

## Spatial Regularities of Localization of Gold Ore Occurrences in the Yana–Kolyma Province

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**Abstract**—To solve the problems of regional forecast within the Yana–Kolyma gold ore province, analysis of the spatial distribution of 2140 orogenic ore objects and their gold grades was carried out. Ore objects with >1 ppm Au are mapped on a scale of 1: 2,500,000, and areas of high mineralization density points are outlined in the sequence: general contour—contours around clusters of points with high Au grade—contours around proximal clusters of points—long axes of anisotropic contours. The curves obtained after the interpolation between the axes, with regard to the actual position of the ore objects, are interpreted as intersections of the recent topographic surface with the planes of faults that were active at the time of ore formation (ore-hosting faults). We propose to call the curves intersecting the known deposits “trends” (arched and linear). If no deposits have been revealed, the curves should be called “ore lineaments”, regardless of their curvature. The shape of the general contour around the gold ore occurrences and the distribution of ore objects within this contour permit outlining the Upper Indigirka (UID) and Central Kolyma (CKD) megadistricts.

The geometry and spatial position of trends and ore lineaments are compared with the recent structural plan of the area, with geophysical fields, and with the existing ideas of the kinematic types of faults arising under certain geodynamic regimes of evolution of structures in the Yana–Kolyma province.

It is suggested that the ore-hosting faults formed successively during the collisional interaction of the passive margin of the Siberian continent with the Kolyma–Omolon superterrane and during the formation of the volcanic arcs of the Okhotsk–Chukchi volcanic belt. Trends and ore lineaments can be correlated with the groups of structures of ore fields formed at the late collisional and subduction (post-collisional) stages of the area evolution. The trends and ore lineaments of NW orientation are attributed to the folded reverse faults and thrusts and to shears of different kinematics. At the postcollisional stage, the ore lineaments and trends of NE orientation formed in the zones of tectonomagmatic activity, subparallel to the strike of volcanic arcs of the Okhotsk–Chukchi volcanogenic belt. The distribution of clusters of gold ore occurrences and “empty” intervals between them along the strike of the recognized structures probably corresponds to the distribution of areas of extension and compression in the plane of the ore-hosting faults.

The correlation among the trends, ore lineaments, and ore-hosting faults permits forecasting for the position and approximate size of new ore bodies within the Yana–Kolyma province. Prospective areas for a gold ores prospecting and exploration have been outlined on the extrapolated and interpolated extensions of the trends and at the sites of their intersection.

*Keywords:* gold, spatial distribution of gold ore occurrences, ore districts, ore lineaments, trends, collision, regional forecast, Yana–Kolyma province, gold ore prospecting

### INTRODUCTION

In the Yana–Kolyma gold province (YKGP) located in eastern Yakutia and the northwest of the Magadan Oblast, multiple small deposits and ore occurrences with rich ores, as well as several high-tonnage objects with low-grade stockwork ores (Degdekan, Upper Khakchan, Natalka, etc.) and two objects with significant ore body parameters and high or moderate gold contents have been discovered and proved. The latter being the Drazhnoe (over 35 t of gold with the average content of 6.5 ppm) (Aristov et al., 2015)

and the Pavlik (over 150 t of gold with the average content of about 3 ppm) deposits (Savchuk et al., 2018). All these objects are classified as mesozonal orogenic deposits (as interpreted by (Groves et al., 1998)) within the Phanerozoic collisional belt (Goldfarb et al., 2001) or as gold-quartz and gold-rare-metal formations, according to the regional classifications (Goryachev, 1998).

The linear and belt-like distribution of ore and placer occurrences within the YKGP was highlighted by Yu.A. Bilibin (1961), who also identified the Kolyma gold belt. The internal structure of the belt was further detailed, as new placer and ore occurrences were discovered. Ore-hosting faults, such as Ten’ka (Larin, 1949; Shakhtyrov, 1997), Adycha–Taryn (Bychok, 1969; Vladimirov, 1973), Balygchan–Sugoi (Politov, 1972; Zarudnyi and Konstantinov,

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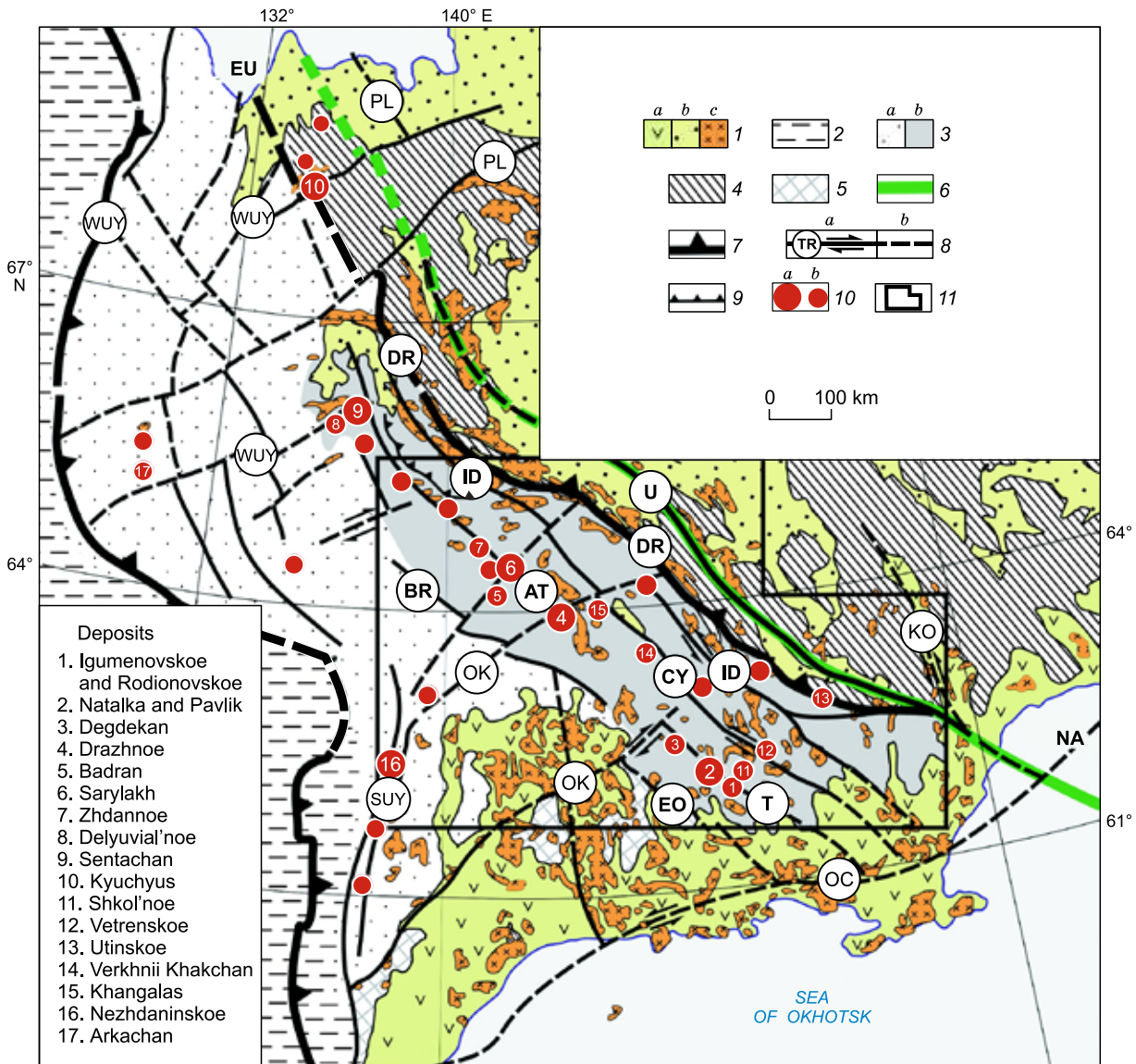
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1981), and some others, which control the location of linear and isometric ore-placer districts, were traced. A deeper understanding of the YKGP was obtained during further research and as a result of the development of geodynamic concepts. The current ideas on the nature of gold-quartz deposit belts within the YKGP and their boundaries were presented most comprehensively by N.A. Goryachev (1998), V.A. Fridovskii (2002), and in several generalizing papers produced by groups of authors (Parfenov and Kuz'min,

2001; Nokleberg et al., 2005; Khanchuk, 2006; Goldfarb et al., 2014; Voroshin et al., 2014).

