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LETTER

The role of the Antofagasta–Calama Lineament in ore deposit deformation in the Andes of northern Chile

Carlos Palacios · Luis E. Ramírez · Brian Townley · Marcelo Solari · Nelson Guerra

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Abstract During the Late Jurassic–Early Oligocene interval, widespread hydrothermal copper mineralization events occurred in association with the geological evolution of the southern segment of the central Andes, giving rise to four NS-trending metallogenic belts of eastward-decreasing age: Late Jurassic, Early Cretaceous, Late Paleocene–Early Eocene, and Late Eocene–Early Oligocene. The Antofagasta–Calama Lineament (ACL) consists of an important dextral strike-slip NE-trending fault system. Deformation along the ACL system is evidenced by a right-lateral displacement of the Late Paleocene–Early Eocene metallogenic belts. Furthermore, clockwise rotation of the Early Cretaceous Mantos Blancos copper deposit and the Late Paleocene Lomas Bayas porphyry copper occurred. In the Late Eocene–Early Oligocene metallogenic belt, a sigmoidal deflection and a clockwise rotation is observed in the ACL. The ACL is thought to have controlled the emplacement of Early Oligocene porphyry copper deposits (34–37 Ma; Toki, Genoveva, Quetena, and Opache), whereas it deflected the Late Eocene porphyry copper belt (41–44 Ma; Esperanza, Telégrafo, Centinela, and Polo Sur ore deposits). These observations suggest that right-lateral displacement of the ACL was active during the Early Oligocene. We propose that the described structural features need to be considered in future exploration programs within this extensively gravel-covered region of northern Chile.

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C. Palacios (✉) · L. E. Ramírez · B. Townley · M. Solari
Departamento de Geología, Universidad de Chile,
Santiago, Chile
e-mail: cpalacio@ing.uchile.cl

N. Guerra
Departamento de Geociencias, Universidad Católica del Norte,
Antofagasta, Chile

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Introduction

The southern segment of the central Andes is one of the most important copper belts in the world, related to 140 Ma of geologic evolution (Fig. 1). The Andean Cordillera is an orogen developed along a convergent plate margin, formed over a long-lived east-dipping subduction system. During the Jurassic, the magmatic arc was located along the current Coastal Range of northern Chile and has since migrated 200 km eastward to its present position along the axis of the Western Andean Cordillera. Two major stages of arc development are recognized in the geological evolution of the southern segment of the central Andes: (1) an Early Jurassic–Early Cretaceous stage, when a magmatic arc–back arc basin pair developed, mainly during an extensional tectonic regime (Maksaev and Zentilli 2002) and (2) a Late Cretaceous–Holocene stage, when the arc system shifted to a compressive tectonic setting in which fold and thrust belts developed (Maksaev and Zentilli 2002). During the Late Jurassic–Early Oligocene interval, hydrothermal copper mineralization events occurred along the orogen, giving rise to four NS-trending metallogenic belts of eastward-decreasing age: Late Jurassic, Early Cretaceous, Late Paleocene–Early Eocene, and Late Eocene–Early Oligocene (Fig. 1; Camus 2003). Each one of these belts is related to intra-arc magmatism and major strike-slip fault systems. Copper-bearing stocks occur along NS-striking master faults within an intra-arc structural system, as well as along subsidiary faults (e.g., Camus 2003; Perelló et al. 2003). However, Richards et al. (2001); Tosdal and Richards (2001); Chernicoff et al. (2002), and Richards (2003) also point out the role of NW-trending, orogen-oblique structures in the control of Andean porphyry copper emplacement. Regional paleomagnetic data reported by Roperch et al. (1999) and Arriagada et al. (2003) indicate clockwise tectonic rotations of up to 65° within the forearc and the pre-Cordillera domains of the southern segment of the central Andes. The apparent relationship between tectonic rotations and structural trends suggests that rotations occurred mainly during the Eocene–Early Oligocene Incaic orogenic event (Arriagada et al. 2003). Furthermore, Arriagada et al. (2003) proposed that the Antofagasta–Calama Lineament (ACL) and the NNE curvature of the Atacama Fault System (AFS) in the Coastal Range were formed during the Incaic deformation event in response to differential EW shortening (Fig. 1). The paleomagnetic results demonstrate that tectonic deformations in the forearc and the western slopes of the Western Cordillera are key elements, which should be taken into account during structural modeling and exploration of ore deposits located in the vicinity of the ACL, as the tectonic rotations are restricted to the south and within the ACL domain (Arriagada et al. 2003).

