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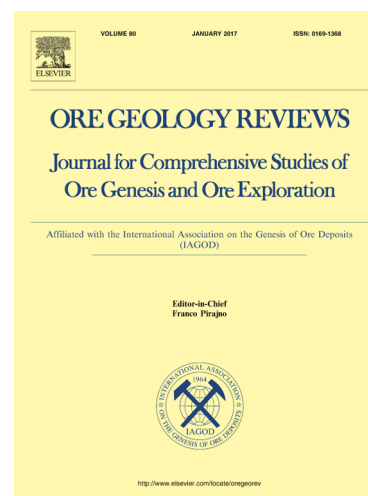
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**Structural control of orogenic gold deposits of the
Verkhoyansk-Kolyma folded region, northeast Russia**

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1. Introduction

The Verkhoyansk-Kolyma folded region (VKFR) is a province known for numerous gold deposits (Fig. 1). Commercial exploitation of the deposits started in the 30s of the 19th century. Since that time over 3370 tons of gold have been produced from the main mining districts known in the region including 200 t from Allakh-Yun, 170 t from Kular, and 3000 t from Yana-Kolyma (Goryachev, Pirajno, 2014). The bulk of the gold mined (91.6%) was recovered from placer deposits.

Formation of large gold deposits in the region was related to the Late Jurassic – Early Cretaceous orogenic events accompanied by deformation and metamorphism followed by the emplacement of granitoids (Parfenov, Kuzmin, 2001; Khanchuk, 2006; Goryachev, Pirajno, 2014). Orogenic geodynamic settings are among the most productive for the formation of large gold deposits (Kolar, Kalgoorlie, Bendigo, Ballarat, Sukhoi Log, Muruntau, Alaska-Juneau, Jamestown, Nataalka etc.) (Groves et al., 1998; Goldfarb et al., 1998, 2005, 2008). Orogenic gold deposits (OGD) are associated with collisional-accretionary tectonics and occur at the boundaries of or within large tectonic structures (Goldfarb et al., 1998, 2001, 2014). The latter are separated by faults which serve as pathways for ascending fluids and control spatial distribution of mineralization. This study aims at recognizing the relationship between the ore-controlling structures and tectonic development of the region and analyzing deformations of different age and the structure of gold deposits within VKFR.

2. Geology and metallogeny of the Verkhoyansk-Kolyma folded region

VKFR is located to the east of the Siberian platform. In the north it is separated from the Chukotka folded region by the South-Anyui suture (Sokolov et al., 2015). In the southeast and north it is overlain by the rocks of the post-accretionary Albian-Late Cretaceous Okhotsk-Chukotka volcanic belt. Several large tectonic units are recognized within VKFR: the Verkhoyansk fold-and-thrust belt, the Kular-Nera and the Polousny-Debin turbidite terranes, and the Kolyma-Omolon superterrane (microcontinent) (Parfenov, 1991; Parfenov, Kuzmin, 2001; Sokolov, 2010). The Verkhoyansk fold-and-thrust belt is situated on the submerged eastern margin of the North Asian craton, and is largely composed of the Ediacaran - Middle Paleozoic

carbonate and the Upper Paleozoic–Mesozoic terrigenous rocks. The Upper Carboniferous – Jurassic sediments constitute the Verkhoyansk terrigenous complex containing economically viable orogenic gold deposits. The structure of the belt is mainly controlled by thrusts and associated diagonal strike slips. Linear concentric folds are common all over the area of the belt (Gusev, 1979). Shear zones with associated similar folds are confined to long narrow areas (Fridovsky, 2002). Magmatic formations of different age are present in the South-Verkhoyansk sector of the Verkhoyansk fold-and-thrust belt (Bakharev, Zaitsev, 2001; Layer et al., 2001; Chernyshev et al., 2012). Formation of the early gabbro-diorite dikes and intrusions is related to the onset of the Late Jurassic subduction process in the Uda-Murgal arc, which is dated at 160 Ma based on the age of the early dislocation metamorphism (Prokopiev et al., 2009). Large granitoids from the central part of the South-Verkhoyansk sector were emplaced prior to the late dislocation metamorphism at 119 ± 0.5 Ma which marked the end of active volcanic and tectonic processes in the Uda-Murgal arc (Bakharev, Zaitsev., 2001; Prokopiev et.al, 2009; Chernyshev et al., 2012; Tretyakov, Prokopiev, 2014).

To the north-east of the Verkhoyansk fold-and-thrust belt lies the Kular-Nera (Kular-Ayan-Yuryakh) terrane (Parfenov, Kuzmin, 2001; Konstantinovskiy, 2007; Konstantinovskiy, and Lipchanskaya, 2011). These structures are separated by the major north-west trending Adycha-Taryn (Adycha-Ten'ka) fault. Recurrent movements have been recorded along the fault, initially of thrust and then of sinistral and dextral strike-slip kinematics. The Kular-Nera terrane is mainly composed of the Upper Permian, Triassic, and Lower Jurassic black shales that are metamorphosed at lower greenschist facies conditions. The Charky-Indigirka and the Chai-Yureya faults separate the Kular-Nera from the Polousny-Debin terrane that is predominantly composed of the Jurassic flyschoid turbidites (Konstantinovskiy, 2007). The terrigenous sediments are intruded by S- and I-type granitoids of the Main batholith belt formed in two successive stages – 149-153 Ma and 137-149 Ma (Akinin et al., 2009; Layer et al., 2001; Newberry et al., 2000; Goryachev, Pirajno, 2014). The Kular-Nera and the Polousny-Debin terranes form the boundary between the Kolyma-Omolon superterrane (microcontinent) and the submerged eastern margin of the North Asian craton (Parfenov, Kuzmin, 2001; Konstantinovskiy, 2007), where a large number of minable gold deposits of northeastern Russia (Natalka, Pavlik, Rodionovskoe, Drazhnoe, Bazovskoe, Badran, Malo-Tarynskoe, etc.) are located.

A complex deformation history has been proposed for the tectonic structures of VKFR (Parfenov, 1991; Parfenov, Kuzmin, 2001; Fridovsky, 2002; Sokolov, 2010). It is defined by the accretion of the Kolyma-Omolon superterrane to the eastern margin of the North Asian craton and subduction processes in the Uda-Murgal island arc which occurred almost synchronously in

Late Jurassic – Early Cretaceous times. These events led to the development of several generations of thrust faults, emplacement of granitoids of the Main and South-Verkhoyansk belts, and formation of Au, Sn and W mineralization.

Systematic studies of gold metallogeny in VKFR began in the late 50s (Matveenko, Shatalov, 1958; Rozhkov et al., 1971; Elovsky, 1972, Ivensen et al., 1975), and were later summarized in (Amuzinsky, 2005; Parfenov et al., 2000, Parfenov, Kuzmin, 2001; Fridovsky, 2000a, 2000b; 2002; Fridovsky, and Prokopiev, 2002; Gamyranin, 2001; Goryachev, 1998, 2003; Goryachev, Edwards, 1999; Nokleberg et al., 2005; and Nokleberg, 2010). The commercial gold deposits in VKFR are mainly of orogenic origin (Goryachev, Pirajno, 2014; Fridovsky, 2002; Voroshin et al., 2014). The deposits are hosted by the Upper Paleozoic and Lower Mesozoic terrigenous sediments metamorphosed at greenschist facies conditions. The deposits form several Late Jurassic–Neocomian metallogenic belts such as Allakh-Yun, Verkhoyansk, and Yana-Kolyma (Parfenov et al., 2000; Fridovsky, 2000a, 2000b, 2002; Parfenov, Kuzmin, 2001; Goryachev, Pirajno, 2014).

3. Types of gold deposits

First classifications of gold deposits of northeast Russia were proposed by Skornyakov (1949), Firsov (1957), and Konishchev (1953). They were mostly based on the ore mineral content and the relation of deposits to magmatic and metamorphic processes. These classifications were further developed by Ivensen and Levin (1975), who subdivided low-sulfide gold-quartz formation into deep-seated (fault-hosted) and syngranitoid subtypes.

Classifications of gold deposits of northeast Russia considering geodynamic environment of their formation have been proposed recently (Goryachev, 1998, 2003; Fridovsky, 2000; Fridovsky, Prokopiev, 2002).

Gold-quartz low-sulfide, gold–rare-metal, gold-silver, gold-antimony and gold-silver-polymetallic formations have been described from the Verkhoyansk-Kolyma orogenic region (Gamyranin, (2001). Goryachev (2006) and Goryachev and Gamyranin (2006) proposed to classify the orogenic gold deposits on the basis of their geological setting, style, age and relationship to orogenic granitoid assemblages. They recognize (1) disseminated sulfides with gold; 2) sediment-hosted and intrusion-hosted gold quartz veins, stockwork zones, and shear zones; and 3) intrusion-(granitoid)-related gold–bismuth lodes.

Taking into account tectonic setting, mineral composition of the ores, timing of formation, and relationship to orogenic granitoids, and considering the results of earlier

investigations (Goryachev, 1998, 2003; Fridovsky, 2000a, 2002) the author identifies three main types of orogenic gold deposits in VKFR:

- early orogenic gold-sulfide disseminated and gold-quartz in shear zones;
- late orogenic gold-quartz in fault zones;
- late orogenic intrusion (granitoid)-related gold-bismuth.

Characteristics of gold deposits in VKFR are given in Table 1.

The *early orogenic gold-sulfide-disseminated and gold-quartz deposits in shear zones* were formed during the early stages of the Oxfordian-Kimmeridgian collisional and accretionary events prior to the emplacement of large orogenic granitoid plutons. Intense linear fold and rupture deformations developed in the ore districts. The ore bodies are conformable to bedding. They form multi-level veins with accompanying cross-cutting apophyses, and are co-deformed into folds with the host rocks. The ores grade is up to hundreds of ppm Au. Gold is free, large-sized, and thus easy to extract. Gold reserves are a few tens of tons and the deposits are mostly concentrated in the foreland zone of the Verkhoyansk fold-and-thrust belt. This type of mineralization is characteristic of the South-Verkhoyansk synclinorium where dislocation and metamorphic processes were related to subduction processes at the Uda-Murgal arc. Gold mineralization occurs in the western part of the synclinorium in a zone up to 50 km wide and more than 300 km long (Yur-Brindakit and Onocholakh ore clusters), and is the source for gold placers that are almost mined out now. Structurally, the location of extensive stratified veins is controlled by shear zones (Fridovsky, 2000c). Rocks are metamorphosed under greenschist facies conditions (sericite-chlorite subfacies). Hydrothermal wallrock alteration (silicification, sericitization, sulphidization and carbonatization) is insignificant. The veins are dominated by quartz (95%) with lesser albite and carbonates. The amount of sulfides and gold does not exceed 1 vol%. Sulfides represented by arsenopyrite with lesser pyrite, galena, sphalerite, chalcopyrite. Fahlore is often present. Mineral associations are pyrite-arsenopyrite metasomatic, pyrite-arsenopyrite-ankerite-quartz (grey and dark-grey quartz) hydrothermal, gold-sphalerite-galena-quartz (milk-white quartz), and bournonite-boulangerite-carbonate. Formation of the early generations of quartz is associated with juvenile-metamorphic fluids, and that of the late generations with magma rising to higher crustal levels (Fridovsky, Gamyagin, Goryachev, 2006).

The largest deposits of northeast Russia (Nezhdaninskoe, Natalka, Drazhnoe, Bazovskoe, Malo-Tarynskoe, etc.) belong to the type of *late orogenic gold-quartz deposits in fault zones*. They form extensive metallogenic belts (Yana-Kolyma, Allakh-Yun), and are localized in the Upper Paleozoic – Lower Mesozoic terrigenous strata. They are associated with the Tithonian-Valanginian S- and I-type granitoids of ilmenite series (Goryachev, Pirajno, 2014). The deposits were formed after the intrusion of granitoids, and are usually found at a distance of

several kilometers away from plutons. Their location is controlled by high-amplitude extensive thrusts and less often by strike-slip faults separating blocks with different geologic structure and tectonic history. Frontal and oblique and frontal and lateral intersections between ramps: are interpreted as a key structural-tectonic factor controlling spatial distribution of gold mineralization (Fridovsky, 2010; Fridovsky et al., 2014, 2015). Structural-morphological types of the ore zones (vein, vein-veinlet, veinlet-disseminated, mineralized tectonite zones) occur in various combinations and proportions. Characteristic feature of the ore bodies is their constant mineral content: 85-95% quartz, 5-15% ankerite, and ~1% ore minerals. Pyrite-arsenopyrite-sericite-quartz metasomatic, pyrite-arsenopyrite-quartz hydrothermal, chalcopyrite-sphalerite-galena and sulfosalt-carbonate mineral associations are typical (Gamyarin, 2001).

The *late orogenic intrusion (granitoid)-related* gold deposits are hosted in dikes of various composition (granite-porphyry, porphyrite, diabase), directly in small granitoid stocks and hornfels from their aureoles. Characteristic mineral associations are quartz-muscovite-pyrrhotite-Co-Ni-sulfoarsenide and bismuth-sulfotelluride (Fridovsky, Gamyarin, Polufuntikova, 2014). Economically viable mineralization of this type is known from the Upper-Verkhoyansk gold-bearing district (Volkov, Egorov, Prokofiev et al., 2008).

The orogenic gold-quartz deposits are superimposed by post-accretionary Au-Sb, Ag-Pb-Zn, Ag-Sb and Ag-Au mineralizations related to subduction event in the Albian – Late Cretaceous Okhotsk-Chukotka volcanogenic belt. Close spatial association of different-aged gold mineralizations within a single repeatedly reactivated tectonic structure is a characteristic feature of large-scale deposits in the Kular-Nera terrane (Fridovsky, Gamyarin, Polufuntikova, 2014).

Structural characteristics of orogenic gold deposits of the Verkhoyansk-Kolyma folded region are discussed below.

3.1. Ore-controlling structures of the early orogenic gold-sulfide disseminated and shear zone-associated gold-quartz vein deposits

Structures of the early orogenic disseminated gold-sulfide mineralization and gold-quartz veins in shear zones are considered using the Yur-Brindakit ore cluster in the Allakh-Yun metallogenic zone as an example (Fridovsky, 2000c, 2002; Fridovsky, Prokopiev, 2002).

