The Role of Preexisting Geologic Architecture in the Formation of Giant Porphyry-Related Cu ± Au Deposits: Examples from New Guinea and Chile

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Abstract

Development of giant porphyry-related copper and/or gold deposits in New Guinea and northern and central Chile occurred during Tertiary magmatic events that overprinted earlier extensional tectonic settings. The earlier tectonic settings consisted of a Mesozoic passive margin in New Guinea, a Jurassic-Cretaceous back-arc basin in northern Chile, and an Oligocene intra-arc basin in central Chile. The preexisting architecture of the basement rocks, the fault systems, and the stratigraphic packages associated with these settings played a strong role in controlling development of the giant deposits.

Although the extensional tectonic settings in these terranes were different, they share a number of elements that were used during formation of the Tertiary ore deposits. These were the presence of coupled systems of deeply detached, listric synsedimentary faults and steep transverse faults, and the presence of a relatively flat-lying heterogeneous volcano-sedimentary rock package. During Tertiary collision the deeply detached listric faults were inverted and strongly focused uplift, exhumation, and associated overpressuring-induced failure and fluid flow. In addition, steep transverse faults were activated to form wrench systems, with attendant steep, deeply tapping pathways for magma and/or fluid associated with dilatant jogs, flexures, or fault intersections. Ore deposits are commonly located in the hanging wall of the thrust faults.

Under compression associated with collision, the competent units of flat-lying stratigraphic packages formed plates overlying the folded, weaker units underneath and separated by a detachment or otherwise faulted contact. Examples of the competent upper units include the Darai/Mendi Limestone or equivalents in New Guinea and the lavas of the Farellones Formation in central Chile. These plates appear to have impeded magma ascent and formed a cap on a magma and/or fluid system pressurized by collision and orogenesis. This geometry provided an ideal location for focusing of magmas and magmatic hydrothermal fluids.

From these three example terranes a set of exploration indicators have been constructed to highlight belts that are prospective for giant porphyry Cu systems. These indicators include (1) the presence of magmatic arcs that migrated into preexisting extensional architectures; (2) coupled systems of deeply detached, listric synsedimentary faults and steep transverse faults; (3) rigid basement blocks that could form regional stress field perturbations; and (4) fold belts with a major plate (to 50 km wide) of competent, relatively undeformed or gently folded stratigraphy overlying more complexly folded and faulted parts of the sequence.

Introduction

TERTIARY magmatism associated with development of giant porphyry-related copper and/or gold deposits in New Guinea and central and northern Chile overprinted a variety of preexisting extensional crustal architectures. The preexisting architectures developed in three tectonic settings, including a Mesozoic passive margin in New Guinea (Hill and Gleadow, 1989), a Jurassic-Cretaceous back-arc setting in northern Chile (Mpodozis and Ramos, 1989), and the Oligocene Coya Machalí intra-arc basin in central Chile (Godoy et al., 1999). These authors, together with numerous other workers, have studied and documented the influence of the preexisting architectures on development of the giant ore deposits in these three terranes. We attempt to synthesize some of that previous work by examining the relationships between different parts of the regional architecture in each terrane that have not been considered together in previous publications, as well as including new data sets. Common themes delineated from the three terranes can assist discovery of new deposits in other terranes that are not direct analogs but show some of the same geologic attributes.

In order to understand the influence of the different preexisting geologic elements on ore formation and localization, we consider the geologic architecture in three parts. The basement architecture concerns the rocks that existed before the main extensional events, the structural architecture concerns the faults that developed during the extensional events, and the stratigraphic architecture concerns the geometry and properties of the volcano-sedimentary sequences that host the deposits.

The compositions of the magmas and fluids that formed the deposits are not considered in detail. Several basic assumptions are made, including (1) that Tertiary porphyry-related Cu and/or Au deposits formed from dominantly magmatic fluids (Gustafson and Hunt, 1975) ± a basinal or wall-rock–derived fluid component (Bowman et al., 1987); (2) that the deposits formed close to a hot intrusive system, possibly with the aid of an advective hydrothermal system (Dilles and Einaudi, 1992); and (3) that the deposits formed at collisional plate margins (Sillitoe, 1972).

This paper reviews and compares regional-scale geologic elements or processes that may be recognized from large-scale data sets that are easily collected or widely available today. These include traditional geologic and interpreted tectonic maps, modern data sets such as regional-scale topographic, satellite-derived, and potential field geophysical

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data, as well as more focused detailed structural mapping, seismic and geochronological data sets.

Evolution of the Continental Arcs

The following brief summary of the geologic evolution of the Chilean and New Guinea collisional margins is derived largely from Hill (1991), Hill et al. (2002) and references therein for New Guinea and Mpodozis and Ramos (1989) for the Chilean margin.

Development of the New Guinea margin

The Papuan fold belt formed in a collision zone between the northern margin of the Australian plate and the Pacific and Philippine plates. The process of break-up and accretion that produced the modern day collision zone (Fig. 1) consisted of the following four main episodes: (1) Triassic-Jurassic (245–140 Ma) rifting of the northeastern margin of the Indo-Australian plate formed the Papuan basin, (2) Continued subsidence and deposition of the sedimentary pile was interrupted by a period of uplift (60–50 Ma) associated with Coral Sea spreading during the Paleogene, (3) Miocene collision of the Ontong Java plateau (20 Ma) from the east caused subduction of the Solomon Sea plate and produced the middle Miocene Maramuni Volcanic arc within the mobile belt, and (4) late Miocene collision of the Melanesian arc (12 Ma) caused the onset of compression that propagated southward and formed the Papuan fold belt.

The Papuan fold belt is a zone of south-directed thrusting, with 30 to 50 percent total shortening (Hill, 1990). Basement-cored anticlines formed due to movement along deep-seated thrusts and detachment surfaces between approximately 10 and 1 Ma (Hill and Gleadow, 1989; Weiland and Cloos, 1996; Crowhurst et al., 1997; Hill, 1997). Some of the thrust faults are inverted Mesozoic normal faults (mapped from thickening of the sedimentary section) and reactivated arc-normal transfer structures are inferred (see below).

There were three main phases of intrusion and/or volcanism during the Tertiary in the Papuan fold belt and the mobile belt of New Guinea (Fig. 2). They included voluminous intrusive activity in the Frieda and Sepik areas (25–20 Ma) and in much of the mobile belt (16–12 Ma) and lower volume, more structurally focused intrusive activity during a period of greater compression from 8 to 1 Ma. Pleistocene volcanic rocks were then deposited in the central fold belt area. Figure 2 provides a summary of the spatial extent of the three phases of igneous activity in the eastern half of mainland New Guinea. In Papua New Guinea igneous activity migrated from the north to the south and to a lesser degree from the east to the west. These directions are broadly consistent with the subduction of the Solomon Sea plate from the northeast as envisaged in the tectonic models of Hill et al. (1993).

The New Guinea margin differs from the Chilean margin in that the collision zone is complicated by the presence of three small plates (the Caroline, Bismarck Sea, and Solomon Sea plates) between the Australian and Pacific plates (Fig. 1). Direct links between subduction, magmatism, and mineralization are much less clear than in Chile. On the basis of seismicity data, Ripper (1982) proposed that the doubly subducting
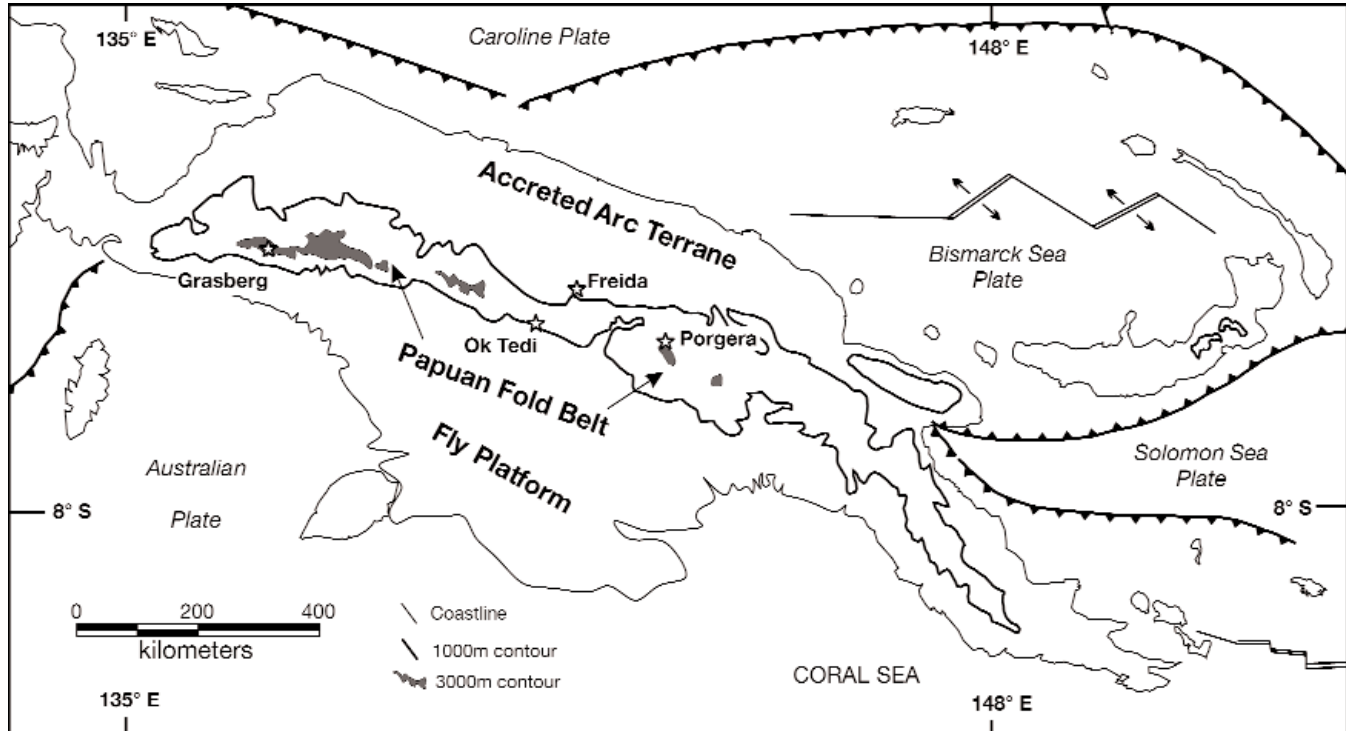

