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Overview of early cretaceous gold mineralization in the orogenic belt of the eastern margin of the Siberian craton: geological and genetic features

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The giant Verkhoyansk-Kolyma gold province, producing more than~ 3700 t of gold, is one of the most important metallogenic provinces for orogenic gold deposits in the world. The province is located on the eastern margin of the Siberian craton. The main types here are multistage orogenic Au-As and orogenic-like Au-Sb types of mineralization, related to the Late Jurassic-Early Cretaceous metallogeny and the evolution of the convergent margin. These deposits were formed in the environment of late orogeny during two metallogenic stages—the Late Jurassic-Early Cretaceous collision-related (early stage/stage one, 135–150 Ma) and the Early Cretaceous subduction-related (late stage/stage two 114–130 Ma). The common features, differences and genetic nature of the deposits of these two metallogenic stages have been debated for a long time. To improve the understanding of these problematic issues and the genesis of deposits, and control over them by the mantle lithosphere, we consider here the Early Cretaceous orogenic belts of the eastern margin of the Siberian craton. Orogenic belts are related to the development of the paleo-Arctic and paleo-Pacific margins of Siberia. The tectonic, geochronological, mineralogical and geochemical specificity of the deposits of the orogenic belts are shown. A regional metallogenic overview of gold deposits is performed using data on the age of mineralization and the isotopic composition of sulfur sulfides. A preliminary model of the origin of late stage mineralization is proposed in connection with the processes of the Okhotsk-Koryak orogenic belt formation. Increased concentrations of siderophilic and chalcophilic elements, the Ni, Bi minerals presence in the ores, relatively high fineness of gold, predominance of juvenile sulfur in the isotopic composition of sulfide sulfur, and the control by large trans-crustal faults as well as spatial and chronological association with initial (dike) magmatism indicate mantle sources of ore fluids. This mineralization within the orogenic belts of the eastern margin of the Siberian craton assumingly appeared due to dehydration of the submerged slab and local upwelling in the mantle in the rear of the active continental margin. The possibility of the gold-bearing fluids existence in such conditions is estimated. The metallogenic specific nature of collision-related and subduction-related orogenic Au is defined. The proposed model can be useful for the analysis of polychronous orogenic Au-As and orogenic-like Au-Sb metallogeny of orogenic belts on craton margins globally.

KEYWORDS

orogenic gold deposits, geology and isotope geochemistry, model of origin, Yana-Kolyma and Okhotsk-Koryak orogenic belts, Northeast Asia

1 Introduction

Approximately 30% of the world's gold reserves are located in orogenic gold deposits (Goldfarb et al., 2005; 2019). This type of deposits is one of the most important producers of gold in the world (Frimmel, 2008). Orogenic gold deposits are formed at convergent margins, usually in a subduction and less often a collision environment (Goldfarb et al., 2005; Groves et al., 2020a; Deng et al., 2020; Yang et al., 2021; Zhao et al., 2022.). They are controlled by faults or shear zones (Groves et al., 1998; Wang et al., 2022; Zhao et al., 2022). Genesis of the deposits is highly controversial (Goldfarb and Groves, 2015 and references therein). Crustal (e.g., Goryachev, 2003; Tomkins and Grundy, 2009; Phillips and Powell, 2010), as well as sub-crustal sources of fluid and metals (e.g., Kerrich and Wyman, 1990; Hronsky et al., 2012; Deng et al., 2020; Wang et al., 2020) are supposed. Recently, evidence has emerged on multi-stage orogenic gold within the same block of convergent orogen during its metallogenic evolution (Yang et al., 2021). In addition, the orogenic gold of collisional orogens differs from oceanic subduction settings (Deng et al., 2022). Analysis of geological and genetic features multi-stage orogenic gold is important to explain its connection with the geodynamic evolution of the orogen and control by the mantle lithosphere and for conceptual exploration targeting (Groves et al., 2020a).

Orogenic gold deposits of the Verkhoyansk-Kolyma province at the eastern margin of the Siberian craton provide an opportunity to better understand the origin of multi-stage orogenic gold. This province is one of the most important metallogenic provinces for orogenic gold deposits in the world, producing more than~ 3700 t of gold. The main types here are multi-stage orogenic Au-As and orogenic-like Au-Sb types of mineralization, related to the Late Jurassic-Early Cretaceous metallogeny and the evolution of the convergent margin. These deposits were formed in the environment of late orogeny during two metallogenic stages—the Late Jurassic-Early Cretaceous collision-related and the Early Cretaceous subduction-related (Goryachev and Pirajno, 2014; Fridovsky, 2018).

An important aspect of orogenic deposits origin is their close connection with the processes of orogenic metamorphism (Goldfarb et al., 2001; 2005; Goldfarb and Groves, 2015) as well as, in our case, of granitoid magmatism, which is apparent for the early Late Jurassic-Early Cretaceous mineralization (Goryachev, 2003) but not always obvious for the distinguished Early Cretaceous deposits. This requires an analysis of the geological and tectonic position and of mineral and geochemical characteristics of these deposits to see if there are differences between them, how interconnected the processes of these deposits formation are, and how does their origin correspond to the gold-stibnite mineralization.

The eastern margin of the Siberian craton is represented by a passive continental margin, deformed, in the Late Mesozoic, due to the Late Jurassic-Early Cretaceous orogeny (Parfenov and Kuzmin, 2001; Nokleberg et al., 2005) (Figure 1). For a long time, within the Late Jurassic-Early Cretaceous Yana-Kolyma orogenic belt (YaKOB) (Nokleberg et al., 2000; 2005; Parfenov and Kuzmin, 2001), entire orogenic gold mineralization was considered monostage, related to orogenic plutonic-metamorphic processes of the Late Jurassic—Early Cretaceous age (Goryachev, 1998; 2003; Nokleberg et al., 2005), despite the rare Early Cretaceous (125–120 Ma) dates for large gold-stibnite deposits (Berger et al., 1978), in terms of localization very similar to orogenic gold deposits. Over time, new Early Cretaceous Ar-Ar and Re-Os dates appeared for typical orogenic gold deposits in the Yana-Kolyma orogenic belt (Newberry et al., 2000; Pachersky et al., 2021). Besides, the typical orogenic gold mineralization, known within the deformed passive continental margin in the Allakh-Yun zone (AYuZ), also turned out

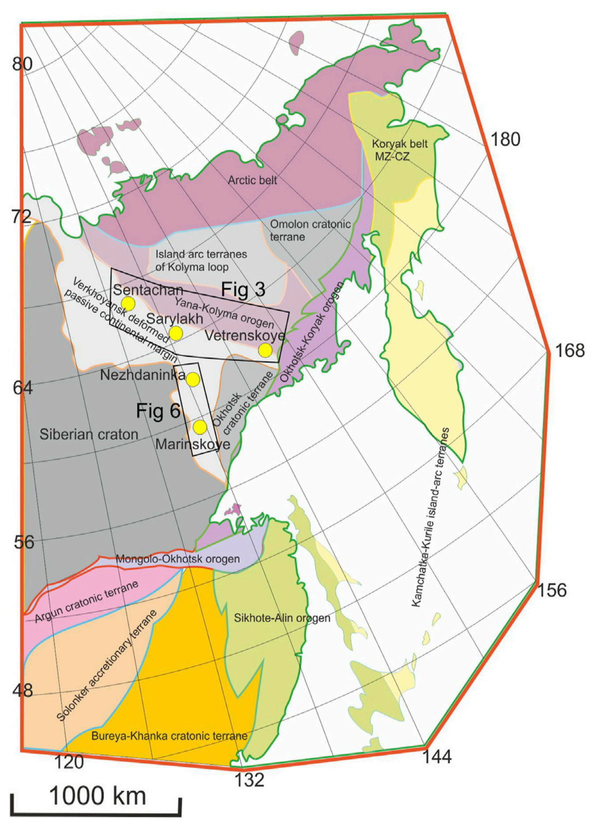

FIGURE 1
The position of the studied mineralization in the structures of the Northeast Asia.

to be the Early Cretaceous 125–118 Ma (Bakharev et al., 2011; Borisenko et al., 2012). Consequently, in generalizing publications (Goldfarb et al., 2014; Goryachev and Pirajno, 2014), two stages in orogenic gold deposit formation were identified for the territory of Northeast Asia: early (Late Jurassic-Early Cretaceous), chronologically related to the final of the Late Mesozoic orogenic event, and late (Early Cretaceous, namely, Aptian-Albian) related to the processes of the Okhotsk-Koryak (OKOB) or Oloy-Chukotka orogenic belts formation (Parfenov and Kuzmin, 2001; Khanchuk, 2006; Goldfarb et al., 2014; Goryachev and Pirajno, 2014; Fridovsky et al., 2021). In addition, commercial gold-stibnite mineralization of complex genesis and ambiguous age is known in the YaKOB (Early Cretaceous—Berger et al., 1978; or Late Cretaceous—Indolev et al., 1980). By its mineralogical features, this mineralization is of deep origin (Amuzinsky et al., 2001); simultaneously, according to its mineral composition and position in fault zones, these are typical orogenic ores similar to those found in the Murchison province in South Africa.

Here, we present the results of a comprehensive analysis on geochronological and isotope-geochemical data, data on the structural position of the mineralization in the YaKOB and OKOB structures, with an assessment of their geodynamic position. We also characterize gold mineralization, exemplified by the Vetrenskoye, Nezhdaninskoye, and Marinskoye deposits, as Early Cretaceous, identifying its specific mineral and isotopic composition.

