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ARTICLE

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Iron oxide-copper-gold deposits: an Andean view

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Abstract Iron oxide-copper-gold (IOCG) deposits, defined primarily by their elevated magnetite and/or hematite contents, constitute a broad, ill-defined clan related to a variety of tectono-magmatic settings. The youngest and, therefore, most readily understandable IOCG belt is located in the Coastal Cordillera of northern Chile and southern Peru, where it is part of a volcano-plutonic arc of Jurassic through Early Cretaceous age. The arc is characterised by voluminous tholeiitic to calc-alkaline plutonic complexes of gabbro through granodiorite composition and primitive, mantle-derived parentage. Major arc-parallel fault systems developed in response to extension and transtension induced by subduction roll-back at the retreating convergent margin. The arc crust was attenuated and subjected to high heat flow. IOCG deposits share the arc with massive magnetite deposits, the copper-deficient end-members of the IOCG clan, as well as with manto-type copper and small porphyry copper deposits to create a distinctive metallogenic signature.

The IOCG deposits display close relations to the plutonic complexes and broadly coeval fault systems. Based on deposit morphology and dictated in part by lithological and structural parameters, they can be separated into several styles: veins, hydrothermal breccias, replacement mantos, calcic skarns and composite deposits that combine all or many of the preceding types. The vein deposits tend to be hosted by intrusive rocks, especially equigranular gabbrodiorite and diorite, whereas the larger, composite deposits (e.g. Candelaria-Punta del Cobre) occur within volcano-sedimentary sequences up to 2 km from pluton contacts and in intimate association with major orogen-parallel fault systems. Structurally localised IOCG deposits normally share faults and fractures with pre-mineral mafic dykes, many of dioritic composition, thereby further emphasising the close connection with mafic magmatism. The deposits formed in association with sodic, calcic and potassic alteration, either alone or in some combination, reveal evidence of an upward and outward zonation from magnetite-actinolite-apatite to specular hematite-chlorite-sericite and possess a Cu-Au-Co-Ni-As-Mo-U-(LREE) (light rare earth element) signature reminiscent of some calcic iron skarns around diorite intrusions. Scant observations suggest that massive calcite veins and, at shallower palaeodepths, extensive zones of barren pyritic feldspar-destructive alteration may be indicators of concealed IOCG deposits.

The balance of evidence strongly supports a genetic connection of the central Andean IOCG deposits with gabbrodiorite to diorite magmas from which the ore fluid may have been channelled by major ductile to brittle fault systems for several kilometres vertically or perhaps even laterally. The large, composite IOCG deposits originated by ingress of the ore fluid to relatively permeable volcano-sedimentary sequences. The mafic magma may form entire plutons or, alternatively, may underplate more felsic intrusions, as witnessed by the ore-related diorite dykes, but in either case the origin of the ore fluid at greater, unobserved depths may be inferred. It is concluded that external 'basinal' fluids were not a requirement for IOCG formation in the central Andes, although metamorphic, seawater, evaporitic or meteoric fluids may have fortuitously contaminated the magmatic ore fluid locally. The proposed linkage of central Andean and probably some other IOCG deposits to oxidised dioritic magmas may be compared with the well-documented dependency of several other magmatic-hydrothermal deposit types on igneous petrochemistry. The affiliation of a spectrum of base-metal poor gold-(Bi-W-Mo) deposit styles to relatively reduced monzogranite-granodiorite intrusions may be considered as a closely analogous example.

Keywords Iron oxide-copper-gold deposits · Metallogeny · Central Andes · Diorite · Extensional tectonics · Volcano-plutonic arcs

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Introduction

Iron oxide-copper-gold (IOCG) deposits comprise a broad and ill-defined clan of mineralization styles which, as the name implies, are grouped together chiefly because they contain hydrothermal magnetite and/or specular hematite as major accompaniments to chalcopyrite ± bornite (e.g. Ray and Lefebure 2000). Besides the copper and by-product gold, the deposits may also contain appreciable amounts of Co, U, REE, Mo, Zn, Ag and other elements. IOCG deposits currently account for <5 and <1%, respectively, of the world's annually mined copper and gold production, much of it derived from Olympic Dam and Ernest Henry in Australia and Candelaria and Mantoverde in Chile. Notwithstanding their modest economic contributions, IOCG deposits have become fashionable exploration and research objectives over the past few years.

One of the best developed, but perhaps rather poorly appreciated, IOCG provinces is located in the South American Coastal Cordillera and immediately adjoining areas of northern Chile and southern Peru (latitudes 13–33°30′S; Fig. 1), where it is closely associated with Mesozoic batholiths and major arc-parallel fault systems. The origin of IOCG deposits has recently become the subject of considerable debate, with both metal-bearing magmatic brine (e.g. Hitzman et al. 1992; Pollard 2000) and external 'basinal' brine heated by intrusions (e.g. Barton and Johnson 1996; Hitzman 2000) being proposed as viable ore-forming fluids. In view of the fact that the central Andean IOCG province is the world's youngest, is largely unaffected by the complicating effects of later metamorphism and deformation and is relatively well documented geologically, it provides an ideal example with which to assess the competing genetic models. Understanding the origin of

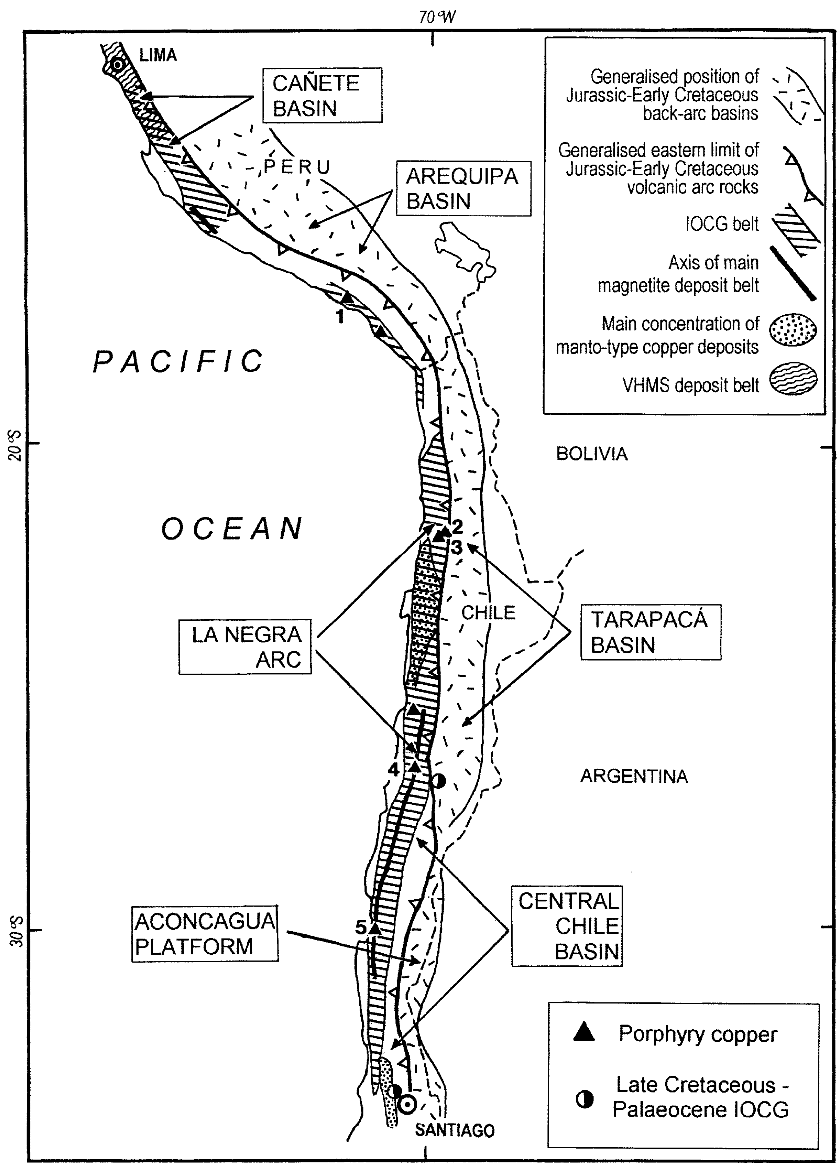

Fig. 1 Position of the central Andean IOCG belt of northern Chile–southern Peru with respect to the Jurassic–Early Cretaceous magmatic arc and a series of interconnected back-arc basins along its eastern side. Approximate locations of arc segments and intra- and back-arc basins mentioned in the text are shown. Also marked are: two post-Early Cretaceous IOCG deposits located east of the main IOCG belt; axes of the two main belts of 'Kiruna-type' massive magnetite deposits; the two main concentrations of manto-type copper-(silver) deposits; the area occupied by VHMS deposits; and selected Jurassic and Early Cretaceous porphyry copper-(gold) deposits (*1* Tía María; *2* Galenosa-Puntillas; *3* Antucoya-Buey Muerto; *4* Mercedita; *5* Andacollo)

IOCG deposits is, of course, also fundamental to their effective exploration.

This article reviews the geological and metallogenic settings of the IOCG province in the Coastal Cordillera of Chile and Peru and then the styles and salient features of the IOCG deposits themselves, with particular emphasis on smaller, higher-grade deposits as well as the large, better-documented examples like Candelaria and Mantoverde (Table 1). On balance, the evidence favours a magmatic-hydrothermal origin for central Andean IOCG deposits, besides revealing several features and relationships of potential use during deposit- and district-scale exploration.

Geological setting

General features

In the Coastal Cordillera and immediately adjoining physiographic regions of northern Chile and southern Peru, major Mesozoic plutonic complexes are emplaced into broadly contemporaneous arc and intra-arc volcanic products and underlying penetratively deformed metasedimentary units of Palaeozoic age. Early Proterozoic cratonic basement of the Arequipa-Antofalla massif underpins the central segment of the Coastal Cordillera (Shackleton et al. 1979) and the adjoining Andean Cordillera, between about latitudes 14 and 26°S (Ramos and Aleman 2000). Extensive longitudinal brittle fault systems and/or ductile shear zones, including the Atacama Fault System in northern Chile (e.g. Scheuber and Andriessen 1990) and deeply penetrating faults that localised the Cañete basin in Peru (Atherton and Aguirre 1992), were active during the Mesozoic volcanism and plutonism. Widespread extension induced tilting of the volcano-sedimentary sequences. Immediately east of the Mesozoic arc terrane of the Coastal Cordillera in northern Chile and southern Peru, sedimentary sequences accumulated in a series of interconnected, predominantly marine back-arc basins (Mpodozis and Ramos 1990).

Early to mid-Jurassic through mid-Cretaceous volcanism and plutonism throughout the Coastal Cordillera and immediately adjoining regions are generally considered to have taken place under variably extensional conditions in response to retreating subduction boundaries (slab roll-back) and steep, Mariana-type subduction (Mpodozis and Ramos 1990; Grocott and Taylor 2002). Nevertheless, Atherton and Aguirre (1992) questioned the existence of subduction during the Early Cretaceous in southern Peru and favoured extension at a passive continental margin. Throughout much of the Coastal Cordillera of northern Chile and southern Peru, western portions of the Mesozoic arc terrane (and the corresponding fore-arc) seem likely to have been removed by subduction erosion or lateral translation (Rutland 1971; Dalziel 1986; Mpodozis and Ramos 1990) or, at the very least, lie below sea level.

Volcano-sedimentary rocks

The Middle to Late Jurassic La Negra Formation, up to 5,000–10,000 m of subaerial to locally shallow-submarine basalt, basaltic andesite and andesite lavas, tuffs and minor intercalated sedimentary rocks, and correlative formations comprise the arc and intra-arc

Table 1 Tonnage and grade of selected IOCG deposits, central Andes

Deposit (Fig. 4)	Tonnage[a] (million tonnes)	Cu(%)	Au(g/t)	Ag(g/t)	Data source
Raúl-Condestable, Peru	>25	1.7	0.9	6	de Haller et al. (2002)
Eliana, Peru	0.5	2.7			Injoque (2002)
Monterrosas, Peru	1.9	1.0–1.2	6	20	Injoque (2002)
Mina Justa, Peru	209	0.86	Minor	Present	Rio Tinto Mining and Exploration Ltd. (unpublished data, 2003)
Cobrepampa, Peru	3–5	2–5	Present	15	Injoque (2002)
Tocopilla, Chile	~2.4 (0.31)	3.1 (16)	Present locally		Ruiz and Peebles (1988)
Montecristo, Chile	~15	1.6	0.6		J. Esquivel (personal communication, 2003)
Cerro Negro, Chile	249 (49)	0.4 (0.71)	~0.15		Atna Resources (press release, 2002)
Teresa de Colmo, Chile	70	0.8	Trace		Hopper and Correa (2000)
Mantoverde, Chile	~230 oxide, >400 sulphide	0.55 oxide, 0.52 sulphide	0.11		Zamora and Castillo (2001)
Candelaria, Chile	470	0.95	0.22	3.1	Marschik et al. (2000)
Punta del Cobre, Chile	~120	1.5	0.2–0.6	2–8	Marschik and Fontboté (2001b)
Carrizal Alto, Chile	3	5			Ruiz et al. (1965)
Panulcillo, Chile	~3 (10.4)	2.7–3.5 (1.45)	Up to 0.1		Hopper and Correa (2000)
Tamaya, Chile	>2 (0.9)	12 (20)			Ruiz and Peebles (1988)
Los Mantos de Punitaqui, Chile	~2 (gold zone only)		4		R. Muhr (personal communication, 1998)
El Espino, Chile	~30	1.2	0.15		Correa (2003)
La Africana, Chile	3.3	2.5			N. Saric (personal communication, 2003)

[a]Cumulative production and/or reserves, only approximate for mines active before the 20th century
Alternative tonnage and corresponding Cu grade

successions in northern Chile (Boric et al. 1990; Pichowiak 1994; Figs. 1 and 2). La Negra lavas overlap the tholeiitic and calc-alkaline compositional fields (Pichowiak et al. 1990). The volcanic arc appears to have been topographically subdued and to have developed close to sea level (Fig. 2). Late Jurassic to Early Cretaceous arc volcanism occurred along the eastern side of the Coastal Cordillera, at least from latitudes 26–29°S, where it is represented by up to 3,000 m of basaltic andesite, andesite and dacite volcanic rocks now assigned to the Punta del Cobre Group (Lara and Godoy 1998), host to the Candelaria-Punta del Cobre IOCG district (e.g. Marschik and Fontboté 2001a).

The Jurassic and Early Cretaceous back-arc domain between latitudes 21 and 27°S in northern Chile, the Tarapacá basin (Fig. 1), is dominated by marine carbonate and continental terrigenous sequences, although interbedded andesitic volcanic rocks also occur locally (Muñoz et al. 1988; Mpodozis and Ramos 1990; Ardill et al. 1998). Evaporite horizons appear locally, especially in the Late Jurassic (Fig. 2; Boric et al. 1990; Ardill et al. 1998). In the back-arc basin of central Chile (Aconcagua Platform; Fig. 1), south of about latitude 31°30′S, a Jurassic marine carbonate sequence, including a thick gypsum horizon, is overlain by Late Jurassic continental red beds and Early Cretaceous marine carbonates, while

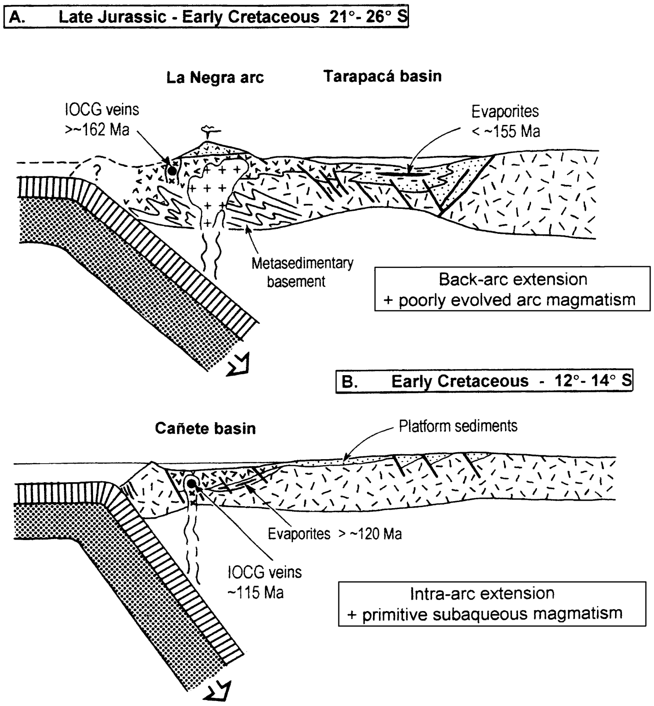

Fig. 2 Schematic tectonic sections of the central Andean margin at **A** latitudes 21–26°S in the Late Jurassic–Early Cretaceous and **B** latitudes 12–14°S in the Early Cretaceous, showing steep subduction at a retreating convergent boundary. Note in **A** that IOCG deposits occur in a subaerial arc paralleled eastwards by a sediment-dominated back-arc basin, whereas in **B** IOCG deposits occur in a subaqueous intra-arc basin. Approximate ages of evaporites and IOCG deposits (see text) are also shown. Sections adapted from Ramos and Aleman (2000)

farther west up to 5,000 m of Early Cretaceous volcanic and volcaniclastic sedimentary rocks accumulated in an intra-arc basin formed in response to vigorous extension (Aberg et al. 1984; Mpodozis and Ramos 1990; Ramos 2000). Most of the volcanic rocks range in composition from basalt to andesite and are high-K calc-alkaline to shoshonitic in composition; parts of the sequence display compositional bimodality (Levi et al. 1988).

Mesozoic arc rocks in southern Peru include the Río Grande and Chala Formations of mid-Jurassic age, both of which comprise basaltic andesite of medium- to high-K calc-alkaline affinity (Romeuf et al. 1995). The back-arc domain includes the Arequipa basin (Fig. 1) in which up to 1,500 m of Early Jurassic basaltic volcanic rocks belonging to the Chocolate Formation are overlain by several thousand metres of mainly terrigenous, Middle to Late Jurassic sedimentary rocks (Vicente 1990; Sempere et al. 2002a, 2002b). The Cañete basin (Fig. 1), the southern portion of the West Peruvian trough (Wilson 1963), is dominantly Early Cretaceous in age (Cobbing 1978) and probably best interpreted as a product of advanced intra-arc extension (Ramos and Aleman 2000). The Copará and Quilmaná Formations in the Cañete basin are dominated by high-K calc-alkaline to shoshonitic basalt and basaltic andesite, although subordinate dacite and rhyolite impart a bimodal signature to the latter formation (Atherton and Aguirre 1992). These volcanic formations are underlain by a clastic-carbonate succession containing very minor amounts of evaporite minerals (Palacios et al. 1992).

The Jurassic and Early Cretaceous arc and intra-arc sequences throughout the Coastal Cordillera are dominated by basaltic andesite, appear to possess greater amounts of lava than other volcanic or volcaniclastic products and lack volumetrically important felsic volcanic rocks. Furthermore, there is little evidence of major volcanic edifices typical of most subduction-related arc terranes, and the volcanic environment may well have been more akin to flood basalt provinces.