Other arguments suggesting that the ACL corresponds to a major fault system are:

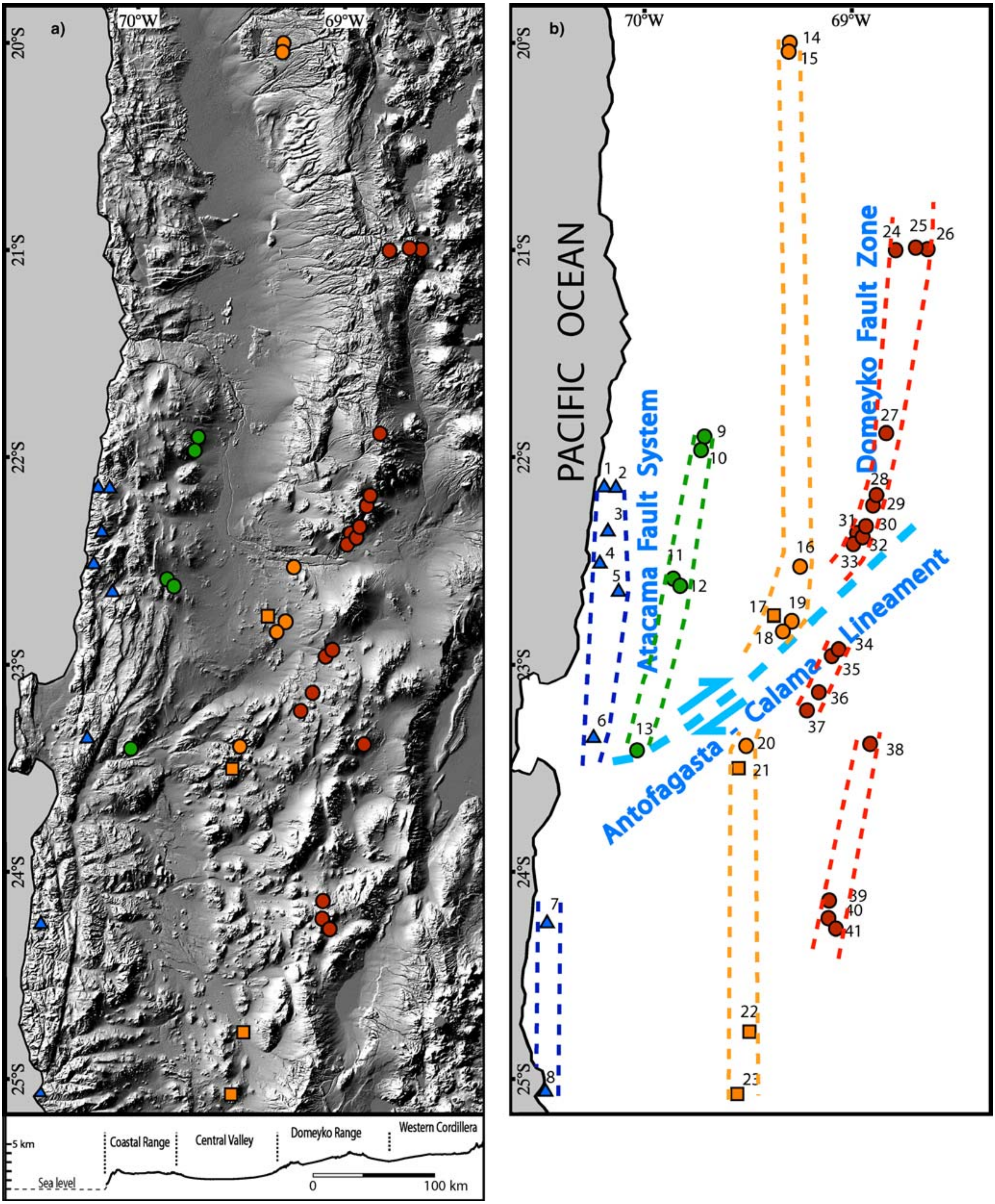
- Behn et al. (2001), using the residual intensity of the total magnetic field of an aeromagnetic survey, demonstrated a NE-trending lineament. This lineament coincides with the ACL.
- Cameron et al. (2002), Cameron and Leybourne (2005), and Leybourne and Cameron (2006), based on topographic lineament and recent epicenters of major earthquakes locations, proposed the ACL as a probably major fault zone.
- Götze and Krause (2002) evidenced that high-gravity anomalies deviate substantially at the Coastal Range and the pre-Cordillera, after the strike of the ACL.
- Jacques (2003) recognized a NNE-trending lineament in the Pacific Ocean floor, which coincides with the southwestern projection of the ACL.
- Simple observation of the satellite image (Fig. 1) allows us to note that the Central Valley is dextrally displaced by the ACL.

