Multistages mineralization and transformation of terrigenous rocks in the Vyun ore field, Yana-Kolyma metallogenic belt, Northeast Asia: insight from the sedimentary, diagenetic and hydrothermal sulfides and geochemistry of ore-hosting rocks

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Abstract. The article presents the results of studying the sulfidization zone of the Charky-Indigirka thrust fault within the Vyun ore field in the Upper Adycha sector of the Yana-Kolyma metallogenic belt. The purpose of the research is to study the composition and distribution of basic and trace elements in terrigenous rocks of the Upper Triassic and Middle Jurassic, as well as in distal metasomatites on the territory of the Vyun ore field. The petrochemical features of weakly altered terrigenous rocks, conditions of their formation and changes of composition during epigenetic processes were analyzed. Three generations of pyrite were identified: diagenetic Py1, metamorphogenic Py2 and metasomatic Py3. Typomorphic trace elements and variations of their distribution in pyrites were determined. Composition analyses of weakly altered sedimentary rocks of the Upper Triassic (V/(V+Ni)=0.5-0.8, V/Cr=0.1-2.9 and Ni/Co=2.5-10.3) and Middle Jurassic (V/(V+Ni)=0.7-0.9, V/Cr=0.2-2.0 and Ni/Co=1.3-8.8) yielded the conclusion that changes in oxygen conditions to disoxic and anoxic, as well as the enrichment of terrigenous material with ore elements, lead to the formation of authigenic sulfide mineralization at the early stages of the sedimentary strata formation. The subsequent multistage development of the territory was accompanied by an active migration of chemical elements, their input and redistribution.

1. Introduction
Regional zones of sulfidization are recognized in the Yana-Kolyma metallogenic belt. They are located both within the orogenic gold deposits (Natalka, Malo-Taryn, Khangalass, etc.) [1-4], and at a distance from them [5, 6]. A large belt of sulfidized rocks is confined to the Charky-Indigirka thrust, separating the Kular-Nera terrane from the Polousny-Debin terrane. The nature of this sulfidization zone and participation of sulfidized rocks in ore formation is still unclear. The zone of sulfidization of the Charky-Indigirka thrust fault was studied in the lower reaches of the Burgandja river (the right tributary of the Elgandja river) within the Vyun ore field located in the Upper Adycha sector of the Yana-Kolyma metallogenic belt (Figure 1). The Vyun orogenic gold deposit and several points of mineralization are located here [7]. Mineralization is represented by hydrothermal veins and veinlets of quartz, carbonate-quartz, chlorite-carbonate-quartz composition confined to trachybasalts, andesites, trachyandesites, dacites, and granodiorites dikes, crush belts and sandstone strata. Mineralization was formed after the Late Jurassic dikes (151-145 Ma, zircon, U-Pb SHRIMP-II) [8, 9]. Disseminated sulfide mineralization
is characteristic of terrigenous rocks and dikes that host mineralization. Sulfide content typically does not exceed 1%, increasing up to 10% in certain local areas.

A set of analytical studies was conducted, including the determination of the composition of rocks and disseminated sulfide mineralization. Identification of rock-forming oxides was carried out using wet chemistry (analyst L. T. Galenchikova, DPMGI SB RAS, Yakutsk). In order to determine the elemental composition of minerals and rocks, the atomic emission spectroscopy was performed on the iCAP 6300 DuoThermoScientific spectrometer (analyst A. S. Vasilyeva, NEFU, Yakutsk). The chemical composition of pyrite and arsenopyrite was determined with the use of X-ray spectrometry on the Cameba-Micro microanalyzer (analyst N. V. Khristoforova, DPMGI SB RAS, Yakutsk).

Figure 1. Geological structure scheme of the study area. Inset: KOS – Kolyma-Omolon superterrane, VFTB — Verkhoyansk fold and thrust belt, AT – Adycha-Taryn fault.

2. Results and discussions
On the studied territory, the Upper Triassic and Middle Jurassic rocks are exposed and characterized by alternation of sand- and siltstones strata. The clastic component of sandstones is mainly represented by quartz. Feldspars are observed in the form of individual grains (less than 1%). The size of the clastic grains varies from 0.1 to 0.3 mm. Separate wavy curved scales of muscovite are characteristic of arenaceous varieties. Siltstones are often coarse-grained with argillaceous cement, and massive, not well-bedded texture. Mineral composition is presented by quartz, clastic muscovite. The grain size is 0.05-0.1 mm. The cement is interstitial, basal, with argillaceous composition. Diagenetic pyrite (Py1) is
observed in the rocks. It forms small, often layered impregnation, clusters and veinlets. It is characterized by spherical and frambooidal aggregates of microcrystalline pyrite and pyrite-marcasite nodules. Py1 is often observed as relics in the central part of crystals of later generations.