The *Yur-Brindakit ore cluster* is located in the southern part of the Allakh-Yun metallogenic zone, on the western side of the Minor-Kideriki fault (Fig.2). The fault is a major metallogenic structure controlling the location of different-aged the Nezhdaninskoe and the Zaderzhnoe deposits, and the Dyby ore field that are related to various geodynamic events. The

thickness and facies composition of the rocks change in the fault walls. The fault is clearly defined by local magnetic anomalies.

A distinctive feature of the Yur-Brindakit ore cluster is its changing structure along strike. Specifically, a series of symmetric and inclined linear folds of western and eastern vergence with steep slaty cleavage (Geroy, Duet, Dukat) can be seen in the Yur-Brindakit ore field. In the most northern Mar ore field symmetric fault-propagation folds with a steep eastern wall and a gentle western one are common. The axial surface of the folds is parallel to slaty cleavage and is gently dipping ($10-30^{\circ}$) to the west-northwest.

The sedimentary rocks of the Yur-Brindakit ore cluster are represented by the Upper Carboniferous – Lower Permian terrigenous strata composed of interlayered siltstones, sandstones, and mudstones (Fig.1). The ore bodies are conformable with the competent rocks and/or localized at the contacts of rocks of contrasting competence, forming several levels of gold-quartz veins. They are hosted by rhythmically alternating rock units with thicknesses of a few tens to a few hundreds of meters with a horizon of coarse-grained psammite-psephite rocks at the base overlain by siltstones and mudstones. The rocks are metamorphosed under greenschist facies conditions. They are characterized by quartz+albite+muscovite+chlorite mineral association, lepidogranoblastic structure and schistosity. According to Nemenman (1991) P-T metamorphic conditions are 2 - 4 kb and 150 - 250 °C.

In the Yur-Brindakit ore cluster the Yur, Duet, Fin, Brindakit, Nekur, Mar and others deposits are known as a source for gold placers that are almost mined out by now. The ore bodies consist of concordant veins up to 2 km long and up to 10 m thick (avg. 0.5-2.5 m) confined to sandstones or to their contacts with shales and siltstones. Sometimes concordant ore bodies associate with cross-cutting veins that are also ore-bearing. The grade is from a few ppm up to tens of hundreds ppm, with 10-30 ppm as an average grade. Hydrothermal wallrock alteration includes silicification, sericitization, sulphidization and carbonatization.

The main ore-controlling structures are shear zones associated with slaty cleavage, shear folds, mullion- and boudinage-structures, and transposition features (Fig. 3). The shear zones are listric-type, and represent branches of a detachment structure, which is assumed to be present at the base of the Verkhojansk fold-and-thrust belt. They have eastern vergence.

The Yur deposit is confined to a gentle monocline complicated by small (amplitude up to 100 m) folds which define the shape of the ore bodies (Fig. 4). The host rocks are the Upper Carboniferous sandstones and siltstones of the upper unit of the Surkechen Formation. The ore bodies occur at the base of a sandstone sequence up to 1-20 m thick. They are banded-structured at the contacts and massive in their axial parts. Thickness of the ore bodies is 0.5-5 m. Intensity of folding increases near the shear zones, where tight and isoclinal folds have developed.

The Nekur deposit is located at the intersection of a sandstone layer at the base of the Upper Carboniferous Surkechen Formation and a longitudinal shear zone steeply dipping to the west (Fig. 5). Gold mineralization is represented by stratabound veins with accompanying cross-cutting veinlets (stratabound-stockwork type) (Fig. 5, B). The shear zone is up to 300 m wide, and is associated with tight and isoclinal similar folds, boudinage and mullion-structures (Fig. 5, C, D, E). The intensity of deformations and gold content decrease in the directions away from the shear zone. The contacts of the ore bodies with the host rocks are composed of banded grey quartz while their central parts are made up of massive and brecciated milk-white quartz. The best values of gold occur in the banded margins of the veins and in silt-clay intercalations within them. Thickness of the ore bodies is up to 5-6 m. The veins and the shear zone exhibit arsenopyrite haloes.

The Mar deposit is hosted by mudstones and siltstones intercalated with calcareous and silty sandstones of the Upper Carboniferous Natali Formation (Fig. 6). The host rocks contain disseminated pyrite (up to 1-3 vol%). The prevailing low-angle ($20-25^{\circ}$) eastern dip of the rocks is complicated by steep (up to 75°) overturned bedding. A characteristic structural feature is slaty cleavage gently dipping ($15-25^{\circ}$) to the west and northwest, which becomes steeper in the tectonized zones (Fig. 6, B, C). Folds with increased rock thicknesses in the crests are common. Hinges b1 and lineation of intersection of bedding and cleavage L_{ox1} are gently (20°) inclined to the southwest, and axial surfaces of the folds are parallel to cleavage (dip az. $270-290 \angle 30-40^{\circ}$). Mullion-structures are developed in interlayered sandstones and siltstones (Fig. 6, D). Overturned bedding is widely manifested, as indicated by the relationship between cleavage and bedding.

Besides concordant ore bodies, vein, vein-veinlet, and veinlet-disseminated types of mineralization are present. They are controlled by shear zones up to a few tens of meters wide and no less than 350 m long. Gold content in the zones vary from 5 to 15 ppm (Fridovsky, Polufuntikova, 2011; Okunev, Fridovsky, 2012).

A vertical zonation pattern is observed for the deposits of the Yur-Brindakit ore cluster, and is correlated with the distance to the detachment (Tabl. 2) (Fridovsky, 2002; Fridovsky, Polufuntikova, 2008). Changes in the dip angle of the shear zones (as indicated mainly by cleavage), structural paragenesis, the degree of microdeformation of the host rocks, and the type of ore-controlling structures can be clearly observed in the direction away from the detachment. Structural zoning is evidenced, among other things, by changing morphologic types of microstructures and by strain-indicators of the degree of rock metamorphism. Four morphologic types of microstructures are identified in the Yur-Brindakit ore cluster (Fig. 7) (Fridovsky, Polufuntikova, 2007). The first platy-shear type is characterized by aggregate cleavage and the

coefficient of deformation (Cd) of single grains from 1.0 to 2.0 (Fig. 7, A). Irregular angular fragments of variously oriented grains can be observed in thin sections. The second shear-cataclastic morphologic type (Cd from 2.0 to 3.0) exhibits combined aggregate and intergranular cleavage (Fig. 7, B). The third cataclastic-segregation morphologic type (Cd from 3.0 to 4.5) is distinguished by a wide distribution of lentelliptical grains of rock-forming minerals in a finely-crystalline matrix and by intergranular cleavage (Fig. 7, C). The rocks of the fourth segregation-striate morphologic type (Cd >5.0) contain lenticular segregations of quartz and feldspar in an intensely linearized mylonite groundmass (Fig. 7, D).

The observed structural zoning defines the morphology of ore bodies: vein-veinlet and veinlet-disseminated types of mineralization (Mar occurrence) change into stratabound stockworks (Nekur deposit), and then into concordant ore bodies (Yur deposit) (Tabl. 2) (Fridovsky, Polufuntikova, 2009).

The early orogenic gold-sulfide-disseminated and shear zone-associated gold-quartz deposits are also found in the Verkhoyansk metallogenic belt (Dyandinskoe) and on the northwestern side of the Yana-Kolyma metallogenic belt (Emelyanovskoe, Emisskoe, and Kyllakhscoe). Gold prospects are known in the Allakh-Yun metallogenic zone (Zorinsk, Zvezdochka, Allakh, Kenne-Burkhala, Simbirsk, Khokhsolakh, Erykchan, Setaninskoe) (Fridovsky, 2000, a; Okunev, Fridovsky, 2012).

3.2. Structures of the late orogenic fault-controlled gold-quartz deposits

The late orogenic gold-quartz deposits in fault zones are considered as an example of the Yana-Kolyma belt. The largest deposits (Natalka, Pavlik, Rodionovskoe, Drazhnoe, Bazovskoe, Malo-Tarynskoe etc.) occur in the Kular-Nera (Kular-Ayan-Yuryakh) terrane and adjacent areas. Spatial distribution of the deposits is largely controlled by the Adycha-Taryn (Adycha-Ten'ka) and the Chai-Yureya faults. In the central part of the Kular-Nera terrane, deposits are localized within the Mugurdakh-Selirikan, Adycha Taryn and Olchan-Nera tectonic zones (Fig. 8).

The Badran deposit is confined to the 34 m thick Nadvigovaya thrust fault within the Mugurdakh-Selirikan tectonic zone (Fig. 9) (Goryachev and Fridovsky, 2013). The host rocks are the Upper Triassic terrigenous sediments. The thrust fault zone is characterized by varying strike and dip. Its northern and southeastern segments have NS strike and high dip angles up to 50-60°, while the central part dips gently (24-30°) to the northeast (dip az. 40-65°). Ore mineral content of the Badran deposit is discussed in (Anisimova, 1993; Amuzinsky, Anisimova, Balandin, 1998; Amuzinsky, 2005). The veins consist mainly of quartz, calcite, and dolomite. Ore minerals include pyrite, goethite, arsenopyrite, galena, sphalerite, and tetrahedrite with

admixtures of chalcopyrite, antimonite, bournotite, and native gold (>1%). Gold is lumpy and interstitial, with fineness varying from 689‰ to 1000‰. The estimated gold reserves are 10.8 t with the average grade of 13.8 ppm Au, probable reserves are 89.9 tones with average grade of 7.9 ppm Au (Gold deposits of Russia, 2010).

Three morphologic types of the ore bodies are recognized here: vein, vein-veinlet, and veinlet-disseminated (Fig. 10). The main type includes plate-like quartz veins up to 4.2 m thick and up to 200 m long (Fig. 10, A), which occur in mineralized tectonized zones. They are accompanied by thin quartz veinlets most abundant in places where the veins pinch out (vein-veinlet type) (Fig. 10, B). The third-type quartz veinlets and pyrite and arsenopyrite disseminations are localized in mylonite zones (Fig. 10, C). Orientation parameters (strike and dip) of the veinlet-type ore bodies allow restoring the kinematics of the ore-controlling faults (Fig. 10, B). Specifically, thrust motions were established for the central part of the deposit.

Stress analysis performed for Nadvigovaya fault zone shows paleostress orientation along the fault (Fridovsky, 1999). In the central part of the fault zone axes of main compressive stress are sub-horizontal to moderately plunging to the southwest. Axes of the main tensile stresses are sub-vertical or inclined at angles of 65 to 70° to the northeast or southwest. In the fault walls orientation of the axes of compressive stresses remains unchanged, while axes of tensile stresses are sub-horizontal or gently inclined at angles of 20 to 28°. Thrust motions are established for the central part of the fault changing to left-lateral strike slips with some reverse faulting on the sides.

Folds of two generations are identified here (Fridovsky, 2002). The early concentric northwest-trending folds F1 are widely developed in the walls of the Nadvigovaya thrust fault. In the allochthon there is an overturned open fold with hinge b1 inclined to the southeast at 50° (dip az. 120°) (Fig. 11, A). That steep dip angle of the hinge might be due to the superimposed strike slip deformations. Cleavage of two types is developed – bedding cleavage in the siltstone units and transverse cleavage in the fold crest. Folds with hinges inclined at 30° to the northeast (Fig. 11, B) are superimposed on the first generation folds F1. Away from the Nadvigovaya thrust fault, motion occurs as bedding-plane slip (Fig. 11, C).

The Bazovskoe deposit is hosted by the Upper Triassic terrigenous sediments in the northwestern part of the Adycha-Taryn tectonic zone (Fig. 12). The amount of sandy siltstones and siltstones increases up section. Thickness of the sandstone layers is up to 80 m, and that of siltstones is 20-40 m. Magmatic formations include rare west-east-striking dikes of the Late Jurassic dioritic porphyrite. The ore bodies consist of northwest-striking mineralized tectonized zones (East, Central, Middle, West), which were traced over a distance up to 6.5 km during geological exploration. The intensely folded mineralized zones with thicknesses up to few tens

of meters consist of mylonites and tectonic breccias with quartz veins and veinlets. There are several systems of sheeted quartz veins oriented parallel to the ore-controlling zones and sandstone layers (Fig. 13). Veins of the first system Q^1_1 are concordant with the host rocks and tectonized zones, and have invariable parameters. Quartz veins of system Q^2_1 dip to the west and southwest at different angles. They are non-persistent in thickness, contain rock crystal druses, pinch out rapidly in the direction away from veins Q^1_1 , and fill individual segments of en-echelon tension fissures. Veins of system Q^3_1 are conformable with σ_1/σ_3 and transverse to the ore-controlling faults and sandstone layers.

Branching of the ore zones and alternation of swells and pinches are typical. Mineralization belongs to the low-sulfide gold-quartz formation. The ore mineral content is dominated by arsenopyrite and pyrite, with lesser galena, sphalerite, chalcopyrite, fahlores and native gold. Probable resources of gold are 110 tons with average grade of 13 ppm Au (Konstantinov, 2010).

The main rupture dislocations in the deposit area have northwest strike conformable to that of the regional-scale Adycha-Taryn (Adycha-Ten'ka) fault, which is represented here by the NW-striking Diagonalny fault and numerous sub-parallel mineralized tectonized zones (West, Central, East). They are associated with veins, veinlets, lenses, and nests of quartz-carbonate composition, which are localized in sandstones and interlayered sandstones and siltstones. The mineralized zones are confined to the contacts of rocks of different composition (sandstones and siltstones), and dip at 30-60° to the northeast (Fridovsky, 2010). The thrusts are associated with concentric-type linear folds F1 with prevailing northwest strike and south-western vergence (Fig. 14, A, B). Open folds predominate, with less important tight folds. Overturned folds are mapped in the zones where the influence of the faults is strongly manifested. The sandstone layers show boudinage.

The superimposed deformations are represented by strike slips which probably were reactivated along earlier thrusts, and by cross folds of NE and WE strike (Fig. 14, C, D). Late conical and cylindrical folds F with gentle and steep hinges b inclined to the northeast and east are typical. The folds are symmetric, rarely asymmetric, up to several meters in width and amplitude.

The Malo-Tarynskoe deposit is located in the southeast of the Adycha-Taryn tectonic zone, at the border between the hinterland zone of the Verkhoyansk fold-and-thrust belt and the Kular-Nera terrane (Fig. 15). That specific tectonic setting caused recurrent reactivation of tectonic and magmatic processes there and the formation of different-aged deposits often spatially associated within long-lived tectonic zones (Fridovsky et al., 2015). Malo-Tarynskoe deposit is confined to the south-western limb of the Malo-Taryn syncline, and is mainly

composed of the Upper Triassic and Lower Jurassic siltstones and sandy siltstones with lesser mudstones and sandstones. The age of mineralization is 130 ± 4 Ma (K-Ar dating) (Akimov et al., 2004; Akimov, 2004).