It is important to indicate that most of the ACL is covered by gravels as an alluvium-filled morphologic depression. The most recent exploration successes in northern Chile have occurred in covered areas along the ACL (e.g., Spence, Toki, Genoveva, Quetena, Opache, and Esperanza porphyry copper deposits). In this study, we discuss the role played by the ACL in the displacement of the different NS-trending metallogenic belts in the Andes of northern Chile, suggesting the importance of the ACL on the distribution and deformation of the longitudinal metallogenic belts. Our aim is to provide insight on a possible structural tool for mining exploration within an extensively gravel-covered region of northern Chile.

Fig. 1 **a** Image of the southern segment, Central Andes of northern Chile showing the location of ore deposits. Shaded relief image was obtained from Shuttle Radar Topographic Mapping Mission 90 m digital elevation model (DEM) of northern Chile. Copper deposits of the Late Jurassic (*blue triangles* stratabound volcanic-hosted deposits), Early Cretaceous (*green circles* porphyry copper and breccia-style hydrothermal deposits), Late Paleocene–Early Eocene (*orange circles* copper porphyries; *orange squares* epithermal deposits) and Late Eocene–Early Oligocene (*red circles* copper porphyries). **b** Ore deposit distribution and location of metallogenic belts. In *sky blue* is the Antofagasta–Calama Lineament. The location of the Atacama Fault System and the Domeyko Fault Zone are also indicated. Ore deposits: *1* Buena Esperanza; *2* Gimena; *3* Mantos de la Luna; *4* Mantos del Pacífico; *5* Carolina de Michilla; *6* Iván; *7* Caleta del Cobre; *8* Santo Domingo; *9* Puntillas; *10* Posadas; *11* Antucoya; *12* Buey Muerto; *13* Mantos Blancos; *14* Mocha; *15* Cerro Colorado; *16* SN; *17* Faride; *18* Spence; *19* Sierra Gorda; *20* Lomas Bayas; *21* San Cristóbal; *22* El Peñón; *23* Guanaco; *24* Quebrada Blanca; *25* Ujina; *26* Collahuasi; *27* El Abra; *28* Radomiro Tomic; *29* Chuquicamata; *30* M & M; *31* Toki; *32* Quetana y Genoveva; *33* Apache; *34* Esperanza; *35* Telégrafo; *36* Centinela; *37* Polo Sur; *38* Gaby Sur; *39* Chimborazo; *40* Zaldívar; *41* La Escondida ▶

