

Exploration and mining potential for cobalt mineral resources in Chile

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Executive Summary

The present report on the state of the art on cobalt mineral resources in Chile was prepared as part of the study “Exploration and mining potential for cobalt mineral resources in Chile” requested by the Non Metallic Mining Committee of Corfo. The following topics are described in this document: Cobalt mining in Chile, past and present; Metallogenic evolution and metallic mineral deposits in Chile; Historic cobalt mining districts in Chile; Mineral resources for cobalt in Chilean deposits, and Mining exploration and mining potential of the historic cobalt mining districts.

Cobalt mining in Chile, past and present

Chile has a long mining history, in the past, global producer of nitrates (salitre) and at present, the world’s top copper producer. The countries focus on main production of a single commodity at present and past has made Chile economically vulnerable and very dependent of its prime resource and price variations of these in the international markets. Present dependence on copper is intrinsically related with the characteristics of the Chilean Andean margin, a subduction related continental volcanic arc type environment in which geological processes have favored formation of world class porphyry copper type deposits, as well as the formation of smaller copper strata bound, iron oxide copper-gold (IOCG) and copper skarn deposits. Other metals, gold, silver, iron and minor cobalt occur in precious metals epithermal vein and breccia, iron oxide apatite (IOA), and copper-gold-cobalt manto and vein type deposits respectively. It must be noted that molybdenum, gold, silver and some other metals are recovered as mining sub products of copper mining, mainly from the porphyry copper type deposits.

Cobalt mining and production begun in Chile in 1865, initially from copper-gold-cobalt vein and manto type deposits in the San Juan district (near the city of Huasco) as well as from vein type deposits near the city of Copiapó, both in the Atacama region. Additional production came from copper-gold-cobalt manto, breccia and vein type deposits in the Tambillos district, Coquimbo region. Cobalt production was also reported from smaller vein type deposits located in the El Volcán – Cajón del Maipo valley, Metropolitan region. Cobalt production ceased in 1944 with closure of the La Cobaltera mine, San Juan district. Peak production of cobalt was reached during the II World War, driven by strong demand for steel allows.

Metallogenic evolution and metallic mineral deposits in Chile

Chile has a great wealth of metallic mineral deposits, mainly copper, these dating back to the very beginnings of the tectonic-magmatic evolution of the Andean margin, in Paleozoic times. Mineral deposits and metallogenic evolution are related to a long history of subduction along a convergent tectonic plate margin, types of deposits and distribution controlled by tectonic and magmatic conditions in time and space. The main type of deposits and distribution, from oldest to youngest are shown in figures 1 and 2, and briefly described as follows (from Makshev et al., 2007):

- Paleozoic: Porphyry copper deposits, all small and low volume, non-economic in Chile.
- Upper Jurassic: Strata bound copper deposits, copper vein and gold-silver vein deposits.
- Lower Cretaceous: Discrete occurrence of porphyry copper deposits; iron oxide apatite (IOA), iron oxide copper-gold (IOCG), strata bound copper, iron and copper skarns and epithermal and mesothermal gold-base metal deposits.
- Upper Cretaceous: gold-copper and silver vein deposits of discrete occurrence and minor occurrences of small, low grade, porphyry copper deposits.
- Paleocene: World class porphyry copper deposits as well as precious metals epithermal deposits and minor occurrences of copper breccia pipe deposits.
- Upper Eocene – Lower Oligocene: Super Giant to Behemothian porphyry copper deposits.
- Miocene: Precious metals epithermal and gold porphyry deposits and Super Giant to Behemothian porphyry copper type deposits.

The distribution of known and mined cobalt mineralization occurs within the Chilean Iron Belt, hosted in Paleozoic metamorphic rocks as well as within intrusive, volcanic and lesser sedimentary rocks of Lower Cretaceous age, in a volcanic arc type environment along the coastal cordillera of the Atacama and Coquimbo regions. Cobalt mineralization mined in El Volcán – Cajón del Maipo, Metropolitan region, is suspected of similar age, set in a back arc environment.

