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Mesozoic Iron Oxide Copper-Gold Mineralization in the Central Andes and the Gondwana Supercontinent Breakup

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Abstract

The Mesozoic deposits in the Central Andes, especially represented by the dominant iron oxide copper-gold (IOCG) mineralization in southern Peru and northern Chile coastal IOCG belt, has emerged as one of the major exploration targets in the Central Andes in the last two decades. These deposits mainly formed during the Middle-Late Jurassic and Early Cretaceous. The major Cu-rich IOCG deposits are located in the Early Cretaceous mineralization belt, which is also the main Phanerozoic example of this type of ore deposit. The Central Andean IOCG deposits lie in a linear array of interconnected Mesozoic continental margin rift basins that record a major phase of extension accompanying subduction along the western margin of Gondwana. The Mesozoic tectonic evolution of the Central Andes since the initial phase of IOCG mineralization can be subdivided into the following: the Tethyan period (165–155 Ma); the South Atlantic period (145–135 Ma) and the Pacific period (120–100 Ma). Central Andean IOCG mineralization was initiated in the Middle Jurassic (165–155 Ma), associated with the high-angle subduction of the Phoenix plate and coeval with the early stage of Gondwana breakup. Following a relatively weak tectonomagmatic stage (135–120 Ma), the peak in Mesozoic IOCG deposits occurred during the inversion of extensional basins (120–100 Ma), corresponding to the final separation of African and South American tectonic plates.

Introduction

IRON OXIDE copper-gold (IOCG) mineralization, first formally defined by Hitzman et al. (1992) and usually containing abundant (>10%) iron oxides (magnetite or hematite) and economic grade Cu and/or Au (Williams et al., 2005), has been a major exploration target since the discovery of the enormous Olympic Dam Cu-U-Au (-REE) deposit in 1975. After the identification of Proterozoic IOCG systems, e.g., those of the Gawler block of South Australia, the Eastern Mount Isa block of 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 Peru, are now recognized as hosting major IOCG mineralization (Sillitoe, 2003). These Mesozoic Andean IOCG deposits mainly formed in two mineralization epochs, i.e., Middle-Late Jurassic (165–155 Ma) and Early Cretaceous (120–100 Ma), and the major Cu-rich IOCG deposits are located in Early Cretaceous mineralization belt (Sillitoe, 2003; Chen et al., 2010a).

The Andean Mesozoic IOCG centers are hosted by subduction-related, intermediate volcano-plutonic complexes and/or sedimentary strata, and range from the temporally and spatially associated magnetite-dominant systems at Marcona-Pampa de Pongo in Peru (Hawkes et al., 2002; Chen et al., 2010b) and Chilean iron belt in Chile (Naslund et al., 2002), to productive Cu (-Au) 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 Raúl-Condestable–Mina Justa belt in southern Peru (Sillitoe, 2003; de Haller et al., 2006; Chen et al., 2010a). The geologic setting of Mesozoic IOCG centers in southern Peru and northern Chile provides a unique context for the study of the processes involved in the genesis of IOCG deposits in a convergent plate tectonic environment. A direct connection between IOCG ore-forming processes and tholeiitic to calc-alkaline, subduction-related magmatism has been identified (Vila et al., 1996; Marschik and Fontboté, 2001; Rhodes and Oreskes, 1999; Sillitoe, 2003; de Haller et al., 2006). Although field evidence and more recent data from fluid inclusions and stable isotopes have confirmed that the intervention of nonmagmatic fluids, e.g., seawater or evaporite-derived basinal brines, may play an important role in the generation of Cu (-Au) mineralization (Ripley and Ohmoto, 1977; Ullrich and Clark, 1999; Ullrich et al., 2001; de Haller et al., 2002; Benavides et al., 2007; Chen et al., 2011).