FIG. 1. Overview of the key geologic elements of the New Guinea collisional margin. The major Cu and/or Au deposits are shown, as are the 1,000- and 3,000-m simplified topographic contours. Note the narrow linear nature of the Papuan fold belt in West Papua, contrasting with the broad fold belt in Papua New Guinea in the east. This is interpreted to be related to different mechanisms of structural accommodation of Tertiary shortening due to basement rock properties (Hill et al., 2002). Modified from Gow et al. (2002).
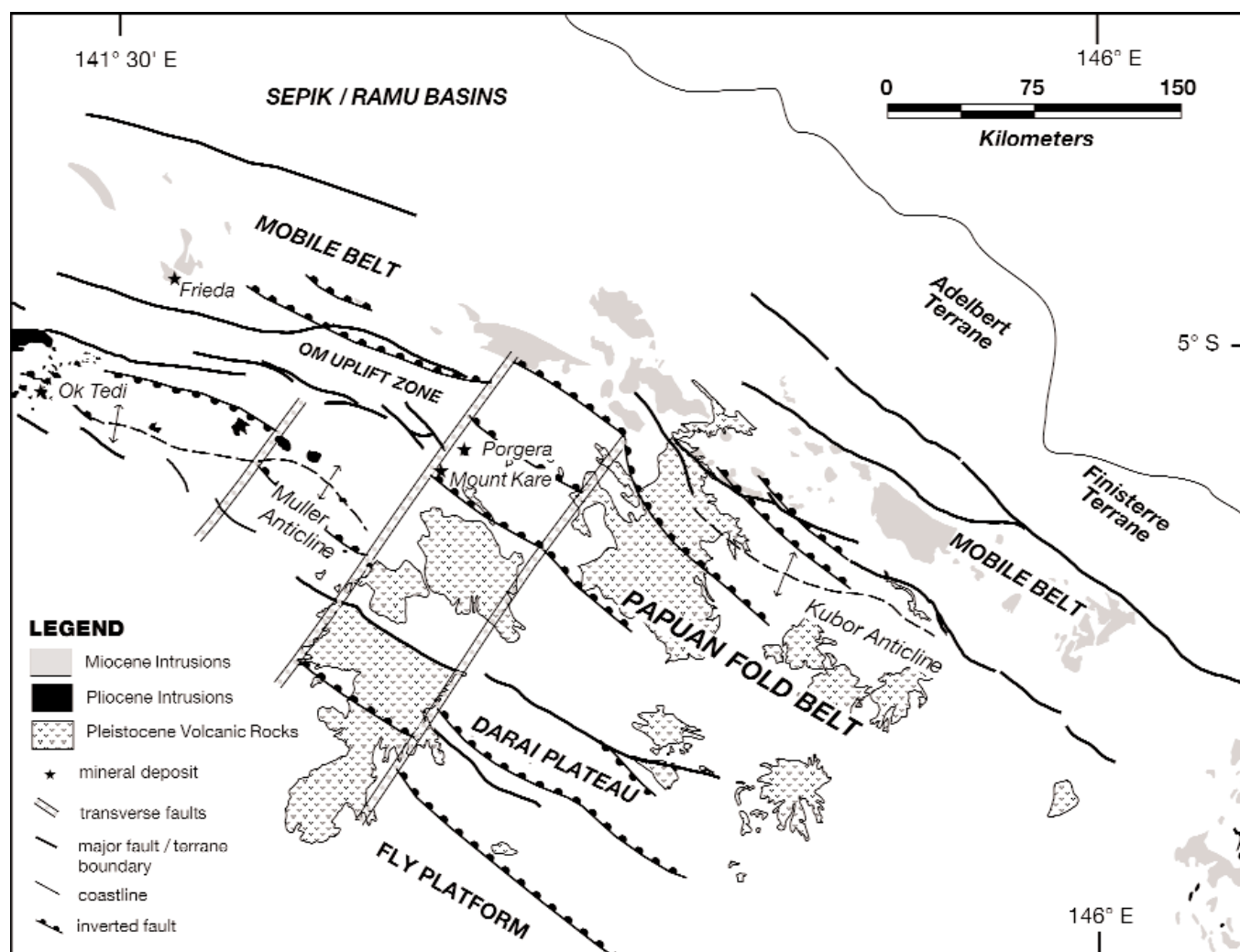
FIG. 2. Summary of the geologic elements of the Papua New Guinea section of the New Guinea fold belt. The location of basement-penetrating faults determined by Hill (1991) is shown. The offsets of these faults determine the location of the transverse set of north-northeast–trending structures.

Solomon Sea plate forms a west-plunging arched slab under eastern New Guinea.

Development of the Chilean margin

The South American continent formed part of the Gondwana supercontinent before its break-up at ~115 Ma. During the early Paleozoic the Chilean margin faced the Paleo-Pacific Ocean. Numerous terranes, including the Sierras Pampeanas, Arequipa, and Chilenia terranes, are interpreted to have accreted to this margin during the Late Proterozoic-Paleozoic (Mpodozis and Ramos, 1989; Ramos, 1994). During the Carboniferous to Triassic subduction continued beneath the accreted terranes with the formation of a Carboniferous-Early Triassic magmatic arc (now the Coastal Cordillera).

The Mesozoic in Chile was characterized by the formation of back-arc basins in the early Mesozoic with a basin thickness in northern Chile of up to 2,500 m (Prinz et al., 1994). Ramos (1994) suggested a strong northwest trend to the rift basins, a structural grain apparent in various lineament studies (Salfity, 1985; Richards et al., 2001). The back-arc basins were overlain and intruded by magmatic products of the eastward-migrating Cretaceous magmatic arc. During the mid-Cretaceous the initial opening of the Atlantic Ocean caused the onset of a more strongly compressional tectonic phase along the South American margin. This increased compression played a role in the change in subduction style from steeper, Mariana-style subduction to shallow, Chilean-style subduction that now characterizes the margin.

The Cenozoic history of central Chile is dominated by the formation of the Farellones arc (Hollings et al., 2005, and references therein), developed in the Tertiary back-arc basin, which migrated eastward. In northern Chile, the modern arc of the Western Cordillera has been active since the early Miocene (Reutter et al., 1996), forming in a prevailing arc-normal compressional environment (Scheuber et al., 1994). As in central Chile, the magmatic arc has migrated eastward from the Triassic to the present day.

Basement Architecture

The impact of basement architecture on the development of large mineralizing systems in continental arcs and other settings that host epigenetic hydrothermal mineral deposits involves both mechanical and chemical processes. We focus here on the mechanical processes. Specifically, in continental arcs the mechanical properties of the basement affect (1) intensity and geometry of fault development, (2) the localization of fault systems, and (3) the magnitude of displacement, in particular vertical movement and erosional unroofing rates. The chemical properties of the basement may affect the chemistry of the magmas associated with the genesis of the porphyry deposit, in addition to the composition of any nonmagmatic fluids that may be involved in ore genesis (Dilles and Lang Farmer, 2001; Selby et al., 2001).