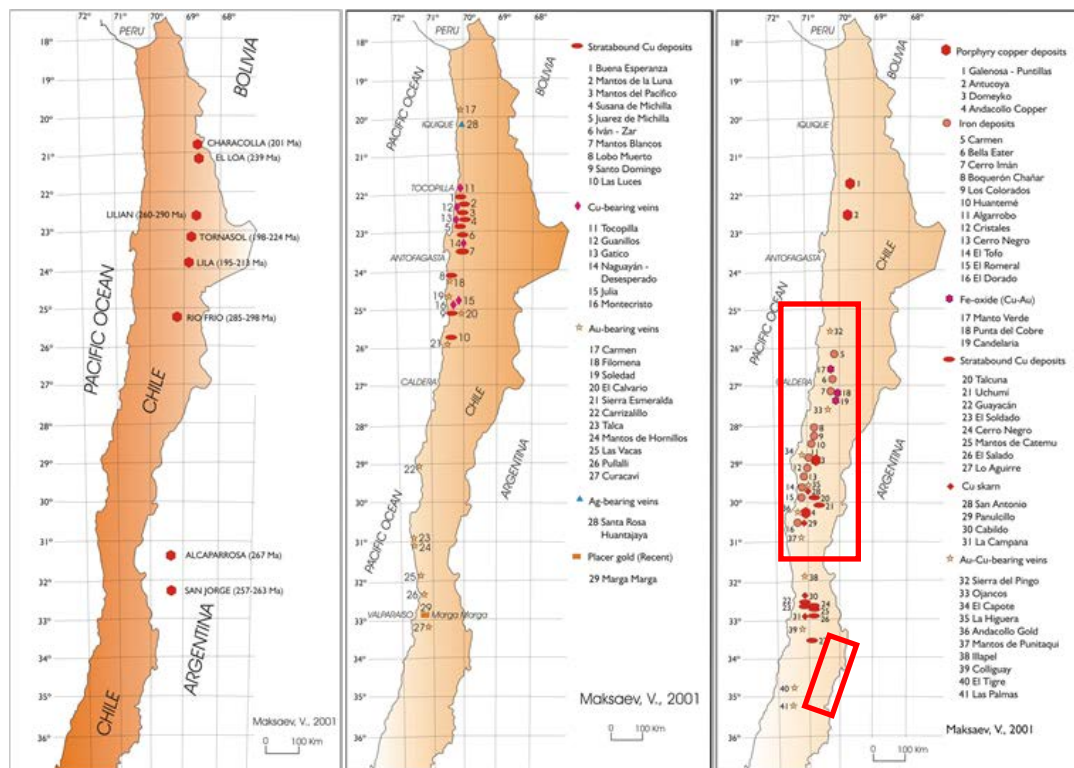


Figure 1. Metallogenic belts, deposit types and distribution of main metallic deposits in Chile (Maksaev et al., 2007; Maksaev, 2001). From left to right: Paleozoic, Upper Cretaceous, Lower Cretaceous. Red rectangles: regions in which known occurrences of primary cobalt ore deposits are documented from past mining and/or in which main deposits could be evaluated for cobalt sub product credits.

