U–Pb age constraints on Variscan magmatism and Ni–Cu–PGE metallogeny in the Ossa–Morena Zone (SW Iberia)

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Abstract: New U–Pb zircon ages from the Santa Olalla Igneous Complex have been obtained, which improve the knowledge of the precise timing of Variscan magmatism in the Ossa–Morena Zone, SW Iberia. This complex has a special relevance as it hosts the most important Ni–Cu–platinum group element (PGE) mineralization in Europe: the Aguablanca deposit. U–Pb zircon ages have been obtained for seven samples belonging to the Santa Olalla Igneous Complex and spatially related granites. With the exception of the Cala granite (352 ± 4 Ma), which represents an older intrusion, the bulk of samples yield ages that cluster around 340 ± 3 Ma: the Santa Olalla tonalite (341.5 ± 3 Ma), the Sultana hornblende tonalite (341 ± 3 Ma), a mingling area at the contact between the Aguablanca and Santa Olalla stocks (341 ± 1.5 Ma), the Garrote granite (339 ± 3 Ma), the Teuler granite (338 ± 2 Ma), and dioritic dykes from the Aguablanca stock (338.6 ± 0.8 Ma). The Bodonal–Cala porphyry, which has also been dated (530 ± 3 Ma), comprises a group of sub-volcanic rhyolitic intrusions belonging to the Bodonal–Cala volcano-sedimentary complex, which hosts the igneous rocks. The knowledge that emplacement of the Aguablanca deposit was related to episodic transtensional tectonic stages during the Variscan orogeny will be fundamental in future mineral exploration in the Ossa–Morena Zone.

The geochronological constraints on the magmatic events associated with orogenic processes contribute to a better understanding of the overall evolution of an orogen. Magmatism plays a major role during the orogenic process as a way of extracting elements from the mantle that could be emplaced in the upper crust at economic concentrations. The Aguablanca ore is an unusual type of Ni Cu platinum group element (PGE) mineralization hosted in the Santa Olalla Igneous Complex, located between the provinces of Badajoz, Sevilla and Huelva in SW Spain. The age of this deposit of magmatic sulphides has been controversial. Two contrasting hypotheses have been considered: a Cambrian Ordovician age related to a rifting tectonic stage (Ortega *et al.* 2004), a possibility consistent with the fact that many magmatic sulphide deposits elsewhere in the world occur in rift environments (Lesher 2003; e.g. Noril'sk, Distler & Kunilov 1994; the Duluth Complex, Hauck *et al.* 1997; Pechenga, Melezhik *et al.* 1994; Lesher & Keays 2002), or a Late Palaeozoic age related to the oblique collision during the Variscan orogeny (Casquet *et al.* 2001). This latter interpretation linked the Aguablanca stock with the Santa Olalla stock, the age of which has been traditionally considered to be similar to that of a group of calc-alkaline Variscan intrusions cropping out in the region (Castro *et al.* 2002). The main objective of this study is to establish the crystallization age of the Ni Cu PGE ore of Aguablanca, to constrain the geodynamic context of this deposit. The geochronological data will be fundamental to building a theoretical genetic model for the mineral exploration of similar deposits in the region. The ages obtained in this study have been correlated with those for other similar intrusions previously dated in the zone and interpreted within the current proposed evolution of the Variscan orogen in this area.

Geological setting

The Santa Olalla Igneous Complex is located on the southern limb of the Olivenza Monesterio antiform (Fig. 1), a major WNW ESE-trending Variscan structure occupying a central position within the Ossa Morena Zone. The Ossa Morena Zone forms one of the SW divisions of the Iberian Massif, which corresponds to the westernmost outcrops of the Variscan orogen in Europe (Ribeiro *et al.* 1990). The Ossa Morena Zone has been interpreted as a poly-orogenic terrane accreted to the Central Iberian Zone during the Cadomian orogeny (620 530 Ma), the suture of which is exposed along the Badajoz Córdoba shear zone (Quesada 1990, 1991, 1997; Eguiluz *et al.* 2000). A rifting event culminating in formation of a new oceanic tract (Rheic Ocean?) during Cambro-Ordovician times is recorded in the Ossa Morena Zone (Liñán & Quesada 1990; Expósito *et al.* 2003; Sánchez-García *et al.* 2003). A passive margin stage then followed, until the onset of the Variscan orogeny in mid-Devonian times. In this part of the orogen, Variscan tectonics started with oblique subduction of the Rheic Ocean beneath the southern margin of the Ossa Morena Zone, where accretion and eventual obduction of oceanic fragments led

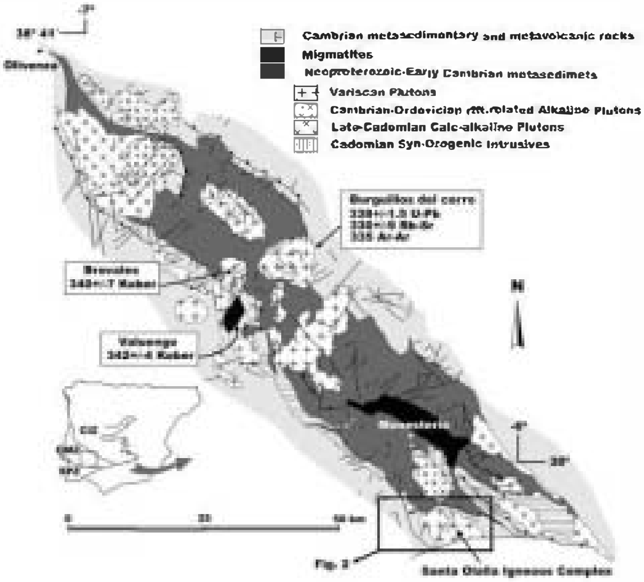

Fig. 1. Map of the plutonic rocks of the Olivenza–Monesterio antiform showing the location of Figure 2, which corresponds to the Santa Olalla Igneous Complex. Inset: southern divisions of the Iberian Massif (CIZ, Central Iberian Zone; OMZ, Ossa–Morena Zone; SPZ, South Portuguese Zone). The Variscan ages of other plutonic complexes in the area are shown.

to the formation of the Pulo do Lobo accretionary prism and Beja–Acebuches Ophiolite (Munhá *et al.* 1986; Silva 1989; Quesada 1991; Quesada *et al.* 1994), at the same time as a modest arc was growing on the hanging-wall, Ossa–Morena plate (Santos *et al.* 1987). Consumption of the ocean finally led to oblique (sinistral) collision with the South Portuguese Zone, widely thought to be underlain by Avalonian basement that was previous amalgamated to Laurussia, which diachronously propagated southeastwards from the Late Devonian to the late Viséan (Ribeiro *et al.* 1990; Quesada 1991). Subsequent orogenesis consisted of sinistral continental subduction of the outer margin of the South Portuguese Zone under the Ossa–Morena Zone until its waning in Early Permian times. Throughout the orogenic process, the Ossa–Morena Zone acted as the upper plate being subjected to a transpressional tectonic regime, as a result of which the pre-existing Cadomian suture was reactivated under sinistral wrench conditions (Badajoz–Córdoba shear zone) and now constitutes the northern boundary of the Ossa–Morena Zone (Ribeiro *et al.* 1990; Abalos *et al.* 1991; Quesada 1991; Quesada & Dallmeyer 1994).

