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U-Pb Zircon Geochronology of Granitic Rocks from the Chuquicamata-El Abra Porphyry Copper Belt of Northern Chile: Excimer Laser Ablation ICP-MS Analysis*

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Abstract

This study reports the results of a comprehensive geochronological study of Tertiary plutonic rocks in the Chuquicamata-El Abra porphyry copper belt of northern Chile. Zircon U-Pb isotope ages of 22 intrusions from the composite Los Picos-Fortuna-Pajonal-El Abra igneous complex, Radomiro Tomic mine, and Opaque prospect were determined by excimer laser ablation-inductively coupled plasma-mass spectrometry (ELA-ICP-MS). The dated samples from the Pajonal-El Abra complex show a continuous age range from 42.7 to 37.2 Ma, indicating that the intrusions were emplaced over a period of at least 5.5 m.y. Only the youngest of these, the El Abra mine porphyry, is ore bearing. The five units that were dated from the Los Picos-Fortuna complex range in age from 42.3 to 38.0 Ma and none host significant economic mineralization. An increase in the abundance of inherited zircons with decreasing age in the intrusive rocks is interpreted to indicate that magmatic activity in the source region of the Los Picos-Fortuna-Pajonal-El Abra igneous complex increased steadily from about 55 Ma.

The five dated units from the Los Picos-Fortuna igneous complex have the same age, within analytical uncertainty, as petrologically equivalent units in the Pajonal-El Abra complex to the north, supporting the correlation suggested by previous workers. Because these complexes are now on opposite sides of the West fissure and separated by 35 km, the correlation constrains the net sinistral displacement on the fault subsequent to ca. 33 Ma.

Ore-bearing porphyries at Chuquicamata, El Abra, Radomiro Tomic, and Opaque span an age range of almost 5 m.y. from 37.9 to 33.3 Ma. The ore-bearing intrusions of the Chuquicamata Igneous Complex are 3.5 m.y. younger than the youngest intrusions of the Los Picos-Fortuna-Pajonal-El Abra igneous complex, which makes it unlikely that they are genetically related. The Opaque porphyry, on the other hand, which is on the same side of the West fissure as the Los Picos-Fortuna complex and has the same age as the El Abra mine porphyry, could have formed during the final stages of crystallization of that complex.

Introduction

THE CHUQUICAMATA-EL ABRA belt in northern Chile hosts some of the largest porphyry copper deposits in the world. It is part of a more extensive north- to south-trending corridor of porphyry copper deposits of Eocene-Oligocene age that

includes Collahuasi, Escondida, and Potrerillos (Sillitoe, 1992). Despite its economic importance there has been no comprehensive geochronologic study of the igneous rocks associated with the porphyry copper deposits. This paper presents crystallization ages for 22 samples from the Chuquicamata-El Abra belt that were determined by excimer laser ablation inductively coupled plasma mass spectrometry (ELA-ICP-MS) analysis of U-Th-Pb isotopes in zircon. The U-Pb system in zircon is a robust method for accurately assessing the

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crystallization ages of igneous rocks affected by extreme hydrothermal alteration or slow cooling because of the chemical resistance of zircon and the high closure temperature of Pb diffusion in zircon (Lee et al., 1997; Cherniak and Watson, 2000). Furthermore, because inheritance has been observed in conventional analyses of zircons from intrusions in the Chuquicamata-El Abra belt (Zentilli et al., 1994), *in situ* analysis of the type provided by ELA-ICP-MS is essential.

Sillitoe (1973), in his study of the Chuquicamata mine, suggested that the West fissure may have upthrown the mineralized Chuquicamata porphyries on the eastern side of the fault relative to their uneconomic Los Picos-Fortuna complex root zone to the west of the fault. An alternative hypothesis was suggested by R. C. Baker in ca. 1969 (see Dilles et al., 1997) who argued that the West fissure may be responsible for ca. 35 km net sinistral strike-slip displacement between the Los Picos-Fortuna complex in the south and petrologically similar Pajonal-El Abra complex in the north (Dilles et al., 1997; Tomlinson and Blanco, 1997a, b). If the latter hypothesis is correct, the Pajonal-El Abra complex and associated porphyry copper mineralization could have originally formed as part of the Los Picos-Fortuna complex and subsequently been displaced ca. 35 km north on the West fissure. A correlation between the Los Picos-Fortuna complex and the Pajonal-El Abra complex would support the strike-slip hypothesis, whereas a correlation between Los Picos-Fortuna and the Chuquicamata porphyries would validate Sillitoe's (1973) hypothesis. In either case, the Los Picos-Fortuna complex would represent the eroded roots of a productive ore system. Alternatively, if Los Picos-Fortuna does not correlate with either of the ore-bearing complexes, it may be a barren igneous suite that is unrelated to ore. Having established the area's igneous chronology, the timing relationships can then help to evaluate whether productive porphyries developed at a specific point in time or whether they spanned an extended age range and were controlled by other factors.

Geologic Setting

The Chuquicamata, El Abra, and Fortuna intrusive complexes are located in the Antofagasta region of northern Chile, approximately 250 km northeast of the city of Antofagasta. These complexes are hosted within the Domeyko Cordillera (Fig. 1), one of the three mountain ranges recognized in north Chile. The geologic history of the Chuquicamata-El Abra area presented here is a summary of previous field mapping and reports by Boric et al. (1990), Maksaev et al. (1994), Tomlinson et al. (1995), Maksaev and Tomlinson (1995), and Ossandón et al. (2001). The oldest exposed rocks in the Chuquicamata-El Abra area are Precambrian to lower Paleozoic in age and have been variably deformed and metamorphosed to produce schists, gneisses, and migmatites. Intrusive and extrusive igneous rocks were emplaced throughout the late Carboniferous to Middle Triassic. These were then followed by the deposition of Upper Triassic to Jurassic marine sediments with minor volcanic intercalations. The Lower Cretaceous was marked by volcanic activity and some sedimentation, whereas in the Upper Cretaceous extensive continental sedimentary sequences were deposited. Significant magmatism followed during the Eocene and Oligocene. The Tertiary igneous complexes include plutons of dioritic to

FIG. 1. Sketch map of the Chuquicamata-El Abra porphyry copper belt in northern Chile (modified from Maksaev and Tomlinson, 1995; Tomlinson et al., 1995; Pardo, 1998; Reynolds et al., 1998), showing the approximate outline of the Los Picos-Fortuna complex, the Pajonal-El Abra complex, the Chuquicamata intrusive complex, and the locations of igneous rock samples used for zircon dating. Open symbols indicate barren units and closed symbols intrusions that are associated with porphyry copper mineralization. CIC = Chuquicamata intrusive complex.

granitic composition that now crop out over a significant portion of the area. At the Chuquicamata, Radomiro Tomic, El Abra, and Opache mines, and prospects, and probably the Mansa Mina mine, Eocene and Oligocene porphyritic intrusions are associated with porphyry copper mineralization (Sillitoe et al., 1996; Cuadra et al., 1997; Ossandón and Zentilli, 1997; Pardo and Rivera, 1999; Ossandón et al., 2001). Miocene to Holocene cover sequences that consist of alluvial, colluvial, and aeolian sediments, as well as some volcanic flows, were deposited after emplacement, uplift, and erosion of the porphyries.

Since the Jurassic, regional contraction associated with subduction of the Phoenix, Farallon and then Nazca plates along the western margin of South America (Duncan and Hargraves, 1984) has been responsible for deformation in the Chuquicamata-El Abra area. Variation in the stress field with time has led to extensional, thrust, and strike-slip faulting as well as widespread folding. The West fissure zone, which is part of the north-south Domeyko fault system that extends for over 2,000 km, is a product of this deformation (Lindsay et al., 1995; Reutter et al., 1996; Dilles et al., 1997; McInnes et al., 1999). In the Chuquicamata pit, the West fissure separates ore-bearing Chuquicamata mine porphyries in the east from the unproductive Fortuna complex in the west.

