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MESOZOIC IOCG MINERALISATION IN THE CENTRAL ANDES: AN UPDATED REVIEW

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Abstract - The Mesozoic iron oxide-copper-gold (IOCG) mineralisation of the southern Perúvian and northern Chilean coastal belt has emerged as one of the major exploration targets in the Central Andes in the last two decades. These Mesozoic Andean IOCG deposits were formed during two mineralising epochs, i.e., Middle to Late Jurassic (170 to 150 Ma) and Early Cretaceous (130 to 95 Ma), with the major copper-rich IOCG deposits being confined to the Early Cretaceous belt. Early studies of some IOCG centres supported a magmatic-hydrothermal model for both copper-rich IOCG deposits and broadly contemporaneous copper-poor "Kiruna-type" iron-oxide-apatite magnetite deposits. However, more recent evidence from field investigations, geochronology, fluid inclusions and stable isotopes, show that in the major Central Andean deposits, e.g., Raúl-Condestable and Mina Justa in southern Perú, and La Candelaria-Punta del Cobre and Mantoverde in northern Chile, the incursion of evaporite-sourced basinal brines, or seawater, may be a prerequisite for economic copper mineralisation. Moreover, some of the copper-poor massive magnetite deposits could be interpreted as being the product of iron oxide melts, although many have been classified as magmatic-hydrothermal replacement without evidence of the involvement of external fluids. Therefore, the copper-rich IOCG and copper-poor massive magnetite deposits could represent different ore-forming process, although they may both be temporally associated with the same regional magmatism. Ore modelling for both the Middle to Late Jurassic and Early Cretaceous metallogenic epochs of the Central Andes is reconstructed.

Introduction

Iron oxide-copper-gold ("IOCG") mineralisation, first formally defined by Hitzman *et al.* (1992), has been a major exploration target since the discovery of the enormous Olympic Dam copper-uranium-gold (-REE) deposit in 1975. Following the identification of Proterozoic IOCG systems (e.g., these of the Gawler craton in South Australia, the Eastern Mount Isa block in Queensland and the northern Fennoscandian shield), the Central Andean orogen, and especially the volcano-plutonic arcs of Jurassic and Cretaceous age exposed in the Cordillera de la Costa of northern Chile and central and southern Perú, are now recognised as hosting major IOCG mineralisation, e.g., the Raúl-Condestable and Mina Justa deposit cluster in Perú (de Haller *et al.*, 2006; Moody *et al.*, 2003), and La Candelaria-Punta del Cobre and Mantoverde in Chile (Ryan *et al.*, 1995; Vila *et al.*, 1996).

IOCG-style deposits are defined primarily by an abundance of magnetite and/or hematite, although the complexity in morphology, metal endowment, tectonic setting, temporal and spatial relationships with granitoids, and particularly, alteration facies, have resulted in uncertainty in the ore-genetic modelling. This directly reflects the controversy regarding the source of mineralising fluids and mechanisms of ore formation of IOCG systems (Hitzman, 2000; Williams *et al.*, 2005 and references therein). Proximity to granitoid intrusives, intense high-temperature hydrothermal alteration, and extensive hydrothermal brecciation have been interpreted by many (e.g., Sillitoe, 2003; Pollard, 2006) as supporting a direct genetic relationship between IOCG deposit development and hydrous fluid exsolution from crystallising silicate melts, with the abundance of iron, copper, gold and, locally, cobalt being ascribed to a mafic parental magma. Such essentially magmatic-hydrothermal models prompt analogies with, particularly, molybdenite-poor porphyry copper-gold deposits, the vast majority of which are magnetite-rich (e.g.,Ulrich *et al.*, 2002; Pollard *et al.*, 2005). In contrast, Barton and Johnson (1996, 2000, 2004) argue that the global geological and palaeogeographic setting and evolution of IOCG systems imply that the incursion of "exotic", in part evaporite-sourced, brines is essential to economic copper (-gold) mineralisation. A commodious classification which incorporates magmatic and non-magmatic hydrothermal fluid origins has been recently advocated for IOCG deposits by Williams *et al.* (2005) and updated by Hunt *et al.* (2007). A radically different perspective on the genesis of IOCG mineralisation is provided by the proposal that the majority of magnetite-dominated, so-called "Kiruna-type" (Geijer, 1931), deposits are the product of silica-poor, iron oxide-rich melts (e.g., Nyström and Henríquez, 1994; Naslund *et al.*, 2002; Henríquez *et al.*, 2003). The contribution of oxide melts to IOCG genesis remains controversial (cf. Rhodes *et al.*, 1999; Sillitoe and Burrows, 2002, 2003), while recent classification has precluded the major "Kiruna-type" magnetite deposits from the "IOCG continuum" (Sillitoe, 2003; Williams *et al.*, 2005).

The Andean Mesozoic IOCG centres are hosted by subduction-related, intermediate volcano-plutonic complexes and/or sedimentary strata, and range from the magnetite-dominant systems at Marcona-Pampa de Pongo in Perú (Hawkes *et al.*, 2002) and the Chilean Iron Belt in Chile (Naslund *et al.*, 2002), to productive copper (-gold) deposits, such as those of the Candelaria-Punta del Cobre and Mantoverde districts in northern Chile (Ryan *et al.*, 1995; Vila *et al.*, 1996; Benavides *et al.*, 2007) and the Raúl-Condestable-Mina Justa belt in southern Perú (Sillitoe, 2003; de Haller *et al.*, 2006). The geological setting of Mesozoic IOCG centres in southern Perú and northern Chile provides a unique context for the clarification of the processes involved in the genesis of IOCG deposits in a convergent plate tectonic environment which would point to a direct connection between IOCG-ore forming processes and