The late Jurassic and Early Cretaceous copper belts

The AFS, exposed along the Coastal Range of northern Chile, is comprised of a complex association of NS-trending mylonitic, cataclastic and brittle fault zones (Scheuber and González 1999). It has a long history of deformation ranging from the Early Jurassic to Recent. The Jurassic–Early Cretaceous tectonic evolution of the Coastal Range has been interpreted in terms of coupling and decoupling between the SE-bound downgoing oceanic plate and the overriding South American continent. Between 195 and 155 Ma, an intra-arc magmatic belt system was spatially related with the NS-trending left-lateral AFS. However, between 160 Ma and the end of the Jurassic and due to foundering of the subducting plate, subduction rollback, and decoupling, an EW-trending extensional regime developed. At the end of the Jurassic to the Early Cretaceous, seismic coupling of the subducted plate is suggested by the return of sinistral strike-slip style deformation (Scheuber and González 1999). During the Paleocene Incaic E–W compression, the faults of the AFS were reactivated, and the formation of the present Coastal Range probably occurred (Arriagada et al. 2003). Regional paleomagnetic data indicate local 25 to 40° clockwise block rotations in the Coastal Cordillera, south and within the ACL during the Paleocene, as a response to the Incaic deformation (Roperch et al. 1999; Arriagada et al. 2003). Two NS-aligned copper belts developed along the AFS domains. The oldest belt comprises Late Jurassic strata-



bound, volcanic-hosted, and vein-type copper deposits, located along the western side of the Coastal Range and formed between 155 and 170 Ma (Boric et al. 1990; Vivallo and Henríquez 1998; Maksaev et al. 2006a; Tristá et al. 2006). The second metallogenic belt consists of Early Cretaceous breccia-style hydrothermal mineralization and porphyry copper deposits, occurring along the eastern slope of the Coastal Range of northern Chile (Perelló et al. 2003;

Camus 2003; Ramírez et al. 2006). Although K/Ar sericite ages indicate that the porphyries were formed between 132 and 137 Ma (Perelló et al. 2003), recent U-Pb zircon SHRIMP data indicate that the porphyries were emplaced between 141 and 142 Ma (Maksaev et al. 2006b). A similar age is reported in the Mantos Blancos breccia-style copper deposit (Ramírez et al. 2006). The largest deposit in the Coastal Range is Mantos Blancos (500 Mt at 1.0% Cu) in which the feeder of mineralization is a magmatic-hydrothermal breccia complex (Ramírez et al. 2006). The Mantos Blancos orebody is located close to the north of the ACL, where the NNE curvature of the AFS occurs (Fig. 2a). Paleomagnetic data in the deposit indicate a clockwise block rotation between 30 and 40° (Ramírez 2006). Geophysical and geologic restoration of the Mantos Blancos orebody suggest that the faults controlling the mineralization were originally NS aligned, coinciding with the inferred extensional direction regime during the Late Jurassic–Early Cretaceous (Fig. 2b; Ramírez 2006).

Late Paleocene–Early Eocene porphyry copper and precious-metal epithermal belt

In the Central Valley, located east of the Coastal Range, several NS- and NE- to NNE-striking faults and lineaments occur. The NS-trending faults are mainly sub-vertical dextral strike-slip structures, whereas the NE- to NNE-striking faults are SE-verging imbricate reverse faults or right-lateral structures (Williams 1992; Arriagada et al. 2003). In this zone, a NS-trending belt occurs, which comprises porphyry copper and Au-Ag epithermal mineralization formed between 53 and 60 Ma (Fig. 1; Camus 2003). However, close to the north and south of the ACL, the Spence and Lomas Bayas porphyry copper deposits are N20°E aligned (Fig. 3b and c; Rowland and Clark 2001; Camus 2003; Cameron and Leybourne 2005). Paleomagnetic data in the Lomas Bayas district evidence a 20° clockwise block rotation (Arriagada et al. 2003). A simple restoration indicates that the stocks and breccia pipes of the Lomas Bayas porphyry copper probably were originally NS aligned, following the general orientation of the orogen. Furthermore, a discontinuity of the Late Paleocene–Early

