,

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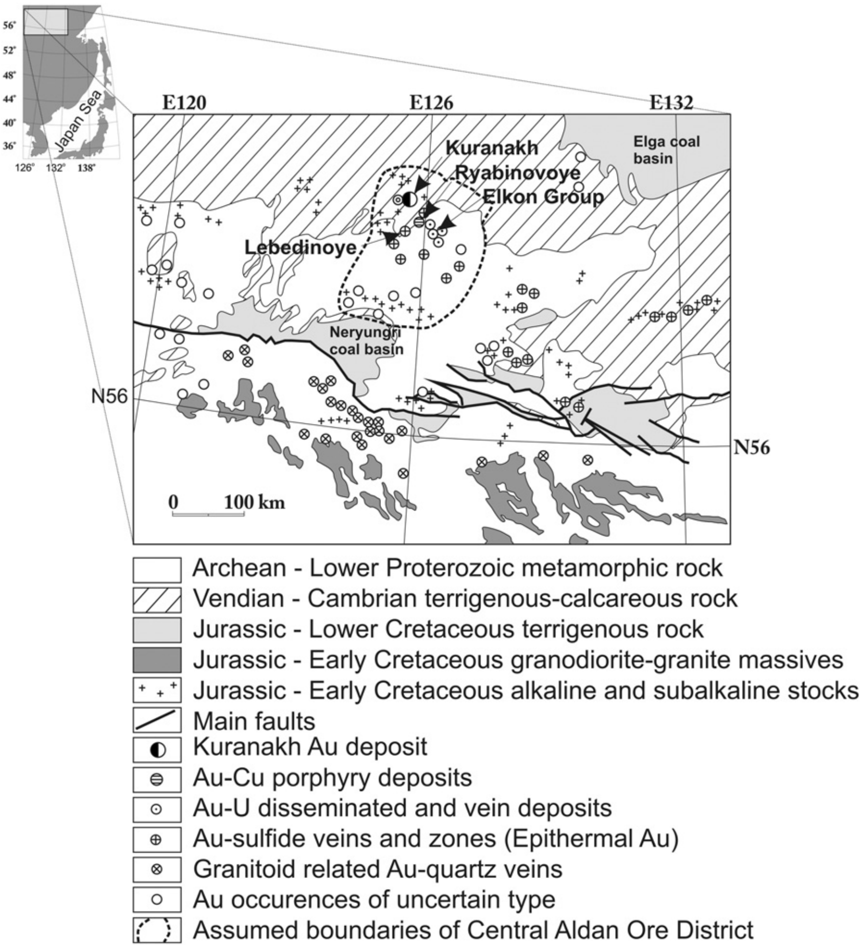

Fig. 1. Geologic setting of Central Aldan District (adapted from Vetluzhskikh and Kim, 1997).

filling the graben-like depressions. The ages of these rocks are older than 1800 Ma, as they are intruded by 1800 to 1750 Ma granite (K–Ar, bulk rock samples). Rare interlayers and sills of diabase, with ages of 1350 Ma (K–Ar, bulk rock samples), occur in places within the Lower Proterozoic sequence. Vendian–Cambrian marine terrigenous–calcareous sequences, forming the platform cover, are widespread in the northern part of the CAD. The age of glauconite from the bottom and top of Vendian–Cambrian sequence varies from 650 to 580 Ma (Drugova et al., 1985; Kozlovskiy, 1988).

The Mesozoic sedimentary basins are filled with Jurassic and, partly, Lower Cretaceous coal-bearing terrigenous deposits, which are interpreted to have formed in response to collision of the Siberian platform with the Bureya superterrane (Natal'in, 1991; Parfenov, 1984, 1997; Parfenov et al., 1983, 1995). The continued collision resulted in intensive folding of Mesozoic sedimentary rocks with development of complex systems of gentle folds, isoclinal folds, and overturned folds (Mokrinsky, 1961), as well as numerous northward thrusts.

Widespread Mesozoic magmatic activity in the Aldan Shield is commonly related to the heating of the lithosphere, generally occurring in extensional settings. Horizons of tuffaceous and pyroclastic material, 0.5 to 2.0 m thick, occur in lower part of Mesozoic sequence (Ishina, 1968; Syundyukov et al., 1979; Zhelinsky, 1980).

Potassium–argon ages of the CAD magmatic rocks vary from 98 to 190 Ma (Fig. 2). Mesozoic magmatic rocks are subdivided into several complexes that reflect different stages of tectonic evolution (Kochetkov et al., 1981; Maksimov, 1991; Maksimov and Seredin, 1982; Maksimov and Uyutov, 1990; Kochetkov, 1991; Uyutov, 1991).

The Early Jurassic stage was manifested by the formation of sill-like intrusions of sub-alkaline syenite, syenite–porphyry, and quartz syenite, as well as alkaline trachyte flows that are preserved mainly as xenoliths in syenite. Magmatic rocks of the Early Jurassic stage are rare in the Aldan Shield and have been found only within the CAD (Maksimov, 1991). Formation of the main structural elements of the district and origin of the initial magmatic melts from peridotite mantle is assumed to be related to this early stage of Mesozoic tectonic evolution (Maksimov and Seredin, 1982; Maksimov and Uyutov, 1990; Uyutov, 1991).

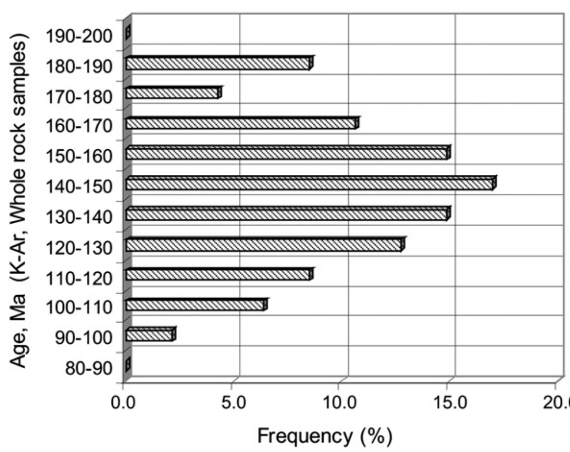

Fig. 2. K–Ar ages of the intrusive rocks of Central Aldan District (Kozlovskiy, 1988).

The Middle and Late Jurassic magmatism of the second stage is characterized by ultra-alkaline and alkaline volcanic flows, dikes, and sills of alkaline syenite, monzodiorite, and alkaline gabbroids that form large sill-like bodies, far from the volcanic centers.

The third magmatic stage (Late Jurassic to Early Cretaceous) was manifested by formation of a small volume of volcanic flows and intrusion of numerous stocks and laccoliths of aegirine, nepheline, pyroxene, and pyroxene–hornblende syenite, granosyenite porphyry, alkaline syenite, and monzonite.

The fourth stage (late Early Cretaceous) is characterized by formation of relatively rare dikes, stocks, and small explosive bodies of alkaline trachyte, explosive breccia, grorudite, bostonite, alkaline minette, alkaline syenite, sub-alkaline syenite, alkaline syenite, alkaline picrite, shonkinite, and alkaline granite (Kochetkov et al., 1981; Uyutov, 1991).

