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Morphology of Orebodies and Genesis of Uranium Deposits in the Khiagda Ore Field

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Abstract—The localization controls of uranium lodes at deposits in the Khiagda ore field are considered in this paper on the basis of detailed documentation of borehole cores, geological sections, and maps. Detailed mapping has been carried out at four of eight deposits of the ore field; additionally, three deposits were studied fragmentary using separate sections and boreholes. We have shown that the idea of the lenticular shape of orebodies in section and their ribbonlike shape in plan view only partially corresponds to reality. The revealed morphological features of orebodies along with spatial relationships with epigenetic alteration of host rocks and faults indicate that mineralization was formed by mixing of the oxygen- and uranium-bearing subsurface water descending downdip the seam and the reductive subsurface water ascending from the basement along faults. The available data on the composition of subsurface water currently contained in the basement of ore field give grounds to assume that water similar in composition could have participated in uranium ore deposition. The special properties of this water, interacting for a long time with flows of formation water under conditions of the local geological setting, have imparted those features to the studied deposits, which differentiate them from other economic sandstone-hosted deposits, including those localized in paleovalleys.

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INTRODUCTION

The deposits of the Khiagda ore field (KOF) located on the Amalat volcanic plateau (Vitim Plateau, Buryatia) belong to the economic sandstone-hosted type and more specifically to that variety which is localized in the paleovalleys cut down into the crystalline basement (Mashkovtsev et al., 2010)[1].

The Miocene host rocks that fill erosion paleovalleys are represented by gray and variegated poorly graded coarse-grained terrigenous sediments with volcanic material in the upper part of the section, including basaltic lavas and tuffs. This sequence is cut through by necks and overlain by thick (up to 200 m) cover of plateau basalts. Geological data provide evidence for the almost coeval deposition of ore-bearing terrigenous sediments, volcanic activity, and ore formation. According to Il'ichev et al. (1990), the sedimentary and volcanosedimentary rock filling of paleovalleys, the plateau basalts, and the underlying crystalline basement have become "a field of complex interaction of endogenic and exogenic processes of mobilization, transfer, deposition of ore elements, and transformation of ore-bearing and surrounding rocks." Precisely for this reason, the deposits from KOF stand out among other sandstone-hosted deposits by abundance of convergent attributes, which assume different genetic treatments of the phenomena observed at these deposits. Owing to this, some authors regard them as genetically controversial objects.

A branched network of paleovalleys was formed around the NE-trending arched Baisykhan Uplift (Fig. 1). The origin of this uplift and network of paleovalleys is related to neotectonic stage and block differentiation of the basement in the Transbaikal region, which started at the end of Oligocene.

Uranium orebodies are known primarily in lateral offsets of the main Amalat and Atalanga paleovalleys (paleoravines) to the south and north of the uplift, respectively. The paleoravines extend for 3–10 km, having a width from 300 m to 1.5 km. Several separate ore lodes are combined into eight deposits, which make up an ore field that occupies both slopes of the Baisykhan Uplift.

The paleovalleys and their lateral offsets have been downcut into the basement, composed largely of the Middle–Late Paleozoic porphyry-like biotite–hornblende granodiorite and medium-grained leucogranite of the Vitimkan Complex, distinguished by a high uranium content. These granitic rocks could have been a source of ore matter for exogenic deposits. The release of uranium and other elements was facilitated by the Late Mesozoic lateritic weathering. The upper

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[1] Due to the style of localization, the deposits of this kind are often named basal.

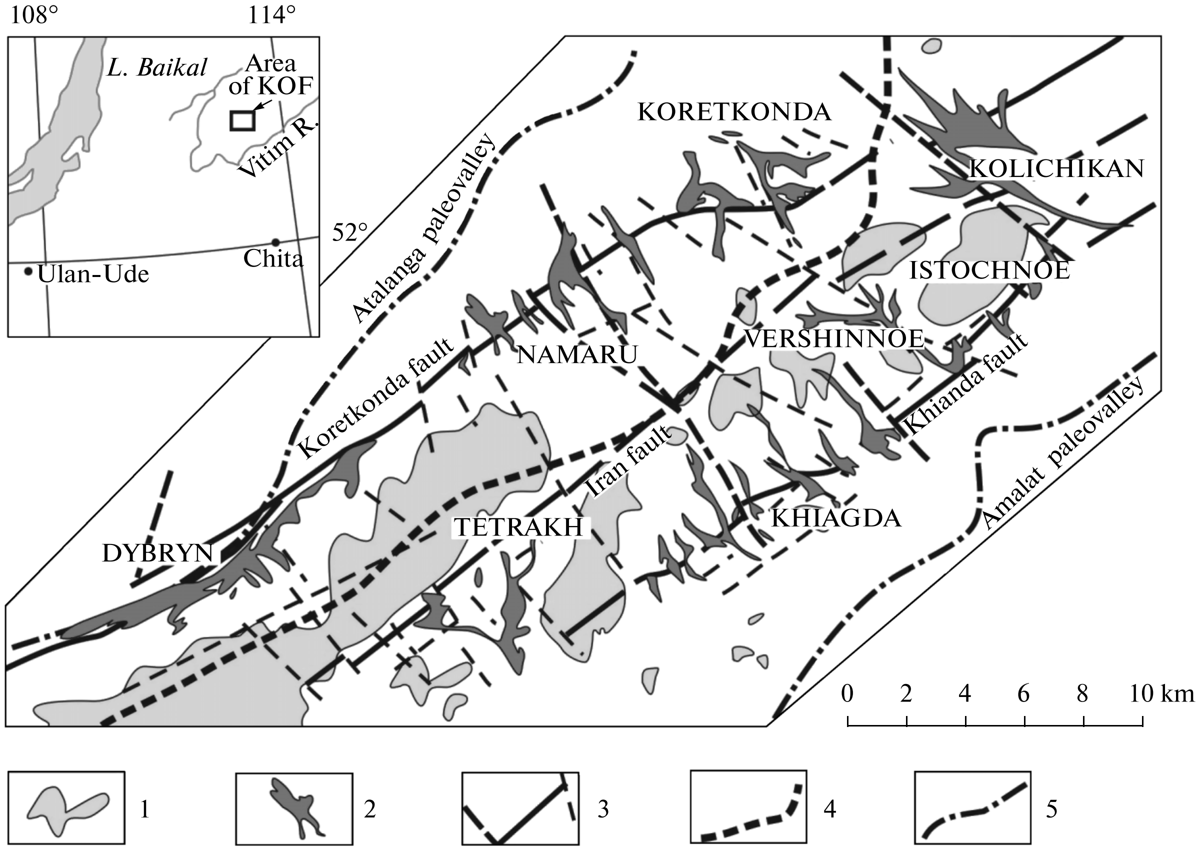

Fig. 1. Schematic geological map of Khiagda ore field, after data of Rusburmash ZAO. (1) Basement rocks outcropped from under Neogene plateau basalts; (2) projections of uranium ore lodes on surface; (3) faults of various scale; (4) axis of Baisykhan Uplift; (5) axis of paleovalley.

part of weathering mantle has been eroded and the weathered rocks redeposited during formation of sedimentary cover.

The rocks of sedimentary cover combined into the Dzhilinda Formation are subdivided (from the bottom to the top) into terrigenous, volcanic–terrigenous, and volcanic members. The two lower members fill the network of paleovalleys, while the upper member overlies the underlying rocks as a continuous cover of basaltic lavas and tuffs.

The uranium mineralization is primarily hosted in terrigenous sediments of the lower member at one or several levels and occasionally penetrates into both the uppermost volcanic–sedimentary member and the basement rocks.

The absence of indications of oxidative epigenesis near boundaries of orebodies is one of the convergent features of the Vitim deposits that allow equivocal explanations. In particular, a popular viewpoint assumes the drowning of the ore-bearing unit by reductive waters at the postore stage.