Two case histories from the New Guinea and northern Chilean margins are presented in which we interpret that contrasts in the mechanical properties of the basement influenced deposit locations.

New Guinea

Drill hole and outcrop data from Papua New Guinea and West Papua (formerly Irian Jaya), which respectively represent the eastern and western portions of the New Guinea fold belt, indicate that the basement rock types differ markedly. The pre-Mesozoic basement in Papua New Guinea has been sampled in drill holes from the Fly platform (Fig. 1) and consists of deformed Paleozoic sedimentary rocks with Paleozoic and Triassic felsic intrusions (Davies, 1990; Struckmeyer et al., 1993). In contrast, the pre-Mesozoic basement of West Papua consists of undeformed Paleozoic sedimentary rocks overlying Precambrian basement (Hill et al., 2002). In addition to the contrasting rock types in the basement along the New Guinea margin, a thermal weakening has been interpreted for the eastern end of the margin in mainland New Guinea (Abers and Lyon-Caen, 1990). The thermal event was associated with Paleocene to early Eocene (60–50 Ma) heating and uplift, evident in the sedimentary record (Home et al., 1990) and resulting from spreading in the Coral Sea.

The transition between the contrasting basement blocks of New Guinea is interpreted to be located near the international border between Papua New Guinea and West Papua. This transition is evident in the digital elevation data as a subtle north-northeast–trending 350-km-long fault scarp of approximately 10-m relief (Fig. 3). Other parallel fault scarps farther to the east have reliefs of up to 80 m. There is a significant change in the width and height of the main mountain belt across this change in basement geology. To the east, the New Guinea highlands consist of a wide (to 230-km) plateau with a peak zone at approximately 2,600 m elevation (Fig. 1). The highlands in West Papua consist of a steeply sloping plateau with a maximum width of 160 km, with a zone up to 40 km wide of between 3,000- and 4,000-m elevation. Hill et al. (2002) interpreted this notable contrast in the relief of the mountain range to be related to the contrasting strength of the basement blocks and the consequent different style of fault development during the Mesozoic extension and the Tertiary collision. In West Papua, where the basement consists of less deformed Proterozoic rocks, extension during the
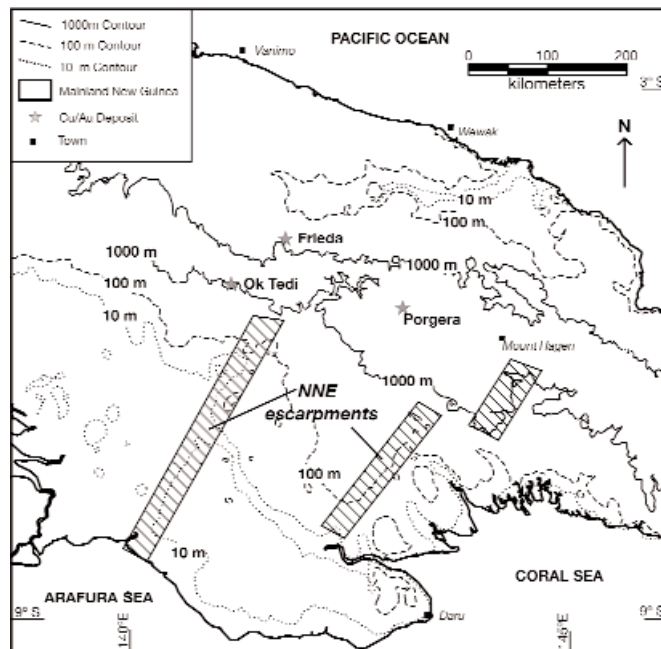

FIG. 3.   Contours of the topographic data (GTOPO30, Smith and Sandwell, 1997) from New Guinea, showing the north-northeast–trending fault escarpments evident as vertical offsets of up to 80 m over lateral distances of greater than 200 km. The major escarpment south of Ok Tedi is also evident in the offshore satellite gravity data extending to the south across the Arafura Sea and into northern Australia (Gow, 1998).

Mesozoic development of the passive margin was accommodated dominantly by a large shelf-edge structure termed the Mapenduma fault (Hill et al., 2002), mapped approximately 30 km south of the Grasberg deposit. During Tertiary collision this fault accommodated much of the shortening with at least 30 km of reverse movement. In contrast, the basement rocks in Papua New Guinea, which can be interpreted as weaker due to greater deformation, accommodated Mesozoic extension by formation of more numerous normal faults with less displacement. With the onset of Tertiary collision, shortening and uplift were accommodated in Papua New Guinea in a greater number of faults over a broader distance. The weakening of the crust during the Paleocene to early Eocene spreading in the Coral Sea event also may have contributed to the crustal weakening in New Guinea.

A consequence of highly localized shortening accommodated along the Mapenduma fault in West Papua was that uplift and unroofing must have proceeded rapidly. A high rate of unroofing has been documented from the Grasberg district by Weiland and Cloos (1996), who concluded based on apatite fission track analysis, that the unroofing rate on the middle part of the southern slope of the highlands averaged 1.7 km/m.y. between 2.3 Ma and the present. The focused shortening in the Mapenduma fault and the episodic nature of faulting suggests that the uplift and unroofing would have occurred at even higher rates during discrete fault movement. High rates of exhumation have been suggested as aiding the formation of large porphyry Cu-Au deposits through fracturing induced by reduction of confining pressure (Sillitoe, 1998). Thus, the high rate of exhumation in the Grasberg

district during the Pliocene, as a result of the development of the Mapenduma fault in strong Proterozoic crust, would have provided strong thermal and pressure gradients that in turn could have contributed to the large metal accumulation at the Grasberg deposit.

Northern Chile

Knowledge of the basement rock types of northern Chile is available from the known outcropping inliers including the Limon Verde block (Lucassen et al., 1999) and the Belen metamorphic complex (Wörner et al., 2000). Geophysical data collected and published by the Freie Universität Berlin (Reutter et al., 1994) and the ANCORP Working Group (ANCORP Working Group, 1999) provided insight into the properties of

the basement. The gravity data reported by Götze et al. (1991) is perhaps the most useful single data set for understanding the basement characteristics. One of the key features evident from the gravity data is the presence of an anomalous high-density block in the area surrounding the Salar de Atacama. The northern portion of the high-density block is approximately 120×200 km in size (Fig. 4A) and is modeled to be between 10 and 38 km deep with a density contrast of 0.15 gm/cm^3. Götze and Krause (2002) interpreted this anomalous zone as a buried Ordovician continental volcanic arc, with mafic magmatic rocks or obducted ophiolites causing the high-density anomaly. The gravity anomaly trends to the south-southeast, with the modeled source body shallowing to the north and crosscut by fault zones to create
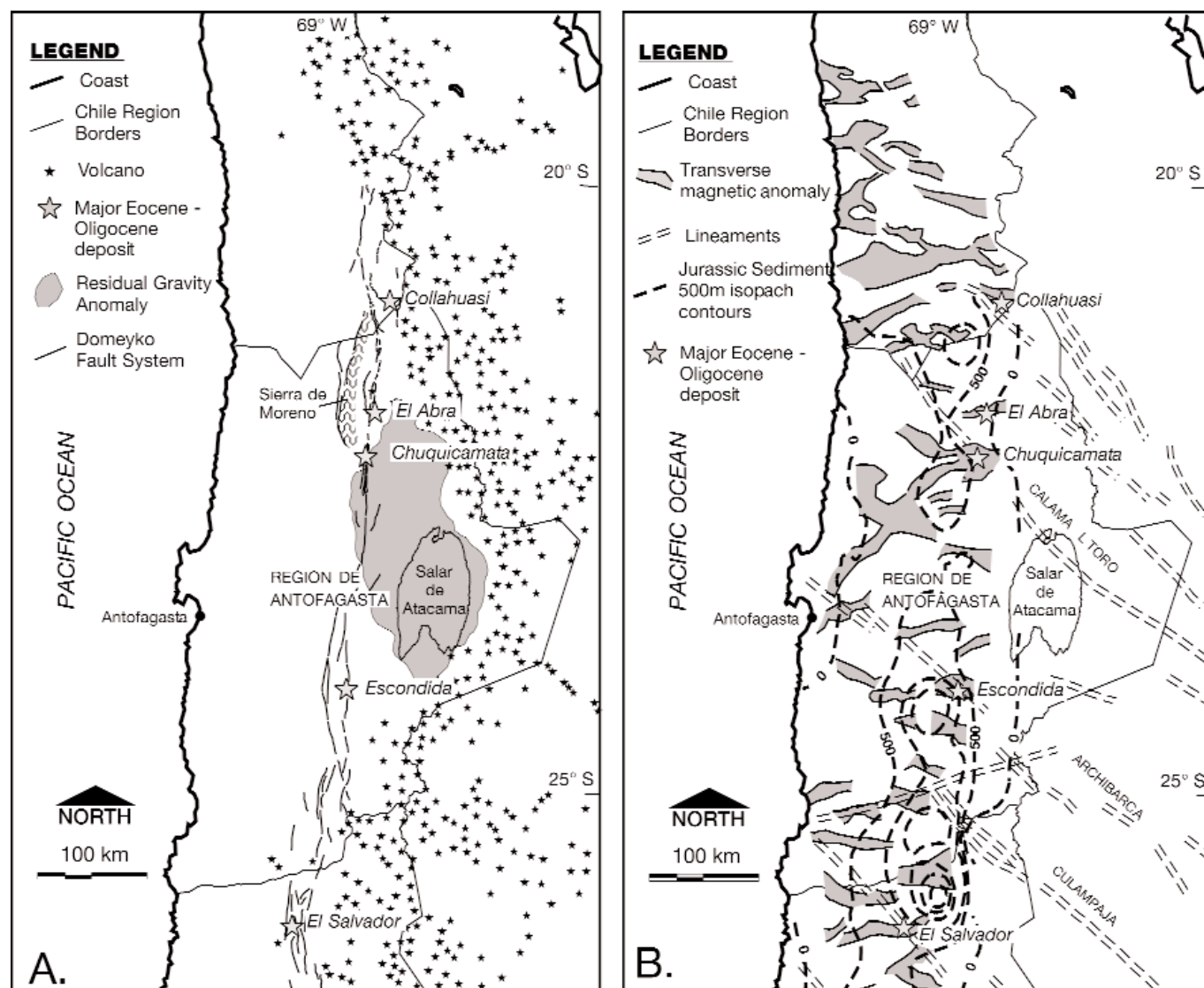