Several types of mineralization are recognized here: 1- metamorphogenic quartz-chlorite-carbonate; 2 – gold-bismuth; 3 – the main commercial low-sulfide gold-quartz; 4 – berthierite-antimonite; and 5 – epithermal silver-antimony (Fridovsky et al., 2015). The earliest is the metamorphic-hydrothermal mineralization represented by rare quartz-chlorite-carbonate (ankerite, calcite) veins scattered over the area. The Ar-Ar age of sericite from the veins is 142.7 ± 1.4 Ma (Fridovsky et al., 2015). Thickness of individual veins does not exceed 15-20 cm. Gold-bismuth mineralization consists of thin (2-4 cm) branching sub-vertical veinlets hosted in sandstones. Mineral associations are quartz-muscovite-pyrrhotite-Co-Ni-sulphoarsenide and bismuth-sulphotelluride (Fridovsky et al., 2015). The deposit is similar to the well known Ergelyakh gold-bismuth deposit for which K-Ar age of 114-125 Ma was determined on the wallrock sericite (Gamyagin et al., 2003). Mineral composition of the gold-quartz low-sulfide mineralization is: 89-95% quartz, 5-15% carbonate (ankerite), and ~ 1-2% ore minerals. Mineral associations are pyrite-arsenopyrite-quartz metasomatic, pyrite-arsenopyrite-quartz hydrothermal, gold-chalcopyrite-sphalerite-galena, and sulphosalt-carbonate. Berthierite-antimonite mineralization occurs in quartz veins and veinlets. It is superimposed on the quartz-gold low-sulfide mineralization, which caused intensive corrosion of the early milk-white quartz and sulfides in the veins and metasomatites. Silver-antimony mineralization has wide areal extent not only in Malo-Tarynskoe deposit but along the whole of the Adycha-Taryn fault zone. Epithermal mineralization is represented by veins and veinlets of spherulite and cryptogained or colloform-reniform quartz with poor sulfide dissemination.

The Malo-Taryn branch of the Adycha-Taryn fault is the major tectonic structure of Malo-Tarynskoe deposit. It represents a set of faults and fractured zones of prevailing north-west, less often west-east and north-south strike (Fig. 16, A). Mineralized tectonized zones, stockwork-like zones, and lenticular ore bodies are typical here. The crush zones have NS to NW strike (Fig. 16, A). The manifested structural paragenesis is associated with the early thrust and reverse fault deformations (D1) of the Late Jurassic – Early Cretaceous accretionary stage of the region development. Slickenlines parallel to the rock dip are observed on S0 surfaces. Ramps and sandstone boudins often found in siltstones. Symmetric, asymmetric and overturned cylindrical folds F1 with sub-horizontal hinges of north-northwest orientation are common (Fig. 16, A). Fracture cleavage of the axial surface is clearly defined. Cleavage is most intensely manifested in the siltstones and is fading out in coarser-grained varieties. In the fault zones, the cleavage is deformed into folds F2 generally conformal to folds F1 (Fig. 16, A).

Statistical analysis of the orientation (strike and dip) of quartz veins and veinlets at the Malo-Tarynskoe deposit shows that their formation is closely associated with motions on the bedding-plane and cross thrust faults (Fig. 16, A). As can be seen, the veins and veinlets form systems that are regularly oriented relative to the faults. One group of systems is normal to S_0 and the ore-controlling fault S, irrespective of strike. Another group extends, in general, parallel to S_0 and S, but the veins and veinlets dip to the east and west at different angles. The orientation of the same system of veins may differ in different parts of the ore field, but their relation to the ore-controlling deformational structures remains unchanged.

The deformations that are superimposed on the gold-quartz mineralization are strike slips and are reactivations of the early thrusts (Fig.16, B). The sinistral strike-slip motions along the ore-controlling faults favoured gold-antimonite mineralization, which is most widely developed along the axial part of the Adycha-Taryn fault (Fridovsky et al., 2014) (Fig. 8). The strike slip motions are associated with NE-trending folds of various morphology, from open symmetric folds to tight overturned ones . These folds normally occur near the faults and rapidly fade out away from the ore zones (Fig.16, B). Their hinges dip at 20° to 80° . The analysis of the local stress field of the gold–antimony phase showed that the axis of maximum compression σ_1 dips south-west at an angle of 34° , the axis of minimum compressive stress σ_3 plunges to the southeast (bearing 146, dip 26), and the position of the intermediate axis σ_2 coincides with the hinge of syn-fault fold F (bearing 60, dip 40) (Fig.16, B).

3.3. Structures of the late orogenic intrusion (granitoid)-related gold deposits

Late orogenic intrusion (granitoid)-related small-size deposits are widespread in VKFR (Gamyandin et al., 2003; Volkov et al., 2008; Goryachev, Pirajno, 2014; Parfenov, Kuzmin, 2001). They are localized in dikes, small granitoid stocks and their hornfels aureoles (Levo-Dybinskoye, Ergelyak, Novoe, Solur, Chistoye, and Malysh-Dubach deposits).

The Levo-Dybinskoye deposit is located in the north of the Allakh-Yun belt, northward of the Nezhdaninskoe gold deposit. Thin quartz veins and veinlets are hosted by the granitoids of the Dyby massif and the Upper Permian hornfelsed sandstones on the limbs of a dome-shaped fold (Fig. 17). Mineral associations of the deposit are quartz-feldspar-muscovite, sulfide arsenide and bismuth-sulfotelluride (Gamyandin, 1993). Gold fineness ranges widely from 672‰ to 969‰. Early Fe-Co-Ni arsenides, diarsenides, and a complex of bismuth minerals comprising bismuthine, various bismuth sulfotellurides, native bismuth and fine gold are present. The Ar-Ar age of the mineralization is 124.8 Ma (Borisenko et al., 2012).

The ore bodies consist of typical ladder veins confined to sandstone strata. The veins pinch out at the contacts of sandstones and siltstones, slightly penetrating into the latter. Thickness of the veins varies from a few millimeters to 0.2-0.3 m. Along with the ladder veins quartz-rich sandstone layers and quartz veinlet zones form stratabound stockworks. The veins normally have northeast strike and dip steeply. Rare concordant veins tend to occur at the contacts of sandstones and siltstones.

In course of the Late Jurassic orogenic events, a NS-trending linear fold F1 was developed along with the axial surface cleavage and NE-striking faults. At the time of emplacement of the Dyby stock, a dome-shaped fold F2 was formed. It has an elliptical form in plan, with the long axis oriented to the northwest-southeast conformably to the strike of the Dyby stock crest. The fold is round in cross-section, shows no cleavage, and is fading out in the direction away from the stock. Noteworthy is the reduced thickness of the rocks in the core of the fold as compared to that on the limbs where deformations of the regional cleavage are developed.

4. Discussion

The performed investigations revealed close relation between the ore-controlling structures of gold deposits and the tectonic evolution of VKFR. The deformation structure of the region evolved in association with several tectonic events that took place along the eastern margin of the North Asian craton (Parfenov, 1991; Parfenov, Kuzmin, 2001; Fridovsky, 2000, a; Fridovsky, 2002; Goryachev, Pirajno, 2014; Sokolov, 2010). These events were different in different parts of the region.

In the northeastern part of VKFR, formation of precious metal deposits (Verkhoyansk and Yana-Kolyma metallogenic belts) was related to the Late Jurassic-Early Cretaceous accretion of the Kolyma-Omolon superterrane to the eastern margin of the North Asian craton (Parfenov, Kuzmin, 2001). The accretion was frontal at the early stages. It was accompanied by faulting and folding, stage-by-stage structural-metamorphic transformation of the Late Paleozoic and Early Mesozoic sedimentary rocks, and the formation of productive ore-forming systems. The fold and fault structures are intruded by granitoids of the Main batholith belt aged at 153-137 Ma (Akinin et al., 2009; Layer et al., 2001; Newberry et al., 2000; Goryachev, Pirajno, 2014). In the Verkhoyansk and Yana-Kolyma metallogenic belts, most commercially important are the late orogenic fault-controlled deposits of gold-quartz type. According to Ar-Ar data, they were formed in the period from 148 Ma (Ryzhyi deposit) to 125 Ma (Vetrenskoye deposit) (Voroshin et al., 2004; Newberry et al., 2000) and therefore are younger than orogenic

granitoids. Gold deposits with the age of 140-130 Ma prevail in the area (Goryachev, Pirajno, 2014).

The main ore-controlling structures are thrust faults forming imbricate fan systems. Frontal and oblique ramps and systems of bedding and cross thrusts forming duplexes are common. It is notable that mineralized tectonized zones commonly develop along thrusts at the contacts of rocks of contrasting competence. The thrusts are associated with linear concentric northwest-trending and southwest-verging folds forming zones of intense folding up to a few hundred meters thick. Within the Olchan-Nera tectonic zone, the folds are superimposed on the earlier fold and thrust deformations (D1) (Fridovsky et al., 2003; Prokopiev, and Tronin, 2004).

The superimposed structures are recognized from the early cleavage deformations. Folds F3 are often chevron type, open or tight, with hinges b3 dipping to the northwest. They are most common in the fault zones and thought to be associated with thrusts that developed along the pre-existing structures.

In the Late-Neocomian-Aptian, the Kolyma-Omolon superterrane started moving to the west (Parfenov, Kuzmin, 2001). As a result, sinistral strike-slip motions were accommodated along the Adycha-Taryn fault as reactivations of the earlier thrust faults. At that time, granitoids of the North and Transverse belts were emplaced in the northwestern Kolyma-Omolon superterrane (Parfenov, Kuzmin, 2001), and sub-volcanic granite porphyries were formed in the Upper Indigirka tectonic zone (Bortnikov et al., 2010). The strike slips were associated with cross open folds.

In the Yana-Kolyma metallogenic belt, the orogenic gold deposits are superimposed by Sb mineralization most widely manifested along the axial part of the Adycha-Taryn fault (Sarylakh, Sentachan) (Bortnikov et al., 2010). The deposits are controlled by left-lateral strike-slip faults (Fridovsky et al., 2014). Gold-quartz and Sb deposits occur both separately and in combination within the multiply reactivated fault zones. Northeast-trending folds of different morphology – from open symmetric to tight overturned ones are typical. Cleavage is conformable with the axial surfaces of the folds.

In the South Verkhoyanye area (Allakh-Yun metallogenic zone), the early deformations were related to subduction processes in the Uda-Murgal island arc and accretion of the Okhotsk terrane to the eastern margin of the North Asian craton. Fig. 18 shows a model for the formation of orogenic and post-orogenic deposits implying the South Verkhoyanye area as an example. According to Ar-Ar data, accretionary events and the synchronous early dislocation magmatism occurred at 160 Ma (Prokopiev et al., 2009). The early orogenic gold-sulfide disseminated deposits and gold-quartz deposits in shear zones show similar age (155 Ma, Rb-Sr) (Zaitsev, Nenashev, 1999). It is supposed that frontal accretion of the Okhotsk terrane in W-N-W direction

was accompanied by the development of plastic deformations, similar folds F1, a linear band of zonal metamorphism, thermal anomaly, palaeogenetic granite chambers, and generation of metamorphic-hydrothermal fluids and their ascending to ore-deposition zones (Fig. 18, A). It should be noted that terrigenous rocks of the Verkhoyansk passive continental margin are rich in gold and arsenic, which is favorable for mobilization of these elements during metamorphism (Kokin, Silichev, 1987; Kokin et al., 1999; Polufuntikova, Fridovsky, 2015). The regional background of Au in the South Verkhoyansk synclinorium is 7.2 ppb for siltstones and 6.0 ppb for sandstones. The productive Upper Carboniferous deposits are characterized by higher gold content, that is 10.0 ppb for sandstones and 12.2 ppb for siltstones.

Shear zones with thrust motions along them served as pathways for ascending fluids and the host structures for the early gold-sulfide-disseminated and gold-quartz vein deposits. In the South Verkhoyane area and in Kular district, the shear zones form systems of listric-type imbricate fans which join the detachment of the Verkhoyansk fold-and-thrust belt (Fridovsky, 2000, a). In the West Verkhoyane area, the early orogenic gold deposits known from the Kharaulakh, Orulgan, Kuranakh and Baraya anticlinoria are controlled by culminations of blind autochthonous roof duplexes of the carbonate complex (Prokopiev, 1998; Prokopiev et al., 2001). Formation of the early orogenic veins and first metamorphic alterations of the rocks occurred before the emplacement of S-granitoids (Uemlyakh, Tarbagannakh). This is evidenced from superposition of the contact-metamorphic mineral assemblages on the veins and regionally metamorphosed rocks and by the age of granitoids (Bakharev, Zaitsev, 2001; Layer et al., 2001; Prokopiev et al., 2009). The question of the source for the formation of gold deposits in Allakh-Yun metallogenic zone is still open to discussion. Some authors believe that the ore-forming solutions are metamorphogenic, others propose they are juvenile, while the third group of researchers suggests they have combined metamorphic-magmatic origin (Andriyanov, 1973; Buryak et al., 1990; Gamyarin, 2001; Zaitsev, Nenashev, 1999; Konstantinov, Kosovets, 1996; Mirzekhanov, Mirzekhanova, 1991). However, metamorphic-hydrothermal origin of the ore-forming fluids is more widely accepted.

The following Aptian stage of accretion in the South Verkhoyane area resulted in the late dislocation metamorphism dated by the Ar-Ar method at 119.4 Ma (Prokopiev et al., 2009), final phases of the emplacement of the granitoid plutons, and intrusion of lamprophyre dikes (Bakharev, Zaitsev, 2001; Chernyshev et al., 2012) (Fig. 16, B). Close ages were obtained for large plutons from the central part of the South Verkhoyane area: 123 Ma (U-Pb, Prokopiev et al., 2009) for the Tarbagannakh pluton and 129 Ma (Ar-Ar, Layer et al., 2001) for the Uemlyakh one. At that time, late orogenic fault-hosted gold-quartz deposits were formed away from the plutons, e.g., Nezhdaninskoe and Zaderzhnoe deposits dated at 120 Ma (Chugaev, et al., 2010;

Chernyshev et al., 2012) and 123.5 Ma (Kondratieva et al., 2010), respectively. The late orogenic intrusion (granitoid)-related deposits (e.g., Levo-Dybinskoye) were formed in the vicinity of plutons in close association with dynamic processes affecting the host rocks.

