

Tectonic Evolution and Structural Control of Dikes-Hosted Orogenic Gold Deposits in The Yana-Kolyma Collision Orogen, Eastern Siberia: Insights from Terranes of the Eastern Margins of the Siberian Craton

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Article

Tectonic Evolution and Structural Control of Dikes-Hosted Orogenic Gold Deposits in The Yana-Kolyma Collision Orogen, Eastern Siberia: Insights from Terranes of the Eastern Margins of the Siberian Craton

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Abstract: The Yana-Kolyma collision orogen is one of world-class gold economic belts, where the large gold deposits are localized, mainly in the Upper Paleozoic and Lower Mesozoic clastic rocks. Dikes-hosted orogenic gold deposits have been to a lesser extent, but they are important for analyzing the structural control of mineralization within the framework of the tectonic evolution of the host orogen. Orogenic gold deposits of the Vyun ore field are hosted in Tetonian mafic and felsic dike, but they have no genetic connection with dikes. The late formation of deposits leads to the fact that previously reactivated polydeformed structures turn out to be mineralized. Study of the structural control of mineralization is also complicated by superimposed late tectonic events. Based on the analysis of collected field materials, the paper presents the results of the study of deformation structures of the Vyun ore field within the framework of the Mesozoic evolution history throughout the geological time of the eastern convergent margin of the Siberian craton. Four stages of deformations are identified. The pre-mineralization deformations, metamorphic and magmatic events share a common NE-SW shortening (D1), which is related to the subduction of the Oymyakon oceanic slab and collision of the Kolyma-Omolon superterrane from the eastern margin of the Siberian Craton. These deformations are characterized by multiphase history of superposition of several tectonic events under conditions of compression and progressive deformations (D1/1 and D1/2). Ore mineralization was formed at the end of compression in the same stress field (D1/2). Its structural control is determined by reactivation of older dikes and faults. Dikes are areas of heterogeneous stress and heterogeneous strain, being favorable for the concentration of ore fluids. The metallogenic time of formation of the gold mineralization is synchronous to the tectonic event likely reflects the final stages of the Kolyma–Omolon microcontinent – Siberian Craton collision of the Valanginian during crustal thickening. The main impulse of Au mineralization coincided with a slowdown in convergence. Postmineralization tectonic regime was related to the Aptian-Late Cretaceous tectonic transition from compression to transpression. Transpressional tectonics was determined accordingly by W-E (D2) and N-S (D3) stress fields caused by several accretion events in the Cretaceous on the northern and eastern margins of Siberia. D4 tension strains are caused by the opening of the Eurasian Oceanic basin in the Arctic in the Paleocene. The obtained results of the relation between polydeformed structures and associated mineralization have important implications to contribute to a proper understanding of the structural control of orogenic gold deposits and their relationship to the evolution of the host orogen and the conceptual exploration targeting orogenic gold deposits in Phanerozoic terranes of craton margins.

Keywords: polydeformed structures; tectonic event; dikes-hosted orogenic gold deposits; Yana-Kolyma orogeny; Eastern Siberia

1. Introduction

The eastern margin of the Siberian Craton is known for world-class orogenic gold deposits (review in [1–9]. Most of the deposits are located in the Yana-Kolyma orogenic belt (YKOB), where they are grouped into trends of the northwestern strike along regional faults in the Upper Permian – Lower Jurassic terrigenous strata (Nataika, Degdekan, Pavlik, Drazhnoye, Badran, Malo-Tarynskoye, Khangalas and others). There are also known orogenic deposits localized in dikes (Utinskoye, Sturmovskoye, Srednekanskoye, Krokhalinnoye, Berezitovoye and others). Less common are intrusive-related deposits (Shkolnoye, Butarnoye, Ekspeditsionnoye, Ergelyakh and others) [10–12]. Interest in them was aroused by the successful development of economically important Fort Knox, Pogo, Dublin Gulch and others deposits in the Tintina gold belt in Alaska and Yukon [13]. Dikes-hosted orogenic gold deposits are widespread in the Jurassic deposits of the Upper Kolyma sector of YKOB. Some of the largest of these deposits were developed in the 30-50s of the twentieth century [14]. Attention to gold mineralization in dikes and small magmatic bodies has emerged in recent years [14–17]. They are again becoming objects of evaluation and development. One of them is the Vyun deposit and the occurrences of the Vyun ore field, located in the western sector of the Yana-Kolyma orogenic belt (Figure 1).

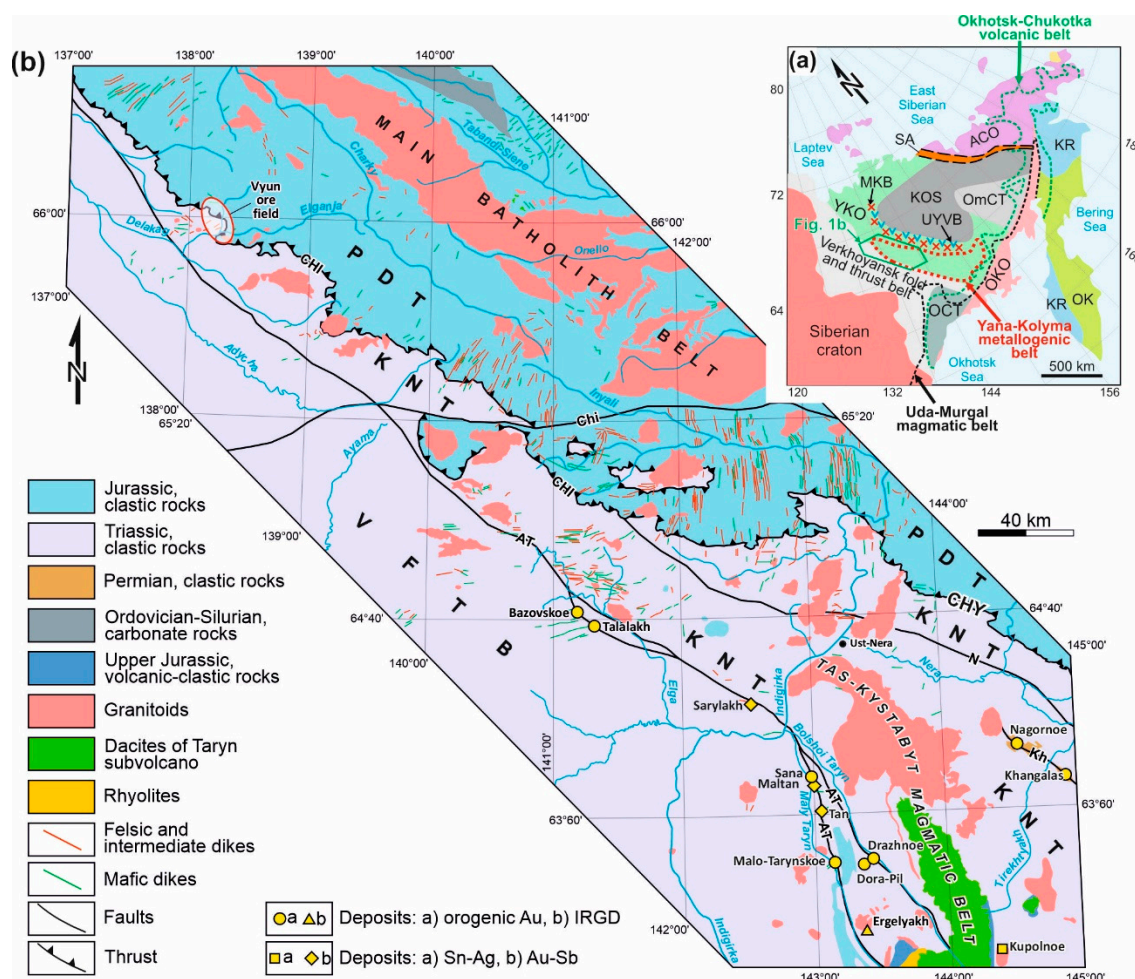


Figure 1. Generalized geological map showing major tectonic structures and metallogeny of Eastern Siberia (a) (revised and supplemented from [2,33]) and (b) Regional geologic map of the Kular-Nera and Polousno-Debin terranes, showing position of the Vyun ore field, main rock units, structures and the distribution of deposits Au and Au-Sb (revised and supplemented from [33]). Abbreviations: Abbreviations: SK – Siberian craton, VFTB – Verkhoyansk fold-and-thrust belt, KNT – Kular-Nera terrane, PDT – Polousno-Debin terrane, OmCT – Omolon craton terrane, OCT – Okhotsk craton terrane, KOS – Kolyma-Omolon superterrane, ACO – Arctic and Chukotka terranes; Mesozoic-Cenozoic orogens: OK – Olyutor-Kamchatka, OKO – Okhotsk-Koryak, KR – Koryak; MKB –

Late Jurassic Main Kolyma belt, UYVB – Late Jurassic Uyandina-Yasachnaya volcanic belt. Faults: AT – Adycha-Taryn, Chi – Chibagalakh, CHY – Chai-Yureya, N – Nera, Kh – Khangalas, CHI – Charky-Indigirka thrust.

The Vyun deposit was discovered in 1974 by L.P. Komarova and F.I. Shatrov. In the 1975-1980, exploration and evaluation work was carried out. In the 1990s exploration work was carried out by trenching and underground mining workings, reserves of ~2.5 tons of Au with a content of 7.5 g/t have been calculated. The study was continued in 2005-2009 by JSC "Yanskaya Mining Company", in 2017-2020 by "Dalzoloto" LLC and a factory was built. In 2020-2021, gold mining was carried out underground. The main emphasis in the research of YKOB gold mineralization, spatially associated with dikes and small magmatic bodies, was placed on the features of the deposit geology, the mineralogy and paragenetic sequence, the conditions of their formation [14–17], geochemistry, geochronology and petrology of spatially associated magmatism [17,18]. The structural control of mineralization in dikes is not clear, its relationship with the evolution of the orogen is debatable.

It is generally accepted to assess the important contribution of structural control to the localization of orogenic gold deposits (OGD) [19–21]. As part of the evolution of the host orogen, these deposits are usually formed in a suprasubduction and seldom in a collisional geodynamic setting before orogenic collapse [2,20,22–25]. The late periods of formation of deposits lead to the fact that reactivated previously repeatedly deformed structures turn out to be mineralized. The study of the structural control of mineralization is also complicated by superimposed late tectonic events.

This paper, based on the analysis of thoroughly collected field materials, represents the results of studying the deformation structures of the Vyun ore field in the context of the Mesozoic evolution history throughout the geological time of the eastern convergent margin of Siberia. In the Vyun ore field, two terranes are separated by regional thick Charky-Indigirka fault zones. In this area, several tectonic events occur; their relationship with mineralization is not clear and is complicated by the presence of dikes. Orogenic gold ore mineralization in dikes is not typical for YKOB. For this reason, the analysis of the relationship between polydeformed structures and associated mineralization is a key argument for a proper understanding of structural control of orogenic gold deposits and their relationship to the evolution of the host orogen, and for conceptual exploration targeting OGD in Phanerozoic terranes of craton margins.

2. Regional Geology, Magmatism and Metallogenic Setting

2.1. Regional Geology

One of the major Late Mesozoic gold-forming episodes in Siberia and East Asia is related to the evolution of the Yana-Kolyma orogenic belt [2,3,6–8,26,27]. Summary information about this region is given in [26–28]. The orogen is located between the Verkhoyansk fold-thrust belt of the eastern margin of the Siberian craton and the structures of the Kolyma-Omolon superterrane (microcontinent) (Figure 1A). It is part of the Verkhoyansk-Chukotka province of the Mesozoic-Cenozoic collages comprising the Precambrian cratonic terranes and accreted the Late Paleozoic to Cenozoic turbidite to island arc terranes [26]. Deformation processes, magmatism and metallogenesis in the Yana-Kolyma orogen in the Late Jurassic–Valanginian is related to the closure of the small Oymyakon paleocean and the subsequent collision of the Kolyma-Omolon superterrane and the eastern margin of the Siberian craton [2,26]. At the beginning of the Early Cretaceous, the collision process spread towards the Siberian platform and was accompanied by the formation of the Verkhoyansk fold-thrust belt [26]. At the end of the Early Cretaceous after the closure of the South-Anyu Ocean, there was a collision of the Chukotka microcontinent (a fragment of the Arctic Alaska-Chukotka microplate) with the structures of the Proto-Arctic active margin of Siberia [29]. The Cretaceous tectonic-thermal events were also caused by continuous subduction of the Paleo-Pacific Plate on the eastern margin of Siberia.

The main structures of central part of the Yana-Kolyma orogen are determined by systems of extended thrusts and linear folds. Differently directed movements are identified along the faults–

early thrust of several generations and late sinistral- and dextral-strike-slip faults. Transverse NE and NS faults (oblique ramps), mainly of strike-slip and normal-strike-slip fault kinematics, dividing the thrusts into separate segments, are also identified [7,30–32].