Low-grade, non-deformative, diastathermal (burial) metamorphism induced by elevated geothermal gradients consequent upon crustal thinning was active during accumulation of all the Mesozoic arc and intra-arc volcanic sequences, with the resulting metamorphic grade commonly attaining the prehnite-pumpellyite facies and, at depth, greenschist facies (Levi et al. 1989; Atherton and Aguirre 1992). This low-grade regional metamorphism is not directly related to pluton emplacement, which gave rise to fairly restricted and easily distinguishable contact aureoles similar to that related to the Tierra Amarilla batholith near the Candelaria IOCG deposit (Tilling 1976; Marschik and Fontboté 1996, 2001b).

Plutonic rocks

The plutonic complexes, ranging in composition from primitive early gabbro and diorite through quartz diorite and quartz monzodiorite to tonalite and granodiorite and, uncommonly, monzogranite were emplaced throughout the Jurassic and Early Cretaceous as a series of relatively short pulses, each estimated to last roughly 3 to14 M.Y. where extensively dated between latitudes 25°30′ and 27°30′S (Dallmeyer et al. 1996; Lara and Godoy 1998; Grocott and Taylor 2002). Hence, unsurprisingly, multiple ages of any particular intrusive rock type occur throughout the Coastal Cordillera; for example, the early gabbros from latitudes 23–24°S in northern Chile are dated at 196–185 Ma (Early Jurassic) (Pichowiak et al. 1990), whereas those farther north in the Cañete basin of Peru are clearly assignable to the mid-Cretaceous (Regan 1985). Plutons are irregular in outline but markedly elongate parallel to the orogen, northerly in northern Chile and northwesterly in southern Peru. Typical plutons exceed 50 km in longitudinal dimensions. During the Mesozoic, the locus of plutonism in northern Chile migrated ~50 km or so eastwards to reach the eastern border of the Coastal Cordillera by the Early Cretaceous (Farrar et al. 1970; Berg and Baumann 1985; Parada 1990; Dallmeyer et al. 1996; Lara and Godoy 1998; Fig. 3), and an apparently similar but still poorly defined progression also took place in southern Peru (Clark et al. 1990).

Abundant andesite, basaltic andesite and basalt dykes cut many of the plutons and their host rocks (e.g. Pichowiak and Breitkreuz 1984; Regan 1985; Scheuber and Gonzalez 1999; Taylor and Randall 2000; Sempere et al. 2002b). Both synplutonic emplacement features (Moore and Agar 1985; Regan 1985) and radiometric dating (Dallmeyer et al. 1996) show that the dykes are broadly synchronous with host or nearby plutons. Furthermore, individual dyke swarms tend to be centred on single plutonic complexes, beyond which they cannot be traced very far (Taylor and Randall 2000).

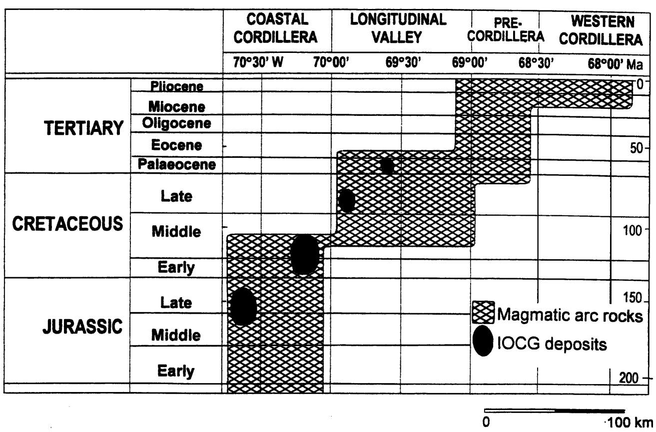

Fig. 3 Generalised spatial and temporal distributions of magmatic arc rocks (from Hammerschmidt et al. 1992) and IOCG deposits (this study) in northern Chile. Note the systematic eastward migration of both the arc and contained mineralization, and the marked decline of IOCG mineralization from the Late Cretaceous onwards

In northern Chile and southern Peru, the Jurassic and Early Cretaceous intrusive rocks, most of them hornblende-bearing, are largely metaluminous and calc-alkaline (Parada 1990; Pichowiak 1994), although early gabbros are tholeiitic in character (Regan 1985; Pichowiak et al. 1990). All the intrusive rocks are oxidised and belong to the magnetite-series (Ishihara and Ulriksen 1980). Initial strontium isotope ratios for plutonic rocks decrease markedly eastwards across the Coastal Cordillera of northern Chile, in general from 0.704–0.705 for the Middle–Late Jurassic to 0.703–0.704 for the Early Cretaceous rocks (McNutt et al. 1975; Berg and Baumann 1985; Pichowiak 1994; Parada et al. 1999), a pattern that may be interpreted to imply maximal extension and crustal thinning and, as a consequence, minimal crustal contamination during the Early Cretaceous period. Nevertheless, the mantle wedge remained the main site of magma generation throughout the Jurassic–Early Cretaceous interval (Rogers and Hawkesworth 1989).

The plutonic complexes of the Coastal Cordillera between about latitudes 26 and 27°30′S were emplaced syntectonically during the Early to Middle Jurassic as gently inclined, sheet-like bodies up to several kilometres thick, controlled by east-dipping extensional fault systems (Grocott et al. 1994; Grocott and Taylor 2002), but thereafter probably as steep, slab-like bodies localised by ductile shear zones (Grocott and Wilson 1997). Roof lifting and floor depression both enabled pluton emplacement (Grocott and Taylor 2002). In accord with this intrusion mechanism, the outcropping plutons were emplaced at relatively high crustal levels, $<\sim$10 km between about latitudes 22 and 28°S (Dallmeyer et al. 1996; Scheuber and Gonzalez 1999), and cooled rapidly as shown by concordance between U-Pb zircon ages and $^{40}Ar/^{39}Ar$ isotope-correlation ages (Berg and Baumann 1985; Dallmeyer et al. 1996), as well as by relatively restricted (<4 km) contact-metamorphic aureole development.

The Coastal Cordillera became amagmatic after ~90 Ma, and most of the Late Cretaceous and younger plutonism, including emplacement of the main Coastal Batholith of southern Peru, was restricted to belts farther east (Cobbing 1985; Taylor et al. 1998; Grocott and Taylor 2002).

Structural elements

The Atacama Fault System follows the axis of the Coastal Cordillera for >1,000 km between about latitudes 20 and 30°S where it is made up of a series of concave-west segments comprising NNW-, N- and NNE-striking ductile and brittle faults which underwent variable motion, including sinistral strike-slip (e.g. Hervé 1987; Scheuber and Andriessen 1990; Brown et al. 1993). Transient ductile deformation, charted by greenschist and amphibolite facies mylonites (Scheuber and Andriessen 1990; Scheuber et al. 1995), occurred at shallow crustal levels (< 10 km) in close association with Mesozoic pluton emplacement, but gave way to brittle behaviour during arc cooling (Brown et al. 1993). The brittle faults tend to be localised by pre-existing mylonite zones, commonly along pluton margins (Brown et al. 1993). Fault displacement on the Salado segment of the Atacama Fault System, between latitudes 25 and 27°S, changed from normal slip to left-lateral transtension at ~132 Ma (Grocott and Wilson 1997; Grocott and Taylor 2002), as apparently it also did as far north as latitude 22°S (Scheuber and Gonzalez 1999). Nevertheless, sinistral motion of Jurassic (pre-155 Ma) age has been interpreted between latitudes 22 and 26°S (Scheuber et al. 1995; Scheuber and Gonzalez 1999). The Atacama Fault System is the best documented of three principal orogen-parallel fault systems in the Coastal Cordillera between latitudes 25°30′ and 27°S, where it is paralleled westwards and eastwards, respectively, by the ductile to brittle Tigrillo and Chivato systems (Grocott and Taylor 2002; Fig. 5). The three fault systems, in concert with the plutonism, young eastwards from Jurassic–Early Cretaceous in the case of the normal-slip Tigrillo system to Early Cretaceous for the left-oblique extensional Chivato system. East-side-down displacement on the fairly shallowly inclined Tigrillo fault exceeds 1 km, and only a few kilometres of strike-slip offset are deduced for the Atacama Fault System (Grocott and Taylor 2002).

In southern Peru, a series of poorly known, orogen-parallel faults exist in the arc terrane, including the Cañete intra-arc basin, as well as localising the Arequipa back-arc basin. The prominent Treinta Libras fault zone along the eastern margin of the Coastal Cordillera underwent dextral strike-slip motion in the Jurassic–Early Cretaceous, and is marked by a broad dyke swarm (Caldas 1978; Injoque et al. 1988).

During the early Late Cretaceous, transpression triggered by final opening of the Atlantic Ocean basin caused tectonic inversion of the formerly extensional back-arc basins (Mpodozis and Ramos 1990; Ladino et al. 1997). At the same time, the Chivato fault system, a set of northwest-striking transverse faults throughout the Coastal Cordillera and other structural elements between at least latitudes 18 and 30°S, underwent reactivation in the transpressive regime (Taylor et al. 1998; Grocott and Taylor 2002). Positive tectonic inversion also affected southern Peru in the early Late Cretaceous (Benavides-Cáceres 1999) and caused demise of the Cañete basin (Cobbing 1985). The far more subdued deformation in the Coastal Cordillera of northern Chile and southern Peru since the mid-Cretaceous took place in a fore-arc setting.

Metallogenic setting

The Coastal Cordillera of northern Chile and southern Peru is endowed with iron, copper and subordinate gold, silver and zinc resources, all of mainly Early Jurassic to mid-Cretaceous age. In addition to the IOCG deposits highlighted in this article, 'Kiruna-type' massive magnetite-(apatite), porphyry copper-(gold), manto-type copper-(silver) and volcanic hosted massive sulphide (VHMS) zinc-copper-barite deposits are the principal ore types.

Magnetite deposits

The massive magnetite deposits occupy the same belt as many of the IOCG deposits over a longitudinal distance of nearly 700 km between latitudes 25 and 31°S in northern Chile and a similar distance in southern Peru, although large deposits there are far more restricted in latitudinal extent (Fig. 1). Many investigators subscribe to a hydrothermal-replacement origin for the magnetite and minor associated actinolite and apatite (e.g. Ruiz et al. 1965, 1968) and locally developed clinopyroxene (e.g. Fierro Acarí, southern Peru; Injoque 2001), although some advocate emplacement mainly as intrusions and minor extrusions of iron oxide melt (e.g. Espinoza 1990; Nyström and Henríquez 1994; Naslund et al. 2002). A number of small magnetite deposits occur as veins in diorite intrusions, which both Ménard (1995) and Injoque (2001) favour as the magmatic-fluid source for the magnetite deposits in general. Several large magnetite deposits, including El Romeral and El Algarrobo in northern Chile, are steep, lens-like bodies within intrusion-bounded screens of Early Cretaceous andesitic volcanic rocks along strands of the Atacama Fault System (Ruiz et al. 1968; Bookstrom 1977). However, the major Marcona deposit in Peru is different, being a series of strata-bound bodies (mantos) replacing principally early Palaeozoic but also Jurassic (Río Grande Formation) carbonate horizons west of, rather than within, the major Treinta Libras fault zone (Injoque et al. 1988; Injoque 2002).

Inclusion of the magnetite deposits as end-members of the IOCG clan (Hitzman et al. 1992) is supported by the abundance of early-stage magnetite in many IOCG deposits, the occurrence of late-stage pyrite, chalcopyrite and gold in and near some massive magnetite deposits (e.g. Marcona, El Romeral, Cerro Negro Norte; Bookstrom 1977; Injoque et al. 1988; Vivallo et al. 1995) and the commonality of certain alteration and gangue minerals, especially actinolite and apatite, although nowhere are the two deposit types observably transitional. Nevertheless, magnetite veins and lens-like bodies occur widely in both Jurassic and Early Cretaceous IOCG vein districts, including some of the more important ones like Los Pozos (Mantoverde; Vila et al. 1996), Naguayán and Montecristo (Boric et al. 1990). There are also several examples of IOCG deposits located alongside major concentrations of massive magnetite (e.g. Mina Justa in the Marcona district; Moody et al. 2003). Thus, the genetic model for the massive magnetite bodies in the Coastal Cordillera is likely to possess major components in common with that preferred for the IOCG deposits.

Porphyry copper deposits

Porphyry copper deposits, some relatively enriched in gold, are distributed throughout the Coastal Cordillera of northern Chile (Fig. 1), where most of them appear to be of Early Cretaceous age (~135–100 Ma) (Munizaga et al. 1985; Boric et al. 1990; Perelló et al. 2003). The best-known deposit, and the only producer, is Andacollo where a zone of supergene chalcocite enrichment is exploited; however, several others have been extensively drill tested (e.g. Galenosa-Puntillas, Antucoya-Buey Muerto, Mercedita; Fig. 1). Several prospects also exist in the Coastal Cordillera of southern Peru (Fig. 1), where Tía María is likely to be Jurassic in view of available radiometric ages for nearby plutonic rocks (Clark et al. 1990). The deposits are typically much smaller (<~300 million tonnes) than those in the Tertiary porphyry copper belts farther east (Fig. 4), and hypogene grades are relatively low (up to ~0.4% Cu). The deposits are related to small stocks of quartz diorite to granodiorite porphyry emplaced into arc plutonic or volcanic rocks, and tend to be dominated by potassic alteration.

The porphyry copper and IOCG deposits in the Coastal Cordillera are readily distinguishable because the potassic alteration and copper-(gold) mineralization in the former are centred on, and largely confined to, porphyry stocks, which are absent from the latter. Furthermore, the characteristic quartz veinlets containing all or part of the chalcopyrite in the porphyry copper deposits as well as the pyrite-dominated, sericite-bordered D-type veinlets are also absent from the IOCG deposits, and the iron oxides that define the IOCG class are sparsely represented in the porphyry copper deposits.

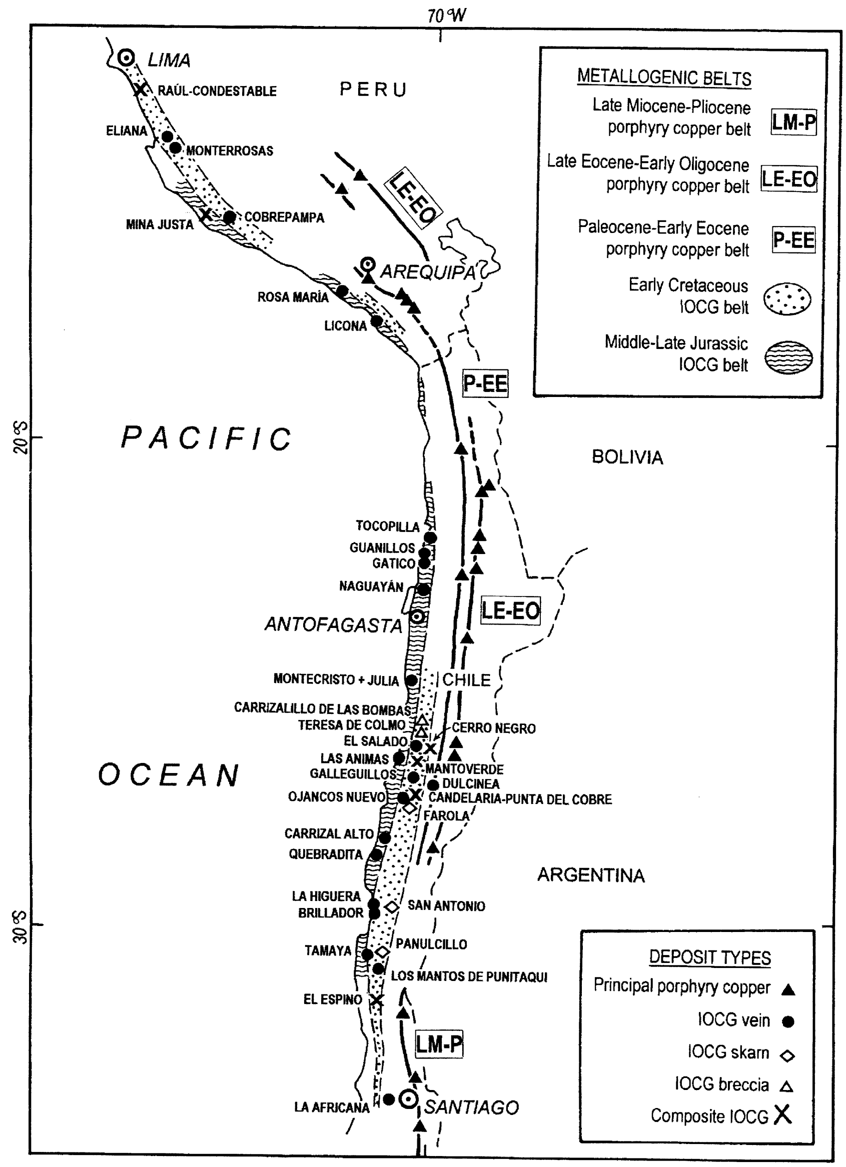

Fig. 4 Subdivision of the central Andean IOCG province into western Middle–Late Jurassic and eastern Early Cretaceous belts, showing distribution of different deposit styles discussed in the text. Also marked are axes of Palaeocene–Early Eocene, Late Eocene–Early Oligocene and Late Miocene–Pliocene porphyry copper belts, including locations of principal deposits

Manto-type copper deposits

Manto-type copper deposits occur as strata-bound disseminated bodies, as steep hydrothermal breccias around barren, finger-like gabbro to diorite plugs and as related veins, mostly within basaltic to andesitic arc volcanic sequences of the La Negra Formation between latitudes 22 and 25°S (Fig. 1). However, the largest deposit, Mantos Blancos, is unusual in being partly hosted by felsic volcanic rocks and plugs (Ramírez 1996). Broadly similar copper-silver deposits, including El Soldado, are widespread in the Early Cretaceous volcanic and sedimentary rocks of the Central Chile intra-arc basin (e.g. Fig. 1; Maksaev and Zentilli 2002).

The highest-grade parts of manto-type deposits, typically controlled by the permeability provided by faults, hydrothermal breccias, dyke contacts, vesicular flow tops and flow breccias, are characterised by hypogene chalcocite and bornite, which grade outwards and downwards through chalcopyrite to minor distal concentrations of pyrite. The chalcocite-bornite cores of large deposits commonly abut original redox boundaries in the host stratigraphic packages and are overlain or flanked by sulphide-deficient zones containing hypogene hematite (Sillitoe 1992; Kirkham 1996). Albite, quartz and chlorite are the main alteration minerals in the cores of the deposits. Opinion is divided between magmatic-hydrothermal (e.g. Holmgren 1987; Wolf et al. 1990) and metamorphogenic (e.g. Sato 1984; Sillitoe 1990, 1992) fluid origins for the manto-type deposits, although the latter alternative is favoured by the obvious similarities to stratiform, sediment-hosted copper deposits (Kirkham 1996). Nevertheless, emplacement of plutonic complexes may have been instrumental in causing the fluid circulation that resulted in manto-type copper formation (Maksaev and Zentilli 2002).

The manto-type deposits comprise a distinctive class of copper mineralization uncommon outside the Coastal Cordillera of northern and central Chile (Sillitoe 1992; Kirkham 1996). Although many manto-type copper deposits contain albite alteration, calcite and minor hematite, and some are spatially related to gabbro and diorite bodies—features shared with some central Andean IOCG deposits (see below)—the manto-type style appears to be distinguished by its asymmetrical sulphide-oxide zonation and marked deficiency in gold. Caution is necessary, however, because it will be recalled that the breccia-hosted IOCG deposit at Olympic Dam in South Australia is also characterised by similar asymmetrical sulphide-oxide zonation, with distal pyrite giving way through chalcopyrite and bornite-chalcocite to overlying hematite (Reeve et al. 1990).