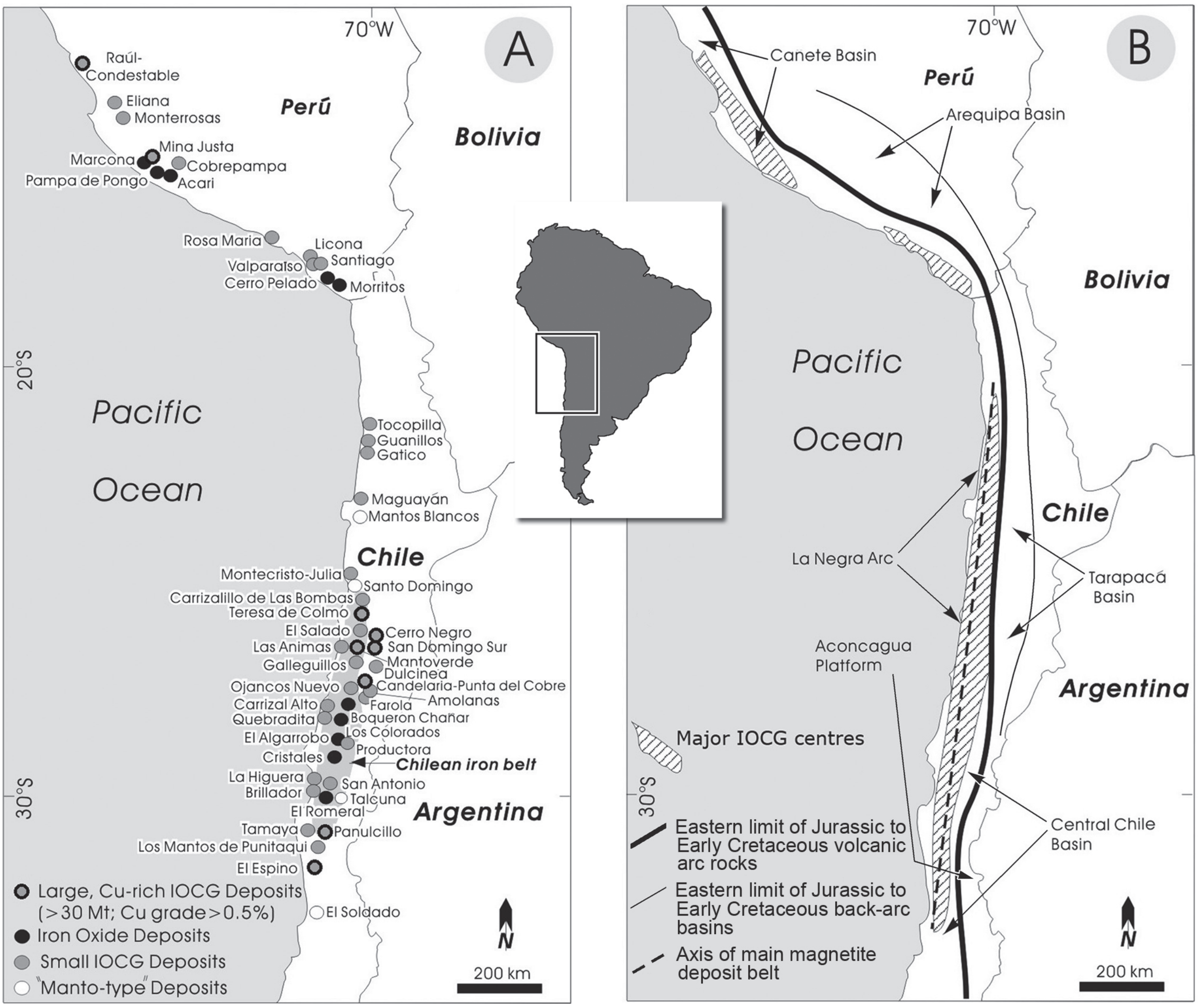

Figure 1: **A** - Locations of the Cu-rich IOCG, principal iron and manto-type deposits in Perú and Chile (from Clark *et al.*, 1990; Hawkes *et al.*, 2002; Maksaev and Zentilli, 2002; Sillitoe, 2003; Oyarzun *et al.*, 2003 and Benavides *et al.*, 2007). **B** - Position of the Central Andean IOCG belt of northern Chile and southern Perú (from Sillitoe, 2003).

tholeiitic to calc-alkaline, subduction-related magmatism (Vila *et al.*, 1996; Marschik and Fontboté, 2001; Rhodes and Oreskes, 1999; Sillitoe, 2003; de Haller *et al.*, 2006). These authors have argued that the mineralising processes are primarily associated with hydrothermal fluids exsolved from dominantly dioritic to gabbroic plutons, and channelled by major ductile to brittle fault systems. A SiO_2-poor and Fe-rich melt origin for the major iron oxide deposits has been precluded (Rhodes and Oreskes, 1999; Sillitoe and Burrows, 2002, 2003), and the involvement of external fluids in major Andean IOCG systems either not considered or only attributed a minor role (Marschik and Fontboté, 2001; Sillitoe, 2003; de Haller *et al.*, 2006). However, field evidence and more recent data from fluid inclusions and stable isotopes have confirmed that the magnetite-dominant deposits (e.g., Marcona, Chilean Iron Belt and El Laco) may have an iron-oxide melt origin (Nyström and Henríquez, 1994; Naslund *et al.*, 2002; Henríquez *et al.*, 2003; Chen, 2008), while the intervention of exotic fluids, e.g., seawater or evaporate-derived basinal brines, play an important role in the generation of copper (-gold) mineralisation in the Raúl-Condestable (Ripley and Ohmoto, 1977; de Haller *et al.*, 2002), La Candelaria (Ullrich and Clark, 1999; Ullrich *et al.*, 2001), Mantoverde (Benavides *et al.*, 2007) and Mina Justa (Chen, 2008), representing four major currently productive IOCG deposits in the Central Andes.

Regional Geological Setting

The Central Andean IOCG deposits lie in a linear array of interconnected Mesozoic continental margin rift basins (Fig. 1; Atherton *et al.*, 1983; Mpodozis and Ramos 1990), which record a major phase of extension (Atherton and Aguirre, 1992; Mpodozis and Allmendinger, 1993) accompanying subduction along the western margin of Gondwana, prior to supercontinent breakup and the major Cenozoic compressive episodes and crustal thickening which generated the Andean Cordillera (Benavides-Cáceres, 1999; Ramos and Alemán, 2000). In the Coastal Cordillera of northern Chile and southern Perú, major Mesozoic plutonic complexes were emplaced into broadly contemporaneous arc and intra-arc volcanic rocks and underlying deformed Palaeozoic metasedimentary units. The volcanic arc is underlain by high-grade metamorphic rocks of the Mesoproterozoic Arequipa-Antofalla Massif (Shackleton *et al.*, 1979; Wasteneys *et al.*, 1995) which were accreted onto the Amazonian Craton at ca. 1.0 Ga (Loewy *et al.*, 2004). Extensive longitudinal brittle fault systems and ductile shear zones, including the Atacama Fault System in northern Chile (Scheuber and Andriessen 1990) and deeply penetrating faults that are located in the Cañete basin in Perú, e.g., the Treinte Libras fault system (Caldas, 1978; Atherton and Aguirre 1992), were active during the Mesozoic volcanism and plutonism.

The most voluminous units hosting the Andean IOCG mineralisation are Middle Jurassic to Lower Cretaceous volcanic products generated in the arc and aborted marginal back-arc basins, e.g., the Río Grande-Chala Formations in the Cañete-Arequipa basin in southern Perú (Caldas, 1978; Romeuf *et al.*, 1993), and the La Negra-Punta del Cobre Formations adjacent to the Tarapacá basin in northern Chile (Boric *et al.* 1990; Sillitoe, 2003). Both of these units comprise basaltic-andesitic to andesitic lava flows, with subordinate volcaniclastic and marine sedimentary units (Aguirre, 1988; Sillitoe, 2003), while the Perúvian formations may have a medium- to high-K calc-alkaline affinity (Aguirre, 1988; Romeuf *et al.* 1995). These volcanic units commonly exhibit low-grade, non-deformational hydrothermal-burial metamorphism (Aguirre, 1988; Atherton and Aguirre, 1992). The Middle to Upper Jurassic units in this succession, which host the major IOCG deposits, e.g., Mantoverde and Mina Justa, were intruded by gabbroic plutons and dykes (Atherton and Webb, 1989; Pichowiak *et al.* 1990), and then, from the Early Cretaceous, by the enormous dioritic to tonalitic Coastal Batholith (Pitcher and Cobbing, 1985; Grocott and Taylor 2002; de Haller *et al.*, 2006), which probably formed through wrench tectonics along the crustal lineaments associated with oblique subduction (Polliand *et al.*, 2005). However, the Early Cretaceous volcanism, while being broadly contemporaneous with the Coastal Batholith plutons, also hosts major IOCG mineralisation, e.g., the Punta del Cobre Formation which contains the La Candelaria-Punta del Cobre deposits (Marschik and Fontboté, 2001).

Central Andean IOCG Mineralisation

Volumes, Grades and Epochs

The Perúvian IOCG belt (Fig. 1), which is approximately 70 km wide and extends discontinuously for 800 to 1000 km along the Perúvian littoral from Lima to the Ilo-Ite area (Clark *et al.*, 1990; Hawkes *et al.*, 2002; Injoque, 2002), developed in the Cañete Basin in the north, and along the axis of the Jurassic to Cretaceous shallow-marine volcano-plutonic arc to the south. Ore deposits and mineral occurrences in this belt that may be classified as IOCG-style include Raúl-Condestable, Eliana, Monterrosas, Mina Justa, Cobrepampa, Rosa María, Licona, Valparaïso and Santiago. Associated sulphide-bearing magnetite deposits include Marcona, Pampa de Pongo, Acarí, Cerro Pelado and Morritos (Clark *et al.*, 1990; Hawkes *et al.*, 2002;

Table 1: Tonnages, grades and ages of selected Mesozoic IOCG and related deposits in the Central Andes.