The magmatic evolution of the Ossa–Morena Zone (Casquet & Galindo 2004; Galindo & Casquet 2004) is mainly controlled by the geodynamic history outlined above. Apart from highly deformed and metamorphosed igneous rocks exposed in the exhumed central core of the Badajoz–Córdoba shear zone (reactivated Cadomian suture), whose assignation to any specific unit or sequence is extremely controversial but where the oldest rocks so far dated in the Ossa–Morena Zone occur (*c.* 611–550 Ma; U–Pb discordia, Schäfer 1990; U–Pb sensitive high-resolution ion microprobe (SHRIMP), Ordóñez Casado 1998), the main magmatism related to the Cadomian orogeny corresponds to a significant volume of calc-alkaline rocks, showing a classical arc signature (Sánchez Carretero *et al.* 1990; Galindo & Casquet 2004). Both volcanic and plutonic rocks characterize this magmatic event, which has been dated in the range *c.* 587–532 Ma (U–Pb discordia, Schäfer 1990; U–Pb, Ochsner 1993; U–Pb SHRIMP, Ordóñez Casado 1998). The Cambro-Ordovician rifting event recorded in the Ossa–Morena Zone was accompanied by a voluminous bimodal igneous activity, now represented by volcanic, subvolcanic and plutonic rocks of tholeiitic and alkaline affinity (Mata & Munhá 1990; Sánchez García *et al.* 2003) that have provided ages in the range *c.* 530 Ma to *c.* 470 Ma (U–Pb, Ochsner 1993; K–Ar, Galindo *et al.* 1990; U–Pb SHRIMP, Ordóñez Casado 1998; Pb–Pb Kober, Salman & Montero 1999; Pb–Pb Kober, Montero *et al.* 2000).

The last main magmatic event recorded in the Ossa–Morena Zone took place during the Variscan orogeny and is also represented by volcanic and plutonic rocks. Variscan plutonism, which is most relevant to this study, is characterized by intermediate to acid calc-alkaline compositions ranging from metaluminous tonalite and granodiorite to peraluminous granite and leucogranite, and by volumetrically minor gabbroic plutons. The main Variscan plutonic complex in the Olivenza–Monesterio antiform is the subcircular group of plutons formed by Valencia del Ventoso, Bazana, Brovales (340 ± 4 Ma obtained by Pb–Pb Kober, Montero *et al.* 2000), Valuengo (342 ± 4 Ma obtained by Pb–Pb Kober, Montero *et al.* 2000) and Burguillos del Cerro (330 ± 9 Ma obtained by whole-rock Rb–Sr, Bachiller *et al.* 1997; 335 Ma obtained by Ar–Ar, Dallmeyer *et al.* 1995; 338 ± 1.5 Ma obtained by U–Pb in the allanite mineralization of Mina Monchi, Casquet *et al.* 1998).

Separated from this group of plutons, 50 km to the SE, is the Santa Olalla Igneous Complex, the subject of this study. It is mainly composed of tonalite, with smaller quantities of granite and gabbro, and some ages have already been determined (359 ± 18 Ma obtained by Rb–Sr using all the rocks of the complex, Casquet *et al.* 2001; 332 ± 3 Ma obtained by Pb–Pb Kober in the Santa Olalla tonalite, Montero *et al.* 2000). Finally, an extensional Permian event generated a set of NW–SE-trending diabase dykes (250 ± 5 Ma obtained by K–Ar, Galindo *et al.* 1991) that can be found in several locations in the Ossa–Morena Zone.

Geology of the Santa Olalla Igneous Complex

Igneous rocks

The Santa Olalla Igneous Complex is formed by two main plutons: the Santa Olalla stock and the Aguablanca stock (Fig. 2). The Santa Olalla stock, the larger pluton, is made up of amphibole–biotite quartz-diorite in the northern area grading to the main tonalitic facies in the centre and to a small body of monzogranite towards the southern limit. This change in the igneous facies has been interpreted as due to a reverse compositional zoning (Velasco 1976; Casquet 1980). Towards the NW there is a mafic apophysis called Sultana (Apalategui *et al.* 1990), composed of hornblende–biotite tonalite and quartz-diorite.

In the north part of the complex the Aguablanca stock, a mafic subcircular pluton, occurs. It is composed of phlogopite-rich gabbro-norite and norite, grading to the south to diorite. This intrusion has undergone significant endo-skarn processes along the northern contact induced by contact with carbonate in the Cambrian host rocks (Casquet 1980).

Three granitic intrusions can be found around the Santa Olalla Igneous Complex: Garrote, Teuler and Cala. The Garrote alkaline intrusion is a hornblende-bearing syenitic granite located near the northern boundary of Aguablanca stock. The Teuler intrusion is located on the western side of the Santa Olalla stock;