Notwithstanding these apparent differences, some investigators treat at least selected large manto-type deposits (e.g. Mantos Blancos) as members of the IOCG class (Williams 1999; Pollard 2000), include the two deposit types in a broader manto-type category (Injoque 2000) or propose that manto-type deposits are shallow manifestations of the IOCG type (Vivallo and Henríquez 1998; Orrego et al. 2000). However, manto-type deposits are apparently nowhere observed to be directly related or transitional to IOCG deposits; while an intimate genetic connection cannot be precluded at present, substantive geological support is a clear necessity.

VHMS deposits

Several VHMS deposits of Kuroko type were formed in central and northern Peru during the Early Cretaceous. The VHMS belt overlaps with the northern recognised limit of the IOCG belt in the Cañete intra-arc basin (Fig. 1; Injoque 2000). The deposits display classic massive and stringer types of mineralization and are particularly noted for their zinc and barite contents (Vidal 1987), although copper besides zinc is important at Cerro Lindo, the most southerly deposit (Ly 2000). These ore textures and metal contents, besides the deficiency of magnetite and hematite, clearly distinguish the Peruvian VHMS from central Andean IOCG deposits.

IOCG deposits

Sites of mineralization

In northern Chile, mainly between latitudes 22 and 31°S, most of the IOCG deposits are hosted by the La Negra Formation arc volcanics and their stratigraphic equivalents farther south as well as by the Late Jurassic and Early Cretaceous plutons that intrude them (Table 2). Candelaria-Punta del Cobre and some smaller IOCG deposits, however, were generated near Early Cretaceous plutons emplaced near the contact between Late Jurassic–Early Cretaceous volcanogenic sequences (Punta del Cobre Group) and Neocomian marine carbonate sequences. Most IOCG deposits documented from southern Peru, between latitudes 12°30′ and 14°S, are confined to the Cañete intra-arc basin (Fig. 1). The copper-bearing Marcona magnetite district, including the Mina Justa IOCG deposit, and several minor magnetite and IOCG deposits farther south pre-date formation of the Cañete basin and occur within the Jurassic arc terrane (Fig. 4).

The latitudinal extent of Mesozoic IOCG deposits in the central Andes is closely comparable with that of Tertiary porphyry copper deposits (Fig. 4), although known IOCG deposits are apparently few and relatively minor between latitudes 16 and 22°S where the westernmost part of the IOCG belt may now lie beneath sea level. The Coastal Cordillera IOCG province spans three structurally, stratigraphically and metallogenically distinct tectonic segments of long standing, and is delimited by fundamental transverse segment boundaries at roughly latitudes 13° (the Pisco-Abancay deflection) and 33°30′S.

Table 2 Selected geological features of principal IOCG deposits, central Andes

Deposit (Fig. 4)	Host rocks	Principal ore control	Closely related intrusive rock(s)	Deposit age (Ma)	Deposit style	Ore-related alteration	Main hypogene opaque minerals	Associated metals	Data source(s)
Raúl-Condestable	Andesitic lava, tuff, limestone	NW, NE faults	Diorite body, dacite porphyry dykes	~115	Veins, mantos, disseminated bodies	Scapolite, albite, actinolite	Mg, hem, py, cp, po	Co, Mo, Zn, Pb, As, LREE	Vidal et al. (1990); de Haller et al. (2002)
Eliana	Gabbrodiorite, volcaniclastic siltstone	Base of sill	Gabbrodiorite sill	114–112	Mantos	Amphibole, scapolite	Mg, py, cp	As, Zn, Mo, Co	Vidal et al. (1990)
Monterrosas	Gabbrodiorite	N70°W fault	Gabbrodiorite		Vein	Actinolite, epidote, chlorite, scapolite	Mg, cp, py, po	Zn, Co, Mo, Pb	Vidal et al. (1990)
Mina Justa	Andesitic volcaniclastics, andesite porphyry sill	NE listric normal fault	Andesite porphyry dykes, dacite porphyry dykes	160–154	Irregular vein-like replacement body	Actinolite, K-feldspar, chlorite, clinopyroxene, apatite	Mg, cp, bn, cc, py		Moody et al. (2003)
Cobrepampa	Monzonite-diorite	NW faults	Monzonite-diorite pluton		Veins	K-feldspar, actinolite, garnet, tourmaline	Mg, hem, py, cp, bn	Co, Mo, Zn, Pb	Injoque (2002)
Tocopilla	Diorite-granodiorite	N70°E faults and fractures	Mafic dykes	~165	Multiple veins (6 main veins), local stockworks	Uncertain	Mg, hem, py, cp	Mo, U, Co, Ni, Zn, Sb, As	Ruiz et al. (1965)
Gatico	Quartz diorite-granodiorite	N80°W, N70°E faults and fractures	Mafic dykes		Veins	Chlorite	Mg, py, cp, bn	As, Mo, U, Co, Ni	Boric et al. (1990)
Julia	Granodiorite	N-N10°E fault	Diorite-gabbro dyke (30 m wide)	~164	Veins	Chlorite, epidote, albite	Hem, mg, cp, bn, py	Mo	Boric et al. (1990)
Teresa de Colmo	Andesitic volcanics and volcaniclastics	NNW, WNW faults	Diorite body and dykes		Breccia pipe	Albite, chlorite	Hem, cp, py		Hopper and Correa (2000)
Cerro Negro	Andesitic lava and tuff	NNE faults	Diorite pluton		Breccia mantos, stockworks, veins	Sericite, chlorite	Hem, mg, cp, bn		Gelcich et al. (1998)
El Salado	Andesitic lava	NE fault	Diorite dykes		Veins	Biotite, chlorite, sericite, epidote, scapolite	Mg, hem, py, cp	Zn	Gelcich et al. (1998)
Las Animas	Diorite and metasedimentary rocks	N60–90°W faults and fractures	Microdiorite bodies	~162	Veins	Actinolite, biotite, K-feldspar, epidote	Mg, py, cp	U, As, Zn	Gelcich et al. (1998)
Mantoverde	Andesitic lava and volcaniclastics	N15–20°W fault	Diorite dykes	123–117	Vein breccia, stockworks, breccia manto	K-feldspar, chlorite, sericite	Hem, mg, py, cp	LREE	Vila et al. (1996)
Dulcinea	Andesitic lava and tuff	N10°W fault	Mafic dyke	65–60	Vein	Chlorite, sericite	Hem, mg, py, cp	Mo, Zn, Pb	Ruiz et al. (1965)
Candelaria-Punta del Cobre	Andesitic-basaltic lava and volcaniclastics	NW, NNW faults	Diorite and dacite dykes	116–114 or 112–110	Mantos, breccias, veins, stockworks	Biotite, K-feldspar, quartz, actinolite/chlorite, albite, sericite	Mg, hem, cp, py, po	Mo, LREE, Zn, As	Marschik and Fontboté (2001b)
Carrizal Alto	Diorite	N50–70°E faults	Mafic dykes	~150	Veins	Chlorite, actinolite, epidote, quartz	Py, ars, po, cp, mg	Mo, Co, As, U	Ruiz et al. (1965)
Panulcillo	Limestone and andesitic volcanics	NNW fault	Diorite intrusion	~115	Skarn horizons, volcanic-hosted lenses	Garnet, diopside, scapolite, amphibole, albite, K-feldspar, biotite	Cp, po, sph, py, mg, bn	As, Mo, Pb, Zn, Co, U	Hopper and Correa (2000); Sugaki et al. (2000)

Table 2 (Contd.)

Deposit (Fig. 4)	Host rocks	Principal ore control	Closely related intrusive rock(s)	Deposit age (Ma)	Deposit style	Ore-related alteration	Main hypogene opaque minerals	Associated metals	Data source(s)
Tamaya	Andesitic and trachytic volcanics, lutite	N10°E fault	Uncertain		Veins	Uncertain	Hem, mg, bn, cp, py	Mo, Ni, As	Ruiz et al. (1965)
Los Mantos de Punitaqui	Andesitic volcano-sedimentary rocks	NNE fault	Monzodiorite/diorite intrusion		Vein	Sericite	Hem, mg, cp, py	Hg	McAllister et al. (1950); Ruiz et al. (1965)
El Espino	Andesitic volcanics	N fault	Diorite intrusion	~108	Mantos, veins	Albite, epidote, chlorite, actinolite, sericite	Hem, mg, cp, py	Mo, Co	Correa (2003)
La Africana	Diorite	N10°W fault	Diorite		Vein	Chlorite, quartz	Cp, py, hem, mg		Saric (1978)

Mineral abrevations: *ars* arsenopyrite; *bn* bornite; *cp* chalcopyrite; *hem* hematite; *mg* magnetite; *po* pyrrhotite; *py* pyrite; *sph* sphalerite

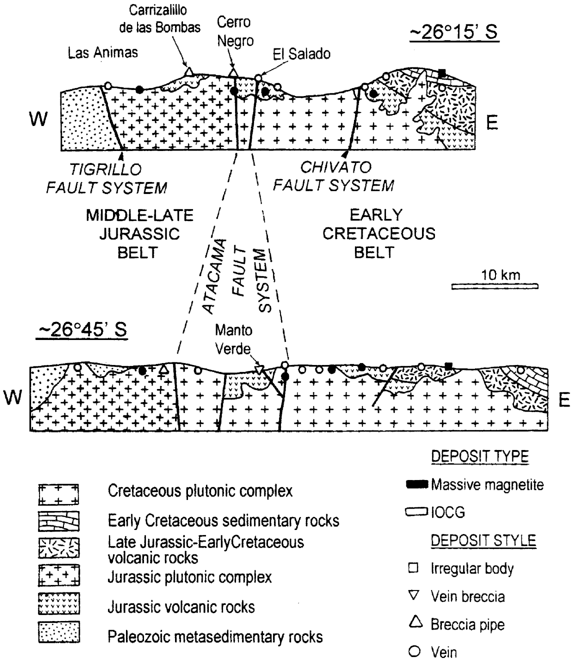

Fig. 5 Schematic east–west sections of the Middle–Late Jurassic and Early Cretaceous IOCG belts in northern Chile, showing distributions of plutonic, volcanic and sedimentary rocks and main fault systems. Selected IOCG and massive magnetite deposits, coded on the basis of deposit style, are projected onto the sections. Note the eastward migration of plutonic and volcanic rocks and their contained mineralization with time, the structural localisation of some of the deposits and the close spatial association between IOCG and magnetite deposits. Taken with slight modification from Espinoza et al. (1999) and Gelcich et al. (1998), with fault additions schematised from Grocott and Taylor (2002)

Metallogenic epochs

The relatively restricted radiometric age data, provided for gangue (actinolite) or alteration (biotite, sericite) minerals by the K-Ar method unless stated otherwise, suggest that the principal IOCG deposits in northern Chile and southern Peru were mainly generated in Middle–Late Jurassic (170–150 Ma) and Early Cretaceous (130–110 Ma) epochs (Fig. 4), although a few Late Cretaceous and Palaeocene examples are also known (Figs. 1 and 4). The metallogenic epochs migrated eastwards in concert with spatially related plutonic belts (Figs. 3, 4 and 5).

The Middle–Late Jurassic deposits are located near the Pacific coast. In northern Chile, they include Tocopilla (165 ± 3 Ma), Guanillos (167 ± 7 Ma), Naguayán (153 ± 5 Ma), Montecristo and Julia (164 ± 11 Ma; Boric et al. 1990), Las Animas (162 ± 4 Ma; Gelcich et al. 1998) and, based on ages of ~150 Ma for the host diorite pluton (Moscoso et al. 1982), probably Carrizal Alto. In southern Peru, the large Mina Justa deposit and other copper mineralization in the Marcona district (154 ± 4.0 and 160 ± 4.0 Ma; Injoque et al. 1988) and Rosa María (ca. 160 or 145 Ma; Clark et al. 1990) are assigned to the same overall metallogenic epoch.

Most of the major IOCG deposits and numerous smaller examples are located farther east in the Coastal Cordillera and are Early Cretaceous in age (Fig. 4). This epoch includes: Candelaria (116–114 Ma, $^{40}Ar/^{39}Ar$ and Re-Os; Marschik and Fontboté 2001b; Mathur et al. 2002; or 112–110 Ma, $^{40}Ar/^{39}Ar$; Ullrich and Clark 1999; Arévalo et al. 2000; Ullrich et al. 2001), Mantoverde (123 ± 3, 121 ± 3 and 117 ± 3 Ma; Vila et al. 1996; Orrego et al. 2000), Galleguillos (121 ± 4 Ma; R.H. Sillitoe and M. Orrego, unpublished data, 1999), Brillador (contiguous pluton dated at 108.5 Ma; Moscoso et al. 1982), Panulcillo (115 ± 3 Ma; R. Ardila in Sugaki et al. 2000) and El Espino (nearby pluton dated at 108 ± 3 Ma; Rivano and Sepúlveda 1991) in northern Chile; and Raúl-Condestable (116.5–113 Ma, U-Pb on sphene; de Haller et al. 2002; A. de Haller, personal communication, 2003) and Eliana (115 ± 5.0 and 113 ± 3.0 Ma; Vidal et al. 1990) in southern Peru. Additionally, district-wide hydrothermal alteration at the Productora IOCG occurrence, near latitude 29°S, is centred on an albitised diorite intrusion (Ray and Dick 2002) dated at 129.8 ± 0.1 Ma (U-Pb, zircon; Fox 2000), although K-feldspar associated with the IOCG mineralization returned an average age of $\sim$91 Ma ($^{40}Ar/^{39}Ar$; Fox 2000; Fox and Hitzman 2001), probably due to re-setting during subsequent batholith emplacement (G.E. Ray, personal communication, 2003).

The largest of the younger IOCG deposits is Dulcinea, situated about 12 km east of the eastern border of the Coastal Cordillera (Figs. 1 and 4), which is hosted by a diorite-monzodiorite intrusion and andesitic metavolcanic rocks assigned ages of 65–60 Ma (Iriarte et al. 1996). The La Africana deposit, at the southern extremity of the IOCG belt and also previously mined formally, cuts a diorite of presumed Late Cretaceous age (Saric 1978). The El Espino deposit may also be Late Cretaceous or Palaeocene rather than Early Cretaceous, as stated above, if the Late Cretaceous–Palaeocene age favoured for the nearby diorite intrusion by Rivano and Sepúlveda (1991) is substantiated. A few small and less-important IOCG deposits, as well as several small massive magnetite deposits, of Late Cretaceous or Palaeocene age are also present immediately east of the Coastal Cordillera in northern Chile. Minor IOCG vein deposits also occur in the coastal batholith of Peru, where they are likely to be of Late Cretaceous age (Vidal 1985).

The age distribution of IOCG deposits and occurrences in the Coastal Cordillera is certainly more complex than the two broad epochs defined above would suggest, as witnessed by K-Ar ages obtained for numerous mineral occurrences, many containing iron oxides, copper and gold, in the Coastal Cordillera between latitudes 26 and 28°S (Díaz and Vivallo 2001). Based on the ages, these workers proposed four metallogenic epochs: 188–172, 167–153, 141–132 and 130–98 Ma, which coincide with four eastward-younging plutonic belts of broadly the same ages.

Tectonic controls

Only limited information is available on the detailed tectonic environments of IOCG formation in the Coastal Cordillera, although all major deposits were generated during regional extension or transtension, and localised by ductile to brittle faults and fractures of varied strike (Table 2). At least between latitudes 22 and 27°30′S, the Late Jurassic deposits were generated in association with normal fault systems displaying east-side-down displacements, whereas those dated as later than $\sim$132 Ma, essentially all the Early Cretaceous deposits, were localised by sinistral transtensional structures within or related to the Atacama and Chivato fault systems (Grocott and Wilson 1997; Scheuber and Gonzalez 1999; Grocott and Taylor 2002), but typically beyond the main north–south splays (Fig. 5). The control of the Mantoverde deposit, for example, has been interpreted as a strike-slip duplex or side-wall ripout (Brown et al. 1993; Taylor et al. 1998) or, alternatively, as a strike-slip relay ramp breached by the ore-controlling Mantoverde fault (C. Bonson in Grocott and Taylor 2002).

In contrast to the steep attitudes of most IOCG-controlling faults, a low-angle listric normal fault, >1 km in down-dip extent but giving rise to little apparent offset, in combination with a series of steep hanging-wall splays localised the Mina Justa IOCG deposit in the Marcona district of southern Peru (Moody et al. 2003). The fault may merge eastwards with the major Treinta Libras strike-slip fault zone (see above).

Most, but perhaps not all, of the ductile deformation in individual fault systems pre-dated related IOCG deposit formation, as clearly observed at Mantoverde and elsewhere. Syn-mineralization ductile shearing was, however, proposed at the Panulcillo deposit by Hopper and Correa (2000), and is observed to have been active during early magnetite introduction at several of the IOCG deposits. Opinion concerning the tectonic setting of the major Candelaria-Punta del Cobre deposit is divided: Martin et al. (1997) and Arévalo et al. (2000) believed that mineralization took place during transtension while low-angle ductile shearing was still active because of thermal mediation by the nearby plutonic complex (cf. Dallmeyer et al. 1996; Grocott and Taylor 2002). Biotite schist is believed to have formed concurrently with the early stages of magnetite and chalcopyrite precipitation (Arévalo et al. 2000). In stark contrast, Marschik and Fontboté (2001b) and Ullrich et al. (2001) proposed a less-likely interpretation that copper-gold mineralization post-dated schist formation and coincided with initial back-arc basin inversion and concomitant uplift. A similar notion, gabbro and diorite emplacement and, by association, IOCG generation during initial tectonic inversion, was favoured by Regan (1985) and Injoque (2001) for the Cañete basin, although an extensional setting for the mafic magmatism would seem to be more reasonable. The relatively minor Late Cretaceous and Palaeocene IOCG deposits were formed after the early Late Cretaceous tectonic inversion event, during subsequent extensional episodes (e.g. Cornejo and Matthews 2000).

Deposit styles

The IOCG deposits of northern Chile and southern Peru include representatives of most common mineralization styles, either alone or in varied combinations (Table 2, Fig. 4). Vein deposits are by far the most abundant, with many hundreds of them occurring throughout the Coastal Cordillera belt, especially in northern Chile. There, the IOCG veins accounted for Chile's position as the world's leading copper producer in the 1860–1870s, although most of them have not been the focus of attention over the last 40 years or so because of their relatively small size (Table 1) and the fact that many of the mines are severely depleted. The veins, products of both replacement and associated open-space filling, typically occur as swarms of up to 40 occupying areas up to several tens of square kilometres (Fig. 6). The principal veins are 1–5 km long and 2–30 m wide, with ore shoots worked for at least 500 m down the dip of the veins, and attaining 700 m at Tocopilla and 1,200 m at Dulcinea.

