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**MINISTRY OF MINING AND HEAVY INDUSTRY**

# METHODICAL RECOMMENDATION APPLIED FOR CLASSIFICATION OF MINERAL RESOURCES AND CERTAIN TYPE DEPOSITS' RESERVES OF MONGOLIA

# (NICKEL, COBALT)

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The METHODICAL RECOMMENDATION applied for classification of mineral resources and certain type deposits' reserves of Mongolia:

# NICKEL AND COBALT DEPOSITS

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This recommendation is designed for employees of enterprises and organizations operating in the sector of subsoil use, regardless of their departmental affiliation (or subordination) and ownership.

Obtaining the information regarding geological settings and/or exploration from this methodical recommendation, its quality and completeness, is useful for making decisions on carrying out further exploration, whether to develop into active mining on explored deposits, to renovate existing mining and processing plants, or to construct new plants.

**CONTENT**

**PREFACE**

This methodical recommendation is prepared based on specific types of minerals according to the laws, orders, procedures, and instructions of “State Policy on Mineral Resources”, Article 16 of the “Minerals Law”, “Action Plan of the Government of Mongolia for 2016-2020”, “Regulations on mineral prospecting and exploration activities” approved by Order No. A/20 on February 05, 2018 by the Minister of Mining and Heavy Industry, and “Classifications and instructions of mineral resources and reserves specific to type of minerals” approved by Order No. 203 by the Minister of Mining and Heavy Industry on September 11, 2005. This methodical recommendation contains guidelines for the application of mineral resources and reserves classifications for nickel and cobalt deposits. This recommendation is aimed at providing practical assistance to companies, geologists, and miners holding exploration and mining licenses to explore nickel and cobalt deposits, to perform resource/reserve estimations, to register them in the state registration of mineral resources/reserves, and/or to perform modifications in registrations.

A total of three small nickel deposits and …… medium and small occurrences of nickel and cobalt have been identified as a result of multistage geological mapping, prospecting, and exploration surveys conducted in the territory of Mongolia. Nickel and cobalt deposits and occurrences in Mongolia fit into the worldwide classification of mineral deposits with the purpose of exploration that are used with regards to ore geneses, industrial types, and morphological patterns.

This recommendation is intended to help geologists carefully observe the different industrial types of nickel and cobalt deposits regarding their primary and by-products, exploration methods, and processing technologies, and to aid in selecting appropriate methods. It has become totally possible in recent years to learn online about various methods of borehole defection and geophysical and geotechnical measurements based on technological advances and implement them in exploring all types of ore deposits. Preliminary quality assurance and quality control of assays for geostatistical analysis to estimate reserves is becoming increasingly important during the exploration stage to facilitate mining the deposit to its full extent in an optimal way.

# 1. BASIC CONCEPTS

## 1.1. Nickel

### 1.1.1. Basic concepts of nickel, its applications, and significance

Nickel is a silver-grey metal with a density between 8.35–8.90 g/cm$^3$, which melts at 1452°C and boils at 2913°C. It has ferromagnetic features, strong luster, can take a high polish, is malleable and ductile and, therefore, can be beaten and drawn out into a wire. It is the 28$^{th}$ element in the periodic table with an atomic mass of 58.71. Naturally occurring stable isotopes of nickel include $^{58}Ni$, $^{60}Ni$, $^{61}Ni$, $^{62}Ni$ and $^{64}Ni$. Among these isotopes, $^{58}Ni$ is the most abundant with 68.077% of abundance. The average crustal abundance of Ni is 0.0058%, while its abundance in felsic rocks decreases to 0.0008% but increases to 0.12% in mafic and ultramafic rocks. In nature, it often combines with sulfur and iron. Geophysical surveys for the purpose of studying the deep Earth have revealed that the inner and outer cores of the Earth contain enormous amounts of nickel. Additionally, meteorites found on earth contain much nickel.

Nickel has been mixed with various other metals to produce strong alloys from ancient times due to nickel’s high-melting point. In modern times, 80% of nickel production is used in metallurgical plants to produce various nickel alloys. Nickel alloys are further used in production of cars, tractors, base machines and electrical components. Nickel alloys with copper, zinc, and aluminum are broadly used in industries; as well, copper and iron alloys are often used to produce coins. Pure nickel is often used in the production of cookware and transfer tubes in chemical and food-processing industries.

Most of the world’s nickel production (65%) is used in heat-resistant industrial tools and machines, as well as corrosion-resistant metal alloys. Twenty percent is used for producing high-performance metal alloys by mixing with iron, chromium, copper, zinc, and other metals. Additionally, 7% of production is used to coat the surface of other types of metals and alloys with electrolyte coatings. Finally, nickel is used in manufacturing car batteries and as a catalysator in chemical industries.

### 1.1.2. Nickel-bearing ore minerals

There are over 40 naturally occurring Ni-bearing minerals in the form of simple and complex sulphide, arsenide, and sulfarsenide compounds. Additionally, around ten minerals occur in the form of hydrous silicate compounds. Nickel and cobalt are present as isomorphic mixtures in adsorbed form in about 100 mineral structures. The main/primary nickel ore minerals are shown in Table 1.

**Nickel- and Cobalt-bearing primary ore minerals**

Table 1.

| Minerals and their chemical formulas | Concentrations, % | |
|---|---|---|
| | Nickel | Cobalt |
| **I. SULFIDES** | | |
| Pentlandite $(Fe, Ni)_9S_8$ | 22–42 | 1–3 |
| Nickeliferous pyrrhotite FeS | 0.4–0.7 | – |
| Millerite NiS | 61–64 | 0.1–0.5 |
| Linnaeite $Co_3S_4$ | – | 40–53 |
| Cobalt-bearing pyrite $(Fe, Co)S_2$ | – | 0.05–3 |
| **II. ARSENIDES, SULFOARSENIDES AND ARSENATES** | | |

| | | |
|---|---|---|
| Skutterudite $CoAs_3$ | 0–9 | 11–20 |
| Safflorite (Co, Fe)$As_2$ | 0–0.3 | 10–30 |
| Smaltine – Chloantite (Co, Ni)$As_2$ | 1–21 | 4–24 |
| Cobaltite CoAsS | 0.5–2 | 26–34 |
| Erythrite $Co_3(AsO_4)_2 \cdot 8H_2O$ | 0–6 | 20–30 |
| **III. SILICATES, HYDROUS NICKEL SILICATES AND HYDROXIDES** | | |
| Garnierite $(Ni, Mg)_4[Si_4O_{10}]\,(OH)_4 \cdot 4H_2O$ | 16–35 | 0–0.1 |
| Revdinskit $(Ni, Mg)_8[Si_4O_{10}]\,(OH)_8$ | 16–35 | 0.0–0.1 |
| Nickeliferous kerolite $(Mg, Ni)_4[Si_4O_{10}]\,(OH)_4 \cdot 4H_2O$ | 10–15 | Ул мөр |
| Nontronite $m\{Mg_3[Si_4O_{10}](OH)_2\} \cdot p\{(Al, Fe)_2 \cdot [Si_4O_{10}]\,(OH)_2\}$ | 0.5–2.0 | Ул мөр |
| Nickeliferous serpophit $(Mg, Ni, Fe)_6[Si_4O_{10}]\,(OH)_8$ | 4–5 | Ул мөр |
| Nickeliferous hydrochlorite $(Mg, Al, Fe)_6\,[(Si, Al)_4O_{10}] \cdot (OH)_8. \cdot nH_2O$ | 2–6 | 0.03–1.2 |
| Asbolane and psilomelanvade $m(Co, Ni)O \cdot MnO_2 \cdot nH_2O$ | 0.8–20 | 0.8–32 |
| Heterogenite $CoO \cdot 2Co_2O_3 \cdot 6H_2O$ | – | 10–20 |

### 1.1.3. Nickel mineralization and ore genesis

Large copper-nickel deposits are associated with large igneous bodies that formed during reactivation of ancient platform and rifting. In the Kambalda region of Western Australia, nickel deposits formed in association with ancient komatiitic and basaltic extrusions. Giant nickel sulphide deposits form in association with mafic to ultramafic magmatism that occurred along fault systems within ancient platforms. Nickel-cobalt deposits form in association with granitoid rocks emplaced in orogenic development. Exogenic silicate nickel deposits are formed by surface weathering of the platform. Depending on whether the composition of country rock is silicate or carbonate, orebodies occur as veins, strata, or complex.

Nickel ore deposits formed in various metallogenic epochs. Large copper-nickel sulphide deposits formed in Archean (Western Australia), Proterozoic (Canada, Baltic Shield, South Africa) and Mesozoic (Siberian platform). The largest ore districts include Sudbury and Thompson in Canada, Kambalda in Australia, and the Norilsk district in Russia. There are over thirty nickel sulphide deposits formed in association with komatiite and basalt of ultrabasic magmatism in the Proterozoic Era in Western Australia. During the early Paleozoic, large nickel deposits formed in northwestern Europe; the Ringer deposit in Norway represents the largest of these. Although no known large cobalt-nickel deposits formed during the late Paleozoic, hydrothermal cobalt-nickel deposits (Khovu-Aksy, Tuva) and lateritic deposits (Urals) formed during that time. During the Mesozoic, giant deposits formed in Russia (Norilsk) and the Republic of South Africa. Large silicate nickel deposits are found in the south Urals, northwestern Kazakhstan, and Brazil. Silicate nickel deposits mostly formed during the Cenozoic. Silicate nickel deposits formed by the surface weathering of mafic and ultramafic intrusive rocks are found in the Urals, Cuba, New Caledonia, the Philippines, and Australia. Larger deposits are found in Southeast Asia, and Central and South America.

Nickel deposits form in association with basic and ultrabasic magmatism. Olivine in mafic and ultramafic rocks contains nickel in its crystalline structures wherein Ni content reaches 0.13–0.41%. If magma contains sulfur, nickel as well as iron, copper, and cobalt (platinum group elements in some instances) are combined with sulfur and form sulphide minerals which result in the formation of immiscible copper-nickel deposits that serve as the primary source of nickel production. During magmatic-hydrothermal stages, nickel combines with cobalt, arsenic, sulfur, and, in some cases, bismuth, uranium, and silver to form arsenides or sulfides. In this case, cobalt-dominated sulphide and sulphide-arsenide deposits are formed.

When mafic and ultramafic rocks weather in an exogenic environment, nickel is released from minerals such as serpentinite and olivine through dissolution and tends to accumulate in layers of surface weathering.

Copper-nickel sulphide deposits (from which 37% of world nickel resources and 10% of cobalt resources come) are directly genetically associated with differentiated mafic and ultramafic intrusive rocks (peridotite, gabbro-norite, gabbro and gabbro-diabase). Copper-nickel orebodies normally occur at the basal section of the intrusive body and sometimes occur in the country rocks. Ore minerals normally occur as disseminated and veins but can occur as massive and brecciated ores in rare cases. Orebodies are normally large, up to 100 m in thickness and continuing several km along strike and dip, and mostly lay horizontally or subhorizontally, but sometimes form tilted and tabular bodies with steep dip, stratabound, lens, veins and complex orebodies. If the orebody is stratabound and concordant with the host rock, it tends to have disseminated ore minerals. Ores confined to the side of the orebodies form separate strata, layers, lenses and veins, composed of massive, brecciated and densely disseminated varieties. One characteristic of sulphide mineralization is that ores have a specific mineral assemblage. The primary ore minerals include pyrrhotite, pentlandite, chalcopyrite, and magnetite; as secondary minerals pyrite, cubanite, millerite, violarite, PGE-bearing minerals; and rarely chromite, mackinawite, and native gold. This type of deposit also contains copper, cobalt, PGE mineralization besides nickel and lesser selenium, tellurium, gold, silver, and sulfur. World and Russia’s nickel resource and production dominantly come from magmatic sulphide ore deposits.

Lateritic deposits that contain nickel silicates (63% of the world nickel resources and 58% of cobalt resources) form due to weathering of mafic and ultramafic rocks near the surface. Lateritic deposits are classified into the following categories based on geological setting, shape of orebody, and weathering rocks: 1) areal (Buruktalskoy, Saharinskoy, Serovskoy); 2) linear (Sinarskoy); 3) combination of linear and areal (Cheremshanskoy). Silicate nickel orebodies vary in shape depending on mineralization type with lengths that range from a few hundred meters up to 1-2 km, and with thickness from 1 m to 30-50 m. Orebodies occur to be generally cloak-like, sheet-like with complex contours in plan. Sometimes they occur to be lenticular, often with pocket-shaped depressions, wedge-shaped and socket-shaped bodies that do not have clear geological boundaries and are contoured according to sampling data. The orebodies are usually horizontal or gently sloping except for the contact and karst subtypes within the weathering crust (Cheremshanskoy). Ore mineral assemblage is complex/diverse. Nickel is included in many different mineral structures, such as silicate and oxide minerals. In ores, cobalt occurs in manganiferous minerals ocher and gossan within serpentinites besides nickel. In these types of deposits, ore minerals occur in dispersed fine-grained or amorphous forms within various types of mineral structures.

Residual regolith in the weathering surface contains secondary serpentinite, ferrisapolite, nontronite, goethite-hydrogoethite, maghemite (martite), secondary magnetite, cobalt-nickel-bearing asbolane, and iron-silicate minerals.

In infiltration zones, nickel and magnesium-nickel bearing serpentinites and magnesium-nickel minerals similar to talc (kerolite, pimelite) or their combinations form. Nickel berthierite, secondary magnetite, maghemite, millerite, magnesium-nickel serpentine and amesites form in the reaccumulated weathering zones. This type of mineralization is classified into ferrous (gossan, leptochloritized, hematitized) and magnesium (serpentine with nickel silicate) based on mineral assemblage and compositions (nickel and cobalt, iron, magnesium, silica and clay). Silicate nickel ores are generally low in grade and therefore difficult to process using the traditional method, but hydro or pyrometallurgical methods are commonly used. Ore grade ranges between 0.5% and 1-2%. Copper and chromium are toxic impurities in silicate nickel ores, while during the melting ferronickel and phosphorus are considered to be toxic impurities. This type of ore is often considered as the main source of nickel and cobalt in many countries around the world.

Arsenide and sulfarsenide nickel and cobalt deposits form as veins filling fractures and open spaces, as well as hydrothermal disseminated and vein-type where cobalt (Khovu-Aksy) is dominated. Veins are complex with sudden widening or thinning plus disappearing. It is common that feather-like veins then turn into lens or veinlets or disseminated ore minerals.

Besides the main ore minerals, loellingite, native silver, argentite, electrum, native bismuth, arsenopyrite, tennantite, antimony, cinnabar, rarely sphalerite and galena can occur. In oxidized zones, cobalt-nickel arsenics such as erythrite–annabergite occur commonly. The main vein minerals are quartz, calcite, dolomite, and, rarely, ankerite and chlorite. Cobalt, nickel, copper, silver, gold, bismuth, and arsenic are common in ore minerals. This type of deposit, however, does not commonly occur and thus does not play an important role in nickel and cobalt production.

Besides the genetic and industrial types of nickel deposits mentioned above, there are nickeliferous ilmenite-magnetite (Norway), nickeliferous massive sulphide (Finland) and vein-type deposits (five-elements ore type; South Africa) identified, and 1% of nickel production around the world come from these deposits.

#### 1.1.4. Production of nickel

Nickel production around the world comes from nickel sulphide deposits as well as silicate nickel and mixture ore deposits. Sulphide ores contain Ni between 0.5–2.0% and higher, while silicate ores contain 1.3% of nickel. Mixtures of sulphide and arsenide nickel ores contain significantly high contents of nickel, cobalt, silver, and, in some instances, gold, bismuth, and uranium. Most of the nickel production around the world comes from magmatic copper-nickel sulphide, nickel silicate-bearing lateritic deposits, and hydrothermal nickel-cobalt-bearing arsenide and sulfarsenide deposits (Table 2).

#### 1.1.5. Nickel production and its perspective

If the cut-off grade of nickel is 0.5%, then the world resource of nickel is approximately 300 million tons and 60% of these resources belong to the lateritic deposits with the rest belonging to sulphide deposits (USGS Open file report, 2021). As of today, 80% of total historical nickel production occurred in the last 30 years, and it is speculated that nickel will be extracted from seafloor deposits in the future. It is calculated that seafloor Fe-Mn (Ni-Cu-Co-Mo) deposits contain approximately 290 million tons of nickel.

In 2019, 60% of total nickel production was used by the steel industry and 10% was used to produce lithium-ion batteries in the renewable energy industry. As a result of research, lithium-ion batteries consumed 38% of the nickel in 2016, an amount speculated to increase to 76% by 2025.

