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DISCUSSION

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Discussion on "Giant versus small porphyry copper deposits of Cenozoic age in northern Chile: adakitic versus normal calc-alkaline magmatism" by Oyarzun et al. (*Mineralium Deposita* 36:794–798, 2001)

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In a recent thought-provoking article, Oyarzun et al. (2001) argue that Late Eocene-Early Oligocene fast, oblique convergence between the South America and Nazca-Farallon plates led to flat subduction and direct melting of the subducting plate. The result of this process was the formation of adakite magmas which generated giant porphyry copper deposits related to the Late Eocene-Early Oligocene structural belt of northern Chile, known as the West Fissure fault system.

Unfortunately, no additional information was presented by Oyarzun and co-workers to distinguish whether this adakitic signature, or TTG-type magmatism as described by Cornejo and Matthews (2000) at the El Salvador deposit, reflects melting of the base of an overthickened crust, high-pressure crystallization of mantle-derived hydrous magmas, or slab melting followed by crustal contamination during ascent through the Andean crust. Furthermore, current contrasting views on flat-slab subduction settings introduce additional uncertainties to the model proposed by Oyarzun and co-workers.

Recently published, high-precision $^{40}Ar/^{39}Ar$ dating (Ballard et al. 2001; Richards et al. 1999, 2001), in conjunction with previous age information (Maksaev et al. 1988; Cornejo et al. 1997; Dilles et al. 1997; Marsh et al. 1997; Clark et al. 1998) on giant porphyry copper deposits from the Paleogene of northern Chile, allows to constrain the age of formation of copper ores and associated magmas between ~42 and 33 Ma. This fact poses a strict timing constraint to the petrotectonic processes responsible for their genesis.

Causes of the Late Eocene-Oligocene flat-slab subduction in the central Andes

It has long been clear that the subducting Nazca-Farallon plate is close to neutral buoyancy beneath the Andes and probably has been so for the past 50 million years (James and Sacks 1999, and references therein). Under the convergence rates and buoyancy conditions of the Nazca-Farallon plate, subduction of an aseismic ridge (overthickened oceanic crust) is sufficient to produce flat-slab subduction (James and Sacks 1999; Gutscher et al. 2000b; Yañez et al. 2001). Modern examples of this tectonic process include the subduction of the Nazca and Juan Fernández ridges beneath Peru and central Chile, respectively (Gutscher et al. 2000b). Based on this view and in order to explain the volcanic null in southern Peru (Late Eocene) and northern Chile (Oligocene), James and Sacks (1999) proposed that a period of flat subduction for the northern Chilean region (limited to at least 24°S) extends from 35 to ~27 Ma, following a relatively rapid transition from normal subduction between ~38 to 35 Ma.

Oyarzun et al. (2001) consider the flat-slab subduction as a result of the coupled effect of oblique and fast convergence. Nevertheless, according to plate-motion reconstruction models of the Nazca-Farallon plate (e.g., Pardo-Casas and Molnar 1987; Somoza 1998), a relatively slow subduction rate (5–6 cm/year) and only a moderately oblique convergence (~60° mean azimuth) predominated during most of the critical period of magmatism and copper mineralization (~42 to 33 Ma). High subduction rates in the range of 8–10 cm/year were achieved only after ~27–28 Ma (Pardo-Casas and Molnar 1987; Somoza 1998), 6 to 7 million years later than the formation of the youngest giant porphyries. This widely known, strong acceleration of convergence during the Late Oligocene has been recognized as the beginning of the formation of the modern central Andes (Somoza 1998; James and Sacks 1999, and references therein).

Therefore, no indications of unusual kinematic conditions (convergence velocities or directions) which could have led to flat subduction are obvious in the subducting Nazca-Farallon plate during the main period of formation of giant copper deposits in northern Chile. The change to flat-slab subduction in this region during the Oligocene seems to be more related to plate structure and composition (overthickening by younger aseismic ridges), as proposed by James and Sacks (1999), rather than to kinematic factors (oblique and fast subduction) as proposed by Oyarzun et al. (2001). This further implies that only the last 2 million years of the porphyry copper mineralizing event (42–33 Ma) of northern Chile were in fact under a regime of flat-slab subduction (35–27 Ma).

Flat subduction, slab melting and mineralization

Recently, several studies have emphasized the important implications which episodic flat subduction has on mineralization and associated magmatism in the Andes (James and Sacks 1999; Kay et al. 1999, and references therein). The hypothesis by Oyarzun et al. (2001), however, goes one step further, suggesting that slab

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flattening led to slab melting and subsequently to adakitic magmatism and mineralization.