Deposit	**Tonnage** (Mt)	**Fe** (%)	**Cu** (%)	**Au** (g/t)	**Ag** (g/t)	**Mineralisation age**	**Data source**
Peruvian Coastal Belt:							
Raúl-Condestable	>32	ne	1.7	0.3	6.0	116-113	de Haller *et al.*, 2006
Eliana	0.5	ne	2.7	0.9		114-112	Injoque, 2002
Monterrosas	1.9	ne	1.1	6	20	~115	Injoque, 2002
Marcona [1]	~1940	55.4	0.12	trace		162-156	Shougang Hierro Perú SA., 2003; Chen *et al.*, *in press*
Mina Justa	347	ne	0.71	0.03	3.83	104-95	Chariot Resources, 2006; Chen *et al.*, *in press*
Pampa de Pongo [1]	953	44.7	trace			<109	Cardero Resource Corp., 2005
Rosa María						160 (145)	Clark *et al.*, 1990
Chilean Coastal Belt:							
Mantos Blancos [2]	500	ne	1.0			~140	Ramírez *et al.*, 2006
Tocopilla	2.4	ne	3.1	trace		~165	Ruiz and Peebles, 1988
Julia						~164	Boric *et al.*, 1990
Chilean iron belt [1,3]	2000	60	trace			130-110	Oyarzun *et al.*, 2003
Teresa de Colmo	70	ne	0.8	trace			Hopper and Correa, 2000
Cerro Negro	249	ne	0.4	0.15			Sillitoe, 2003
Mantoverde [4]	400	ne	0.52	0.11		117-128	Benavides *et al.*, 2007; Vila *et al.*, 1996
Santo Domingo Sur	140	ne	0.59				Far West Mining Ltd. 2007
Las Animas						~162	Gelcich *et al.*, 1998
Candelaria	470	ne	0.95	0.22	3.1	110-116	Marschik and Fontboté, 2001
Punta del Cobre	>120	ne	1.5	0.2-0.6	Zn	110-117	Marschik and Fontboté, 2001
Productora	30-70 m[5]	ne	0.3-0.6	trace	U, Co	~130	Ray and Dick, 2002
Panulcillo	~15	ne	~ 1.45	≤ 0.1		~115	Hopper and Correa, 2000
El Espino	30	ne	1.2	0.15		~108	Sillitoe, 2003
El Soldado [2]	>200	ne	1.4			~108	Boric *et al.*, 2002

[1] assigned as "Kiruna-type" deposit; [2] classified as a hematite-rich hydrothermal breccia deposit or manto-type; [3] including five large deposits (200 to 400 Mt), viz. Boquerón Chañar, Los Colorados, Algarrobo, Cristales and El Romeral; and many small deposits with 20 to 100 Mt; [4] Hypogene protore; [5] mineralised drill core intersection; ne: not economic

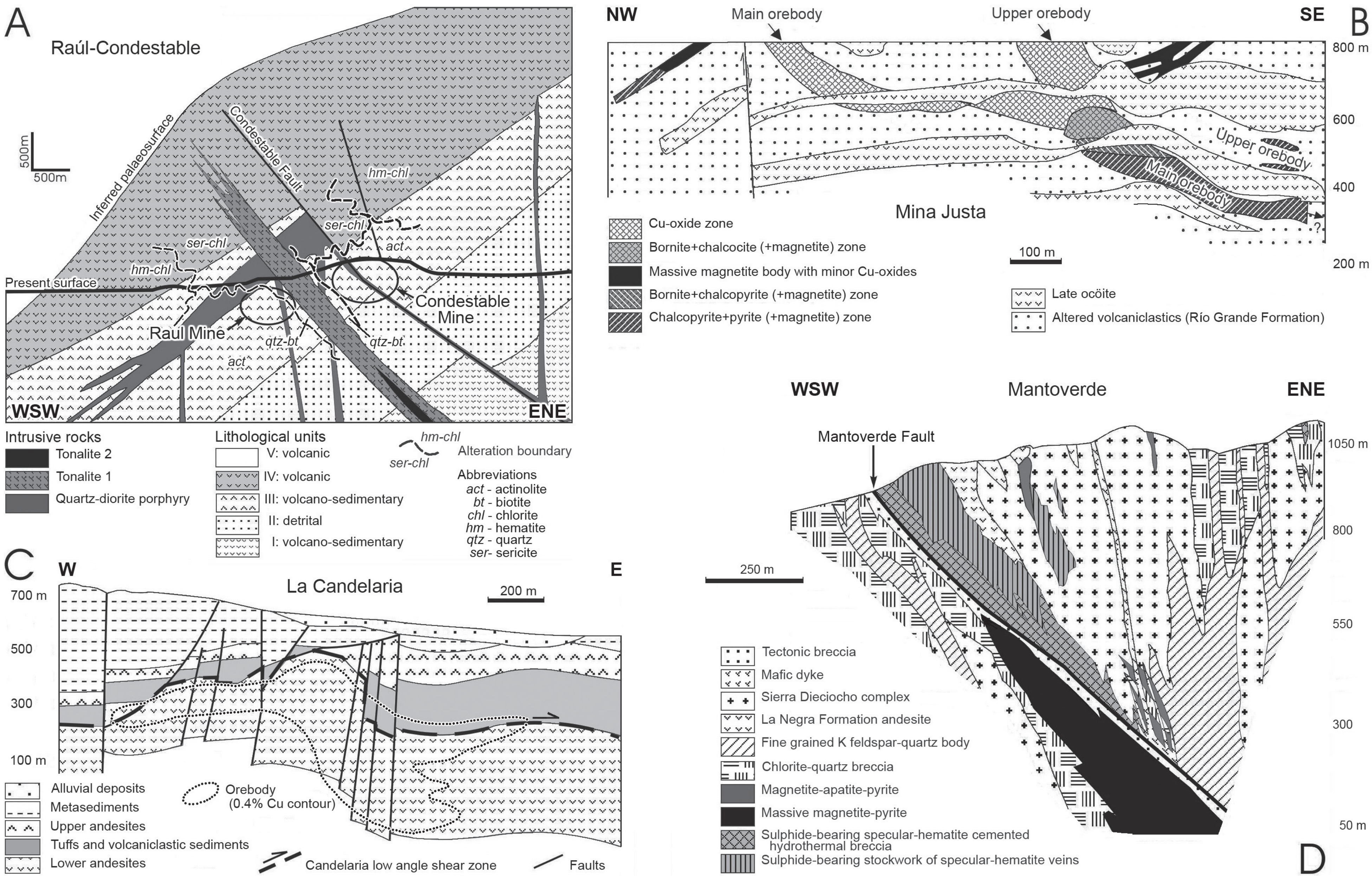

Figure 2: Geological sections of major IOCG deposits in the Central Andes. **A** - Raúl-Condestable Cu-Au deposit, Perú (de Haller *et al.*, 2006); **B** - Mina Justa Cu (-Ag) deposit, Perú (Chen, 2008); **C** - La Candelaria Cu-Au deposit, Chile (Arévalo *et al.*, 2006); **D** - Mantoverde Chile Cu (-Au) deposit (Benavides *et al.*, 2007).

Sillitoe, 2003; Fig. 1). Of these, the newly-discovered Mina Justa copper (-silver) prospect is the largest example of copper-rich IOCG mineralisation (Table 1), with an indicated resource of 346.6 Mt at an average grade of 0.71% Cu, ~3.8 g/t Ag and ~0.03 g/t Au at a cut-off grade of 0.3% Cu, and an inferred resource of 127.9 Mt at 0.6% Cu (Mining Journal, Nov. 24, 2006, p. 8). Located at 15°10'S, 75° 5'W, the deposit was discovered by Rio Tinto Mining and Exploration and is under development by Chariot Resources. The Marcona magnetite mine, which is some 3 to 4 km southwest of Mina Justa, has current reserves of 1551 Mt at 55.4% Fe and 0.12% Cu, and represents the largest known concentration of high-grade magnetite ore in the central Andes (Table 1).