2 Geological and metallogenic background of the eastern margin of the siberian craton

The eastern margin of the Siberian Craton comprises the following tectonic units (Figure 1): The Verkhoyansk fold and thrust belt; the Yana-Kolyma, the Okhotsk–Koryak, and the Arctic orogens; the Omolon and Okhotsk cratonic terranes attached to the craton in the east; the Mesozoic–Cenozoic collage of oroclinally-bent island arc terranes of the Kolyma Loop and Indigirka–Kolyma accretionary wedge terranes. The age of the orogenic events is Jurassic to Early Cretaceous (Yana-Kolyma and Okhotsk–Koryak) and Early Cretaceous (Arctic). All these orogens reveal a different pre-Mesozoic history, with basements of different ages, ranging from the Archean to the Paleozoic. Proterozoic rock assemblages form the basement of Yana-Kolyma as well as part of Arctic orogens. The Late Mesozoic orogens resulted from the Late Jurassic to Early Cretaceous (135–160 Ma) and Cretaceous (100–130 Ma) events. These orogens are of collisional (Yana-Kolyma), accretionary–collisional (Arctic orogen), and accretionary–transform margin (Okhotsk–Koryak accretionary orogens) origin and can be considered products of interaction between the Pacific and Protoarctic oceanic plates and the Siberian craton.

The Verkhoyansk fold and thrust belt lies on the Archean-Proterozoic basement and is composed of the Mesoproterozoic–Devonian carbonate-clastic and carbonate rocks, and the Carboniferous–Middle Jurassic clastic rocks of the Siberian craton passive continental margin. The Yana-Kolyma orogen includes accreted Late Jurassic terranes of various origins (Khanchuk, 2006). Late Valanginian deformation processes and magmatism in the orogen are related to the small Oymyakon paleoocean closure as well as the subsequent collision of the Kolyma-Omolon superterrane and the eastern margin of the Siberian craton (Parfenov and Kuzmin, 2001; Goryachev and Pirajno, 2014). Collisional S- and I-type granitoids in the Yana-Kolyma orogen are represented by the Main Kolyma granitoid belt, which, according to U–Pb SHRIMP (Akinin et al., 2009) and Ar–Ar data, was formed in 149–153 Ma and 137–149 Ma, respectively (Newberry et al., 2000; Layer et al., 2001). Mineralization is hosted in Paleozoic and Mesozoic terrigeneous, carbonate, and, more rarely, volcano-clastic rocks. The types of ore deposits and associated metallogenic epochs of the Yana-Kolyma orogen include preaccretionary (Cu, Pb–Zn, Fe, Au in the Omolon and Prikolyma terranes), orogenic (Au, Sn, W in the Yana-Kolyma metallogenic belt), and post-orogenic (Au–Ag, Sb–Hg, Ag–Sb, Sn in the Okhotsk–Chukotka magmatic arc) (Nokleberg et al., 2005; Khanchuk, 2006).

In Okhotsk–Koryak accretionary orogen, the major orogenic event took place in the Early Cretaceous time, marked by deformation, local metamorphism, and granitoid intrusions (Khanchuk, 2006). The period of collisional granitoids intrusion, according to K–Ar data, was 110–134 Ma (Goryachev, 2005). Mineralization is hosted in the Late Paleozoic and Mesozoic volcano-clastic and terrigeneous rocks and in the Precambrian metamorphic rocks in the Okhotsk and Omolon cratonic terranes. The types of ore deposits and metallogenic epochs are pre-accretionary (Cu, Mo, Au–Ag in the Uda-Murgal magmatic arc), orogenic (Au, Sn, Co, Li, Be in the Okhotsk–Koryak metallogenic belt), and post-orogenic (Au, Ag, Sn, W, Mo, Cu, U in the Okhotsk–Chukotka magmatic arc) (Goryachev, 2005; Nokleberg et al., 2005; Khanchuk, 2006).

The tectonic event responsible for the deformation in the Arctic orogen took place in the Early Cretaceous and is characterized by Barrovian-style greenschist and amphibolite facies metamorphism as well as by granitoid intrusions. The Paleozoic and Mesozoic volcano-clastic, mafic, ultramafic, granitoid, and terrigeneous rocks are the principal hosts for the gold mineralization. The ore deposits and metallogenic epochs of the Arctic orogenic belt include pre-orogenic (Cu, Mo, Au–Ag, Pb–Zn), orogenic (Au, Sn), and post-orogenic (Au–Ag, Sn, W, Mo) (Nokleberg et al., 2005; Khanchuk, 2006).

3 Analytical methods

The article is based on a regional metallogenic analysis of the distribution and location of different types of gold deposits, their associations with magmatic and metamorphic processes and tectonic-geodynamic analysis of their location in the main structures of the eastern margin of the Siberian craton. New data on the isotopic composition of sulfur sulfides and Ar-Ar dating are given.

3.1 S isotope analysis

The S isotopic composition ($\delta^{34}S$) was determined using local and bulk methods in the Laboratory of Stable Isotopes of the Center for Collective Use of the Far East Geological Institute, Far East Branch, Russian Academy of Sciences (FEGI FEB RAS, Vladivostok,

TABLE 1 Dating of the Early Cretaceous gold deposits YaKOB and OKOB.

Ore deposit name	Belt	Ore deposit type	Mineral	Age, Ma	Method	References
Surmyanaya	YaKOB	Dikes-hosted orogenic gold deposits (DHOGD)	Sericite	126.3	$^{40}Ar/^{39}Ar$	Newberry et al. (2000)
Yukhondza	YaKOB	Sediment-hosted orogenic gold deposits (SHOGD), veins	Sericite Quartz	130	K-Ar	Goryachev (1998)
Goltzovy	YaKOB	SHOGD, veins	Sericite	128.2	$^{40}Ar/^{39}Ar$	Voroshin et al. (2004)
Nadezhda	YaKOB	DHOGD, veins	Sericite + Quartz	126.5	$^{40}Ar/^{39}Ar$	Newberry et al. (2000)
				115.9	K-Ar	Author data
Vetrenskoye	YaKOB	SHOGD, veins	Sericite	125	Ar-Ar	Newberry et al. (2000)
				125–117	K-Ar	Narseev (1988)
Krohaliny	YaKOB	DHOGD, veins?	Hydromica	125	K-Ar	Berger et al. (1978)
Sarylah	YaKOB	DHOGD, veins	Hydromica	124	K-Ar	Berger et al. (1978)
Sentachan	YaKOB	DHOGD, veins	Hydromica	118	K-Ar	Berger et al. (1978)
Talalakh	YaKOB	DHOGD, veins	Sericite	126	$^{40}Ar/^{39}Ar$	Prokopiev et al. (2018)
Dora-Pil	YaKOB	DHOGD, veins	Sericite	126	$^{40}Ar/^{39}Ar$	Prokopiev et al. (2018)
Expeditionnoe	YaKOB	DHOGD, veins	Arsenopyrite	116	Re-Os	Pachersky et al. (2021)
Nezhdaninskoye	OKOB	DHOGD, veins/veinlets and Au-sulfide-disseminated	Sericite	119	$^{40}Ar/^{39}Ar$	Bakharev et al., 2011 Borisenko et al., 2012
				118.4	$^{40}Ar/^{39}Ar$	Author data
				119	K-Ar	
Zaderzhnoye	OKOB	DHOGD, veins/veinlets and Au-sulfide-disseminated	Sericite	123.5	$^{40}Ar/^{39}Ar$	Kondratieva et al. (2010)
Marinskoye	OKOB	DHOGD, veins	Sericite	119.4	$^{40}Ar/^{39}Ar$	Author data
Levo-Dybin	OKOB	Intrusion related gold	Sericite	124.8	$^{40}Ar/^{39}Ar$	Prokopiev et al. (2018)
				125	$^{40}Ar/^{39}Ar$	Goryachev and Pirajno (2014)

Russia) following standard methods published in (Ignatiev et al., 2019; Velivetskaya et al., 2019). The analysis was performed using a Flash EA-1112 elemental analyzer (Thermo Scientific, Dreieich, Germany) in the S configuration according to the standard protocol for converting sulfur from sulfide to SO_2. The sample preparation for mass spectrometric sulfur isotope analysis was carried out with the local laser method using an NWR Femto femtosecond laser ablation complex the $^{34}S/^{32}S$ isotope ratios were measured on a MAT-253 mass spectrometer (Thermo Fisher Scientific, Germany) in continuous He flux mode. The measurements were performed against a standard laboratory gas, SO_2, calibrated according to international standards IAEA-S-1, IAEA-S-2, IAEA-S-3, and NBS 127. The results of the $\delta^{34}S$ measurements are provided in reference to the international VCDT standard. Determination accuracy: $\delta^{34}S \pm 0.2\%$ (1σ).

3.2 $^{40}Ar/^{39}Ar$ dating

$^{40}Ar/^{39}Ar$ analyses were carried out in the at the analytical center of the V.S. Sobolev Institute of Geology and Mineralogy SB RAS (IGM SB RAS, Novosibirsk). The research was carried out by the stepwise heating method using a quartz reactor with a fast-response external heating furnace. The $^{40}Ar/^{39}Ar$ dating technique is described in detail by (Travin et al., 2009).

