

Gold deposits in Chile

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ABSTRACT. A review of gold and gold bearing base metals deposits in Chile, indicate the existence of at least six different type of ore deposits, most largely formed during the Cenozoic with predominance in the Miocene. Mesozoic deposits are common but less relevant regarding their size and gold content. These hydrothermal ore deposits are genetically associated with subduction related Andean arc magmatism. Due to its relationship with episodic magmatism migrating eastward, there is a tendency for the deposits to be in distinct, north-south trending, belts with a progressive west to east decrease in mineralization age. After analysing 82 cases in total, main gold concentration can be assigned to high-sulfidation epithermal and porphyry type deposits. Low-sulfidation epithermal, IOCG and mesothermal type appears as less relevant. Gold bearing copper deposits constitute an important part of Chile's total gold production. Both IOCG type but especially porphyry copper deposits are and will remain as a substantial source to supplement the future output of the gold in the country. The 82 deposits with their tonnage and grade studied, represent a total gold content of 11,662 t equivalent to 375 Moz, excluding past production for those exploited. A number of probable gold bearing base metals high tonnage deposits (IOCG and porphyry copper) do not include their gold content in public format, hence the number delivered could be estimated conservative. Methodical geochronological, ore types and zonation studies are required to better appreciate this metallogenic setting widening current understanding and future exploration results.

Keywords: Andean magmatism, Gold deposits belts, Ore deposit type, Tonnage and grade.

RESUMEN. Yacimientos de oro en Chile. Una revisión de yacimientos de oro y de metales básicos con oro, indican la existencia de por lo menos seis diferentes tipos de yacimientos, mayormente formados durante el Cenozoico con predominancia en el Mioceno. Los depósitos de edad mesozoica son de ocurrencia frecuente, pero menos relevantes en cuanto a tamaño y contenido de oro. Estos yacimientos hidrotermales están genéticamente vinculados con arcos magmáticos andinos, de orientación norte-sur, asociados a subducción. Debido a su relación con un magmatismo episódico migrante hacia el este, los yacimientos presentan una tendencia a distribuirse en diferentes franjas de orientación meridional, con una progresiva disminución de la edad de la mineralización hacia el este. Del análisis de un total de 82 yacimientos, la principal concentración de oro puede asignarse a depósitos tipo epitermal de alta sulfuración, pórfidos aurífero y pórfidos de cobre. Los yacimientos tipo epitermal de baja sulfuración, IOCG y mesotermal aparecen como menos importantes. Yacimientos cupríferos con mineralización aurífera subordinada constituyen una importante parte del total de la producción de oro en Chile. Los yacimientos tipo IOCG, y sobre todo los pórfidos cupríferos son y permanecerán como importantes recursos para contribuir a la futura producción de oro en el país. Los 82 depósitos con tonelaje y ley estudiados, representan un total de 11.662 t de oro contenido equivalente a 375 Millones de onzas excluyendo la producción pasada para los yacimientos que han sido explotados. Sin embargo, un número importante de yacimientos con gran tonelaje de metales básicos con oro subordinado (IOCG y pórfidos cupríferos) no publican su contenido de oro, por lo que las cifras acá entregadas podrían ser consideradas conservadoras. Estudios sistemáticos de geocronología, tipos de yacimientos y zonación, son necesarios para ampliar su entendimiento metalogénico, así como futuros resultados en exploración.

Palabras clave: Magmatismo andino, Franjas de yacimientos de oro, Tipo de yacimiento, Tonelaje y ley.

1. Introduction

Chile produced 38 tonnes of gold in 2019 making it the 21th most important gold miner in the world and the fifth in South America after Perú, Brazil, Argentina and Colombia (Sernageomin, 2020). Annual production should increase further as a result of proposed new developments at the Pascua and Cerro Casale projects where annual productions of 20 t and 7.7 t respectively have been projected.

Even if gold production exists from pre-Hispanic times, recognition of Chile as an important gold province (Fig. 1) is in part the result of exploration successes in the last five decades (Sillitoe, 1995, 2000, 2010; Cabello, 1999, 2002).

Although in detail more complex, the geology of the Chilean Andes can be interpreted as a sequence of eastward migrating Mesozoic and Cenozoic magmatic arcs built over Paleozoic and Precambrian basement (Hervé *et al.*, 2007). Hydrothermal gold deposits are more common in northern and central Chile (*ca.* 18°–34° S; Fig. 1) where they are closely related to several discrete magmatic arcs generated during Mesozoic to Miocene time. Gold deposits, in common with the magmatic arcs that contain them are progressively younger eastward (Davidson and Mpodozis, 1991). Several isotopic studies indicate a general trend of increasing crustal contamination throughout the Cenozoic arc evolution (Miller and Harris, 1989), but apparently there is no influence in the magmatism related to gold mineralization of the same age (Sillitoe, 1991).

The most important gold deposits are of epithermal and porphyry type (Table 1). Mesothermal, skarn, or stratabound are less prominent. Placer type gold deposits, common in central-southern Chile, realized important production from 1541 to the end of the sixteenth century (Cuadra and Dunkerley, 1991). Gold-bearing copper deposits have contributed an important component to Chile's total gold production (today about 50%). IOCG type deposits and especially porphyry coppers are and will remain significant sources of gold production (Table 2 and 3). All-important gold bearing base metals deposits are Mesozoic or Cenozoic in age (Maksaev *et al.*, 2007).

This article intends to update the knowledge originated previously by different authors (Ruiz and Peebles, 1988; Camus, 1990; Sillitoe, 1991; Cabello, 1992; Kojima, 1999; Maksaev *et al.*, 2007), including

information about deposits that were less known or unknown in the previous century.

2. Geological setting

The Andes of Chile are the southernmost part of the Cordilleran igneous and tectonic region that is continuous along the western margins of the North and South American plates from Alaska to Chile (Davidson and Mpodozis, 1991; Charrier *et al.*, 2007). This margin of South America has faced the Pacific Ocean throughout the Phanerozoic and has been a convergent plate margin since late Paleozoic.

The magmatic and tectonic evolution of the Chilean Andes has been the subject of several studies (e.g., Mpodozis and Ramos, 1990; Kay *et al.*, 1999; Charrier *et al.*, 2007; Parada *et al.*, 2007). Although exceptionally broad and geologically complex, the Chilean sector of the Andes can be interpreted as a sequence eastward-migrating Mesozoic and Cenozoic magmatic arcs (Coira *et al.*, 1982; Stern, 2004; Mpodozis and Cornejo, 2019), built over Paleozoic and Precambrian basement. These arcs were formed by active subduction of the oceanic plate beneath the South American plate at least since Paleozoic times. The pre-Jurassic basement is made up of a collage of discrete fragments of Precambrian to early Paleozoic allochthonous or displaced terranes belonging to the Gondwana Continent (e.g., Oliveros *et al.*, 2020). Existing geologic provinces owe their distribution to segmentation of the subducted Nazca plate (Jordan *et al.*, 1983; Tassara *et al.*, 2006; Bloch *et al.*, 2018).

An early Carboniferous magmatic arc appears to have been established over Precambrian and early Paleozoic rocks along the length of the Chilean Andes (Coloma *et al.*, 2017). This arc was bounded by an accretionary prism oceanward and by a foreland sedimentary basin toward the continental interior (Willner *et al.*, 2009; Deckart *et al.*, 2014). Calc-alkaline, mantle-derived granitoids of late Carboniferous ages are well exposed in parts of central-northern Chile (Nasi *et al.*, 1985; Charrier *et al.*, 2014). A large Permian to Triassic silicic volcanic field and associated shallow-level plutons generated by crustal melting in an extensional setting overlies and intrudes the Carboniferous arc (Mpodozis and Kay, 1990; Ramos and Folguera, 2016).

In contrast to the Paleozoic, the Mesozoic-Cenozoic Andes lack evidence of major terrane collisions (Dalziel, 1986; Forsythe *et al.*, 1987).

