Deposits of the Udokan-Chineysky ore-magmatic system of Eastern Siberia

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Abstract. The aggregate of ore deposits localized in the Udokan–Chineysky ore district is unique and is the result of multi-stage, polygenetic formation. The deposits of copper and other metals formed at various depths occur within a limited area. The oxide and sulfide ore are spatially associated in the sedimentary rocks pertaining to the Paleoproterozoic Udokan Supergroup and the intrusive mafic–ultramafic rocks of the Chineysky Complex. The granite rocks of the Kodar Complex and gabbro rocks of the Chineysky Complex also date back to Paleoproterozoic. The same age has been established for metasomatic Nb–Ta–Zr–REE–Y and U mineralization in the albitized terrigenous rocks of the Udokan Supergroup (Katugin deposit and Chitkanda prospect) and U–Pd prospects hosted in terrigenous rocks. The U–REE mineralization superposed on the titanomagnetite deposits in the Chineysky pluton has not analogues in the world’s practice. The occurrences of uranium mineralization have been noted in form of pitchblende and U–Th rims around chalcopyrite grains at the Unkur copper deposit hosted in sedimentary rocks. The enrichment in U and Pb has been documented in crosscutting quartz veinlets with bornite mineralization at the Udokan deposit.

1. Introduction
The Northern Transbaikal region in the western Aldan Shield is one of the largest metallogenic provinces in Russia. The world-class Udokan copper deposit containing more than 26,7 Mt of identified Cu reserves, the Fe–Ti–V deposits with 30 Bt of hypothetical ore resources in the Chiney pluton, the large Katugin Ta–Nb deposit, as well as PGE, Ag, Au, and U deposits and prospects are localized in this province [1, 2]. All they were formed in the Paleoproterozoic, which is regarded as the most productive era for concentration of various metals. The formation conditions of this mineralization remain insufficiently ascertained, and further progress in this respect would be helpful for discovery of new deposits in the complexly built Kodar–Udokan ore–magmatic system, which is distinguished by significant vertical extent. The ore deposits and prospects formed at different depths are now exposed at the surface and thus are accessible for comprehensive study. In addition to magmatic Fe–Ti–V oxide mineralization in the Chiney and Luktur layered mafic and ultramafic plutons, the primarily postmagmatic copper and noble–metal sulfide deposits are localized in the endo– and exocontact zones of these plutons (Rudnoe, Upper Chiney, Skvoznoe, Kontaktovoe, Magnitnoe, Etyrko deposits and prospects) [2, 3, 4].
Figure 1. Geological map of the Udokan–Chiney district. Various types of deposits are shown. Superlarge ore deposits: I–Udokan, II–Chiney, III–Katugin; other ore deposits: 1. Klukvennoye, 2. Sakinskoye, 3. Pravoingamakitskoye, 4. Maylav, 5. Rudnoye, 6. Verkhnechineyskoye, 7. Skvoznoye, 8. Kontaktovoye, 9. Luktur, 10. Unkur, 11. Krasnoye, 12. Burpala, 13. Chitkanda (U), 14. Niznechineyskoye (U–REE). Modified data of Chitageologiya.
The giant Udokan sandstone–hosted copper deposit is distant from intrusive bodies and bears attributes of hydrothermal sulfide mineralization. The same can be said about the Right Ingamakit, Sak, Unkur, and other vein–type deposits. New genetic types have been revealed recently in layered plutons and their frameworks, e.g., Au–PGE–Cu and REE–U mineralization [5]. Taken together, all these manifestations of magmatic activity and ore deposition make up the Udokan – Chiney ore–magmatic system.