In general, the KOF deposits are primarily interpreted in terms of their exogenic infiltration mechanism with complications related to supply of carbonated water from the basement. For this reason, the KOF deposits can be attributed to the class of reductive epigenesis in classification of Shmariovich and Lisitsin (1982)[2]. The abundant convergent features of these deposits give an infrequent opportunity to verify and specify the theory of exogenic infiltration uranium ore formation elaborated in the USSR and the USA in the 1960s (Batulin et al., 1965; Finch, 1967). The practical value and heuristic capability of this theory have been proved by the discovery of hundreds sandstone-type deposits all over the world, including several objects unique in reserves. Unusual deposits are informative as abnormal deviants and thus allow us to learn what is the norm. They make it possible to understand the conditions that facilitate appearance of anomaly and to define more distinctly the necessary and sufficient formation conditions of the deposits pertaining to this important economic type.

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[2] Reductive epigenesis means a complex of rock transformations accompanied by gain of elements in reduced forms (sulfide sulfur, ferrous ion, organic carbon, etc.).

RECONSTRUCTION OF ORE-CONTROLLING OXIDATION ZONING

The most striking feature of ore mineralization at the KOF deposits is its confinement to the zone of bleached rocks. The composition of these rocks give enough grounds to deem that they represent a former zone of stratal or ground oxidation altered by carbonated water during the postore stage (Mashkovtsev et al., 2010; Kockin et al., 2013, 2014). In its properties, this water pertains to the glei type. The term *glei* was proposed by Perelman (1968) for a special type of the reductive subsurface water devoid of hydrogene sulfide, which is important for exogenic uranium ore formation. Under reductive H_2S-free conditions, the ferrous ion, in contrast to uranium, remains mobile and enables redistribution in a wide range of Eh–pH.

The orebodies are hosted in the initially gray rocks and adjoin the bleaching zone, occupying an asymmetric position, which is characteristic of exogenic infiltration uranium deposits. Orebodies do not appear in zones that are free of bleached rocks pertaining to the Dzhilinda Formation. As follows from the observations made at the KOF deposits, elevated concentrations of uranium are localized not only in sediments, but also in basalts or granitois related to the oxidation zone, the former attributes of which are noted in the same or the nearest boreholes. These indications themselves commonly bear an indirect character.

Almost all iron hydroxides, which are rather widespread in host rocks, are of a discharge nature, i.e., iron was supplied here as ferrous ions along with subsurface water. Other iron oxides have been formed still in the process of weathering and transported to ore-bearing sediments by mechanical means. Pseudomorphs of iron hydroxides after pyritized and coalified remains are met occasionally (Kochenov et al., 1990). We can add a number of other examples of direct indications of oxidation. Relics of nonoxidized coalified organic matter sealed in poorly permeable sediments are noted among the repeatedly reduced permeable sedimentary rocks. The sporadic iron hydroxide crusts can be interpreted in some cases as a result of oxidation of diagenetic iron disulfide segregations. The oxidized chlorites in fractures dissecting basalts, as well as olivines in basaltic cover oxidized along fractures are described more frequently. The penetration of oxidation in basalt at the boundary with sediments directly points to a pressure infiltration regime in the main permeable seam. This fact explains the penetration of ore mineralization in both basalts and the crystalline basement.

Inasmuch as the ore-controlling oxidation zoning and the host rocks as a whole at the KOF deposits are markedly transformed by postore processes, we had to use reconstructions to map it. The principles of reconstruction of the former stratal or ground oxidation zones, which do not differ from each other in mineralogy or geochemistry (Shmariovich and Lisitsin, 1982), are based on conventional methods (Kashirtseva, 1964; Shmariovich, 1973; Shmariovich et al., 1977). These methods primarily rely on relationships between colors in permeable or poorly permeable interlayers, the occurrence or absence of carboniferous matter, iron disulfides, or uranium mineralization in rocks. Most rarely they are based on such direct indications as iron hydroxide pseudomorphs. The areas of primary brown-colored rocks at headwaters of paleoravines and the retained fragments of weathering mantle with iron hydroxides are also related to the oxidation zone, as a medium for transit of U-bearing water at the stage of oxygen infiltration.

The classic ore-controlling oxidation zoning, which develops in primary gray sediments, comprises (i) a zone of gray rocks devoid of epigenetic oxidation, (ii) a zone of regenerated uranium ore hosted in gray rocks, and (iii) a zone of stratal oxidation with a number of subzones differing in degree of oxidation of clastic and authigenic minerals (Kashirtseva, 1964; Batulin et al., 1965; Finch, 1967). The ore-controlling zoning at the KOF deposits currently appears as follows. The oxidation zone superposed on initially gray rocks is altered under influence of glei solutions into so-called whitish rocks completely devoid of organic remains and iron disulfides. Discharged iron hydroxides are noted locally. The zone of bleached brown-colored rocks and/or weathering mantle occurs closer to feeding region, where the sites with relict brownish color and discharge iron hydroxides are combined with whitish rocks. The variegated coloration of these rocks is emphasized by another term: zone of variegated alteration (Il'ichev et al., 1990). The brown primary and/or weathered rocks retain their initial color only very close to feeding region beyond the reach of clei solutions. Bleached rocks as products of the influence of carbonated solutions also occur among gray rocks proper, including mineralized varieties. It is assumed that because of the similar appearance of secondary reduced whitish rocks and bleached gray rocks, a boundary between them can not always be drawn with confidence (Kochkin et al., 2014). This brings a certain uncertainty to the reconstruction of former oxidation zone boundary.

MORPHOLOGY OF OREBODIES

The morphology of orebodies at infiltration deposits mimics the pinch-out of oxidation zones, which develop in pressure or gravity hydrodynamic systems. This boundary itself obeys the distribution of permeable ore-bearing rocks (Shmariovich and Lisitsin, 1982). The permeability of host rocks at the KOF deposits is distinguished by a complex heterogeneous structure, which is determined by a combination of pore permeability of sedimentary rocks and fracture permeability of crystalline basement rocks and basalts, as well as by faults that ensure a hydraulic link of porous and fractured reservoirs with one another and the basement. The sediments themselves are characterized by nonuniform grading of clastic material, which is often represented by khlidolites and contains discrete fine- or coarse-grained interbeds. In this connection, depicting bleached rock boundaries and pinch-out of oxidation zone, as well as tracing of orebody contours from one borehole to another, strongly depend on the bias of the geologist.

It is conventionally asserted that orebodies at the Vitim deposits hosted in sediments of the Dzhilinda Formation generally are elongated (up to 3–5 km) in plan view, have ribbonlike shape with lenticular cross section, and are localized primarily in the thalweg (channel-line) part of paleovalleys. The lodes are 200–600 m wide, a few meters thick, and reach 20 m and more in bulges (Mashkovtsev et al., 2010).

It should be noted that the complex structure of the section makes it possible to combine ore intersections not only into discrete lenses in the vertical direction, but also to draw the roll form characteristic of infiltration deposits with stratal oxidation zoning, where mineralization is hosted in gray or bleached rocks at the boundary with reconstructed oxidation zone. The Vershinnoe deposit is an example of the orebody with lenticular morphology. The section in Fig. 2 represents a middle part of this deposit. Significant segments of the oxidation zone and the zone of gray sediments are bleached. Low-quality uranium mineralization hosted in the fractured bleached granite underlying sediments is characteristic of this deposit.

In the cross section, the orebodies in paleoravines commonly look like bilateral rolls complicated by intermediate wings. The main mineralization is often localized at several levels of sediments related to partly isolated oxidation tongues. The continuous zone of oxidized rocks, which is observed closer to the region of subsurface water feed, is divided into two or more levels stable in the section, and each of them can be accompanied by ore intersections near pinch-out. The dismembering of the common oxidation zone is probably caused by intercalation of the pressure stratal aquifer by poorly permeable layers. In some cases, orebodies occupying different levels, including basalts, are juxtaposed in plan view up to the formation of a single body, which is drawn in conventional style as a bulge of the common lenticular body. Such a bulge, drawn in the roll style, is shown in Fig. 3.

In general, the multilevel structure of orebodies at the KOF deposits is their common feature. Mineralization frequently occupies a through position from the underlying crystalline basement via sedimentary sequence to the overlying basalt. We should call attention to the fact that sediments above the paleoravine thalwegs frequently retain the initial gray color (Fig. 4).

At all deposits there are cases where the bleached areas in the basement controlled by crush or fracture zones spatially coincide with the areas of bleached sediments and bulges of orebodies or when orebodies localized at different levels are juxtaposed in plan view. This fact is illustrated by the above examples (Figs. 2–4).