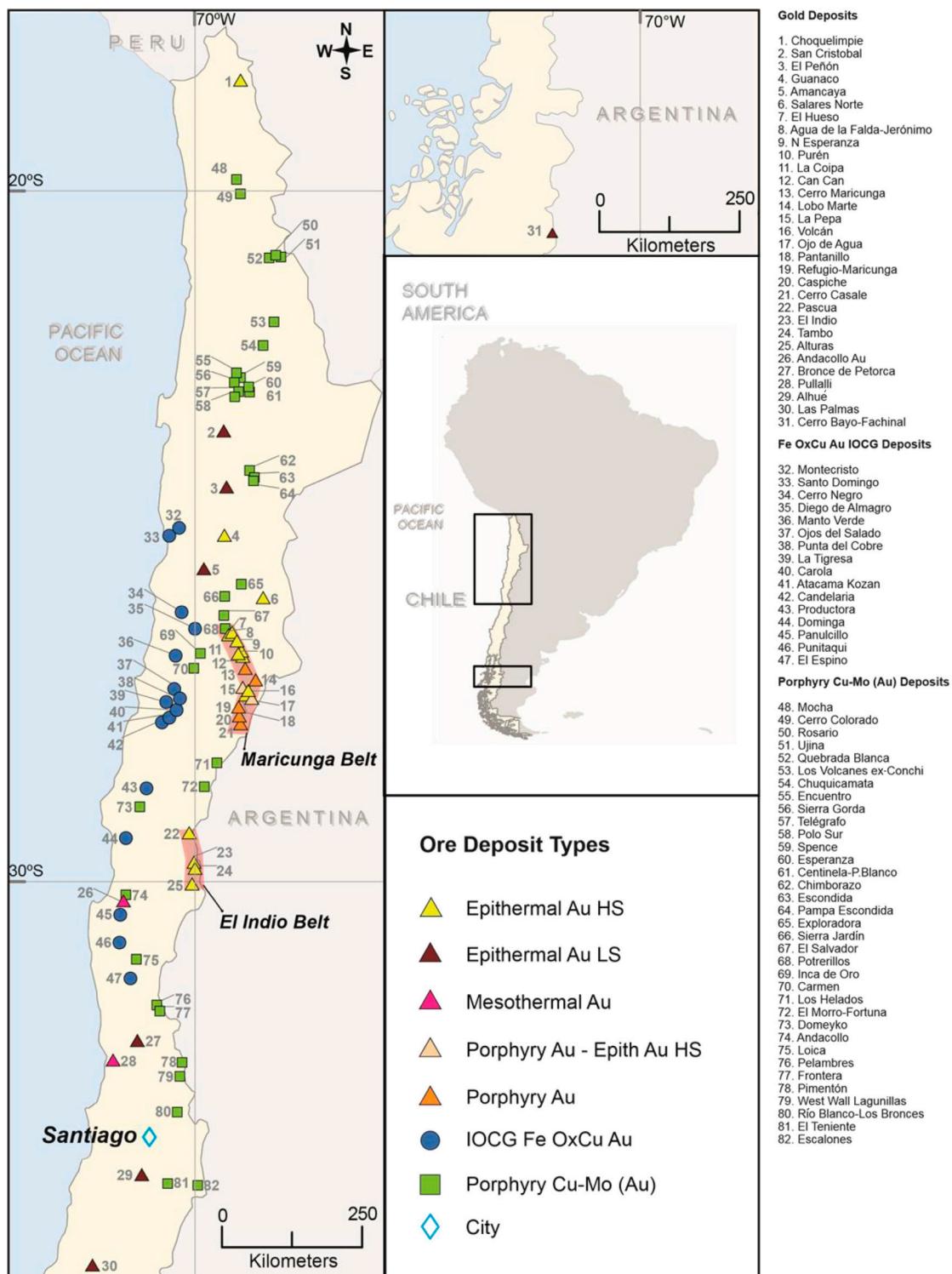


Fig.1. Distribution of the main gold deposits and other important gold bearing ore deposits type in Chile.

TABLE 1. MAIN GOLD DEPOSITS IN CHILE.

Name	Deposit Type	Ore M Tons	Au gt	Ag gt	T Au	M Oz Au	Age	References
Choquelimpie	EpithAu HS	11.00	2.23	60	24.53	0.79	Miocene	Sillitoe, 1999
San Cristóbal	EpithAu LS	25.00	0.90	3	22.50	0.72	Paleocene-Eocene	Cabello, 2002
El Peñón	EpithAu LS	32.40	8.20	249	265.68	8.54	Paleocene-Eocene	Zuluaga, 2018
Guanaco	EpithAu HS	28.00	1.43	6	40.40	1.29	Paleocene-Eocene	Nat Res Holdings, 2013
Amancaya	EpithAu LS	1.40	7.90	73	11.06	0.36	Paleocene-Eocene	Yamana Gold, 2018
Salares Norte	EpithAu HS	26.80	3.90	48.9	104.52	3.36	Miocene	Brewer <i>et al.</i> , 2017
El Hueso	EpithAu HS	16.00	1.68	2	26.88	0.86	Eocene-Oligocene	Cabello, 2002
Agua de la Falda Jerónimo	EpithAu HS	16.50	6.00	3	99.00	3.18	Eocene-Oligocene	Thompson <i>et al.</i> , 2004
N Esperanza	EpithAu HS	39.40	0.39	66	15.37	0.49	Miocene	Kingsgate, 2016
Purén	EpithAu HS	17.00	0.90	278	15.30	0.49	Miocene	Arribas <i>et al.</i> , 2005
La Coipa	EpithAu HS	88.00	0.80	84	70.40	2.26	Miocene	Cabello, 2002
Can Can	EpithAu HS	6.00	1.30	na	7.80	0.25	Miocene	Cabello, 2002
Cerro Maricunga	PorphAu	474.00	0.39	na	184.86	5.94	Miocene	Nat. Res. Holdings, 2013
Lobo Marte	PorphAu	311.00	0.98	na	304.78	9.80	Miocene	Nat. Res. Holdings, 2013
La Pepa	Porph Au-Epith Au HS	187.00	0.56	na	104.72	3.37	Miocene	Nat. Res. Holdings, 2013
Volcán	EpithAu HS	431.00	0.69	na	297.39	9.56	Miocene	Nat. Res. Holdings, 2013
Ojo de Agua	EpithAu HS	18.60	0.85	na	15.81	0.51	Miocene	Andina Minerals, 2012
Pantanillo	Porph Au-Epith Au HS	47.00	0.69	na	32.43	1.04	Miocene	Simon <i>et al.</i> , 2010
Refugio-Maricunga	PorphAu	382.00	0.66	na	252.12	8.11	Miocene	Nat. Res. Holdings, 2013
Caspiche	PorphAu	1,602.00	0.48	1.14	768.96	24.72	Miocene	Goldecorp, 2017
Cerro Casale	PorphAu	1,990.00	0.51	1.44	1,014.90	32.63	Miocene	Goldcorp, 2017
Pascua	EpithAu HS	662.00	1.20	40	794.40	25.54	Miocene	Nat. Res. Holdings, 2013
El Indio	EpithAu HS	23.20	6.60	50	153.12	4.92	Miocene	Sillitoe, 1999
Tambo	EpithAu HS	37.00	4.10	na	151.70	4.88	Miocene	Cabello, 2002
Alturas	EpithAu HS	211.00	1.00	na	211.00	6.78	Miocene	Barrick, 2016
Andacollo Au	MesoAu	253.00	0.39	-	91.00	2.93	Cretaceous	Slater <i>et al.</i> , 2012
Bronce de Petorca	EpithAu LS	7.60	4.60	14	34.96	1.12	Cretaceous	Camus, 2011
Pullalli	Stratabound	9.00	1.60	na	14.30	0.46	Cretaceous	Pegasus Gold Inc., 1997
Alhué	EpithAu LS	17.00	3.60	na	61.20	1.97	Cretaceous	Nat. Res. Holdings, 2013
Las Palmas	EpithAu LS	2.00	4.50	na	9.00	0.29	Cretaceous	Cabello, 2002
Cerro Bayo-Fachinal	EpithAu LS	5.90	3.30	170	19.47	0.63	Cretaceous	Poblete, 2011
Subtotal					5,227.00	168.03		

The gold deposits considered are mainly Epithermal ore deposits of high sulfidation (Epithermal HS) and low sulfidation (Epithermal LS), porphyry gold type (Porphyry Au) and Mesothermal. Total resources in million tons (Mt) of ore, the ore grade in g/t for Au and Ag, the total Au contained in the deposits is in tons (t) and million ounces (Moz).

TABLE 2. MAIN IRON OXIDES COPPER GOLD (IOCG) DEPOSITS IN CHILE.