The Yana-Kolyma orogen belt includes several Late Jurassic terranes, the main ones are Kular-Nera and Polousno-Debin [27]. The Kular-Nera terrane (KNT) consists of sequences of the Upper Permian, Triassic and Lower Jurassic terrigenous sedimentary rocks corresponding to the distal clastic deposits of the continental slope and foot of the Siberian Craton passive continental margin [26,34]. These rocks are metamorphosed to the initial stages of the greenschist facies. The KNT can be traced in the north direction for a distance of about 1100 km, has a width from 10-20 to 100-150 km [26]. From the southwest of the adjacent structures of the Verkhoyansk fold-thrust belt. The Kular-Nera terrane is separated by the trans-crustal Adycha-Taryn fault. It is an important metallogenic unit with Au, Au-Sb, W-Sn and Mo-W mineralization. The latter is 40 km wide and over 1500 km long, including the Ten'ka fault to the southeast and the Baky-Bytantay fault to the northwest. From the northeast, the Triassic clastic sediments of the Kular-Nera region are separated by the Charky-Indigirka thrust (CIT) from the Jurassic clastic sediments of the Polousno-Debin terrane. The amplitude of the thrust movement is up to 35-50 km [35]. In the area of the Kolyma Loop, the thrust strike changes from NW to N and NE and it is called the Lower-Yana (Yana) overthrust fault with an amplitude of movement up to 90-100 km [36]. In this segment, the overthrust fault is involved in the distribution of Au-Sb-Hg mineralization [37]. The Charky-Indigirka thrust is expressed by intense folded and crush zone, tectonic melange with a thickness up to several tens of meters. Along the contacts of rocks of different competence, there are numerous disruptions decollements subconformable to the thrust, which are separated by tectonic zones of various structures. According to the decollements, early thrust and late mainly strike-slip movements are identified [37,38]. A zone of pyritization of rocks with a thickness from several tens to the first hundreds of meters is associated with the thrust. The content of sulfides usually does not exceed 1%, in some areas it increases to 10%.

The Polousniy-Debin terrane is mainly composed of the Upper Triassic-Jurassic clastic rocks. To the east, they are replaced by the Paleozoic and Early Mesozoic volcano-sedimentary sequences of the Nagondzhinsky and Omulevka terranes [26].

The Kolyma-Omolon superterrane, located to the northeast, is formed by a collage of terranes of various geodynamic nature, amalgamated in the Middle Jurassic (continental, oceanic and island arc terranes) [26,27,39].

2.2. *Magmatism*

Most of the magmatic formations of the Yana-Kolyma orogen and adjacent territories belong to the Main Kolyma belt and Uyandina-Yasachnaya volcanic belt, which stretches along the Polousno-Kolyma suture, on the border of the eastern margin of the Siberian craton and the Kolyma-Omolon superterrane [17,18,26,27,38].

2.2.1. Main Kolyma Belt

The Main Kolyma belt has a length of about 1110 km with a width of 150 to 200 km (Figure 1). The total area of granitoids on the daytime surface is about 73,000 km². The area of individual plutons is up to several hundred km². They form one of the largest salic igneous provinces (SLIP) of Central and Northeast Asia [40]. The batholiths of this belt are composed mainly of granodiorites and granites, intruding the rocks of marginal-continental terranes and fragmentary volcanogenic-sedimentary formations of the the Uyandina-Yasachnaya volcanic arc [41]. The U-Pb age of zircons from the granitoids of the Main Kolyma belt is in the range of 158-144 million years (Kimmeridgian-Berriasian), peak 150 ± 3 Ma [42,43,64]. ⁴⁰Ar/³⁹Ar cooling time of granitoids by biotites is 143-138 Ma [18,44] and reflects the completion time of the superterrane collision with the Siberian craton. These granitoids correspond to the S- and I-geochemical types of granites [2]. Their formation is considered as in connection with the collision of the Kolyma-Omolon superterrane with the margin of the

Siberian craton [26,27,45], as well as subduction-related, which is confirmed by the close age with the Uyandina-Yasachnaya volcanic arc [42,64].

2.2.2. Uyandina-Yasachnaya Volcanic Belt

The Uyandina-Yasachnaya volcanic belt 1000 km long and 150 km wide, is located parallel to the Main Kolyma belt on its northeastern flank (Figure 1). Volcanogenic sedimentary and volcanogenic rocks with a thickness of several hundred meters to 3,500 m consist of basalts, andesites, rhyolites, tuffs of different composition and associated sedimentary rocks [46,47]. They fragmentally overlap the strata of the Lower-Middle Paleozoic carbonate-terrigenous, carbonate, less Upper Paleozoic-Lower Mesozoic fine-detrital rocks of the Omulevka terrane and adjacent sections of the Polousno-Debin terrane [26]. The U-Pb age for zircons from acidic and intermediate volcanic rocks of this belt is in a narrow range 153 ± 2 Ma [48,49], close to the crystallization age of plutons of granitoids of the Main Kolyma belt [64]. The formation of the Uyandina-Yasachnaya arc is related to a subduction zone [26], which the direction of dipping under the Siberian craton was westward, which is argued by many researchers [17,18,34,41,50,51,64].

2.2.3. Transverse Magmatic Series

The Yana-Kolyma orogen records widely distributed transverse, northeast-trending magmatic series of granitoids and dike swarms, orthogonal to the main northwestern tectonic structures of the central part of the Kular-Nerska and Polousno-Debin terranes and the Main Kolyma belt (Figure 1A) [17,18,41]. The series begin from the Main Kolyma belt batholiths, cross structures of the Polousno-Debin and Kular-Nera terranes and fade to the southwest in the hinterland structures of the Verkhoyansk fold-thrust belt. Areas of intersection of the NW regional faults and the transverse series of granitoids and dikes are spatially associated with mineralization of the Late Jurassic-Early Cretaceous Yana-Kolyma Metallogenic belt (YKMB).

2.3. Regional Metallogenic

The ore deposits of the YKMB belt include, in fact, orogenic (Au, Sn, W) and postorogenic (Au-Ag, Au-Sb, Ag-Sb, Sn) deposits [2,27,52].

2.3.1. Orogenic Metallogeny

Numerous large Au deposits belong to the orogenic type (Natalka, Pavlik, Degdekan, Drazhnoye, Malo-Tarynskoye, Badran, etc.). They are mainly localized in trans-crustal fault zones or subsidiary faults in clastic Upper Paleozoic rocks, less often in dikes and small intrusive bodies [2,3,8,30,31]. There are also small occurrences of intrusion-related classes Au deposits (Shkolnoe, Butarnoe, Ekspeditsionnoe, Ergelyakh, etc.) [10–12]. The available data on isotope dating of ores from orogenic gold deposits of the Yana-Kolyma belt form two clusters (million years) — 142–148 and 130–138 [2,18,53]. Early and late orogenic deposits have similar mineralogical and geochemical composition; they were formed in a compressional condition. Isotope-geochemical parameters are characteristic of metamorphic and sub-crustal ore-forming systems [5,8,54]. The deposits were formed at the end of the collision of the Kolyma-Omolon superterrane and the eastern margin of the Siberian craton.

2.3.2. Post-Orogenic Metallogeny

Post-orogenic metallogeny is related to the development in the Cretaceous of an active Andean-type continental margin in eastern Siberia and the formation of the Uda-Murgal and Okhotsk-Chukotka volcanic-magmatic arcs by continuous subduction of the slab of the Paleo-Pacific Plate. Au-Ag, Au-Sb, Ag-Sb, Sn mineralization occurs, forming metallogenic zones both independent and superimposed on the orogenic Au mineralization.

There are several metallogenic zones within the western sector of the Yana-Kolyma metallogenic belt (Inyali–Debin, Olchan–Nera, Adycha–Tarynskaya) [55]. Deposits and occurrences of the Vyun ore field, considered in this article, are located on the border of Olchan–Nera and Adycha–Tarynskaya metallogenic zones.

2.4. District Geology and Mineralization

The main tectonic structure style of the Vyun ore field is determined by longitudinal NW folds and faults, transverse NE faults, as well as the structures of the Charky-Indigirka thrust (Figure 2) [17,38]. In the lying side of the thrust, mainly the Upper Triassic terrigenous deposits of the Kular-Nera terrane are exposed, in hanging side – Jurassic sandstones with layers of siltstones and mudstones of the Polousno-Debin terrane. The ore-hosting Upper Triassic deposits of the Nyakuninskaya formation are divided into three sub-formations. Lower and upper sub-formations have siltstone-mudstone composition with a subordinate role of sandstones. The middle sub-formation is characterized by alternating layers of sandstones and siltstones.

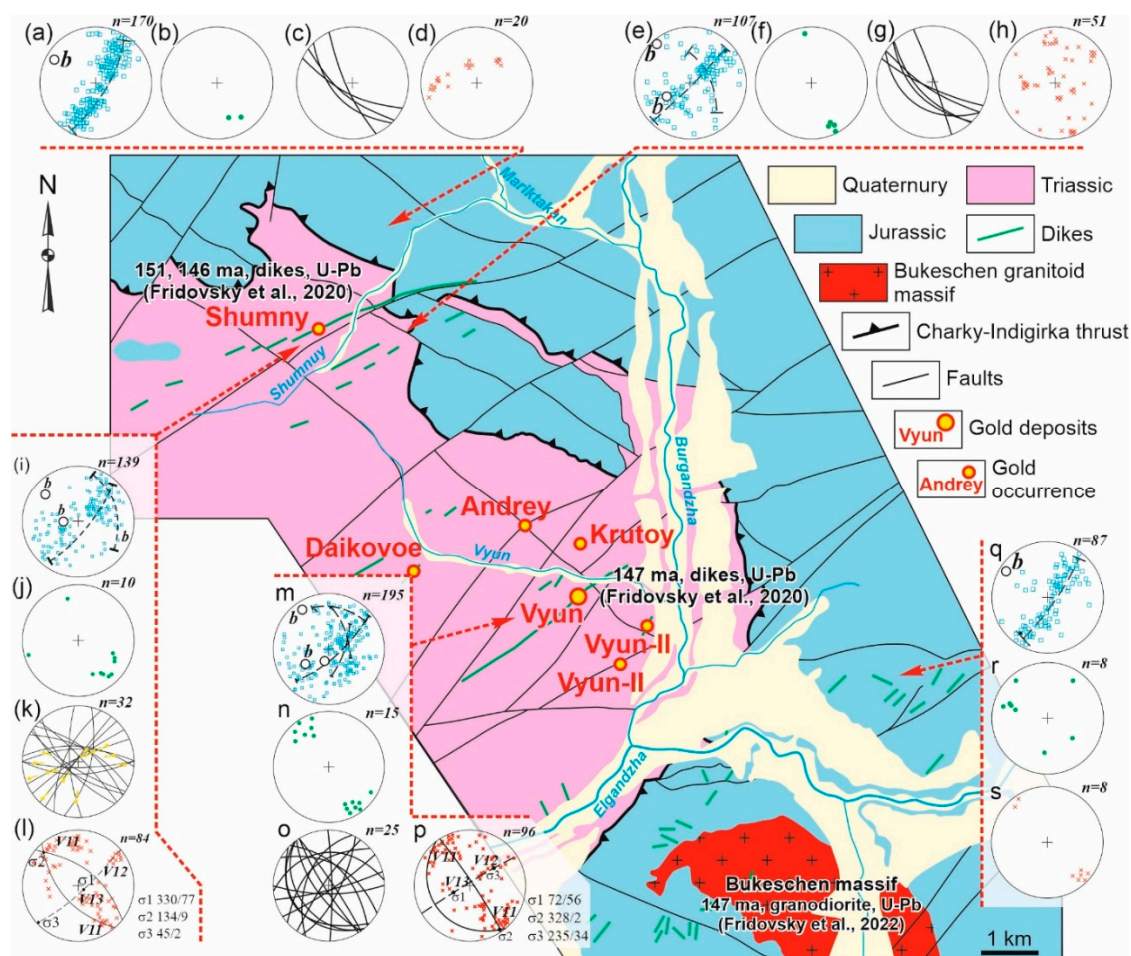


Figure 2. Simplified geologic map of the Vyun ore field, showing the position of the Vyun deposit and the Shumny area, main rock units, structures (revised and supplemented from [38]). Diagrams show: bedding poles (a, e, i, m, q), poles of dikes (b, f, j, n, r), faults (c, g, k, o), poles of quartz veins and veinlets (d, h, l, p, s). The plotings are made on the upper hemisphere of the Wulff net. Symbols in diagrams and figures here and hereafter are: dashed line – π -circle, empty circles – calculated position of the fold hinges (b), solid black lines – position of fault or ore zone (S), yellow dots with line/arrow – projections of slickenlines (l), blue empty squares – bedding (S0) poles, green dots – poles of dikes (D), red crosses – poles of quartz veins and veinlets (V), n – number of measurements. Explanations in the text.