The Yana–Kolyma gold province includes the eastern part of the Yana–Kolyma fold system (YKFS). The fold system is located between the eastern (Chara–Aldan) part of the Siberian platform and the western part of the Kolyma–Omolon accretionary superterrane (Fig. 1).

In terms of composition, the YKFS corresponds to the Upper Yana passive continental margin carbonate-terrege-



**Fig. 1.** Tectonic scheme of the Upper Yana–Kolyma fold belt (Gusev, 1979; Parfenov and Kuz'min, 2001). 1, Upper Jurassic–Cenozoic formations: volcanogenic formations of the Okhotsk–Chukotka volcanic belt (a), terrigenous and molasse (b), granitoid (c); 2, 3, North Asian (Siberian) craton: 2, Siberian Platform, 3, Yana–Kolyma fold system (YKFS): Upper Yana fold-thrust belt (a), Yana–Kolyma fold belt (b); 4, Kolyma–Omolon superterrane: island-arc, oceanic, and continental terranes; 5, Okhotsk terrane; 6, present lithospheric plate boundaries (NA, North American, EU, Eurasian, according to (Parfenov and Kuz'min, 2001)); 7, back and frontal thrust systems bounding the YKFS; 8, the largest shear faults: verified (a), assumed (b); 9, thrusts; 10, orogenic gold deposits: over 100 t in reserves and resources (a), below 100 t in reserves and resources (b); 11, area for detailed study. Fault systems and individual faults: circles, semibold: Indigirka–Kolyma fault system: EO, East Okhotsk; BR, Bryungada; T, Ten'ka; AT, El'gi (Adycha–Taryn and Sentachan); CY, Nera and Chai-Yur'ya; ID, Inyali–Debin; DR, Darpir; U, Ulakhan; circles, light: OC, Okhotsk–Chukotka (Priokhotsk) fault system; OK, Okhotsk fault system; SUY, Southern Upper Yana fault system; WUY, Western Upper Yana fault system; KO, Kolyma–Omolon fault system; PL, Polousnyi fault system.

nous sedimentary basin on the continental crust, with sedimentation beginning in the Vendian (Parfenov and Kuz'min, 2001). The pre-upper Carboniferous evolution of the territory is associated with accumulation of subarkosic terrigenous and chemogenic carbonate sediments, whose thickness increases within Devonian riftogenic structures. Polymictic silty sand shelf-deltaic and flyschoid depositions of the Upper Yana complex aged from the late Carboniferous to Middle Jurassic with thicknesses up to 10–15 km are the most widespread at the current section level (Konstantinovskii, 2009). Horizons with siderite concretions and regionally encountered carbonate (ankerite-siderite), pyrite, and marcasite impregnation haloes were formed during diagenesis.

The YKFS includes the following elements:

— The Yana–Kolyma fold belt (YKFB), which generally matches with the Yana–Kolyma terrane as interpreted in (Shpikerman, 1998), excluding the northern part of the Kular–Nera terrane (Polousnyi synclinorium and Kular uplift);

— The Upper Yana terrigenous fold-thrust belt (UYFTB) (within the boundaries proposed by A.V. Prokopiev and A.V. Deikunenko (Parfenov and Kuz'min, 2001)), including the Okhotsk terrane (in the Magadan Oblast).

Large linear folds throughout the YKFB are linked to fault zones and may be inherited. It is especially typical for the fault-associating synclines, whose cores are composed of Lower Triassic and Lower Jurassic rocks. Short synclinal folds located in echelon fashion in shear zones or lengthier anticlines in reverse fault and thrust zones are observed. In the UYFTB, the folding associated with the general compression of the territory is classified as concentric (Sborshchikov, 1973; Gusev, 1979). The folds are large, often extended, and have NW and meridional orientation. Hinge line undulations and virgations are not typical for the system. The main detachment surface dips smoothly from west to east.

The faults are inter- and intraformational detachments, thrusts, reverse faults, and shears. Longitudinal and transverse shears are identified depending on the folding axes. Consecutively developing dextral low-amplitude (Shakhtyrov, 2010) and sinistral high-amplitude longitudinal shears (Konstantinovskiy, 2007) are considered the main structures of the YKFB. In the UYFTB, the role of sinistral- and dextral transverse shears associated with thrusts and reverse faults is highlighted (Gusev, 1979). According to D.N. Zadorozhnyi (2002), the shears within the UYFTB are included in the post-thrust structural parageneses with feathering reverse faults, faults, granitoid intrusive bodies, and silver-polymetallic deposit orebodies. One could assume that these shears correspond to late collisional transverse shears and transverse-series granitoids zones with matching orientations, whose significance in terms of regional metallogeny is emphasized by many researchers (Politov, 1972; Volkov et al., 2014).

In general, the Yana–Kolyma fold system (YKFS) syn-collisional structure is a system of thrust sheets bounded by the detachment along the basement surface at the bottom

and in the west and by a back thrust in the east. The western boundary of the YKFS corresponds to extended systems of flat thrusts and above-fault folds, i.e., the detachment zone fragments (Parfenov and Kuz'min, 2001). The southern boundary is defined by a series of shears with NE orientation, which belong to the Okhotsk fault system. The Darpir fault, which separates the Mesozoic deposits of the Inyali–Debin synclinorium from the Paleozoic deposits of the Kolyma anticlinoria, is accepted as the NE boundary of the YKFS (Shpikerman, 1998). We attribute the anticlinorium belt to the hinterland based on (De Paor, 1988).

The isometric uplifts associated with intrusive-tectonic processes of the late and postcollisional evolution stages were less well studied. Focal ore-concentrating concentric structures, i.e., the Upper Kolyma and Indigirka mega-arches, were identified by Tomson et al. (1984), and, according to the authors, they defined the metallogeny of the Central Kolyma and Upper Indigirka areas respectively. Lowest-order concentric structures include, for example, the Upper Indigirka ring structure (with the center in the Taryn subvolcanic area) discovered by Sharov et al. (1979) and studied in detail by Bakharev et al. (1997).

Batholiths and syncollisional granitoid stocks of the Kolyma and Ten'ka sequences (Palymskii et al., 2015) (*S*-type, ilmenite series), as well as subvolcanic formations of hypersthene dacites are concentrated exclusively within the YKFB and in the adjacent hinterland. The beginning of granitoid crystallization is dated at  $150 \pm 3$  Ma (U–Pb SHRIMP zircon dating (Akinin et al., 2009)). The end of crystallization is attributed to the beginning of the Early Cretaceous. Granite formation is closely linked to the evolution of the regional zonal metamorphism of the biotite, chlorite-biotite, and chlorite-sericite subfacies, as well as partial transformation of diagenetic pyrite into pyrrhotite and development of pyrite impregnation haloes.

The intrusion of transverse-series granitoids within the UYFTB was dated at 137.1 to 109.4 Ma (Ar–Ar biotite and amphibole dating) (Layer et al., 2001). The development of ultrapotassic acidic volcanic rocks of the Okhotsk–Chukotka volcanic belt (OCVB) dated at  $134.6 \pm 1.3$  Ma by U–Pb SHRIMP zircon dating (Akinin and Miller, 2011) may be attributed to the same stage.

The beginning of the evolution of the latest calc-alkalic volcanoplutonic associations of the Okhotsk, Even, and Yana sequences is attributed to the end of the Early Cretaceous ( $97 \pm 5$  Ma based on averaged data (Akinin and Miller, 2011) for granitoids of Ulakhan and Neorchan massifs). Its end (basalt dikes and blanket basalt formation) is attributed to the end of the Late Cretaceous (Palymskii et al., 2015). Granites of these associations are widespread in close vicinity of the OCVB and synchronous with its volcanic activity.

According to (Goryachev, 1998), orogenic gold deposits are syn- and postbatholithic and associate with specific regional metamorphic subfacies.