All preceding examples are related to the orebodies localized along the thalwegs of tributaries. These orebodies are hosted in relicts of gray-colored rocks located in the back part of oxidation zone. As seen from these examples, uranium mineralization occupies the entire gray-colored space or envelops it from the side of oxidation zone. The next example (Fig. 5) characterizes a case, exotic for KOF, where an orebody is localized in the main paleovalley at the frontal pinch-out of oxidation zone. The rocks referred to the oxidation zone are composed here of graded alluvium and have been reduced for the second time. Only interlayers of the redeposited weathering mantle and sporadic lenses of primary khlidolite in the lower part of section have retained their yellow-brown color.

It is also known that uranium mineralization also occurs in the vent facies of volcanic domes. In fact, uranium mineralization in the necks, which cut through sedimentary rocks of the Dzhilinda Formation in the ore field, nevertheless is an extraordinary phenomenon and does not have a high quality. This only indicates that suitable conditions for the localization of infiltration ore are created in volcanic bodies as well.

As follows from the morphology of orebodies in section, the idea of their lenticular shape does not correspond to reality, and actually this shape is much more diverse. The same can be said about the ribbonlike shape of orebodies in plan view. This shape can be assumed, if the integral projection of all ore intersections on the horizontal plane is considered, however, even in this case, the elongated (linear) shape of orebodies is not universal. As a matter of fact, the morphology of orebodies in plan view combines elements of linearity and amoeba-like shape. Isometric bodies irregular in shape are referred to the latter type.

The lodes of the Vershinnoe deposit serve as an example of an orebody with linear morphology (Fig. 6). In this example, the channel line of paleoravine, orebodies, and zone of bleaching spatially coincide with fracture zone in the basement revealed by documentation of cores from exploration boreholes. Various treatments of this fact are possible. Our genetic interpretation will be given below.

Certain ore lodes of the Koretkonda deposit are an example of complexly combined amoeba-like and linear orebodies (Fig. 7). The linear (a) body located to the south of the Koretkonda Fault extends along left wall of the paleoravine (Fig. 7). The location of this body is controlled by the fracture zone penetrated by boreholes in the basement similarly to the lode at the Vershinnoe deposit (Fig. 6). An isometric (b) body irregular in shape is situated to the north of the Koretkonda Fault (Fig. 7). This orebody envelops a relic of gray-colored rocks from the side of the suggested influx of oxygen-bearing water from feeding region. Farther to the east, this body becomes elongated (c).

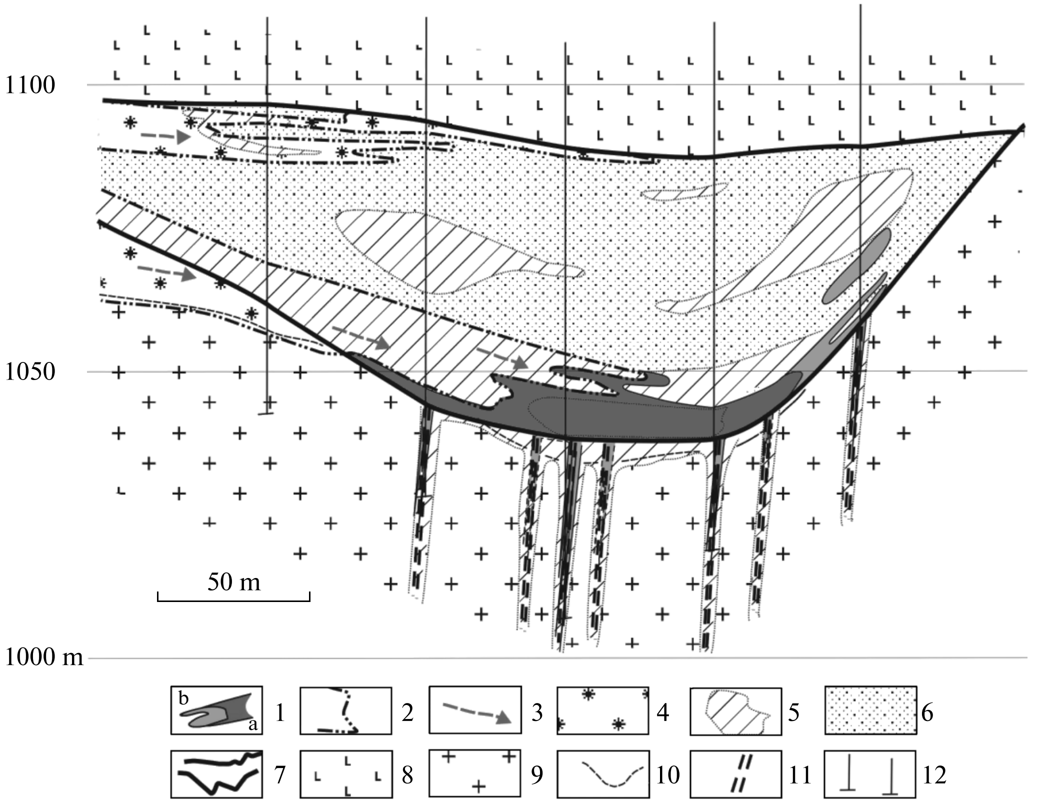

Fig. 2. Vershinnoe deposit. Cross section of lode 1 along exploration line 89. Orebodies are hosted in the lower part of terrigenous member and in basement. (1) Orebodies with (a) high-grade and (b) low-grade uranium mineralization; (2) pinch-out line of reconstructed oxidation zone; (3) inferred direction of oxygen-bearing water flow at stage of ore formation; (4) yellow-colored segments of oxidation zone; (5) bleached areas of terrigenous member and weathered basement and their boundaries; (6) gray-colored sediments of terrigenous member; (7) upper and lower boundaries of terrigenous member; (8) unaltered basalts and volcanosedimentary rocks; (9) unaltered granitic rocks; (10) boundary of weathered granitic rocks; (11) fracture and crush zones in basement; (2) exploration boreholes.

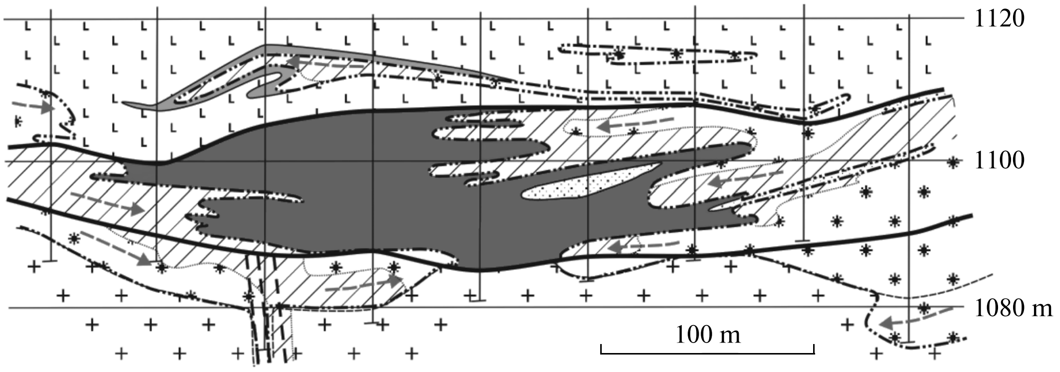

Fig. 3. Dybryn deposit. Cross section of lode 6 along exploration line 124. Orebodies are hosted in terrigenous member and basalts. See Fig. 2 for legend.

The area with an isometric (b) body coincides with zones of secondary reduction of sediments in oxidation zone. One more amoeba-like (d) body is located to the east, and a small remnant of gray-colored rocks has been established within it (Fig. 7). The main frontal pinch-out of oxidation zone in the north of the given part of deposit remains poorly studied and quite can control (e) orebodies as is depicted (Fig 7). In general, the orebodies in this area occupy only limited areas in the paleoravine.