Name	Deposit Type	Model	Ore Tons	Cu %	Au gt	T Au	M Oz Au	Age my	Age	References
Montecristo	IOCG	FeOxCuAu	15	1.60	0.600	9.00	0.29	164	Cretaceous	Sillitoe, 2003
Santo Domingo	IOCG	FeOxCuAu	485	0.32	0.043	20.86	0.67	-	Cretaceous	Brimage <i>et al.</i> , 2011
Cerro Negro	IOCG	FeOxCuAu	249	0.40	0.150	37.35	1.20	-	Cretaceous	Atna Resources, 2002
Diego de Almagro	IOCG	FeOxCuAu	70	0.65	0.050	3.50	0.11	120-100?	Cretaceous	Herrera <i>et al.</i> , 2008
Manto Verde	IOCG	FeOxCuAu	440	0.56	0.120	52.80	1.70	128-117	Cretaceous	Richards <i>et al.</i> , 2016
Ojos del Salado	IOCG	FeOxCuAu	17	1.32	0.270	4.59	0.15	-	Cretaceous	Cabello, 2002
Punta del Cobre	IOCG	FeOxCuAu	120	1.50	0.200	24.00	0.77	-	Cretaceous	Sillitoe, 2003
La Tigresa	IOCG	FeOxCuAu	8	0.56	0.270	2.16	0.07	-	Cretaceous	Cabello, 2013
Carola	IOCG	FeOxCuAu	10	1.80	0.500	5.00	0.16	-	Cretaceous	Vivallo <i>et al.</i> , 2008
Atacama Kozan	IOCG	FeOxCuAu	50	1.60	0.350	17.50	0.56	-	Cretaceous	Cabello, 2002
Candelaria	IOCG	FeOxCuAu	501	0.54	0.130	65.13	2.09	116-110	Cretaceous	Richards <i>et al.</i> , 2016
Productora	IOCG	FeOxCuAu	214	0.48	0.100	21.40	0.69	130-128	Cretaceous	Marquardt <i>et al.</i> , 2015
Dominga	IOCG	FeOxCuAu	2	0.12	0.014	28.00	0.90	127	Cretaceous	Garrido, 2013
Panulcillo	IOCG	FeOxCuAu	15	1.45	0.100	1.50	0.05	115	Cretaceous	Chen <i>et al.</i> , 2013
Punitaqui	IOCG	FeOxCuAu	10	na	3.000	30.00	0.96	-	Cretaceous	Cabello, 2002
El Espino	IOCG	FeOxCuAu	123	0.66	0.240	29.52	0.95	100-94	Cretaceous	López <i>et al.</i> , 2014
Subtotal						352.31	11.32			

Ore resources in million tons (Mt), the ore grade in g/t for Au, the total Au contained in the deposits is in tons (t) and million ounces (Moz).

During Jurassic and early Cretaceous time, the Andean region was characterised by a series of magmatic arcs and back arc basins in a steep-angle subduction regime dominated by back-arc extension and subsidence (Mpodozis and Ramos, 1990; Ramos, 2010), resembling a Mariana-type tectonic setting (Oliveros *et al.*, 2007). From the earliest Mesozoic, huge volumes of calc-alkaline volcanic rocks and related plutons were emplaced along a belt parallel to the present coastline in northern and central Chile. Magmatic rocks from this period represent a well-defined and exposed, linear magmatic arc built over late Paleozoic fore-arc assemblages (Díaz-Alvarado *et al.*, 2019). The arc was bounded to the east by a system of ensialic back-arc basins filled with sediments or thick volcanoclastic successions (Ramos, 2010).

A major middle Cretaceous tectonic break in the Andean evolution occurred between 100 and 88 Ma, with the inception of South Atlantic spreading and consequent increase in the westward velocity of the South American plate, a change from low-stress Mariana-type subduction to a compressive

subduction system (Chilean type) was produced (Mpodozis and Ramos, 1990). This resulted in the closure and collapse of the back arc basins. From this time onward, the calc-alkaline magmatic arc remained as the major tectonic element but a calm in igneous activity occurred in the late Cretaceous (Coira *et al.*, 1982; Charrier *et al.*, 2007).

Intense calc-alkaline magmatism resumed in northern Chile during Paleocene to Eocene times (Charrier *et al.*, 2015). Volcanic centres were displaced eastward with respect to the extinct Jurassic-Early Cretaceous magmatic arc located in the present Coast Range (Charrier *et al.*, 2007). Magmatism ceased in the Eocene as a consequence of the Incaic deformation event, to be followed by a late Eocene-early Oligocene period of relative magmatic quiescence associated with strike-slip faulting (Herrera *et al.*, 2017). A second period of Neogene magmatism began in the late Oligocene when the modern Andean arc was established in the Western Cordillera, even farther east (Jordan and Gardeweg, 1988; Stern, 2004).

TABLE 3. MAIN PORPHYRY COPPER-MOLYBDENUM-GOLD DEPOSITS IN CHILE.

Name	Deposit Type	Ore Tons	Cu %	Au gt	tAu	M oz Au	Age	References
Mocha	Porphyry MoAu	2,100.00	0.35	0.04	84.00	2.7	Paleocene	Churuta, 2019
Cerro Colorado	Porphyry MoAu	450	0.90	0.10	45.00	1.45	Paleocene	Cabello, 2002
Rosario	Porphyry MoAu	3,108	0.82	0.01	31.08	1.00	Eocene-Oligocene	Camus, 2003
Ujina	Porphyry MoAu	1,081	0.81	0.03	32.43	1.04	Eocene-Oligocene	Cabello, 2002
Quebrada Blanca	Porphyry MoAu	1,09	0.72	0.10	109.00	3.5	Eocene-Oligocene	Singer <i>et al.</i> , 2005
Los Volcanes ex Conehi	Porphyry MoAu	1,874	0.50	0.03	56.22	1.81	Eocene-Oligocene	AMSA, 2017
Chuquicamata	Porphyry MoAu	7,521	0.55	0.04	300.84	9.67	Eocene-Oligocene	Camus, 2003
Encuentro	Porphyry MoAu	1,222	0.42	0.15	183.30	5.89	Eocene-Oligocene	Perelló <i>et al.</i> , 2010
Sierra Gorda	Porphyry MoAu	2,918	0.35	0.05	140.06	4.5	Paleocene	López and Ristorcelli, 2011
Telégrafo	Porphyry MoAu	2,489	0.38	0.12	298.68	9.6	Eocene-Oligocene	Perelló <i>et al.</i> , 2010
Polo Sur	Porphyry MoAu	1,388	0.34	0.05	69.40	2.23	Eocene-Oligocene	AMSA, 2017
Spence	Porphyry MoAu	405	1.10	0.18	72.90	2.34	Paleocene	Camus, 2003
Esperanza	Porphyry MoAu	1,204	0.45	0.15	180.60	5.81	Eocene-Oligocene	Perelló <i>et al.</i> , 2010
Centinela-P. Blanco	Porphyry MoAu	322	0.38	0.05	16.10	0.52	Eocene-Oligocene	AMSA, 2017
Chimborazo	Porphyry MoAu	236	0.60	0.70	165.20	5.31	Eocene-Oligocene	Singer <i>et al.</i> , 2008
Escondida	Porphyry MoAu	4,86	0.97	0.25	1,215.00	39.06	Eocene-Oligocene	Singer <i>et al.</i> , 2005
Pampa Escondida	Porphyry MoAu	7,44	0.45	0.06	446.40	14.35	Eocene-Oligocene	BHP, 2018
Exploradora	Porphyry MoAu	100	0.50	0.20	20.00	0.64	Eocene-Oligocene	Camus, 2003
Sierra Jardín	Porphyry MoAu	50	0.25	0.20	10.00	0.32	Eocene-Oligocene	Camus, 2003
El Salvador	Porphyry MoAu	974	0.63	0.10	97.40	3.13	Eocene-Oligocene	Camus, 2003
Potrerillos	Porphyry MoAu	670	0.60	0.15	100.50	3.23	Eocene-Oligocene	Camus, 2003
Inca de Oro	Porphyry MoAu	769	0.36	0.10	76.90	2.47	Cretaceous	Richard <i>et al.</i> , 2016
Carmen	Porphyry MoAu	100	0.32	0.38	38.00	1.22	Cretaceous	Llaumett, 2009
Los Helados	Porphyry MoAu	1,28	0.40	0.15	192.00	6.17	Mid-Pliocene	NGEX, 2016
El Morro-Fortuna	Porphyry MoAu	1,442	0.41	0.34	490.28	15.76	Eocene-Oligocene	Lambert <i>et al.</i> , 2012
Domeyko	Porphyry MoAu	58	0.48	0.40	23.20	0.75	Cretaceous	Camus, 2003
Andacollo	Porphyry MoAu	417	0.34	0.12	50.04	1.61	Cretaceous	Teck Res. Ltd., 2016

table 3 continued.