The observed relations between structures, intrusive formations, and orebodies are explained by the evolution of the collisional interaction of the Kolyma–Omolon superterrane (microcontinent) with the structures of the North Asian (Siberian) craton and further subduction of the Okhotsk Sea plate beneath the craton with the formation of the OCVB (Parfenov and Kuz'min, 2001; Khanchuk, 2006). Most geodynamic concepts consider terranes with continental crust included in the superterrane as fragments of the continental margin detached from it to the Panthalassa Ocean in the middle Paleozoic. The Oymyakon basin that formed as a result was consecutively closed during the terrane accretion at the beginning of the Middle Jurassic. Flat detachments and near-fault fold zones were formed within the Upper Yana passive continental margin at the initial collision stages, which was followed by development of longitudinal shear faults of various kinematic types during the clockwise rotation of the superterrane. The geodynamic evolution scheme of Eastern Asia in the Late Jurassic–Cretaceous considered in (Goldfarb et al., 2014) assumes that the development stages of the fault-fold structure, granitoid magmatism, and gold mineralization in the YKFS are defined by consecutive terrane accretion from the eastern, northern, and southern sides of the craton passive margin. The subduction direction, i.e., whether the craton was subducted beneath the microcontinent or vice versa, remains unknown (Goldfarb et al., 2014). Some researchers deny the existence of the suboceanic basin (Prokopiev and Tronin, 2004) and consider the interaction between the microcontinent and the North Asian (Siberian) craton as an example of the *A*-type subduction (Nekrasov, 2017). Volcanic arcs evolved simultaneously with the termination of collision events, and their structures were located transversely to the strike of the collision zone.

Ore formation processes have an overlapping nature and could have arisen both during the collision (Khanchuk, 2006) (Late Jurassic–Early Cretaceous) and in postcollisional conditions (Tret'yakov and Prokopiev, 2014) associated with the evolution of the Uda–Murgal (Early Cretaceous) and Okhotsk–Chukotka (Albian–Campanian) volcanic arcs within the OCVB. An Early Cretaceous age was identified for the sericites and potassium feldspars presumably synchronous with gold mineralization of the YKGP (149–124 Ma (Goldfarb et al., 2014)),  $132 \pm 7$  Ma (Akinin and Voroshin, 2006)) and for the sericites and galena of gold and polymetallic associations of the Southern Upper Yana segment ( $120 \pm 1.3$  Ma (Prokopiev et al., 2009; Chernyshev et al., 2011)). A Late Cretaceous age is assumed for the meta-somatites associated with the antimony mineralization overlapped with gold-quartz mineralization of the Sarylakh and Sentachan deposits (Bortnikov et al., 2010). The more accurate data obtained by Rb–Sr and Ar–Ar dating based on gold-silver deposit adulars at the adjacent territory of the OCVB (Struzhkov and Konstantinov, 2005) make it possible to identify the Neocomian ( $136 \pm 3$  Ma) and Coniacian–Campanian ( $79.5 \pm 7.5$  Ma) ore formation stages correlating

with the late collisional and postcollisional ore formation stages in the YKGP.

## PROBLEM STATEMENT

Despite the province territory being well researched, the problems of regional forecasting of the prospective areas for a gold ores prospecting and exploration and prospectivity ranking remain topical. The current drilling practice for the known vein formations showed insufficient efficiency in terms of discovering large mineralization and the lack of direct relation between the scales of vein and veinlet-impregnated mineralization.

Metallogenic forecasting based on terrane analyses of the fold-thrust belts appears to place deposits at the margins of terranes, and they are often included in the respective metallogenic belt by arbitrary decisions. This can be confirmed simply by comparing tectonic, metallogenic zoning, and mineral resource maps of the YKGP (for instance, [http://www.vsegei.ru/ru/info/gisatlas/dvfo/magadanskaya\\_obl](http://www.vsegei.ru/ru/info/gisatlas/dvfo/magadanskaya_obl)). The Yakutian gold-antimony belt controlled by the Adycha–Taryn fault zone is an illustrative example. Most researchers of the regional tectonics (Parfenov and Kuz'min, 2001) draw the boundary between the structures of the deformed passive margin and pericratonic terranes along this fault. However, gold ore deposits, such as Deluvialnoe, Badran, Malotarynskoe, Yakutskoe, Kim, as well as multiple smaller gold-ore occurrences, are located to the west from this boundary (in the UYFTB), while the Sentachan, Sarylakh, Maltan, Tan, and Drazhnoe deposits are located to the east from it. Hence, when mesoscale metallogenic zoning is performed, the authors either abstain from drawing the boundaries of metallogenic units (Parfenov and Kuz'min, 2001) or combine proximal ore objects within more or less feasible and geometrized outlines that cross geological and tectonic borders (Amuzinskii, 2005; Politov et al., 2008). Similarly, the border between the formation complexes of the Kular–Nera and Inyali–Debin terranes divides ore occurrences that are almost identical in terms of mineralogy and geochemistry (for example, Burustakh, Zolotoi Rog, Khangalas, Nagornoe and Svetloe, Vetrenskoe). The unique placer gold mineralization of the southern part of the Inyali–Debin terrane and its almost complete sterility in terms of gold to the north-west from the Indigirka River also remains unexplained from the metallogenic zoning perspective based on terrane analysis. Here, it is not only true for sedimentary formations, but for the granitoid ones as well, as they are in no way different from the granitoids located further to the south.

The situation is explained by the fact that gold-bearing mineral associations are attributed to late collisional formations. These associations overlap with synaccretionary rock complexes, including the granitoid formations and the accompanying metamorphic haloes. Thus, rock complexes and tectonic structures formed specifically under continental orogeny conditions are to be isolated. We find the following

quote from (Tomson et al., 1984) quite fitting for the territory of the Yana–Kolyma province: “...traditional tectonic zoning methods, such as facies and deposit thickness analysis, are of limited use under continental orogeny (tectogenesis) conditions due to reduced geological record. Here, structural ore-controlling factors come into the forefront”. One may assume that the problem may be partially solved based on “lineament metallogeny” (Smirnov, 1982). However, the present structural plan of the province does not fully match the one in place during the ore formation due to intense neotectonic activity. This complicates the forecasting based on space or geophysical data analysis. To solve problems of uncovering the regularities behind the distribution of the known gold ore occurrences and forecasting locations of new occurrences within the Yana–Kolyma province, we deciphered the gold mineralization data with simultaneous isolation and interpretation of ore lineaments (metallic lineaments, according to (Kats et al., 1986)).

The goal of the paper is to demonstrate the possibility of regional forecasting of gold-quartz mineralization in terrigenous complexes of the Yana–Kolyma province based on reconstruction of the structural plan that coexisted with ore forming by analyzing the spatial distribution of gold ore occurrences.

One may assume that revealing new spatial distribution regularities for gold ore occurrences will make it possible to predict the prospects, where hidden or overlapped gold ore bodies develop, localize prospecting efforts, and, thus, significantly reduce geological prospecting costs.

## RESEARCH METHODS

The analysis of spatial distribution peculiarities of gold deposits is a type of generally accepted geological anomaly method, which is primarily used as a prediction tool (Struzhkov and Konstantinov, 2005). Most often the spatial distribution is analyzed for ore occurrences and deposits with uniform mineralogical and geochemical parameters. Based on this analysis, a preliminary outline of metallogenic taxons is produced, ore trends and belts are identified, a “mineralization step” between the bodies is determined, and hidden ore-controlling structures are predicted. When the ore bodies of the same age are used, the mapped distribution of the deposits may convey information on the kinematic types of fault systems, which is indicated in (Micklethwaite, 2007) based on the analysis of spatial distribution of deposits in North America.