3. Regional gold metallogeny

Several different types of gold deposits (Vetluzhskikh and Kim, 1997) occur within the CAD (Fig. 3). The center of the system can be inferred near the Mesozoic alkaline porphyry Au mineralization at Ryabinovoye, accompanied by extensive (>20 km long) Mesozoic Au–U vein zones of Elkon cluster and Lunnoye deposit (Kazanskiy, 2004; Nazarov, 2010). They are all hosted within the Precambrian basement of the Aldan Shield, forming the Elkon horst (Fig. 3). Within the Phanerozoic cover, the gold mineralization occurs on continuation of the Elkon horst, possibly controlled by some of its faults in the basement that continue under the cover. As a result, the Kuranakh, Ryabonovoye and Lunnoye deposits are possibly controlled by the western-southwestern flank of the Elkon horst, whereas the Nizhne–Yakokitskoye and Elkon clusters may occur along the northeastern flank of the horst. The Mesozoic reactivation of the Elkon horst can be explained by its proximity to the terrane boundary in the Precambrian basement, which follows the river Aldan (Fig. 3) along its northeastern limit (Rosen et al., 2006).

The principal deposit types within the Phanerozoic cover are quartz–gold veins and skarns in association with the Mesozoic alkaline intrusions (Lebedinoye deposit) and, most importantly, the Kuranakh group of gold deposits occurring along the contact between

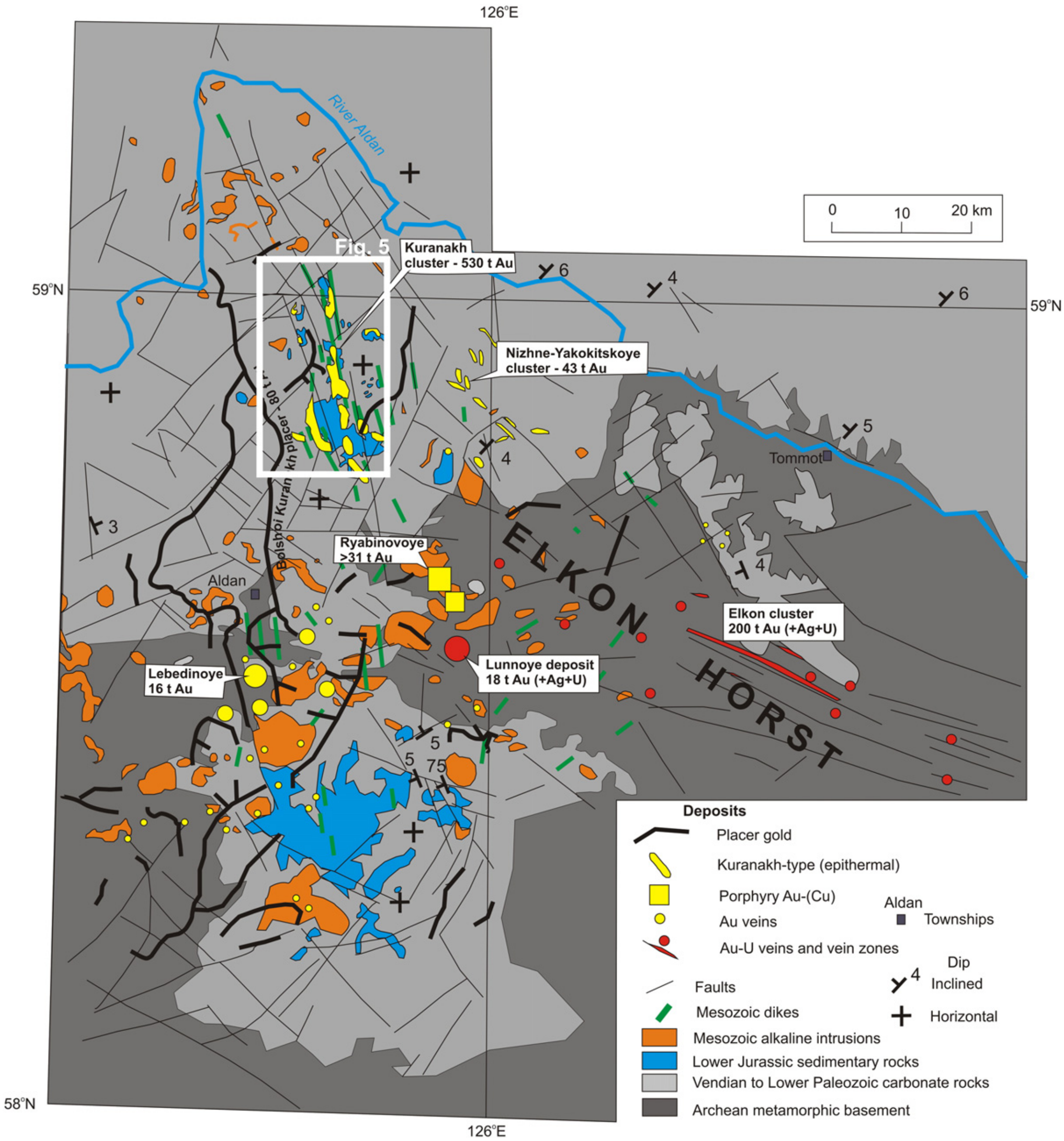

Fig. 3. Metallogeny of the Central Aldan District (compiled using Telega, 1963; Lukonina, 1964; Malkov, 1968; Vetluzhskikh, 2001; Volkov and Kochetkov, 2009).

the flat-lying Cambrian (Cowie and Rozanov, 1983) and Jurassic sedimentary rocks. All these diverse deposits form a single metallogenic system of CAD (Maksimov et al., 2010), with alkaline porphyritic and non-porphyritic intrusions probably being the main driver of the auriferous fluids. The Kuranakh group of gold deposits probably represents the shallowest expression of this metallogenic system (Figs. 3, 4). The total endowment of CAD exceeds 900 t of gold.

The Ryabinovoye porphyry Au–(Cu) deposit in the central part of CAD has a reported resource of 31 t of gold (Micon International, 2012), with total endowment (including Russian-style prospective resources of P category) of 75.4 t of gold. It is a stockwork with gold-sulfide mineralization, related to alkaline syenite stock, accompanied by sericite, microcline, pyrite, and ankerite alteration (Terekhov, 2012). Disseminated and veinlet-controlled ore contains pyrite, chalcopyrite, bornite, and native gold.

The Elkon district with vein-style and disseminated Au–U mineralization occurs within the Archean basement (Nazarov, 2010), but the mineralization is believed to be of Mesozoic age; this is related to feldspar–pyrite–carbonate and fluorspar–carbonate–quartz altered rocks within breccia zones. Gold-bearing lens-shaped orebodies are hundreds of meters long and 10 to 30 m thick. Gold grade varies from 0.1 to 100.0 g/t. The estimated resource contains more than 200 t of gold averaging 0.82 g/t (Terekhov, 2012). This system is viewed primarily as a uranium resource, potentially hosting between 300,000 and 600,000 tonnes of uranium (only brannerite ores) in approximately 20 deposits, as well as 90,000 tonnes of molybdenum (Terekhov, 2012) and silver (Volkov and Kochetkov, 2009). Atomredmetzoloto is planning to start uranium production (with by-product gold) from these deposits by 2024, with annual output of some 5000 t of uranium.