4 General characteristics of the early cretaceous gold deposits of the eastern margin of the siberian craton

4.1 Analysis of mineralization dates

Unfortunately, so far not very many dates of the YaKOB ore mineralization have been published (Table 1; Figure 2). This mainly concerns either the total analysis of altered rocks, or the sericite-quartz aggregate of ore veins. Earlier (1970–1997), dating was performed exclusively the K-Ar method (Berger et al., 1978; Nenashev, 1979), to which Ar-Ar dating of sericite/muscovite was later added (Layer et al., 1994; Newberry et al., 2000; Voroshin et al., 2004; Goryachev and Pirajno, 2014; Prokopiev et al., 2018), and, finally, the first Re-Os dates were obtained by the method of native gold and gold-bearing arsenopyrite (Fridovsky et al., 2021; Pachersky et al., 2021). The combination of dates for

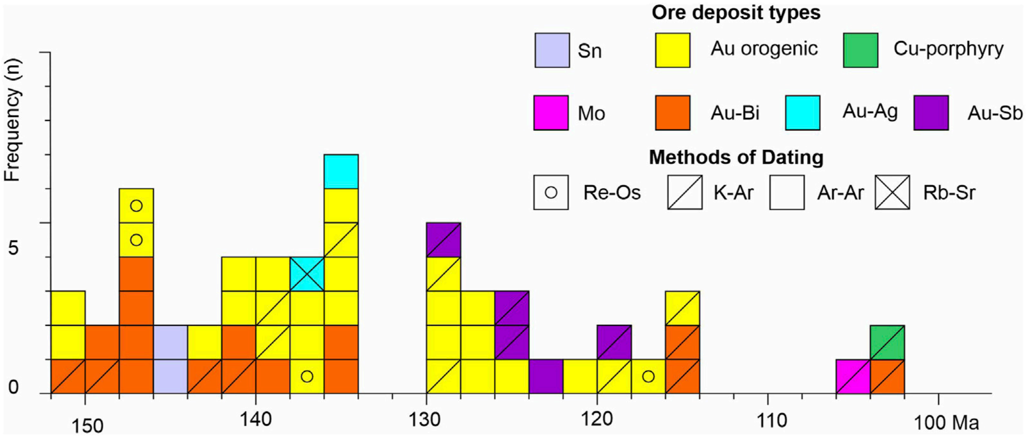

FIGURE 2
Histogram of datings of orogenic ore deposits of YKOB according to Table 1 and the data from (Goryachev and Pirajno, 2014; Fridovsky et al., 2021).

these sources (Figure 2) permits to identify two groups of dates: the Late Jurassic-Early Cretaceous of the YaKOB orogenic deposits (135–150 Ma, average 140.2 Ma) (early stage/stage one) and the Early Cretaceous of the OKOB (114–130 Ma, average 122.8 Ma) (late stage/stage two).

The large scale of age dates is related to the weak resistance of argon isotope systems to thermal impacts and indicates only the presence of two such extensive stages of mineralization, which, judging by the Re-Os dates for native gold, may be narrower (137–147 Ma) for the early stage. A certain reliability for the age interval of the second stage (Table 1) is given by the coincidence of Ar-Ar and K-Ar dates (116–130 Ma) of different samples from the same deposit (e.g., Vetrenskoye, Nadezhda) (Goryachev, 1998), fairly clear and even Ar-Ar plateaus (122.5–126 Ma, feldspars, plagioclase, Newberry et al., 2000; Voroshin et al., 2004; Fridovsky et al., 2022a), and their concordance with the dates for pre-ore and post-ore dikes obtained by the U-Pb methods (126.00 Ma, zircon, Shpikerman et al., 2016).

As noted above, an important feature of the Early Cretaceous gold mineralization is the presence of gold-stibnite deposits in its composition, most of their K-Ar dates lying in the range of 115–128 Ma (Table 1). The discussion on this mineralization age persists to these days (Amuzinsky et al., 2001; Parfenov and Kuzmin, 2001; Bortnikov et al., 2010). It is associated, on the one hand, with the obviously late active superimposition of the main stibnite mineralization of these ores on early quartz, often gold-bearing, with its redepositing, and, on the other hand, with ambiguity of the available mineralization dates obtained by the K-Ar method for the largest (about 100 thousand tons of Sb extracted) Sarylakh deposit: 145, 124, 115, 54 Ma (Berger et al., 1978; Indolev et al., 1980). The latter might be due to the possible sampling of minerals from different stages of mineral formation or to the quality of the K-Ar analysis. However, the Early Cretaceous dating is still preferrable, since a nearby dacite stock, on which ore mineralization zones are superimposed, has dates of 130, 120, 115, 102 Ma, (Amuzinsky et al., 2001). There are also assumptions on the young age of gold-stibnite mineralization (Indolev, 1975; Amuzinsky et al., 2001; Bortnikov et al., 2010). In particular, Obolensky and Obolenskaya, (1972) prove its superimposition on the Late Cretaceous dikes of basaltoids and the relationship of mineralization and magmatism with deep reservoirs. But the age data of these dikes are ambiguous (Nenashev, 1979). Questionnable remain the dates for such deposits as Talalakh and Dora-Pil, which do not differ, in any way, from the Basovskoye and Malo-Tarynskoye orogenic deposits located nearby, where native gold is Re-Os dated by137–147 Ma, while the sericite from these ores is Ar-Ar dated by 142 Ma, with an overlaid event dating back to about 125 Ma.

4.2 Distribution of the early cretaceous mineralization in the YaKOB

The distribution area of the Early Cretaceous orogenic objects is located in the central part (Indigirka sector) and on the southern part (Kolyma sector) of the YaKOB (Figure 3). Curiously, this area embraces some objects of the intrusion-hosted type gold-stibnite profile (Krokhalinoye, etc.). Regionally, these objects are localized in the zones of large-scale faults in the southern margin of the YaKOB: Chay-Yuryinsky (Vetrenskoye), Debinsky (Nadezhda). In the central (Indigirka) sector, all mineralization with the Early Cretaceous dates is controlled by the Adycha-Taryn fault, as well as all gold-stibnite objects (Sarylakh, Sentachan, Maltan, and others), localized in a narrow strip no wider than 10 km and 500 km long, from the Taryn River (right tributary of the Indigirka River) in the southeast to the basin of the Yana River in the northwest (Indolev et al., 1980). The structural analysis shows their localization in connection with late sinistral strike-slip fault movements along these faults (Fridovsky et al., 2014). It should be noted that, according to geophysical data (Transects - Profiles 2-DV and 3-DV, and regional profiles), these faults can be traced in the YaKOB for the full thickness (42–48 km) of the Earth crust (Gayday et al., 2020). Besides, the spatial association of this mineralization with the occurrences of alkaline basaltoids and lamprophyres deep dikes, whose K-Ar dates (Indolev et al., 1980) coincide with Au-Sb ores, also attracts attention, and the only U-Pb SHRIMP date (126.0 ± 2.0 Ma) (Shpikerman et al., 2016) clearly corresponds to this stage. We obtained a close $^{40}Ar/^{39}Ar$ date on feldspar from the

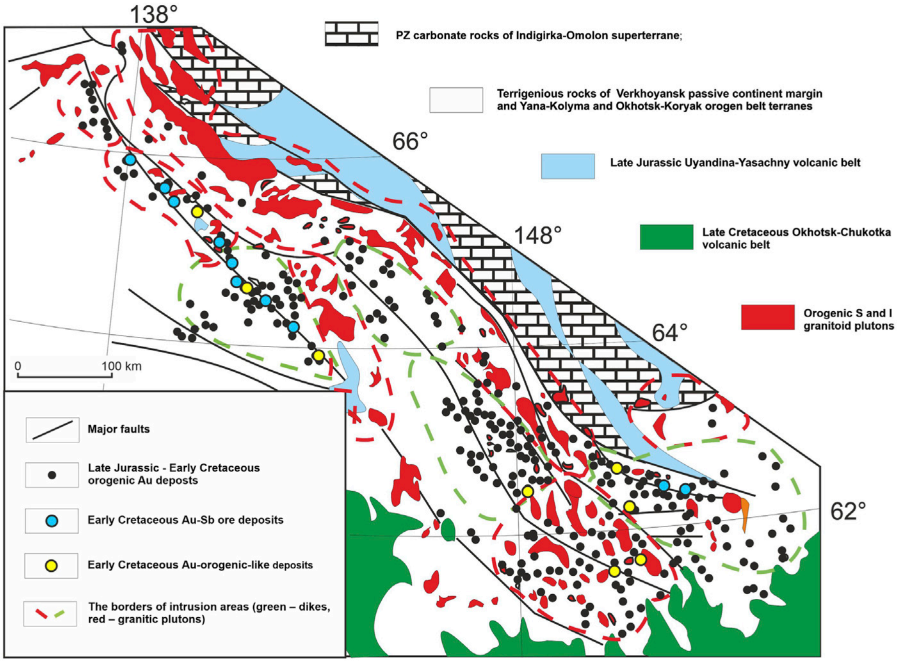

FIGURE 3
Location of the Early Cretaceous deposits in the YaKOB structures, dike areas, granite plutons and early orogenic gold-quartz deposits areas.

Au-Sb trachybasalt dike of the Maltan deposit (125.9 ± 4.0 Ma, standard deviation = 0.38, p = 0.77, yield ^{39}Ar = 72.5% by four steps (Fridovsky et al., 2022b). Dikes belong to rocks from the low-potassium calcic-alkaline to shoshonite series, have negative Ta and Nb anomalies and flat distribution spectra of heavy REE. The concentrations of the highest field strength elements in these rocks are close to transitional values between OIB and E-MORB, and large-ion lithophile Rb, K, and Ba, while the highest field strength elements, like Th and U, are higher than OIB (Fridovsky et al., 2022b). Such an association with magmatites of the similar age allowed I.Y. Nekrasov to talk on their paragenetic relationship as "products of single deep (mantle) foci" (Nekrasov, 1991, p.35).

Thus, the main geological feature of the Early Cretaceous mineralization in the YaKOB is the stringent control of its distribution by zones of regional faults, characterized by strike-slip kinematics of movements as well as its spatial association with dike areas containing deep magma generating chambers.

4.3 Mineralogical and geochemical features of the early cretaceous mineralization in the YaKOB

The Early Cretaceous deposits listed in Table 1 are characterized by various degrees of exploration. Quite outstanding in size are the large commercial Sarylakh and Sentachan gold-stibnite deposits and the Vetrenskoye orogenic gold deposit. These deposits, especially gold-stibnite, have been repeatedly and comprehensively characterized, in monographs as well (Berger et al., 1978; Indolev et al., 1980; Amuzinsky et al., 2001), with a detailed discussion of their mineralogical features, indicating their deep sources.