Although strongly debated over a number of years, the significance of relationships between plate tectonic settings and ore types is becoming better appreciated (Meyer, 1981; Sawkins, 1984; Barley and Groves, 1992; Groves et al., 2005). With improved geochronological methods and better plate tectonic reconstructions (e.g., Condie, 2005), the temporal distribution of mineral deposits associated with supercontinent assembly and breakup have been documented for many important ore types, such as orogenic gold deposits (Goldfarb et al., 2001), volcanic-hosted massive sulfide deposits (Huston et al., 2010), and sediment-hosted lead-zinc deposits (Leach et al., 2010). Most Precambrian IOCG deposits are believed to have been distributed in intracratonic settings, typically 100 to 200 km inland from cratonic margins, and appear to form during episodes of supercontinent breakup (Groves et al., 2010). In the case of the Central Andes, Mesozoic IOCG mineralization was associated with an active continental margin (Sillitoe, 2003; Chen et al., 2010a). The remelting of mafic crust generated by upwelling mantle was inferred in both Central Andean and Precambrian IOCG tectonic regimes

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(Atherton et al., 1983; Pollard et al., 1998; Groves et al., 2010). With the help of recent precise geochronological data, in this paper we reconstruct the tectonic evolution of the Central Andes during Gondwana breakup and examine its relationship with Mesozoic IOCG mineralization in detail.

Mesozoic IOCG Mineralization in the Central Andes

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) attending subduction along the western margin of Gondwana, prior to the major Cenozoic compressive episodes and crustal thickening that generated the Andean Cordillera (Benavides-Cáceres, 1999; Ramos and Alemán, 2000). In the Coastal Cordillera of northern Chile and southern Peru, major Mesozoic plutonic complexes are emplaced into broadly contemporaneous arc and intra-arc volcanic rocks and underlying deformed Paleozoic 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 was accreted onto the Amazonian craton at ca. 1.0 Ga (Loewy et al., 2004). The most voluminous units hosting the Andean Mesozoic deposits are Middle Jurassic to Lower Cretaceous volcanic-derived rocks generated in the arc and aborted marginal back-arc basins in southern Peru (Caldas, 1978; Romeuf et al., 1993) and northern Chile (Boric et al. 1990; Grocott et al., 1994), both of which comprise basaltic andesitic to andesitic lava flows with subordinate volcaniclastic and marine sedimentary units (Aguirre, 1988; Sillitoe, 2003), and the Peruvian formations may have medium to high K calc-alkaline affinity (Aguirre, 1988; Romeuf et al. 1993). Extensive longitudinal brittle fault systems and ductile