At that time, the geodynamic environment was characterized by a change in the direction of subduction in the Uda-Murgal arc from WNW to N, which caused reactivation of the early thrusts with strike-slip motions accommodated along them (Parfenov, Kuzmin, 2001; Fridovsky, 2002). The most intense strike-slip motions were accommodated on a series of NE-striking faults in the northern part of the South Verkhoyanye area. The strike-slip models for the structure of gold deposits can plausibly explain specific localization of mineralization in the region (Fridovsky, 2002; Tretyakov, Prokopiev, 2014).

The post-orogenic stage is associated with the development of the Albian-Late Cretaceous Okhotsk-Chukotka subduction zone (Fig. 18, C). This time was marked by Upper Cretaceous magmatism aged at 106-92 Ma (Ar-Ar, Layer et al., 2001). Within this range are IDTIMS U-Pb dates obtained for the Kurum massif (91 Ma) and Rb-Sr age determinations for the Geldy stocks (92 Ma) (Chernyshev et al., 2011). At the post-orogenic stage, Au-Sb, Ag-Pb-Zn, Ag-Sb and Ag-Au deposits were formed either individually or in spatial association with the late orogenic fault-controlled gold-quartz deposits.

5. Conclusions

In VKFR, deformation structures hosting mesothermal orogenic gold deposits were formed in association with the Late Jurassic-Barremian frontal accretion prior to transpressional deformation between the Pacific oceanic plates and the margin of the North Asian craton. The accretionary events were different in different parts of VKFR. In the Allakh-Yun metallogenic zone this was the accretion of the Okhotsk terrane to the eastern margin of the North Asian craton, and in the Verkhoyansk and Yana-Kolyma metallogenic belts the accretion of the Kolyma-Omolon superterrane to the same craton. These events were nearly synchronous.

The main tectonic structures controlling the location of deposits in VKFR are extensive thrust faults. The early orogenic gold-sulfide-disseminated and gold-quartz deposits are hosted by shear zones forming systems of listric-type imbricate fans closely associated with the detachment of the Verkhoyansk fold-and-thrust belt. The late orogenic fault-hosted gold-quartz deposits are controlled by intersections of thrusts with lateral and oblique ramps and by the related folds. Cross-cutting faults divide the ore-controlling faults into segments with different structure. Formation of the ore-controlling structures of the late orogenic intrusion (granitoid)-related gold deposits is associated with the dynamic effect of intruding magma on the host rocks.

The ore-controlling structures of the Verkhoyansk-Kolyma folded region are characterized by long-lasting formation, recurrent reactivation, superposition of different-aged metamorphic-hydrothermal processes and, in consequence, frequently observed spatial association of orogenic and post-orogenic mineralization of varying composition within them.

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Fig.1. Tectonic structures and metallogenic belts of the Verkhoyansk-Kolyma folded region and adjacent areas (modified after Parfenov et al., 2003; Goryachev, 2006; Goryachev, Pirajno, 2014; Fridovsky, 2000a).

VR – Verkhoyansk deformed passive continental margin; Mesozoic orogenic belts – VK-Verkhoyansk-Kolyma, SA – South Anyui, CH – Chukotka; Cratonic terranes: OH – Okhotsk, OM – Omolon. Orogenic gold deposits: 1-13 – Allakh-Yun metallogenic belt: 1 – Yur, 2 – Nekur, 3 – Mar, 4 – Zorinskoe, 5 – Zvezdochka, 6 – Allakhscoe, 7 – Kenninskoe, 8 – Simbirskoe, 9 – Khokhsolakhskoe, 10 – Setaninskoe, 11 – Levo-Dybinskoe, 12 – Nezhdaninskoe, 13 – Zaderzhnoe; Verkhoyansk metallogenic belt: 14 – Dyandinskoe; Yana-Kolyma metallogenic belt: 15 – Emelyanovskoe, 16 – Emisskoe 17 – Kyllakhskoe, 18 – Bazovskoe, 19- Badran, 20 – Drazhnoe, 21 – Malo-Tarynskoe, 22 – Khangalasskoe, 23 – Tin-Yuryuete, 24 – Natalka, 25 – Pavlik, 26 – Rodionovskoe.

Fig.2. (A) Yur-Brindakit ore field, (B) stratigraphic column for Permian and Carboniferous clastic sediments.

Fig.3. Deformation types of shear zones: (A, B) mullion-structures; (C) shear folds; (D) transposition structures.

Fig.4. (A) Yur deposit, (B) local cross sections.

Fig.5. (A) Nekur deposit, (B) local cross sections, (E) field photos showing position of ladder veins in a Carboniferous sandstone layer. Hereafter all elements are plotted on the Wulff upper hemisphere projection.

Fig.6. (A) Mar deposit (Fridovsky, Polufuntikova, 2011). (B) slaty clivage Lower Permian diamictites; (C) oriented structure of cleaved Upper Carboniferous siltstones, (D) mullion-structures.

Fig.7. Morphologic types of microstructures (Fridovsky, Polufuntikova, 2007). (A) platy-shear; (B) shear-cataclastic; (C) cataclastic-segregation; (D) segregation-striate.

Fig.8. Regional position of gold and gold-antimony deposits in the central part of the Kular-Nera terrane and adjacent areas.

Faults: CH-I – Charky-Indigirka, CH – Chay-Yureya, AT – Adycha-Taryn.

Fig.9. Badran gold deposit (Fridovsky, 2002).

Fig.10. Morphologic types of ore bodies at Badran deposit: (A) vein, (B) vein-veinlet, (C) veinlet-disseminated.

Fig.11. Deformation structures of Badran deposit: (A) early NW-striking folds F1, (B) late NE-striking folds, (C) ramps.

Fig.12. Ore zones of Bazovskoe deposit. Schematic block models for: (A) relationship between ore zones and gold-quartz veins and kinematics of their formation; (B) ore-controlling thrust structures.

Fig.13. (A) Quartz veins in fault zones, Bazovskoe deposit; (B) sheeted quartz vein, (C) ladder-type quartz veinlets in Triassic sandstones.

Fig.14. Different-aged fold deformations, Bazovskoe deposit. (A, B) early folds F1 associated with thrusts; (C, D) late folds associated with strike slips.

Fig.15. Regional position of the Malo-Tarynskoe deposit.

Fig.16. (A) A mineralized crush zone with Au-Q veins, Malo-Tarynskoe deposit, (B) zones of intense crush with vein-veinlet Au-Sb mineralization, Malan deposit (Fridovsky et al., 2014, 2015).

Fig.17. Levo-Dybinskoe intrusion (granitoid)-related gold deposit.

Fig.18. Metallogenic-geodynamic model for the formation of orogenic and post-orogenic gold deposits of the Verkhoyansk-Kolyma folded region (as exemplified by the Allakh-Yun metallogenic zone).

(A) origination of ore-magmatic systems, development of plastic deformations D1, zonal metamorphism, formation of early orogenic gold-sulfide-disseminated and shear zone-hosted gold-quartz deposits. (B) fold and fault deformations D2, formation of intermediate and shallow-depth magma chambers, generation of plutogenic fluids, metamorphism, formation of fault-hosted gold-quartz and intrusion (granitoid)-related gold deposits. (C) formation of volcanic-plutonic complexes, Au-Ag, Sn-Pb-Ag and Au-Hg deposits, and transpression deformations D3. Under favorable conditions, young mineralization is superposed on orogenic one, which results in the formation of polygenic deposits. Sketches not to scale.

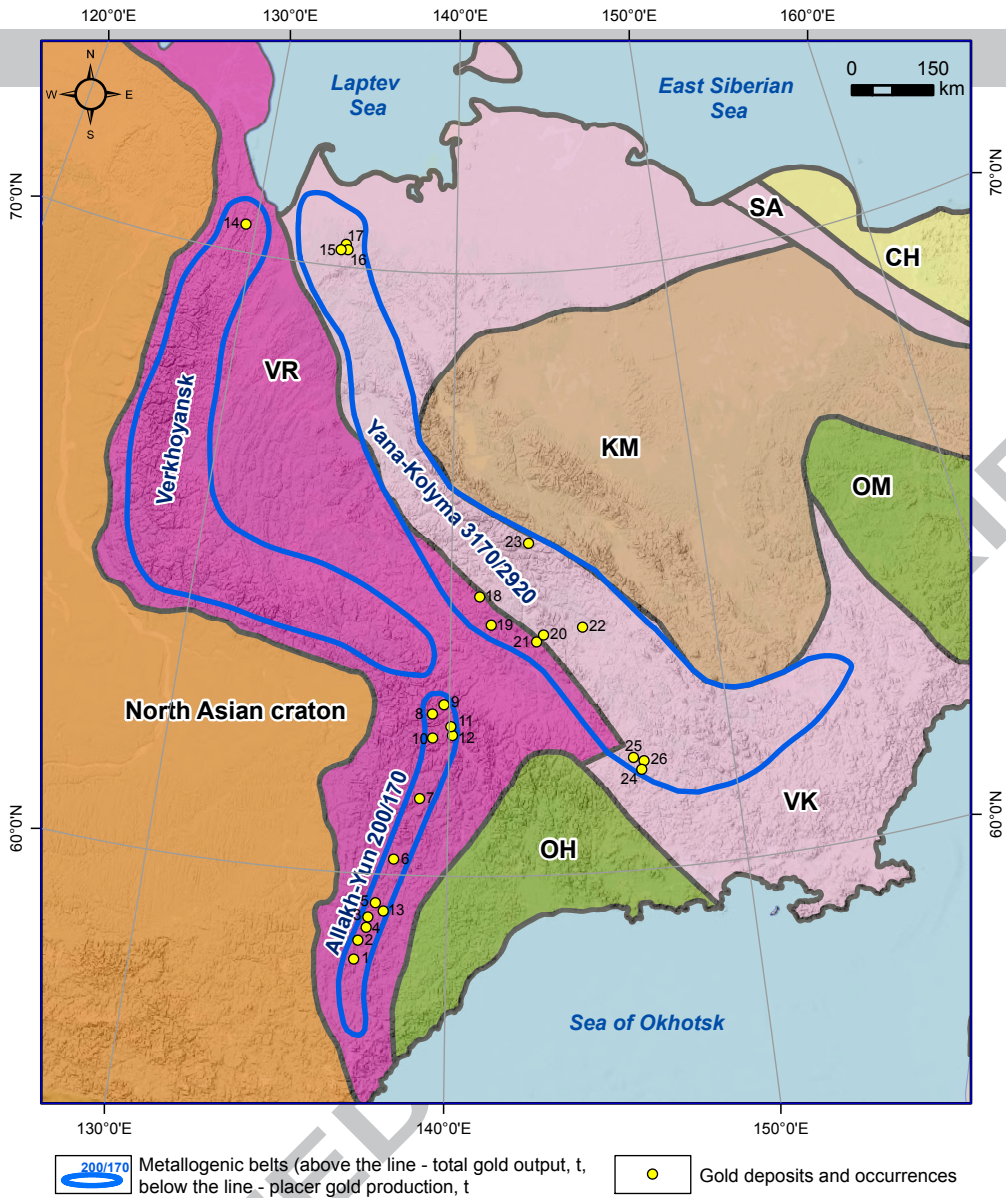
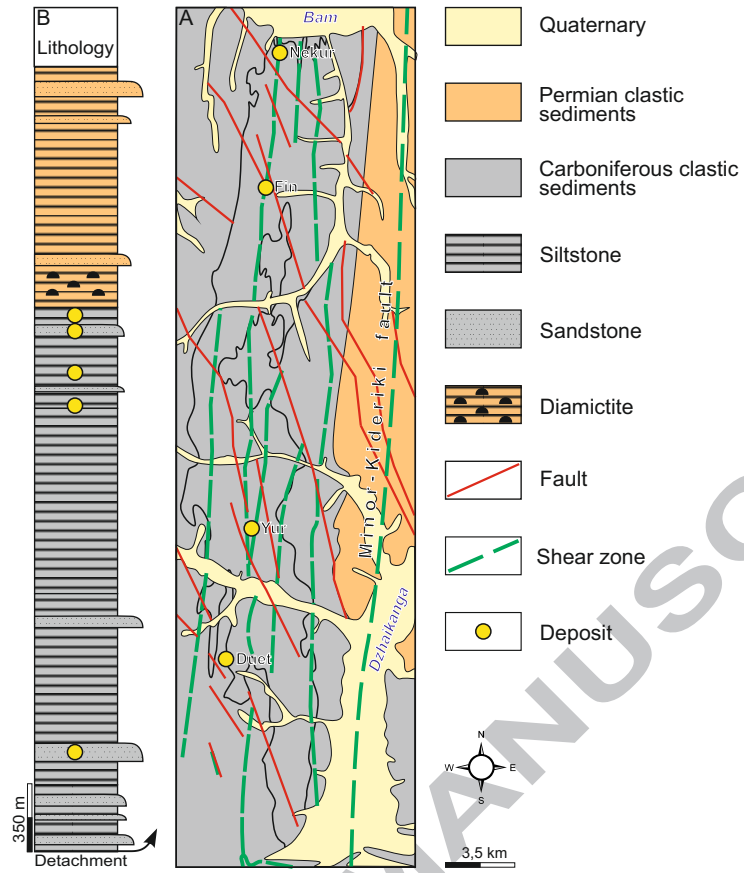