Fig. 4. Summary diagram of the geologic and geographic elements of northern Chile. A. Location of the major Eocene-Oligocene copper deposits and their spatial coincidence with the Domeyko fault system. Also shown is the area represented by the 30-mGal residual gravity anomaly partly coincident with the Salar de Atacama and modeled as a high-density upper crustal block (Götze et al., 1994). The volcanoes that comprise the current volcanic arc are shown; their location deflects around the gravity anomaly. B. The location of various lineaments in the region (from a summary by Richards et al., 2001), the magnetic transverse anomalies (from Behn et al., 2001), and the location of the Jurassic back-arc basins as delineated by the 500-m isopach contours (from Prinz et al., 1994).

four segments. The outline of the two northern segments is shown in Figure 4A.

Comparing the location of porphyry-related Cu deposits in the region and the residual gravity data indicates a spatial link between the large deposits at Chuquicamata and Escondida and the high-density block. The Chuquicamata and Escondida deposits are located adjacent to the northern and southern ends of the anomalous zone, respectively (Fig. 4A). We interpret this to reflect a regional-scale strain shadow associated with broadly east-west compression during deposit formation in the Eocene-Oligocene. The giant porphyry deposits formed where this strain shadow impinged in the Domeyko fault zone. The high-density block also appears to have played a role in the geologic evolution at deeper crustal levels, as suggested by Recent volcanism. Figure 4A shows the location of Recent volcanism, which continues to both the north and south but appears to be strongly deflected 70 km to the east around the high-density block. The mafic material causing the higher density anomaly appears to retard injection and migration of magma, possibly due to its higher melting temperature.

Fault Architecture

The New Guinea and northern Chilean margins both record a component of extensional tectonics. Extension occurred during the Mesozoic in New Guinea when what is now southern New Guinea formed the northern passive margin of the Australian continent (Hill and Gleadow, 1989). In northern Chile a back-arc tectonic setting is recorded in the Jurassic volcano-sedimentary section of the Tarapacá basin (Mpodozis and Ramos, 1989) and by associated fault architectures (Skarmeta, 1991). Comparison of data from these two terranes highlights the similar fault geometries in the extensional record of both areas. This includes typically steep margin-transverse structures, with shallower margin-parallel synsedimentary normal faults with listric geometries. This is a well-documented architecture in extensional settings in general (Lister et al., 1986), but it is not easily delineated in terranes with a strong magmatic overprint such as northern Chile and, to a lesser extent, New Guinea. Data supporting these geometries are provided by Hill (1991) in New Guinea and reported by McClay et al. (2002) in northern Chile. Seismic data, combined with detailed restored cross sections have proved useful in both of these terranes in understanding the previous extensional architecture. Two case histories, from New Guinea and northern Chile, illustrate the common features of these settings and show how the faults have been reactivated during later compression and magmatism.

Extensional and/or thrust fault systems in New Guinea

The Tertiary thrust systems of the New Guinea fold belt have been well documented because of active hydrocarbon exploration in the region. The presence of both thin-skinned and basement-involved thick-skinned thrusting and associated deformation is evident from the cross sections that have been constructed and restored across the fold belt as well as the presence of large basement-cored ramp anticlines (e.g., the Kubor and Muller anticlines; Fig. 2). Mapping by several workers (Hill, 1991; Mason, 1997) has proven that many of the basement-involved thrusts are in fact reactivated Mesozoic faults, with thickening of hanging-wall rocks into the

faults attesting to the Mesozoic synsedimentary normal-sense movement in the faults. The largest of these faults is the Mapenduma fault in West Papua (Kendrick, 2000). Stratigraphic thicknesses derived from mapping in the Grasberg district indicate that the sedimentary section thickened by 7.5 km to the north across this fault (Hill et al., 2002).

There is a strong spatial relationship between the giant porphyry-related Cu and/or Au systems in the New Guinea Highlands and mapped thrust faults. Figure 5 illustrates this
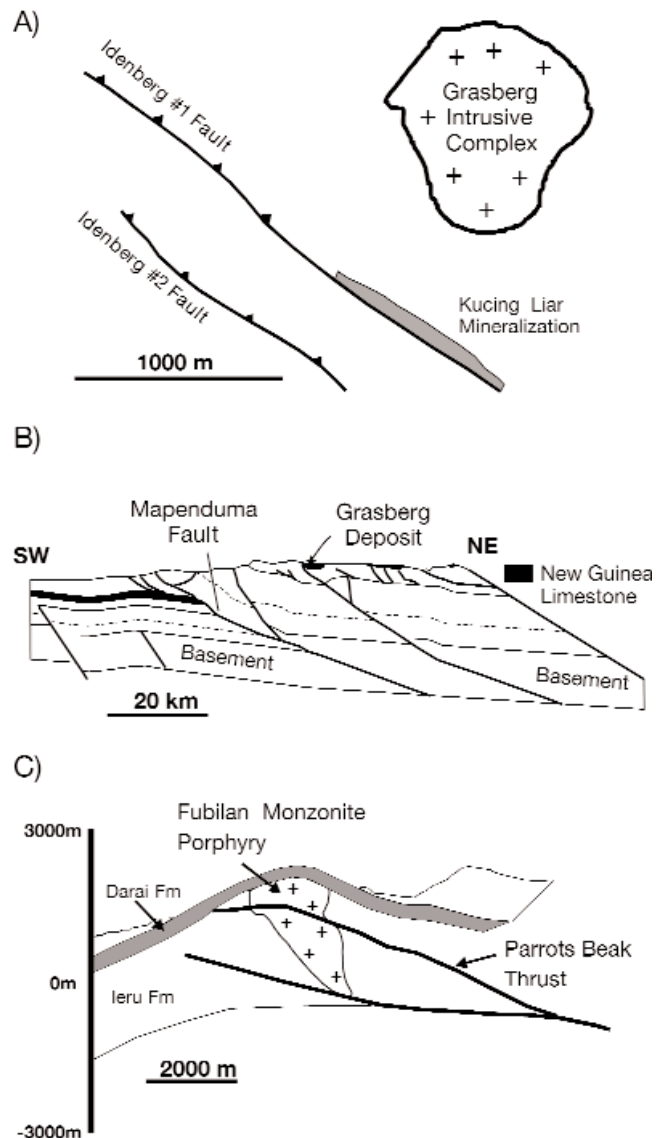

FIG. 5. Illustration of the relationship between thrust faults and deposits in the New Guinea fold belt. A. Plan of the Grasberg Intrusive Complex that hosts the Grasberg Cu-Au deposit. The complex is located in the hanging wall of the southwest vergent Idenberg 1 fault, which also hosts the Kucing Liar skarn mineralization. Simplified from Widodo et al. (1998). B. South to north regional-scale balanced cross section from Hill et al. (2002), highlighting the location of the major shelf-edge Mapenduma fault that was reactivated during Tertiary collision with the Grasberg deposit formed in the hanging wall to the thrust. C. South to north cross section near the Fubilan Monzodiorite Porphyry that hosts the Ok Tedi Cu-Au deposit. The pluton is located in the hanging wall of several south-directed thrusts. Simplified from Mason (1994).

relationship from the Grasberg, Ok Tedi, and Porgera deposits. These deposits are all located in the hanging wall of south-directed thrust faults. The timing of thrust fault development is constrained in the Ok Tedi case by the Pliocene intrusions that both cut, and are cut by, thrust faults. In the other cases the timing of fault movement cannot be so clearly constrained, but the timing of formation of the deposits confirms that they were emplaced in the compressional regime that formed the fold and thrust belt. The location of the deposits in the hanging walls of the thrusts may be related to highly focused fault-controlled magma emplacement and/or fluid-flow regimes. Thermal gradients surrounding the Porgera deposit were mapped by Gunson et al. (2000), who utilized a coloration index for foraminifera from the bathyal Cretaceous Chim Formation mudstones, together with illite crystallinity and vitrinite reflectance methods, to determine the hydrothermal fluid temperature. The results showed the presence of high- and low-temperature zones (ranging from 205°–415°C) across major faults that they interpreted to be upflow and recharge zones consistent with a convective fluid circulation system.