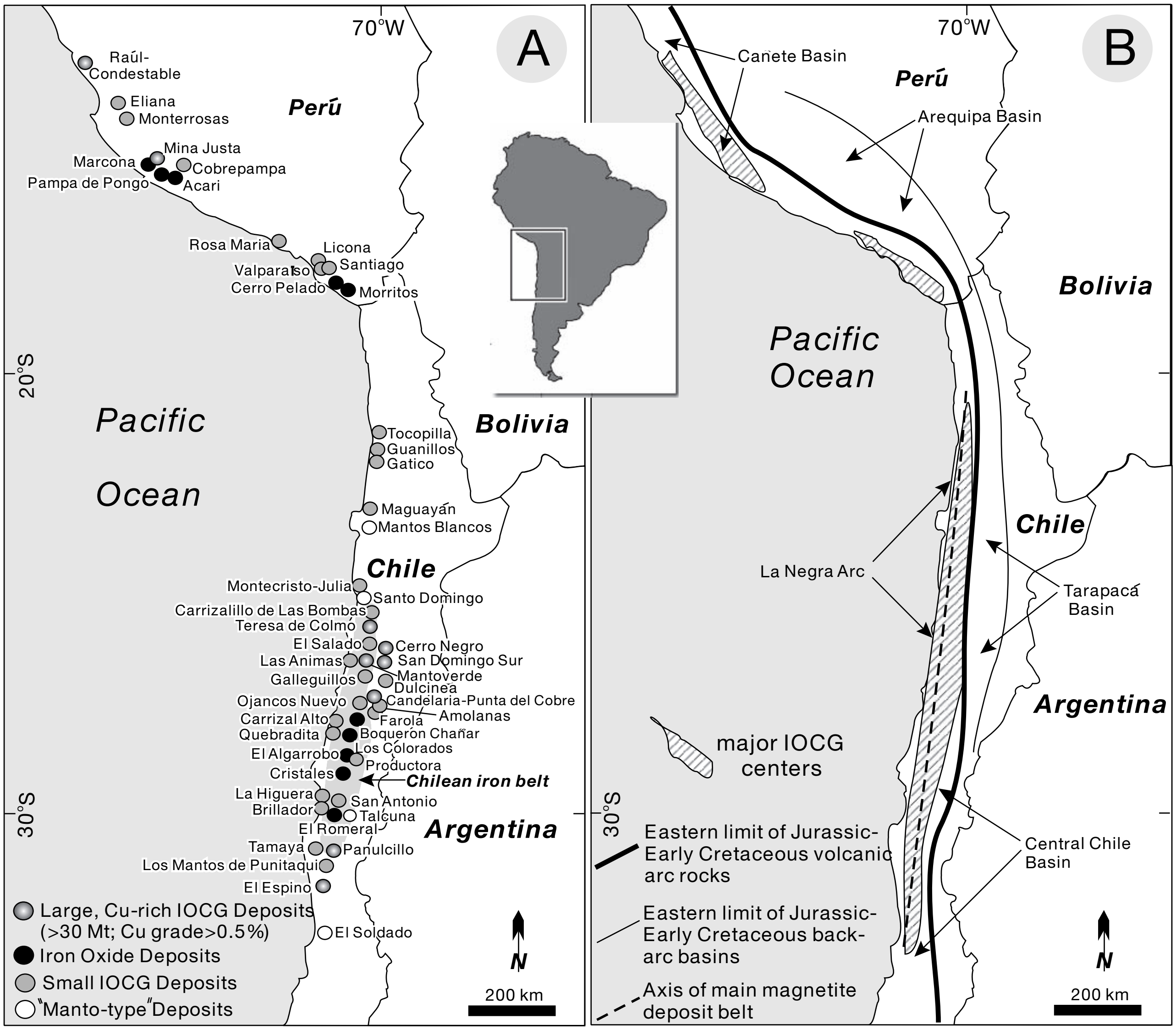

FIG. 1. A. Locations of the Cu-rich IOCG, principal iron and manto-type deposits in Peru and Chile (from Clark et al., 1990; Hawkes et al., 2002; Sillitoe, 2003; Oyarzun et al., 2003; Benavides et al., 2007; and Chen et al., 2010a). B. Position of the Central Andean IOCG belt of northern Chile and southern Peru (from Sillitoe, 2003).

shear zones, including the Atacama fault system in northern Chile (Scheuber and Andriessen 1990) and deeply penetrating faults located in the Cañete basin in Peru, e.g., Treinte Libras fault system (Caldas, 1978; Atherton and Aguirre 1992), were active during Mesozoic volcanism and plutonism.

The Peruvian IOCG belt (Fig. 1), approximately 70 km wide and extending discontinuously for 800 to 1,000 km along the Peruvian littoral from Lima to the Ilo-Ite area (Clark et al., 1990; Hawkes et al., 2002; Injoque, 2002; Chen et al., 2010a), developed in the Cañete basin and, to the south, along the axis of the Jurassic-Cretaceous shallow-marine volcano-plutonic arc. Ore deposits and mineral occurrences in this belt assignable to the IOCG clan include Raúl-Condestable, Eliana, Monterrosas, Mina Justa, Cobrepampa, Rosa María, Licona, Valparaïso, and Santiago. Associated sulfide-bearing magnetite deposits include Marcona, Pampa de Pongo, Acarí, Cerro Pelado, and Morritos (Fig. 1, Clark et al., 1990; Hawkes et al., 2002; Sillitoe, 2003; Chen et al., 2010b). Of these, the newly discovered Mina Justa Cu (-Ag) prospect is the largest Cu-rich IOCG mineralization (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 (Chen et al., 2010a). The IOCG deposits in northern Chile, mainly between latitudes 22° and 31°S (Fig. 1), are controlled by the regional Atacama fault system and largely hosted by the La Negra and Punta del Cobre Formations arc volcanic rocks and their stratigraphic equivalents (Sillitoe, 2003). Two major Cu-rich IOCG deposits, La Candelaria and Mantoverde, which both contain over 400 Mt of ore grading 0.7 to 1% Cu, together with other smaller IOCG mineralization, e.g., the newly explored Santo Domingo Sur prospect (Table 1), make northern Chile one of the most productive IOCG provinces globally. Broadly contemporaneous and possibly related mineralization in this belt includes the Chilean iron belt magnetite deposits and the "manto-type" Cu deposits, e.g., Manto Blancos and El Soldado (Fig. 1; Table 1).

