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THE IRON OXIDE COPPER-GOLD BELT OF THE OSSA MORENA ZONE, SOUTHWEST IBERIA: IMPLICATIONS FOR IOCG GENETIC MODELS

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Abstract - The Ossa Morena Zone (OMZ), in southwestern Iberia, is considered one of the most significant metallogenic belts in Europe. It has a complex, polyphase geologic history, and hosts a variety of classic and unusual ore styles, including magmatic nickel-copper and a number of IOCG-style deposits. These ores are only slightly metamorphosed and deformed, in contrast to older deposits elsewhere, allowing detailed studies to establish their origin and evolution. The OMZ hosts two main styles of IOCG mineralisation: (1) mesozonal albitite-related, replacive magnetite deposits of both Cambrian and Variscan age, and (2) shallower, complex, hydrothermal magnetite-(copper-gold) replacements related to trans-crustal shear zones. Both of these IOCG-styles coexist with Early Cambrian stratabound iron oxide-rich mineralisation found in the same area. The albitite-related deposits reflect complex magmatic-hydrothermal processes, in the form of genetically associated magmatic albite±magnetite rocks which are the product of anatectic rejuvenation of earlier iron-rich (chemical) sediments. The depth extension of the structurally-related shear hosted ores is unknown, although they are also interpreted to be the result of remobilisation of earlier mineralisation by metamorphic fluids channelled along major structures. Coexistence of IOCG deposits with pre-existing stratabound iron-rich sediments is a feature common in many IOCG belts world-wide, suggesting that in many cases, IOCG mineralisation can be derived from hydrothermal/magmatic remobilisation of pre-existing mineral accumulations.

Introduction

The Ossa Morena Zone (OMZ) is one of the southernmost terranes of the European Variscan Belt (Fig. 1), and probably the most complex and discussed geological area within the Iberian Massif. Recent interpretations propose that it includes a Cadomian volcanic arc, formed during the accretion of an exotic terrane to the Iberian Autochthon in Cadomian (620 to 550 Ma) times (Dallmeyer and Quesada, 1992; Eguíluz *et al.*, 2000). Subsequently, during Variscan times (372 to 332 Ma), it hosted a second magmatic belt, formed during the oblique collision of the already amalgamated Iberian Terrane (including the OMZ) and the South Portuguese Zone (Silva *et al.*, 1990; Quesada, 1992).

The OMZ hosts abundant ore deposits and mineral occurences, related to both the Cadomian and Variscan orogenic cycles, as well as to an intermediate rift stage of Early Palaeozoic age. This complex geologic history has built up many different styles of mineralisation in a rather restricted area, including stratabound copper-zinc-lead and iron rich volcano-sedimentary, sedimentary-exhalative and sediment hosted lenses, iron oxide-(copper-gold) deposits, podiform chromite, magmatic nickel-copper, copper-gold-bismuth and zinc-lead veins, as well as different types of skarn and replacive mineralisation. Most of these deposits and related igneous rocks are controlled by transcrustal strike slip structures (Liñan and Quesada, 1990; Tornos *et al.*, 2004). These large, west to westnorthwest trending faults have controlled sedimentation, magmatism and hydrothermal activity within the OMZ since the Late Proterozoic (Quesada *et al.*, 1987), and have been episodically rejuvenated. At least during the Variscan orogeny, spatially restricted extensional zones, such as pull-apart structures and dilational jogs within the overall compressional setting, have been the loci of preferred intrusion and hydrothermal activity (Tornos *et al.*, 2002).

The OMZ has been a significant contributor to the mineral wealth of Europe, and during different periods was a major producer of lead, zinc and iron. Currently, the only active mines are Aguablanca (nickel-copper) and Cala (iron). The recent discovery of new styles of mineralisation and their unusual geologic evolution, has promoted active exploration, mostly focused on magmatic nickel-copper, IOCG and orogenic gold deposits.

Recent studies (Tornos and Casquet, 2005; Tornos and Carriedo, 2006), have shown that not all the iron-rich deposits of the OMZ can be classified as sedimentary-exhalative or skarn-like mineralisation, as has been traditionally accepted. Some of these deposits share features with the IOCG family of deposits, and although usually exploited for magnetite, some also have significant accompanying copper and gold grades. Furthermore, there are magnetite-poor, but copper-gold-rich prospects that have geochemical features similar to IOCG-style mineralisation, suggesting that the area includes a broad spectrum of deposits formed by different mechanisms, but all sharing some common characteristics.

Geological Setting

The stratigraphy of the OMZ includes two Proterozoic sequences and one complete Early Palaeozoic succession (Fig. 2). Late Palaeozoic rocks are only found in some restricted syn-orogenic basins, while Mesozoic sediments are absent. The Proterozoic commences with the Serie Negra Formation of Late Neoproterozoic (Vendian) age (Schäfer, 1990; Dallmeyer and Quesada, 1992; Ordoñez-Casado, 1998), composed of dark schist and meta-greywacke, with interbedded lenses of black quartzite and amphibolite. This unit is unconformably overlain by the Malcocinado Formation, a synorogenic Cadomian volcano-sedimentary sequence with dacitic, rhyolitic-andesitic lava and volcaniclastic rocks interbeded with phyllite, greywacke and heterolithic breccias. This calc-alkaline volcanism is broadly synchronous with a complex suite of geochemically similar plutonic rocks of Vendian to Early Cambrian age (Quesada and Dallmeyer, 1989;

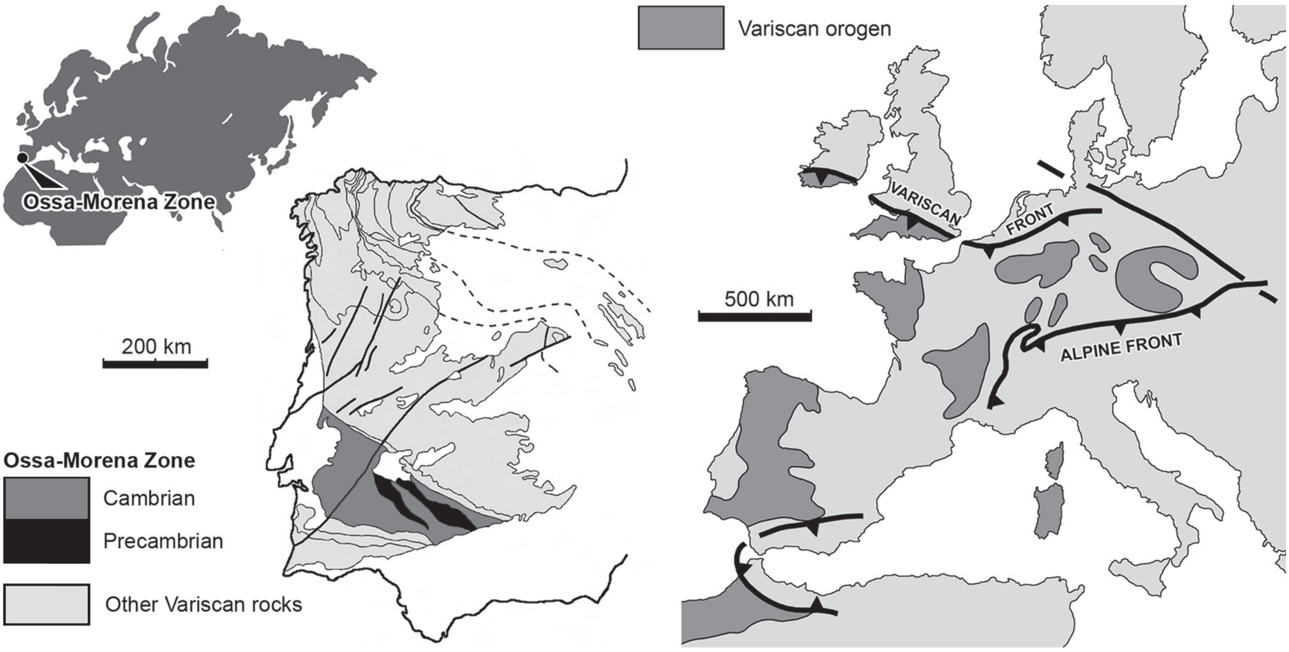


Figure 1: Geographic distribution of the Variscan Orogen in Europe (right), location of the Ossa Morena Zone within the Iberian Massif (centre; modified from Julivert *et al.*, 1974) and Eurasia (top left).

Galindo *et al.*, 1990; Ochsner, 1993; Ordoñez-Casado, 1998). Together, they are interpreted to be the products of Andean-style, arc-related magmatism developed during the southward subduction of an oceanic plate beneath the OMZ (Sanchez Carretero *et al.*, 1990; Martinez Poyatos, 1997; Pin *et al.*, 2002), culminating in the accretion of this exotic volcanic arc and the underlying basement (the current OMZ) onto the autochthonous Central-Iberian Zone (Quesada, 1990; Quesada, 1992).

Cambrian sedimentation was synchronous with waning Cadomian deformation and the onset of a rifting event. Progressive extension produced an evolution from subaerial to shallow marine conditions, with the deposition of a major carbonate shelf. This was followed by widespread bimodal volcanism, comprising basaltic and rhyolitic rocks of alkaline to tholeiitic composition, also deposited in a shallow marine environment. The dominant felsic rocks are fragmental volcaniclastics, with only small outcrops of coherent facies. Mafic rocks include pillow lavas and related hyaloclastites with subordinate volcaniclastic rocks (Sagredo and Peinado, 1992; Giese and Bühn, 1993). This Early Cambrian sequence is followed by monotonous, fine-grained, detrital sedimentation, with minor intercalations of siliciclastic sandstone, carbonates and volcanic rocks of Late Cambrian to Ordovician age.

The extensional regime was also accompanied by the intrusion of large volumes of a complex suite of plutonic rocks, grouped in two different batches of magma emplacement at 530±5, and 517 to 502±2 Ma (Sánchez-García *et al.*, 2008). This heterogeneous magmatism includes early felsic per-aluminous rocks with related anatectic and core-complex structures in mid to upper crustal environments, and younger epizonal (<7 km depth) plutonism, representing the roots of the bimodal volcanism.

The Variscan (370 to 330 Ma) deformation is controlled by sinistral strike-slip faults (Quesada, 1990; Ribeiro *et al.*, 1990; Abalos *et al.*, 1991; Quesada, 1991; Quesada and Dallmeyer, 1994). Complex transpressional-transtensional deformation produced a major compartmentalisation of the OMZ and, as stated above, controlled both magmatism and hydrothermal activity. The Variscan orogeny commenced with the oblique subduction of the Rheic Ocean beneath the southern margin of the OMZ, accompanied by obduction of oceanic fragments (Munhá *et al.*, 1986; Munhá *et al.*, 1989; Silva *et al.*, 1990; Quesada and Dallmeyer, 1994; Simancas *et al.*, 2001) and by the coeval growth of a modest magmatic arc on the Ossa Morena plate. Subduction of this oceanic crust culminated in oblique collision with the South Portuguese Zone (Ribeiro *et al.*, 1990; Quesada, 1991) that lasted until Early Permian times. The main synorogenic sedimentation took place between the Devonian and Early Carboniferous, coinciding with an extensional stage between two compressive episodes, of Devonian and Late Carboniferous ages respectively. During this period, sedimentation occurred in two separated marine basins, located near the southern and northern boundaries of the OMZ, separated by an emergent high over which continental sedimentation is only recorded in small isolated basins (Gabaldon *et al.*, 1985; Quesada, 1990). With the exception of four discrete areas which include medium to high grade metamorphic rocks, the regional Variscan metamorphism is of low to very low grade (López-Munguira and Nieto Garcia, 2004).

The most significant geologic event related to the Variscan orogeny was the intrusion of large plutons of subvolcanic I-type, high-K, calc-alkaline rocks. These intrusions are widespread within the OMZ and record crystallisation ages of between 352± 4 and 332±3 Ma (Dallmeyer *et al.*, 1995; Casquet *et al.*, 1998; Montero *et al.*, 2000, Romeo *et al.*, 2006). They are generally zoned, and are mainly composed of diorite, tonalite and granodiorite, with minor gabbroic and noritic cumulates. Discrete granitic and leuco-granitic stocks and dyke swarms of per-aluminous affinity were intruded late in the Variscan magmatism. Magma emplacement took place at depths of between 1.5 and 3 km (Sanchez Carretero *et al.*, 1990; Dallmeyer and Quesada, 1992; Ochsner, 1993), and produced large contact metamorphic aureoles.

The origin of these plutonic rocks is uncertain, as they are not related to major volcanic activity typical of magmatic arcs. Recent seismic profiles have shown that the OMZ is underlain by a large reflective body (the IRB, or IBERSEIS Reflective Body) with geophysical features compatible with a large (150 to 170 km long x 1 to 5 km thick), discontinuous, sub-horizontal, mafic-ultramafic intrusion (Simancas *et al.*, 2004). This slab was emplaced in a mid-crustal decollement zone at a depth of 15 to 20 km and was likely emplaced along a major tectonic discontinuity reflecting the brittle-ductile transition where the major Variscan thrusts are rooted. The presence, and interpretation, of the IRB as a complex of large layered intrusions is supported by a regional magnetic anomaly and systematic juvenile $^{207}Pb/^{206}Pb$ signatures of Variscan mineralisation (Tornos and Chiaradia, 2004). The tectonic reconstruction of the area shows that the IRB crops out in the Aracena Metamorphic Massif (southwest of the Olivenza Monesterio Antiform; Fig. 4) where highly crust-contaminated mafic-ultramafic rocks dated at 336±2 Ma are hosted by high-temperature/low-pressure metamorphic rocks (Tornos *et al.*, 2008). It is very likely that the IRB has controlled most of the magmatism and related mineralisation in the area. Intrusion of large amounts of juvenile rocks into the low metamorphic grade middle crust produced major crust-melt interaction, and the formation of water-rich, highly contaminated melts, synchronous with high-T/low-P metamorphism and widespread anatexis. Both processes are regarded as having been critical to the formation of magmatic nickel(-copper) and IOCG deposits (Tornos and Casquet, 2005).

Most of the ore deposits of the OMZ are located in the Olivenza-Monesterio belt (Locutura *et al.*, 1990; Tornos *et al.*, 2004) that broadly coincides with the Olivenza-Monesterio structure, a major regional antiform with a northwest-southeast trend and southwest vergence. The core of this structure includes basement rocks of the Serie Negra Formation, which are unconformably overlain by Early- to Middle-Cambrian siliciclastic and carbonate sediments, and abundant interbedded bimodal volcanic rocks. The innermost zone includes widespread magmatism, ranging in age from Proterozoic to Permian. One of the most significant features of the Olivenza-Monesterio belt is the presence of abundant and large bodies of albite-rich leucogranite (albitite). Detailed mapping, geochemistry and geochronology (Sánchez-García *et al.*, 2008) show that there are two major groups of albitite. The dominant group includes discrete, up to kilometre-sized, mesozonal (~7 to 15 km depth) intrusions (containing 65 to 78 wt.% SiO_2) of Cambrian (530 to 500 Ma) age (Sánchez-García *et al.*, 2008). The albitite is made up of sparse quartz and albite phenocrysts in a coarse-grained groundmass of sub-euhedral albite. There are local ghosts of likely phenocrysts of amphibole almost totally replaced by albite. Apatite, titanite, magnetite, fluorite, monazite and zircon are ubiquitous accessory minerals. Preliminary melt inclusion data (Tomé and Tornos, unpublished data) suggest that the albitite is a primary magmatic rock and not the product of metasomatic alteration of leucogranite by Na-rich fluids, as has been proposed as the main mechanism for albitite formation in other areas (Schwartz, 1992; Zhu *et al.*, 2001). A second group includes equivalent rocks, sometimes rich in magnetite, that occurs as small elongated stocks or dyke swarms with aplitic to pegmatitic textures. These rocks crosscut the large Variscan plutons that have been dated at 340±4 Ma (Montero *et al.*, 2000), and have also been described by Bachiller (1996) in the Burguillos del Cerro pluton (Fig. 4). They have been dated at 337±7 Ma (Rb-Sr; Bachiller, 1996).