Gold-stibnite mineralization. Since its discovery at the turn of the 1970s, the well-known area of commercial gold-stibnite mineralization in the YaKOB Indigirka sector has constantly attracted the attention of researchers (Indolev, 1975; Berger et al., 1978; Indolev et al., 1980; Amuzinsky et al., 2001), especially in the issues of its origin. Stibnite mineralization in gold ore objects is quite common (Gamyanin and Zhdanov, 1999; Gamyanin, 2001) and had not attract much attention before the discovery of the Sarylakh deposit, being recorded withinin orogenic gold deposits and in stibnite ore occurrencesas well as in the ores of epithermal deposits in the Okhotsk-Chukotka volcanic belt (OCVB). However, the discovery of the Sarylakh and, later, of the Sentachan deposits, with reserves exceeding 100 thousand tons of stibnite in each, drew attention to this type of mineralization and revealed a kind of linear area of its distribution, confined to the large Adycha-Taryn fault (see mentioned) (Indolev et al., 1980). Considering the general area of this mineralization distribution within the YKOB, the southeastern border of the area can be extended to the Orotukan River basin in the southeast (Figure 3). A distinctive feature of ores of this type is (Berger and Mamonov, 1988): 1) practical absence of Ag, Hg, and near-surface genesis minerals in ores; 2) high (940‰–999‰) fineness of native gold (according to V.A.Amuzinsky and co-authors (2001), single samples from the Sarylakh field show from 1000‰ to 893‰, while at Sentachan, with a span from 1000‰ to 930‰, there were sites with a fineness of 648‰ and 761‰); 3) beresite (pyrite-arsenopyrite-sericite-carbonate) type of near-vein (?) alteration rocks, and 4) localization of mineralization in fault zones of strike-slip reverse fault kinematics. The specifics of the mineral composition of this type ores, in our opinion, should also include the noticeable presence of aurostibite and mustard gold in their composition (Gamyanin et al., 1984; 1987; 1988; Amuzinsky

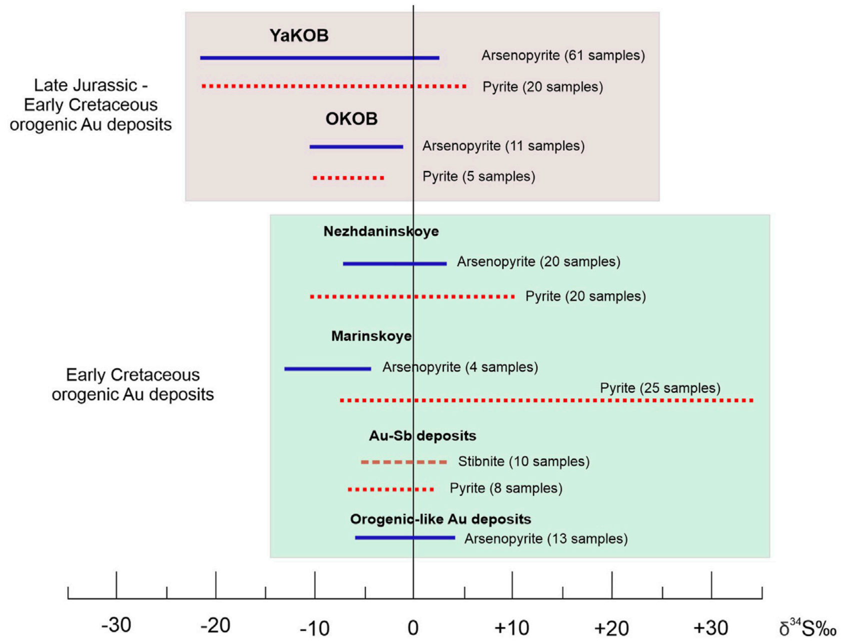

FIGURE 4
Histogram of values of sulfur isotopic composition of gold deposits of the Yana-Kolyma orogenic belt and the Allakh-Yun folded zone of the Okhotsk-Koryak orogenic belt.

et al., 2001), as well as of other native phases (native Al, Cr, Sb, Ag), nickel minerals (ulmanite), in addition to native gold (Amuzinsky et al., 2001). According to these researchers, pyrite in gold-stibnite ores contains 1.70–2.05 wt% As and is characterized by an admixture of Ni (up to 0.07 wt%), while sulfurous arsenopyrite is typically characterized by 0.03–0.05 wt% Ni and 0.11%–0.28% wt% Sb. It should be noted that the isotopic composition of sulfur of pyrite, arsenopyrite, and stibnite from gold-stibnite deposits is characterized by variations from +2.6 to −5.5% (Gamyanin et al., 2003), thus taking an intermediate position between the orogenic objects (Figure 4).

In the Sarylakh ore, according to the results of the atomic emission spectral analysis of 33 representative samples, the concentration of Ni varies from 5 to 100 g/t with an average content of 36.5 g/t (Amuzinsky et al., 2001). An important feature of the studied mineralization, exemplified by the Sarylakh deposit, is its spatial-temporal association with bodies of dacite composition (from 102 ±2 to 130 ± 5 Ma, K-Ar), containing high concentrations of Cr (210–260 g/t), and accessory native iron and garnet (13%–28% pyrope) as well as with gabbroid (lamprophyres and basaltoids with high Cr contents = 200–260 g/t) dikes (Amuzinsky et al., 2001 and our data). It should also be noted that the lamprophyre dike with a U-Pb date of 126 Ma, determined in the YaKOB Kolyma sector, turned out enriched with Cr (352 g/t) and Ni (43.2 g/t), according to the ICP-MS analysis, noticeably (multi-fold) exceeding the content of these elements in other YaKOB complexes of different ages (Shpikerman et al., 2016). This emphasizes the connection of gold-stibnite mineralization with deep mantle foci, as I. Ya. Nekrasov remarked earlier (1991). It should be noted that the supposed connection of the gold-stibnite deposits formation with the metamorphism processes (Berger and Mamonov, 1988) has not been confirmed, since the early orogenic gold deposits in the zone of the Adycha-Taryn fault do not bear signs of metamorphic transformations of ores and metasomatites, which indicates the Late Jurassic-Early Cretaceous time of this metamorphism (Goryachev, 2003).

Early Cretaceous orogenic-type gold deposits within the YaKOB Kolyma sector are represented by the Vetrenskoye, Ekspeditsionnoe, Nadezhda, and other relatively small objects with poorly studied mineralization.

The Vetrenskoye orogenic-like field has been studied not too deeply and more in the geological sense, as typically orogenic, of the same type as Natalka, the largest in the region, and other orogenic deposits in the southeastern flank of the YaKOB (Gold Deposits of the USSR, 1988; Konstantinov et al., 1992; Goryachev, 1998; Gold Deposits of Russia, 2010). The Early Cretaceous dates of sericite ore bodies within this deposit, which differ from those for the closely located Natalka (137 Ma), Degdekan (about 150 Ma), and other deposits (Table 1; Figure 2), structural and morphological characteristics of mineralization, and its tectonic position in the zone of one of the YaKOB largest faults, as well as some mineralogical and geochemical features of ores (Sotskaya, 2017), brought us to the necessity for a more comprehensive consideration of these features as possibly typical for this type of deposits. The Vetrenskoye gold ore deposit (Gold Deposits of the USSR, 1988; Konstantinov et al., 1992) is localized in the zone of the large Chay-Yurya fault of thrust kinematics. Dikes of porphyrites and kersantites intruded the fault zone. The ore bodies are represented by intensely deformed quartz veins and vein-disseminated quartz-sulfide mineralization among mylonitized and graphitized (to 10% C) Early Jurassic mudstones and siltstones. Within the deposit, 20 of such ore bodies, 10–30 m thick and 120–250 m long (Figure 5), traced to a depth of 300 m,

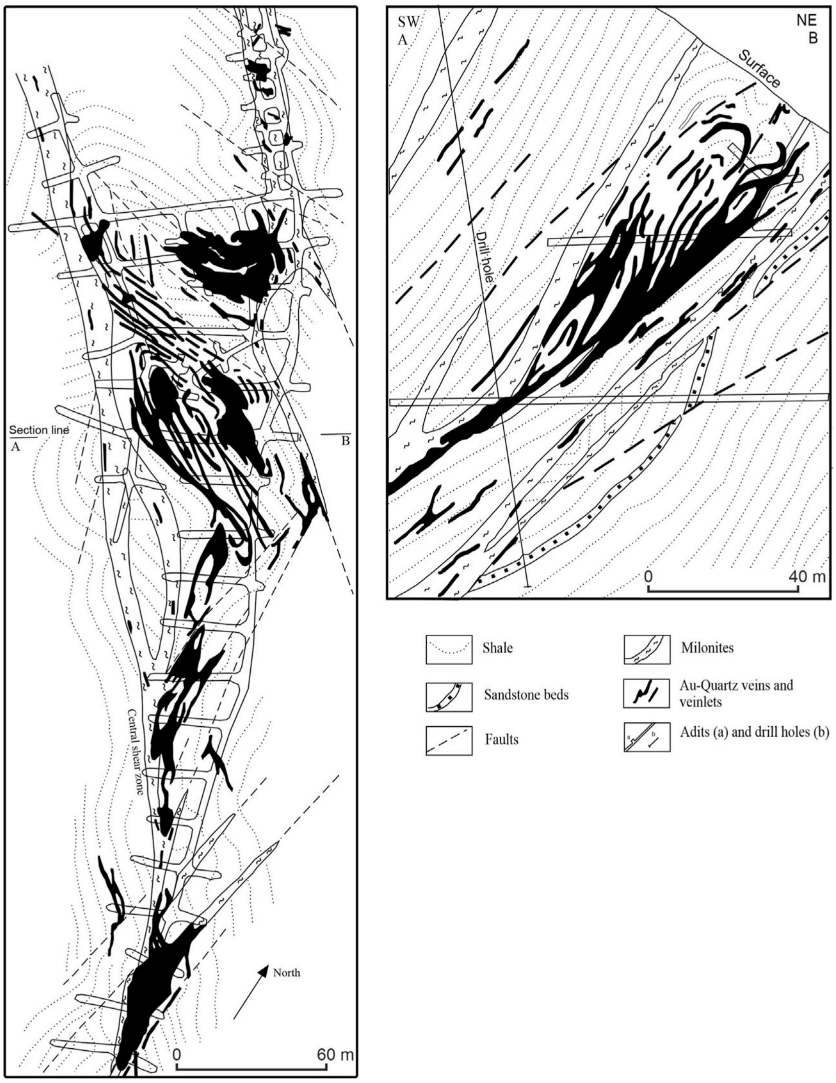

FIGURE 5
Example of one of the ore bodies of the Ventrenskoye deposit: Plan (on the left) and section along the A-B line (on the right) of ore body No. Three of the Vetrenskoye deposit (Gold deposits of Russia, 2010).