Cambrian calcareous rocks on the south-west flank of the district host flat-laying high grade (10–30 g/t Au on average, but locally 100.0 g/t and more) gold-sulfide veins of very complicated morphology, which produced 16.4 t of gold from the Lebedinoye deposit (Benevolskiy, 2002). They also host zones of disseminated gold-sulfide mineralization that occur at depths varying from 0–20 to 135–140 m. The ore contains pyrite, pyrrhotite, galena, hematite, magnetite, sphalerite, native gold, rare cinnabar, native bismuth, native silver, and tetrahedrite. Au/Ag ratio varies from 10/1 to 5/1.

The vein-type deposits were probably a source of placer gold (Benevolskiy, 2002). The largest gold resource of some 80 t of gold is known in the Bolshoi Kuranakh placer deposit (Fig. 3).

The Kuranakh goldfields, with endowment in excess of 530 t of gold, host stratabound low-sulfidation gold mineralization at the contact of Jurassic sedimentary and Cambrian calcareous rocks in the northern part of CAD, just 20 km northwest from the Ryabinovoye deposit.

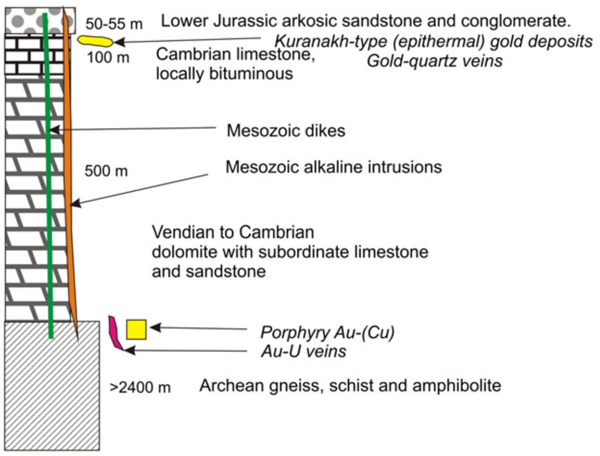

Fig. 4. Stratigraphic position of principal types of gold mineralization in the Central Aldan District (compiled using Telega, 1963). Note that all gold mineralization is Mesozoic in age, but occurs at different stratigraphic levels.

Similar to Kuranakh is the Niznhe–Yakokitskoye group of deposits, located some 20 km east. Its heap leachable resources are 42.7 t of gold (Anonymous, 2007). The Kuranakh low-sulfidation cluster of gold deposits is presently the most economically important in the district.

4. Geology of the Kuranakh deposit

The Kuranakh deposit is situated topographically lower and stratigraphically higher than most gold occurrences of the CAD. Jurassic clastic rocks, which are the predominant host rocks of the Kuranakh-type, are preserved within a shallow sedimentary basin. It trends north–south and extends onto the edge of the Siberian platform sedimentary rocks (Figs. 1, 3). The blanket-shaped mineralization occupies an area of 15 × 5 km.

4.1. Stratigraphy

The stratigraphy of the Kuranakh deposit is composed of approximately 1000 m of Cambrian dolomite and limestone, unconformably overlain by 40 to 70 m thick Jurassic sandstone and pebble conglomerate (Fig. 4). Most of the Cambrian carbonate sequence is dolomitic, with the upper 80 to 100 m yielding to limestone. The uppermost horizon of Cambrian calcareous sequence is composed of pure limestone and spotted-banded dolomitic limestone with a thickness of 1 to 5 m. The rock is characterized by the presence of finely disseminated organic material and irregularly disseminated and oxidized pyrite. Epigenetic fluorite occurs rarely. The horizon of organic bearing rock (1 to 5 m thick) is one of the most important horizons for the localization of gold mineralization. Cambrian limestone and dolomite lie almost horizontally or dip at low angles (no more than 30°) in various directions. Local small folds occur in places.

An upper contact of the Cambrian sequence is marked by the presence of *terra rossa* of variable thickness. The unit generally varies from zero to 15 m in thickness, but may be considerably thicker at some localities, and consists of clay and weathered limestone. It is mapped and logged by the mine geologists as "limestone weathering crust" and contains some gold.

The Jurassic sequence is predominantly composed of medium-bedded, medium- to coarse-grained, light gray to tan or buff arkosic sandstone with lenses of conglomerate and regionally some lignite or bituminous-rich horizons. The unit is estimated at 40 to 70 m thick, but its fuller sequence is preserved only in the cores of the synclines.

The Jurassic rocks lie almost horizontally, occupying the table-shaped water divides (Fig. 3). The Vendian to Cambrian rocks form a broad north-northwest trending syncline, with its axis running through the Kuranakh deposit, where they lie horizontally. Both west and east of the deposit the strata dip at only 3 to 4° in proximity to the contact with the Precambrian basement (Fig. 3). Very rarely the strata dip at up to 75° near the intrusions.

The Cambrian and Jurassic strata are also faulted with a network of north-northwest and east-northeast faults, forming almost a rectangular grid (Fig. 3). The faulting took place in the Late Jurassic to Early Cretaceous, possibly in relation to collisional events in the Mongol–Okhotsk suture zone to the south (Yakubchuk and Edwards, 2000), followed by extensional events (Goryachev and Pirajno, 2014). The faults are often intruded by dykes of diverse composition. The mineralizing seems to be controlled by both the dykes and north-northwest trending faults.

The Jurassic unit hosts most of the gold ores at Kuranakh. The lowermost part of this suite includes a discontinuous and interrupted layer (about 1 m thick) of tuff-like breccia composed of quartz and flint fragments cemented by quartz-feldspathic material. The described breccias are the second most favorable horizon for hydrothermal alteration and gold-ore deposition.

The upper units of the carbonate bedrock of Kuranakh goldfield are intensively karstified in places. A surface of pinnacles and slots developed with slot depths up to 70 m and an irregular pinnacle spacing of between 30 and 200 m. Areas between pinnacles are filled with fragments from mass wasting and insoluble minerals. A thick clay-rich residual soil (epikarst) developed with a typical feature—thin on the steep slopes and thick in the slots and over the pinnacles. The karstogenic bodies are composed principally of altered Jurassic rocks. Cone-like, valley-like, and pot-hole-like karsts, up to 100 m thick, have formed several bands, 2 to 3 km wide, and up to 20 to 30 km long. The relationship of karst bands location to pre-Jurassic faults is likely. The bottoms of the largest bodies are located below the present level of erosion. Clay with relict lamination of limestone and containing limestone inclusions is found in the base of the bodies. The main part of the colmatite is composed of unsorted clastic material cemented with a ferruginous sandy–clayey aggregate. The groundmass contains about 30 to 50% clay; 40% of which is kaolin. The clastic material consists of ferruginous quartzite, quartz–feldspar rocks, arkosic sandstone, conglomerate, and limestone. The most spectacular and highest gold grades are consistently encountered in the karst sinkholes.