Hill et al. (2002) suggested that thrust fault systems on a larger scale also have controlled porphyry-related Cu and/or Au deposit development. They noted that the Grasberg, Porgera, and Ok Tedi deposits are all located at between 8 and 20 km vertically above the preinversion surfaces of crustal-scale inverted extensional faults. Hill et al. (2002) determined the geometries and detachment depths of these faults from restored cross sections, and all are associated with sedimentary thickening and/or major facies changes during Mesozoic and/or Miocene sedimentation. They suggested that fault intersections of these major crustal structures with steep transverse faults (see below) facilitated tapping of deeply sourced magmas to form the giant deposits.

Transverse faults in New Guinea

Although the thrust faults and inverted extensional faults are one key component of the structural architecture, a set of transverse or arc-normal faults also has been recognized throughout the New Guinea fold belt (Hill, 1991; Corbett 1994). Recognition of these faults is not easy, as most of the discrete fault-plane movement has occurred in the basement rocks with little surface expression in the outcropping Mesozoic-Tertiary sedimentary pile. Hill (1991) compiled regional-scale serial cross sections over a significant portion of the fold belt (approx 300 km) and showed that the contrast in structural style along the fold belt and the offset of interpreted basement faults provided indicators to the location of the major transverse faults. A summary of Hill's (1991) results is included in Figure 2. Hill (1991) determined the location of the basement-involved thrust faults from line-length balancing and reconstruction of the regional cross sections. The location of the transverse structures is delineated by the truncation or offset of these basement-involved faults. Based on apatite fission track analysis thermochronology data collected along the New Guinea fold belt in Papua New Guinea, Hill and Gleadow (1989) showed that the different compartments delineated by the transverse structures have different uplift and exhumation histories, with the cooling ages through ~100°C varying irregularly along the fold belt from 4 to 1 Ma.

Evidence for the north-northeast–trending transverse structures is also present in four other data sets:

1. Detailed structural mapping by Mason (1996) around the Ok Tedi deposit indicates that fracture sets and fold axes in the Mesozoic-Tertiary sedimentary pile have been rotated by movement in underlying north-northeast–trending basement faults.

2. Similar structural mapping near the Porgera deposit shows that the intrusive and hydrothermal system was related to a major north-northeast–trending fault termed the Porgera transfer structure (Corbett, 1994; Hall, 1995). The Mount Kare deposit to the south of Porgera is also located along this structure. Corbett (1994) also provided other examples from the New Guinea fold belt where these structures are interpreted to be associated with mineralization, including the Wafi gold prospect and the Cu-Au systems of the Kainantu field.

3. The alignment of Pleistocene eruptive centers, particularly in the Bosavi area, has been cited as evidence that north-northeast–trending structures controlled volcanism and/or intrusion (Davies, 1990).

4. Notable offsets in the topography occur along the fold belt at these locations (Fig. 3).

Corbett (1994) suggested that the genetic relationship between the transverse structures and the development of giant porphyry-related Cu and/or Au deposits is linked to development of dilational sites along the structures. Hill et al. (2002) proposed that these faults produce deeply tapping magma plumbing systems where they intersect the crustal-scale inverted extensional faults at depth. Gow et al. (2002) presented numerical models that illustrate how vertical strain partitioning into the wall rocks to these major faults could have localized vertical extension and magma emplacement.

Normal and/or thrust fault systems in northern Chile

The structural style is variable across the Andean collisional margin. In the Subandean Ranges fold and thrust belt of northern Argentina and Bolivia the thin-skinned deformation geometries of classic fold and thrust belts, including shallowly detached duplexes, are common (Schmitz, 1994; González-Bonorino et al., 2001). In contrast, the mineralized Oligocene belt of northern Chile shows evidence of thick-skinned basement-involved thrusting. One well-exposed example is the Sierra de Moreno, a 500-m-high north-south–trending topographic ridge associated with a 120-km-long west-verging reverse fault that emplaces Paleozoic metamorphic rocks (Boric et al., 1990) over Late Triassic-Jurassic marine sedimentary rocks. Evidence for movement in this and similar faults during Tertiary collision includes localization of Tertiary intrusions within relays or accommodation zones in the reverse-thrust fault systems (McClay et al., 2002) and deposition of the Tertiary Sichal Formation (Skarmeta and Marinovic, 1981) as fault scarp talus associated with these faults, that is then folded with continued fault movement.

Transverse structures in northern Chile

Numerous studies have highlighted the presence of long (to 500 km) highly arc-oblique faults or lineaments in central-northern Chile and Argentina. Alderete et al. (1985), Salfity

(1985), Ramos (1994), Sasso and Clark (1998), and Richards et al. (2001) have suggested that major northwest- or northeast-trending faults are present, including the Calama-El Toro, Archibarca, and Culampajá lineaments in northern Chile (Fig. 4B). The evidence for these faults is similar to that in New Guinea, including orientation of drainage patterns, breaks in data evident in satellite imagery and topographic data sets, as well as regional geophysical (aeromagnetic and gravity) data sets. A spatial correlation between the location of the major Eocene-Oligocene porphyry Cu deposits (Collahuasi, Chuquicamata, Escondida, and El Salvador) and the intersection of these lineaments with the Domeyko fault system has been noted (Richards et al., 2001).

Another set of transverse structures has been proposed by Behn et al. (2001) based on broadly east-west or highly arc-oblique, 5- to 10-km-wide belts of negative residual intensity evident in aeromagnetic data. The negative residual intensity of the aeromagnetic data is associated with the strongly dipolar response of magnetic bodies at low latitudes. Again there is a spatial correlation with the large porphyry-related ore deposits (Fig. 4B). These belts have a spacing along the arc of 50 to 100 km. They have been interpreted by Behn et al. (2001) to be related to the presence of preferentially emplaced magmas along arc-transverse paths during eastward migration of magmatism from the Triassic to Recent. Some of the negative anomalies span the entire orogen in Chile from the coastal range to the present volcanic front, whereas others are restricted to certain magmatic arcs of Cretaceous to Recent age, suggesting that the spatial control on magma emplacement was not always present during each magmatic episode along each path.

The location of transverse structures and consequent structural compartmentalization is further constrained by the isopach map of the Late Triassic-Jurassic sedimentary sequence compiled from drill hole data by Prinz et al. (1994). The isopach map is summarized in Figure 4B. The contours of the Late Triassic-Jurassic sediment thickness outline the subbasins that developed during the Jurassic back-arc sedimentation of the Tarapacá basin. Sediment thickness in the subbasins attained a maximum of 2,500 m, in the southernmost subbasin located north of the El Salvador deposit. The subbasins have a consistent lateral dimension of between 100 and 140 km along the arc. We interpret that the subbasins are separated by the transverse faults discussed above and are broadly consistent with the geometries of the transverse faults recognized in New Guinea. Five of the large porphyry-related Cu deposits (Collahuasi, El Abra, Chuquicamata, Escondida, and El Salvador) are located at the margins of the subbasins, where transverse faults would be located. Notably the eastern margin of the main basin coincides with the Domeyko fault system, suggesting that the Domeyko fault system may have formed the eastern bounding faults of the Jurassic-Cretaceous back-arc basin. Padilla et al. (2001) suggested these faults were probably inverted during the Late Cretaceous with the onset of compression.