**Main industrial types of nickel and cobalt ore deposits**

Table 2.

| Main industrial types | Structure and morphology of orebodies | Main ore minerals | Ore grade | | Main by-products | Examples of deposits |
|---|---|---|---|---|---|---|
| | | | Nickel | Cobalt | | |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Copper-nickel sulphide | Consonant sheet-like deposits, lenses | Nickeliferous pyrrhotite, pentlandite, chalcopyrite, (Talnakhit, mooihoekite), cubanite, magnetite | From 0.1% up to several % | 0.01-0.1% | PGE, gold, silver, selenium, tellurium | Norilsk-I, Talnakh, Oktyabrkskoy, Zhdanovskoy, Semiletka (Russia), Sudbury (Canada), Insizwa (South Africa), Mikola-Nivola (Finland), Kambalda (Australia) |
| Silicate nickel in weathering surface | Stratiform, cloak-like podiforms | Garnierite, revdinskite, kerolite, nontronite, hydrochlorite | 0.7–0.8 % хэдэн % | 0.01-0.1% | Iron | Serovskoye, Buruktalskoye, Sakharinskoye (Russia), deposits of Kempirsaiskaya (Kazakhstan), Pobuzhskaya group (Ukraine), New Caledonia, Cuba, Brazil, Indonesia, Australia |
| Nickel-cobalt arsenide and sulfarsenide with cobalt dominating | Fractured veins, vein-like bodies | Schmaltin, chloantite, nickelin, skutterudite, cobaltite | From 0.1% to several % | 1-2% | Gold, antimony, mercury | Hovuaksy (Russia), Bou-Azzer (Morocco), deposits of the Cobalt region (Canada) |

## 1.2. Cobalt

### 1.2.1. Basic concepts of cobalt, its applications, and significance

Cobalt is a bright metal with a reddish hue and is the 27$^{th}$ element in the periodic table with an atomic mass of 58.93. Its melting temperature is 1493°C and its density is 7-8.9 g/cm$^3$. It is a strongly stable ferromagnetic metal with malleable and ductile qualities. The average crustal abundance is 0.0036%, but it is more associated with ultramafic rocks.

Cobalt, as a pure metal or oxide compound (up to 40%), is used as an additive to a range of metal alloys to produce heat-resistant alloys and steels. Twenty percent of total cobalt production is used for magnetic alloy with an increased magnetic energy per unit volume. Sixteen percent of cobalt production is used for chromium, tungsten, titanium, and carbon alloys, cast iron (stellite), and metallic ceramic alloy (kermet).

Twenty percent of cobalt is used in chemical and ceramic industries as a catalysator and for pigments. In recent years, cobalt has been used for lithium-cobalt batteries and power source. The radioactive isotope $^{60}Co$ is often used in the medical field and in agricultural industries.

### 1.2.2. Cobalt-bearing main ore minerals

Over 30 cobalt-bearing minerals are found in nature, most in the form of simple and complex sulfides, arsenides, and sulfarsenides. Nickel and cobalt occur as isomorphic mixtures in the adsorbed form in about 100 mineral structures. The primary ore minerals are listed in Table 3.

**Cobalt ore minerals (Hazen et al., 2016)**

Table 3.

| Minerals | Formula | Average grade (%) | | | Example deposits |
|---|---|---|---|---|---|
| | | Co | Ni | Cu | |
| Skutterudite | $(Co,Ni)As_{3-x}$ | 17.95 | 5.96 | - | Skutterud Mine (Norway), Bou Azzer (Morocco) |
| Cobaltpentlandite | $Co_9S_8$ | 49.33 | 9.06 | - | Sudbury (Canada) |
| Smaltite | $(Co,Fe,Ni)As_{3-x,\ 0.5<x}$ | 28.20 | - | - | Bou Azzer (Morocco), Langis Mine (Canada) |
| Safflorite | $(Co,Fe)As_2$ | 21.25 | - | - | Elizabeth Mine (Romania) |
| Cobaltite | CoAsS | 35.52 | - | - | Sudbury (Canada), Broken Hill (Australia) |
| Alloclasite | (Co,Fe)AsS | 26.76 | - | - | Elizabeth Mine (Romania), Silverfields Mine (Canada) |
| Glaucodot | (Co,Fe)AsS | 26.76 | - | - | Hakansboda (Sweden) |
| Carrollite | $Cu(Co,Ni)_2S_4$ | 28.56 | 9.48 | 20.53 | Chambishi, Mutanda (DRC), Carroll County (USA) |
| Linnaeite | $Co_2+Co_{23+S}$ | 57.95 | - | - | Bou Azzer (Morocco), Norilsk (Russia) |
| Siegenite | $(Ni,Co)_3S_4$ | 14.51 | 43.36 | - | Jungfer Mine (Germany) |
| Cattierite | $CoS_2$ | 47.89 | - | - | Shinkolobwe (DRC) |
| Bravoite | $(Fe,Ni,Co)S_2$ | 4.88 | 9.71 | - | Langis Mine (Canada), Bou Azzer (Morocco) |
| Willyamite | (Co,Ni)SbS | 20.78 | 6.90 | - | Broken Hill (Australia) |
| Co-pentlandite | $(Co,Ni,Fe)_9S_8$ | 54.18 | 15.69 | - | Langis Mine (Canada), Sotkamo (Finland) |
| Erythrite | $Co_3(AsO_4)_2 \cdot 8(H_2O)$ | 29.53 | - | - | Bou Azzer (Morocco), Daniel Mine (Germany) |
| Roselite | $Ca_2(Co,Mg)(AsO_4)_2 \cdot 2(H_2O)$ | 9.95 | - | - | Rappold Mine (Germany), Rosas Mine (Italy) |
| Heterogenite | CoO(OH) | 64.10 | - | - | Katanga Province (DRC) |
| Asbolane | $(Ni,Co)_{2-x}Mn_4+(O,OH)_4 \cdot n(H_2O)$ | 3.30 | 9.85 | - | Koniambo Massif, Goro (New Caledonia) |
| Co-Lithiophorite | $(Al,Li,Ni,Co)(Mn,Fe,Mg) O_2(OH)_2$ | 1.90 | 1.90 | - | Tiebaghi (New Caledonia), Shinkolobwe (DRC) |
| Kolwezite | $(Cu,Co)_2(CO_3)(OH)_2$ | 17.84 | - | 39.05 | Musonoi, Kamoto, Mupine, Mashamba Mines (DRC) |
| Spherocobaltite | $CoCO_3$ | 49.55 | - | - | Tenke Fungurume (DRC), Schneeberg district (Germany) |
| Bieberite | $CoSO_4 \cdot 7(H_2O)$ | 20.96 | - | - | Schneeberg district (Germany), Jachymov (Czech Republic) |
| Aplowite | $(Co,Mn,Ni)SO_4 \cdot 4(H_2O)$ | 15.66 | 2.60 | - | Magnet Cove Mine (Canada) |
| Freboldite | CoSe | 42.74 | - | - | Steinbruch Trogtal Mine (Germany) |
| Trogtalite | $CoSe_2$ | 27.18 | - | - | Musonoi Mine (DRC), |
| Penroseite | $(Ni,Co,Cu)Se_2$ | 8.14 | 16.22 | 2.93 | Pacajake Mine (Bolivia) |
| Tyrrellite | $(Cu,Co,Ni)_3Se_4$ | 10.59 | 3.52 | 22.84 | Goldfields District (Canada), Petrovice deposit (Czech Republic) |

### 1.2.3. Cobalt mineralization, ore genesis

Cobalt deposits with arsenide and sulfarsenide ores are dominant wherein the ore minerals occur in open space- and fracture-filling veins and veinlets, and form vein-like bodies with disseminated and veinlet-disseminated ores of hydrothermal origin (Khovu-Aksy). Veins are irregular in thickness, suddenly thickening or tapering and then disappearing. Feather-like veins turn into lens-like bodies or veinlets and disseminated ores. Besides main ore minerals, loellingite, native silver, argentite, electrum, native bismuth, arsenopyrite, tennantite, antimony, cinnabar, and rarely sphalerite and galena can be found. In oxidized zones, cobalt-nickel arsenates, namely erythrite-annabergite, can be broadly found. Minerals in veins include quartz, calcite, dolomite, and rarely ankerite and chlorite. Ores include cobalt, nickel, copper, silver, gold, bismuth, and arsenic. This type of deposit is not widely distributed and their contribution to cobalt and nickel resources is not much. Cobalt-bearing deposits are classified into 11 types in terms of ore genesis (Robert et al., 2017):

1. Copper-nickel-cobalt sulphide deposits (Ni-Cu, Ni-Co-PGE)
2. Stratiform sediment-hosted deposits (Cu-Co)
3. Lateritic deposits (Ni-Co, Cu-Co)
4. Five-element vein-type deposit (Bi-Co-Ni, Cu-Ni)
5. Black shale-hosted Co deposits (Co)
6. Metasedimentary-rock-hosted deposits (Co-Cu-Au)
7. Iron oxide-hosted stratiform deposits (IOCG-Co, U, REE)
8. Volcanics-hosted deposits (Cu-Pb-Zn-Co)
9. Seafloor sedimentary deposits (1. Fe-Mn /Ni-Co-Cu/, 2. Fe-Mn /Co-Mo-REE)
10. Contact metasomatitic (Skarn) deposits
11. Seafloor Fe-Mn (Ni-Cu-Co-Mo) deposits (Table 4).

**Ore geneses of cobalt-bearing deposits (Mudd et al., 2013).**

Table 4.

| Deposit type | Brief description | Deposit size (million tons of ore) | Cobalt ore minerals | Examples of deposits and cobalt grade |
|---|---|---|---|---|
| **Copper-nickel-cobalt sulphide deposit (Ni-Cu, Ni-Co-PGE)** | Massive and disseminated minerals hosted in mafic and ultramafic rocks. | 5–>500 | Carrollite, linnaeite, pentlandite, siegenite, cobaltite, glaucodot | Norilsk-Talnakh, Russia (Co-0.061%); Voisey's Bay, Canada (Co-0.13%); Kambalda, Asutralia (Co-0.21%) |
| **Stratiform sediment-hosted Cu-Co deposits (Cu-Co)** | Mineralization hosted in clastic or carbonate rocks. | 10–500 | Carrollite-linnaeite, cobaltite, cattierite, (heterogenite, spherocobaltite in weathering zones) | Tenke Fungurume, DRC (Co-0.245%); Kisanfu, DRC (Co-1.08%); Nchanga, Zambia (Co-0.026%) |
| **Lateritic deposits (Ni-Co, Cu-Co)** | Lateritic surface during the weathering of mafic and ultramafic rocks. | 10–800 | Erythrite, heterogenite, asbolane, garnierite | Moa, Cuba (Co-0.13%); Goro deposit, New Caledonia (Co-0.11%); Murrin Murrin, Australia (Co-0.078%) |
| **Five metals vein-type deposit (Ni-Co-As-Ag-Bi)** | Mineralization is hosted in hydrothermal veins | < 20 | Co-arsenides, sulfides, sulfarsenides | Bou Azzer, Morocco (Co-1%) |
| **Black shale-hosted deposits** | Disseminated sulphide mineralization hosted in sulfur-rich black shales | >500 | Pentlandite, pyrrhotite | Sotkamo, Finland (Co-0.02%) |
| **Metasedimentary-rock-hosted deposits (Co-Cu-Au)** | Rift-related strata, lenses, veins, and breccias with high contents of disseminated and massive sulfide mineralization | <1–31 | Co-arsenide, sulfide, sulfarsenide | Modum district, Norway (Co-0.26%) |
| **Iron oxide-hosted deposits (Ag-U-REE-Co-Ni) (IOCG)** | Magmatic-hydrothermal, structurally controlled replacement deposits; | 5–>9 000 | Cobaltite, glaucodot | Olympic Dam, Australia (Co-0.02%) |
| **Volcanogenic Massive Sulphide deposits (VMS) Cu (-Zn-Co-Ag-Au)** | Cobalt occurrence in mafic and ultramafic rocks within the seafloor massive sulfide deposits | <10–300 | Cobalt, cobaltpentlandite | Kylylahti, Finland (Co-0.15%) |
| **Mississippi-Valley type deposits (MVT) Zn-Pb (–Co-Ni)** | Mineralization associated with veins that crosscut dolomite and limestone | 7 (medium-sized deposits) | Siegenite, bravoite, gersdorffite, pyrite | Higdon, USA (Co-0.14%) |
| **Skarn deposits Ag-Ni-As-Bi)–Co** | Mineralization hosted in calcareous-silicate rocks | 100–500 | Cobaltite, carrollite-linnaeite, pyrite, safflorite | Cornwall, USA (Co-0.03%); Goroblagodat, Russia (Co-0.02%) |
| **Seafloor Fe-Mn (Ni-Cu-Co-Mo) орд** | | 100-500 | | Mine La Motte, Fredericktown, USA (Co-0.8) |

### 1.2.4. Industrial types cobalt mineralization

Cobalt grade within a deposit can vary from 0.01% up to several tens of percent. The dominant portion of cobalt production comes from complex cobalt-bearing deposits. These complex deposits include copper-nickel sulphide deposits, silicate nickel ores as well as sedimentary copper deposits, shales, and iron ore (magnetite) and copper massive sulphide deposits.

Sediment-hosted Cu-Co and shale-hosted stratiform deposits are found in Congo, Zambia, and Uganda in African. Orebodies in these deposits are stratified with rare veins. Cobalt is found in pyrite, linnaeite, and carrollite that are paragenetically associated with uranium and copper minerals in these deposits. Cobalt grade is high in sulphide minerals, reaching 0.3%, while in oxide minerals it reaches 0.25-2.0%. These types of deposits are large and contain 50% of cobalt resources and are responsible for 40% of cobalt production.

Cobalt is found in pyrite and sometimes in magnetite, but rarely in arsenide or sulfo-arsenide in iron ore deposits. Cobalt ore grade ranges between 0.007-0.028% in these types of deposits. These deposits are distributed widely around the world, with many of them found in Russia. Cobalt is not processed as a co-product during the processing of iron ores, and, therefore, additional technology is required to extract cobalt which depends on feasibility studies.

Copper massive sulphide deposits contain cobalt dominantly as isomorphic mixture in pyrite and as cobaltite and linnaeite in some cases. Cobalt grade ranges between 0.013-0.07%. Cobalt-bearing massive sulphide deposits can be found in Finland, Norway, and Russia; however, cobalt is extracted from these only in Finland.

It is assumed that a new industrial type of cobalt is the formation of iron-manganese nodules at depths of 4500-5000m on ancient and modern seafloor. The Clarion-Clipperton area (1500 × 2000 км) found on the seafloor of the Pacific Ocean is the main representative of this type of mineralization. Accumulation of iron-manganese nodules varies largely in terms of abundancy per unit area (per 1 $m^2$ on the seafloor) and sometimes reaches 30 кg/$m^2$. The strata with nodules contain complex deposits with Mn, Ni, Co, and Cu mineralization. Nodule diameter varies between 0.1–$n$·10 cm with dominant size of 3-7 cm. Metal contents in nodules are: Mn=25–30%, Fe=6–12%, Ni=1–2%, Co=0.2–1.5%, Cu=1–1.5%, and P=0.5–1%. Additionally, Mo, REE, V, PGE, Au, and other metals can be found as byproducts.

Near the mid-ocean ridges at depths of 3000-4000 m on modern seafloor, sediments with cobalt-iron manganese nodules are of interest. These nodules form a cover from several mm up to 10 cm thick over the oceanic crust and sediments. This cover contains Mn-, Ni-, Cu-, Co-, and P-bearing iron hydroxides.

In recent years, there has been an increased re-utilization of man-made deposits of nickel, cobalt ores and low-grade ores, as well as concentrates (pyrrhotite concentrate, waste) and metallurgical deposits (slag, cake).

Internal structure and ore composition of man-made deposits directly depend on the origin and type of production of the primary deposit, mining methods, processing technology scheme, low-grade ore storage, storage methods, and stockpile time. Therefore, in the case of man-made deposit exploration and economic evaluation, the methodology developed for this type of deposit should be followed.

### 1.2.5. Cobalt production and its perspective

Cobalt is broadly used in superalloys production in modern society with fast science and technological advancement *(Shedd 2013a, b)*, in rechargeable batteries that are used in high technology industry, and in catalysator and carbide production (Donachie 2002). Additionally, cobalt is used in the production of electric cars, to stabilize alloy temperatures, and for turbine engines in jet aircraft (Donachie 2002). In 2019, 46% of cobalt production was used in manufacturing rechargeable batteries in the high technology industry, while 17% was used for making superalloys (Petavratzi et al., 2019).

In 2019, 168,000 tons of cobalt was produced around the world (Brown et al., 2019), of which 65% was extracted from stratiform deposits hosted in clastic sedimentary rocks in Democratic Republic of Congo (DRC). Other producing countries include New Caledonia, China, Canada, and Australia. In 2019-2020, 49% of cobalt production came from nickel sulphide deposits, 32% came from copper sulphide deposits, and 19% came from nickel laterite deposits (USGS., 2017, 2020).

Total resource of cobalt is 154 Mt in 2020 and 121 Mt of which is speculated to be produced from seafloor deposits (Mudd et al., 2013).