The IOCG-style deposits in northern Chile, which are mainly between latitudes 22 and 31°S (Fig.1), are controlled by the regional Atacama Fault system, and are largely hosted by the arc volcanics of the La Negra and Punta del Cobre Formations and their stratigraphic equivalents (Sillitoe, 2003). Two major copper-rich IOCG deposits, La Candelaria and Mantoverde, which each contain over 400 Mt of economic grade (0.7 to 1% Cu) mineralisation, together with other smaller IOCG-style occurrences, e.g., the recently tested Santo Domingo Sur prospect (Table 1), make northern Chile one of the world's most productive IOCG provinces. Broadly contemporaneous, and possibly related mineralisation in this belt include the Chilean Iron Belt (CIB) magnetite deposits and the "manto-type" copper deposits, e.g., Mantos Blancos and El Soldado (Fig. 1 and Table 1).

The principal IOCG-style deposits in northern Chile and southern Perú were mainly generated in the Middle to Late Jurassic (170 to 150 Ma) and Early Cretaceous (130 to 95 Ma) epochs (Table 1; Sillitoe, 2003 and references therein). The Middle to Late Jurassic deposits are located near the Pacific coast, west of the Early Cretaceous belt. In southern Perú, the large sulphide-bearing Marcona magnetite deposit in the Marcona district (162 to 156 Ma) and copper-rich Rosa María prospect in the Cocachacra district (ca. 160 or 145 Ma; Clark *et al.*, 1990) are assigned to this metallogenic epoch. In northern Chile, Middle to Late Jurassic IOCG-style deposits include the copper-rich Tocopilla (165±3 Ma), Guanillos (167±7 Ma), Naguayán (153±5 Ma), Montecristo-Julia (164±11 Ma; Boric *et al.*, 1990) and Las Animas (162±4 Ma; Gelcich *et al.*, 1998). However, most of the major IOCG (e.g., Mina Justa, Mantoverde and La Candelaria), magnetite associated (e.g., Pampa del Pongo, Acarí and those of the CIB) and some "manto-type" copper deposits (e.g., El Soldado) are located farther east in the Coastal Cordillera and are Early Cretaceous in age. Copper-rich IOCG-style deposits in this epoch include Raúl-Condestable (116.5 to 113 Ma), Eliana (114 to 112 Ma), Monterrosas (115 Ma; Injoque, 2002), Mina Justa (104 to 95 Ma) in southern Perú, and Candelaria (116 to 110 Ma), Mantoverde (128 to 117 Ma), Panulcillo (115±3 Ma), El Espino (108±3 Ma) and Productora (130 Ma) in northern Chile (Fig. 1 and Table 1).

Salient Features of the Major IOCG Deposits in the Central Andes

The major Andean copper-rich IOCG-style deposits share many characteristics. Four that are well documented, are selected for comparison in this paper (Table 2; Fig. 2). They are Raúl-Condestable and Mina Justa in southern Perú, and Mantoverde and La Candelaria-Punta del Cobre in northern Chile.

These four major Central Andean IOCG deposits were all formed in the Early Cretaceous, between 130 and 95 Ma (Table 2), with a relatively concentrated period bracketing the main copper (-gold) mineralisation stages (120 to 95 Ma), although the intense hydrothermal activity at Mina Justa is a little younger than the mineralisation in the other three centres (i.e., ~15 Ma; Table 2). The economic copper (-gold or -silver) orebodies are hosted by Middle Jurassic to Lower Cretaceous basaltic-andesite and andesite, i.e., the ~160 Ma La Negra and Río Grande Formations at Mantoverde and Mina Justa respectively, while the ~130 Ma Punta del Cobre and Copara Formations are the corresponding hosts at La Candelaria and Raúl-Condestable. Syn-mineralisation plutons, mainly comprising granodiorite, tonalite, quartz-diorite and monzogranite, have been identified in all four centres, outcropping either in the zone of mineralisation (e.g., La Candelaria and Raúl-Condestable), or within the surrounding district (e.g., Mantoverde and Mina Justa; Table 2).

The orebodies at each of these deposits are clearly controlled by regional north- or northwest-trending strike-slip or normal fault systems, e.g., the Atacama Fault System in northern Chile and the Treinte Libras fault system in southern Perú. On a local scale at Candelaria, a low-angle, east-dipping, extensional shear zone controls the distribution of mineralisation and the morphology of the orebodies (Fig. 2C and Table 2). The mineralisation is dominated by hydrothermal breccias and veins, locally occurring as massive ore, together with magnetite. At Mina Justa, the mineralised bodies characteristically incorporate a massive magnetite-sulphide core, enclosed within hydrothermal breccias composed of strongly altered host rock clasts in a magnetite+sulphide matrix. These breccias are in turn surrounded by an extensive zone of stockwork veining (Chen, *et al.,* 2010), which exhibits textural relationships similar to those in the main orebodies at Olympic Dam in Australia (Robert and Hudson, 1983).

Distinct alteration and mineralisation zonation patterns were developed in most Andean IOCG deposits, e.g., at Mantoverde, the main copper orebody overlaps the deeper massive magnetite-dominated part of the deposit located in the lower plate of the ore-controlling Mantoverde fault (Fig. 2D). With or without magnetite, the main copper (-gold) mineralisation commonly postdates albite, biotite-magnetite (e.g., La Candelaria) and magnetite-actinolite alteration (e.g., Mina Justa) which are generally copper and gold (-silver)-barren (Fig. 3). The major hypogene copper-sulphide mineral in these deposits is chalcopyrite, although it may be locally dominated by bornite and chalcocite, e.g., at Mina Justa, where the major sulphides are zoned upwards, and locally laterally outward, from pyrite-chalcopyrite to bornite-chalcocite (±digenite), accompanied by an increase in copper grade (Fig. 2B). Hematite is identified in association with copper (-gold) mineralisation in all Andean IOCG-style deposits and plays an important role in both the Mina Justa and Mantoverde mineralisation systems (Fig. 3). Other major gangue minerals in the copper (-gold) stage include calcite, quartz and locally actinolite (e.g., at La Candelaria).

Compared to magmatic-hydrothermal fluid-derived porphyry copper-gold systems, the ore-forming fluids of the copper-gold mineralising stages of the major Andean IOCG deposits had a much wider and lower temperature range, i.e., 450 to 85°C (Table 2), and were apparently cooler than the early magnetite-dominated stages. $\delta^{34}S$ values of fluids for magnetite alteration stages are commonly between 0 and 5‰ which indicates a direct magmatic source (Fig. 4).

Table 2: Salient features of the major Central Andean copper-rich IOCG-style deposits