Another example that illustrates the complex morphology of orebodies is the eastern part of the Namaru deposit. The conventional-style depicting of orebodies oriented along channel lines of paleoravines based on

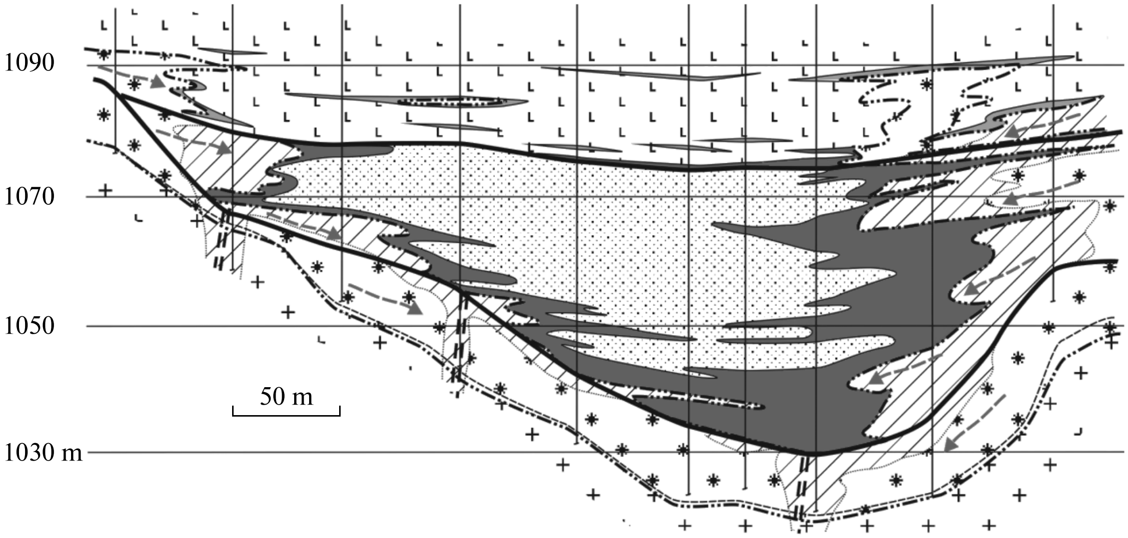

Fig. 4. Kolichikan deposit. Cross section along exploration line 117. Multilevel orebodies hosted in terrigenous and volcanic–sedimentary members of main paleovalley, See Fig. 2 for legend.

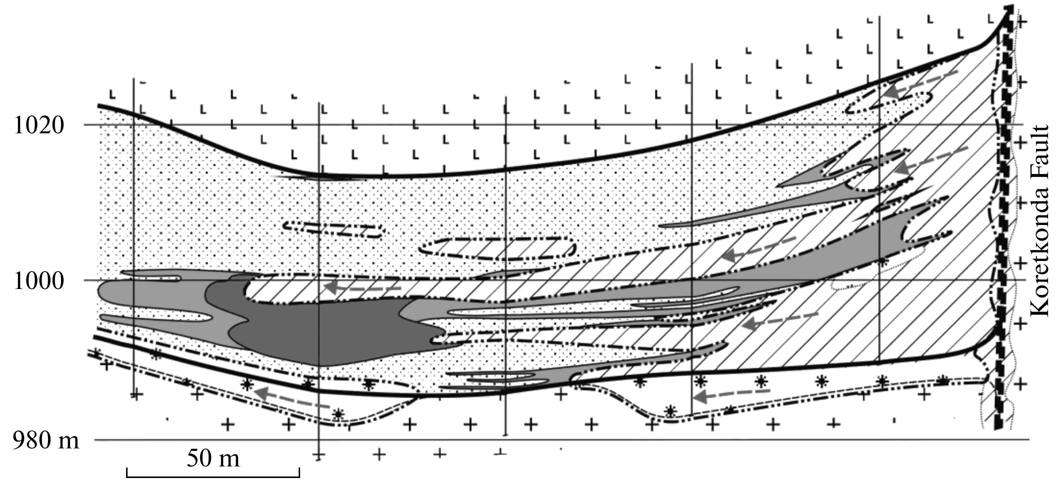

Fig. 5. Dybryn deposit. Cross section of lode 1 along exploration line 843. Orebodies are localized at frontal pinch-out and hosted in terrigenous member of main paleovalley. See Fig. 2 for legend.

the data of Urangeolrazvedka (2008) is compared with the alternative depicting controlled by pinch-out of the reconstructed oxidation zone (Fig. 8b, orebody (e)). The general orientation of the orebody in both figures coincides with the strike of paleoravine, which in this area is oriented obliquely to the other paleoravines and the general dip of slope of the Baisykhan Uplift. This is seen from the sharp change of the thalweg strike. The frontal pinch-out of the reconstructed oxidation zone and ore mineralization in this area have very intricate morphology (Fig. 8b). The orientation of the pinch-out boundary considered in detail corresponds to the most probable direction of oxygen-bearing water filtration from feeding region. The main western pinch-out segment in this area was drilled rather well. In the east, the pinch-out remains unstudied, although it also can control orebodies.

STRUCTURAL CONTROL OF OREBODIES

As has been exemplified in particular examples, the KOF orebodies frequently extend along the thalwegs of ravines, which are in some cases rectilinear. Based on this linearity, one can suppose that the ravines inherit faults in the basement. This is often corroborated by documentation of fracturing in the cores recovered from the basement, e.g., at the Vershinnoe deposit (see above). These facts illustrate spatial relationships between orebodies and faults in the basement; various genetic senses can be enclosed in such

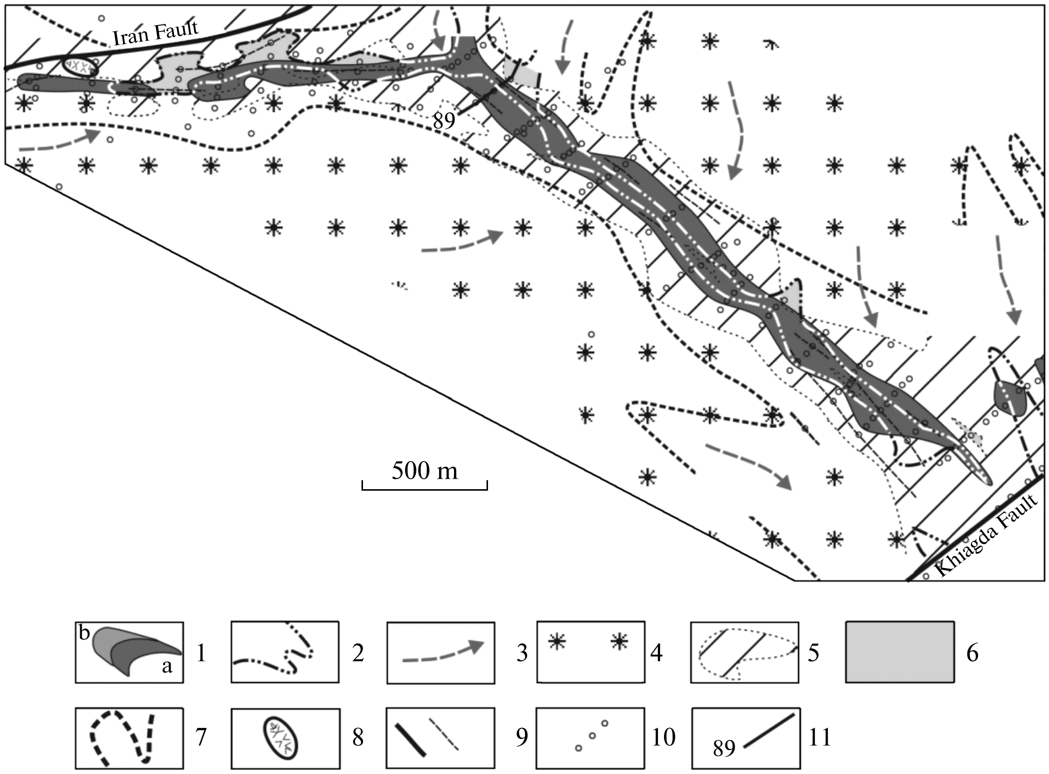

Fig. 6. Vershinnoe deposit: a fragment. Linear morphology of orebodies in lower part of terrigenous member. See also section along exploration line in Fig. 2. (1) Orebodies with (a) high-grade and (b) low-grade uranium mineralization; (2) pinch-out line of reconstructed oxidation zone; (3) inferred direction of oxygen-bearing water flow at stage of ore formation; (4) yellow-colored segments of oxidation zone; (5) bleached areas of terrigenous member and weathered basement and their boundaries; (6) gray-colored sediments of terrigenous member; (7) boundary of paleoravine; (8) basaltic apparatus (basaltic neck); (9) faults: solid line – major high-amplitude normal fault; dashed line – fracture zone in basement revealed by documentation of cores and in structural sections; (10) exploration boreholes; (11) section and exploration line number.

relationships. However, the linearity of certain orebodies does not exhaust all diversity of their morphology. This also has been shown by examples.