The Chuquicamata deposit (Fig. 2) lies at the southern end of the 14- by 2-km north-trending Chuquicamata Igneous Complex (Tomlinson et al., 1995; Makshev and Tomlinson, 1995; Pardo and Rivera, 1999). This late Eocene-Oligocene igneous complex (Makshev and Zentilli, 1988; Zentilli et al., 1994; Ossandón et al., 2001) consists of three recognizable porphyritic units in the mine, distinguished by varying texture and phenocryst mineralogy. These units are (1) the granodioritic to monzogranitic East porphyry, with medium to coarse phenocrysts in scarce groundmass; (2) the monzogranitic to granodioritic West porphyry, containing phenocrysts set in a saccaroidal groundmass; and (3) the monzodioritic Bench porphyry, with a bimodal distribution of phenocryst sizes set in an aphanitic groundmass. Volumetrically, the East porphyry dominates the Chuquicamata Igneous Complex. West porphyry crops out in the north of the pit, but its boundaries have not been clearly delimited. Bench porphyry crops out

along the eastern flank of the mine as a series of north-trending dike-like bodies offset by faults. East of the CIC, but within the mine, a poorly-defined contact is observed between the barren Tertiary Elena Granodiorite (Lindsay et al., 1995) and mid-Triassic East Granodiorite (Makshev et al., 1994).

The Radomiro Tomic deposit is located about 7 km north of the Chuquicamata pit within the Chuquicamata Igneous Complex. Here, the ore-bearing porphyries are associated with Tertiary calc-alkaline igneous rocks that have intruded Permian granitoids, Mesozoic volcanic and sedimentary rocks (Cuadra et al., 1997). Dextral strike-slip deformation, linked to the West fissure zone and associated local structures, is likely to have controlled the orientation of copper mineralization within the pit (Cuadra et al., 1997). Evidence from recent core logging suggests that the Chuquicamata Igneous Complex in the Radomiro Tomic pit consists of two principal intrusive porphyries, a major (ca. 95 vol %) and a minor (<5 vol %) facies (V. Romo, 2000, pers. commun.). Texturally, the major facies porphyry shares features of the both the East and West Chuquicamata porphyries, whereas the minor facies is generally finer grained with a darker color index. Mid-Miocene alluvial gravels, which locally reach a thickness of 200 m, cover the deposit (Cuadra et al., 1997).

The Opache deposit is a porphyry copper system located due west of the town of Calama, about 6 km west of the West fissure and approximately 20 km south-southwest of Chuquicamata. Preliminary work suggests that Opache consists of a series of hypabyssal dacite and tonalite porphyries intruding andesite volcanic units, which are in turn cut by hydrothermal breccias (S. Williams, unpub. report for Corporación del cobre de Chile, 1997). The basement in this part of the district is thought to consist of Paleozoic to Cretaceous metamorphic rocks, an observation which is supported by the presence of clasts of Paleozoic to Cretaceous rocks found in some hydrothermal breccia samples (S. Williams, 1997). A significant thickness of limestone overburden covers the Opache prospect, which can reach a thickness of over 200 m (Pardo and Rivera, 1999).

Immediately west of the Chuquicamata mine, Eocene intrusive rocks crop out but none host economic mineralization. From oldest to youngest, these lithologic units consist of Los Picos quartz monzodiorite (Dilles et al., 1997), Fortuna Antena (Gris) granodiorite, Fortuna Fiesta (Clara) hornblende granodiorite, and the San Lorenzo rhyodacitic porphyries (alternative terminology, used by CODELCO workers, is given in brackets). Collectively, the latter three units, Antena, Fiesta, and the San Lorenzo, together with minor leucocratic intrusions, are termed the Fortuna complex (Rosas, 1999). The Los Picos quartz monzodiorite crops out as a north-south belt along the western extremities of the Fortuna complex and as isolated roof pendants within the Fortuna complex. Los Picos is thought to consist of multiple plutons, evidenced by monzonitic bodies intruding diorites (Rosas, 1999). Overall, the Fortuna complex intrudes Los Picos along its eastern and northern margins, forming a continuous linear outcrop approximately 20 km (north-south) by 5 km (east-west). Generally, it is thought to young eastward from Antena to Fiesta (Rosas, 1999).

Forty-five kilometers north of the Chuquicamata mine and 2 km east of the West fissure, the El Abra complex intrudes

FIG. 2. Sketch map of the Chuquicamata mine and surrounding area (modified from Chong and Pardo, 1994), showing the locations of samples dated in this study. The sample numbers correspond to the following units: Los Picos (1–3), Fortuna Antena (Gris) (4), Fortuna Fiesta (Clara) (5–6), San Lorenzo porphyry (7), leucocratic intrusions (8–10), Opache mine porphyry (11), Radomiro Tomic major facies porphyry (12), and Radomiro Tomic minor facies porphyry (13). The locations of the West, Bench, and East porphyries are given by Ballard et al. (2001). The Montecristo intrusive sample is located west of this map at 480708 E, 7535180 N (see Fig. 1). Sample 3 is a roof pendant of Los Picos in Fortuna that is too small to show on the scale of the map.

upper Carboniferous to Middle Triassic plutonic and volcanic rocks as well as Cretaceous continental sediments (Boric et al., 1990; Makshev and Tomlinson, 1995; Tomlinson et al., 1995). The northern section of the El Abra intrusive rocks are defined by a sharp contact with older Pajonal diorite (Dilles et al., 1997). The principal units in the El Abra complex are the El Abra granodiorite, which in the mine is subdivided into Dark, Central, and Equis, the South granodiorite, and the El Abra porphyry (Graichen et al., 1995). The El Abra granodiorites and porphyries host the bulk of the ore at El Abra (Ambrus, 1977; Makshev et al., 1994).

Together, the four productive systems in the Chuquicamata-El Abra belt examined in this study host a significant copper resource. Chuquicamata is historically the world's largest copper producer. In 1997 its original resource was estimated to be nearly 8.5 Gt at 0.79 wt percent copper, of which over 2 Gt at 1.54 percent Cu has been mined (Ossandón and Zentilli, 1997). In June 1995, El Abra had a mineable reserve of 0.77 Gt of leachable copper oxide at 0.55 percent Cu, supplemented by 0.45 Gt of copper sulfide at 0.64 percent Cu (Dean et al., 1996). In addition, Radomiro Tomic is also a significant copper producer with estimated reserves of 2.3 Gt at 0.59 percent Cu (Ossandón and Zentilli, 1997). Finally, Opathe, an important new discovery, has an estimated resource in the order of 0.3 Gt at an average grade of 0.6 percent Cu (Pardo and Rivera, 1999).

Methods

The zircons analyzed in this study were separated, using standard heavy liquid and magnetic procedures, from 2-kg samples collected from drill cores or outcrop (Figs. 2, 3). Details of sample locations are given in Table 1. The zircon grains from the least magnetic fraction were mounted in epoxy and polished to expose their interiors. All zircons were examined using a combination of cathodoluminescence and optical

FIG. 3. Sketch map of the El Abra area, showing the location of samples analyzed for U-Th-Pb geochronology (modified from Tomlinson et al., 1995, and Graichen et al., 1995). The sample numbers correspond to the following units: Pajonal diorite (1); Dark diorite (2); Central diorite (3); South granodiorite (4), and El Abra mine porphyry (5).

microscopy prior to analysis. The areas selected for analyses were free of visible inclusions and, with some exceptions, free

TABLE 1. Location of Samples Dated in this Study

Sample no.	Unit	Drill hole	Depth	East	North	Elevation
98-521	Los Picos quartz monzodiorite			500337	7536098	
98-525	Los Picos quartz monzodiorite			501231	7534345	
98-530	San Lorenzo Porphyry			505509	7537767	
98-533	Los Picos quartz monzodiorite			504992	7530629	
98-535	Fortuna Fiesta			504180	7527834	
98-565	Fortuna leucocratic intrusion			509955	7541636	
98-555	Fortuna leucocratic intrusion			507111	7538417	
98-569	Fortuna leucocratic intrusion			507490	7541783	
98-570	Fortuna Fiesta			508504	7538370	
98-576	Fortuna Antena			508826	7537406	
98-603	Chuquicamata bench porphyry	DD2532	90	3496	5000	2506
98-609	Chuquicamata west porphyry	DD2712	168	3646	5800	2712
98-610	Chuquicamata east porphyry	DD5446	143	3698	4604	2402
98-626	Montecristo intrusion			480708	7535180	
98-695	Radiomiro Tomic porphyry major facies	DD3978	237	512523	7542636	
98-698	Opache porphyry	DD310	400	503651	7517301	
00-081	Radiomiro Tomic porphyry minor facies	DD4156	329	511819	7541642	
00-131	El Abra granodiorite central facies	DD138	50	518315	7575983	3988
00-165	El Abra south granodiorite	EA220	240	517492	7575656	3720
00-176	El Abra mine porphyry	EA245	74	517451	7576443	3883
00-180	El Abra granodiorite dark facies	EA257	28	517857	7576738	3998
00-195	Pajonal diorite			519138	7578049	