The Vyun ore field has an Au deposit of Vyun and several ore occurrences (Vyun-II, Vyun-III, Shumny, Daikovoe, Andrey and Krutoy) (Figure 2). The last two are localized in mineralized crushing zones, the rest are confined to dikes. Geological characteristic, ore mineralogy, wall-rock alterations of the Vyun deposit and Shumny ore occurrence are given in the works [15,38,56–58] and are typical of orogenic gold deposits [2,59].

Ore veins and disseminated refractory ores hosted in dike and clastic rocks are the main ores (Figure 3). Ore veins have quartz, carbonate-quartz, chlorite-carbonate-quartz composition and are confined to dikes and seldom to faults. The disseminated ores are confined to arsenopyrite-pyrite-sericite-carbonate-quartz altered rocks [15,56,58]. Thickness of the sulfidization zone can reach up to several tens of meters. The content of sulfides usually does not exceed 1-3%, in local areas it increases to 10 %. Several generations of pyrite are described: synsedimentary/diagenetic Py1, metamorphic Py2, metasomatic arsenic Py3 and Apy1, veined Py4 and Apy2 [56,58]. Ores contain native gold of high/medium fineness (800–900 ‰) in quartz veins and invisible gold in arsenic pyrite-3 and arsenopyrite-1. The host alterations have arsenopyrite-pyrite-sericite-carbonate-quartz composition [58]. Similar changes are typical for orogenic gold deposits of the Yana-Kolyma metallogenic belt (for example, Khangalas, Badran, Malo-Tarynskoye [8,58,60]. The main vein mineral is quartz, the secondary one is carbonate [15]. Sulfides in ore bodies are unevenly distributed, their content does not exceed 1-3%. Arsenopyrite prevails among the ore minerals. Less commonly noted are pyrite, galena, sphalerite, chalcopyrite, antimonite, native gold and sulfosalts (tetrahedrite, freibergite, argentotetrahedrite, bournonite). There are four ore and two post-ore different stages of mineral formation were macroscopically and microscopic studied in the Vyun ore field [15]. Ore stages are pyrite-arsenopyrite metasomatic, pyrite-arsenopyrite-quartz, chalcopyrite-sphalerite-galena-quartz, fahlore-quartz. Post-ore stages – antimonite-carbonate-quartz and oxide oxidation zones. Enriched subcrustal lithospheric mantle and metamorphic systems were the main source of sulfur, gold and mineralizing fluids of the mineralization of the Vyun ore field, probably, as well as for other orogenic gold deposits of the YKMB [5,18,33,54,61].

Terrigenous rocks of the Vyun ore field are intruded by Late Jurassic-Early Cretaceous dikes and massifs of granitoids of the small intrusion complex (Figure 2) [17,18,38]. The compositions of dikes include trachybasalts, trachyandesites, dacites, and granodiorites. The dikes on all studied sites and occurrences are dipping at mainly steep angles and associating with various faults. The dikes are boudinaged and bent. Individual dikes have been traced to a distance of 4.0-4.5 km, their thickness ranges between tens of cm and 5-7 m, seldom reaches 30-40 m. Dike bodies, like small massifs, have a NE strike, they form the Nitkan transverse belt 10–15 km wide and 30–40 km long. The NE strike of the dikes dominates in both walls of the Chakry–Indigirka thrust, and fewer dikes have sublatitudinal and NW strikes. At the stage of formation of the gold mineralization, dikes, as well as faults, were concentrators of ore-forming fluids. The dikes have been transformed into quartz-sericite-chlorite-carbonate aggregate with sulfide dissemination.

Both the intensely altered mafic and the slightly altered intermediate and felsic rocks of the dikes have close trace element contents, which are also close to those of the Late Jurassic mafic and felsic dikes and small intrusions. These trace element concentrations correspond to rocks between the E-MORB and OIB with middle ocean ridge basalt (MORB)-like HREE content. The U–Pb SHRIMP-II dates obtained for the dikes corresponded to the Late Jurassic interval of 151–145 Ma (Figure 2) [17,38].

The Bukeschen small granodiorite massif has an area up to 6×3 km² (Figure 2) [18]. The Bukeschen massif is composed of diorites, quartz diorites, granodiorites, leucocratic granites, subalkaline granites and leucogranites. The concordant age for the peripheral parts of zircon grains from the granodiorite of the Bukeschen massif is 144.5 ± 0.9 million years [18,33]. Similar geochemical and isotopic (Sm–Nd and Rb–Sr) characteristics have been determined for granitoids of the Bukeschen massif and Late Jurassic dikes of various compositions [18,33].

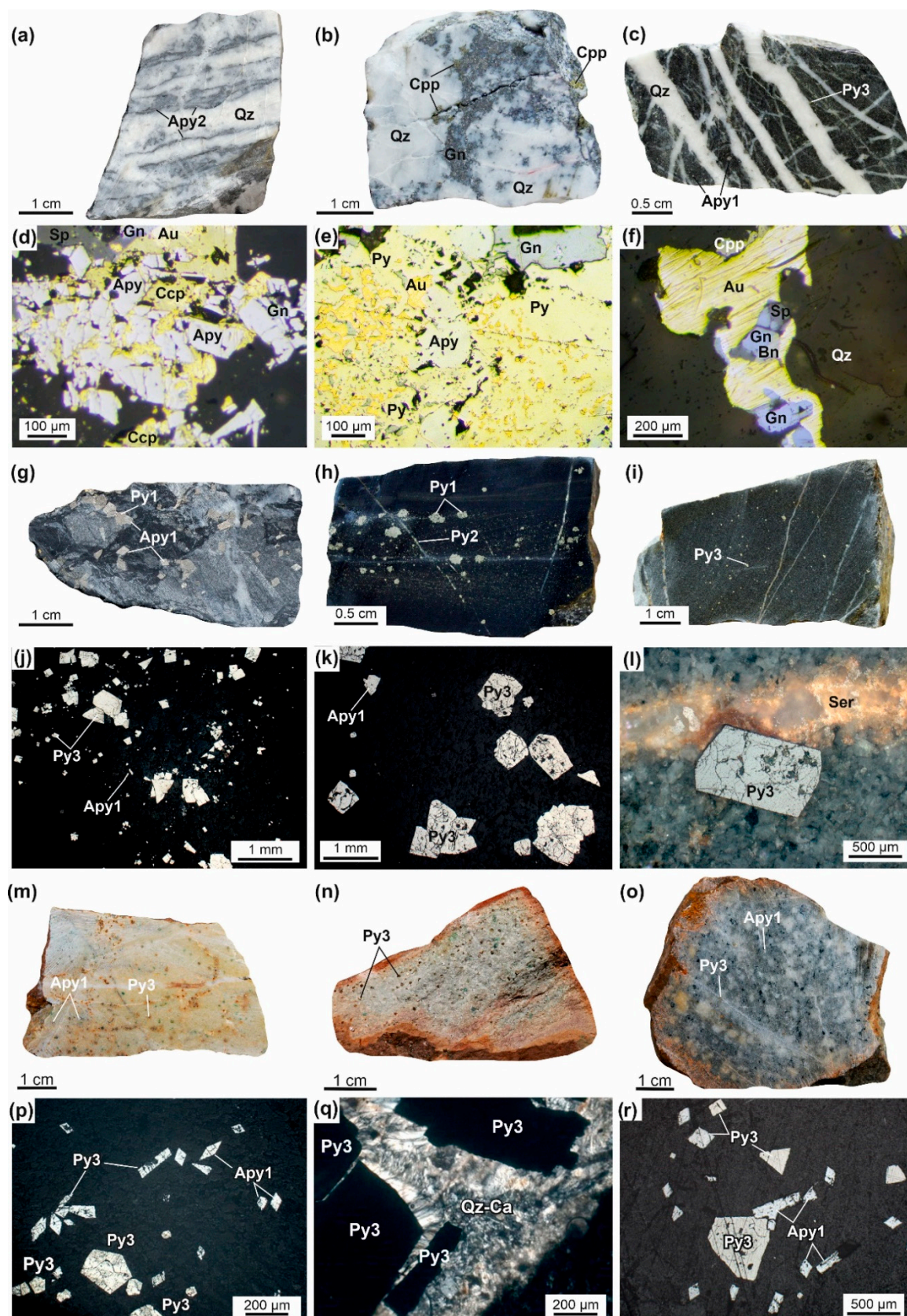


Figure 3. Characteristics of vein style (a-c) and disseminated style (g-i, m-o) ores of the Vyun deposit and Shumny area (Reflected light photomicrographs showing mineral assemblages of the vein (d-f) and disseminated (j-l, p-r) style ores). (a) Coarse-banded texture of quartz with arsenopyrite-2 dissemination; (b) Quartz containing galena and chalcopyrite ; (c) – quartz vein of veinlet structure containing pyrite-3 and arsenopyrite-1 ; d – myrmekitic and oval particles of native gold in pyrite, associated with arsenopyrite and galena; e – replacement

of cataclastic arsenopyrite crystals with native gold, chalcopyrite, galena and sphalerite in quartz; f – native gold with inclusions and in growth with chalcopyrite, with galena, sphalerite and burnonite in quartz. The visible gold appears to be paragenetically late; G – quartz veinlets with arsenopyrite-1 and pyrite-3; h – veinlet-disseminated mineralization in siltstone, caused by spherulitic and layered accumulations of diagenetic pyrite-1 and thin metamorphogenic pyrite-quartz veinlets with pyrite-2; i – metasomatic veinlet-disseminated mineralization with pyrite-3 and quartz; j-k – disseminations of pyrite-3 and arsenopyrite 1 in sandstone; l – the metasedimentary rock is sericite-pyrite-altered; m-o – disseminated sulfide mineralization with metacrystals of pyrite-3 and arsenopyrite-1 in dikes of trachyandesite (M-N) and andesite (O); p – dissemination of pyrite-3 and arsenopyrite-1: pentagondodecahedral shape and zoning are characteristic of individual large pyrite crystals; q – rod-like rims of quartz-carbonate composition; r – dissemination of pyrite-3 and arsenopyrite-1 in the alteration of dikes. Abbreviation: quartz – Qz; sericite – Ser; native gold – Au; arsenopyrite – Apy; pyrite – Py; galena – Gn; chalcopyrite – Cpp; sphalerite – Sp; bournonite – Bn.

3. Materials and Methods

The research was based on detailed field work and observations of ore bodies and their relationship with tectonic structures (folds, faults, foliations, kinematic indicators). Structural-kinematic studies in the Vyun ore cluster were conducted using up-to-date methods [7,62–65]. The morphology of ore veins in natural exposures was studied and their relations with geological structures and dikes were also established. Measurements of planar and linear structures (bedding, cleavage, vein-veinlet bodies, faults, ore zones, jointing, fold hinges, boudinage, slickenlines, etc.) were made. The slip direction was determined using several types of kinematic indicators – slickenlines, drag folds, tension gashes, and others. The kinematics of main deformation stages and the paleo-orientation of stress were reconstructed relative to major deformation structures of NW strike. Structural data were statistically analyzed and plotted on the upper hemisphere of the Wulff stereographic net. The nomenclature of structural elements is taken from [7,9,66]. Planar structures (i.e., S0 – bedding, V – veins, S – faults /cleavage, D – dike) are given as dip azimuth/dip angle (e.g., 60/70 denotes eastward dip at 70). In the vein index V11, V12, the first digit indicates the relative time of the deformation event, the second – the system of structural elements to which the vein belongs. For example, in this case, the veins are related to the first stage of deformations D1 and belong to the first and second systems, respectively. For linear structures (i.e., b – fold axes, L – boudinage, l – slickenlines), denotation plunge azimuth/plunge angle is used (e.g., 110/50 means plunge azimuth of 110 and plunge angle of 50). Signs S1 and l1 denote the relation of a structural element to a particular deformation stage (D1) event.

4. Results

The Vyun ore field is one of the key areas of the Yana-Kolyma orogen to study the tectonic and metallogenic evolution structures between the Kular-Nera and Polousno-Debin terranes. In the ore field, these tectonic units are separated by the Charky-Indigirka thrust, which paraautochthon and autochthon have different structures and metallogeny. Mapping of geological structures shows many superimposed structures, which reflect a long – term multiphase (pre-mineralization, mineralization, post-mineralization) deformation history (Figure 2).

4.1. Structural Analysis of Two Au Districts in the Parautochthon of the Charky-Indigirka Thrust

In the parautochthon of the Charky-Indigirka thrust there are the Vyun gold deposit (65°97'33.3" N, 138°25'06.1" E) and the Shumny gold area (66°01'58.7" N, 138°14'90.4" E).