Fig.1



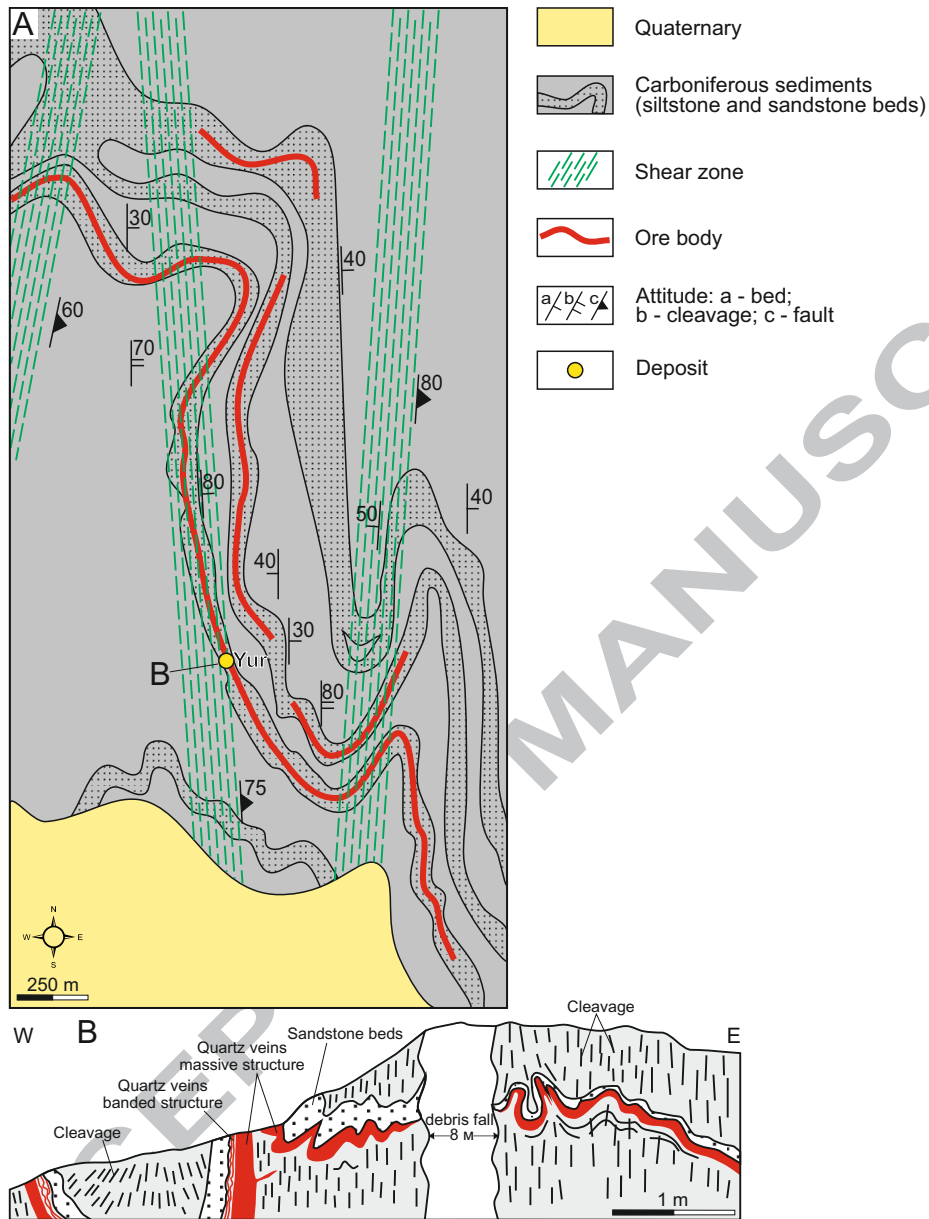


Fig.3

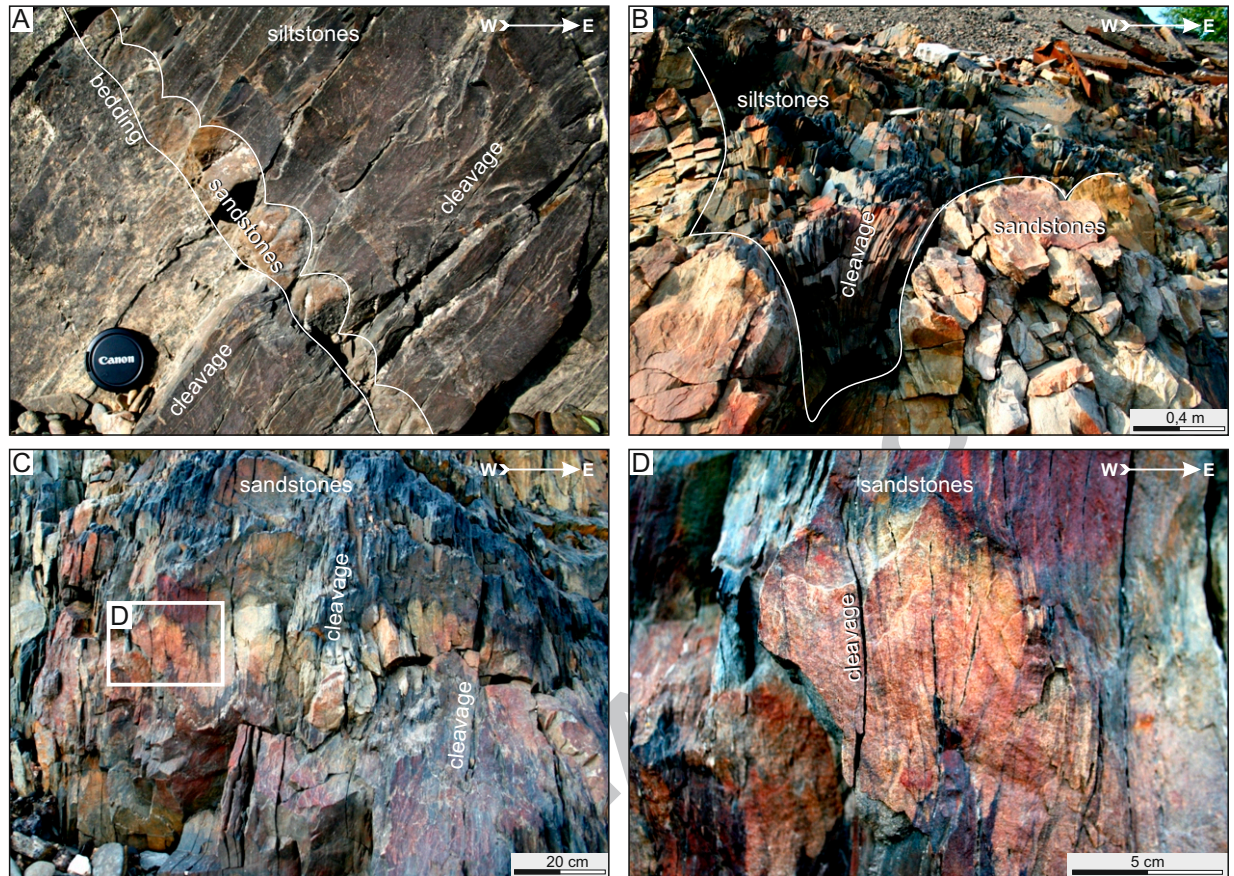


Fig.4

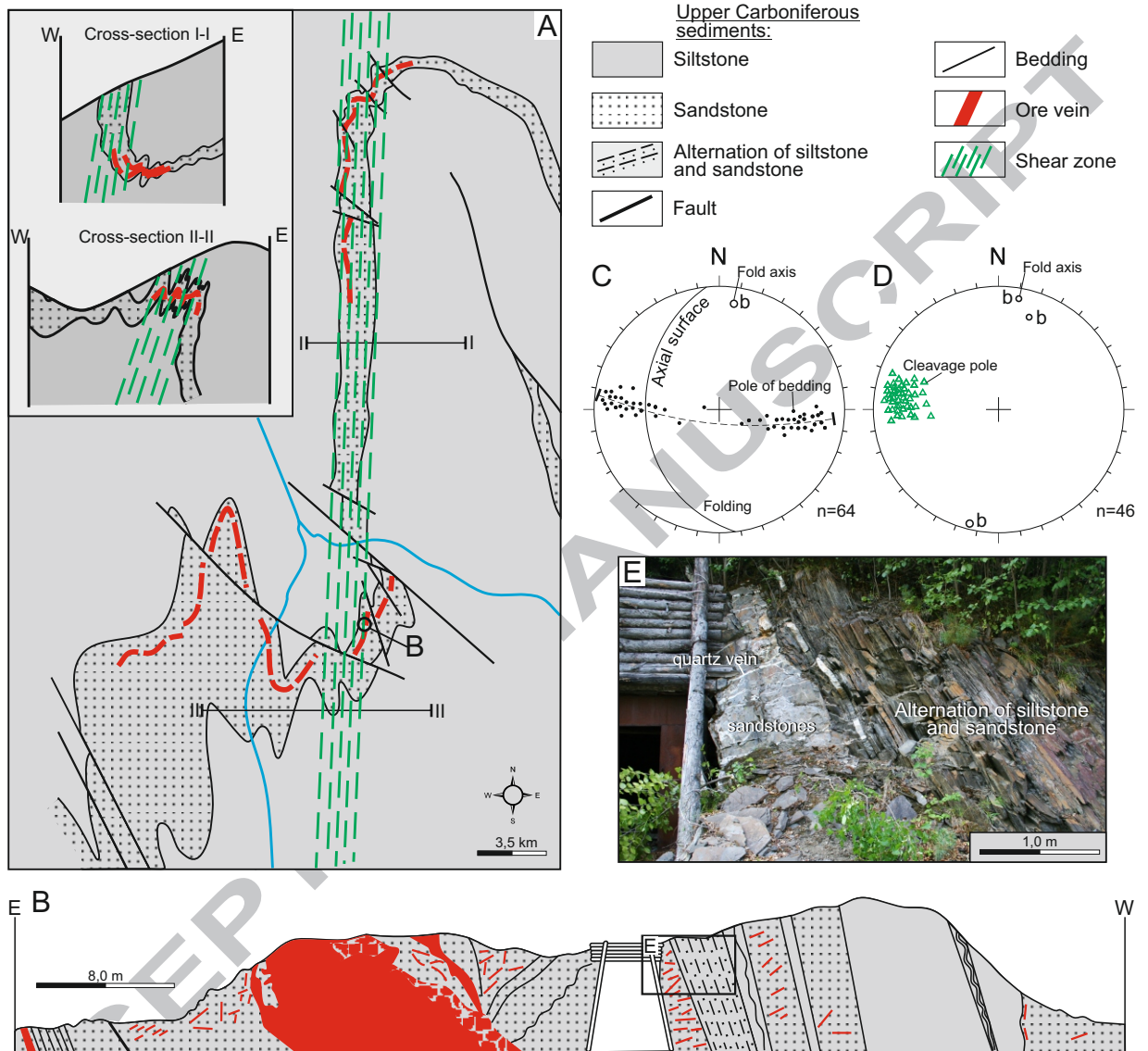


Fig.5

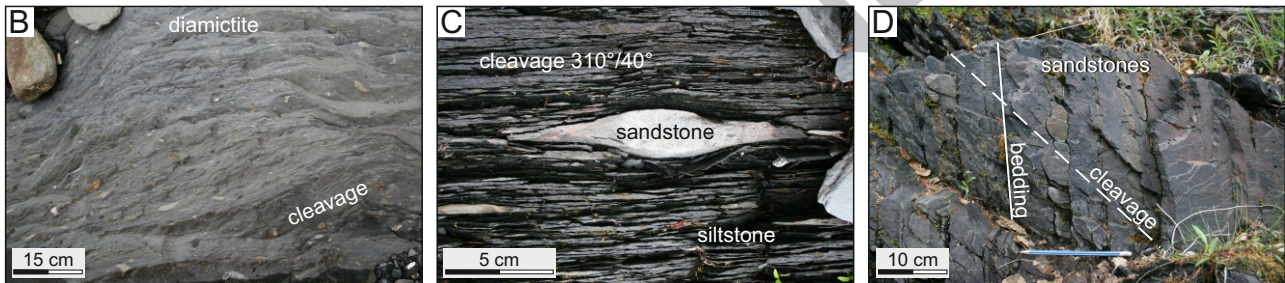
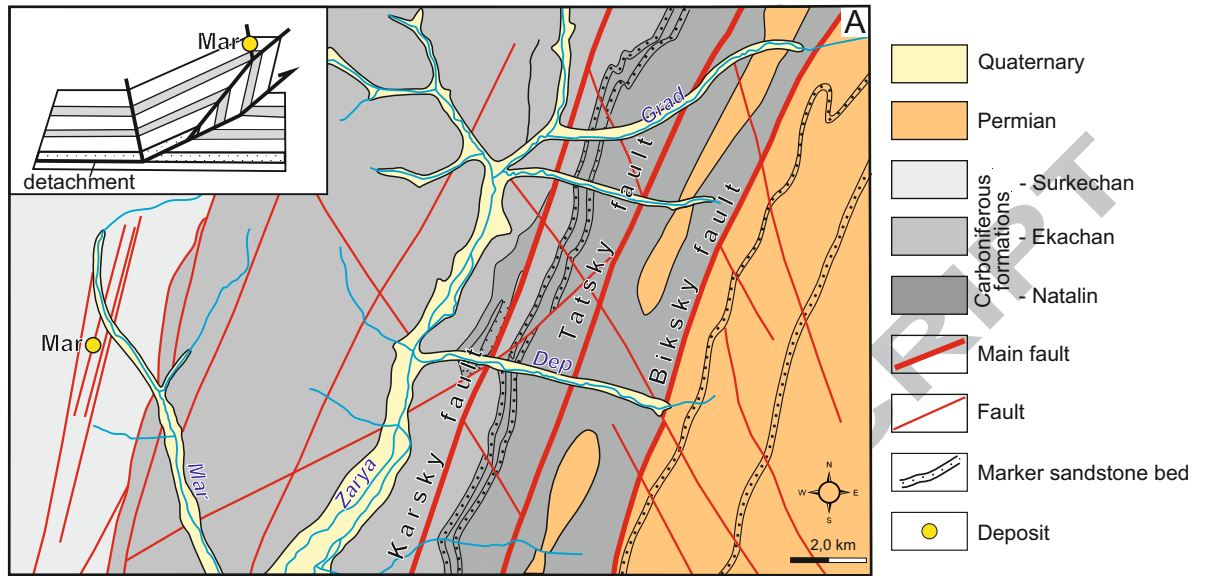


