COBALT MINERAL RESOURCES IN CHILE EXPLORATION & MINING POTENTIAL

CORFO | Comité Minería No Metálica | Sernageomín

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Preliminary report |
Overview

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- Historic cobalt mining districts of Chile
- Cobalt mineral resources in Chilean ore deposits
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  - Cobalt as a sub product
  - Cobalt in tailing deposits
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Cobalt Mining in Chile
Past & Present
Chile has a long history of mining, in the past a prime producer of nitrates (“salitre”) and at present the world’s largest copper producer. Chile’s strong focus on copper makes the country economically vulnerable and highly dependent on its prime mineral resource.

Copper dependence is intrinsically related with the characteristics of the Chilean Andean Margin, a subduction related continental arc environment in which progressive geological processes favored the formation of world class to behemothian size copper deposits, the largest being the porphyry copper deposits, and the smaller being of the stratabound copper, iron oxide copper gold (IOCG), skarn and vein type deposits. Other metals also occur, such as base metal skarn and vein type deposits, precious metals vein and breccia epithermal and mesothermal type deposits, iron – apatite (IOA) type deposits, and copper-gold-cobalt vein and manto deposits.
At present Chile’s mineral wealth stands mostly on copper, yet other metal resources are exploited as primary ores, such as iron, manganese, gold and silver, and to a lesser degree, zinc. Other important sub products are also recovered from copper mining, including molybdenum, gold, silver, among others.

Cobalt is not presently exploited in Chile, yet in past history Chile contributed to global cobalt production, having peaked in production during the II World War, yet having closed all cobalt operations in 1944.
Cobalt in Chile was exploited starting in 1865, initially from copper-gold-cobalt vein and manto deposits located in the San Juan district, near the city of Huasco, Atacama region, as well as from smaller vein deposits near Copiapó, in the same region.

Additional production came from manto, vein and breccia copper-gold-cobalt deposits of the Tambillos district, Coquimbo region, and minor production from vein deposits in the El Volcán – Cajón del Maipo sector in the Metropolitan region. Cobalt production ceased in 1944, when the La Cobaltera, San Juan district, was closed.
Cobalt production in Chile was mainly developed for its use in steel allows, having peaked for this reason during the II World War.

Despite that cobalt production ceased over 70 years ago, the San Juan and Tambillos districts have observed discrete periods of mining activities through time, mostly small scale and at present medium scale, but these for copper and lesser gold, cobalt ore minerals likely in tailings and/or waste.

In the San Juan district present mining is aimed at high grade copper oxidized mineralization, and in the Tambillos district at copper sulfide mineralization.
Metallogenic evolution and metallic mineral deposits in Chile
• Chile has a large wealth of metallic ore deposits, mostly copper mineralization, starting from the very beginnings of the Andean margin tectonic – magmatic evolution in Paleozoic times.

• Mineral deposits and metallogenic evolution are related to a long history of subduction along the convergent plate tectonic margins of Chile, mineral deposit types and distributions controlled by the tectonic and magmatic conditions in time and space.

• Ore grade cobalt mineralization has only been documented and exploited from lower Cretaceous deposits, yet potential as a sub product of the Chilean copper and/or iron mining activities has not been evaluated.

• The main types and distributions of ores deposits are described as follows, these from oldest to youngest (based on Maksaev 2001 and Maksaev et al., 2007).
**Paleozoic**

- Only porphyry copper deposits, all small and low grade, non-economic.
- Distributed along the main axis of the Chilean northern Andes and central Argentina.
- Ages between 298 – 195 Ma.

**Upper Jurassic**

- Stratabound copper deposits, copper bearing veins, and gold and silver bearing veins.
- Stratabound copper deposits concentrated along the coastal cordillera of northern Chile.
- Gold and silver vein deposits occur along the coastal cordillera of north and north central Chile, discrete and small.
Lower Cretaceous

- Porphyry copper deposits occur discretely, small and low grade, yet economic. Distributed along the eastern flank of the coastal cordillera, in the Antofagasta, Atacama and Coquimbo regions.