The origin and petrogenetic significance of the albitite is controversial. The Cambrian leucogranite has been interpreted as the sub-volcanic equivalent of the rift-related volcanism of Early Cambrian age (Sánchez-García *et al.*, 2008). Their REE patterns are interpreted as consistent with a derivation from the crystallisation of residual melts produced during the fractional crystallisation of juvenile basalt, i.e., being equivalent to the oceanic plagiogranite. However, preliminary radiogenic isotope data from the Variscan albitite seems to reflect mixing between magmas of dioritic derivation, with a dominant crustal component, likely resulting from the partial melting of siliciclastic rocks (Bachiller, 1996).

The Valuengo Area

The ellipsoidal (20°, or NNE-trending), dome-like Valuengo structure (Fig. 4) which covers an area of 28 km^2, has a core of high grade metamorphic rocks, including meta-pelitic and meta-volcaniclastic gneiss and schist, and widespread migmatisation and anatectic granitoids (Apraiz and Eguíluz, 1996). This core is bounded by low angle extensional faults that abruptly juxtapose underlying high-temperature/low-pressure metamorphism amphibolite facies rocks, with peripheral/overlying Early Cambrian greenschist facies meta-sediments and volcanic rocks, and related stratabound iron oxide mineralisation.

All of these observations taken together, suggest that this structure represents a metamorphic core complex, linked with extension and exhumation associated with gravitational collapse of a swelled crust. The Lora del Rio Core Complex, located on the southeastern margin of the Olivenza-Monesterio antiform, has analogous characteristics (Apraiz and Eguíluz, 2002), including ductile shearing at medium and lower crustal levels and localised brittle deformation during the final stages of exhumation.

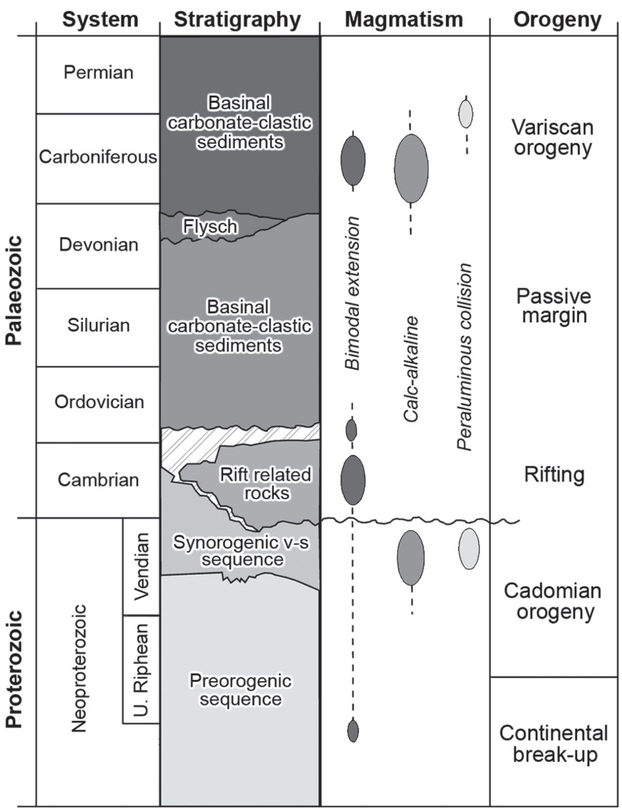


Figure 2: The stratigraphic succession and temporal correlation of the main igneous and tectonic events of the Ossa Morena Zone, southwestern Iberia (adapted from Quesada, 1992).

Partial melting and migmatite formation within the Lora del Río core, as well as related high-temperature/low-pressure recrystallisation, took place at 340±13 Ma (SHRIMP zircon U-Pb age, Ordoñez Casado 1998).

The Valuengo dome is bounded to the west by the major Monesterio Shear Zone, a feature of regional significance that probably separates different terranes within the OMZ (Quesada, 1991). Abundant plutonic rocks surround the whole Valuengo dome. In the east, there are intrusions of albitite dated at ca. 520 Ma (Carriedo, *in litt.*), while to the west, the major Variscan, calc-alkaline, Brovales pluton (Fig. 4), which has been dated at 340±7 Ma (Montero *et al.*, 2000), was probably intruded along the Monesterio Shear Zone. The latter intrusion is similar to, and coeval with, the other Variscan calc-alkaline intrusions of the area, which are systematically associated with magnetite skarn mineralisation. Albitite is always related to carbonate-rich rocks of Early Cambrian age, with limestone found as roof pendants and replaced by barren calcic skarns and IOCG mineralisation.

Regionally, the Early Cambrian stratabound iron mineralisation can be traced along both limbs of the Olivenza-Monesterio structure, forming discontinuous magnetite-rich horizons 5 to 6 km long (Vázquez and Fernández Pompa, 1976; Coullaut, 1979). Where the metamorphic grade and deformation are low, the mineralisation appears as fine grained magnetite, interbedded with volcaniclastic sandstone and underlying limestone.

Stratabound Iron-rich Deposits

The Early Cambrian sequence of the OMZ hosts abundant iron oxide mineralisation, usually either interbedded with volcanic rocks, or located at the contact with underlying limestone. Minor lenses are interbedded with the associated siliciclastic sediments or replacing carbonates (Dupont, 1979). The host rocks have been subjected to pervasive hydrothermal alteration, modified by superimposed metamorphism, resulting in an assemblage that includes actinolite, albite, quartz, chlorite and sericite. These deposits are especially common on the southern limb of the Olivenza-Monesterio antiform, where Cambrian volcanism was widespread and essentially submarine (Etxebarria *et al.*, 2006). They occur as stratabound lenses, sub-parallel to bedding, and up to 1 km long and 20 m thick. There is no major evidence of underlying feeder zones, although some sporadic stockwork developments have been recognised with associated pervasive silicification of the footwall rocks. The ore lenses comprise around 80% magnetite-hematite with variable amounts of barite (up to 2000 ppm Ba), quartz, pyrite and chalcopyrite. Trace amounts of arsenopyrite, galena, tetrahedrite, pyrrhotite and gold are also common (Tornos *et al.*, 2004). Highly silicified exhalites are locally found interbedded with the volcaniclastic rocks.

The rheology contrast between these iron-oxide-rich units and the hydrothermally altered host rocks makes the margins of the mineralised zones a favorable local focus of Variscan deformation (Fig. 5c illustrates the degree of deformation on a micro-scale). Consequently, orebodies are usually located at, or are bounded by, major shear zones and thrusts. Although most original depositional features are obliterated by superimposed deformation and recrystallisation, in some restricted, undeformed areas, sedimentary structures such as bedding parallel and cross laminations, ripple marks and slump structures can be recognised (Fig. 5a).

Significant deposits, which include Bilbaína (78 Mt @ 52% Fe), Bóveda (unknown original tonnage @ 52% Fe) and Alconchel (12 Mt @ 44% Fe), were mined between 1910 and 1982 (IGME, 2006). Local elevated copper and gold grades of up to 0.28% Cu and 2.9 g/t Au (IGME, 2006) seem to be late and associated with a second mineralising event of Variscan or even Alpine age, related to the circulation of later fluids. At these localities, the iron oxide mineralisation acted as a geochemical trap for copper- and gold-bearing minerals. In fact, there is a direct relationship between deformation or proximity to intrusive rocks and high copper-gold grades within these stratabound iron-rich bodies.

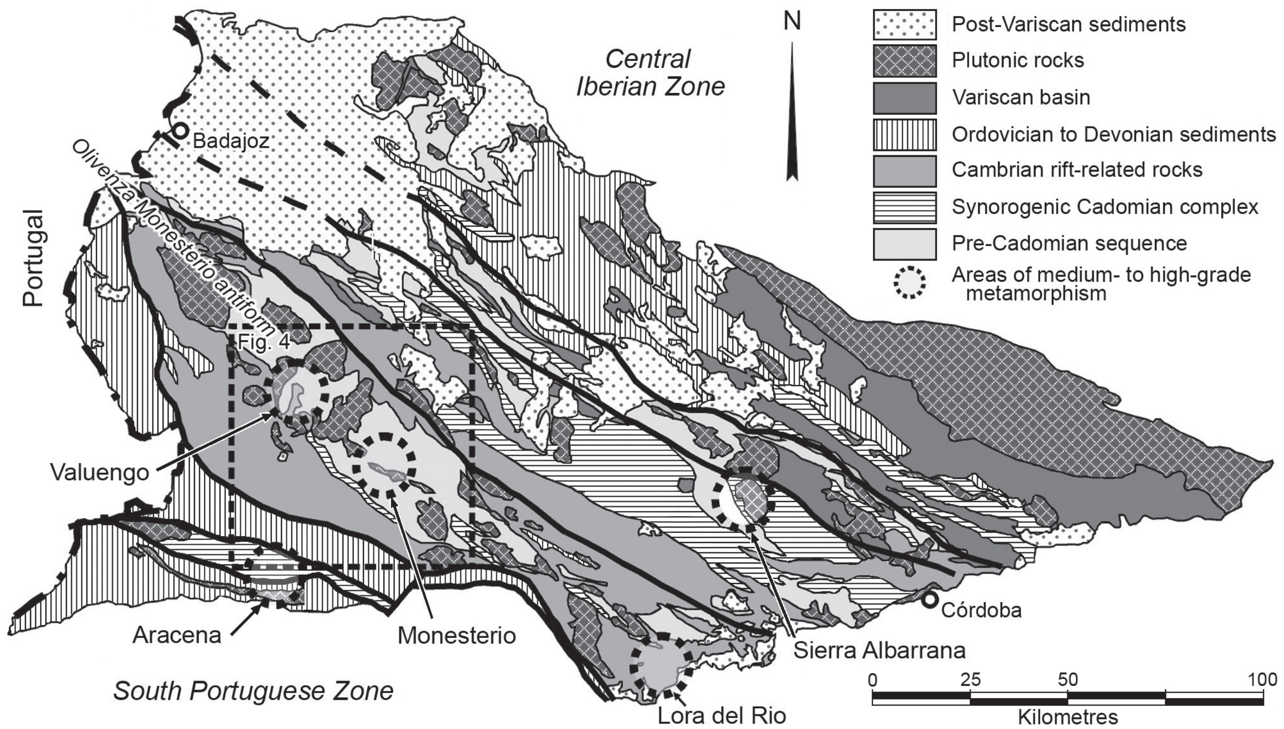


Figure 3: Geological map of the Ossa Morena Zone, showing the limits, main tectonic structures and distribution of sedimentary and igneous rocks, as well as the study area (Fig. 4) within the Olivenza Monesterio Antiform. Modified from Tornos & Chiaradia, 2004.

The Nd isotope composition of these magnetite ores reveals εNd_i values of -4.7 to -3.1 (Galindo *et al.*, 1995), indicating that magnetite was probably derived from primitive sources (Darbyshire *et al.*, 1998), very likely by the leaching of juvenile magmatic rocks or their volcaniclastic equivalents, with only minor crustal contamination. Likely source candidates include mafic rocks of either the host sequence, or the syn-orogenic Cadomian succession, which have εNd_i values ranging from 4.8 to 7.7 (Galindo, unpublished data) and 2.8 (Schäfer 1990) respectively. Moreover, preliminary sulphur isotope values ($\delta^{34}S$= 3.6 to 12.4‰) show that sulphur was mostly derived from the thermo-reduction of seawater sulphate to H_2S, with a minor but variable input of biogenically derived reduced sulphur in an open system (Tornos *et al.*, 2004). There has been no precise dating of these deposits. Poorly constrained dating presented by Darbyshire *et al.* (1998), suggest Sm-Nd ages of ca. 500 Ma.

These ore deposits are interpreted to have formed by the venting of hydrothermal fluids into shallow oxidised basins (Dupont, 1979; Locutura *et al.*, 1990), with the formation of both exhalative and shallow replacive mineralisation. The most likely source of fluids is convecting seawater, with iron having been leached from mafic rocks.

Skarn-type Deposits

Iron-rich, calcic-skarns are widespread in the OMZ (Casquet and Velasco, 1978; Casquet and Tornos, 1991). Most are located at the contacts between Variscan plutons of mafic to intermediate composition, and carbonate rocks of Early Cambrian age. The largest concentration of skarn deposits is associated with the Burguillos del Cerro Pluton (Fig. 4), replacing limestone, dolostone and locally pelitic hornfels that occur as roof pendants within the intrusion. Skarns are also developed to a lesser extent adjacent to the Santa Olalla and Brovales intrusions (Fig. 4). Most of these skarns replace wall rocks peripheral to the plutons, with only minor endoskarns.

These skarn show the typical zonation described elsewhere (e.g., Einaudi *et al.*, 1981). Calcic exoskarns