are identified. The average gold grade is 5–10 g/t. The estimated Au reserves are about 30 tons. The main ore minerals are pyrite, arsenopyrite, minor scheelite, galena, chalcopyrite, sphalerite, pyrrotite, Bi sulfotellurides, and Pb-Bi sulfosalts (Goryachev and Goryachev, 2023a; Goryachev et al., 2023b). Native gold forms particles of 0.05–1.5 mm mainly in quartz, arsenopyrite, and galena. Average fineness of gold is 880‰–890‰. The veins are dominated by quartz, while the alterations are dominated by sericite and arsenopyrite. The Ar-Ar age of mineralization is 125 Ma (Goryachev, 1998; Newberry et al., 2000) (Table 1).

Three consecutive mineral associations have been identified in the ores: 1) early quartz with pyrite and arsenopyrite; 2) late quartz with arsenopyrite, scheelite, gold, and abundant sericite, and 3) the main productive—gold-galena with bismuth minerals (Goryachev et al., 2023b). According to ICP-MS data, ores and altered rocks of the Vetrenskoye deposit are characterized by a significant admixture of Ni (average 50–56 ppm), V (to 160 and more ppm), Cu (20–50 ppm), Sb (to 21 ppm), Bi (to 1.4 ppm), Se (to 1.9 ppm). The grade level of these elements in the ores of the Vetrenskoe deposit significantly (several times) exceeds their concentrations in the ores of the Natalka deposit, the largest representative of the YaKOB early orogenic deposits (Goryachev et al., 2023b). An important feature shared by the Early Cretaceous deposits is the unusual presence of Bi minerals in the ores (typical minerals for Intrusion-Related Gold Deposits of the region) together with Pb sulfosalts, common for all orogenic deposits in the YaKOB (Goryachev, 2003; Goryachev et al., 2023b). Sericite is rather widely spread in the vein bodies of these deposits: according to our observations, its amount reaches 10%–15% (Nadezhda, Vetrenskoye, Yukhondzha), whicih also sharply distinguishes them from widespread early deposits, where the amount of sericite rarely reaches 2%–3%. Curiously, as well, the isotopic composition of arsenopyrite sulfur from the Vetrenskoe deposit ores (+0.7 - +3.9%) turned out abnormally heavy, compared to the isotopic composition of ores from the major orogenic deposits in the region (Figure 4).

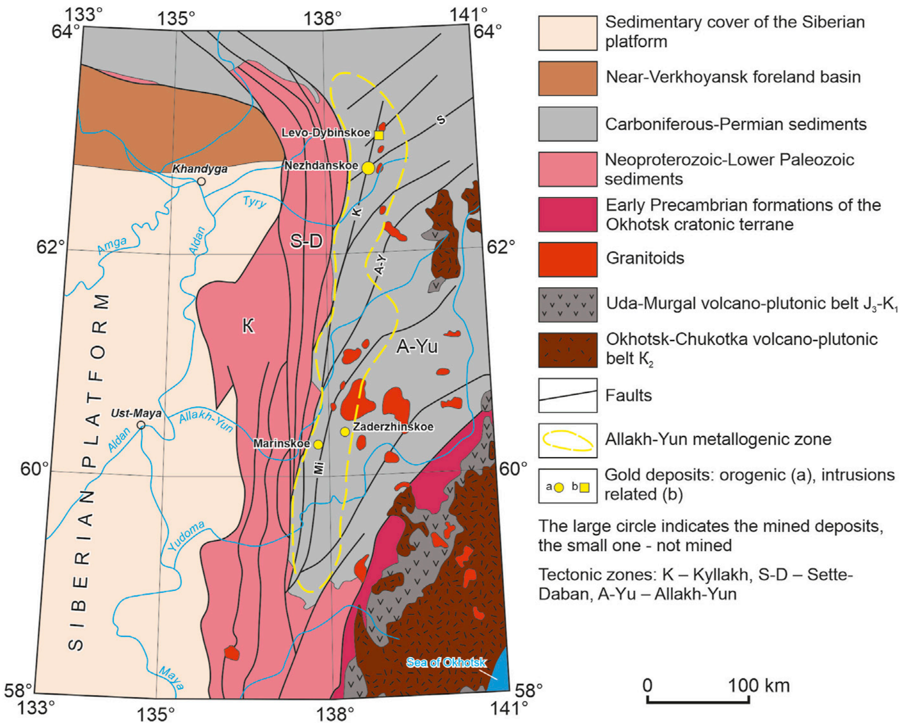

FIGURE 6
Position of the Allakh-Yun metallogenic zone in the structures of the western sector of the Okhotsk-Koryak orogen belt and major gold deposits discussed in this paper. Faults: Mi—Minorsk, A-Yu—Allakh-Yunsk, K—Kiderikinsk, S—Suntarsk.

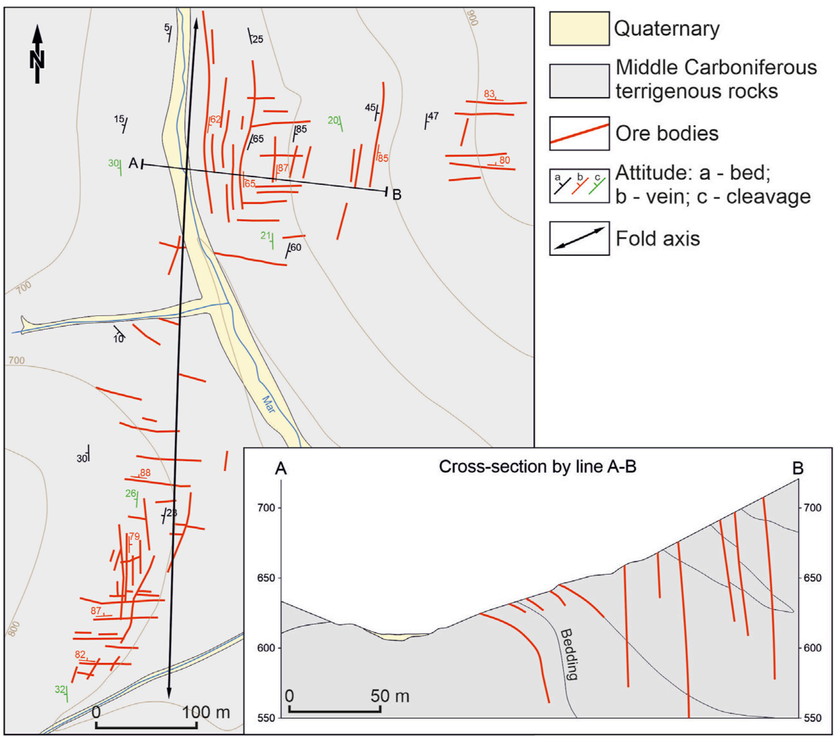

FIGURE 7
Geologic map and simplified cross-sections of the sediment-hosted Marinskoye orogenic gold deposit.

4.4 The Early Cretaceous gold mineralization of the Allakh-Yun zone in the OKOB

We will consider this mineralization using the examples of the Marinskoye and Nezhdaninskoye deposits (Figure 6). *The Marinskoye* orogenic gold deposit is localized in the southern part of the J_3-K_1 Allakh-Yun metallogenic zone of the Okhotsk-Koryak orogenic belt. It was discovered in 1972, with 4.2 t of Au reserves; average gold grade, 2.5 g/t. The deposit is located in the western wing of the regional Minorsky fault in the hinge of asymmetric meridional-strike anticline (Figure 7) (Fridovsky and Polufuntikova, 2011). The eastern wing of the anticline is steep, with overturn elements; the western one is gentle. The axial surface of the fold is parallel to the shale cleavage of a gentle (10°–30°) fall to the WNW. The host rocks are the Middle Carboniferous deposits in the basal part of the Verkhoyansk terrigenous complex. Ore bodies are represented by concordant and intersecting quartz and quartz-carbonate veins, to 1.0–1.5 m thick and 50–200 m long. Three stages of mineral formation have been identified: 1) pyrite-arsenopyrite-ankerite-quartz, 2) gold-polysulfide-quartz, 3) gold-silver-siderite (Tarasov et al., 2022). Pyrite-quartz-sericite metasomatites occur in the exocontacts of ore bodies. The isotopic composition of sulfide sulfur (pyrite, arsenopyrite, galena) from vein bodies and metasomatites of the deposit varies abnormally widely in $\delta^{34}S$ value (−16.2 . . . +34.1%, n=38), which may indicate the involvement of several sources of sulfur in ore formation (Tarasov et al., 2022). The formation time of the Marinskoye deposit, determined by ore vein sericite $^{40}Ar/^{39}Ar$ dating was ~119 Ma. This age is close to the time of crystallization of large (hundreds of km^2) granitoid massifs located to the north: Tarbagannakhsky (120 Ma, U-Pb SHRIMP-II, zircon, (Fridovsky et., 2023a)), Uemlyakhsky (120 Ma, U-Pb SHRIMP-RG, zircon (Prokopiev et al., 2006)), to the time of the greenschist dislocation metamorphism (119 Ma, $^{40}Ar/^{39}Ar$, biotite, (Prokopiev et al., 2018), and to the previously identified age of ore genesis in late-orogenic gold deposits ~124–119 Ma (Zaderzhninskoe, Nezhdaninskoye) of the Allakh-Yun metallogenic zone (Chugaev et al., 2010; Bakharev et al., 2011; Kondratieva et al., 2018).

