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Giant Porphyry Deposits: Characteristics, Distribution, and Tectonic Controls

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Abstract

More than half of the 25 largest known porphyry copper deposits, defined in terms of contained copper metal, formed during three time periods: the Paleocene to Eocene, Eocene to Oligocene, and middle Miocene to Pliocene. These giant deposits are clustered within three provinces, central Chile, northern Chile, and southwest Arizona-northern Mexico. Other giant deposits occur in Montana, Utah, Panama, Peru, Argentina, Irian Jaya, Mongolia, and Iran. Compressive tectonic environments, thickened continental crust, and active uplift and erosion were associated with the formation of many of these deposits. Calc-alkalic magmas are most favorable for the formation of giant porphyry copper deposits, although several of the largest systems are associated with high K calc-alkalic intrusions.

The 25 largest gold-rich porphyry deposits are concentrated in the southwest Pacific and South America, with other occurrences in Eurasia, British Columbia, Alaska, and New South Wales. Many of the deposits formed in the last 13 m.y. The largest of the deposits are associated with high K calc-alkalic intrusions. Many calc-alkalic porphyritic intrusions have also produced giant gold-rich porphyries.

In the last 20 m.y., the formation of giant porphyry copper-molybdenum and copper-gold deposits in the circum-Pacific region has been closely associated with subduction of aseismic ridges, seamount chains, and oceanic plateaus beneath oceanic island and continental arcs. In several examples, these tectonic perturbations have promoted flat-slab subduction, crustal thickening, uplift and erosion, and adakitic magmatism coeval with the formation of well-endowed porphyry and/or epithermal mineral provinces. Similar tectonic features are inferred to be associated with the giant porphyry copper-molybdenum provinces of northern Chile (Eocene-Oligocene) and southwest United States (Cretaceous-Paleocene).

Topographic and thermal anomalies on the downgoing slab appear to act as tectonic triggers for porphyry ore formation. Other factors, such as sutures in the overriding plate, permeability architecture of the upper crust, efficient processes of ore transport and deposition, and, in some cases, formation and preservation of supergene enrichment blankets are also vital for the development of high-grade giant ore deposits. A low-grade geochemical anomaly may be the final product of mineralization, if ore-forming processes do not operate efficiently, even in the most favorable geodynamic settings.

Introduction

PORPHYRY DEPOSITS are significant repositories of copper, gold, and molybdenum. They are most commonly discovered in continental and oceanic arcs of Tertiary and Quaternary age, notably around the Pacific Rim, but they have also been discovered in ancient fold belts. Over one hundred years of exploration and research has provided an excellent understanding of their geology and geochemistry. The deposits are characterized by low-grade copper, gold, and/or molybdenum mineralization developed within and around a porphyritic intrusive complex. Vein stockworks and hydrothermal breccias are common. Widespread and distinctive zones of hydrothermal alteration provide a useful footprint for explorers. Recent reviews of these characteristics are provided by Sillitoe (1997, 2000), Hedenquist and Richards (1998), Kerrich et al. (2000), Tosdal and Richards (2001), Camus (2002), Richards (2003), and Cooke et al. (2004).

From the perspective of porphyry exploration, two vital questions that need to be addressed are: why and how have giant, high-grade porphyry deposits formed? Both questions are addressed in papers contained within this issue on the giant, porphyry-related mineral deposits of the Andean and Papua New Guinea-Irian Jaya fold belts. This paper attempts to address the first of these two questions (why?) by reviewing the characteristics of the 25 largest porphyry copper deposits, defined in terms of contained copper and gold-rich

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porphyry deposits (in terms of contained gold), and by examining their occurrences in space and time. We discuss the geology of provinces that contain giant deposits, magma compositions, metal grades, and the tectonic environments of ore formation for some of the youngest porphyry copper-gold and copper-molybdenum systems. We highlight the spatial coincidence of many of the world's largest porphyry systems in Tertiary to Quaternary magmatic arcs with regions where subduction of submarine ridges, oceanic plateaus, and seamount chains has occurred and speculate on the importance of these tectonic "triggers" (defined here as perturbations to the steady-state conditions of subduction) for porphyry-style mineralization. Possible mechanisms of high-grade hypogene mineralization are discussed in other papers contained within this special issue.

Grade and Tonnage Data

Grade and tonnage data for the world's 25 largest porphyry copper deposits, based on contained copper metal, and gold-rich porphyry deposits, based on contained gold, are listed in Tables 1 and 2, respectively, and shown in Figure 1. Deposit and district locations are shown on Figure 2.These data have been compiled from several sources. The Geological Survey of Canada database published by Kirkham and Dunne (2000) contains information for 1,022 ore zones from a total of 783 porphyry and related epithermal and skarn deposits, occurring in a total of 62 countries. This has been the principal data source used for porphyry deposits outside of Chile. The U.S. Geological Survey database of giant porphyry-related systems published online by Mutschler et al. (1999) contains information for 234 giant (>2 million metric tons (Mt) copper or >100 t gold; Singer 1995) and 49 near-giant mining camps and was used to supplement the Kirkham and Dunne (2000) database. Resource estimates also have been taken from Camus (2002, 2005), Sillitoe (1999, 2000), Sokolov (1998), Bank of Montreal (BMO; Nesbitt Burns, unpub. data, 2002), Tethyan Copper Company Ltd. (unpub. data, 2004), Ivanhoe Mines (2004), and Wilson et al. (2004), among others.

Giant Deposits

In terms of contained metal, Singer (1995) classified the largest 10 percent of base and precious metal ore deposits as giants and the largest 1 percent as supergiants. For copper deposits, he defined the giants as those with >2 Mt copper and the supergiants as those with >24 Mt copper. The giant gold deposits contain >100 t gold, and the supergiant deposits contain >1,200 t gold. Clark (1993) proposed the following size subdivisions for copper porphyry systems: <0.1 Mt contained copper (small); 0.1 to 0.3162 Mt (moderate); 0.3162 to 1.0 Mt (large); 1.0 to 3.162 Mt (very large); 3.162 to 10 Mt (giant); 10 to 31.62 Mt (supergiant); >31.62 Mt (the largest, informally referred to as "behemoths").

TABLE 1. The Twenty-Five Largest Known Porphyry Copper Deposits, Based on Contained Copper Metal

	Deposit	Province	Age (Ma)	Tonnage (Gt)	Cu (wt %)	Cu (Mt)	Mo (wt %)	Mo (Mt)	Au (g/t)	Au (t)	References
1	El Teniente	Central Chile	4.8	12.48	0.63	94.35	0.02	2.50	0.035	437	1
2	Chuquicamata	Northern Chile	33.6	7.52	0.55	66.37	0.024	1.81	0.04	300.8	1
3	Río Blanco-Los Bronces	Central Chile	5.4	6.99	0.75	56.73	0.018	1.26	0.035	244.7	1
4	Butte	Montana	61	5.23	0.67	35.11	0.03	1.44	0.042	217.0	2, 3, 4, 5
5	La Escondida	Northern Chile	38	2.26	1.15	32.49	0.021	0.48	0.19	429.8	1,3
6	Cananea	Mexico	58	7.14	0.42	30.00	0.01	0.57	0.012	82.0	3, 6, 7
7	Bingham	Utah	38.8	3.23	0.88	28.46	0.02	0.81	0.497	1603	2, 3
8	Grasberg	Irian Jaya	3	2.48	1.13	28.02			1.05	2604	2, 3, 8
9	Los Pelambres-El Pachón	Central Chile	10	4.19	0.63	26.88	0.016	0.67	0.02	83.86	1
10	Rosario	Northern Chile	34.1	3.11	0.82	25.49	0.024	0.75	0.01	31.08	1
11	Lone Star	SW Arizona	58	5.53	0.45	24.74					2, 3, 9, 10
12	Morenci-Metcalf	SW Arizona	56.6	4.69	0.52	24.59		0.086	0.006	30.0	2,3
13	Oyu Tolgoi	Mongolia	411	2.47	0.83	20.57			0.32	790.2	11
14	Cerro Colorado	Panama	4.3	4.50	0.45	20.25			0.11	160.71	2, 3, 12, 13
15	Radomiro Tomic	Northern Chile	32.7	4.98	0.39	19.93	0.015	0.75			1, 14
16	La Granja	Northern Peru	10	3.20	0.61	19.52	0.013	0.08	0.04	128	2, 3, 8, 15
17	Cujaone	Southern Peru	52.3	2.17	0.60	17.14	0.03	0.65			1, 16
18	Sar Cheshmeh	Iran	12.2	1.20	1.2	14.40	0.03	0.36	0.27	324	2, 3, 17, 18
19	Escondida Norte	Northern Chile	39–36	1.62	0.87	14.05					19
20	Pima	SW Arizona	58–57	1.90	0.69	13.06		0.03			3
21	Aktogay-Aiderly	Kazakhstan	Carb?	3.13	0.4	12.50					2, 20
22	El Salvador	Northern Chile	41	0.97	0.63	11.29	0.022	0.21	0.1	97.4	1
23	Kal'makyr	Uzbekistan	Carb?	2.70	0.39	10.64			0.51	1374.3	3, 20
24	Ray	SW Arizona	61–60	1.58	0.68	10.79		0.04	0.002	3.20	2, 3
25	Toki	Northern Chile	39–36	2.41	0.45	10.85					19

Notes: Blank spaces equate to a lack of information for a given deposit and do not necessarily indicate that a given metal is not present in detectable concentrations; L. Jur. = Late Jurassic, K-T = Cretaceous-Tertiary

References: 1 = Camus (2002), 2 = Kirkham and Dunne (2000), 3 = Mutschler et al. (1999), 4 = Meyer et al. (1968), 5 = Brimhall (1977); 6 = Salas (1991), 7 = Bushnell (1988), 8 = Bank of Montreal (BMO; Nesbitt Burns, unpub. data, 2002), 9 = Langton and Williams (1981), 10 = Bouse et al. (1999), 11 = Ivanhoe Mines (2004), 12 = Kesler et al. (1977), 13 = Clark et al. (1977), 14 = Cuadra and Camus (1998), 15 = Schwartz (1982), 16 = Clark et al. (1990), 17 = Samani (1998), 18 = Porter (1998), 19 = Camus (2005), 20 = Sokolov (1998)

TABLE 2. The Twenty-Five Largest Known Gold-Rich Porphyry Copper Deposits, Ranked on Contained Gold