Transformations of both clastic part and cement of the rocks are associated with post-catagenic processes, such as regional rock submergence and local dynamothermal activation. Siltstone varieties are cleaved (Figure 2, A), the processes of mechanical deformation, dissolution under pressure and regeneration are widely developed in the elastic components, with replacement of sandstone cement (Figure 2, B). Newly formed minerals are observed in the cement: hydromicas, sericite, carbonate (Figure 2, B). Authigenic minerals participated in the formation of hydromica-argillaceous and sericite-hydromica-argillaceous cement rocks. The processes of recrystallization-granulation blastesis and polycrystalline granulation are observed in sandstones. Blastopsammitic and lepidogranoblastic structure structures occur in the rocks. The zones of metamorphogenic Py2 formation are spatially associated with discontinuities. It is represented by cubic crystals, ranging in size from 2-3 mm to 2-4 mm, that form intergrowths, pockets and veinlets.

Figure 2. Micrographs of the altered rocks of the Vyyn ore field. A – penetrative slightly wavy intergranular cleavage on silty sandstone; B – recrystallization blastic microstructures of quartz; B – pre-ore metasomatite, sericite scales are located around elastic grains; Г–Д – sulfide mineralization: Г – euhedral, short prismatic crystals of arsenopyrite (Apy); Д – clusters of frambooidal and metasomatic pyrite (Py) consistent with the siltstone stratification; Е – quartz (Q) - ankerite (Ank) rim around pyrite crystal; Ж – ankerite (Ank) veinlet with a comb structure; З – carbonate-sulfide beresite; И – quartz-sericite-sulfide beresite.

Pre-ore metamorphosed rocks are superimposed with syn-ore metasomatites, which are represented by carbonate-sulfide, sericite-sulfide and quartz-sericite-sulfide varieties. Quartz-carbonate veins are
present in the rocks, in which quartz and carbonates are crystallized in the form of heteroblastic aggregates and often form a comb structure. The thickness of the veinlets varies from 0.2 mm to 2 mm, and sometimes up to 10 mm. Quartz grains are highly altered, resorbed, cloudy extinction is observed throughout, recrystallization is developed along the periphery of the grains. Proximal metasomatites are characterized by the development of early pyrite-arsenopyrite metasomatic mineralization. Grains of pyrite (Py3) and arsenopyrite (Apy 1) form pockets, clusters, veinlets, interbeds and flasers (Figure 2, Г-Д). The grain size of sulfides ranges from 0.1 to 5.0 mm. Rims of quartz-carbonate and sericite-carbonate composition are often observed around the grains of pyrite, less often arsenopyrite. Fractures in sulfides are filled with material of the same composition. In Py3, crystal heterogeneity (corrosion of the central part), chemical zonation and sectorial structure are often observed, which indicates the multistage formation of crystals.

The content of rock-forming elements and trace elements is characterized by a wide range of variations (Table 1). The chemical composition of siltstones is less consistent, which is related to the redistribution of the substance in the cementing matrix. Sandstones are characterized by high content of SiO₂, which is associated with the regeneration of elastic quartz grains.

