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The Role of a Detachment Fault in the Spatial Distribution of Ore-Bearing Paleofluid Flows in the Central Kolyma Region: A Nonconventional Approach to Predictive Metallogenic Modeling

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Abstract—The Central Kolyma region is the main gold-bearing part of the Verkhoyansk–Kolyma fold-and-thrust belt. Analysis of the developed geodynamic models of fold and thrust belt formation mechanisms, the Verkhoyansk–Kolyma belt in particular, suggests the leading role of subhorizontal movements on the detachment zone (decollement) at the base of an orogen as the "sole," on which nappes detached at an early stage and with which major reverse strike-slip listric faults were directly associated at the collisional stage. In our opinion, the role of a detachment fault, the most important regional structure, is obviously underestimated in predictive metallogenic models. The detachment fault zone is complicated by transverse NE-trending faults, where its thickness and the fluid permeability can occur. The paper proposes a variant that links previously discovered gold deposits and occurrences in five gold mineralization strips along the inferred paleofluid flow routes. Here, the paleofluid flow route is the horizontal projection of the most probable migration pathway of released fluids from their generation zone to the ore deposition zone, which is drawn across the largest ore accumulations.

Keywords: Central Kolyma, fold-and-thrust, ore–placer cluster, gold, placer, detachment, paleofluid flows

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INTRODUCTION

Predictive metallogenic studies targeted at gold mineralization in the Verkhoyansk–Kolyma foldbelt, of which the Central Kolyma region is a part, were carried out according to standard methods (Narseev et al., 1986; *Printsipy* ..., 2010), giving priority to point sources of ore material specific to an individual gold deposit or group of closely spaced gold occurrences, referred to as ore–placer clusters (Fig. 1).

Nonexhumed plutons were assumed to be their ore parent rocks, and ore–magmatic systems with deep mantle roots, indicated by the presence of intrusive rocks of the granitoid series, were recognized (Gel'man, 2000; Goryachev, 1998, 2003; Sobolev, 1989; Firsov, 1985; Trunilina et al., 2008; Shkodzinskii, 2001; Fridovsky, 2018). Also, the position of gold occurrences in the zone of influence of the nearest deep-seated fault, a ring structure, was taken into account, and metalliferous mantle fluid migration along fault zones was assumed to be sub vertical (Rusinov, 2005).

In spite of the indubitably significant success of the methodological approach applied, the recognition of the ore–placer clusters (OPCs) enabled the delineation of concentrated exploration areas, on the one hand, but actually excluded vast remaining territories from exploration activities, on the other. To correct this situation and recognize other promising areas, new "nonconventional" predictive metallogenic models are needed, which can be done with geodynamic modeling.

The developed geodynamic models of the fold-and-thrust belt formation mechanism, which are based, among other things, on palinspastic reconstructions (*Tektonika* ..., 2001; Khain and Lomize, 2005; etc.), suggest the leading role of subhorizontal displacements along the detachment plane at the base of an orogen as a "sole," on which nappes detached at an early stage and with which major reverse strike-slip listric faults were directly associated at the collisional stage.

The authors attempted to include a detachment zone along which nappes moved onto the continental margin in the genetic model of orogenic gold deposits as the main fluid concentrating surface. It was along this surface, along the faults it was complicated by, that ore-bearing hydrothermal fluids flowed. The authors substantiate the possibility of invasion of high-tem-

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[†] Deceased.

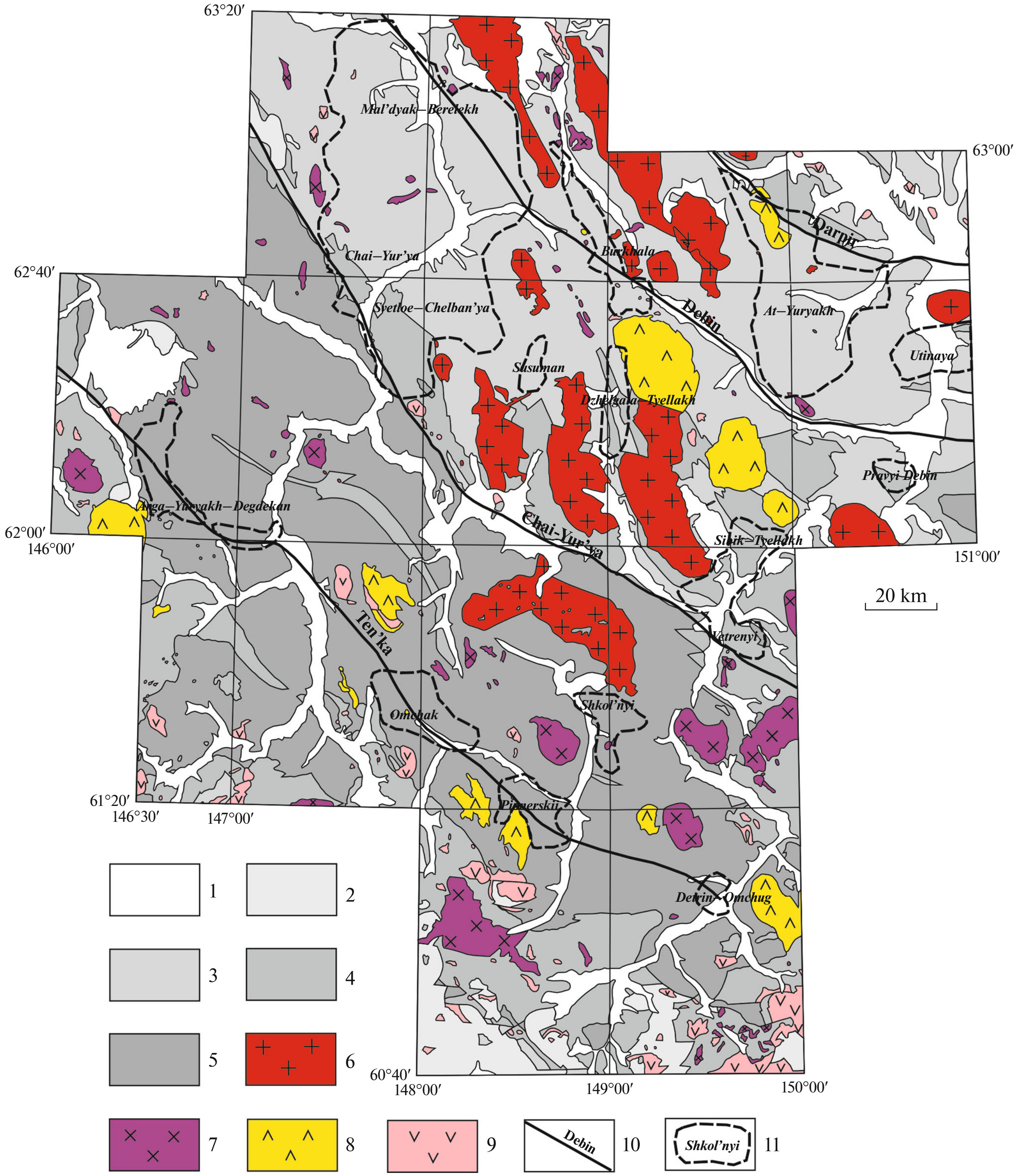


Fig. 1. Schematic geological map of Central Kolyma region (based on State Geological Maps at a scale of 1 : 200000 and data in (Struzhkov et al., 2006f)). (1) Quaternary alluvial sediments; (2) Upper Jurassic–Cretaceous (molasse); (3) Jurassic (siltstone–sandstone flyschoid turbidites); (4) Triassic (sandshales of outer shelf); (5) Permian (carbonaceous siltstone–mudstone turbidites); (6–9) igneous rocks (after Palymskii et al., 2015): (6) Late Jurassic granitoids of Kolyma suite; (7) Late Jurassic–Early Cretaceous granodiorite–granites of Ten'ka suite; (8) Late Cretaceous granitoids of Okhotsk suite; (9) subvolcanic rocks; (10) deep-seated reverse strike-slip faults; (11) ore–placer clusters (modified after Struzhkov et al., 2009).

perature ore-bearing hydrothermal fluids from the underlying sections of the underthrust zone and their subsequent migration in the thermogradient field of the detachment zone as separate streams—paleofluid flows—and ore deposition in the widespread collisional fault systems.