2. Brief geology
The Kodar–Udokan ore district occupies the narrow salient of western end of the Aldan Shield in the southern Siberian Platform between the Baikal–Muya and Mongolia–Okhotsk mobile belts [6]. According to the currently accepted concept, the Siberian Craton had been created by the end of Paleoproterozoic (2.0–1.8 Ga) and then was incorporated into the Columbia supercontinent, where continental blocks have been assembled as a result of accretion and collision [7, 8]. In contrast to many other shields of the world, the Aldan Shield and the Baikal Fold Region were involved in rifting from Early Precambrian to present time [9]. The most important tectonomagmatic events in the region are marked by intrusion of mafic melts (Paleoproterozoic Chiney Complex, Neoproterozoic Doros Complex, Mesozoic dikes and volcanic rocks, Neogene–Quaternary basaltic lava plateau and dikes). All the aforementioned rocks occur at the intersection of the northwestern tectonic sutures as splays of the Syulban Deep Fault and the near–latitudinal structural elements accompanying the Stanovoy Deep Fault. The Chineysky massif occurs in the Kodar–Udokan trough [4] in Paleoproterozoic sedimentary rocks of the Udokan Super Group.

3. Results and discussions
3.1. The internal structure of the Udokan–Chineisky ore region
3D modeling of the deep structure of the area using gravitational and magnetic fields (CosCAD–3D software package, MGRI–RGGRU) shows that the studied stratified mafic–ultramafic massifs (Chineisky, Luktursky) represent only the upper parts of vertical columns of high–density bodies. Such columns are a series of magmatic chambers of different depths and at a depth of 18–20 km are connected to the magmatic chamber, which, in turn, is intermediate and feeds the upper chambers – stratified massiv.

Figure 2. Cross section of gravity mass distribution across the Luktur and Chiney massifs and the Unkur and Namlinga synclines with cupriferous sandstone deposits (Unkur and Udokan). Scale for gravity field is given in arbitrary [4].
The results of modeling the conditions of formation of ore giants of the Udokan–Chinei ore region (Figure 2) illustrate the stages of formation of ore–forming magmatic and fluid–magmatic systems with Fe–Ti–V–Cu mineralization (+Au, PGE), similar to the general trend of development and the environment of formation of the Olympic Dam deposit in South Australia (IOCG – Fe, Cu, Au, U) [10].

3.2. Iron–silver (gold) copper deposits in terrigenous rocks.
Udokan, Pravoingamakitskoe, Sakukan, Klukvennoe, Unkur, Krasnoe, Burpala and other deposits and ore prospects [3]. The main features of the Udokan Supergroup of terrigenous rocks are as follows: (1) great thickness, up to 12–15 km; (2) breaks in sedimentation; (3) pyrrhotite and pyrite mineralization throughout the Udokan Supergroup from lower to upper formations; (4) discrete localization of chalcocite–bornite sulphide ore from the Chitkanda to the Sakukan levels; (5) compositional diversity of sulfide and oxide minerals in ore (Fe, Cu, S, Ag, Au, U, REE, etc.); (6) significant differences in mineral composition of ore and isotopic composition of sulfur between the Udokan and other sulfide deposits which are referred to its satellites; (7) high Ag and Au contents in ore of the Pravoingamakitsky, Krasnoe and Unkur deposits in contrast to Udokan; (8) stratiform ore lodes comprise crosscutting veins and orebodies concordant with bedding (Fig. 3c); (9) breccia zones with sulfide cement (Fig. 3d). The magnetite laminas which were not affected by recrystallization, occur along with newly formed magnetite metacrysts occupying up to 50% of chalcocite ore volume at a distance of 2–3 cm between either of magnetite generations.