### Table 1. Chemical composition of rock-forming elements, wt.%

| Oxides, modules | Upper Triassic sediments | Middle sediments |
|-----------------|--------------------------|------------------|
|                 | sandstone | siltstone | sandstone | siltstone |
|                 | VZh-17  | Sh-43 | VZh-84 | VK-35 | VZh-209 | VK-44 | BG-10 | VZh-71 | VZh-158 |
| SiO₂            | 74.39  | 70.07 | 59     | 66.41 | 68.52 | 72.73 | 68.32 | 70.06 | 63.31 | 45.24 | 67.27 | 59.23 |
| TiO₂            | 0.68   | 0.68  | 0.91   | 0.62  | 0.71  | 0.73  | 0.46  | 0.63  | 0.75  | 0.42  | 0.73  | 0.86  |
| Al₂O₃           | 9.59   | 15.28 | 13.4   | 15.59 | 15.47 | 14.36 | 14.88 | 14.74 | 16.47 | 10.97 | 16.6  | 16.51 |
| FeO             | 1.76   | 1.15  | 9.13   | 1.54  | 1.34  | 0.82  | 0.0   | 1.48  | 2.71  | 0.87  | 1.05  | 5.38  |
| FeO             | 1.66   | 2.29  | 3.46   | 2.86  | 2.5   | 1.84  | 3.23  | 1.79  | 1.85  | 1.51  | 2.74  | 2.75  |
| MnO             | 0.04   | 0.04  | 0.07   | 0.04  | 0.02  | 0.02  | 0.05  | 0.03  | 0.07  | 0.44  | 0.04  | 0.03  |
| MgO             | 0.71   | 1.22  | 2.76   | 1.64  | 1.33  | 0.99  | 0.28  | 1.11  | 1.1   | 1.76  | 1.56  | 1.48  |
| CaO             | 1.91   | 0.54  | 0.31   | 1.01  | 0.99  | 0.34  | 2.29  | 1.33  | 2.51  | 17.96 | 0.49  | 0.44  |
| Na₂O            | 2.28   | 4.21  | 1.81   | 3.45  | 3.01  | 3.55  | 4.02  | 3.61  | 2.91  | 3.53  | 3.64  | 3.89  |
| K₂O             | 1.5    | 2.97  | 1.52   | 3     | 3.07  | 2.58  | 3.23  | 2.97  | 3.15  | 1.8   | 3.12  | 2.23  |
| H₂O₁            | 0.16   | 0.45  | 0.46   | 0.32  | 0.4   | 0.23  | 0.42  | 0.41  | 0.39  | 0.18  | 0.43  | 0.48  |
| H₂O₂            | 1.14   | 1.18  | 1.34   | 2.02  | 2.42  | 1.72  | 1.51  | 1.52  | 0.71  | 0.14  | 2.31  | 2.65  |
| P₂O₅            | 0.16   | 0.15  | 0.2    | 0.3   | 0.2   | 0.14  | 0.12  | 0.16  | 0.26  | 0.35  | 0.18  | 0.26  |
| CO₂             | 2.95   | 0.48  | 0.25   | 0.96  | 0.64  | 0.42  | 1.35  | 0.67  | 2.59  | 14.26 | 0.40  | 1.00  |
| S               | 1.29   | 0.02  | 5.67   | 0.22  | 0.11  | 0.06  | 0.05  | 0.06  | 1.94  | 0.36  | 0.06  | 3.39  |
| F               | 0.04   | 0.04  | 0.09   | 0.08  | 0.07  | 0.06  | 0    | 0.07  | 0.08  | 0.06  | 0.05  | 0.07  |
| S               | 100.1  | 100.29 | 99.88  | 99.72 | 100.38 | 100.35 | 99.79 | 100.2 | 100.39  | 99.65 | 100.32 | 100.15 |
| POPR            | 0.02   | 0.02  | 0.04   | 0.03  | 0.03  | 0.03  | 0    | 0.03  | 0.03  | 0.03  | 0.02  | 0.03  |
| HM              | 0.18   | 0.28  | 0.46   | 0.31  | 0.29  | 0.24  | 0.27  | 0.27  | 0.34  | 0.3  | 0.31  | 0.43  |
| TM              | 0.07   | 0.04  | 0.07   | 0.04  | 0.05  | 0.05  | 0.03  | 0.04  | 0.05  | 0.04  | 0.04  | 0.05  |
| SM              | 0.24   | 0.28  | 0.14   | 0.22  | 0.19  | 0.25  | 0.27  | 0.24  | 0.18  | 0.32  | 0.22  | 0.24  |
| PM              | 0.16   | 0.19  | 0.11   | 0.19  | 0.2   | 0.18  | 0.22  | 0.2  | 0.19  | 0.16  | 0.19  | 0.14  |
| AM              | 1.52   | 1.42  | 1.19   | 1.15  | 0.98  | 1.38  | 1.24  | 1.22  | 0.92  | 1.96  | 1.17  | 1.74  |
| IM              | 0.34   | 0.22  | 0.88   | 0.27  | 0.24  | 0.18  | 0.21  | 0.21  | 0.27  | 0.25  | 0.22  | 0.47  |
| NAM             | 0.39   | 0.47  | 0.25   | 0.41  | 0.39  | 0.43  | 0.49  | 0.45  | 0.37  | 0.49  | 0.41  | 0.37  |
| Na₂O/K₂O        | 1.52   | 1.42  | 1.19   | 1.15  | 0.98  | 1.38  | 1.24  | 1.22  | 0.92  | 1.96  | 1.17  | 1.74  |
| K₂O/Al₂O₃       | 0.16   | 0.19  | 0.11   | 0.19  | 0.2   | 0.18  | 0.22  | 0.2  | 0.19  | 0.16  | 0.19  | 0.14  |
**Modules:** (HM = (TiO$_2$+Al$_2$O$_3$+Fe$_2$O$_3$+FeO+MnO)/SiO$_2$) hydrolyzate; (TM=TiO$_2$/Al$_2$O$_3$) titanium. (SM= Na$_2$O/Al$_2$O$_3$) sodium. (PM=K$_2$O/Al$_2$O$_3$) potassium; (AM=Na$_2$O/K$_2$O) alkaline; (IM=(Fe$_2$O$_3$+FeO +MnO)/(TiO$_2$ + Al2O3)) iron; (NAM=(Na$_2$O + K$_2$O)/Al$_2$O$_3$) normalized alkalinity module [10].