Fig.6

Fig. 7

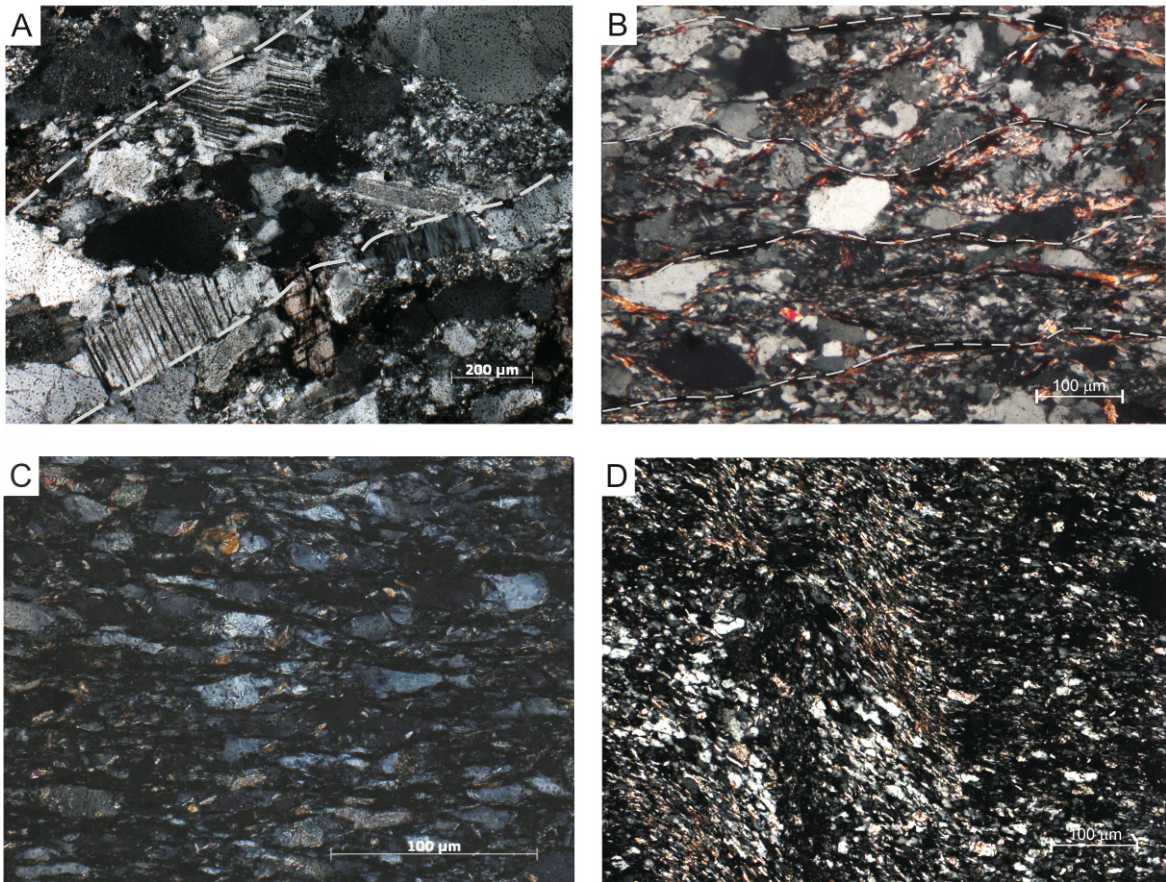
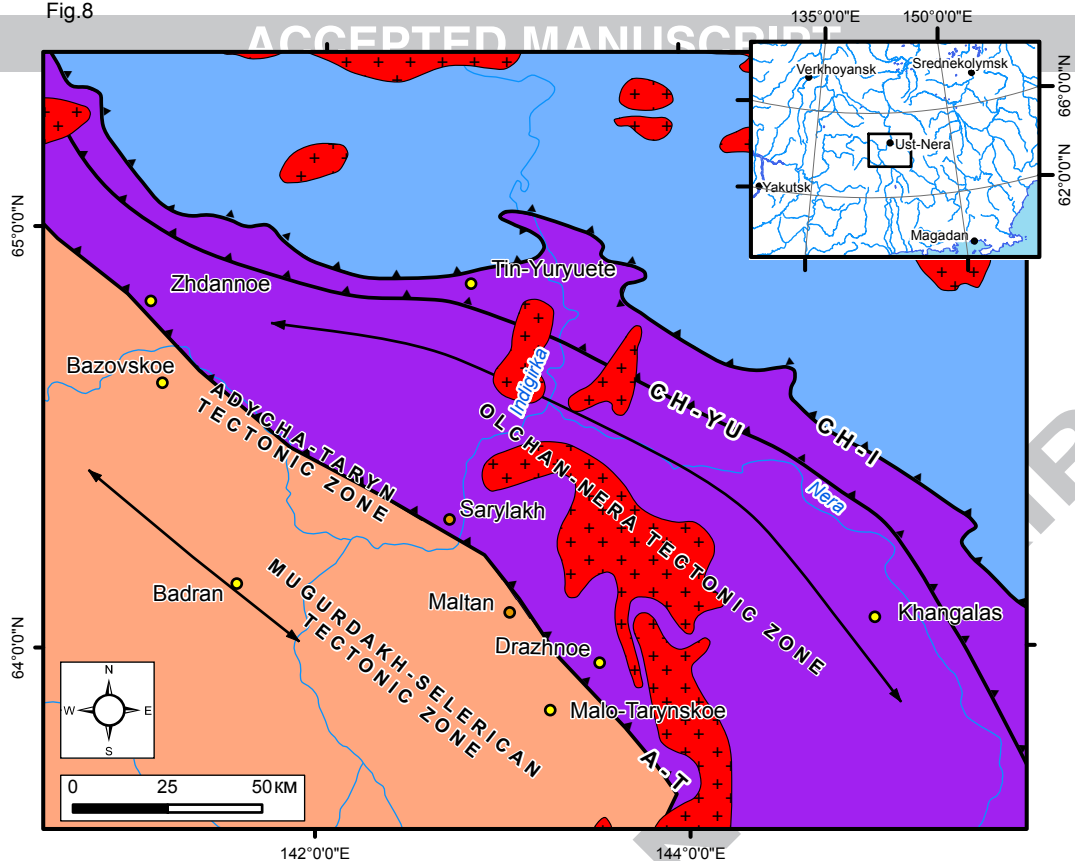


Fig.8



Polusny-Debin terrane

Kular-Nera terrane

Verkhoyansk fold-and-thrust belt

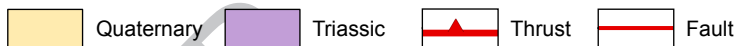
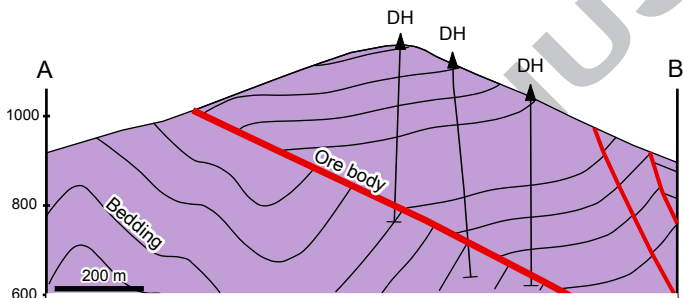
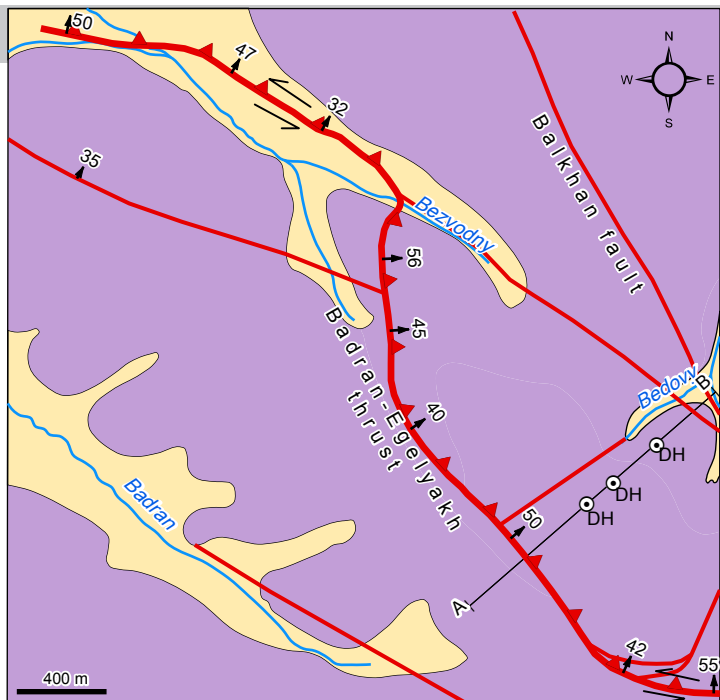
Granitoids