Deposit	Raúl-Condestable [1]	Mina Justa [2]	Mantoverde [3]	La Candelaria – Punta del Cobre [4]
Magmatism that is broadly coeval with mineralisation	*Coastal Batholith (~115 Ma)*: quartz diorite porphyry, tonalite (Y)* *Volcanic rocks (~115 Ma)*: Casma Formation - calc-alkaline dacitic to andesitic flows	*Acarí Pluton* (*~110 Ma*): Granodiorite, tonalite, porphyritic dacite (N)* *Volcanic rocks* (*<110 Ma*): upper Copara Formation	*Las Tazas Pluton* (*~130 Ma):* granodiorite (Y)*; *Sierra Dieciocho pluton* (*~120 Ma)*: quartz-diorite (N) *Volcanic rocks* (*~130 Ma):* Intramineral andesitic and dacitic dikes, Punta del Cobre Formation	*San Gregorio Pluton (~112 Ma)*: monzogranite (Y)* Intramineral dacite porphyry dike (Y)*
Host rocks	Copara Formation (*~130 Ma)*: basalt, basaltic andesite and andesite	Upper Rio Grande Formation (*~160 Ma)*: andesite and volcanic sediments	La Negra Formation (≥ *150 Ma*): andesite	Punta del Cobre Formation (*~130 Ma)* : andesite
Age of mineralisation	*ca.* 115 Ma (titanite-magnetite stage)	101-104 Ma (Magnetite-pyrite stage) 95-99 Ma (Cu stage)	126-130 Ma (magnetite stage) 118-120 Ma (part of Cu stage)	Initiated at > 125 Ma *(at Punta del Cobre)* 112 - 115 Ma (main ore stage)
Structures	Regional NW-striking normal faults; orebodies (veins) controlled by NW and NE-striking normal (?) faults	Regional NW-striking strike-slip faults; orebodies are controlled by extensional normal faults	N (or NW)-striking strike-slip Atacama fault	N (or NW)-striking strike-slip Atacama faults; orebodies controlled by low-angle E-dipping extensional Candelaria shear
Alteration/mineralisation zonation and style	Lateral; breccias and veins	Upward and lateral; breccias and veins	Upward; breccias and veins	Not clear, but hematite to south; breccias and veins
Alteration types **	(1) biotite alteration (2) magnetite-actinolite / or chlorite-sericite alteration (3) Cu-mineralisation with/without magnetite and hematite	(1) Na and K-Fe metasomatism (2) actinolite (-magnetite) alteration (3) Potassic alteration with magnetite-pyrite mineralisation (4) Cu mineralisation with calcite-hematite	(1) albitisation (not in mine area) (2) K-feldspar-magnetite alteration (3) Chlorite-sericite-scapolite-pyrite alteration (4) Hematite-chalcopyrite-calcite	(1) Na-metasomatism (2) biotite-magnetite alteration (3) main-stage Cu mineralisation with magnetite and amphibole alteration (Ca-metasomatism) (4) Hematite-calcite-chalcopyrite
Relationship between iron oxides and Cu (-Au) mineralisation	Cu-Au mineralisation partially associated with magnetite/hematite	Cu-mineralisation clearly later than magnetite-pyrite stage	Cu-mineralisation clearly later than magnetite stage;	Main-stage Cu-Au mineralisation is closely associated with magnetite, but followed main Fe metasomatism. Minor late hematite-Cu sulphide veins
Mineralisation assemblage	cp-py-po-qtz±mt	cp-bn-cc-cal-hm	cp-hm (-cal-qtz)	cp-po-qtz-amph±mt
Mineralisation conditions	320-360°C; CO_2-?	85-200 (av. 140)°C, CO_2-poor	150-360 (av. 240)°C; CO_2-poor	300 - 450°C; CO_2-rich
Ore-forming fluid compositions (including iron oxide stage)	Magmatic hydrothermal fluids for magnetite stage; external high-salinity, high $\delta^{34}S$ fluids (seawater or basinal fluids) involved in Cu-mineralisation	Magmatic hydrothermal fluids for magnetite stage; external low-temperature, high-salinity, Cu-Ca-rich, and high $\delta^{34}S$ fluids (basinal fluids) dominant at Cu-mineralisation stage	Magmatic hydrothermal fluids for magnetite stage; external low-medium temperature, high $\delta^{34}S$ fluids (basinal fluids) dominant at Cu-mineralisation stage	Magmatic hydrothermal fluids for early magnetite-biotite stage; low-medium temperature, Ca-rich, high $\delta^{34}S$-value fluids (basin brines) involved increasingly in Cu-mineralisation stage
Mineralisation mechanism	Fluid mixing (as at Olympic Dam); and hydrothermal replacement of host rocks	Cu-rich fluid replacement of early magnetite-pyrite bodies	Cu-rich (?) fluid mixing with magmatic fluids, and replacement of early magnetite stage	Fluid mixing (similar to Olympic Dam); and hydrothermal replacement of host rocks
Possible Cu source	Evidence of magmatic source	No evidence of magmatic source	No evidence of magmatic source	Clear evidence for magmatic contribution
Relationships to other deposits	Small Cu-rich IOCG deposits	Giant IO (Marcona); small IO and Cu-rich IOCG deposits	Small Iron oxide and Cu-rich IOCG deposits	Small Iron oxide and "manto-type" Cu (-Ag) deposits
Common features	(1) Regional strike-slip fault system (with local extensional faults controlling the orebodies); (2) hosted by low-grade metamorphic volcanic or volcanic-sedimentary rocks (partly Cu-rich); (3) commonly associated with small iron oxide deposits; (4) Cu-mineralisation emplaced during the 95-120 Ma interval.			

(Y)*: in the immediate mine area; (N): not in the immediate mine area; (?) indicate no enough evidence; ** numbers indicate the approximate paragenesis sequence. Sources: [1] de Haller *et al.*, 2006; [2] Chen, 2008; [3] Benavides *et al.*, 2007; [4] Ullrich and Clark, 1999; Pop *et al.*, 2000; Marschik and Fontobé, 2001; Arévalo *et al.*, 2006. Mineral abbreviations: amph = amphibole; bn = bornite; cal = calcite; cc = chalcocite; cp = chalcopyrite; hm = hematite; mt = magnetite; po = pyrrhotite; py = pyrite; qtz = quartz.

However, high δ^{34}S-value fluids (i.e., >20‰), possibly indicate that basinal brines and/or seawater sources, were involved in the copper-mineralising stage. Such involvement of external fluids is also supported by oxygen and hydrogen isotope data (Fig. 5 and cf. Ripley and Ohmoto, 1977; Ullrich *et al.*, 2001; Benavides *et al.*, 2007; Chen, 2008).

Although all of these centres share many characteristics, there are also significant differences between them, which may be evidence of differing ore-forming processes and/or hydrothermal fluid sources. Both the Raúl-Condestable and La Candelaria-Punta del Cobre districts are dominated by magnetite-rich copper mineralisation assemblages which formed at higher temperatures than those of the magnetite-deficient copper mineralisation stages at Mina Justa and Mantoverde (Table 2 and Fig. 5). Syn-mineralisation granitoid plutons were emplaced adjacent to the orebodies in the former two deposits, but not at Mina Justa or Mantoverde. This would support a more important contribution of magmatic fluids at Raúl-Condestable and La Candelaria, although external fluids are still considered necessary for copper mineralisation. Fluid mixing between magmatic and "exotic" fluids may have been the dominant mechanism responsible for copper mineralisation in the higher temperature deposits, where the hydrothermal fluids were CO_2-rich, while the reduction of Ca-rich, low-T and CO_2-poor external fluids by early magnetite bodies was a critical factor in the copper mineralisation at Mina Justa and possibly at Mantoverde. The ore metals, i.e., copper, gold and silver, were probably derived from both magmatic and non-magmatic fluids, but could have been largely introduced by external fluids at Mina Justa (Table 2).

An Iron Oxide Melt Origin for Marcona and Some CIB Magnetite Deposits ?

The abundance of early-stage magnetite in many IOCG-style deposits, and the occurrence of late-stage pyrite, chalcopyrite and gold in and near some massive magnetite orebodies (e.g., Kiruna, Marcona, El Romeral; Bookstrom 1977; Frietsch, 1978; Injoque *et al.* 1985) support an inclusion of the latter as end-members of an "IOCG continuum" (Hitzman *et al.* 1992), which is also suggested by the commonality of certain alteration and gangue minerals, especially actinolite and apatite. However, a clear transition between the two deposit types has not been observed, with most magnetite-rich examples containing <0.1% Cu (Sillitoe, 2003). In recent classifications, magnetite deposits, although broadly contemporaneous with IOCG mineralisation in many centres, have been precluded from being classified as IOCG-style, which only comprise copper (-gold)-rich deposits (cf. Sillitoe, 2003; Williams *et al.*, 2005, Hunt *et al.*, 2007). However, it is still not clear why most deposits in the Andes and elsewhere did not evolve from a magnetite-dominated ("IO") to an economically significant chalcopyrite±gold-rich ("CG") stage, especially the giant magnetite deposits, e.g., Kiruna, Marcona, El Romeral and El Laco.

Recent studies of Marcona in Perú, the largest magnetite deposit in the Central Andes with a Middle Jurassic age, and observations from the Early Cretaceous Chilean Iron Belt and younger Pliocene El Laco deposit in northern Chile, show that their main magnetite orebodies share numerous mineralogical, textural and geochemical similarities with the Kiruna magnetite deposit in northern Sweden.