	Deposit	Province	Age (Ma)	Tonnage (Mt)	Au (g/t)	Au (t)	Cu (wt %)	Cu (Mt)	Mo (wt %)	Mo (Mt)	References
1	Grasberg	Irian Jaya	3	2,480	1.05	2,604	1.13	28.02			1, 2, 3
2	Bingham	Utah	38.8	3,228	0.50	1,603	0.88	28.46	0.02	0.81	1, 2
3	Kal'makyr	Uzbekistan	310-294	2,700	0.51	1,374	0.40	10.80			2, 4
4	Lepanto-Far South East	N. Luzon	1.5–1.2	685	1.42	973	0.80	5.48			2, 3, 5
5	Cerro Casale	Chile	13.5	1,285	0.70	900	0.35	4.50			1, 2
6	Cadia	NSW	440	1,070	0.77	823	0.31	3.38			6
7	Panguna	Bougainville	3.5	1,415	0.57	799	0.46	6.51			1, 2
8	Oyu Tolgoi	Mongolia	411	2,467	0.32	790	0.83	20.57			7, 8, 9
9	Batu Hijau	Indonesia	3.7	1,644	0.35	572	0.44	7.23			1, 2, 10
10	Minas Conga	Northern Peru	20	641	0.79	506	0.30	1.92			2, 3
11	Ok Tedi	PNG	1.2–1.1	700	0.64	446	0.64	4.48			1, 2
12	El Teniente	Central Chile	4.8	11,845	0.035	437	0.63	94.35	0.02	2.50	7
13	La Escondida	Northern Chile	38	2,262	0.19	430	1.15	32.49	0.021	0.48	2, 7
14	Peschanka	Kamchatka	L. Jur.	940	0.42	395	0.51	4.79			2
15	Dal'neye	Uzbekistan	310–294	545	0.69	376	0.59	3.21			2, 4
16	Bajo de la Alumbrera	Argentina	8–7	551	0.67	369	0.52	2.87			1, 2, 11
17	Frieda River	PNG	14–11	1,103	0.32	354	0.61	6.73			1, 2
18	Pebble Copper	Alaska	90	1,000	0.34	340	0.30	3.00			2, 3
19	Tampakan	Philippines	3.3–2.2	1,400	0.24	336	0.55	7.70			12, 13
20	Atlas	Philippines	61	1,380	0.24	331	0.50	6.90			2
21	Sar Cheshmeh	Iran	12.2	1,200	0.27	324	1.20	14.40	0.03	0.36	1, 2, 14, 15
22	Chuquicamata	Northern Chile	33.6	12,066	0.04	301	0.55	66.37	0.024	1.81	7
23	Sipilay	Philippines	K-T	884	0.34	301	0.50	4.42	0.01	0.09	2
24	Prosperity	BC, Canada	79	631	0.46	290	0.25	1.58			1, 2, 3, 16
25	Reko Diq	Pakistan	Miocene?	855	0.33	282	0.65	5.56			17

Notes: Blank spaces indicate no information for a given deposit and do not necessarily indicate that a given metal is not present in detectable concentrations; Carb? = Carboniferous

References: 1 = Kirkham and Dunne (2000), 2 = Mutschler et al. (1999), 3 = Bank of Montreal (BMO; Nesbitt Burns, unpub. data, 2002), 4 = Sokolov (1998), 5 = Hedenquist et al. (1998), 6 = Wilson et al. (2004), 7 = Camus (2002), 8 = Perelló et al. (2001), 9 = Ivanhoe Mines (2004), 10 = Garwin (2002), 11 = Ulrich and Heinrich (2001), 12 = Sillitoe (1999), 13 = Middleton et al. (2004), 14 = Samani (1998), 15 = Porter (1998), 16 = Caira et al. (1995), 17 = Tethyan Copper Company Ltd. (unpub. data, 2004)

A total of 17 of the largest systems are classified as copper ± molybdenum deposits in terms of contained metal. Four of the deposits are classified as copper-gold-molybdenum deposits (containing 0.1 g/t gold or more: La Escondida, Bingham, Sar Cheshmeh, and El Salvador), and four are copper-gold deposits (Grasberg, Cerro Colorado, Oyu Tolgoi, and Kal'makyr).

El Teniente, Chuquicamata, Río Blanco-Los Bronces, Butte, and Escondida exceed Clark's (1993) threshold for the largest copper deposits (Fig. 1A). The remaining 20 deposits in Figure 1A are supergiants. The three largest deposits stand out as anomalous in terms of their contained copper. The other 22 deposits define a gradual trend in terms of decreasing amounts of contained copper (Fig. 1A).

Using Singer's (1995) classification scheme, three of the largest gold-bearing porphyry deposits (Grasberg, Bingham, and Kal'makyr) are supergiants, and the remaining 22 are giant deposits. Two of the 25 deposits plotted in Figure 1B are copper-molybdenum deposits (El Teniente, Chuquicamata), four are copper-gold-molybdenum deposits (La Escondida, Pebble Copper, Sar Chesmeh, Sipilay), and the remaining 19 are porphyry copper-gold deposits. As for the giant copper deposits (Fig. 1A), there is a significant increase in the metal endowment between the largest three gold-rich porphyry deposits and the next largest deposits (Fig. 1B).

Grades

Figure 3A shows the copper grades of the 25 largest porphyry copper deposits, with respect to total tonnage. The grades are combined figures, encompassing hypogene ore together with any supergene, skarn, and/or high-sulfidation mineralization within an individual system. The following arbitrary classification has been applied to the copper porphyries: low grade (<0.5 wt % copper), moderate grade (0.5–0.75% copper), and high grade (>0.75% copper). One of the largest deposits (Escondida) and six supergiant deposits are classified as high grade. The remaining four largest deposits have moderate grades, as do most of the supergiant deposits. Of the seven systems classified as low grade, one is in Panama, two are in northern Chile, two are in southwestern Arizona-Mexico, and two are in the southwestern region of the former Soviet Union (Aktogay-Aiderly and Kal'makyr). Sillitoe (1998) attempted to define large, high-grade hypogene deposits as those containing >1 billion tons and averaging ≥1 percent copper. Unfortunately, this scheme is not particularly useful. Only Grasberg would be classified as a large, high-grade hypogene porphyry copper deposit using the data listed in Table 1 (Fig. 3A). The other deposits that plot within Sillitoe's (1998) high-grade field in Figure 3A (Sar Cheshmeh and La Escondida) have significant supergene resources that contribute to their high grades.

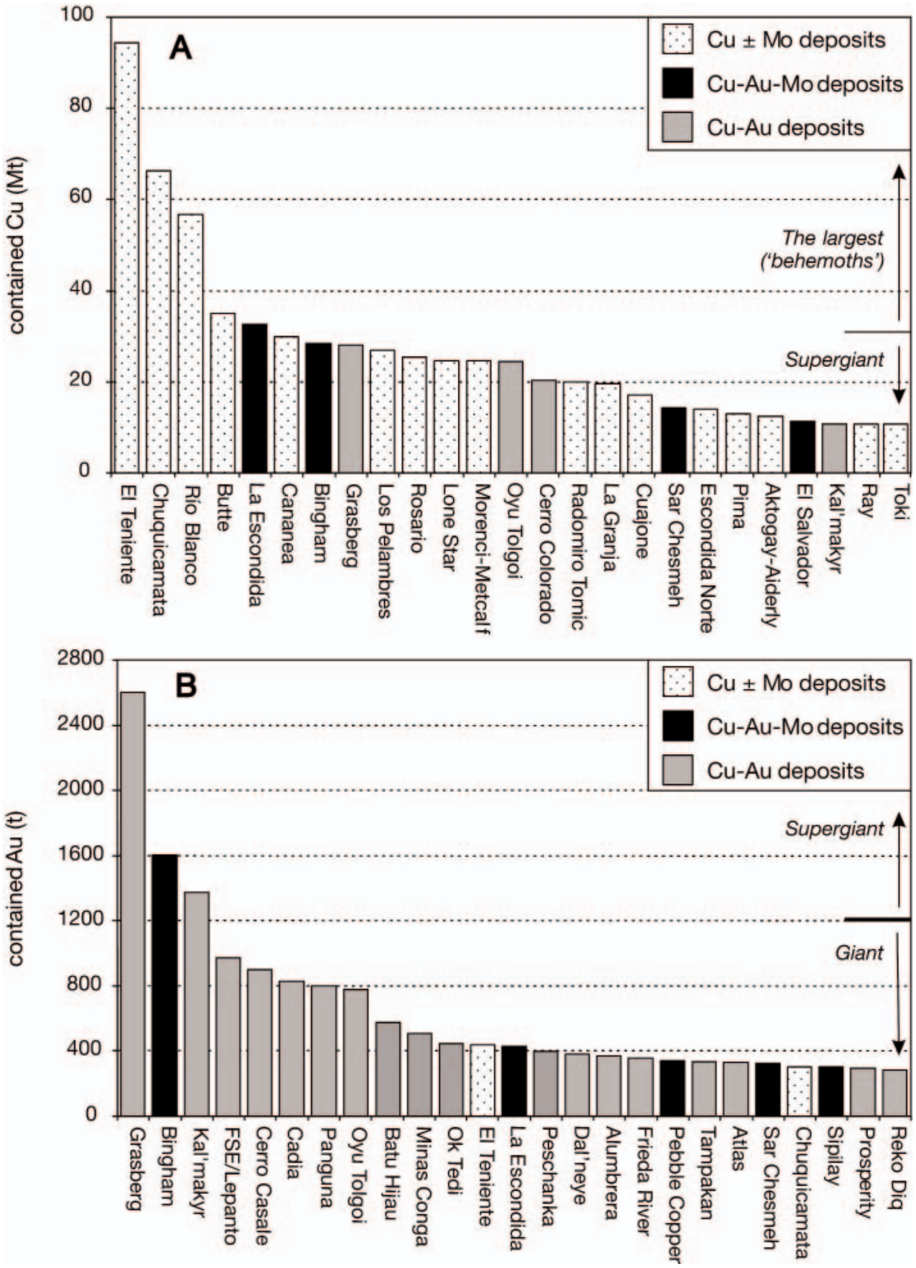

FIG. 1. A. The 25 largest porphyry copper deposits, based on the tonnage of contained copper metal. Also shown are Clark's (1993) subdivisions of supergiant and the largest porphyry deposits (the "behemoths"). Data listed in Table 1. B. The 25 largest gold-endowed porphyry copper deposits, based on contained gold metal (metric tons). Also shown are Singer's (1995) subdivisions of supergiant and giant gold deposits. Data listed in Table 2.