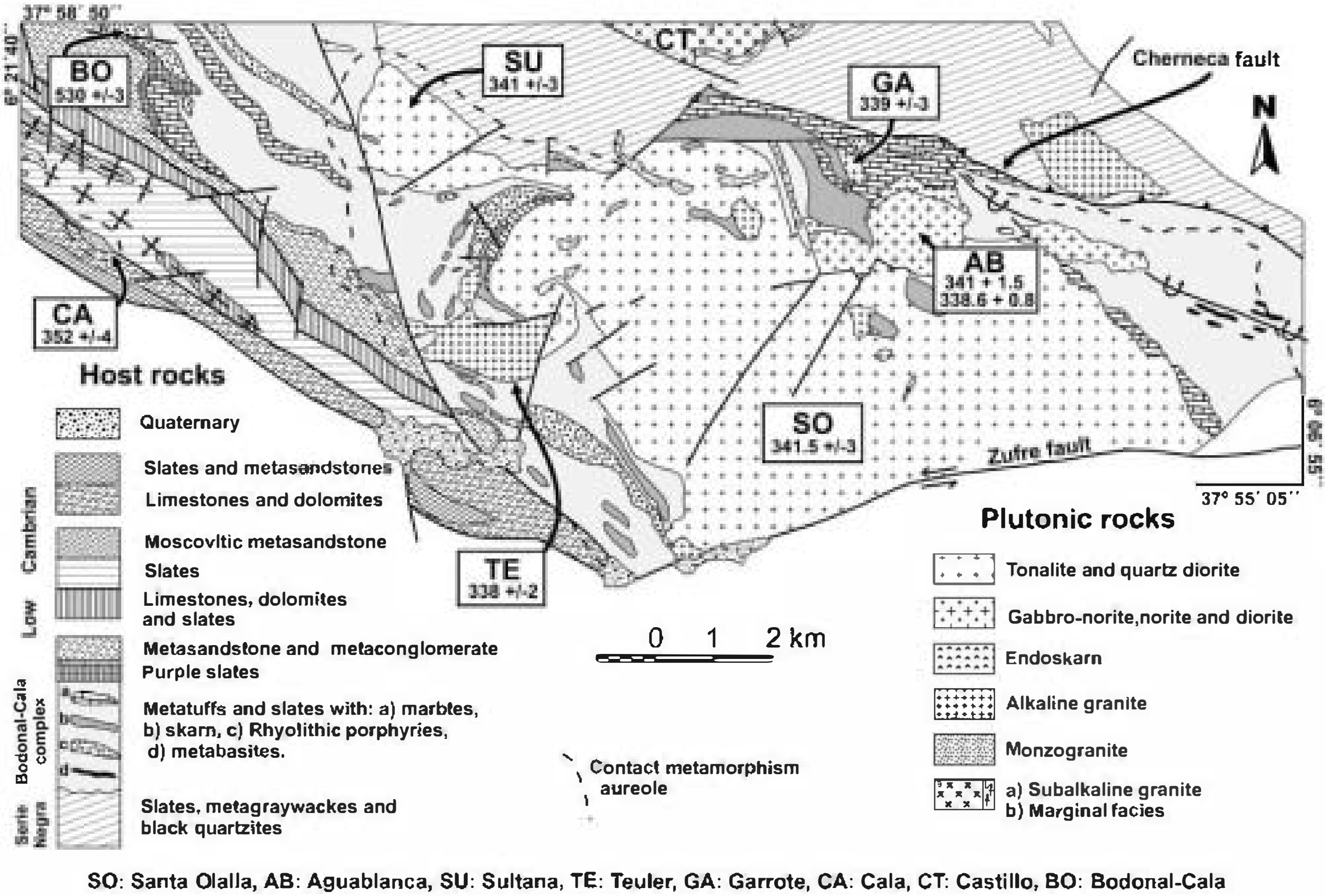

Fig. 2. Geological map of the Santa Olalla Igneous Complex, showing the location of the dated intrusive bodies.

it is a fine-grained biotite monzogranite that generates a magnesian skarn with a magnetite mineralization (Tornos *et al.* 2004*a*). The Cala monzogranite is a very small outcrop located about 8 km west of the Santa Olalla stock (Fig. 2), and hosts the magnetite mineralization of Minas de Cala (Doetsch & Romero 1973; Casquet & Velasco 1978; Velasco & Amigó 1981).

In terms of structural geology the Santa Olalla Igneous Complex is located in a wedge limited by two main faults: the Zufre fault, a sinistral strike-slip fault with a N80° strike, and the Cherneca Fault, which trends parallel to the general Variscan direction in this zone (N120°) and has sinistral strike-slip kinematics (Fig. 2).

Host rocks

The Santa Olalla plutonic complex intrudes two stratigraphic units, both affected by low-grade regional metamorphism. In the NW margin the host rocks are alternating pyrite-bearing black slate and meta-greywacke with thin intercalations of metavolcanic rocks and black quartzite (the Tentudia succession, which is part of the Neoproterozoic Serie Negra, Eguiluz 1988). Towards the north, east and west the igneous rocks intrude the Early Cambrian Bodonal–Cala complex (Eguiluz 1988), which lies unconformably above the Tentudia succession, and it is made up of a volcano-sedimentary sequence of rhyolite, crystalline tuffs, fine tuffs, cinder slates and coarse-grained feldspar-phyric rhyolite (Bodonal–Cala porphyry). The Bodonal–Cala Complex also shows intercalations of carbonate rocks, more abundant towards the top, and their contacts with the igneous rocks produce an exo-skarn characterized by garnetite, marble and calc-silicate rocks (Casquet 1980).

The host rocks are affected by a regional metamorphism of low to very low grade and show an intense superimposed contact metamorphism. The aureole is more than 2 km wide, and consists of albite–epidote facies in the external zone grading into a hypersthene hornfels facies near the igneous body.

The Santa Olalla stock contains numerous roof pendants of the host rock, scattered throughout the igneous rocks. This implies that the upper contact is subhorizontal and has been only incipiently eroded. This interpretation has been corroborated by the dominant subhorizontal planar fabric defined by the orientation of biotite in the Santa Olalla stock (Eguiluz *et al.* 1989)

Ni Cu PGE ore of Aguablanca

The Aguablanca Ni–Cu–PGE deposit (Lunar *et al.* 1997; Ortega *et al.* 1999, 2000, 2004; Tornos *et al.* 1999; Casquet *et al.* 2001; Tornos *et al.* 2001) is hosted by the Aguablanca gabbro-norite and is closely associated with a subvertical (dipping 70–80°N), funnel-like magmatic breccia (250–300 m wide north–south and up to 600 m long east–west) situated in the northern part of this pluton. The breccia comprises barren or slightly mineralized ultramafic–mafic cumulate fragments enveloped by hornblende- and phlogopite-rich gabbro-norite containing disseminated and semi-massive Ni–Cu–Fe magmatic sulphides. Within the breccia, the mineralization is concentrated mainly in subvertical orebodies that are truncated by N40°-trending postmineralization sinistral strike-slip faults.

In detail, the breccia is dominated by a matrix of hornblende- and phlogopite-rich gabbro-norite containing Ni Cu Fe sulphides that host barren or slightly mineralized mafic ultramafic rock fragments. Within the fragments, sulphide occurrences are restricted to weak disseminations (often associated with hydrothermal amphibole) and to chalcopyrite veinlets that cross-cut both fragments and host rocks (Piña *et al.* 2006). In the ore-bearing matrix, mineralization occurs mostly as disseminated and semi-massive sulphide ore. In the disseminated ore, sulphides occur as polymineralic aggregates interstitial to the silicate framework, representing less than 20 modal %. Leopard-textured sulphides (Evans-Lamswood *et al.* 2000), reaching modal proportion as high as 85% but commonly between 20 and 70%, form the semi-massive ore. This texture comprises black spots consisting of idiomorphic silicates (mostly pyroxene, olivine and/or plagioclase) enclosed in a yellowish groundmass of magmatic sulphides.

The Ni Cu PGE ore has been described in detail by Ortega *et al.* (2000, 2004). According to those workers, the main ore minerals forming the magmatic sulphide assemblage are pyrrhotite, pentlandite and chalcopyrite. Accessory minerals include magnetite, ilmenite, rutile, native gold and various platinum-group minerals. The latter are mainly Pt and Pd tellurides and bismutho-tellurides, namely michenerite, merenskyite, palladian-bismuthian-melonite and moncheite, with minor sperrylite and Ir Os As S-bearing-phases. This association is overprinted by hydrothermal pyrite related to the skarn processes.

Recently Piña *et al.* (2006) have performed systematic chemical and mineralogical analyses of a variety of igneous fragments with cumulate textures that the breccia has entrained wrapped in the mineralized sulphide liquid, to reconstruct the sequence of the original cumulate magmatic chamber. The compositions of the various cumulate fragments can be linked by fractional crystallization processes. With the present knowledge of the ore the following genetic hypothesis may be outlined. The segregation of an immiscible sulphide melt took place during the early stages of the evolution of the magma coeval with the crystallization of peridotite. Because of its high density, this sulphide-rich melt settled to the base of the chamber while, above this, the silicate fluid generated the cumulate sequence by crystal fractionation processes. Finally, a new magma pulse intruded the chamber and mingled with the sulphide liquid, breaking into fragments the differentiated complex generated above. Magma overpressure at this position within the chamber, combined with availability of coeval extensional (transtensional) fractures, led to the explosive emplacement of the sulphide-cemented breccias along the fractures into shallower environments.