The Nezhdaninskoye orogenic gold deposit is located in the west of the Okhotsk-Koryak orogen, in the Late Jurassic-Early Cretaceous Allakh-Yun metallogenic zone. It was discovered in 1951; underground gold mining began in 1973; surface mining, in 2021. Au reserves and resources of the deposit are 415.7 t, with the average content of 3.7 g/t (https://www.polymetalinternational.com/ru). This is the second largest gold deposit in Russia's North-East and the fourth in the Russian Federation. The geological structure of the deposit, the mineral composition of ores, the typomorphism of minerals, magmatism, and conditions of the ore mineralization formation have been discussed in numerous publications (e.g., Grinberg et al., 1970; Gamyanin et al., 1985; 2000; 2003; Bortnikov et al., 1998; 2007; Gamyanin, 2001; Goryachev, 2003; Chugaev et al., 2010; Chernyshev et al., 2011; 2012). The Nezhdaninskoye field is localized in the northern part of the South-Verkhoyansk sector of the Verkhoyansk fold-and-thrust belt, formed during the thrusting of the Okhotsk microcontinent in the rear of the Uda-Murgal (J_3–K) marginal-continental magmatic arc. The Verkhoyansk fold-and-thrust belt lies on the Archean-Proterozoic basement and is composed by the Mesoproterozoic–Devonian carbonate-clastic and carbonate rocks and Carboniferous–Middle Jurassic clastic rocks of the Siberian craton passive continental margin. The Nezhdaninskoye deposit structure is determined by the linear anticline of the NNE strike and variously oriented (NNE, NS, NW, EW) brittle ruptures in the zone of the regional NNE Kiderikin fault (Figure 8).

The deposit is built by the Lower Permian terrigenous sediments in the core of a large anticline. Host rocks are metamorphosed to the level of the initial stages of the metamorphism greenschist facies. Near 50–200 m wide ore zones, rocks are altered; sericite, chlorite, quartz, ferruginous dolomite develop. Magmatic formations of two tectonic thermal events are manifested. The Early Cretaceous tectonic thermal event, according to geochronological data for igneous rocks in the deposit area, occurred in the Aptian time. This event is relayed to formation of lamprophyre dikes (~121, zircon, U-Pb (ID-TIMS) (Chernyshev et al., 2012)) at the Nezhdaninskoye deposit and of granites located to the south of the Dybin pluton (122 Ma (Layer et al., 2001). The gold mineralization of the deposit has a close age of 120–119 Ma, according to the results of Rb-Sr quartz dating (Chugaev et al., 2010) as well as to those of Ar-Ar and K-Ar dating of sericite from near-ore altered rocks (Bakharev et al., 2011). The Late Cretaceous event (the boundary of the Cenomanian and Turonian centuries) was manifested by small (the first km^2) stocks of granite-granodiorite, diorite, and granitoid composition (94 Ma, zircon U-Pb (ID-TIMS) (Chernyshev et al., 2012)). According to the existing models of geodynamic development, both magmatic events are related to the development of the Late Mesozoic active continental margin of Siberia and to the subduction of the Paleo-Pacific slab (Prokopiev et al., 2009).

Over 50 ore bodies formed by combinations of two types correlated with extended faults have been identified at the deposit: 1) the disseminated type of sulfides (5%) with "invisible" gold in pyrite (10–150 ppm Au) and arsenopyrite (30–500 ppm Au), associated with numerous quartz veinlets and stockworks in shear zones (grading about 5–9 g/t Au) and 2) the vein type with sub-vertical plate-like quartz veins, to 2 m thick and 200–400 m long, and grading 10–2000 g/t Au (Goryachev and Pirajno, 2014). The host rocks are pervasively altered (sericite, chlorite, quartz, Fe–dolomite), forming 50–200 m wide alteration haloes. The main ore zone (No.1) is located in a sub-vertical fault; it is 1–40 m thick, 7 km long, and 1600 m deep. Based on geological observations, the Nezhdaninskoye deposit was formed in three stages: 1) quartz-carbonate metamorphogenic, low Au grade (less than 2 g/t), 2) main gold–quartz veined and pyrite-arsenopyrite disseminated hydrothermal, and 3) silver-base metals (Gamyanin et al., 1985; 2000; 2003; Goryachev, 1998). The age of mineralization is 122–119 Ma (Gamyanin, 2001; Gamyanin et al., 2003; Chugaev et al., 2010). The fluid mode of the main stage ore formation (T_{hom}—314°C, C_{salt}—3.5 wt.%-eq. NaCl, P—1.3 kbar) is typical for mesothermal orogenic deposits (Bortnikov et al., 2007). The isotopic composition of O, C, S, Pb, as well as the distribution of rare elements in minerals, altered, intrusive, and terrigenous sedimentary rocks indicate the igneous and metamorphic sources involvement in ore formation (Bortnikov et al., 2007; Chugaev et al., 2010; Chernyshev et al., 2011).

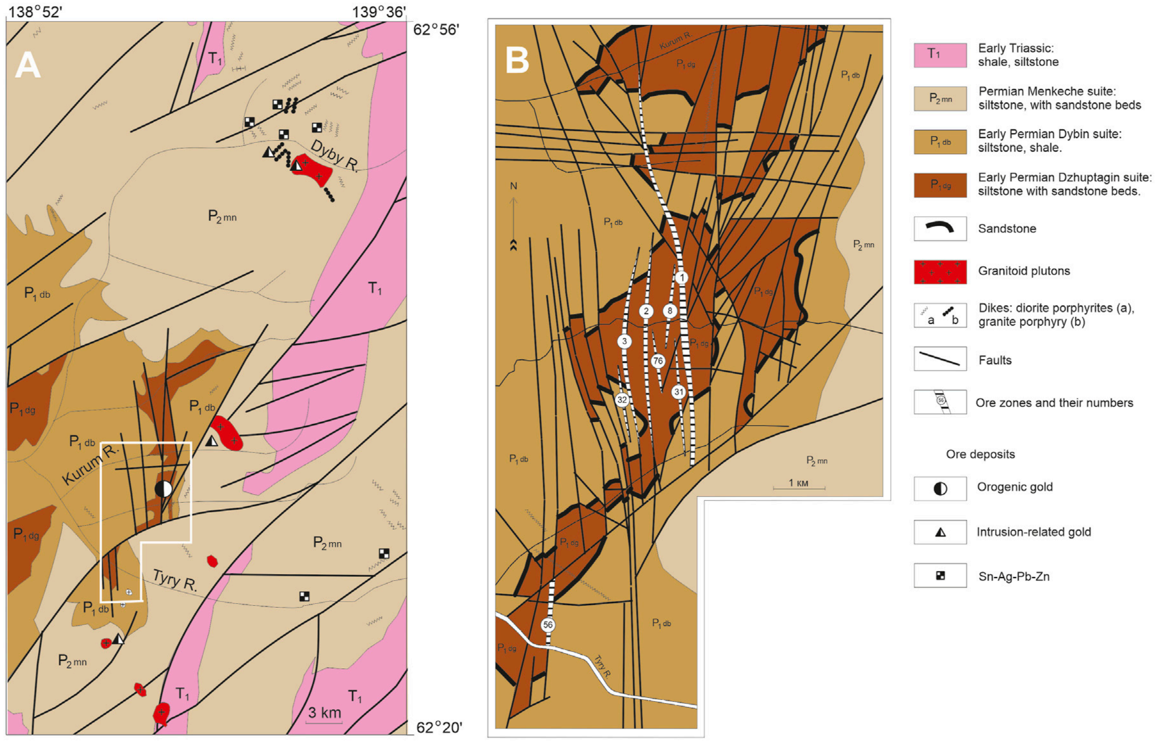

FIGURE 8
Geological map of the area of the Nezhdaninskoye deposit **(A)** and Nezhdaninskoye ore field **(B)**.

5 Discussion

5.1 On the types of early cretaceous deposits within the eastern margin of the siberian craton

The analysis of published and authors' materials shows that the orogenic gold mineralization, which we refer to the Early Cretaceous stage of formation, bears certain similarities with typical orogenic deposits (Goldfarb et al., 2001; 2005; Goldfarb and Groves, 2015) and a number of specific features that distinguish it from the generally recognized orogenic gold deposits of the main stage of the Late Mesozoic orogeny in the eastern margin of the Siberian craton (Table 2). The geological features of the YaKOB Early Cretaceous deposits include 1) structural control of large trans-crustal faults placement, 2) spatial and chronological association with initial (dike) magmatism, which is characterized by increased concentrations of Cr and Ni regardless of silica acidity, as well as the presence of a highly pyrope granate. This indicates a deep, subcrustal magma source.