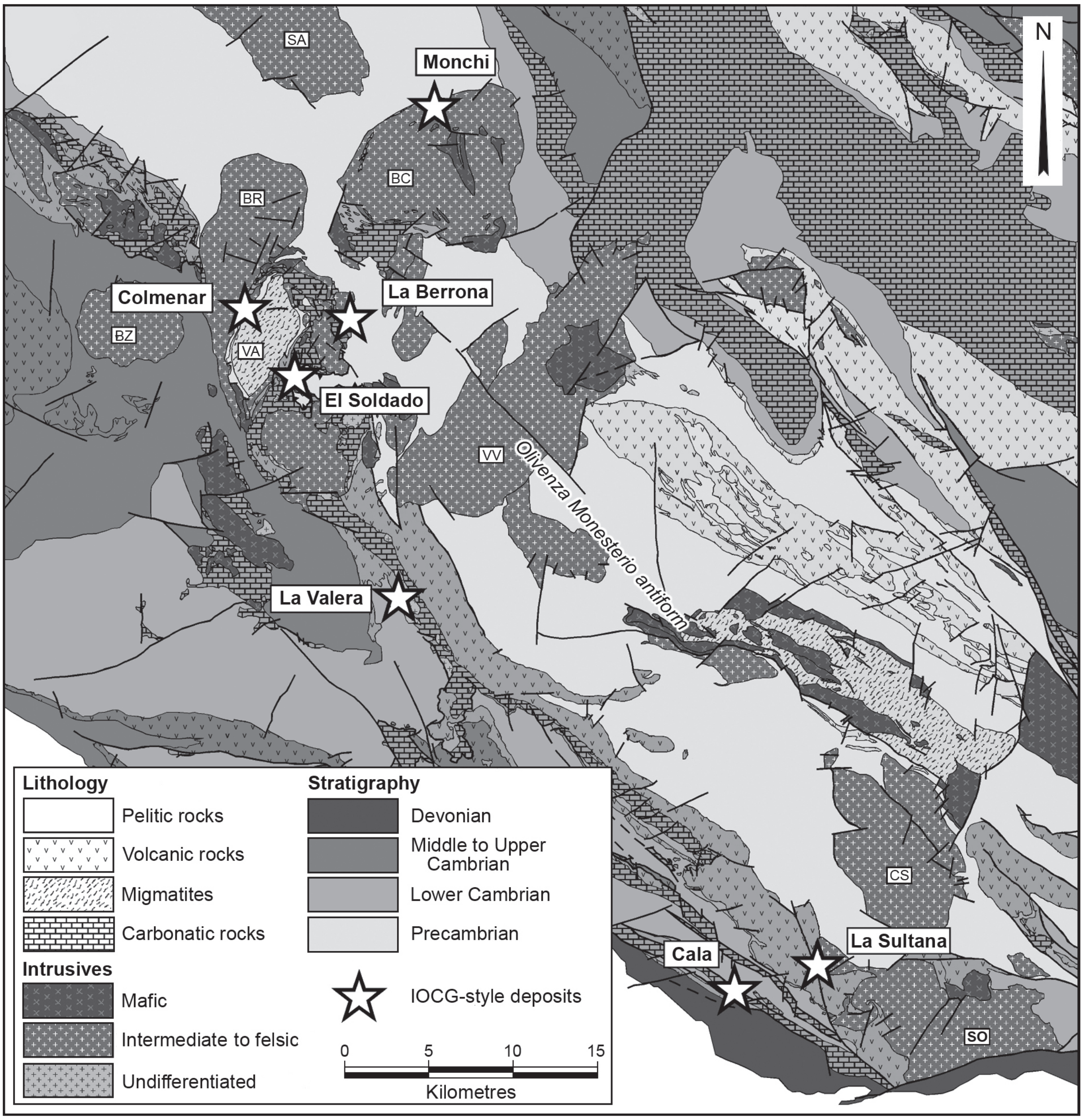
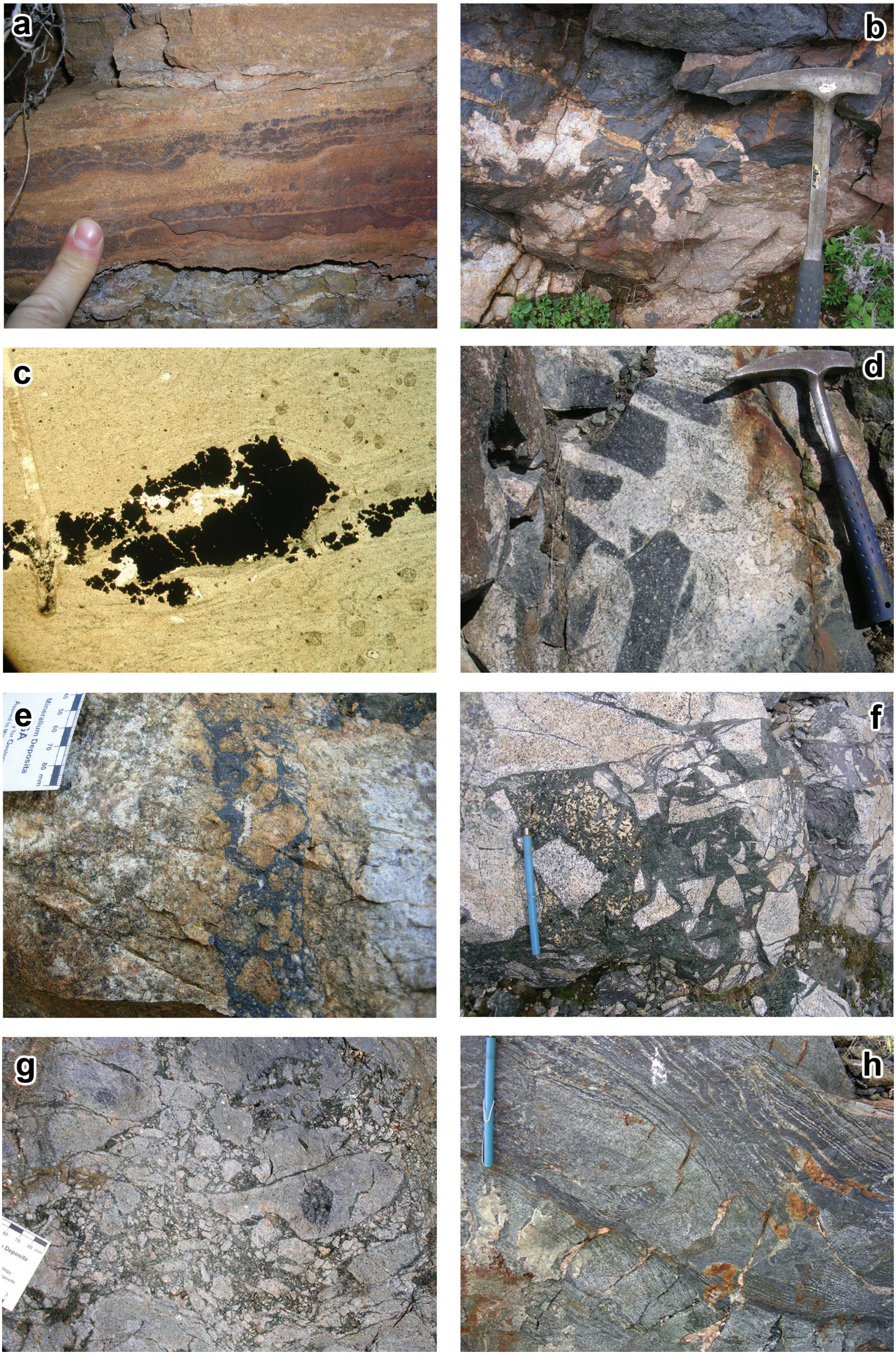


Figure 4: Geological map of the study area within the Olivenza-Monesterio antiform, showing the location of the key IOCG deposits and the main igneous/metamorphic complexes cited in the text: VA: Valuengo; SO: Santa Olalla; CS: Castillo; BZ: La Bazana; VV: Valencia del Ventoso; BR: Brovales; BC: Burguillos del Cerro; SA: Salvatierra de los Barros. Modified from Quesada and Sanchez García, 2002.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are characterised by a dominant prograde garnet (andradite-ferrosalite) - clinopyroxene (diopside-hedenbergite) assemblage that is replaced by a retrograde mineralogy of clinoamphibole (ferroactinolite-hornblende) with minor amounts of quartz, epidote and calcite. The mineralisation occurs as heterogeneous intergrowths within the retrograde skarn, comprising magnetite, with trace amounts of pyrite, chalcopyrite, ilvaite, pyrrhotite and bornite (Casquet and Tornos, 1991). Magnesian skarns, which replaced dolostones, are much less common, and include a zonal arrangement from distal dolomitic-marble, through calcite+spinel, diopside±spinel to forsterite zones, proximal to the unmodified plutonic rock (Casquet and Tornos, 1991). A phlogopite aposkarn, usually transformed to vermiculite, was developed within the clinopyroxene+spinel zone, and has been mined in the past (Velasco *et al.*, 1981). The magnesian skarn, which was locally early, was subsequently overprinted by calcic skarn with diopside being replaced by more iron-rich clinopyroxene, grandite and later retrograde calcic skarn. Forsterite is locally replaced by serpentine. Only small magnesian endoskarn developments are recorded within the plutonic rocks, comprising either garnet skarn, or more commonly, an actinolite+epidote+feldspar assemblage (Tornos *et al.*, 2004).

IOCG-style Deposits

All iron oxide mineralisation in the OMZ has previously been interpreted as being either exhalative- or skarn-type (Velasco and Amigó, 1981; Locutura *et al.*, 1990; Casquet and Tornos, 1991). A long standing debate persists regarding the source of the iron within these deposits that are adjacent to major intrusions or shear zones, namely, is it (1) of magmatic-hydrothermal derivation, i.e., exsolved from a coeval intrusion, or (2) due to Variscan hydrothermal remobilisation or metamorphic recrystallisation of pre-existing Early Cambrian exhalative mineralisation (Calvo, 1980). The fact that all of the iron oxide deposits occur in the same Early Cambrian sequence makes interpretations ambiguous. However, Nd-Sr data (Darbyshire *et al.*, 1998; see below) show that the isotope geochemistry of the Variscan magnetite is consistent with that of the adjacent granitoids and not with the Early Cambrian mineralisation and related volcanic rocks. Thus, if iron is derived from the stratabound iron-rich sediments, it must have been equilibrated with the plutonic rocks prior to precipitation.

Re-evaluation of some of these deposits shows that not all have a classical skarn-like mineralogy, zonation and prograde garnet-pyroxene assemblage. The style of replacement, the hydrothermal assemblage and the relationship with major structures are very similar to those observed at the Osborne deposit, in the Cloncurry district of northwest Queensland in Australia (Baker *et al.*, 2001; Williams and Pollard, 2003; Mark and Oliver, 2006). The deposits in the Cloncurry district, as well as those in the Fennoscandian shield (Edfelt *et al.*, 2005; Martinsson, 2003; Niiranen *et al.*, 2007), share features not commonly observed in skarn deposits, including, (1) a relationship with pervasive alkaline-Ca-Fe alteration, (2) an association with transcrustal shear zones, (3) a likely local relationship with apatite-bearing iron oxide mineralisation, (4) high U-REE contents, (5) a sulphide-poor assemblage, or (6) an abundance of volatile or fluxing elements such as F, B or P (Tornos and Casquet, 2005). These characteristics are typical of the IOCG family of deposits (Hitzman *et al.*, 1992; Williams *et al.,* 2005). However, it should be appreciated that skarn-like alteration can be widespread in IOCG systems, as it only represents the product of the reaction between a fluid and a rock in disequilibrium. 'Skarns' may form under a wide range of conditions and only describes an observed mineralogy, free of genetic implications (Einaudi *et al.*, 1981). Fluids related to the formation of IOCG mineralisation can produce skarn-like assemblages when encountering Ca- or Mg-rich rocks.

Perhaps the most distinctive feature of the iron oxide deposits of the OMZ is that they show varied styles of mineralisation formed at different times. Deposits in the two major IOCG bearing zones, the Valuengo dome and the Santa Olalla area (Fig. 4), are different. Mineralisation in the Valuengo dome is mesozonal, related to albitite, and poor in copper and gold, while the Cala deposit in the Santa Olalla area, is epizonal, is associated with major shear zones, and is richer in copper and gold.

Figure 5: (Facing page) **a)** Sedimentary structures [ripple marks] recognised in a banded iron oxide-rich sediment close to the El Soldado mine; **b)** Albite rich leucogranite crosscutting iron oxide mineralisation at the Alfredo Mine; **c)** Folded millimetric magnetite bands within dacites belonging to the iron oxide mineralisation mined at Bilbaina (magnification 3.2X); **d)** Brecciated gabbro at the Colmenar mine, supported by a matrix of albite, minor titanite and amphibole; **e)** Brecciated albitite at the La Valera mine, with jigsaw textures and a matrix composed of massive magnetite; **f)** Hydrothermal breccias cross-cutting the Colmenar Pluton, with fragments of granodiorite supported by an actinolite-magnetite matrix at the Colmenar Mine; **g)** Magmatic-hydrothermal breccia with fragments of albitite from the La Berrona pluton supported by a magnetite-actinolite-albite-quartz matrix; **h)** Hydrothermal replacement of limestone at La Berrona, where the main mineralisation has a banded texture of albite-magnetite-actinolite composition.

Deposit Descriptions

Alfredo: The Alfredo mine was continuously exploited for iron between 1959 and 1968, with a total production of 2.3 Mt @ 54% Fe (Doestsch, 1973). It is located on the northern limb of the Olivenza Monesterio antiform (10 km north of the area shown on Fig. 4), at the contact between carbonate and pelitic rocks of Early Cambrian age, and adjacent to, or hosted by, the Feria Stock. The Feria Stock is one of the largest intrusions of Cambrian albitite, and is dated at 514±3 Ma (Sánchez-García *et al.*, 2008). In detail, the mineralisation occurs in a number of different styles: (1) as tabular bodies of magnetite and siderite, with accompanying clinoamphibole and traces of sulphides, located at the contact between limestone and underlying shale, sandstone and chert, with all the features of exhalative chemical sedimentation, or early diagenetic deposition, i.e., Early Cambrian volcanism related iron-rich sediments (Dupont, 1979); (2) as elongated, discontinuous bodies of massive magnetite within the Feria pluton (Fig. 5b), and; (3) as veins and associated hydrothermal breccias, the late phases of which are richer in sulphides. Our preferred interpretation is that the bodies within the albitite probably represent immiscible iron melts exsolved from the albitite, with the hydrothermal breccias being the product of late fluid exsolution.

La Valera: The La Valera mine is located on the southwestern limb of the Olivenza Monesterio Antiform (Fig. 4), and is also associated with a small intrusion of albitite, which crosscuts an Early Cambrian sequence of carbonate rocks with some interbedded dacite and rhyodacite. The albitite shows pervasive silicification as well as superimposed chlorite+calcite alteration, although these assemblages appear unrelated to the iron mineralisation. Magnetite, with smaller amounts of hematite, is found as a cement supporting rounded, variably sized, fragments of albitite (Fig. 5e) within irregular to ellipsoidal breccia bodies.

Locally, magnetite has been fractured, forming a pattern resembling columnar joining. Coullaut *et al.* (1980) have described pyroclastic rocks of dacitic composition with interbedded layers rich in fragmental magnetite. As in all of the albitite-related deposits, fluorite is a common component in late fractures. Sulphides are virtually absent. The lack of widespread related hydrothermal alteration, and the presence of likely columnar jointing, strongly suggest that these magnetite bodies formed by the crystallisation of immiscible iron oxide melts, similar to those described at El Laco (Naslund *et al.*, 2002) or Kiruna (Martinsson, 2003). If this holds true, the presence of intercalated dacitic pyroclastics and fragmental magnetite indicates that some of these iron oxide melts were extruded at the surface.

La Berrona: The La Berrona deposit is found adjacent to one of the stocks of albitite surrounding the Valuengo dome (Fig. 4), dated at ca. 520 Ma (Carriedo, *in litt.*). This albitite was emplaced into Early Cambrian limestone, calc-silicate hornfels and schist, all of which were affected by irregular amphibole-albite-rich alteration that is spatially associated with the intrusion. Mineralisation is located in the innermost zones of this alteration halo, adjacent to the contact with the albitite (Fig. 6). It occurs as irregular and lensoid bodies with sharp to irregular transitional rims with both the amphibole-albite-rich alteration and igneous rocks. It comprises a banded to massive actinolite-albite-magnetite rock with minor amounts of epidote, quartz, scapolite, pyrite, apatite, titanite, pyrrhotite and calcite. Late chlorite alteration is observed in discrete zones, followed by younger veins of quartz and calcite.

Banding, which is interpreted to be of metasomatic origin and unrelated to bedding, comprises alternating albite-rich and magnetite-actinolite-bearing layers (Fig. 5h), sub-parallel to the intrusive contact with the albitite. This replacement appears to be coeval with the formation of sub-vertical bodies of hydrothermal breccia found in the apical sections of the albitite intrusion. These breccias are composed of angular fragments of albitite, supported by a matrix of actinolite, magnetite and quartz (Fig. 5g). Some small bodies of prograde garnetite skarn are found in the vicinity, although these appear to be unrelated to the albite-actinolite alteration and the magnetite mineralisation.

Fluid inclusion, and stable and radiogenic isotope data, indicate that the mineralisation is related to the circulation of iron-rich aqueous brines, equilibrated with, and likely exsolved from, the albitite. Dating of albitite in the Valuengo complex yielded U-Pb ages of 480 to 460 Ma (Montero *et al.*, 2000), indicating that the deposit is broadly synchronous with the Cambrian extensional stage.

El Soldado: Only a few kilometres south of La Berrona, El Soldado, another tabular replacive deposit, is located at the contact between limestone and overlying schist, and adjacent to a further stock of albitite. The mineralisation includes an assemblage of magnetite and fluorite in similar proportions, as well as minor albite, phlogopite, calcite and hematite (Fig. 8d). There is a clear zonation, with fluorite-phlogopite decreasing away from the albitite. However, one striking feature of this deposit is that nearby, there are some old workings which exploited stratabound magnetite that is located in almost the same stratigraphic position, and in which the magnetite shows pristine sedimentary structures such as cross bedding and ripple marks (Fig. 5a). Thus, the exact timing of this mineralisation remains uncertain.

Monchi: The Monchi Mine (northeast of the Burguillos pluton) exploited five high-grade magnetite-vonsenite (66% Fe) ore lenses, each of 5 to 8 m in thickness and 500 m long. These lenses occur as large enclaves, along with marble, and pelitic and calc-silicate hornfels, surrounded by calc-alkaline granodiorite and diorite of the Burguillos del Cerro Plutonic Complex, which has been dated at 335.7±1.8 Ma (García Casquero, 1995). Casquet *et al.* (1998) interpret these large xenoliths to have been associated with, and aligned along, a major syn-magmatic shear zone.