Name	Deposit Type	Ore Tons	Cu %	Au gt	t Au	M oz Au	Age	References
Loica	PorphyryCuMoAu	100	1.25	0.20	20.00	0.64	Eocene-Oligocene	Camus, 2003
Pelambres	PorphyryCuMoAu	6,024	0.51	0.05	301.20	9.68	Mio-Pliocene	AMSA, 2017
Frontera	PorphyryCuMoAu	700	0.52	0.10	70.00	2.25	Mio-Pliocene	Perelló <i>et al.</i> , 2009
Pimentón	PorphyryCuMoAu	400	0.40	0.43	172.00	5.53	Mio-Pliocene	Pardo, 2006
West Wall Lagunillas	PorphyryCuMoAu	750	0.54	0.05	37.50	1.21	Mio-Pliocene	Irrázaval, 2011
Río Blanco-Los Briones	PorphyryCuMoAu	6,99	0.75	0.04	244.65	7.86	Mio-Pliocene	Frikken <i>et al.</i> , 2005
El Teniente	PorphyryCuMoAu	12,842	0.63	0.04	513.68	16.51	Mio-Pliocene	Camus, 2003
Escalones	PorphyryCuMoAu	420	0.41	0.05	21.00	0.68	Mio-Pliocene	Anmitage and Davis, 2012
Subtotal				6,082.40	195.50			

Principal porphyry copper-molybdenum-gold deposits in Chile (PorphyryCuMoAu), total ore resources in million tons (Mt) ore grade (%Cu, g/t Au). Total Au contained in the deposits is in ton (t) and million ounces (Moz).

Between 27° S and 33° S, the same Paleocene-Eocene magmatic event is recognised, followed by discrete Late Oligocene-Early Miocene, Mid-Miocene, and Late Miocene magmatic episodes. In this segment of the Andes magmatism ceased in the Late Miocene, when the subduction angle shallowed beneath this region, which today constitutes the non-volcanic, “flat slab” segment of the Chilean Andes (Kay *et al.*, 1987; Sepúlveda *et al.*, 2015; Ramos and Folguera, 2016).

South of Santiago (33° S), where the dip of the Benioff zones is again steep (30°) Quaternary volcanism is widespread. No evidence of Paleogene magmatism has been recognized and Miocene volcanics directly overlie the Cretaceous sequences of the main Cordillera, where coeval Miocene granodioritic stocks intrude them (Rivano and Sepúlveda, 1991; Kay and Godoy, 2005).

3. Hydrothermal gold deposits

In general, in Chile, main gold producing deposits are hydrothermal (mainly epithermal) polymetallic in a broad geochemical sense with gold content being a minority participant respect to other metals like copper, silver and molybdenum among others. The higher economic value of gold, allow to consider them gold deposits (Kojima and Campos, 2011).

3.1. Mesozoic gold deposits

Several gold deposits formed during the Mesozoic time are important today. In the Andacollo mining district (Fig. 1, Table 1), immediately west of the Andacollo porphyry copper, separated by a NS trending normal fault, there are several volcanic hosted gold deposits of manto type and veins. The stratabound mantos located 1 to 3 km northwest of the Andacollo porphyry copper deposit are considered to be of contact metasomatic origin (Sillitoe, 1988). Gold mineralization (pyrite, chalcopyrite, sphalerite, galena and cinnabar) is disseminated in volcanic rocks with associated K feldspar alteration (Llaumett, 1980). The mantos are developed in felsic and intermediate volcanic rocks, with thickness between 10 to 20 m and 1 to 1.5 km length. A closely related predominantly EW oriented and steeply dipping vein swarm and range from centimetres up to 6 m wide with similar mineralization as the stratabound mineralization, is also present (Reyes, 1991).

Oyarzún *et al.* (1996) indicate that the fluid, which deposited the stratabound gold mineralization, was of moderate salinity and cooled from approximately 365° to 100°. This observation, combined with restoration of the deposits to their pre-faulting configuration, led the writers to conclude that the 91±6 Ma gold mantos (Reyes, 1991) are not derived laterally from the 100 Ma Andacollo porphyry system, but rather from a younger, concealed intrusive located vertically below the gold mantos. To the south of the Andacollo district, Los Mantos de Punitaqui (Fig. 1, Table 1) is a pluton-related vein deposit (Sillitoe, 1991) part of a Mesozoic batholith. Mineralization occurs as veins within a main shear zone and along northwest shear fractures. Gold is contained in a 3.5 km long quartz vein up to 25 m wide and known to a maximum depth of 350 m. Hematite, minor magnetite and chalcopyrite are intergrown in quartz veins with subordinate calcite.

In the Coastal Range of the Atacama-Coquimbo Region (26°-32° S), several vein type gold deposits are known: Faro, Costa Rica, Rescatada, Capote, Carrizal Alto, Burladora, Colluntua and Jote (Fig. 1). Henríquez *et al.* (1991) have classified these gold deposits as mesothermal. Gold deposits are mainly veins hosted in jurassic granitic and granodioritic intrusives or in cretaceous volcanic rocks without alteration halos. They can extend as far as 4 km in length, but the economic ore bodies tend to be 200 to 400 m in length reaching depths between 350 and 450 m. Main sulfide minerals are pyrite, chalcopyrite and arsenopyrite in a quartz gangue.

An equivalent setting is also known in the Central Chile coastal range (32°-36° S) (Gröpper, 2011; Camus, 2018) including several gold mining districts: El Bronce de Petorca, Alhué, Chancón and Las Palmas (Fig. 1, Table 1), among others less relevant.

The El Bronce de Petorca district (Fig. 1, Table 1) is composed by an epithermal low sulfidation vein system hosted by Cretaceous volcanic andesitic sequences (Camus *et al.*, 1991). Nearly 90 ore bodies, mostly polymetallic veins, some copper veins, and one copper breccia pipe have been recognized. A 1 km vertical zonation is described, with a barren upper part followed by sub economic gold plus base metals, then the main gold and base metals zone ending in a sub economic gold plus silver with no base metals lower zone. The most significant and productive ore deposit is the El Bronce vein, emplaced in a 7 km long, NS-N20E striking fault. Diverse lenticular,

structurally controlled ore shoots are detected along the fault, fluctuating from 100-600 m in length, 200-400 m in depth, and 1-20 m in width (Camus *et al.*, 1991). The vein mineralogy is composed of quartz, pyrite, sphalerite, galena, tetrahedrite, barite and calcite. Ore shoots occurs as massive sulfide fillings, stockworks and disseminations.

The Pullalli deposit (Fig. 1, Table 1) consists of fractured and faulted stratabound-like siliceous bodies in a Triassic dome complex intruded by Jurassic granites (Shatwell, 1999). The siliceous bodies are composed of microcrystalline and massive quartz and stockworks of quartz micro veinlets with disseminated pyrite and associated gold. Quartz-sericite and argillic alteration surrounds the siliceous bodies. Maksaev *et al.* (2007) classified this deposit as mesothermal.

Alhué (Fig. 1, Table 1) is another low-sulfidation epithermal vein district hosted andesitic rocks of Upper Cretaceous age intruded by a granodiorite of the same age (Camus, 1990; Moncada *et al.*, 2015). The ore bodies of this old district, exploited since the XIX siècle, occur as east-west sub vertical veins and consists of a central brecciated portion surrounded by a quartz veinlets stockwork that gradually diminishes in vein density outward. Alteration associated with mineralization is manly silicification, which grades outward into propilitic envelopes. Gold is mainly associated with quartz and pyrite with lesser chalcopyrite and sphalerite. Fluid inclusion studies indicate a vertical zonation with a deeper mesothermal character evolving to an upper epithermal zone (Quintana, 2018)

The Las Palmas is located in the coastal range of south central Chile (Fig.1, Table 1). It is low sulfidation epithermal gold vein district hosted by andesites and volcanic tuffs probably of Middle Jurassic age (Camus and Duhalde, 1982; Gröpper, 2011). Host volcanic rocks have been affected by a propilitic alteration associated with the emplacement of Upper Cretaceous intrusives. Several veins are identified, some of them with a length up to 1.5 km. Veins are mostly filled with quartz, chlorite, pyrite, sphalerite, galena, chalcopyrite and locally magnetite including quartz-sericitic alteration grading to silicification at depth.

Cerro Bayo-Fachinal district, in southern Chile (Fig. 1, Table1), is a low to intermediate sulfidation epithermal vein (0.5 to 5 m wide) and hydrothermal breccia (up to 1m wide) system (Wheeler, 1991; Boetsch, 2014) hosted by Jurassic rhyolite to

dacitic volcanic ash-flow/tuffs. Veins and breccias consists of quartz with disseminated pyrite, and a complex series of silver sulphosalts with free gold and silver. Minor amounts of sphalerite, lead sulfide and chalcopyrite are also recognized. Illite-smectite are the major alteration minerals in the district (Poblete, 2011). Los Domos is a prospect located nearby Cerro Bayo with similar characteristics (Equus Mining Ltd., 2017).