U–Pb geochronology

Sample preparation and analytical methods

The analytical work was carried out in the Department of Earth Sciences of the Memorial University of Newfoundland, Canada. The method used was similar, in general terms, to that described in detail by Dubé *et al.* (1996). The heavy mineral fraction was concentrated using a Wifley table and heavy liquids, and then a Frantz separator was used to discriminate fractions with different magnetic susceptibilit
the least magnetic fractions yielded the best quality zircons, which were selected according to criteria of morphology and clarity under a microscope.

The zircons were abraded following the air abrasion technique of Krogh (1982) to remove the external surface of the grains in an attempt to minimize Pb loss. The abraded zircons were cleaned and purified using HF and HNO_3, and the ion exchange chemistry was performed in microcolumns following the technique described by Krogh (1973) but reducing the volume of the columns and the reagents in a ratio of 1/10. Finally, the isotopic measurements were performed using a Finningan MAT 262 thermal ionization mass spectrometer.

Uncertainties on the isotopic ratios were calculated at 2σ, considering the uncertainty of the measurements by mass spectrometry, isotopic fractionation and the proportion of initial common lead and its isotopic composition according to Stacey & Kramers (1975). The ages were calculated using Isoplot (Ludwig 1999) and uncertainties are reported at the 95% confidence level.

Sample description and results

The sampling was carried out with the main objective of establishing the crystallization age of the Aguablanca stock and therefore that of the Ni–Cu–PGE ore; to constraint this, two samples were taken. One sample (D7) belongs to the post-mineralization dioritic dykes that cut the gabbroic rocks of the Aguablanca stock, and the other (D6) belongs to a small outcrop of cogenetic hybrid rocks of more felsic compositions that show mingling relationships with the Aguablanca stock. This sample appears completely surrounded by the gabbroic facies of the Aguablanca stock, and forming spectacular mingling contact area that has been the subject of detailed studies (Bateman *et al.* 1992).

The remaining samples were chosen to determine the age of each main igneous body, the Santa Olalla tonalite (D1), the Garrote granite (D8), the Teuler granite (D2), the Cala granodiorite (D3), the Bodonal–Cala porphyry (D4) and the Sultana hornblende tonalite (D5).

***D1, Santa Olalla** (744.77E, 4200.60N UTM29).* A 17 kg sample was collected from fresh rock in a quarry located on the road from Santa Olalla de Cala to Real de la Jara at km 1. It is a granodiorite with small amount of alkaline feldspar belonging to the Santa Olalla stock that yielded large to medium-sized clear high-quality zircons. The grains show shapes from stubby (3:2:2) to large and fine (6:1:1). There is also a small amount of flat, square-shaped euhedral prisms (4:4:1). A group of the largest clear euhedral prisms was selected for abrasion, and three analyses were performed and plotted on a concordia diagram (Fig. 3a). Fraction Z1 gives a $^{207}Pb/^{206}Pb$ age of 352 Ma, whereas Z2 and Z3 give ages of 341 and 342 Ma. The best age estimate is considered to be the weighted average of the $^{207}Pb/^{206}Pb$ ages of these two analyses, which is 341.5 ± 3 Ma (MSWD = 0.05; probability of fit, $P = 0.83$).

***D2**, Teuler (738.92E, 4202.11N UTM29).* This sample was collected from the western part of the Teuler stock, a small granitic intrusion located on the western side of the Santa Olalla stock. D2 is a fine-grained muscovite-bearing biotite monzogranite. This 12 kg sample yielded different shaped zircons that were separated into three fractions: fraction Z1 comprised nine clear large to medium-sized euhedral prism fragments, Z2 consisted of five large elongated prisms, and Z3 contained small clear prisms. These abraded fractions provided two data points with inheritance (fractions Z1 and Z3) and one concordant point (fraction Z2), from which a $^{206}Pb/^{238}U$ crystallization age of 338 ± 2 Ma (Fig. 3b) can be interpreted (Table 1). Although this age has not been duplicated, fraction Z3, despite giving a data point displaced from the concordia as a result of inheritance, yields a similar age of 339.6 ± 2 Ma.

***D3, Cala** (733.00E, 4203.50N UTM29).* The Cala granite appears in a very small (700 m × 300 m) elliptical outcrop located 7 km east of the Santa Olalla stock, and it is responsible for the magnetite mineralization of Minas de Cala. This body is hosted by Early Cambrian sedimentary rocks. The zircons obtained from D3 (a 15 kg sample) are of small size and low quality. The main family of zircons seems to have inherited rounded cores and new rims giving a bipyramidal shape, but two types grains were separated for analysis: fraction Z1 composed of 11 very fine clear euhedral elongated prism fragments (3:1:1 to 5:1:1), and fractions Z2 and Z3 comprising medium-sized elongated prisms with longitudinal fluid inclusions along their cores. The results (Fig. 3c) indicate that Z1 contains inherited cores, but Z2 and Z3 are interpreted to be free of