- Iron – apatite (IOA) type deposits, the main source of the Chilean iron ores, these occur along the Chilean iron belt, within the Lower Cretaceous volcanic arc and distributed along the Atacama Fault Zone (AFZ), coastal cordillera of Atacama and Coquimbo regions.

- Iron oxide copper – gold (IOCG) type deposits. These occur within the Lower Cretaceous volcanic arc, hosted within the AFZ, as well as on the eastern margin of the volcanic arc, at transition from arc to the Lower Cretaceous back arc basins.

- Stratabound copper and copper skarn deposits. These occur along the coastal cordillera of Coquimbo, Valparaiso and Metropolitan regions of north central Chile.

- Gold-copper (base metal) veins of epithermal and mesothermal type. These are distributed along the coastal cordillera of Coquimbo, Valparaiso, O’Higgins and Maule regions of central north and central Chile.

- Cobalt mineralization occurs within the Chilean Iron Belt, hosted within paleozoic metamorphic rocks as well as within lower cretaceous intrusives and lower cretaceous volcanic and sedimentary sequences in the volcanic arc environment.

- Cobalt mineral occurrences in El Volcán – Cajón del Maipo, Metropolitan region, are suggested as similar age.
Upper Cretaceous
- Discrete gold-copper vein and silver vein deposits distributed along the frontal Andean cordillera along the Upper Cretaceous volcanic arc, from Antogasta to O’Higgins region.
- Small and discrete porphyry copper occurrences in the Inca de Oro district, Atacama region.

Paleocene
- World class porphyry copper deposits extending from SE Perú down to the Atacama region, along the western flank of the main Andean cordillera.
- Epithermal gold and silver vein deposits along the western flank of the Andean cordillera, regions of Tarapacá, Antofagasta and Atacama.
- Copper breccia pipe type deposits in the western flank of the Domeyko cordillera, Atacama region.
Upper Eocene – Lower Oligocene

- Super giant to Behemothian porphyry copper deposits distributed along the main Andean cordillera, Domeyko cordillera, hosted along the Domeyko Fault System. These deposits are distributed from the Arica & Parinacota region in the north to the Atacama region in the south.

Miocene

- Epithermal gold and porphyry gold deposits in the Maricunga Belt and epithermal gold deposits in the El Indio – Pascua-Lama district, both along north central Chile, Atacama and Coquimbo regions. These deposits occur along the main Andean cordillera, near the Chile – Argentina border.
- Super giant to Behemothian porphyry copper deposits of Central Chile. These deposits occur within the main Andean cordillera, near the Chile – Argentina border.
Potential primary ore cobalt deposits

- Based on the main types of metallic ore deposits present in Chile, the only documented evidence of cobalt primary ore mineral deposits occur within the Lower Cretaceous arc and back arc environment.
- In particular, the main known deposits occur within the Chilean Iron Belt, along the coastal cordillera and spatially related with the Atacama Fault Zone, both in the Atacama and Coquimbo regions.
- Other evidence points out to potential cobalt vein and manto deposits in volcanic and sedimentary rocks of the Lower Cretaceous back arc of central and central south Chile (El Volcán – Cajón del Maipo, Metropolitan region, and Laguna del Maule, region del Maule).

Cobalt as a sub product

- Cobalt and cobalt minerals have an affinity for copper, nickel, arsenic and iron sulfide minerals, commonly occurring in association in hydrothermal ore deposits.
- Given cobalt affinity for copper, arsenic and iron, and based on Chilean metallogenesis, all copper and iron deposits could bear potential for cobalt sulfide/arsenide, specially those arsenic-rich.
- The prime targets to evaluate cobalt as a potential sub product are the IOCG deposits, followed by the IOA and to a lesser extent, the porphyry copper deposits.
- In these deposits cobalt should be considered a potential credit, depending much on mineralogy and metallurgy.
Historic cobalt mining districts of Chile
Primary ore cobalt deposits in Chile have only been mined in the regions of Atacama, Coquimbo and Metropolitana, consisting of vein, breccia and occasionally manto deposits, hosted within metamorphic, volcanic, intrusive and in some cases sedimentary rocks.