The principal IOCG deposits in northern Chile and southern Peru were mainly generated in Middle-Late Jurassic (165–155 Ma) and Early Cretaceous (120–100 Ma) epochs (Table 1; Sillitoe, 2003 and references therein; Chen et al., 2010a). The Middle-Late Jurassic deposits are located near the Pacific coast, west of the Early Cretaceous belt. In southern Peru, the large, sulfide-bearing Marcona magnetite deposit in the Marcona district (162–156 Ma) and Cu-rich Rosa María prospect in the Cocachacra district (ca. 160 Ma) are assigned to this metallogenic epoch. In northern Chile, the Middle-Late Jurassic IOCG deposits include Cu-rich Tocopilla, Guanillos, Montecristo-Julia, and Las Animas. However, most of the major IOCG deposits (e.g., Mina Justa, Mantoverde, and La Candelaria), and associated magnetite deposits (e.g., Pampa del Pongo, Acarí, and deposits in Chilean iron belt) and some manto-type Cu deposits (e.g., El Soldado) are located farther east in the Coastal Cordillera and are Early Cretaceous in age. The Cu-rich IOCG deposits in this epoch include Raúl-Condestable, Eliana, Monterrosas, Mina Justa in southern Peru, and Candelaria, Mantoverde, Panulcillo, and El Espino in northern Chile (Fig. 1; Table 1).

TABLE 1. Tonnages, Grades and Ages of Selected Mesozoic IOCG and Allied Deposits in the Central Andes

Deposit	Tonnage (Mt)	Fe (%)	Cu (%)	Au (g/t)	Ag (g/t)	Mineralization age (Ma)	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	Chen et al., 2010a
Mina Justa	347	ne	0.71	0.03	3.83	104–95	Chen et al., 2010a
Pampa de Pongo[1]	953	44.7	Trace			<109	Chen et al., 2010a
Rosa María						160 (145)	Clark et al., 1990
Chilean coastal belt							
Guaillos						~167	Boric et al., 1990
Tocopilla	2.4	ne	3.1	Trace		~165	Ruiz and Peebles, 1988
Julia						~164	Boric et al., 1990
Las Animas						~162	Sillitoe, 2003
Mantos Blancos[2]	500	ne	1.0			~140	Ramírez et al., 2006
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
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		110–117	Marschik and Fontboté, 2001
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

Note: ne = not economic

[1] Assigned as "Kiruna-type" deposit

[2] Classified as a hematite-rich hydrothermal breccia deposit or manto-type

[3] Including five large deposits (200–400 Mt): Boquerón Chañar, Los Colorados, Algarrobo, Cristales, and El Romeral, and many small deposits with 20–100 Mt

[4] Hypogene protore

Gondwana Breakup and IOCG Mineralization in the Central Andes

The Mesozoic tectonic evolution in the Central Andes can be subdivided into six stages (Table 2) and mineralization is mainly associated with three stages (Jaillard et al., 2000; Fig. 2): Tethyan (165–155 Ma), South Atlantic (145–135 Ma) and Pacific periods (120–100 Ma). Major IOCG mineralization occurred in the Pacific period (Chen et al., 2010a).

Since the late Early Jurassic, divergence of the Phoenix and Farallon plates resulted in the Phoenix plate being subducted under the Andean margin at South America in an east-southeast direction, resulting in extensive magmatism along the Central Andean Coastal Cordillera. Such tectomagmatism was enhanced by emerging of the Pacific Plate Triangle in the Middle Jurassic and generated intensive mineralization in the Central Andes (Fig. 2A; Jaillard et al., 1990). Distinct mineralization related to the local tectonic regime formed in metallogenic sub-provinces during this period (Fig. 2A; Table 2). Whereas the Marcona massive magnetite deposit formed in a newly developed extensional submarine basin (Chen et al., 2010a), the Cachuyo porphyry Cu (-Mo-Au) mineralization in the Cocachacra district in southern Peru was genetically related to broadly coeval 165 to 160 Ma granitoid intrusions emplaced during contraction and uplift (Clark et al., 1990). Numerous iron oxide-rich Cu veins (e.g., Tocopilla, Julia, and Las Animas) constitute the major deposits in northern Chile in the Middle Jurassic. Their formation was controlled by transform faults (Fig. 2A; Sillitoe, 2003).