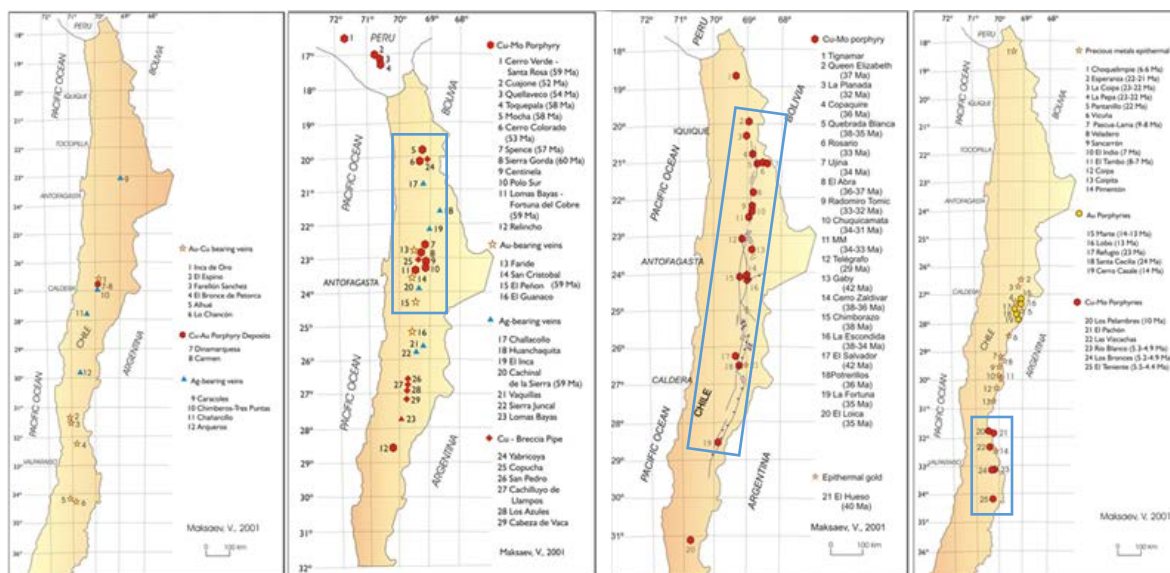


Figure 2. Metallogenic belts, deposit types and distribution of main metallic deposits in Chile (Maksaev et al., 2009; Maksaev, 2001). From left to right: Upper Cretaceous; Paleocene; Upper Oligocene – Lower Eocene; Miocene. Blue rectangles: regions in which porphyry copper deposits could be evaluated for cobalt sub-product credits.

Based on the main types of metallic mineral deposits in Chile, the only documented occurrences of primary cobalt ore deposits are found in the Lower Cretaceous arc and back arc environments. These occur within the Chilean Iron Belt, along the coastal cordillera of the Atacama and Coquimbo regions, mainly hosted within the Atacama Fault System, and to a minor extent in volcanic and sedimentary rocks of the back arc environment of Central Chile (El Volcán – Cajón del Maipo, Metropolitan region; Fig. 1, red marked rectangles).

Cobalt and cobalt minerals have a close affinity with copper, nickel, arsenic and iron sulfides, commonly forming mineral associations in hydrothermal ore deposits. Given this affinity all iron deposits could have potential for cobalt sulfide/arsenide minerals, in particular those presenting arsenic-rich sulfide mineral zones. The main deposit types in which to evaluate cobalt as a potential sub-product are the IOCG, followed by the IOA (Fig. 1, both types marked in red rectangle) and to a lesser extent, the porphyry copper (Fig. 2, blue marked rectangles). Evaluation of potential cobalt sub-product credits is highly dependent on mineral occurrence and metallurgy.

Historic cobalt mining districts in Chile

Primary cobalt ore deposits in Chile have only been mined from vein, breccia and occasionally manto type deposits, these in the Atacama, Coquimbo and Metropolitan regions. Host rocks to these deposits include metamorphic, volcanic, intrusive and in some cases, sedimentary rocks. Significant past production was only developed in two districts, the San Juan district, Atacama region, and the Tambillos district, Coquimbo region.

In the San Juan district primary cobalt mineralization occurs mainly as cobaltite, a cobalt sulfo-arsenide. At surface cobalt occurs as a secondary oxidized mineral, erythrite, a cobalt arsenate. Mineralization occurs mainly in veins and minor mantos, with average cobalt concentrations of 1.6% for primary ore, and up to 6.4% for secondary oxidized ore.

In the Tambillos district copper-gold-cobalt mineralization occurs within manto, vein and breccias type deposits. In past times the main ores were copper and cobalt, and this district was likely the largest cobalt producer in Chile. At present mines within this district continue active, but are only mined for copper, gold recovered as a sub product, with no information regarding cobalt. In 1942 reported cobalt ore grades ranged between 4 and 5% for primary ore. Later exploration data indicate average cobalt concentration at 1%.

In the Metropolitan region, historic production data of the Las Merceditas mine, located in El Volcán – Calón del Maipo valley, reported sulfo-arsenide cobalt mineralization with average ore grades ranging between 2.4 and 2.58%.