4.1.1. Vyun Gold Deposit

Ore bodies of the Vyun gold deposit are represented by gold-quartz veins and disseminated pyrite-arsenopyrite mineralization with "invisible" gold in the dike and the surrounding terrigenous rocks (Figure 4) [57,58]. Mineralization dominates in the dike and its contacts with sandstones and siltstones of the Nyakuninskaya formation of the Upper Triassic (Figure 5). Au content in pyrite in alteration rock after dikes between 0.3 and 25.8 ppm, after sandstones and siltstones between 0.3 and 159.5 ppm, arsenopyrite alteration rock after sandstones and siltstones between 28.9 and 58.4 ppm [58]. The dike of trachyandesites and dacites has an east-northeast (60-70°) strike, a thickness of 2-5 m, a length of about 800 m [15,38]. The dike dips north-west and south-east at angles 47-800. On the northeastern flank, quartz veins are removed from the dike by 30-40 m. The gold content in veins is up to 190 g/t (average 8-14 g/t) [15].

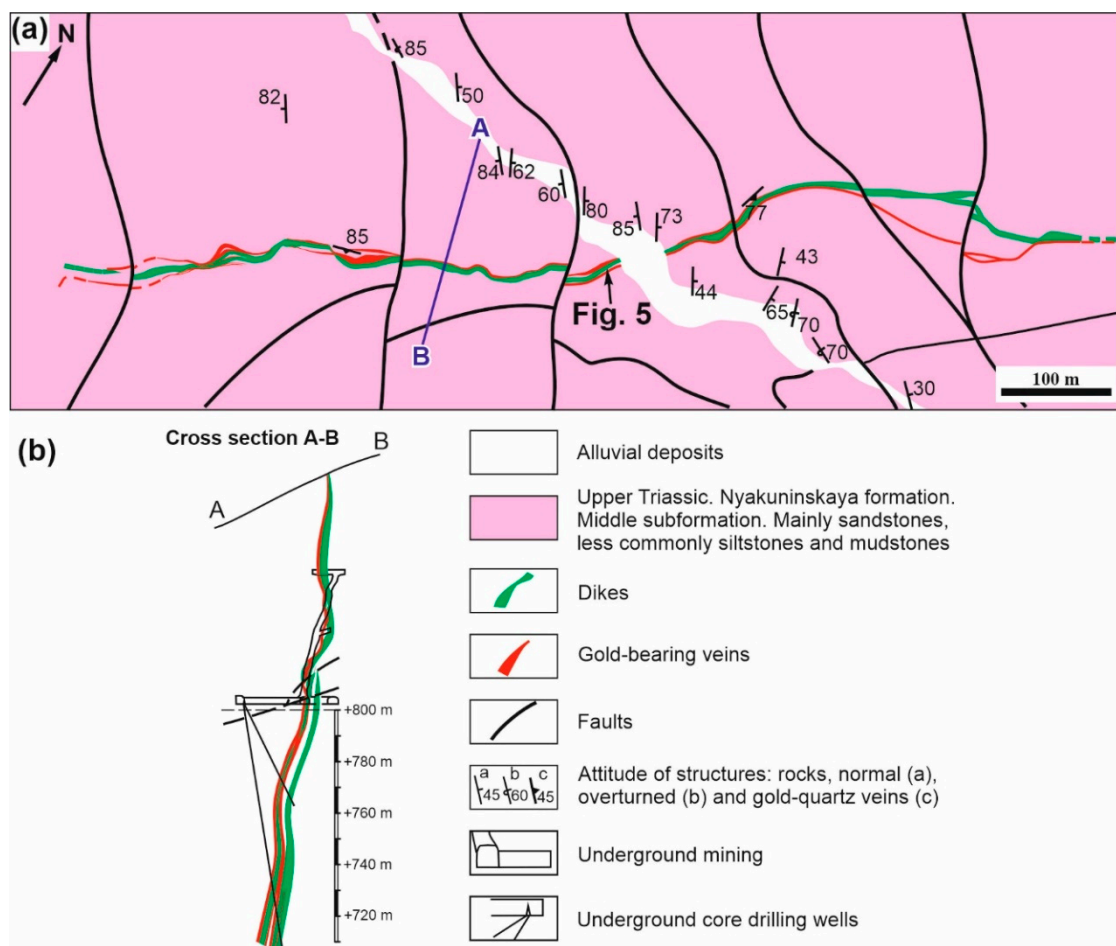


Figure 4. (a) Geological sketch map showing structure, dike position, stratigraphic divisions and gold ore bodies; (b) Schematic E-S-trending section from A to B across the Vyun deposit (modified from [15] and our field observations).

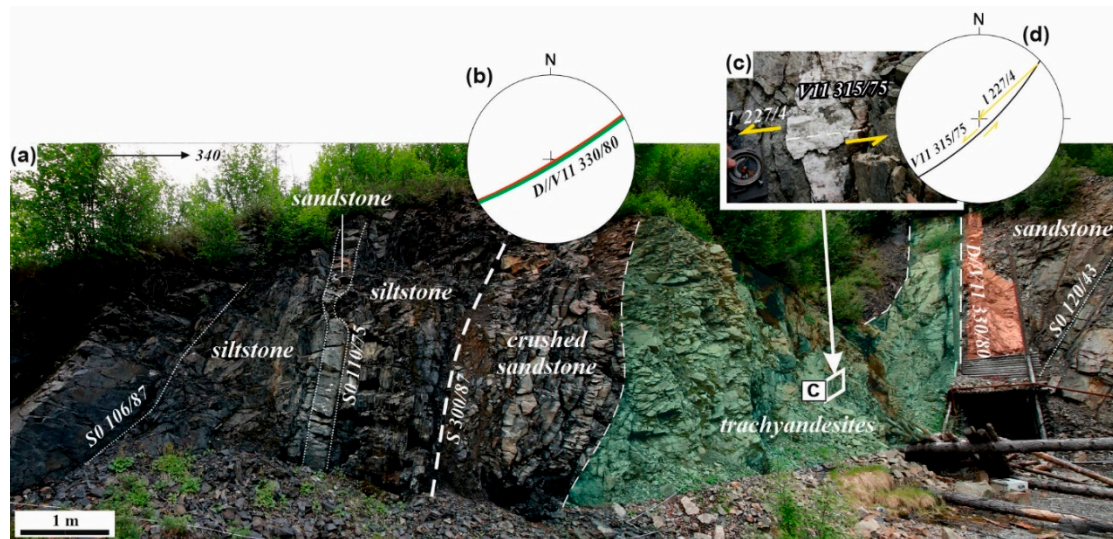


Figure 5. Photographs showing the relationship and structures of gold veins and trachyandesite dike in the Vyun deposit (a); (b) – concordant orientation Au orebody and dike; (c) – sinistral strike-slip accretionary slickenlines of the quartz hanging walls. Arrows show the direction of displacement of the quartz hanging walls. Enlargement of post-ore fault plane and steps of quartz slickensides, indicate sinistral strike-slip movement; (d) – projections of slickenlines of the quartz hanging walls.

Various deformation structures occur at the Vyun deposit. The most widespread are the early cylindrical symmetrical and asymmetric folds of the NW strike with gentle ($b - 4-14^\circ$) hinges and steep axial surfaces (Figure 6). Asymmetric anticlinal folds with long northeast and short southwest limbs, what is related to the southward direction of rock transport during J_3-K_1 accretion-collision events. There are folds with a round hinge (Figure 6, a-c), chevron folds with a sharp lock (Figure 6, d, e). The visible width of the folds is between the first meters and several hundred meters. The early folds are accompanied by a cleavage conformable to bedding. It is platy, rarely shelly-platy, and its intensity depends on the rock composition. The most intense cleavage is visible in siltstones, whereas in sandstones it becomes coarse-platy. Its regional NW strike changes in areas of superposed strike-slip deformation. Overturned recumbent folds with flat axial surfaces are also mapped (Sas 20/12) (Figure 6, e, h). The superposition of these folds on the early folds occurred in a coaxial stress field, what is typical for progressive deformations (Figure 6, e).

All mentioned above and close orientations of the folds suggest that the early fold-thrust structures (F1/1, S1/1, F1/2) were formed under conditions of progressive deformation D1 (Figure 6). Such a possibility of the formation of complex folds during progressive deformation is described in [67,68].

Post-ore structures are related to strike-slip strains. Folds with steep hinges are common. They are noticeable in the dike walls and quartz vein of the Vyun deposit (Figure 7a, b). Z-type folds with the hinge plunge to the ESE ($b - 104/66$ and $108/44$) (Figure 7b, c). Asymmetric anticlines with a long NE (S0 42-50/66-77) and short SE (S0 120-130/43-69) limbs are typical. The hinge of the fold is near perpendicular to the direction of the accretion slickenlines (I 227/4) at the contact of the quartz vein V1 315/75 (Figure 7b, diagram). On the limbs of early folds in siltstones in sandstones, intraplate drag folds of NW strike can be observed ($b3 130/44$) (Figure 7d, e, f). Such folds were formed during reverse-dextral strike-slip displacements on the structures of the north-western strike and reverse-sinistral strike-slip displacements by the faults of north-eastern strike associated with them (Figure 7c). Dikes and faults of NE strike are also displaced by dextral post-ore strike-slip faults (Figure 7g, h).

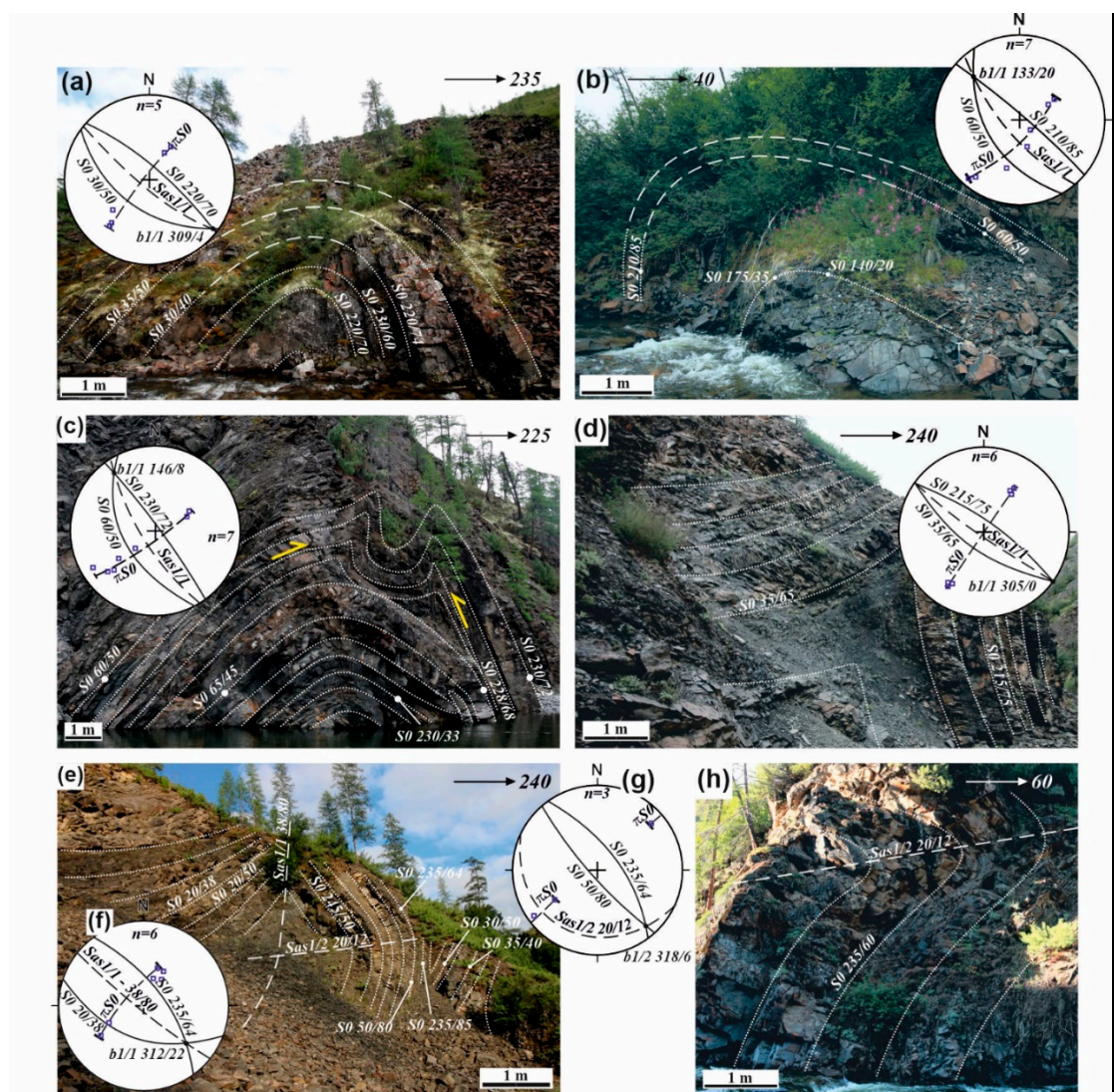


Figure 6. Photographs showing the folds from the Vyun gold deposit. (a, b, c, d, e, f) F1/1 folds with rounded (a, b, c) and sharp (d, e) hinges and steep axial surfaces Sas1/1 and diagrams of bedding poles; (g, h) – recumbent fold F1/2 with a gently sloping axial surface Sas1/2 and diagram of bedding poles.