Meaningful cobalt production has only been developed in two districts, the San Juan district in the region of Atacama, and the Tambillos district, in the region of Coquimbo.

In the San Juan district cobalt mineralization occurs mainly as cobaltite, a cobalt sulfo-arsenide. Mineralization occurs mostly in veins, lesser mantos, with average cobalt ore grades up to 1.6% Co.

In the mines within the San Juan district past mining was focused on the exploitation of secondary ores, oxidized, mainly eritrite, a cobalt arsenate. Mineral bodies presented ore grades up to 6.4% Co.
In the Tambillos district, region of Coquimbo, manto, vein and breccia copper – gold – cobalt deposits occur. In past mining copper and cobalt were the prime ores exploited, at present only copper is considered, gold recovered as sub product, no information on cobalt existing.

In 1942 cobalt ore grades ranged between 4 and 5% Co, exploration data having reported average cobalt ore grade at 1% Co.

In the Metropolitan region, historic production data from vein deposits in the El Volcán – Cajón del Maipo sector (Merceditas Mine) reported sulfide/arsenide ore rocks with average grades between 0.5 and 0.7% Co, and maximum ore grades of 2.4 to 2.58% Co.
Cobalt mineral resources in Chilean ore deposits: Primary cobalt ore

- Chilean Iron Belt (IOA and IOCG)
- San Juan & Carrizal Alto districts, region of Atacama
- Tambillos District, region of Coquimbo
San Juan District

Main cobalt mineral zones

1- Mineral de Labrar
2- Quebradita
3- El Romero
4- Fraguita and
La Cobaltera

Sernageomin
Vivallo et al., 2008

SIMBOLOGÍA DE LOS YACIMIENTOS

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Nota: Se incluyen yacimientos de base de datos Exaro no habilitados, por ej. E-01
Geoexploraciones (1983) – Exploration summary of the San Juan District

Samples of primary ore rocks from mineral piles, trenches and vein outcrops in the San Juan District yielded values between 0.001 and 1.95% Co. In addition, copper values range between 7.9 and 0.037%, gold between 1.1 and 0.1 g/t, silver between 8.8 and 0.5 g/t, nickel between 0.49 and 0.023% and cadmium between 4.7 and 0.023 g/t. From results different prospective areas were selected. Red: Cortadera, Paulita, Verde sectors (2 x 4 km², cobalt > 0.5%). Old mines recommended for detailed study are La Cobaltera, Prosperidad, Blanca, Verde, Lea, Delirio and Rosa Amelia. Blue: Labrar, Quebradita Norte, Romero 2 and Fraguita sectors, with cobalt concentrations between 0.1 y 0.5%.
Mineral resources in the San Juan district and surrounding region

• **Geoexploraciones (1983)**
  
  • Indicate *in-situ* mineral reserves of 1,300 Mt, and 3,960 Mt in mineral piles, all over 1% Co, for Zone 1. In addition, 62,000 Mt in mineral piles of the Santa Rosa mine (Zone 2) are indicated, these with cobalt concentrations ranging between 0.05 and 0.24% Co, and with an average copper grade of 2.44%. Further study and mineral resource evaluation is recommended.

• North of the San Juan District, and slightly north of the town of Freirina, Minera Santa Marta reports approximately 500,000 Mt of tailings with average cobalt concentrations at 0.11% and average copper concentrations at 0.23% (INTEC, 1988).