The Paraná flood basalt eruption in the Late Jurassic-Early Cretaceous (140–130 Ma; Stewart et al., 1996) is related to the initial opening of the South Atlantic Ocean and possibly to associated plume activities (Fig. 2B; Renne et al., 1996). At this time, only weak tectonic movement from the Phoenix plate occurred (Jaillard et al., 2000) and the tectonic regime in the Central Andes was dominated by transtension associated with the Paraná eruption and related Atlantic extension (Lucassen et al., 2007). Magmatism at this stage was relatively dormant (Jaillard et al., 2000), while hydrothermal alteration was localized at Marcona-Mina Justa district (Chen et al., 2010a). The enigmatic rhyolite-hosted hydrothermal Mantos Blancos Cu-Ag deposit (140 Ma; Ramírez et al., 2006) is the only large Cu deposit known to have formed in the Central Andes during this time (Fig. 2B).

Plate interactions in the Central Andes region were reorganized in the middle Cretaceous (Jaillard et al., 2000; Oyarzun et al., 2003), most likely triggered by the development of a mid-Pacific superplume (Larson, 1991) and coincident with the final separation of the South American and African plates (Fig. 2C; Siedner and Miller, 1968; Thomaz-Filho et al., 2000). Coupling of the converging Phoenix and South America plates, with a northeast vector, ended a long period of orthogonal extension and sinistral transtension along the central South American littoral, and gave rise to dextral transtension and the formation of mid-Cretaceous basins (Polliand et al., 2005). Basin formation, intense volcanism, and weak mineralization occurred during the early stage (135–120 Ma) before a period of stronger magmatism and major mineralization during basin inversion characterized by dioritic-granodioritic intrusive rocks (the so-called "Coastal batholith") intruding the early volcano-sedimentary units along the margins of aborted mid-Cretaceous basins (Table 2). The Coastal batholith is parallel to the major N-S–trending regional structures (Oyarzun et al., 2003) and is temporally associated with the major IOCG deposits. It may have contributed to the mineralization either as a heat engine to circulate fluids in the host rocks (Chen et al., 2011) or as a direct ore-forming fluid source (Marschik and Fontboté, 2001). During basin formation, rift-related attenuation and mantle upwelling generated intensive mantle-derived basaltic-andesitic volcanic rocks that are also the precursor of later Coastal batholith intrusions associated with basin inversion (Atherton et al., 1983). Such mantle-related magmatism has also been identified in many

TABLE 2. Major Tectonic Evolution Stages and Associated Mineralization of the Central Andes in the Mesozoic

Stage	Period	Tectonics	Magmatism	Mineralization
Stage I	Early Tethyan (180–165 Ma)	Sinistral transtension and extension; basin formation	Intensive volcanism; Lower Rio Grande, Chalcolate (Peru) and La Negra (Chile) Formation	No mineralization
Stage II	Late Tethyan (165–155 Ma)	Extension at Marcona, Peru Compression at Cocachacra, Peru Extension at Ilo, Peru Sinistral transtension at northern Chile	Upper Rio Grande Formation Granitoid intrusive rocks Cuanerous Formation Granitoids and volcanic rocks	Marcona magnetite Porphyry deposits No mineralization IOCG veins and porphyry deposits
Stage III	Transition (155–145 Ma)	Weak transtension	Jahuay and Yauca Formation	No mineralization
Stage IV	South Atlantic (145–135 Ma)	Generally transtension	Strong magmatism only in northern Chile (21–26°S)	Mantos Blancos Cu deposit
Stage V	Early Pacific (135–120 Ma)	Dextral transtension and extension; basin formation	Intensive volcanism; Casma-Copara (Peru) and Punta del Cobre (Chile) Formation	Weak mineralization
Stage VI	Late Pacific (120–100 Ma)	Dextral transtension and compression; uplift and basin inversion	Coastal batholith, Peru Granitoids and volcanic rocks, Chile	IOCG deposits IOCG, Chilean iron belt, Manto-type and porphyry deposits