At the same time, the relations of both linear and amoeba-like orebodies to channel lines of ravines merit special attention. To explain this fact, it is commonly suggested that a flow of oxygen-bearing subsurface water from walls of paleoravine was not enough to oxidize the gray-colored rocks enriched in carbonaceous matter in the thalweg part. This explanation is realistic for the ground flow at ravine slopes but is unfit for pressure hydrodynamic system that arose beneath plateau basalts as a regional confining bed. From general knowledge on regional geological history and theoretical concepts, it can be inferred that immediately after formation of the basaltic confining bed the flow of pressure subsurface water at slopes of the Baisykhan Uplift became oriented downslope toward the areas of discharge located somewhere in axial zones of the main paleovalleys. Small ravines or paleotributaries of these valleys filled with permeable sediments gave additional filtration advantages to this flow concentrating it. This implies that in the thalwegs, i.e., in the most permeable part of sedimentary section, the oxidation zone must be advanced into the sedimentary sequence to the greatest extent. Instead of this, at the KOF deposits, the swells of orebodies related to relics of gray-colored rocks are the most frequent exactly in the thalwegs of paleoravines.

There are no lithologic prerequisites, e.g., enrichment in clay, for the retention of orebody bulges or counter rolls in the ravine thalwegs. Moreover, large areas of back-ore gray sediments appear between counter rolls in the lower reaches of paleotributaries. In the absence of lithological prerequisites, the retention of orebodies and gray-colored sediments can only be explained by a hydrodynamic screen that prevents filtration of oxygen-bearing water in the preferable directions. The inflow of ascending water from basement into the sedimentary fill enables the creation of this screen.

It is known that the morphology of orebodies and their structural control at the infiltration deposits of reductive epigenesist have their features, which are caused by hydrodynamic mixing of the formation water and the fluids ascending along the faults. Vartanyan (1968) was the first to call attention to the dynamics of fluid mixing in the near-surface zone by studying

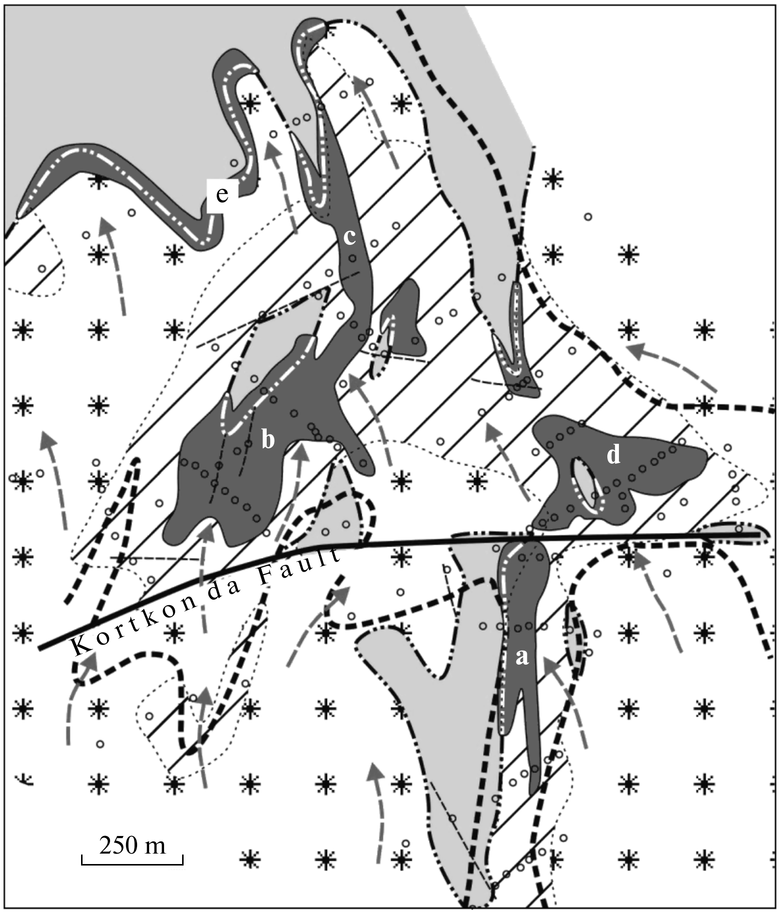

Fig. 7. Koretkonda deposit: a fragment. Morphology of orebodies in plan view. See text and Fig. 6 for symbols.

the areas of mineral waters. Later, mathematical and physical simulation of the mechanism governing mixing of two heterogeneous flows in permeable reservoir rocks was carried out (Vasil'ev, 1971; Belova et al., 1982). These investigations made it possible to establish the factors that determine location of the boundary dividing the flows and to explain the dispersion character of mixing.

Owing to a difference in pressure, the water supplying into the seam pushes off the formation water for a certain distance. The shape of boundary between two flows moving in the common hydraulic field is determined by the proportion of consumptions (Fig. 9). Ascending solutions create a dome above the conduit, whereas the flow of formation water turns round this dome above and on sides. Variation of consumption proportions changes the position and shape of the boundary.

The model of uranium ore formation stated on the basis of this mechanism by Belova et al. (1982) made it possible to explain the earlier established stadial and pulsatory character of ore formation at the deposits in Ferghana and Kyzylkum (Shmariovich, 1970; Bulatov and Shchetochkin, 1970). This phenomenon is a consequence of the variable proportion of two flows. The sharp prevalence of the ascending flow terminates the uranium supply with oxygen-bearing water and gives rise to a conservation of orebodies. The same model explains the morphology of fault-line orebodies and their spatial relationships with synore and postore epigenetic transformations (Kochkin, 1988, 1989).

The adaptability of this model to the KOF is illustrated by the central area of the Dybryn deposit. The plans of four oxidation zone levels in the ore-bearing Dzhilinda Formation and the orebodies localized therein are shown in Fig. 10. The direction of oxygen-bearing water filtration (dashed arrows) shown according to reconstructed boundaries between oxidized and gray-colored rocks is generally oriented along the ravines. The current lines of oxygen-bearing water vary locally in plan view up to the intersection with drainage divides between paleoravines, turning round relics of gray-colored rocks, which jut out far into oxidized rocks from frontal boundary of oxidation zone. The site in the right part of each plan illustrates juxtaposition of mineralization at all levels (orebody (k) on Fig. 10); also see section in Fig. 3. The orebodies, which are amoeba-like in plan view, are located

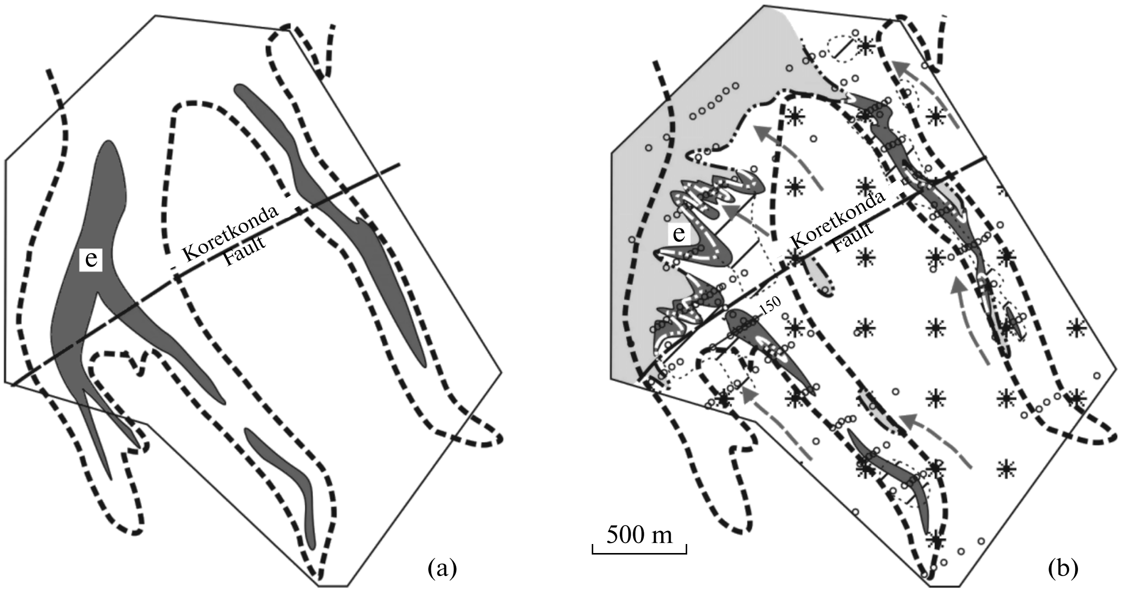

Fig. 8. Namaru deposit: a fragment. Morphology of orebodies: (a) conventional depicting of orebodies along paleoravine thalwegs (before detailed exploration), (b) depicting of orebodies along boundary of reconstructed oxidation zone (with allowance for results of detailed exploration). See Fig. 6 for legend.