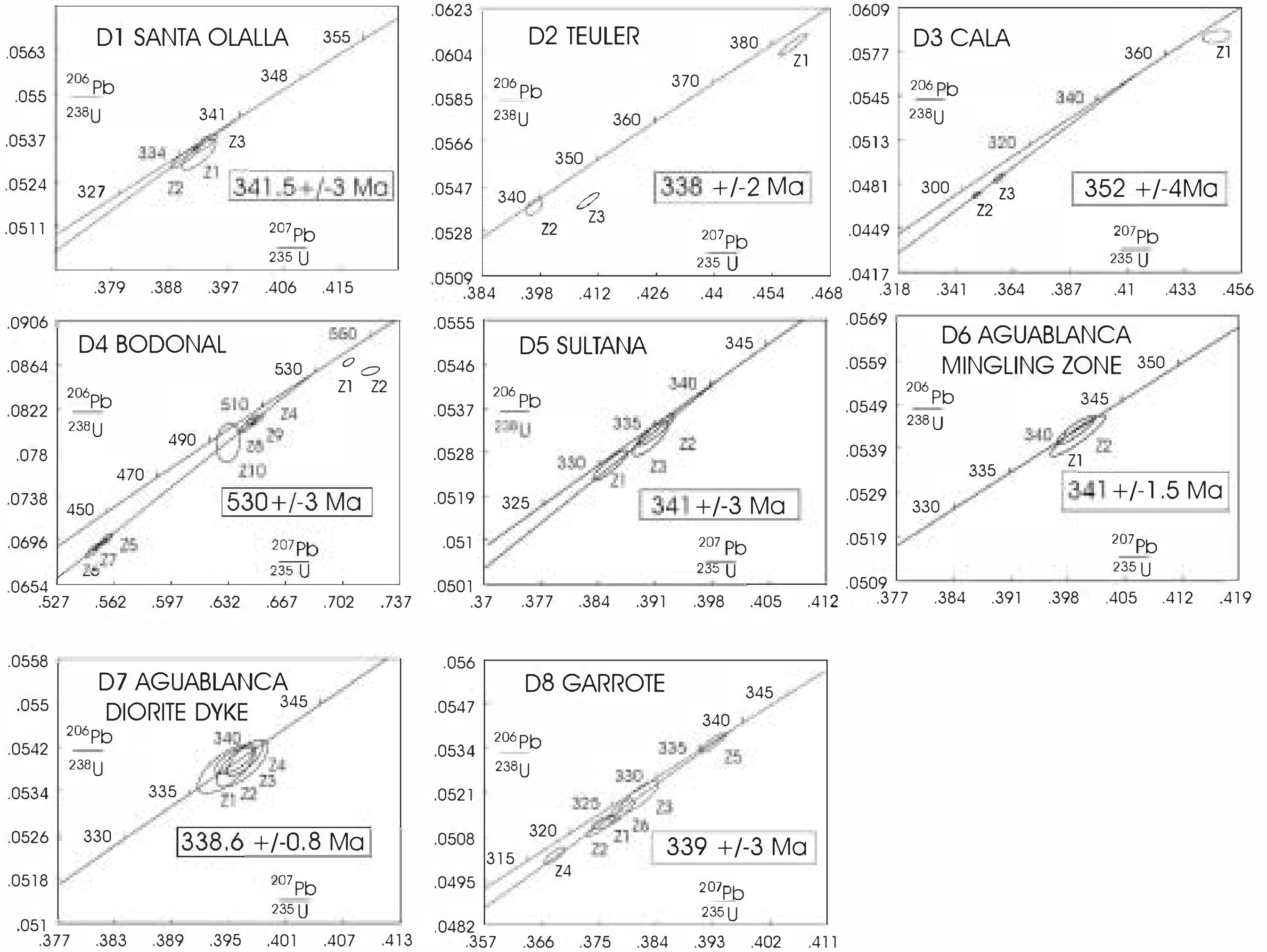

Fig. 3. Concordia diagrams for the eight samples of this study. Error ellipses are plotted with 2σ uncertainties. All the ages are calculated as weighted averages using Isoplot (Ludwig 1999) and uncertainties are reported at the 95% confidence interval.

inheritance, and they provide an age of 352 ± 4 Ma as the weighted average of the $^{207}Pb/^{206}Pb$ ages (MSWD = 0.07, $P = 0.79$).

D4, Bodonal–Cala porphyry (731.00E, 4210.45N UTM29). This sample belongs to the coarse-grained feldspar-phyric rhyolitic subvolcanic intrusions located in the Bodonal–Cala Complex that hosts the Santa Olalla Igneous Complex. The Bodonal–Cala porphyry has been dated at 514 ± 9 Ma (U–Pb SHRIMP on zircons, Ordóñez Casado 1998). This sample was initially collected to compare its age with that of the Aguablanca stock, considering the possibility of an Early Cambrian age for Aguablanca. A 13 kg sample (D4) yielded various shapes of zircons. Fractions Z1, Z2 and Z3 were composed of large to small clear euhedral equant prisms that contained inherited older cores, but fractions Z4–Z10, composed of long and thin prisms and needles, yield consistent collinear data points and the weighted average of the $^{207}Pb/^{206}Pb$ ages of Z4–Z10 is 530 ± 3 Ma (MSWD = 0.74, $P = 0.61$).

D5, Sultana (738.94E, 4205.69N UTM29). The Sultana tonalite has been interpreted (Apalategui *et al.* 1990) as a mafic apophysis of the Santa Olalla Stock. It is a subcircular intrusion located in the NW of the complex and is composed of biotite–hornblende tonalite and quartz diorite that hosts Cu–Au mineralization (Tornos & Velasco 2002; Tornos *et al.* 2004*a*), the exploitation of which is now abandoned. The Sultana body intrudes across the unconformable contact between the Neoproterozoic Tentudia succession (Serie Negra) to the north and the Early Cambrian Bodonal–Cala Complex to the south, being the only body of the complex that shows a contact with the Tentudia succession. A 15 kg sample of tonalite yielded a large amount of coarse-grained colourless high-quality prisms with shapes ranging from elongated (8:1:1) to elongated flat (7:2:1). About 90 clear euhedral grains were selected for abrasion. Fractions Z1, Z2 and Z3, composed of large clear euhedral prisms, yielded high U contents of 170 and 492 ppm (Table 1) and are 2–3% discordant. The weighted average of the $^{207}Pb/^{206}Pb$ ages yields a crystallization age of 341 ± 3 Ma (MSWD = 0.85, $P = 0.43$).

D6, Aguablanca mingling zone (746.62E, 4204.06N UTM29). The Aguablanca stock shows a mingling zone in which the gabbronorite is mingled with a more felsic hybrid rock. The felsic rocks appear completely surrounded by the gabbroic rocks of the Aguablanca stock. This outcrop is located near the contact with the Santa Olalla tonalite, which is modified by brittle faults, in the eastern margin of the Rivera de Cala River. The 13 kg sample yielded a bimodal size distribution of zircon crystals that might be interpreted to be a product of the hybridization process. Small grains are very abundant, whereas only a few large ones were found. A selection of 22 large cloudy euhedral prisms and clear fragments were abraded, with shapes ranging from stubby (3:2:2) to flat stubby (4:3:2) and sharply faceted. Two analyses were carried out on these zircons, both concordant and yielding 341 ± 1.5 Ma as the weighted average of the $^{206}Pb/^{238}U$ ages (MSWD = 0.32, $P = 0.57$, Fig. 3a).