Mineral resources for cobalt in Chilean deposits

San Juan District

The San Juan district is located south of the town of Freirina, near the larger cities of Huasco on the coast, and Vallenar, inland from Freirina. The geology in this district (Vivallo et al., 2008; Fig. 3) is comprised by a Paleozoic metamorphic basement towards the west which underlies Upper Jurassic volcanic and sedimentary rocks south and east. Both the basement and the volcanic and sedimentary rocks are intruded by Upper Jurassic and Lower Cretaceous intrusives. In this district a total of 118 vein deposits are recognized in an area of 5x10 sqKm, all closely related with the Atacama Fault System. These veins are grouped in the Fragueta, El Romero, Cobaltera, Quebradita and Labrar mineral zones (Fig. 3). Exploration samples from primary mineral ore rocks (Geoexploraciones, 1983), these from mineral piles, small mine workings as well as from outcrops, indicate cobalt concentrations between 0,001% and 1,95%, together with variable contents for copper (7,9% - 0,037%), gold (1,1 g/t a 0,1 g/t), silver (8,8 g/t a 0,5 g/t), nickel (0,49% a 0,023%) and cadmium (4,7 g/t a 0,023 g/t). Based on their exploration and evaluation campaigns conducted in 1983, Geoexploraciones divided the district in two zones. As a result they indicated remaining *in-situ* stock pile mineral resources for two piles in Zone 1, one with 1,300 mT, the second with 3,960 mT, both with average cobalt ore grades above 1%. In Zone 2 they determined 62,000 mT in mineral stock piles of the Santa Rosa mine, these with cobalt concentrations ranging between 0.05 and 0.24% Co, as well as with an average copper grade of 2.44%. More detailed studies were recommended for this zone.

North of the San Juan district, slightly north of the town of Freirina, Santa Marta Mining Company reported approximately 500,000 mT of tailings with average cobalt concentrations of 0.11%, together with copper concentrations at an average of 0.23% (INTEC, 1988).

Other reports on tailing deposits in the proximities of Freirina indicate cobalt concentrations of 221 and 358 ppm, these from discrete surface samples. Reports for the Capote tailings deposit, also for discrete surface samples, indicated cobalt concentration values of 325 and 426 ppm.