Adakitic magmas are uncommon and their genesis is generally linked to unusual conditions in the subducting plate, including not only slab age (young/hot) but also its kinematics and geometry (Defant and Kepezhinskas 2001; Yogodzinski et al. 2001). Current geophysical, tectonic and petrologic evidence from the Aleutian-Kamchatka area supports the idea that relatively old (~50 Ma) oceanic crust can melt in arc systems. Here, however, an unusual tectonic environment involving a combination of highly oblique (e.g., near-parallel to the arc), fast (e.g., 8–10 cm/year) subduction and slab tearing are the causes of melting of the old slab (Yogodzinski et al. 1995; Defant and Kepezhinskas 2001; Yogodzinski et al. 2001). Flat-slab subduction settings (e.g., Ecuador) have also been linked to adakitic magmatism (Defant and Kepezhinskas 2001) but, once again, the geodynamic context in which these adakites occur is rather special. Beneath the Ecuadorian Andes, a complex combination of ridge collision and subduction of a major tear zone separating two distinct segments of oceanic crust is taking place (Monzier et al. 1999), implying that more than only a flat-subduction geometry is necessary to account for this adakitic magmatism. In addition, melting along the edge of a torn plate is possible in all cases of ridge subduction and slab-window formation (Yogodzinski et al. 2001). None of these complex tectonic conditions have yet been recognized in northern Chile for the critical 42- to 33-Ma time span.

In the model of Oyarzun et al. (2001), the slab melts are accounted for based on a recent thermal model of buoyant, overthickened oceanic crust subduction (Gutscher et al. 2000a). Essentially, this thermal model suggests that, in a flat-slab subduction setting, the slab is prone to be heated enough to melt during horizontal motion, and predicts melting of oceanic crust up to ~50 Ma old. However, this view of Andean arc magmatism is a significant departure from previous geophysical models (e.g., James and Sacks 1999).

As noted in James and Sacks (1999), many seismic studies of Cenozoic flat-slab subduction in the central Andes have confirmed the absence of a low-Q (velocity) wedge of asthenospheric material between the oceanic crust and overlying continental lithosphere. Moreover, abnormally low heat flow in these environments constitutes one of the most remarkable and anomalous characteristics of flat subduction zones. James and Sacks (1999) also suggest that this thermal anomaly can be achieved only through fluid flux involving the whole of the continental lithosphere. In their model, this advective cooling is driven by fluids generated by dewatering of the slab during flat subduction. In turn, this lithospheric-scale hydration has a profound implication for Andean tectonism (see James and Sacks 1999). In addition to the expected cooling by retraction of the hot asthenospheric wedge during slab flattening, the above geophysical view clearly suggests an additional cooling of the whole mantle wedge via fluid flux (advection) from slab dehydration. In this "cooling" model there is not much leeway for a hot asthenospheric "tongue" leading to slab melting, as proposed by Gutscher's thermal model.

The discrepancies between the two models underscore the need of improving our understanding of flat-subduction dynamics and the physical conditions of the slab and mantle wedge beneath arcs in order to successfully model magmatism and metallogenesis in these particular tectonic settings.

The application of Gutscher's thermal model to explain the formation of giant porphyry copper deposits in northern Chile has additional limitations. Due to the transient character of the melting event (Gutscher et al. 2000a), this event may not last more than ~2 millon years below a specific area (for a 6 cm/year subduction rate and >25-Ma-old oceanic crust). Consequently, the model can not account for the genesis of magmas associated with deposits located in the same area having age differences greater than ~2 Ma, for example, El Salvador (~41–42 Ma) and Potrerillos (~36 Ma; Marsh et al. 1997). Furthermore, porphyries older than ~35 Ma formed during the transition from normal to flat-slab subduction (~38–35 Ma; James and Sacks 1999), may not be satisfactorily explained by the slab-melting model. According to the flat-slab melting model, during the early magmatic stage a broad adakitic arc approximately 100 km wide is formed (Gutscher et al. 2000a). This is in sharp contrast with the narrow Late Eocene-Early Oligocene belt of northern Chile.