## 2. GROUPING DEPOSITS BY GEOLOGICAL COMPLEXITY IN ORDER WITH EXPLORATION PURPOSES

Based on the shape and size of the orebody, changes in its thickness and internal structure, and the distribution characteristics of nickel and cobalt content in the ore, deposits are classified into three groups for exploration purpose, following the instruction "Mineral Resources and Deposit Classification and Guidelines" approved in 2015. However, for cobalt deposits, a fourth group is added based on its complexities.

2.1. Group I deposits include the following:

- Stratiform deposits with simple geological setting, disseminated ore minerals, and relatively thick and mineralized with regularly distributed nickel grade (podiform orebodies with disseminated ore minerals from Norilsk-1 and Talnakh-Oktyabrks districts) copper-nickel sulphide deposits and their parts.
- The orebody thickness varies between 300 m and 1.5 km with length reaching several km.
- The orebody thickness is 30-40 m in average and thins to 5-10 m toward its edges while thickening to 60-100 m in the central portion.

2.2. Group II deposits include the following:

- Copper-nickel sulphide deposits with complex geological setting, large orebodies that are layered or tabular, invariable thickness that could bulge out or thin at some places, and branched to the edge, distribution of nickel grade is not constant (ore-rich podiform of Oktyabrsk and Talnakh deposits, Zhdanovskoy, Zapolyarnoy, Kotselvaara-Kammikivi and Semiletka deposits) and their parts.

- Orebodies range from hundreds of meters to several kilometers in length, with almost the same width and low slopes, and some steep slopes follow up to 1.5 km. Thickness of orebody varies between 1-2 m and 100 m.
- Silicate nickel deposits with uneven distribution of nickel content with layers, mantles, meshes, wedge-shaped large and medium-sized, sometimes small, unstable in thickness, sometimes forming large nests, or narrowed orebodies (Buruktalsk, Cheremshansk, Serovsk, and Saharinsk deposits).
- Orebodies are normally horizontal, but sometimes can be tilted slightly, with thickness varying from 1 m up to 30-50 m, and length from several 100 m up to several km.

2.3. Group III deposits include the following:

- Medium and small copper-nickel sulphide deposits with complex geological setting, orebodies with lens and/or vein-shaped, variable thickness of orebodies with many branches, thickens and thins, sometimes cut into shorter sections and their parts. Nickel grade varies largely in orebodies.
- Orebodies stretch from several tens of meter up to 100-200 m along the strike and dip. Thickness is normally 1-2 m, but sometimes can be 10 m (Sputnik, Shanuch, Oktyabrsk and Talnakh copper-bearing ores).
- Weathering silicate nickel deposits with orebodies of medium and small-sized narrow wedge-shaped, with variable thickness.
- Orebodies are no more than 100-200 m along the strike and dip. Thickness of orebodies range from 1 m up to 10-20 m (Kungursk, Pokrovsk, Sinarsk deposits).

2.4. Group IV deposits include the following:

- Nickel-cobalt and cobalt-dominant arsenide and sulfarsenide deposits with very complex geological setting, crosscut and displaced by many small fractures and complex orebody with many branches, with ore grade being highly variable.
- Orebodies are 100-400 m along the strike and 20-600 m along the dip with thickness between 0.5-1.0 m (Khovu-Aksy deposit).

When deposits are classified into groups based on their complexity of geological setting, one should consider the geological setting which contains more than 70% of the deposit's reserve. It is possible to take into account the quantitative statistical evaluation of the main mineralization characteristics when classifying a deposit as a group due to its complex geological setting (Appendix 1).

2.5. Nickel and cobalt deposits can be classified as big, medium and small, according to its size of reserve. Nickel and cobalt bearing ore can be classified as rich, medium and poor, according to its grade content. Size of deposits and grade of ore is shown on table below.

| Metall | Classification of reserve size of nickel and cobalt deposit, thousand tn | | | Classification of ore grade of nickel and cobalt, % | | |
|---|---|---|---|---|---|---|
| | Big | Medium | Small | Rich | Medium | Poor |
| Nickel | >200 | 30-200 | <30 | >2 | 0.5-2 | 0.3-0.5 |
| Cobalt | >15 | 2-15 | <2 | >0.5 | 0.1-0.5 | 0.05-0.1 |

## 3. GEOLOGICAL SETTING OF ORE DEPOSITS AND STUDY ON ORE MINERAL ASSEMBLAGES

**3.1.** For an explored deposit, it is necessary to have accurate information on the size of the deposit, its geological setting, and a topographic map at an appropriate scale that reflects local landscape-geomorphological conditions. Topographic maps and plans for nickel and cobalt deposits are usually generated at a scale of 1:1000 to 1:5000. All exploration and operational workings' excavations (trenches, pits, tunnels, shafts, and boreholes), profiles, and stations of detailed geophysical surveys, as well as natural outcrops of orebodies and ore zones should be tied through surveyors' measurements and reflected on a topographic map. Underground mine workings and boreholes should be plotted to the plain maps at every horizon according to the engineering surveys (markscheider work). Surveying plans of mining horizons are usually generated at scales from 1:200 to 1:500, whereas the consolidated (unified) plans should be made at scale 1:1000 or larger. The coordinates where boreholes intersect the roof and bottom of the orebody should be measured by engineering surveys, and their locations plotted on plans in planeview and cross-section.

**3.2.** The geological setting of the deposit should be studied in detail and plotted on the geological map at a scale from 1:1000 to 1:10000 depending on the size and complexity of the deposit (as well as a map of the development of the weathering crust of the same scale in case of silicate nickel deposits), and on geological sections, plans, projection planes, and, if necessary, on block diagrams and 3D models. Geological and geophysical studies on a certain deposit should be conducted in detail, and the resulting data should be sufficient for the calculation of ore reserves by determining the size and shape of orebodies, the conditions of their locations, their internal structure and continuity (degree of enrichment of ore for mineralized zones), the nature of wedging out of orebodies, the change features of host rocks and the relationship of orebodies with said host rocks, folded structures and tectonic faults, and their relationship to the host rocks. Additionally, the deposit should be studied to the extent that the data can provide sufficient insights and assumptions for estimating resources by determining the nature of thinning of orebodies, alteration features within the country rocks, the relationship between orebodies and folded structures and tectonic faults, as well as the nature of weathered surface in case of silicate nickel deposits (linear and areal) and their primary unaltered rock types before weathering, as well as tectonic faults and their intensity. In cases where the deposit resource is assessed at a grade of Predicted P1-classification, the geological boundaries and prospecting criteria that determine the location of the prospective area should be justified.

**3.3.** Orebodies, mineralized zones, outcrops in the weathered zones, and peripheral areas must be investigated with excavation methods that include trenches along the strikes, pits, pits with shafts (orebodies are intersected by horizontal excavations from the lower part), tranchee ore tunnel, and shallow boreholes, as well as geophysical and geochemical methods.

Determining the shape and the condition of orebodies, the weathered surface and oxidized zones and their depth, the degree of sulphide ores' oxidation, the changes in composition of ore mineral and technological properties, and the grades of nickel and cobalt ores are sufficient to estimate reserve of the ore deposit based on distinguished industrial (technological) types.

**3.4.** Copper-nickel sulphide and silicate nickel ore deposits must be explored with drilling methods at depth (must be combined with surface excavations for complex deposits, especially for arsenide and sulfarsenides deposits), and geophysical surveys must be conducted in surface and underground excavations and boreholes. Exploration methods – the ratio of excavations to number of boreholes, types of excavations, types of drilling, the geometry and density of exploration grids, and types of samplings and their methods must meet the requirements that correspond to the level at which the reserve and/or resource will be estimated. Exploration method is determined based on the geological setting of the deposit, the possibility of using excavation, drilling and geophysical equipment for exploration, and the experience of exploring and mining similar deposits. Finally, the feasibility parameters and timeframes for the various exploration options must be compared and analyzed to select the optimal exploration system.

**3.5.** The maximum yield of well-preserved cores needs to be obtained from drilling to the extent that the characteristics of orebodies and host rocks, their thickness, internal structure of orebodies, the alteration types in vicinity of the orebody, the distribution of different types of ores, their structure and texture can be fully determined, and the sampling can fully represent the deposit. Recent experience in geological exploration shows that the core yield should be at least 90% for each drilling run. In order to accurately determine the linear output of the core, it must be regularly monitored by weight and volume methods.

In determining the nickel and cobalt content and the cross-sectional thickness of the ore, whether or not the core is subject to selective abrasion must be investigated to ensure that it is representative of the core. For this purpose, the results of borehole and sludge sampling analyses by different types of ore (cross-sections with different outputs) must be compared to that of samples obtained from controlling excavation or by other means of drilling (percussion, gas percussion and pellets), as well as diamond core drilling with increased core yield. If the core yield is low or the sampling result is significantly distorted due to selective abrasion and tear, a different technique should be used. If the exploration is carried out on a deposit with fluffy or loosely compacted ore (weathering surface), using advanced technology specially developed to improve the yield of the drill core (unwashed drilling, short-run drilling, use of special drilling fluids, etc.,) is needed. In order to improve the reliability of drilling and its informative quality, it may be necessary to use complex methods of borehole geophysical research, which will be determined depending on the objectives, specific geological and geophysical conditions of the deposit, and modern advanced methods of geophysical methods. Comprehensive logging measurements are required to identify all ore sections and to determine their parameters, so it is necessary to conduct them for all exploration wells drilled in the deposit.

All vertical and inclined boreholes drilled to a depth of more than 100 m at the surface and underground shall be required to have their azimuth and zenith angles determined every 20 m. The results of these measurements should be used to make geological sections and plans, and to calculate the thickness of the ore section. In case of excavation that intersected the borehole, the location of the intersection point shall be determined by surveyor's measurements.

The slope of the boreholes shall be selected so that the orebody is intersected at an angle of no less than 30°. Artificial bending of the borehole is possible if the orebody is intersected at an acute angle. It is useful to drill multi-bench holes and drill underground from horizontal underground excavations to improve the results of exploration. It is better to drill a hole of the same diameter through the ore.

**3.6.** Excavations (including exploration boreholes) are the main means of studying the internal structure, shape, conditions of the orebody's locations, mineral composition and continuity of orebodies, and to monitor the information obtained from drilling and geophysical surveys, as well as to collect technological samples. Excavations including exploration holes are the main method of detailed study to determine the location, shape, internal structure, and mineral composition of the orebody for arsenide and sulfarsenide ores.

Excavation can be used to adequately study the continuity of orebodies, their thickness along the strike and dip, and their ability to represent changes in nickel and cobalt content. Low-thickness orebodies are studied by the longitudinal penetration along the strike and the upward penetration along the dip. Thicker bodies can be explored through a system of horizontal boreholes through a hole, penetration, or compacted mesh. Excavation will begin at the site and levels where the deposit is planned to be commissioned in the first instance.

**3.7.** The location of exploration excavations and the distance between them should be selected for each structural-morphological type of orebody in accordance with their shape, size, and geological setting. Information on the density of exploration grids used in the exploration of nickel and cobalt ores is shown in Table 5 as an example, and while it can be used to plan geological exploration work, it does not necessarily mean that the same size of grid will be used. The density and optimal shape of the exploration grid must be determined based on a detailed study of each deposit, geological and geophysical surveys of similar deposits, and analysis of operational data.

**3.8.** Exploration must be carried out in more detail in certain areas of the deposit to confirm the reliability of resource estimates. These sections must be studied and sampled with a denser exploration grid than other parts of the deposit. In the case of group I deposits, the exploration reserves in this more detailed area must be explored to the extent that they meet the requirements for estimating reserves for Proved (A) and Measured (B), for group II deposits for Measured (B) and for group III and IV deposits for Indicated (C). In the case of group III deposits, however, the detailed study area should be at least twice the size of the exploration grid used to estimate the Indicated (C) grade. If geostatistical methods are used in the calculation of the deposit's reserves, the density of the exploration grid and the sample shall meet the requirements for calculations in spatial directions.

The parts with detailed studies should reflect the shape and location characteristics of the orebodies containing the main part of the deposit, as well as the dominant features of the ore. Where possible, such areas should be located within the boundaries of the resource to be mined in the first instance. If the areas to be mined in the first place have their own characteristics that do not represent the entire deposit in terms of geological setting, ore quality, and mining-geological conditions, it is necessary to find and study in detail areas that do meet this requirement. The subsoil user shall determine the number of areas to be studied in detail at the deposit level in each case.

The geological information obtained from the detailed study areas is used to confirm and assess the complexity of the deposit and to ensure that the equipment, methodology and exploration grid selected for exploration and its shape are appropriate to the geological setting of the deposit; it is used to assess the credibility of the results and to assess the conditions under which the deposit will be used as a whole. In the case of mined deposits, the results of exploration and production will be used for this purpose.

**Table 5. Information on the density of exploration grid used for exploration of nickel and cobalt deposits**

| Deposit group | Characteristics of ore bodies | Type of workings | Distances between intersections of ore bodies by workings for the reserve category, m | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | A | | B | | $C_1$ | |
| | | | Along strike | Along dip | Along strike | Along dip | Along strike | Along dip |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| **I** | Large sheet-like deposits of disseminated ores of simple structure with sustained thickness and relatively uniform distribution of nickel | Wells | 100 | 100 | 200 | 200 | 400 | 400–600 |
| **II** | Large sheet-like and slab-like deposits of a complex structure of unsustainable thickness or with an uneven distribution of nickel | Wells | – | – | 50–100 | 50–100 | 100–200 | 75–100 |
| | Large, medium and small sheet-like, mantle-like and lenticular deposits of unsustainable thickness with uneven distribution of nickel | Wells | – | – | 20–50 | 20–50 | 50–100 | 50 |
| **III** | Medium and small deposits of very complex shapes with a very uneven distribution of nickel | Wells | – | – | – | – | 50 | 25–50 |
| **IV** | Small complex veins of unseasoned power with a very uneven distribution of nickel and cobalt | Mine working and wells | – | – | – | – | Contin uous trackin g | 30–40 |
| | | | – | – | – | – | 50 | 50 |

***** *At the evaluated deposits with category P, the exploration network for category C is sparse by 2–4 times, depending on the complexity of the geological structure of the deposit.*

At deposits with discontinuous mineralization (Group IV), the reserves of which are estimated without geometrization of specific ore bodies in a generalized contour using ore-bearing coefficients, based on determining the spatial position, typical shapes and sizes of conditioned ore plots, as well as the distribution of reserves by the thickness of ore intervals, the possibility of selective mining should be assessed.

**3.9.** All exploration excavations, orebodies and surface outcrops shall be documented in accordance with established procedures and forms. Sampling results will be recorded on initial documentation and verified by geological records.

The completeness and quality of the primary documentation, whether it corresponds to the geological features of the deposit, the correct spatial position of the structural elements, compiling sketches, and their documentation are routinely verified by an accredited geologist, and its compliance with the consolidated geological materials in the documentation should be monitored.

In addition, the quality of geological and geophysical sampling (whether the sample weight and sample cross-section are stable, whether the sampling direction corresponds to the geological setting of the part, the density and continuity of sampling, whether control sampling and their results are present), mineralogical-technological, engineer-hydrogeology, and specific density must be determined. Additionally, the ability of analytical samples related to mining operations to represent the deposit must be evaluated and appropriate samples selected.

**3.10.** All ore sections discovered during the exploration excavations required to investigate the quality of the minerals, to determine the boundaries of the orebodies, and to estimate the reserves, as well as all mineralized outcrops, must be sampled.

**3.11.** The sampling options (geological and geophysical) and their methods depend on the characteristics of the geological setting of the deposit, the physical properties of the minerals and host rocks, and the techniques and equipment used in the exploration. The selection shall be made at the initial stage of evaluation and exploration work. The methodology and methods chosen for sampling must be credible in order to obtain results in a highly productive and cost-effective manner. When several different types of sampling methods are used, the accuracy and reliability of their results should be compared and analyzed.

The choice of sampling type (geological, geophysical) and method (core, furrow, burrow, etc.,) should follow the guidelines for assessing the quality of the specimen and the reliability of specimen processing.

**3.12.** Exploration section sampling shall be carried out under the following conditions:

- The sampling grid should be stable, and its density should be determined by the geological characteristics of the deposit areas under study, which are usually determined based on experience in the exploration of similar deposits, and experimentally at new sites. Samples shall be taken in the direction in which the mineralization pattern is most variable. In the event that the orebody is intersected at an acute angle in the direction of maximum variation during exploration excavations (especially boreholes), the possibility of using the sample results of these sections for resource calculations should be ensured by performing control sampling and comparing the results (if the specimen's representativeness is in doubt).
- Sampling shall be carried out by covering the entire thickness of the orebody and a certain amount of host rocks. The amount of penetration and sampling in the host rocks should not be less than the standard requirement for the thickness of the hollow rock within the reserve. For orebodies without clear geological boundaries, it is possible to sample the entire exploration section, and for orebodies with clear geological boundaries, it is possible to sample the orebody with a sparse mesh. In addition to the main orebodies, their weathering products should also be sampled in trenches, pits, and tranchees.
- The host rocks, altered rocks, mineralized rocks of orebodies, and natural types of ore should all be sampled separately. The length of each specimen (typical specimens) is determined by the internal structure of the orebody, changes in the composition of the ores, textural and structural features, physical-mechanical, and other properties, whereas in the case of drill cores, the length of each specimen is determined based on the drill run. Samples from the borehole (cores and sludge) can vary depending on the type and quality of drilling. If the kernel (sludge) yield is different, different sections of borehole diameter shall be sampled separately. In the event of a certain amount of selective abrasion and tear on the core, the core and the sludge containing the abrasion material shall also be sampled and analyzed

separately. If the drilling diameter is small and the distribution of ore minerals is very uneven, the core should be fully sampled.