• Other reports on tailing deposits within the vicinities of Freirina indicate on discrete samples cobalt concentrations between 221 and 358 ppm, and report from tailings in Capote, 80,305 Mt with discrete surface cobalt concentrations between 325 and 426 ppm.
Tambillos District
Region of Coquimbo

Sernageomin
Díaz et al. (2009)
Mineral resources in the Tambillos district

• No updated information exists in relation to cobalt resources and ore grades for the Buitre and Minillas mines. It is presumed that remaining mineral piles may contain cobalt concentration values below 1%.

• At present tailing deposits generated from mining exploitation of the stratiform mineral deposits in this district, by Cía. Minera Florida, should potentially contain cobalt minerals, so far undetermined by present owners.

• Ore bodies, veins, breccias and mantos, are at present object of exploration, the prime objective, estimation of copper and cobalt resources in the Tambillos district.

• At present mining drifts are under construction, these to access and exploit the Farellon mine. Exploration drilling campaigns are also underway (Comet Exploration).
Regional exploration for Cobalt – Atacama and Coquimbo regions

Sernageomin - (Lacassie et al., 2016)
Sernageomin carried out regional sampling of mineralization and hydrothermal alteration zones in the metallogenic province of the coastal cordillera of the regions of Atacama and Coquimbo. The data was processed and analyzed by artificial neural nets (ANN), the results summarized below in table and plotted in map.

Attention is set on groups of potential ore deposits (red ellipses) in which a first order Ni-Co signature is detected. The average cobalt values reach 1242 ppm, together with 200 ppm Ni, 2.2% Cu and 585 ppm Mo.

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Regional exploration for Cobalt - Atacama and Coquimbo regions

Sernageomin - (Lacassie et al., 2016)

Cobalt concentrations in mineral deposits in other zones (Z1 to Z6) of the metallogenic province of the Coastal cordillera of Atacama and Coquimbo.

Some of the prime areas of interest for cobalt occur within the known districts described previously, but potential targets may occur within the following districts:

- Sierra Santo Domingo district (Z1)
- Las Ánimas district (Z2)
- Algarrobo – El Roble, Relincho, San Ramón – Zorroquina and Quebrada Seca districts (Z3)
- Punta del Cobre district and Las Pintadas district (Z4)
- Descubridora de Quebrada Seca, Sierra El Tiuque, Totoral Norte and Quebrada Los Loros, Sierra La Noria y Sierra Algarrobillla districts (Z5)
- Carrizal Alto, Astillas, Sierra La Bandera and Quebrada del Medio districts (Z6)
Conclusions
Conclusions

- Cobalt mineral resources were exploited in Chile until 1944, historic districts still holding potential for medium scale mining.

- The prime districts are San Juan and Carrizalillo Alto in the region of Atacama, and the Tambillos district in the region of Coquimbo.

- Exploration for copper-cobalt-gold deposits in these regions shows potential for small to medium scale deposits, veins, breccias and mantos along the coastal cordillera, within the Chilean Iron Belt.

- Exploration for copper-cobalt-gold veins and manto deposits should also consider the high Andean cordillera of central and south central Chile, along the Chilean – Argentinean border, hosted in mezozoic volcanic and sedimentary rocks.
Conclusions

• IOCG and IOA deposits in the lower Cretaceous metallogenic province of Atacama and Coquimbo regions may have good potential for cobalt recovery as a sub product of iron and/or copper production.

• Tailing deposits of all IOA and IOCG deposits of the regions of Atacama and Coquimbo should be evaluated for potential remaining and unrecovered cobalt resources.

• In Chile, copper porphyry deposits of Paleocene and younger ages should be evaluated for potential cobalt sub products.

• Copper production has dwarfed mining of other mineral resources, and despite that precious metals and iron ores are also exploited in Chile, no relevance is given to other potential mineral resources, be it as primary ore deposits, as sub products of the present mining industry, or as potential unrecovered resources present in tailing deposits.