The faults of the NW and NE strike prevail (Figure 3). Northwestern thrusts and reverse faults of predominantly SW vergence limit tectonic plates, within which there is a change in the intensity of deformations. The thrust faults are associated with steep NE faults – lateral ramps of the Bukeschen-Elgendzhinskaya system with dominant strike-slip kinematics. These faults determine the position of the Tithonian dikes and orogenic gold-quartz mineralization.

Quartz, quartz-carbonate, quartz-chlorite-carbonate veins are common in the Vyun deposit and the Shumny area. They occur in dikes, on their contacts with host rocks and in sandstones. Analysis of the attitude of quartz veins and veinlets revealed three variously-oriented systems (Figure 4). Veins of the first system V11 have persistent parameters; they are conformable with the NE strike of the dikes (Figures 4 and 8). The veins V11 are the thickest, extended, localized along the plane σ_3/σ_1 . Quartz veins of the second system V12 are conformable with the bedding plane and thrust sheets, whereas veins of the third system V13 oriented are conformable with V12, but they dip in the opposite direction. Quartz veins of 2 and 3 systems are thin (up to the first centimeters). Such systems of quartz vein mineralization, which are related to the reverse and thrust fault stress field, are also found at other gold deposits in the central part of the Kular-Nera terrane (Bazovskoye, Malo-Tarynskoye, Khangalas, Badran, Levoberezhnoye and Sana) [7,8,31,32,58,69–71,76]. Subvertical position of the plane σ_3/σ_1 indicates a reverse/thrust stress field during the formation of gold-quartz bodies of the

Vyun area. The calculated values of the paleo stress fields are as follows: $\sigma_1 - 72/56$, $\sigma_2 - 328/2$, $\sigma_3 - 235/34$.

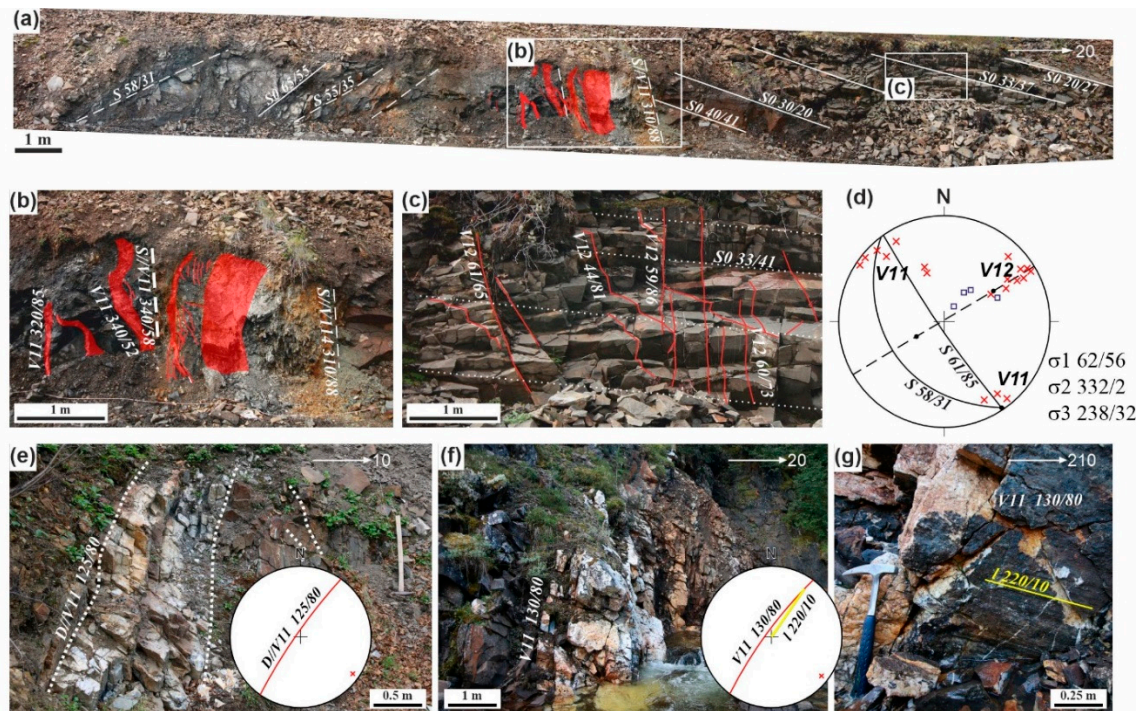


Figure 8. Photographs showing the morphology of quartz veins from the Vyun gold deposit. (a) quartz veins localized in the NW fault; The labels of images (b) and (c) show the photo locations in bottom row; (d) – diagram of the poles of quartz veins shown in Figure 8a, b, c; (e,f) – quartz veins of the NE strike; (g) – sinistral strike-slip accretionary slickenlines of the quartz walls. Arrows show the direction of displacement of the quartz hanging walls.

4.1.2. The Shumny Area

The Shumny area is dominated by the disseminated mineralization of pyrite in the dike of trachybasalts, trachyandesites, andesites, dacite, granodiorites and sandstones [61]. Au content in pyrite from alteration rock after dikes between 9.8 and 53.9 ppm, after sandstones between 2.3 and 38.4 ppm [58]. On the SW flank, the dike has a basic and medium, acidic on the NE, and a mixed composition in the center (Figure 9). The host rocks are sandstones and siltstones of the Middle-Upper Nyakunyinskaya formation of the Upper Triassic. The dike is subvertical of the ENE strike. At certain intervals, its occurrence changes to NNW, probably due to late sinistral strike-slip faults. They also shift the dike to a distance of the first tens of meters (Figure 9). The apparent thickness of the dike is up to 30 m, the length is about 4.5 km.

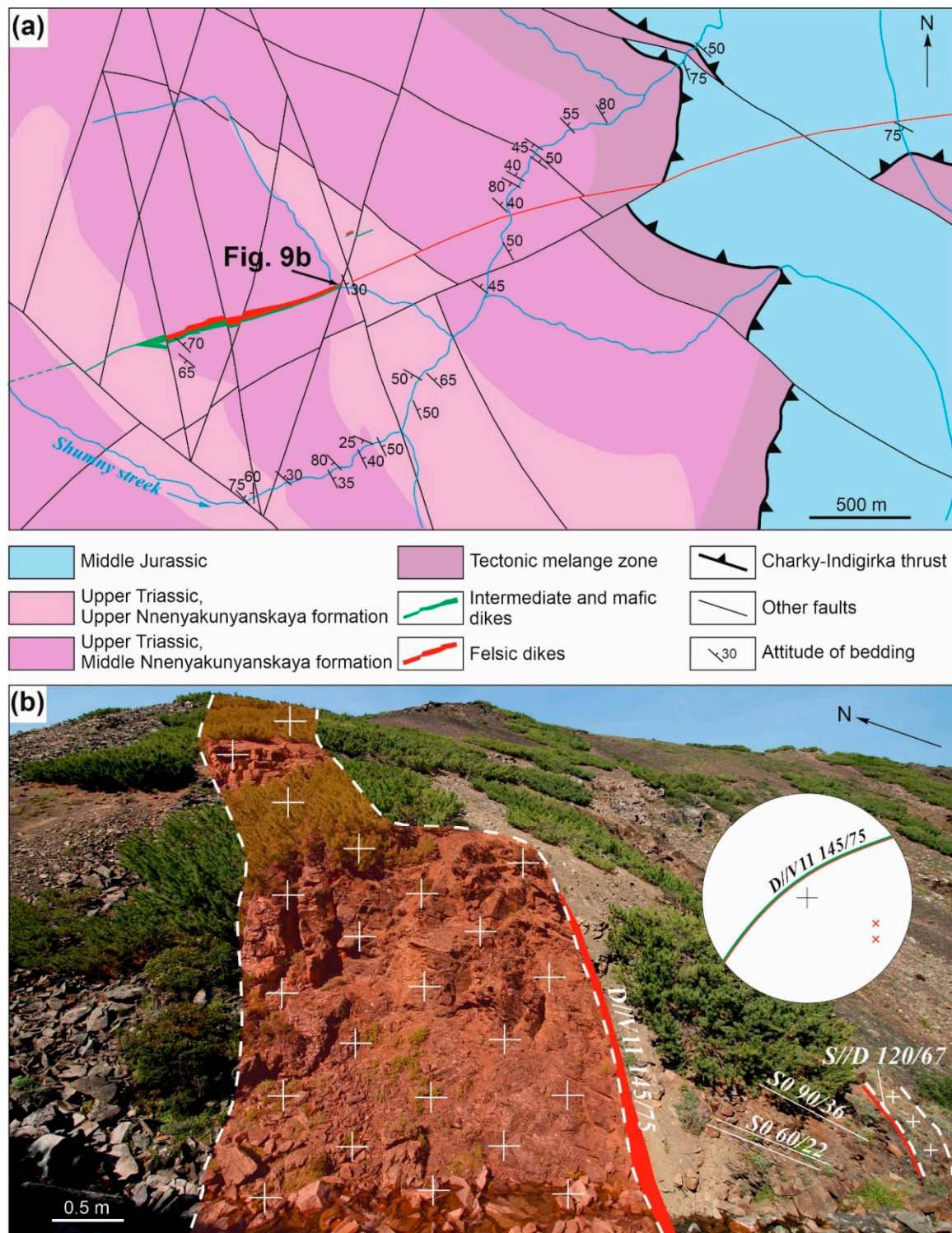


Figure 9. Geological sketch map showing structure (a) (modified after internal company data and our field observations). Photographs of dike and Au-quartz vein V1/1 (b), Shumny area.

Features of the deformation structures of the Shumny area are determined by the proximity to the Charky-Indigirka thrust, which separates the Triassic clastic deposits of the Kular-Nera terrane from the Jurassic clastic deposits of the Polousno-Debin terrane. In the lower reaches of the Shumny creek, the axial part of the thrust and the zone of intense deformations and tectonic melange with an apparent thickness of about 500 m are exposed (Figure 10). In thrust front, the Triassic terrigenous rocks are crushed into isoclinal and compressed folds F1/1 of the north-western strike with gently sloping ($4-12^\circ$) hinges (Figure 10b, c). Boudinage structures develop parallel to the hinges (I 123/8

(Figure 10d), l 320/8 (Figure 10f). Superimposed deformations are represented by Z-type axonoclines (b 275/48), related to the dextral strike-slip faults (Figure 10e).

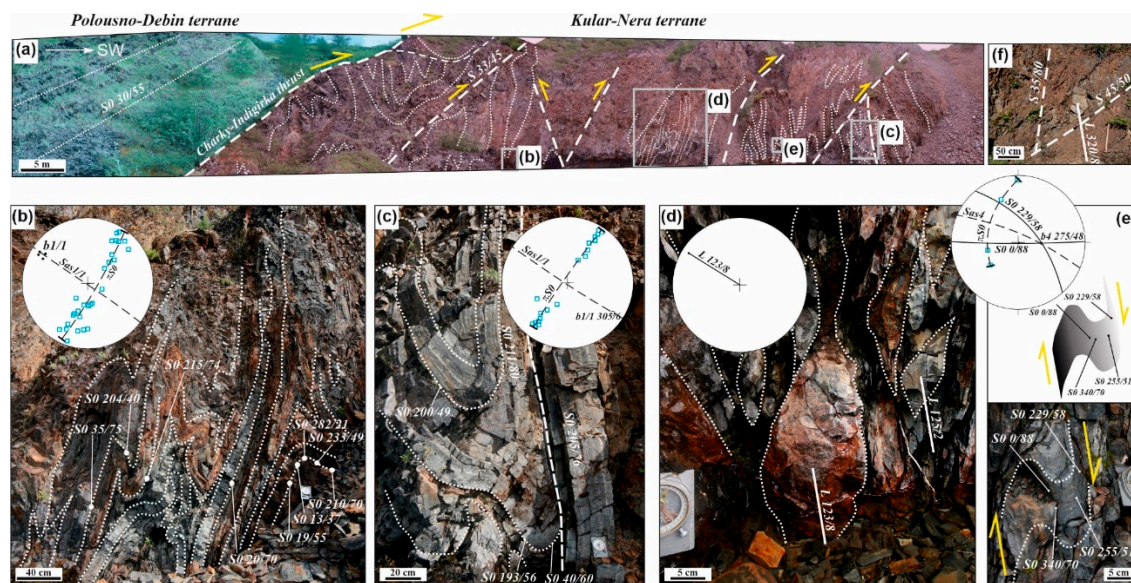


Figure 10. Photographs showing the deformation styles of the Charky-Indigirka thrust from the Shumny area (section view). (a) tectonic contact along the gently dipping ore-ore fault of the Middle Jurassic clastic deposits of the Polousno-Debin terrane and the Triassic clastic deposits of the Kular-Nera terrane. The labels of images (b), (d), (e) and (c) show the photo locations in bottom row; (b, c) isoclinal folds F1/1 of the NW strike and diagrams of bedding poles; (d) boudinage structures with l axes coaxial to the position of the hinges of the isoclinal folds F1/1 and diagram of the position of the budina axis (e) – post-ore Z-type axonoclines and diagram of bedding poles.