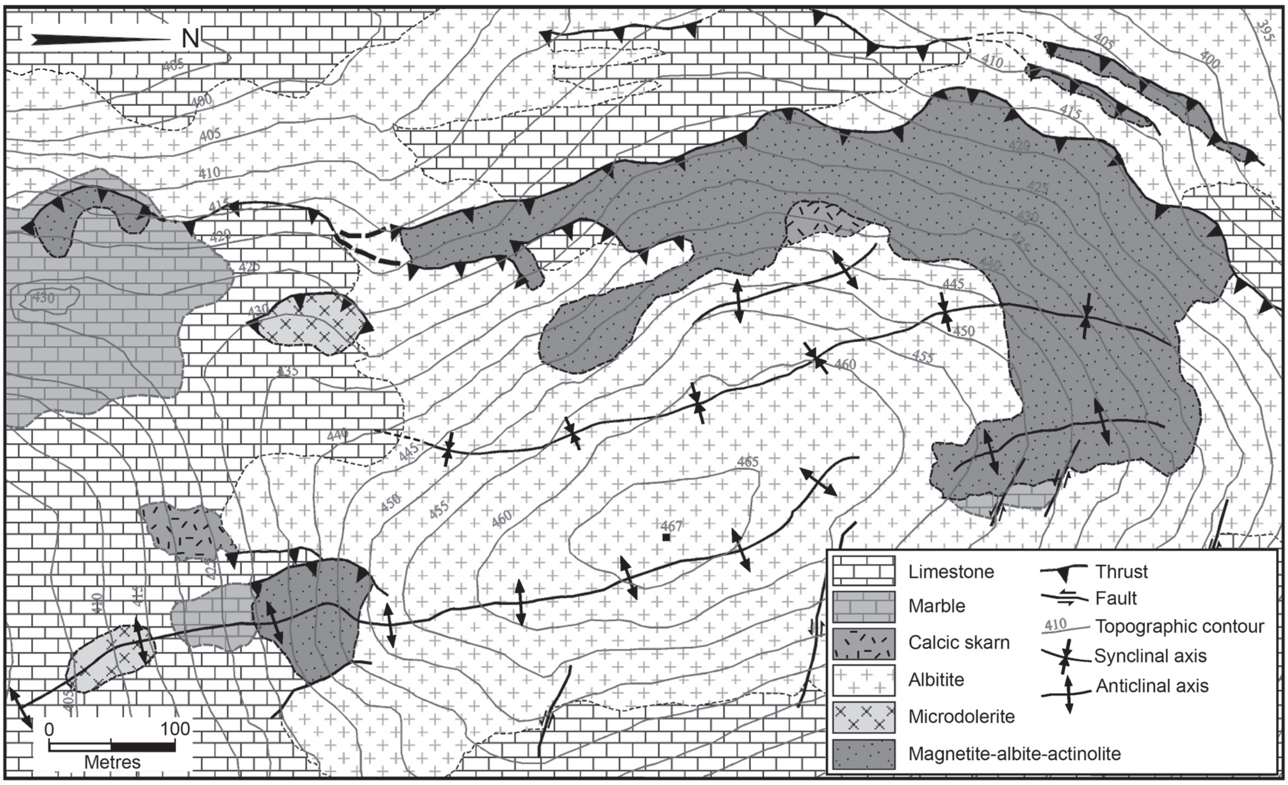


Figure 6: Geological map of the La Berrona deposit, based on drill core data (IGME, 1962), and supported by field mapping. Note the distribution of the mineralisation at the contact between the albitite (an albite-rich leucogranite) and the host Cambrian limestones.

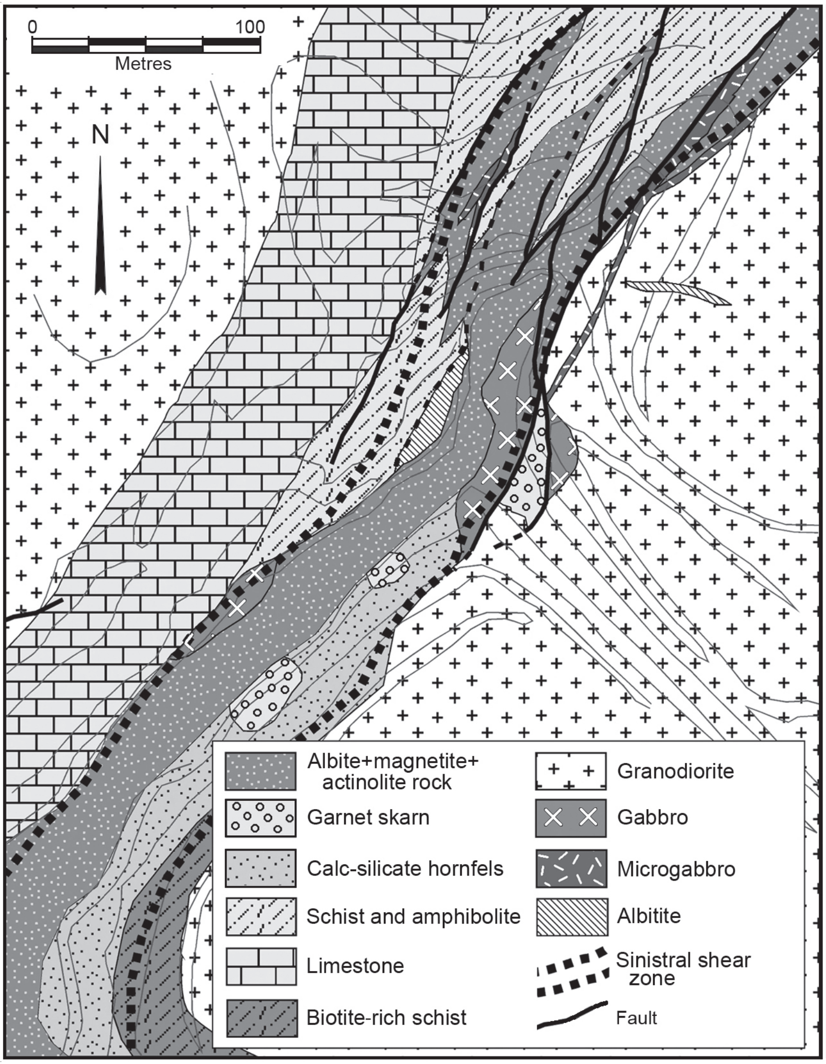
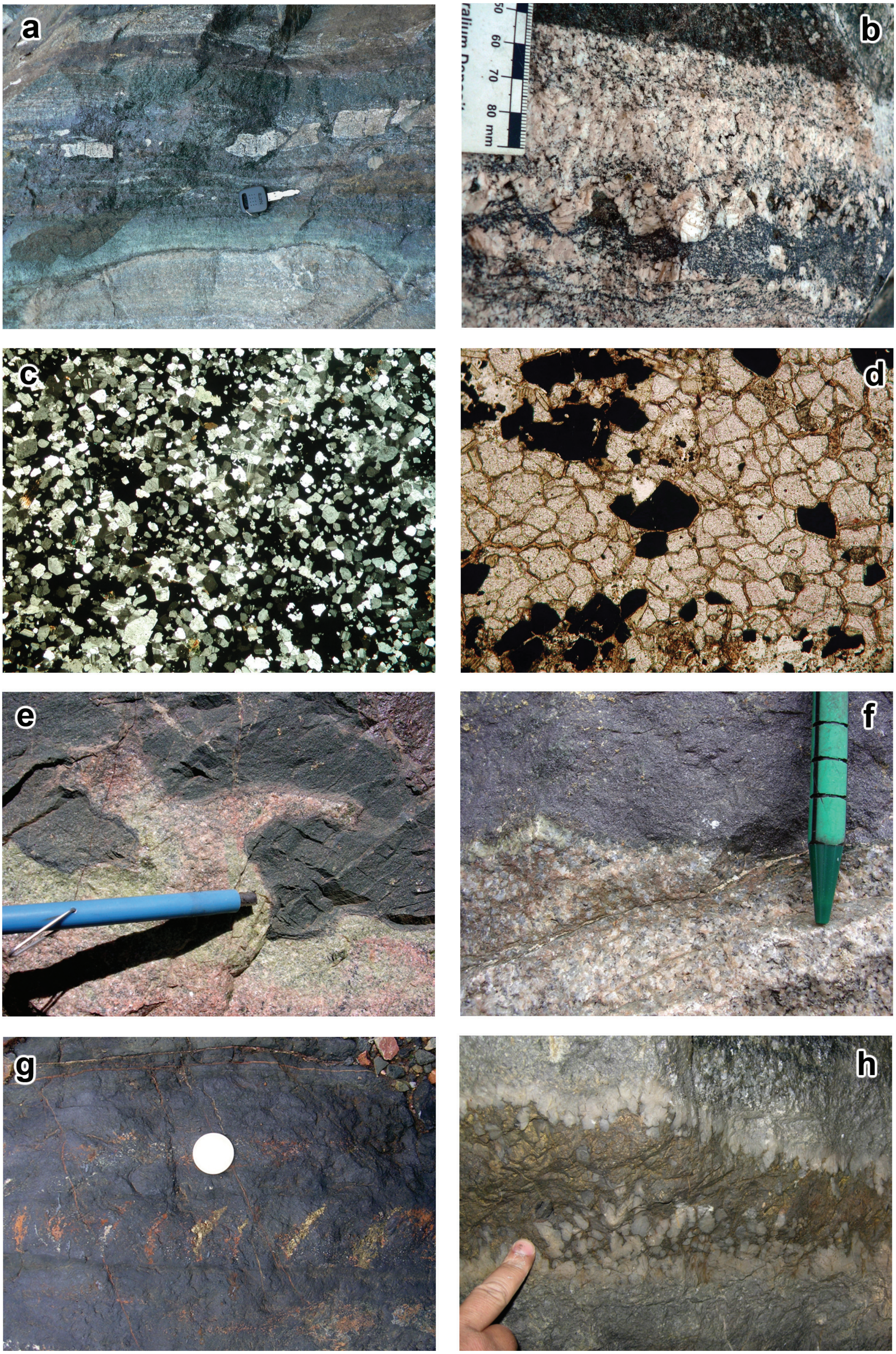


Figure 7: Geological map of the Colmenar mine, where the main orebody is distributed along the sinistral shear zone deforming the Cambrian host rocks, separating two granodioritic instrusions of the Brovales Pluton.

The ore lenses are dominated by massive magnetite and vonsenite, with minor ilvaite, showing a conspicuous lineation and widespread metamorphic recrystallisation. The magnetite-vonsenite rock is associated with massive hedenbergite, which is rich in allanite and uraninite, and irregular bodies of alkaline pegmatite rich in K feldspar, clinoamphibole, axinite and quartz. Younger calcic (garnet-rich) and magnesian (forsterite-diopside-rich) skarns are developed replacing marble and calc-silicate hornfels. Allanite from the hedenbergite-rich rock has been dated by U-Pb as 338±1.5 Ma (Casquet *et al.*, 1998). In detail, the intrusion of the host granitoid postdates the magnetite-vonsenite rock, the hedenbergite skarn and the alkaline pegmatites, but appears to be associated with the younger skarns. Late discordant veins of massive, coarse-grained magnetite with actinolite-hornblende, crosscut all of the previous rocks. Other ore minerals at Monchi are scarce and irregularly distributed, but include a somewhat unusual assemblages of pyrrhotite, cobaltite, chalcopyrite, pyrite, arsenopyrite, Co-gersdorffite, safflorite, löllingite, bismuthinite, molybdenite, scheelite and gold. Preliminary geochemical data suggest that the isotopically heavy magnetite ($\delta^{18}O$ >7.2 to 8.6‰) crystallised at temperatures higher than 600ºC (Tornos *et al.*, 2003). These values could be consistent with the magnetite-vonsenite rock being derived from an unusual B-rich melt. Fluid inclusions within the associated pegmatite are hypersaline and probably record fluids exsolved from this melt.

Colmenar: The Colmenar deposit is located in a structurally complex area between the Brovales pluton (tonalite-granodiorite) and the westernmost Valuengo dome, within a Variscan, north-south-trending, ductile-brittle domain, sinistral to extensional shear zone (Fig. 7). In detail, the mineralisation is hosted by a highly deformed sequence that includes discontinuous lenses of calc-silicate hornfels, limestone, schist, amphibolite and stratabound magnetite mineralisation of likely Late Neoproterozoic to Early Cambrian age. The presence of a foliated magmatic fabric indicates that the intrusion of the Brovales pluton was broadly coeval with shearing. Small intrusions of gabbro, predating both the Brovales pluton and the shear zone, are common in the mineralised area.

The main orebody is a 10 to 30 m thick and 500 to 700 m long stratabound lens, parallel to both the bedding and shear fabric. The host metasediments are replaced by a hydrothermal rock composed of albite, magnetite and Fe-actinolite, with locally abundant scapolite, and minor apatite, titanite and monazite. This hydrothermal halo includes a zone of magnetite plus actinolite surrounding a core of massive coarse-grained magnetite. Mineralised breccias, in which granodiorite-tonalite fragments are supported by a magnetite-actinolite matrix (Fig. 5f) are also common. The mineralisation has a mylonitic fabric with a conspicuous foliation and common boudin-like structures (Fig. 8a). Textural relationships suggest that the metasomatic replacement was synchronous with shearing.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Sulphides are common, mostly comprising pyrite, with minor millerite, pyrrhotite, chalcopyrite, bornite and traces of gold, all closely postdating the iron oxides and occurring in late brittle fractures, and as associated replacements. Small patches of calcic skarn, composed of grandite replaced by later epidote and calcite, are found in zones marginal to the main orebody and always adjacent to the granodiorite-tonalite contact. This calcic skarn is late and postdates deformation.

There is a direct spatial relationship between the replacive mineralisation and some unusual centimetre-scale thick dykes of K feldspar-oligoclase-quartz leucogranite containing immiscible zones of albite-magnetite (Fig. 8c). Accessory phases in the immiscible albite-magnetite zones include quartz, K feldspar, actinolite, biotite and titanite. The absence of hydrothermal alteration within the dykes, the presence of pegmatite-like structures with local stockscheider (unidirectional) growth zones (Fig. 8b), and the evidence of immiscibility with a granite strongly suggest that the mineralisation within the dykes is magmatic in origin. These dykes grade upward into hydrothermal breccias supported by a dominant magnetite-actinolite(-albite-titanite) matrix (Fig. 5f), and then to the previously described albite-magnetite-actinolite replacement mineralisation of the ore zone (Fig. 8a).

Below these same dykes, there are magmatic breccias with a matrix of coarse-grained albite or albite-magnetite (Fig. 5d; with variable amounts of titanite), rooted in zones of anatexis imposed upon magnetite-rich siliciclastic meta-sediments and amphibolites belonging to the Early Cambrian mineralised sequence. In the zones of anatexis, discrete domains of leucosome sometimes show migmatitic fabrics and grade into albite-rich dykes. The nature of the protolith appears to control the composition of the resultant albitite, ranging from pure albite when sediments are iron-poor, to albite and magnetite when derived from magnetite-bearing meta-sediments.

$\delta^{18}O$ and δD signatures from the main albite-magnetite-actinolite ore assemblage of 9 to 12‰ and -44 to -13‰ respectively, suggest equilibration temperatures of >500°C and ore forming fluids compatible with a metamorphic derivation (Tornos *et al.*, 2003). The garnet skarn yields somewhat equivalent temperatures and $\delta^{18}O$ fluid compositions of 8 to 11‰. $\delta^{18}O$ equilibrium temperatures for the albite-magnetite dykes are in the range 640 to 720ºC, and fluids exsolved should have consistent and equivalent $\delta^{18}O$ values. The εNd_i, $^{87}Sr/^{86}Sr_i$ and Pb isotope values (εNd_i = -7.8 to -5.1, $^{87}Sr/^{86}Sr_i$ = 0.7082 to 0.7116; μ = 9.6; w = 37.6) of the albite-magnetite-actinolite orebody (Galindo *et al.*, 1990; Darbyshire *et al.*, 1998; Tornos and Chiaradia, 2004) indicate equilibration of fluids with crustal rocks, with negligible input from a mantle reservoir. As quoted above, these values are significantly more crustal than those of the iron-rich sediments, indicating these orebodies are not a product of the simple metamorphic recrystallisation of pre-existing stratabound mineralisation, and that they have likely been equilibrated with the adjacent granitic rocks.