In addition to the veins, isolated breccia pipes (Carrizalillo de las Bombas, Teresa de Colmo) and calcic skarns [San Antonio, Panulcillo, Farola (Las Pintadas)] also occur locally (Fig. 4). The major IOCG deposits, however, are typically composite in style and comprise varied combinations of breccias, stockworked zones and replacement mantos besides veins, as observed at Candelaria-Punta del Cobre (Martin et al. 1997; Marschik and Fontboté 2001b), Mantoverde (Vila et al. 1996; Zamora and Castillo 2001), Cerro Negro and Raúl-Condestable (Vidal et al. 1990; de Haller et al. 2002). Breccias, both hydrothermal and tectonic in origin, are common components of the composite deposits (Table 2), in particular at Mantoverde where they comprise the shallower, currently mined parts of the main fault-controlled vein structure (Vila et al. 1996) and the associated Manto Ruso strata-bound deposit (Fig. 7; Orrego and Zamora 1991). The predominant breccias at Cerro Negro also comprise strata-bound mantos. Composite deposits, including Candelaria-Punta del Cobre (Marschik and Fontboté 2001b) and Raúl-Condestable (Vidal et al. 1990), contain bodies of dispersed mineralization controlled in part by stratal

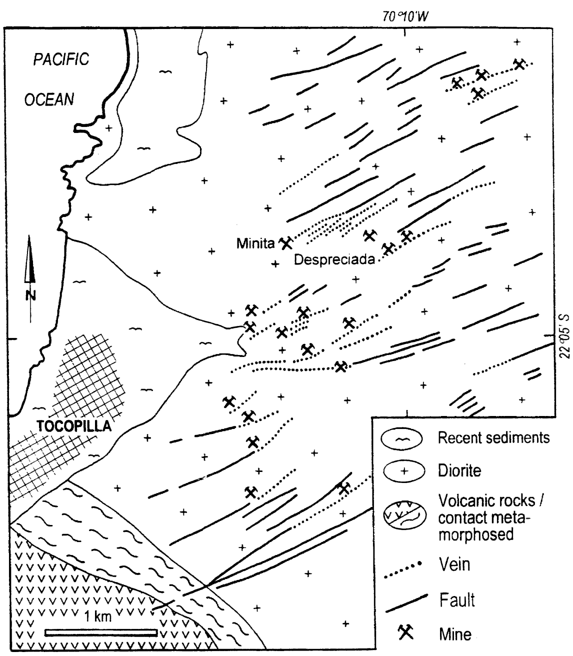

Fig. 6 Pluton-hosted IOCG veins and controlling faults in the Tocopilla district, northern Chile. Principal mined deposits are named. Taken from Boric et al. (1990)

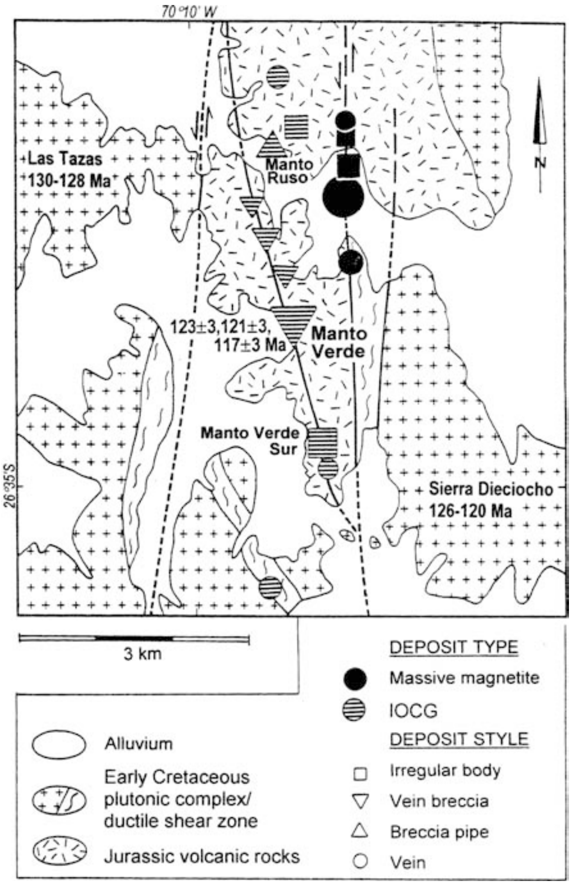

Fig. 7 Geological sketch of the Los Pozos (Mantoverde) district, showing its confinement to a fault-bounded screen of Jurassic volcanic rocks (La Negra Formation) and tight control by the transtensional Atacama Fault System. Also shown are the two contiguous plutonic complexes and the different styles and relative sizes of IOCG and massive magnetite mineralization that comprise the district, along with their respective radiometric ages. Note the temporal and probable genetic relationship between the Sierra Dieciocho diorite-monzodiorite complex and the Mantoverde IOCG deposit based on their age similarities. Map slightly modified after Espinoza et al. (1999) and radiometric ages summarised from sources cited in the text

permeability provided by fragmental volcanic or volcaniclastic horizons. The large Mina Justa deposit in the Marcona district consists of irregular patches, veinlets and breccia fillings of well-zoned sulphide mineralization within a low-angle fault zone that transgresses the host stratigraphy (Moody et al. 2003).

Hornfelsing of volcano-sedimentary host rocks to IOCG deposits is ubiquitous and may have predisposed them to widespread brittle fracturing and consequent permeability enhancement. Typically, however, the thermal effects are difficult to discriminate from metasomatic products, including widespread and pervasively developed biotite, actinolite, epidote, albite and related minerals. Permeability barriers, especially marbleised or even little-altered carbonate sequences, may have played an important role in the confinement and ponding of hydrothermal fluid in some deposits, such as Candelaria-Punta del Cobre and El Espino (Correa 2003). Nevertheless, if fluid penetration is more effective, carbonate rocks may be transformed to skarn and constitute integral parts of some composite deposits (e.g. Raúl-Condestable; Vidal et al. 1990).

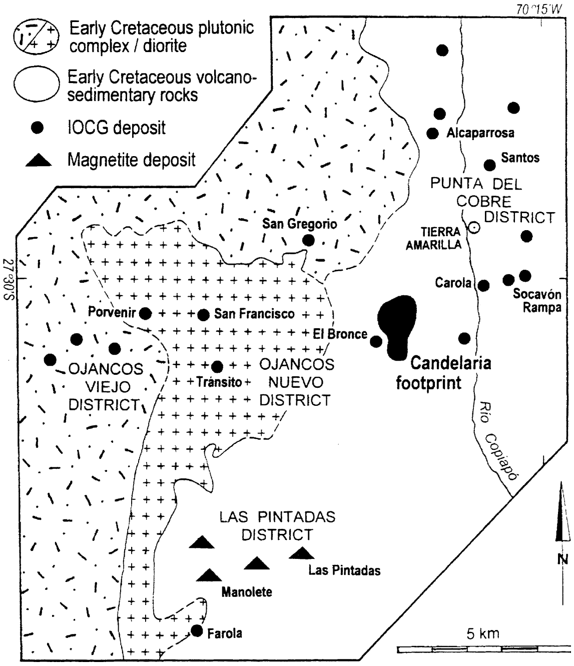

Fig. 8 Spatial relations of IOCG and carbonate-hosted massive magnetite deposits, including the major Candelaria deposit and related deposits in the Punta del Cobre district, to the Ojancos plutonic complex, in particular the diorite phase. The rest of the complex comprises monzodiorite, tonalite and monzogranite. The Farola deposit is a garnet-rich skarn (Ruiz et al. 1965). Although a case may be made for a genetic relationship between the diorite and deposits hosted by both volcanic (Punta del Cobre Group) and sedimentary (Chañarcillo Group) rocks, it should be noted that the pluton-hosted IOCG veins share faults with pre-ore 'diabase' dykes, suggesting that the unobserved magmatic source of the dykes may be more closely related genetically to the mineralisation than the outcropping diorite itself. Compiled from Díaz et al. (1998) and Marschik and Fontboté (2001b)

Intrusion relations

In common with many IOCG deposits worldwide (e.g. Ray and Webster 2000), a number of the Andean examples lack clear genetic relations to specific intrusions despite being located in close proximity (< 2 km) to outcropping plutonic complexes, including early dioritic phases (e.g. Sierra Dieciocho pluton east of Mantoverde; Fig. 7; Zamora and Castillo 2001; and Ojancos plutonic complex west of Candelaria; Fig. 8; Marschik and Fontboté 2001b). Mantoverde and Candelaria-Punta del Cobre are typical examples of deposits where the IOCG mineralization and nearby plutonic complexes are not observed to be in contact, although radiometric dating has shown that the intrusive activity and alteration-mineralization episode overlap temporally (Fig. 9). For example, at Mantoverde, K-Ar ages of 123 ± 3, 121 ± 3 and 117 ± 3 Ma (Vila et al. 1996; Orrego et al. 2000) for hydrothermal sericite are encompassed by U-Pb zircon, whole-rock Rb-Sr isochron, $^{40}Ar/^{39}Ar$ hornblende and K-Ar ages of ~127–120 Ma for the contiguous Sierra Dieciocho plutonic complex (Figs. 7 and 9; Berg and Baumann 1985; Dallmeyer et al. 1996; Espinoza et al. 1999).

Similarly, preferred ages of 116–114 Ma (Marschik and Fontbote 2001b; Mathur et al. 2002) or 112–110 Ma (Ullrich and Clark 1999; Arévalo et al. 2000; Ullrich et al. 2001) for copper mineralization at Candelaria fall within the 117.2 ± 1.0- to 110.5 ± 1.7-Ma emplacement span for the contiguous Ojancos plutonic complex ($^{40}Ar/^{39}Ar$; Ullrich et al. 2001).

In clear contrast, however, most of the principal IOCG vein deposits in northern Chile, such as Tocopilla, Gatico, Montecristo, Julia, Las Animas, Ojancos Nuevo, Carrizal Alto, Quebradita and La Africana (Fig. 4), are hosted by plutons, most of them dioritic in composition. Several of the IOCG vein deposits and their host intrusions have been shown to possess similar ages, a relationship that is particularly clear at Las Animas where alteration biotite is dated at 162 ± 4 Ma (K-Ar) by Gelcich et al. (1998) and the nearby diorite at 161 ± 4 (K-Ar, biotite), 159.7 ± 1.6 (U-Pb, zircon) and 157.6 ± 2.6 Ma (Rb-Sr, whole rock; Fig. 9; Dallmeyer et al. 1996). Furthermore, in southern Peru, the Monterrosas and Eliana veins are hosted mainly by gabbrodiorite (Atkin et al. 1985; Vidal et al. 1990).

Irrespective of whether host rocks are dioritic or more felsic plutons (e.g. Julia) or their nearby wall rocks (e.g. Brillador, Tamaya; Table 2), the IOCG veins normally share localising faults with mafic to intermediate dykes. They are variously described as andesite, basalt, dolerite, diabase, diorite, gabbro or simply mafic in composition, and are typically of pre- or syn-ore timing (Table 2; Ruiz et al. 1965; Boric et al. 1990; Espinoza et al. 1996), but locally mapped as post-ore (e.g. La Africana; Saric 1978). Additionally, syn- to late-mineralization diorite dykes occur alongside the volcanic-hosted Mantoverde vein-breccia deposit (Vila et al.

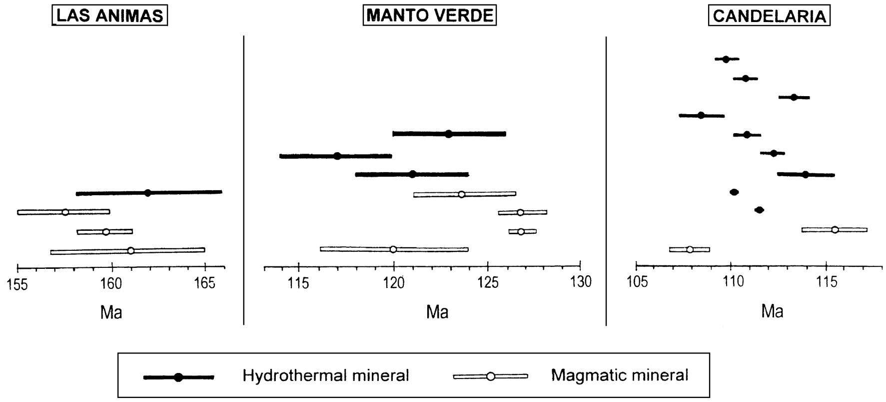

Fig. 9 Comparisons of radiometric ages for hydrothermal minerals from IOCG deposits and magmatic minerals from host (Las Animas) or contiguous (Mantoverde, Candelaria) plutonic complexes determined using a variety of methods. Note the overall temporal coincidence of hydrothermal and intrusive events within the error limits of the methods employed. See text for further details. Data compiled from Gelcich et al. (1998), Espinoza et al. (1999), Ullrich and Clark (1999), Orrego et al. (2000), Marschik and Fontboté (2001b), Ullrich et al. (2001) and Mathur et al. (2002)

1996; M. Orrego, personal communication, 2002), pre- and post-breccia diorite dykes are associated with the Teresa de Colmo breccia (Correa 2000; Hopper and Correa 2000) and diorite dykes are present in the El Salado vein district (Browne et al. 2000) and at Punta del Cobre. Typically, the dykes observed by the writer are best described in hand sample as fine- to medium-grained diorite porphyries.

It is particularly instructive to point out that the Ojancos Nuevo veins lie within, and the Farola copper skarn abuts, an areally extensive diorite phase of the Ojancos plutonic complex, which, as noted above, is <2 km from the Candelaria-Punta del Cobre deposit and of broadly the same age (Figs. 8 and 9). The Panulcillo copper-gold skarn deposit, the southernmost in an 80-km long, north-trending belt of small copper skarns extending as far as San Antonio (Fig. 4), lies adjacent to an albitised diorite intrusion (Sugaki et al. 2000), as do the breccia mantos at the Cerro Negro deposit. Drilling also intersected an albitised diorite intrusion containing low-grade chalcopyrite mineralization about 500 m beneath the Teresa de Colmo chalcopyrite-bearing breccia (Correa 2000; Hopper and Correa 2000).

Notwithstanding the apparently widespread association between IOCG deposits and broadly dioritic plutons and minor intrusions, some of them intensely albitised, in the Coastal Cordillera, it should also be mentioned that volumetrically minor dacite porphyry dykes, documented as either syn- or inter-mineral in timing, occur within the Punta del Cobre (R.H. Sillitoe, unpublished data, 1992; Marschik and Fontboté 1996; Pop et al. 2000), Raúl-Condestable (de Haller et al. 2002) and Mina Justa (Moody et al. 2003) deposits. At Raúl-Condestable, zircon from the dacite porphyry yields U-Pb ages of ~115 Ma, closely similar to that for hydrothermal sphene associated with the IOCG mineralization (de Haller et al 2002; A. de Haller, personal communication, 2003).

Geochemistry and mineralogy

Long before the iron-oxide-bearing copper deposits of northern Chile were assigned to the IOCG clan, Ruiz and Ericksen (1962) and Ruiz et al. (1965) (see also Ruiz and Peebles 1988) subdivided them into magnetite-dominated and (specular) hematite-dominated subtypes. Most members of their two subtypes are chalcopyrite ± bornite-bearing veins, but the hematite-rich subtype also includes the vein breccia at Mantoverde and the veins, breccias and mantos at Punta del Cobre. No doubt Candelaria would have been assigned to the magnetite-rich category had it been known at that time! Subsequent work has shown that at least some of the hematite-rich veins are transitional downwards to the magnetite-rich variety (Fig. 10), as observed at Julia (Espinoza et al. 1996), Las Animas (Gelcich et al. 1998) and, as a result of recent deep drilling, at both Mantoverde (Zamora and Castillo 2001) and El Salado (Browne et al. 2000), in keeping with the generalised vertical zonation of IOCG deposits proposed by Hitzman et al. (1992). A similar upward and outward change from magnetite to hematite is also documented at the district scale at Candelaria-Punta del Cobre (Marschik and Fontboté 2001b). An appreciable proportion of the magnetite in the hematite-rich veins is the mushketovite variety: pseudomorphous after specular hematite (Ruiz et al. 1965). Late-stage hematite also cuts and replaces some of the magnetite. Widespread development of magnetite after hematite was recently re-emphasised at Candelaria-Punta del Cobre (Marschik and Fontboté 2001b), Raúl-Condestable (de Haller et al. 2002) and Mina Justa (Moody et al. 2003). The iron oxides are typically post-dated by pyrite and copper-bearing sulphides (e.g. Ruiz et al. 1965), although temporal overlap is observed locally.

The magnetite-rich veins contain appreciable actinolite, biotite and quartz, as well as local apatite, clinopyroxene, garnet, hematite and K-feldspar, and possess narrow alteration haloes containing one or more of

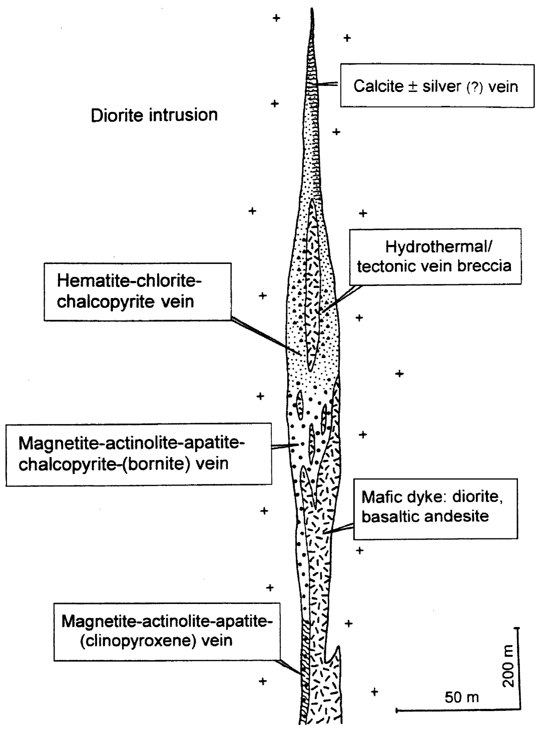

Fig. 10 Idealised section of an IOCG vein in the Coastal Cordillera showing upward zonation from magnetite to hematite domination, and the possibility of coarse calcite (± silver mineralisation) in its top parts and copper-poor massive magnetite at depth. Much of the magnetite is the mushketovite variety. Hematite zone may display hydrothermal/tectonic brecciation. Note shared fault/fracture control with pre-vein mafic dyke. Expanded from Espinoza et al. (1996)

actinolite, biotite, albite, K-feldspar, epidote, quartz, chlorite, sericite and scapolite (Table 2; Ruiz et al. 1965; Boric et al. 1990; Espinoza et al. 1996; Injoque 2001, 2002). In contrast, the hematite-rich veins tend to contain sericite and/or chlorite, with or without K-feldspar or albite, and to possess alteration haloes characterised by these same minerals (Table 2). Tourmaline may be a constituent of either subtype, but is perhaps most common where hematite is more abundant than magnetite. Both IOCG subtypes tend to be relatively poor, but by no means deficient, in quartz, while especially the specular hematite-rich variety is commonly associated with coarse-grained calcite and ankerite, either as early or late additions or as a distal equivalent (Fig. 10; Ruiz et al. 1965). Monomineralic chalcopyrite may be intergrown with these carbonate minerals.