here at four levels including basalt. The largest (h) orebody (Fig. 10d) is related only to the lower level of oxidation zone and localized in the uplifted wall of the Koretkonda Fault. Neither the oxidation zone nor the mineralization adjoins close to the fault here. The frontal boundary of the oxidation zone has been established in the thalweg of the main paleovalley behind the Koretkonda Fault. The section with orebodies at its pinch-out is located a little to the east (Fig. 5). In the subsided block, the oxidation zone develops at several levels throughout the section of terrigenous sequence.

A generalized model of orebody formation in the central site of the Dybryn deposit is shown in Fig. 11.

The model is based on the concept characterizing morphology of the orebodies forming at the boundary between formation water and ascending subsurface water. The (k)-site is a complexly built dome of gray rocks which occupies all four levels of oxidation zone (Fig. 11). According to the accepted model, this dome was formed by the hydrodynamic head of the solutions that were injected into permeable sediments from the basement and propped up oxygen-bearing formation water. It is inferred that the complex structure of the dome was caused by its formation above several points of ascending water discharge, which predetermined retention of gray-colored rocks deep in the oxidation zone. All these points are probably controlled by the fault that intersects the paleoravine across its strike. The echeloned orebodies turn round the dome of gray rocks up to pushing the upper body off toward basalts. A similar attitude of the orebodies above the dome of gray-colored rocks is known at the Sulucheka deposit in southeastern Kazakhstan (Kochkin et al., 1990).

The orebody at site (h) is elongated in plan view at the lower level of the host terrigenous member. According to the model, this orebody is controlled by a linear zone of ascending water discharge along the extended segment of the Koretkonda Fault. The hydrodynamic screen at this site probably occupied the entire thickness of sediments, and because of this a flow of oxygen-bearing water and oxidation zone turn round it from both the south and the north, where they penetrate into the subsided block. The absence of significant mineralization at higher levels of the (h) site is explained merely by insufficient supply of uranium-bearing oxidative water. As is shown in Fig. 11a–10c, the oxidation zones at higher levels pinch out to the southeast except for a few insignificant tongues of oxidation, which are accompanied by small bodies of low-grade ore primarily at the middle level.

The supply of reductive water along the subordinate fault on the (o) site (Fig. 11) predetermined the retention of an extensive field of gray sediments at all levels. Unfortunately, a potentially ore-bearing pinch-out of the oxidation zone to the east of this discharge area was not drilled, probably, because of its location mainly at a drainage divide.

The elongated (h) orebody occupies thalweg of paleoravine (Fig. 11). As an illustration of the accepted model, it is rather typical. Like at other site (k), the ascending fluids were supplied here along the fault that intersected the ravine across its strike, but much less intensely.

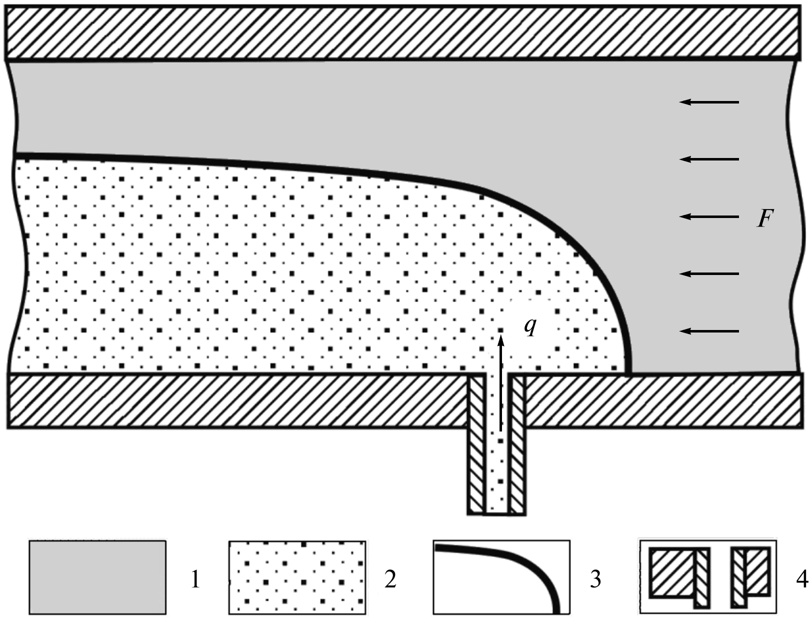

Fig. 9. Experimental model of permeable layer filling at consumption ratio $F/q = 0.5$, where F and q are descending and ascending water flows, respectively. Location of reaction zone between two interacting liquids was marked by formation of sediment. After Belova et al. (1982). 1 – area with formation water flow; 2 – area with ascending water flow; 3 – boundary between two flows; 4 – details of the experimental set.

In those cases, when the fluid-conducting fault coincides with the strike of paleoravine, the orebodies have the best-expressed linear shape, e.g., at the Vershinnoe deposit (Fig. 6).

Finally, orebodies' morphological feature of localization within bleached rocks is reasonably explained by the influx of reductive water with substantial prevalence of ascending flow consumption over that of descending flow. The areas of secondary reduction of oxidation zone at each level are shown in Fig. 10, and a generalized contour of these levels is depicted in Fig. 11. As is seen, the domain of secondary reduction spreads deeply into oxidized rocks framing remnants of gray-colored rocks along with orebodies. According to the accepted model, the stage of secondary reduction comes due to the abrupt shift of consumption proportion in favor of ascending flow irrespective of causes. This shift could have been a result of terminated or attenuated infiltration of oxygen-bearing water, which, in turn, could have been initiated by tectonic or climatic variations or, on the contrary, by the injection of an additional volume of ascending fluids owing to tectonic movements along feeding channels. It is noteworthy that in that case the ascending fluid filtrated not only through oxidized rocks but also through gray sediments, including ore-bearing varieties, and induced their alteration. This was primarily expressed in the bleaching of gray rocks and a part of the orebodies hosted therein.

DISCUSSION

Our observations of orebody morphology and alteration of rocks at the KOF deposits confirm the structural control of uranium mineralization. In general, orebodies follow the boundary between gray-colored and oxidized sediments (including secondary reduced varieties) with allowance for aforementioned deviations. The boundary of oxidation is locally controlled in plan view by the discharge of ascending water into permeable sediments. In turn, the localization of discharge points is controlled by faults in the basement.

As seen from Fig. 12, almost all ore lodes at the KOF deposits are spatially related to the Koretkonda and Khiagda master faults, whereas many linear lodes extend along the transverse faults. This fact can be interpreted as localization of areas of mixing of ascending fluids and infiltration water above the zone influenced by subordinate transverse faults, where additional favorable conditions for the deposition of uranium were created due to the appearance of epigenetic reductants along with carbonic detritus as a syngenetic reductant. Afterward, the ascending fluids ensured the conservation of uranium mineralization under reductive conditions.