Table 1. *Geochronological data*

	Weight (mg)	Concentration		Measured			Corrected atomic ratios[1]						Age (Ma)		
		U (ppm)	Pb rad (ppm)	Total common Pb (pg)	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	±	$^{207}Pb/^{235}U$	±	$^{207}Pb/^{206}Pb$	±	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
D1, Santa Olalla															
Z1 11 lrg clr prm	0.077	86	4.8	9.9	2262	0.1537	0.05321	36	0.3927	22	0.05352	22	334	336	351
Z2 2 lrg clr euh prm	0.014	441	24.6	12	1672	0.1698	0.05312	26	0.3903	18	0.05329	12	334	335	341
Z3 lrg euh prm	0.045	42	2.4	5.7	1149	0.157	0.05356	20	0.3937	14	0.05331	14	336	337	342
D2, Teuler															
Z1 9 lrg clr frags	0.063	55	3.7	6.1	2195	0.2085	0.06074	38	0.4591	28	0.05481	12	380	384	405
Z2 5 lrg elong prm	0.015	47	2.8	2	1225	0.2414	0.05384	28	0.3966	16	0.05342	24	338	339	347
Z3 15 clr sml prm	0.015	81	5.0	6.3	683	0.275	0.05409	28	0.4096	21	0.05491	14	340	349	409
D3, Cala															
Z1 11 sml frags	0.033	20	1.2	4.5	556	0.1726	0.05882	38	0.4459	46	0.05499	56	368	374	412
Z2 1 med prm, melt icl	0.002	490	23.6	2.8	1079	0.1301	0.04733	18	0.3494	13	0.05354	14	298	304	352
Z3 3 med prm, melt icl	0.006	210	10.4	2.3	1683	0.1262	0.04851	26	0.3583	17	0.05357	18	305	311	353
D4, Bodonal Cala															
Z1 3 lrg clr euh	0.027	39	3.5	16	377	0.1548	0.08662	32	0.7058	28	0.0591	18	535	542	571
Z2 10 sml clr euh	0.02	38	3.2	13	331	0.065	0.08579	32	0.7192	45	0.06081	34	531	550	632
Z3 4 lrg prm	0.012	183	16.8	2.2	5608	0.1123	0.09096	50	0.8002	37	0.0638	20	561	597	735
Z4 6 sml prm	0.012	199	15.5	4.2	2930	0.0563	0.08114	42	0.6499	30	0.05809	14	503	508	533
Z5 8 clr long prm	0.016	385	25.6	2.9	9230	0.0503	0.06981	44	0.558	27	0.05797	24	435	450	529
Z6 8 clr thin long prm	0.012	369	24.4	2.3	8469	0.0595	0.06871	52	0.5497	36	0.05802	24	428	445	531
Z7 10 clr thin long prm	0.015	446	29.6	2.7	10618	0.0551	0.06924	46	0.554	35	0.05802	12	432	448	531
Z8 7 pieces needles	0.014	153	11.9	1.2	8731	0.0629	0.08057	54	0.6438	35	0.05795	24	500	505	528
Z9 9 pieces needles	0.018	247	19.3	2.5	8991	0.058	0.08111	40	0.6471	27	0.05786	18	503	507	525
Z10 8 pieces needles	0.016	89	6.8	10.2	706	0.0682	0.07893	150	0.632	58	0.05808	116	490	497	533
D5, Sultana															
Z1 10 lrg clr euh	0.07	170	10.3	15	2679	0.2865	0.05253	26	0.3855	18	0.05323	12	330	331	339
Z2 10 lrg clr euh	0.05	492	30.1	3.3	24781	0.2804	0.05325	26	0.3912	18	0.05328	10	334	335	341
Z3 8 lrg clr euh	0.04	375	22.9	3.2	15814	0.2853	0.05307	28	0.3904	18	0.05336	16	333	335	344
D6, Aguablanca mingling zone															
Z1 6 lrg euh	0.03	383	23.6	22	1788	0.268	0.05419	38	0.3993	27	0.05344	14	340	341	347
Z2 4 lrg cloudy euh	0.02	198	12.1	4.1	3310	0.2507	0.05432	26	0.399	19	0.05328	12	341	341	341
D7, Aguablanca dioritic dykes															
Z1 6 lrg frags	0.042	50	3.0	4.7	1551	0.2282	0.0538	36	0.3947	24	0.05321	26	338	338	338
Z2 6 lrg clr euh	0.042	90	5.5	5.5	2349	0.2691	0.05395	20	0.3955	16	0.05317	16	339	338	336
Z3 3 lrg clr euh frags	0.015	184	11.4	7.1	1338	0.272	0.0539	34	0.3964	22	0.05334	24	338	339	343
Z4 10 sml clr euh	0.015	142	8.6	4	1826	0.2506	0.054	26	0.3967	16	0.05328	16	339	339	341
D8, Garrote															
Z1 3 clr euh prisms	0.01	396	21.6	4.7	2754	0.1837	0.05124	18	0.3762	18	0.05324	18	322	324	339
Z2 5 clr euh prisms	0.015	687	38.0	5.7	5794	0.2044	0.05112	26	0.3754	18	0.05326	12	321	324	340
Z3 8 clr euh prisms	0.024	239	13.3	3.8	4923	0.1868	0.05198	38	0.3814	24	0.05322	22	327	328	338
Z4 2 lrg frags	0.008	1092	58.4	4.6	6010	0.1842	0.05024	20	0.3681	13	0.05314	12	316	318	335
Z5 3 lrg prisms	0.009	243	13.9	2.5	2913	0.1858	0.05357	22	0.393	16	0.05321	12	336	337	338
Z6 6 lrg clr frags	0.018	297	16.5	2.7	6395	0.1948	0.05159	26	0.3787	16	0.05323	16	324	326	339

Z, zircon fraction; clr, clear; lrg, large; sml, small; euh, euhedral; frags, fragments; prm, prisms; melt icl, melt inclusions.
[1]Corrected for fractionation, spike, laboratory blank of 1–5 pg of common lead and initial common lead at the age of the sample calculated from the model of Stacey & Kramers (1975), and 1 pg U blank. Uncertainties (2σ) are reported after the ratios and refer to the final digits. All fractions were abraded (see Krogh 1982).

D7, Aguablanca dioritic dyke(747.17E, 4205.44N UTM29). The drilling performed by Rio Narcea Gold Mines during the exploration of the Ni–Cu–PGE mineralization of Aguablanca crossed various lithologies that host the ore, ranging from norite and gabbronorite to diorite. The diorite, as the more felsic facies of Aguablanca, was selected for the U–Pb measurement, and D7 belongs to a dioritic post-mineralization dyke. A 10 kg sample from the drill-hole (AGU-37 from 121.9 to 125.0 m, Rio Narcea drilling) was processed, and yielded a large amount of clear euhedral zircon prisms and fragments, which were abraded. The four analyses (fractions Z1–Z4) are all concordant (Fig. 3g), giving 338.6 ± 0.8 Ma as the weighted average of the $^{206}Pb/^{238}U$ ages (MSWD = 0.29, P = 0.83).

D8, Garrote (746.21E, 4205.88N UTM29). The Garrote intrusion is a very small pluton of hornblende syenite granite located inside the contact aureole of the Aguablanca stock. A 4 kg sample from the Garrote granite from drill-hole AGU-51 (Rio Narcea drilling), was processed, and yielded some euhedral clear to somewhat altered zircon prisms and fragments. In general, two morphologies of grains were separated for abrasion: medium-sized clear euhedral prisms with shapes grading from stubby (3:1:1) to flat stubby (4:2:1) that yielded fractions Z1–Z3, and large prisms and fragments (fractions Z4–Z6). All the measurements fit a discordia line to 0 Ma (Fig. 3h). The weighted average of the $^{207}Pb/^{206}Pb$ ages of all analyses except the most discordant (fraction Z4) gives an age of 339 ± 3 Ma (MSWD = 0.09, prob. of fit = 0.98).