Stratigraphic Architecture

In New Guinea the rock package that hosts the largest porphyry-related deposits is dominated by passive margin sedimentary rocks, whereas in both the northern and central Chilean porphyry belts the package is a mixed volcanic and/or sediment sequence. The stratigraphic architecture, or more specifically, the geometry and distribution of gross physical properties of the volcano-sedimentary rock packages that host the giant porphyry deposits, are similar in the porphyry belts of New Guinea and both central and northern Chile. All three terranes have only low-grade metamorphic overprints, and the volcano-sedimentary packages are generally coherent, with an apparent "layer-cake" stratigraphy that has been faulted and folded but not overturned or isoclinally folded on a regional scale. Importantly, the rock packages have a heterogeneous distribution of rock strength and permeability through the stratigraphic section. In New Guinea there are strength contrasts between the Mesozoic clastic rocks (the Ieru and Chim Formations) and the Tertiary carbonates (the Darai Limestone in Papua New Guinea and its equivalent the New Guinea Limestone in West Papua). In central Chile a similar strength contrast exists between the volcaniclastic sandstones, siltstones, and breccias of the Abanico and Coya Machalí Formations and the andesite lavas of the overlying Miocene Farellones Formation. The strength contrast becomes evident in the variable deformation styles and strong strain partitioning through the stratigraphy. In particular, under compression associated with collision, the stratigraphic packages develop fault planes or detachments along the base of the competent units with more complex fold patterns developing in the less competent units underneath. This has been documented in the central Chilean porphyry belt by Godoy et al. (1999), who noted the development of a detachment fault along the basal ignimbrite of the Farellones Formation in the Españoles Ridge area approximately 40 km north-northeast of Santiago. In New Guinea the presence of coherent Tertiary limestone units locally in fault contact with underlying folded siltstones has been documented by Mason (1996) in the Ok Tedi district and by Gunson et al. (2000) near the Porgera mine.

Stratigraphic plates

At a regional scale the strain partitioning and differing structural styles is evident in the development of broadly coherent subhorizontal plates of the competent unit overlying the folded weaker units underneath (Fig. 6). The underlying folded units are exposed at the front of the fold belts and also behind the plate in the fold belt in both New Guinea and central Chile. In both cases, the exposure of the underlying folded units appears to be associated with thrust movement in the major faults that bound the fold belts and with the thrust stacking of the upper plate to form topographic ranges. This geometry essentially forms regional-scale synclines as the lower stratigraphic units are exposed by rapid erosion that occurs on the flanks of the highland ranges. In New Guinea, the bounding faults of the fold belt are the foreland thrusts on the southward advancing fold belt and the continental and/or oceanic suture to the north. In central Chile, the faults may be the Fierro fault to the east (equivalent to the foreland thrust in New Guinea) and either an unknown fault to the west, or a series of backthrusts (see Godoy et al., 1999, figs. 5, 6). Identification of a similar flat-lying stratigraphic plate in northern Chile is problematic.

A competent plate in the fold belts appears to have localized the vertical level of intrusion either immediately below
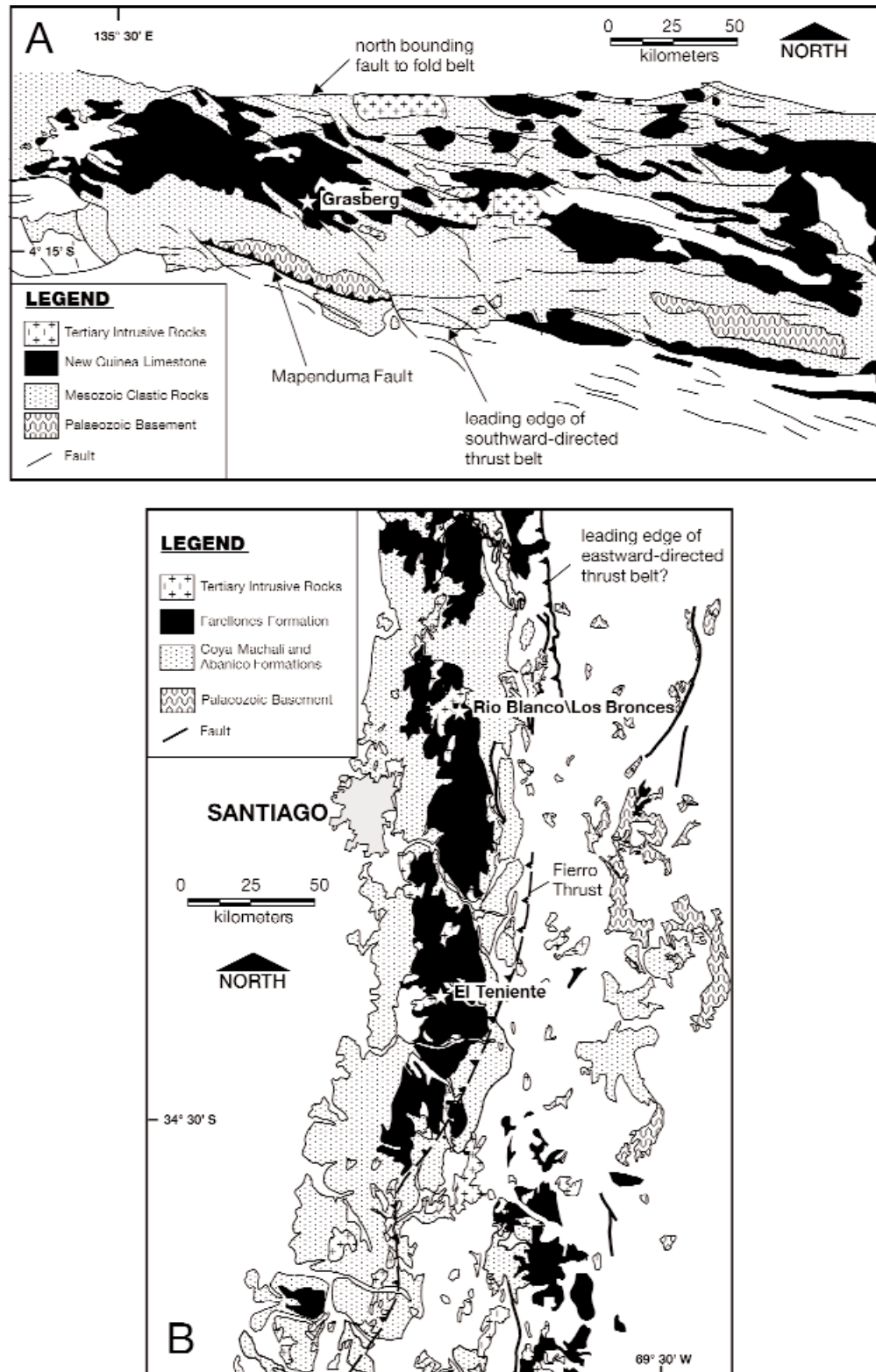
FIG. 6. Same-scale regional plan view maps of (A) the New Guinea fold belt in Irian Jaya and (B) the Chilean segment of the Mesozoic-Tertiary central Chilean magmatic arc. The Fierro thrust location is simplified from Godoy et al. (1999). Note the remnant plates of the competent New Guinea Limestone and Farellones Formation in the center of the New Guinea and central Chilean fold and thrust belts, respectively. The units immediately underlying the competent plates comprise Mesozoic clastic packages in New Guinea and the Coya-Machalí and Abanico Formation volcaniclastic packages in central Chile. These underlying units are typically more highly deformed and folded and are exposed on both sides of the competent plate.

or within the plate. In New Guinea, the Porgera, Ok Tedi, and Grasberg deposits sit on or around the basal contact of the New Guinea Limestone or equivalent. In addition to forming a mechanical seal on the magmatic systems, this plate also may have acted as a fluid and/or gas seal in the hydrothermal systems. The high effective stresses would have promoted overpressuring, and fracturing may have been caused by reduction of confining pressure associated with exhumation during the development of the fold belt.

Geodynamics

Detailed geochronology of exhumation, intrusion, and mineralization is required to determine the succession of events leading to porphyry copper deposit formation in continental arcs. Data from New Guinea are discussed briefly and tabulated below before a discussion of possible causal relationships.

Chronology of exhumation and intrusion

In the Mobile belt of New Guinea, the phase of Miocene intrusion (23–12 Ma) predated the onset of collision and uplift (10–5 Ma). Hill (1997) attributed this phase of intrusion to plutonism in an extensional environment in the overriding plate prior to collision. However, less voluminous (or less deeply eroded) late Miocene to Pliocene intrusions, typically with porphyry-type plutons, show a temporal correlation with uplift (Table 1). There is a strong contrast in the size and geometry of the plutons associated with extension (23–12 Ma) and the less abundant but perhaps more highly focused Pliocene intrusions emplaced during compression and uplift between 10 and 2 Ma (Fig. 2).