- In the case of excavations, the entire thickness of the orebody shall be sampled from two horizontal and vertical excavation walls, and in the case of excavations along the extension of the orebody, the bench shall be sampled. When sampling from excavation benches excavated along the orebody, the distance between the samples is usually 2-4 m, 1-2 m in arsenide and sulfarsenide ore deposits (if the distance is increased, it should be confirmed by the sample results). When sampling horizontally excavated orebodies with a vertical dip, samples should be taken from a predetermined stable height and the parameters used should be confirmed by experimental work. The use of the sampling method used in excavations should be based on the study of the presence of adhesions and fissures of ore and non-ore minerals.
- The results of geological and geophysical sampling obtained from boreholes and excavations will be used to assess the irregularity of the mineralization and to determine the presence of radioactivity. Therefore, large-scale samples should be taken in each section in uniform steps (ordinary samples) or 1 m. If the mineralization parameters are very stable, the length of the sample can be increased, while if it is very uneven, it can be reduced to less than 1 m. The results of the sampling can be used to quantify the distribution of poor (non-standard) or empty strata contained in the resource estimates of the deposit, such as documentation of boreholes and rock samples from excavations.

**3.13.** The sampling quality of each of the main ore types should be monitored regularly to assess the reliability and accuracy of the results. It is necessary to check in a timely manner the position of the samples relative to the elements of the geological structure and the reliability of the contouring of ore bodies in terms of thickness, the consistency of the accepted parameters of the samples and the compliance of the actual mass of the sample with the calculated one based on the accepted section of the furrow or the actual diameter and core output (deviations should not exceed ± 10–20%, taking into account ore density variability).

The accuracy of furrow sampling should be controlled by conjugated grooves of the same section, core sampling in the case of dividing the core into halves - by sampling from the second halves of the core. The sampling methodology used and the reliability of the sampling methods must be monitored by taking a sample that is more representative and comparing the results.

In the case of geophysical surveys, natural measurements should be made to monitor the stability of the measuring equipment, using routine measurements and repeated measurements. Logging results are confirmed by the results of high-yield (90%) specimens. If there are any deficiencies in the accuracy of the sampling, the ore interval shall be re-sampled (or repeated logging).

If the drill core is subject to selective abrasion, which will have a significant effect on the sampling results, the accuracy of the borehole data will be confirmed by adjacent excavation sampling.

The control of the sampling method is carried out by sampling the specimens in a more representative way and comparing the results. In addition, determination of sampling credentials requires using results of technological samples and bulk samples from celiacs to determine the specific gravity, and information obtained from deposit extraction.

In the case of operating production, the sampling methodology should be tested by comparing the results of resource blocks and mine levels limited by excavations or boreholes. The size of the control samples should be sufficient for statistical processing and for a reasonable conclusion as to whether there is a persistent (systematic) error, and if necessary, for introducing correction factors.

**3.14.** Sample processing will be carried out according to a scheme developed for each deposit, taking into account the distribution of minerals and the shape and size of the mineral grains they contain. The main and control samples are to be processed according to the same scheme. The quality of processing shall be regularly monitored for all activities, including the basis of the "K" coefficient and adherence to the processing scheme. The cleaning of the crushing equipment should be monitored regularly during sample processing. The processing of control bulk samples shall be carried out according to a specially developed program.

**3.15.** A comprehensive study of the chemical composition of the ore will be conducted to identify the main products and by-products and toxic impurities. Their ore content will be determined by chemical, spectral, physical and other analytical methods in the samples in accordance with state approved standards.

The study of ancillary minerals in the ore shall be carried out in accordance with the requirements of the methodological recommendations for the study of ancillary minerals for the purpose of comprehensive study and exploitation of minerals. If this type of guideline has not been developed, a similar one can be used, for example the Russian "Methodological recommendations for the comprehensive study of locations and the calculation of reserves of combined mineral reserves and components, 2007".

For all ordinary samples, the main mineral component is determined, and the results are used to draw the orebody boundaries and to estimate reserves. In copper-nickel sulfide ore deposits, typical samples shall be tested for nickel, copper, cobalt, and, if these elements are high in content, gold and platinum group elements shall be analyzed as well. Other elements (silver, selenium, tellurium) and toxic compounds (zinc, lead, arsenic, fluorine, cadmium, bismuth), as well as slag-forming compounds ($SiO_2$, $Fe_2O_3$, FeO, $Al_2O_3$, MgO ба CaO), etc., will be determined in grouped samples.

In silicate nickel ore deposits, the content of nickel, cobalt, and iron (in ferrous ores) is determined in ordinary samples. Grouped samples will be analyzed for their nickel, cobalt, iron, and slag-forming compounds ($SiO_2$, $Al_2O_3$, MgO, $Fe_2O_3$, CaO, sometimes FeO, MnO, $TiO_2$) and toxic compounds ($Cr_2O_3$, Cu, $P_2O_5$). Ordinary samples from arsenide- and sulfarsenide-bearing nickel and cobalt ore deposits will be analyzed for their nickel, cobalt, and sometimes for their arsenic contents while grouped samples will be analyzed for their copper, arsenic, bismuth, gold, silver, sulfur, antimony, lead, zinc, and slag ($SiO_2$, CaO and MgO) contents.

The procedure for combining ordinary samples into group samples, their placement and total number should ensure uniform sampling of the main varieties of ores for associated and slag-forming components and harmful impurities and clarify the patterns of changes in their contents along the strike and dip of ore bodies. At deposits of silicate nickel ores, slag-forming components must be studied in all wells in a network corresponding to category C . Phase analysis is required to determine the degree of oxidation of sulfide, arsenide, and sulfarsenide ores, to map the boundaries of the oxidized zone, and to determine the amount of nickel and cobalt associated with the silicate.

**3.16.** The quality of the sample analysis should be regularly monitored, and the results processed in a timely manner in accordance with the relevant methodological guidelines. Geological monitoring of specimens should be performed throughout the life of the mining project, independent of internal laboratory monitoring. In addition to the main useful components, the ancillary and toxic compounds shall be included in the analytical control.

**3.17.** To determine the magnitude of random errors, it is necessary to carry out internal control by analyzing encrypted control samples taken from duplicate analytical samples in the same laboratory that performs the main analyzes. To identify and evaluate possible systematic errors, external control should be carried out in a laboratory that has the status of a control one. Duplicates of internally inspected specimens shall be sent to the laboratory where the main analysis was performed for external inspection. In the case of standard-compliant specimens that are similar to the specimens being analyzed, external monitoring may be performed by analyzing the standard specimens in the laboratory of the main analyte within the group of conventional specimens to be analyzed. Samples sent for internal and external inspection should be large enough to represent all types and grades of ore in the deposit. All specimens with extremely high grades must be included in the internal control.

**3.18.** The amount of internal and external controls should be representative of each stage of the analysis (quarterly, semi-annually, etc.,) selected from each class of content. When distinguishing classes, one should take into account the parameters of conditions for calculating reserves - cut-off and minimum commercial grade. If the number of samples to be tested is very high (2000 or more per year), 5% of the samples should be sent for control analysis. If the number of samples tested for each group of content is small, at least 30 control samples from each group shall be tested during the control period.

**3.19.** For each group of content, the processing of internal and external monitoring information is to be performed at a certain frequency (quarterly, semi-annually, annually) for each type of analysis and the laboratory that performed the main analysis. The assessment of systematic discrepancies in the results of standard sample tests shall be performed in accordance with the methodology for statistical processing of test data. The relative mean square error calculated as a result of the internal control shall not exceed the values given in Table 6. In the event it exceeds these values, the results of the main analysis of the group of content and the results of all samples taken during the laboratory analysis will be invalidated and the samples will be re-analyzed in conjunction with internal geological control. The laboratory that performed the basic analysis must identify the cause of the error and take corrective action.

**3.20.** If, according to external control data, systematic discrepancies are detected between the results of analyzes of the main and control laboratories, arbitration control is carried out. This control is carried out in a laboratory that has the status of arbitration. Analytical duplicates of ordinary samples stored in the laboratory (in exceptional cases - the remains of analytical samples), for which there are results of ordinary and external control analyzes, are sent for arbitration control. 30–40 samples are subject to control for each class of contents for which systematic discrepancies are revealed. If there are SOCs similar to the samples under investigation, they should also be included in encrypted form in the lot of samples submitted for arbitration. For each SOS, 10-15 results of control analyzes should be obtained.

When systematic discrepancies are confirmed by arbitration analysis, their causes should be clarified and measures should be developed to eliminate shortcomings in the work of the main laboratory, as well as to decide whether it is necessary to re-analyze all samples of this class and the period of work of the main laboratory or to introduce an appropriate correction factor into the results of the main analyzes. Without arbitrage analysis, the introduction of correction factors is not allowed.

**Table 6. Mean square error of tolerance**

| **Composition** | **Groups by ore grades*, %** (Au, Ag, Se, Te, g/t)* | **Mean square error of tolerance, %** | **Compositio n** | **Groups by ore grades*, %** (Au, Ag, Se, Te, g/t)* | **Mean square error of tolerance, %** |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 |
| Ni | 1–2 | 5 | Te | 100–500 | 17 |
| | 0.5–1 | 7 | | 50–100 | 22 |
| | 0.2–0.5 | 10 | | 20–50 | 25 |
| Co | >1 | 2.5 | | 5–20 | 30 |
| | 0.5–1.0 | 3.5 | | 1–5 | 30 |
| | 0.1–0.5 | 6.0 | $Cr_2O_3$ | 10–20 | 2.5 |
| | 0.05–0.1 | 10 | | 5–10 | 3 |
| | 0.01–0.05 | 25 | | 1–5 | 5 |
| Cu | 1–3 | 5.5 | | 0.1–1 | 8.5 |
| | 0.5–1 | 8.5 | $P_2O_5$ | 0.1–0.3 | 11 |
| | 0.2–0.5 | 13 | | 0.05–0.1 | 15 |
| | 0.1–0.2 | 17 | | 0.01–0.05 | 25 |
| S | 30–40 | 1.2 | | 0.001–0.01 | 30 |
| | 20–30 | 1.5 | $SiO_2$ | >50 | 1.3 |
| | 10–20 | 2 | | 20–50 | 2.5 |
| | 2–10 | 6 | | 5–20 | 5.5 |
| | 1–2 | 9 | | 1.5–5 | 11 |
| Au | 4–16 | 18 | $Fe_2O_3$ | 10–20 | 3 |
| | 1–4 | 25 | | 5–10 | 6 |
| | 0.5–1 | 30 | | 1–5 | 12 |
| | <0.5 | 30 | FeO | 5–12 | 5.5 |
| Ag | 100–300 | 7 | | 3.5–5 | 10 |
| | 30–100 | 12 | | <3.5 | 20 |
| | 10–30 | 15 | MgO | 20–40 | 3 |
| | 1–10 | 22 | | 10–20 | 4.5 |
| | 0.5–1 | 25 | | 1–10 | 9 |
| Se | 100–500 | 15 | $Al_2O_3$ | 15–25 | 4.5 |
| | 50–100 | 20 | | 10–15 | 5 |
| | 20–50 | 25 | | 5–10 | 6.5 |
| | 5–20 | 30 | | 1–5 | 12 |
| | 1–5 | 30 | | | |
| * *In case of deviations from the values specified in the group of content of the deposit, the permissible standard error is determined by interpolation.* | | | | | |

**3.21.** Controls for sampling, processing, and analysis should be used to assess possible errors in the differentiation of ore sections and the determination of their parameters.

**3.22.** The mineral composition of natural varieties and industrial types of ores, their textural and structural features and physical properties should be studied using mineralogicalpetrographic, physical, chemical and other types of analysis. At the same time, along with a description of individual minerals, a description of their physical properties, a quantitative assessment of their abundance is also made. Special attention needs to be paid to nickel-, cobalt-, copper-, and PGE-bearing minerals in Co-Ni sulphide, arsenide, and sulfarsenides deposits, and these minerals must be quantified, as well as textural relationships between these minerals and other minerals (associations, mode of occurrence, and size), and grain size being defined.

The amount of nickel and cobalt non-sulphide-bound ores needs to be determined in tailings after processing sulphide ores.

In the case of silicate nickel ores formed on the weathering surface of ultramafic rocks, special attention should be paid to their chemical composition and the distribution of nickel, cobalt, slag-forming compounds, chromium trioxide and other toxic impurities in the orebody. For silicate nickel ores of the weathering crust of ultramafic rocks, information about their chemical composition, patterns of distribution within the ore bodies of nickel, cobalt, slag-forming components, chromium trioxide, and other harmful impurities is of paramount importance. Along with this, the mineral composition should be determined, and minerals containing nickel and cobalt should be carefully studied.

It is also necessary to study the mineral composition of the ores in detail and to determine the individual minerals containing nickel and cobalt. Especially in silicate ores containing nickel and cobalt, it can be difficult to distinguish minerals by optical microscopy, so special mineralogical methods such as XRD (X-ray phase analysis) and Laser Raman Spectrometer should be used. During the mineralogical studies, the distribution of primary and byproducts of ores must be combined with the distribution of toxic compounds, and distributional balance should be investigated for mineral compatibility.

**3.23.** Determination of bulk density and moisture content must be made for each selected natural variety of ores, intraore substandard interlayers and host rocks, guided by the relevant regulatory and methodological documents. The volumetric mass of loose, highly fractured and cavernous ores, as a rule, is determined in pillars. Determination of the bulk mass can also be carried out by the method of absorption of scattered gamma radiation in the presence of the necessary amount of verification work. Simultaneously with the determination of the bulk density, the moisture content of the ores is determined on the same material. Samples and samples for determination of bulk density and moisture should be characterized mineralogically and analyzed for major components.

**3.24.** As a result of studying the chemical, mineral composition, textural and structural features and physical properties of ores, their natural varieties are established and industrial (technological) types of ores are preliminarily outlined, requiring selective mining and separate processing. The final selection of industrial (technological) types and grades of ores is carried out based on the results of a technological study of the natural varieties identified at the deposit.

## 4. STUDY OF ORE TECHNOLOGICAL CHARACTERISTICS OF NICKEL AND COBALT ORE DEPOSITS

**4.1.** In order to conduct research on nickel and cobalt ore technology, samples first need to be tested for all types of natural (mineralogical) and technological ores. These samples, depending on the type of deposit, shall be taken to fully represent the deposit in accordance with established methods and procedures.

**4.2.** Ore beneficiation tests shall be performed for mineralogical-technological, low-technological, laboratory, enlarged laboratory, semi-industrial specimens at laboratory and semi-industrial conditions.

**4.3.** In the case of easily enriched ores, laboratory-level technological research methods may be used as a reference for ore processing technology with similar properties. If the processing method is difficult or complicated, or there is no experience of concentrating such ores as the ores are a new type, if necessary, a special program of ore technology research will be conducted in consultation with the organization interested in the enriched ore product.

**4.4.** In order to differentiate the types and grades of ore technology, geological and technological mapping shall be carried out and, based on this, the sampling grid shall be selected depending on the number and frequency of occurrence of natural ore types.

**4.5.** Mineralogical-technological and small-scale technological samples collected with a certain grid should be taken in such a way as to represent all natural types of ore found at the deposit. As a result of their preliminary technological experiments, geological-technological types of ore will be identified, ore production (technological) types and varieties classified, and spatial changes in ore composition, physico-mechanical and technological properties studied within the classified production (technological) types to create technology maps, plans, and sections.

**4.6.** Laboratory and enlarged laboratory samples will be used to study the technological characteristics of all types of ore (production), to select the optimal ore processing technology scheme, and to determine the main parameters of the processing technology and the resulting product. In this case, the optimal degree of ore crushing will be determined, and the maximum amount of minerals will be extracted, and the least amount of minerals will be dumped into the processing plant waste.

**4.7.** Semi-industrial technology testing shall be performed to verify the ore processing technology scheme and to clarify the ore enrichment parameters determined by laboratory tests. Semi-industrial technology testing shall be carried out in accordance with a specially prepared program on the basis of a contract with a specialized organization for technological testing. Samples for semi-industrial testing should only be used in accordance with the methodology specifically designed for this project.