3.3. Iron – gold – (PGM) – copper deposits in igneous rocks
Deposits of Fe–Ti–V oxide (Magnitnoe, Etyrko) and Cu–PGE (Rudnoe, Verkhchineyskoe, Skvoznoe, Kontaktovoe sulfide ores of Chineisky massive [3]. Allocation of different groups of rocks of the Chiney massif – 1) “altered anorthosites”, gabbro, monzodiorites, pyroxenites; 2) high–titanium gabbroids; 3) low–titanium gabbroids; 4) magmatic, fluid–magmatic breccias with lamprophyre and gabbronorite cement is an important link in the study of the development of ore–magmatic systems and the sequence of crystallization of host rocks and the telescoping of magmatic oxide and sulphide ores. The second feature of the ore district is the occurrence of oxide and sulfide ore in mafic plutonic rocks of the Chineisky intrusive complex [1, 4]. The sulfide ore are localized as stockworks in the internal part of plutons and in endo– and exo–contact zones in form of massive (Fig. 3a), disseminated, vein (Fig. 3) and breccia (Fig. 3b) ore bodies. The following types of ore are recognized in the best studied Chineisky pluton: (1) early and late magmatic Fe–Ti–V oxide ore associated with high–Ti gabbro rocks; (2) syngenic titanomagnetite disseminations in low–Ti gabbro rocks; (3) magmatic stockwork sulfide zones in high–Ti gabbro rocks; (4) post–magmatic hydrothermal ore related to fluid–magmatic breccia and quartz veins of the Pravoingamakitsky deposit [3, 4], and (5) pyrrhotite–chalcocystal lodes distal from the pluton. The age of gabbroids of the Chiney Complex was determined by various methods as 1811–1880 Ma [3] and the age of the postorogenic granites of the Kodar Complex, as 1876–1873 Ma [11]. The late Paleoproterozoic Concordia age of 1896.2 ± 6.2 Ma for disseminated and veinlet titanites effectively dates formation of the Udokan Cu–Ag deposit [12].

3.4. U–REE deposits and prospects in metasomatically altered terrigenous and igneous rocks
The REE and U mineralization in terrigenous and igneous rocks is widespread in the ore district. In addition to the large Paleoproterozoic Katugin deposit [13] situated in the southern part of Kodar–Udokan district. This type of mineralization is known in immediate proximity to the Udokan and Chinei deposits, where it is hosted in the albitized magnetite and copper sandstones of the Chitkanda.
Figure 3. a–b – Rudny deposit, fluid–magmatic breccias, fragments of recrystallized terrigenous rocks are cemented with chalcopyrite; c–d – Udokan deposit, mouth of adit 14, veinlets and isometric nest of massive chalcocite–bornite ores, e–f – quartz fragments cemented with chalcocite, bornite; Pravoingamakitskoe deposit, fragments of quartz and terrigenous rocks cemented by sulfides (pyrite, chalcocite); g–h Burpala deposit, Skalisty area; nests of uranium minerals in albite–mica interlayers and breccia cement, radiography, photo Gladkikh I.F.
and Aleksandrovka formations of the Udokan Group (Fig. 3g, h) and in the albities of tectonic zones (Chitkanda, etc.) [14], in titanomagnetite gabbroic rocks of the Chinei pluton (Gudym and Basaltic prospects), in albities after tectonized and graphitized silty sandstone of the Aleksandrovka Formation (15). New prospects of uranium mineralization were found in the rocks of the Chiney pluton and surrounding rocks only in the beginning of the twenty-first century. Mineralization is related to metasomatized rocks and is represented by brannerite, uraninite, and other minerals. Inside the Chiney pluton, many rare earth minerals were found as well [2].