Discussion

The geochronological results obtained in this study clearly define a Variscan age (Tournaisian Viséan) for all the plutonic rocks analysed, ranging, with errors at the 95% confidence interval, from 336 to 356 Ma (Fig. 4). The data obtained from samples of the Aguablanca Stock D6 and D7 (341 ± 1.5 and 338.6 ± 0.8 Ma, respectively), indicate that the Ni Cu PGE ore has a Carboniferous age rather than being Cambro-Ordovician. This has important implications in the genetic model for this deposit, as it means that the mineralization developed during a collisional tectonic regime rather than being related to rifting, traditionally considered the most favourable geodynamic context for the formation of Ni Cu PGE ores (Lesher 2003). The recent Ar Ar (phlogopite) results obtained by Tornos *et al.* (2004*b*) indicate a similar age for the stock and the mineralized breccia: an age of 338 ± 3 Ma was obtained from the gabbronorite that hosts the breccia and 335 ± 2 Ma from a gabbronorite fragment of the mineralized breccia. The two ages should be equivalent, as the breccia intruded at 1000 1400 °C (Tornos *et al.* 2001), so the closure temperature was reached during the *in situ* subsolidus cooling of the mineralized breccia and the gabbro together. These Ar Ar results from Tornos *et al.* (2004*b*) should be compared

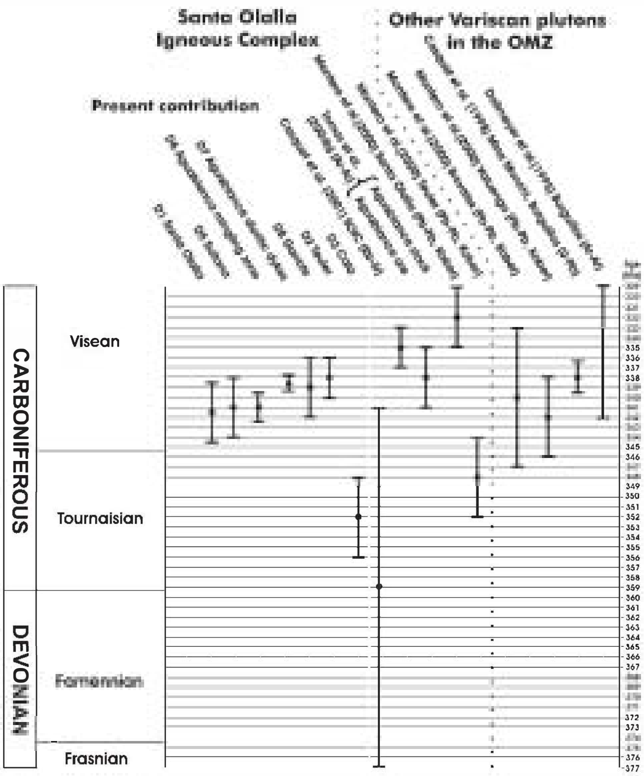

Fig. 4. Comparison of newly obtained ages for the Santa Olalla Igneous Complex with previous ages of rocks of this complex and other similar intrusions of Variscan age in the Ossa–Morena Zone.

with the age of D6 (341 ± 1.5 Ma), which belongs to felsic hybrid rocks of the mingling zone found within the Aguablanca gabbro. The ages obtained in this study are slightly older but the interval of 339–341 Ma is represented in both the U–Pb and Ar–Ar datasets.

Although the new data are all restricted to a short period (336–356 Ma), different intrusive stages can be defined using both the absolute U–Pb results and relative temporal cross-cutting relationships found in the field.

The earliest intrusive body in this area is the Cala granite (352 ± 4 Ma); it is a small outcrop separated from the rest of the rocks of the area. The skarn processes associated with this intrusion generated the magnetite mineralization of Minas de Cala (Doetsch & Romero 1973). The Cala granite could be related to the same source as the Santa Olalla Igneous Complex, but formed by a magma pulse *c.* 10 Ma earlier.

The next intrusive event generated the main rocks of the complex. The U–Pb ages determined for this second stage are 341 ± 1.5 Ma (Aguablanca mingling zone), 341.5 ± 3 Ma (Santa Olalla stock) and 341 ± 3 Ma (Sultana hornblendic tonalite). This corresponds to the main magmatic stage that generated the Aguablanca stock, the Santa Olalla stock and its mafic apophysis Sultana. The Santa Olalla Igneous Complex had been interpreted to have formed by two different intrusions, the Aguablanca stock and the Santa Olalla stock (Casquet 1980; Casquet *et al.* 1998), but the present absolute age constraints and the mingling zone located in the south of the Aguablanca stock seems to indicate that the two plutons correspond to different pulses of a single intrusive event. These igneous rocks, emplaced 341 + 4/− 3 Ma ago, were probably derived from a complex source or sources, as was postulated by Eguiluz *et al.* (1989) and Bateman *et al.* (1992).

The Santa Olalla stock seems to be post-kinematic with respect to the penetrative deformation of the host rocks but is affected by left-lateral strike-slip faults of late Variscan age (e.g. the Zufre fault). This indicates that the main Variscan deformation was completed in this part of the Ossa–Morena Zone before *c.* 341 Ma or that this area was already exhumed to shallow crustal depths at the time of Santa Olalla Igneous Complex intrusion.

The Santa Olalla stock and the Teuler granite were previously dated (Montero *et al.* 2000; Salman 2004) by the Pb–Pb Kober technique (Kober 1986, 1987) and yielded ages of 332 ± 3 Ma and 348 ± 4 Ma, respectively. These results are clearly in contrast to the U–Pb ages obtained in this study (341 ± 3 Ma for the Santa Olalla stock and 338 ± 2 Ma for the Teuler granite). The reason for this discrepancy is difficult to elucidate, as the Kober technique does not give the U–Pb information needed to plot the data on a concordia diagram; thus it is not known if these results would have been concordant or very discordant. For the age determinations by the Pb–Pb Kober technique (Montero *et al.* 2000; Salman *et al.* 2004) several grains were wrapped in one Re ribbon and heated over a series of temperature steps. Each step yields an 'age' that can be calculated from the lead measurements, but their significance is unclear. One poor quality zircon might give off a lot of lead at lower temperature, and contain more common lead, whereas another, high-quality zircon might not break down and release its lead until much higher temperature. Thus these data are difficult to interpret. We consider that the most likely crystallization age for the Santa Olalla stock is 341.5 ± 3 Ma and for the Teuler granite is 338 ± 2, determined here using isotope dilution thermal ionization mass spectrometry (ID-TIMS; see Fig. 3).

The last magmatic stage was characterized by the emplacement of dioritic dykes in the Aguablanca stock and by the intrusion of the Garrote and Teuler granites. These rocks have yielded similar ages of 338.6 ± 0.8, 339 ± 3 and 338 ± 2 Ma, respectively. The age of the dioritic dykes (slightly younger than the age attributed to the Aguablanca stock) is consistent with the observed relationships in the field, where the dioritic dykes always occur cutting the gabbronorite of the Aguablanca stock. The age for D8 (Garrote granite) overlaps, within uncertainties, the ages of samples of the main magmatic stage (D1, Santa Olalla; D5, Sultana; D6, Aguablanca mingling). However, during the exploration campaign for the Aguablanca ore, the drilling exposed a contact between the Aguablanca stock and the Garrote granite (these two bodies are separated at the surface level by Cambrian marbles). In the contact zone aplitic dykes and veins from the Garrote granite cut the gabbronorite of the Aguablanca stock (Fig. 5), an observation that agrees with the younger age obtained for D8, Garrote.