GEOLOGICAL OVERVIEW OF THE TERRITORY

The Verkhoyansk—Kolyma foldbelt is composed of Permian to Jurassic marine terrigenous sediments of nearshore and more open-sea facies, metamorphosed to early greenschist facies. Most of the recognized stratigraphic units consist of black shale turbidites or fine-grained flysch with occasional coarse clastic and olistostrome horizons. The main tectonic events that led to formation of the foldbelt took place during Late Jurassic—Early Cretaceous. A.V. Prokop'ev and A.V. Tronin (2004) recognize several deformation stages during the Early Cretaceous, including thrusting and subsequent folding. A series of lengthwise NW—SE- and submeridionally trending faults, surface reflections of deep-seated collisional transpressional shear zones, began at that time: the Darpir, Debin, Chai-Yur'ya, and Ten'ka faults (Shakhtyrov, 2009, 2010). Disseminated sulfide mineralization zones, confined to these large fault zones, have been reported (Volkov et al., 2008; Sidorov et al., 2009; Goryachev et al., 2020), which indicates high hydrothermal activity along them. Due to the different northeastward dip angles, they are sometimes interpreted as thrusts. In addition, younger transverse NE-trending normal and reverse faults have been recognized (Milovskii et al., 2018).

The Main Kolyma batholith belt was formed at the same time. N.A. Goryachev and N.V. Berdnikov (2006) recognized three groups of granitoids within it: S-type orogenic granites of the ilmenite series (predominant), I-type orogenic granites of the ilmenite (I_{ilm}) and magnetite (I_m) series, and A-type postorogenic granitoids of the magnetite series. According to recent studies (Goryachev and Palymskii, 2012; Palymskii et al., 2015), the Kolyma suite of Late Jurassic granitoids and the Ten'ka suite of Late Jurassic—Early Cretaceous granodiorite—granite massifs southwest of the Main belt have been recognized within the study area. A close age range of the intrusions has been established; the peak weighted average $^{238}U/^{206}Pb$ ages, determined by the SHRIMP method, was around 150 ± 3 Ma for most intrusions, and single datings by the more reliable TIMS method returned the same values (Akinin et al., 2009). The dikes of the Nera—Bokhapcha suite formed during the Late Jurassic, i.e., prior to or simultaneously with the collision: from the Oxfordian, at least 162 Ma according to Rb—Sr geochronology (Zaitsev et al., 2019) until the latest Tithonian, according to the U—Pb SHRIMP-II datings of zircons from felsic rocks, 151—145 Ma (Fridovsky et al., 2020).

These datings of transformation of the isotope systems of granitoids acquire geological meaning from the analysis of other events that took place near the area of the Main Batholith belt. The calc-alkaline volcanic rocks of the Uyandina—Yasachnaya belt, adjacent to the batholith belt in the northeast, formed during the Middle—Late Jurassic time (Paraketsov and Paraketsova, 1989; Fridovsky et al., 2020). This belt emerged as a result of convergence of the Siberian Craton with the Kolyma—Omolon massif. Opinions differ on the polarity of the paleoseismofocal zone that controlled volcanic activity (Kotlyar et al., 2016; Fridovsky et al., 2020). For instance, L.M. Parfenov (1984) interprets the rocks of the In'yali—Debin synclinorium as the deposits of a fore-arc turbidite trough, which subducted eastward, whereas the suprasubduction Uyandina—Yasachnaya volcanic belt and the belt of granite batholiths presumably formed as a result of collision between the craton and the Kolyma—Omolon superterrane (Parfenov et al., 1993, 2003). V.Yu. Fridovsky et al. (2020), following (Ged'ko, 1998; Stavskii et al., 1994), substantiate subduction beneath the Siberian Craton, and in this case, the Uyandina—Yasachnaya arc is located on the continental margin, whereas the traces of the small Oymyakon ocean are located northeast of it. With such interpretation, the Verkhoyansk—Kolyma belt occupies a back-arc position.

The more recent Okhotsk plutonic suite includes intrusive complexes located in the outer zone of the Okhotsk—Chukotka volcanic belt and its perivolcanic part. Here the granitoids of the Ulakhan massif were dated at 98 ± 1 Ma by the U—Pb SHRIMP method (Akinin et al., 2011). These granitoids metamorphose gold—quartz veins at the Igumenovskoe and Rodionovskoe deposits (Firsov, 1956, 1958; Skornyakov, 1949) and are, in this case, post-ore for the orogenic gold—sulfide—quartz mineralization.

AGE OF GOLD MINERALIZATION

Data on the age of gold mineralization in the Central Kolyma region are ambiguous. For instance, the results of $^{40}Ar/^{39}Ar$ dating for 17 objects in the region (Voroshin and N'yuberri, 2001; Voroshin et al., 2004; Goldfarb et al., 2014) fall in the interval of 125—139 Ma, which is not associated with any major endogenous thermal events in the region, such as igneous intrusions or regional metamorphism. According to these data, the datings of mineralization are 10—25 Ma younger than the granite emplacement time. Worthy of notice are vein and veinlet—disseminated (stockwork-type) gold occurrences in terrigenous sequences and dikes (referred to as Strednekan-type) have been conventionally distinguished in the Central Kolyma region (Figs. 2e—2f).

Based on the data of isotopic geochronometers of magmatic rocks, I.N. Kotlyar et al. (2016) suggested that the synchroneity of (1) the youngest $^{206}Pb/^{238}U$ datings, (2) minima on the K–Ar histograms, (3) the moments of reactivation of the Rb–Sr and Ar–Ar clocks implies that all of them record a single thermal event that took place 150–140 Ma ago and, most likely, corresponded to the gold–quartz ore formation process in the Yana–Kolyma gold belt (Rusakova and Kotlyar, 2003). It was also noted that the time gap of at least 15 Ma between the granitoids and ores remains unexplained (Kotlyar et al., 2010).

Thus, irrespective of some discrepancies in the datings of granitoid magmatism, as well as gold mineralization, a delay of ore formation from the emplacement of intrusive massifs by 10–25 Ma is established. But, according to the widely accepted postmagmatic ore formation model, in which metalliferous fluids are expelled from the cooling intrusion and migrate upward to the level of ore deposition, a significant time gap like that is unlikely. What happened during this time period? Possibly, it may indicate the duration of movement of the mobilized fluid along zones of weakness.

Let us discuss the processes that took place during this period and provoked tectonic, magmatic, and mineralization events. The gold–sulfide–quartz mineralization of the Verkhoyansk–Kolyma foldbelt that formed during the latest Jurassic to the earliest Cretaceous and was close in time to the collision between the Kolyma–Omolon superterrane and the Siberian craton (Parfenov et al., 1993; *Tektonika* ..., 2001; Nokleberg et al., 1998; Fridovsky et al., 2020). This collision was accompanied by the structural–metamorphic reworking of rocks within the Verkhoyansk–Kolyma foldbelt. The mobilization of fluids and metals took place in the course of the progressive transformation of sedimentary strata (Tyukova and Voroshin, 2007), starting from lithogenesis and ending with regional metamorphism, the peak of which coincides with the melting of collisional granites.

N.A. Goryachev and N.V. Berdnikov (2006) note that the melting of I-type and S-type collisional granitoids of the ilmenite series is a chronologically and tectonically single process, but takes place at various levels, the lower (I-type) and upper (S-type) crust, and, therefore, all transformations, from metamorphism and the associated fluid generation to melting, affect different levels of the subducting crust. When describing the sequence of ongoing events, it is noted (Goryachev et al., 2020) that two nearly synchronous processes (magmatic and hydrothermal) are recorded at each stage: (1) the intrusion of the dikes of the Nera–Bokhapcha suite and the advancing wave of hydrothermal fluids, the products of which are represented at ore deposits by pyrite dissemination (barren and ore-bearing) along the main ore-controlling faults (Figs. 2c, 2e) and (2) the formation of large granitoid massifs and the deposition of gold–quartz mineralization in the same faults (Fig. 3). Such linkage suggests the postmagmatic origin of the ore-bearing hydrothermal fluids. But, in our opinion, allowance for the discreteness of metamorphic transformation process during the subsidence to significant depths and fluid generation, induced by this process, is more consistent with the observed facts and the general course of foldbelt evolution.