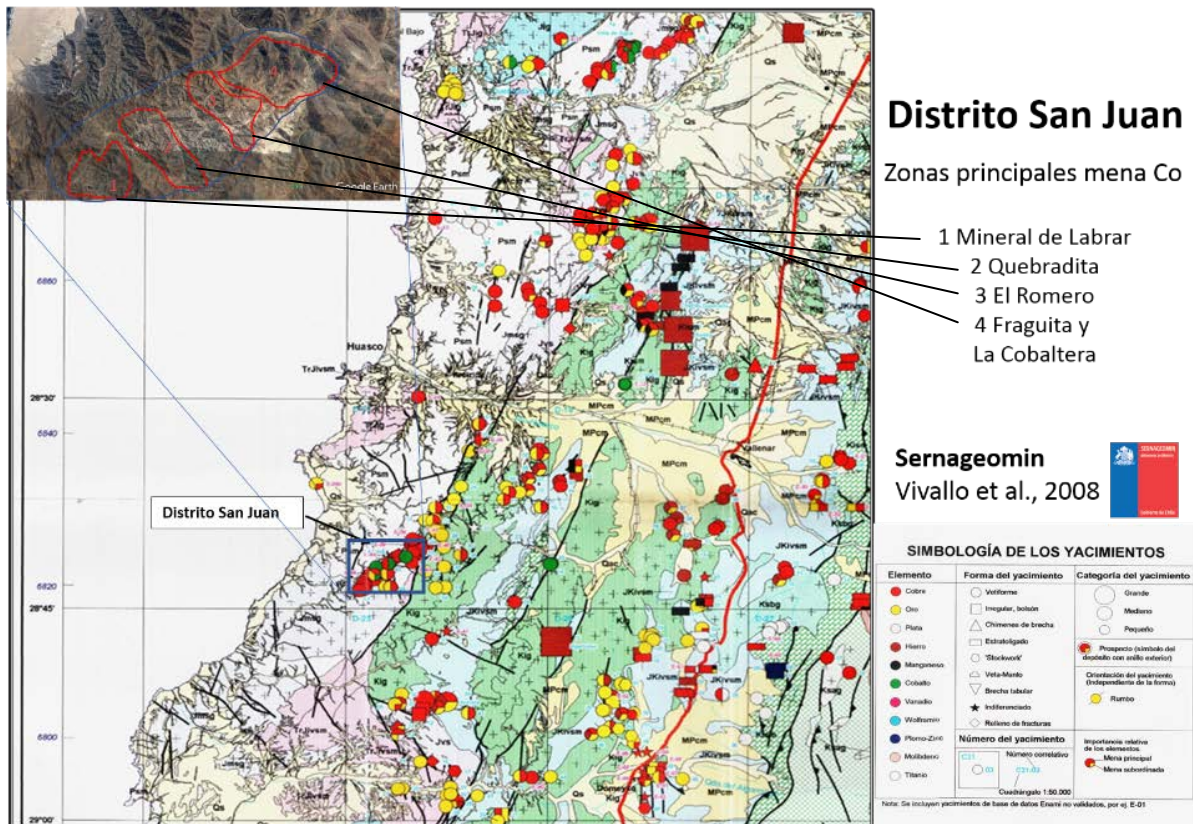


Figure 3. Geology and mineralization of the San Juan district, Atacama region. The Labrar, Quebradita, El Romero and Fragueta – La Cobartera mineral zones are indicated in upper left detail. Map modified from Vivallo et al., 2008 (Sernageomin), mineral zones base on Geoexploraciones (1983).

Tambillos District

The Tambillos district is located 33 Km south of the city of La Serena, in the region of Coquimbo. Mineralization in this district include IOCG type vein deposits hosted in Lower Cretaceous intrusive and Upper Cretaceous subvolcanic rocks, as well as within Upper Jurassic – Lower Cretaceous volcanic and sedimentary rocks (Arqueros Formation; Fig. 4; Díaz et al., 2009). Stratiform IOCG mineralization also occurs within the base of the Arqueros Formation, hosted with sedimentary and volcanic sequences. All these rock units occur west of the main El Romeral Fault System, and have been affected by high grade contact metamorphism associated with the emplacement of the Lower Cretaceous intrusions.

The historic cobalt mines in this district are the El Buitre and Minillas mines, both manto type deposits hosted within sedimentary and volcanic stratified sequences. The El Buitre mine had the largest development for cobalt exploitation. In 1975 it had three different levels, ore bodies having estimated cobalt content at about 1%, and remaining mineral piles at estimated 0.46% Co. The Minillas mine, immediately south of El Buitre presents similar characteristics, and is at present in preparation for exploitation, this aimed at the remaining copper oxidized ore. The only active medium scale mining operation is the Florida mine, near El Buitre, it holds similar characteristics. This mine is exploited for copper, ore rocks processed locally, the tailings potentially holding cobalt potential.

At present there is no updated data in relation to cobalt potential resources or ore grades, no data reported for El Buitre, Minillas or Florida mines. It is suspected that the remaining old mineral piles may hold potential cobalt resources at grades lower than 1%.