Figure 3B is a grade-tonnage plot for the 25 largest gold-rich porphyry deposits, using an arbitrary classification of gold grade as by-product (<0.1 g/t), low grade (0.1–0.5 g/t), moderate grade (0.5–0.75 g/t) and high grade (>0.75 g/t). Using this scheme, one of the three supergiants and three of the 22 giants in Figure 3B are high grade (Grasberg, Lepanto-Far South East, Minas Conga, and Cadia). The remaining two supergiants and six of the giant deposits have intermediate gold grades. Eleven of the giant porphyry gold deposits are classified here as low grade (Fig. 3B). The remaining two deposits (El Teniente and Chuquicamata) have very low gold grades (0.035 and 0.04 g/t, respectively) but are classified as giant gold deposits due to the extremely large resources, which have allowed large tonnages of gold to be recovered as a by-product from these systems (Camus, 2002). Of the four low-grade giant gold-rich porphyry deposits, gold is a significant byproduct of copper mining operations at Batu Hijau, La Escondida, Atlas, Sipilay, and Sar Chesmeh. Gold will also be an important by-product at Pebble Copper, Tampakan, Prosperity, and Reko Diq if these deposits are ever mined. Grasberg is distinct from all of the other porphyry systems plotted in Figure 3A in terms of its combined high-grade and large

FIG. 2. A. Location of giant porphyry copper deposits. Numbers correspond to deposits listed in Table 1. Letters A, B, and C denote provinces that contain more than one giant system. Stippled patterns represent belts defined by porphyry deposits. A = central Chile province (El Teniente, Río Blanco-Los Bronces, Los Pelambres). B = northern Chile province (Chuquicamata, La Escondida, Radomiro Tomic, Rosario, El Salvador, El Abra). C = southwest Arizona-Sonora province (Cananea, Lone Star, Morenci-Metcalf, Pima, Ray). B. Location of giant porphyry gold deposits. Numbers correspond to deposits listed in Table 2. D and E denote provinces that contain more than one giant system. D = Papua New Guinea-Irian Jaya province (Grasberg, Ok Tedi, Panguna, Frieda River). E = Philippines province (Far South East-Lepanto, Tampakan, Atlas, Sipilay).

tonnage hypogene resource. Grasberg contains more than three times as much gold as the other two high-grade gold-rich porphyry systems.

Locations

In his review of the characteristics of giant and small porphyry deposits, Clark (1993, p. 213) concluded that "on the basis of the criteria selected, there are no systematic *qualitative* differences between outsize and smaller examples of the porphyry clan." However, Clark (1995) also highlighted the importance of provinciality, in that giant porphyry deposits tend to cluster within mineral provinces. This implies that geodynamic setting and crustal architecture played important roles in localizing the giant deposits.

Porphyry and epithermal deposits occur in arc-related settings of various ages throughout the world. However, giant systems are restricted to only a few mineral provinces and time periods. Figure 2A shows the locations of the 25 largest copper porphyries. Fourteen of these giant deposits occur in only three mineral provinces (Table 1). The late Miocene-Pliocene central Chile province (loc A, Fig. 2A) contains two of the largest (El Teniente and Río Blanco-Los Bronces) and

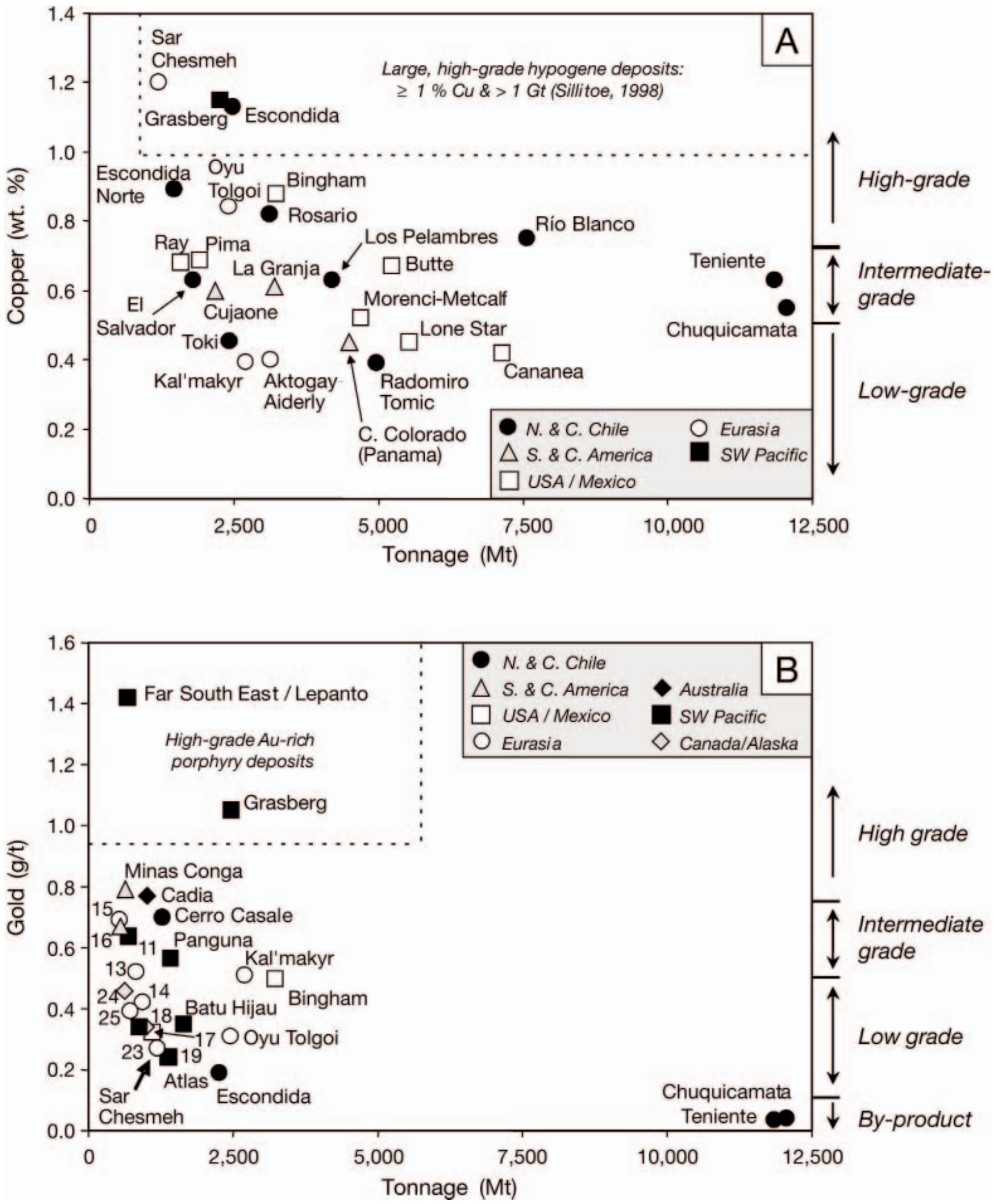

FIG. 3. Grade vs. tonnage plots for giant porphyry deposits. A. The 25 largest porphyry copper deposits subdivided arbitrarily on the basis of metal grades (high grade: >0.75 wt % copper; intermediate grade: 0.5–0.75 wt % copper; low grade: <0.5 wt % copper) and also subdivided on the basis of geographic location. Sillitoe's (1998) proposed subdivision of large, high-grade hypogene deposits is also shown. Data listed in Table 1. B. The 25 largest gold-rich porphyry copper deposits, plotted as a function of resource tonnage vs. gold grades and subdivided on the basis of geographic location. Metal grades arbitrarily subdivided as follows: high grade: >0.75 g/t gold; intermediate grade: 0.5–0.75 g/t gold; low grade: 0.1–0.5 g/t gold; by-product: <0.1 g/t gold. This diagram clearly discriminates the high-grade gold-rich porphyry deposits from the giant copper-molybdenum systems with very low gold grades, where gold has been recovered as a by-product during ore processing. Data listed in Table 2.

one supergiant deposit (Los Pelambres-El Pachón). The Eocene-Oligocene province of northern Chile (loc B, Fig. 2A) contains one giant, five supergiants, and one of the behemoths, plus several other large deposits. Six supergiant systems occur in the Laramide province of southwest Arizona and Mexico (loc C, Fig. 2A). Some of the other deposits are the largest example in a province that contains several smaller systems (e.g., Sar Chesmeh, Tethyan Belt; Grasberg, Papua New Guinea-Irian Jaya fold belt; La Granja, northern Peru; Cujaone, southern Peru). Deposits that appear to be isolated occurrences include Cerro Colorado (Panama), Bingham (Utah), and Butte (Montana). Grasberg (Irian Jaya), Sar Chesmeh (Iran), Oyu Tolgoi (Mongolia), Aktogay-Aiderly (Kazakhstan), and Kal'makyr (Uzbekistan) are the only known supergiant copper porphyry deposits outside of the Americas (Fig. 2A).

In contrast to the copper porphyries, there is a high concentration of large gold-rich porphyry deposits in the southwest Pacific (nine deposits; Table 2, Fig. 2B). This includes the supergiant Grasberg deposit and the giant Ok Tedi and Frieda River deposits in the Papua New Guinea -Irian Jaya fold belt (loc E, Fig. 2B). Peru, Chile, and Argentina contain six of the largest gold-bearing porphyry systems, although only three of these (Cerro Casale, Minas Conga, and Bajo de la Alumbrera) have gold grades higher than 0.5 g/t (Table 2). Uzbekistan is host to one supergiant and one giant gold-rich porphyry deposit (Kal'makyr and Dal'neye, respectively; Fig. 2B). The Tethyan belt contains two giant gold-rich porphyries (Sar Chesmeh, Reko Diq). Of the remaining systems shown in Figure 2B, four occur in mineral provinces that contain other, smaller gold-rich porphyry deposits: Prosperity (British Columbia), Cadia (New South Wales), Turquoise Hill (Mongolia), and Pebble Copper (Alaska). Bingham (Utah) and Peschanka (Kamchatka) are apparently isolated deposits.