Also, this time is characterized by the development of the fold–block structure of the territory with significant movements along the longitudinal deep-seated reverse strike-slip faults (Figs. 1, 3). For example, V.G. Shakhtyrov (2009) recognized the following evolution stages for these faults: (1) the kinematically dextral synfolding stage of the fluid- and deformation-related reworking of the carbonaceous terrigenous strata of the Verkhoyansk complex (J_3), accompanied by weakly manifested magmatism in the form of dikes or small stocks, the progressive stage of regional metamorphism, and the gold–sulfide mineralization with fine invisible gold; (2) the kinematically sinistral stage of metamorphic–hydrothermal gold–quartz mineralization with coarse reworked gold and sulfides (K_1). This stage was accompanied by more intense magmatism in the form of dikes, stocks, and medium sized massifs and the regressive stage of regional metamorphism. Gold mineralization develops according to the postmagmatic hydrothermal model with the deposition of gold–rare metal mineralization enriched in bismuth, tellurium, molybdenum, tin, and tungsten; (3) the subsequent deformation stages are responsible for the formation of post-magmatic gold–antimony ore occurrences etc.

The discreteness of ore formation, noted, e,g,, by Shakhtyrov (2009), can be due not only to a spasmodic breakup and, consequently, to pressure release in the tectonic process, but also to the stepwise involvement in dehydration of huge sedimentary rock masses with an increase in *PT* parameters. It is this mechanism precisely that can explain the numerous results of geochemical and isotopic studies of ore mineralization, obtained in recent years, which contradicted the conventional models, because they testified to predominantly crustal rather than purely mantle origin of various components of metalliferous fluids at gold deposits (Volkov et al., 2016; Sotskaya, 2017). The striking similarity of the parameters of these solutions (including composition, temperature, pressure, etc.), reflected in the composition of gold mineralization, suggest that they belong to genetically similar hydrothermal ore-forming systems or to a single regional fluid system, rather than numerous separate sources, associated each with an individual isolated intrusion.

Based on this model and considering the vast resource potential of gold mineralization in the region (total production of around 3200 t gold and estimated

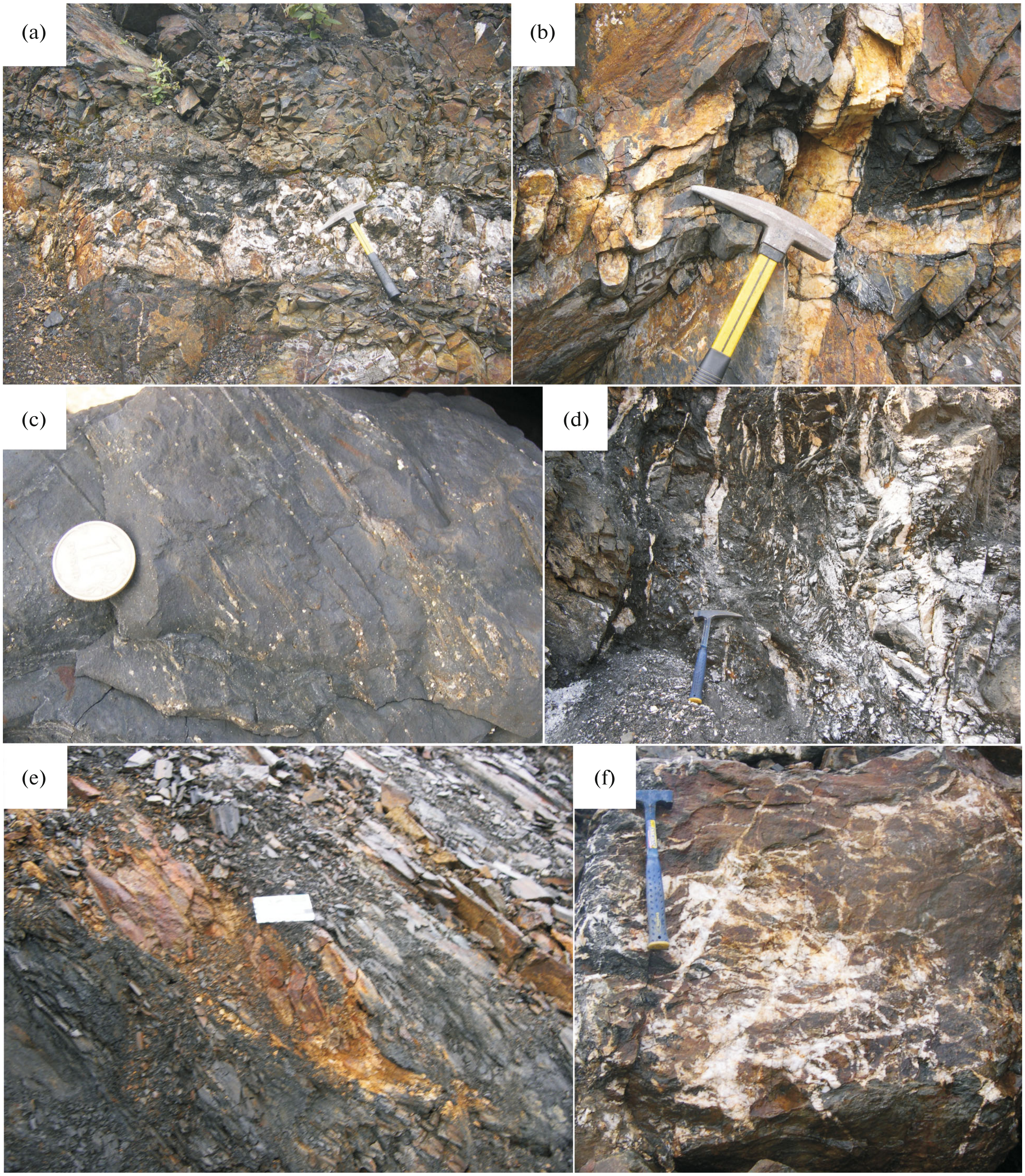
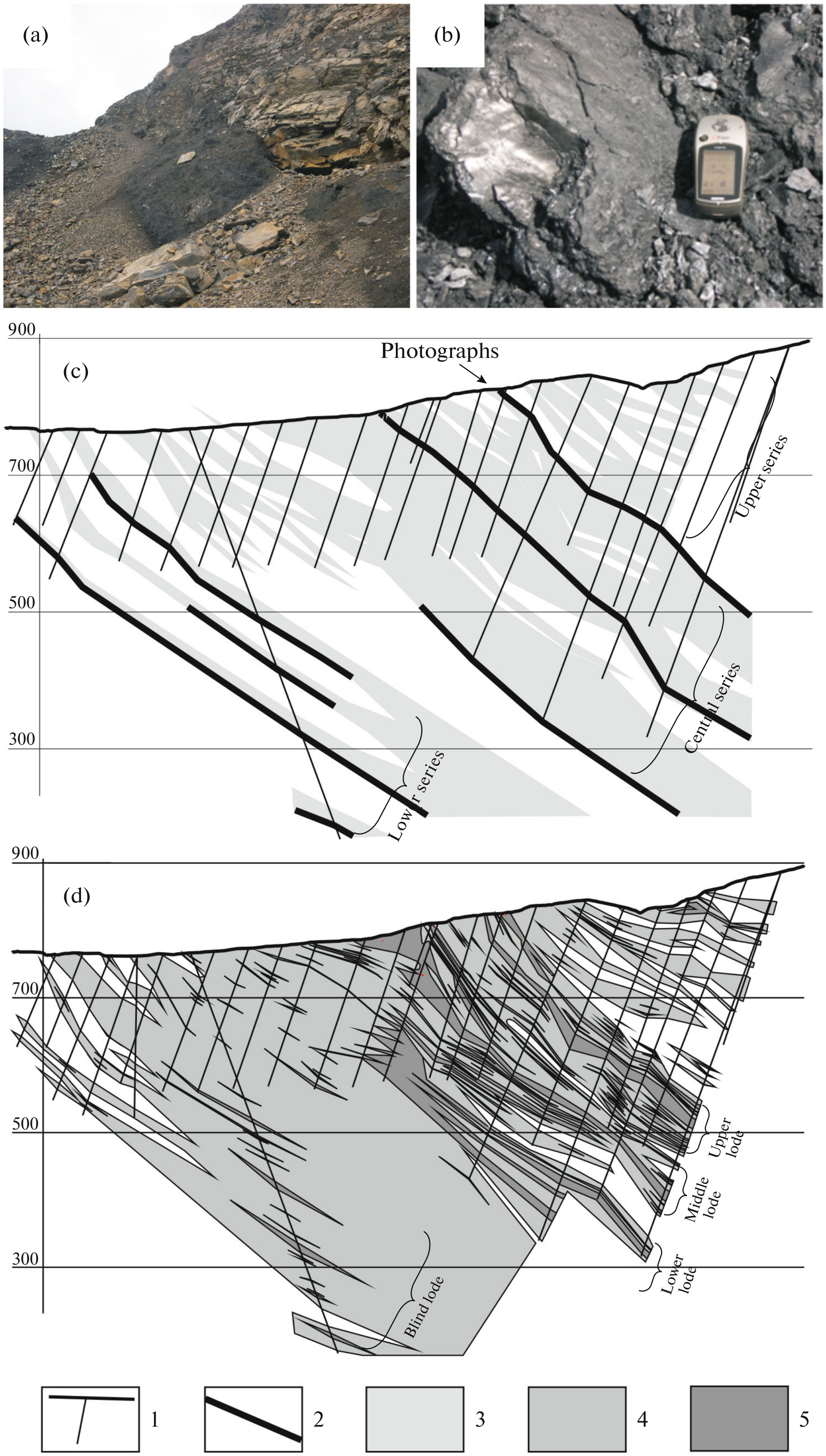