The idea of migration of gold-bearing hydrothermal solutions along regional tectonic faults with gold being deposited at geochemical (electrochemical) and/or thermobaric barriers (Kerrick et al., 2000) acts as the theoretical base of the technique used. Given the uniformity of the rock mass, an increased rock fracturing is required for these barriers to exist. Relative homogeneity of the hosting environment (Upper Yana terrigenous complex), semiconstant composition

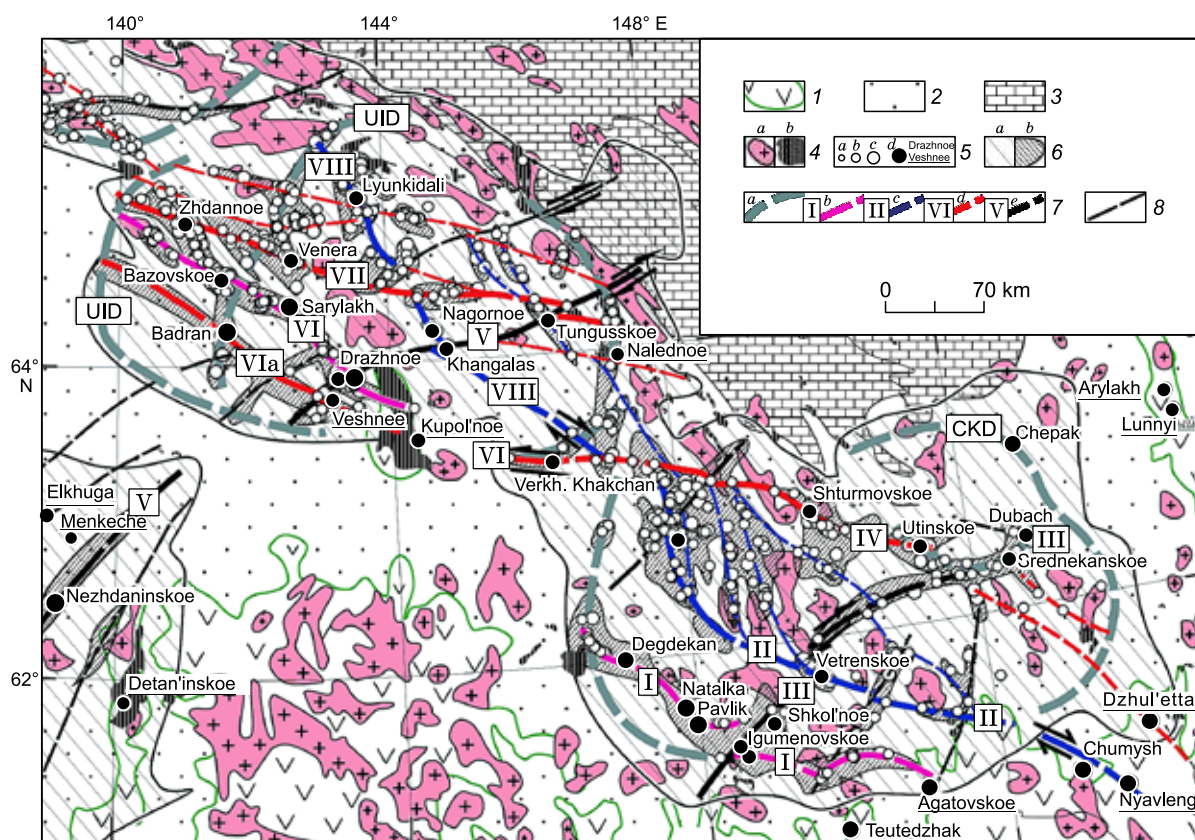
and stable deposition sequence of productive mineral associations in orogenic gold ore bodies of the YKGP make it possible to assume that the spatial distribution of gold ore bodies reflects the fault placement during ore deposition.

The plot in Fig. 2 uses the rock chip sampling data from 2140 ore occurrences located outside the OCVB and accounted for in the cadastral record for the Yana–Kolyma interfluvial area. The materials were supplemented by the data obtained by the author in course of his work in the region from 2000 to 2014. In addition to highly prevalent gold-quartz and gold-rare-metal formation occurrences (associated with granitoids), gold mineralization occurrences in silver-polymetallic, tin ore, tungsten, and antimony ore bodies were taken into account. The trends were derived considering the placer occurrence distribution indicated on mineral resource maps on a scale of 1:500 000 (Kuznetsov et al., 1998; Mannafov et al., 1999) and the plots (Shilo, 2002; Skryabin, 2010). Late Cretaceous gold-silver deposits within the OCVB were discarded.

Rock chip sampling points were mapped on a scale of 1:2,500,000 and marked with one of three gold content levels: low content of 1–5 ppm; medium content of 5–300 ppm, and high content of over 300 ppm. Here, the maximum gold content value obtained during the chip sampling was used. It should be noted that rock chip samples fulfilled the extremum condition, and the whole sample satisfied the uniformity condition, since the geologists select the best ore samples for testing. Gold content varied from 0.1 to 13,600 ppm (Fig. 3). Values below 1 ppm were discarded to improve the sample accuracy (assay test sensitivity varies between 0.2 and 0.5 ppm, while the other types of tests were only used sporadically). Main deposits (e.g., Natalka, Pavlik, Sarylakh) were attributed to the high content category.

With the ore bodies mapped, areas of the high density of mineralization points are outlined in the sequence: general contour–contours around clusters of points with high Au contents–contours around proximal clusters of points–long axes of anisotropic contours. The curves obtained after the interpolation between the axes, with regard to the actual position of the ore bodies, are interpreted as intersections of the recent topographic surface with the planes of faults that were active at the time of ore formation. These curves are highlighted and indicated in the plots in a way that their orientations, shapes, and proportions agree with the available reconstructed kinematics of the ore-hosting faults (Kalinin, 1992; Fridovskii, 2002; Shakhtyrov, 2010; Chitalin, 2016; Voitenko and Zadorozhnyi, 2015), as well as our own observations (Aristov et al., 2017a). Contours around proximal clusters of mineralization points were drawn considering the possibility of discovering arc or semicircular structures.

We propose the term “trends” (arched and linear) for the curves including the known deposits. If no deposits have been revealed, the curves should be called “ore lineaments”, regardless of their curvature. Some (most often large) ore bodies were included in two or three trends based on their



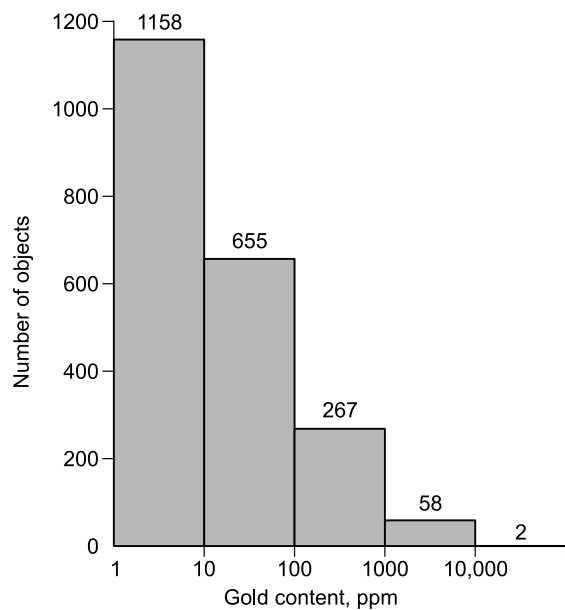
**Fig. 2.** Distribution structure of gold mineralization in terrigenous complexes of the southern Yana–Kolyma gold ore province. 1, Cretaceous volcanic rocks (lavas, tuffs, and subvolcanic bodies); 2, terrigenous rocks of the Upper Yana complex; 3, pre-upper Carboniferous basement rocks with superimposed Jurassic–Quaternary troughs; 4, intrusive (a) and subvolcanic (b) bodies; 5, (a–c): gold contents (ppm) based on assay tests of rock-chip samples: a, less than 3, b, 3 to 300, c, over 300; d, reference gold and silver deposits (underlined); 6, isoconcentrations mapped based on denser distribution of deposits and ore occurrences (a) with increased gold contents (b); 7, ore trends: arched (a), linear with NW strike (b–d): the first group (b), the second group (c), the third group (d); linear with NE strike (e); 8, ore lineaments (colors similar to 7). Main ore trends are indicated by digits: I, Ten’ka; II, Chai-Yur’ya; III, Pautovka; IV, Detrin; V, Suntar–Indigirka; VI, El’gi–Taryn (VIa, Badran); VII, Ol’chan–Delyankir; VIII, Nera. The scheme is produced using the cadastral records for the maps of the Magadan Oblast on a scale 1:200 000 (Mannafov et al., 1997; Kuznetsov et al., 1998), archive materials (cadastral records on mineral resources on the territory surveyed by OAO Yangeologiya, cadastral records on mineral resources on the territory surveyed by GUGGP Yakutskgeologiya), and the data collected by the author.

scale and the presence of mineralogical or geochemical indicators of significant changes in deposition conditions at later mineral formation stages in gold ore bodies. Positions of the identified linear structures were compared with the mapped faults using primarily the plots produced by G.S. Gusev (1979) and fault descriptions from (Khanchuk, 2006).