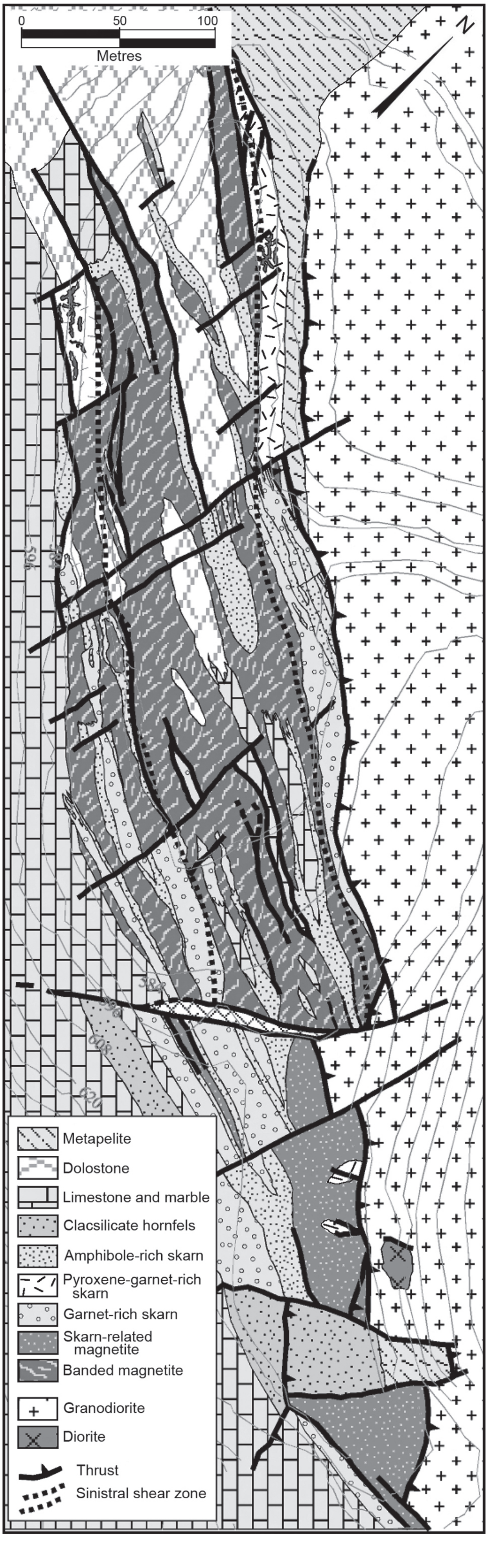
U-Pb dating (340 to 338 Ma; Carriedo, *in litt.*) indicates that the albite-magnetite dykes are contemporaneous, (within error) with the Brovales Pluton. Furthermore, Sm-Nd dating of magnetite from the orebodies has yielded an equivalent age of 334±32 Ma (Darbyshire *et al.*, 1998), indicating that the mineralisation is also Variscan in age and broadly coeval with the adjacent intrusive rocks. This is consistent with the relationships between magmatism and the shear zone, and the presence of hydrothermal breccias with fragments of plutonic rocks supported by a magnetite-actinolite matrix (Fig. 5f).

Figure 8: (Facing page) **a)** Layered mineralisation at the Colmenar mine, characterised by syntectonic replacement of calc-silicate hornfels and marble by an ab+act+mt assemblage; **b)** ab+mt dykes at the Colmenar mine showing sharp rims and stockscheider textures; **c)** ab+mt mosaic texture of the Colmenar dykes; **d)** Mineralisation at El Soldado, composed of mosaic textures of mt+fl+phl; **e)** Granodiorite porphyry-type intrusions at the Cala mine, showing exoskarn and endoskarn development; **f)** Massive magnetite xenolith within the Cala Stock; **g)** Tension gashes filled by sulphides in the layered mt-rich ore of the Cala mine; **h)** Mineralised lodes at the Sultana mine, composed of quartz, chalcopyrite and pyrite, with high values of gold. **Mineral abbreviations:** mt=magnetite, ab=albitite, act=actinolite, fl=fluorite, phl=phlogopite.

Cala: The largest iron deposit of the OMZ is at the Cala Mine, with an original resource of more than 90 Mt @ 39% Fe and 0.5% Cu. The copper grade distribution is irregular, although there are large zones hosting economic grades. The total size of the orebody is unknown as it remains open at depth. This deposit is very different from those described previously, in that its sulphide content is significantly higher, it shows no obvious spatial relationship with albitite, and was formed in a shallow crustal (epizonal) environment. Although originally described as a typical calcic skarn (Casquet and Velasco, 1978; Velasco and Amigó, 1981; Casquet and Tornos, 1991), recent work shows that it is a complex mineralised body with a protracted polyphase evolution (Carriedo and Tornos, 2007).

The Cala deposit is located within Early Cambrian meta-sedimentary rocks on the overturned southern limb of the Olivenza Monesterio antiform (Fig. 4). It occurs at the tectonic contact between two terranes represented by the slates of the Herrerías unit to the north, and the interbedded slate, marble and calc-silicate hornfels of the Cumbres-Hinojales unit to the south. Within the deposit area, all of these rocks have been transformed into pelitic and calc-silicate hornfels, and marble through contact metamorphism. Sinistral transpressional deformation during the Variscan orogeny led to the development of a small, kilometre-sized, pull apart structure (Tornos *et al.*, 2002) that influenced the emplacement of magmatic units and repeated hydrothermal circulation. The ore occurs as hydrothermal replacements of the pelitic-carbonatic sequence (Fig. 9), with two well constrained types of mineralisation. Thus, at least two major ore forming events are represented at the Cala deposit:

(1) *Shear Zone Related Mineralisation (SZRM)* - The oldest magnetite-rich orebodies occur as lenses that are several hundred metres in length and up to 10 m thick. These lenses show widespread evidence of intense shearing, and are affected by a sub-vertical, sinistral, bedding-parallel, northwest-southeast-trending brittle-(ductile) shear zone that is interpreted to be synchronous with the replacement of the host sequence. The shearing and mineralisation are also accompanied by the intrusion of dykes of microgabbro. The ore assemblage includes dominant magnetite with quartz, ankerite, pistomesite, sericite, chlorite and iron-rich biotite, oriented to impart a conspicuous tectonic banding. These ore lenses are accompanied by a hydrothermal alteration aureole of ankerite and hematite, which is only apparent in carbonate hosts, and are surrounded by a halo of dolomitisation. Sulphides (pyrite and chalcopyrite) are late in the paragenetic sequence and replaced magnetite in tension gashes (Fig. 8g) or other tectonic discontinuities. This alteration has been dated at 374±3 Ma by Re-Os geochronology of associated



pyrite and magnetite (Stein *et al.*, 2006). The magnetite of this event comprises the dominant (ca. 80%) ore of the deposit.

Preliminary oxygen isotopic data show that fluids involved in the SZRM are of deep derivation, with $\delta^{18}O$ values ranging from 9.9 to 11.1‰. Few pristine fluid inclusions of undoubted primary origin have been found in these highly deformed rocks. They occur in embayments within the magnetite and related to zoned quartz crystals (Tomé *et al.*, 2009), and record the circulation of immiscible aqueous brines (35 to 40% $NaCl_{equiv.}$) and a CO_2, CH_4 and N_2-rich phase of likely metamorphic origin at temperatures of 500±80ºC.

Initial Os ($^{187}Os/^{186}Os_i$ = 0.59±0.04; Stein *et al.*, 2006) and Sr ($^{87}Sr/^{86}Sr_i$ = 0.7150±0.0002; Carriedo, *in litt.*) values of these rocks are consistent with the equilibration of fluids with crustal rocks, probably the underlying sequence. S isotopes on sulphides ($\delta^{34}S$ = -1 to 20‰; Tornos *et al.*, unpublished) are consistent with the leaching of reduced sulphur from the underlying shale.

(2) *Skarn Related Mineralisation (SKRM)* - While the shear zone related mineralisation is found in the lowermost part of the open-pit, a dramatically different style, separated by a set of late imbricated thrusts (see below), is exposed in the easternmost and upper sections of the deposit (Fig. 9). In these latter areas, the pelite-carbonate host sequence is replaced by an undeformed calcic garnetite-skarn dominated by grandite ($Ad_{47\text{-}53}$, $Gr_{38\text{-}40}$, $Sp\text{-}Al_{l8\text{-}12}$) and calcic amphibole (actinolite-ferroactinolite), with banding inherited from the protolith. The garnetite shows abundant cavities, infilled by late, calcic-poor garnet (Ad_{47}, Gr_4, $Sp\text{-}Al_{49}$), pink calcite, epidote, ferroactinolite, and minor magnetite and pyrite. Here, the bulk of the mineralisation is associated with a massive retrograde alteration of the prograde skarn, with magnetite and actinolite, and minor amounts of epidote, pyrite, chalcopyrite, pyrrhotite, nickeline, skutterudite, arsenopyrite, molybdenite and gold.

This skarn is interpreted to be related to an early granodiorite porphyry that has been dated at 338±0.4 Ma (TIMS U/Pb; Carriedo, *in litt.*) and is only sparsely exposed, occurring as minor anastomosing and irregular dykes (Fig. 8e), or as enclaves in younger intrusives. The granodiorite porphyry has been pervasively altered, and where adjacent to the exoskarn, exhibits strong potassic alteration characterised by secondary K feldspar, biotite and magnetite, replaced by epidote, magnetite and sulphides.

Fluid inclusion data (Tomé *et al.*, 2009) reveal that skarn-forming fluids are very different from those of the SZRM. They exhibit a typical evolution from early high temperatures (>550ºC) in the garnetite, to progressively lower temperatures and higher salinities (370±40ºC; 26 to 40 wt.% $NaCl_{equiv.}$) in vuggy quartz. These late fluid inclusions coexist with others that are CO_2-rich and immiscible, suggesting an increase in the CO_2 content of the fluid with time. The oxygen isotope composition of garnet and pyroxene from the prograde

Figure 9: Geological map of the Cala Mine. Mineralisation occurs as hydrothermal replacement of the carbonate-rich Cambrian host rocks, representing two types of mineralisation: (1) banded magnetite within a sinistral shear zone in the western-most part of the deposit; and (2) fine grained heterogeneous mineralisation related to the development of a calcic skarn.

skarn are consistent with the circulation of fluids of magmatic or metamorphic derivation, having $\delta^{18}O$ fluid values of 10 to 11‰. $\delta^{18}O$ values of clinoamphibole and magnetite from the retrograde skarn reflect the later influx of modified meteoric fluids ($\delta^{18}O$, 5.1 to 5.6‰; δD, -17 to -13‰) as has been recorded elsewhere (e.g., Einaudi *et al.*, 1981).

The most prominent magmatic rock in the area is the small, northwest-southeast trending, elliptical, Cala Stock, which has been dated at 342.2±4.2 Ma (SHRIMP U/Pb; Carriedo, *in litt.*). It is composed of granodiorite and quartz-monzodiorite, and has been subjected to both irregular potassic and pervasive sericitic alteration. The stock was emplaced at a depth of approximately 3 km, where it developed a narrow contact metamorphic aureole with maximum temperatures in the 500 to 600ºC range (Velasco and Amigó, 1981). However, although it has been traditionally interpreted as the source of the adjacent mineralisation, our field data strongly suggest that this intrusion is barren, crosscutting the skarn-related rocks and only produced minor recrystallisation of the host rocks. It incorporates xenoliths of massive magnetite without evidence of metasomatic modification (Fig. 8f), consistent with the iron oxide mineralisation predating the intrusion, although, isotope geochronology indicates that the age of the Cala stock overlaps within error the age of the skarn-type mineralisation.

The Cala Stock and the host rocks, including the magnetite-rich orebodies, are cut by several structures that are enriched in copper, bismuth and gold. These are especially prevalent along the contact between the Cala Stock and one of the SZRM orebodies, where high copper-gold grades were mined prior to the dominant and more recently exploited magnetite ore.

All of these rocks were affected by a late, north-south brittle compression of unknown (possibly Alpine) age, that produced the southwest directed thrusting of the Cala Stock to its position structurally overlying the orebody. In detail, the bulk displacement is associated with several tens of small-scale thrusts, with individual displacements of less than 10 m, averaging around 1 m each. The thrust planes are systematically infilled with quartz, chlorite and ankerite precipitated under extensional conditions, indicating a phase of extension that postdated the thrusting. The selvages of these veins are replaced by sericite and chlorite.

Sultana: The Santa Olalla Pluton is a larger intrusion, equivalent to the Cala Stock, dated by U-Pb in zircon at 341±3 Ma (Romeo *et al.*, 2006). There are several copper-gold-bearing lodes on its northern margin, the largest of which was exploited by the Sultana Mine. This vein has been considered to be the richest gold deposit in Spain, with an average grade of near 3.1% Cu and 15 g/t Au, and ore shoots carrying up to 800 g/t Au (Tornos and Velasco, 2002). The deposit includes low to moderately dipping (20 to 60ºW), 160º-striking veins, distributed in an *en echelon* pattern, and hosted by tonalite of the Santa Olalla Pluton at the contact with Late Neoproterozoic to Early Cambrian calc-silicate hornfels, schist and metavolcanic rocks (Fig. 8h). The ore is dominated by chalcopyrite, bismuthinite and maldonite, associated with a gangue assemblage of quartz, ankerite and sericite. Vein selvages exhibit strong sericite and ankerite alteration, with local tourmalinisation. Fluid inclusion studies indicate that hydrothermal fluids were complex, immiscible, H_2O-CO_2-CH_4-NaCl-$CaCl_2$-KCl brines with salinities of up to 30 wt.% $NaCl_{equiv.}$ (Velasco *et al.*, 1995). The deposition temperature of the copper-gold assemblage was 380 to 290ºC. $\delta^{18}O$ values of quartz and carbonates (4.7 to 7.5‰) suggest equilibrium with deep fluids (Tornos and Velasco, 2002), while the heavy sulphur isotope signatures ($\delta^{34}S$ = 10.4 to 15.6‰) are indicative of sulphur leaching from the host sedimentary rocks (Tornos *et al.*, 2004). The copper-bismuth-gold veins of the Cala Mine have similar assemblages and geochemistry indicating that they were probably coeval with, and in part responsible for, the copper-gold enrichment. These veins also show ore assemblages and fluid compositions that are strikingly similar to those reported from Tennant Creek (Australia), where copper-gold-bismuth ores are hosted by irregular to pipe-like hydrothermal ironstone bodies (Stolz and Morrison 1994; Zaw *et al.*, 1994; Skirrow, 2000).

Discussion

Since their first recognition as an 'ore-class or continuum' by Hitzman *et al.* (1992), IOCG deposits have been described from around the world (e.g., Williams *et al.*, 2005). Nevertheless, their geologic and genetic relationships remain controversial. Most share common features, including (1) a low-sulphur mineralogy; (2) a dominance of magnetite and/or hematite with low Ti:Fe ratios; (3) an association with crustal-scale structures or other localised strong structural controls; (4) the presence of generally extensive alkaline-calcic (sodic, sodic-calcic and/or potassic) alteration; (5) a relationship with the circulation of brines of likely deep origin; and (6) accompanying, usually high, tenors of U, REE and Co. Most studies of the evolution and origin of these systems are inconclusive. Many major IOCG provinces are located in highly deformed and metamorphosed Archaean and Palaeoproterozoic to Neoproterozoic belts, such as the Carajás mineral province in Brazil (Xavier *et al.*, 2010), Cloncurry District in Australia (Baker *et al.*, 2001; Williams and Pollard, 2003; Mark and Oliver, 2006), Fennoscandian shield in Sweden (Edfelt *et al.*, 2005; Williams *et al.*, 2005; Niiranen *et al.,* 2007) or the Great Bear Zone in Canada (Corriveau, 2007), among others. In these regions, ore forming processes are commonly masked by the superposition of several geological events. Consequently, clues to the evolution of IOCG systems might be better preserved in more recent and less deformed belts, such as the Jurassic-Cretaceous deposits of the Central Andes (Injoque, 2002; Sillitoe, 2003; De Haller *et al.*, 2006) or the Palaeozoic deposits of the OMZ (Tornos *et al.*, 2003; Tornos and Casquet, 2005; Carriedo and Tornos, 2007).