Fig. 2. Various types of ores from deposits in Central Kolyma region: (a), (b) Rodionovskoe: systems of gently and steeply dipping quartz veins and veinlets; (c), (d) Degdekan: pyrite veinlets and dissemination and quartz veinlet zones in carbonaceous mylonites; (e), (f) Srednekan: altered porphyry diorite dike with pyrite and arsenopyrite dissemination, fringed by quartz veinlets. (a) Gently dipping quartz vein in thrust zone with numerous host rock xenoliths; (b) view of cross quartz veins above shallow-dipping thrust zone; (c) pyrite dissemination and veinlets; (d) internal structure of veinlet silicification zone in carbonaceous mylonites; (e) apophysis of an altered dike with quartz veinlet; (f) reticulate silicification in dike selvages.


(a)
(b)
900
Photographs
(c)
700
Upper series
500
Central series
300
Lower series
900
(d)
700
500
Upper lode
Middle lode
300
Lower lode
Blind lode
1
2
3
4
5

reserves of 5000 t (Mikhailov, 2007; Struzhkov et al., 2009; *Gosudarstvennyi* ..., 2019)), there must have been a giant hydrothermal fluid generation zone that could have mobilized ore elements.

Thus, considering the recently developed scenario of the geodynamic history of the region (Fridovsky et al., 2020) and the large extent or lateral extension of various gold mineralization occurrences in the Central Kolyma region (and the Verkhoyansk–Kolyma belt as a whole) from southeast to northwest, the only paleozone responsive to all requirements are the deep-seated levels of the underthrust of the margin of the Siberian craton beneath the Kolyma–Omolon superterrane: the crustal material here is submerged to considerable depths with high *PT*-parameters, where metamorphic transformations lead to the release of huge masses of high-temperature fluids and up to ultrametamorphism and melting. A strip along the Darpir fault, in which the granitoid massifs and the Nera–Bokhapcha dike suite are most widespread—the Polousnyi–Kolyma suture, according to (Fridovsky et al., 2020)—can be considered as the surface expression of such zone for the Central Kolyma region.

However, this model does not explain the wide development and spatial distribution of the most significant gold mineralization at a large distance from this suture and further westward within the foldbelt. The significant time gap between the emplacement of intrusions and ore deposition also remains unclear. A legitimate question arises: how and in what ways such a volume of high-temperature fluids can move many tens to hundreds of kilometers from the zone of fluid generation? As in the traditional hydrothermal model, pressure and temperature gradient can be assumed as a driving force; it is also logical to determine the direction of movement: from the deep levels of the subduction–collision zone towards the foldbelt, where ore was deposited, i.e., mostly lateral rather than vertical movement. But in this case a weakness zone, along which this migration took place, must exist. The only zone responsive to all requirements is the detachment fault zone!

DETACHMENT FAULT

Due to the absence of typical ophiolites—relics of the oceanic crust, the presence of which would suggest a subduction-related mechanism for the closing of the paleobasin during foldbelt formation—within the Verkhoyansk–Kolyma foldbelt, the collision-related mechanism (Goryachev and Berdnikov, 2006) or the small size of the closed basin and the back-arc position of the region (Fridovsky et al., 2020) were proposed as alternatives. It should be noted that, irrespective of the scenario, it is necessary to make allowance for the significant reduction in the primary transverse dimensions of the sedimentary paleobasin. A.V. Prokop'ev and A.V. Tronin (2004), for instance, concluded that the total reduction in the area of the Kular–Nera belt and the In'yali–Debin synclinorium due to folding and thrusting is 35–65%. But such a reduction is impossible without lateral displacements of the large blocks of sedimentary sequence. The main deep-seated structure, along which the connection of the structural features recorded on the surface with the deeper levels takes place and the movements of these blocks are carried out is the detachment fault zone (Khain and Lomize, 2005).

The detachment fault is an indispensable feature in fold regions (Prokop'ev et al., 2004). In the case of the Urals, e,g,, V.N. Puchkov (2000, p. 18) notes that, at a depth of 5–10 km, “the main, although hidden structural feature of the foreland is the main detachment surface (detachment plane) with listric thrusts, extending upward from this surface as well as folds generated by movements along these thrusts”.

V.I. Shpikerman (1998) identified the lower, middle, and upper (Triassic–Jurassic terrigenous rocks) seismic horizons and the underlying granitized basement of the Siberian craton at a depth of 7–8 km within the Yana–Kolyma terrane in cross sections along the Debin–Taskan fragment of the reflection seismic profile, compiled using ground-based magnetic and gravity data and reflection seismic data. A.V. Prokop'ev and A.V. Deikunenko (2001) draw a fault contact between the Paleozoic and the crystalline basement, located at depths of 12–13 km, to which listric reverse faults adjoin, in the section across the Barai anticlinorium of the Verkhoyansk foldbelt. They draw the boundary between the upper and lower crust at a depth of 20 km, and the total thickness of the crust is estimated at 30–33 km.

The existence of a detachment fault zone in the region is also confirmed by a fragment of the seismic section along the reference geophysical profile 3-DV, which made it possible to distinguish the main layers of the earth's crust and to trace faults (Gashko and Gaidai, 2016; Gaidai et al., 2020). The upper, most energy saturated layer of the crust in the model occupies the interval from the daylight surface to a depth of about 15 km. The base of the upper layer of the crust is traced along the reflecting horizon (detachment plane). The upper layer of the crust is the most tectonized and includes numerous thrusts and reverse faults of the Mesozoic–Cenozoic age. According to E.Yu. Goshko and N.A. Gaidai (2016), the Ten'ka

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Fig. 3. Pavlik deposit. (a) General view of a gently dipping reverse strike-slip fault in open pit; (b) shapes of carbonaceous flow rolls in reverse strike-slip fault zone; (c), (d) cross sections along exploratory line 14: (c), thrust and volume fracturing zones; (d), veining and metasomatic alteration intensity. (1) Boreholes; (2) reverse strike-slip fault zones; (3) extensive fracturing and crush zones; (4) veinlet–metasomatic aureole (0.01–0.79 g/t Au); (5) intense alteration: ore zones (0.8 g/t Au and higher).

and the Kheidzhan–Mylta fault zones are accompanied by uplift and stacking of the lower layer of the crust, which attests to their thrust-related collisional origin. The junction of the Debin NW-trending and Pravyi Orotukan NE-trending fault systems, conversely, is accompanied by subsidence of the lower layer of the crust to a depth of 50 km. The subsidence of individual slabs of the lower crustal layer in the central part of this fault zone ends with the "dissolution" of the Moho discontinuity. This suggests the existence of a subduction zone of the Sea of Okhotsk Plate beneath the southeastern margin of the North Asian Craton in the lower layer of the crust under the Balygychan uplift (*Geodinamika* ..., 2006).