The data were interpreted using the digital models of gravitational and magnetic fields developed at the Research Institute of Exploration Geophysics (VIRG) in the form of matrices on the grid of  $0.5 \times 0.5$  km and gravitational and magnetic field maps produced based on these digital models. The primary geophysical data for the state geological map on a scale 1:1,000,000 along with the results of mesoscale geophysical surveys (1:200,000–1:50,000) were used as the initial data. D.S. Zelenetskii used a standard technique to perform additional gravity field transformations (which, among other things, made it possible to isolate its local and regional components).

## MAIN RESULTS

The obtained scheme (Fig. 2) shows the distribution structure of gold ore occurrences of central and southern parts of the Yana–Kolyma province. The way ore occurrences are distributed makes it possible to lay out the contours of the Upper Indigirka (UID) and Central Kolyma (CKD) megadistricts with increased gold deposit concentrations. Also present on the scheme are fragments of two other megadistricts (Southern Upper Yana and Adychan). Approximate megadistrict borders, i.e., arched (concentric) trends, are traced not only by ore objects, but by smaller subvolcanic bodies as well. Megadistrict borders in the form of arched trends have no clear matches in the tectonic schemes available. To the east of the Darpir fault, gold ore bodies are encountered sporadically and most of the revealed ore trends are not observed. The Darpir fault zone bounds the Omulevka terrane from the southwest and is



**Fig. 3.** Distribution of peak gold grades in rock chip samples from the ore occurrences of the Yana-Kolyma province by decimal classes (the total of 2140 objects).

traced to the distance of over 800 km with thicknesses of 0.3 to 3.0 km (Khanchuk, 2006). Vertical displacement amplitude is 3–5 km (Chekhov, 1973). There are spots, where the fault is transformed into a thrust with displacements of individual blocks in the SW direction reaching 40–50 km.

The linear sizes of the CKD are  $390 \times 280$  km with the area of about 85,765 km<sup>2</sup>, for UID these are  $420 \times 238$  km and about 78,500 km<sup>2</sup>. These parameters significantly exceed the values generally accepted for ore districts (Tomson, 1988; Struzhkov and Konstantinov, 2005), hence the term ‘megadistrict’. Matching the megadistricts with anomalies on gravitational field transformation maps (Fig. 4A, B) showed that they correspond to increased density areas at depths of about 15 km. It agrees well with the ideas (Buryak et al., 2002) of a link between the gold mineralization in CKD and mafic formations. The largest deposits (Badran, Drazhnoe, Nataalka, and Pavlik) are concentrated along the western periphery of the megadistricts. Presumable megadistrict centers derived based on decreasing radiuses of arched trends gravitate towards the eastern boundary of the YKFS and are displaced eastward relative to the concentric structures identified earlier (Tomson et al., 1984), which have centers in the areas of granitoid formation clusters. Megadistrict sizes are slightly lower than those of the concentric structures. Asymmetric megadistricts are intersected by linear trends and ore lineaments of NW and NE orientations. If we consider the extension of these structures beyond the megadistricts, the number of ore occurrences decreases dramatically. The lineaments of NW orientation crosscut the axes of fold structures and are close in their strike to riftogenic paleostructures (Chekhov, 2000) with Jurassic and Early Triassic sedimentary filling. The lineaments

of NE orientation match in strike with the main structures of the OCVB. Some trends, especially within the CKD, coincide with linear anomalies of the magnetic field (Fig. 4C).

The largest trends within CKD and UID are as follows.

1. NW strike trends crosscutting the axes of large structural elements (the trends form three groups based on possible links between them):

The first group: I, Ten’kaj VI, El’gi–Taryn; corresponding to the southern part of the Adycha–Taryn gold-antimony ore belt;

The second group: II, Chai-Yur’ya; VIII, Nera.

The third group: IV, Detrin; VIa, Mugurdakh–Selerikan (Badran), VII, Ol’chan–Delyankir, traced by the largest placer deposits of the UID.

2. NE strike trends transverse to the main fold structures: III, Pautovka; V, Suntar–Indigirka.

**NW strike trends.** El’gi–Taryn (VI) and Ten’ka (I) trends are accompanied by a wide (10–15 km) halo of placer (Adychan, Taryn, and Omchak) and gold-quartz objects. The Bazovskoe, Malotarynskoe, Drazhnoe, and, probably, Verkhniy Khakchan and Kontrand’inskoe deposits are attributed to trend VI. The Ten’ka trend (I) includes the large and unique gold contents of the Degdekan, Nataalka, and Pavlik deposits. Gold-bearing trends partially match with the Adycha–Taryn fault zone (ATF) (Shakhtyrov, 1997). The match is established at ATF fragments from the Adycha River to the upper reaches of the El’gi River (Adychan trend, not shown in Fig. 1), from the middle reach of the Elga River to the upper reaches of rivers Bolshoi Taryn and Malyi Taryn (El’gi–Taryn trend (VI)) and at the fragment corresponding to the Ten’ka trend (I). In contrast to the ATF zone itself, the trends of this group are deformed, which is highlighted by their curved shape in plan view. The El’gi–Taryn and Ten’ka trends are divided by approximately 150 km long interval showing no signs of ore mineralization.

The Chai-Yur’ya trend (II) includes the Vetrenskoe deposit with medium reserves and several smaller bodies (Svetloe, Mal’dyak, etc.), as well as feathering ore lineaments with significant number of small ore bodies located between granitoid formations of the Main Batholithic Belt. The continuation of the trend (II) towards the southeast into the OCVB is spatially associated with the Chumysh and Nyavlenga deposits with small and medium gold contents with Early Cretaceous ore mineralization. The Nera trend (VIII) with the Khangalas and Nagornoe deposits and several prospective areas at the bank of the Indigirka River, including the Lyunkidali gold-silver deposit, may be considered a continuation of the Chai-Yur’ya trend in the NW direction. An ore lineament subparallel to trends II and VIII and linked to trend II by nonextensive noncommercial mineralization zones is traced to the north-east from them by the series of small gold ore bodies of unidentified commercial value (Burkhalinskoe, Fart, etc.). A wide placer gold mineralization area (which includes the unique Chai-Yur’ya placer) develops, where trend II approaches the lineament. The