Skarns type deposits (Maksaev, 2005), are also part of the Mesozoic mineralization but none is known as important regarding its gold content. Several are mentioned as copper deposits (with only one case of a zinc-lead body) with gold as a by-product. Mainly located in the Coastal Range hosted by Lower Cretaceous carbonate rocks. From North to South, Lagarto near Iquique, San Antonio near La Serena, Panulcillo in the Coquimbo Region are IOCG type with some skarn development (Narváez and Aguirre, 2015; Castellón, 2017), Mantos Grandes in the Limarí Province, Cabildo in the Valparaíso Region, La Campana north of Santiago and El Toqui (Zn, Pb, Au) in the Chilean Patagonia are all examples of skarn type deposits with noticeable gold content.

A relevant characteristic for the Mesozoic is the abundance of gold and gold-copper veins many times described as mesothermal (Ruiz *et al.*, 1965; Boric *et al.*, 1990; Vivallo *et al.*, 2008; Camus, 2011; Gröpper, 2011; Arredondo *et al.*, 2017). Most of these deposits are less important regarding their size and unfortunately, information about tonnage-grade is often unknown. Additionally, the Jurassic-Early Cretaceous magmatic arc is characterized by a large variety of ore deposit types including mesothermal and epithermal gold, IOCG, porphyry copper as well as stratabound copper-silver deposits. This gave place due to its geographic location to a definition of a Costal Range Metallogenic Belt (Vivallo *et al.*, 2009). An interesting zonation and lineaments pattern for porphyry copper, IOCG, stratabound Cu-Ag and stratabound Au deposits was also suggested for this belt (Morel, 2009).

3.2. Cenozoic gold deposits

Most of the Cenozoic gold deposits seem to be related to eroded volcanic centres and/or sub volcanic intrusives (Davidson and Mpodozis, 1991) and all of them are part of discrete magmatic arcs, parallel to the current coastal line (Cabello, 1986, 1992).

The Paleocene-Eocene magmatic event started some 70 Ma ago, increasing in intensity during the Paleocene due to faster plate convergence (Pardo-Casas and Molnar, 1987). This magmatism is well exposed in northern Chile as a NS trending belt and these volcanic rocks host the Faride, San Cristóbal, Guanaco and El Peñón gold deposits (Fig. 1).

Faride is a low sulfidation epithermal gold-silver deposit located *ca.* 80 km north of the San Cristóbal Gold deposit (Fig. 1, Table 1). It is associated with an eroded volcanic centre (Camus and Skewes, 1991; Iriarte, 1993; Garofalo, 2009). Vein type ore bodies extend roughly 2 km, filling discontinuous portions of faults. The veins are oxidized and the hypogene mineralization below 200 m comprises specularite, chalcopyrite galena, sphalerite and copper-silver sulfosalts, while gangue minerals include quartz, barite, rhodochrosite and siderite with quartz-sericite envelopes around the veins.

San Cristóbal mesothermal gold deposit (Fig. 1, Table 2) (Eggert and Kasaneva, 1995) is hosted in a 54 Ma complex of felsic porphyries and granitoids intruded by a series of quartz porphyries and hydrothermal breccias (Maksaev, 1990). The deposit comprises low grade disseminated mineralization and gold bearing NS quartz veins up to 2 km long and 1 m average thickness associated with potassic, propilitic and phyllitic alteration. The bulk gold resource includes four ore shoots irregularly distributed forming a NW elongated body 1 km long, 300 m across and 200 m deep, which formed where the vein system crosses a sub volcanic complex.

Guanaco (Fig. 1, Table 1) is a high-sulfidation gold-copper district probably situated above a porphyry copper system and genetically related to a caldera with dacitic flows and domes (Puig *et al.*, 1988; Cuitiño *et al.*, 1988; Jovic *et al.*, 2015). The gold mineralization is contained in ledges of vuggy silica up to 50 m wide with sulphides which includes enargite, auriferous pyrite, arsenopyrite and sparse chalcopyrite (Vidal *et al.*, 2019). Ore bearing ledges are surrounded by advanced argillic alteration comprising alunite, pyrophyllite, kaolinite and dickite.

Discovered in 1994, El Peñón deposit is the largest gold-silver deposit associated with the Paleocene volcanic event. The deposit is a low sulfidation epithermal vein system genetically related with a Paleocene-age rhyolite flow dome complex (Arancibia *et al.*, 2006). The fault controlled mineralization has been K-Ar dated at 52 to 53 Ma (Warren *et al.*, 2008),

broadly coincident with the $^{40}\text{Ar}/^{39}\text{Ar}$ age of 53–51 Ma for vein adularia (Arancibia *et al.*, 2006). Gold-silver mineralization is associated with a variety of quartz vein textures and grain sizes. Chalcedonic to coarse-grained quartz occurs in banded, spheroidal, comb and bladed carbonate replacement vein textures. Hydrothermal breccias are common and constituted important structural preparation for vein formation. The oxidized zone of the deposit extends 250 to 280 m below the surface. Mineralogy consists largely of silver halides, native silver and electrum with a gangue of quartz, adularia, calcite, rhodochrosite, dolomite and other carbonate minerals (Bissig *et al.*, 2007). Trace amounts of sphalerite, galena and chalcopyrite are present below the oxidized zone. Some 10 km north of El Peñón, a high sulfidation gold porphyry system named El Anillo has been described (Marquardt *et al.*, 1994), associated to a younger episode of intrusive activity (48–42 Ma).

The Amancaya gold deposit is located south of El Peñón mine. It is a low sulfidation, epithermal deposit, hosted in a steeply dipping, structurally controlled, quartz vein (Altman *et al.*, 2017).

The Late Eocene-Early Oligocene period was characterised by a clear magmatic intensity decrease (McKee and Noble, 1990), immediately following initiation of the Upper Eocene compressive stage. During this period, several of the most important Andean porphyry copper deposits or districts were formed (*e.g.*, Collahuasi, Chuquicamata, Centinela, Escondida, El Salvador, Fig. 1.), associated with transcurrent north-south faults related to crustal weakness (Maksaev and Zentilli, 1988).

At least three high sulfidation gold deposits, apparently related to porphyry copper systems, of this age have been described:

El Hueso and Agua de la Falda-Jerónimo (Fig. 1, Table 1), both located close to the Potrerillos porphyry copper system (Colley *et al.*, 1989; Marsh *et al.*, 1997); and the Cantaritos prospect located in the vicinity of La Fortuna porphyry copper (Perelló *et al.*, 1996). At El Hueso Jurassic-Cretaceous limestones and silstones intruded by dacitic-andesite stocks and overlain by siliceous tuffs and breccias host the epithermal ore deposit. Much of the ore occurs as tabular and steeply dipping silicified zones in limestone and volcaniclastics. Agua de La Falda-Jerónimo is located 2 km East of El Hueso. Here stratabound gold and sulfide mineralization was mainly deposited in silicified calcareous sandstones

(Thompson *et al.*, 2004). Pyrite is by far the main sulfide mineral, but marcasite, arsenopyrite, sphalerite, galena, bournonite and pyrargirite are also found. In the Cantaritos prospect inland of Vallenar city, alunite-vuggy silica alteration occurs 1 km SE of the El Morro-La Fortuna copper-gold porphyry prospect (Fig. 1, Table 1). Advanced argillic alteration at Cantaritos has yielded a 32 Ma age, similar to that of the porphyry deposit (Salazar and Coloma, 2016). Two other small low sulphidation epithermal occurrences associated with volcanic rocks of the same age have also been reported: they are the Choja and Tinaja diatreme related prospects (not included in the location map), inland of the Iquique and Copiapo cities (Sillitoe, 1992).

Volcanic rocks of Upper Oligocene-Late Miocene age host some of the larger gold deposits. Volcanism of this period, was formed during a time of faster and less oblique plate convergence (Pilger, 1984). A shallowing subduction zone generated a greater width of the related volcanic arc, as well as of the associated mineralization (Sillitoe, 1992). Two types of gold deposits are in this magmatic belt: high sulfidation epithermal deposits in the so-called Maricunga and El Indio belts and porphyry gold deposits also occurring in the Maricunga region (Vila and Sillitoe, 1991). These gold deposits formed from 10 to 6.2 Ma (Bissig *et al.*, 2001; Sillitoe, 2008), after andesitic volcanism in the region had ceased (Kay *et al.*, 1999) and the magmatic activity had moved to the east (Bissig *et al.*, 2003). Volcanic rocks in both districts overly Upper Paleozoic granitic and felsic volcanic basement with clear evidence of crustal assimilation (Davidson and Mpodozis, 1991). Considering the tonnage and grade information available (Table 1) can be reported a gold content of 3,189 t for the Maricunga belt (14 deposits) and 1,310 t for the El Indio belt (4 deposits).