We can state that a gently dipping regional detachment plane, a detachment fault zone, is located at depths of 7–15 km in the Verkhoyansk–Kolyma foldbelt and the Central Kolyma region in particular. According to the model proposed by (Fridovsky, 2018), this detachment fault, which accommodated the lateral movement of the large blocks of the sedimentary sequence, developed at the contact of the Mesozoic terrigenous and Paleozoic carbonate deposits, and the listric reverse strike-slip faults crosscut this tectonic structure and extend down to the Archean–Proterozoic basement. Apparently the elongate flattened shape of the large S- and I-type granitoid massifs (Fig. 1) is due to the location of their lower parts near this gently dipping fault surface.

RESULTS AND DISCUSSION

Large-scale predictive prospecting operations imply the necessity to identify and trace the signs of the fluid regime of the past and to map the accumulation zones and migration pathways of the metalliferous solutions based on the spatial distribution of the zones of local permeability of the lithosphere (Abramovich and Klushin, 1987). As opposed to the previously developed models, which were based on the existence of an independent hydrothermal fluid source for virtually every ore deposit, orefield, or ore cluster regardless of their genesis, we propose the possibility of functioning of a plane surface, along which the migration of released hydrothermal fluids took place, to be discussed below.

N.A. Goryachev et al. (2020) note that "many studies of large orogenic belts have long raised the question of the existence of such regional fluid flows, structured by large faults and providing for the manifestations of zonal metamorphism and mineralization". In the Verkhoyansk–Kolyma foldbelt we have: (1) an underthrust zone, the surface expression of which is the Uyandina–Yasachnaya arc and the strip saturated with magmatic manifestations along the Darpir fault; (2) the processes of dehydration and melting, which occur at the deeper levels of the underthrust zone; (3) ore districts with large mesothermal deposits, apparently associated with this zone but remote from it. The questions arise concerning the relationship between these circumstances, where can these regional fluid flows exist, and what are these weakness zones, along which the ore-bearing fluids moved, their physical expression and signatures? Let us try to answer these questions.

In foldbelts, a certain number of ore occurrences are usually grouped into ore clusters, located along regional deep-seated faults at certain intervals (Shakhtyrov, 2010); i.e., the same structures are both barren and ore-bearing throughout their length, although both have undergone significant hydrothermal reworking, which we demonstrated with reference to the Northern and Subpolar Urals (Savchuk and Volkov, 2020). V.L. Rusinov (2005) wrote about the role of regional strike-slip faults in hydrothermal activity and the possible formation of "compact fluid–magmatic columns," associated with the formation of alkaline and gabbro–diorite magmas in the lower crust and granite magmas in the upper crust. But, as noted above, mineralization in our case is much younger than the emplacement of intrusions and, therefore, the regional shear zones recognized during geological mapping (Shakhtyrov, 1997, 2009) and their complications can only serve as ore-feeding and ore-bearing structures (Savchuk et al., 2018), and the gold content of their particular section depends on some other factors.

V.E. Khain and M.G. Lomize (2005) note the significant fluidization of the detachment fault and the presence of pore fluids with ultrahigh pressures, caused by a multistage dehydration process, in its zone. Considering the huge volumes of rocks involved in these processes we may suggest that detachment fault is the main channel for the collection and movement of fluids in a collisional orogen. An important feature of the detachment fault should be noted. With generally low-angle bedding, it dips in the direction opposite to thrusting, i.e., from the foreland to the hinterland. Temperature and, to a lesser extent, pressure must change in the same direction along this regional fault zone. Important here is the effect of hydraulic fracturing as a result of reaching abnormally high formation pressures: high pressure reduces rock porosity and permeability, whereas cleavage and fractures provide pathways for the inflow of large masses of hot hydrothermal fluids from the underlying sections of the underthrust zone (Savchuk and Mukhin, 1993). Such properties of the detachment fault (fluidization) facilitate the movement of nappes along its surface substantially.

Also, it is necessary to take into account the presence of transverse basement faults (NE-trending and sublatitudinal in our case), which introduced "disturbances" into the topography of the low-dipping detachment plane. For instance, it was noted that the transverse NE-trending fault zones play a pivotal role in the spatial distribution of orefields and magmatic

Table 1. Recognition criteria of ore mineralization strips

1	Ore-geological	Presence of locally concentrated gold deposits, gold occurrences, and ore spots, linked into strips that are traced across the foldbelt
2	Mineralogical	Presence of altered rock and metasomatite zones, quartz veins, and heavy concentrate halos
3	Geochemical	Presence of gold and pathfinder element dissemination halos
4	Geophysical	Anomalies by various geophysical methods, indicating hydrothermal alteration in fault zones

bodies of various ages in the central part of the Upper Indigirka region, which is located north of the study area and is geologically similar to it (Fridovskii et al., 2017). Similar northeast trending faults have been also recognized in the Central Kolyma region (Milovskii et al., 2018). It is possible that these intersections of the detachment zone by transverse faults are responsible for its local thickening and increase in faulting, which affected the overall permeability of this gently dipping tectonic surface. Thus, it is proposed to accept that the movement of the released ore-bearing hydrothermal fluids took place along the detachment fault plane at the base of the foldbelt, and not as a solid flow but as separate high-temperature paleofluid flow streams confined to the intersections. The fluids moved this way until they reached intersection with a regional deep-seated strike-slip fault, where a part of the fluids rose up along the listric fault and ore was deposited in its splays and complications. This explains why the ore deposition temperatures of gold mineralization constantly exceed the parameters of regional dynamothermal metamorphism, which usually does not exceed the greenschist facies. The hydraulic fracturing mechanism explains the occurrence of various ore-bearing breccias in quartz vein deposits (Kempe et al., 2016).

Thus, the direction of auriferous fluid migration could be guided by the temperature and pressure gradient along the detachment zone, i.e., from the higher- temperature regions up the dip of the gently sloping detachment zone and then upward along the cross faults into the regional strike-slip zones. This rather complicated and lengthy pathway can account for the gap in time between the granitoid magmatism, when the ore material is supposed to be mobilized by the hydrothermal fluids released as a result of increase in metamorphism and melting, and ore deposition proper due to a fluid pressure drop at the upper levels

It is necessary to note one more important feature of the ongoing processes: a certain amount of mantle fluids can enter along the detachment zone and along the transverse basement faults and mix with the hydrothermal fluids released during the dynamothermal metamorphism. The active role of the crust–mantle interaction in the formation of orogenic gold deposits is reflected in the mineral composition of ores and their geochemical spectrum, which was noted by N.A. Goryachev (2014). This can explain the appearance of hybrid associations, e.g., Sb and Hg mineralization at some gold occurrences (Bortnikov et al., 2010).

IDENTIFICATION OF PALEOFLUID ROUTES

Substantiation of the ore-feeding role of the detachment and transverse basement faults is very important, because it provides a possibility to identify the routes of paleofluid flows, the ore potential of which could be implemented within the zone of influence of regional longitudinal strike-slip faults when favorable thermodynamic conditions are achieved. In this case, *paleofluid flow route is a horizontal projection of the most probable migration pathway for the released fluid streams from their generation zone to ore deposition zone, drawn across the largest ore accumulations*. Let us discuss the option of identifying paleofluid flow routes along a gently dipping detachment plane with reference to the Central Kolyma segment of the Verkhoyansk–Kolyma fold region.

On daylight surface, these routes are expressed by the strips of elevated gold mineralization, including virtually all ore occurrences of various scales. These strips are mapped on the basis of a number of ore geology-related, mineralogical, geochemical, geophysical, and other data on a scale of 1 : 500000 and 1 : 200000 (Table 1).

Two hundred and seventy gold occurrences of various scales, ranging from unique and large deposits to single gold-bearing vein occurrences, have been registered in the study area[1]. Ore mineralization within them occurs either as separate orebodies in a clastic sequence or as altered and veined dikes. Paleofluid flow tracing can be aided by the orientations of gold occurrences, e.g., bodies, veins, or deposits, which are often inherited from those of the ore-feeding deep-seated faults or indicate their splays. The northwestern orientation is characteristic of 120 gold occurrences (i.e., 44.4%), out of which 69 measurements have been plotted on the diagram (Fig. 4a). The northeastern orientation of orebodies is displayed by 40 occurrences (i.e. 14.8%), of that 14 are put on the diagram (Fig. 4b). It should be noted as well that, although ore occurrences are associated with major faults, the out-

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[1] S.F. Struzhkov, “Assessment of Gold Potential of the Central Kolyma Region. Report of Ministry of Natural Resources of the Russian Federation,” Magadan–Moscow, 2006.