Both the magnetite- and specular hematite-rich IOCG veins contain chalcopyrite and generally subordinate pyrite, but in a few cases bornite accompanies the chalcopyrite (Table 2). The main Tamaya vein was dominated by bornite to a depth of 400 m (Ruiz et al. 1965). The irregular but broadly vein-like Mina Justa deposit contains concentrically zoned sulphide assemblages, with a bornite-chalcocite core grading outwards through bornite-chalcopyrite and chalcopyrite-pyrite to a broad pyrite halo (Moody et al. 2003). Similar zoning, albeit without chalcocite in the central zone, is also described from Panulcillo (Hopper and Correa 2000). As in many vein deposits, the copper is concentrated in well-defined ore shoots separated by barren or low-grade vein segments. Copper contents, without any influence by supergene processes, tend to diminish in some vein systems at depths of several hundred metres, in response to increasing pyrite (La Africana) or pyrrhotite (Carrizal Alto) contents. Gold contents are higher, but typically undetermined, in the hematite-rich than in the magnetite-rich deposits (Ruiz et al. 1965). A few of the hematite-rich veins were worked as small, stand-alone gold deposits, including Los Mantos de Punitaqui (Table 2) where the economically dominant metals are uniquely zoned from copper through gold to mercury over a distance of 4.5 km (McAllister et al. 1950; Ruiz et al. 1965).

Both IOCG vein subtypes are characterised by highly anomalous amounts of Co, Ni, As, Mo and U (Table 2), as shown by the widespread occurrence of minor amounts of cobaltite, safflorite, danaite (all with Co and As), niccolite, chloanthite (both with Ni and As), molybdenite and uraninite (Ruiz et al. 1965). The Carrizal Alto veins contain as much as 0.5% Co in places (Ruiz et al. 1965). Arsenic, as arsenopyrite, may also occur commonly, especially at Tocopilla, and is also reported at Candelaria-Punta del Cobre (Hopf 1990). Cobalt and Mo contents are also anomalously high at Raúl-Condestable (Atkin et al. 1985), Candelaria (Marschik and Fontboté 2001b) and El Espino (Correa 2003). Ilmenite is recorded as an ancillary hydrothermal mineral in several deposits, especially in southern Peru (Injoque 2002), although the magnetite from IOCG deposits is typically low in titanium (Hitzman et al. 1992; G.E. Ray, personal communication, 2003). Minor, typically late-stage Zn and, in some examples, Pb are present in several of the vein deposits (e.g. Espinoza et al. 1996) as well as at Raúl-Condestable (Vidal et al. 1990; de Haller et al. 2002), whereas the anomalously high zinc contents in parts of the Candelaria-Punta del Cobre deposit appear to accompany the final stage of copper introduction (N. Pop, personal communication, 1999; Marschik and Fontboté 2001b). Several hundred parts per million of LREE are reported in parts of the Candelaria-Punta del Cobre deposit and Productora prospect, at least partly in allanite (Marschik et al. 2000; C. Osterman in Ray and Dick 2002), as well as at Raúl-Condestable (A. de Haller, personal communication, 2003).

Alteration related to the large composite deposits is typically complex and rather varied in character (Table 2). Widespread, early sodic or sodic-calcic alteration characterised by albite with or without actinolite occurs in some of the IOCG districts (e.g. Candelaria-Punta del Cobre; Marschik and Fontboté 1996, 2001b), but is apparently absent elsewhere (e.g. Mantoverde; Vila et al. 1996; Cornejo et al. 2000). Pervasive biotite-quartz-magnetite ± K-feldspar alteration immediately preceded copper introduction at Candelaria-Punta del

Cobre, an event associated even more closely with formation of actinolite (Ullrich and Clark 1999; Arévalo et al. 2000; Marschik and Fontbote 2001b). Significantly, the same minerals also comprise narrow alteration haloes to the IOCG veins within the contiguous Ojancos plutonic complex (Díaz et al. 1998). Albite, chlorite and calcite become predominant in the shallowest parts of the Punta del Cobre deposit (Marschik and Fontbote 2001b) as they are in the Teresa de Colmo breccia pipe (Correa 2000; Hopper and Correa 2000). High-grade mineralization at Mina Justa is intergrown with actinolite, clinopyroxene and apatite, and is closely associated with K-feldspar-chlorite-actinolite alteration (Moody et al. 2003). In the Mantoverde vein-breccia, however, sericite besides K-feldspar and chlorite is closely associated with copper mineralization, and biotite is scarce (Vila et al. 1996; Cornejo et al. 2000). In contrast, at Raúl-Condestable, potassic alteration is not evident and early albite, scapolite and a variety of calcic amphiboles are followed by iron oxides, chlorite and sericite (Vidal et al. 1990; de Haller et al. 2002). Potassic alteration is also unreported at El Espino where early albite is overprinted by epidote, chlorite and lesser amounts of actinolite and sericite (Correa 2003). Prograde garnet dominates the skarn-type IOCG deposits (Fréraut and Cuadra 1994) and, at Panulcillo (Table 2), is observed to be paragenetically equivalent to K-feldspar-albite-quartz and biotite-magnetite assemblages in contiguous andesitic volcanic rocks (Hopper and Correa 2000).

Metallogenic model

Geological synthesis of the Coastal Cordillera IOCG province in northern Chile and southern Peru at regional, district and deposit scales enables construction of a preliminary metallogenic model.

Regional- and district-scale aspects

Most of the IOCG deposits were generated during the early development of the ensialic Andean orogen, when the crust was variably extended and attenuated and unusually hot, and magmatism was relatively primitive. IOCG formation took place during both extensional and transtensional tectonic regimes. The greatest number of IOCG deposits, including some of the largest, were generated during the Early Cretaceous when crustal attenuation attained a maximum.

The deposits are controlled principally by brittle faults, although ductile deformation locally overlapped with the early stages of mineralization. The voluminous tholeiitic to calc-alkaline intrusions that either host or occur in proximity to the IOCG deposits possess a dominantly mantle source, lack appreciable crustal contamination and are oxidised, in common with their thick volcanic-dominated host-rock sequences. These basaltic to andesitic sequences were tilted above zones of extensional detachment, and subjected to prehnite-pumpellyite and greenschist facies diastathermal (burial) metamorphism in response to elevated geothermal gradients prior to and possibly also during IOCG ore formation. The IOCG deposits, along with massive magnetite, manto-type copper and small porphyry copper deposits, provide a distinctive metallogenic signature to the Jurassic and Early Cretaceous Coastal Cordillera (cf. Oyarzún 1988; Maksaev and Zentilli 2002). Once compression, crustal thickening and more evolved magmas became widespread in response to the early Late Cretaceous tectonic inversion, IOCG (as well as massive magnetite and manto-type copper) deposit formation diminished dramatically in the Late Cretaceous and only very locally persisted into the Palaeocene.

In contrast to many IOCG provinces worldwide, especially those of Precambrian age, the relationship of the Andean IOCG deposits to intrusive rocks is substantially clearer. In particular, a number of the deposits are hosted by or occur near gabbrodiorite or diorite intrusions. Even where somewhat more felsic plutonic phases act as host rocks, broadly contemporaneous diorite dykes commonly share controlling faults with the IOCG veins, implying that relatively primitive magma sources existed at depth just before and potentially during copper mineralization. Therefore there is strong suggestion of an intimate connection between relatively primitive, poorly fractionated and little-contaminated gabbrodiorite to diorite magmas and the IOCG deposits (Table 2; Fig. 11). In this regard, it should be remarked that Marschik and Fontbote (1996; but not 2001b) linked the Candelaria-Punta del Cobre IOCG deposit to nearby diorite of the Ojancos plutonic complex, which,

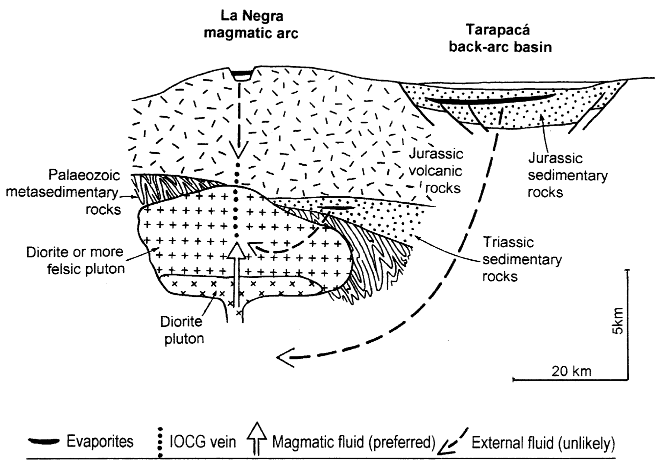

Fig. 11 Cartoon of Jurassic IOCG vein in the La Negra arc of northern Chile to show possible sources of ore fluid. Vertically ascendant magmatic fluid supplied from an unobserved diorite magma source at depth is preferred. See text for further discussion. Note Triassic evaporites are very restricted in both volume and extent, whereas those in both the overlying intra-arc basin and back-arc basin are too young to have contributed to the ore fluid, being deposited after IOCG formation

as noted above, itself hosts IOCG veins and skarns. Similarly, the IOCG deposits in the Cañete basin have been related genetically to gabbrodiorite intrusions (Vidal et al. 1990; Injoque 2001, 2002). Furthermore, it should also be recalled that Ménard (1995) concluded that the massive magnetite deposits within the Atacama Fault System are also genetically related to diorite intrusions. Notwithstanding the compelling evidence in favour of a gabbrodiorite to diorite intrusive source for the IOCG ore fluids, it should be re-emphasised that very minor volumes of dacitic magma, in addition to the more mafic melt, were also clearly available during copper mineralization in the case of at least three of the deposits (Candelaria-Punta del Cobre, Raúl-Condestable, Mina Justa), although not necessarily sourced from the same part of the parental magma chamber as the metalliferous fluid.

This inferred genetic association with relatively mafic plutonism would nicely explain the Cu-Au-Co-Ni-As-Mo-U signature, bearing in mind that a similar metal suite, albeit subeconomic with respect to copper, characterises some calcic iron skarns associated with dioritic intrusions (Einaudi et al. 1981; Meinert 1992; Ray and Lefebure 2000). The Larap magnetite deposit in southeastern Luzon island, the Philippines, part of a Neogene island arc, provides an instructive example. The magnetite skarn, developed from both carbonate and noncarbonate lithologies, is part of a low-grade porphyry copper system related to diorite porphyry intrusions, and is enriched in Co, Ni and U, besides Cu, Mo and Au (Sillitoe and Gappe 1984). Wang and Williams (2001) reported a similar Cu-Au-Ni-Co-Te-Se suite from the Mount Elliott skarn deposit in the Cloncurry IOCG district of Queensland, Australia.

Magmatic-hydrothermal provision of copper and, to a lesser degree, gold in the Coastal Cordillera province is unequivocally confirmed locally by the existence of the Mesozoic porphyry copper-(gold) deposits in association with volumetrically restricted albeit somewhat more felsic porphyry stocks. Indeed, the extensional, as opposed to compressive, stress regime prevalent during porphyry copper formation in the Coastal Cordillera is believed to be a major factor responsible for the small sizes and low hypogene grades of these deposits (cf. Sillitoe 1998; Tosdal and Richards 2001). Therefore, the widely exposed, deeper plutonic complexes, from the tops of which porphyry copper stocks may have already been eroded, may also reasonably be expected to have had the capacity to generate broadly similar magmatic-hydrothermal fluids for IOCG genesis (cf. Oyarzún 1988). Available sulphur isotopic results for several of the IOCG deposits fall in a fairly narrow range centred around 0 per mil (Fig. 12; Fox 2000; I. Ledlie in Hopper and Correa 2000; Marschik and Fontboté 2001b), entirely consistent with a largely magmatic source for the sulphide sulphur; however, an origin by leaching from Mesozoic igneous rocks cannot be entirely ruled out. Sulphur isotopic values consistent with a magmatic origin (Fig. 12) even characterise the Teresa de Colmo deposit, which cuts an evaporite sequence (Correa 2000; Hopper and Correa 2000). Raúl-Condestable presents an apparent exception, however, with both highly positive and highly negative $\delta^{34}S$ values being interpreted in terms of the involvement of seawater or evaporitic sulphur and biogenic sulphur, respectively (Fig. 12; Ripley and Ohmoto 1977; de Haller et al. 2002).

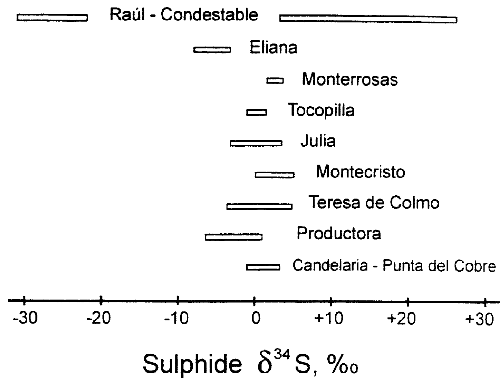

Fig. 12 Sulphur isotope values for sulphide minerals, mainly chalcopyrite and pyrite, from selected IOCG deposits and prospects in northern Chile and southern Peru. Data taken from Vivallo and Henríquez (1998), Fox (2000), I. Ledlie in Hopper and Correa (2000), Injoque (2001), Marschik and Fontboté (2001b) and de Haller et al. (2002). The markedly high and low values at Raúl-Condestable are attributed to reduction of evaporitic or seawater sulphate (Ripley and Ohmoto 1977; de Haller et al. 2002) and biogenic sulphur (de Haller et al. 2002), respectively, whereas values for the other deposits suggest a dominance of magmatic sulphur

In porphyry copper deposits, metal-bearing, magmatic-hydrothermal fluid is channelled upwards from parent magma chambers via steep, typically cylindrical porphyry stocks, within and around which much of the copper and gold are eventually concentrated in response to declining fluid temperature. Alteration and mineralization are, therefore, relatively confined, although zones of >5 km^2 may be affected by potassic alteration in giant systems (e.g. El Teniente, Chile; Skewes et al. 2002). In the case of large composite IOCG deposits, such confinement of alteration and mineralization is not so apparent, especially where sodic-calcic alteration either presages or accompanies the copper mineralization. Alteration in the Candelaria-Punta del Cobre district, for example, occupies >30 km^2 (Marschik and Fontbote 2001b). Nevertheless, the alteration associated with simple IOCG veins, breccia pipes and skarns is generally just as volumetrically restricted as that with non-IOCG deposits of these types.

The tendency for alteration and mineralization to be unusually widespread in many IOCG districts, especially in association with large composite IOCG deposits, may be ascribed to the existence of magmatic-hydrothermal fluid sources at considerable depth within either the host or contiguous plutonic complexes. Fluid ascent on approach to ore-forming levels appears to be guided by second- and lower-order splays of the major localising fault zones, intrusive contacts and permeable stratigraphic horizons, and therefore may not be as tightly focused as in most porphyry copper deposits. The precise locations of the source intrusions remain to be clarified, although these could potentially be at considerable palaeodepths, perhaps as great as 10 km, given inferred depths of pluton emplacement and the association of the IOCG deposits with crustal-scale ductile to brittle fault zones (e.g. Grocott and Wilson 1997). In the case of the vertically extensive veins and other deposit styles hosted by gabbrodiorite and diorite, it may reasonably be presumed that the mineralizing fluids were exsolved during final consolidation of the deep, compositionally similar portions of the plutons (Fig. 11). However, where diorite dykes and the IOCG veins share controlling faults cutting more felsic plutons, derivation of both the dyke magma and metalliferous fluid from deeper, more mafic and less-fractionated parts of the plutonic complexes may be inferred. Replenishment of magma chambers by more primitive mantle melts could result in underplating of plutonic complexes by more mafic material as well as acting as a potential trigger for liberation of sulphur- and metal-charged fluid, in the manner proposed recently by Hattori and Keith (2001). Hypothetically, IOCG ore fluids might be supplied by mafic intrusive phases anywhere within host or nearby plutonic complexes, which range from several to perhaps 10 km in vertical extent (e.g. Grocott and Taylor 2002), assuming that they were efficiently tapped by steep, through-going faults. Such a deep origin for IOCG fluids in the central Andes accords with a postulated deeper source of magmatic fluids in IOCG than in porphyry copper deposits, inferred from higher CO_2 contents (Pollard 2001), in keeping with those documented in fluid inclusions from Candelaria (Ullrich and Clark 1999). The elevated geothermal gradients that existed in the extensional Mesozoic arc terranes of the Coastal Cordillera would have favoured prolonged ascent and even lateral flow of the deeply derived magmatic fluid before cooling was sufficient to cause wholesale metal precipitation.

Consideration of alternative fluid sources

A non-magmatic origin for IOCG ore fluids and their contained metals in the Andean province gains little support from the overall geological settings of many of the deposits. Hitzman (2000) and Kirkham (2001) favoured chloride-rich basinal brine produced by evaporite dissolution as perhaps the most likely fluid for copper and gold transport and IOCG deposit formation in the Coastal Cordillera of northern Chile. Evaporites, albeit predominantly sulphates rather than halite, are preserved in the Tarapacá and Aconcagua back-arc basins, as noted above (Fig. 11; Muñoz et al. 1988; Mpodozis and Ramos 1990; Ardill et al. 1998) and occur in minor amounts at depth in the Cañete intra-arc basin (Palacios et al. 1992). Although a genetic model involving such external fluids is perhaps not unreasonable for IOCG deposits within the Cañete basin (e.g. Raúl-Condestable) and along the eastern edge of the Coastal Cordillera (e.g. Teresa de Colmo) and, hence, close to the back-arc environment, it seems a far less likely possibility for the majority of the deposits occurring within the volcanic arc itself. It would seem to be especially convoluted to invoke basinal brine access as a means of forming the IOCG veins, many of which are sealed within sizeable plutonic complexes and possess original depth extents of >1 km (Fig. 11). Most of these veins were formed immediately following emplacement of their host plutons (Fig. 9), clearly while they were still hot and therefore even less likely to permit the ingress of external brine.

Provision of brine from a back-arc sedimentary basin by means of gravity-induced flow is precluded by palaeo-topographic considerations, given that an at least partially subaerial arc must be higher in elevation than a marine back-arc basin. The extensional setting also precludes tectonically induced brine expulsion at the times when most of the IOCG deposits were generated. The only other alternative, crustal-scale convection (Fig. 11; Barton and Johnson 1996, 2000), also seems implausible, especially in the case of the Middle to Late Jurassic La Negra arc, because fluid circulation across an $\sim$50-km width of a pluton-dominated arc would need to be invoked. Furthermore, some of the oldest (latest Middle Jurassic) IOCG veins in northern Chile were generated at least 7 M.Y. before evaporite formation at $<\sim$155 Ma in the adjoining back-arc basin (Fig. 2; Ardill et al. 1998). Finally, it is important to note that the Mesozoic IOCG belts of the central Andes span 19° of latitude, within and alongside only parts of which evaporites are documented.

Even less likely is an evaporite or formational brine source within or beneath the Mesozoic plutonic complexes of the IOCG-bearing La Negra arc in northern Chile. Triassic sedimentary sequences locally beneath the arc and the thin Jurassic sedimentary intercalations within it are preserved only discontinuously and are volumetrically minor (Fig. 11). Moreover, the only known potential brine sources would appear to be the extremely limited sabkha facies described locally as part of Triassic rift sequences, but such material would be restricted to the region between approximately latitudes 24 and 27°S (Suárez and Bell 1992, 1994). Palaeozoic meta-sedimentary sequences and older crystalline basement are the most common substrate to the plutonic complexes and clearly could not have acted as brine sources during the Mesozoic (Fig. 11). Indeed, the host plutons for the Las Animas, Carrizal Alto and Quebradita vein deposits directly intrude the metasedimentary rocks (Ruiz et al. 1965).