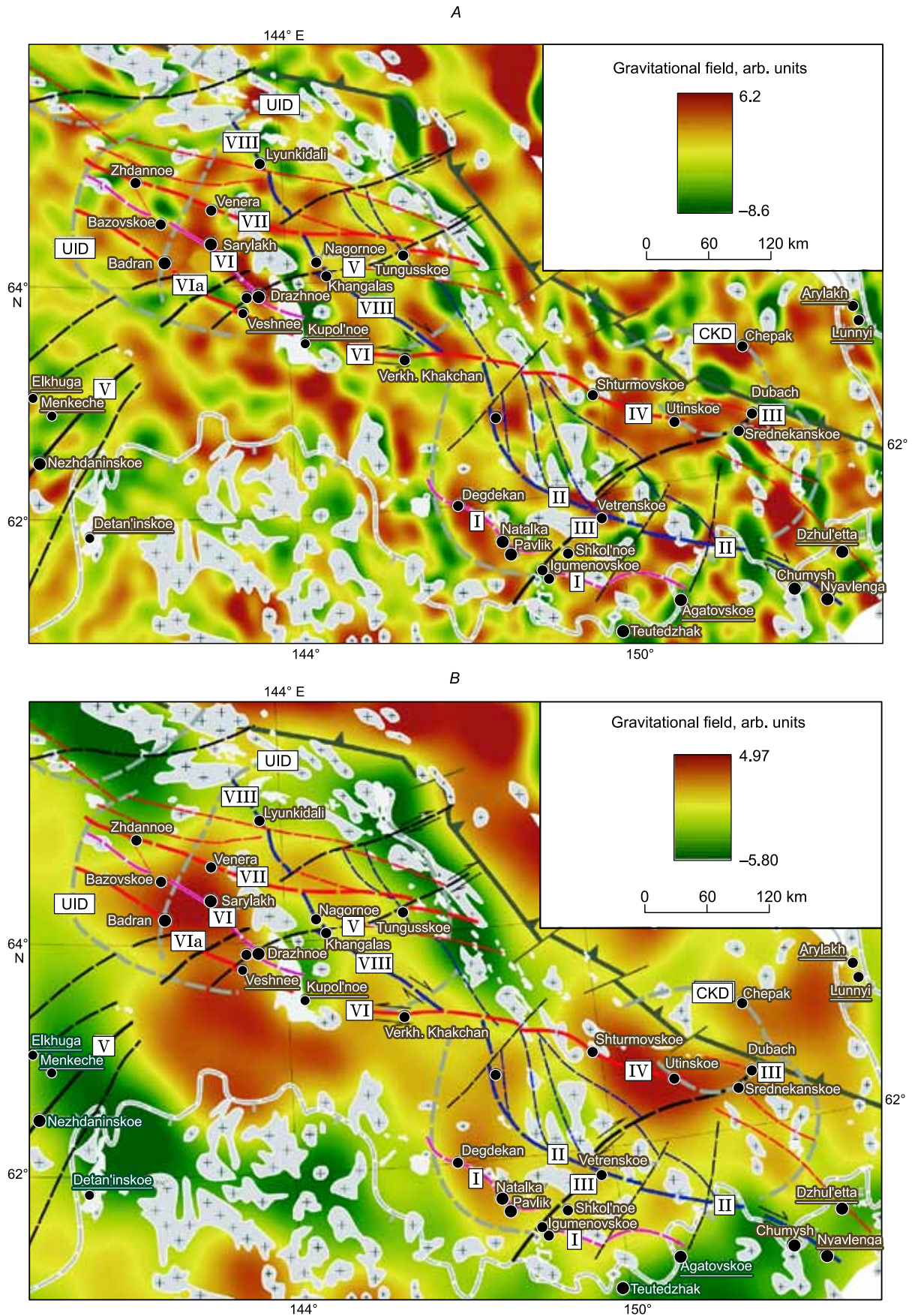
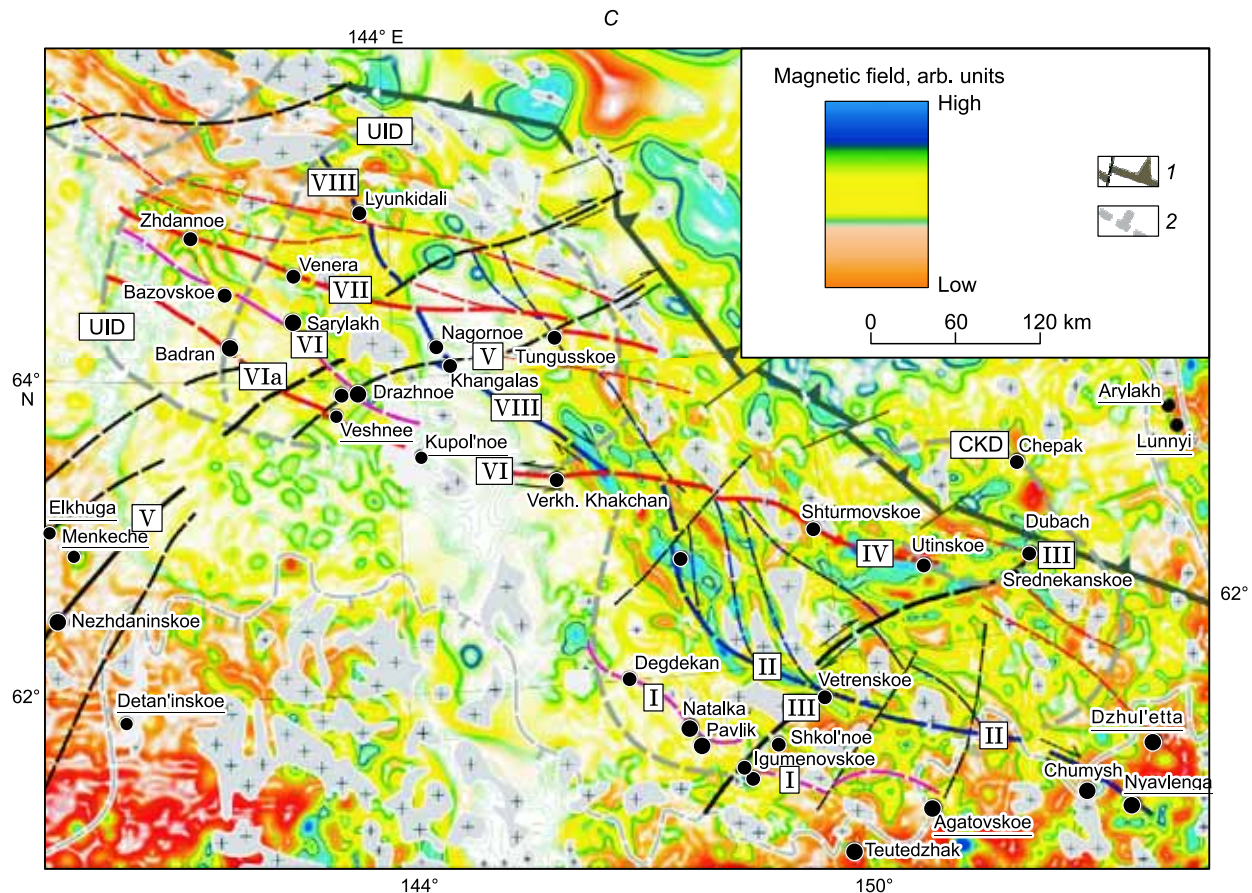


Fig. 4 (to be continued).





**Fig. 4.** Locations of the main deposits and ore trends in the gravitational (*A*, *B*) and magnetic (*C*) fields. *A*, frequency behavior corresponds to the section level of 5 km; *B*, section level of 15 km. 1, Kolyma–Omolon superterrane boundary; 2, volcanic rocks of the OCVB. See the key in Fig. 2.

Chai-Yur'ya trend matches with the shear zone of the same name to the south from 62° N. The Chai-Yur'ya fault zone (Chekhov, 1973) is about 1000 km long, has thickness of about 1 km, and separates Jurassic sediments of the Inyali–Debin terrane from Permian and Triassic sediments in the Ayan–Yuryakh terrane and Adycha–El'gi terrane. Vertical displacement amplitude estimate along the fault is 1–3 km, while dextral displacements reach tens of kilometers (Chekhov, 1973). In the northern direction, the fault is transformed into a thrust (Charky–Indigirka), along which horizontal amplitude reaches several dozen kilometers.

The Detrin trend (IV), in which gold deposits with medium and small reserves closely linked to dikes and small intrusions (Shturmovskoe and Utinskoe) are concentrated, is identified within CKD. The Mugurdakh–Selerikan (Badran) trend (VIa) is located on the continuation of the Detrin trend. Along the SE–NW direction, it includes the Ergelyakh deposit, Veshnee silver-polymetallic deposit, Badran deposit, and prospective Syurampa occurrences. The southeastern part of the trend VIa is understudied. The Detrin and Mugurdakh–Selerikan trends roughly match the Bryungade fault, as shown in the scheme proposed by N.A. Goryachev (2010).