Data on the petrochemical modules indicate that studied rocks can be classified as polymictic sandstones and siltstones with normal ferruginous (IM = 0.18-0.46) and high alkaline (NAM = 0.25-0.49) content. Positive correlation between the modules TM and IM (r = 0.65) (Figure 3, A), negative correlation between NAM and NM (r = -0.66) (Figure 3, B)[10], and low values of K$_2$O/Al$_2$O$_3$ (0.11-0.22) (Table 1) indicate that the rocks belong to the "first cycle" formations [11]. On the PM - NAM graph, location of the figurative points between average values of chemical compositions of andesites and dacites signifies the predominance of acidic material in the provenance (Figure 2, 3, C).

![Figure 3](image)

**Figure 3.** Figurative points of the Upper Triassic and Middle Jurassic sandstone and siltstone compositions on the NAM –HM; IM – TM; HM – NAM diagrams.

Periodic changes in sea level, high sediment burial rates affected the change in the redox conditions of the bottom water that were present during the formation of sedimentary strata. Analyses of changes in the redox conditions of sedimentary strata formation were conducted on samples of the weakly altered sandstones and siltstones using the V/(V+Ni), V/Cr and Ni/Co Ni/Co ratios (Figure 4).

Figure 4 shows that the oxygen content in the bottom waters was unstable during the formation of sedimentary strata. Changes in oxygen conditions to disoxic and anoxic were also observed. Considering that terrigenous material transferred from the provenance was originally enriched with a number of ore elements, the change of redox conditions was a favorable factor for the formation of authigenic sulfide mineralization.
Figure 4. Varieties of the redox setting indices: 1 – for the Jurassic sediments; 2 – for the Upper Triassic sediments; 3 – minimum-average-maximum. Indices Ni/Co and V/Cr [12]; V/(V+Ni) [13].

Spectral analysis showed that the weakly altered terrigenous deposits of the Upper Triassic and Middle Jurassic were enriched in As, Pb, Mo, Cd, Cr, Li and Rb relative to bulk earth values in Earth's crust (Figure. 5, A). High concentrations of Ni, V and Ta are detected in the Upper Triassic sediments. In comparison with the Upper Triassic rocks, the Jurassic deposits are characterized by decreased content of most ore components, however, increased contents of Ba and Li are present in them.

According to the correlation analysis, the most stable relationship is observed in a Co-Ni-Zn-V-Sc-Cd multicomponent geochemical association. The Jurassic sediments are also distinguished by the As-Mo pair (r = 0.83). Analysis of the trace elements ratios in wallrock metasomatites and weakly altered rocks of the Upper Triassic indicates the removal of the majority of ore elements from metasomatites and input of As, Pb and Cr (Figure 5, B).

The As content increases tenfold in wallrock metasomatites. Most of the correlations are preserved and 2 geochemical associations are distinguished: Co-Ni-Zn and V-Sc-Nb-Zr. Thus, an active migration of chemical elements is observed both along the section and in the rock-metasomatite system, thereby affecting the composition of sulfides.

Figure 5. Trace elements distribution: A – in weakly altered host rocks. The contents are normalized to the average values for the upper crust [14]; B – in wallrock metasomatites. The contents are normalized to the weakly metamorphosed rocks of the Upper Triassic.
The typomorphic trace elements of pyrites are As, Co, Ni, Cu and Sb (Table 2-4). The As content in pre-ore pyrites Py1 and Py2 does not exceed 0.2 wt.% (arsenic-free pyrites are frequently found), and in metasomatic Py3 it ranges from 0.30 to 2.83% (Cav = 1.16%).