Notes: Six and seven digit numbers are international GPS coordinates and four digit numbers are Chuquicamata mine coordinates

of visible cores. The exceptions were cores that were specifically targeted to test for inheritance. The zircon-bearing mount was placed in a custom-designed sample cell with circulating Ar and He (Eggins et al., 1998). Laser ablation was conducted by a pulsed ArF LambdaPhysik LPX 120I UV excimer laser operated at a voltage between 21 and 23 kV at 5 Hz, with a spot diameter of 29 μm . The ablated material was carried by He-Ar gas via a custom-built flow homogenizer to an Agilent 7500s ICP-MS. Raw count rates for ^{29}Si , ^{31}P , ^{96}Zr , ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th , and ^{238}U were recorded in time-resolved mode by peak hopping. The integration time for the isotopes was 20 ms for ^{29}Si , ^{31}P , and ^{96}Zr , 300 ms for ^{206}Pb and ^{207}Pb , 200 ms for ^{208}Pb , and 50 ms for ^{232}Th and ^{238}U . Data were collected in both pulse counting and analog mode with the transition at 1×10^6 counts/s. Data were acquired for 20 s with the laser off and 40 s with the laser on, giving approximately 120 mass sweeps for a penetration depth of ca. 20 μm . Zircons were ablated in a rotation of 26 analyses, as follows: Temora standard (1 analysis); Los Picos internal zircon standard (2 analyses); 8 unknown zircons (2 grains analyzed from each of 4 samples); Temora zircon standard (2 analyses), Los Picos, internal zircon standard (2 analyses); 8 unknown zircons (2 grains analyzed from each of 4 samples); QNGG, internal zircon standard (1 analysis); NIST 612, standard silicate glass (1 analysis), and Temora zircon standard (1 analysis). Each cycle took approximately 45 min to complete.

Corrections were made for background, instrumental mass bias drift, depth-dependent elemental fractionation, and common Pb. After laser triggering, it took 3 s for the counts to reach a maximum and stabilize (Fig. 4). These initial data were excluded from the analysis. Depth-dependent interelement fractionation of Pb, Th, and U, documented by previous workers (i.e., Hirata and Nesbitt, 1995; Horn et al., 2000), were corrected by reference to the Temora standard zircon, with $^{206}\text{Pb}/^{238}\text{U} = 0.06680$ (Black et al., 2004). The average factor required to lower the $^{206}\text{Pb}/^{238}\text{U}$ of the standard

Temora zircon from the measured value to the accepted value of 0.0668 for each mass sweep was calculated from multiple measurements of the standard. This factor was then applied to the appropriate mass sweep for each of the unknowns, making the assumption that there is no variation in the depth-dependent correction factor between standard and unknown zircons. A typical $^{206}\text{Pb}/^{238}\text{U}$ depth profile, before and after the depth-dependent fractionation correction is applied to each time slice, is shown in Figure 4. Black et al. (2004) described the characteristics of the Temora standard, including laser ICP-MS analyses of this material. Note, however, that SL13 was used as the standard zircon for the analyses of the three Chuquicamata porphyries (East, West, and Bench) reported by Ballard et al. (2001).

Common Pb was added or subtracted after drift and depth-dependent fractionation corrections. Laser ICP-MS cannot measure ^{204}Pb due to interference from ^{204}Hg so it is not possible to correct for common Pb by the ^{204}Pb method. The two alternative common Pb correction methods were used: the ^{208}Pb and the ^{207}Pb methods. The ^{208}Pb method is based on the difference between the measured and expected $^{208}\text{Pb}/^{206}\text{Pb}$, as calculated from the $^{206}\text{Pb}/^{238}\text{U}$ age and the measured $^{208}\text{Pb}/^{232}\text{Th}$, according to method of Compston et al. (1984), using the glass NIST612 as the standard for $^{208}\text{Pb}/^{232}\text{Th}$ (Pearce et al., 1997). The difference in the measured and expected $^{208}\text{Pb}/^{206}\text{Pb}$ is attributed to common Pb. The appropriate amount of common Pb, as determined from the common Pb model of Cummings and Richard (1975), is then added (or subtracted) to correct this imbalance and the $^{206}\text{Pb}/^{238}\text{U}$, $^{207}\text{Pb}/^{235}\text{U}$, and $^{207}\text{Pb}/^{206}\text{Pb}$ ratios are adjusted accordingly. After correction by this method most analyses were concordant at the 1σ level. The ^{207}Pb method assumes that the zircons have not lost Pb and that any excess $^{207}\text{Pb}/^{206}\text{Pb}$ is due to common Pb. The common Pb composition assumed is again that of Cummings and Richards (1975). This assumption of concordance is reasonable given that the zircons analyzed in this study are too young to have undergone significant radioactive damage and are therefore unlikely to have lost Pb (Lee et al., 1997). This argument is supported by the observation that less than 1.5 percent of the grains analyzed in this study show evidence of detectable Pb loss (see Table 2). The ^{208}Pb method is preferred to the ^{207}Pb method and has been used in this study. Both methods give dates that, with rare exceptions, agree within analytical error.

Because of uncertainty in the common Pb correction, discordant grains have been rejected from the date calculation. Grains are deemed discordant if their ^{208}Pb -corrected Pb- $^{206}\text{Pb}/^{238}\text{U}$ age, divided by their ^{208}Pb -corrected Pb- $^{207}\text{Pb}/^{235}\text{U}$ age, is greater than 1 ± 0.1 including 1σ uncertainties, where $^{207}\text{Pb}/^{235}\text{U}$ is normally calculated (except for high U grains) from the measured $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$, assuming $^{238}\text{U}/^{235}\text{U} = 137.88$.

The reported uncertainty for each U-Th-Pb zircon date is the 2σ standard error from the observed variance of the mass sweeps used to calculate the date of an individual grain and is termed the "observed error." This can be compared with the expected error for the same mass sweep interval based on counting statistics.

Most of the areas selected for dating were close to grain margins to minimize the risk of intersecting an old core

FIG. 4. Plot demonstrating how standardization against a known zircon eliminates "downhole" fractionation effects in laser-ablation analyses of unknown zircons. In this example from Los Picos, the $^{206}\text{Pb}/^{238}\text{U}$ ratios, which have been background corrected, increase with increasing depth (mass scan) in a grain known to be of homogeneous age. When those same ratios are fractionation corrected with reference to the Temora standard zircon, the result is a constant ratio at all depths, with the exception of the first few analyses at the start of laser ablation. These early mass sweeps are omitted from the date calculation. The age presented (horizontal line) is the weighted mean for analyses between the vertical lines.

TABLE 2. Summary of Age Data for Granitic Rocks from the Chuquicamata-El Abra Porphyry Copper Belt