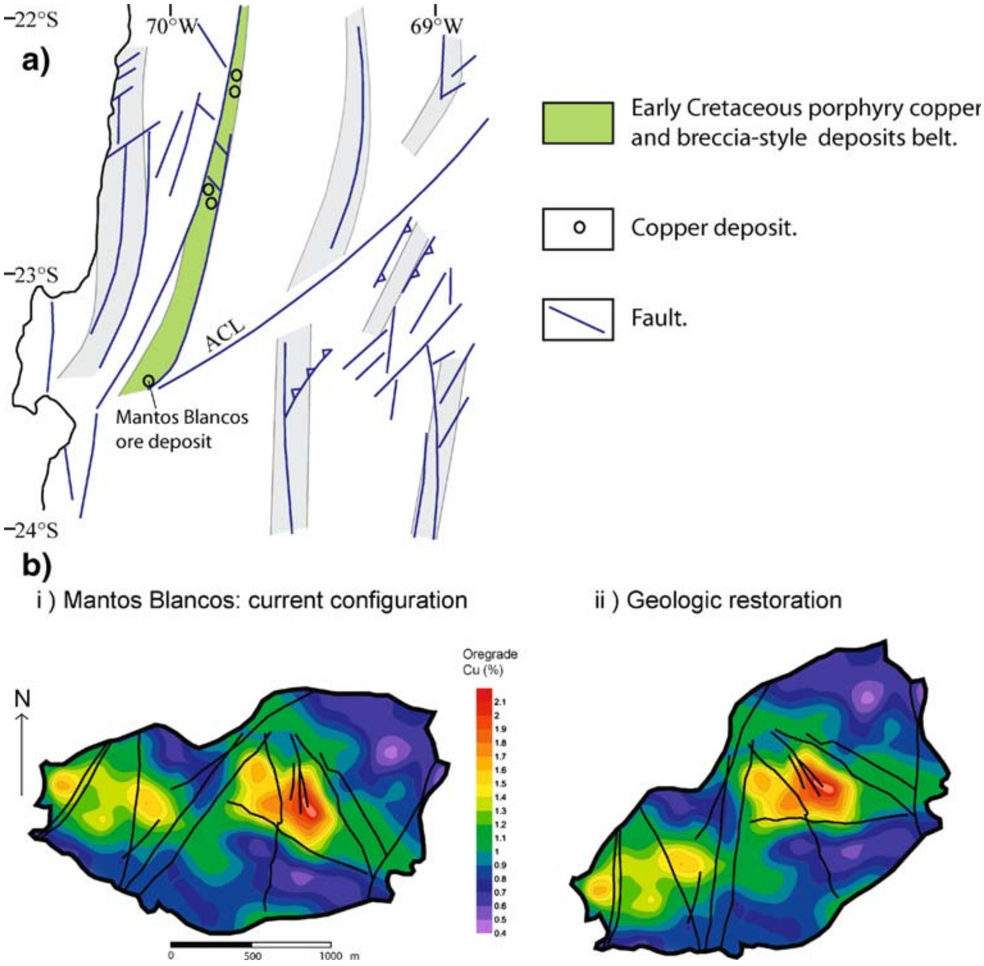


Fig. 2 **a** Distribution of the main Late Jurassic and Early Cretaceous copper deposits. **b** Details of the Mantos Blancos orebody indicating ore grade distribution at the elevation of 700 m above the sea level. *i* Current position of the deposit (Ramírez et al. 2006), *ii* Geologic restoration of the deposit before the clockwise block rotations (~30°) as a consequence of activity of the ACL (Ramírez 2006)