At a distance from the thrust, the deformation structures are identical to those described for the Vyun deposit. The open, cylindrical folds F1 of the NW strike occur here (Figure 11a-c). Overturned and compressed folds of the NW orientation also occur (Figure 11d-e). In case of late normal fault in combination with sinistral strike-slip movements on the faults of the NW strike and normal fault in combination with dextral strike-slip movements on the NE faults (S 315/85), transverse folds F2 with a vertical axial surface Sas2 and a moderately steep hinge b2 are formed (Figure 11f).

In the left side of one of the right tributaries of the Shumny creek, you can observe the dike boudins and near-fault folds can be observed F3 (Figure 12). In the lying wall of the intrastratal fault S/SO 45/55 a boudinaged (l 87/46) dike with a thickness of about 3 m is exposed. In the proximal contact of the fault, the siltstones are crushed into a fold with a moderately steep hinge b 125/30. The Z-shaped morphology of the fold indicates reverse-dextral strike-slip kinematics of movements on the fault. A small boudin of the dike l 135/35 is identified in the hanging contact. The close position of the axes of the boudin dikes and the hinge of the fold indicates their syngenetic character.

The poles of quartz veins and veinlets of the Shumny area form 3 differently oriented systems in diagrams (Figure 2, l). Veins of the first system V11 have persistent parameters; they are conformable with the NE strike of dikes (Figure 9). V11 veins, as well as on the Shumny area, are the thickest, extended, they are localized along the plane σ_3/σ_1 , parallel to the dikes (Figure 2, l). Quartz veins of the second system V12 are conformable to the bedding plane and thrust sheets, veins of the third system V13 oriented conformable to V12, but they dip in the opposite direction. Quartz veins of V12 and V13 systems are thin (up to the first centimeters). They are also grouped along a vertical plane σ_3/σ_1 , which indicates reverse/thrust stress field during the formation of gold-quartz bodies with the following stress fields of stage D1: σ_1 – 330/77, σ_2 – 134/9, σ_3 – 45/2 (Figure 2, l).

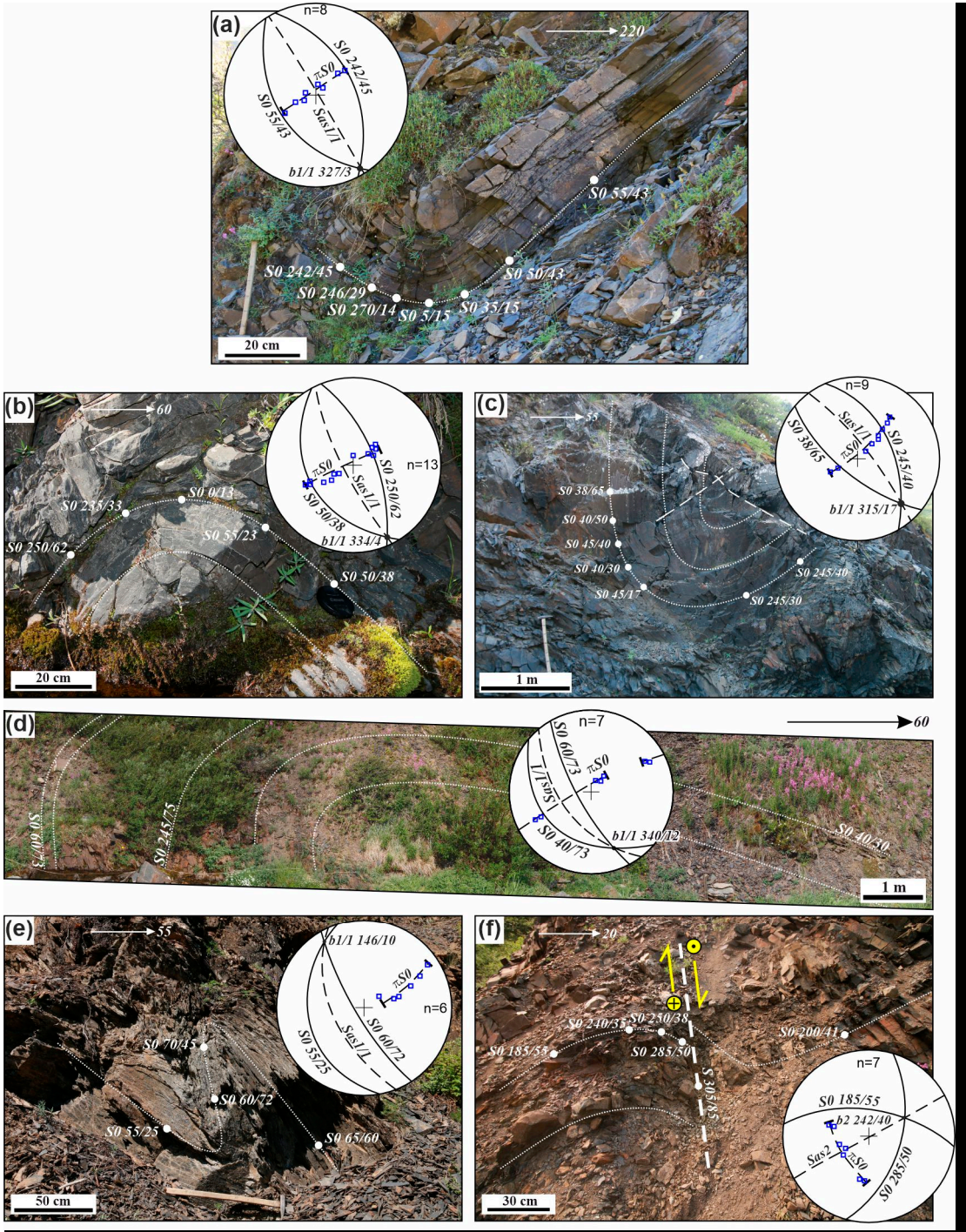


Figure 11. Photographs showing the folds from the Shumny area. (a-c) northwest normal folds with steep axial surfaces Sas1/1 and diagram of bedding poles; (d, e) overturned folds F1/1 with moderately steep axial surfaces Sas1/1 and diagram of bedding poles; (f) – transverse fold F2 with vertical axial surface Sas2 and a moderately steep hinge b2, associated with normal fault in combination with dextral strike slip movements on NE faults and normal fault in combination with sinistral strike slip movements on the NW faults and diagram of bedding poles.

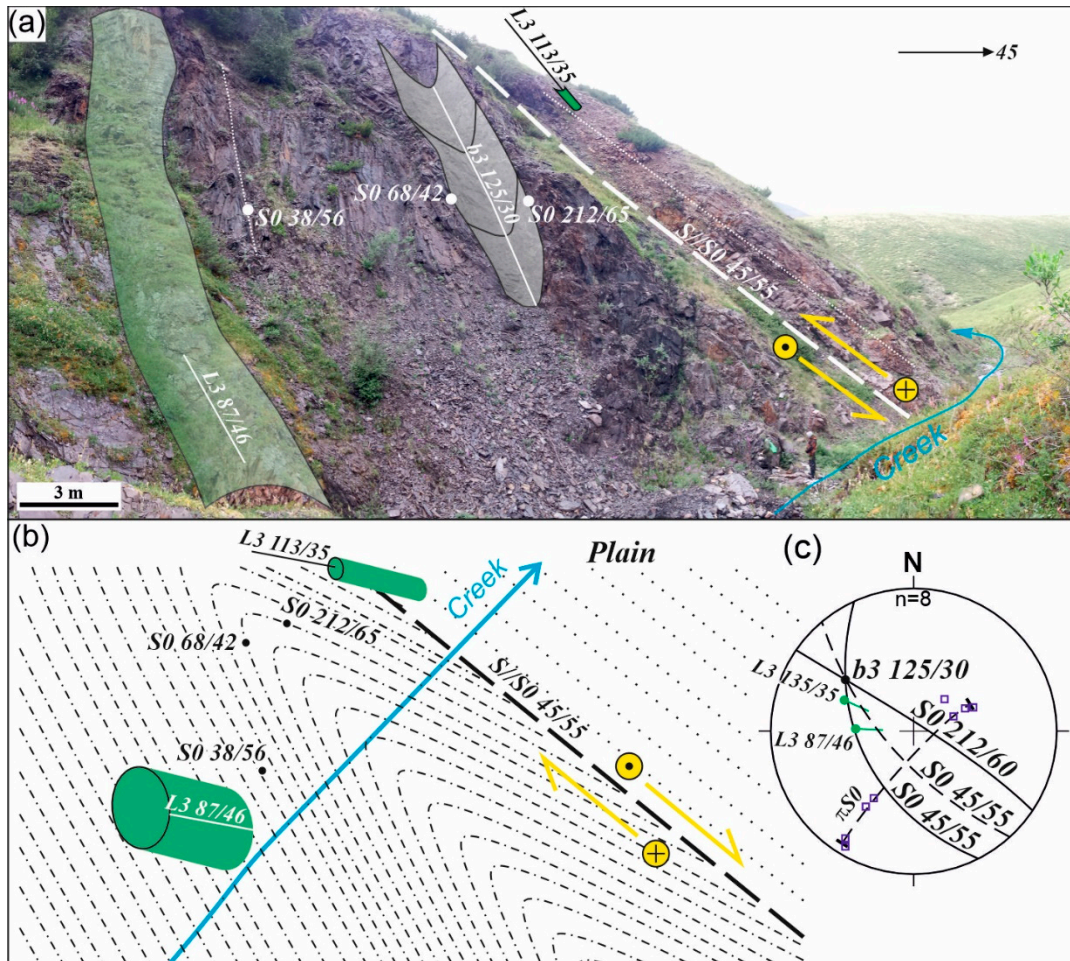


Figure 12. Photograph (a), kinematic scheme (b) and diagram of bedding poles (c) showing relations of boudines of dikes, folds and intraplate fault from the Shumny area. Green dots with lines – boudin axes.

4.2. Structural Analysis of Allochthon of the Charky-Indigirka Thrust

In the allochthon of the Charky-Indigirka thrust (Polousno-Debin terrane), there are open, rarely compressed folds F1/1 with hinges b gently dipping to the SE (Figure 2, 13). They are morphologically close to the folds F1/1 visible in paraautochthon (Figure 6, 11). F1/1 folds are accompanied by a boudinage, the axes of which are coaxial to the position of the hinges b1 (Figure 13d).

There are also F1/2 folds with gently sloping axial surfaces Sas1/2 – 68/35 (Figure 14 a). Shear deformations D2 and D3 have not been detected, but they are assumed. The late fault structures of the stage are revealed D4 (Figure 14b and c). These are low-amplitude up to 4 m gently sloping faults of the submeridional strike S4 255/40 (Figure 14a, b). There are also systems of conjugated steep faults S4 – 295/63 and S4 – 145/66. Economically significant occurrences of gold mineralization in allochthon have not been established.