Table 3: Characteristics of major copper-poor "Kiruna-type" iron deposits.

Deposits	Kiirunavaara, Sweden	Marcona, Perú	El Romeral (CIB*), Chile	El Laco, Chile
Tonnage/grade	2600 Mt @ 60% Fe	1940 Mt @ 55% Fe; 0.12% Cu	~400 Mt @ 60% Fe	500 Mt @ >60% Fe
Age of mineralisation	~1900 Ma	~160 Ma	~110 Ma	~2 Ma
Host rocks	Trachytic and syenitic rocks	Silicic metasediments, andesite-dacite	Andesite	Andesite, dacite
Major mineral assemblages in orebody	Magnetite+apatite+ actinolite	Magnetite+actinolite (tremolite)+biotite	Magnetite+actinolite+ apatite	Magnetite+diopside +apatite+quartz
Dominant alteration associated with magnetite mineralisation	Albite-scapolite	K-silicate (biotite - K-feldspar)	Actinolite	Ca-metasomatism (diopside)
Magmatic features	Columnar, platy or dendritic magnetite; vesicular; octahedral crystals, magnetite flow; "ore breccias"; droplets	Mesoscopic contact relationships; local vesicles; local columnar octahedral magnetite crystals; local "ore breccias"	Columnar, platy magnetite; dendritic amphibole; vesicles; octahedral crystals; magnetite flows; "ore breccias"	Columnar, platy magnetite; dendritic pyroxene; vesicles; octahedral crystals; magnetite flows; "ore breccias"
Magnetite composition	High V, low Cr and Ti	High V, low Ti	High V, low Cr and Ti	High V, low Cr and Ti
Ore-forming environment	Subaerial/submarine	Submarine	Subaerial ?/submarine	Subaerial
Tectonomagmatic setting	Extensional, intracratonic basin ?, anorogenic magmatism	Basin formation in an extensional andesitic-dacitic arc	Inversion of basins contiguous to an extensional arc	Eruption of a subaerial andesitic-dacitic arc in an extensional environment
Relationship with Cu-rich IOCG deposits	Spatially and temporally with small IOCG's: Pahtohavare and Rakkurijärvi	Spatially with large IOCG: Mina Justa	Temporally with large IOCG, but only locally overlapping in space	Spatially and temporally with small IOCG's: Rio Grande and Arizaro
References	Frietsch, 1978; Nyström and Henríquez, 1994	Injoque *et al.*, 1985 Chen, 2008	Bookstrom, 1977; Nyström and Henríquez, 1994; Naslund *et al.*, 2002	Nyström and Henríquez, 1994; Naslund *et al.*, 2002

*CIB - Chilean Iron Belt, with a total tonnage of ~2000 Mt and average grade of 60% Fe (Oyarzun *et al.*, 2003).

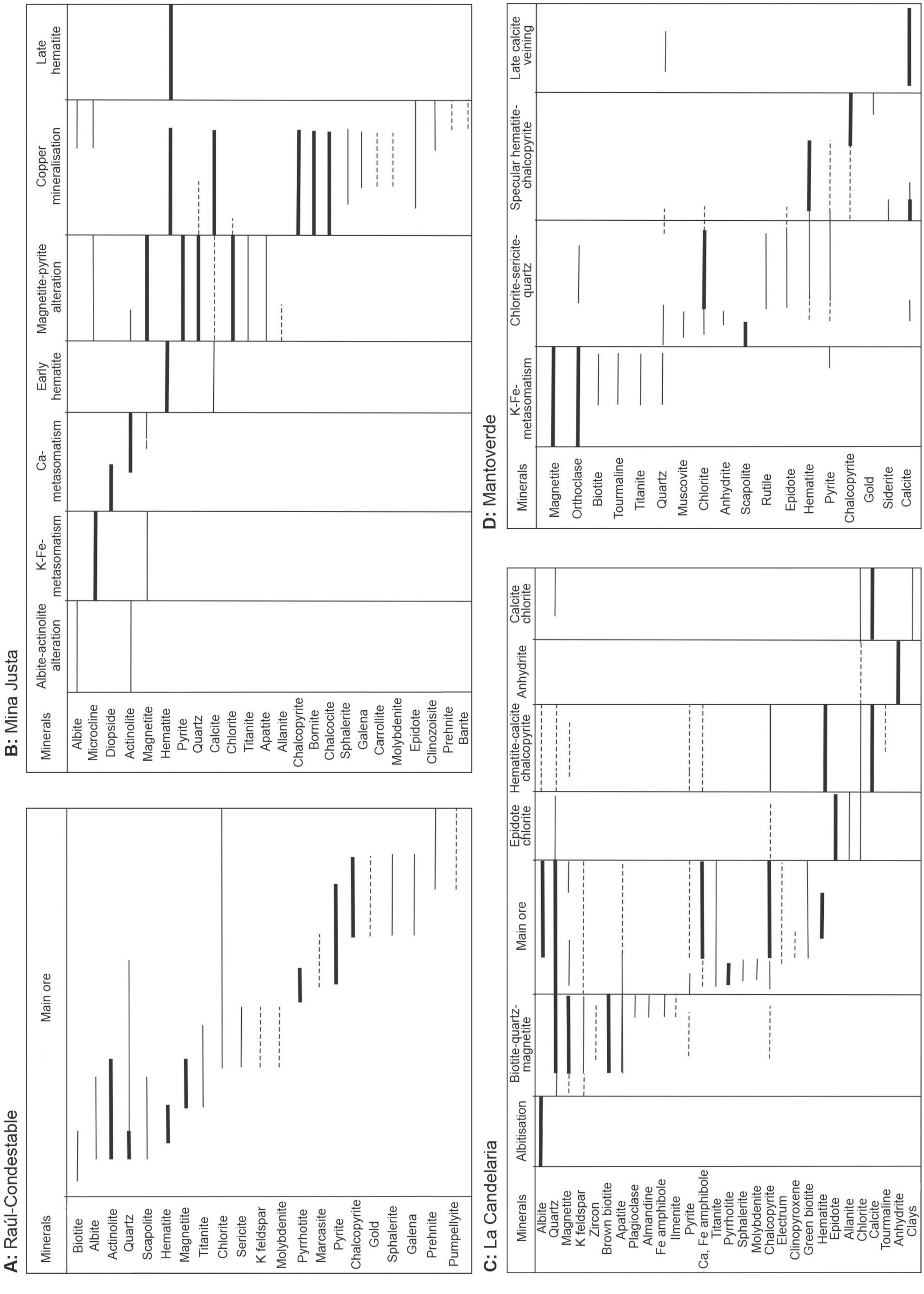

Figure 3: Alteration and mineral paragenesis of the major Central Andean IOCG deposits. **A** - Raúl-Condestable (de Haller *et al.*, 2006); **B** - Mina Justa (Chen *et al.*, *in press*); **C** - La Candelaria (Ullrich and Clark, 1999); **D** - Mantoverde (Benavides *et al.*, 2007).

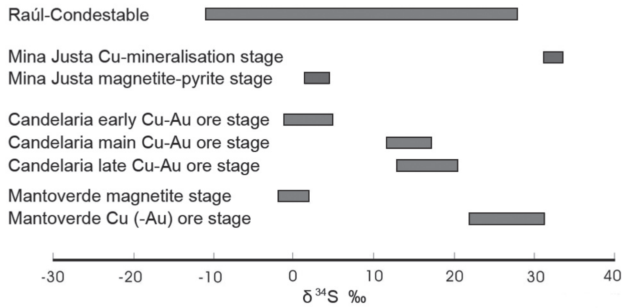

Figure 4: $\delta^{34}S$ values of ore fluids at major IOCG deposits (data from de Haller *et al.*, 2002, Chen, 2008; Ullrich and Clark 1999; Benavides *et al.*, 2007).