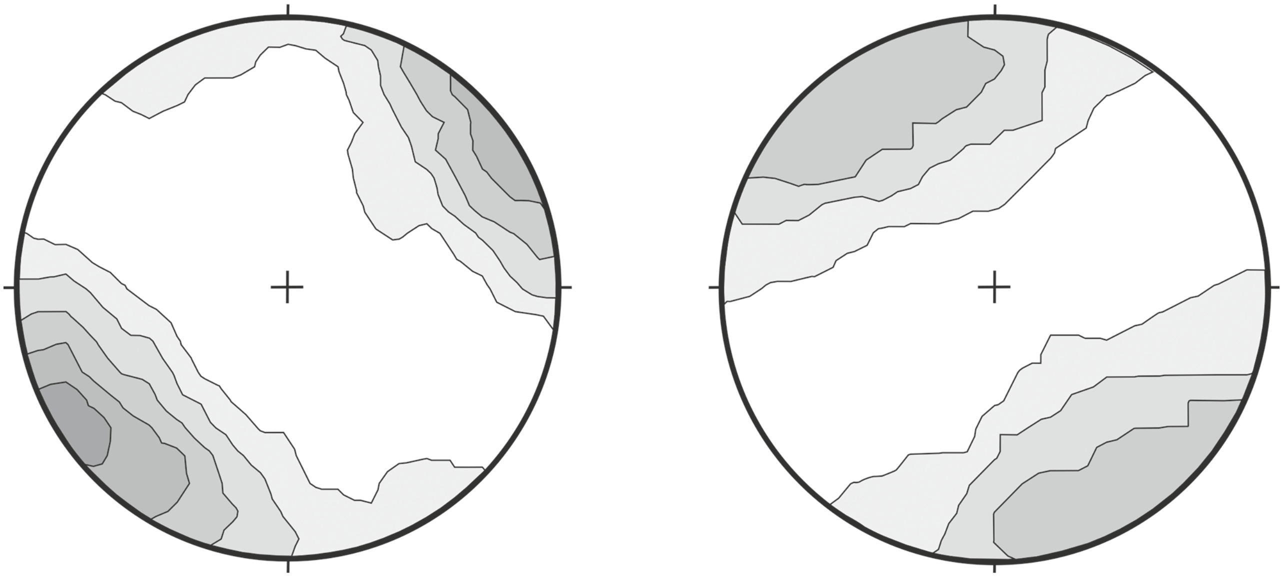

Fig. 4. Orientations of orebodies, veins, and lodes: aggregated (left) and northeastern (right).

lines of the ore–placer clusters are often not conformal to these faults and sometimes extend across their strike (Fig. 1). Probably the predominant northwestern orientation of the mineralization is inherited from the collision-related transpressional reverse strike-slip faults that cross the entire area: the Ten'ka, Chai-Yur'ya, Debin, and Darpir faults.

The northeastern orientations, as suggested by (Fridovsky et al., 2017) for the Adycha–Taryn mineragenic zone, may reflect the strikes of transverse faults in the deeply submerged basement. In addition, antimony and mercury mineralization is known at gold ore occurrences in the region, which attests to the deep-seated sources of the ore. As mentioned above, these faults could create heterogeneities in the structure of detachment fault surface, more favorable for paleofluid migration.

Based on a set of criteria, the areas extending across the generalized strike of the regional strike-slip faults of the collisional stage, i. e., in compliance with the assumed direction of hydrothermal fluid migration, are delineated in the schematic mineralization map (Fig. 5), showing gold occurrences of various scales. The northeastern orientations of a part of gold occurrences are already taken into account here. These areas are initially allocated in the zones of locally clustered ore deposits, occurrences, and ore spots (ore-geological criteria). After that, the boundaries of these areas are interpolated and traced to less auriferous territories. The mapped zones of altered rocks, metasomatites, and quartz veins (mineralogical criteria), as well as geochemical dispersion halos of Au and pathfinder elements (geochemical criteria) can provide significant aid in this regard.

Let us note V.G. Shakhtyrov's (2009) identification of the kinematically sinistral (post-folding) longitudinal ore-controlling zones and kinematically dextral (synfolding) transverse ore-controlling zones in the schematic map of the metallogenic zoning of gold mineralization in the Verkhoyansk–Kolyma region. These transverse zones have northeastern and sublatitudinal orientations, and their position is very close to the paleofluid flow routes, which we identified, although they do not always contain gold occurrences.

Thus, five strips of various widths (from 8 to 35 km) have been delineated, crossing the Central Kolyma region in the northeastern direction and including the overwhelming majority of gold occurrences (Fig. 5). They are located at a certain interval, which suggests the rhythmic manifestation of the northeast trending weakness zones, sufficiently permeable for fluid flows, along the detachment zone. An indirect evidence for the inheritance of these weakness zones from the earlier basement faults is the presence of antimony and mercury mineralization within them.

The northern strip is the widest (Table 2) and includes two closely spaced flow routes with the Arga–Yuryakh, Chai–Yur'ya, Svetloe–Chelban'ya, and Mal'dyak–Berelekh OPCs with a total potential (sum of the placer and lode gold extracted) of about 994 t, according to S.F. Struzhkov et al (2009). The next strip includes the Degdekan and Snezhnoe deposits, the Susuman and Burkhala OPCs, and the Shturmovskoe deposit with a total potential of around 152 t. Then the strip including the Omchak, Dzhelgala–Tyellakh, and At-Yuryakh OPCs with a potential of 754 t, not including the Natalka and Pavlik deposits with total explored reserves of more than 1680 t (*Gosudarstvennyi* ..., 2019). The strip including the Pioner-