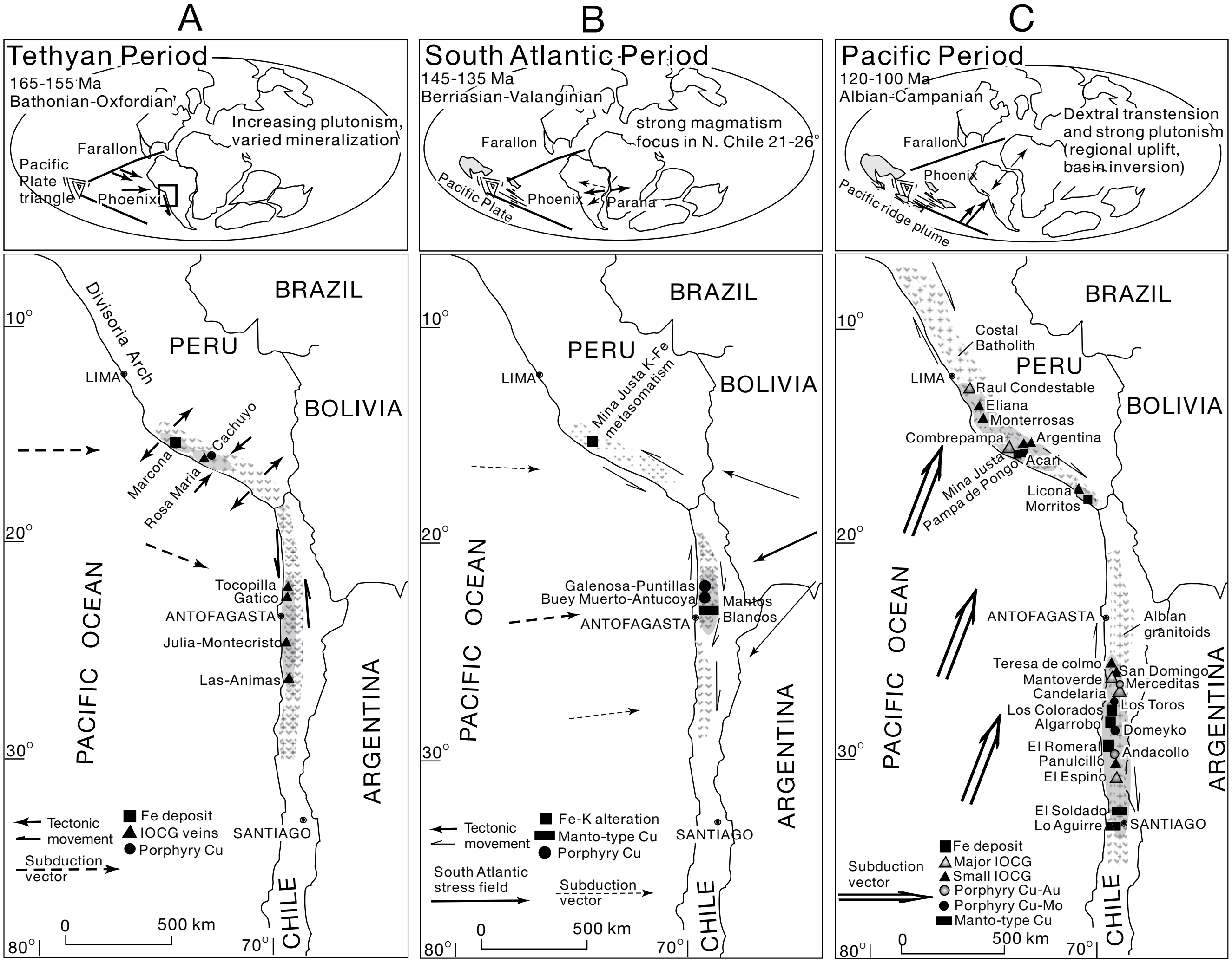

FIG. 2. Tectonomagmatic evolution of the Mesozoic metallogenic subprovinces in the Central Andes. A. The Tethyan period (165–155 Ma); B. The South Atlantic period (145–135 Ma); C. The Pacific period (120–100 Ma)

other IOCG centers around the world. They are interpreted to reflect sublithospheric underplating at the base of the subcontinental lithospheric mantle, or subcrustal intraplating immediately below the Moho density filter. The basaltic-andesitic rocks were potentially derived from long-lived chambers of fractionating mantle-derived magma generated by either mantle plume impact, or crustal delamination and detachment triggered by collision or rift-related attenuation (Porter, 2010). However, the intimate relationship between Mesozoic basins and IOCG deposits in the Central Andes may indicate that external basinal fluids and structural controls play important roles in IOCG mineralization.