These deposits are considered by most workers to be the product of oxide melt crystallisation (Table 3; Nyström and Henríquez, 1994; Naslund *et al.*, 2002; Lledó, 2005; Chen, 2008), although, a magmatic-hydrothermal origin for CIB magnetite deposits and El Laco is preferred by others (Bookstrom, 1977; Rhodes *et al.*, 1999; Sillitoe and Burrows, 2002, 2003). Recent review studies show that iron oxide mineralisation in central Chile may represent either or both iron oxide melts, and magmatic hydrothermal fluids exsolved from sub-volcanic intrusions, representing different parts of a series of large sub-eroded magmatic-hydrothermal systems (Tornos and Velasco, 2009).

The mineralisation at Marcona has a halo composed of zones of intense K-metasomatism (biotite and K feldspar alteration), rather than the strong Na- or Ca-metasomatism surrounding other such iron deposits, evidence for a K-rich parental magma. The significant, if sub-economic, average copper content (0.12%) at Marcona is ascribed herein to the involvement of seawater (Chen, 2008). Although Marcona and at least part of the Andean "Kiruna-type" magnetite deposits could be interpreted as a largely endogenous product of arc magmatism, with minimal intervention by non-magmatic fluids, these iron deposits were formed in different tectono-magmatic settings (Table 3), viz.: Marcona during basin formation in an extensional andesitic-dacitic arc; the Cretaceous Chilean Iron Belt deposits during the inversion of basins contiguous with an extensional arc; and El Laco during the eruption of a subaerial andesitic-dacitic arc in an extensional environment (Kay and Kay, 1993; Marrett *et al.*, 1994).

Metallogenic Modelling of Andean Mesozoic IOCG Mineralisation

Middle to Late Jurassic

The 162 to 159 Ma Marcona magnetite orebodies constitute the most significant mineralisation within the Middle Jurassic metallogenic sub-province of the Central Andes (Chen *et al.,* 2010), unparalleled in scale elsewhere in the Middle Jurassic Cordillera de la Costa (Fig. 6A). Indeed, several of the larger individual magnetite orebodies at Marcona are comparable in size to the major deposits of the CIB, with the 25 km² Marcona district incorporating more economic magnetite than the entire 10 000 km² CIB. While Marcona formed in a newly-developed extensional submarine basin, broadly coeval porphyry copper (-molybdenum-gold) mineralisation in the Cocachacra district in southern Perú (Clark *et al.*, 1990) was associated with 165 to 160 Ma granitoid intrusions emplaced during orogenic contraction and uplift (Quang, 2003). In contrast to central-south and southern Perú, transtensional regimes dominated in the Middle Jurassic of northern Chile, controlling the emplacement of numerous iron oxide-rich copper veins, e.g., Tocopilla, Julia and Las Animas (Maksaev, 1990; Sillitoe, 2003). These small deposits are largely hosted by Lower Jurassic submarine to subaerial andesitic strata (Cornejo *et al.*, 2006), and are considered to be genetically related to Bathonian to Callovian intrusive granitoids (Maksaev, 1990). Thereafter, with the increasing coupling of the convergent plates in northern Chile during the Valanginian (Jaillard *et al.*, 2000), shallow dioritic and granodioritic plutons (Maksaev and Zentilli, 2002) were probably responsible for the "manto-type" Mantos Blancos stratabound hematite-rich copper deposit (500 Mt at 1.0% Cu; 142 to 141 Ma; Ramírez *et al.*, 2006; Oliveros *et al.*, 2006). However, only weak magmatism and magmatic-hydrothermal alteration occurred in central-south and southern Perú in the Late Jurassic, e.g., the K-Fe metasomatism in the Mina Justa area (ca. 142 Ma; Chen *et al.,* 2010). The Marcona magnetite deposit apparently represents a unique mineralisation type in the late-Jurassic evolution of the Central Andes. A conjunction of conditions,

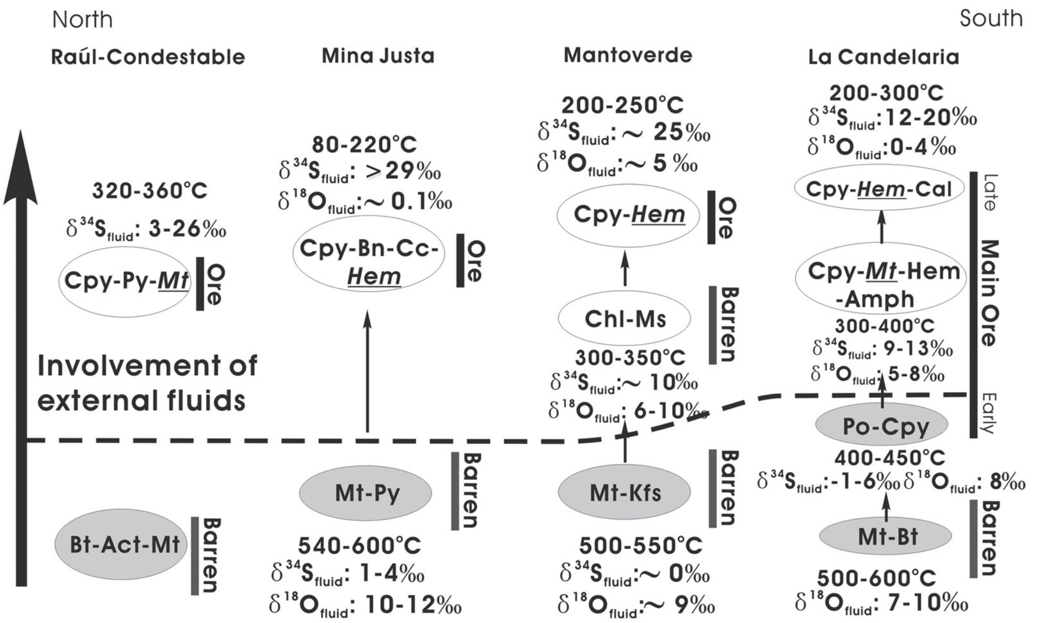

Figure 5: Comparison of the major Central Andean IOCG deposits (data from de Haller *et al.*, 2002, 2006; Chen, 2008; Ullrich and Clark, 1999; Ullrich *et al.*, 2001; Benavides *et al.*, 2007).