Table 2. Average values of the chemical composition of diagenetic and metamorphogenic pyrite (Py1. Py2). The Middle Jurassic, wt.%.

| Sample No | \(VJ-19; n=10\) | \(VJ-20; n=13\) | \(VJ-29; n=15\) | \(VJ-106; n=9\) | \(VJ-143; n=7\) | \(VJ-159; n=11\) |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Fe        | 47.42 – 46.73   | 46.89 – 46.19   | 47.12 – 46.15   | 46.63 – 44.65   | 46.85 – 45.57   | 47.27 – 46.04   |
| S         | 53.95 – 52.49   | 53.98 – 52.24   | 53.71 – 51.89   | 53.94 – 52.90   | 54.00 – 52.68   | 54.17 – 53.12   |
| As        | 0.016           | 0.009           | 0.112           | 0.135           | 0.034 – 0.030   | 0.18 – 0.017    |
| Co        | 0.037 – 0.008   | 0.029 – 0.001   | 0.041 – 0.005   | 0.139 – 0.008   | 0.074 – 0.003   | 0.137 – 0.005   |
| Ni        | 0.107 – 0.074   | 0.017 – 0.007   | 0.047 – 0.001   | 0.457 – 0.009   | 0.093 – 0.005   | 0.452 – 0.004   |
| Cu        | 0.466 – 0.002   | 0.014 – 0.012   | 0.010 – 0.004   | 0.041 – 0.005   | 0.055 – 0.005   | 0.233 – 0.003   |
| Sb        | 0.036 – 0.001   | 0.021 – 0.001   | 0.033 – 0.007   | 0.024 – 0.007   | 0.019 – 0.005   | 0.034 – 0.004   |
| Co/Ni     | 5.5 – 0.2       | 4.4 – 0.1       | 9.0 – 0.4       | 5.67 – 0.26     | 3.7 – 0.3       | 9.0 – 0.2       |

Table 3. Average values of the chemical composition of diagenetic and metamorphogenic pyrite (Py1. Py2). The Upper Triassic, wt.%.

| Sample No | \(Ch-141; n=8\) | \(VJ-94; n=17\) | \(ChU-80; n=9\) | \(VS-21; n=10\) | \(V-45; n=10\) | \(B-68\) |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|---------|
| Fe        | 46.72 – 45.63   | 46.80 – 45.31   | 47.21 – 46.64   | 47.22 – 46.51   | 46.99 – 46.64   | 47.62 – 46.57 |
| S         | 54.52 – 53.84   | 54.00 – 52.66   | 53.97 – 53.13   | 54.10 – 53.43   | 52.69 – 51.50   | 53.56 – 52.04 |
| As        | 0.023           | N.d.            | 0.011           | 0.199 – 0.018   | 0.062 – 0.002   | 0.217 – 0.034  |
| Co        | 0.180 – 0.008   | 0.042 – 0.020   | 0.071 – 0.016   | 0.063 – 0.002   | 0.055 – 0.003   | 0.077 – 0.001  |
| Ni        | 0.111 – 0.012   | 0.004 – 0.002   | 0.039 – 0.003   | 0.019 – 0.003   | 0.095 – 0.003   | 0.577 – 0.008  |
| Cu        | 0.046 – 0.011   | 0.020 – 0.001   | 0.007 – 0.002   | 0.044 – 0.005   | 0.017 – 0.003   | 0.201 – 0.006  |
| Sb        | 0.040 – 0.001   | 0.021 – 0.001   | 0.022 – 0.011   | 0.011 – 0.002   | 0.047 – 0.009   | 0.221 – 0.006  |
| Co/Ni     | 2.07 – 2.01     | 2.05 – 1.98     | 2.03 – 1.97     | 2.05 – 1.97     | 1.97 – 1.91     | 1.97 – 1.93    |
|          | 0.6             | 16 – 10.5       | 17.3 – 2.1      | 9.0 – 0.18      | 1.7 – 0.2       | 0.5 – 0.1      |
Table 4. Average values of the chemical composition of Metasomatic pyrite (Py3)