Descent of brine from overlying sources, proposed in some shield areas (Gleeson et al. 2000) and elsewhere (Haynes 2000), might be invoked as a means of generating the IOCG deposits within the arc, but widespread descent of fluid for at least 1 km down pluton-hosted faults to generate veins at palaeodepths as great as 5 km or more seems highly improbable (Fig. 11). Indeed, the widespread pseudomorphing of specular hematite by magnetite, suggestive of thermally prograding hydrothermal systems, not to mention formational temperatures of > 500 °C for the magnetite (e.g. Marschik and Fontboté 2001b), would seem to be more easily explicable in terms of ascent rather than descent of the ore fluid, in keeping with more conventional concepts of vein formation. Furthermore, there are no known Mesozoic sedimentary accumulations that are either capable of copious brine generation or sufficiently widespread to have overlain the numerous IOCG deposits in the Mesozoic arc of northern Chile, bearing in mind that significant copper mineralization was active during both Middle–Late Jurassic and Early Cretaceous epochs. Moreover, the well-known evaporite occurrence in the restricted Coloso basin, at latitude 23°50′S, is appreciably younger than nearby IOCG deposits formed in the Middle–Late Jurassic epoch (Flint and Turner 1988).

A perhaps more reasonable non-magmatic ore fluid would be metamorphic brine of the type believed by some investigators to have been responsible for the manto-type copper deposits (see above). Generation of metamorphic fluid accompanied subsidence of the intra-arc basins transgressed by the central Andean IOCG belts (Aguirre et al. 1999), and such a fluid has been considered as a possible, even the sole, contributor to the IOCG deposits in the Cañete basin of southern Peru (Vidal et al. 1990; Injoque 2000), and perhaps also to those in the Coastal Cordillera of northern Chile (Hitzman 2000). However, ingress of metamorphic fluid to large cooling plutons to generate the IOCG veins confronts some of the same difficulties as those considered above for other externally derived brines.

Heated seawater is another fluid that may have been available during pluton emplacement and IOCG formation in the intra-arc basin environment, and has been proposed at Raúl-Condestable in the northern part of the Cañete basin on the basis of the sulphur isotopic values (Ripley and Ohmoto 1977; de Haller et al. 2002). Certainly, seawater may be inferred to have played a key role in VHMS formation only slightly later in the same part of the Cañete basin (Vidal 1987).

On the basis of this discussion of possible external fluid sources, it is concluded that evaporitic, metamorphogenic and seawater brines all seem unlikely to have been solely responsible for the genesis of the IOCG deposits in the Coastal Cordillera, although their local involvement, along with that of locally derived meteoric water, remains feasible. Given that a single fluid type rather than different or blended fluids would seem to be required to explain the common characteristics of the IOCG deposits throughout the 1,700-km-long Coastal Cordillera belt, the magmatic-hydrothermal model discussed above is believed to gain further support.

Deposit-scale aspects

Pluton-hosted IOCG deposits in the Coastal Cordillera, chiefly veins, tend to be localised by minor faults and fractures and to be relatively small in size, albeit of appreciable horizontal and vertical extents (Fig. 13). Nevertheless, the large vein districts, like Tocopilla, may be areally extensive (Fig. 6). In contrast, IOCG deposits in volcanic and sedimentary host rocks to plutons are

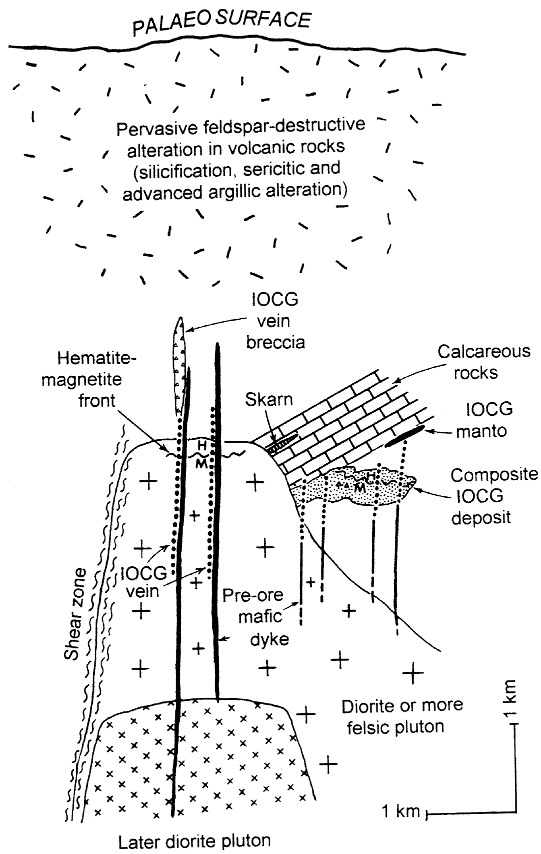

Fig. 13 Schematised styles of IOCG deposits in the Coastal Cordillera of the central Andes. Note the fundamental control imposed by faults, commonly shared with pre-ore mafic (basaltic andesite/diorite) dykes. Large deposits are composite, in the sense of comprising several closely spaced mineralization styles, and localised by zones of high structural and lithological permeability, possibly confined beneath carbonate or other lithologically determined aquitards. Vein breccias (and breccia mantos and pipes) tend to occur at relatively shallow palaeodepths and, hence, are typically confined to volcanogenic wallrocks. There is an upward change in the predominant hydrothermal iron oxide from magnetite to specular hematite. The IOCG system may be concealed beneath an extensive zone of barren feldspar-destructive alteration containing pyrite. A deeply derived magmatic fluid guided upwards along the dyke-filled faults, and possibly sourced from the same magmatic reservoir as the dyke rock itself, is hypothesised. Note that telescoping of alteration types (e.g. potassic over sodic-calcic) and mineralisation styles, especially within composite deposits, is a possibility locally; however, the phenomenon is considered to be far less widely developed in the low-relief extensional arcs of the Coastal Cordillera than it is in the highly uplifted compressive arcs that host the Tertiary porphyry copper deposits farther east

variable in size, but include all the largest deposits. The largest host-rock deposits appear to be those where fault-guided magmatic-hydrothermal fluid permeates one or more porous stratigraphic horizons (Fig. 13), which in the case of Candelaria span a 350-m-thick rock package (Ryan et al. 1995; Marschik and Fontboté 2001b). Low-angle fault or shear zones may also enhance syn-mineralization permeability. Fluid ponding beneath aquitards, such as marbleised carbonate sequences, may also favour the formation of large composite deposits (Fig. 13). Known copper-gold skarn deposits in the Coastal Cordillera are small, but clearly an integral component of the IOCG spectrum, thereby rendering redundant any discussion of the generic difference between these skarns and other IOCG deposits in the belt. This assertion is amply supported by observations at Panulcillo, where Hopper and Correa (2000) charted the equivalence of garnet skarn and potassic assemblages developed in contiguous andesitic volcanic rocks.

Marschik and Fontboté (1996) considered the Punta del Cobre IOCG deposit to be intermediate in overall style between massive magnetite and porphyry copper deposits, both of which occur fairly close by in the Coastal Cordillera (Fig. 1). However, IOCG and porphyry copper deposits, as discussed above, are clearly distinct and apparently not directly related; nevertheless, they may display certain features in common, including occurrence of hydrothermal magnetite and/or hematite and potassic, potassic-calcic and/or sodic-calcic alteration (cf. Pollard 2000; Lang and Thompson 2001).

Many gold-rich porphyry copper deposits worldwide contain abundant hydrothermal magnetite ± hematite as a component of both early, barren sodic-calcic and later, ore-related potassic-(calcic) alteration assemblages (e.g. Sillitoe 2000). Magnetite contents at Grasberg, for example, attain 15 vol% in parts of the potassic alteration zone (MacDonald and Arnold 1994), not volumetrically dissimilar to some IOCG deposits. Furthermore, in a few porphyry copper deposits, sodic-calcic alteration, defined by sodic plagioclase, clinopyroxene, amphibole and magnetite, rather than the more normal potassic assemblages directly hosts all or part of the copper-gold mineralization (Sillitoe 2000), especially in the case of deposits in the Intermontane belt of British Columbia, Canada (Lang et al. 1995). Moreover, two of the deposits in the Intermontane belt (Afton and Ajax) constitute late stages of the Iron Mask batholith, which happens to contain magnetite-apatite veins like those in the Coastal Cordillera belt (Cann and Godwin 1983; Snyder and Russell 1995).

Interestingly, copper mineralization in several central Andean IOCG deposits (e.g. Raúl-Condestable, El Espino) is exclusively present in zones of sodic-calcic alteration, although potassic alteration or combinations of this with sodic-calcic alteration phases are more typical hosts. This situation may be a product of vertical alteration zoning, not just radically different fluid chemistries, as it is in the case of at least some porphyry copper-(gold) deposits (e.g. Sillitoe 2000). Moreover, if this comparison between the upward transition from sodic-calcic to potassic alteration in some IOCG and porphyry copper deposits is valid, then similar fluid evolutions, perhaps controlled by declining temperature, might be invoked in both cases. Zoning in IOCG deposits of the Coastal Cordillera is still poorly documented, although observations from several vein districts and Candelaria-Punta del Cobre show that magnetite-actinolite-apatite is transitional upwards to hematite-chlorite-sericite at both the individual vein and district scales (Figs. 10 and 13). Sizeable hydrothermal breccia veins, pipes and mantos appear to be largely restricted to this shallower, hematite-dominated IOCG zone (Fig. 13), where fluid overpressures may develop more readily.

The close association of magnetite-dominated IOCG and massive magnetite-(apatite) veins containing minor copper in several districts, especially but not limited to those of Middle–Upper Jurassic age, may be taken to suggest that the two deposit types are transitional and, furthermore, that copper contents of IOCG veins may decrease downwards, giving rise to massive magnetite veins (Fig. 10; cf. Espinoza et al. 1999; Naslund et al. 2002; Ray and Dick 2002). The same relationship is also favoured by the tendency of IOCG mineralization to occur alongside some massive magnetite deposits, perhaps suggestive of a crude zonal relationship (e.g. Mina Justa, Mantoverde). The deeper massive magnetite bodies, with or without copper, lack hydrothermal biotite and K-feldspar and are accompanied by sodic-calcic alteration, in keeping with the conclusions of several previous workers (Hitzman et al. 1992; Pollard 2000; Ray and Dick 2002). The district- and deposit-scale geological evidence, especially the intimate association between IOCG and massive magnetite deposits in parts of the Coastal Cordillera, does not support radically different fluid sources for the two deposit types, as recently proposed on the basis of differences in their $^{187}Os/^{188}Os$ ratios (Mathur et al. 2002).

Hydrothermal magnetite in porphyry copper deposits is normally considered to result from precipitation of iron partitioned directly from the source magma into magmatic-hydrothermal brine (e.g. Arancibia and Clark 1996). However, at least part of the iron present as iron oxides in some of the massive magnetite (Ruiz et al. 1968; Ménard 1995) and IOCG (Cornejo et al. 2000) deposits of the Coastal Cordillera may have resulted from leaching by hot hypersaline magmatic fluid of ferromagnesian minerals in igneous rocks adjoining the sites of mineralization. Zones of mafic-poor, albite-K-feldspar-altered rocks developed in the vicinities of many large massive magnetite and some IOCG deposits, including Candelaria (Marschik and Fontboté 2001b) and Mantoverde (Cornejo et al. 2000), provide the supporting evidence.

The upward extensions of IOCG deposits are even less well known than their roots, although there is limited observational evidence for occurrence of coarse-grained calcite veins (Fig. 10), even immediately above large composite deposits like Candelaria-Punta del Cobre. Small copper-gold skarns located above the Candelaria deposit (Ryan et al. 1995) are probably more a reflection of the carbonate protolith than uppermost manifestations of the entire Candelaria-Punta del Cobre district. Ray and Dick (2002) concluded that a 1.5-km-wide, down-faulted block of massive silicified tuff containing pyrite, sericite and minor dumortierite represents the shallowest alteration facies at the Productora IOCG prospect. This proposal would be in keeping with the widespread occurrence of extensive zones of pyritic feldspar-destructive alteration affecting volcanic sequences locally throughout the Coastal Cordillera, some of them in proximity to IOCG districts. Silicification accompanied by sericitic and/or advanced argillic alteration is commonly recorded.

Exploration consequences

The preceding discussion highlights several geological features and relationships of possible use in IOCG exploration in the Coastal Cordillera of the central Andes and, potentially, in similar extensional environments elsewhere:

1. Middle–Late Jurassic and Early Cretaceous plutonic belts in the Coastal Cordillera are more prospective for IOCG deposits than the younger magmatic arcs farther east. The latter coincide with the principal porphyry copper belts of the central Andes (Fig. 4), thereby underlining an inverse correlation between major IOCG and porphyry copper deposits.
2. Large IOCG deposits seem more likely to form within major orogen-parallel, ductile to brittle fault systems that underwent extension or transtension than in association with either minor or compressional fault structures.
3. Receptive rock packages cut by gabbrodiorite, diorite or more felsic plutons containing IOCG veins or bordered by skarns may be especially prospective for large composite IOCG deposits. The intrusive rocks are likely to display at least localised zones of weakly developed potassic-(calcic) and/or sodic-calcic alteration.
4. Fragmental volcanic or volcaniclastic host rocks characterised by high intrinsic and/or structurally imposed permeability favour the formation of large composite IOCG deposits if suitable progenitor intrusions and deeply penetrating feeder faults are present. High- or low-angle faults or shears may create the structural permeability.
5. Relatively impermeable rocks, such as massive marbleised carbonate units, may be conducive to fluid ponding and the consequent development of immediately subjacent IOCG deposits (Fig. 13). Such impermeable units may even still conceal IOCG deposits and, as at Candelaria (Ryan et al. 1995), minor copper skarn occurrences may represent hanging-wall leakage anomalies (Fig. 13). The possible relationship of calcic skarns to IOCG deposits should not be overlooked.
6. Broad, strongly developed contact-metamorphic (hornfels) and metasomatic (sodic-calcic and/or potassic alteration) aureoles to gabbrodiorite or diorite intrusions are a favourable indicator for large composite IOCG deposits.
7. Intense and pervasive hydrothermal alteration is a prerequisite for large, composite IOCG deposits, although the copper-gold mineralization may be accompanied by potassic, potassic-calcic or sodic-calcic assemblages.
8. Mineralized hydrothermal breccia and the predominance of specular hematite over magnetite both suggest relatively shallow palaeodepths and, hence, persistence of IOCG potential at depth (Fig. 13). By the same token, widespread development of magnetite and actinolite indicate fairly deep levels in IOCG systems, with less likelihood of encountering economic copper-gold contents at appreciable depth.
9. Some, but by no means all, composite IOCG deposits have irregularly and asymmetrically developed pyrite haloes that may provide useful vectors to ore.
10. Coarsely crystalline calcite or ankerite veins may be either the tops or distal manifestations of IOCG deposits.
11. Speculatively, extensive zones of barren feldspar-destructive alteration, including silicification, sericite, pyrite and even advanced argillic assemblages, within volcano-sedimentary sequences may either conceal underlying IOCG deposits or intimate their presence nearby. In essence, such zones are lithocaps, comparable to those well documented from the porphyry copper environment (e.g. Sillitoe 2000).
12. The distal fringes and immediate surroundings of massive magnetite deposits may be prospective for IOCG deposits if suitable structural preparation and volcano-sedimentary host rocks are present.
13. Notwithstanding point 12, districts dominated by massive magnetite bodies or veins may imply relatively deep erosion levels unfavourable for major IOCG deposit preservation.

Concluding remarks

This review of the central Andean IOCG province concludes that the most likely ore fluid is of magmatic parentage, although inadvertent participation of non-magmatic fluids, of the types generated during low-grade diastathermal (burial) metamorphism, seawater circulation or evaporite dissolution, cannot be ruled out locally and, indeed, have been proposed at Candelaria-Punta del Cobre (Ullrich et al. 2001) and Raúl-Condestable (Ripley and Ohmoto 1977; Vidal et al. 1990; de Haller et al. 2002). Metals, with the possible exception of some of the iron, are also thought most likely to have been provided directly by the same magmatic source, for which a primitive gabbrodiorite to diorite composition at appreciable depths beneath the deposit sites is preferred. It is salutary to recall that Buddington (1933) proposed this same genetic relationship between diorite intrusions and veins rich in magnetite, Cu, Au, Co and Ni. No evidence for involvement of alkaline magmas, as implied for IOCG deposits in general by Groves and Vielreicher (2001), is present in the central Andean province.

Notwithstanding this fundamental genetic conclusion, the disparate and poorly defined nature of the IOCG deposit clan does not necessarily imply that all other iron oxide-rich copper-gold deposits worldwide are generated in the same or even a similar manner. Indeed, a non-magmatic brine origin for some IOCG provinces, as advocated by Barton and Johnson (1996, 2000), Haynes (2000) and others, may remain a possibility. Nevertheless, although the IOCG deposit class is too all-encompassing as presently defined, the obvious similarities between several large IOCG deposits, including Candelaria-Punta del Cobre in Chile, Sossego in the Carajás district, Brazil and Ernest Henry in the Cloncurry district of Queensland, Australia (e.g. Mark et al. 2000; Leveille and Marschik 2001), may be taken to suggest that broadly similar, probably pluton-related hydrothermal systems were operative periodically from the Archaean to the Mesozoic. Indeed, diorite and/or gabbro also abut both the Sossego and Ernest Henry orebodies, although current wisdom would consider it to possess no direct genetic connection with, and to predate, the copper-gold introduction. In all three cases, the plutonism and deeply penetrating fault zones proximal to ore are products of regional extension, in either subduction-related arc or intracontinental rift settings (cf. Hitzman 2000).

If the genetic relationship to oxidised, primitive, dioritic magmatism proposed herein for the Coastal Cordillera province and, possibly, some deposits elsewhere is correct, then at least a selection of deposits assigned to the IOCG class would seem to constitute an extended clan in the same manner as proposed by Thompson et al. (1999) and Lang et al. (2000) for base metal-poor, lithophile element (Bi-W-Mo)-enriched gold deposits in association with highly fractionated and relatively reduced felsic intrusions. In both cases, a broad range of deposit styles, including pluton-hosted veins, skarns, breccias and replacement mantos, is evident. The even broader spectrum of copper and gold deposits linked to alkaline magmatism (Jensen and Barton 2000; Sillitoe 2002) may be cited as yet another example of the same fundamental metallogenic influence exerted by magma type, as detailed by Blevin and Chappell (1992) and others for common mineralization types like porphyry copper and tin-tungsten deposits. Acceptance of this proposal might provide an explanation for the occurrence of IOCG deposits in association with petrochemically similar intrusions in both subduction-related arcs and intraplate settings, in an analogous manner to formation of lithophile-element enriched gold deposits both along the landward sides of Cordilleran arcs and in collisional settings (Thompson et al. 1999).