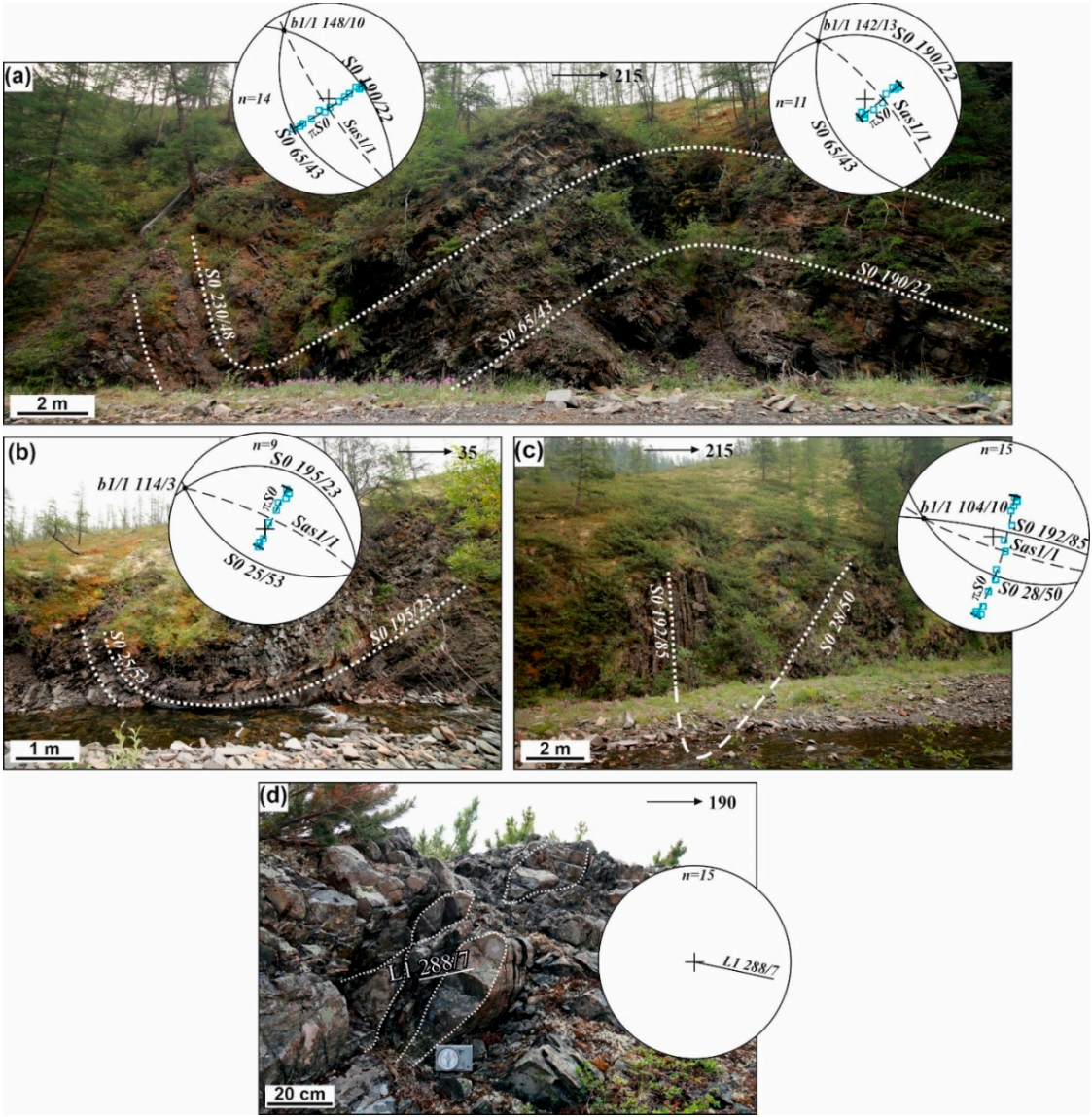


Figure 13. Photographs showing the deformation styles of allochthon of the Charky-Indigirka thrust from the Shumny area (section view): (a-c) northwest folds with steep axial surfaces Sas1/1 and near-horizontal hinges b1/1 and diagram of bedding poles; (d) boudinage L coaxial to hinges b1 104-114/3-10.

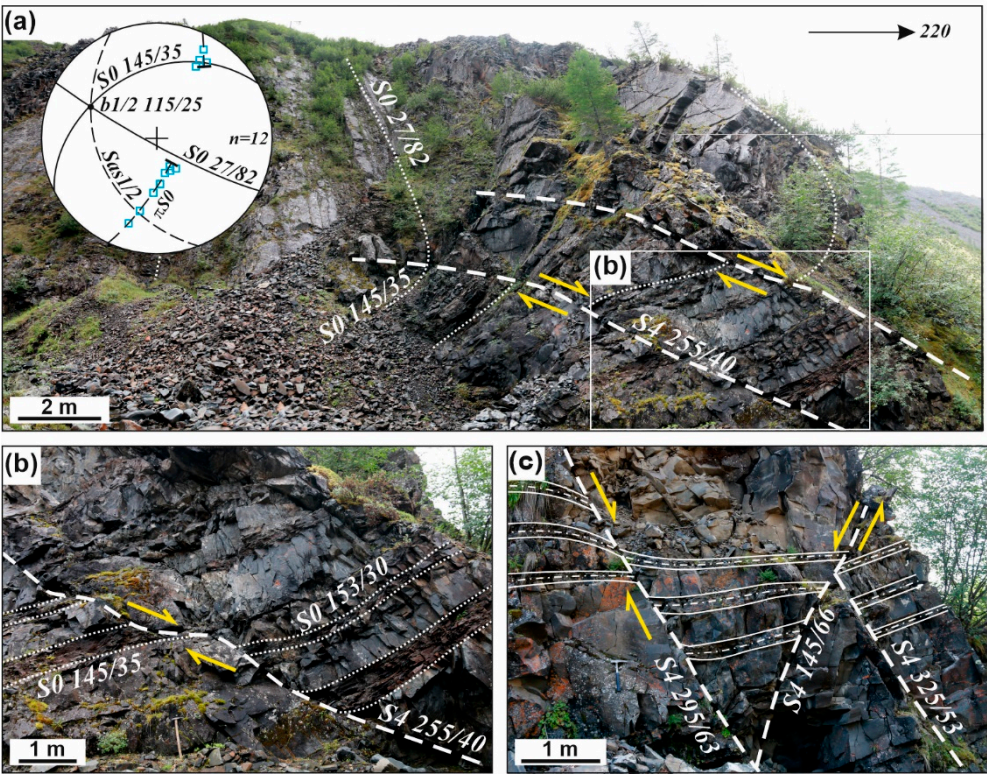


Figure 14. Photographs showing the deformations in allochthon of the Charky-Indigirka thrust: (a) recumbent fold F1/1 and diagram of bedding poles; (b) gently sloping normal faults S4; (c) conjugated system of steeply dipping normal faults S4.

5. Discussion

5.1. Style of Deformation, Space-Time Distribution and Structural Control

The obtained results of structural observations, as well as data [7,38,57,58,66] are summarized in Table 1, where the main deformation and mineralization events, magmatism, metamorphism of the wall rock in the Vyun deposit and Shumny area are shown.

Table 1. Summarizing of structures, magmatism, mineralization and deformation events in the Vyun deposit and Shumny area of the Yana-Kolyma orogenic field.

Features	Deformation events			
	D1	D2	D3	D4
Structures	NW-SE folds (F1/1) with a steep axial surface Sas1/1 and b1/1 dipping 0° to 10°; S1: interlayer decollements, intrastratal ramps, NW thrusts, transverse and oblique ramps, cleavage of the fault, boudinage (L1); slickenlines	S-type N-S, NW-SE, NE-SW folds (F2) with b2 dipping 40° to 80°; S2: NW-SE sinistral strike-slip fault, horizontal slickenlines (I2)	Z-type E-W folds (F3) with b3 dipping 40° to 80°; NW-SE dextral strike-slip fault, horizontal slickenlines (I3), boudinage (L3)	Low-amplitude normal faults S4 of the fault kinematics of NE and NNW strike, slickenlines downdip the faults
	downdip the rocks (I1); N-W folds F1/2 c			

	with gently dipping axial surface Sas1/2 and b1/2 dipping 0° to 10°			
Kinematics of NW faults	Thrust	Sinistral strike-slip fault	Dextral strike-slip fault	Normal fault
Mineralization	Au Ore veins and disseminated refractory ores			
Metamorphism	Greenschist metamorphism of the wall rock			
Magmatism, age	Pre-ore magmatism: mafic, intermediate and felsic dikes, strike NE-SW 151-145 Ma; granitoids, 144.5 Ma			
Orientation maximum principal stress	NE-SW	E-W	N-S	W-E
Graphical model				

5.1.1. Pre-Mineralization

Strike of the early F1/1 folds and slope of their axial surfaces (Sas1/1), as is the vergence are interpreted to indicate an NE-SW compressional stress field D1 (Table 1, Figure 15a). At this stage, the main regional faults (Adycha-Taryn, Charky-Indigirka), transverse and oblique ramps are formed. The hinges b1/1 of the early folds F1/1 are conformable to the hinges b1/2 of the superimposed overturned recumbent folds of the NW strike with gently sloping axial surfaces F1/2. Superimposition of F1/2 folds on the early F1/1 folds occurred in a coaxial stress field with NE-SW compressional stress field. Such recumbent folds and those close to them in morphology have a regional distribution in the Charky-Indigirka thrust front [6,7,17,66].

Field observations of the relationship of folds F1/1 and F1/2 and reliably dated dikes [17,38] and granitoid plutons [18] show that the folds were formed earlier (Figure 15). Dikes and granitoids were intruded at the beginning of the Berriasian–Tithonian (144.5-151 Ma) after the peak of metamorphism of the greenschist facies of the wall rock. Dike swarms and granitoid plutons form transverse northeast-trending series orthogonal to the main northwestern tectonic structures of central part of the Yana-Kolyma orogen and Main Kolyma belt. Their position and localization in the extensional structures indicate NE-SW compressional stress field during the formation of these magmatic complexes. Dike swarms of mafic rocks mark the relations between ore-forming fluid pathways and deep lithosphere. However, there is no genetic link between dikes and mineralization. Considering these and the above given structural data we assume that the described fold-thrust deformation events D1 occurred no later than the Oxfordian at the turn of the Middle and Late Jurassic in the conditions of a single continuous (non-stop) tectonic regime during frontal convergence of the Kolyma-Omolon superterrane with the eastern margin of the Siberian craton [17].

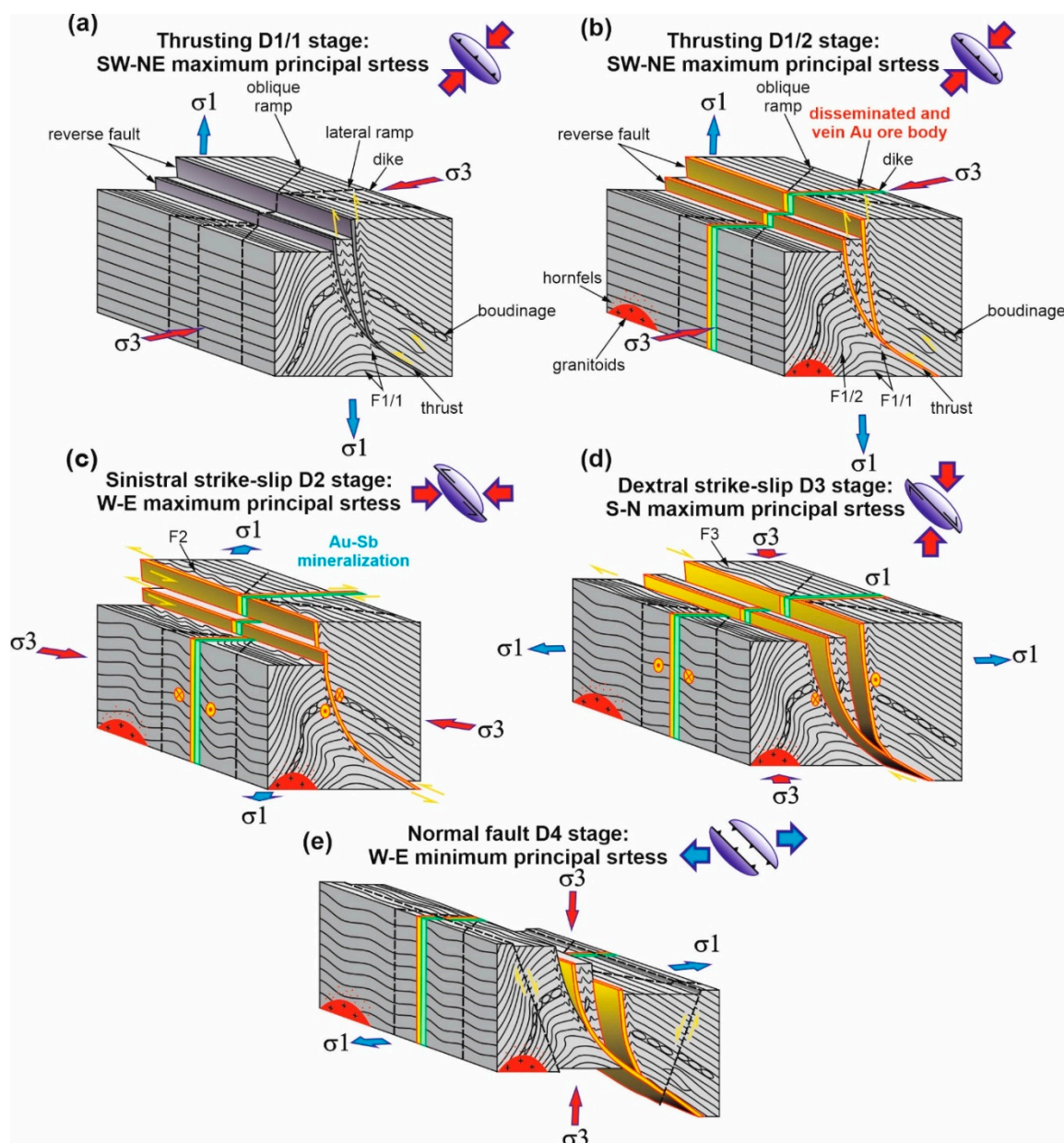


Figure 15. Schematic diagrams illustrating the geologic history and structural setting for the Vyun deposit and Shumny area, Yana-Kolyma orogen, eastern Siberia. (a) NE-SW compressional stress field (D1/1) prior to mineralization formed folds F1/1, F1/2, NW regional faults S1, metamorphism; (b) magmatism, reactivation of older faults and resulted Au mineralization are related to NE-SW compressional stress field (D1/2); (c) post-ore E-W compressional stress field (D2) is related S2 sinistral strike-slip faults and S-folds F2; (d) N-S maximum compressional stress field (D3) is related dextral strike-slip fault S3, Z-folds F3; (e) extension event (D4), normal fault S4.