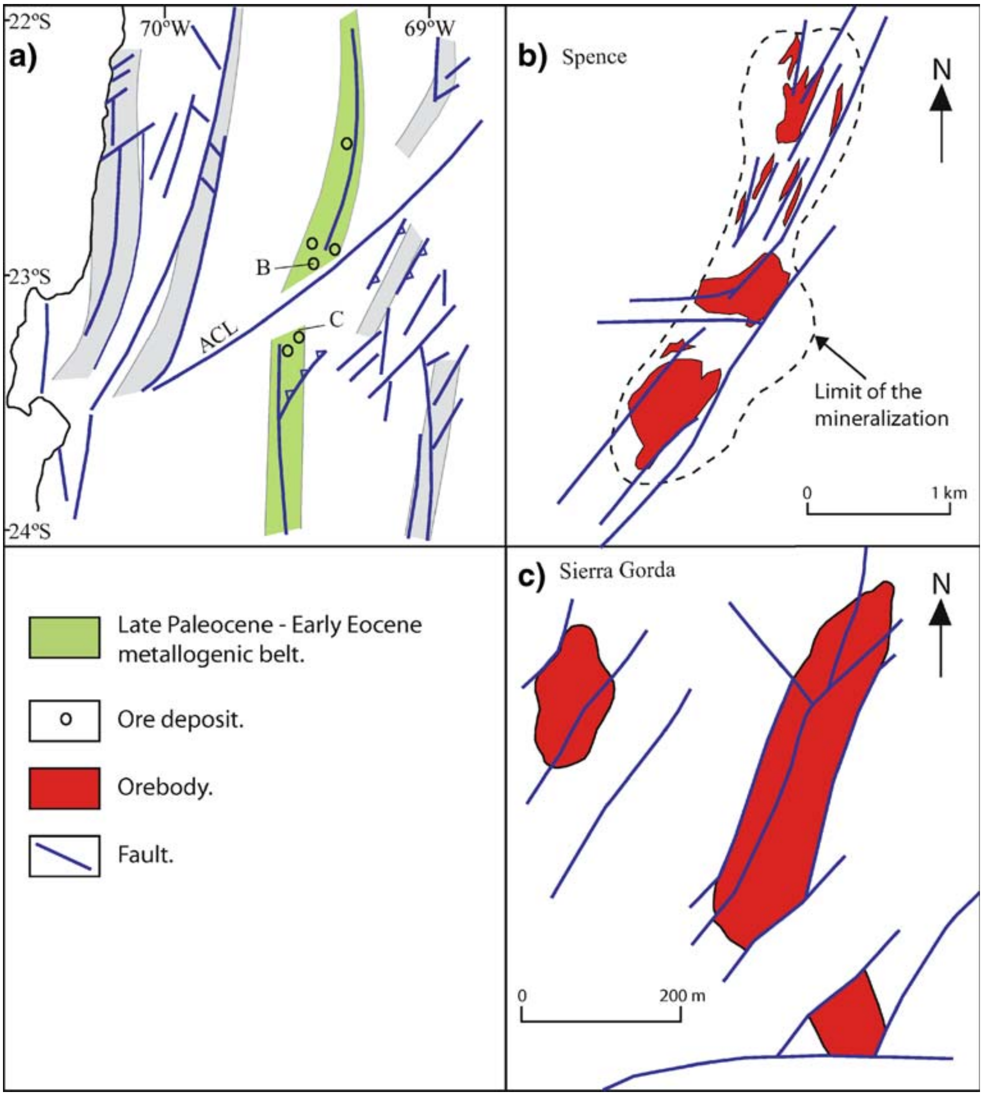


Fig. 3 **a** Distribution of Late Paleocene–Early Eocene epithermal and porphyry copper deposits. Details of the Spence (**b**) and Sierra Gorda (**c**) copper porphyries

Eocene metallogenic belt supports a right-lateral displacement along the ACL (Fig. 1).