Ages

Twenty-two of the 25 largest porphyry copper-molybdenum deposits formed during three discrete time periods (Fig. 4A, Table 1). During the Paleocene-early Eocene (65–50 Ma), the Butte deposit formed in Montana. Several supergiant and giant deposits formed in the southwest Arizona-Mexico province and in the Paleocene belt of southern Peru and northern Chile. During the Eocene-Oligocene (42–33 Ma), two behemothian, six supergiant, and several giant copper-molybdenum-(gold) systems formed in northern

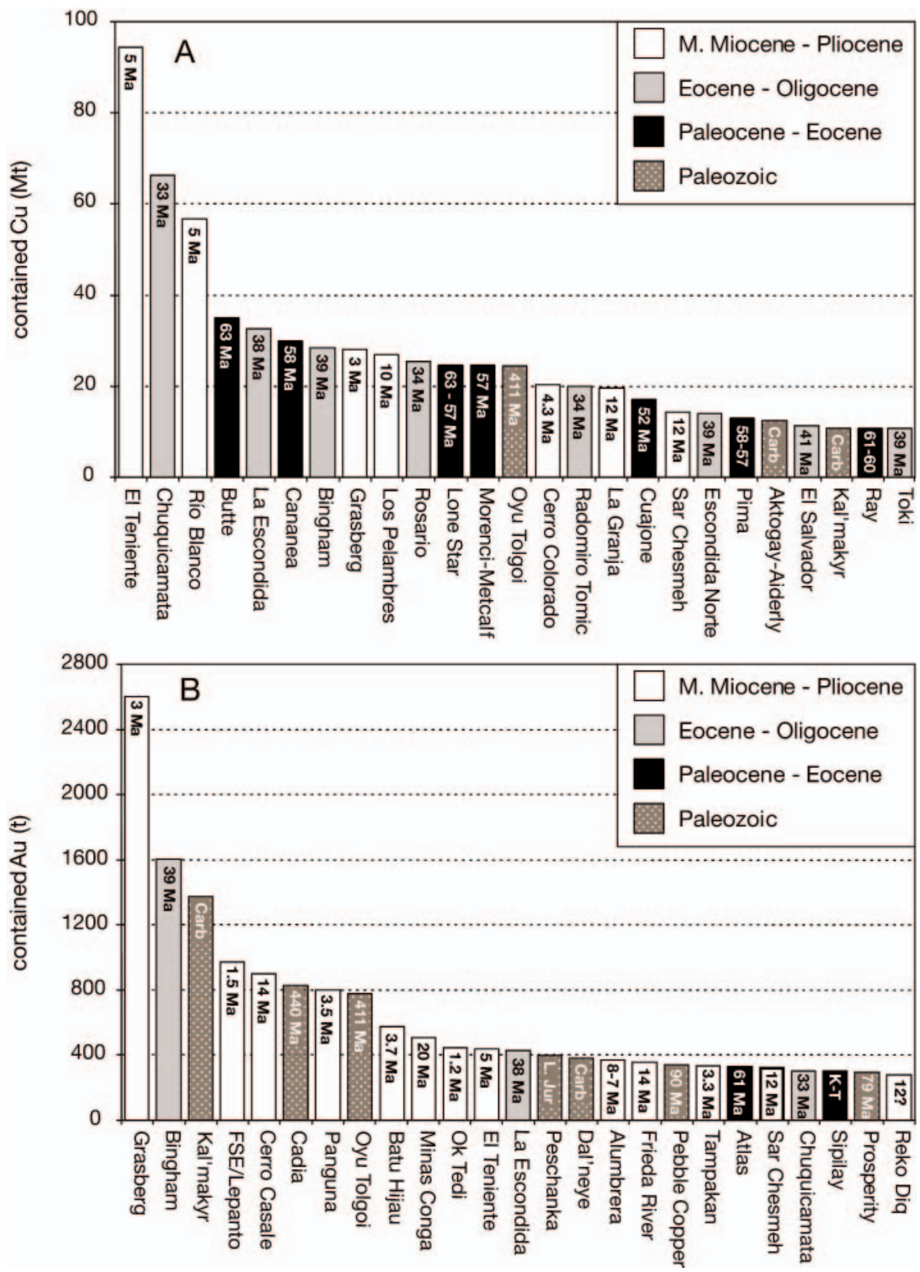

FIG. 4. The 25 largest porphyry deposits, identified by age. A. Giant copper deposits. Data listed in Table 1. B. Giant gold deposits. Data listed in Table 2.

Chile, while at the same time the supergiant copper-gold-molybdenum deposit formed at Bingham Canyon (Utah). The copper-molybdenum systems of central Chile and northern Peru and supergiant copper-gold deposits at Grasberg (Irian Jaya), Cerro Colorado (Panama), and Sar Chesmeh (Iran) formed during the middle Miocene-Pliocene (12–3 Ma). Oyu Tolgoi (411 Ma), Aktogay-Aiderly (Late Carboniferous), and Kal'makyr (Late Carboniferous; Table 1) formed during the Paleozoic.

Thirteen of the largest gold-rich porphyry and epithermal deposits formed in the middle Miocene to Recent period, three during the Eocene-Oligocene and two during the Paleocene-Eocene (Fig. 4B, Table 2). In addition, giant gold-rich systems formed at 440 Ma (Cadia), 411 Ma (Oyu Tolgoi), Late Carboniferous (Kal'makyr and Dal'neye), Late Jurassic (Peschanka), 90 Ma (Pebble Copper), 79 Ma (Prosperity), and at the Cretaceous-Tertiary boundary (Sipilay).

A significant number of the giant porphyry deposits are less than 20 m.y. old. This most likely relates to the preservation potential of porphyry deposits, rather than anything unique about Tertiary and Quaternary metallogenesis. Uplift and erosion has probably destroyed at least part or all of older giant systems. This situation applies to both the copper-molybdenum and copper-gold porphyry deposits, both of which form at depths of 1 to 3 km in the Earth's crust (e.g., Camus, 2003; Cooke et al., 2004). Because supergene enrichment is important to the economics of many of the giant porphyry copper-molybdenum deposits, there is a trade-off between weathering and excessive erosion. There are several Paleozoic examples of giant porphyry deposits, particularly the gold-rich varieties (Fig. 4). Uplift and erosion of these systems must have been minimal at the time of ore deposition or ceased immediately after the deposit formed. Burial may have promoted preservation, perhaps caused by a transition to an extensional setting after ore formation. Preservation of the deposits also requires that major structural disruptions did not occur during later orogenic events.

Magma series

Porphyry deposits can be classified in terms of the geochemical composition of their associated porphyritic intrusions (e.g., Barr et al., 1976). Most of the 25 largest porphyry copper deposits, including the five largest deposits, are associated with calc-alkalic intrusions (Fig. 5A). The gold-rich porphyry deposits at Grasberg, Bingham Canyon,and Kal'makyr are exceptions, with the mineralizing intrusions having high K calc-alkalic compositions.

Sillitoe (1997) and Mueller and Groves (2000) highlighted the affinity between high K calc-alkalic rocks and gold-rich porphyry systems. The three supergiant gold deposits and four of the giant deposits in Figure 5B are associated with high K calc-alkalic intrusions, in contrast to the giant copper porphyry deposits. The Cadia district is the largest known accumulation of gold associated with an alkalic porphyry system (Wilson et al., 2003; Cooke et al., 2004).

Tectonic Settings

Solomon (1990), Sillitoe (1997), Kerrich et al. (2000), and others have highlighted the importance of tectonic change as a trigger for porphyry ore formation. Porphyry deposits are not the products of typical arc volcanism. Rather, some perturbation of the prevailing tectonic regime triggers the formation of porphyry systems. Sillitoe (1998) identified five key attributes of compressional regimes that are ideal for the formation of porphyry copper deposits: (1) compression impedes magma ascent through the upper crust, thus inhibiting volcanism (e.g., McClay et al., 2002; Skarmeta et al., 2003; Gow and Walshe, 2005); (2) the resultant shallow magma chambers in these compressional settings are larger than those that form beneath extensional arcs; (3) because fractionation of these magma chambers is promoted by their inability to erupt, volatile saturation and generation of large volumes of magmatic-hydrothermal fluids can occur; (4) compression restricts the number of apophyses that can form on the roof of a large magma chamber (possibly due to the lack of steep extensional faults), providing better, more efficient fluid focusing into a single stock rather than a cluster of intrusions; and (5) rapid uplift and erosion promotes efficient extraction and transport of magmatic-hydrothermal fluids due to abrupt decompression (e.g., Masterman et al., 2005).

Sillitoe (1998) noted that crustal thickening associated with compressive tectonism was synchronous with the formation of giant porphyry copper systems in central and northern Chile, southwest Arizona, Irian Jaya, and Iran. He argued that transpressive tectonism in the South American Paleocene-early Eocene arc resulted in a compressive segment in southern Peru, promoting the formation of the supergiant Cujaone and giant Toquepala deposits, and an extensional segment in northern Chile, where smaller porphyry copper-molybdenum deposits occur (Spence, Cerro Colorado, Mocha, and Lomas Bayas). Camus (2003) considered this correlation of deposit size and tectonic regime in the Paleocene belt to be incorrect, arguing that the extensional segment was located farther south (between 24° and 26°S), where only epithermal deposits have been discovered.

Tectonic triggers for porphyry ore formation are ephemeral in nature, and direct evidence for them may be completely consumed by plate subduction within a few million years. The following discussion reviews briefly the tectonic setting of several young (<20 Ma) mineral provinces of the circum-Pacific region and examines the tectonic elements that may have played a role in the formation of giant deposits. In particular, we discuss the correlation of some giant porphyry and epithermal deposits with zones of low-angle (flat-slab) subduction in several of the important mineral provinces of the Pacific Rim. Kerrich et al. (2000) and Gutscher et al. (2000) have also noted this association. James and Sacks (1999) summarized the effects of transitions from normal to flat and back to normal subduction, based on their study of the Paleocene to Oligocene rocks of southern Peru and northern Chile. These included: (1) a broad zone of decreased alkalic magmatism; (2) horizontal shortening via thrusting; (3) hydration of the lithosphere above the flat slab (most intense above the zone of normal subduction and above the initial zone of flat subduction); (4) abnormally low heat flow due to advective cooling of the lithosphere (as a result of dehydration of the oceanic plate?); (5) a return to normal subduction and interaction of hot asthenosphere and hydrated mantle, causing wet melting; (6) substantial crustal melting due to passage of mantle melts through the continental lithosphere; and (7)