4.2. Igneous rocks

Within the general vicinity of the mine (Fig. 5), the igneous rocks present are Mesozoic (Early Cretaceous?) dikes and some plugs and sills of vogesite, biotite–pyroxene porphyry, shonkinite, syenite–porphyry, trachyte, bostonite, microgabbro, and minette. In the vicinity of the mine, these rocks comprise only a small volume of the bedrock. The dikes have a close spatial relationship with the gold ores and may be related to the same thermal event that gave rise to the deposits. The dikes are medium- to fine-grained, black, light brown upon weathering, and sometimes display flow banding and chilled contacts; abundant hornblende is exhibited by some of the dikes. The dikes vary in width from 3 to 20 m, and some have been traced by mapping and geophysical surveys for distances of 10 km or more. In general, these igneous bodies dip nearly vertical and show little disruption due to faulting. This implies that faulting most likely predated the igneous activity.

The dikes can be crudely grouped into three swarms—eastern, central, and western (Fig. 5), which appear to verge towards the north. Mineralization is strongly spatially associated with dikes in the central swarm. The dikes are intensely altered. The typical alteration assemblage contains feldspar (adularia), smectite, and minor calcite. The high degree of alteration, the presence of gold and relict sulfide mineralization, and the spatial association of dikes and orebodies all provide evidence that the fractures, now occupied by dikes, acted as conduits for hydrothermal fluids.

Some small plugs and sills occur in addition to the dikes. Good exposures of these irregular intrusive bodies are found approximately 6 km northwest of the central part of the deposit. Such intrusives have been traced northwards for a considerable distance from the main orebodies. Many of these are unaltered, porphyritic, with phenocrysts of plagioclase and hornblende. Some thermal alteration of the limestone host rocks is evident.

Compositionally, the magmatic rocks vary from intermediate to felsic (Fig. 6a). Two petrographic groups of different ages are identified. The earliest one includes relatively more mafic rocks, such as minette, vogezite, biotite–pyroxene porphyry, shonkinite, hornblende-enriched syenite–porphyry, and rare alkaline gabbro. The late one, immediately pre-ore, includes trachyte, bostonite, and syenite–porphyry. The magmatic rocks of the Kuranakh goldfield are of I-type, according to the classification of Chappel and White (1974) and to the magnetite series of the Ishihara (1977) classification (Fig. 6b, c).

There is a strong spatial relationship between gold and the long, continuous bostonite dike that runs down the center of the Kuranakh goldfield (Fig. 7). The average gold grade of 4481 assayed dike samples is 2.061 g/t, indicating that the dikes are, on average, well mineralized. However, the spatial distribution of that mineralization is not very

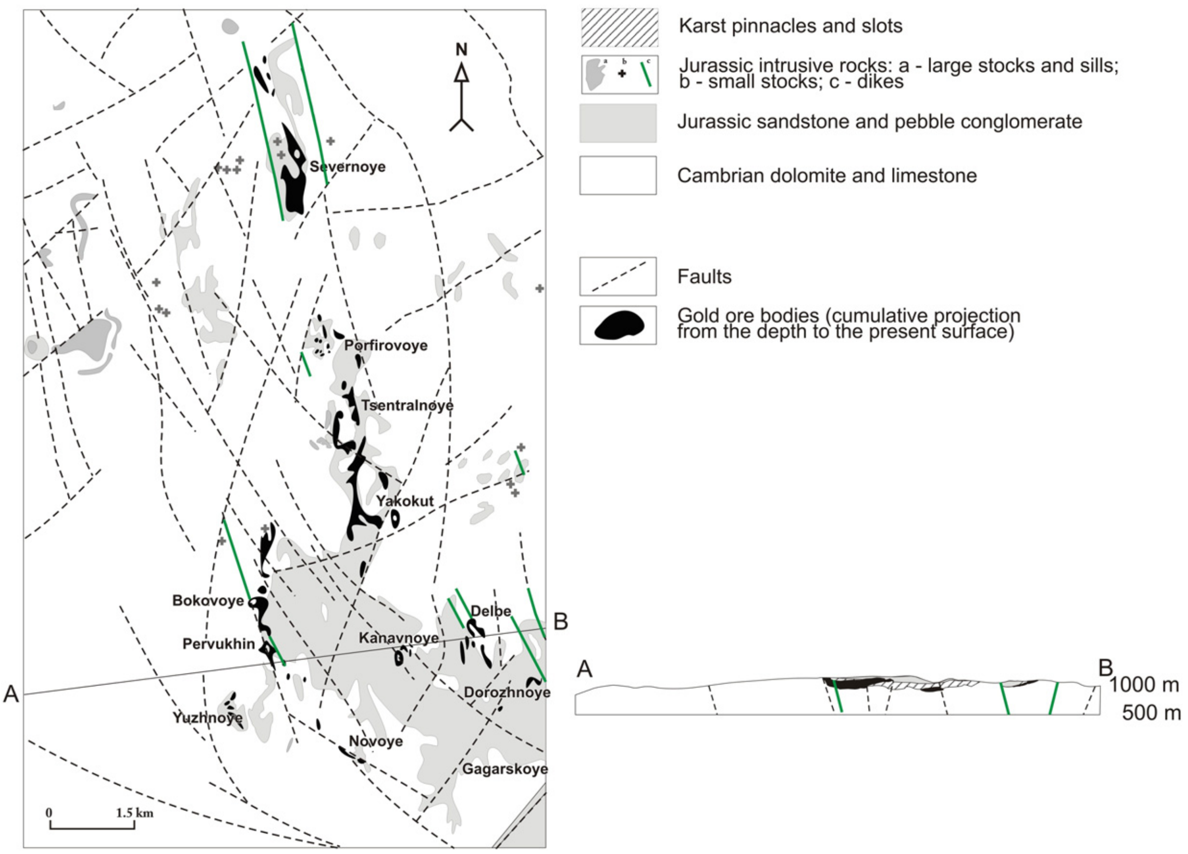

Fig. 5. Geologic map of the Kuranakh gold deposit (adapted from Kazarinov, 1969).