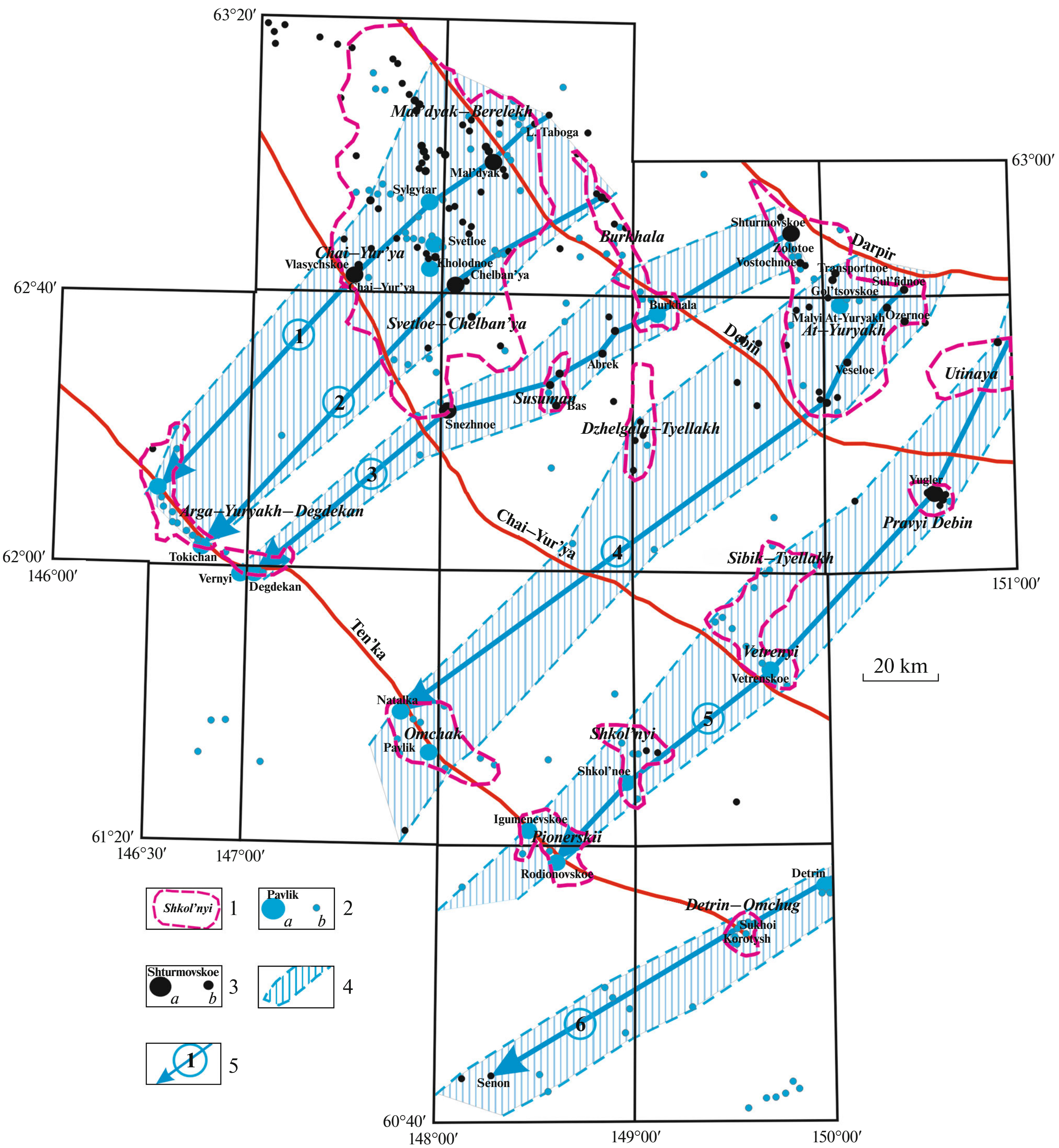

Fig. 5. Gold mineralization strips and paleofluid flow routes along detachment zone. (1) Ore–placer clusters; (2–3) gold–sulfide–quartz occurrences: (2) lode gold deposits and large occurrences (a), small occurrences (b); (3) veins and veinlets in dikes—gold deposits and large occurrences (a), small occurrences (b); (4) gold mineralization strips; (5) paleofluid flow routes and their numbers.

skii, Shkol'nyi, Vetrenyi, Sibik–Tyellakh, Pravyi Debin, and Utinaya OPCs is estimated at 250 t. And the south-easternmost strip includes the Detrin–Omchug OPC with a potential of 22 t. The range of the total potential values of the mineralization strips is from 22 t to 772 t. It is clear that, taking into account the resource estimates that are proposed for some ore occurrences, these figures can be much higher and reach 2400–2500 t of gold.

When analyzing ore potential variations along the recognized strips, sometimes anomalous ore content

Table 2. Parameters of ore mineralization strips in Central Kolyma region

Seq	Width, km	Length, km	Ore–placer clusters	Total ore potential, tons (after Struzhkov et al., 2009)*	Main objects
1	20–35	145	Mal'dyak–Berelekh; Chai–Yur'ya; Arga–Yuryakh	772	Burovoe, Mal'dyak, Chai–Yur'ya, Kovboi
2	10–20	145	Svetloe–Chelban'ya; Arga–Yuryakh	222	Svetloe, Chelban'ya, Tokichan
3	8–20	175	At–Yuryakh; Burkhala; Susuman; Degdekan	152	Shturmovskoe, Burkhala, Obryvistyi, Degdekan
4	20–32	200	At-Yuryakh; Dzhelgala–Tyellakh; Omchak	754**	At-Yuryakh, Natalka, Pavlik
5	18–26	200	Utinaya; Pravyi Debin; Sibik–Tyellakh; Vetrenyi; Shkol'nyi; Pionerskii	250	Utinskoe, Yugler, Vetrenskoe, Shkol'noe, Igumenovskoe, Rodionovskoe
6	14–16	120	Detrin–Omchug	22	Detrin, Sukhoi, Korotysh, Senon

*, total production from gold placers and ore deposits; **, not including reserves of Natalka (1500 t) and Pavlik (180 t) deposits (*Gosudarstvennyi* ..., 2019).

(up to bonanza grades) but small sizes of gold occurrences are noted in the "root" OPCs (e,g,, the Mal'dyak–Berelekh etc.). On the contrary, the most remote OPCs (Omchak) often have the largest scale of gold mineralization, but relatively low grades. In this connection we can assume that the productivity of individual segments of the ore-bearing strips can be guided by the extent of faulting (development of splay faults) in the zones of influence in the upper part of the main collisional shear zones, on the one hand, and by variations of ore component concentrations in hydrothermal fluids, on the other. Based on these premises, the large width of the gold mineralization strips with the development of numerous small occurrences in their "root" part (the most tectonized part of the foldbelt) and the relatively small number of the closely spaced comparatively large deposits in the most remote narrow part become clear.

In spite of the obvious confinement to major collisional reverse strike-slip faults of a significant part of OPCs (Fig. 5), the largest gold deposits are located remote from them and either in footwalls or in hanging walls of these faults. These auriferous structural positions have been studied with reference to the Pavlik deposit (Savchuk et al., 2018). The ore zones confined to the footwall of the Ten'ka deep-seated fault (the Omchak reverse strike-slip fault) are localized in its Pavlik reverse–thrust splay fault zone (Fig. 6a) and consist of a combination of veins, veinlets, and metasomatic and breccia-like silicification zones connected by various mutual transition zones.

Two types of faulting have been distinguished: the first is a series of thrust zones expressed by carbonaceous mylonites (Figs. 3a, 3b) and varying from a few meters to 10 m or more in thickness, and the second is represented by the vast intense fracturing and crush zones up to 10 m or more in thickness, filled with small quartz and quartz-carbonate veinlets. Both types of fault zones develop in an interrelated manner and, as a rule, thrust zones are axial and border fault blocks, whereas crushing occurs in the inter-thrust space (Fig. 3c). These features account for the development of a gently sloped ore stockwork dipping northeastward at 40°–45° (Fig. 3d).

In order to identify the inferred paleofluid flow routes at the Pavlik deposit (Savchuk et al., 2018), statistical processing of core sampling data from exploratory boreholes on the best studied profiles 10–30 was performed (Fig. 6b). The thicknesses of ore intervals were multiplied by the average grade and summed up for each borehole. The resulting values of total productivity per running length were put on the map and isolines were drawn (in m × g/t). The identified areas of maximum values extend along paleofluid flow