In the Maricunga belt, La Coipa (Fig. 1, Table 1) (Oviedo *et al.*, 1991; Gamonal *et al.*, 2015) is the most important gold-silver high sulfidation epithermal deposit formed between 19 and 14 Ma, including tabular and irregular bodies hosted by Triassic sedimentary rocks and Eocene-Oligocene stratovolcanic and dacitic-block rhyolite dome complexes (Kay *et al.*, 1999; Belanger, 2003; Callan, 2019). Another high sulfidation example is the Chimberos-Esperanza silver-gold deposits, also associated with dacitic dome complexes (Vila, 1991a; Lagos, 2010). Here exists a highly silicified, structurally localised hydrothermal

breccia containing high silver grades and minor gold values. A case related to a somehow recent discovery is the Volcán deposit (Lewis *et al.*, 2011), where mineralization is related to the emplacement of Miocene age calc-alkaline volcanic and sub-volcanic units over basement rocks of Paleozoic to Cenozoic age. The structural setting of the Volcán deposit (Fig. 1) is related to, and associated with, the Copiapó stratovolcano and may also be related to regional northerly-trending high angle reverse faulting. The gold deposit includes an arrangement of gold bearing quartz-pyrite veinlets with outer disseminated pyrite developed in argillic-silica altered tuffaceous and porphyritic dacitic volcanic rocks, as well as in dacitic dome complex. The most recent discovery of this prolific belt is the Salares Norte deposit, a high sulphidation epithermal system with pyritic sulfide mineralization, hosted by a breccia complex close to the contact of two volcanic domes of andesitic and dacitic composition (Brewer *et al.*, 2017). The ore is mainly oxidized gold mineralization.

La Pepa (Fig. 1, Table 1) is a high sulfidation vein and breccia hosted epithermal system with an associated low-grade porphyry style deposit, named Cavancha (Muntean and Einaudi, 2001). Predominant host rocks are dacites, dacitic tuffs and brecciated rhyolites. Alteration mainly corresponds to advanced argillic with dominant quartz and alunite replacements. Kaolin and halloysite crosscut both quartz and alunite. Gold mineralization is largely associated with pyrite, limonite, and minor enargite. Gangue minerals are quartz, alunite, barite and clays.

A distinctive feature of the Maricunga belt is the presence of several gold rich porphyry systems emplaced beneath andesitic stratovolcanoes and related with dioritic to quartz-dioritic porphyritic intrusives and vast hydrothermal alteration zones (Vila and Sillitoe, 1991; Muntean and Einaudi, 2001; Gamonal and Bissig, 2019; Naranjo *et al.*, 2019). They mainly include gold-(copper) mineralization in well-developed quartz stockworks. Iron oxides, both early magnetite and late hematite, constitute up to 10 percent of mineralized rocks. The Marte and Lobo deposits are classified as porphyry gold deposits but Refugio and Cerro Casale are closer to gold rich porphyry coppers (Vila and Sillitoe, 1991). A number of those porphyry systems present an overprint of advanced argillic alteration including quartz-alunite, pyrite, bornite, native sulphur and enargite (Vila, 1991b). Other new example is the

Caspiche gold-copper deposit (Fig. 1, Table 1) related to a dioritic stock beneath post mineral cover where most of the gold and copper (pyrite-chalcocite) was introduced during the potassic alteration stage partially overlapped by a molybdenum-rich halo. An upper advanced argillic alteration is also present (Sillitoe *et al.*, 2013). Cerro Maricunga, also known as Fenix (Fig. 1, Table 1), is another addition to this belt with gold mineralization in dacitic and andesitic intrusive domes restricted to a NW-SE strip with a porphyry and breccia complex limited by faults including pyrite-magnetite mineralized zones usually associated to black banded quartz veinlets (Easdon, 2010).

The El Indio belt (Fig. 1), is a 200-km long near continuous belt of hydrothermal alteration centers (Maksaev *et al.*, 1984; Siddeley and Araneda, 1990; Bissig *et al.*, 2002) preserved within a north-south graben system, controlled by high angle faults (Nasi *et al.*, 1990). The extended hydrothermally altered zones appear related to porphyritic stocks. Gold mineralization occurs in various styles: Vein systems (El Indio and Sancarrón), fault and hydrothermal breccias (Tambo) and stratabound deposits (Pascua). The El Indio (Fig. 1, Table 1) high -sulfidation precious metals deposits are characterised by sulfide -rich mineralization in two principal type of veins: those dominated by copper (mainly enargite), and those dominated by gold. The Tambo deposits are sulfate-rich and have native copper and free gold mineralization that is mainly contained in tectonic-hydrothermal breccias associated with alunite and barite (Jannas *et al.*, 1999). Alturas is a recently discovery in this belt, announced in 2015. Correspond to a pervasively oxidized disseminated high sulfidation epithermal gold deposit related to subvolcanic dacitic flows and domes as well as a diatreme complex including a shallow steam heated zone in a typical advanced argillic alteration. Mineralization appears associated to a silicification event. (Astorga *et al.*, 2017).

During the Upper Miocene time, in northern Chile (18° - 28° S) an important Miocene to Recent volcanic zone (Gardeweg and Ramírez, 1984) known as the Central Volcanic Zone developed. This zone was characterised by stratovolcanoes, calderas, and ignimbritic sequences with associated advanced argillic and solfataric hydrothermal alteration zones. These alteration zones could present important contents of native sulphur, exposed if the volcanic edifices have been eroded (Davidson and Mpodozis, 1991). Research on sulphur isotopes of the Copiapó volcano

(Zentilli *et al.*, 1988, 1991) suggests a correlation between solfataric alteration zones and precious metal epithermal systems. At least two gold occurrences are known to be associated with this Miocene magmatic arc. The main one is the Choquelimpie high sulfidation epithermal deposit (Fig. 1). Gold-silver mineralization occurs in veins and hydrothermal breccias hosted in an eroded dacitic-andesitic stratovolcano intruded by similar composition domes (Cabello, 1986; Gröpper *et al.*, 1991). The second case is the Pimentón mine located in the Andes cordillera of central Chile. Here epithermal high sulfidation gold veins are probably related to a porphyry copper system. Individual veins typically form ore shoots up to 450 m long, up to 50 cm wide, containing massive pyrite and chalcopyrite with a gangue of barite (Pardo, 2006; McGregor and Brady, 2016).

4. Placer gold deposits.

The first historic period of gold production in Chile was from 1541 to the end of the sixteenth century, when a series of gold rich alluvial deposits, mainly located in the central-south portion of the country, produced an estimated 1 or 2 metric tons of gold annually (Cuadra and Dunkerley, 1991). At that time, some of the main producing fields were Andacollo, Marga-Marga, Casablanca, Catapilco, Nirivilo, Lonquimay, Carahue and Madre de Dios. In the nineteenth century, alluvial gold was discovered in Tierra del Fuego (Río del Oro) in the far south of Chile with production for a period of about 40 years including some dredge operations. Chilean secondary gold deposits can be classified as alluvial, eluvial and beach placers (Ruiz and Peebles, 1988; Portigliati *et al.*, 1988; Greiner, 1991). Currently, placer gold mining in Chile is at a very low scale having almost no impact in the country production statistics.

5. Gold as a by-product of copper deposits.

From the 2019 reported mining production (Sernageomin, 2020), it is estimated that 64% of Chile's annual gold production can be attributed to by-product production from copper (largely) and lead-zinc deposits. The following copper deposits are known as important regarding their gold content and production:

The Iron Oxide-Copper Gold (IOCG) belt contains deposits as Mantoverde, La Candelaria, Atacama

Kozan and Punta del Cobre near the coastal range of the Atacama Region (Marschik *et al.*, 1997; Richards *et al.*, 2016). These deposits seem to be confined to a belt of early Cretaceous magnetite-apatite deposits of probable magmatic-hydrothermal origin and may be considered as copper-rich end member of these iron dominated deposits (Sillitoe, 1994, 2003; Vivallo, 2009). Hosted by Lower Cretaceous andesites and sedimentary sequences they appear to be associated to mid-Cretaceous dioritic to granodioritic plutons and their late stage differentiates (Marschik *et al.*, 2000). Orebodies are stratabound concentrations of magnetite, pyrite, chalcopyrite, and gold but also include stockworks, breccias, disseminations, veins and massive replacements by the same minerals. Gold content in these deposits varies between 0.05 to 0.6 g/t Au, with an estimated average of 0.2 g/t based on the 14 deposits here reported (Table 2). Regarding its total gold content the most important is Candelaria (65 t), followed by Mantoverde (52 t) and Cerro Negro (37 t).