Chronology of intrusion and mineralization

As expected there is a close relationship between the ages of intrusion and mineralization. In several cases, most notably at Ok Tedi, Porgera, and Frieda River, intrusion occurred over a period of several million years before mineralization (Table 2). There was a distinct time gap between postemplacement cooling of at least the early intrusions and the hydrothermal alteration and mineralization. For example, the plutons within an ~10-km radius of the Ok Tedi deposit have K-Ar ages of 2.6 ± 0.3 Ma (Sydney monzonite), 2.2 to 2.4 Ma (Mt. Frew microdiorite), 1.9 ± 0.2 Ma (Mt. Ian gabbro), and 0.97 ± 0.06 Ma (Mt. Anju andesite). Mineralization was late in the magmatic episode at Ok Tedi at 1.1 to 1.2 Ma (Page, 1975). K-Ar ages for emplacement and mineralization of the Antares Monzonite (~30 km north of Ok Tedi) are 4.9 to 6.9 and 2.3 to 3.1 Ma, respectively (Page, 1975). Likewise, the intrusive rocks of the Frieda Complex have ages of emplacement ranging from ~12 to 17 Ma, with porphyry copper mineralization occurring late between 13.6 and 11.9 Ma (Whalen et al., 1982). At Porgera the rocks appear to be more clustered in time, with most intrusive phases recording K-Ar ages between 6.3 and 5.9 Ma and with alteration and mineralization occurring between 5.9 and 5.1 Ma.

Convergence rate and mineralization

The geochronology from New Guinea suggests the geodynamic sequence of (1) collision causing uplift and exhumation, then (2) intrusion during or shortly after exhumation, and finally (3) the mineralizing event during the late stages of the intrusive system.

TABLE 1. Exhumation and Intrusion Geochronology of New Guinea.

Area	Timing of uplift	Timing of intrusion	Notes
Bena Bena terrane	10–7 Ma	8.3 Ma	Apatite fission track analysis (AFTA) age (Hill, 1997); K-Ar age on Elandora Porphyry (Page, 1976)
Landslip terrane	8–5	?	AFTA age (Crowhurst et al., 1997)
Porgera	7.4	6.0 ± 0.3	AFTA age (K. Hill, pers.comm., 2002); Porgera Intrusive Complex (Richards and McDougall, 1990)
Muller anticline	4 Ma	5.0, 2.7	AFTA age from Strickland gorge (Hill and Gleadow, 1989); K-Ar dates on Tabe and Bolivip stocks (Page, 1976)
Grasberg and/or Ertsberg	3.7–2.0	3.6 - 2.6	AFTA ages (Weiland and Cloos, 1996); K-Ar ages on Grasberg and/or Ertsberg intrusions (McDowell et al., 1996); Ar-Ar ages (Pollard et al., 2005)

TABLE 2. Intrusion and Mineralization ages in New Guinea

Region	Timing of intrusion (Ma)	Timing of mineralization (Ma)	Notes
Ok Tedi	2.6–0.97	1.2–1.1	K-Ar whole-rock and biotite dates on altered and mineralized Mt. Fubilan porphyry (Page and McDougall, 1972)
Antares (north of Ok Tedi)	6.9–4.9	3.1–2.3	K-Ar dates on primary hornblende and biotite of the Antares Monzonite and probable secondary biotite from weakly mineralized monzonite (Page, 1975)
Frieda	17–12	13.6–11.9	K-Ar dates on hornblende and secondary biotite, sericite, alunite (Whalen et al., 1982)
Porgera	7.4–6.0	6.1–5.1	K-Ar dates on biotite, hydrothermal illite, and roscoelite (Richards and McDougall, 1990)

The example of the Chilean margin illustrates how such a system is driven by plate tectonics. Pardo-Casas and Molnar (1987) calculated the absolute convergence velocity between the Nazca and South American plates for the period from 68 Ma to the present. Figure 7A shows this convergence by tracing the location of a point on the Nazca plate between 68 Ma and the present. Figure 7B shows the absolute convergence velocity plotted with time. The two peaks in absolute convergence velocity broadly correlate with the Incaic (50–38 Ma) and Quechua (~12 Ma) orogenic phases. Notably, the two periods of giant porphyry Cu development in northern and central Chile occur at the waning end of the absolute velocity peaks. The reason for this is unclear, but possibilities include (1) the relaxation of compressive stresses allowed fault systems to dilate and facilitated magma and/or fluid migration; (2) crustal thickening that occurred during the shortening caused the dehydration reaction of amphibole to garnet at midcrustal levels with a time lag before the fluid release prompted magma generation and emplacement at shallow crustal levels;

or (3) exhumation of the orogens that formed during maximum compression brought existing magma systems to the vertical level where fluid and/or magmatic pressure overcame the lithostatic load and produced hydrofracturing, thus allowing rapid fluid expulsion and consequent decompression and cooling.

Discussion and Conclusions

Relationships to ore genesis

The three terranes of New Guinea and central and northern Chile show similarities in the geometries of early extensional architectures. The examples presented above highlight the similar processes that acted in the terranes, including stress and strain partitioning associated with competency contrasts in the basement rocks, rapid vertical movement, and inversion of sedimentary or volcano-tectonic basins in deeply detached extensional faults, localized magma intrusion associated with steep deeply tapping extensional faults, and the formation of stratigraphic plates overlying the host stratigraphy. The following discussion elaborates on the large-scale tectonic processes and their possible relationships to ore genesis and presents some easily recognized indicators that may aid discrimination of fertile from barren terranes.

Inversion of extensional basins

Two key examples of the correlation between inversion of extensional basins and development of large deposits occur in West Papua and central Chile, where much of the movement has been accommodated in the large listric Mapenduma and Fierro thrust faults, respectively. Kendrick (2000) has shown that the Mapenduma fault in the Grasberg district of West Papua is a reactivated crustal-scale extensional or shelf-edge fault. There is no evidence that the Fierro fault was a major basin-bounding fault, and its shallow dip and shallow detachment level (2–5 km; Godoy et al., 1999) suggest that it is part of the thin-skinned thrust system. In both cases, however, rapid unroofing, broadly temporally coincident with mineralization, has been documented. Weiland and Cloos (1996) documented exhumation rates of between 0.7 and 1.7 km/m.y. in the Grasberg district based on apatite fission track data, and Kurtz et al. (1997) suggested exhumation rates between 0.55 and 3.0 km/m.y. in central Chile based on $^{40}Ar/^{39}Ar$ geochronology. Relationships between rapid uplift and associated exhumation and the development of large deposits have been discussed by numerous authors (Skewes and Stern, 1994; Sillitoe, 1998). It is thought that these processes promote generation of overpressuring and fracturing and/or brecciation induced by exsolution of magmatic fluids and rapid reduction of confining pressure. The rapid fracturing aids fluid focusing and provides the opportunity for either fluid-fluid or fluid–wall-rock interaction. It can also promote large gradients in fluid temperature, pressure, and chemistry, all of which can aid metal precipitation by processes such as phase separation. One of the contributing factors to the very large tonnage and high grade of the Grasberg system may have been that the uplift was rapid and spatially focused simply by the presence of the deeply detached Mapenduma fault. Pollard et al. (2005) present $^{40}Ar/^{39}Ar$ ages from the Grasberg district that indicate the deposits were formed by several cycles of intrusion and alteration between 3.3 and 2.6
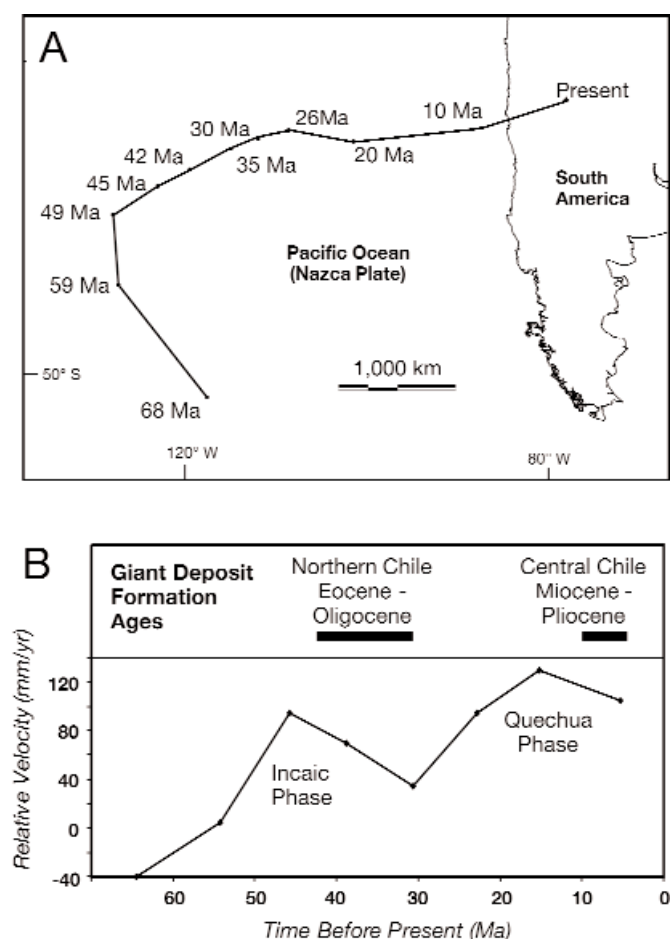

FIG. 7. A. Position of a point on the Nazca plate beginning at 68 Ma, plotted with respect to South America, between 68 Ma and the present (from Pardo-Casas and Molnar, 1987). The latitude at which the point crosses the coast is ~25° S. B. Absolute relative convergence velocity normal to the Chilean subduction (modified from Pardo-Casas and Molnar, 1987). The two peaks in absolute convergence velocity broadly correlate with the Incaic (50–38 Ma) and Quechua (~12 Ma) orogenic phases. The two periods of giant porphyry Cu development in northern and central Chile occur at the waning end of the absolute velocity peaks.

