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## GEOLOGY

# Riphean Riftogenic Ophiolites and Conjugated Minerageny of the Southern Urals

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The initial Early Riphean geodynamic environment of the Southern Urals and adjacent regions of the East European Platform was governed by the formation of a specific uplift of the Archean–Early Proterozoic crystalline basement with a rugged mountainous topography related to the ascent of an unconsolidated mantle diapir (Fig. 1a).

Initiation and evolution of the Early Riphean rift was followed by the accumulation of coarse-clastic molassoid sediments mainly composed of fragments of granitic–gneissic rocks transported from walls of the rift and interior horsts of the Taratash Ridge type. The accumulation of coarse-clastic material in rifts was accompanied by volcanic activity on walls of the rift. Consequently, the lower portion of the Riphean section was covered with trachybasalts up to 250–300 m thick. The upper portion of the section accumulated low-Ti and high-alumina basalts of the tholeiite type [1, 2].

The Middle Riphean (Yurmatinian) stage was marked by the initiation of a rift east of the Early Riphean deposits (Fig. 1b). In the Bashkirian anticlinorium, basal units are represented by the Mashak Formation (conglomerates with quartz and feldspar–quartz sandstones); in the Sysert–Il'menogorsk anticlinorium, by intensely metamorphosed rocks of the Arakul Formation; and in the Kochkar metamorphic complex, by the Eremkin sequence. The latter sequence is mainly composed of biotite, garnet–biotite, and garnet–biotite–staurolite rocks (with sillimanite and cordierite), as well as amphibole and other crystalline schists containing marble and graphitic quartzite interlayers with traces of subaerial continental origin [3, 4].

The middle and late Yurmatinian stages were marked by slow transgression on the flat land and the formation of terrigenous shallow-water and shoal deposits. The shallow-water carbonate sediments began to accumulate in the Middle Riphean section only at the end of the Middle Riphean (Avzyan) time [4, 5]. Phosphorite mineralization is related to these sediments [1, 6].

Active heating of the lithosphere by the mantle diapir, ascent of isogeotherms, and input of volatile components promoted the amphibolite-facies metamorphism. These processes also created crustal sources of melting and produced the Berdyaush pluton. The pluton is composed of rapakivi-granites, syenites, nepheline syenites, and granites of the Ryabina subvolcanic body, which are magmatic analogues of the Kuvash rhyolite body. The ascent of isogeotherms, the intrusion of basaltic magma into lower horizons of the volcanosedimentary graben, and its subsequent differentiation were responsible for the layering of Ti-bearing gabbroic rocks of the Kusa and Kopan massifs. The stratified gabbro, gabbro diabase, and ultrabasic–gabbro massifs incorporate titanium, chromite, chromite–platinum, rare metal, and copper–nickel mineralizations. Migmatites and small bodies of anatectic anorthoclase granites, alkali granosyenites, and carbonatites with rare earth mineralization are widespread in Proterozoic (Taratash, Aleksandrov, and Ufalei) blocks [7].

Continued extension of the region provoked listric faulting, thinning, and breakdown of the continental crust (Fig. 1c). These processes fostered the formation of an oceanic-type crust with ophiolite associations in the axial trough (Maksyuta, Kushtumga, Kurta, Saitovo, Svetlino, and other groups). Extension of the Riphean paleocean was probably insignificant. Therefore, the volcanosedimentary component of ophiolitic associations accumulated a large amount of felsic silica-rich (feldspar–quartz) material transported from the walls of the pull-apart continental massifs. Fracturing of the continental crust and initiation of the oceanic crust slightly postdated the initial stages of rifting. Ophiolites probably also continued to accumulate in the Late Riphean [1, 8]. The proposed model is generally similar to the scenario of rifting in the Red Sea. Blocks reconstructed for the study region presumably