Several iron oxide, iron oxide-copper-gold and even copper-gold deposits of the OMZ show characteristics common to IOCG-style mineralisation. The deposits of the Valuengo area are associated with pervasive albite-actinolite-(scapolite) alteration that is texturally and mineralogically identical to that found in the Cloncurry district (Australia), where hydrothermal alteration is structurally controlled by large trans-crustal faults and spatially related to felsic batholiths. Intrusive rocks, rich in albite, have been described in the Cloncurry District (Perring *et al.*, 2001), although the albite-magnetite assemblage is interpreted as hydrothermal and due to the replacement of previous magmatic assemblages. Recently, some hydrothermal Na-Ca-rich rocks in this same district have been interpreted as being related to the downward circulation and later upflow of evaporite-derived fluids during early deformation and metamorphism (Oliver *et al.*, 2009). In the Valuengo area however, there is little doubt that the albite-magnetite-rocks are of primary magmatic origin, and that the Na-Ca alteration is directly related to fluids exsolved from plutonic rocks.

Many IOCG belts also include Kiruna-type magnetite-apatite deposits, as has been described in the Coast Range of the Andes in Chile and Perú (Hitzman, 2000; Gelcich *et al.*, 2005; Chen, 2008), and the Fennoscandian shield (Martinsson, 2003; Edfelt *et al.*, 2005). However, the link between magnetite-apatite and IOCG deposits has, in some cases, been strongly debated. In the OMZ, there are several apatite-poor but REE, U and B-rich, Ti-poor magnetite deposits that are associated with albitite and sometimes show evidence of representing the crystallisation of immiscible iron oxide melts. Magnetite-bearing magmatic albitite also represents another iron oxide-rich rock, not previously described in many equivalent systems. Thus, the distribution of mesozonal albitite-related magnetite deposits in the OMZ may provide some clues into the origin of these IOCG systems. These deposits (e.g., Colmenar, as described above), show that anatectic partial melting of iron-rich metasediments during high-temperature/low-pressure metamorphism, or assimilation of equivalent rocks during the intrusion of albitite, can produce magnetite concentrations ranging from immiscible iron melts, to

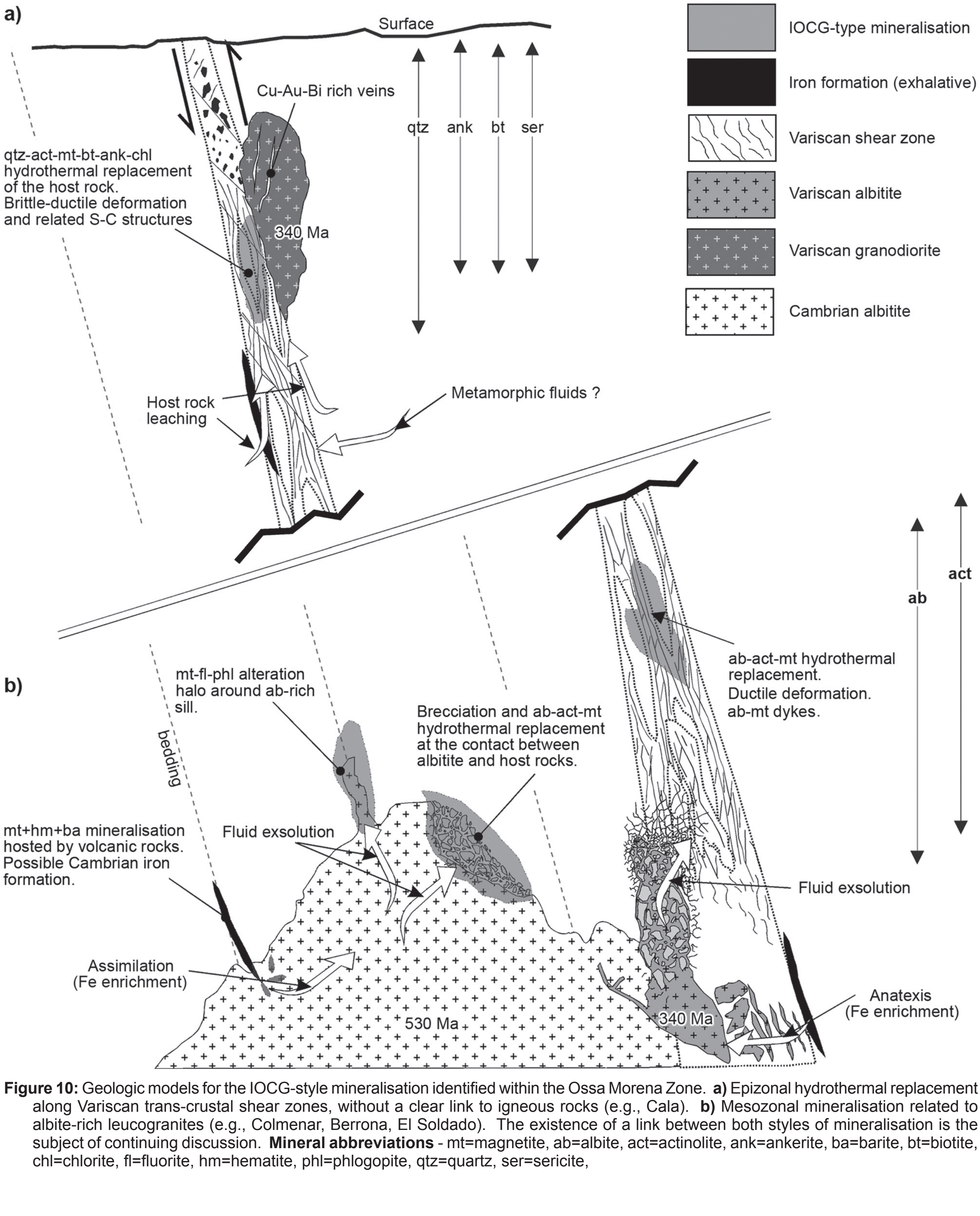


Figure 10: Geologic models for the IOCG-style mineralisation identified within the Ossa Morena Zone. **a)** Epizonal hydrothermal replacement along Variscan trans-crustal shear zones, without a clear link to igneous rocks (e.g., Cala). **b)** Mesozonal mineralisation related to albite-rich leucogranites (e.g., Colmenar, Berrona, El Soldado). The existence of a link between both styles of mineralisation is the subject of continuing discussion. **Mineral abbreviations** - mt=magnetite, ab=albite, act=actinolite, ank=ankerite, ba=barite, bt=biotite, chl=chlorite, fl=fluorite, hm=hematite, phl=phlogopite, qtz=quartz, ser=sericite,

albite-magnetite rocks, or iron-saturated magmatic fluids exsolved from albitite that can form replacive orebodies. What controls the formation of the different styles of magnetite mineralisation appears to be the iron, and perhaps fluxing content, of the protolith (Tornos and Carriedo, 2008). It is worth noting that these magnetite deposits are rich in fluxing agents or volatiles, although the proportions vary from one to the next. About 50% by volume of the ore in the El Soldado mine is composed of fluorite, while at Monchi the main ore mineral was vonsenite ($2FeO.FeBO_3$), and axinite is a common phase in the associated pegmatite. While these deposits are phosphorous-bearing (0.1 to 4.5% P_2O_5), in the form of fluorapatite, the phosphorous contents are not as elevated as those at Kiruna, or the magnetite-apatite deposits of the Coast Range of the Andes (>23% P_2O_5; Clark and Kontak, 2004). Uranium mostly occurs in the form of uraninite, while the REE are hosted by monazite, allanite and apatite.

The albitite-related, mesozonal magnetite deposits of the OMZ have low grades of both copper and gold, possibly reflecting the deficiency of those same metals in the protolith, and the fact that the albitite lacks evidence of fractional crystallisation processes necessary to concentrate incompatible metals in the residual fluid phase.

The classification of the deposits in the Cala area as IOCG-style mineralisation is more controversial. The mineralisation is shear zone-related but has no associated sodic or sodic-calcic alteration. The assemblage, dominated by quartz, ankerite, biotite, sericite and chlorite would seem to be more compatible with that found in shallow IOCG systems, as described by Hitzman *et al.* (1992) and Sillitoe (2003). Recent work undertaken by Carriedo *et al.* (*in litt.*; quoted above) shows this mineralisation to be ca. 30 Ma younger than the spatially associated igneous rocks and related skarn. Our best interpretation is that it corresponds to a shallow (<1 kb) IOCG system. Stable and radiogenic isotopes suggest that this system is rooted in metamorphic rocks, and that these are the source of fluids, metals and sulphur. The iron oxide-poor, but copper-gold-rich veins of the Sultana area are here assigned to the iron oxide-poor end member of the IOCG continuum (Tornos and Velasco, *in press*). The ore forming, immiscible complex aqueous brines and CO_2-CH_4-rich fluids at Sultana, are almost identical to those found in the late copper-gold stage at the Cala Mine. Furthermore, these veins are accompanied by an early albite-rich alteration and show conspicuous boron enrichment. Similar mineralisation is widespread in many IOCG provinces, e.g., at the Candelaria (Marschik and Fontboté, 2001) and Raúl-Condestable (De Haller *et al.*, 2006) deposits in the Coast Range of the Andes of Chile and Perú respectively, or at Ernest Henry, Mount Elliot and Mount Dore in the Cloncurry district in Australia (Williams and Skirrow, 2000).

Timing also seems to be critical to the formation of the IOCG systems in the OMZ. High precision U-Pb dating of magmatic and hydrothermal rocks, coupled with geological relationships, show that there are three major events leading to similar mineralisation. The first event is of Cambrian age, related to the major Cadomian post-orogenic extension and volcanism. IOCG-associated albitite of this event has been dated at 520 Ma (Carriedo, *in litt.)*, an age similar to the 530 to 502 Ma obtained by Sanchez *et al.* (2008) for the widespread alkaline magmatism of the area. A second ore forming event commenced at 374 Ma (Stein *et al.*, 2006), with a phase of mineralisation (e.g., the SZRM at the Cala deposit) that was synchronous with the onset of Variscan deformation and the first development of pull apart basins caused by sinistral transpression. There is insufficient data to indicate if the second event is continuous with, or separate from a third phase of IOCG mineralisation which took place at ca. 340 Ma, an age that appears to be critical to ore forming processes in the OMZ. Recent dating has shown that most Variscan plutonism is related to a short, but voluminous pulse of magmatism between 352 and 332 Ma (Pin *et al.*, 1999; Montero *et al.*, 2000, Romeo *et al.*, 2006), including the large volumes of intermediate to mafic rocks of the laminar IRB magmatic complex (Simancas *et al.*, 2004), that was injected along a detachment at the lower-upper crust interface at ca. 340-335 (Tornos *et al.,* 2004). Some IOCG-style deposits share these ages indicating that the intrusion of the IRB complex had a profound effect on the ore forming processes during this period.

The emplacement of the large and high temperature, primitive mantle-derived magma of the IRB, and interaction with the low metamorphic grade continental crust, resulted in the formation of water-rich highly contaminated melts, producing high-T/low-P metamorphism and widespread anatexis (Tornos and Casquet, 2005; Tornos *et al.*, 2005). The anatexis of the iron-rich metasediments and interbedded volcanic rocks produced magnetite-rich magmatic albitite and related albite-salite-actinolite-magnetite hydrothermal replacement. Contamination of the primitive melt induced separation of sulphide melts and formation of nickel-copper mineralisation such e.g., Aguablanca. Equivalent processes in reduced, sulphur-poor, settings probably led to the formation of the immiscible iron oxide melts of the Monchi Mine (338±1.5 Ma; Casquet *et al.*, 1998). Variable fractional crystallisation led to the intrusion of gabbro to granodiorite, with further exsolution of hot hypersaline brines, that where responsible for the formation of the abundant iron skarns, while equivalent fluids subsequently mixed with aqueous-carbonic metamorphic fluids resulted in copper-gold mineralisation, that occurs as veins, or as replacements of earlier magnetite-rich rocks. The contribution of the IRB to IOCG style and related mineralisation is supported by the juvenile lead isotope signature of sulphides within the OMZ, consistent with a significant input of mantle-derived lead. Similarly, the Sr-Nd isotope geochemistry of the igneous rocks and mineralisation imply extensive interaction between crustal rocks and deep magmas of mantle derivation on a district scale (Tornos *et al.*, 2005 and sources quoted therein).

It has been generally accepted that, while there is commonly a temporal correlation between IOCG-style deposits and igneous rocks, which are almost invariably present within IOCG provinces, there is in most cases, no clear spatial association between individual ore deposits and specific intrusions (e.g., Williams *et al.*, 2005). The igneous rocks range from felsic, variably alkalic, granitoids, to intermediate arc-related rocks, to mafic intrusions (Williams *et al.*, 2005) variously interpreted as I- or A-type granitoids (Williams *et al.*, 2005 and sources quoted therein; Corriveau, 2007) and primitive calc-alkaline arc magmas in the Andean belt (Sillitoe, 2003). There has been considerable debate when trying to ascribe IOCG systems to specific igneous rocks, if a magmatic origin is assumed, although Williams *et al.* (2005) note that large copper and gold deposits are generally associated with those of intermediate to felsic compositions. The IOCG systems in the Coast Range of the Andes are interpreted to be associated with calc-alkaline diorite with minor crustal contamination (Sillitoe, 2003), while in the Cloncurry district, extensive potassic, I-type, metaluminous alkaline to calc-alkaline granites dominate the region (Williams and Skirrow, 2000), and in the Kiruna area there are voluminous S-Type potassic granitoids (Niiranen *et al.*, 2007). All of these examples are large-scale batholithic intrusions. The various IOCG systems of the OMZ are associated with different igneous intrusives, suggesting no unequivocal and direct relationship with any specific magmatic rocks. Mineralisation in the Valuengo area is related to albitite, while that of the Burguillos and Santa Olalla plutons occurs within calc-alkaline I-type intrusions, and at Cala there is no evidence of the influence of any magmatic rocks.

All of the IOCG-style mineralisation in the OMZ is hosted by a Late Neoproterozoic to Early Cambrian sequence in which volcanic rocks coexist with limestone, and stratabound iron oxide mineralisation was deposited in shallow, restricted and oxygenated basins. Although no evaporates have been found, the abundance of stratabound scapolite and stromatolites (Liñan and Perejón, 1981) strongly suggests that evaporites were originally developed within this sequence. In the Valuengo area, albitite is interpreted to have been derived from the partial melting of this same sequence, with the related exsolving fluids forming hydrothermally altered rocks rich in scapolite. Barton and Johnson (1996) suggest evaporites are one of the potential sources of Cl as a metal transport ligand in hypersaline IOCG systems, especially in the Coast Range of the Andean belt, where evaporites are very common.

Within the zone of anatexis exposed in the OMZ, the iron content of the protolith seems to influence the composition of the migmatitic leucosomes that are segregated. Our data suggest that, sodic-calcic alteration is not only formed from the circulation of basinal brines originating from the exsolution of magmatic fluids, but also by fluids derived from the anatexis of iron-rich metasediments and metabasic rocks. When subjected to anatexis, iron-poor sediments produced almost pure albite or albite-actinolite magmatic rocks, while those having significant proportions of iron oxide formed albite-magnetite rocks, or even immiscible feldspathic and magnetite melts. Thus, it seems likely that at least some of the IOCG deposits of the OMZ represent magmatic-hydrothermal re-concentration and re-deposition of the constituents of pre-existing stratabound mineralisation, as illustrated in the Colmenar deposit description above. This perhaps also holds true for other deposits within the OMZ, since all are hosted by the same sequence, and the magmatic and hydrothermal rocks of the region show clear evidence of widespread crustal contamination. Older iron-rich mineralisation is evident in many IOCG provinces elsewhere in the world, e.g., the Coast Range of the Andean belt, the Olympic Dam IOCG province, the Cloncurry district, the Carajás mineral province and the Fennoscandian shield (Williams *et al.*, 2005; Niiranen *et al.*, 2007). The presence of highly saline fluids (26 to 40% $NaCl_{equiv.}$ recorded in OMZ deposits), also seems to be critical to the ore-forming processes, and is probably related with the capacity of the hydrothermal fluids to transport large amounts of iron as well as copper and gold.