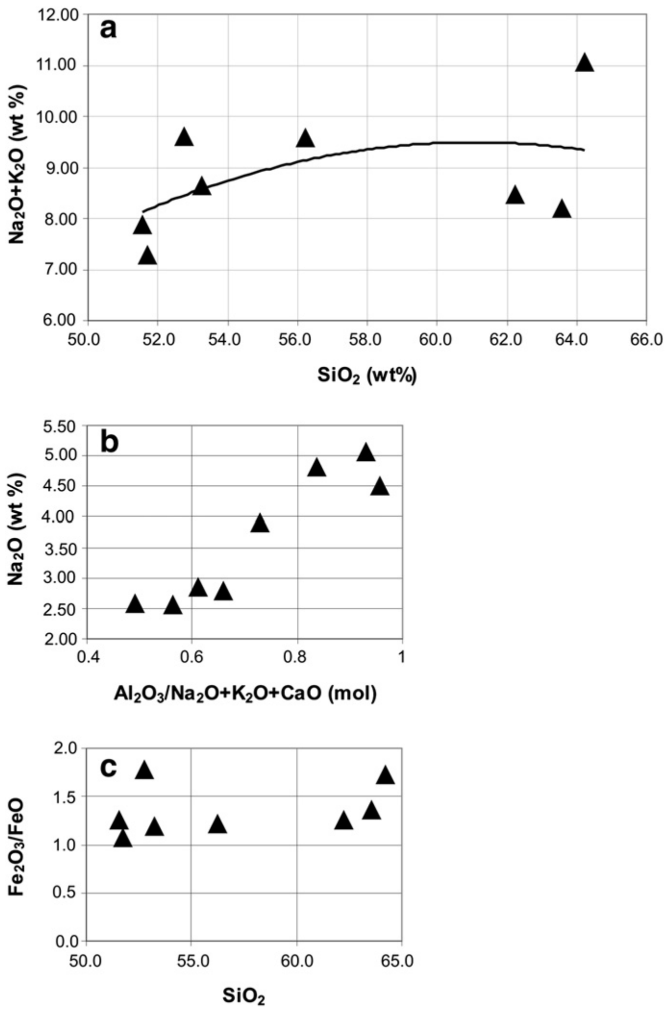

Fig. 6. Chemical composition of Kuranakh goldfield magmatic rock. (a) SiO_2 vs. $Na_2O + K_2O$; (b) $Al_2O_3/Na_2O + K_2O + CaO$ vs. Na_2O; (c) SiO_2 vs. Fe_2O_3/FeO.

even; at some localities, the relationship is not as pronounced, and in some parts of the goldfield, the dikes do not appear to be present. Certainly the bostonite dike of the central part of the deposit and some dikes of southern part of the goldfield are pre-ore in age, although likely emplaced only shortly prior to mineralization and probably associated with the same high heat flow event. The case with the other dikes is not so clear. The relationships are somewhat obscured by poor exposures and the high degree of weathering.

4.3. Structure

The ore-bearing Jurassic sandstone has been preserved in the broad shallow synclines that have their long axis oriented north-northwest. The synclines appear to plunge gently towards the north (Fig. 3). Structural deformation is predominantly expressed by steeply dipping or near vertical normal faults (Voitovich, 1992). The predominant set of fractures is oriented 054°NE; a second grouping is found at approximately 335–345°NW. Net displacement on the faults is relatively small, usually measured in single digit meters. Movement is generally south side down. In the Kuranakh goldfield the overall pattern of faulting, with the north side up, has resulted in lower portions of the stratigraphic section exposed towards the northwest. Indeed, the most widespread exposures of the Cambrian calcareous formation are found in the northwest corner of the area.

Folding and faulting very weakly deform both the underlying Cambrian and the overlying Jurassic rocks. Coincidence of the folding axis orientation of Cambrian and Jurassic rock ($F_1 = 253/3$ and $278/8$; $F_2 = 190/45$ and $200/15$, respectively; Fig. 8) is a possible result of two stages of post-Early Jurassic compression stresses: (1) 160–180; and (2) 100–110. The compressional event is therefore encompassed between Early and Late Jurassic, since dikes are not folded.

Much of the NW-oriented faulting appears to be older than both the Mesozoic dikes or the gold mineralization since the dikes can be traced for great distances, without disruption, except rare faults of ENE–WSW orientation. In addition, it appears that the preponderance of faulting and fracturing took place prior to deposition of the Jurassic sandstone. The thick troughs of sandstone are likely developed over slots in the limestone that were themselves developed along fractures (Fig. 7). The axis of the troughs is interpreted as reflecting the underlying pre-Jurassic and pre-ore fractures. The orientation of these interpreted fractures closely mimics that mapped in the surrounding terrane giving credence to the concept that the underlying fracture system, which guided dissolution of the carbonates, was in existence prior to deposition of the Jurassic sandstone.

Disruptions of the orebodies due to faulting are minor (Fig. 7). However, a number of small post-ore faults, trending E–W, are present. One of these is well exposed in the southern portion of the Kuranakh goldfield and has displaced the Novoye orebody; drag on the fault suggests north side up, which is typical for many faults in the district. It is likely that the dike, running through the center of the Porfirovoye–Tsentralnoye–Yakokut orebodies is also disrupted by an E–W trending fault. An apparent right-lateral offset is indicated.

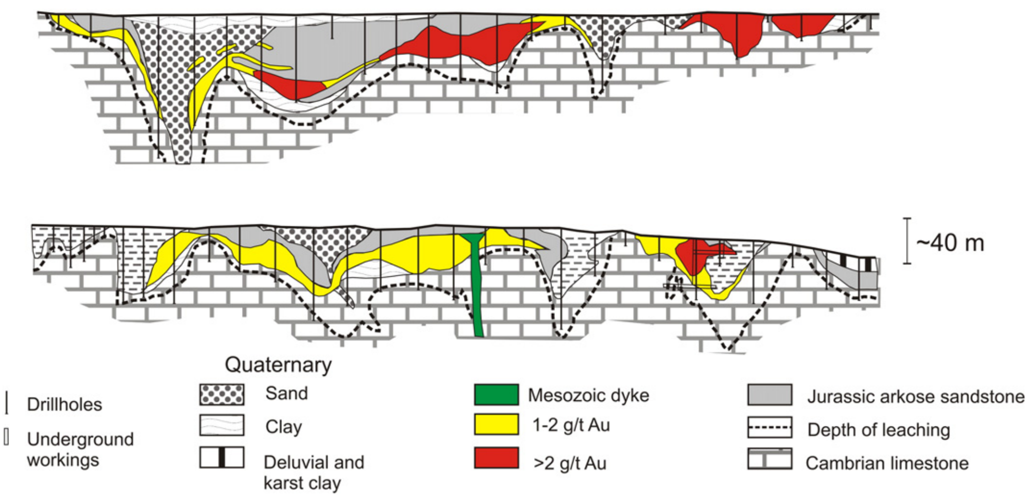

Fig. 7. Geological cross-sections of the Tsentralnoye orebody of the Kuranakh deposit (adapted from Kazarinov, 1967).