Finally, scarce yet important Os isotopic data of some giant porphyry copper deposits of northern Chile yield no support for a slab-melting origin for the magmas associated with these deposits. Osmium isotopic studies provide a useful avenue to monitor the process of oceanic crustal recycling, because Re/Os ratios in the oceanic lithosphere are up to several orders of magnitude higher than those in mantle peridotite, and both Re and Os display chalcophile and siderophile behavior (Brandon et al. 1996, and references therein). Mathur et al. (2000) found no evidence of radiogenic Os involved in the earliest mineralizing event at the giant Chuquicamata deposit (~35 Ma; Ballard et al. 2001). In addition, these authors suggest that the low initial $^{187}Os/^{188}Os$ ratios (~0.15) in the Chuquicamata deposit are nevertheless more radiogenic than those expected for the mantle beneath continental arcs, indicating that the crust – probably the lower crust – contributes Os to the magmatic processes which generate these giant porphyry copper deposits. Furthermore, these authors noticed that, in Chilean porphyry copper deposits, the lower the initial $^{187}Os/^{188}Os$ ratio in sulfides, the higher the total metal content of the deposits.

Alternatives to slab melting

The adakitic signature in the giant porphyry copper deposits of northern Chile merits additional considerations. As argued by Kay and Mpodozis (2002), the chemical definition of adakite by Drummond and Defant (1990) allows essentially any andesitic to dacitic magma equilibrated with an eclogitic mineral residue (e.g., garnet-bearing, plagioclase-poor) to be classified as an adakite, whether garnet is (1) in the downgoing slab (e.g., Kay et al. 1987), (2) in a magmatically or tectonically thickened continental crust, either as a cumulate or as a restite (Hildreth and Moorbath 1988; Atherton and Petford 1993; Ducea 2001), or (3) in a crust mechanically removed from beneath the arc or fore-arc (Stern and Skewes 1995). For instance, all of the Neogene Chilean lavas with adakitic character associated with flat-slab subduction are interpreted as having source components from a thickened lower crust or from fore-arc crust recycled into the mantle as a result of fore-arc tectonic erosion (Kay and Mpodozis 2002). Similarly, the adakitic components in active Ecuadorian volcanoes associated with flat-slab subduction are also alternatively interpreted as being derived by partial melting of garnet-bearing basement rocks (Arculus et al. 1999). The adakitic signature of the syntectonic plutons associated with the El Salvador deposit is likewise explained by invoking crustal processes (e.g., eclogitization of Andean lower crust; Cornejo and Matthews 2000).

Using published chemical data from igneous complexes associated with porphyry copper deposits (e.g., Sierrita, Bagdad, Copper Basin, Safford, Ray, and Christmas) and barren intrusives formed in the back-arc interior zone of the Laramide orogen in the southwestern USA, it is also possible to recognize an adakitic signature in the mineralized porphyries (see Sr/Y vs. Y diagram; Fig. 1). However, it must be emphasized in this case that chemical and isotopic results clearly preclude any petrogenetic model of slab melting. These porphyries are better explained by having their principal, but not necessarily exclusive, source in the lower crust in which anatexis and assimilation of amphibolitic rocks took place (Anthony and Titley 1988; Lang and Titley 1992, 1998).

Concluding statement

The adakitic fingerprint of numerous magmatic complexes associated with porphyry copper deposits, including those from northern Chile, appears to be the result of the involvement of high-pressure, mafic crustal reworking processes. For many of them, the

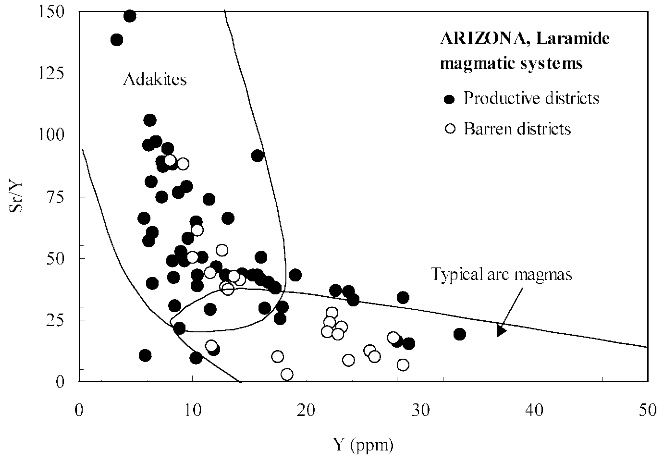

Fig. 1 Sr/Y vs. Y diagram of igneous complexes associated with porphyry copper deposits (*closed dots*) and barren intrusives (*open dots*) formed in the back-arc interior zone of the Laramide orogen in the southwestern USA (data from Anthony and Titley 1988, and Lang and Titley 1998). For the Sierrita deposit, Yb/10 was used instead of Y

question remains as to whether the mafic crustal component is either lower continental crust, as in some porphyries from the southwestern USA (Anthony and Titley 1988; Lang and Titley 1992, 1998), or oceanic crust, as may be the case for some Philippine copper deposits (Thiéblemont et al. 1997; Sajona and Maury 1998; see also Castillo et al. 1999). Regardless of the type of mafic crust involved, its reworking under high-pressure conditions seems to be an important and widespread process linked to copper metallogenesis in island arcs and continental regions (Rabbia and Hernández 2000).