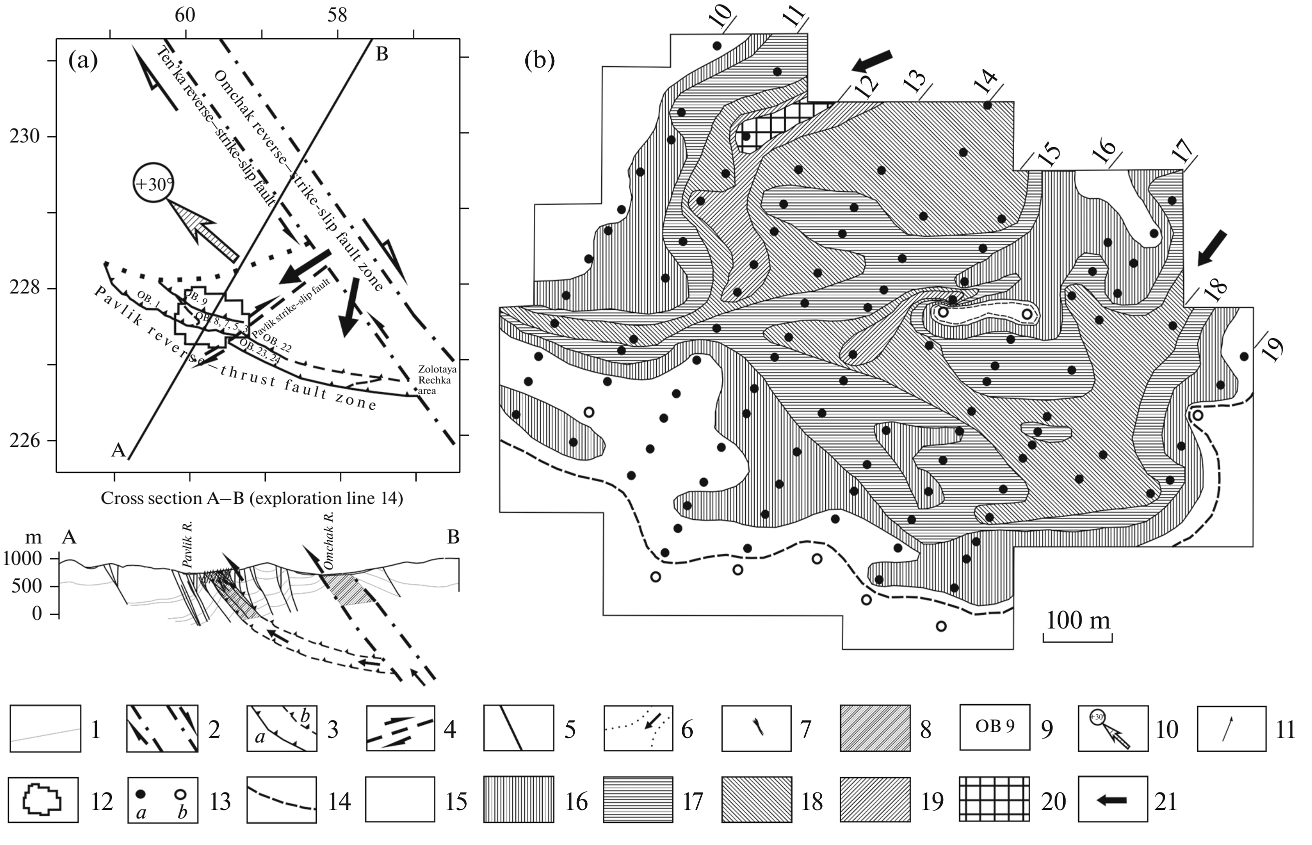

Fig. 6. Structural–kinematic model and cross section of Pavlik deposit (a) and a sketch map of positions and orientations of paleofluid flows (projection onto a horizontal plane) based on exploratory borehole sampling data (b). (1) Lithological and stratigraphic boundaries in cross section; (2) dextral strike-slip movements along Omchak reverse–strike-slip zone (pre-ore stage); (3) Pavlik reverse–thrust fault line, known (*a*) and suspected (*b*); (4) dextral strike-slip movements along Pavlik strike-slip fault; (5) faults in cross section; (6) direction of metalliferous hydrothermal fluid migration and their influence zone: area promising for blind and deeply located mineralization; (7) orebodies in cross section; (8) stockwork-type carbonate–quartz metasomatites in cross section; (9) orebodies (OB) and their numbers; (10) direction of movement of block bounded by Pavlik reverse–thrust zone during sinistral ore deposition stage; (11) boreholes of exploration line 14 in cross section; (12) outline of sketch map (*b*); (13–21) in sketch map: (13) boreholes drilled along exploration lines (numbers at top): with ore intervals (*a*) and barren (*b*); (14) boundary of occurrence of ore mineralization in well sections; (15–20) areas of different gold mineralization intensity (in summed m g/t per well): (15) 1–9, (16) 10–49, (17) 50–99, (18) 100–199, (19) 200–299; (20) ≥ 300 m g/t; (21) inferred direction of auriferous hydrothermal paleofluid migration.

routes from northeast to southwest. Based on these data, the root segments of the paleofluid flows are promising for the discovery of the thickest and richest mineralization zone, and this conclusion can serve as an additional argument in favor of their selection as priority exploration targets.

The result of the predictive metallogenic modeling should be the recognition of the promising areas corresponding to an orefield or an ore cluster in parameters. In the proposed option, ore controlling elements of certain structures vary depending on the scale of the model (Table 3).

Table 3. Objects of forecast

Scale	Predicted objects	Ore controls
1 : 500000–1 : 200000	Gold mineralization strips	Main paleofluid flow routes
1 : 50000	Orefield, ore cluster	Intersection of gold mineralization strip with collisional fault zones
1 : 25000–1 : 10000	Position of deposit	Orientation of splay fault series
1 : 5000–1 : 500	Positions of orebodies	Splay faults and local fluid flow orientation

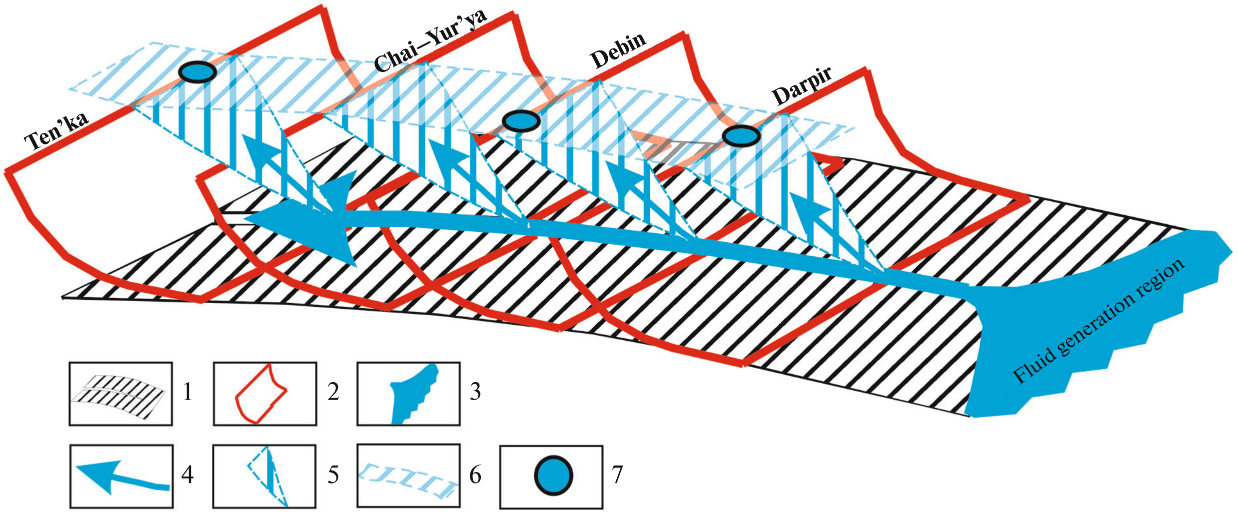

Fig. 7. Model of orogenic deposit formation in collisional shear zones of fold and thrust belts. (1) Surface of deep-seated detachment fault zone and northeast–trending basement fault that complicates it; (2) collisional shear zones; (3) fluid generation region; (4) paleofluid flow route and direction of mobile phase movement along basement fault that complicates detachment plane; (5) upwelling of hydrothermal fluids along collisional shear zones; (6) ore mineralization strip; (7) positions of gold deposits in splay faults of collisional shear zones.

CONCLUSIONS

The Central Kolyma region has the richest ore mineralization in the Verkhoyansk–Kolyma foldbelt. A wide range of igneous, structural–metamorphic, and metalliferous formations are manifested here. The relatively high exploration coverage allows it to be taken as a reference standard and, on this basis, it is possible to develop the most feasible new options in the course of predictive metallogenic modeling within Mesozoic–Cenozoic fold areas. The main ore accumulations at the deposits of this region were emplaced much later than the magmatic intrusions, although some ore lodes occur within dikes and near them. This position of ore mineralization induced the creation of the genetic models of ore formation in the intercontinental fold and thrust belts, based on the collisional scenario of paleobasin closing, which implies that the fluids, released from subducting rock blocks as a result of metamorphism up to anatexis, leached ore elements (gold) and, rising upward along fault zones, created ore concentrations. However, this model did not explain the location of the largest ore accumulations at a significant distance from the collision zone, delay of ore deposition by 10–25 Ma of ore deposition from magmatism, and the lack of relationship with specific intrusive massifs.

An attempt was made to overcome this series of inexplicable facts by including a detachment fault as the main structure, along which nappes moved toward the continental margin, into the genetic model. This tectonic zone extends beneath the entire fold and thrust belt and is complicated by transverse basement faults. Ore-bearing hydrothermal fluids moved along these complications of the detachment fault surface.

The possibility of the invasion of high-temperature ore-bearing hydrothermal fluids from the underlying sections and their subsequent migration in the thermogradient field of the detachment zone as separate streams, paleofluid flows, and ore deposition in the widespread collisional fault systems is substantiated. To summarize, the detachment fault in the presented model (Fig. 7) serves as the main fluid-concentrating and draining structure; the collisional reverse strike-slip faults, as ore-feeding structures; and their splay faults, as ore-bearing structures (Savchuk et al., 2018).

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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