Unit/sample no.	SHRIMP $^{207}\text{Pb}/^{238}\text{U}$ age	2 std. error	^{208}Pb corr'd $^{206}\text{Pb}/^{238}\text{U}$ age	2 std. error	<i>n</i>	N	MSWD	Inherit	Obs/exp	Discord	Subdy older pop	Subdy younger pop
Los Picos-Fortuna												
Los Picos intrusion 525			41.8	0.3	35	36	1.17	0	0	1	0	0
Los Picos intrusion 533	43.1	0.6	42.2	0.2	116	163	1.40	1	18	21	4	3
Los Picos intrusion 521			38.8	0.6	23	45	1.94	11	0	11	0	0
Antena 576 ¹			38.1	0.4	18	45	0.58	11	0	11	5	0
Antena 576			39.4	0.5	21	43	0.87	8	0	12	0	2
Fiesta 570			38.2	0.3	24	38	0.93	2	0	1	9	2
Fiesta 535 ¹			38.8	0.5	32	38	3.54	2	0	1	1	2
Fiesta 535			38.2	0.8	12	47	1.56	5	1	23	5	1
San Lorenzo porphyry 530			42.0	0.5	14	17	2.02	0	3	0	0	0
Fortuna leucocratic intrusion 569			39.0	0.7	15	43	0.68	11	0	17	0	0
Fortuna leucocratic intrusion 565			38.6	0.4	24	33	1.57	3	1	1	2	2
Fortuna leucocratic intrusion 555												
Pajonal-El Abra												
Pajonal qtz monzodiorite 195 ¹			42.0	0.4	12	33	0.99	0	8	6	7	0
Pajonal qtz monzodiorite 195			42.7	0.5	19	33	2.35	0	8	6	0	0
El Abra granodiorite (dark) 180			40.4	0.6	18	39	2.02	1	7	10	2	1
El Abra granodiorite (central) 131		40.6	0.3	24	39	0.84	0	1	14	0	0	0
South granodiorite 165			37.9	0.4	28	43	1.31	5	1	8	0	1
El Abra porphyry 176			37.2	0.4	21	33	0.96	10	0	2	0	0
Chuquicamata												
Opache porphyry 698	37.3	1.0	37.7	0.6	23	38	2.97	4	1	10	0	0
East porphyry 610	35.2	0.4	34.5	0.3	69	113	1.99	6	8	23	3	4
West porphyry 609	34.0	0.3	33.6	0.2	81	117	1.85	9	7	15	0	5
Bench porphyry 603	34.1	0.3	33.1	0.3	67	116	2.17	12	10	17	8	2
Radomiro Tomic Major 695 ¹	35.0	0.3	34.3	0.3	33	40	1.38	0	0	2	5	0
Radomiro Tomic Major 695			34.5	0.4	38	40	2.57	0	0	2	0	0
Radomiro Tomic Minor 081			33.9	0.4	27	38	2.50	6	2	1	0	2
Montecristo												
Montecristo 626 ¹			62.7	0.5	22	40	0.77	3	3	6	6	0
Montecristo 626			63.4	0.8	28	40	2.01	3	3	6	0	0

Notes: MSWD = mean sum of the weighted deviates; *n* = selected subpopulation, *N* = total number of analyses, std. error = standard error; the last 5 columns list basis for rejection from age calculation and the number of rejected analyses: Inherit = grains considered to be inherited, i.e., clearly older than the main population; obs/exp = the ratio of the observed uncertainty to that expected was greater than 2; discord = the difference of the two U/Pb ages differed by more than 10%; subdy older and younger populations determined by inspection of cumulative probability plots

¹ Preferred age

during analysis. Although cathodoluminescence and optical microscopy are valuable aids for selecting these areas they are less effective for laser ICP-MS dating than they are for ion probe dating. The reason is that the pit produced by an ion beam is typically $<2\ \mu\text{m}$ deep compared with the ca. $20\text{-}\mu\text{m}$ pit produced during laser ablation. The deeper pits produced by the laser are, therefore, much more likely to pass through cores or rims that are not exposed at the surface than pits produced by ion beams. To guard against these possibilities, U/Pb and trace element depth profiles were monitored for each grain during data processing. Most of the grains selected for analyses were free of age zoning and inclusions. However, some laser pits intersected older cores or apatite inclusions that were not visible in the cathodoluminescence or optical images. Examples are illustrated in Figures 5 and 6. Our procedure allows for exclusion of those parts of the $^{206}\text{Pb}/^{238}\text{U}$ profile that show evidence of age zonation.

The zircon populations included in this study were analyzed during seven separate analytical sessions. Zircon inheritance was recognized in most samples even though the rims of the grains were specifically targeted. Where a rim yielded an age that is older than the crystallization age of the rock the implication is that all of the grain is inherited, not just the core. To further test the importance of inheritance, ELA-ICP-MS sessions were undertaken specifically targeting zircon cores identified by cathodoluminescence and optical microscopy.

Errors, which include the uncertainty in the measurement of the standards, and mean square of weighted deviates (MSWD) were calculated for each analysis. The uncertainty in the standard is derived from the standard deviation of multiple measurements of the standard glass NIST 612 and is about 1 percent for $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ and 0.4 percent for $^{207}\text{Pb}/^{206}\text{Pb}$. All dates reported in this study are ^{208}Pb -corrected $^{206}\text{Pb}/^{238}\text{U}$ ages and the errors quoted are 2σ standard errors, unless otherwise noted.

Selected samples were also analyzed by sensitive high resolution ion microprobe (SHRIMP) following well-established

FIG. 5. Core-rim age relationships in an East porphyry zircon. Intersection of both an older core and rim in one ablation was rare in this study. Here the entire spectrum gives a mixed age with a high ratio of observed to expected uncertainty. If the spectrum is divided into 2 plateaus, two dates can be calculated, a Tertiary rim, and a Late Jurassic core, although the older core is somewhat noisy and would be rejected using our usual criteria as observed to expected uncertainty exceeds 2.

FIG. 6. Laser-ablation analyses of Los Picos zircon with an apatite inclusion. Counts for P, La, and ^{208}Pb in the lower panel show that La is below detection limits (1 count) in the zircon and rises to a maximum of about 700 counts in the inclusion. Similarly, P and Pb rise in the inclusion. The $^{206}\text{Pb}/^{238}\text{U}$ ratios for corresponding times are shown in the upper panel, and the excess (common) Pb in the apatite is clear. The entire spectrum results in a discordant point with a large ratio of observed to expected uncertainty (2.5). As inclusions can be visually detected and avoided, only the first two-thirds of the signal was used in this calculation, resulting in a concordant 44.1 Ma age with observed to expected uncertainty of ~ 1 .

analytical procedures (Claoué-Long et al., 1995; Allen et al., 1998). These included the Radomiro Tomic major intrusion, the Opathe mine porphyry, Los Picos, and the three Chuquicamata mine porphyries. The SHRIMP ages of the unknown zircons were calculated against standard zircon AS3 for which $^{206}\text{Pb}/^{238}\text{U} = 0.18588$ and corresponds to an age of 1099 Ma (Paces and Miller, 1993). The standard AS3 was used for the SHRIMP analyses in preference to Temora because AS3 has more variable U concentrations than Temora, which makes it a better standard for SHRIMP $^{206}\text{Pb}/^{238}\text{U}$ dating.

Data selection

The zircon dates obtained in this study are summarized in Table 2. The complete data set for the ELA-ICP-MS analyses is available as a digital supplement to this paper, at http://www.segweb.org/EG/papers/Abs_101-7_files/Campbell_Appendix.pdf.

The short ICP-MS analytical time ($<2\ \text{min}$) makes it practical to analyze more than 30 zircons per rock sample, allowing the following criteria to be used in obtaining the final age determinations. Grains or parts of grains that exhibit (1) internal age zoning, (2) apatite inclusions, (3) postcrystallization Pb loss, or (4) evidence of inheritance were rejected from the final date calculation. Objective criteria have been developed to make these decisions in order to avoid operator bias.

As shown in Figure 5, internal age zonation can be recognized from variations in the $^{206}\text{Pb}/^{238}\text{U}$ ratio depth profile. Grains that showed continuous age zonation record a meaningless mixed age and were not processed for date calculations. Other zoned grains show a plateau in their $^{206}\text{Pb}/^{238}\text{U}$ ratio profile. Dates were calculated for these plateaus if they were more than 10 mass sweeps wide. For example, a date was calculated for both the core and rim for the zoned zircon shown in Figure 5.

There are two circumstances where mixed ages are difficult to detect—where an ablation pit orthogonally straddles a core-rim boundary and where there is only a subtle age difference between a core and rim. The observed to expected error ratio can be used to eliminate such grains objectively. Grains that were eliminated because they show obvious age zonation have observed to expected errors ratios $\gg 2$. For example, if the rim and core of the grain depicted in Figure 5 are treated as having a single age, the date obtained is 82.1 ± 10.0 Ma and the observed to expected error ratio is 21.7. The high observed to expected error ratio is a consequence of the obvious age zonation within the grain. If the rim and core are processed separately the date obtained for the core is 155.5 ± 2.9 Ma and the date for the rim is 33.2 ± 0.7 Ma, with observed to expected ratios of 3.1 and 1.1 respectively. This is an extreme case where the age zonation is obvious. However, in other grains the age zonation is subtle, for example the core of the zircon in Figure 5. Our experience, working with standard zircons and other well-behaved grains, suggests that the observed to expected error ratio should be < 2 if the zircon has no age zonation. Grains that have observed to expected error ratios > 2 are assumed to have age zonation in their $^{206}\text{Pb}/^{238}\text{U}$ depth profiles that is too subtle to observe visually. These grains, which make up about 6 percent of all of the analyzed grains, have also been eliminated from consideration.