In the ore field as a whole, the pinch-out of the oxidation zone has been studied in detail only in the lower member of the Dzhilinda Formation largely in thalwegs at headwaters of tributaries of main paleovalleys (Fig. 12). The oxidation zone and orebodies in the subsided block of the Kopetkonda Fault at the Dybryn

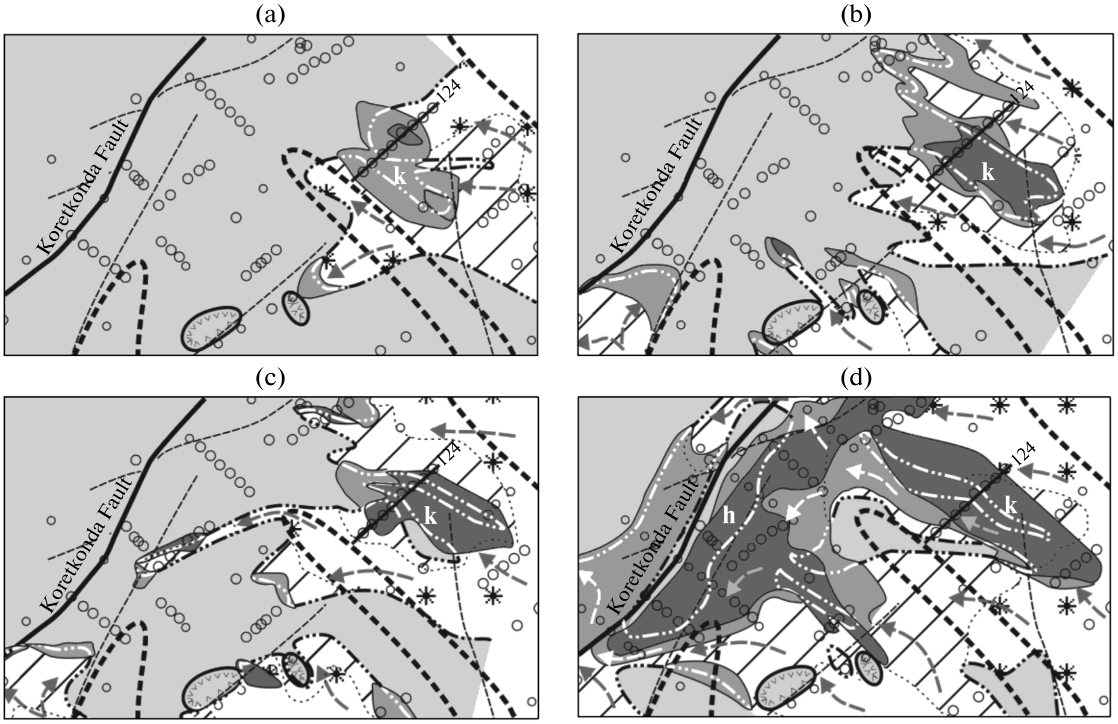

Fig. 10. Dybryn deposit, central part. Location of orebodies and epigenetic alterations at different levels of the Dzhilinda Formation: (a) volcanic–sedimentary member; (b–d) upper, middle, and lower levels of terrigenous member. See Fig. 6 for legend.

deposit localized at the headwaters of the Atalanga paleovalley are only exceptions. The pinch-out of the oxidation zone in the lower reaches of tributaries and thalwegs of the main paleovalleys at a distance from axis of the Baisykhyn Uplift remains unstudied, although might bear uranium mineralization (Novgorodtsev et al., 2013; Novgorodtsev and Martynenko, 2013). The syngenetic accumulations of coalified plant detritus can be reductants of uranium beyond the zones of master faults as the main purveyors of epigenetic uranium reductants. It is known that gray sediments that fill the main paleovalleys and their tributaries are characterized by high (up to fractions of a percent) contents of coalified organic matter (Kochenov et al., 1990; Mashkovtsev et al., 2010).

Morphology of orebodies and alteration of host rocks at the KOF deposits show obvious attributes of participation of ascending waters in ore formation. Some morphological features of orebodies indicate that they were formed due to the mixing of descending and ascending waters. The localization of uranium mineralization in the member of terrigenous rocks regardless of their facies and spreading of mineralization into basaltic cover and granitoids of the basement clearly indicate that epigenetic uranium reductants participate in ore formation. Without their participation it is hardly possible to explain the high quality of ore in the lodes unrelated to coalified detritus. The ascending water could have been a supplier of epigenetic reductant.

In the case where epigenetic reductants are supplied to host rocks via a fault, the area of ore formation remains immobile. Under conditions of prolonged supply of uranium along with oxygen-bearing water to the immobile barrier, the quality of mineralization depends on the duration of system existence and theoretically can be arbitrarily high. Ore formation on stationary barrier explains both extremely high quality of ore and general independence of ore mineralization from facies of host rocks at the KOF deposits.

Only the basic properties of ascending fluids are though to provide an immobile reducing barrier with this amount of reductants, which is sufficient for precipitation of uranium and conservation of mineralization at the postore stage. Lisitsin (1975) supposed that ascending fluids supply H_2S, H_2, and bitumen. Specific and substantiated suggestions remain limited. In general, they are concerned with the composition of subsurface water in the basement or sedimentary cover. For example, the carbon dioxide–bitumen alteration expressed in formation of newly formed calcite, dolomite, bitumen, as well as pyrite, quartz, kaolinite, and other minerals was explained by their deposition in the hydrocarbon medium (Shchetochkin, 1970; Shchetochkin et al., 1975). Sulfide enrichment of secondary reduced rocks is commonly interpreted by neighborhood with petroliferous basins, the waters of which are enriched in hydrogen sulfide and hydrocarbons (Shmariovich, 1971; Goldhaber et al., 1983). In contrast, at the Sulucheka deposit, orebodies

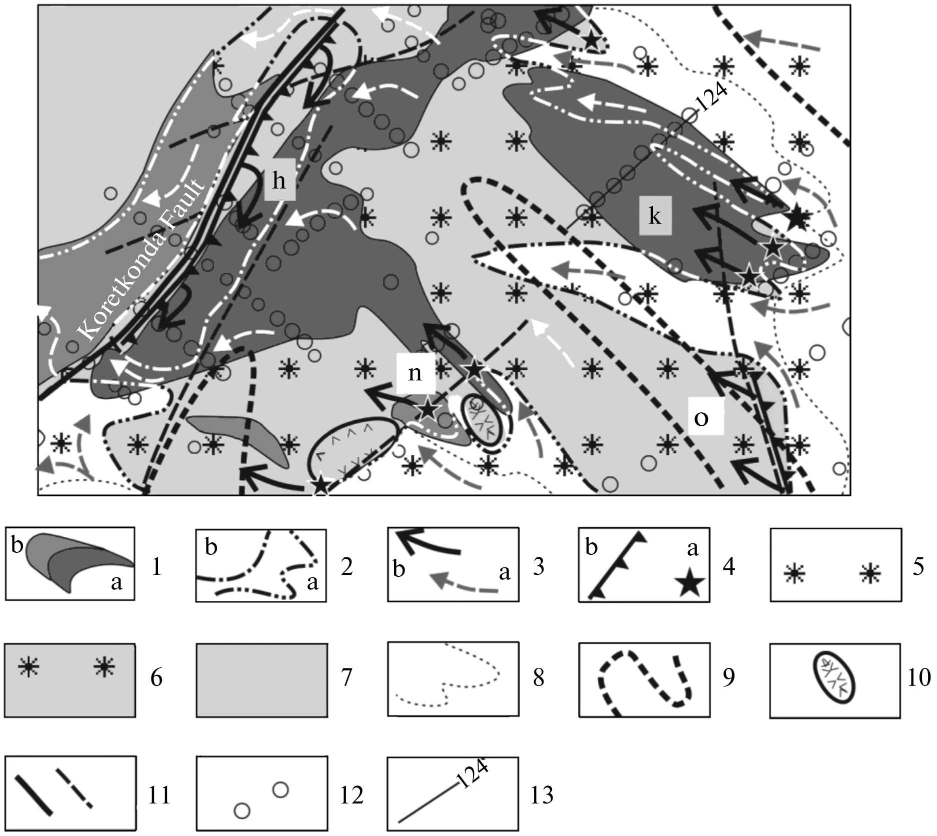

Fig. 11. Model of uranium mineralization formed in central part of Dybryn deposit. (1) Generalized contour of orebodies with (a) high- and (b) low-grade uranium mineralization; (2) boundary of (a) minimum and (b) maximum spreading of reconstructed oxidation zone in ore-bearing rocks; (3) inferred direction of filtration of (a) oxidative and (b) reductive waters at stage of ore formation; (4) inferred areas of supply of ascending reductive waters with (a) dotty and (b) linear geometries; (5) area of completely oxidized section; (6) area of relict gray-colored rocks among oxidized rocks; (7) area of completely gray-colored section; (8) contour of maximum spreading of secondary reduced rocks; (9) contour of paleoravine; (10) volcanic dome; (11) faults variable in reliability degree; (12) exploration boreholes; (13) section along exploration line 124 (see Fig. 3). See text for symbols.

are conserved without evidence for secondary reduction of oxidized rocks, and this is explained by the flooding of ore-bearing layer with oxygen- and H_2S-free nitrogen thermal water with hydrogen as a sole reductant (Kochkin et al., 1990). In any case, it was suggested that these fluids migrated from underlying or adjacent hydrogeological units, where subsurface waters are enriched in reductants. The authors of the given work followed the same reasoning.