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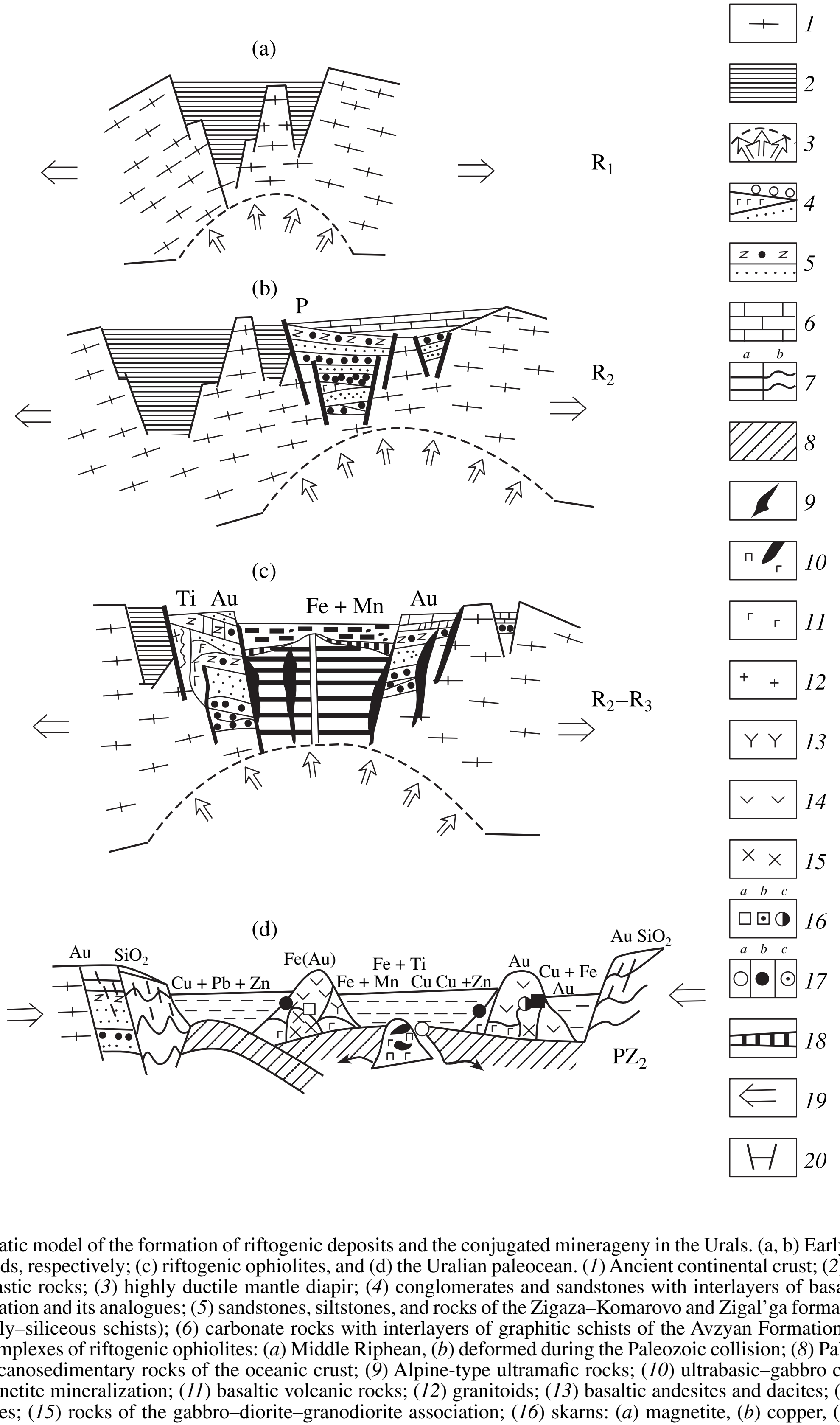

**Fig. 1.** Kinematic model of the formation of riftogenic deposits and the conjugated minerageny in the Urals. (a, b) Early and Middle Riphean periods, respectively; (c) riftogenic ophiolites, and (d) the Uralian paleocean. (*1*) Ancient continental crust; (*2*) Early Riphean coarse-clastic rocks; (*3*) highly ductile mantle diapir; (*4*) conglomerates and sandstones with interlayers of basaltoids of the Mashak Formation and its analogues; (*5*) sandstones, siltstones, and rocks of the Zigaza–Komarovo and Zigal'ga formations (coaly–shaly and coaly–siliceous schists); (*6*) carbonate rocks with interlayers of graphitic schists of the Avzyan Formation and its analogues; (*7*) complexes of riftogenic ophiolites: (*a*) Middle Riphean, (*b*) deformed during the Paleozoic collision; (*8*) Paleozoic ophiolites and volcanosedimentary rocks of the oceanic crust; (*9*) Alpine-type ultramafic rocks; (*10*) ultrabasic–gabbro complex with titanium–magnetite mineralization; (*11*) basaltic volcanic rocks; (*12*) granitoids; (*13*) basaltic andesites and dacites; (*14*) rhyolites and rhyodacites; (*15*) rocks of the gabbro–diorite–granodiorite association; (*16*) skarns: (*a*) magnetite, (*b*) copper, (*c*) gold–base metal; (*17*) massive sulfide deposits: (*a*) copper, (*b*) base metal, (*c*) copper–zinc; (*18*) ferromanganese rocks; (*19*) stress orientation; (*20*) riftogenic faults.

represented a single structure that underwent metamorphism of the epidote–amphibolite and amphibolite facies. Consequently, siliceous ferromanganese sediments were transformed into metamorphogenic gondite, rhodonite, and jaspilite deposits. Primary phosphorite lodes were altered into apatite deposits.

In the Early Paleozoic, Riphean riftogenic ophiolites broke down into fragments oriented parallel to the spreading zone of the Uralian paleocean (Fig. 1d) underlain by weakly metamorphosed volcanic-rich rock complexes of Paleozoic ophiolites [8].