**4.8.** Samples taken for laboratory enlarged and semi-industrial technology testing shall be capable of representing the chemical and mineral composition, structural-textural characteristics, average physical, and other characteristics of the ore production (technological) type, taking into account potential contamination during operation and enrichment during sorting. The granulometric composition of the sample should be in accordance with the technological scheme to be used for ore beneficiation of the deposit.

**4.9.** When testing ore technology, it is recommended that the possibility of radiometric (radiographic and other) separation of the ore be studied. Guided by the relevant methodological documents, the physical properties that can be used to differentiate the ore mass, the emissions of the ore by its composition, and the radiometric emissions that can be differentiated at different values of the ore composition should be evaluated. A radiometric segregation should be conducted, the types of ore production (technology) required to classify the ore should be identified, the possibility of bulk mining of the ore mass should be ensured, and a radiometric enrichment scheme should be developed. In conducting further ore processing tests, the following should be considered to assess the economic significance of the radiometric ore beneficiation technology scheme: In addition to screening of different groups of ore particles to determine the crushing and grinding quality of the ore, the decomposition rate of mineral phases, and the leaching quality of the ore, gravity analysis of the washed ore and washed sludge and magnetic analysis of the fine particles should be performed. The ore beneficiation technology scheme shall be selected, and the number and stages of crushing and grinding shall be determined. Methods of enrichment, concentrates and semi-finished products, and ways to recover the minerals contained in them shall be identified.

**4.10.** While studying the quality of sulfide and arsenide ores, the degree of oxidation of the ore, its mineral composition, its structure, and the presence of accompanying minerals and toxic impurities, if any, should be determined by technological mineralogy. Sieve analysis and gravity analysis of different ore groups will be performed to determine the crushing and grinding quality of the ore, the decomposition rate of the mineral phases, and the washability of the ore. The ore beneficiation technology scheme shall be selected, and the number and stages of crushing and grinding shall be determined. Methods of enrichment, concentrates and semi-finished products, and ways to recover the minerals contained in them shall be identified.

**4.11.** As a result of the study of the technological characteristics of the ore, the main data required to obtain a technological scheme for the enrichment of the ore and the extraction of all types of industrially significant minerals contained in it must be identified.

**4.12.** Types and sorts of ore production (technological) must meet pre-planned standards, and basic parameters of processing and chemical processing technology must be determined (concentrate yield and quality during gravity, magnetic separation and flotation depend on the content of rare metals, other ancillary minerals and toxic impurities). In addition, tailings dams and detoxification issues must be addressed, taking into account the special operations for re-processing the concentrate and extracting the associated minerals and the consumption of reagents used in their extraction (grain size, residual concentration of reagents).

**4.13.** The reliability of the technological scheme obtained as a result of semi-industrial testing shall be assessed by calculating the balance of technology and final products during production. The difference between the test results and the product balance shall not exceed 10% and shall be proportional to the mass of metal in the concentrate and to the waste. Recycling parameters should be compared with those of modern nickel and cobalt concentrators. The quality of the concentrate must be regulated at regular intervals in accordance with the agreement between the miner and the metallurgical plant, or in accordance with appropriate standards and specifications. Currently, there are no national or industry technical standards for nickel and cobalt concentrates in Mongolia.

**4.14.** In the case of ancillary minerals, there is no "Methodological recommendations for comprehensive study of deposits and estimates of subsidiary mineral and mineral reserves" approved by the Ministry of Mining and Heavy Industry of Mongolia. Therefore, in accordance with the "Guidelines for comprehensive study of deposits and estimation of reserves of ancillary minerals and mineral resources" developed in Russia, it is necessary to determine the forms of occurrence and the balance of their distribution in the products of enrichment and processing of concentrates, as well as to establish the conditions, possibility and economic feasibility of their extraction.

**4.15.** The proposed technological scheme should include recommendations for the possibility of recycling concentrate waste and water used for enrichment, for example for processing concentrate waste into micro-fertilizers and for wastewater treatment.

**4.16.** There are currently no nickel and cobalt deposits in Mongolia currently being mined or processed. However, the Russian example shows that there are two main types of ores, i.e., copper-nickel sulfide and silicate nickel (may include listwanite) associated with the weathering surface.

**4.17.** Copper-nickel sulfide ores are divided into two main types depending on their nickel content: rich (massive) and ordinary (disseminated).

- Copper-nickel concentrate is produced from ordinary (Pechenga type) ore. Ordinary Norilsk-type ore is enriched by the gravity-flotation method to produce nickel, copper, pyrrhotite, and gravity concentrates. Gravity concentrate is a product enriched in platinum group metals.
- For rich (Pechenga type) ore, the nickel content is 1.5% or more, so it is sent directly to the smelter. Norilsk-type rich ore is usually processed according to a concentrator scheme to separate light fractions containing conventional inlaid ore, as well as nickel, copper, pyrrhotite, and gravity concentrates. Some rich ores are sent directly to the metallurgical plant for processing without passing through a concentrator.
- Copper-nickel concentrate is sent to a special workshop, burned, and rounded to produce pellets. Today, this process has been replaced by concentrate briquetting. Pellets are processed in a smelting plant with rich ore to produce the final product, copper-nickel Feinstein.
- The light fraction obtained during enrichment is processed together with disseminated ores at the processing plant to obtain selective concentrates.
- Partially nickel concentrate after preliminary agglomeration and copper concentrate after drying are sent for pyrometallurgical processing.
- Pyrrhotite concentrate, which is a sulfide middling product, is processed separately by hydrometallurgical autoclave-oxidation technology to produce sulfide concentrate, while iron hydrates remain in the tailings. The specified concentrate is further processed together with a part of nickel and copper concentrates from concentrating plants according to the flash smelting scheme to obtain Feinstein, anode copper and technical

sulfur.

- Gravity concentrate is combined with copper flotation concentrate and processed in a copper plant.
- All types of byproducts produced during beneficiation are separated by further metallurgical processing. Cobalt is separated from the converter slags produced during nickel processing by hydrometallurgical methods in a cobalt plant.
- Sulfuric acid and technical sulfur are extracted from the gases emitted during the smelting of Feinstein and anode copper.
- Precious metals, selenium, and tellurium accumulate in the anode slag during the production of nickel and copper, and the platinum concentrate extracted during pyrometallurgical and hydrometallurgical processing is sent to a refinery to produce pure metal.
- Toxic impurities of copper-nickel sulfide ore shall be zinc, lead, arsenic, fluorine, cadmium, and bismuth, and the maximum content of these metals shall be determined by technical conditions.
- The final products of copper-nickel sulfide ore are nickel and copper electrolytes, metal cobalt, platinum group metals, gold, silver, selenium, tellurium, technical sulfur, and sulfuric acid.

**4.18.** Silicate nickel ore has a natural (geological) and technological type depending on the combination of ore-forming minerals. Ore after preliminary agglomeration or briquetting are subjected to a pyrometallurgical process – mine reduction sulfidizing smelting into matte, which is subsequently processed into metallic nickel. Coking coal, limestone (marble), pyrite, and gypsum are used in smelting. This technology scheme is the most effective method that is widely used in practice. The main disadvantages of this method are that the technological scheme is complex (multi-stage), makes high use of expensive and rare coking coal, renders a low nickel concentrate yield and an especially low cobalt yield, and that all the iron in the ore is converted into waste. Cobalt is separated from the converter slag by a more sophisticated technology in the form of metal and cobalt oxide.

In western countries, silicate nickel ores are processed according to the pyrometallurgical scheme – electric smelting of ores that have previously undergone reduction roasting for ferronickel, or according to hydrometallurgical schemes – ammonia leaching to obtain a commercial product “sinter” and sulfuric acid leaching to obtain a sulfide concentrate with a nickel content of up to 50% and cobalt 5-6%.

Toxic impurities of silicate nickel ores are phosphorus when smelted for ferronickel, and copper, chromium, and the maximum content of these metals is determined by technical conditions.

**4.19.** In the case of non-concentrated ore being sent to the processing plant, the quality of the ore, the extracted and classified concentrates, and the output from the plant must be regulated by agreement between the ore supplier (mine, concentrator) and the metallurgical (gyrometallurgical) plant.

## 5. STUDIES OF HYDROGEOLOGY, ENGINEERING GEOLOGY, GEO-ECOLOGY AND OTHER NATURAL CONDITIONS OF ORE DEPOSITS

**5.1.** Depending on the nature, climate, and geographical location of Mongolia, the hydrogeological, engineering-geological, and geo-ecological conditions of deposits vary depending on whether the deposits are above or below the erosion base (erosion level) of the region.

The study of hydrogeological condition of the deposit is based on "Instruction for conducting Hydrogeological Surveys during Thematic, Medium and Large-scale Hydrogeological Mapping and Mineral Resource Exploration Works, and Requirements to the Exploration Activities" approved by order No. A/237 on December 12$^{th}$, 2017 by the Minister of Mining and Heavy Industry, Mongolia.

During the exploration work, previous research on the hydrogeology of the deposit and its environment must be fully used and additional research and observation must be conducted and clearly reflected in the “Hydrogeological conditions of the deposit” chapter.

**5.2.** The hydrogeological study of the deposit must include the main aquifers and reservoirs that may be at risk of flooding during operation, determine the maximum water area and zones in the deposit, and estimate the amount of water entering the mine.

Each aquifer must be determined with regards to its thickness, lithological composition, collector type, relationship with surface water, groundwater level movement, composition, and other parameters to be reflected in the future feasibility study before the extraction. In addition, special attention should be paid to the following:

- In case of flooding, the chemical composition, bacteriological condition, corrosivity of concrete products, metals, and polymers, and beneficial and harmful impurities of the groundwater must be determined, and the chemical composition of mine water and wastewater must be determined.
- Also, the feasibility of using the drainage water into industrial water supply of the future mine enterprises and to extract and process useful components from the mine water must be assessed. The condition of drainage water disposal, the impact of mine water discharge and water reservoirs on the hydrogeological condition of the deposit area, and possible changes in the condition must also be determined.
- It is necessary to give a recommendation whether subsequent detailed study is required or not. Additionally, it is necessary to evaluate the impact of mining water on the environment.
- In addition, potential sources of household and technical water supply for future extraction and processing plants must be considered.

If it is planned to use pumped water from the mine site, the assessment of the exploitable resource shall be guided by appropriate normative and methodological documentation. The results of the hydrogeological survey will provide recommendations for the processing of mine planning in the following areas: draining geological massifs, water drainage, use of drained water, source of water supply, and environmental protection issues.

**5.3.** Engineering-geological surveys of deposits during exploration are intended to provide information for developing mining projects (to make basic calculation of open-pit and pillars and to process passport of drilling-blasting and mounting works) as well as improving the safe access of mining excavation work. Engineering-geological surveys determine the physical and mechanical properties of ores and host rocks, cover sequence in their natural and water-saturated conditions, engineering-geological features of rock massifs in deposits, their anisotropy, rock composition, cracking, tectonic faulting condition, features of texture, characteristics of karst in rocks, fracturing in weathering zones, and other major trouble-causing factors for mining operations. Special attention must be paid to tectonic faulting, fractured zones, level and property of ore crushing, filling materials of faults, the possibility of water flows along the strike and dipping, as well as blocky structure of massif structure. For permafrost areas, the temperature regime of the sedimentary rocks, the upper and lower permafrost boundaries, the distribution boundaries and depth of thaw areas, and possible changes in the physical properties of rock during permafrost melting and re-freezing should be determined. The results of the engineering-geological surveys should include the documents to be used to estimate the stability of the excavation and to calculate the main parameters of a quarry. If there are underground and open pit mines around the deposit located in similar hydrogeological and engineering-geological conditions, data on engineering-geological conditions and watering of the underground and open pit mines should be used to characterize the explored area.

Nickel and cobalt mining operations can be open pit, underground, or combined. In the case of combined mining, the maximum depth for open pit is determined by the maximum stripping coefficient, i.e., the value which is equal to the cost of extraction. The choice of method depends on the geological conditions of the orebodies in the deposit, mining and technical parameters, and the ore mining scheme and is based on the condition/benchmark of the feasibility study. Silicate nickel ore deposits are mined only by open pit.

**5.4.** In deposits where natural gas (methane, hydrogen sulfide, etc.,) has been detected, the composition and content of the gas should be studied to determine the pattern of changes in the deposit area and depth.

**5.5.** Factors affecting human health (lungs, high levels of radiation, geothermal conditions, etc.,) should be studied and identified.

**5.6.** Areas with no mineral resources should be identified for the placement of industrial and residential-civil facilities, as well as depositing waste rocks and tailings in the area of new deposits. In addition, it is required to provide information about whether there are construction materials in the region and cover and host rocks of the deposit may be used as raw construction materials.

**5.7.** Ecological surveys should cover the following issues:

- To determine basic parameters of the natural environment including the degree of radiation, air quality, surface and underground water quality, characteristics of topsoil, characteristics of animal and plants, etc.,
- To predict potential impacts of the proposed construction on the surrounding environment including emission of dust into the neighboring area, surface and underground water and soil contamination by mine or processing plant wastewater, air pollution, etc.,
- To evaluate natural resources allowed for mining operation including woods and water resource for technical application, and land for main and subsidiary

plant facilities, and for overburden, host rocks and uneconomical commodity dump, etc.,

- To assess character of impacts, intensity, the dynamics of the sources of contamination, and the boundaries of their areas of impact, etc.,

In the case of nickel and cobalt ores, the impact of man-made sources on the environment is specific to certain atmospheric and water pollutants (sulfurous gas) that cannot be fully processed during mining (underground or open pit), flotation, or metallurgy (hydrometallurgy, autoclave leaching). In order to solve issues associated with biological rehabilitation, the thickness of soil cover must be determined, agrochemical studies of sediments must be conducted, and the level of impact of the cover sediments and the possibility of vegetation formation on them must be determined. It is also necessary to give recommendations to protect subsoil, to remove environmental pollution, and to carry out biological rehabilitation. Technical issues related to storage and protection of low-grade ores and waste rock generated during the development of the deposit should be studied and identified along with their impact on the environment. Additionally, the possibility of reusing water must be studied, as well as the possibility of reusing any of the wastes from ore processing scheme, and the evaluation must be carried out for technical water use and treatment and the recommendations must be developed.

**5.8.** In the case of very complex hydrogeological, engineering-geological, and other natural conditions during mining operations where special surveys are required, the amount of work, timeframe, and regulations must be discussed between the subsoil user and project organization.

**5.9.** In the case of mineral resources found within country rocks and cover sediments of the deposit, these mineral resources must be studied to determine their industrial significance and potential applications.

## 6. ESTIMATION OF RESERVES OF NICKEL AND COBALT DEPOSITS

**6.1.** Reserve estimations and their classification based on the degree of exploration on nickel and cobalt deposits are completed in accordance with the guidance and classification stated in the appendix of order No.203 by the Ministry of Mining Industry of Mongolia dated September 11, 2015.

**6.2.** In this guidance, mineral resource is classified into geological resource and industrial reserve. Geological resource is estimated as a result of exploration work, while industrial reserve is estimated based on feasibility study.

**6.3.** In order to estimate geological resource and industrial reserve, benchmarks (conditions) must first be determined and then resource/reserve estimations will be completed accordingly. Common benchmarks that are used in estimation of geological resource and ore reserve include:

- Minimum production grade, %
- Cut-off grade that contours the orebody, %
- Minimum thickness of the orebody, m
- Low industrial grade of sections with ore reserve estimates, %
- Thickness of non-standard ore and hollow rock in the orebody, m

**6.4.** The market value of a single element is one of the main criteria in calculating the reserve benchmark. If one of the elements in the deposit, such as nickel, cobalt, or copper (possibly lead and zinc), is predominant (high grade), the element may be considered as the main representative element and other low-grade elements may be considered as by-products. This is similar to the transfer of equivalent values to deposits of many elements (silver- mixed metals, molybdenum-tungsten-tin etc.,). This economic criterion for calculating reserve benchmarks is a key factor in keeping the deposit economically viable. In particular, the use of a high-grade element as the main representative of a deposit will prevent that element from being absorbed into the price of the deposit's composite metal and reducing its market value. Furthermore, it will be possible to select the most economically viable standard option by calculating the preliminary feasibility study of deposits containing nickel, cobalt, and these metals as byproduct minerals and comparing them with other indicators.

**6.5.** Ore reserve is estimated by blocks divided based on the complexity of the geological formation and the level of exploration. Each block of the deposit and orebodies that are part of a reserve estimation shall meet the following requirements:

- The amount of ore reserve and the quality of ores should be studied and explored to the same extent;
- The orebodies must have the same geological setting, relatively stable thickness, and have less variability in thickness and internal structure of orebodies, similar material composition, the main indicators of quality and technological properties of ore;
- Orebodies within the reserve blocks must be stable in terms of structural attitude and located in the same structural setting (such as fold limb, core, or tectonic block bounded by faults);
- Mining and technical conditions should be the same;
- The reserve blocks should be divided by the horizons of mining operations or boreholes in dipping direction of the orebodies, while along with strikes – by exploration lines (profiles), considering the planned sequence of reserve exploitation;
- At impossibility of geometrization and contouring of orebodies or industrial (technological) types of ores, it should be statistically determined volume of ore types that are economic (balanced) reserves and economic reserves in certain circumstances (off-balanced).