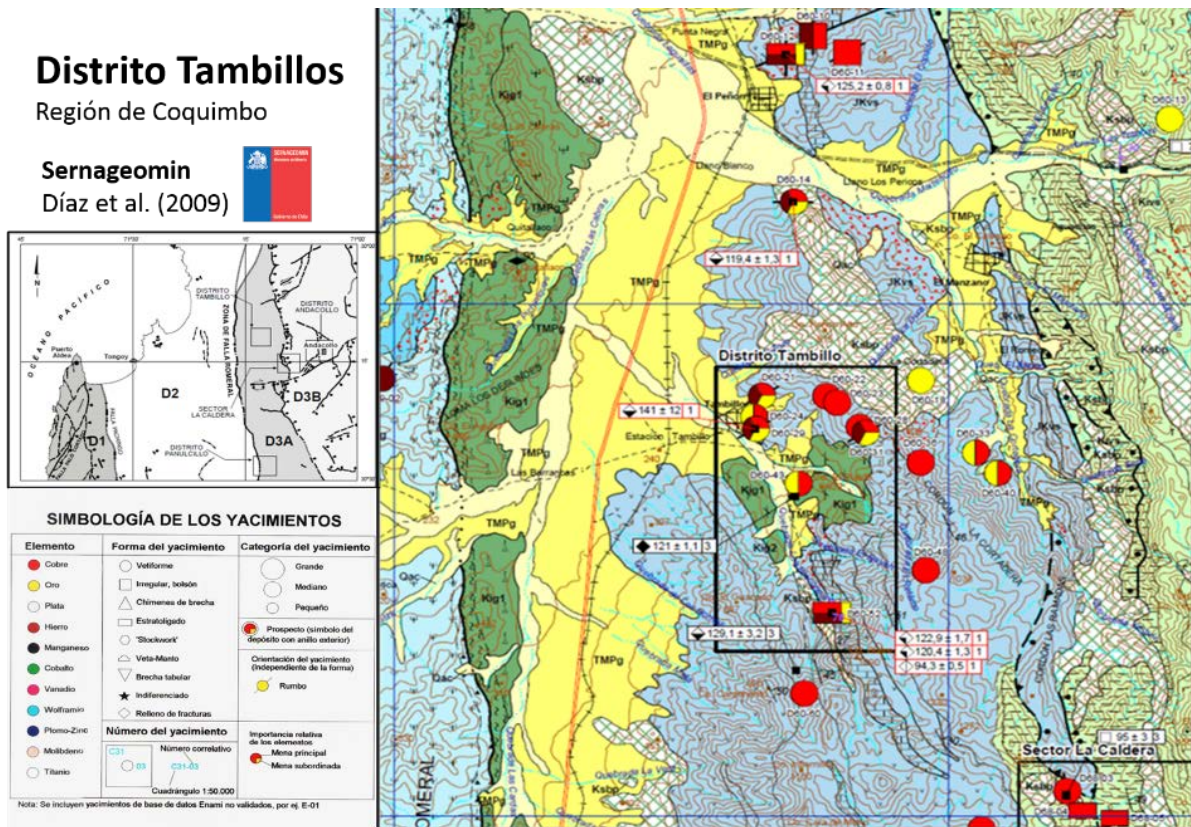


Figure 4. Geology and mineralization of the Tambillos district. Map modified from Díaz et al., 2009 (Sernageomin).

At present, the tailing deposits generated from the mining exploitation of the stratiform deposits in the district, this by Florida Mining Company, potentially should hold cobalt, not determined as of yet by the current owners. Mining exploration for veins, breccias and manto type deposits is currently on-going, both for copper and cobalt potential. Exploration tunnels and drilling is underway (COMET Exploration).

Mining exploration and mining potential in the historic cobalt mining districts

Most recently Sernageomin carried out regional sampling of mineralization and hydrothermal alteration systems in the metallogenic province of the coastal cordillera of the Atacama and Coquimbo regions (Lacassie et al., 2016). Geochemical data was processed and analyzed by means of Artificial Neural Nets (ANN), the results described as follows (Fig. 5a and b):

- Deposits in which a strong first order Ni-Co signature is determined, with average cobalt concentrations reaching 1,242 ppm, together with 200 ppm Ni, 2.2% Cu and 585 ppm Mo. These deposit groups are marked in red circles in figure 5.
- Other deposits with a high cobalt signal, these including Fe-P, Fe, Ca, and La-Ce, hold geochemical signatures which are associated with IOA and IOCG type deposits, as well as

for mesothermal copper-gold deposits, these hosted in Upper Jurassic to Lower Cretaceous rocks.

The main cobalt exploration districts remain within those historically known and previously described, but other potential areas for cobalt are described for a total of six clusters, shown in figure 5b (Z1 to Z6), some of the main areas of interest listed below:

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

Main conclusions

Within the main conclusions of the present state of the art review of cobalt mineral potential in Chile the following statements are derived:

- Primary cobalt ore mineral deposits were mined in Chile until the year 1944, the historic known districts holding potential for medium scale mining, these being the San Juan and to a lesser extent the Carrizalillo Alto districts, both in the Atacama region, and the Tambillos district, in the region of Coquimbo.
- Both the San Juan and Tambillos districts are presently explored and mined for copper-gold, yet cobalt potential remains, in some zones possibly as a primary ore, in others a potential sub product of copper and gold production.
- Geochemical exploration and mineral deposit geochemical signatures clearly indicate potential for cobalt in the Chilean Iron Belt, along the Lower Cretaceous metallogenic belt of the coastal cordillera of the Atacama and Coquimbo regions. Primary cobalt ore deposits lie within these provinces, controlled by the Atacama Fault System.
- Within the Chilean Iron Belt IOA and IOCG deposits may hold potential for cobalt as a sub product credit of iron mining, and of copper-gold mining, not yet evaluated.
- Tailing deposits of the IOA and IOCG deposits should be evaluated for potential recovery of cobalt.
- Exploration for copper-gold-cobalt vein and manto deposits should also consider the high Andes of central and south central Chile, along the Chilean – Argentinean border, hosted in volcanic and sedimentary Mesozoic rocks of the back arc environment, such as that present in the Las Merceditas mines, Metropolitan region.
- Finally, Paleocene and younger porphyry copper deposits should be considered for evaluation of cobalt as a potential sub product credit, added on other existing sub products.