Ma, each of which lasted approximately 100,000 yr. This is consistent with a model whereby magmatism and fluid release is associated with discrete episodes of movement in the Mapenduma fault. Where uplift is caused mainly by thrust stacking and the formation of duplexes, rather than movement on a single deeply detached structure such as the Mapenduma fault, the probability of rapid uplift is reduced.

Figure 8 shows the location of the major Tertiary porphyry Cu deposits in Chile and the interpreted location of the deep marine sedimentation in the Triassic to Early Jurassic back-arc basin (Pindell and Tabbutt, 1995). The data presented above suggest that this strong spatial relationship is not coincidence but that inversion of the back-arc extensional architecture played an active role in controlling development of large porphyry deposits in the region.

Deeply tapping plumbing systems

Extension favors the formation of steep, deeply penetrating faults that may aid the formation of porphyry-related deposits by two processes. First, lower crustal or mantle-derived magmas that may be related to deposit formation can be accessed (Hill et al., 2002). Using Re-Os data from seven porphyry copper deposits, Mathur et al. (2000) proposed a strong correlation between total copper content and lower initial Os ratios. They interpreted this data as indicating that the largest deposits sampled deeper, more primitive magmatic sources. Second, the steep structures may be easily reactivated in a wrench or strike-slip regime, as evident in the oblique collisional settings of New Guinea and Chile during the Tertiary. Such reactivation will produce steep conduits that may lead to rapid magma ascent with little loss of heat or volatiles.

Stratigraphic plates

Coherent, broadly flat-lying stratigraphic plates may play two key roles in controlling deposit formation. Trapping magmas and halting magma ascent may lead to fractionation and exsolution of magmatic fluids. Trapping of magma may be indicated by an absence of significant volcanic rocks coeval with the mineralized intrusive systems. In New Guinea there is a distinct lack of coeval volcanic rocks with porphyry-related mineralization, with the possible exceptions of the Debom Volcanics in the Freida district and the Dalam phase at the Grasberg deposit (MacDonald and Arnold, 1994). Trapping fluids, volatiles, and metals beneath an impermeable stratigraphic plate would also prevent the loss of metals from the system and could locally elevate effective stress to promote overpressuring and associated tensional fracturing.

Exploration indicators

The examples presented above illustrate how the preexisting architecture of the basement and the regional structure and stratigraphy may play a role in both the temporal and spatial localization of large porphyry-related Cu and/or Au deposits. Although some features of these regions are also common to many mineralized porphyry terranes that do not host giant ore deposits, we propose that those belts with a combination of the following elements will be most prospective for large deposits.

1. Evidence for magmatic arcs that migrate into the overlying plate. In particular, we propose that magmatic episodes
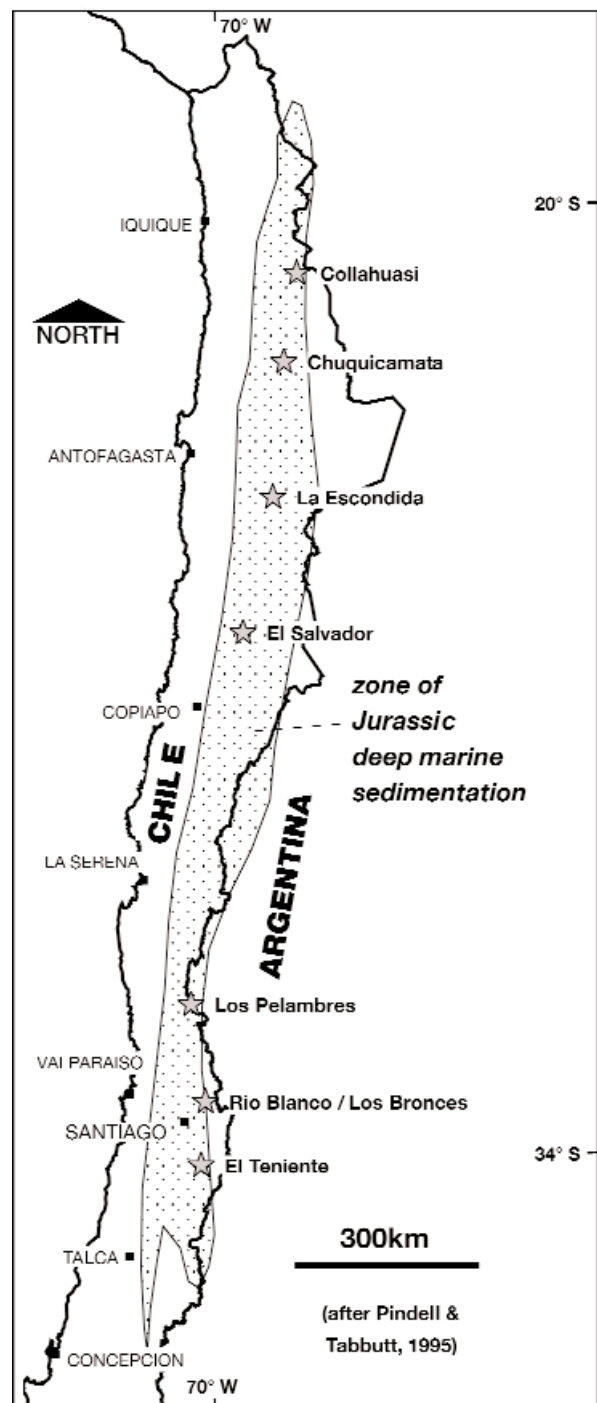

FIG. 8. Map of central and northern Chile indicating the location of the major late Eocene-Oligocene and late Miocene-Pliocene porphyry Cu deposits. Note the deposits are located in the <120-km-wide band of Early Triassic-Jurassic deep marine sedimentation (from Pindell and Tabbutt, 1995) that corresponds to the location of the Jurassic back-arc basin.

that are spatially coincident with the bounding faults of back-arc basins will be associated with the largest deposits. In Chile, arc migration caused the Tertiary magmatic arc to overprint the Jurassic-Cretaceous back-arc Tarapacá basin in northern Chile and the Oligocene Coya-Machalí intra-arc basin in central Chile.

2. Segmentation of arcs by major geologic breaks at spacings of 50 to 150 km. Examples include the 50- to 100-km spacing of the transverse magnetic anomalies in northern Chile, the 100- to 140-km dimensions of the Jurassic sub-basins in northern Chile, and the 80- to 100-km dimensions of the major structural domains in New Guinea.

3. Evidence for a major preexisting extensional architecture with steep transverse faults and deeply detached basin bounding faults that had the potential to tap the lower crust. These architectures may not be immediately obvious but can be inferred from the type of sediment package and interpreted tectonic setting.

4. Major listric faults in a favorable orientation for reactivation during collision. Large and rapid movement in these faults will force rapid uplift ± exhumation, with the deposits formed in the hanging wall to the faults. These major faults can be delineated by the presence of large or basement-cored anticlines.

5. Rigid basement blocks that may have formed strain shadows, reoriented or perturbed favorable host structures (e.g., the Domeyko fault system in northern Chile), or otherwise produced deformation of the overlying host volcano-sedimentary package.

6. Fold belts with a major plate (to 50 km wide) of competent, relatively undeformed or gently folded stratigraphy overlying more complexly folded and faulted parts of the sequence. We propose that porphyry-related deposits are most likely to have formed at or near the base of the competent stratigraphic plate.

Comparison of three terranes hosting giant porphyry-related copper and/or gold deposits illustrates that the premineralization geologic architecture associated with extensional tectonic phases may play a major role in development of the giant ore deposits. There is no single extensional tectonic setting that is most favorable; the examples presented here include a passive margin, a back-, and an intra-arc basin. Instead, the architectural elements that form in many, if not most, extensional settings appear to be most important. Integration of many data sets at different scales is required for recognition of these elements.

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