The geological setting described is mainly characterized by the development of ultrabasic rocks of the dunite–harzburgite association that are usually accompanied by dolerite dikes and tholeiitic basalts. The oceanic tholeiitic basalts incorporated submarine massive sulfide copper deposits of the Dombarov (Cyprus) type. The island-arc setting promoted the formation of ensimatic volcanic belts composed of differentiation products of sodic basaltic magmas. The volcanic belts, which extend symmetrically relative to the oceanic structure, host auriferous massive sulfide deposits of the Ural (massive sulfide Cu–Zn association) and Baimak (massive sulfide barite–base metal or massive sulfide base metal association) types. The belts also incorporate gold–base metal and auriferous porphyry Cu deposits (gold–base metal and porphyry copper associations, respectively). Zones dominated by basalts include stratified deposits of sedimentary magnetite–hematite and hematite–manganese ores. Manganese ore lodes are confined to cherts and volcanosedimentary rocks.

Metaultrabasic rocks of the Riphean ophiolite groups host small deposits and occurrences of massive and disseminated chromite ores in the Itkul, Vyazov, and Kagan massifs. However, the more well-known gold mineralization is represented by auriferous magnetite veinlets and serpentinite veins confined to antigorite serpentinites. Commercial gold mineralization is recorded in intensely schistosed and altered antigorite serpentinites. This type of gold mineralization is characterized by high contents of Cu (up to 30 wt %) and Hg (up to 1.2 wt %) [9, 10].

Black shales developed in the Riphean ophiolite complexes incorporate polygenous and polychronous gold occurrences and deposits of the Avzyan type. The formation of the ophiolite complex was accompanied by the accumulation of a small amount of sulfides in carbon-rich rocks. The clarke-level (2.1–3.6 mg/t) gold concentration in these rocks is related to their metamorphogenic-hydrothermal alteration. Gold was extracted by fluids from high-temperature deep zones, transported to low-temperature zones along fissure systems, and accumulated in carbon-rich rocks that served as the geochemical barrier. Ore-bearing zones are composed of quartz–sericite and quartz–sericite–chlorite assemblages. Ore minerals are mainly represented by pyrite (usually, 3–5%). At the early collision stage, auriferous quartz veins formed in shear and foliation zones within the carbon-rich rocks. In some places (e.g., the Svetlino and other gold deposits), quartz–biotite and biotite–chlorite metasomatites formed after the emplacement of veins including stringer–disseminated mineralization. Biotitization is accompanied by the alteration of ore minerals related to early stages of ore formation.

Analysis of the distribution of quartz vein mineralization in the Middle–Central Uralian province showed that commercial quartz vein fields are confined to the Riphean riftogenic ophiolite domain (Novotroitsk, Karoyanov, Kyshtym, Itkul, Vyazovo, Larino, Svetlino, and other ore deposits and occurrences). This is related to the high Si content in the Riphean ophiolites, in contrast to the Paleozoic ophiolite complexes. The genetic type of quartz vein deposits and many technological properties of quartz are governed by the metamorphism grade of enclosing rocks; their tectonic transformation; and, correspondingly, the temperature and pressure of the mineral-forming medium, which are fairly consistent with *PT* constraints of the preceding metamorphism. An increase in the crystallization temperature fosters the introduction of major impurities (Al and alkali metals) into the quartz lattice, whereas an increase in pressure has the reverse effect. The influence of the crystallization temperature on the concentration of structural impurities in quartz is one order of magnitude higher than that of pressure [10–12].

Analysis of *PT* conditions revealed that quartz (particularly, the very pure variety) is preferentially deposited in high-pressure suture zones with a relatively low-temperature metamorphogenic-metasomatic alteration of enclosing rocks [10–12]. The suture shear zones, which represent deep fault zones that accompany the origination and subsequent evolution of the Riphean riftogenic ophiolites, are characterized by the maximal concentration of energy in the Earth's crust. The combination of tectonic stress and mechanic heat released during the motion of blocks along faults can explain many regularities in the geological and thermodynamic setting of suture zones, such as the occurrence of intense heat fluxes, the development of fault-line metamorphic zonality (increase in the metamorphism grade of rocks near the axial sector of faults), the presence of chloritoid and glaucophane schists at the upper and distal levels, the gradual transition to kyanite-containing varieties in deeper zones, and the development of higher *PT* facies [10, 12–14].

Thus, collisional processes altered the mineral and ore assemblages of the Riphean ophiolitic association. These processes were responsible for the tectonic and metamorphic transformation of ophiolite complexes (metamorphism of rocks and ores in the ilmenite–titanomagnetite, chromite, and other deposits), on the one hand, and the formation of new types of metallic and nonmetallic concentrations (deposits of rare metals, gold, granulated quartz, micas, and others). The data presented above indicate that paleoreconstruction of the Riphean ophiolite association has both theoretical and applied significance for the Urals, because this method provides new insights into the evolutionary history of the region and makes it possible to carry out a more reliable mineragenic regionalization.

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