Phosphorus was monitored to detect the intersection of apatite grains during analyses. Apatite has a large amount of common Pb, which results in additional uncertainty if included in the date calculation. Parts of $^{206}\text{Pb}/^{238}\text{U}$ ratio profiles that intersected apatite inclusions were therefore excluded from the date calculations (Fig. 6).

Mean standard weighted deviates were calculated for each population following the method of Wendt and Carl (1991). The MSWD provides a statistical measure of the ratio between the observed and the expected scatter of the data. Where the MSWD equals 1, the assigned errors are the only source of scatter (Ludwig, 2000). Where the MSWD is in excess of the calculated upper limit, either the analytical errors are underestimated or nonanalytical scatter is included in the data. Where the MSWD is considerably below the lower limit, the analytical errors are likely to have been overestimated (Ludwig, 2000), for example, by rejecting too many old or young grains as outliers.

Most of the zircon populations analyzed in this study showed evidence of inheritance and/or, to a lesser extent, Pb loss. Inclusion of inherited zircons and/or zircons that have suffered Pb loss in the date calculation was found to be the principal cause for some of the dated zircon populations having high MSWD (> 2). Inherited grains and grains that have suffered Pb loss need to be omitted from the date calculation. This has been done using cumulative probability plots, which

allow zircons that belong to either of these categories to be identified objectively. Cumulative probability plots have a nonlinear x-axis scale that is calibrated so as to represent the data from a normal distribution as a straight line with a positive slope. Two end-member examples of the way cumulative probability plots have been used to eliminate inherited grains and grains that have undergone Pb loss are illustrated in Figure 7.

Figure 7a, which represents Los Picos 525, is an example of a sample that yields a single age population on a cumulative probability plot. Most of the data lie on a single straight line with the exception of small tails at each end, which have a lower gradient than the bulk of the data due to expansion of the scale in this region. The MSWD for the population is 1.17.

Sample 610, from the East porphyry, includes both inherited grains and grains that have suffered Pb loss (Fig. 7b). If all grains are included in the date calculation the age obtained is 34.4 ± 0.3 Ma and the MSWD is 3.14. Sample 610 includes both a distinct inherited population and a Pb-loss population. Cumulative probability plots represent two populations as two straight lines, separated by a zone of inflection, and three populations as three straight lines separated by two zones of inflection. The oldest and youngest age populations in sample 610 have means of $38.5 \pm$ Ma ($n = 3$) and 31.8 Ma ($n = 4$). The

FIG. 7. Two examples of the use of cumulative probability plots. The example in (a) is one judged to be a single zircon age population. The plot lacks obvious inflections and the MSWD for the 41.8 Ma intrusion is 1.17. Example (b) has three age populations separated by two inflection points (arrows). Taken as a whole, (b) gives an age of 34.4 ± 0.4 Ma with an MSWD of 3.5, a value that indicates scatter well above the expected analytical scatter. Three zircons are interpreted to be inherited grains (~ 38.5 Ma) and four grains are judged to be younger than the main population due to Pb loss (~ 31.8 Ma). If these grains are omitted from the date calculation the age becomes 34.5 ± 0.3 Ma with an analytically acceptable MSWD of 1.99.

arrows mark the zones of inflection that separate these populations from the main population. The oldest population is interpreted to be inheritance and the youngest population is attributed to Pb loss. The Pb-loss age correlates with an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 31.4 ± 0.4 Ma by Reynolds et al. (1998) for quartz-sericite alteration and with an apatite He age of ca. 31 Ma by McInnes et al. (1999), which suggests that the younger U/Pb zircon population is dating a real event. If these populations are removed from the date calculation, the mean age becomes 34.5 ± 0.3 Ma ($n = 69$) and the MSWD is reduced to 1.99.

Quality control

The reproducibility of the ELA-ICP-MS analytical method was monitored using a Los Picos sample (98-521) as an internal standard that was analyzed during each session. The seven analytical sessions give crystallization ages for Los Picos that lie almost within analytical error of each other, once Pb loss and/or inherited grains have been removed (Fig. 8). This result confirms that the ELA-ICP-MS technique gives reproducible data.

The accuracy of the ELA-ICP-MS technique has previously been confirmed through repeat analyses of three Chuquicamata mine porphyry samples by SHRIMP (Ballard et al., 2001). Further verification of the ELA-ICP-MS technique by SHRIMP analyses was made during this study through a similar comparison of the crystallization age of Radomiro Tomic major facies porphyry (34.6 ± 0.4 Ma by laser, compared to 35.0 ± 0.3 Ma by SHRIMP) and the Opaque mine porphyry (37.9 ± 0.2 Ma by laser, compared to 37.3 ± 1.0 Ma by SHRIMP), which agree within analytical error (Table 2). The accuracy of the ELA-ICP-MS results is compared with conventional TIMS U/Pb zircon and $^{40}\text{Ar}/^{39}\text{Ar}$ dates in Table 3.

Results

All samples have been processed following the procedures outlined above. The mean age and MSWD of each population is listed in Table 2 together with the number of grains that have been rejected from the age calculation and the reason for rejection. Concordia and cumulative probability plots for Los Picos-Fortuna-Pajonal-El Abra intrusions are given in Figure 9.

The interpretations of four of the samples, Fortuna Antena (576), Fortuna Fiesta (535), Pajonal quartz monzodiorite (195), and Radomiro Tomic major (695), were ambiguous and two interpretations have been presented. The preferred interpretation for Fortuna Antena (576) is an age of 38.8 Ma with an MSWD of 1.94. However, there is a suggestion of a point of inflection in the cumulative probability plot at ~40 Ma. If zircons older than 40 Ma are interpreted as inherited, the mean age of the remaining grains is 38.1 Ma and the MSWD falls to 0.58. The former interpretation is preferred because the associated MSWD of 1.94 is not unacceptably high. In the case of Fortuna Fiesta (535) the old grains that lie above the point of inflection at 39.5 Ma have been rejected as inherited. Including these grains increases the age from 38.2 to 38.8 Ma and increases the MSWD from 0.93 to 3.54. The latter value is unacceptably high. Similarly the Pajonal quartz monzodiorite (195) data show a point of inflection at

43 Ma. If the older data are included the mean age is 42.7 Ma and the MSWD is 2.35, whereas if they are rejected the age is 42.0 Ma and the MSWD is 0.99. The latter interpretation is preferred because of the better MSWD but, in this case, the choice is less clear-cut. Finally, the data for the Radomiro

FIG. 8. A summary of multiple-day analyses of the internal standard zircon Los Picos 98-521. 117 of 163 analyses passed our selection criteria.

TABLE 3. Comparison of LA-ICP-MS U-Pb Zircon Ages to Other Geochronology

Unit	ICP-MS age (Ma)	TIMS U-Pb (Ma)	Ar-Ar (Ma)
Radimiro Tomic major facies porphyry	34.6 ± 0.4		31.8 ± 0.3 ¹ 32.6 ± 0.3 ¹ 33.0 ± 0.3 ¹
West porphyry	33.5 ± 0.2		31.1 ± 0.3 ⁴ 33.4 ± 0.3 ⁴
Antena (Gris)	39.1 ± 0.4	39.3 ± 0.4 ³	
Fiesta (Clara)	38.5 ± 0.4	37.6 ± 0.7 ³	
Dark diorite	40.2 ± 0.5		39.1 ± 1.2 ²
Central diorite	40.6 ± 0.3		
South granodiorite	38.0 ± 0.3	37.5 ± 0.5 ³	36.7 ± 0.6 ²
El Abra mine porphyry	37.4 ± 0.3		36.8 ± 0.6 ²

Note: Ages are averages of multiple analyses

¹ Cuadra et al. (1997; ages represent a sampling of data in this publication)

² Maksiyev (1990)

³ Dilles et al. (1997)

⁴ Reynolds et al. (1998)

Tomic major intrusion (695) show a weak point of inflection at ~36 Ma. Including the ages above the inflection point gives ages of 34.5 ± 0.4 Ma and an MSWD of 2.57, whereas rejecting them reduces the age to 34.3 ± 0.3 Ma and the MSWD to 1.38. The second interpretation is preferred because it results in a better MSWD, but the choice is again unclear.