Mineralogical and geochemical features of the YaKOB Early Cretaceous orogenic type should include increased concentrations in ores and altered rocks Ni, V, Cu, Zn, Sb, Bi, Te; high fineness of native gold (Vetrenskoye—890‰), bringing this type closer to gold-stibnite (980‰–990‰); the presence of Ni-Sb minerals in the ores composition (Sotskaya et al., 2012); minerals Bi (sulfotellurides and sulfosalts), atypical for the Late Jurassic-Early Cretaceous orogenic gold deposits; and the predominance of a heavy sulfur isotope in composition of arsenopyrite (Table 2). Besides, the major minerals of arsenopyrite, pyrite, and pyrrhotite ores often contain an Ni admixture to the first percent (Goryachev et al., 2023b), i.e., in addition to the Early Cretaceous dates, we have mineralogical and geochemical evidence of the independence of the mineralization type under research.

Increased concentrations of siderophiles and chalcophiles in ores can be considered an evidence of a deep source involvement in the ore-forming system. And relatively high concentrations of Sb, high fineness of gold, geological factors of localization in large faults and in association with specific magmatism of small intrusive forms with basic and acidic composition, bring the mineralization of this type close to the specific gold-stibnite mineralization, which also has signs of the deep mantle origin (Nekrasov, 1991; Amuzinsky et al., 2001). These deposits were formed way after the Orogen metamorphism stage; therefore, we coin them orogeny-like. However, Au deposits the Allakh-Yun zone are characterized by almost complete similarity with early orogenic deposits (Table 2) and a close connection with the Early Cretaceous processes of orogenic magmatism and metamorphism formation, which permits to consider them typically orogenic and associated with the Early Cretaceous OKOB formation (Khanchuk, 2006). Therefore, they can be referred to typically orogenic deposits (Goldfarb et al., 2014; Goryachev and Pirajno, 2014). Thus, the available data indicate that the formation of the orogenic-type gold mineralization in the eastern margin of the Siberian craton occurred in two stages: 1) Late Jurassic-Early Cretaceous (YaKOB), and 2) Early Cretaceous (OKOB).

However, despite certain similarities with the above-mentioned deposits, the Early Cretaceous gold and gold-stibnite orogenic-like

TABLE 2 Comparative characteristics of orogenic gold deposits of the Eastern framing of the Siberian craton.

Signs	Main orogenic deposits of the YaKOB	Early cretaceous deposits of the YaKOB	Early cretaceous deposits of the AYuZ OKOB
Age, Ma	135–148	116–130	118–125
Geodynamic setting	Collision	Accretionary	Accretionary
Metallogeny	Yana–Kolyma metallogenic belt	Okhotsk-Koryak metallogenic belt	Okhotsk-Koryak metallogenic belt
Plutonism	140–155 Ma, crustal granite plutons of type I and S, of ilmenite series, dikes of porphyrites and granite porphyry, crustal-mantle dikes trachybasalts, andesites, trachyandesites, dacites, and granodiorites	Dikes of porphyrites, lamprophyres and small intrusions of deep origin	120–125 Ma, granite I-S type plutons of the ilmenite series and dikes of porphyrites and lamprophyres
Metamorphism	135–155 Ma, plutonic-metamorphic association of zonal type	No	118–122 Ma zonal metamorphism of large faults, possibly zonal plutonic-metamorphic association
Structural control	Folded structures and zones of large faults with feathering faults	Zones of large faults of deep formation	Folded structures and zones of large faults with feathering faults
Ore bodies	Mineralized faults with Au-quartz veins/veinlets and Au-sulfide-disseminated	Mineralized faults with Au-quartz veins/veinlets and Au-sulfide-disseminated	Mineralized faults with Au-quartz veins/veinlets and Au-sulfide-disseminated
Alteration	Pyrite–arsenopyrite–sericite–carbonate–quartz	Pyrite–arsenopyrite–sericite–carbonate–quartz	Pyrite–arsenopyrite–sericite–carbonate–quartz
Geochemical associations of ores	Au-As-Sb-Pb-Ag-W	Au-As-Sb-W-Pb-Bi-Ni-Cu	Au-As-Sb-Pb-Ag-W
Ore mineralogy	Early quartz with pyrite, arsenopyrite, scheelite and gold; late gold-polymetallic-sulfoantimonite	Early quartz with pyrite, arsenopyrite and gold; late quartz with arsenopyrite, scheelite, gold and sericite; the main productive gold-stibnite, or gold-galena with minerals Bi and Sb	Early quartz with pyrite, arsenopyrite, scheelite and gold, late gold-polymetallic-sulfoantimonite
PTX results of the fluid inclusions estimate	T_{hom}—320°C—220°C	T_{hom} −304—190°C	T_{hom}—370–267°C
	C_{salt}—<5 wt% NaCl-eq	C_{salt}—<6.8 wt.%-eq. NaCl-eq, P—1.4—0.3 kbar	C_{salt}—<8.3 wt.%-eq. NaCl-eq, P—1.9—0.6 kbar
	P—1.5—0.8 kbar		
$\delta^{34}S$, ‰	+5.4 ÷ −21	+4 ÷ −5.5	+34 ÷ - 16
Examples of deposits	Natalka, Drazhnoye, Malo-Tarynskoye, Basovskoye, Khangalas, Svetloye, Utinskoye and etc	Vetrenskoe, Ekspeditsionnoe, Nadezhda, Krokhalinoe, Sarylakh, Sentachanetc.	Nezhdaninskoye, Marinskoye, Zaderzhninskoeetc.
Main references	Goryachev, 1998, 2003	Bortnikov et al., 2010; Goryachev and Goryachev, 2023a, Goryachev et al., 2023b; Goldfarb et al., 2014; Goryachev and Pirajno, 2014	Bortnikov et al., 2007; Gamyanin, 2001
	Gamyanin et al., 2003	Fridovsky et al., 2022b; Kryazhev and Fridovsky, 2023; Author's data	Gamyanin et al., 2000; Gamyanin et al., 2003; Goldfarb et al., 2014; Goryachev and Pirajno, 2014; Fridovsky and Polufuntikova, 2011, 2023a; Tarasov et al., 2022; Author's data
	Goldfarb et al., 2014; Goryachev and Pirajno, 2014		
	Fridovsky et al., 2020, 2021, 2022a, 2023b; Kryazhev and Fridovsky, 2023; Author's data		

deposits of the YaKOB do not show any connection with the orogenic metamorphism and granitoid magmatism processes. This part of YaKOB contains no granitoids with such dates (Akinin et al., 2009), and those U-Pb dated within 120–129 Ma (Shpikerman et al., 2016) are located in the outer part of the Uda-Murgal arc (UMA), an integral part of the OKOB (Khanchuk, 2006), outside the area of the researched mineralization and much closer to the UMA subduction zone, or in the Allakh-Yun tectonic zone of the OKOB. This means that the mineralization under discussion cannot belong to a classically orogenic type, and its emergence within the structures of the eastern margin of the Siberian craton requires an explanation. It is evident that the common features and differences of multi-stage orogenic Au of the eastern margin of the Siberian craton are determined by the geodynamic conditions of formation. The Early Cretaceous orogenic Au OKOB was formed directly during slab devolatilization during oceanic subduction, but for the Late Jurassic-Early Cretaceous orogenic Au YaKOB, fertility of the pre-collision mantle lithosphere was crucial. The latter is typical for the orogenic Au deposits in Tibet (Deng et al., 2022).

5.2 On the origin of the early cretaceous orogenic-like mineralization

Based on geochronological data, we can consider the emergence of the studied Early Cretaceous YaKOB orogenic and gold-stibnite mineralization parallel to the processes of OKOB formation in the rear of the UMA, at a distance of 500–1000 km. Localization of deposits in deep faults at the UMA border, which serve as trans-crustal conductors of ore-bearing fluids, is quite natural. However, it is hardly possible to link the formation of this type of mineralization with the subduction process in the UMA, as it was proposed for the Nezhdaninskoye deposit by A.G. Bakharev (Bakharev, 1999; Bakharev et al., 2002), since the distance is quite large, and, judging by the dates, the subduction itself in the UMA lasted almost until the middle of the Albian (Khanchuk, 2006). However, there is an indubitable general connection with this process. This may result from changes in the direction and rate of the Izanagi plate subduction in the period of 125–135 Ma, with the formation of a large mantle wedge with deep slab dehydration and upwelling of asthenospheric material (Zhao et al., 2010) in the rear of the UMA.

In the first half of the Cretaceous, in the Panthalassa region, the seabed expansion rate increased accompanied with the collapse of individual large plates at the turn of 120 Ma, with a change in the movement of the Izanagi plate due to an increase in the convergence rate, and with a change in the convergence angle in the Panthalassa northern part, bordering on eastern Laurasia (Seton et al., 2012). Zhao et al. (2013) assume a stagnant slab under the Kolyma and the Aldan regions, at a depth of about 1000—1200 km. Similarly van der Meer Douwe et al. (2018) show that there is a slab that flattens out at a depth of about 600 km (according to one model) and about 400 km (according to another model), but the first tomographic model (U UP 07) notices the slab bifurcation and sort of superimposition of the young slab on the broken remains of the old UMA at depths of 1000–1400 km, while according to the second model, it is at depths of 500–800 km (upper + lower mantle model = SL2013+S40RTS). Documentation of slab remains under the areas of the Early Cretaceous gold-stibnite and gold orogenic-like deposits, the presence of crustal faults and areas of deformation of the Moho layer along the YaKOB strike (Gayday et al., 2020), mantle marks of associated Early Cretaceous magmatic bodies, specific nature of mineral composition and geochemical profile of ores suggest an active mantle influence on the origin of the deposits under discussion. The mantle wedge model implies the interaction of the mantle matter with the stagnant slab during its dehydration and the release of gold-bearing fluid flows.