Late Eocene–Early Oligocene porphyry copper belt

Along the Domeyko Range, the NS-trending Domeyko Fault Zone (DFZ) is the main structural feature. It consists of transpressional as well as left-lateral and right-lateral Late Eocene to Early Oligocene strike-slip faults (Reutter et al. 1996; Dilles et al. 1997; Richards et al. 2001; Richards 2003). In the DFZ, the most significant Chilean porphyry copper belt developed, constituting the largest copper concentration in the world (Fig. 1). The copper-bearing stocks occur along NS-striking DFZ master faults (e.g., Chuquicamata porphyry copper; Fig. 4b), forming a more than 1,000 km long metallogenic belt (Richards 2003). The age of mineralization is well documented between 31 and 43 Ma (Camus 2003). However, along the northern boundary of the ACL (Figs. 1 and 4c), the porphyry copper belt is deflected to 35–45°E, with dike-like Early Oligocene (34–37 Ma) mineralized magmatic bodies (e.g., Genoveva, Toki, Quetena, and Opache; Camus 2003; Rivera and Pardo 2004). South of the ACL, the porphyry copper belt is displaced to the southwest, where orebodies form a 40 km long, N30°E-trending zone of Late Eocene (41–44 Ma) ore deposits (e.g., Esperanza, Telégrafo, Centinela, and Polo Sur; Camus 2003; Perelló et al. 2004). At Esperanza, the porphyry-related rocks are dikes and stocks with surface dimensions of 8 to 60 m in width and lengths of up to 400 m in a dominantly NE direction. At the deposit scale, NE-trending faults control the orientation and shape of the porphyry dikes (Perelló et al. 2004; Fig. 4d). Paleomagnetic data on Paleocene rocks near the Esperanza porphyry copper deposit and between the Polo Sur and Centinela orebodies indicate clockwise block