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References

Aberg G, Aguirre L, Levi B, Nyström JO (1984) Spreading-subsidence and generation of ensialic marginal basins: an example from the early Cretaceous of central Chile. In: Kokelaar BP, Howells MF (eds) Marginal basin geology: volcanic and associated sedimentary and tectonic processes in modern and ancient marginal basins. Geol Soc Lond Spec Publ 16:185–193

Aguirre L, Féraud G, Morata D, Vergara M, Robinson D (1999) Time interval between volcanism and burial metamorphism and rate of basin subsidence in a Cretaceous Andean extensional setting. Tectonophysics 313:433–447

Arancibia ON, Clark AH (1996) Early magnetite-amphibole-plagioclase alteration-mineralization in the Island Copper porphyry copper-gold-molybdenum deposit, British Columbia. Econ Geol 91:402–438

Ardill J, Flint S, Chong G, Wilke H (1998) Sequence stratigraphy of the Mesozoic Domeyko Basin, northern Chile. J Geol Soc Lond 155:71–88

Arévalo C, Grocott J, Pringle M, Martin W (2000) Edad $^{40}Ar/^{39}Ar$ de la mineralización en el yacimiento Candelaria, Región de Atacama. Actas 9th Congr Geol Chileno 2:92–96

Atherton MP, Aguirre L (1992) Thermal and geotectonic setting of Cretaceous volcanic rocks near Ica, Peru, in relation to Andean crustal thinning. J S Am Earth Sci 5:47–69

Atkin BP, Injoque-Espinoza JL, Harvey PK (1985) Cu-Fe amphibole mineralization in the Arequipa segment. In: Pitcher WS, Atherton MP, Cobbing EJ, Beckinsale RD (eds) Magmatism at a plate edge. The Peruvian Andes. Blackie, Glasgow, pp 261–270

Barton MD, Johnson DA (1996) Evaporitic source model for igneous-related Fe oxide-(REE-Cu-Au-U) mineralization. Geology 24:259-262

Barton MD, Johnson DA (2000) Alternative brine sources for Fe-oxide (-Cu-Au) systems: Implications for hydrothermal alteration and metals. In: Porter TM (ed) Hydrothermal iron oxide copper-gold and related deposits: A global perspective. Australian Mineral Foundation, Adelaide, pp 43–60

Benavides-Cáceres V (1999) Orogenic evolution of the Peruvian Andes: The Andean cycle. In: Skinner BJ (ed) Geology and ore deposits of the central Andes. Soc Econ Geol Spec Publ 7:61–107

Berg K, Baumann A (1985) Plutonic and metasedimentary rocks from the Coastal Range of northern Chile: Rb-Sr and U-Pb isotopic systematics. Earth Planet Sci Lett 75:101–115

Blevin PL, Chappell BW (1992) The role of magma sources, oxidation states and fractionation in determining the granite metallogeny of eastern Australia. Trans R Soc Edinburgh Earth Sci 83:305–316

Bookstrom AA (1977) The magnetite deposits of El Romeral, Chile. Econ Geol 72:1101–1130

Boric P. R, Díaz F. F, Maksaev J. V (1990) Geología y yacimientos metalíferos de la Región de Antofagasta. Serv Nac Geol Miner Bol 40:1–246

Brown M, Díaz F, Grocott J (1993) Displacement history of the Atacama fault system 25°00′S–27°00′S, northern Chile. Geol Soc Am Bull 105:1165–1174

Browne QJ, Thompson TB, Maher BJ (2000) Shear-hosted copper mineralization within the Atacama Fault Zone, El Salado district, northern Chile. In: Cluer JK, Price JG, Struhsacker EM, Hardyman RF, Morris CL (eds) Geology and ore deposits 2000: The Great Basin and beyond Proc Symp Geological Society of Nevada, Reno, pp 467–472

Buddington AF (1933) Correlation of kinds of igneous rocks with kinds of mineralization. In: Ore deposits of the Western States (Lindgren Volume). Am Inst Mining Metall Eng, New York, pp 350–385

Caldas V. J (1978) Geología de los Cuadrángulos de San Juan, Acarí y Yauca. Hojas: (31-m, 31-n, 32-n). Inst Geol Miner Bol 30:1–78

Cann RM, Godwin CI (1983) Genesis of magmatic magnetite-apatite lodes, Iron Mask batholith, south-central British Columbia. In: Geological fieldwork 1982. BC Ministry Energy Mines Petrol Resources, Pap 1983–1, pp 266–284

Clark AH, Farrar E, Kontak DJ, Langridge RJ, Arenas F. MJ, France LJ, McBride SL, Woodman PL, Wasteneys HA, Sandeman HA, Archibald DA (1990) Geologic and geochronologic constraints on the metallogenic evolution of the Andes of southeastern Peru. Econ Geol 85:1520–1583

Cobbing EJ (1978) The Andean geosyncline in Peru and its distinction from Alpine geosynclines. J Geol Soc Lond 135:207–218

Cobbing EJ (1985) The tectonic setting of the Peruvian Andes. In: Pitcher WS, Atherton MP, Cobbing EJ, Beckinsale RD (eds) Magmatism at a plate edge. The Peruvian Andes. Blackie, Glasgow, pp 3–12

Cornejo P, Matthews SJ (2000) Relación entre magmatismo-tectónica y su implicancia en la formación de sistemas de pórfidos cupríferos: Yacimiento El Salvador, II Región, Chile. Actas 9th Congr Geol Chileno 1:184–188

Cornejo P, Matthews S, Orrego M, Robles W (2000) Etapas de mineralización asociadas a alteración potásica en un sistema de Fe-Cu-Au: Yacimiento Mantoverde, III Región de Atacama, Chile. Actas 9th Congr Geol Chileno 2:97–101

Correa A (2000) Geología del yacimiento de Fe-Cu Teresa de Colmo, Región de Antofagasta, Chile. Actas 9th Congr Geol Chileno 2:102–106

Correa A (2003) El Espino, un nuevo depósito del tipo Fe-Cu (Au) en Chile. Comuna de Illapel, Región de Coquimbo. Tésis de Magister, Universidad Católica del Norte, Antofagasta, Chile, 69 pp

Dallmeyer RD, Brown M, Grocott J, Taylor GK, Treloar PJ (1996) Mesozoic magmatic and tectonic events within the Andean plate boundary zone, 26°–27°30′S, north Chile: constraints from $^{40}Ar/^{39}Ar$ mineral ages. J Geol 104:19–40

Dalziel IWD (1986) Collision and Cordilleran orogenesis: an Andean perspective. In: Coward MP, Ries AC (eds) Collision tectonics. Geol Soc Lond Spec Publ 19:389–404

de Haller A, Zúñiga A. J, Corfu F, Fontboté L (2002) The iron oxide-Cu-Au deposit of Raúl-Condestable, Mala, Lima, Peru. Resúmen 11th Congr Geol Peruano

Díaz A, Vivallo W (2001) Metallogenic events in the Coastal Cordillera of Copiapó region, northern Chile (26–28°S). In: Proc 3rd S Am Symp Isotope Geology, Ext Abstr Vol, Sociedad Geológica de Chile, Santiago, CD-ROM, pp 468–471

Díaz C. A, Lledó V. H, Vivallo S. W (1998) Yacimientos metalíferos de la Hoja Los Loros, Región de Atacama. Serv Nac Geol Miner Mapa Recursos Mineral Chile 2:1–25

Einaudi MT, Meinert LD, Newberry RJ (1981) Skarn deposits. In: Skinner BJ (ed) Econ Geol 75th Anniv Vol, pp 317–391

Espinoza P. C, Gelcich E. S, Vivallo S. W (1999) Yacimientos metalíferos de la Hoja Quebrada Salitrosa, Región de Atacama. Serv Nac Geol Miner Mapa Recursos Mineral Chile 4:1–21

Espinoza S (1990) The Atacama-Coquimbo ferriferous belt, northern Chile. In: Fontboté L, Amstutz GC, Cardozo M, Cedillo E, Frutos J (eds) Stratabound copper deposits in the Andes. Soc Geol Appl Mineral Dep Spec Publ 8:353–364

Espinoza R. S, Véliz G. H, Esquivel L. J, Arias F. J, Moraga B. A (1996) The cupriferous province of the Coastal Range, northern Chile. In: Camus F, Sillitoe RH, Petersen R (eds) Andean copper deposits: New discoveries, mineralization styles and metallogeny. Soc Econ Geol Spec Publ 5:19–32

Farrar E, Clark AH, Haynes SJ, Quirt GS, Conn H, Zentilli M (1970) K-Ar evidence for the post-palaeozoic migration of granitic intrusion foci in the Andes of northern Chile. Earth Planet Sci Lett 9:17–28

Flint S, Turner P (1988) Alluvial fan and fan-delta sedimentation in a forearc extensional setting: the Cretaceous Coloso basin of northern Chile. In: Nemec W, Steel RJ (eds) Fan deltas: Sedimentology and tectonic settings. Blackie, Glasgow, pp 387–399

Fox KA (2000) Fe oxide (Cu-Au) mineralization and alteration at the Productora prospect, Chile. MSc Thesis, Colorado School of Mines, Colorado, 141 pp

Fox KA, Hitzman MW (2001) Superimposed magnetite and iron oxide Cu-Au mineralization at Productora, Chilean iron belt. Geol Soc Am Abstr Prog 33(6):A-129

Fréraut R, Cuadra W (1994) Mineralización de Fe, Cu y Au en la franja cretácica de la Costa. Regiones III y IV de Chile. Actas 7th Congr Geol Chileno 2:1046–1050

Gelcich E. S, Espinoza P. C, Vivallo S. W (1998) Yacimientos metalíferos de las Hojas Chañaral y Diego de Almagro, Región de Atacama. Serv Nac Geol Miner Mapa Recursos Mineral Chile 3:17

Gleeson SA, Yardley BWD, Boyce AJ, Fallick AE, Munz I-A (2000) From basin to basement: the movement of surface fluids into the crust. J Geochem Explor 69–70:527–531

Grocott J, Taylor GK (2002) Magmatic arc fault systems, deformation partitioning and emplacement of granitic complexes in the Coastal Cordillera, northern Chilean Andes (25°30′S to 27°00′S). J Geol Soc Lond 159:425–442

Grocott J, Wilson J (1997) Ascent and emplacement of granitic plutonic complexes in subduction-related extensional environments. In: Holness MB (ed) Deformation-enhanced fluid transport in the Earth's crust and mantle. Chapman and Hall, London, pp 173–195

Grocott J, Brown M, Dallmeyer RD, Taylor GK, Treloar PJ (1994) Mechanisms of continental growth in extensional arcs: an example from the Andean plate boundary zone. Geology 22:391–394

Groves DI, Vielreicher NM (2001) The Phalaborwa (Palabora) carbonatite-hosted magnetite-copper sulfide deposit, South Africa: an end-member of the iron-oxide copper-gold-rare earth element deposit group? Miner Deposita 36:189–194

Hammerschmidt K, Döbel R, Friedrichsen H (1992) Implications of $^{40}Ar/^{39}Ar$ dating of early Tertiary volcanic rocks from the north-Chilean Precordillera. Tectonophysics 202:55–81

Hattori KH, Keith JD (2001) Contribution of mafic melt to porphyry copper mineralization: evidence from Mount Pinatubo, Philippines, and Bingham Canyon, Utah, USA. Miner Deposita 36:799–806

Haynes DW (2000) Iron oxide copper (-gold) deposits: their position in the ore deposit spectrum and modes of origin. In: Porter TM (ed) Hydrothermal iron oxide copper-gold and related deposits: A global perspective. Australian Mineral Foundation, Adelaide, pp 71–90

Hervé A. M (1987) Movimiento sinistral en el Cretácico Inferior de la zona de falla Atacama al norte de Paposo (24°S), Chile. Rev Geol Chile 31:37–42

Hitzman MW (2000) Iron oxide-Cu-Au deposits: what, where, when, and why. In: Porter TM (ed) Hydrothermal iron oxide copper-gold and related deposits: A global perspective. Australian Mineral Foundation, Adelaide, pp 9–25

Hitzman MW, Oreskes N, Einaudi MT (1992) Geological characteristics and tectonic setting of Proterozoic iron oxide (Cu-U-Au-REE) deposits. Precamb Res 58:241–287

Holmgren D. C (1987) Antecedentes para un modelo genético del yacimiento El Soldado, V Región de Valparaíso, Chile. Rev Geol Chile 30:3–18

Hopf S (1990) The Agustina mine, a volcanic-hosted copper deposit in northern Chile. In: Fontboté L, Amstutz GC, Cardozo M, Cedillo E, Frutos J (eds) Stratabound copper deposits in the Andes. Soc Geol Appl Mineral Dep Spec Publ 8:421–434

Hopper D, Correa A (2000) The Panulcillo and Teresa de Colmo copper deposits: two contrasting examples of Fe-ox-Cu-Au mineralisation from the Coastal Cordillera of Chile. In: Porter TM (ed) Hydrothermal iron oxide copper-gold and related deposits: A global perspective. Australian Mineral Foundation, Adelaide, pp 177–189

Injoque J (2000) Distribución de yacimientos de sulfuros masivos (VMS) y de cobre tipo manto (CuTM) en el arco volcánico cretácico de los Andes peruanos y sudamericanos. Bol Soc Geol Perú 90:19–34

Injoque J (2001) Segmentación de los gabros y dioritas tempranos del Batolito de la Costa (Superunidades Patap y Pisco), la fase deformativa Mochica y mineralización asociadas, como parte de la segmentación cretácea de la Costa Peruana. Bol Soc Geol Perú 92:7–21

Injoque E. J (2002) Fe oxide-Cu-Au deposits in Peru: An integrated view. In: Porter TM (ed) Hydrothermal iron oxide copper-gold and related deposits: A global perspective, vol 2. PGC Publishing, Adelaide, pp 97–113

Injoque E. J, Atkin B, Harvey P, Snelling N (1988) Mineralogía, geochímica y geocronología del skarn geotermal de hierro de Marcona. Bol Soc Geol Perú 79:65–80

Iriarte D. S, Arévalo V. C, Mpodozis M. C, Rivera H. O (1996) Mapa geológica de la Hoja Carrera Pinto, Región de Atacama. Serv Nac Geol Miner Mapas Geol 3

Ishihara S, Ulriksen CE (1980) The magnetite-series and ilmenite-series granitoids of Chile. Min Geol 30:183–190

Jensen EP, Barton MD (2000) Gold deposits related to alkaline magmatism. In: Hagemann SG, Brown PE (eds) Gold in 2000. Rev Econ Geol 13:279–314

Kirkham RV (1996) Volcanic redbed copper. In: Eckstrand OR, Sinclair WD, Thorpe RI (eds) Geology of Canadian mineral deposit types. Geol Surv Can Geol Can 8:241–252

Kirkham RV (2001) Sediment-hosted stratiform copper (SSC), other stratabound base metal deposits and the importance of basinal brines and/or evaporites, halotectonics and halokinesis. In: Piestrzyñski A et al. (eds) Mineral deposits at the beginning of the 21st century. Proc Joint 6th Biennial SGA-SEG Meeting, Kraków, AA Balkema, Lisse, pp 15–18

Ladino M, Tomlinson A, Blanco N (1997) Nuevos antecedentes para la edad de la deformación cretácica en Sierra de Moreno, II Región de Antofagasta—norte de Chile. Actas 8th Congr Geol Chileno 1:103–107

Lang JR, Thompson JFH (2001) Alkalic porphyry Cu-Au deposits: Magmatic-hydrothermal mineralization with similarities to Fe-oxide Cu-Au deposits. Geol Soc Am Abstr Prog 33(6):A-3

Lang JR, Stanley CR, Thompson JFH (1995) Porphyry copper-gold deposits related to alkalic igneous rocks in the Triassic–Jurassic arc terranes of British Columbia. In: Pierce FW, Bolm JG (eds) Porphyry copper deposits of the American Cordillera. Ariz Geol Soc Dig 20:219–236

Lang JR, Baker T, Hart C, Mortensen JK (2000) An exploration model for intrusion-related gold systems. Soc Econ Geol Newsl 40:1, 6–14

Lara P. L, Godoy P-B. E (1998) Hoja Quebrada Salitrosa, Región de Atacama. Serv Nac Geol Miner Mapas Geol 4

Leveille RA, Marschik R (2001) Iron oxide copper-gold deposits in South America. In: Proc 2nd Congr Int de Prospectores y Exploradores, Lima, 2001, Inst de Ingenieros de Minas del Perú, Lima, CD-ROM, 6 pp

Levi B, Nyström JO, Thiele R, Aberg G (1988) Geochemical trends in Mesozoic–Tertiary volcanic rocks from the Andes in central Chile and tectonic implications. J S Am Earth Sci 1:63–74

Levi B, Aguirre L, Nyström JO, Padilla H, Vergara M (1989) Low-grade regional metamorphism in the Mesozoic–Cenozoic sequences of the Central Andes. J Metamorph Geol 7:487–495

Ly Z. P (2000) Yacimiento Cerro Lindo. In: Primer volumen de monografías de yacimientos minerales peruanos. Historía, exploración y geología. (Volumen Luis Hochschild Plaut) Inst de Ingenieros de Minas del Perú, Lima, pp 349–358

MacDonald GD, Arnold LC (1994) Geological and geochemical zoning of the Grasberg igneous complex, Irian Jaya, Indonesia. In: van Leeuwen TM, Hedenquist JW, James LP, Dow JAS (eds) Mineral deposits in Indonesia—Discoveries of the past 25 years. J Geochem Explor 50:143–178

Maksaev V, Zentilli M (2002) Chilean strata-bound Cu- (Ag) deposits: An overview. In: Porter TM (ed) Hydrothermal iron oxide copper-gold and related deposits: A global perspective, vol 2. PGC Publishing, Adelaide, pp 185–205

Mark G, Oliver NHS, Williams PJ, Valenta RK, Crookes RA (2000) The evolution of the Ernest Henry Fe-oxide-(Cu-Au) hydrothermal system. In: Porter TM (ed) Hydrothermal iron oxide copper-gold and related deposits: A global perspective. Australian Mineral Foundation, Adelaide, pp 123–136

Marschik R, Fontboté L (1996) Copper(-iron) mineralization and superposition of alteration events in the Punta del Cobre belt, northern Chile. In: Camus F, Sillitoe RH, Petersen R (eds) Andean copper deposits: New discoveries, mineralization styles and metallogeny. Soc Econ Geol Spec Publ 5:171–190

Marschik R, Fontboté L (2001a) The Punta del Cobre Formation, Punta del Cobre-Candelaria area, northern Chile. J S Am Earth Sci 14:401–433

Marschik R, Fontboté L (2001b) The Candelaria-Punta del Cobre iron oxide Cu-Au (-Zn-Ag) deposits, Chile. Econ Geol 96:1799–1826

Marschik R, Leveille RA, Martin W (2000) La Candelaria and the Punta del Cobre district, Chile. Early Cretaceous iron oxide Cu-Au(-Zn-Ag) mineralization. In: Porter TM (ed) Hydrothermal iron oxide copper-gold and related deposits: A global perspective. Australian Mineral Foundation, Adelaide, pp 163–175

Martin W, Díaz R, Nuñéz R, Olivares R, Calderón C, Calderón P (1997) The updated Candelaria geologic mine model. Actas 8th Congr Geol Chileno 2:1063–1067

Mathur R, Marschik R, Ruiz J, Munizaga F, Leveille RA, Martin W (2002) Age of mineralization of the Candelaria Fe oxide Cu-Au deposit and the origin of the Chilean iron belt, based on Re-Os isotopes. Econ Geol 97:59–71