The Ol'chan–Delyankir trend (VII), in which the small Tungusskoe, Venera, Bezmyannoe, and Zhdannoe deposits spatially linked to rhyolite, diorite porphyrite, and lamprophyre dikes are known, is parallel to trend IV in the UID (Aristov et al., 2017a).

**NE strike trends** match rather closely with the transverse fault zones with dikes and small intrusions (TMA). These zones are of transit nature relative to megadistrict boundaries. Their ore mineralization parameters are close to porphyry or intrusion related mineralization occurrences and anomalous compared to the typical regional mineralogical and geochemical background (increased role of silver, bismuth, and copper in productive mineral associations).

The northeastern part of the isolated Pautovka trend (III) is characterized by development of gold ore mineralization in granitoids or in their neighborhood (Igumenovskoe–Shkol'noe–Srednekanskoe–Dubach, etc.). The Pautovka trend is subparallel to the major Pautovka fault with NE strike. This fault (Khanchuk, 2006) separates the Kular–Nera terrane from the Balygychan terrane and is oriented in accordance with the general strike of the OCVB. The fault zone is represented by a wide strip of proximal faults and multiple gravity and magnetic field anomalies. From a kine-

matic perspective, it is a reverse fault (thrust) dipping southward.

The Suntar–Indigirka trend (V) is isolated within the TMA area, whose main feature is the linear distribution of gold ore occurrences, with the paired silver ore bodies observed within the radius of 50–70 km from them. Relatively large bodies in the UID are represented by the following pairs: Tunguskoe(Au)–Nalednyi(Ag), Khangalas(Au)–Kupol’noe(Ag), and Drazhnyi(Au)–Veshnee(Ag), and in the Southern Upper Yana district—by Nezhdaninskoe(Au)–Verkhnenemenkechenskoe(Ag) and at the ore lineament, which duplicates the main trend—by Lazurnyi(Au)–Elkhuga(Ag). In its southern part, the trend partially matches with the Suntar dextral shear zone (Korostelev, 1982), and in its northeast—with the tectonic fault traced by intrusive body rotation at the south contact of the Nel’kan massif, going along the isolated dike belt on left and right banks of the Nera River, along the orientation of the Khulamrin subalkaline granitoid formation and a series of subvolcanic bodies (Mark massif). Two subparallel ore lineaments are located to the north of the main trend, and one to the south. The northernmost lineament partially matches with the so-called Indigirka fault, which, according to (Berger, 1978), bounds the main ore zones of the Sarylakh deposit from southeast.

## DISCUSSION

Regular linear distribution of ore occurrences in structures of different scale levels was observed as early as an empirical evolution stage of geology. Planetary ore belts (Urals, Caucasus, Pacific, etc.) are considered as elements of the geological structure of fold systems (Volkov, 1986; Radkevich, 1987, Krivtsov and Ruchkin, 2002). Ore occurrences within the belts are concentrated in linear or isometric structures, i.e., ore districts (Tomson, 1988). Linear distribution or ore bodies in Kazakhstan allowed M.A. Favorskaya to derive the concept of ore-concentrating structures and emphasize the importance of tectonic ore-controlling factors. Pronounced belt-like distribution of ore bodies in the Transbaikalia region was used by A.D. Shcheglov (1980) to confirm the vision of the TMA areas as a special type of crustal structures. At present, the position and metallogenic specialization of planetary and regional ore belts is adequately explained from a geodynamic perspective by lithospheric plate tectonics (i.e. they are confined to zones, where tectonic plates with various crust types interact) (Kerrich et al., 2000).

Linear bodies distribution is also observed inside ore districts in the form of so-called ore belts of ore districts (Vol’fson, 1955), which is explained by the association of the deposits to specific faults. In foreign literature, ore belts of ore districts correspond to the “trends” characterized by spatially proximal occurrences of uniform mineral associations confined to the same fault zone. The Sierra Foothills trend includes linear zones of gold-quartz veins of the Moth-

er Lode and Grass Valley deposits. Commonly known gold ore trends are Carlin and Gatchell as well as Australian greenstone belts, and many others. Linear distribution peculiarities of ore occurrences are rather widely used for various theoretical generalizations and in applied prospecting. The Carlin trend identified on closely spaced gold bodies may be taken as an example of a successful forecast using spatial distribution analysis of ore bodies. Tracing the trend in course of prospecting works made it possible to discover hidden gold deposits within it (for example, the Meikle deposit) (Teal and Jackson, 1997; Konstantinov, 2006). Based on the distribution analysis of commercial gold ore bodies in the North and South Cordillera, Sillitoe (2008) identified 22 belts formed during compression or extension in magmatic arc or back-arc settings and recommended the exploration works to be carried out within these belts.

An unexpected result of the analysis performed was that nonuniform distribution of gold deposits in the Yana–Kolyma province appeared to be described by a relatively simple fault paleonetwork geometry. Comparing the geometry of the identified network of trends and ore-bearing lineaments with geological and tectonic schemes shows that orientations of ore-bearing lineaments are close to strikes of the known fault structures, summarized description of which is presented by S.G. Byalobzheskii et al. (Khanchuk, 2006). At the same time, the linear structures that we identified only partially match with major faults. The trends and ore lineaments are interpreted as fragments of major fault zones, which existed, when gold-bearing ores were formed. Distribution of gold ore clusters and empty intervals between them along the strikes of the fault structures probably matches with the distribution of extension and compression zones within the ore-hosting fault plane. Increasing the scale of analysis and utilizing additional geological and geochemical data may reveal the internal structure of these zones. Presumably, it could be similar to the structure of ore-hosting dislocation zones identified by V.M. Yanovskii (1990).

The identified trends and ore lineaments may be matched with groups of ore field structures formed at the late collisional and subduction (postcollisional) evolutionary stages of the territory, according to (Fridovskii, 2002), as well as specific structural groups (deformation phases), based on which A.I. Kalinin (1992) defined structural types of gold-quartz formation deposits.

The Ten’ka (I) and El’gi–Taryn (VI) trends can be matched with folded reverse faults and thrusts. It is possible that these trends corresponded to fault boundaries of individual thrust sheet within the Yana–Kolyma fold system. They gravitate towards the southwestern periphery of megadistricts and include the largest ore deposits (Pavlik, Natalka, Degdekan, Drazhnoe, and Sarylakh). The significant curvature of the trends, their general NW strike direction, as well as ore-hosting fault planes dipping in the NE direction at various angles make it possible to consider these trends as structures inheriting the position of the listric fault zone in the frontal (western) part of the YKFB.

Morphological features of the remaining NW strike trends and cluster-like distribution of ore occurrences on them do not contradict the assumption of the main stages of ore deposition on gold-bearing bodies being linked to sinistral shear displacements during the syncollisional interaction of the Kolyma–Omolon microcontinent with the North Asian (Siberian) cratonic margin, which is shared by the majority of researchers. The distribution of gold ore occurrences is seemingly affected by faults with dextral shear kinematics, which may be interpreted as preceding to the sinistral ones (Shakhtyrov, 2010) or synkinematic with them. The Nera (VIII) and Chai-Yur'ya (II) trends are associated with folded dextral shears, and the Mugurdakh–Selerikan (VIa), Detrin (IV), and Ol'chan–Delyankir (VII) trends—with sinistral shears.

We refined positions of the ore-controlling zones of NE orientation (transverse diagonal-slip fault zones subparallel to the main OCVB faults) with the sinistral shear component and found that in most cases they act as ore-confining zones, displace the earlier trends, and sometimes host commercial mineralization. These zones were formed at the postcollisional stage. Mineralization in transverse structures always occurred later than in the main trends. Dislocations in TMA mesozoides zones can be matched with the Suntar–Indigirka (V) and Pautovka (III) trends. The geodynamic position of

the NE-oriented ore trends (Fig. 5) is probably similar to the position of ore trends in the state of Nevada (Carlin and other). Development of these trends (Grauch et al., 2003) is associated with ancient basement structures transverse to the strike directions of the main thrusts and interfaces of blocks with different crust types. Transverse zones may be similar to the traces of ore-magmatic fluid migration zones in South Tien Shan (Savchuk and Mukhin, 1993).

No trends were identified that could be matched with plastic and terminal deformation phases (Kalinin, 1992) or early-collision structures (Fridovskii, 2002).