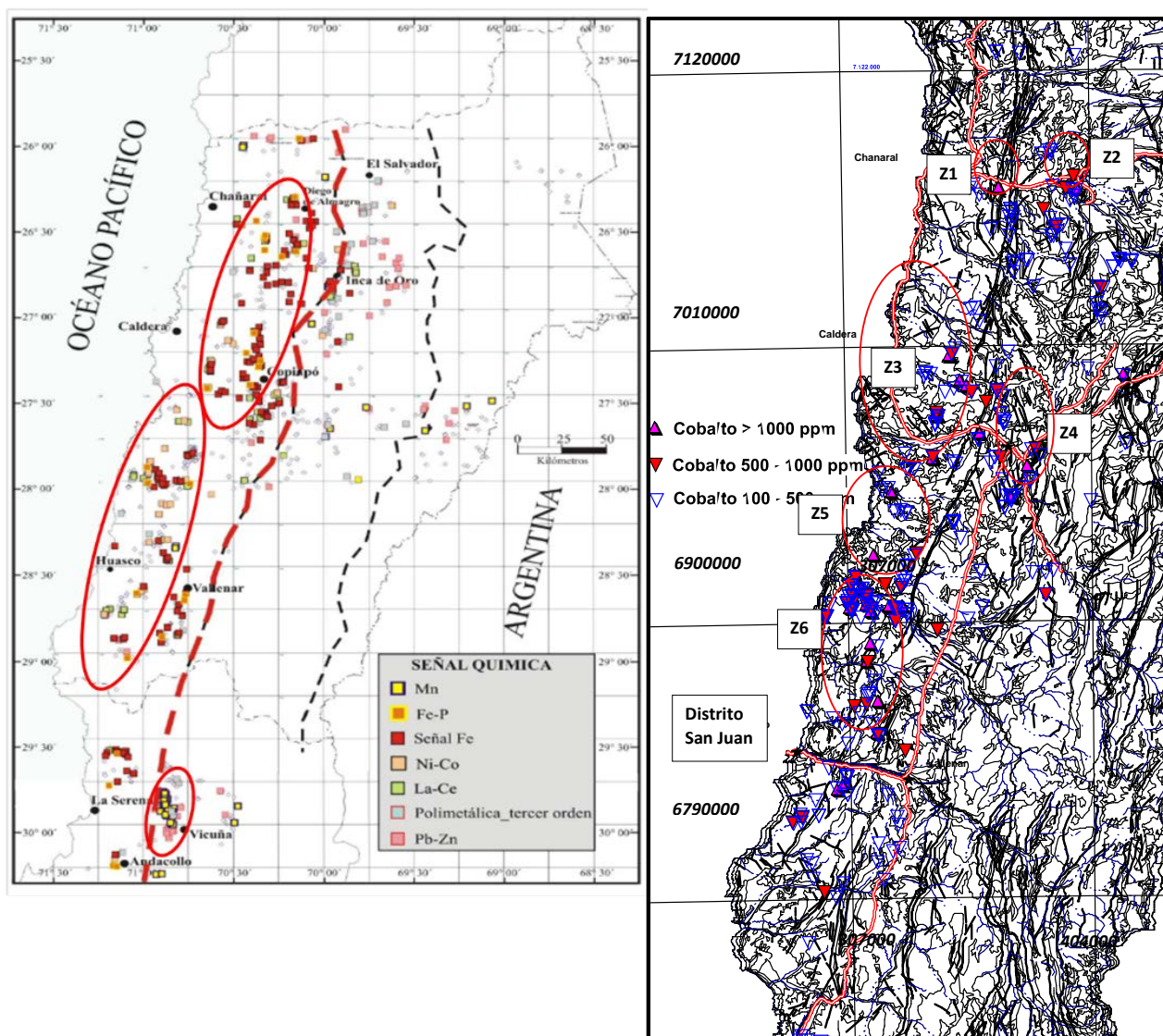


Figure 5. (a) Geochemical signals based on Neural Net Analysis of data from samples taken from mines, outcrops and other showings of mineralization and hydrothermal alteration in the coastal Lower Cretaceous metallogenic province. (b) Cobalt concentrations and selection of cobalt exploration potential zones in the same metallogenic province (Z1 to Z6). Both maps and geochemical studies from Lacassie et al., 2016 (Sernageomin).

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