Using the criteria set out above, four of the rocks have a high percentage of rejected analyses: the three El Abra granodiorite samples and the San Lorenzo porphyry. Using no common Pb correction, or 207, instead of 208, based common Pb correction, makes little difference to the interpreted age or the rejection rate.

The age range for the dated Los Picos-Fortuna intrusions is 42.2 to 38.2 Ma and is between 42.0 and 37.2 Ma (Table 2) for the Pajonal-Abra intrusions, showing that the magmatic activity that formed these complexes lasted for at least 5 m.y. The absolute ages obtained for the intrusions of the Los Picos-Fortuna complex indicate an intrusive sequence that is consistent with their known intrusive relationships which, from oldest to youngest, are Los Picos, Fortuna Antena, Fortuna Fiesta, and the San Lorenzo porphyries. The three samples from Los Picos cover a range of ages between 41.8 ± 0.3 and 43.1 ± 0.6 Ma, showing that the intrusions that make up this unit were emplaced over a period of time. Similarly, the

minor leucocratic intrusions of the Fortuna complex, which are geochemically distinct from the other Fortuna-El Abra intrusions (Ballard, 2002), were intruded between 38.6 and 42.0 Ma. This age range is similar to the range of ages of all of the other units that make up the Fortuna and El Abra complexes. The intrusive sequence of the Pajonal-El Abra intrusions, implied by the laser ICP-MS dating, is Pajonal diorite, Central diorite, Dark diorite, South granodiorite, and the El Abra mine porphyry (Fig. 9). Again this sequence is consistent with known crosscutting relationships.

The age range of the Chuquicamata Igneous Complex is from 34.6 to 33.3 Ma, and the implied intrusive sequence is East porphyry and/or Radomiro Tomic major facies porphyry, Radomiro Tomic minor facies porphyry, West porphyry, and then Bench porphyry (Table 2). The ages of other intrusions dated in this study are the Opathe mine porphyry at 37.9 Ma and the Montecristo intrusion at 63.2 Ma. Concordia and cumulative probability plots for the Montecristo intrusion and the Chuquicamata porphyries are given in Figures 10 and 11.

Subtle inheritance

During the analysis of the 22 intrusions for their crystallization ages, it became apparent that some zircons were inherited from previous events. For example, the Los Picos-Fortuna and Pajonal-El Abra complexes have inherited zircons with ages varying between slightly older than their emplacement ages to at least 80 Ma. A further analytical session was undertaken, to better understand the meaning of these age patterns, exclusively targeting zircon cores that were identified in the cathodoluminescence. The resulting inheritance ages, which are illustrated in Figure 12, show that the Los Picos-Fortuna, Pajonal-El Abra, and Chuquicamata Igneous Complex all record evidence of abundant zircon growth back to 55 Ma, with scattered inheritance extending back as far as 80 Ma.

The most likely interpretation of the inherited zircons is that they are igneous and crystallized from earlier melts in the Los Picos-Fortuna source region. The steady increase in the number of the inherited grains with decreasing age, especially in Los Picos-Fortuna between 55 and 43 Ma and in the Chuquicamata Igneous Complex between 50 and 35 Ma (Fig. 12), is consistent with this interpretation. An alternative interpretation of the dates is that they represent resetting of preexisting zircons. Zircon texture can be used to distinguish between these possibilities. If the zircons are recording primary igneous crystallization ages, they should retain their primary igneous oscillatory zoning, whereas if their ages have been reset the oscillatory zoning will be destroyed (Williams, 2001). The zircon analyzed in this study shows the fine oscillatory zoning characteristic of igneous growth. Furthermore,

FIG. 9. Concordia and cumulative probability plots for zircons from 17 Eocene (Oligocene) rocks arranged in order of increasing age. Open circles are those points not incorporated in age calculation because they are (1) discordant, (2) have observed to expected uncertainties greater than 2, and (3) are judged not to belong to the main age population on the basis of the accompanying cumulative probability plots and corresponding MSWD. Filled circles are accepted analyses, and crosses with error bars are the corresponding ²⁰⁸Pb common lead-corrected values. Open diamonds in cumulative probability plots are those points regarded as subtly inherited grains (ages greater than the mean) or grains that have had Pb loss (those below the mean). Filled diamonds are those used in age calculation. A normal data distribution expresses itself as a straight line of positive slope, the slope reflecting the variance in the data. Multiple populations, therefore, appear as multiple straight-line segments punctuated by inflections (see Fig. 7).

FIG. 9. (Cont.)

FIG. 9. (Cont.)

FIG. 9. (Cont.)

many of the analyzed areas that gave old ages were from the margins of grains, indicating that the entire grain is inherited and not just the core. We are therefore confident that the inherited zircons are recording igneous ages. The steady increase in zircon inheritance between 55 and 43 Ma is interpreted to represent a build-up in magmatic activity in the lower or middle crust beneath the Los Picos-Fortuna intrusions over that period.

It is common to find inherited zircons that are only slightly older than the crystallization age of the intrusion being dated (e.g. Harris et al., 2004; Liang et al., 2006), a phenomena that

we call subtle inheritance. We suggest that this is because the ascent of magmas is driven by buoyancy and that the magmas rise until they reach their own density level in the crust (the neutral buoyancy level; Ryan, 1987). Successive magmas from the same source can be expected to have similar compositions and therefore similar densities. If they rise through the same crust they will form intrusions at similar levels and, as a consequence, younger intrusions can be expected to intrude into slightly older intrusions that formed at the same crustal level. It is suggested that these slightly older intrusions are partially assimilated into younger intrusions, introducing subtly older inherited zircon into the magma.

Discussion

The correlation between the Los Picos-Fortuna and Pajonal-El Abra complexes

Previous studies of the relationship between the Los Picos-Fortuna and Pajonal-El Abra igneous complexes suggested a correlation between the two, based on geologic mapping, petrology, geochronology, and chemical data (Dilles et al., 1997; Tomlinson and Blanco, 1997a, b). However, this is the first study to present the crystallization ages for all these units, using the same analytical method. The results of the current study, which are summarized in Table 2, provide strong support for the proposed correlation. Applying the results of this study, and guided by previous work, the following correlations are suggested: (1) the Los Picos quartz monzodiorite complex with the Pajonal diorite, (2) the Fortuna Antena granodiorite with the El Abra granodiorite, (3) the Fortuna Fiesta granodiorite with the South granodiorite, and possibly (4) the San Lorenzo porphyries with the El Abra mine porphyry (Table 2). The close link between the crystallization ages for intrusions on both sides of the West fissure supports the hypothesis of R.C. Baker (reported in Dilles et al., 1979) that the intrusions were once part of the same large igneous complex and have now been displaced sinistrally by ca. 35 km of sinistral displacement along the West fissure.

Porphyry copper mineralization

In addition to resolving the relationship between the Los Picos-Fortuna and Pajonal-El Abra igneous complexes, the zircon U-Th-Pb geochronological results can be used to constrain the timing of porphyry copper intrusions relative to

FIG. 10. Concordia and cumulative probability plots for the Monte Cristo intrusion. Symbols as in Figure 9. Note one analysis with several percent common Pb (filled circle, far right) corrects well, its corresponding cross lost in the cluster in concordia. Five grains with a weighted mean of 66.6 Ma are judged to be inherited by the 62.7 Ma intrusion from a slightly older igneous rock.