McAllister JF, Flores W. H, Ruiz F. C (1950) Quicksilver deposits of Chile. US Geol Surv Bull 964-E:361–400

McNutt RH, Crocket JH, Clark AH, Caelles JC, Farrar E, Haynes SJ (1975) Initial $^{87}Sr/^{86}Sr$ ratios of plutonic and volcanic rocks of the central Andes between latitudes 26° and 29° south. Earth Planet Sci Lett 27:305–313

Meinert LM (1992) Skarns and skarn deposits. Geosci Can 19:145–162

Ménard J-J (1995) Relationship between altered pyroxene diorite and the magnetite mineralization in the Chilean Iron Belt, with emphasis on the El Algarrobo iron deposits (Atacama region, Chile). Miner Deposita 30:268–274

Moody TC, Hawkes N, Ramos D, Loader S, Panez R, Abbott C, Carbonell J, Sillitoe RH (2003) The Marcona iron oxide-copper deposits, Peru. In: Proc 3rd Congr Int de Prospectores y Exploradores, Lima, Conferencias, Inst de Ingenieros de Minas del Perú, Lima, CD-ROM, 2 pp

Moore ND, Agar RA (1985) Variations along a batholith: the Arequipa segment of the coastal batholith of Peru. In: Pitcher WS, Atherton MP, Cobbing EJ, Beckinsale RD (eds) Magmatism at a plate edge. The Peruvian Andes. Blackie, Glasgow, pp 108–118

Moscoso D. R, Nasi P. C, Salinas Z. P (1982) Hoja Vallenar y parte Norte de La Serena, Regiones de Atacama y Coquimbo. Serv Nac Geol Miner Carta Geol Chile 55:1–100

Mpodozis C, Ramos V (1990) The Andes of Chile and Argentina. In: Ericksen GE, Cañas Pinochet MT, Reinemund JA (eds) Geology of the Andes and its relation to hydrocarbon and mineral resources. Circum-Pacific Council Energy Min Resour Earth Sci Ser 11:59–90

Munizaga F, Huete C, Hervé F (1985) Geocronología y razones iniciales Sr^{87}/Sr^{86} de la 'Faja Pacífica' de 'Desarrollos Hidrotermales'. Actas 4th Congr Geol Chileno 3:357–379

Muñoz N, Elgueta S, Harambour S (1988) El sistema Jurásico en el curso superior de la quebrada de Azapa, I Región: Implicancias palaeogeográficas. Actas 5th Congr Geol Chileno 1:A403–A415

Naslund HR, Henríquez F, Nyström JO, Vivallo W, Dobbs FM (2002) Magmatic iron ores and associated mineralization: Examples from the Chilean High Andes and Coastal Cordillera. In: Porter TM (ed) Hydrothermal iron oxide copper-gold and related deposits: A global perspective, vol 2. PGC Publishing, Adelaide, pp 207–226

Nyström JO, Henríquez F (1994) Magmatic features of iron ores of the Kiruna type in Chile and Sweden: Ore textures and magnetite geochemistry. Econ Geol 89:820–839

Orrego M, Zamora R (1991) Manto Ruso, un yacimiento de cobre ligado a la Falla de Atacama, norte de Chile. Actas 6th Congr Geol Chileno 1:174–178

Orrego M, Robles W, Sanhueza A, Zamora R, Infanta J (2000) Mantos Blancos y Mantoverde: depósitos del tipo Fe-Cu-Au? Una comparación con implicancias en la exploración. Actas 9th Congr Geol Chileno 2:145–149

Oyarzún J (1988) Algunos temas principales de la metalogénesis cretácica en el norte y centro de Chile. Actas 5th Congr Geol Chileno 3:G37–G52

Palacios M. O, Caldas V. J, Vela V. C (1992) Geología de los Cuadrángulos de Lima, Lurín, Chancay y Chosica. Hojas 25-i, 25-j, 24-i, 24-j. Carta Geol Nac Inst Geol Min Metal Bol 43:1–163

Parada MA (1990) Granitoid plutonism in central Chile and its geodynamic significance; A review. In: Kay SM, Rapela CW (eds) Plutonism from Antarctica to Alaska. Geol Soc Am Spec Pap 241:51–66

Parada MA, Nyström JO, Levi B (1999) Multiple sources for the Coastal Batholith of central Chile (31–34°S): geochemical and Sr-Nd isotopic evidence and tectonic implications. Lithos 46:505–521

Perelló J, Martini R, Arcos R, Muhr R (2003) Buey Muerto: porphyry copper mineralization in the Early Cretaceous arc of northern Chile. In: Resumenes 10th Congr Geol Chileno (in press)

Pichowiak S (1994) Early Jurassic to Early Cretaceous magmatism in the Coastal Cordillera and the Central Depression of north Chile. In: Reutter K-J, Scheuber E, Wigger PJ (eds) Tectonics of the southern central Andes. Springer, Berlin Heidelberg New York, pp 203–217

Pichowiak S, Breitkreuz C (1984) Volcanic dykes in the North Chilean Coast Range. Geol Rundsch 73:853–868

Pichowiak S, Buchelt M, Damm K-W (1990) Magmatic activity and tectonic setting of the early stages of the Andean cycle in northern Chile. In: Kay SM, Rapela CW (eds) Plutonism from Antarctica to Alaska. Geol Soc Am Spec Pap 241:127–144

Pollard PJ (2000) Evidence of a magmatic fluid and metal source for Fe-oxide Cu-Au mineralisation. In: Porter TM (ed) Hydrothermal iron oxide copper-gold and related deposits: A global perspective. Australian Mineral Foundation, Adelaide, pp 27–41

Pollard PJ (2001) Sodic(-calcic) alteration in Fe-oxide-Cu-Au districts: an origin via unmixing of magmatic H_2O-CO_2-$NaCl\pm$-$CaCl_2$-KCl fluids. Miner Deposita 36:93–100

Pop N, Heaman L, Edelstein O, Isache C, Zentilli M, Pecskay Z, Valdman S, Rusu C (2000) Geocronología de las rocas igneas y los productos de alteración hidrotermal relacionadas con la mineralización de Cu-Fe (Au) del sector Adriana-Carola-Cobriza (parte este del distrito Punta del Cobre-Candelaria), en base a dataciones U-Pb en circón, $^{40}Ar/^{39}Ar$ y K-Ar. Actas 9th Congr Geol Chileno 2:155–160

Ramírez R. RD (1996) Geology of the Mantos Blancos mine. In: Green SM, Struhsacker E (eds) Geology and ore deposits of the American Cordillera. Field trip guidebook and compendium. Geological Society of Nevada, Reno, pp 466–481

Ramos VA (2000) The southern central Andes. In: Cordani UG, Milani EJ, Thomaz Filho A, Campos DA (eds) Tectonic evolution of South America. In: Proc 31st Int Geol Congr, Rio de Janeiro, pp 561–604

Ramos VA, Aleman A (2000) Tectonic evolution of the Andes. In: Cordani UG, Milani EJ, Thomaz Filho A, Campos DA (eds) Tectonic evolution of South America. In: Proc 31st Int Geol Congr, Rio de Janeiro, pp 635–685

Ray GE, Dick LA (2002) The Productora prospect in north-central Chile: An example of an intrusion-related Candelaria type Fe-Cu-Au hydrothermal system. In: Porter TM (ed) Hydrothermal iron oxide copper-gold and related deposits: A global perspective, vol 2. PGC Publishing, Adelaide, pp 131–151

Ray GE, Lefebure DV (2000) A synopsis of iron oxide ± Cu ± Au ± P ± REE deposits of the Candelaria-Kiruna-Olympic Dam family. In: Geological fieldwork 1999. BC Ministry Energy Mines Pap 2000–1, pp 267–271

Ray GE, Webster ICL (2000) Characteristics of the Fe oxide-Cu-Au family and the potential for these deposits in British Columbia. In: Iron oxide copper-gold deposits: Separating fact from fantasy. Short course notes. Vancouver Mining Association, BC Yukon Chamber Mines, Vancouver, pp F1–F47

Reeve JS, Cross KC, Smith RN, Oreskes N (1990) Olympic Dam copper-uranium-gold-silver deposit. In: Hughes FE (ed) Geology of the mineral deposits of Australia and Papua New Guinea, vol 2. Aust Inst Min Metall Monogr 14:1009–1035

Regan PF (1985) The early basic intrusions. In: Pitcher WS, Atherton MP, Cobbing EJ, Beckinsale RD (eds) Magmatism at a plate edge. The Peruvian Andes. Blackie, Glasgow, pp 72–89

Ripley EM, Ohmoto H (1977) Mineralogic, sulfur isotope, and fluid inclusion studies of the stratabound copper deposits at the Raul mine, Peru. Econ Geol 72:1017–1041

Rivano GS, Sepúlveda HP (1991) Hoja Illapel, Región de Coquimbo. Serv Nac Geol Miner Carta Geol Chile 69:1–132

Rogers G, Hawkesworth CJ (1989) A geochemical traverse across the North Chilean Andes: evidence for crust generation from the mantle wedge. Earth Planet Sci Lett 91:271–285

Romeuf N, Aguirre L, Soler P, Féraud G, Jaillard E, Ruffet G (1995) Middle Jurassic volcanism in the northern and central Andes. Rev Geol Chile 22:245–259

Ruiz F. C, Ericksen GE (1962) Metallogenic provinces of Chile, S.A. Econ Geol 57:91–106

Ruiz F. C, Peebles L. F (1988) Geología, distribución y génesis de los yacimientos metalíferos chilenos. Editorial Universitaria, Santiago, 334 pp

Ruiz F. C, Corvalán J, Klohn C, Klohn E, Levi B (1965) Geología y yacimientos metalíferos de Chile. Instituto de Investigaciones Geológicas, Santiago, 305 pp

Ruiz F. C, Ortiz F, Moraga A, Aguilar A (1968) Genesis of the Chilean iron ore deposits of Mesozoic age. Rep 23rd Int Geol Congr 7:323–338

Rutland RWR (1971) Andean orogeny and ocean floor spreading. Nature 233:252–255

Ryan PJ, Lawrence AL, Jenkins RA, Matthews JP, Zamora G. JC, Marino W. E, Urqueta D. I (1995) The Candelaria copper-gold deposit, Chile. In: Pierce FW, Bolm JG (eds) Porphyry copper deposits of the American Cordillera. Ariz Geol Soc Dig 20:625–645

Saric R. N (1978) Geología y mineralización del yacimiento La Africana. Rev Geol Chile 6:31–40

Sato T (1984) Manto type copper deposits in Chile—a review. In: Special issue for overseas geology and mineral resources (I)—calc-alkaline magmatism and related mineralization in Chile. Bull Geol Surv Jpn 35:565–582

Scheuber E, Andriessen PAM (1990) The kinematic and geodynamic significance of the Atacama Fault Zone, northern Chile. J Struct Geol 12:243–257

Scheuber E, Gonzalez G (1999) Tectonics of the Jurassic–Early Cretaceous magmatic arc of the north Chilean Coastal Cordillera (22°–26°S): a story of crustal deformation along a convergent plate boundary. Tectonics 18:895–910

Scheuber E, Hammerschmidt K, Friedrichsen H (1995) $^{40}Ar/^{39}Ar$ and Rb-Sr analyses from ductile shear zones from the Atacama Fault Zone, northern Chile: the age of deformation. Tectonophysics 250:61–87

Sempere T, Carlier G, Soler P, Fornari M, Carlotto V, Jacay J, Arispe O, Néraudeau D, Cárdenas J, Rosas S, Jiménez N (2002a) Late Permian–Middle Jurassic lithospheric thinning in Peru and Bolivia, and its bearing on Andean-age tectonics. Tectonophysics 345:153–181

Sempere T, Jacay J, Pino A, Fornari M, Marocco R, Flores A, Acosta J, Bedoya C (2002b) Adelgazamiento litosférico Triásico–Jurásico en el extremo sur del Perú. In: Resúmenes 11th Congr Geol Peruano

Shackleton RM, Ries AC, Coward MP, Cobbold PR (1979) Structure, metamorphism and geochronology of the Arequipa massif of coastal Peru. J Geol Soc Lond 136:195–214

Sillitoe RH (1990) Copper deposits and Andean evolution. In: Ericksen GE, Cañas Pinochet MT, Reinemund JA (eds) Geology of the Andes and its relation to hydrocarbon and mineral resources. Circum-Pacific Council Energy Min Resour Earth Sci Ser 11:285–311

Sillitoe RH (1992) Gold and copper metallogeny of the central Andes—past, present, and future exploration objectives. Econ Geol 87:2205–2216

Sillitoe RH (1998) Major regional factors favouring large size, high hypogene grade, elevated gold content and supergene oxidation and enrichment of porphyry copper deposits. In: Porter TM (ed) Porphyry and hydrothermal copper and gold deposits. A global perspective. Australian Mineral Foundation, Adelaide, pp 21–34

Sillitoe RH (2000) Gold-rich porphyry deposits: Descriptive and genetic models and their role in exploration and discovery. In: Hagemann SG, Brown PE (eds) Gold in 2000. Rev Econ Geol 13:315–345

Sillitoe RH (2002) Some metallogenic features of gold and copper deposits related to alkaline rocks and consequences for exploration. Miner Deposita 37:4–13

Sillitoe RH, Gappe IM Jr (1984) Philippine porphyry copper deposits: Geologic setting and characteristics. United Nations ESCAP CCOP Tech Publ 14, 89 pp

Skewes AM, Arévalo A, Floody R, Zuñiga PH, Stern CR (2002) The giant El Teniente breccia deposit: Hypogene copper distribution and emplacement. In: Goldfarb RJ, Nielsen RL (eds) Integrated methods for discovery: Global exploration in the twenty-first century. Soc Econ Geol Spec Publ 9:299–332

Snyder LD, Russell JK (1995) Petrogenetic relationships and assimilation processes in the alkalic Iron Mask batholith, south-central British Columbia. In: Schroeter TG (ed) Porphyry deposits of the northwestern Cordillera of North America. Can Inst Min Metall Petrol Spec Vol 46:593–608

Suárez M, Bell CM (1992) Triassic rift-related sedimentary basins in northern Chile (24°–29°S). J S Am Earth Sci 6:109–121

Suárez M, Bell CM (1994) Braided rivers, lakes and sabkhas of the Upper Triassic Cifuncho Formation, Atacama Region, Chile. J S Am Earth Sci 7:25–33

Sugaki A, Campos E, Kojima S (2000) Mineralogy of the Panulcillo skarn copper deposit, Coquimbo Region, Chile. Rev Geol Chile 27:139–155

Taylor GK, Randall DE (2000) Structural analysis of dyke emplacement directions as an aid to palaeomagnetic studies: an example from northern Chile. Geophys J Int 141:253–258

Taylor GK, Grocott J, Pope A, Randall DE (1998) Mesozoic fault systems, deformation and fault block rotation in the Andean forearc: a crustal scale strike-slip duplex in the Coastal Cordillera of northern Chile. Tectonophysics 299:93–109

Thompson JFH, Sillitoe RH, Baker T, Lang JR, Mortensen JK (1999) Intrusion-related gold deposits associated with tungsten-tin provinces. Miner Deposita 34:323–334

Tilling R (1976) El Batolito Andino cerca de Copiapó, Provincía de Atacama. Geología y petrología. Rev Geol Chile 3:1–24

Tosdal RM, Richards JP (2001) Magmatic and structural controls on the development of porphyry Cu ± Mo ± Au deposits. In: Tosdal RM, Richards JP (eds) Structural controls of ore deposits. Rev Econ Geol 14:157–181

Ullrich TD, Clark AH (1999) The Candelaria copper-gold deposit, Región III, Chile: Paragenesis, geochronology and fluid composition. In: Stanley CJ et al. (eds) Mineral deposits: Processes to processing, vol 1. In: Proc 5th Biennial SGA Meeting and 10th Quadren IAGOD Symp, London, AA Balkema, Rotterdam, pp 201–204

Ullrich TD, Clark AH, Kyser TK (2001) The Candelaria Cu-Au deposit, III region, Chile: Product of long-term mixing of magmatic-hydrothermal and evaporite-sourced fluids. Geol Soc Am Abstr Prog 33(6):A-3

Vicente J-C (1990) Early Late Cretaceous overthrusting in the Western Cordillera of southern Peru. In: Ericksen GE, Cañas Pinochet MT, Reinemund JA (eds) Geology of the Andes and its relation to hydrocarbon and mineral resources. Circum-Pacific Council Energy Min Resour Earth Sci Ser 11:91–117

Vidal CE (1985) Metallogenesis associated with the Coastal Batholith of Peru: a review. In: Pitcher WS, Atherton MP, Cobbing EJ, Beckinsale RD (eds) Magmatism at a plate edge. The Peruvian Andes. Blackie, Glasgow, pp 243–249

Vidal C. CE (1987) Kuroko-type deposits in the Middle-Cretaceous marginal basin of central Peru. Econ Geol 82:1409–1430

Vidal C. CE, Injoque-Espinoza J, Sidder GB, Mukasa SB (1990) Amphibolitic Cu-Fe skarn deposits in the central coast of Peru. Econ Geol 85:1447–1461

Vila T, Lindsay N, Zamora R (1996) Geology of the Mantoverde copper deposit, northern Chile: A specularite-rich, hydrothermal-tectonic breccia related to the Atacama Fault Zone. In: Camus F, Sillitoe RH, Petersen R (eds) Andean copper deposits: New discoveries, mineralization styles and metallogeny. Soc Econ Geol Spec Publ 5:157–169

Vivallo W, Henríquez F (1998) Génesis común de los yacimientos estratoligados y vetiformes de cobre del Jurásico Medio a Superior en la Cordillera de la Costa, Región de Antofagasta, Chile. Rev Geol Chile 25:199–228

Vivallo W, Henríquez F, Espinoza S (1995) Los depósitos de hierro del tipo magnetite-apatita: geoquímica de las rocas volcánicas asociadas y potencialidad de la mena de hierro como fuente de mineralización de oro. Rev Geol Chile 22:159–175

Wang S, Williams PJ (2001) Geochemistry and origin of Proterozoic skarns at the Mount Elliott Cu-Au(-Co-Ni) deposit, Cloncurry district, NW Queensland, Australia. Miner Deposita 36:109–124

Williams PJ (1999) Fe-oxide-Cu-Au deposits of the Olympic Dam/Ernest Henry-type. In: New developments in the understanding of some major ore types and environments, with implications for exploration. In: Proc Prospectors and Developers Association of Canada Short Course, Toronto, pp 2–43

Wilson JJ (1963) Cretaceous stratigraphy of central Andes of Peru. Bull Am Assoc Petrol Geol 47:1–34

Wolf F, Fontboté L, Amstutz GC (1990) The Susana copper(-silver) deposit in northern Chile. Hydrothermal mineralization associated with a Jurassic volcanic arc. In: Fontboté L, Amstutz GC, Cardozo M, Cedillo E, Frutos J (eds) Stratabound copper deposits in the Andes. Soc Geol Appl Mineral Dep Spec Publ 8:319–338.

Zamora R, Castillo B (2001) Mineralización de Fe-Cu-Au en el distrito Mantoverde, Cordillera de la Costa, III Región de Atacama, Chile. In: Proc 2nd Congr Int de Prospectores y Exploradores, Lima, Conferencias, Inst de Ingenieros de Minas del Perú, Lima, CD-ROM, 13 pp