At least some 34 porphyry copper deposits and/or districts of different ages are known to contain gold (Table 3). In spite of their mostly low gold content, due to their sometimes huge reserves, porphyry coppers represent a major source of gold in the Chilean Andes. The gold content of the Chilean porphyries has been only partially documented yet (Perelló and Cabello, 1989) but seems to be enough to realize their importance regarding the content of this precious metal. Previous studies mentioned as deposits with important gold content the cases of Andacollo (Llaumett *et al.*, 1975), Quebrada Blanca (Hunt *et al.*, 1983), El Salvador (Roschmann, 1979) and Potrerillos (Marsh *et al.*, 1997). According to the compilation presented in table 3, publicly reported average gold content varies between 0.01 to 0.7 g/t, resulting in 0.15 g/t average content for the 34 cases included. As in the Mesozoic case there are a few mentions of skarn type mineralization related to porphyry copper: they occur in the Centinela District at the Mirador deposit (Apablaza, 2015) as well as in Potrerillos and Escalones, but is not clear yet its influence in gold content for those deposits. Reviewing their gold total content, the first place is for El Teniente (513 t) (Camus, 2003) followed by El Morro-Fortuna District (490 t) (Perelló *et al.*, 1996, Lambert *et al.*, 2012) and Pampa Escondida (446 t) (BHP, 2018), all these cases are obviously influenced by their huge tonnage. The Esperanza and Escondida

porphyry copper deposits are mentioned as the current more important gold producer for this ore deposit type. Several other porphyry copper deposit including some recently discovered could have a gold content not known or publically reported yet: Radomiro Tomic, Ministro Hales, Escondida Norte-Zaldívar, Escondida Este, Vizcachitas, San Enrique-Monolito, La Huifa among others. Considering their important mineralized volumes, they could provide significant additional gold resources.

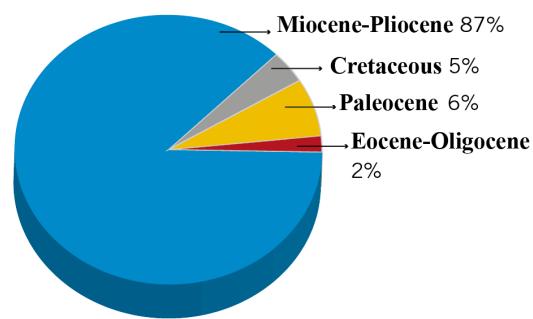
6. Gold mineralization: geological ages, ore deposit types, and mineral belts

The grade and tonnage for the different ore deposits considered in this work are presented in tables 1, 2 and 3. A note is made regarding the gold resources reported in this article: all is public information estimated to be valid at the time when obtained. Therefore, past mined gold statistics was not available for current or closed mines identified in this paper. Using this information was calculated the amount of gold concentrated during the different geological epochs and its relationship to the diverse ore deposit types both of precious and base metals (Figs. 2-7).

If we consider those (Table 1) defined as gold deposits group (31 cases), mainly epithermal precious metals deposits and porphyry gold, the gold concentrations are (Fig. 2): Mesozoic, 238 t (5%), Paleocene, 339 t (6%), Eocene-Oligocene 126 t (2%) and Miocene, 4,524 t (87%). Within the same group but according to the gold content in the different deposit types, the following distribution is obtained (Fig. 3): mesothermal 113 t (2%), epithermal LS 424 t (8%), epithermal HS 2,027 t (39%) and porphyry Au 2,663 t (51%).

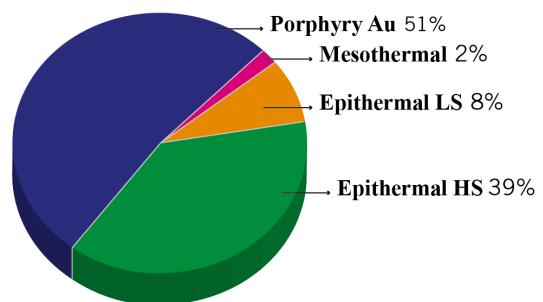
In the porphyry copper group (35 cases) the distribution of gold content is (Fig. 4): Mesozoic, 188 t (3%), Paleocene, 342 t (6%), Eocene-Oligocene, 3,842 t (63%) and Mio-Pliocene, 1,675 t (28%).

And if we take all 82 deposits types (this means those defined as gold deposits plus porphyry coppers and IOCG) the gold content distribution according the geological age is (Fig. 5): Mesozoic, 778 t (7%), Paleocene, 681 t (6%), Eocene-Oligocene, 3,968 t (34%) and Mio-Pliocene, 6,234 t (53%). But based on the deposit type, the following gold distribution is obtained (Fig. 6): gold deposits 5,227 t or 168 Moz (45%), IOCG 352 t or 11 Moz (3%) and porphyry copper 6,082 t or 195 Moz (52%).



Miocene-Pliocene	4,524 t
Paleocene	339 t
Cretaceous	238 t
Eocene-Oligocene	126 t

Fig. 2. Gold content (%) in different geological epochs and periods based on 31 main gold deposits (Table 1). Cretaceous 238 t (6 deposits), Paleocene 339 t (4 deposits), Eocene-Oligocene 126 t (2 deposits), Miocene 4,524 t (19 deposits).



Porphyry Au	2,663 t
Epithermal HS	2,027 t
Epithermal LS	424 t
Mesothermal	113 t

Fig. 3. Gold content (%) in different deposit types based on 31 main gold deposits (Table 1). Mesothermal 113 t (2 deposits), Epithermal LS 424 t (7 deposits), Epithermal HS 2,027 t (15 deposits), Porphyry Au 2,663 t (7 deposits).

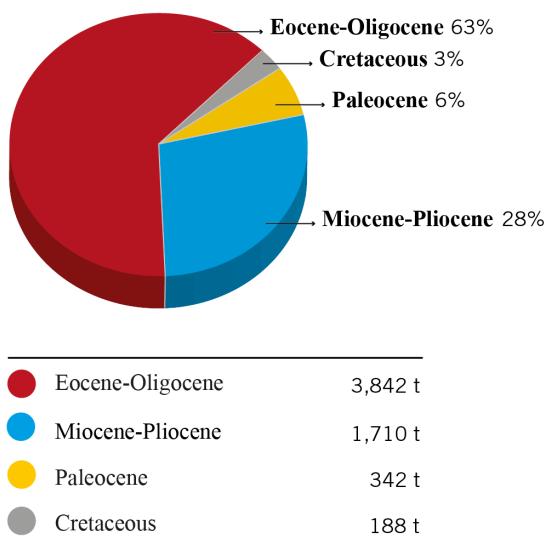


Fig. 4. Gold content (%) in different geological epochs and periods based on 35 porphyry Cu-Mo-Au deposits (Table 3). Cretaceous 188 t (4 deposits), Paleocene 342 t (4 deposits), Eocene-Oligocene 3,842 t (19 deposits), Miocene-Pliocene 1,710 t (8 deposits).

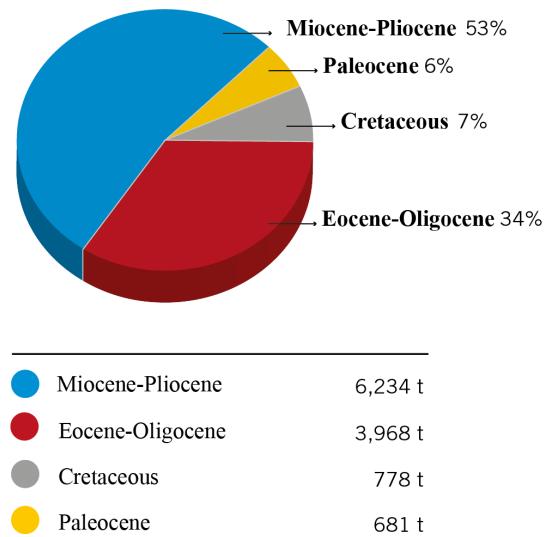


Fig. 5. Gold content (%) in different geological epochs and periods based on 82 deposits (Tables 1, 2, 3). Cretaceous 778 t (26 deposits), Paleocene 681 t (8 deposits), Eocene-Oligocene 3,968 t (21 deposits), Miocene-Pliocene 6,234 t (27 deposits).