A similarity is observed between the local structural control and composition of mineralization in major deposits of the YKFS and gold-quartz occurrences in allochthon plate boundaries in accretionary prisms (active margins), such as Muruntau (linear regional thrust zones of South Tien Shan (Savchuk and Mukhin, 1993)), Bakyrchik (diagonal-slip faults of the West Kalba zone (Rafailovich, 2009)), Mother Lode (reverse faults and thrusts of the Sierra Foothill belt (California) (Sillitoe, 2008)). Equally clear is the similarity with gold-quartz deposits in the deformed passive margin deposits (para-autochthonous plates of foreland zones), for example, with Sukhoi Log and Olimpiada deposits (Yakubchuk et al., 2005). This similarity is linked both with the kinematics of fault system forming in transpressional zones

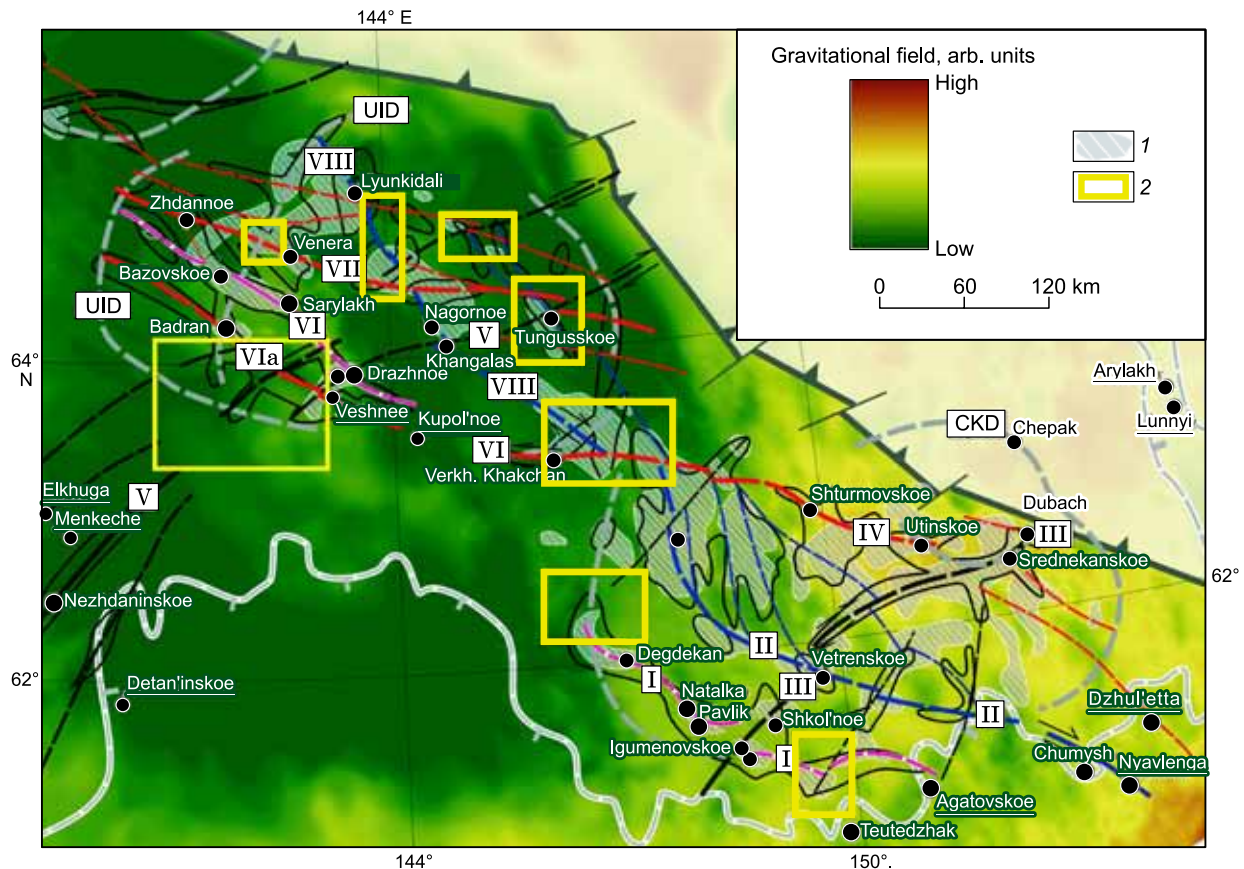


Fig. 5. Prospective areas identified in continuations or at intersections of ore lineaments and trends. 1, placer gold districts; 2, prospective areas. See the key in Fig. 2.

and with the influence of terrigenous complex geochemistry to the ore composition.

Comparison of the trend formation sequence with the established mineral deposition sequence and the data on compositions of ores and fluid inclusions in quartz (Aristov et al., 2015, 2017b), as well as the results of the analysis of geological structures of individual ore occurrences (Aristov, 2009; Aristov et al., 2017a) allow us to assume that folded thrusts and reverse faults concentrated fluid flows generated during metagenetic and metamorphic processes in the sedimentary deposits of the Upper Yana complex, while the later structures, such as folded shears and transverse zone shears, were responsible for ore-bearing fluid distribution. The ore-controlling faults formed during compression at the syncollisional evolutionary stage were partially rejuvenated at the postcollisional stage.

Extrapolation and interpolation of the obtained trends and megadistrict boundaries make it possible to forecast the discovery of large-scale gold ore occurrences in the interference area of UID and CKD, in the zone of interaction between the longitudinal Ol'chan–Delyankir and transverse Suntar–Indigirka trends, as well as in the understudied fault zone of the Suntar–Indigirka trend between the south Upper Yana and Upper Indigirka megadistricts (Fig. 5). Discovery of gold ore bodies in the interference area of the Upper Indigirka and Adychan megadistricts is less likely due to extensive granitoid magmatism.

Identification of ore lineaments and trends adds detail and enhances the traditional regional metallogenic zoning schemes, thereby reducing the prospecting areas. First-priority prospecting works may be aimed at studying the bodies located within the established ore trends and at their intersections. Ore lineaments are considered the second-priority objects.

## CONCLUSIONS

The close link between the orogenic gold ore bodies and paleofault structures makes it possible to reconstruct specific features of the structural plan in place during ore formation and come to some genetic and predictive conclusions.

1. Gold ore occurrences with low gold grade form extensive megadistricts, which have counterpart elements in geophysical fields. Genesis of these structures and their hierarchical relations with linear structures are not yet clear and require further study.

2. Ore bodies with high gold grade are concentrated in arched and linear trends, as well as in ore lineaments. Based on orientation and certain morphological features, the trends are divided into the ones conformal to the fold axis orientation and long-living faults, the crosscutting fold axes (NW), and the ones transverse to the strike direction of fold and fault axes (NE). The trends and ore lineaments of the Yana–Kolyma province have matching elements in late- and post-collisional structures. The NW-oriented trends and ore lin-

eaments are attributed to folded thrusts and reverse faults, as well as shears of various kinematic types. NE-oriented ore lineaments and trends were formed at the postcollisional stage in the transverse TMA zones subparallel to the strike direction of the Okhotsk–Chukotka volcanic belt.

3. All the identified structures act as ore-hosting and ore-concentrating structures. The earlier linear trends acted as fluid-feeding and fluid-concentrating structures for fluids generated at early stages of collision interaction between two continental blocks due to metagenetic and metamorphic processes in the sedimentary deposits. NW-oriented shear faults played the key role as ore-controlling structures at the early ore-formation stage. Generation of increased gold contents at the late stage is associated with NE-oriented faults and concentric structures.

4. The match between the trends, ore lineaments, and ore-hosting faults makes it possible to forecast location and approximate scale of new ore objects within the Yana–Kolyma province. Hosting formations and certain regional features of gold objects may be predicted based on the assumption of overlapping in time of the syncollisional geodynamic regime of interaction between the structures of the Siberian platform and the Kolyma–Omolon superterrane and the subduction geodynamic regime in the area of interaction between the Pacific (Okhotsk Sea) plate and the Siberian Platform.

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