The sulphide content is low in these deposits, rarely exceeding 10%, suggesting that reduced sulphur was a minor component of the ore forming fluid. $\delta^{34}S$ values, which range between -1 and 20‰, are consistent with a non-magmatic derivation of the reduced sulphur, probably leached from the host volcanosedimentary sequence.

Conclusions

The Olivenza-Monesterio belt of the OMZ hosts a number of different varieties of iron oxide (±copper-gold) mineralisation, including iron-rich sediments deposited during Early Cambrian rift-related hydrothermal activity, to younger epigenetic deposits, including skarns and deposits that share features with members of the IOCG-style continuum. Geochemistry and dating show that the IOCG-style deposits were formed at different times and by different mechanisms (Fig. 10). Cambrian (ca. 520 Ma) deposits are interpreted to have formed by magmatic-hydrothermal processes related to the exsolution of fluids from mesozonal albitite, generated by the melting of a sequence containing pre-exisiting stratabound iron mineralisation. Younger Variscan deposits formed at ca. 374 Ma due to the likely metamorphic-hydrothermal remobilisation of equivalent mineralisation during early stages of transpressive deformation. Finally, at ca. 340 Ma a further anatectic pulse led to the formation of magnetite-rich albitite and related replacive mineralisation. The absence of both a prograde calc-silicate alteration assemblage (with garnet and/or pyroxene) and the metasomatic zonation typical of the calcic skarns (Einaudi *et al.*, 1981) in the OMZ, indicate that these deposits cannot be classified as skarns.

Thus, our data show that within the same province, polyphase magmatism and deformation can lead to different styles to IOCG mineralisation, in a similar fashion to that observed in the Cloncurry District (Williams and Pollard, 2003). Furthermore, the presence of earlier iron oxide concentrations can be a critical factor in the development of epigenetic IOCG-style mineralisation, through metamorphic/magmatic-hydrothermal rejuvenation and the reconcentration of metals transported by brines to favourable depositional sites. The data also suggest that magnetite-rich or even magnetite-only orebodies can form by partial melting of these pre-existing stratabound deposits.

The Cala deposit is somewhat different to the other deposits of the Olivenza-Monesterio belt, and could well be the distal expression of the albite-related mineralisation. Alternatively, it could be genetically related to the nearby calc-alkaline intrusions, or even have a different origin, with fluids being non-magmatic and the mineralisation being related to the circulation of metamorphic fluids equilibrated with a deep iron oxide-bearing basement. Compared to the Colmenar- and Berrona-type deposits, Cala formed in a shallower, brittle-ductile domain, with copper-gold enrichment apparently occurring towards the end of, or subsequent to, magnetite formation.

In all the systems studied, copper-gold is late in the hydrothermal evolution and does not appear to be part of the magnetite assemblage. Magnetite-rich rocks acted as a trap for younger copper-gold-bearing fluids, causing changes to their oxidation state and sulphur concentration, and the concomitant precipitation of economic to sub-economic copper-gold bearing assemblages due to the destabilisation of HS-bearing aqueous complexes.

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References

Abalos, B., Gil Ibarguchi, J.I. and Eguiluz, L., 1991 - Cadomian subduction/collision and Variscan transpression in the Badajoz-Córdoba shear belt, southwest Spain; *Tectonophysics*, v. 199, pp. 51-72.

Apraiz, A. and Eguíluz, L., 1996 - El núcleo metamórfico de Valuengo (Zona de Ossa-Morena, Macizo Ibérico): petrografía, termobarometría y evolución geodinámica; *Revista de la Sociedad Geológica de España* v. 9, pp. 29-49. (*in Spanish*)

Apraiz, A. and Eguíluz, L., 2002 - Hercynian tectono-thermal evolution associated with crustal extension and exhumation of the Lora del Río metamorphic core complex (Ossa-Morena zone, Iberian Massif, SW Spain); *International Journal of Earth Sciences*, v. 91, pp. 76-92.

Bachiller, N., 1996 - Las alteraciones hidrotermales de los leucogranitos del complejo intrusivo de Burguillos del Cerro (Badajoz). Edad, Geoquímica y modelo de procedencia y evolución de los fluidos; Master's Thesis, *Universidad Complutense de Madrid*, 151p. (*in Spanish*)

Baker, T., Perkins, C., Blake, K.L. and Williams, P.S., 2001 - Radiogenic and stable isotope constraints on the genesis of the Eloise Cu-Au deposit, Cloncurry district, NW Queensland; *Economic Geology*, v. 96, pp. 723-742.

Barton, D.M. and Johnson, D.A., 1996 - An evaporitic source model for igneous-related Fe oxide-(REE-Cu-Au-U) mineralization; *Geology*, v. 24, pp. 259-262.

Calvo, B., 1980 - Estudio genético del yacimiento de magnetita pirita de Cala (Huelva); *Tecniterrae*, v. 34, pp. 5-10. (*in Spanish*)

Carriedo, J., Tornos, F., Velasco, F. and Stein, H., 2007 - Complex structural and hydrothermal evolution of the Cala magnetite deposit, SW Iberia - an ICOG deposit?; *in* Andrews, C.J., *et al.* (eds.), Digging Deeper, *Irish Association for Economic Geology, Dublin*, v. 2, pp. 1351-1354.

Casquet, C., Galindo, C., Darbyshire, D.P.F., Noble, S.R. and Tornos, F., 1998 - Fe-U-REE mineralization at mina Monchi, Burguillos del Cerro, SW Spain. Age and isotope (U-Pb, Rb-Sr and Sm-Nd) constraints on the evolution of the ores; *GAC-MAC-APGGQ Quebec´98*, Conference Abstracts, v. 23. p. A-28.

Casquet, C. and Tornos, F., 1991 - Influence of depth and igneous chemistry on ore development in skarns; the Hercynian belt of the Iberian Peninsula; *in* Skarns - Their Genesis and Metallogeny, *Theophrastus Publications S.A., Athens*, pp. 555-591.

Casquet, C. and Velasco, F., 1978 - Contribución a la geología de las skarns cálcicos en torno a Santa Olalla de Cala (Huelva-Badajoz). *Estudios Geologicos, Madrid*, v. 34, pp. 399-405. (*in Spanish*)

Chen, H., 2008 - The Marcona - Mina Justa District, south-central Perú: implications for the genesis and definition of the Iron Oxide-Copper (-Gold) ore deposit clan; PhD. Thesis, *Queen´s University, Kingston, Ontario, Canada*, 266p.

Clark, A.H. and Kontak, D.J., 2004 - Fe-Ti-P oxide melts generated through magma mixing in the Antauta subvolcanic center, Perú: implications for the origin of nelsonite and iron oxide-dominated hydrothermal deposits; *Economic Geology*, v. 90, pp. 377-395.

Corriveau, L., 2007 - Iron oxide copper-gold (±Ag ±Nb ±P ±REE ±U) deposits: a Canadian perspective; *in:* Goodfellow, W.D., (ed.), Mineral Deposits of Canada: a synthesis of major deposits-types, district metallogeny, the evolution of geological provinces and exploration methods: *Geological Association of Canada, Mineral Deposits Division*, Special publication no. 5., pp. 309-328.

Coullaut, J.L., 1979 - Geología y metalogenia del criadero de San Guillermo Colmenar, Jerez de los Caballeros, Badajoz; *Curso Rosso de Luna, IGME*, pp. 1-20. (*in Spanish*)

Dallmeyer, R.D., García Casquero, J.L. and Quesada, C., 1995 - $^{40}Ar/^{39}Ar$ Mineral age constraints on the emplacement of the Burguillos del Cerro Igneous complex (Ossa-Morena zone, SW Iberia); *Boletín Geológico y Minero*, v. 106, pp. 203-214. (*in Spanish*)

Dallmeyer, R.D. and Quesada, C., 1992 - Cadomian vs. Variscan evolution of the Ossa-Morena Zone (SW Iberia): field and $^{40}Ar/^{39}Ar$ mineral age constrains; *Tectonophysics*, v. 216, pp. 339-364.

Darbyshire, D.P.F., Tornos, F., Galindo, C. and Casquet, C., 1998 - Sm-Nd and Rb-Sr constraints on the age and origin of magnetite mineralization in the Jerez de los Caballeros iron district of Extremadura, SW Spain; ICOG-9, *Chinese Science Bulletin*, v. 43, p. 28.

De Haller, A., Corfu, F., Fontbote, L., Schaltegger, U., Barra, F., Chiaradia, M., Frank, M. and Alvarado, J.Z., 2006 - Geology, Geochronology and Hf and Pb Isotope Data of the Raúl-Condestable Iron Oxide-Copper-Gold Deposit, Central Coast of Peru; *Economic Geology*, v. 101, pp. 281-310.

Doestsch, J. 1973 - Estado actual de la investigación de criaderos del Suroeste de España; *Boletín Geológico y Minero*, v. 842, pp. 105-129. (*in Spanish*)

Dupont, R. 1979 - Cadre geologique et metallogenese des gisements de fer du sud de la province de Badajoz (Sierra Morena Occidentale-Spagne); PhD Thesis, *Institut Nationale Polytechnique de Lorraine*, 371p. (*in Spanish*)

Edfelt, A., Armstrong, M., Smith, M. and Martinsson, O., 2005 - Alteration paragenesis and mineral chemistry of the Tjarrojakka apatite-iron and Cu (-Au) occurrences, Kiruna area, northern Sweden; *Mineralium Deposita*, v. 40, pp. 409-434.

Eguíluz, L., Gil Ibarguchi, J.I., Ábalos, B. and Apraiz, A., 2000 - Superposed Hercynian and Cadomian orogenic cycles in the Ossa Morena zone and related areas of the Iberian massif; *GSA Bulletin*, v. 112, pp. 1398-1413.

Einaudi, M.T., Meinert, L.D. and Newberry, R.J., 1981 - Skarn Deposits; *Economic Geology 75th Anniversary Volume*, pp. 317-391.

Etxebarria, M., Chalot-Prat, F., Apraiz, A. and Eguiluz, L., 2006 - Birth of a volcanic passive margin in Cambrian time: Rift paleogeography of the Ossa-Morena Zone, SW Spain; *Precambrian Research*, v. 147, pp. 366-386.

Gabaldón, V., Garrote, A. and Quesada, C., 1985 - Geología del Carbonífero Inferior del Norte de la Zona de Ossa-Morena; 5º Reunión Grupo Ossa-Morena, *Temas Geológicos y Mineros, IGME*, pp. 101-137. (*in Spanish*)

Galindo, C., Darbyshire, F., Tornos, F., Casquet, C. and Cuervo, S., 1995 - Sm-Nd geochemistry and dating of magnetites: a case study from and Fe district in the SW of Spain; *in* Pasava, J., Kribek, B. and Zak, K., (eds.), Mineral Deposits: From Their Origin to Enviromental Impacts, *Balkena, Rotterdam*, pp. 41-43.

Galindo, C., Portugal Ferreira, M.R., Casquet, C. and Priem, H.N.A., 1990 - Dataciones Rb-Sr en el Complejo plutónico Táliga-Barcarrota (CPTB, Badajoz); *Geogaceta*, v. 8, pp. 7-10. (*in Spanish*)

García Casquero, J. L., 1995 - Intrusión múltiple y cuerpos ígneos politípicos: el complejo ígneo de Burguillos del Cerro, un Macizo Diorítico Zonado en el basamento Varisco de la Península Ibérica; *Boletín Geológico y Minero*, v. 106, pp. 79-98. (*in Spanish*)

Gelcich, S., Davis, D.W. and Spooner, E.T.C., 2005 - Testing the apatite-magnetite geochronometer: U-Pb and 40Ar/39Ar geochronology of plutonic rocks, massive magnetite-apatite tabular bodies, and IOCG mineralization in Northern Chile; *Geochimica et Cosmochimica Acta*, v. 69, pp. 3367-3384.

Giese, U. and Bühn, B., 1993 - Early Paleozoic rifting and bimodal volcanism in the Ossa-Morena Zone of south-west Spain; *Geologische Rundschau*, v. 83, pp. 143-160.

Hitzman, M.W., 2000 - Iron oxide-Cu-Au deposits: what, where, when and why?; *in* Porter, T.M. (ed.), Hydrothermal Iron-Oxide Copper-Gold and Related Deposits: A Global Perspective, *PGC Publishing, Adelaide*, v. 1, pp. 9-25.

Hitzman, M.W., Oreskes, N. and Einaudi, M.T., 1992 - Geological characteristics and tectonic setting of Proterozoic iron oxide (Cu-U-Au-LREE) deposits; *Precambrian Research*, v. 58, pp. 241-287.

IGME, 2006 - Mapa metalogenético de la provincia de Badajoz. Escala 1:200 000; 192p. (*in Spanish*)

Injoque, J., 2002 - Fe oxide-Cu-Au deposits in Peru: an integrated view. *in* Porter, T.M. (ed.), Hydrothermal Iron-Oxide Copper-Gold and Related Deposits: A Global Perspective, *PGC Publishing, Adelaide*, v. 2, pp. 97-113.

Liñan, E. and Perejón, A., 1981 - El Cámbrico inferior de la Unidad de Alconera, Badajoz (SW de España); *Boletín de la Real Sociedad Española de Historia Natural (Geología)*, v. 79, pp. 125-148. (*in Spanish*)

Liñan, E. and C. Quesada, 1990 - Ossa-Morena Zone: Stratigraphy, rift phase (Cambrian); *in* Martinez, E. and Dallmeyer, R.D. (eds.) Pre-Mesozoic Geology of Iberia, *Springer Verlag*, pp. 259-266.

Locutura, J., Tornos, F., Florido, P. and Baeza, L., 1990 - Ossa-Morena Zone: Metallogeny *in* Martinez, E. and Dallmeyer, R.D. (eds.) Pre-Mesozoic Geology of Iberia, *Springer Verlag*, pp. 321-332.

López-Munguira, A. and Nieto Garcia, F., 2004 - Low-Grade Metamorphism in the Central Sector of the Ossa-Morena Zone; *Journal of Iberian Geology*, v. 30, pp. 109-118.

Mark, G. and Oliver, N.H.S., 2006 - Mineralogical and chemical evolution of the Ernest Henry Fe oxide-Cu-Au ore system, Cloncurry district, northwest Queensland, Australia; *Mineralium Deposita*, v. 40, pp. 769-801.

Marschik, R. and Fontboté, L., 2001 - The Candelaria-Punta del Cobre Iron Oxide Cu-Au (-Zn-Ag) Deposits, Chile; *Economic Geology*, v. 96, pp. 1799-1826.

Martinez Poyatos, D., 1997 - Esctructura del borde meridional de la zona Centroibérica y su relación con el contacto enre las zonas Centroibérica y de Ossa Morena; PhD. Thesis, *Unversidad de Granada*, 222p. (*in Spanish*)

Martinsson, O., 2003 - Characterization of iron mineralizations of Kiruna type in the Kiruna area, northern Sweden; *in* Eliopolous *et al.* (eds.), *Proceedings of the 7th Biennial SGA Conference,* Mineral Exploration and Sustainable Development, Athens, Greece, 24-28 August 2003, pp. 1087-1090.

Montero, P., Salman, K., Bea, F., Azor, A., Expósito, I., Lodeiro, F., Martínez Poyatos, D. and Simancas, F., 2000 - New data on the geochronology of the Ossa-Morena Zone, Iberian Massif; *in* Variscan-Appalachian dynamics: The building of the Upper Palaeozoic basement. *Galicia 2000. Abstracts*.

Munhá, J., Oliveira, J.T., Ribeiro, A., Oliveira, V., Quesada, C. and Kerrich, R., 1986 - Beja-Acebuches ophiolite; characterization and geodynamic significance; *Maleo*, v. 2, p. 31.