The ages obtained for the Teuler and Garrote granites permit these intrusions to be considered part of the Santa Olalla Igneous Complex, a fact that contradicts the hypothesis that these bodies were related to rhyolitic–dacitic porphyries of Cambrian age (Apalategui *et al.* 1990). Only the Bodonal–Cala porphyry, forming part of the host rocks of the Santa Olalla Igneous Complex, has yielded a Cambrian U–Pb age of 530 ± 3 Ma. This is significantly older than the U–Pb zircon age of 514 ± 9 Ma obtained by the SHRIMP technique elsewhere in the region (Ordóñez Casado 1998). The difference may be related to the complexity of the Bodonal–Cala Complex, which may well be diachronous across the Ossa–Morena Zone, as dated cogenetic plutons in other parts of the Olivenza–Monesterio antiform range in age from *c.* 530 to 505 Ma (U–Pb, Ochsner 1983; K–Ar, Galindo *et al.* 1990; U–Pb SHRIMP, Ordóñez Casado 1998;

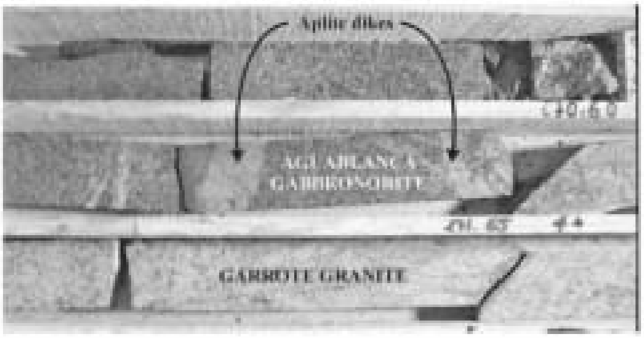

Fig. 5. Photograph showing Garrote granite dykes cutting Aguablanca gabbronorite as exposed by the exploration drilling by Rio Narcea Gold Mines in the Aguablanca ore zone.

Pb–Pb Kober, Salman & Montero 1999; Pb–Pb Kober, Montero *et al.* 2000).

Comparing the magmatic event that generated the Santa Olalla Igneous Complex (336–345 Ma for the main rocks of the complex and 352 ± 4 Ma for the Cala granite) with the rest of the Variscan plutons dated in the Ossa–Morena Zone, that is, Brovales (340 ± 4 Ma, Montero *et al.* 2000), basic rocks from the Valuengo complex (342 ± 4 Ma, Montero *et al.* 2000) and Burguillos del Cerro (335 Ma by Ar–Ar, Dallmeyer *et al.* 1995; 330 ± 9 Ma by whole-rock Rb–Sr, Bachiller *et al.* 1997; 338 ± 1.5 Ma by U–Pb from allanite mineralization of Mina Monchi', Casquet *et al.* 1998), it becomes obvious that both intrusive complexes, the Santa Olalla Igneous Complex and the Burguillos–Brovales–Valuengo complexes, were generated during a main Variscan magmatic event, lasting from 353 to 329 Ma.

Recently, Simancas *et al.* (2003) interpreted a deep seismic reflection profile (IBERSEIS) that completely crosses the Ossa–Morena Zone and the contacts with the Central Iberian Zone to the NE and the South Portuguese Zone to the SW. The most interesting feature revealed by this seismic profile is the so-called Iberseis Reflective Body, a long (>175 km) and wide (1.5 s of average thickness) layer located between the upper and lower crust, characterized by high-amplitude reflections. A mafic–ultramafic layered intrusion has been proposed to explain this feature, in which most of the Variscan igneous rocks could have a source (Simancas *et al.* 2003) but, considering the high electrical conductivity found in the zone where the Iberseis Reflective Body is located (Pous *et al.* 2004), the hypothesis of a single magmatic intrusion cannot be sustained. Pous *et al.* (2004) proposed instead that the Iberseis Reflective Body consists of a complex sheet-like set of intrusions separated by screens of highly conductive graphite-rich rocks from the Serie Negra. The high-amplitude reflections could be explained by the alternation of the mafic–ultramafic igneous rocks and the host rocks of the Serie Negra, and the high conductivity by the presence of interconnected graphite in the Serie Negra. Following this interpretation, the magmatic activity in the upper crust recorded during Variscan times (353–329 Ma) in the Ossa–Morena Zone, including the rocks of the Santa Olalla Igneous Complex dated here, could be a shallow expression of the magmas stored in the hypothetical Iberseis Reflective Body mafic–ultramafic intrusive complex that have undergone fractionation and crustal contamination processes during magma ascent. The presence of a mafic magma source during the time of emplacement of the Santa Olalla Igneous Complex and associated formation of the Aguablanca Ni–Cu–PGE ore gives support to the ore-forming model of Piña *et al.* (2006), in which an ideal mafic–ultramafic magma chamber has been interpreted, based on the geochemical relationships observed between the cumulate mafic–ultramafic fragments of the mineralized breccia. However, the present depth of this possible mafic–ultramafic magma chamber, which has been postulated as the site at which the immiscible separation of the sulphide phase took place (Piña *et al.* 2006), cannot be determined with the present constraints. Although it might be at the hypothetical Iberseis Reflective Body sheeted complex, it is also possible that the chamber was shallower. This is strongly suggested by the fact that all the fragments forming the breccia are mafic and ultramafic cumulates and there are no extraneous fragments from the host rocks. The possibility that the source chamber for the sulphides may occur at an exploitable level is focusing the mineral exploration efforts in the Aguablanca area.

Conclusions

In this geochronological study of the Variscan magmatism in the Ossa–Morena Zone we have determined seven new U–Pb ages from the Santa Olalla Igneous Complex, including: 352 ± 4 Ma for the Cala granite; 341.5 ± 3 Ma for the Santa Olalla tonalite; 341 ± 3 Ma for the Sultana hornblende tonalite; 341 ± 1.5 Ma for a mingling area inside of the Aguablanca stock; 338.6 ± 0.8 Ma for dioritic dykes from the Aguablanca stock; 339 ± 3 Ma for the Garrote granite; 338 ± 2 Ma for the Teuler granite.

The sequence of intrusions in the Santa Olalla Igneous Complex can be summarized as follows: the first stage (352 Ma) is represented by the Cala granite, with which the Cala magnetite deposit is associated; the second stage (341 Ma) involved the emplacement of all the main plutons of the igneous complex, including the Santa Olalla tonalite, the Sultana hornblende tonalite and the Aguablanca gabbronorites; the third stage (338–339 Ma) involved the intrusion of dioritic dykes in the Aguablanca stock and the Gartote and Teuler granites.

The controversial age for the Aguablanca intrusion and its associated magmatic Ni–Cu–PGE deposit has been solved, yielding an age for the stock emplacement of 341 ± 2 Ma, with a later intrusion of a set of dioritic dykes at 338.6 ± 0.8 Ma. The U–Pb ages provide constraints on the possible stratigraphic location of new potentially similar Ni–Cu–PGE deposits in the region, in connection with transtensional stages during the Variscan collision. The uniqueness of this deposit in terms of geological conditions has promoted an extensive and ambitious exploration programme, which has led to the identification of more than 100 targets in the Ossa–Morena Zone with anomalies similar to that at Aguablanca.

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