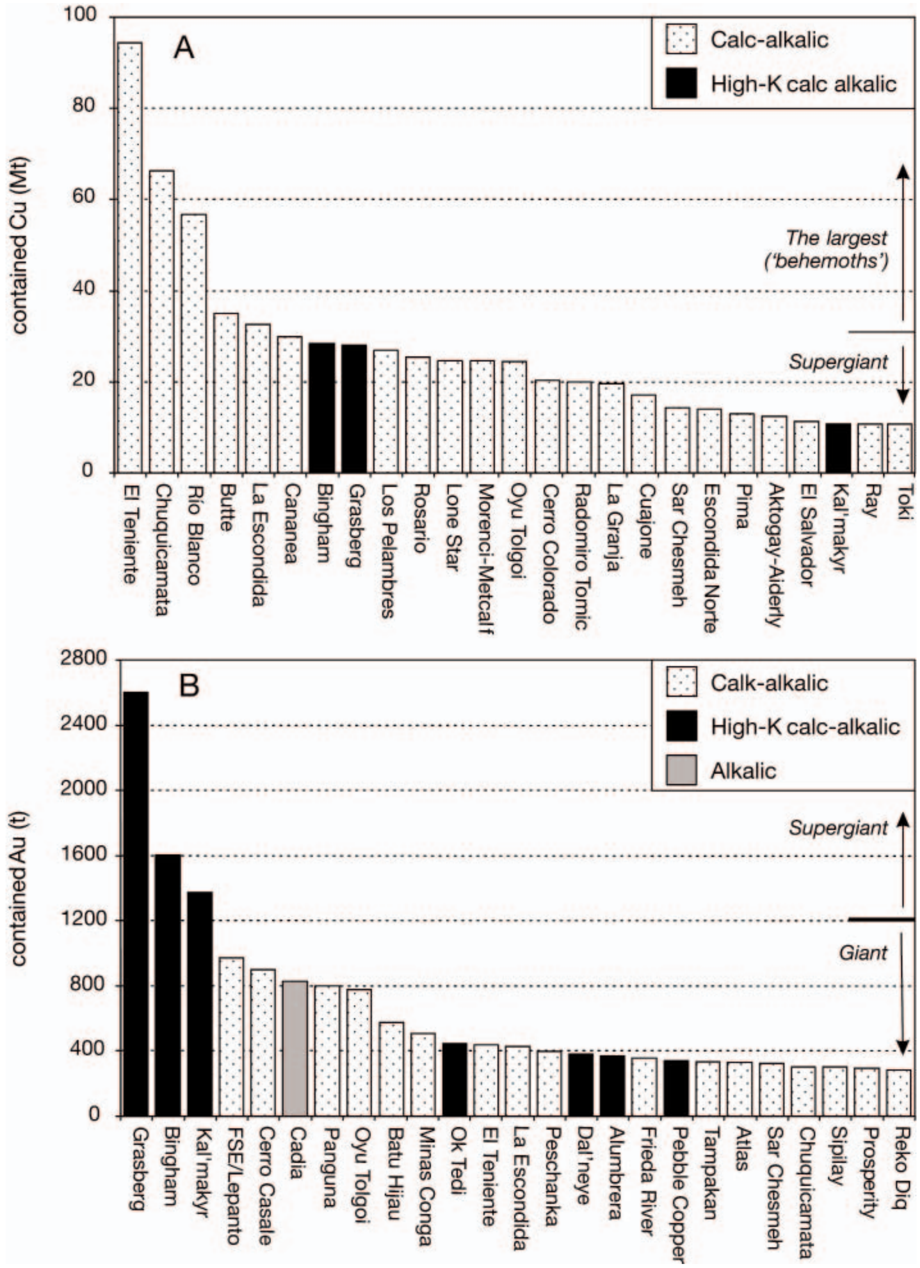

FIG. 5. A. The 25 largest porphyry deposits, identified by magma series. A. Giant copper deposits. Data listed in Table 1. B. Giant gold deposits. Data listed in Table 2.

lithospheric thinning and weakening via heating and fluid advection, leading to intense crustal shortening and uplift (ductile deformation). Similar processes are likely to have occurred in other provinces subjected to low-angle subduction.

Central Chile

Central Chile contains a 550-km-long flat-slab segment (Gutscher et al., 2000) around which a wealth of giant porphyry copper-molybdenum, copper-gold, and high-sulfidation epithermal gold deposits have formed (Fig. 6). A transient peak compressive event began in the late Miocene and continued into the Pliocene due to the subduction of the Juan Fernández Ridge (Fig. 6). This collision has caused slab shallowing, crustal thickening, rapid uplift, and exhumation (Kay et al., 1999; Hollings et al., 2005), producing the highest mountains outside of the Himalayas (e.g., Cerro Aconcagua, 6,962 m asl). Volcanism was mostly shut down during this compressional phase, producing the Chilean volcanic gap above the flat subduction zone (Fig. 6). At the same time, the giant porphyry copper-molybdenum deposits of central Chile formed on the southern flexure from flat to normal subduction (Fig. 6; Hollings et al., 2005). Copper-molybdenum-gold systems formed on the eastern flexure from flat to steep subduction at Bajo de la Alumbrera (Fig. 6; Harris et al, 2005) and also at the smaller Agua Rica and Nevados del Famatina deposits (Losada-Calderon et al., 1994; Landtwing et al., 2002; Cooke

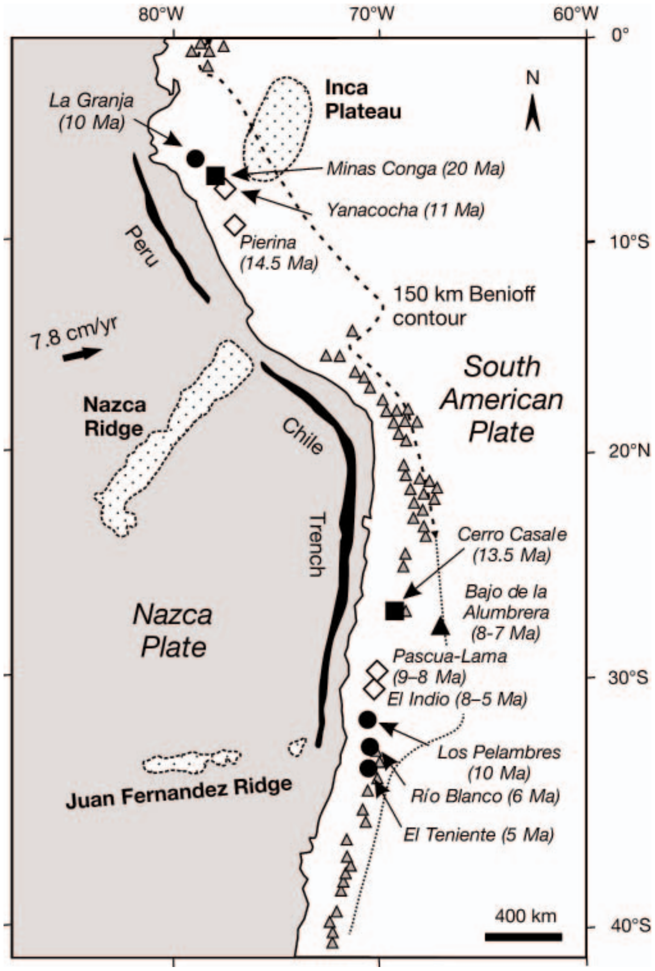

FIG. 6. Tectonic elements of the Andean margin of Chile and Peru and the locations of the young (<20 Ma) porphyry deposits listed in Tables 1 and 2. Also shown are the locations of the Yanacocha, Pierina, Pascua-Lama, and El Indio high-sulfidation deposits. Note the spatial relationship of the giant ore deposits with regions of ridge subduction (Juan Fernández Ridge-Chile). Also shown are the surface projection of the 150-km-depth Benioff contour (dotted line), the location of active volcanoes (gray triangles), and the approximate position of the subducted Inca plateau (Gutscher et al., 1999). Two flat-slab segments in Peru and Chile are highlighted by the gaps in active volcanism. These zones coincide with eastward steps in the 150-km Benioff contour. Diagram modified after Jordan et al. (1983) and Sasso and Clark (1998).

et al., 2003). The giant high-sulfidation gold-silver deposits of the El Indio district (El Indio, Pascua Lama) also formed in this geodynamic setting, directly above the zone of flat subduction (Fig. 6; Sasso and Clark, 1998). The giant gold-rich Cerro Casale deposit, together with several other large porphyry and high-sulfidation epithermal gold deposits, formed in the Maricunga belt at 13 Ma, most likely in association with the onset of this ridge subduction event (Hollings et al., 2005, and references therein).

Peru

Northern Peru contains a spectacular array of middle and late Miocene ore deposits (Fig. 6; Noble and McKee, 1999). The two giant porphyry deposits formed at 10 Ma (Minas Conga copper-gold and La Granja copper-molybdenum deposits; Table 1), with other smaller porphyry deposits known from several locations. The largest known high-sulfidation epithermal gold-silver deposit (Yanacocha, 10.9 Ma) and another giant system (Pierina, 14.5 Ma) also occur in this belt, as does the giant Antamina copper-zinc skarn (9.8 Ma; Noble and McKee, 1999) and a diversity of other carbonate-hosted mineral deposits.

Figure 6 shows the giant porphyry and epithermal deposits of Peru in relation to the major present-day geodynamic elements. Adakite-like volcanism occurred between 6 and 3 Ma in this region, and there is no Quaternary volcanic arc (Gutscher et al., 2000). The giant ore deposits occur above the northern half of the Peruvian flat-slab zone, which extends for 1,500 km, from 2º S to 15º S and is marked by the Peruvian volcanic gap in Figure 6. At almost three times the length of the Chilean flat slab (28º S–33º S), this is the largest known modern-day flat-slab subduction zone (Gutscher et al., 2000). Its exceptional length is due to the presence of both the Nazca Ridge and the now totally subducted Inca plateau (Gutscher et al., 1999; Fig. 6), which have acted to buoy up the subducting oceanic plate in this region. The Inca plateau is an excellent candidate for a hidden tectonic trigger. It was only detected through seismic studies of the subduction zone (Gutscher et al., 1999).

No giant deposits occur above the position of the currently subducting Nazca Ridge (Fig. 6). However, there are several smaller porphyry and epithermal deposits that are spatially and temporally associated with it, including the 7.4 Ma Toromocho porphyry copper-molybdenum deposit (364 Mt at 0.67% Cu, 0.03% Mo; Kirkham and Dunne, 2000; T. Coughlin and C. Muñoz, unpub. data, 2003).

Panama and/or Costa Rica

Western Panama contains the giant Cerro Colorado copper-gold porphyry deposit, which formed 4.3 m.y. ago (Kirkham and Dunne, 2000). Figure 7 shows that this deposit is situated at the point where the Cocos Ridge is being subducted beneath Panama and Costa Rica, in the shortest known present-day zone of flat subduction (250 km long; Gutscher et al., 2000). Abratis (1998) summarized the Miocene to Recent tectonic evolution of this area. Based on his study of igneous rocks from southern Costa Rica, the following sequence of events has been identified: (1) middle to upper Miocene calc-alkalic magmatism; (2) collision of the Cocos Ridge, a hot-spot chain derived from the Galapagos Islands (Fig. 7), with the Central American trench at ~5 Ma, initiating shallow subduction (decrease from 60º dip to 35º–40º dip); (3) cessation of calc-alkalic volcanism in the Pliocene; (4) closure of the ismuth between North and South America in the Pliocene; (5) uplift of the Cordillera de Talamanca above the flat-slab zone from the Pliocene to the present day, at rates of up to 1.4 km/m.y., producing the highest mountains in Central America (up to 3,819 m asl.); (6) development of variable crustal thickness (~40 km in northern Costa Rica; ~20 km in southern Costa Rica); (7) temporal progression of minor alkalic volcanism on the Caribbean side of Costa Rica from the southeast (uppermost Miocene) to the northwest (recent); and (8) adakite volcanism from 3 to 1 Ma.