FIG. 11. Concordia and cumulative probability plots for the East, West, and Bench porphyries presented in Ballard et al. (2001). Whereas they presented ^{207}Pb -corrected data, we chose to use ^{208}Pb -corrected analyses, which yield the same ages within the quoted uncertainties. Symbols as in Figure 9.

other felsic magmatism in the district. At least four porphyry copper systems were generated during the Tertiary in this region: Chuquicamata, Radomiro Tomic, El Abra, and Opache. The U-Th-Pb zircon ages show that the porphyry intrusions that host copper were not emplaced over a narrow time interval but over a period of over 4 m.y., from 37.7 ± 0.6 to 33.1 ± 0.3 Ma. The El Abra porphyry, which hosts the copper ore in the El Abra mine, lies within the Pajonal-El Abra complex on the east side of the West fissure. It is the youngest and most geochemically evolved unit in the related series of intrusions that make up the Pajonal-El Abra complex. This can be illustrated by plotting any of a number of geochemical variables against time, for example MgO or SiO_2 (Ballard, 2002). Figure 13 is a plot of Ce (VI)/(III) in zircon, which is a measure of the oxidation state of the melt, against time for the intrusions of the Chuquicamata-El Abra district (Ballard et al., 2001). Notice that the copper-bearing El Abra porphyry is the youngest and most oxidized member of the Pajonal-El Abra complex. Similarly Opache, which lies on the west side of the West fissure close to the Los Picos-Fortuna complex, is

the youngest, most oxidized member of that complex. However the ore-bearing porphyries at Chuquicamata and Radomiro Tomic are 3 m.y. younger than the youngest intrusion of Los Picos-Fortuna-Pajonal-El Abra complex. Although they have similar Ce (VI)/(III) to the El Abra and Opache porphyries they do not appear to have formed as part of the Los Picos-Fortuna-Pajonal-El Abra complex. By analogy with the Opache and El Abra porphyries we suggest that the Chuquicamata and Radomiro Tomic porphyries are underlain by a large igneous complex similar to the Los Picos-Fortuna-Pajonal-El Abra complex.

Conclusions

This study shows that laser ICP-MS U-Pb zircon dating is a viable alternative to $^{39}\text{Ar}/^{40}\text{Ar}$ and ion probe dating for determining the age of young (<500 Ma) felsic igneous rocks. U/Pb dating of zircon is preferred to $^{39}\text{Ar}/^{40}\text{Ar}$ dating for felsic intrusions associated with ore because the $^{39}\text{Ar}/^{40}\text{Ar}$ systematics are readily disturbed by later hydrothermal events, whereas U/Pb in zircon is rarely reset. Laser ICP-MS dating is less

FIG. 12. Histograms displaying the dates of zircons used to calculate the crystallization ages for the intrusions and inherited zircons from the same intrusions for the Los Picos-Fortuna complex (Lp-Fr), the Pajonal-El Abra complex (Paj-Ab), and the CIC (Chuquicamata mine and Radomiro Tomic mine porphyries). The zircon dates are grouped into complexes so the ages of the youngest inherited zircons from the youngest intrusions overlap the ages of the oldest intrusions for each complex. Note that there is a steady increase in the abundance of inherited zones with decreasing age between ~55 Ma and the age of the oldest intrusion in the complex. This is best seen for the Los Picos-Fortuna complex and the CIC.

expensive than ion probe dating yet can achieve comparable precision in the same analytical time.

The new geochronology confirms the correlation between the Los Picos-Fortuna and Pajonal-El Abra complexes and

FIG. 13. Average zircon $\text{Ce}^{(\text{IV})}/\text{Ce}^{(\text{III})}$ ratios increase systematically from the oldest, most mafic, barren intrusions of the Los Picos-Fortuna-Pajonal-El Abra complex to the youngest, most felsic, and ore-bearing unit, the El Abra mine porphyry. The one outlier to this trend is the Fortuna leucocratic intrusion, which exhibits trace element evidence distinguishing it from the main sequence (after Ballard et al. 2001).

supports the hypothesis that the Pajonal-El Abra complex has been displaced 35 km to the north by sinistral movement on the West fissure. It also shows that the intrusions that make up the Los Picos-Fortuna and Pajonal-El Abra igneous complexes were emplaced over an interval of at least 5 m.y. between ~37 and 42 Ma. Furthermore, the inheritance pattern in the xenocrystic zircons suggests a build-up in magmatic activity in the source region to the Los Picos-Fortuna-Pajonal-El Abra complex between 55 and 42 Ma.

Finally, porphyries associated with copper mineralization in the district range in age from 38 to 33 Ma. There is a significant time gap between the emplacement of the ore-bearing 33 to 35 Ma porphyries of the Chuquicamata Igneous Complex and the youngest intrusions of the Los Picos-Fortuna-Pajonal-El Abra complex, suggesting that they are not genetically related. The 38 Ma ore-bearing El Abra mine porphyry is part of the Pajonal-El Abra complex and is the youngest and most oxidized member of that suite. The 37.7 Ma Opache porphyry has a similar age to the El Abra mine porphyry and probably has a similar genetic relationship to the Los Picos-Fortuna-Pajonal-El Abra complex.