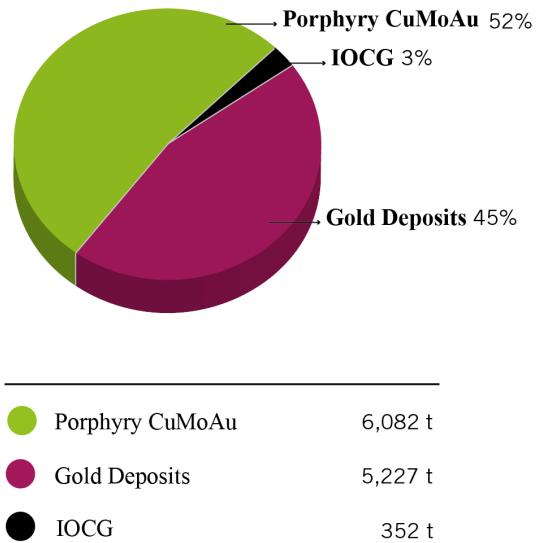


Fig. 6. Gold content (%) in different deposit types based on 82 deposits (Tables 1, 2, 3). Porphyry Cu-Mo-Au 6,082 t (35 deposits), Gold deposits 5,227 t (31 deposits), IOCG 352 t (16 deposits).

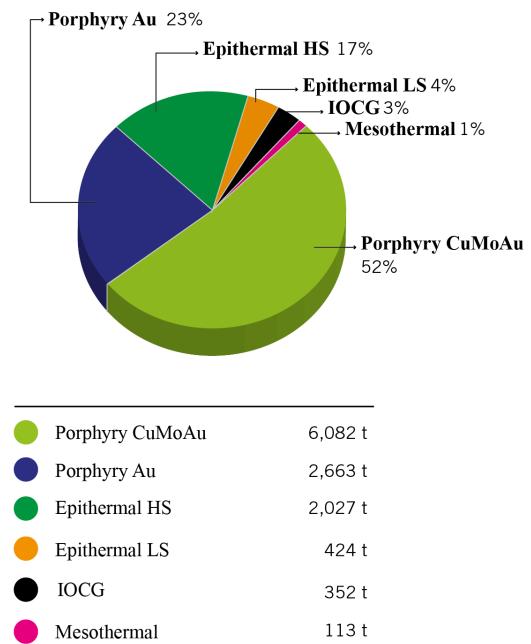


Fig. 7. Gold content (%) in different deposits type based on 31 main gold deposits (Table 1), 16 IOCG deposits (Table 2) and 35 porphyry Cu-Mo-Au deposits (Table 3). Mesothermal 113 t (2 deposits), Epithermal LS 424 t (7 deposits), Epithermal HS 2,027 t (15 deposits), Porphyry Au 2,663 t (7 deposits), IOCG 352 t (16 deposits), Porphyry Cu-Mo-Au 6,082 t (35 deposits).

And when compared (Fig. 7) all the ore deposit types in the 3 groups, the gold concentration is: Mesothermal 1% (113 t), epithermal LS 4% (424 t), epithermal HS 17% (2,027 t), Porphyry Au 23% (2,663 t), IOCG, 3% (352 t) and Porphyry Cu 52% (6,082 t). If we bring together Porphyry Au with Porphyry Cu, they represent 75% (8,745 t) of the gold concentration reflecting their metallogenic and economic relevance.

And all together represent an estimated number of 11,662 t equivalent to 375 Moz similar to a recent publication (Beard and Jowitt, 2019). And should be added that several potential gold bearing base metals deposits (both porphyry copper and IOCG) do not include their gold content in public format, therefore the number provided could be estimated conservative.

The Maricunga and El Indio are clearly the main gold belts in Chile. The Maricunga belt (Sillitoe, 2008) cover a length of approximately 200 km (between 26° and 28° S) with porphyry and high sulfidation epithermal gold deposits occurring in two partly overlapping NS remarkable belts where mineralization considered to be emplaced during two different episodes at 25-20 Ma and 15-13 Ma (Sillitoe *et al.*, 1991). In Maricunga are reported some 14 deposits (7 high sulfidation epithermal gold deposits and 7 porphyry gold), which in total represent 3,189 t of gold (approx. 103 Moz). Further south, the El Indio belt (Bissig *et al.*, 2015; Jara *et al.*, 2019) is about 100 km long (between 29° and 30° S). Gold deposits were formed between 9.5 and 5 Ma (Bissig *et al.*, 2001). No porphyry gold is yet identified here. El Indio belt includes 4 high sulfidation gold deposits as Pascua-Lama, the now historic El Indio, Tambo and the recent discovery of Alturas, accounting altogether for 1,310 t of gold or 42 Moz.

7. Exploration, development and production

In a review of the last five decades, the rate of growth of Chilean gold production is indeed impressive. In the period 1969-1998, gold production increased 27 times from 1,827 to 49,700 kg., after that, the level of production has been kept at a good level always above 35,000 kg per year. Several facts explain that increase of production, the most important being the success of exploration sustained over the same period (Cabello, 1999; Sillitoe, 1995, 2000, 2010).

This resulted in the discovery and development of several world-class deposits which account for a big part of the production increase.

Between 1969 and 1998, at least 18 precious metals discoveries were made. Of these, the most important and best known are El Indio mining district, La Coipa, Pascua, Refugio and Cerro Casale. These 18 discoveries collectively represented an in-ground resource of more than 1,763 t of gold.

In 1979, El Indio was the first of the new gold discoveries to become a mine. Of the 18 discoveries, 13 have been developed into mines. Of these, three were subsequently closed down (Choquelimpie, El Hueso and El Indio).

During the new siècle, the positive exploration trend has continued with several important discoveries like Volcán, Caspiche, Alturas and Salares Norte.

And parallel to these gold deposit discoveries happened important gold bearing copper deposit discoveries including both porphyry coppers and IOCG type deposits. All this is clearly reflected in the mining development and production statistics (Cochilco, 2010; Sernageomin, 2020).

Different technical reports mention future development for deposits like Salares Norte, Nueva Esperanza-Arqueros, Cerro Maricunga, Cerro Casale and Caspiche. Therefore, an increment of the country gold production is expected.

8. Concluding Remarks

The hydrothermal gold deposits in the Chilean Andes are closely associated with subduction related magmatic arcs. Due to its relationship with episodic magmatism migrating eastward, there is a general tendency for hydrothermal gold deposits to be in discrete NS trending belts presenting a progressive west to east decrease in mineralization age.

Excluding Andacollo, El Bronce de Petorca, Pullalli and Alhué, Mesozoic deposits are quite abundant but less relevant regarding their size and gold content. They are mainly vein deposits located in the coastal range and many of the mesothermal gold deposits are hosted in plutonic rocks. Erosion must be a factor to explain importance of intrusive rocks as host rocks with a genetically relationship with gold mineralization.

The Miocene high sulfidation epithermal and gold porphyry type deposits are the most important (La Coipa, Refugio, Cerro Casale, Pascua, El Indio)

suggesting a correlation with a faster and less oblique plate convergence. The same characteristic seems to have occurred in the Upper to Middle Eocene (El Guanaco, El Hueso, and Agua de La Falda-Jeronimo).

In general, the close correlation of Cenozoic gold deposits with volcanic centers and sub volcanic intrusives seems to be clear (Cabello, 1986, 1992; Davidson and Mpodozis, 1991). In addition, the relationship of the Cenozoic deposits with volcanic landform is quite evident in several cases (Choquemilpie, Volcán, Marte and Lobo). An association with dome complexes is reported in Guanaco, La Coipa, and Esperanza as well as in Pullalli and Choquemilpie. In El Guanaco, a caldera type structure is considered important (Puig *et al.*, 1988). El Indio is said to be associated with a caldera structure (Jannas *et al.*, 1990) or alternatively to an eroded stratovolcano (Sillitoe, 1991).

Erosion has an important influence in relation to the absence or presence of gold deposits (Camus, 1990; Sillitoe, 1991). As a rule, it can be pointed out that the level of erosion decreases from west to east in the Andes, explaining the scarcity or absence in the pre and post Miocene periods. In the first case, deep erosion has removed the volcanic edifices, and in the second case erosion has not been sufficient to unroof the potentially mineralized centers.

Gold bearing copper deposits constitute an important part of Chile's total gold production. Both IOCG type but especially porphyry copper are and will remain as significant sources to complement the future output of the gold deposits.

In summary, the 82 deposits with tonnage and grade studied represent gold content as follow: gold deposits 5,227 t or 168 Moz, IOCG 352 t or 11 Moz and porphyry copper 6,082 t or 195 Moz. And all together signify an estimated number of 11,662 t equivalent to 375 Moz. Moreover, should be added that a number of potential gold bearing base metals deposits (both porphyry copper and IOCG) do not include their gold content in public format, hence, the number provided could be estimated conservative. This figures support future maintenance of Chile's current gold production level as well as eventual important increases if undeveloped project come into production.

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