Western Panama and Costa Rica are excellent analogues for central Chile, with many similar tectonic elements and at least one giant porphyry copper deposit. Differences include the thinner crust, apparently greater tectonic complexity (subduction of

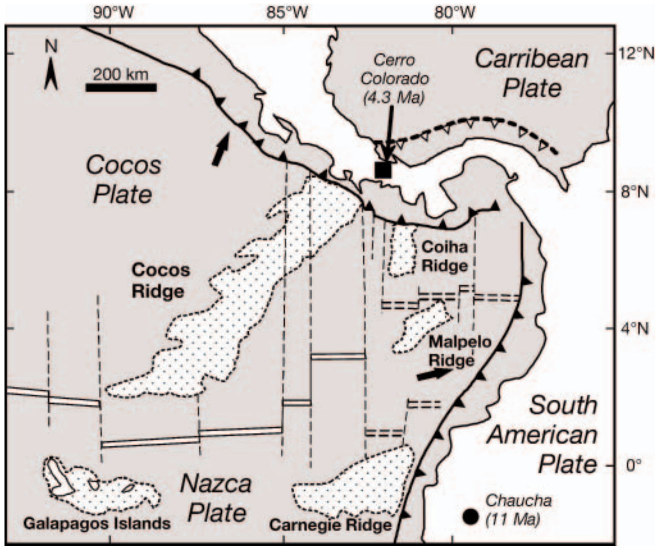

FIG. 7. Tectonic elements of Central America. The locations of the giant Cerro Colorado copper-gold porphyry deposit (Panama) and the small (130 Mt at 0.39% Cu; Kirkham and Dunne, 2000) 10 Ma Chaucha copper-molybdenum deposit (Ecuador) are also shown. Bold arrows indicate the direction of relative plate motions. Diagram modified from Abratis (1998).

both the Cocos and Nazca Plates is currently occurring underneath Panama; Fig. 7), and variable copper-gold metallogeny.

Ecuador

Flat subduction is occurring along a 350-km strike length of southern Ecuador where the Carnegie Ridge is being subducted under the South American plate (Fig. 7; Abratis, 1998). Adakitic volcanism has occurred in this region in the past 3 m.y., but unlike the other flat-slab zones in South and Central America, a Quaternary arc is present (Gutscher et al., 2000). No giant porphyry deposits are known to occur in Ecuador. The largest known young system is Chaucha (11 Ma; 400 Mt at 0.4% copper and 0.03% molybdenum; Mutschler et al., 1999; Fig. 7).

Papua New Guinea-Irian Jaya

A complex array of tectonic elements occur here, with several microplates currently being created and destroyed in the region where the Pacific, Australian, and Caroline plates converge (Fig. 8; Gow and Walshe, 2005; Prendegast et al., 2005). The region is also endowed with spectacular porphyry copper-gold and epithermal gold resources (e.g., Grasberg; Pollard et al., 2005; also Ok Tedi, Porgera, Lihir, and Panguna).

There appear to have been many possible tectonic triggers for porphyry ore formation in the Papua New Guinea-Irian Jaya region. These include southward obduction of the Papuan ultramafic belt and the Finisterre arcs on to the Australian plate in the middle Miocene and Pliocene, with attendant uplift and crustal thickening (Rogerson and McKee, 1990), interaction with the Manus basin spreading ridge (Fig. 8), stress partitioning along arc-normal transfer structures, and contrasting basement lithologies. Any of these could have been important geodynamic and architectural elements in the formation of the giant copper-gold porphyry deposits (e.g., Gow and Walshe, 2005). Also, parts of this region have undergone arc reversal, which has been proposed as a key process for the formation of at least some of the porphyry copper deposits (Panguna, Frieda River; Solomon, 1990).

In addition to the processes outlined above, flat-slab subduction associated with the interaction of the Euripik Rise and the New Guinea trench (Gutscher et al., 2000) appears to have been spatially and temporally associated with the formation of the largest known gold-rich porphyry (Grasberg), as well as the giant Ok Tedi copper-gold and nearby Porgera epithermal gold deposits. Collision of the Euripik Rise has produced a flat-slab zone, 550 km long, beneath mainland Papua New Guinea and Irian Jaya. Adakitic volcanism occurred from 4 to 2 Ma in the Aird Hills on the south side of Papua New Guinea. These volcanoes were apparently localized by a transform fault (Gutscher

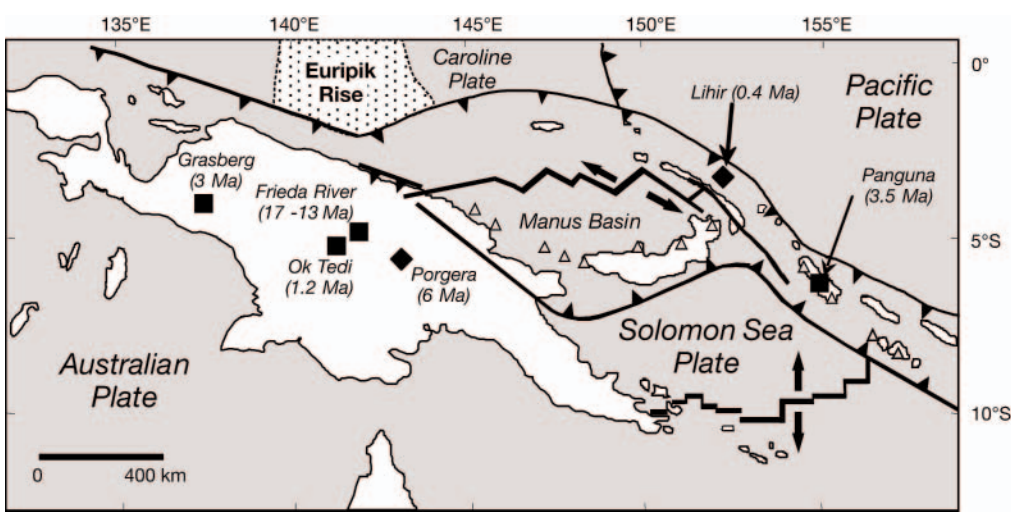

FIG. 8. Tectonic elements of Papua New Guinea, Irian Jaya, and the Solomon Islands. Also shown are the locations of the giant porphyry deposits listed in Tables 1 and 2 plus Lihir, the largest known low-sulfidation epithermal gold deposit. Active volcanoes are denoted by gray triangles. Diagram modified from Gemmell et al. (2004). The approximate position of the Eupirik Rise has been interpreted from bathymetry images of the National Geophysical Data Centre (http://www.ngdc.noaa.gov/ngdc.html).

et al., 2000; Haschke and Ben-Avraham, 2001), which is oriented parallel to the basement structures that controlled the locations of Porgera and Ok Tedi (Gow and Walshe, 2005).

It is difficult to interpret the geodynamic setting for the giant ore deposits that occur offshore from the Papua New Guinea mainland. Panguna (3.5 Ma) occurs near the triple junction between the Pacific, North Bismark, and Solomon Sea microplates, with the Solomon Sea plate being subducted northward beneath the Pacific plate (Fig. 8). Solomon (1990) noted that ore formation occurred after an episode of arc reversal in the middle Miocene, caused by the collision of the Ontong Java plateau with the volcanic arc. The largest known low-sulfidation epithermal gold deposit, Lihir (0.4 Ma; Carman, 2003), overlies a middle to late Miocene island arc which experienced the same arc reversal following the collision of the Ontong Java plateau (Carman, 2003). Lihir Island is part of the Tabar to Feni chain of Pleistocene alkalic volcanoes that formed on extensional structures that are arc normal to New Ireland but which have been reactivated in a back-arc setting during northward-directed subduction of the Solomon Sea plate along the New Britain trench (Carman, 2003; Fig. 8).

It is debatable whether arc reversal, low-angle subduction and/or other processes were the key geodynamic triggers for porphyry-related hydrothermal activity in the offshore island arcs of Papua New Guinea and the Solomon Islands or in the fold belt on mainland Papua New Guinea-Irian Jaya. It may be that they were all contributing factors but resolving their relative importance is difficult. While arc reversal may be an important process for porphyry ore formation in island arcs such as Papua New Guinea and the Philippines, it is not a viable explanation for continental arcs such as Chile and Peru.

Philippines

The Philippine islands are well endowed with porphyry copper-gold deposits and also contain some copper-molybdenum systems (Sillitoe and Gappe, 1984; Fig. 9). The Philippines is a collage of tectonic elements, and porphyry deposits have formed in discrete provinces within this collage at various times since the Cretaceous. In this review, we focus on the Pliocene to Pleistocene porphyry and epithermal deposits, which have formed in southern and eastern Mindanao (e.g., Tampakan; Fig. 9; also King-King and Boyongan) and northeastern Luzon (Lepanto-Far South East, Baguio district, Fig. 9; also Philex, Batong Buhay). No flat subduction is known in this region, although Sajona and Maury (1998) noted that adakitic volcanism has occurred in the Luzon Central Cordillera and eastern Mindanao. They attributed the adakitic magmatism to subduction of young, hot oceanic crust. The Philippine fault is a major left-lateral strike-slip fault system that accommodates oblique convergence caused by east-directed subduction of the South China Sea plate beneath western Luzon and west-directed subduction of the Philippine Sea plate beneath eastern Mindanao. There is an obvious spatial association of young porphyry and epithermal deposits with the Philippine fault (Fig. 9), with the northern Luzon and eastern Mindanao porphyry provinces associated with flexures in the strike-slip fault system (Fig. 9).

In addition to the spatial association with the Philippine fault, the giant Lepanto-Far South East copper-gold system (1.5–1.3 Ma), giant low-sulfidation epithermal gold deposits of the Baguio district (>700 t gold; age <1 Ma), and the giant

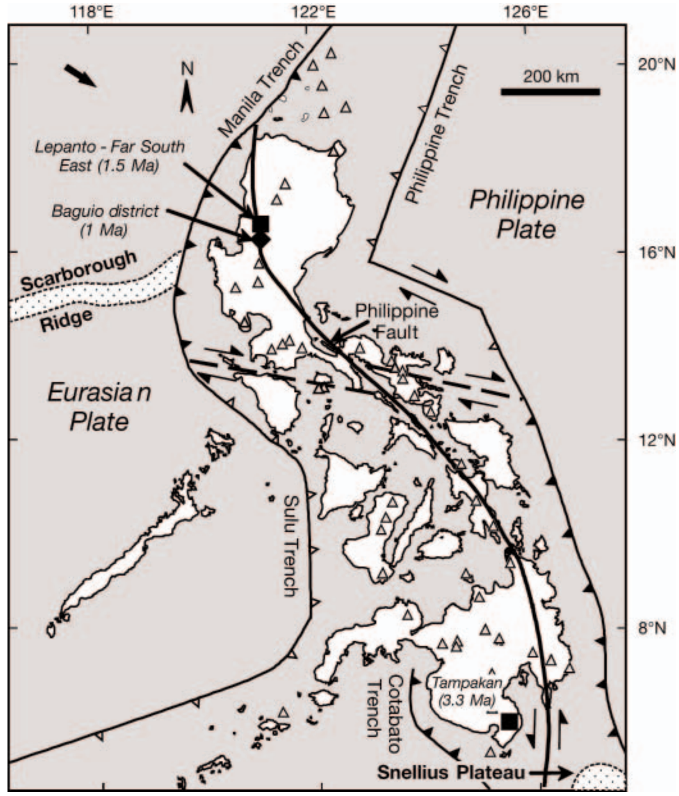

FIG. 9. Tectonic elements of the Philippines and the locations of the young (<20 Ma) giant porphyry deposits listed in Table 2. Active volcanoes are denoted by gray triangles. Diagram modified from Sillitoe and Gappe (1984). The bold arrow indicates the direction of relative plate motions. The approximate position of the Scarborough Ridge has been interpreted from bathymetry images of the National Geophysical Data Centre (http://www.ngdc.noaa.gov/ngdc.html). The approximate position of the Snellius plateau has been estimated from images of Pubellier et al. (1999).