Thrust

Anticlinorium axis

Deposits: a - Au; b - Au-Sb

Fig.9



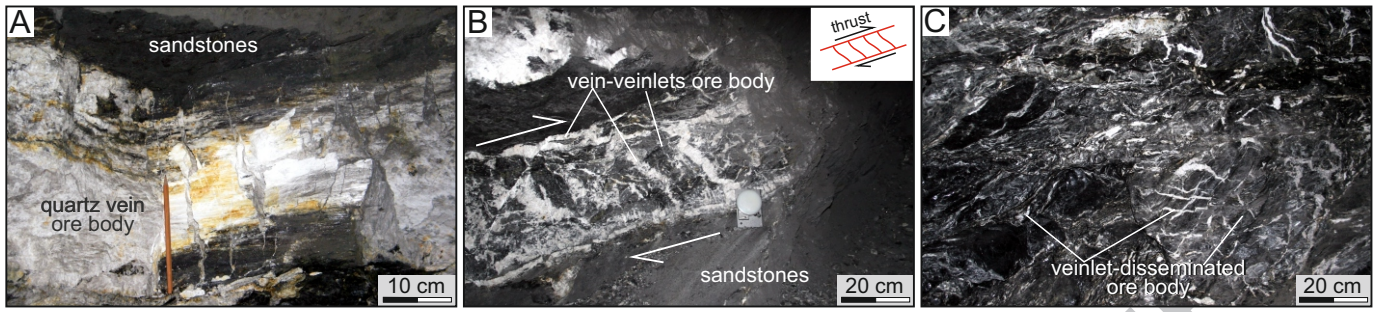


Fig.10

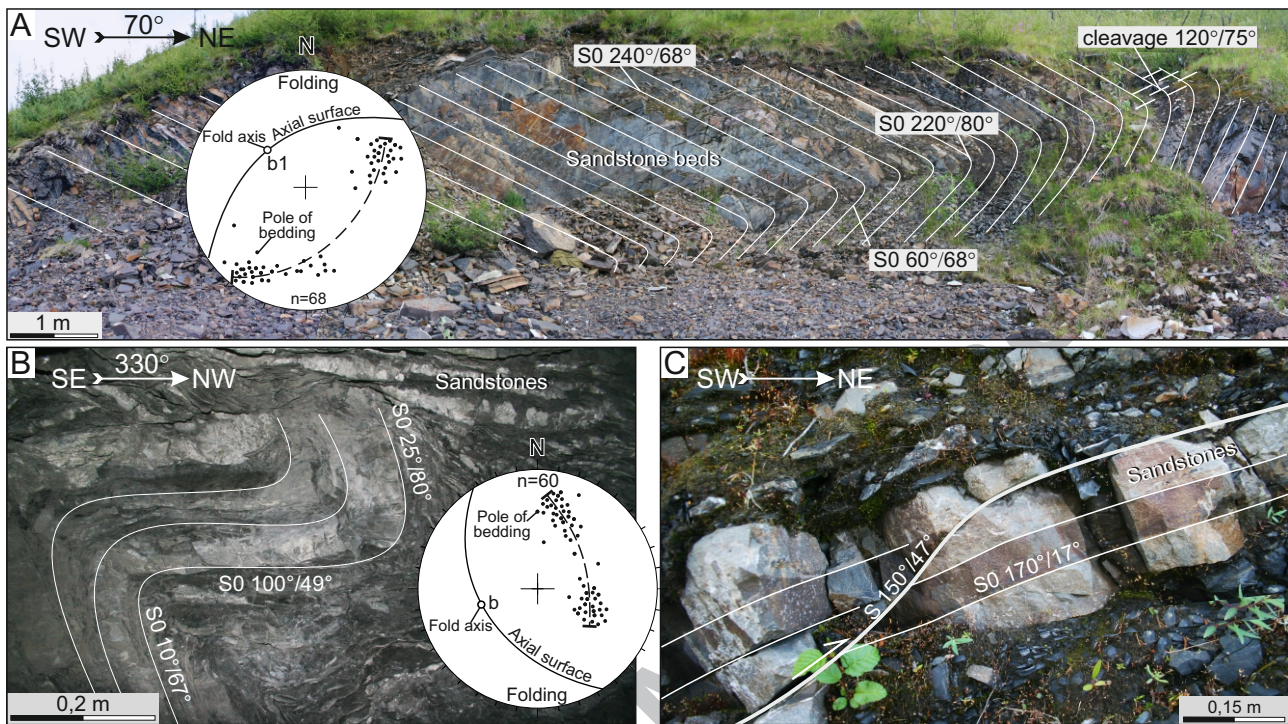


Fig.11

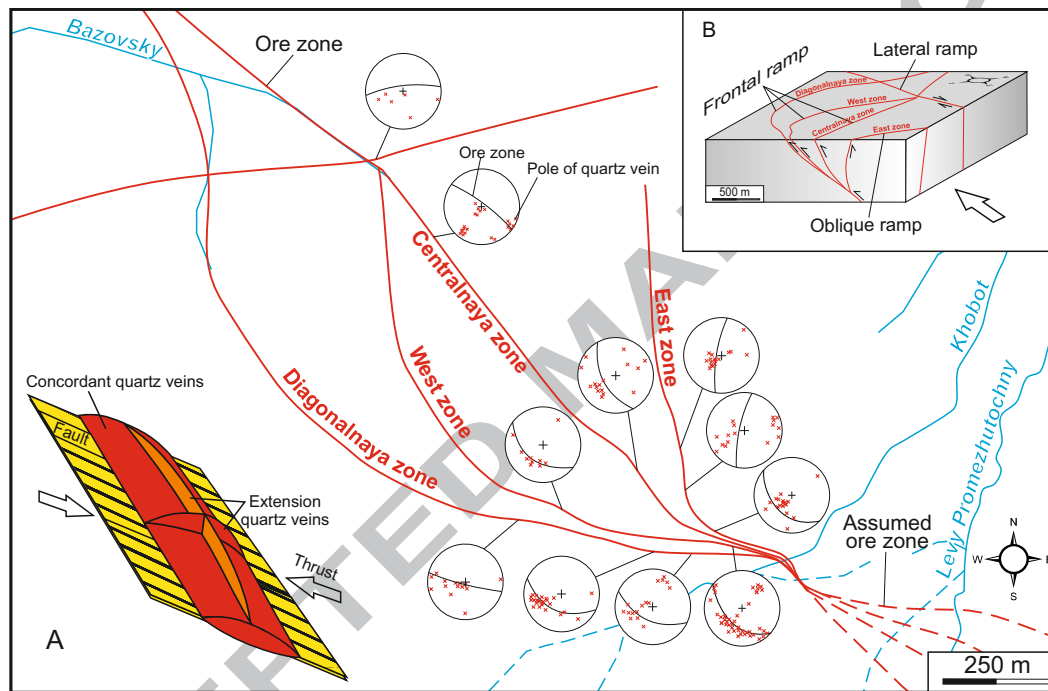


Fig.12

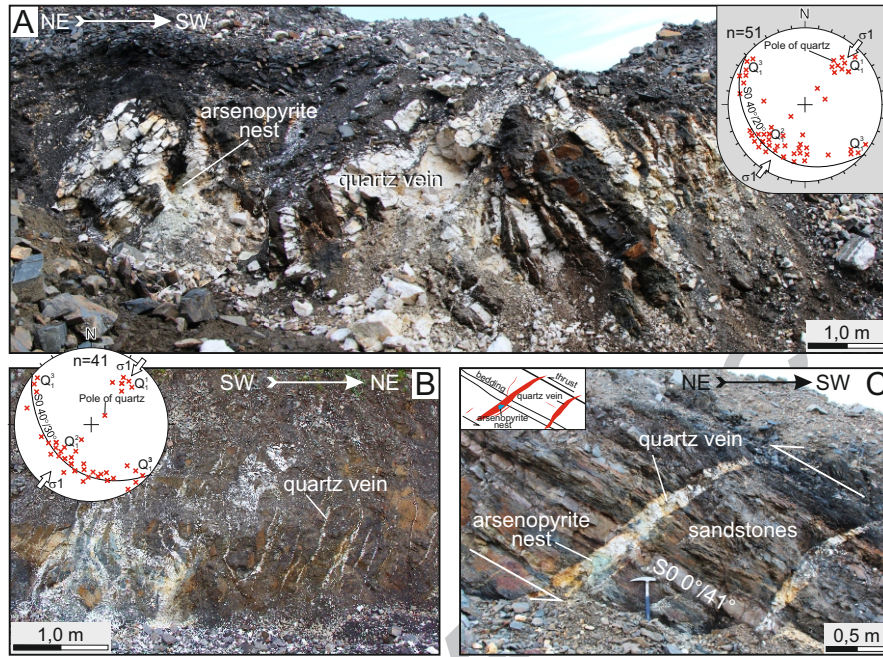


Fig.13

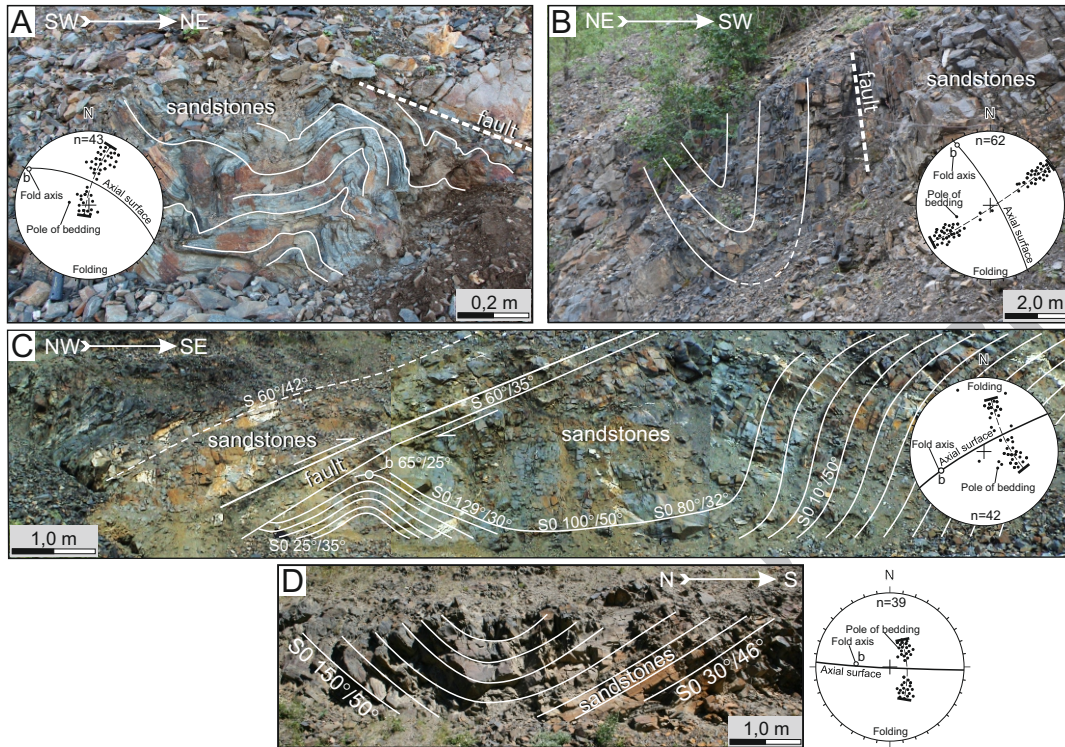


Fig.14

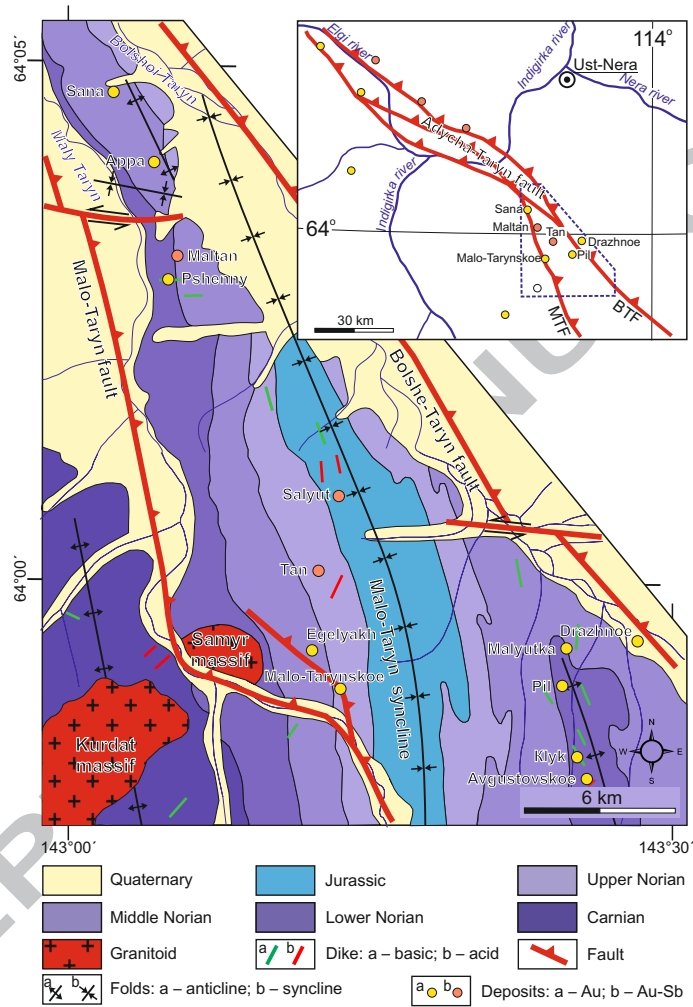


Fig.15

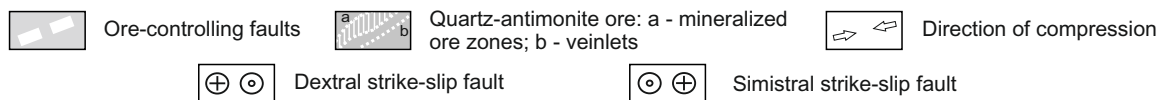
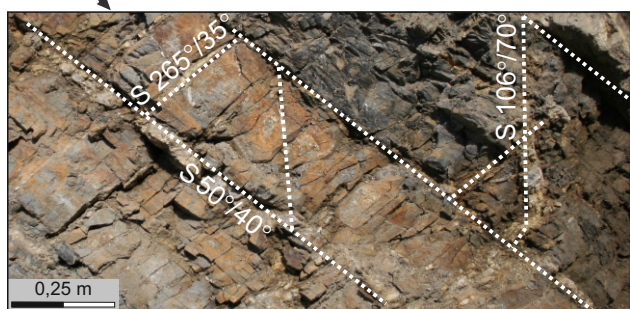
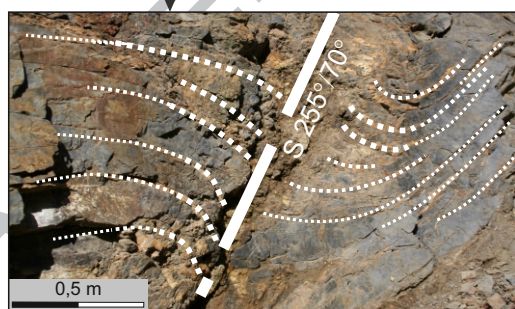
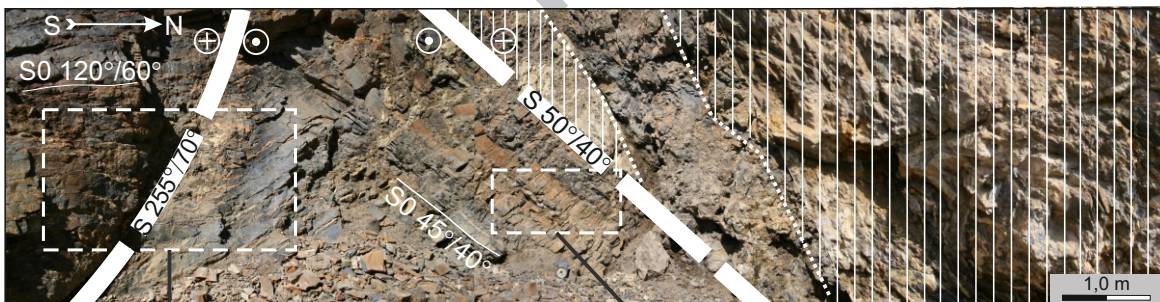
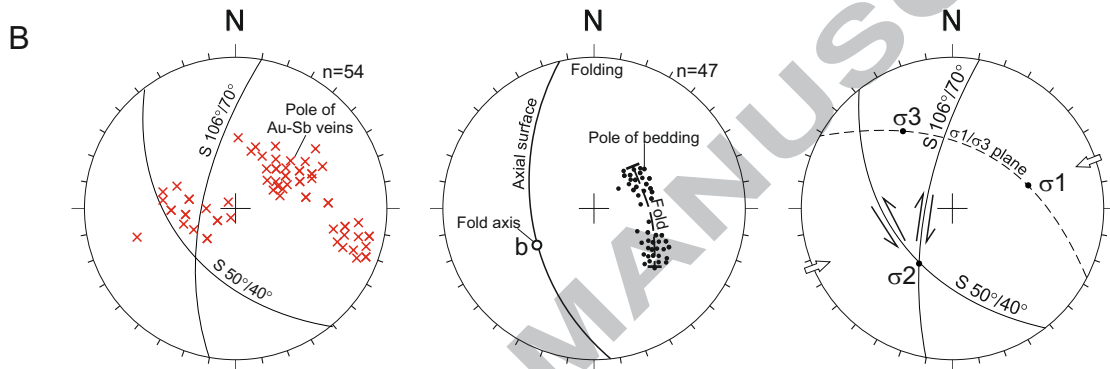
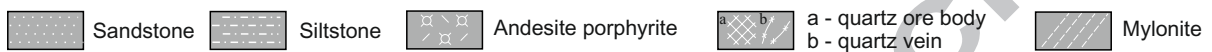
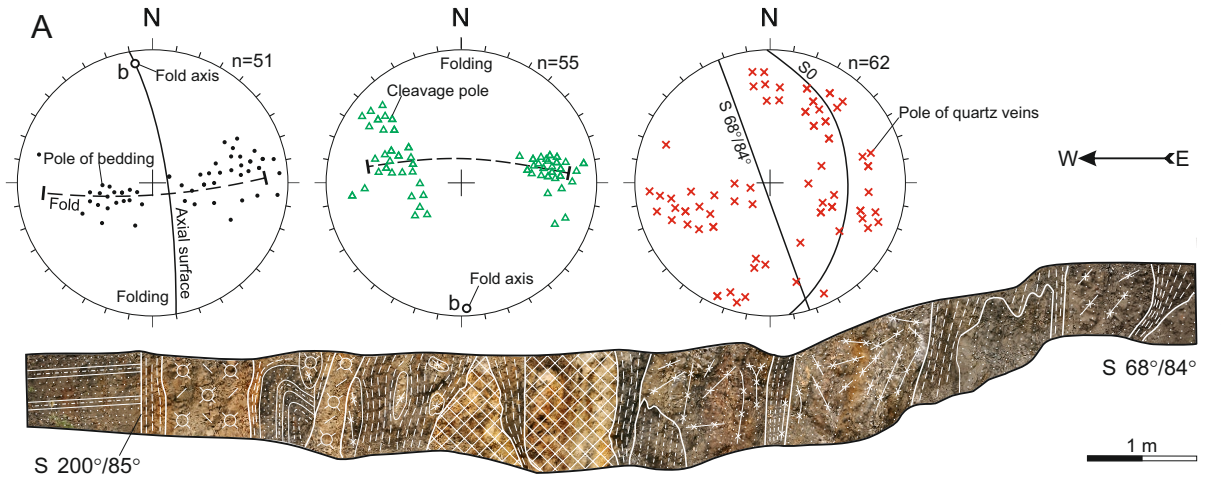