**6.6.** When calculating reserves, the reserves are classified into proved, measured, and indicated that are marked as (A), (B) and (C), respectively.

**Proved (A) category reserves** are calculated only for blocks of group I deposits with detailed excavation and boreholes wherein extrapolation is not needed. Proved (A) category reserves for deposits being mined are calculated based on utilization exploration and mining excavations. Proved (A) category reserves must comply with requirements stated in the "Mineral Resources and Reserves Classification and Guidelines" of Mongolia. The amount of proved (A) reserves estimated for a group I deposit as a result of exploration shall be sufficient to cover the initial investment of the extractive plant. In addition, blocks that meet the requirements of the exploration category and are ready for extraction are included in this category.

**Measured (B) category reserves** are calculated for sections of group I and II deposits with detailed study. Measured (B) category reserves are calculated for deposits and their blocks that are explored in detail and comply with requirements of resource/reserve classification with regards to exploration level. Measured (B) category reserves are delineated without extrapolation by exploration excavations and boreholes (i.e., between excavations and cross-sections of ore) and are defined by sufficient data to represent the ore quality and basic geological characteristics of the orebodies within this boundary. If it is not possible to geometrize the orebody by its spatial location, shape and quality, the above parameters can be determined by geostatistical methods. For deposits where the size of the ore is determined using the mineralization coefficient, measured (B) category reserves must have a mineralization coefficient higher than the average of the deposit, the change in ore saturation is determined by area and depth, and the spatial location and characteristics of the ore blocks may include sections that have been studied to the extent that they can be evaluated for their selective extraction.

Measured (B) category reserves must comply with requirements stated in the “Mineral Resources and Reserves Classification and Guidelines” of Mongolia. For most sections of group II deposits, reserves are estimated as measured (B) category.

**The Indicated C category reserves** are calculated for blocks that are explored with the required density of exploration grids and whose credibility is confirmed by information obtained from the exploration results and mining data from the extracting deposits. For new types of deposits, this is confirmed by the results from the “sections with detailed studies” presented in the exploration grid chapter. If it is impossible to geometrize the orebody by its spatial location, shape, and quality, the above parameters can be determined statistically. In this case, distribution patterns and ore saturation of the parts that meet the requirements for being classified into this category must be studied to a reasonable extent. The boundaries of the Indicated (C) category resources are determined by exploration excavations, whereas for large and continuous orebodies, the boundary is determined by extrapolation which should also be geologically justified, taking into account changes in orebody thickness and shape.

If the deposit is explored enough to classify its resource in the Indicated (C) category, ore resource can be estimated by extrapolation from the ore resource boundary by conducting geophysical surveys to confirm along the dip and strike, geological-structural modeling, regulatory studies on changes in nickel and cobalt ore grades and orebody thickness, and if there is at least a section. In the case of individual orebodies, the reserves are estimated based on geophysical and geochemical studies and information on geological setting in the presence of natural outcrops, excavations, and ore sections identified in boreholes.

Indicated (C) category reserves should comply with requirements stated in the “Mineral resources and reserves classification and guidelines” of Mongolia. Most group III deposit reserves are estimated at an Indicated (C) level.

Identified ($P_1$) category resources are estimated for an orebody discovered with a small number of excavations and boreholes, and for marginal and deep parts of an adjacent orebody with estimated reserves. The boundaries of the section being assessed for the Identified ($P_1$) category resources shall be determined based on the geological setting of the deposit and the results of geophysical surveys, based on the density of the exploration grid used for the Indicated (C) grade, or by widening it.

**6.7.** A feasibility study for a deposit will be developed based on the geological resources of the deposit. Based on this feasibility study, the part of the geological resource that is within the boundaries of the mine to be extracted, including mine waste and pollution, should be included in the industrial reserve and the industrial reserve classified into Proved (A’) and Probable (B’), wherein these classifications should comply with requirements stated in the “Guidelines for classification of mineral resources”. In practice, it is possible to increase or decrease the level of ore resource depending on the mining technical conditions and the assurance of the validity of the resource grade.

**Proved (A’) mineable reserve** is based on the geological Proved (A) and Measured (B) reserves identified by exploration work; and on background of pilot test results selecting mining techniques and technology, relevant assessments and ore technology features; and defined in details the engineering solutions, environmental and occupational safety taking in account hygiene, rights, human resources, management organizational structure, supply infrastructure, social and economic services, and economic efficiency calculations and related factors in accordance to "Feasibility study for deposit exploitation of mineral resources".

**Probable (B') mineable reserve** is based on geological reserves of mineral resources of Measured (B) and Indicated (C) categories; and on background of pilot test results selecting mining technics and technology, relevant assessments and ore technology features; and defined in details the engineering solutions, environmental and occupational safety taking in account hygiene, rights, human resources, management organizational structure, supply infrastructure, social and economic services, and economic efficiency calculations and related factors in accordance to "Feasibility study for deposit exploitation of mineral resources".

The requirements for mineable reserves of the above mentioned 2 categories are essentially the same, the primary differences being that Proved (A') production reserves are based on geological reserves of Proved (A) and Measured (B) categories, while Probable (B') mineable reserve are based on the geological reserves of Measured (B) and Indicated (C) categories. However, while studies conducted on properties of ore technology for geological reserve estimation in Indicated (C) categories are relatively simple, Probable (B') reserves require study at pilot testing levels of production technology, if the deposit part will be exploited in the future.

The reserves are considered to be resources if the feasibility study identifies that they could be economically viable in the future, may be cost-effective if extracted as by-products, and may be stored in stockpiles for future processing with different technologies. When estimating the ore reserves that may be economically viable in the future, the influencing factors (such as economic, technological, mining-geological, hydrogeological, ecological, social, and political, etc.,) for classifying into this group shall be taken into account.

**6.8.** Reserves are calculated separately by categories of exploration, methods of mining (open pit, adit, or horizontal tunnels and shafts), industrial (technological) types, and grades of ores and their economic value. When dividing mineral reserves into classifications, additional indicators such as the accuracy, quantity, and confidence estimates can be used. When it is impossible to determine the relationships and boundaries between the different industrial types and grades of ores, it may be determined statistically.

**6.9.** Ore reserves are calculated on a dry basis with an indication of their moisture content in natural occurrence. Reserves for ores with high moisture and porosity are calculated on the basis of moist ore.

**6.10.** When calculating reserves by traditional methods (geological blocks, sections, etc.,), samples with abnormally high content should be identified, their impact on the average content of exploration sections and reserve blocks should be statistically analyzed, and, if necessary, their impact should be limited. Parts of orebodies with abnormally high content or increased thickness, or parts with higher mineralization coefficient, should be separated into independent reserve blocks and subjected to more detailed exploration.

In developed deposits, exploration and production data should be compared (in particular, to compare the characteristics of the change in distribution of samples grouped in grades with the results of the compacted mesh grid) to determine the extent of abnormally high grade and the method of replacing them.

**6.11.** In developed deposits, ore reserves should be estimated separately depending on whether the overburden is removed, ready to be extracted, or ores in the security pillars of capital mine workings by reserve classification in accordance with their degree of study.

**6.12.** Mineral resources in protected areas with large water reservoirs, rivers, settlements, residential buildings, agricultural facilities, protected areas, or natural, historical, and cultural monuments shall be calculated according to the approved standards and will be included as geological resources.

**6.13.** In order to verify whether the previously registered reserves are being extracted to the full extent, or to confirm the credibility of newly calculated reserves, information on ore reserves determined by exploration, conditions on orebody location, shape, thickness, internal structure, and grades of useful components must be compared to that obtained during mining operation in accordance with the regulations. In Russia, this comparison is conducted according to the “Guidelines for comparing exploration and mining data of mineral deposits”, and these guidelines may be used in Mongolia until similar guidelines are made available.

The comparative materials include information on boundaries of ore reserves previously registered and deducted by the state expertise agency (extracted and left in pillars), boundaries of areas that have been excluded from or added to ore reserves, and information on reserves registered in the state reserve balance (including the balance of previously registered reserves). A table that records changes within the whole deposit and/or sections of orebodies, as well as changes in reserve classification, must be created for the deposit. Additionally, the reserve balance of ore and metal in the contour of depleted reserves and changes due to completion exploration in ore reserves that were discussed and registered during the meeting of the Mineral Resource Professional Council shall be reflected. Waste created during extraction and transportation, outcome of the commodity, and waste from ore processing shall be presented. The results of the comparison are to be accompanied by graphics illustrating the change in ideas about the geological conditions of the deposit.

If the exploration data are generally confirmed by the development, or the existing minor differences do not affect the technical and economic indicators of the mining enterprise, the results of geological and (topo) surveying calculation can be used to compare the exploration and development data.

**6.14.** If the ore reserves and quality registered at the meeting of the Mineral Resources Professional Council are not confirmed during the development of the deposit, it will be necessary to reestimate the reserve using data from completion and extraction exploration, and to evaluate the reliability of the information obtained as a result of these activities.

The comparative analysis must be discussed during the meeting of the Mineral Resources Professional Council, including how and to what extent the parameters used for registered reserves (the area of reserve estimates, mineral content, thickness of orebody, mineralization coefficient, specific gravity, etc.,), the reserve dimensions, and ore quality changed as a result of completion exploration and extraction of ores, and the reasons for these changes should be discussed at the meeting.

**6.15.** In recent years, spatial distribution patterns of the studied properties (concentrations of the useful components, thickness of ore sections, grades, and meter-percent value) have been widely applied for geostatistical modeling methods such as kriging, inverse distance, and nearest neighbor, etc., in the calculation of reserves of ore deposits, and potential error fluctuations have been identified and evaluated. The importance of using geostatistical modeling methods lies in carrying out analysis and modeling of the primary data at a high level of quality based on characteristics of size and quality of primary exploration data and geological setting of an explored deposit (distribution patterns of parameters used for calculation, directions and anisotropic properties, influence of fracture boundaries, structure and quality of experimental variograms, dimensions of search ellipsoids, etc.,). When using the geostatistical method, quantity and density of the exploration cross-section should be sufficient to establish an optimal interpolation formula (results of at least hundreds of samples in three-dimensional modeling). It is recommended to study in detail how the parameters used for calculation change in space in relation to the geological setting of the deposit, and to divide them into blocks.

Variogram calculations are performed in a composite way wherein the initial length of experimental work and sampling on the cross-section of the orebody (vein-type body) or of a length equivalent to the height of the potential mine bench (stockwork and an orebody with a significant thickness). The minimum dimensions of a block for the deposit will be selected, taking into account the proposed mining technology and the density of the exploration grid (the minimum block dimensions should not be less than a quarter of the average density of the exploration grid). The results of reserve estimation can be represented in the following two forms:

1. When calculating with a grid of uniformly oriented blocks, tables of computational parameters must be created for all elementary unit blocks together with the values of the variance of kriging;
2. When calculating for large geological sections with their own geometric shapes, each block needs to be spatially georeferenced and a list of samples within the area of influence created.

All numerical data (sampling information, coordinates of samples and ore sections, and numerical analysis of variograms, etc.,) must be presented along with the results used by the software used in the calculation. Models generated for each direction of the variograms, directions, and their experimental variograms as well as other parameters required for analysis must be clearly illustrated and attached to the report.

The geostatistical methods for reserve estimation allows one to make the most optimal calculations of the average grade without using special methods to reduce the impact of abnormally high grade, to reduce conditional errors resulting from contouring the boundary of orebodies for very complex deposits, and to select the most optimal mining technology. The geostatistical method used for reserve estimates must be interpreted in such a way that it can be re-examined, clearly reflect the main parameters, and be subject to the geological setting of the deposit.

Blocks capable of representing the results of geostatistical modeling and calculations should be compared with the results of traditional reserve estimates.

**6.16.** When the reserve estimation is carried out using geostatistical methods, primary data (coordinates of exploration excavations, lithology, stratigraphic boundaries, inclinometer data, geological data, sampling and its results, etc.,) must be available to be checked and corrected, as well as intermediate calculations and their results (list of standard ore segments, geological sections and plans of economically viable mineralization, projections of orebodies in the horizontal and vertical planes, sections, benches, and calculated dimensions of sections), and overall final estimations. The documents and computer-generated graphics prepared must meet the requirements for the structure, composition, and formatting, etc., of this type of document.

**6.17.** If useful components and subsidiary minerals are found and identified in ores, their resource estimates will be developed in accordance with established procedures. It is recommended to use the "Recommendations for a comprehensive study of deposits and estimates of reserves of subsidiary minerals and mineral resources" developed by the Russian Federation until such recommendations are developed in Mongolia.

**6.18.** If nickel and cobalt deposit contains other metals as by-product, and all metals show good correlation of grade and tonnage and requires same processing technology, grade of by-product mineral can be transmitted to main metal as equivalent grade. The equivalent grade ($Ni_{Eq}$ – equivalent эсвэл $Co_{Eq}$ - equivalent) must be estimated along the following estimation:

$$Ni_{Eq} = Ni\% + ((Cu \text{ г/т} * \$/\text{гр}) + (Au \text{ г/т} * \$/\text{гр}) + (Co \text{ г/т} * \$/\text{гр})) / Ni\% * \$/\text{тн}$$

## 7. STUDY LEVEL OF DEPOSITS (AND THEIR SECTIONS)

**7.1.** As stated in the appendix of "Classification and instructions for mineral resources and reserves" which was approved by order 203 of the Minister of Mining, dated November 11th, 2015, any deposits (their sections) are classified into the following two categories, depending on their study level: evaluated deposits and exploreddeposits. Additionally, the appendix provides the requirements to the estimated reserves and resources through prospecting and exploration work. The study level of the evaluated deposits is determined by whether there is a need to continue the exploration work conducted at objects. Moreover, the study level of the explored deposits is determined by whether the deposit is ready for exploitation.

**7.2.** As a result of the geological-exploration work carried out at the evaluated nickel and cobalt deposits, industrial value and the overall size of the deposit must be determined. Additionally, whether there is a need to continue exploration work, justification for mining operation, and identifying the most prospective areas for the next exploration etc., must be determined. For nickel and cobalt deposits with prospecting-evaluation work completed, industrial significance, value, and the overall size of the deposit as well as prospective sections where the exploration work needs to be carried out with the purpose of exploitation must be identified.

Benchmarks for resource estimation for all newly discovered deposits and their sections, which are sufficient for preliminary feasibility studies, must be determined based on evaluation reports and temporary exploration standards.

Identified resource of the evaluated deposit is included in the "P1" category and geological reserve of some part is included in the Inferred (C) category.

The assumptions about the exploitation methods, systems, and potential scope of exploitation must be considered broadly based on similarities to other extracting projects. An enrichment scheme showing full recovery of raw materials and possible outputs and quality of commercial ore should be determined based on a laboratory technology test.

Capital expenditure for establishing a plant, unit price of the commercial ore, and other economic parameters are determined by enlarged estimation based on comparison with parameters from similar projects.

To assess the industrial significance of ore minerals, mining and utility-drinking water supply issues must be pre-addressed based on existing mine sites, explored deposits, and other potential sources. In addition, a mining operation's impacts on the environment should be considered and evaluated.

The experimental-production mining operation can be carried out for the evaluated deposits to study the shape of orebodies and ore composition, and to carry out detailed surveys for the purpose of developing an ore enrichment scheme. The experimental-production mining operation may be carried out on sections that fully represent the entire deposit and with the most common features of orebodies for up to three years. Additionally, the experimental-production mining operation must be carried out on an exploration stage project with permission from the mining inspection organization. Moreover, the duration and amount of the experimental-production mining operation should be agreed with the state ecology, technology and nuclear inspection agencies. In every case where the experimental-production mining operation is required, its purpose and issues to be solved must be addressed.

The experimental-production mining operation is usually conducted with the purpose to identify characteristics of the geological setting of orebodies (variabilities of internal structure and shape), mining-geological and mining-technical conditions of extraction, and methods of ore mining technology, ore-enrichment, and processing (distinguish primary and technological types of ores and their relationships, and enrichment features, etc.,). These problems can only be solved if the orebodies are excavated to a considerable depth and length.

The experimental-production mining operation can also be conducted when introducing new methods for ore mining, i.e., borehole hydraulic mining of loosened ores from deep and shallow depths, as well as when extracting new or unconventional ore types. In addition, the experimental-production mining operation is carried out with the purpose of experimenting and improving the enrichment scheme in a small plant before proceeding with development of large processing plants in order to mine large and giant deposits.

**7.3.** In order to obtain sufficient decision-making information on conditions to prepare explored deposits for production and on order of procedures as well as to prepare feasibility studies, the quality and quantity of ore reserves, their technological properties, hydrogeological, and mining and ecological conditions of mine development should be studied with boreholes and excavating works. Additionally, such procedures are needed to prepare project proposals on developing mineral deposits into mines and renovating such mines.