In conclusion, given the current level of understanding of flat-slab tectonics as well as the lack of systematic chemical and (Nd–Sr–Pb–Os) isotopic studies in many of the Paleogene deposits of the northern Chilean porphyry copper belt, it is premature to assign any particular source (e.g., slab or lower continental crust) as unique to all the magmas related to the copper deposits in this belt.

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References

Anthony EY, Titley SR (1988) Progressive mixing of isotopic reservoirs during magma genesis at the Sierrita porphyry copper deposit, Arizona: inverse solutions. Geochim Cosmochim Acta 52:2235–2249

Arculus RJ, Lapierre H, Jaillard É (1999) Geochemical window into subduction and accretion processes: Raspas metamorphic complex, Ecuador. Geology 27:547–550

Atherton M, Petford N (1993) Generation of sodium-rich magmas from newly underplated basaltic crust. Nature 362:144–146

Ballard JR, Palin JM, Williams IS, Chambell IH, Faunes A (2001) Two ages of porphyry intrusion resolved for the super-giant Chuquicamata copper deposit of northern Chile by ELA-ICP-MS and SHRIMP. Geology 29:383–386

Brandon A, Creaser R, Shirey S, Carlson R (1996) Osmium recycling in subduction zones. Science 272:861–864

Castillo P, Janney P, Solidum R (1999) Petrology and geochemistry of Camiguin Island, southern Philippines: insights to the source of adakites and other lavas in a complex arc setting. Contrib Mineral Petrol 134:33–51

Clark AH, Archibald DA, Lee AW, Farrar E, Hodgson CJ (1998) Laser probe $^{40}Ar/^{39}Ar$ ages of early- and late-stage alteration assemblages, Rosario porphyry copper-molybdenum deposit, Collahuasi district, I Region, Chile. Econ Geol 93:326–337

Cornejo P, Matthews SJ (2000) Relación entre magmatismo-tectónica y su implicancia en la formación de sistemas de pórfidos cupríferos: yacimiento El Salvador, III Región, Chile. In: Abstr Vol 9th Congr Geológico Chileno, Puerto Varas, 31 July–4 August 2000. Vol 1, pp 184–188

Cornejo P, Tosdal RM, Mpodozis C, Tomlinson AJ, Rivera O, Fanning CM (1997) El Salvador, Chile porphyry copper deposit revisited: Geologic and geochronologic framework. Int Geol Rev 39:22–54

Defant MJ, Kepezhinskas P (2001) Evidence suggests slab melting in arc magmas. EOS, Trans Am Geophys Union 82:65–69

Dilles JH, Tomlinson AJ, Martin MW, Blanco N (1997) El Abra and Fortuna complexes: a porphyry copper batholith sinistrally displaced by the Falla Oeste. In: Abstr Vol 8th Congr Geológico Chileno, Antofagasta, 13–17 October 1997. Vol 3, pp 1883–1887

Drummond M, Defant M (1990) A model for trondhjemite-tonalite-dacite genesis and crustal growth via slab melting: Archean to modern comparisons. J Geophys Res 95:21503–21521

Ducea M (2001) The California arc: thick granitic batholiths, eclogitic residues, lithospheric-scale thrusting, and magmatic flare-ups. GSA Today:4–10

Gutscher MY, Maury R, Eissen JP, Bourdon E (2000a) Can slab melting be caused by flat subduction? Geology 28:535–538

Gutscher MY, Spakman W, Bijwaard H, Engdahl RE (2000b) Geodynamics of flat subduction: seismicity and tomographic constraints from the Andes margin. Tectonics 19:814–833

Hildreth W, Moorbath S (1988) Crustal contributions to arc magmatism in the Andes of Central Chile. Contrib Mineral Petrol 98:455–489

James D, Sacks S (1999) Cenozoic formation of the central Andes: a geophysical perspective. In: Skinner B (ed) Geology and ore deposits of the central Andes. Soc Econ Geol Spec Publ 7:1–26