Fig.16

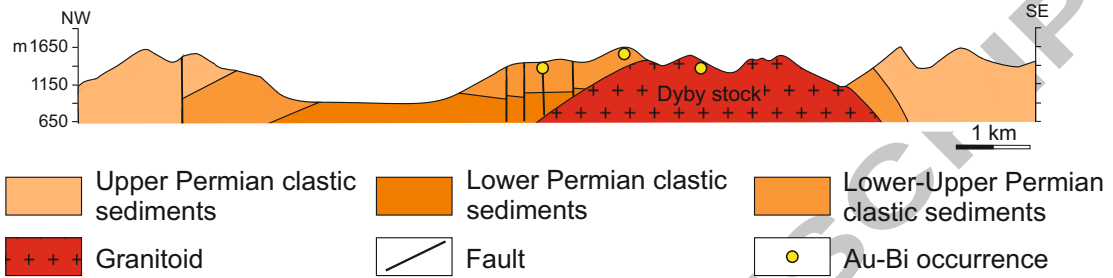
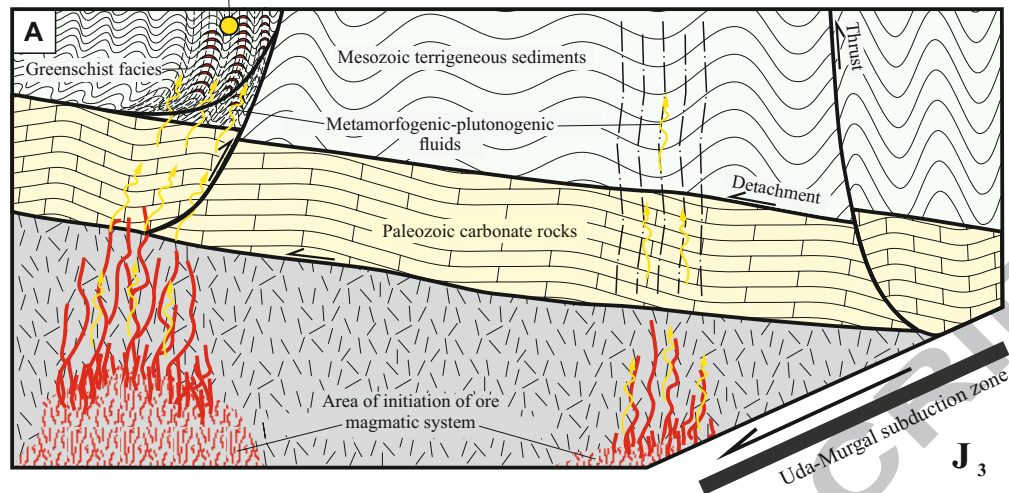


Fig.17

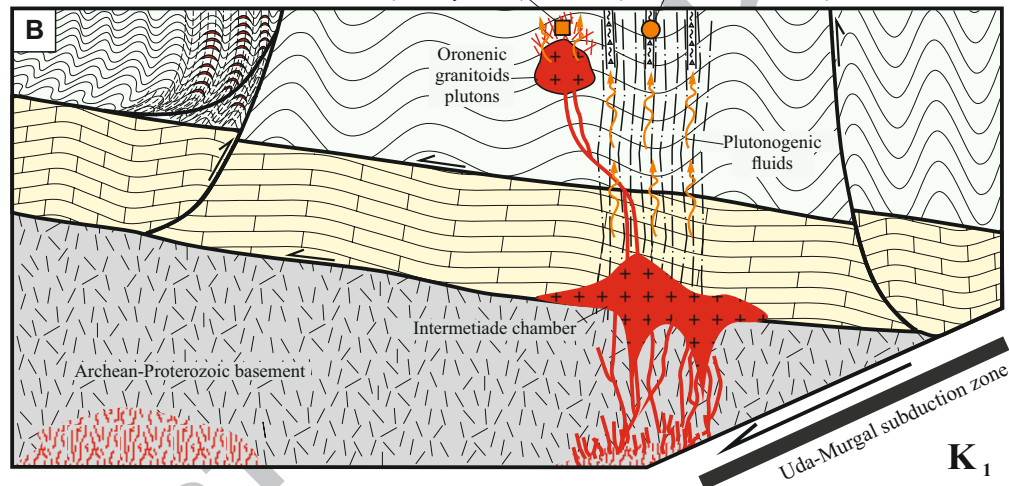
EARLY OROGENIC DEPOSITS

Gold-sulfide-disseminated and
gold-quartz in shear zones (Yur, Mar)



LATE OROGENIC DEPOSITS

Intrusion (granitoid) related
(Levo-Dybinskoe) Au-quartz in fault zones
(Nezdaninskoe, Zaderzhnoe)



POST-OROGENIC DEPOSITS

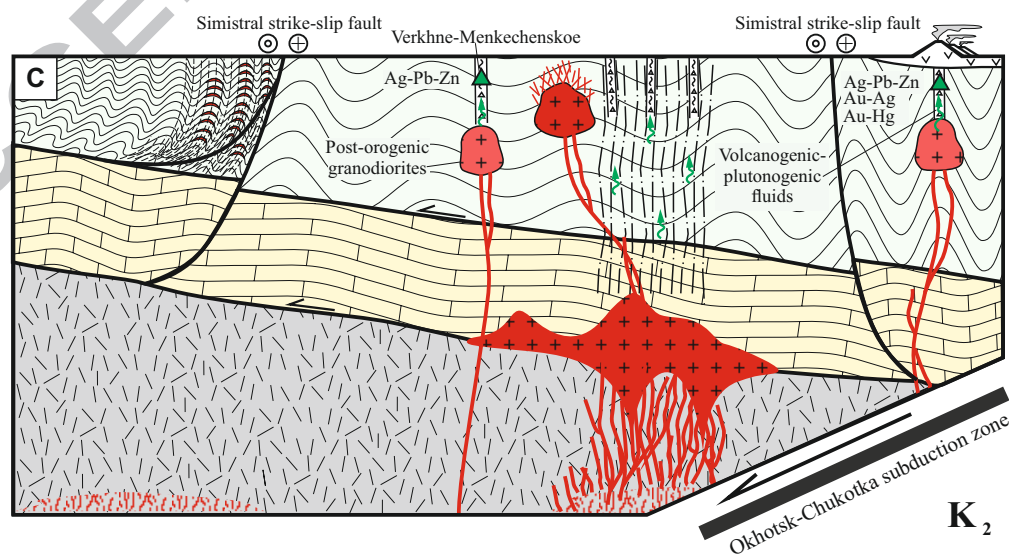




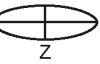
Fig.18

Table 1

Precious metal deposits and occurrences of the Verkhoyansk-Kolyma folded area

Geodynamic Setting	Type of deposit	Mineralization	Ore-controlling tectonic structures	Main fault kinematics	Structural paragenesis	Ore body morphology	Examples of deposits and occurrences
Accretionary J ₃ -K ₁	Early orogenic gold-sulfide disseminated and gold-quartz in shear zones	Au	Shear zones	Thrusts	Shear zones, slaty cleavage, similar shear folds, mullion- and boudinage-structures, transposition elements	Concordant and cross veins, veinlets and disseminations bodies	Duet, Yur, Nekur, Marinskoe, Bular Dyandinskoe, Emelyanovskoe, Emisskoe, Kyllakhskoe
	Late orogenic gold-quartz in fault zones	Au	Longitudinal and diagonal faults	Thrusts, strike-slip faults	Concentric buckle slip folds, zones of intensive fold deformations, boudinage, fracture cleavage	Mineralized crush zones, conformable and cross veins, veinlets and disseminations bodies	Nezhdaninskoe, Natalka, Drazhnoe, Bazovskoe, Malo-Taryn, Zaderzhnoe, Lazurnoe, Badran, Khangallasskoe
	Late orogenic intrusion (granitoid)-related	Au-Bi	Dikes, stocks of granitoids and their exocontacts	Normal faults, strike-slip faults	Above and peri-intrusive structures, competent beds, supratenuous folds	Veins, veinlets, stratabound-stockworks	Levo-Dybinskoye, Ergelyak, Novoe, Solur, Chistoye, Malysh-Dubach
Post-accretionary K ₂	Post-orogenic	Au-Sb, Ag-Pb-Zn, Au-Ag, Au-Hg	Diagonal and cross faults	Strike-slip faults, thrusts, normal faults	Faults, near-fault concentric folds, boudinage	Mineralized crush zones, stockworks	Saryakh, Sentachan, Menkeche, Курун-Урях, Svetlinskoe

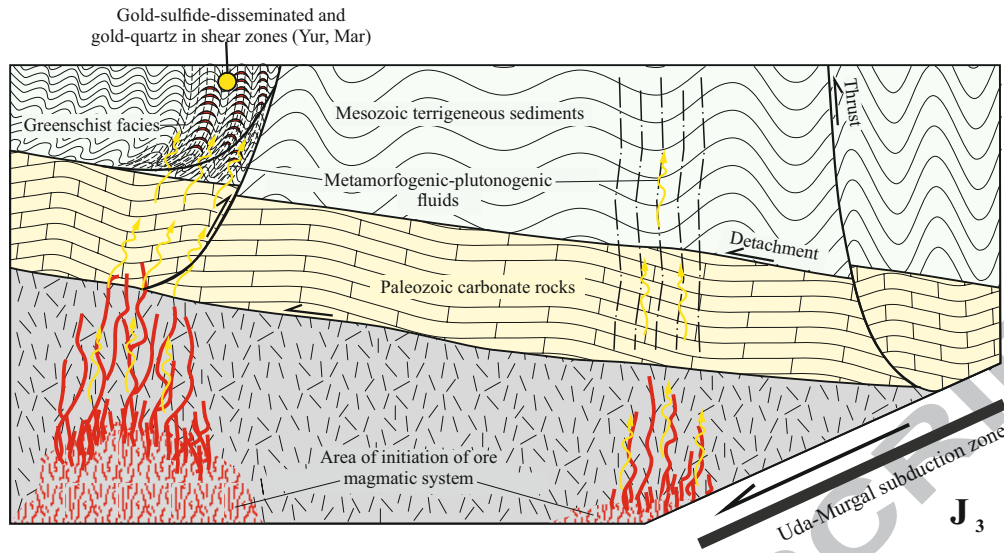
Table 2. Vertical structural zoning of Yur-Brindakit ore cluster

Deformation type	Structural paragenesis	Type and angle of cleavage dip	Ellipsoid of deformations*	Deformation intensity, Cd**	Distance from detachment, km	Morphology of ore bodies	Deposits
Brittle shear zone	Concentric folds, boudinage, cleavage	Fracture cleavage $\angle 50-90^\circ$	 Cd=2,0	2 3 4 5	0 1 2	Concordant ore bodies	Yur, Duet
Brittle-ductile shear zone	Initial transposition structures, mullion-structures, boudinage, cleavage	Slaty cleavage $\angle 30-80^\circ$	 Cd=2,54			Stratabound-stockwork ore bodies	Nekur
Ductile shear zone	Evolved transposition structures, boudinage, cleavage, ptygmatic folds		$\angle 10-40^\circ$	 Cd=3,44			Vein-veinlet and veinlet- disseminated ore bodies

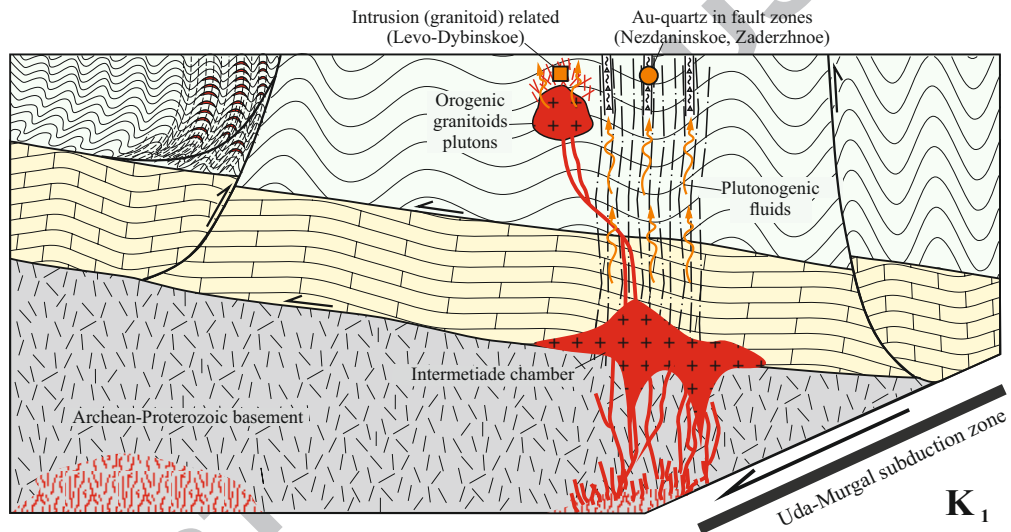
* Fry method (Fry N., 1999)

** Cd = X/Z - petrostructural coefficient of deformation, X - long axis of deformation ellipse; Z - short axis of deformation ellipse, in plan orthogonal to cleavage

EARLY OROGENIC DEPOSITS



LATE OROGENIC DEPOSITS



Highlights

- Orogenic gold deposits are associated with frontal accretion.
- Ore-bearing structures of the early orogenic gold deposits are shear zones.
- Late orogenic gold deposits are controlled by intersections of thrusts and ramps.

ACCEPTED MANUSCRIPT

Abstract

The Verkhoyansk-Kolyma folded region (VKFR) contains numerous Late Jurassic - Early Cretaceous orogenic gold deposits which are the source for large alluvial gold placers. This study is focused on determination of the relationship between ore-controlling structures, tectonic evolution of the region and analyzing different-aged deformations and structure of gold deposits in the region. Tectonic structures of mesothermal orogenic gold deposits were formed as a result of Late Jurassic-Barremian frontal accretion, generally prior to the onset of transpressional deformation. The accretionary events were different in different parts of VKFR. In the Allakh-Yun metallogenic zone this was the accretion of the Okhotsk terrane to the eastern margin of the North Asian craton, and in the Verkhoyansk and Yana-Kolyma metallogenic belts the accretion of the Kolyma-Omolon superterrane to the same craton. Regional-scale thrust faults are main tectonic structures controlling distribution of gold deposits in the area. Ore-controlling structures for the early orogenic gold-sulfide disseminated and gold-quartz lode deposits, which were formed prior to the emplacement of orogenic granitoid plutons, are shear zones. They form systems of listric-type imbricate fans closely associated with a detachment of the Verkhoyansk fold-and-thrust belt. Late orogenic gold-quartz deposits in fault zones, which were formed after the emplacement of orogenic granitoid plutons, are controlled by intersections of thrusts and lateral and oblique ramps and by the related folds. Formation of the ore-hosting structures of the late orogenic intrusion (granitoid)-related deposits is due to the dynamic effect of intruding magma on the host rocks.

Keywords: northeast Russia; orogenic gold deposits; structural control and tectonics