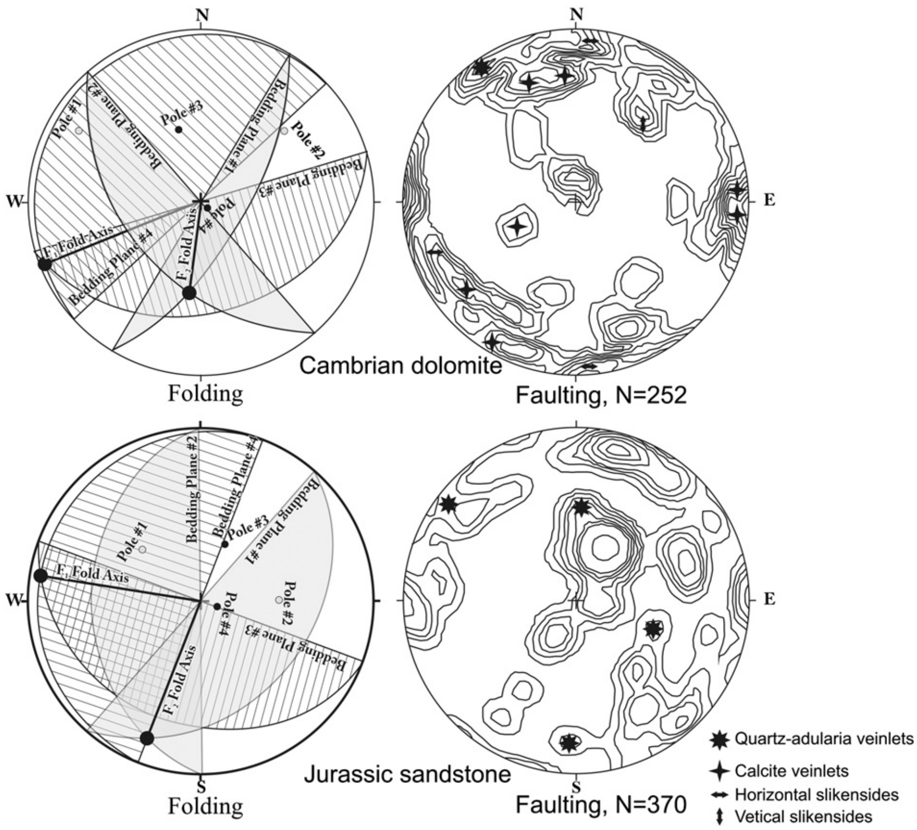

Fig. 8. Folding and faulting of Cambrian (upper diagrams) and Jurassic (lower diagrams) rock of Kuranakh goldfield. Schmidt Net, equal area, lower hemisphere projection.

5. Orebody morphology

In plan view, the orebodies, comprising the Kuranakh deposit, form a shape, resembling an inverted "Y". The deposit extends from the southern end of the Kanavnoye orebody to the northern limits of the Severnoye orebody in the north—a distance of more than 20 km; the field varies from 1 to 11 km in width in an E–W direction (Fig. 5). One of the longest stretches of continuous gold mineralization are the coalescing Porfirovoye, Tsentralnoye, and Yakokut orebodies, whose combined length exceeds 10 km. Although the terrain is only hilly, one of the striking features of the deposits is that the principal orebodies tend to occur along topographic highs. This geomorphic phenomenon is perhaps due to the added resistance to weathering that the Jurassic sandstones have gained through the processes of metasomatic alteration and the fact that the sandstones themselves seem more resistant to weathering than the underlying carbonate rocks.

Morphologically, the orebodies have disjointed blanket-like or ribbon-like shapes in their shortest dimension, with thicknesses that rapidly increase in the areas of the most extreme faulting of calcareous rocks and karst development (Fig. 7). Some disruptions in continuity, perpendicular to the long axis of the orebodies, are due to gentle folding of the deposit and erosion of the limbs; other disruptions are due to the faulting and the considerable relief of the Cambrian–Jurassic contact, which is now incised by erosion. Individual orebodies (>1 g/t Au) have a lenticular shape, strongly oriented NNW–SSE and commonly coalesce or diverge along strike.

6. Mineralization and alteration

At Kuranakh, mineralization is essentially restricted to the basal portion of the Jurassic sandstone and upper portion of calcareous rocks, especially the breccias or karst cavity fillings; the thickness of material grading better than 1 g/t Au may be up to 100 m or more (Fig. 7). The basal section of the sandstones and uppermost section of the limestone has been altered (metasomatized) by hydrothermal fluids and, where intense enough, is distinguished by mine geologists as a separate rock unit—"metasomatite". The "metasomatite" (a clay-potassic feldspar–quartz-bearing rock) is often reddish in color and usually displays myriad druzy quartz veinlets and open space fillings. In some localities, this "metasomatite" resembles jasperoids (giving a reason to Eirish (1998) to classify the deposit as Carlin-type). Sandstone and limestone peripheral to "metasomatites" also displays quartz veinlets, and contains low-grade gold mineralization, differing from the "metasomatite" principally in the intensity of silica and adularia flooding. For example, the progressive transition of the arkosic host rocks to massive quartz-adularia metasomatite is well displayed on the west side of the Severnoye orebody.

The ores display a variable clay content, from a few percent to 20%, and it is difficult to determine how much of this clay is the result of original hydrothermal alteration of potassium feldspars in the arkosic sandstones and how much is the result of the high degree of weathering and oxidation, which the rocks have been subjected to since the Quaternary. Mineralization was likely manifested by a low sulfide content (up to a few percent), but almost no sulfides have survived the thorough oxidation of the ores. Reportedly, the original surface, prior to mining, was littered with resistant boulders of highly silicic metasomatite and blocks of ore that contained some sulfides. Two main types of primary alteration are described for the deposit—feldspar (adularia) and silica (Kazarinov, 1969; Nesterov, 1985).

The primary gold ore contains two generations of pyrite, minor marcasite, chalcopyrite, pyrrhotite, sphalerite, arsenopyrite, and tellurides (Kazarinov, 1969; Kim, 1994; Kim et al., 1988; Nesterov, 1985). Gold is strongly associated with iron oxides and is represented by fine-grained native gold particles measuring from less than 50 to 250 μm, exceptionally up to 4 mm, and by dispersed gold in pyrite of the first generation. Usually no visible gold is observed in the field. Gold fineness is 900–970 in pyrite, whereas native gold has fineness of 700–885.

Gold is not distributed evenly throughout the altered rock and a strong anisotropy is present. Gold is found in all rock types, including the limestone, which previously was considered to be barren. Most of the higher gold values occur in the most altered rock and thus cluster in the unit termed "metasomatic ore". Nonetheless, there is clearly a dispersion of lower grade values (<1.0 g/t Au) above and lateral to the "metasomatic ore". Clearly the best gold values occur in the metasomatite or karst cavity units, but importantly are not restricted to them. In addition, it can be seen that the gold values are dispersed above, below, and lateral to the "metasomatic ore" or karst cavities. Distribution of gold grades at Kuranakh shows a large halo of dispersed gold, implying that the size of the resource is dependant more upon economic cutoff values than any real geologic boundaries to mineralization, except that ore is essentially restricted to the rocks of clastic–carbonate contact zone.

The primary ore was deposited during three stages of hydrothermal activity (Nesterov, 1985). The early stage is characterized by the formation of banded, horizontally lying, quartz veinlets and hydrothermal breccia with quartz cement. Gold-bearing early pyrite, vein adularia and fine-grained sucrosic earlier quartz were deposited during this stage. The second stage is characterized by deposition of medium-grained rice-like late quartz, late pyrite, grained native gold, rare sulfides and silica sinters. Coarse bladed calcite and druzy quartz were deposited during the third barren stage.