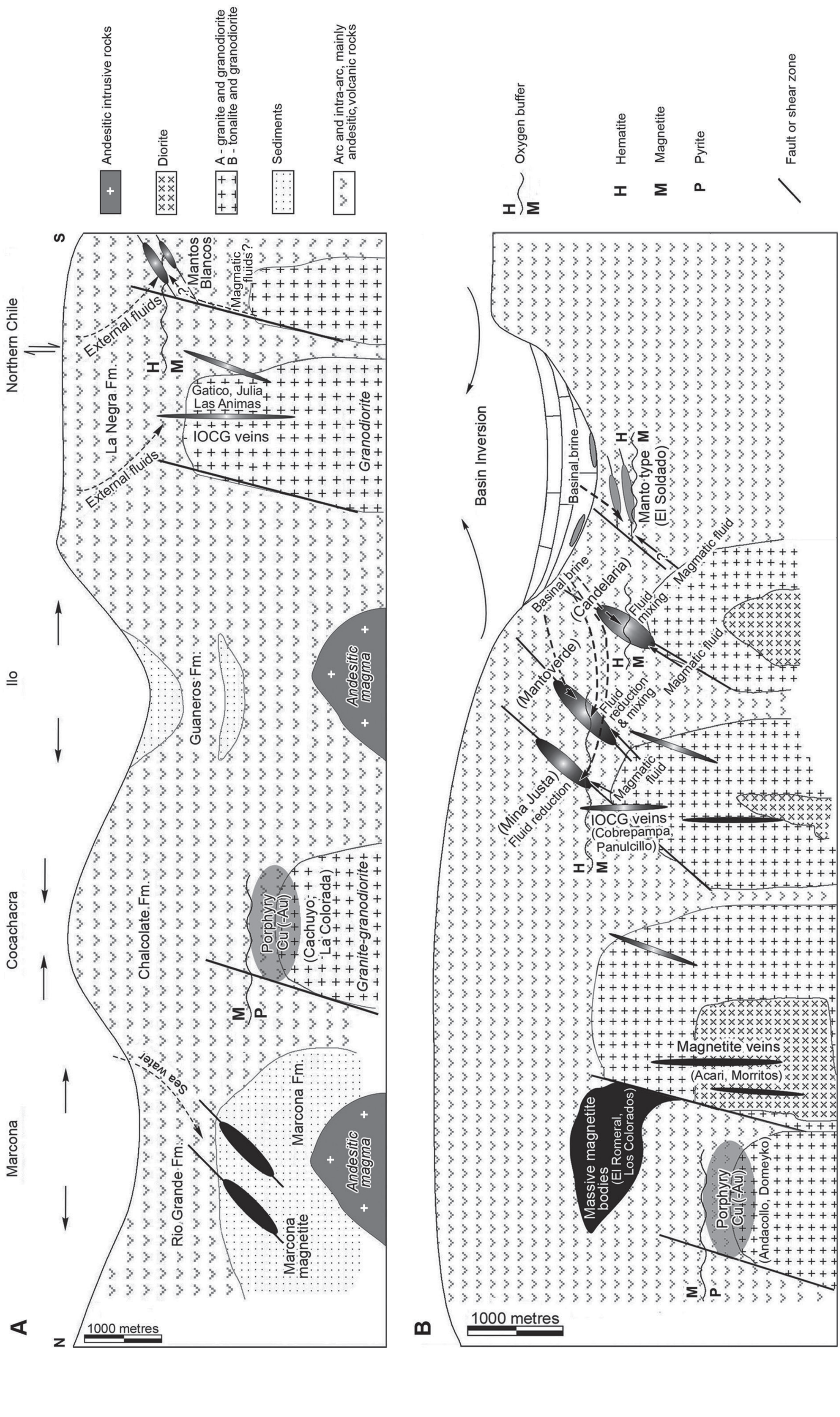

Figure 6: Modelling of Central Andean IOCG-style and related mineralisation during the **A** - Middle-Late Jurassic; and **B** - Early Cretaceous (the deposits are not located geographically).

viz. strongly oxidised magmas, silica-rich host rocks and an extensional environment, all favoured the generation of iron oxide melts, and was probably responsible for this anomaly. In contrast, the slightly younger, rhyolite-hosted Mantos Blancos mineralisation has been ascribed to the repeated boiling of magmatic-hydrothermal fluids due to episodic decompression (Ramírez *et al.*, 2006).

Early Cretaceous

The Lower Cretaceous metallogenic sub-province, incorporating the major copper-rich IOCG-style deposits of the Andes, viz. Raúl-Condestable, Mina Justa, La Candelaria-Punta del Cobre and Mantoverde, as well as the copper-poor CIB iron, several "manto-type" stratabound copper (-silver) and minor porphyry copper (-molybdenum-gold) deposits (Fig. 6B; Sillitoe, 2003), developed in an extensional arc in a transtensional tectonic regime (Polliand *et al.*, 2005). Mineralisation was largely coeval with the shallow emplacement of granitoid plutons along the margins of aborted mid-Cretaceous basins (Oyarzun *et al.*, 2003; Sillitoe, 2003). The 104 to 95 Ma Mina Justa magnetite alteration and superimposed copper mineralisation, as well as the precursor 109 Ma actinolite alteration (Chen *et al.*, 2010), may have been nucleated by plutons of the Arequipa Segment of the Coastal Batholith (≤109 Ma; Vidal *et al.*, 1990), which were also probably responsible for the magnetite mineralisation at Acarí (Injoque, 1985), and iron oxide-rich copper veins and Na- and K-metasomatism at Cobrepampa and La Argentina, 30 to 50 km to the southeast of Mina Justa (Injoque, 2002). The slightly older (115 to 114 Ma) IOCG mineralisation at Raúl-Condestable and Eliana occurred simultaneously with the earliest intrusions of the Coastal Batholith (Arequipa segment) in central-southern Perú (de Haller *et al.*, 2006). All of the Peruvian IOCG-style deposits developed on the western margin of the Early Cretaceous Cañete Basin. Small Albian iron-oxide copper (-gold) deposits (e.g., Cerro Morritos: Clark *et al.*, 1990) and porphyry copper occurrences (e.g., Yaral; Quang, 2003) formed at this time in the Ilo-Tacna area of southernmost Perú. In contrast to southern Perú, the mid-Cretaceous metallogenic belt of northern Chile exhibits a complex and protracted history of mineralisation. Initiated at ~128 Ma (Zentilli, 1974; Gelcich *et al.*, 2002) and persisting until the late Albian (Wilson *et al.*, 2003; Sillitoe and Perelló, 2005), hydrothermal alteration and mineralisation culminated at 125 to 110 Ma, represented by major copper-gold mineralisation at La Candelaria-Punta del Cobre (Ullrich and Clark, 1999, Pop *et al.*, 2000), the El Romeral magnetite (Munizaga *et al.*, 1985) and Andacollo porphyry copper-gold deposits (Sillitoe and Perelló, 2005). Oxide melts may have generated some of the largest CIB deposits (Nyström and Henríquez, 1994), but magmatic-hydrothermal fluids were responsible for the porphyry copper (-molybdenum-gold) mineralisation, the Fe-(K-) metasomatism around some CIB deposits, and the early magnetite bodies in the IOCG deposits (Sillitoe, 2003; Benavides *et al.*, 2007). However, the significant but varying temporal separation of magnetite and economic copper mineralisation in the IOCG deposits, e.g., 2 to 3 m.y. at La Candelaria (Ullrich and Clark, 1999, but cf. Marschik and Fontboté, 2001; Mathur *et al.*, 2002), ~10 m.y. at Mantoverde (Gelcich *et al.*, 2005), and 2 to 5 m.y. at Mina Justa (Chen *et al.*, 2010), probably records the involvement of different ore-forming fluid sources at these stages. The incursion of evaporite-sourced basinal brines may be a prerequisite for economic copper mineralisation, providing both metals and sulphur in some of these deposits, e.g., Mina Justa (Chen, 2008). Basinal connate-metamorphic brines are also advocated as being responsible for copper mineralisation in the El Soldado "manto-type" deposit in central Chile (Boric *et al.*, 2002) and for several small stratabound copper deposits in the Copiapó area, 10 to 20 km east of the La Candelaria-Punta del Cobre IOCG centre and within the Neocomian back-arc basin (Haggan *et al.*, 2003; Cisternas *et al.*, 2006).

Conclusion

Mesozoic Andean IOCG-style and related deposits formed in two epochs of mineralisation, i.e., Middle to Late Jurassic (170 to 150 Ma) and Early Cretaceous (130 to 95 Ma), although the major copper-rich IOCG ores are confined to the latter. While the early, commonly copper (-gold)-barren, magnetite alteration is magmatic fluid-derived, the incursion of evaporite-sourced basinal brines or seawater may be an important contributor to the development of economic copper mineralisation in many of these deposits. The Andean massive magnetite deposits produced in both mineralising epochs, partially share many characteristics with the Kiruna deposit in Sweden, and could be interpreted as a largely endogenous product of arc magmatism, with minimal contributions from non-magmatic fluids, although magmatic hydrothermal fluids may dominate in some of those in the CIB. Thus, although broadly contemporaneous and areally juxtaposed, the copper-rich IOCG deposits, e.g., Raúl-Condestable, Mina Justa, La Candelaria-Punta del Cobre and Mantoverde, and the copper-poor massive magnetite deposits, e.g., Marcona and Chilean Iron Belt deposits, could represent different ore-forming process, although both were probably associated with the same regional magmatism. Temporal separation of the early main magnetite and the subsequent economic copper mineralisation in IOCG deposits is common, and a protracted history of alteration and mineralisation is possibly a characteristic feature of major IOCG centres and districts in the Central Andes.

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