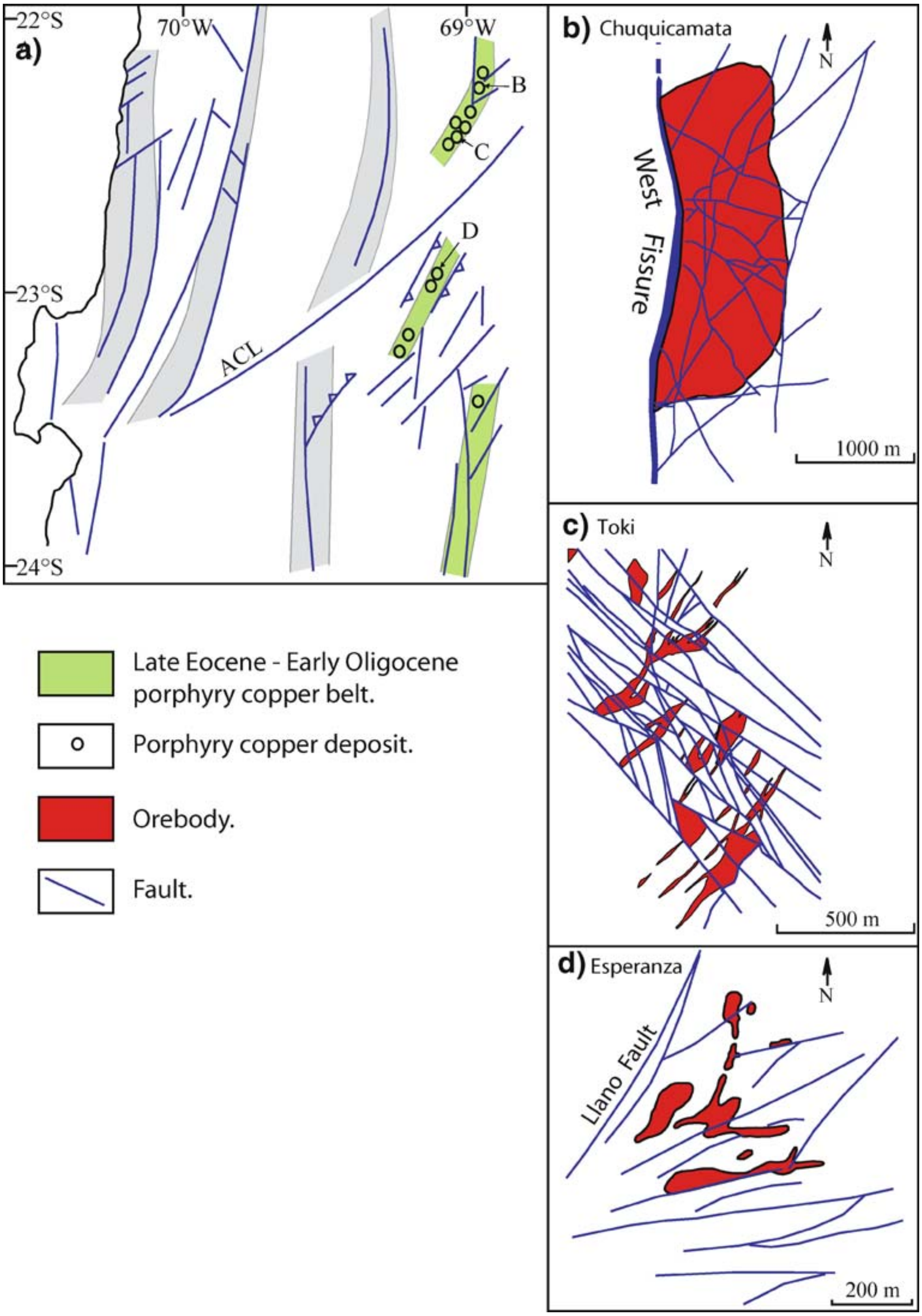


Fig. 4 **a** Distribution of the Late Eocene–Early Oligocene porphyry copper deposits along the DFZ to the north, within, and to the south of the ACL. **b** Chuquicamata porphyry copper deposit (Camus 2003). **c** Toki porphyry copper deposit (Rivera and Pardo 2004). **d** Esperanza porphyry copper deposit (Perelló et al. 2004)

rotations between 35 and 45° (Arriagada et al. 2003). These geophysical and geologic data suggest that this 40 km long segment of the porphyry copper belt rotated and was separated from its original trend. This segment was probably originally aligned NS, following the NS-trending regional Late Eocene–Early Oligocene metallogenic province orientation. A few kilometers to the south, in the Gaby Sur and La Escondida cluster of porphyry copper deposits, the metallogenic belt returns to its original NS-aligned trend (Richards et al. 2001; Richards 2003; Camus 2003).

Discussion

Available information strongly suggests that the ACL corresponds to a major NE-trending strike-slip structure zone oblique to the orogen that was active during the Early Oligocene, locally controlling the emplacement of the 34–37 Ma porphyry copper deposits and also rotated and displaced a Late Eocene (41–44 Ma) segment of the deposits. The ACL also affected the Early Cretaceous and Late Paleocene–Early Eocene metallogenic belts. The Early Cretaceous Mantos Blancos deposit and the Late Paleocene Lomas Bayas porphyry copper deposits were clockwise rotated. Furthermore, the Late Paleocene–Early Eocene belts were dextrally displaced. The occurrence of these types of structure oblique to the N–S orogen should be considered during exploration in the Andean Cordillera. From a metallogenic perspective, the cross faults, particularly the steep strike-slip faults, provide a natural vertical permeability structure along which magma can ascend into the upper crust in an overall compressive environment to form magma chambers that may exsolve a hydrothermal fluid, given the appropriate magma chemistry. From a tectonic perspective, the cross faults provide a means to shorten the arc and balance convergence and crustal thickening across the northern Chilean Andes.

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