Sulfides are only very rarely observed in the pits today. Typically, small amounts of pyrite, arsenopyrite, and rarely galena can be found in some silicified rocks that have remained resistant to weathering and oxidation. From a gross mineralogical standpoint, the metasomatite consists essentially of quartz, in all of its low temperature and cryptocrystalline varieties, clay, iron oxides, adularia, and carbonate minerals.

7. Fluid inclusion studies

Fredericksen et al. (1999) studied thermometry and cryometry of individual inclusions in Kuranakh samples to determine some physical and chemical factors of ore formation. The equipment used allowed analysis of phases and their changes for inclusions greater than 3–5 μm in diameter. Inclusions less than this diameter have been used as accessory material. The accuracy of temperature measurements was ±0.5 °C for the cryocamera and 3 to 5 °C for the thermocamera.

P-correction volumes were added to the homogenization temperatures (T_h) in order to determine the forming temperatures (T_f) and calculated using the data of Potter (1977). According to the petrological and geological data, a depth of formation of ore-bearing rocks at Kuranakh was probably no more than 500 m. Because of the open character of the ore-forming hydrothermal fluid system, pressure corrections were calculated in accordance with the hydrostatic model of fluid pressure. Estimations of the pressures were derived from fluid inclusions on the base of data (Potter and Brown, 1977). In this case, the composition of inclusions is approximated by the system H_2O–NaCl.

We have investigated quartz and calcite from representative Au-bearing ores at the Severnoye, Porfirovoye, Tsentralnoye, and Yuzhnoye orebodies and found that they contain two groups of inclusions. Gas–liquid and liquid inclusions of water solutions predominate. The homogenization temperatures increase southward from the Severnoye orebody towards Yuzhnoye. Apparently, the heat source of the ore-forming solutions was located nearer to the southern edge of the Kuranakh goldfield, at its transition to the Ryabinovoye Au deposit.

Solution concentrations in inclusions for all orebodies are nearly equal; the maximum values do not exceed 10 wt.% NaCl eq. There is no correlation between homogenization temperatures and solution concentrations, though, possibly, a tendency can be envisioned for a decrease in concentrations with increasing temperatures, especially in the "hottest" inclusions. At the same time, a drop in solution concentrations is distinct from primary to secondary inclusions in one same sample.

Fluid composition in inclusions from metasomatic quartz in all orebodies is also similar. They are essentially water solutions of chlorides of sodium and potassium, and rare calcium, magnesium and iron. Very low (−65°, −78° and −79 °C) eutectic temperatures hint at the presence of lithium in one-phase liquid inclusions in quartz from the Severnoye and Yuzhnoye orebodies.

8. Discussion

Although the Kuranakh deposit is one of the largest and longest-producing Russian hard-rock gold mines, the problem of its origin is still under discussion; its origin has been postulated differently due to the stratabound nature of the orebodies, the uncertain relationships between ore and dikes, intensive weathering crust and karst development, and close spatial relation of gold mineralization to karst bodies, as well as strong oxidation. It was described as "near-surface gold–quartz deposit without tellurides" (Borodaevskaya and Rozhkov, 1974), "oxidized gold bearing metasomatites" (Burmin, 1984), "low-sulfide gold deposit within weathering crust" (Nesterov, 1985), "gold bearing karst in a supergene zone" (Mikhailov, 1986), "karst-carbonate ore formation" (Kutyrev et al., 1989), "supergene deposit of chemical weathering crust" (Flerov et al., 1989), "gold low-sulfide stratabound deposit" (Vetluzhskikh and Kim, 1997), possible Carlin style (Eirish, 1998), and epithermal deposit (Yakubchuk, 2009).

Our investigation of the deposit accompanied by intensive exploration and resource drilling, assaying, detailed large-scale mapping, structural, mineralogical and fluid inclusion analyses, as well as available mining and published data gave us an opportunity to propose an epithermal hypothesis of the origin of Kuranakh deposit.

We accept the following as fact: (1) the dolomite and limestone are Cambrian in age, based on sufficient paleontological evidence (Cowie and Rozanov, 1983); (2) the arkose and pebble conglomerates, overlying the carbonates, are Jurassic in age based on substantial paleontological and other correlative evidences to substantiate this; (3) the contact between carbonates and arkose is quite irregular and is marked by a series of troughs and peaks—this is so indicated by abundant drilling, mining, and mapping data (Fig. 7); (4) the upper surface of the Cambrian limestone is marked by a clay-rich horizon of variable thickness—this is evidenced by direct observation and supported by abundant mapping and drilling data; (5) the intrusive rocks are Mesozoic in age—this is substantiated by crosscutting relationships and by isotopic data; (6) gold mineralization is an event younger than the Mesozoic intrusive rocks but not greatly different in age—this is indicated by crosscutting relationships (Fig. 7) and the fact that some dikes are mineralized and others are not (Moiseenko and Eirish, 1996); (7) mineralization is fundamentally epigenetic and hydrothermal in nature according to structural and mineralogical data and fluid inclusion investigation; (8) the ores are strongly oxidized, being originally sulfide-bearing ores—this is evident through direct observation and the fact that pseudomorphs of oxide minerals after primary sulfides can be observed in the ore.

The results of our investigation in view of the above facts on the genesis of the Kuranakh deposit can be summarized as follows below. In latest Vendian and Early Cambrian times, shallow water marine marls and carbonates accumulated on a peneplain of older Precambrian gneiss and granite. Younger Paleozoic rocks were either deposited, and later eroded, or not deposited at all. The emerging carbonate platform was exposed and subjected to weathering; karst topography developed and clays accumulated on the upper surface. Mesozoic collision of Siberian platform and Bureya superterrane resulted in formation of sedimentary basins. The basins filled with a Jurassic terrigenous coal-bearing limnic rock series, to which the Neryungri and Elga high-quality coal basins in areas south and east of Kuranakh, the largest in Siberia, are restricted. A transgressive sequence of terrestrial arkose and pebble conglomerates inundated the carbonate terrain and completely buried the carbonates to a depth of several hundred meters. The Late Jurassic was the timing of suturing in the Mongol–Okhotsk suture zone (Zonenshain et al., 1990), located some 500 km to the south. The effect of this collision can be seen in the thrust-controlled Jurassic coal-bearing basins, some 250 km to the south of Kuranakh. Intensive faulting, gentle folding and widespread magmatic activity took place in the CAD simultaneously with the collisonal events and were therefore related directly or indirectly to the collision processes. The earliest Mesozoic magmatic activity was manifested by the formation of sill-like alkaline and sub-alkaline intrusions and volcanoclastic flows that are preserved like xenoliths in syenite and like horizons of tuffaceous and pyroclastic material in lowest part of Mesozoic sedimentary sequence.