In general, progressive pre-mineralization D1/1 and ore D1/2 compression in the NE-SW direction was the reason for the orientation of regional faults (Charky-Indigirka thrust, Adycha-Taryn fault) and folds F1/1 and F1/2, NE orientation of dike swarms and granitoid plutons of transverse series.

5.1.2. Mineralization

The transverse relationship between dikes and ore bodies determines the young age of mineralization. It is obvious, however, that dikes are favorable structures for creating fluid transit routes and space for ore deposition. They are areas of heterogeneous stress and inhomogeneous strain

[21]. Available ages of orogenic gold mineralization of the Yana-Kolyma belt (reviews in [2,4,33,53]) show that the peak of the formation of orogenic gold mineralization was later than the intrusion of the Late Jurassic dikes of trachybasalts, trachyandesites, dacites, and granitoids of the small intrusion complex [18]. The main Valanginian event of the formation of orogenic gold mineralization is assumed, which is later than the magmatism of the small intrusion complex by about 7-21 Ma and the Late Jurassic regional metamorphism. More specifically, Au mineralization is formed as a result of reactivation of pre-existing structures, which leads to the focusing of the ore fluid and determines the position of the deposits.

Structural analysis of the Au mineralization of the Vyun and Shumny area deposits shows the predominance of intersecting steeply dipping veins of the NW strike V11. Less often, gently sloping veins of the same type and steep veins of the same strike are observed. The formation of these veins is interpreted as related to a NE-SW compressional stress at the end of the event D1/2. Such field stress is assumed for a mineralization event at other orogenic gold deposits of the Upper-Indigirka sector of the Yana-Kolyma orogen [7,32,66]. In general, orogenic deposits hosted by second-order faults subparallel to the (paleo-) suture zones of collision of the Kolyma-Omolon superterrane and the eastern margin of the Siberian craton.

5.1.3. Post-Mineralization

Although there is no obvious Au-Sb mineralization at the Vyun and Shumny area deposit, it is assumed by the presence of rare small finds of stibnite. Similar mineralization is mainly localized to the NW and SE of the studied region, where are the large Au-Sb Sarylakh and Sentachan deposits located in the zone of the Adycha-Taryn fault [72]. Mineralization coincides with the formation of sinistral strike-slip faults of event D2, reactivating NW the regional fault systems, which was formed early in the tectonic history [31]. Sinistral strike-slip faults at the Vyun deposit and Shumny area are confirmed by folds of S-type N-S and NW-SE (F2) with b2 dipping 40° to 80°; sinistral strike-slip accretionary slickenlines of the quartz hanging walls with horizontal slickenlines (l2) (Figure 5c). Such deformations are caused by E-W compressional stress field. The later event NW-SE dextral strike-slip faults is related to N-S maximum principal stress D3 in the Vyun deposit and Shumny area (Table 1). D3 event is related to the E-W folds of Z-type (F3) with b3 dipping 40° to 80°; horizontal slickenlines (l3), boudinage (L3). Late dextral strike-slip faults have been described in other orogenic gold deposits of the Yana-Kolyma orogen [7,30,31,66,70,71]. Normal fault deformations D4 are observed locally. The environment of regional W-E extension could be caused by the development of the Indigirka extension belt in the Paleocene and the opening of the Eurasian Oceanic basin in the Arctic [73].

5.2. Correlation Mineralization and Regional Deformation

The most important for the formation of the Au mineralization of the Vyun deposit and the Shumny area was event D1/2. It correlates with the SW regional transport in the Late Jurassic-Valanginian, which was related to the closure of the small Oymyakon paleocean and the subsequent collision of the Kolyma-Omolon superterrane and the eastern margin of the Siberian craton [2,26]. The enrichment of subcrustal lithospheric mantle (SLM) was crucial for the Late Jurassic-Early Cretaceous metallogeny during subduction of the Oymyakon Ocean slab (Figure 16). It is supposed that subduction involves slab steepening, break-off or delamination of lower continental lithosphere [74]. The participation of mantle sources in the magma formation of the preceding mineralization of the Vyun ore field is confirmed by the geochemical and isotopic composition of the igneous rocks of the transverse series [18,33]. These rocks were formed from a mixed source with the involvement of mantle (OIB- and E-MORB type), lower crust and subduction components, with the Mesoproterozoic-Paleoproterozoic Sm-Nd model estimates of the age of their magmatic sources [18,33].

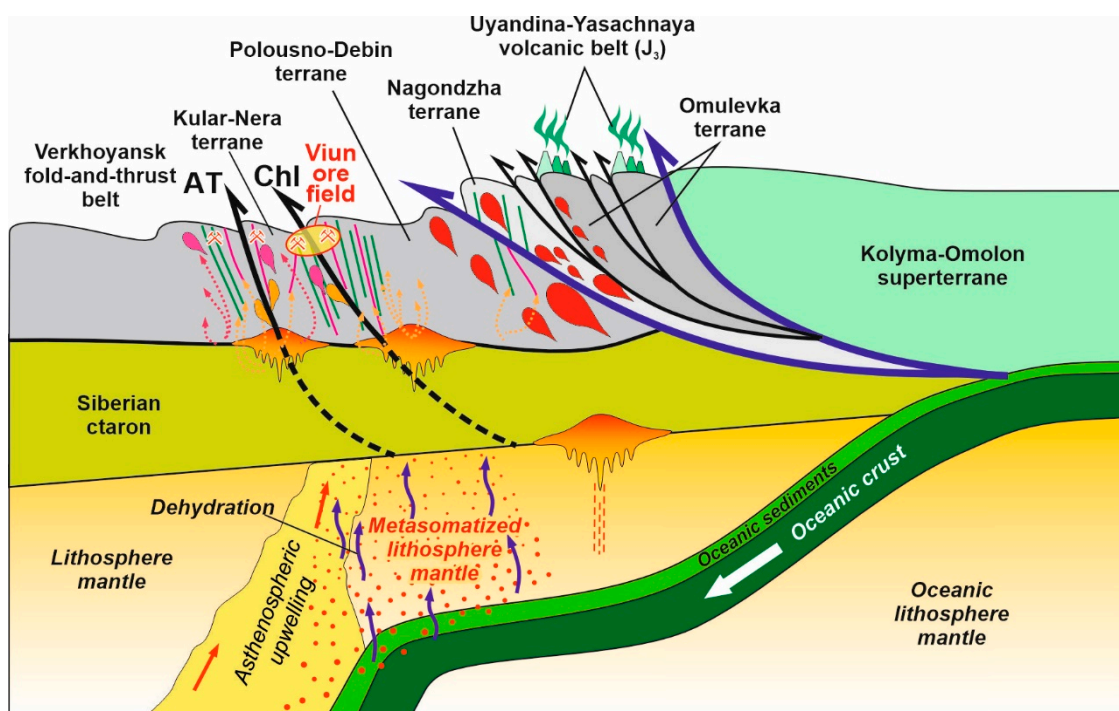


Figure 16. A schematic model illustrating the geodynamic situation in the Berriasian-Valanginian and the structural position of the orogenic gold deposits of the Yana-Kolyma, according to [18] with changes and additions. Orogenic gold deposits were formed with involvement of devolatilization of earlier-fertilized mantle lithosphere with frontal collision of the Kolyma-Omolon superterrane and the eastern margin of the Siberian craton.

The subcrustal lithospheric mantle was fertilized in the time preceding mineralization and was derived directly from the down-going subduction slab and overlying sediment wedge at the closure of the Oymyakon Ocean [8]. Orogenic gold deposits were formed with the involvement of devolatilization of earlier-fertilized mantle lithosphere with frontal collision of the Kolyma-Omolon superterrane and the eastern margin of the Siberian craton [8,58]. Mantle signatures of the isotopic composition of sulfur sulfides and native gold are typical for many orogenic gold deposits in the region [5,8,54,58]. At the Vyun deposit, there is a heterogeneous $\delta^{34}\text{S}$ in the sulfides. The highest variations of $\delta^{34}\text{S}$ are determined in Py from dikes (from -6.4 to $+3.1\text{‰}$, mean -1.9‰ , median -3.3‰). The highest $\delta^{34}\text{S}$ values are determined in Py (from $+2.3$ to $+5.6\text{‰}$, mean $+4.0\text{‰}$, median $+4.1\text{‰}$) and Apy ($+4.4\text{‰}$) from clastic rocks. Analyses of $\delta^{34}\text{S}$ in Py from the alteration of the Shumny are yielded positive values from $+2.1$ to $+5.1\text{‰}$. There are no evident isotopic variations between $\delta^{34}\text{S}$ in Py from sandstones (from $+4.3$ to $+5.0\text{‰}$) or from dikes (from $+2.1$ to $+5.1\text{‰}$, mean $+3.4\text{‰}$, median $+2.5\text{‰}$). The slightly heavier sulfur isotopic composition of sulfides from the Shumny and Vyun intrusion-hosted deposits may indicate a mixture of subcrustal, metamorphic, partially magmatic, and sedimentary sources [58]. The metallogenic time of formation of the gold mineralization is synchronous to the tectonic event and likely reflects the final stages of the Kolyma-Omolon microcontinent – Siberian Craton collision in the Valanginian during crustal thickening [58] (Figure 16).

Obtained results demonstrate combination of the Mesozoic oceanic subduction and accretionary orogeny with continental collision and their relationship with gold metallogeny in the Yana-Kolyma orogen. Critical features and the spatial-temporal distribution of similar deposits are shown [24] using the example of the Cenozoic metallogeny of the Tibet, formed during the continental collision of India-Eurasia.

Post-mineralization events are demonstrated by regional NW strike-slip faults. It was revealed that the lithosphere-scale strike-slip faults overlapped earlier thrust zones. The D2 event determined

by N-S stress field caused by the late Hauterivian-Aptian event was probably a reflection of superimposed tectonic thermal processes occurring in the rear of the Uda-Murgal volcanic-plutonic belt, which was associated with Paleo-Pacific subduction and development of the Proto-Arctic margin of Siberia [8]. The D3 tectonic event was determined by the subduction-accretion tectonic regime on the eastern continental margin of Siberia which is related to the development of the late Cretaceous (~106-76 Ma) Okhotsk-Chukotka volcanic belt. Events D2 and D3 are associated with post-orogenic Au-Sb, Au-Ag, Ag-Sb and Sn mineralization. The opening of the Eurasian ocean basin in the Arctic in the Paleocene caused the D4 tension strains.

6. Conclusions

Orogenic gold mineralization of the Vyun deposit and Shumny area is an excellent example of structural control of mineralization in collisional orogens on the margins of cratons. The main tectonic style of the structure is determined by longitudinal NW fold-rupture systems of the imbricated-thrust type and transverse NE faults. The pre-mineralization deformations, metamorphic and magmatic events share a common NE-SW shortening (D1), which is related to the subduction of the Oymyakon oceanic slab and collision of the Kolyma-Omolon superterrane with the eastern margin of the Siberian Craton. These deformations are characterized by a multiphase history of superposition of several tectonic events under compression conditions and progressive evolution of the host structures. Ore mineralization formed at the end of compression in the same stress field (D1). Its structural control represented reactivation of older dikes and faults. Dikes represent areas of heterogeneous stress favorable for the concentration of ore fluids and structural control of mineralization. Postmineralization tectonic regime is related to the Aptian-Late Cretaceous tectonic transition from compression to transpression. Transpressional tectonics was determined accordingly by N-S (D2) and W-E (D3) stress field caused by several accretionary events in the Cretaceous on the northern and eastern margins of Siberia. In northern margin it was driven by collision of the Chukotka microcontinent with Siberian craton, in eastern margin it was driven by continuous subduction of the Paleo-Pacific Plate.

As important as a general statement, is the involvement of the fertile subcrustal lithospheric mantle in the Late Jurassic-early Early Cretaceous collisional metallogenic epoch in the Yana-Kolyma orogen. The probable trigger of the Hauterivian-Valanginian metallogeny was upwelling of asthenosphere or mantle flow along the transcrustal faults. The main impulse of Au-As mineralization coincided with the slowdown of convergence between the Kolyma-Omolon superterrane and the eastern margin of the Siberian craton. The obtained results demonstrate relationship between gold metallogeny in the Yana-Kolyma orogen with Mesozoic oceanic subduction and continental collision, which contributes to the development of models of the formation of orogenic gold deposits.

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