(328 Mt at 0.34% Cu and 0.61 g/t Au; Kirkham and Dunne, 2000) 1.5 Ma Philex copper-gold porphyry are spatially associated with subduction of the aseismic Scarborough Ridge beneath northern Luzon, which has caused a tear in the subducting slab (Yang et al., 1996; Kerrich et al., 2000; Fig. 9). This also caused a decrease in the angle of subduction, although not flat, and uplift at rates of about 1 km/m.y. (Cooke and Bloom, 1990).

In southeast Mindanao, Pliocene magmatism produced the 4.4 to 3.3 Ma Tampakan high-sulfidation porphyry copper-gold deposit (Middleton et al., 2004; Table 2) and the recently discovered 2.6 to 2.3 Ma Boyongan porphyry copper-gold deposit (Waters, 2004), together with several smaller systems (e.g., King-King, Amacan). There are no obvious perturbations in the sea-floor bathymetry where the Philippine Sea plate is being subducted underneath eastern Mindanao (Fig. 9). Instead, north-directed subduction of the Snellius plateau along the Cotabato trench in southern Mindanao (Pubellier et al., 1999) was a possible tectonic trigger for porphyry mineralization in this region.

Japan

Japan is not known to be endowed with any large porphyry copper deposits, but the island of Kyushu is host to one of the largest known low-sulfidation epithermal gold deposits (Hishikari, 1.25–0.66 Ma, 250 t gold; Izawa et al., 1990; Cooke and Simmons, 2000) and important high-sulfidation gold deposits (e.g., Nansatsu district, 5–3.5 Ma, 36 t gold; Hedenquist et al., 1994; Cooke and Simmons, 2000). These deposits occur above the region where the northern extension of the Kyushu-Palau Ridge is being subducted underneath Japan (Fig. 10). This is another flat-slab zone, extending for 600 km northeast to where the Izu-Bonin arc is interacting with the Nankai trough. As for many of the regions reviewed above, it appears that the architecture of the downgoing slab has broadly influenced the location and timing of formation of magmatic-hydrothermal systems in the overriding plate. It may be that porphyry deposits did form in Kyushu but that the degree of uplift and exhumation has been insufficient to expose the porphyry systems in this region.

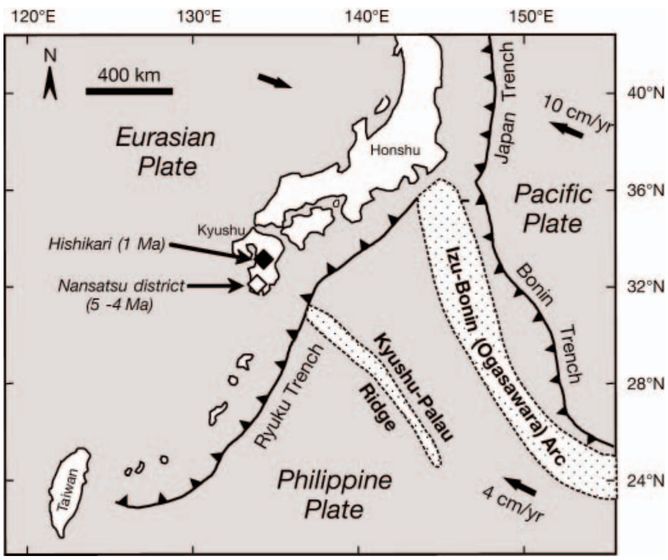

FIG. 10. Tectonic elements of southern Japan. Also shown are the locations of the Hishikari low-sulfidation epithermal deposit and the Nansatsu high-sulfidation district. Diagram modified from Sillitoe (1989). The approximate position of the Kyushu-Palau Ridge has been interpreted from bathymetry images of the National Geophysical Data Centre (http://www.ngdc.noaa.gov/ngdc.html).

Sumbawa

The geodynamic setting of the giant Batu Hijau copper-gold porphyry deposit has been discussed in detail by Kerrich et al. (2000) and Garwin (2002). Batu Hijau formed on the island of Sumbawa 3.7 m.y. ago and is associated with calc-alkalic magmatism in the Sunda-Banda arc (Fig. 11). Kerrich et al. (2000) and Garwin (2002) highlighted the presence of the Roo Rise offshore from the southern coast of Sumbawa. The eastern margin of this plateau correlates with an arc-normal northeast-trending structure that transects the island. Batu Hijau is located within 30 km of this structure, which Garwin (2002, p. 337) relates to "an inferred kink or tear in the subducting slab beneath the Banda arc." In contrast to other areas that contain young giant porphyry deposits, this region has not undergone substantial crustal thickening. Arc reversal has resulted in a chain of Recent alkalic volcanoes forming along the north coast of Sumbawa (Garwin, 2002). Batu Hijau formed at approximately 3.7 Ma, coincident with the collision between the Australian plate and the Timorese segment of the Banda arc (4–2.5 Ma), which is believed to have caused arc-parallel extension (Garwin, 2002).

Tethyan belt

The giant Miocene porphyry deposits of Iran and Pakistan occur in a region undergoing continent-continent collision

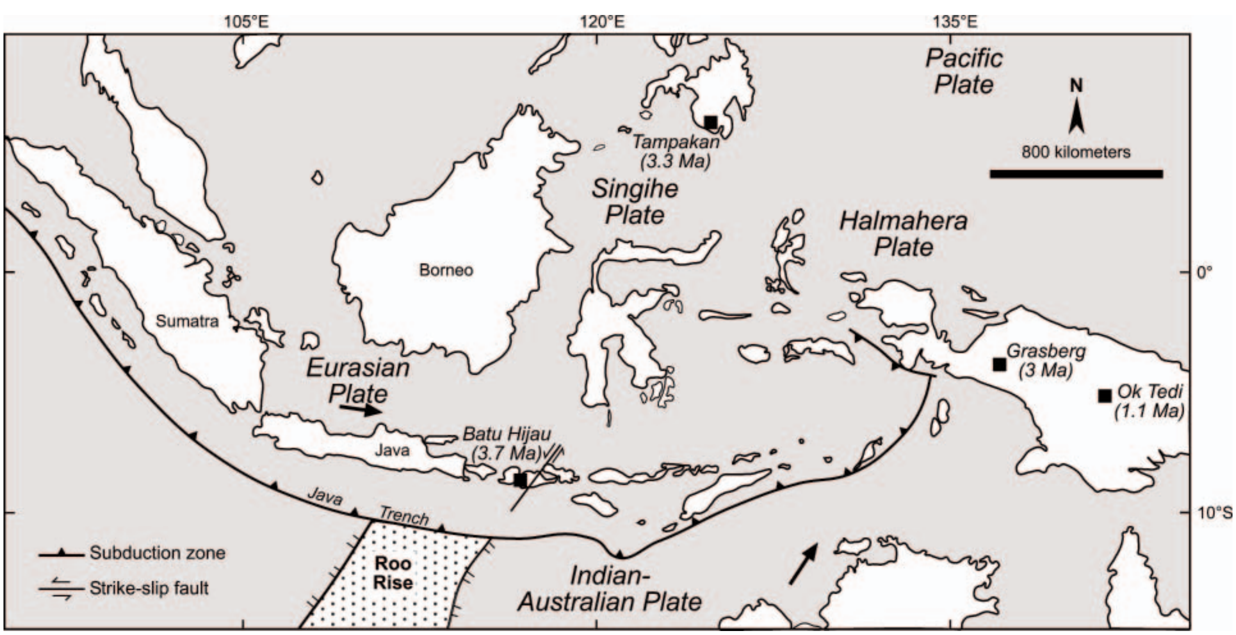

FIG. 11. Tectonic elements of Indonesia and the southern Philippines. Also shown are the locations of the Batu Hijau, Tampakan, Grasberg, and Ok Tedi porphyry copper-gold deposits. Bold arrows indicate the direction of relative plate motions. Diagram modified from Garwin (2002).

(Fig. 12), in contrast to the other systems discussed here. The tectonic environment in the Tethyan belt is clearly distinct from the other districts reviewed above, and the nature of the geodynamic and architectural controls on porphyry formation in this complex tectonic zone are unclear. Leaman and Staude (2002) reviewed the evolution of the composite Tethyan magmatic arc. They noted that Oligocene to Miocene continental arc-style magmatism in the western Tethyan belt produced porphyry copper-molybdenum mineralization at Sungun (northwestern Iran) and the giant gold-rich porphyry copper deposits at Sar Chesmeh (southeastern Iran) and Reko Diq (northwestern Pakistan; Fig. 12), together with the smaller copper-gold porphyry system at Saindak (northwestern Pakistan). The age of Sar Chesmeh is reportedly 12 Ma (Mutschler et al., 1999), Saindak is 19 Ma, and Sungun is approximately 20 Ma (Kirkham and Dunne, 2000). Reko Diq is inferred here to be middle to late Miocene on the basis of correlation with the nearby deposits. It is possible that the attempted subduction of the Arabian plate beneath the Eurasian plate was a trigger for porphyry mineralization. Alternatively, the key Miocene tectonic elements may have been obscured by subsequent tectonic activity. The reason for the change of metallogeny from copper-gold in the southeast of the region to copper-molybdenum in the northwest is unclear. It may have been influenced by the change from subduction of oceanic to continental crust.