The explored deposits should meet the following requirements according to the degree of study:

- Most parts of the reserves should be grouped into one of the appropriate categories based on the complexity of geological setting of the deposit;
- The industrial types of ore deposits and their technological properties must be studied in detail, which should include an optimal technological design of processing to extract all the useful components in a complex, a direction for industrial waste utilization, and an optimal way of storing them;
- Co-existing minerals and complexes with useful components, including overburden and groundwater, must be sufficiently explored and their resource/reserve must be estimated. Additionally, these must be classified into geological reserves or resources on a standard basis, the reserve or resources must be quantified, and the potential direction of use must be determined;
- Hydrogeology, engineering-geology, geocryology, geo-technical, and other natural conditions should be studied accurately enough to provide the initial data necessary for the project development of the deposit, taking into account the requirements of environmental legislation and safety of mining operations;
- The accuracy of data on the geological setting, location condition of orebodies, their shapes, and quantity and quality of the reserve must be confirmed by detailed work carried out on sections that can fully represent the deposit, and in each case, the size and location of the section should be defined depending on the geological features;
- The environmental impact of mining must be considered and recommendations in line with relevant regulations made to minimize and mitigate the expected negative ecological consequences;
- The conditional parameters used for reserve estimation must be established on the basis of feasibility study that allow for determination of industrial significance and scope of the deposit;

The subsoil user and experts of the Mineral Resources Professional Council shall determine the appropriate ratio of different reserve categories considering the level of business risk. The experts of the Mineral Resources Professional Council will determine and decide as a recommendation for each case the possibility to exploit the Probable (C category) reserve fully or partially to develop a plan for mining the deposit. In this case, the solving factors are characteristics of geological setting of orebodies, their thickness, characteristics of mineralization distribution within those orebodies, assessment of random errors of exploration (methodical, technical tool, sampling and analytical, etc.,), and consideration of exploration and exploitation experience of similar deposits.

The explored deposits are considered to be prepared for production after implementation of this recommendation and registration of reserves in accordance with established procedures.

## 8. RE-ESTIMATION AND REGISTRATION OF ORE RESERVES

Re-estimation and re-registration of reserves in accordance with established procedure can be carried out in cases of significant change in the quality and/or quantity of reserves of the deposit and its geological and economic assessment as a result of additional exploration or mining operations that are initiated by a license holder or state administrative and professional inspection agencies. In cases where the economic situation of an extraction deteriorates dramatically, re-estimation and re-registration of reserves may be carried out on the deposit at the initiative of a license holder for the following reasons:

- Results of operations cannot bear out previously registered reserves and ore quality within an entire deposit or specific sections.
- A steady and significant fall (20% or more) of the product's market price while production costs remain stable.
- Changes in industrial requirements for the quality of mineral raw materials.
- When the total amount of unconfirmed reserves during the exploration completion, mining exploration, and extraction stages, the amount of deducted and deductible reserves, or the amount of reserves that cannot be extracted due to technical and economic reasons, exceed or fail to meet the norms and amounts (>20%) set in accordance with the procedure for deducting mineral reserves from the balance of mining industry.

This includes cases where the license holder has increased the amount of reserves by conducting additional exploration for the deposit, or where there is a change in the amount of registered reserve due to carrying out reserve estimation at increased levels of confidence.

- At the initiative of the state administrative and professional inspection agencies, the re-estimation and re-registration of reserves can be carried out on an ore deposit in cases such as the natural resource holder (state)'s rights being violated, or especially unreasonable reductions in the taxable base:

    - increase of 30% and more in deposit's reserves, compared with what was previously registered;
    - a significant (more than 30% of the conditions laid down in the condition of feasibility studies) and stable increase in world market prices for the products;
    - development and introduction of new technologies that significantly improve production capacity;
    - Identifying valuable components or harmful impurities in the ores or host rocks that were not previously taken into account when assessing the deposit and designing the production processes.

- Economic issues of production due to temporary causes (complications in geology, technology, hydrogeology and mining conditions, temporary drop of price in the world market etc.,) are solved with the assistance of conditional mechanisms of exploitation and, therefore, re-estimation and re-registration of reserves are not required.

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## APPENDICES

### Appendix 1. Indicators/criteria used to define complexity of geological setting of ore deposits

Exploration system and density of exploration grid are dependent on several factors of nature: conditions where the orebodies are located and their structural and geological features (geometry of orebodies and their consistencies and properties of contacts) and distribution of primary/main components (the level of changes in mineral quality within orebodies).

There are main parameters to indicate the complexity of orebody: ore presence coefficient ($K_x$) in ore intervals, complexity coefficient of mineralization ($q$), variability coefficient of orebody thickness ($V_m$), and variability coefficient of ore grade ($V_a$) (А.П.Прокофьев, 1973).

a. The ore presence coefficient $K_x$ – is used to distinguish a unit section within the mineral resource with an interrupted mineralization. It is determined by the following equation:

$$K_x = \frac{\sum l_i}{L}$$

where $l_i$ – quotient of the boreholes and excavation-resulted length of the mineralized interval

$L$ – total length of profile within productive mineralizated zone.

b. The complexity coefficient of mineralization $q$ – is determined by the following equation:

$$q = \frac{N_x}{N_x + N_{xг}}$$

where $N_x$ – number of excavations and boreholes revealing mineralization, $N_{xг}$ – number of excavations and boreholes revealing no mineralization.

c. The variability coefficient of orebody thickness is determined by the following equation:

$$V_m = \frac{\sigma_m}{\overline{m}}$$

where $V_m$ – variability coefficient of orebody thickness, $\sigma_m$ – dispersion of orebody thickness, $\overline{m}$ – average thickness of orebody.

d. The variability of ore grade is determined by the following equation:

$$V_a = \frac{\sigma_a}{\bar{a}}$$

where $V_a$ − variability coefficient of ore grades, $\sigma_a$ − dispersion of ore grades, $\bar{a}$ − average ore grade.

The maximum variability coefficients for complexity of orebodies from groups I, II, III and IV deposits are given in Table 6.

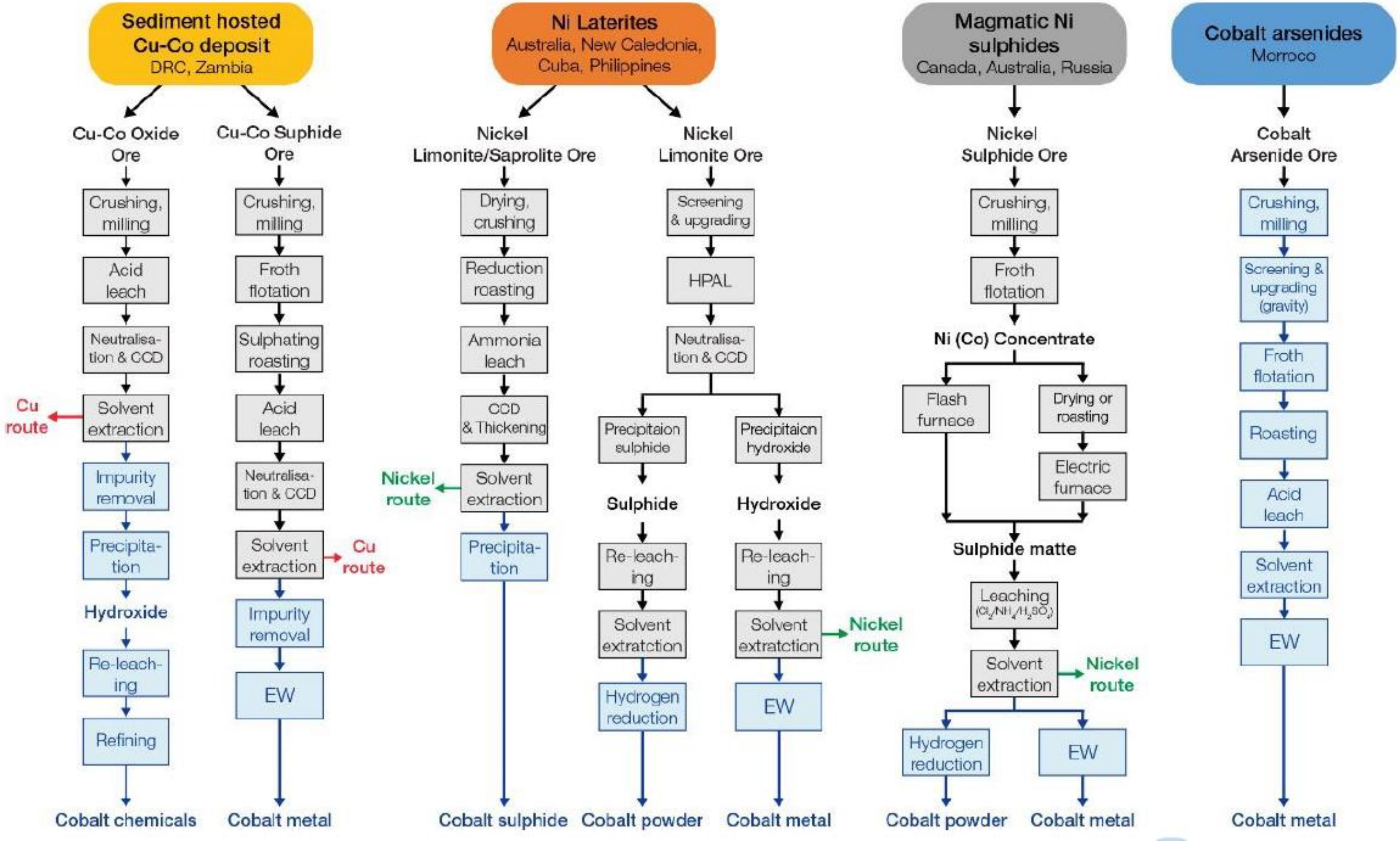
Table 7. **Quantitative indicators to define variability of mineralization features**

| Ore deposit groups | Complexity indicators/criteria of geological setting | | | |
|---|---|---|---|---|
| | $K_p$ | $q$ | $V_m$, % | $V_C$, % |
| Group I | 0.9–1.0 | 0.8–0.9 | < 40 | < 40 |
| Group II | 0.7–0.9 | 0.6–0.8 | 40–100 | 40–100 |
| Group III | 0.4–0.7 | 0.4–0.6 | 100–150 | 100–150 |
| Group IV | < 0.4 | < 0.4 | > 150 | > 150 |

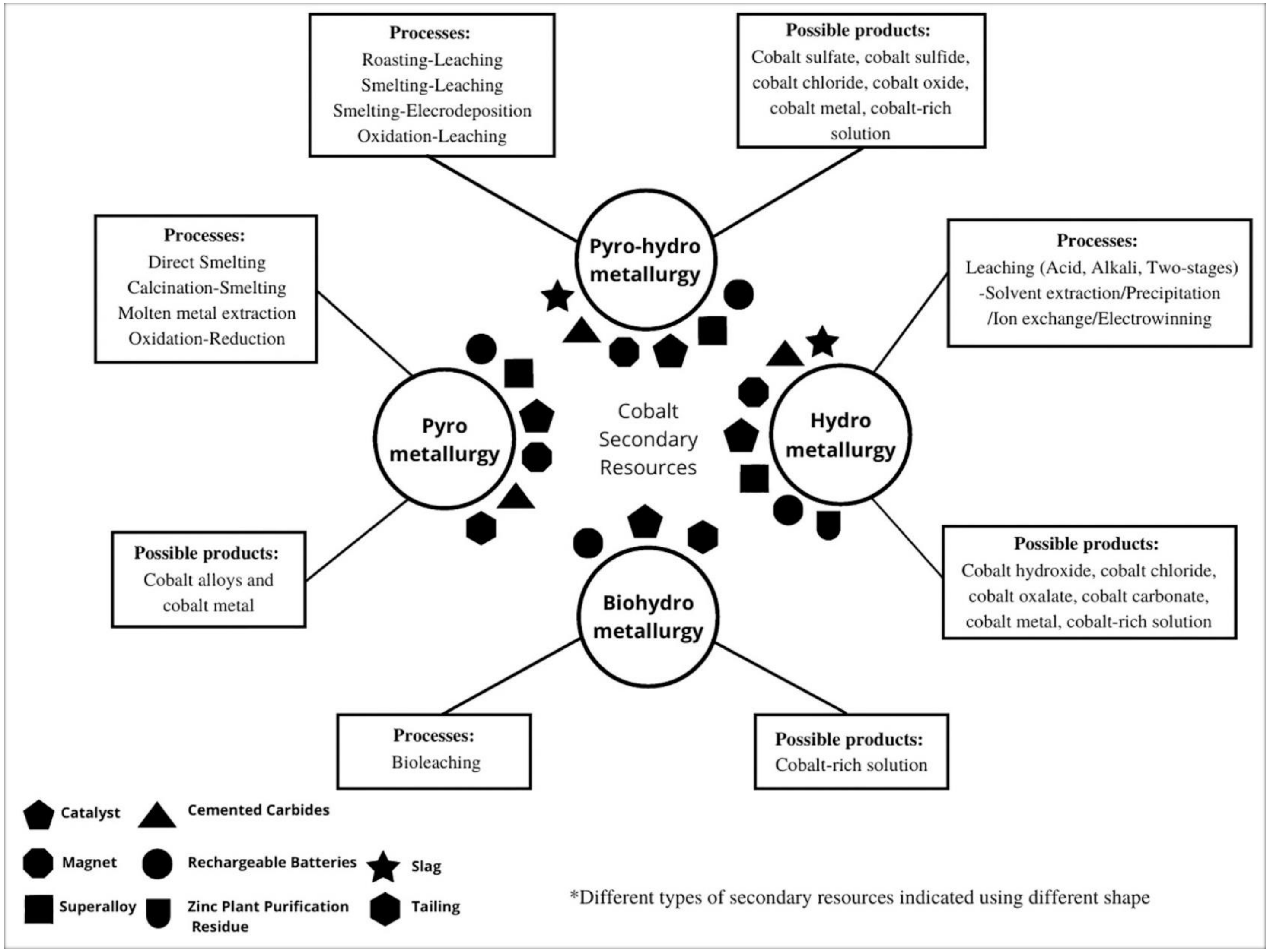
The decision on classifying a deposit into one of these groups is dependent on all geological features that indicate maximum variabilities of orebody shapes and ore grades.

Appendix 2.