Kay SM, Mpodozis C (2002) Magmatism as a probe to the Neogene shallowing of the Nazca plate beneath the modern Chilean flatslab. J S Am Earth Sci (in press)

Kay SM, Maksaev V, Mpodozis C, Moscoso R, Nasi C (1987) Probing the evolving Andean lithosphere: middle to late Tertiary magmatic rocks in Chile over the modern zone of subhorizontal subduction (29–31.5°S). J Geophys Res 92:6173–6189

Kay SM, Mpodozis C, Coira B (1999) Magmatism, tectonism and mineral deposits of the central Andes (22°–33°S latitude). In: Skinner B (ed) Geology and ore deposits of the central Andes. Soc Econ Geol Spec Publ 7:27–59

Lang JR, Titley SR (1992) The influence of processes operating in the lower crust upon igneous-associated metallogenesis. In: AGU Spring Meet. EOS, Trans Am Geophys Union 73: 353

Lang JR, Titley SR (1998) Isotopic and geochemical characteristics of Laramide magmatic systems in Arizona and implications for the genesis of porphyry copper deposits. Econ Geol 93:138–170

Maksaev V, Zentilli M, Reynolds PH (1988) Geocronología $^{40}Ar/^{39}Ar$ de depósitos de tipo pórfido cuprífero del Norte Grande de Chile. In: Abstr Vol 5th Congr Geológico Chileno, Santiago, 8–12 August 1988. Vol 1, pp 109–133

Marsh TM, Einaudi MT, McWilliams M (1997) $^{40}Ar/^{39}Ar$ geochronology of Cu-Au and Au-Ag mineralization in the Potrerillos district, Chile. Econ Geol 92:784–806

Mathur R, Ruiz J, Munizaga F (2000) Relationship between copper tonnage of Chilean base-metal porphyry deposits and Os isotope ratios. Geology 28:555–558

Monzier M, Robin C, Samaniego P, Hall MH, Cotten J, Mothes P, Arnaud N (1999) Sangay volcano, Ecuador: structural

development, present activity and petrology. J Volcanol Geotherm Res 90:49–79
Oyarzun R, Márquez A, Lillo J, López I, Rivera S (2001) Giant versus small porphyry copper deposits of Cenozoic age in northern Chile: adakitic versus normal calc-alkaline magmatism. Miner Deposita 36:794–798
Pardo-Casas F, Molnar P (1987) Relative motion of the Nazca (Farallon) and South American plates since Late Cretaceous time. Tectonics 6:233–248
Rabbia OM, Hernández LB (2000) Quartz diorite trend in porphyry copper deposits: underlying petrological processes and implications in copper metallogenesis. Mineral Metal 6:416–423
Richards JP, Noble SR, Pringle MS (1999) A revised Late Eocene age for porphyry Cu magmatism in the Escondida area, northern Chile. Econ Geol 94:1231–1248
Richards JP, Boyce AJ, Pringle MS (2001) Geologic evolution of the Escondida area, northern Chile: a model for spatial and temporal localization of porphyry Cu mineralization. Econ Geol 96:271–305
Sajona F, Maury R (1998) Association of adakites with gold and copper mineralization in the Philippines. C R Acad Sci Paris, Earth Planet Sci 326:27–34
Somoza R (1998) Updated Nazca (Farallon)-South America relative motions during the last 40 My: implications for mountain building in the central Andean region. J South Am Earth Sci 11:211–215
Stern C, Skewes MA (1995) Miocene to present magmatic evolution at the northern end of the Andean Southern Volcanic Zone. Revista Geol Chile 22:261–272
Thiéblemont D, Stein G, Lescuyer J-L (1997) Epithermal and porphyry deposits: the adakite connection. C R Acad Sci Paris, Earth Planet Sci 325:103–109
Yáñez GA, Ranero CR, von Huene R, Díaz J (2001) Magnetic anomaly interpretation across the southern central Andes (32°–34°S): the role of the Juan Fernandez Ridge in the late Tertiary evolution of the margin. J Geophys Res 106:6325–6345
Yogodzinski GM, Kay RW, Volynets ON, Koloskov AV, Kay SM (1995) Magnesian andesite in the western Aleutian Komandorsky region: implications for slab melting and processes in the mantle wedge. GSA Bull 107:505–519
Yogodzinski GM, Lees JM, Churikovas TG, Dorendorf F, Woerner G, Volynets ON (2001) Geochemical evidence for the melting of subducting oceanic lithosphere at plate edges. Nature 409:500–504