Munhá, J., Ribeiro, A., Fonseca, P., Oliveira, J.T., Castro, P. and Quesada, A.C., 1989 - Accreted terranes in Southern Iberia: Beja-Acebuches ophiolite and related oceanic sequences; *28th International Geolological Congress, (Washington, U.S.A.),* Abstracts with programs, v. 2, pp. 481-482.

Naslund, H. R., Henríquez, F., Nyström, J.O., Vivallo, W. and Dobbs, F.M., 2002 - Magmatic iron ores and associated mineralisation: examples from the chilean high Andes and Coastal Cordillera; *in* Porter, T.M. (ed.), Hydrothermal Iron-Oxide Copper-Gold and Related Deposits: A Global Perspective, *PGC Publishing, Adelaide*, v. 2, pp. 207-226.

Niiranen, T., Poutiainen, M. and Mänttäri, I., 2007 - Geology, geochemistry, fluid inclusion characteristics, and U-Pb age studies on iron oxide-Cu-Au deposits in the Kolari region, northern Finland; *Ore Geology Reviews,* v. 30, pp. 75-105.

Ochsner, A., 1993 - U-Pb Geochronology of the Upper Proterozoic-Lower Paleozoic geodynamic evolution in the Ossa Morena Zone (SW Iberia): Constraints on the timing of the Cadomian Orogeny; PhD. Thesis, *Swiss Federal Institute of Technology, Zürich*, 249p.

Oliver, N.H.S., Rubenach, M.J. and Predictive Mineral Discovery Cooperative Research Centre, 2009 - Distinguishing Basinal and Magmatic-Hydrothermal IOCG deposits, Cloncurry District, Northern Australia; *in* Corriveau, L., Porter, T.M. and Tornos, F., (eds.), Session B6, Genesis of Iron-oxide-copper-gold Deposits, *Proceedings of the 10th Biennial SGA Conference,* 17-20 August, 2009, Townsville, Australia, Extended abstracts, v. 2, pp. 647-649.

Ordoñez Casado, B., 1998 - Geochronological studies of the Pre-Mesozoic basement of the Iberian Massif: the Ossa Morena zone and the allochthonous complexes within the central Iberian zone; PhD. Thesis, *Zürich University*, 235p.

Perring, C.S., Pollard, P.J. and Nunn, A.J., 2001 - Petrogenesis of the Squirrel Hills granite and associated magnetite-rich sill and vein complex: Lighting Creek prospect, Cloncurry district, Northwest Queensland; *Precambrian Research*, v. 106, pp. 213-238.

Pin, C., Liñán, L., Pascual, E., Donaire, T. and Valenzuela, A., 2002 - Late Neoproterozoic crustal growth in the European Variscides: Nd isotope and geochemical evidence from the Sierra de Córdoba Andesites (Ossa-Morena Zone, Southern Spain); *Tectonophysics*, v. 352, pp. 133-151.

Pin, C., Paquette, J.L. and Fonseca, P., 1999 - 350 Ma (U-Pb zircon) igneous emplacement age and Sr-Nd isotopic study of the Beja gabbroic complex (S Portugal); *XV Reunión de Geología del Oeste Peninsular (International Meeting Cadomian Orogens), Diputación de Badajoz*, pp. 217-222.

Quesada, C., 1990 - Precambrian successions in SW Iberia: their relationship to Cadomian orogenic events; *in* D'Lemos, R.S., Strachan, R.A. and Topley, C.G., (eds.), The Cadomian Orogeny, *Geological Society, London, Special Publications*, v. 51, pp. 353-362.

Quesada, C., 1991 - Geological constraints on the Paleozoic tectonic evolution of tectonostratigraphic terranes in the Iberian Massif; *Tectonophysics*, v. 185, pp. 225-245.

Quesada, C., 1992 - Evolución tectónica del Macizo Ibérico (una historia de crecimiento por acrecencia sucesiva de terrenos durante el Proterozoico Superior y Paleozoico); *in* Gutierrez J.C., Saavedra M.J. and Rábano, I., (eds.) *Paleozoico Inferior de Ibero-América*, Junta de Extremadura, pp. 173-192. (*in Spanish*)

Quesada, C. and Dallmeyer, R.D., 1989 - Geochronological constraints to the structural evolution of the Badajoz-Córdoba belt, South-western Iberian Massif; *Geological Society of America*, Annual Meeting, Abstracts. p. A-227.

Quesada, C. and Dallmeyer, R.D., 1994 - Tectonothermal evolution of the Badajoz-Córdoba shear zone (SW Iberia): characteristics and $^{40}Ar/^{39}Ar$ mineral age constraints; *Tectonophysics*, v. 231, pp. 195-213.

Quesada, C., Florido, P., Gumiel, P., Osborne, J., Larrea, F., Baeza, L., Ortega, C., Tornos, F. and Sigüenza, J., 1987 - Mapa geológico-minero de Extremadura; *Consejería de Industria y Energía de la Junta de Extremadura, Mérida*, 131p. (*in Spanish*)

Ribeiro, A., Quesada, C. and Dallmeyer, R.D., 1990 - Geodynamic evolution of the Iberian Massif; *in* Dallmeyer, R.D. and Martinez Garcia, E., (eds.), Pre-Mesozoic Geology of the Iberian Peninsula, *Springer Verlag, Berlin*, pp. 399-409.

Romeo, I., Lunar, R., Capote, R., Quesada, C., Dunning, G.R., Piña, R. and Ortega, L., 2006 - U-Pb age constraints on Variscan magmatism and Ni-Cu-PGE metallogeny in the Ossa-Morena Zone (SW Iberia); *Journal of the Geological Society, London*, v. 163, pp. 837-846.

Sagredo, J. and Peinado, M., 1992 - Vulcanismo Cámbrico de la Zona de Ossa Morena; *in* Gutiérrez-Marco, J.C. Saavedra, J. and Rábano, I., (eds.), Paleozoico Inferior de Iberoamérica, *Universidad de Extremadura, Salamanca*, pp. 567-576. (*in Spanish*)

Sánchez-García, T., Quesada, C., Bellido, F., Dunning, G.R. and González del Tánago, J., 2008 - Two-step magma flooding of the upper crust during rifting: The Early Paleozoic of the Ossa Morena Zone (SW Iberia); *Tectonophysics*, v. 461, pp. 72-90.

Sánchez Carretero, R., Eguiluz, L., Pascual, E. and Carracedo, M., 1990 - Part V (Ossa-Morena Zone): Igneous Rocks; *in* Dallmeyer, R.D. and Martínez García, E. (eds.), Pre-Mesozoic Geology of Iberia, *Springer-Verlag, Berlin-Heidelberg*, pp. 292-313.

Schäfer, H.J., 1990 - Geochronological investigations in the Ossa-Morena Zone, SW Spain; PhD. Thesis, *Zürich University*, 153p.

Schwartz, M.O., 1992 - Geochemical criteria for distinguishing magmatic and metasomatic albite-enrichment in granitoids - examples from the Ta-Li granite Yichun (China) and the Sn-W deposit Tikus (Indonesia); *Mineralium Deposita*, v. 27, pp. 101-108.

Sillitoe, R.H., 2003 - Iron oxide-copper-gold deposits: an Andean view; *Mineralium Deposita*, v. 38, pp. 787-812.

Silva J.B., Oliveira J.T. and Ribeiro, A., 1990 - South Portuguese Zone, structural outline; *in* Dallmeyer, R.D. and Martínez García, E. (eds.), Pre-Mesozoic Geology of Iberia, *Springer-Verlag, Berlin-Heidelberg*, pp. 348-362.

Simancas J.F, Carbonell R., González Lodeiro F., Pérez Estaún A., Juhlin C., Ayarza P., Azor A., Martínez Poyatos D., Almodóvar G. R., Pascual E., Sáez R., Kashubin A., Alonso F., Álvarez Marrón J., Bohoyo F., Castillo S., Donaire T., Expósito I., Flecha I., Galadí E., Galindo Zaldívar J., González F., González Cuadra P., Macías I., Martí D., Martín A., Martín Parra L. M., Nieto J. M., Palm H., Ruano P., Ruiz M. and Toscano M., 2004 - The seismic crustal structure of the Ossa-Morena Zone and its geological interpretation; *Journal of Iberian Geology*, v. 30, pp. 133-142.

Simancas, J.F., Martínez Poyatos, D., Expósito, I., Azor, A. and González Lodeiro, F., 2001 - The structure of a major suture zone in the SW Iberian Massif: the Ossa-Morena/Central Iberian contact; *Tectonophysics*, v. 332, pp. 295-308.

Skirrow, R.G., 2000 - Gold-copper-bismuth deposits of the Tennant Creek district, Australia: a reappraisal of diverse high-grade systems; *in* Porter T.M., (ed.), Hydrothermal Iron Oxide Copper-Gold and Related Deposits: A Global Perspective, *PGC Publishing, Adelaide*, v. 1, pp. 149-160.

Stein, H., Markey, R., Carriedo, J. and Tornos, F., 2006 - Re-Os evidence for the origin of Fe-oxide-(Cu-Au) deposits in SW Iberia at the Frasnian-Famennian boundary; *Geochimica et Cosmochimica Acta*, v. 70, p. A612.

Stolz, J. and Morrison, R.S., 1994 - Proterozoic igneous activity in the Tennant Creek region, Northern Territory, Australia, and its relationship to Cu-Au-Bi mineralisation; *Mineralium Deposita*, v. 29, pp. 261-274.

Tomé, C. M., Tornos, F. and Carriedo, J., 2009 - Hydrothermal Evolution of the IOCG-like Cala Deposit, SW Spain; *in* Corriveau, L., Porter, T.M. and Tornos, F., (eds.), Session B6, Genesis of Iron-oxide-copper-gold Deposits, *Proceedings of the 10th Biennial SGA Conference,* 17-20 August, 2009, Townsville, Australia, Extended abstracts, v. 2, pp. 659-661.

Tornos, F. and Carriedo, J., 2006 - La relación de los depósitos de tipo IOCG con intrusiones laminares profundas: el SO de la Península Ibérica; *Actas del XIII Congreso Peruano de Geología*, pp. 796-799. (*in Spanish*)

Tornos, F. and Carriedo, J., 2008 - The relationship of IOCG deposits and the partial melting of evaporite- and iron-rich metasediments; *in* Corriveau, L. and Beaudoin, G., (eds.), 400 Years of Discovery, *GAC-MAC Quebec 2008, Quebec*, Conference abstracts, v. 33, p. 171.

Tornos, F. and Casquet, C., 2005 - A new scenario for related IOCG and Ni-(Cu) mineralization: the relationship with giant mid-crustal mafic sills, Variscan Iberian Massif; *Terra Nova*, v. 17, pp. 236-241.

Tornos, F., Casquet, C., Galindo, C., 2003 - Hydrothermal iron oxide (-Cu-Au) mineralization in SW Iberia: evidence for a multiple origin; *in* Eliopolous *et al.* (eds.), *Proceedings of the 7th Biennial SGA Conference,* Mineral Exploration and Sustainable Development, Athens, Greece, 24-28 August 2003, pp. 395-398.

Tornos, F., Casquet, C., Relvas, J.M.R.S., Barriga, F.J.A.S. and Saez, R., 2002 - The relationship between ore deposits and oblique tectonics: the SW Iberian Variscan Belt; *in* Blundell, D.J., Neubauer, F. and Von Quadt, A., The Timing and Location of Major Ore Deposits in an Evolving Orogen; *Geological Society of London*, Special Publications, v. 204, pp. 179-198.

Tornos, F., Casquet, C. and Relvas, J.M.R.S., 2005 - Transpressional tectonics, lower crust decoupling and intrusion of deep mafic sills: A model for the unusual metallogenesis of SW Iberia; *Ore Geology Reviews*, v. 27, pp. 133-163.

Tornos, F. and Chiaradia, M., 2004 - Plumbotectonic evolution of the Ossa Morena zone, Iberian Peninsula: tracing the influence of mantle-crust interaction in ore-forming processes; *Economic Geology*, v. 99, pp. 965-985.

Tornos, F., Inverno, C.M.C., Casquet, C., Mateus, A., Ortiz, G. and Oliveira, V., 2004 - The metallogenic evolution of the Ossa-Morena Zone; *Journal of Iberian Geology*, v. 30, pp. 143-181.

Tornos, F., Iriondo, A., Casquet, C. and Galindo, C., 2004 - Geocronología Ar-Ar de flogopitas del stock de Aguablanca (Badajoz). Implicaciones sobre la edad del plutón y de la mineralización de Ni-(Cu) asociada; *Geotemas*, v. 6, pp. 189-192. (*in Spanish*)

Tornos, F. and Velasco, F., 2002 - The Sultana orebody (Ossa-Morena Zone, Spain): Insights into the evolution of Cu-(Au-Bi) mesothermal mineralization; Unpublished abstracts, *GEODE Study Centre, Grenoble*, 25-28 October, 2002, 2p.

Vázquez, F. and Fernández Pompa, F., 1976 - Contribución al conocimiento geológico del SW de España en relación con la prospección de magnetitas; *Memorias del Instituto Geológico y Minero de España*, v. 89, 139p. (*in Spanish*)

Velasco, F. and Amigó, J. M., 1981 - Mineralogy and Origin of the Skarn from Cala (Huelva, Spain); *Economic Geology*, v. 76, pp. 719-727.

Velasco, F., Casquet, C., Ortega Huertas, M. and Rodríguez Gordillo, J., 1981 - Indicio de vermiculita en el skarn magnésico (aposkarn flogopítico) de La Garrenchosa (Sta. Olalla, Huelva); *Boletín de la Sociedad Española de Mineralogía*, v. 2, pp. 135-149. (*in Spanish*)

Velasco, F., Tornos, F., Pesquera, A. and Peña, A., 1995 - Metamorphic hydrothermal fluids in tonalite-hosted copper-gold vein mineralization, Mina Sultana (Cala, Huelva, Spain); *Boletín de la Sociedad Española de Mineralogía*, v. 18, pp. 263-264.

Williams, P.J., Barton, M.D., Johnson, D.A, Fontboté, L., de Haller, A., Mark, G., Oliver, N.H.S. and Marschik, R., 2005 - Iron oxide-copper-gold deposits: Geology, space-time distribution, and possible modes of origin; *in* Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J. and Richards, J.P. (eds.), Economic Geology, 100th Anniversary Volume, *Society of Economic Geologists*, pp. 371-405.

Williams, P.J. and Pollard, P.J., 2003 - Australian Proterozoic iron oxide-Cu-Au deposits: an overview with new metallogenic and exploration data from the Cloncurry district, northwest Queensland; *Exploration and Mining Geology*, v. 10, pp. 191-213.

Williams, P.J. and Skirrow, R.G., 2000 - Overview of iron-oxide-copper-gold deposits in the Curnamona Province and Cloncurry District (eastern Mount Isa block), Australia; *in* Porter, T.M., (ed.), Hydrothermal Iron Oxide Copper-Gold and Related Deposits: A Global Perspective, *PGC Publishing, Adelaide*, v. 1, pp. 105-122.

Xavier, R.P., Monteiro, L.V.S., Souza Filho, C.R., Torresi, I., Carvalho, E.R., Pestilho, A.L.S., Moreto, C.P.N. and Dreher, A.M., 2010 - The iron oxide copper-gold deposits of the Carajás mineral province, Brazil: an updated and critical review; *in* Porter, T.M., (ed.), Hydrothermal Iron Oxide Copper-Gold and Related Deposits: A Global Perspective, *PGC Publishing, Adelaide*, v. 3, pp. 285-306.

Zaw, K., Huston, D.L., Large, R.R., Mernagh, T. and Hoffmann, C.F., 1994 - Microthermometry and geochemistry of fluid inclusions from the Tennant Creek gold-copper deposits: implications for ore deposition and exploration; *Mineralium Deposita*, v. 29, pp. 288-300.

Zhu, J.-C., Li, R.-K., Li, F.-C., Xiong, X.-L., Zhou, F.-Y. and Huang X.-L., 2001 - Topaz-albite granites and rare-metal mineralization in the Limu District, Guangxi Province, southeast China; *Mineralium Deposita*, v. 36, pp. 393-405.