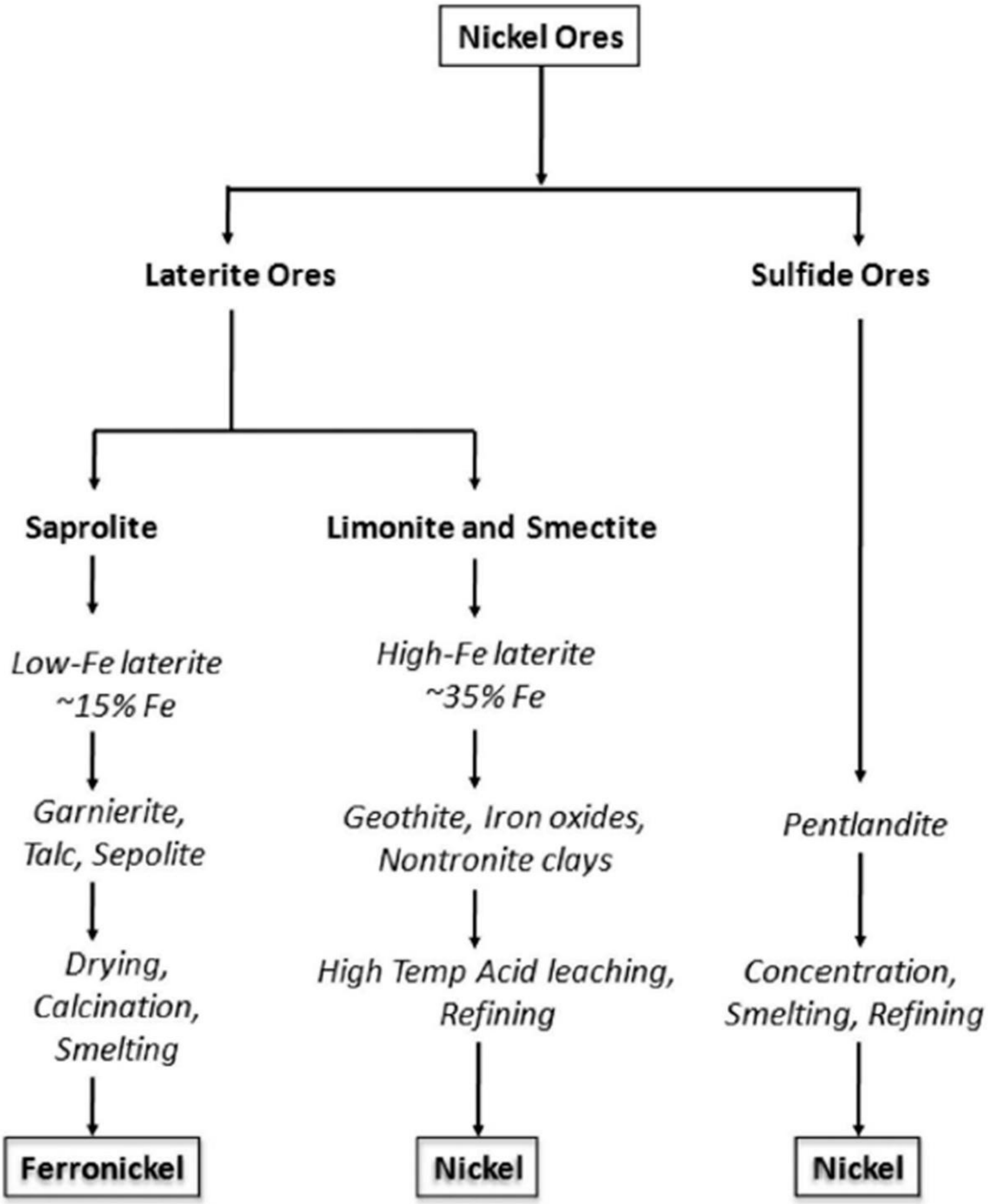
## Processing of nickel, cobalt deposits



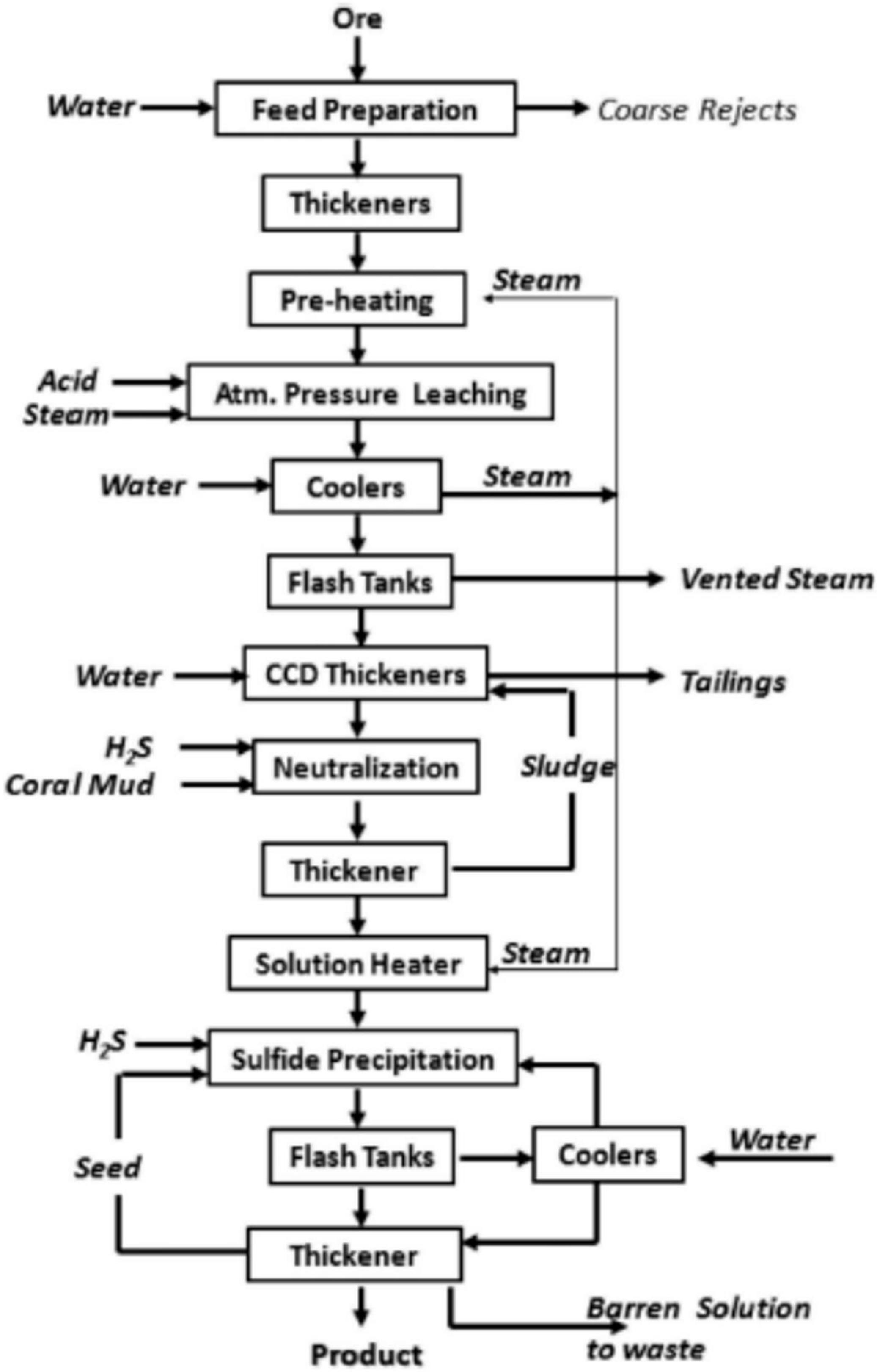
**Processing of cobalt ores depending on ore deposit types**



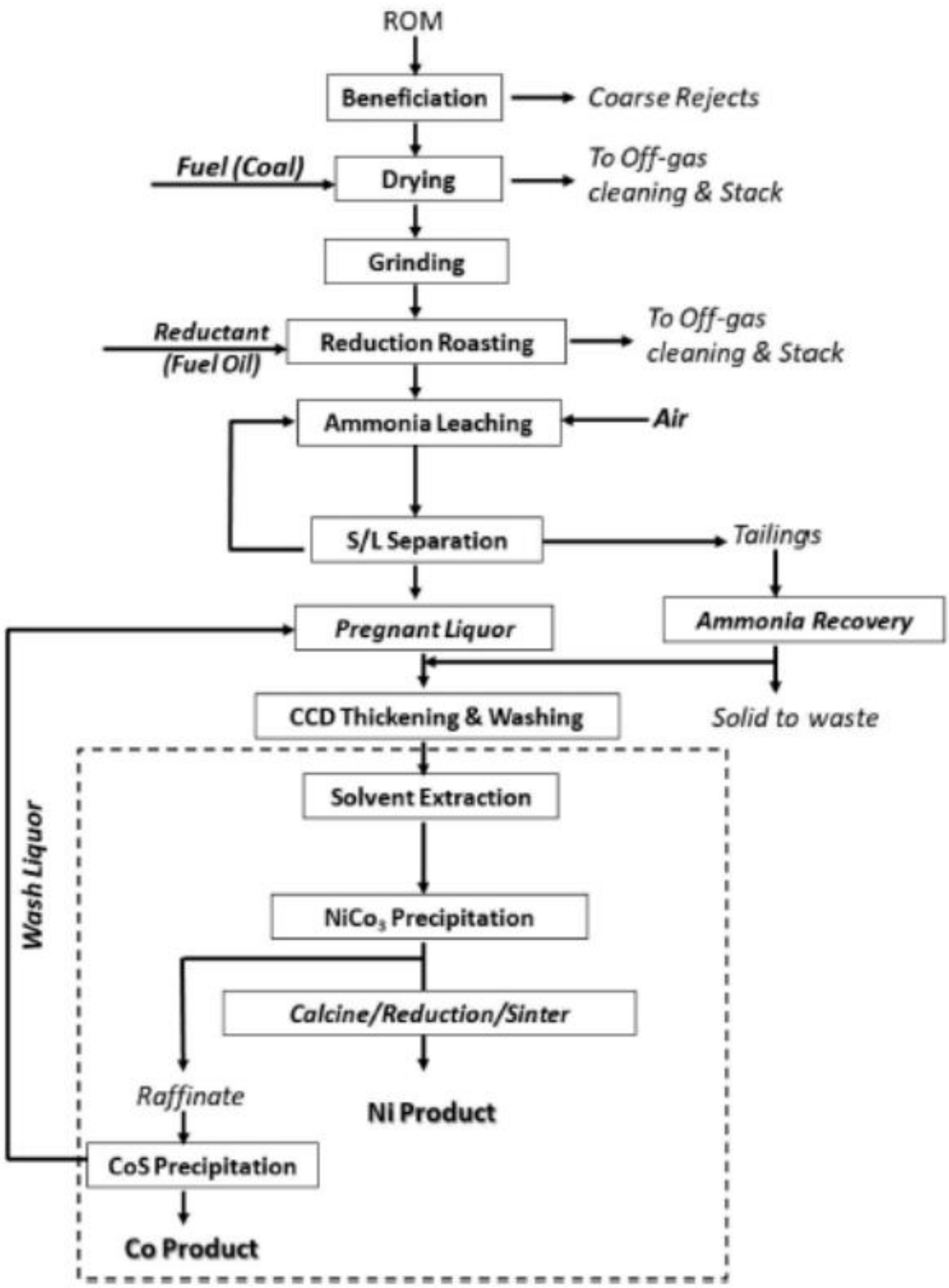

Recycling of cobalt ores from secondary sources



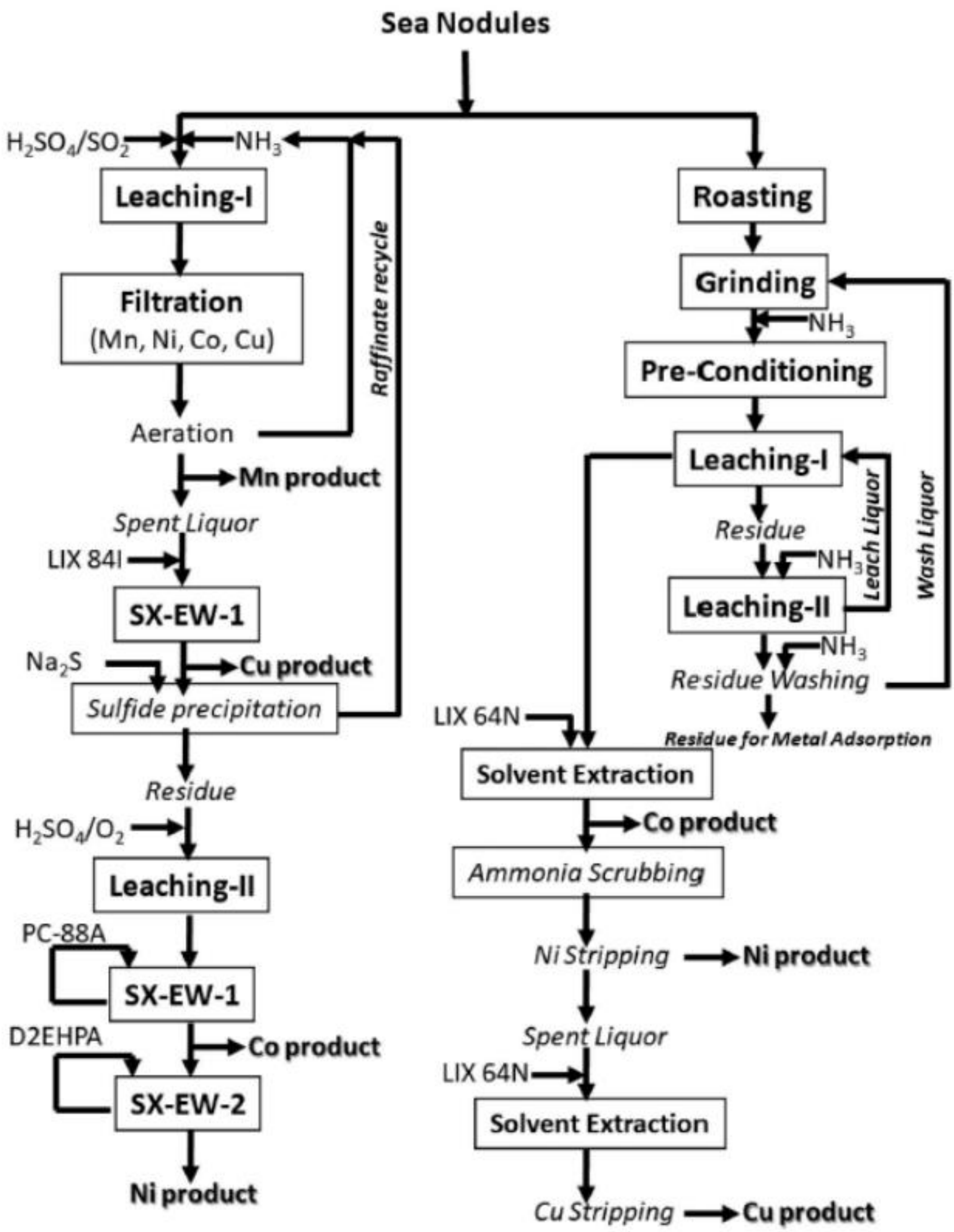

Processing of nickel ores



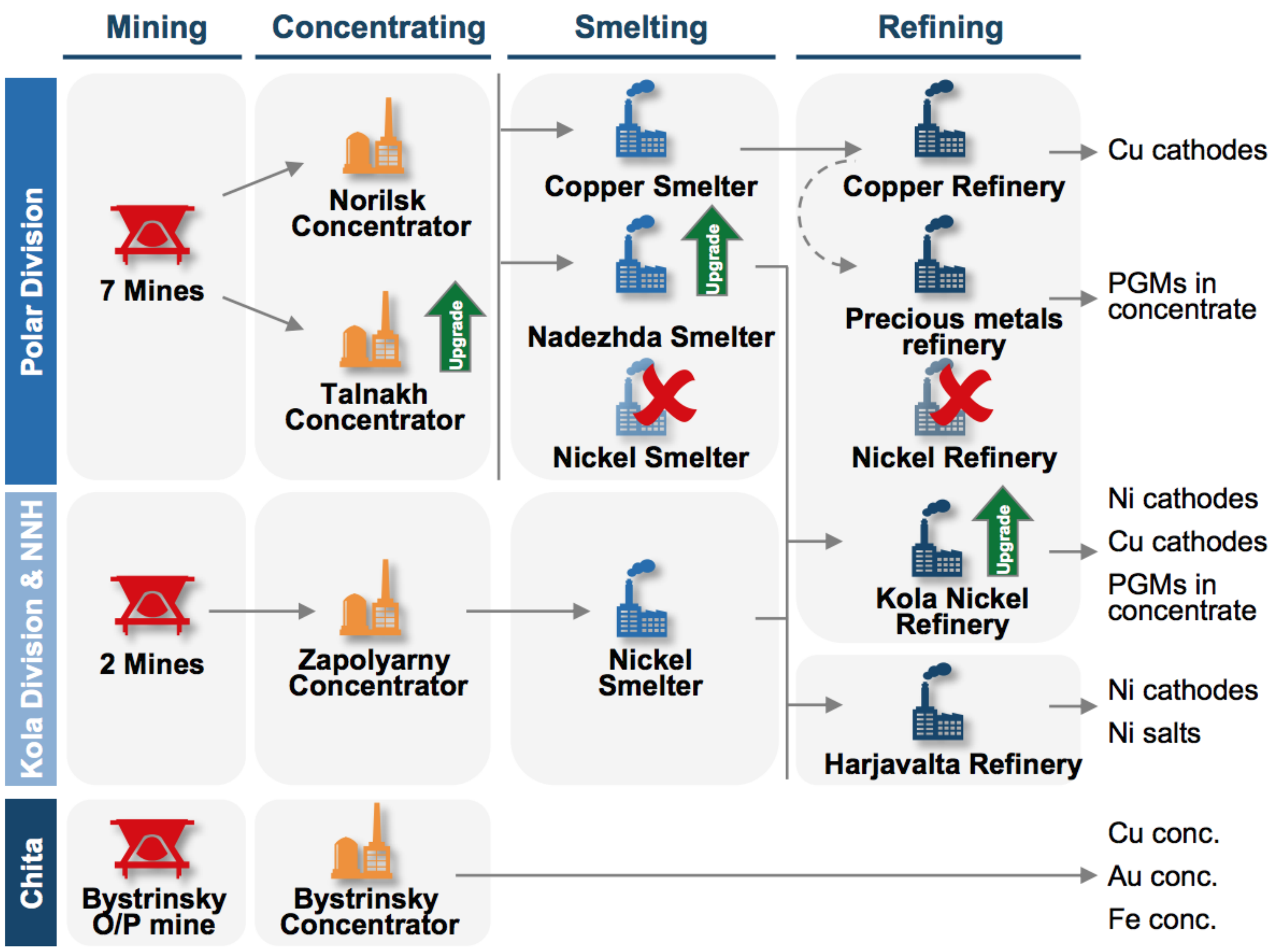

Processing of lateritic nickel ores




Processing stages of high-Fe limonite laterite ores




Processing stages of nickel ores from seafloor nodules




Processing stages of nickel ores at the Norilsk deposit