At the KOF deposits, the cold carbonated water of the basement, the gas-cut springs of which are widespread in the region and known in the ore field, are regarded as reductive fluids. The area of the Vitim deposits is a part of the Daur province of carbonated water, which are widespread in southern Transbaikalia and Buryatia. The low temperature equal to or lower than 10°C, mineralization up to 1.5 g/L, Mg–Ca hydrocarbonate composition, and high concentration (up to 3.3 g/L) of free carbon dioxide are the features of these waters. It is assumed that carbon dioxide has deep (metamorphic (?), postvolcanic) origin, while the water itself is meteoric (*Mineral'nye* ..., 1961; Mashkovtsev et al., 2010). The Cenozoic basalts are widespread in the Vitim district and dated at 20 to 0.5 Ma (Rasskazov et al., 2007). This age almost completely overlaps the historical interval, when the deposits existed. The deposition of the ore-bearing Dzhilanda Formation was also accompanied by volcanic activity.

The available analytical data indicate that the carbonated water participated in postore processes, like its contemporary analog (Kochkin et al., 2014). Taking into account that a significant gap separates ore formation from present time, a certain difference in composition and temperature between contemporary and synore subsurface waters cannot be ruled out. No reliable analytical data on possible composition of ascending synore fluids are available to date. We can only state that they were not aggressive with respect to host rocks. According to Kochenov et al. (1990) and our data, all clay minerals in sediments are terrigenous and similar in composition to minerals of the local weathering mantle. The clastic feldspars do not bear signs of thermal solution influence. No evidence for

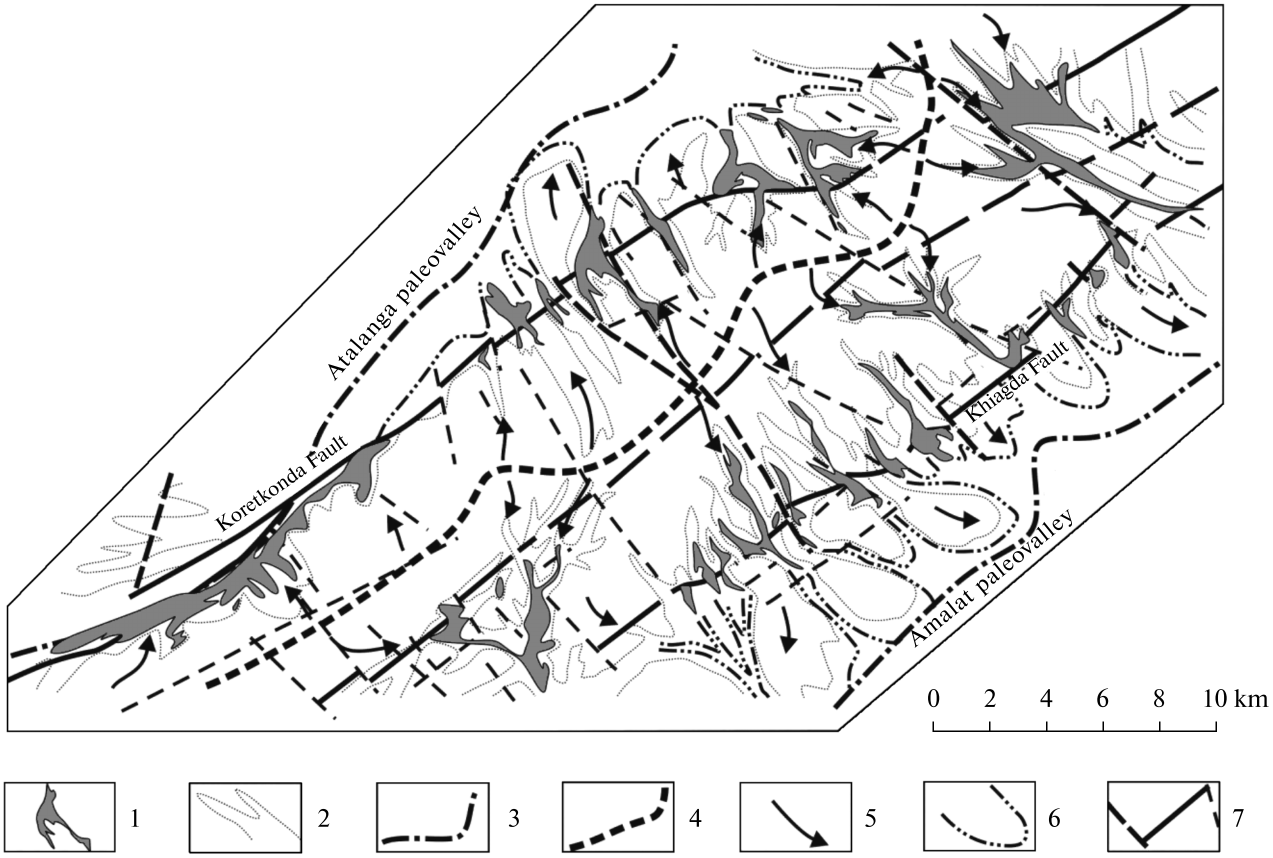

Fig. 12. Khiagda ore field. Location of orebodies at pinch-out of reconstructed oxidation zone, after data of Rusburmash ZAO. (1) Explored orebody; (2) contour of paleoravine; (3) paleovalley axis; (4) main drainage divide of paleoravine network; (5) inferred direction of oxygen-bearing water flow at the stage of ore formation; (6) forecasted pinch-out of oxidation zone in lower part of Dzhilinda Formation; (7) faults of various orders.

extensive processes related to the thermal postvolcanic activity are known except for a few decimeters of thermal quenching at the roof of sediments immediately under lava cover.

CONCLUSIONS

The unique combination of diverse processes within a short time interval of geological history led to formation of abnormal KOF deposits as compared with classic uranium deposits localized at pinch-out of stratal oxidation zones.

The diverse and extremely heterogeneous lithofacies of ore-bearing sediments in paleovalleys—neighborhood and partial intercalation of gray- and brown-colored sediments and occurrence of volcanogenic components—predetermined the extremely complex background of multistage epigenetic oxidation and reduction of ore-bearing rocks.

The conditions favorable for the penetration of oxygen-bearing waters into the near-surface aquifers and along fracture zones into granitoids of the basement and overlying volcanic rocks existed at a certain stage of tectonic reactivation around the Baisykhan Uplift. These waters created oxidation zoning in the sediments.

The prolonged supply of subsurface water from the basement along large faults predetermined various epigenetic processes in the areas of mixing of two types of waters, in particular, the formation of uranium mineralization on the reductive geochemical barrier at the ore stage and iron redistribution at the stage of ore conservation.

Owing to the character of the glei (reductive H_2S-free), the ascending carbonated subsurface water inherent to the extensive Daur region created favorable conditions for deposition of uranium mineralization due to mixing with oxygen-bearing water.

Beyond the zones affected by fluid-conducting faults, the main role in formation of uranium mineralization belonged to the syngenetic reductants at pinch-out of oxidation zones within major paleovalleys, the most extent of which remains unstudied.

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