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REFERENCES

- Allen, C.M., Williams, I.S., Stephens, C.J., and Fielding, C.R., 1998, Granite genesis and basin formation in an extensional setting: the magmatic history of the northernmost New England orogen: *Australian Journal of Earth Sciences*, v. 45, p. 875–888.
- Ambrus, J., 1977, Geology of the El Abra porphyry copper deposit, Chile: *ECONOMIC GEOLOGY*, v. 72, p. 1062–1085.
- Ballard, J.R., 2002, A comparative study of the geochemistry of ore-bearing and barren porphyry systems: Unpublished Ph.D. thesis, Canberra, Australia, Australian National University, 255 p.
- Ballard, J.R., Palin, J.M., Williams, I.S., Campbell, I.H., and 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*, v. 29, p. 383–386.
- Black, L.P., Kamo, S.L., Allen, C.M., Davis, D.W., Aleinikoff, J.N., Valley, J.W., Mundil, R., Campbell, I.H., Korsch, R.J., Williams, I.S., and Foudoulis, C., 2004, Improved $^{206}\text{Pb}/^{238}\text{U}$ microprobe geochronology by the monitoring of a trace-element-related matrix effect: SHRIMP, ID-TIMS, ELA-ICP-MS and oxygen isotope documentation for a series of zircon standards: *Chemical Geology*, v. 205, p. 115–140.
- Boric, P.R., Diaz, F.F., and Maksaev, J.V., 1990, Geología y yacimientos metalíferos de la región de Antofagasta, regional map scale 1: 500,000: Santiago, Chile, Servicio Nacional de Geología y Minería-Chile Bulletin 40, 246 p.
- Cherniak, D.J., and Watson, E.B., 2000, Pb diffusion in zircon: *Chemical Geology*, v. 172, p. 5–24.
- Chong, G., and Pardo, R.C., 1994, Chuquicamata district: Corporación Nacional del Cobre de Chile, gerencia de exploraciones, Calama, map scale 1: 100,000.
- Claoué-Long, J.C., Compston, W., Roberts, J., and Fanning, C.M., 1995, Two Carboniferous ages: A comparison of SHRIMP zircon dating with conventional zircon ages and $^{40}\text{Ar}/^{39}\text{Ar}$ analysis: *Geochronology time scales and global stratigraphic correlation: Society of Economic Paleontologists and Mineralogists Special Publication 54*, p. 3–21.
- Compston, W., Williams, I.S., and Meyer, C., 1984, U-Pb geochronology of zircons from lunar breccia 73217 using sensitive high mass-resolution ion microprobe: *Journal of Geophysical Research*, v. 89 (supplement), p. B525–B524.
- Cuadra, P., Zentilli, M., Puig, A., and Tidy, E., 1997, Dataciones radiométricas en Radomiro Tomic [abs.]: VIII Congreso Geológico Chileno, Abstracts, v. 3, p. 1899–1902.
- Cummings, G.L., and Richards, J.R., 1975, Ore lead isotope ratios in a continuously changing earth: *Earth and Planetary Science Letters*, v. 28, p. 155–171.
- Dean, D.A., Graichen, R.E., Barrett, L.F., and Burton, W.D., 1996, Geologic overview of the El Abra porphyry copper deposit, Chile, in Trip N., Copper and gold deposits of Chile: *Geology and Ore Deposits of the American Cordillera Field Trip Guidebook Compendium*, p. 457–464.
- Dilles, J.H., Tomlinson, A.J., Martin, M.W., and Blanco, N., 1997, El Abra and Fortuna Complexes: A porphyry copper batholith sinistrally displaced by the Falla Oeste: VIII Congreso Geológico Chileno, Proceedings, v. 3, p. 1883–1887.
- Duncan, R.A., and Hargraves, R.B., 1984, Plate evolution of the Caribbean region in the mantle reference frame in the Caribbean-South American plate boundary and regional tectonics: *Geological Society of America Memoir 162*, p. 81–93.
- Eggins, S.M., Rudnick, R.L., and McDonough, W.F., 1998, The composition of peridotites and their minerals: A laser-ablation ICP-MS study: *Earth and Planetary Science Letters*, v. 154, p. 53–71.
- Graichen, R.E., Dean, D.A., Barrett, L.F., Burton, W.D., and Christensen, D.K., 1995, Geologic overview of the El Abra porphyry copper deposit, Chile: El Abra, Cyprus Amax Minerals Company, unpublished report, p. 1–11.
- Harris, A.C., Allen, C.M., Bryan, S.E., Campbell, I.H., Holcombe, R.J., and Palin, J.M., 2004, ELA-ICP-MS U-Pb zircon geochronology of regional volcanism hosting the Bajo de la Alumbrera Cu-Au deposit: Implications for porphyry-related mineralization: *Mineralium Deposita*, v. 39, p. 46–67.
- Hirata, T., and Nesbitt, R.W., 1995, U-Th-Pb isotope geochronology of zircon: Evaluation of the laser probe-inductively coupled plasma mass spectrometry technique: *Geochimica et Cosmochimica Acta*, v. 59, p. 2491–2500.
- Horn, I., Rudnick, R.L., and McDonough, W.F., 2000, Precise elemental and isotope ratio determination by simultaneous solution nebulization and laser ablation-ICP-MS: Application to U-Th-Pb geochronology: *Chemical Geology*, v. 164, p. 281–301.
- Lee, J.K.W., Williams, I.S., and Ellis, D.J., 1997, Pb, U and Th diffusion in natural zircon: *Nature*, v. 390, p. 159–162.
- Liang, H.Y., Campbell, I.H., Allen, C., Sun, W.D., Liu, C.Q., Yu, H.X., Xie, Y.W., and Zhang, Y.Q., 2006, Zircon $\text{Ce}^{4+}/\text{Ce}^{3+}$ ratios and ages for Yulong ore-bearing porphyries in eastern Tibet: *Mineralium Deposita*, v. 41, p. 152–159.
- Lindsay, D., Zentilli, M., and Rojas de la Rivera, J., 1995, Evolution of an active ductile to brittle shear system controlling mineralization at the Chuquicamata porphyry copper deposit, northern Chile: *International Geology Review*, v. 37, p. 945–958.
- Ludwig, K.R., 2000, Users manual for Isoplot/Excel: A geochronological toolkit for Microsoft Excel, v. 2.4: Berkley Geochronological Center Special Publication 1a, 53 p.
- Maksaev, J., and Tomlinson, A.J., 1995, Cuadrángulo Cerros de Paqui, Región de Antofagasta: Servicio Nacional de Geología y Minería y Corporación Nacional del Cobre, Registered Report IR-95–07, map scale 1: 50,000.
- Maksaev, J., Tomlinson, A.J., and Blanco, N.P., 1994, Estudio geológico de la franja longitudinal comprendida entre Quebrada Blanca y Chuquicamata: Servicio Nacional de Geología y Minería y Corporación Nacional del Cobre, propuesta para informe final convenio Codelco-Sernageomin, 79 p.
- Maksaev, V., and Zentilli, M., 1988, Metallogenic framework of the large porphyry copper deposits of the Andes of northern Chile: V Congreso Geológico Chileno, Actas, v. 1, p. B181–B212.
- McInnes, B.I.A., Farley, K.A., Sillitoe, R.H., and Kohn, B.P., 1999, Application of apatite (U-Th)/He thermochronometry to the determination of the sense and amount of vertical displacement at the Chuquicamata porphyry copper deposit, Chile: *ECONOMIC GEOLOGY*, v. 94, p. 937–948.
- Ossandón, C., and Zentilli, M., 1997, El Distrito de Chuquicamata: Una concentración de cobre de clase mundial: VIII Congreso Geológico Chileno, Proceedings, v. 3, p. 1888–1893.
- Ossandón, C., Freraut, C., Gustafson, L.B., Lindsay, D.D., and Zentilli, M., 2001, Geology of the Chuquicamata mine: A progress report: *ECONOMIC GEOLOGY*, v. 96, p. 249–270.
- Paces, J.B., and Miller, J.D., Jr., 1993, Precise U-Th-Pb ages of Duluth complex and related mafic intrusions, northeastern Minnesota: Geochronological insights to physical, petrogenetic, paleomagnetic, and tectonomagmatic processes associated with the 1.1 Ga midcontinent rift system: *Journal of Geophysical Research*, v. 98, no. B8, p. 13997–14013.
- Pardo, R.C., and Rivera, S.C., 1999, Exploración básica de seguimiento distrito Chuquicamata II región, Informe de Resultados: Calama, Calama Exploraciones, Corporación nacional del cobre de Chile, unpublished report API-9701–3, p. 35–39.
- Pearce, N.J.G., Perkins, W.T., Westgate, J.A., Gorton, M.P., Jackson, S.E., Neal, C.R., and Chenery, S.P., 1997, A compilation of new and published major and trace element data for NIST SRM 610 and NIST SRM 612 glass reference materials: *Geostandards Newsletter*, v. 21, no. 1, p. 115–144.
- Reutter, K.-J., Scheuber E., and Chong, G., 1996, The Precordilleran fault system of Chuquicamata, northern Chile: Evidence for reversals along arc-parallel strike-slip faults: *Tectonophysics*, v. 259, p. 213–228.
- Reynolds, P., Ravenhurst, C., Zentilli, M., and Lindsay, D., 1998, High-precision $^{40}\text{Ar}/^{39}\text{Ar}$ dating of two consecutive hydrothermal events in the Chuquicamata porphyry copper system, Chile: *Chemical Geology*, v. 148, p. 45–60.
- Rosas, F., 1999, Geología, Alteración y Mineralización del Proyecto San Lorenzo: Unpublished thesis, Santiago, Chile, Universidad de Chile, p.
- Ryan, M., 1987, Neutral buoyancy and the mechanical evolution of magmatic systems: *Geochemical Society Special Publication 1*, p. 259–287.
- Sillitoe, R.H., 1973, The tops and bottoms of porphyry copper deposits: *ECONOMIC GEOLOGY*, v. 68, p. 799–815.
- 1992, Gold and copper metallogeny of the central Andes—past, present, and future exploration objectives: *Society of Economic Geologists Distinguished Lecture: ECONOMIC GEOLOGY*, v. 87, p. 2205–2216.
- Sillitoe, R.H., Marquardt, J.C., Ramírez, F., Becerra, H., and Gómez, M., 1996, Geology of the concealed MM porphyry copper deposit, Chuquicamata district, northern Chile: *Society of Economic Geologists Special Publication 5*, p. 59–70.
- Tomlinson, A.J., and Blanco, N., 1997a, Structural evolution and displacement history of the West fault system, precordillera, Chile: Part 1. Synmineral history: VIII Congreso Geológico Chileno, Proceedings, v. 3, p. 1873–1877.
- 1997b, Structural evolution and displacement history of the West fault system, precordillera, Chile: Part 2. Postmineral history: VIII Congreso Geológico Chileno, Proceedings, v. 3, p. 1878–1882.

- Tomlinson, A.J., Makshev, J., and Blanco, N., 1995, Cuadrangulo Cerro Jaspe, Region de Antofagasta: Servicio Nacional de Geologia y Minería y Corporación Nacional del Cobre, registered report, IR-95-07, map scale 1: 50,000.
- Wendt, I., and Carl, C., 1991, The statistical distribution of the mean squared weighted deviation: *Chemical Geology (Isotope Geoscience Section)*, v. 86, p. 275–285.
- Williams, I.S., 2001, Response of detrital zircon and monazite, and their U-Pb isotopic systems, to regional metamorphism and host rock partial melting, Cooma Complex, southeastern Australia: *Australian Journal of Earth Sciences*, v. 48, p. 557–580.
- Zentilli, M., Krogh, T.E., Makshev, V., and Alpers, C.N., 1994, Uranium-lead dating of zircons from the Chuquicamata and La Escondida porphyry copper deposits, Chile: Inherited zircon cores of Paleozoic age with Tertiary overgrowths: *Comunicaciones*, v. 45, p. 101–110.