4. Discussion
The established hurricane ore–bearing magmatic and sedimentary formations of ancient cratons is the most vivid, significant feature of the Proterozoic period [7]. The deep melts that rose from the upper mantle were partially accumulated at the cortex–mantle boundary and determined the assimilation of the lower crust. The formation of rift and supercritical troughs was accompanied by the development of stratified mafic plutons, which led to specific metallogeny and unique ore–bearing geodynamic systems, such as the largest ore deposits of Bushveld, Great Dyke [16], Stillwater, and others. The formation of Chineysky massiv took place in two stages. The subsequent repeated introduction of high–titanium magmas determined its stratification and the rhythmic structure of the section. The bulk of the massif is represented by high–titanium gabbroids. Unlike the classical examples (Bushveld, Stillwater, Skergaard, etc.), where titanomagnetite gabbros are associated with the upper parts of these massifs, in the structure of the Chiney massif these rocks are found throughout the section. The increase in the proportion of residual melts rising upward as crystallization resulted in an increase in the thickness of the predominantly mesocratic layers upward along the section and the increase in the power of the rhythms. Further consistent decrease in the proportion melanocratic then mesocratic rocks resulted in the upper section to the formation leucogabbro, anorthosite, and substantially titanomagnetite–plagioclase rocks – “chineite” [3]. Such rocks make up the upper part of the Upper Bushveld Zone [17]. In recent years, the difference between partial sections of stratified massifs is usually explained as a consequence of the activation of intermediate magmatic foci of ancient volcanic–plutonic systems with multiple magmatic inputs [18]. When the Chiney massif is formed, the Bowen and Fenner trends in fractionation are established. In the first case the anorthosites with which titanomagnetite layers are associated crystallized at the final stage, rocks enriched in potassium, volatile components (monzodiorites, etc.) crystallized in the second. Concentration of volatile components, alkalis and silica, reducing the crystallization temperature of the residual melt, formed pneumatic–hydrothermal systems. Such systems are heterogeneous, as multiple magmatic implants have been accompanied by multiple fluid–melt compartments, forming a hydrothermal system. The liquidation of residual fluid melts led to the formation of silicate and sulphide melts.

The giant Udokan iron oxide copper deposit has characteristics typical of a sediment hosted copper deposit. However, the copper ores contains 5 to 50%, dominantly euhedral to subhedral magnetite and elevated gold (often 0.3 to 0.5 g/t Au), and has strong accompanying quartz–chlorite–muscovite–epidote alteration, largely restricted to the zone of copper–iron oxide–gold mineralization [19]. In addition, there are signifi cant cant intervals of sodic (albite) alteration distributed across the ore deposit, associated with faulting and especially brecciation zones which are usually also accompanied by Palaeoproterozoic gabbroic dykes. All of these characteristics would be consistent with an IOCG association shared with the stratabound, sediment hosted nature of the deposits and prospects hosted in sedimentary rocks of the Udokan Supergroup in various localities of the Kodar–Udokan ore district. Immediately after solidification of almost coeval and closely spaced granitic and gabbroic plutons pertaining to the Kodar and Chinei intrusive complexes, the Kodar–Udokan ore district became a large–size and high–temperature thermal anomaly. The heated formation water contained in the sedimentary rocks of the Udokan Supergroup, mixing with postmagmatic solutions most likely separated from plutons, leached Cu and other metals from the evolved gabbro and underlying mafic–ultramafic cumulates to form hydrothermal sulfide deposits. The key features IOCG include the following: (1) The presence of Cu with or without Au as economic metals; (2) hydrothermal vein,
breccia, and/or replacement ore styles, characteristically in specific structural sites; (3) abundant magnetite and/or hematite; (4) iron oxides which have low Ti contents compared to those in most igneous rocks; and (5) absence of clear spatial associations with igneous intrusions.

U–REE mineralization in albitized magnetite and copper sandstones of the Udokan supergroup and albitites of tectonic zones, as well as in propylites of igneous rocks of the Chineysky massif is more recent. This is probably due to the melting of the lower crust and the formation of granites of the Kodar complex.

5. Conclusions
It has been established that hydrothermal processes participated in formation of the localized in the Paleoproterozoic sedimentary rocks especially in the satellite deposits of the Udokan, up to the discovery of unusual hydrothermal ores of the Pravoingamakitsky deposit. These processes led to redistribution of the early ore matter and resulted in the creation of new orebodies. The similarity of the composition and crystallization sequence of the mafic rocks attributed to the Chineysky Complex belonging to a single deep chamber was demonstrated. This broadens the possibilities for discovering new Fe–Ti–V and PGE–Cu–Ni prospects and deposits both on the surface and at shallow depths in the southern part of the Kodar–Udokan Trough. New points of uranium and rare metal mineralization have been discovered. This is a new promising direction of prospecting in the Kodaro–Udokan region.

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