The possibility of such a model is confirmed by the data of the study of fluid inclusions in quartz from the Barremian-Aptian orogenic and orogenic-like gold deposits YKOB and OKOB (Table 2). The mineralization was formed at Thom –370—190°C, Csalt—<8.3 wt.%-eq. NaCl-eq and P—1.9—0.3 kbar from carbon dioxide-water solutions with an admixture of methane. Such parameters are typical for mesothermal gold ore systems of convergent margins of continents related to subduction (Goldfarb et al., 2001; Goldfarb and Groves, 2015). Values of $\delta^{34}S$ show that the sulfur, present in the ore fluid was from the involvement of a deep source of sulfur and was formed during thermochemical sulfate reduction and decay of pyrite or organic sulfur from sedimentary rocks.

This poses the question if fluids can transport gold in such deep conditions. Unfortunately, only a few experimental data on gold solubility under high pressures and temperatures correspond to the implied model. We will discuss them below.

5.3 On the possible existence of supercritical gold-enriched fluids. Prerequisites for the implied origin model

The possibility of gold transfer by high-temperature fluids has been assumed for a long time; however, the main research in the field of experiment and calculations is still based primarily on the study of the gold transfer and deposition conditions, with the formation of rich ores and ore columns, and embrace the temperatures from 500° to 150 °C at pressures not exceeding the first kilobars (Pokrovski et al., 2014). According to traditional studies, only hydrogen sulfide (HS^-) and chloride (Cl^-) can form stable complexes with gold: $(Au(HS)^{2-}$, $Au(HS)S^{3-}$, S^{3-}, and S^{2-}, and $AuCl^{2-})$ in hydrothermal conditions (Pokrovski and Dubessy, 2015; Pokrovski et al., 2015; 2022), although some recent studies indicate the important role of carbon in the hydrothermal geochemistry of gold (Semakin et al., 2019), showing its significant solubility in carbon-containing fluids. Simultaneously, the total concentration of $Au(HS)^{2-}$ and $AuCl^{2-}$ is known to be significantly lower than the solubility of gold in a hydrothermal fluid at high temperatures (>500°C) and high pressures (>1 kbar) (Pokrovski, Dubessy, 2015; Pokrovski et al., 2015). This corresponds to the data by I.Y. Nekrasov (1991, 1996): in 1986 he performed a number of experimental tests to determine the solubility of gold in an aqueous fluid at temperatures of 700°–923°C and pressures from 130 to 700 MPa (at Ni-NiO and Fe_2O_3-Fe_3O_4 buffers).

Based on the data by Baranova et al. (1988), his own experiments, and calculations by E.N. Diman (Diman, Nekrasov, 1987), he came to the conclusion about the stability and high solubility of gold in the form of $Au(OH)^0$ under such conditions. He also showed that at T = 1100° K there is a sharp break in the graphs of change of $Au(OH)^0$ complex ΔG_p, same at different pressures (from 50 to 1000 Mpa), which is recorded both experimentally and by calculations (Nekrasov, 1991; 1996). Such a break, in his opinion, corresponds to a change in the form of gold in the above-critical aqueous fluid from $Au(OH)^0$ to Au^0, with a sharp increase in gold solubility of. These data imply that at temperatures above 1000 K (i.e., above the liquidus of silicate melts) gold is concentrated in the above-critical aqueous fluid in significant quantities and migrates with it. At the same time, according to I.Y. Nekrasov, such a fluid may contain high concentrations of silica (up to 150 g/L), while the presence of chlorides and probably hydrosulfides contributes to the high solubility of gold at temperatures below 1100 K already in the form of $AuCl^0$, $Au(HS)^-$; however, the increase in pressure within the system reduces its solubility in the chloride form (Nekrasov, 1991); therefore, in the conditions of mantle depths, these forms are not the main ones. Unfortunately, judging by the review (Pokrovsky et al., 2014), this direction has not been developed and remains only as wishes for the future. Thus, the I.Y. Nekrasov data (Nekrasov, 1991; 1996) show that, under above-critical conditions, gold dissolves well in a fluid in the form of Au^0, despite the possibility of the presence of halogens and sulfur in the fluid, and it is capable of being transferred by deep fluids. And it is also important that in the products of such systems (deposits), in our case, we are dealing with the genetic association of Au with As and Sb, and, to a much lesser extent, with Bi. This, and especially the high concentration of Sb, allow for the possibility of the existence of hetero-polynuclear

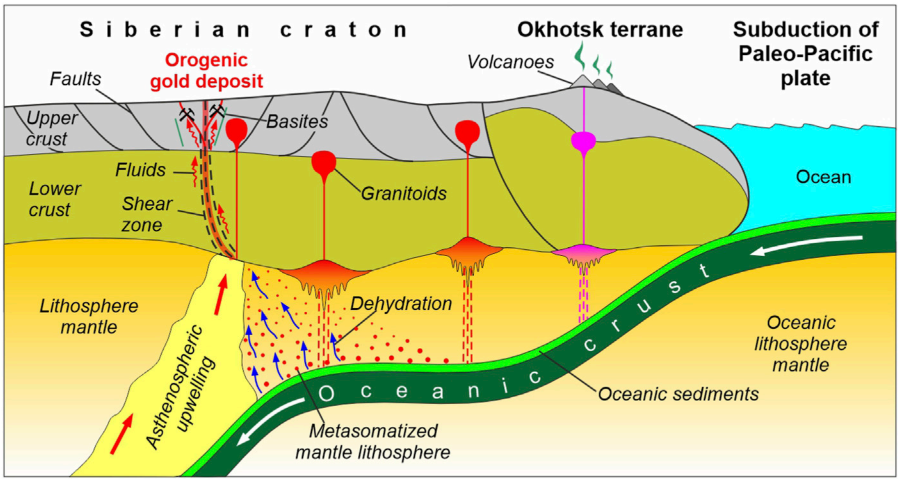

FIGURE 9
A schematic model the formation of the Barrem-Aptian orogenic gold deposits on eastern margin of the Siberian craton. Orogenic gold deposits are formed from a fluid fertilization by ore elements at asthenosphere upwelling heated and devolatilized the subducted altered oceanic crust and overlying oceanic sediments of the paleo-Pacific plate.

complexes Au with Sb, Bi, and As, with the formation of relatively low-temperature (above 550°C) Sb sulfide melts with a high crystal chemical capacity in relation to Au, whose existence temperature limit can be reduced to 300°C due to the presence of chlorides in the system (Nekrasov, 1991). But in modern literature this aspect is still seen only for the future (Pokrovsky et al., 2014), as well. However, despite their fragmentary nature and a small number of experiments, the data by I.Y. Nekrasov (1991,1996) provide a reason to assume a high capacity of above-critical fluids relative to Au and require further study of the large Au amounts transfer in above-critical conditions, taking into account the influence of the semimetal triad on sulfide systems.

Thus, the presence of the remains of the slab in the depth, traces of a noticeable mantle influence on the ore composition at gold-stibnite and gold orogenic-like deposits, their localization in the zones of large trans-crustal faults, data on the study of Au solubility in an above-critical fluid imply the formation of this gold mineralization type according to the model of slab dehydration in the mantle wedge (Figure 9) (Zhao et al., 2010). Unified model for close-aged (ca. 120 Ma) deposits is proposed for giant Jiaodong gold province North China Craton (Goldfarb and Santosh, 2014; Goldfarb and Groves, 2015; Groves and Santosh, 2021). In this model, the gold-bearing aqueous-carbonic fluids and metal derive from dehydration, decarbonization, and desulfidation of sediments and/or the underlying basalts of the subducting paleo-Pacific plate. Change in the direction of movement of the paleo-Pacific plate at ca. 125 Ma could have been the trigger for fluid migration. The fluids permeated the trans-crustal system of the main faults, and then the second-order faults. This model may be typical for many Aptian orogenic gold deposits in the North of East Asia.

However, further research in this direction is required in order to obtain additional evidence of the deep origin of the Early Cretaceous mineralization of the eastern margin of the Siberian craton and to develop its genetic model with due account for the interaction of gold with the triad of accompanying semi-metals As-Bi-Sb (Goryachev and Pirajno, 2014; Goryachev, 2019).

6 Conclusion

Our research has resulted in establishing what follows. The Early Cretaceous gold mineralization, identified on the basis of geochronological data, is characterized by mineralogical-geochemical and structural features that distinguish it from the prevailing Late Jurassic-Early Cretaceous orogenic mineralization. These include:

1) Increased concentrations of siderophilic and chalcophilic elements, the Ni, Bi minerals presence in the ores, relatively high fineness of gold, predominance of juvenile sulfur in the isotopic composition of sulfide sulfur.
2) The structural and geological features include strict placement control by o large trans-crustal faults as well as spatial and chronological association with initial (dike) magmatism of the deep origin.
3) The considered mineralization is spatially and chronologically associated with the Early Cretaceous gold-stibnite mineralization and shares certain structural-geological and mineralogical-geochemical signs with it.
4) The origin of this ore mineralization type is related to the processes of the OKOB formation and is most likely caused by the formation of a large mantle wedge during the UMA slab dehydration and local upwelling in the mantle in the rear of the active continental margin.
5) The specific nature of the processes in the mantle lithosphere explains the metallogenesis of the Late Jurassic-Early Cretaceous collision-related and the Early Cretaceous subduction-related orogenic Au deposits of the eastern margin of the Siberian craton. Fertility of the pre-collision mantle lithosphere was crucial for the Late Jurassic-Early Cretaceous collision-related orogenic Au deposits, whereas in the Early Cretaceous subduction-related orogenic Au deposits, fluids and components were formed directly during slab devolatilization during oceanic subduction. Our

results allow us to better understand the metallogeny of spatially overlapped subduction- and collision-related orogenic Au systems, what is important for assessing the potential of their possible occurrence and specific nature in other orogenic belts on craton margins globally.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

NG conceived of the presented idea. NG and VF did the field investigation and data collection. NG and VF wrote the original draft. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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