The major Central Andean IOCG deposits formed in the middle Cretaceous (Table 1), spatially associated with Cu-poor Chilean iron deposits, "manto-type" strata-bound Cu (-Ag) deposits and subordinate porphyry Cu (-Mo-Au) deposits (Fig. 2C; Sillitoe, 2003). Hydrothermal alteration was initiated at ~128 Ma (Gelcich et al., 2005) and persisted to ~100 Ma (Sillitoe and Perelló, 2005). Mineralization culminated at 116 to 110 Ma (Fig. 3), as represented by the major IOCG deposits of La Candelaria (Marschik and Fontboté, 2001), Mantoverde (Benavides et al., 2007), and Mina Justa (Chen et al., 2010a), and by the El Romeral magnetite deposit (Oyarzun et al., 2003) and the Andacollo porphyry Cu-Au deposit (Sillitoe and Perelló, 2005).

Conclusions

Central Andean IOCG-related mineralization was initiated in the Middle Jurassic (165–155 Ma), associated with the high-angle subduction of the Phoenix plate and coeval with the early stage of Gondwana breakup. The Central Andean Mesozoic mineralization peak and formation of major IOCG deposits occurred during the inversion of extensional basins (120–100 Ma) and corresponded to the final separation between the African and South American tectonic plates. We predict that more Mesozoic IOCG deposits will be discovered around the margin of the former Gondwana Supercontinent.

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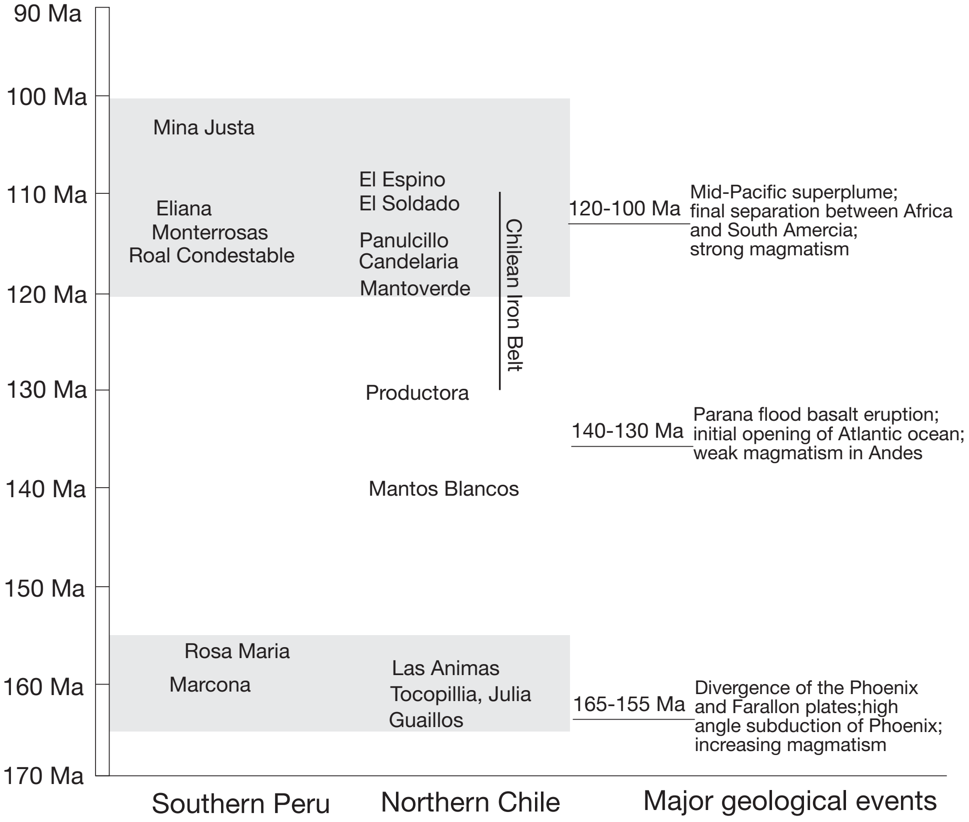

FIG. 3. Timeline of the major Mesozoic IOCG and allied deposits in the Central Andes and major geologic events.

IOCG deposits in the Central Andes. The authors greatly appreciate the comments of the Associate Editor Tim Baker and David Huston and Richard Goldfarb, which considerably improved the quality of this paper.

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