Discussion and Conclusions

Seven of the 25 giant copper and 13 of the 25 giant gold-rich porphyry deposits considered in this review formed in the last 20 m.y. Of these, six of the seven giant copper and nine of the 13 giant gold deposits are known or inferred to be associated with regions where low-angle subduction of aseismic ridges,

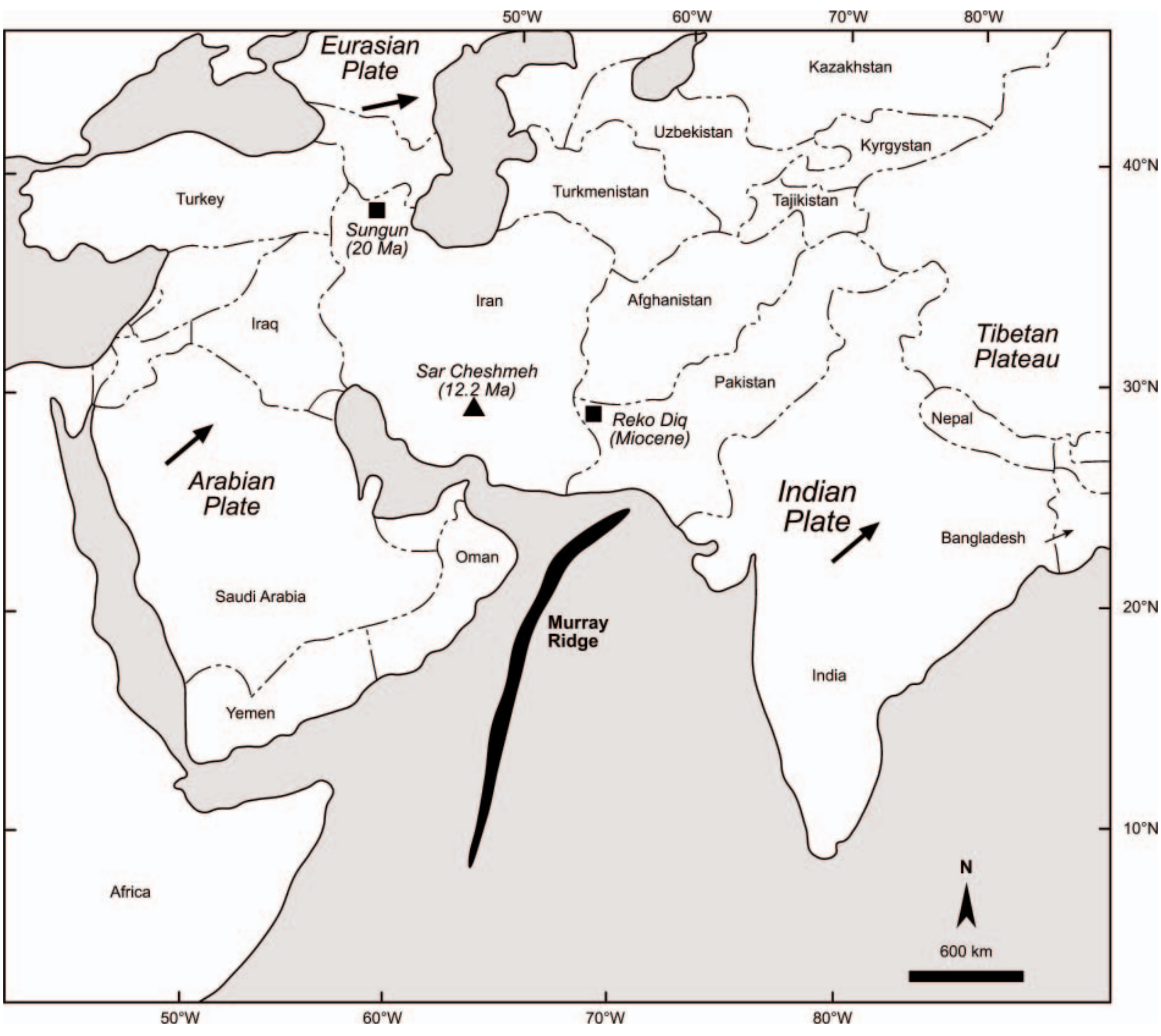

FIG. 12. Tectonic elements of Pakistan, Iran, Afghanistan, and surrounding regions. Also shown are the locations of the Reko Diq and Sar Chesmeh porphyry copper-gold deposits and the Sungun porphyry copper-molybdenum deposit (650 Mt at 0.76% Cu and 0.01% Mo; Kirkham and Dunne, 2000). Bold arrows indicate the direction of relative plate motions. The approximate position of the Murray Ridge has been interpreted from bathymetry images of the National Geophysical Data Centre (http://www.ngdc.noaa.gov/ngdc.html).

seamount chains, or oceanic plateaus was synchronous with ore formation, resulting in crustal thickening, rapid uplift, and exhumation. Of the remaining deposits, the gold-rich Tampakan deposit may be associated with subduction of the Snellius plateau and occurs in a region of the Philippines where adakitic volcanism has occurred (Sajona and Maury, 1998; Gutscher et al., 2000), an association that also occurs in other provinces where ridges have been subducted. For the Iran-Pakistan segment of the Tethyan belt, it is difficult to comment on the plate architecture and geodynamics at the time of ore formation, and a similar problem exists for Frieda River on mainland Papua New Guinea, which formed at 13.6 to 11.5 Ma (Table 2), making it significantly older than the interaction of the Eupirik Rise with the New Guinea trench.

This review has focused on young systems, where the architecture of the downgoing plate can be inferred from seafloor bathymetry. However, similar features can be inferred indirectly in older settings. Murphy (2001) argued that the Laramide orogeny in the southwest United States was associated with flat-slab subduction, because it was characterized by an absence of volcanism, widespread hinterland deformation, and thick-skinned tectonics. He inferred that the flat slab was related to an elongate swell and associated oceanic plateau related to the ancestral Yellowstone hot spot. Six supergiant porphyry copper-molybdenum deposits formed in southwest Arizona and Sonora during the Laramide orogeny (Table 1). Similarly, as discussed above, James and Sacks (1999) argued that southern Peru and northern Chile was the site of flat-slab subduction from 50 to 30 Ma. This period spans the formation of the Eocene to Oligocene porphyry province of northern Chile, the most productive on Earth in terms of copper content (Camus, 2002).

Buoying of the subducting slab by aseismic ridges, seamount chains, and/or oceanic plateaus can provide environments that are favorable for porphyry ore formation. Interaction of these oceanic plate features with subduction zones probably best explain multiple metallogenic cycles of porphyry ore formation in a given region, as typified by the Chilean Andes, where five porphyry metallogenic belts occur in a region where subduction has otherwise continued unabated since the Cretaceous (Sillitoe, 1988; Camus, 2002). In oceanic island arcs, ridge subduction may lead to slab flattening and/or brief episodes of arc reversal. In continental arcs, it appears to lead to protracted episodes of flat subduction (e.g., James and Sacks, 1999).

A number of factors may play a role in the formation of porphyry systems during ridge subduction. Volatiles from the ridge may cause metasomatism of the mantle wedge, possibly accompanied by an increased sulfur flux due to subduction of metalliferous sediments in pressure shadow zones behind highs on the downgoing plate. This may lead to the generation of oxidized melts that can transport copper, gold, and sulfur dioxide from the mantle to the upper crust (e.g., Richards, 2003). Crustal thickening and dehydration also may occur, leading to increased fluid flux (Kay et al., 1999). The associated compressional tectonism, rapid uplift, and exhumation (potentially leading to the superposition of porphyry and epithermal environments) reactivation of basement faults, and a hiatus in volcanism associated with crustal thickening would favor the formation of porphyry copper deposits (Sillitoe, 1998). Although not discussed here, sutures in the overriding plate obviously play vital roles in focusing magmatism and fluid flow (e.g., Richards, 2000, 2003; Gow and Walshe, 2005).

None of these factors are unique to the formation of giant versus small systems. It is the favorable conjunction of many factors, from the crustal to the deposit scale, which appears to result in the formation of the giant deposits. Whereas the total metal endowment may relate to these large-scale processes, the ore grades relate mainly to the hypogene ore-forming processes operating at the trap site. Ore grades are also partly dependent on the structure (permeability architecture) of the district (leaky versus focused hydrothermal fluid-flow regimes), and formation and preservation of supergene enrichment blankets can also be critical to high-grade ore formation. Without efficient mineralizing processes, the most favorable geodynamic processes and crustal architecture may still only produce a giant, low-grade geochemical anomaly.

Scope of this Issue

This issue of *Economic Geology* reports the results of new research into the characteristics and origins of porphyry copper-molybdenum and copper-gold deposits of Chile, Argentina, and Papua New Guinea-Irian Jaya. As we have already shown, the Andean and Papua New Guinea-Irian Jaya fold belts host some of the world's largest and highest grade porphyry deposits and have been subjected to several cycles of mineral endowment during episodes of convergent margin tectonism (e.g., Sillitoe, 1988; Camus, 2002). This review and subsequent papers in the special issue show that the production of major deposits in a terrane is commonly limited to discrete epochs (e.g., Deckart et al., 2005; Hollings et al., 2005; Pollard et al., 2005), implying that fluid production and/or release is episodic and linked to the geodynamic evolution of the terrane. The structural architecture of the province is also critical (e.g., Gow and Walsh, 2005), with reactivation of basement faults a recurring theme in the evolution of porphyry mineral districts.

The productivity of the Andean and Papua New Guinea-Irian Jaya fold belts, in terms of porphyry ore formation, has been a consequence of factors that operated effectively at crustal to mantle and district and deposit scales. Large-scale factors (e.g., geodynamics, lithological, and structural architecture) have constrained total metal endowments by providing effective fluid pathways and controlling the generation, location, nature and size of fluid reservoirs, as well as the timing and manner of release of stored fluids. Hypogene ore grades, in contrast, appear to be controlled mostly by factors that operated at the district and deposit scales. The processes that generated and maintained the physicochemical gradients (temperature, pressure, salinity, acidity, redox, and reduced sulfur) required to form elevated hypogene ore grades remain poorly understood and continue to be debated. Some papers in this special issue investigate processes of mineralization and alteration within individual ore systems (e.g., Cannell et al., 2005; Davidson et al., 2005; Frikken et al., 2005; Harris et al., 2005; Masterman et al., 2005; Prendergast et al., 2005). While most of the available isotopic, fluid, and melt inclusion evidence points toward a preponderance of magmatic-derived fluids in porphyry systems (e.g., Davidson et al., 2005;

Harris et al., 2005), there are data from individual deposits that are not readily explained by a purely orthomagmatic model for ore formation and probably require input of external fluids during the mineralizing processes (e.g., Frikken et al., 2005). Other ongoing controversies regarding porphyry systems that are discussed in this volume include the relative importance of cooling (e.g., Redmond et al., 2004), hydrothermal alteration (e.g., Harris et al., 2005), and fluid mixing (e.g., Frikken et al., 2005) for deposition of high-grade ore in porphyry systems, the relative importance of ridge subduction and flat subduction in the formation of giant porphyry deposits (e.g., Deckart et al., 2005; Hollings et al., 2005), the nature and origin of copper mineralization at the largest of the Andean deposits, El Teniente (e.g., Skewes et al., 2002; Cannell et al., 2005), the duration and timing of magmatic-hydrothermal activity (e.g., Río Blanco-Los Bronces: Deckart et al., 2005; Frikken et al., 2005; El Teniente: Maksaev et al., 2004; Cannell et al., 2005), and the relative importance of strike-slip, compressional and extensional tectonism during the formation of the Eocene-Oligocene porphyry belt of northern Chile (Masterman et al., 2005). Overall, the aim of the special issue is to help explorers and researchers better understand how and where processes of ore formation have combined effectively to produce some of the world's largest high-grade hypogene porphyry copper and gold resources.

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