In Late Jurassic to Early Cretaceous times, the region was uplifted and intruded by bimodal volcanic and sub-volcanic alkaline rocks. Tectonic stresses created a series of fractures and faults, which, in turn, produced a series of grabens and horsts, combined to create a faulted basin. In this district, an area around Kuranakh was the center of igneous activity with dikes and sills extending outwards for hundreds of kilometers. The dikes in the Kuranakh goldfield occupied extensional fractures, trending 341–347 NW. Associated with the intrusive activity was the widespread hydrothermal activity, which resulted in fluid flow upward along the faults and laterally into the arkose–carbonate contact zone. Hydrothermal alteration decalcified the limestone below the clay-rich contact, which initially acted as an aquitard. Dissolution of the limestone caused collapse of the overlying sandstone to created troughs, filled with hydrothermal breccia. Quartz–adularia and argillic alteration affected large areas of the arkose. Sulfides constituted only a few percent of the mineralized rock mass and consisted mostly of pyrite and arsenopyrite with small amounts of base metal sulfides; minor amounts of fluorite and barite were also associated with the ores.

Subsequently, the area was eroded, stripping much of the Jurassic sandstone away such that it was only preserved within the fault basin. During the Tertiary and Quaternary, once the level of erosion was deep enough, the gold ores were oxidized. Oxidation of the sulfide ores produced acidic waters, which may have brought about some degree of karst formation in the underlying carbonates resulting in enlargement of some of the troughs and further collapse of the ores.

The problem of the age of the karst in this region is the most complicated problem. There are several schools of thought as to the origin of the Kuranakh area karst (Akimov and Shadrin, 1988; Kochetkov et al., 1979). In the extreme, all the karst formed either entirely prior to deposition of the Jurassic rocks or entirely after deposition of this arkose cover. However, it remains likely that karst formation and re-activation has occurred several times since the Cambrian and that these multiple episodes of karst formation have greatly complicated the geology, resulting in diverse theories of formation. Nevertheless, the distribution of gold seems to rule out the possibility that karst formation was entirely a Tertiary and younger phenomenon. The most spectacular and highest gold grades are consistently encountered in the karst sinkholes. This almost proves that important amounts of karst formation and filling took place prior to gold deposition and these acted as important host rocks. If karst formation was younger than the gold mineralization and the gold-bearing metasomatites collapsed into the forming sinkholes, then there should not be a significant difference in the gold grades observed within and outside of the karst depressions. This is clearly not the case. There is, however, a strong likelihood that solution weathering and expansion of the existing karst features did occur in Tertiary to Recent times, especially in that period marked by the intense oxidation of the Kuranakh ores. Such weathering of the sulfide-bearing ores would have produced acidic ground waters that could have renewed solution of the carbonate units. Such a process would also help to explain many of the textures observed within the sinkholes in which nodules of competent quartz–adularia metasomatite are surrounded by clay. There also remains a possibility that the karst is not really karst, that it is a pseudo-karst, whose origin is related to massive decalcification of limestone produced by the ascending hydrothermal solutions.

The fluid inclusion study (Fredericksen et al., 1999) suggests a 130–220 °C temperature range of formation at a depth of no more than 1000 m, according to the hydrostatic model, and less than 500 m, in terms of the lithostatic pressure. Interestingly, some inclusions in non-recrystallized relic quartz grains from rocks of the Severnoye and Tsentralnoye orebodies are carbon dioxide rich. Relic quartz is distinguished from the metasomatic quartz by its relatively large crystal size, the presence of carbon dioxide inclusions, and by the presence of biotite laminae and rutile needles. These inclusions disappear towards the grain edges due to later quartz overgrowths. The relic quartz is most likely to be non-recrystallized fragments of the initial source rocks (probably, Archean), which subsequently were subjected to low-temperature alterations. The fact that the formation of carbon-dioxide-rich inclusions bears no relation to the process of hydrothermal alterations is demonstrated by the computations of pressures developing in them. They reach 2.5 kbar—values unreal for epithermal conditions.

According to Roedder (1984), the homogenization temperatures of inclusions in minerals of epithermal deposits do not usually exceed 300 °C. As a rule, temperatures drop during the last stages of the ore-forming process although small temperature trend reversals are sometimes observed. A low salinity (5 wt.% NaCl eq) is characteristic for epithermal solutions. Many researches note the evidence of boiling, the dominant role of meteoric water, and their near-neutral character of the solutions. Circulation of the fluid is usually caused by an intrusive or volcanic heat source, which can furthermore be an additional source of mineralization. The shallow sub-surface character of epithermal deposits explains the water composition of the fluid and the common observation of one-phased (often metastable) inclusions of water solutions. Carbon dioxide and other gases are visually absent in epithermal fluid inclusions, and the concentration of CO_2 does not exceed 4%.

Alteration and mineralization in the epithermal quartz–adularia–sericite (illite)-type deposits is extensively reviewed in the published literature (Hayba et al., 1985; Heald et al., 1987) and it is generally accepted that these deposits formed in complex zones of mixing and boiling in the upper few hundred meters of large geothermal systems. This type of ore fluid is essentially identical to modern geothermal fluids in such low sulfur systems as Steamboat Springs, Nevada and Broadlands, New Zealand (Bonham, 1989).

According to these features, the Kuranakh deposit is rather typical, but with slightly higher salinities (to 10 wt.% NaCl eq.) and lower temperatures (80 to 225 °C) of ore-forming solutions. There is little relation between temperatures of formation and the salinity of solutions. Such relationships are also independent of the composition of the host rocks.

9. Conclusions

Geologic setting, hydrothermal alteration style, mineralogy, and fluid inclusion characteristics define the Kuranakh deposit as a low-sulfidation (quartz–adularia) epithermal gold deposit. The deposit formed just beneath the paleosurface, as evidenced by the preservation of silica sinters over part of the orebodies. Primary gold ore contained auriferous pyrite, minor marcasite, chalcopyrite, pyrrhotite, sphalerite, arsenopyrite, and tellurides. Gold is present as fine-grained native gold (from 0.05 mm up to 0.25 mm, rare—4.0 mm) in goethite and limonites. The deposits have been thoroughly weathered and oxidized throughout their extents. Gold mineralization was accompanied by pervasive vuggy quartz–adularia alteration with the highest grades accumulating in porous sinkhole breccias in the karst; widespread low grade gold is disseminated in the altered and weathered arkose. Mineralization is spatially associated with Mesozoic bostonite dikes that are both pre-ore and post-ore in age. These dikes are volumetrically a minor component of the goldfield.

A fluid inclusion study shows that water solutions of Na and K chlorides, rarely Ca, Mg and Fe chlorides dominate in the inclusions. Maximum solution concentrations are no more than 7.5% NaCl eq. The temperature of ore formation varies from 130 °C to 220 °C. The homogenization temperatures and concentrations decline from early generations of inclusions to the late ones reflecting a depression of these parameters in the late stages of hydrothermal activity.

Presence of syngenetic liquid and gas–liquid inclusions in many samples suggests boiling of solutions during ore formation. Shallow-depth intermittent sealing by mineral deposition may have led locally to pressures exceeding hydrostatic. Tectonic rupture may have been followed by hydraulic fracturing and brecciation resulting in the multiple episodes of fracturing and hydrothermal breccia formation, for low-sulfidation epithermal gold deposits (Hedenquist et al., 1996), and characteristic at Kuranakh.

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