| Sample № | Fe (wt.%) | S (wt.%) | As (wt.%) | Co (wt.%) | Ni (wt.%) | Cu (wt.%) | Sb (wt.%) | Co/Ni |
|----------|-----------|----------|-----------|-----------|-----------|-----------|-----------|-------|
|           | 46.77 - 45.55 | 53.24 - 50.97 | 2.83 - 0.378 | 0.23 - 0.001 | 0.127 - 0.001 | 0.009 - 0.007 | 0.039 - 0.001 | 1.99 - 1.95 |
|           | 46.81 | 51.92 | 1.547 | 0.012 | 0.037 | 0.008 | 0.017 | 1.97 |
|           | 47.23 - 46.54 | 52.57 - 51.14 | 1.31 - 0.297 | 0.055 - 0.001 | 0.056 - 0.001 | 0.024 - 0.001 | 0.057 - 0.005 | 1.96 - 1.91 |
|           | 46.83 | 51.71 | 0.588 | 0.020 | 0.017 | 0.012 | 0.026 | 1.92 |
|           | 45.81 | 52.20 | 1.931 | 0.016 | 0.060 | 0.015 | 0.010 | 1.98 |
|           | 47.01 - 46.16 | 53.63 - 52.35 | 1.34 - 0.312 | 0.058 - 0.001 | 0.135 - 0.006 | 0.036 - 0.003 | 0.018 - 0.001 | 2.05 - 1.93 |
|           | 46.58 | 52.92 | 0.739 | 0.041 | 0.077 | 0.021 | 0.041 | 2.02 - 1.94 |
|           | 47.45 | 53.60 | 0.97 | 0.046 | 0.133 | 0.008 | 0.003 | 1.98 |

Total content of the trace elements of Co, Ni, Cu and Sb is on average 0.07-0.08% (Figure 6). High content of either of these elements is of a local nature and leads to the chemical heterogeneity of individual crystals. Co is a constant trace element in pyrites with the lowest fluctuations of the content. The lowest Co content is characteristic of the marginal zones of Py3 crystals. Trace elements of Ni vary widely, with increased concentrations observed in Py3 (C_{Ni}=0.13-0.22%). The correlations between Co and Ni are variable, ranging from moderate (r = 0.43-45) in the early pyrites to maximum values (r = 0.76) in Py3 (Figure 6, C). In metamorphic pyrite Py2, the proportion of Sb trace element is increased (max C_{Sb}=0.06%).

![Figure 6](image-url)  
**Figure 6.** Distribution of the trace elements in pyrites. Varieties in the content of pyrites from the Upper Triassic (A) and Middle Jurassic (B) deposits (A). Figurative points of the Ni – Co diagram for Py2 and Py3 (C).

3. Conclusions

Microscopic studies allowed us to identify groups of rocks that replace each other from weakly altered sedimentary rocks to ore zones, forming a metasomatic column:
1. Rocks altered due to the regional metamorphism are characterized by the structures of dissolution, regeneration and polycrystalline granulation of clastic grains, and rims formation of the regenerated quartz and hydromicas. The cement is quartz-carbonaceous-micaceous, interstitial, and filmy.

2. Zones of dislocated strata, characterized by the processes of recrystallization and blastesis. Blastopamsmitic and lepidogranoblastic structures occur in the rocks. The cement of the rocks is interstitial, basal, with hydromica-argillaceous, sericite-hydromica-argillaceous composition.

3. Syn-ore metasomatites represented by:
   - distal carbonate-sulfide metasomatites with carbonaceous veinlets, sericite-carbonaceous and sericite-hydromica-carbonaceous cement, and basal and granoblastic structures.
   - Proximal quartz-sericite-sulfide metasomatites represented by occurrences of rock silicification, with pyrite-arsenopyrite mineralization in direct proximity to the ore zones.

Analyses of the composition of weakly altered sedimentary rocks of the Upper Triassic and Middle Jurassic revealed that changes in oxygen conditions to disoxic and anoxic, as well as the enrichment of terrigenous material with ore elements, contributed to the formation of authigenic sulfide mineralization at the early stages of the sedimentary strata formation. The subsequent multistage development of the territory was accompanied by an active migration of chemical elements, and their input and redistribution. The primary sulfide mineral of the host rocks of the Vyun ore field is pyrite represented by two pre-ore pyrite generations Py1 and Py2 and metasomatic pyrite, characterized by an increased admixture of As (up to 2.8%). Zonation and sectorial structure are characteristic of Py2 and Py3. Typomorphic trace elements of pyrite are Co, Ni, Cu, and Sb, with total content not exceeding 0.08%. Pre-ore pyrites (Py1 and Py2) have a stoichiometric composition, and Py3 is characterized by isomorphic replacement (S→As).

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