

## NEW DATA ON THE OPHIOLITIC VMS DEPOSITS OF MOECHE (CABO ORTEGAL COMPLEX, NW SPAIN)

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*As a result of the variscan collision, several allochthonous complexes were emplaced on the Iberian margin in Devonian times, among them the Cabo Ortegal Complex comprising the Moeche ophiolitic sequence. Copper has been won from several mines (Piquitos I & II, Barqueira, Maruxa) from disseminated ores and thin massive sulphide layers in the Moeche Unit, a strongly deformed meta-volcanic sequence comprising mainly quartz-chlorite schists and mylonites, which defines the top of the ophiolite. The ores were metamorphosed and strongly deformed under brittle conditions (for pyrite), but their textures are often apparently post-deformational, due to very common solution-transfer processes; they are composed mostly of pyrite and chalcopyrite, with minor sphalerite, pyrrhotite, etc., and with traces of native gold and PGE. The geology, mineralogy, and geochemistry of the orebodies relate closely to VMS of the Cu-Zn (Cyprus) type. Fluid inclusion studies allowed an estimation of metamorphic conditions at pressures of ~ 2/2.5 kb and T ~325/350°C. New determinations using the chlorite geothermometer yield temperatures around 320 °C, corresponding to pressures near 2 kb according to the isochores deduced from the fluid inclusion study, although in the Barqueira mine higher temperatures, up to 350 °C, are found, corresponding to pressures up to 2.5 kb. Pb isotopic compositions of pyrite point to a double source of Pb, i.e. a main mantle and a subordinate crustal source. The values for <sup>87</sup>Sr/<sup>86</sup>Sr in pyrite support this interpretation, but some results suggest later mobilization in an open system, corresponding to solution-transfer. Age determinations of pyrite deduced from the Pb isotope uranium graph, ≈ 480 Ma, do not fit with the metamorphic ages published for the Moeche Unit, and might point to the age of Pb extraction from the mantle.*

**Key words:** *Volcanogenic Massive Sulphide (VMS) deposits. Ophiolitic. Metamorphism. Fluid inclusion analysis. Cabo Ortegal complex, Spain.*

The orebodies mined at the various Moeche mines are a typical cluster of small, 2-3 km spaced, VMS (Cyprus type) deposits, comprising a lower stockwork body and various massive sulphide layers, deposited in the the Rheic ocean, probably shortly before its closure by collision between Gondwana and Avalonia / N.America. They were emplaced at their present position on the NW margin of Gondwana / Iberian Massif by obduction during the variscan collision, which is also related to their metamorphism and deformation, in epizonal conditions, in upper devonian times (2).

The main metatect is the Moeche Unit (4), particularly the pyrite-quartz-chlorite schists (sea-floor basaltic to andesitic meta-volcanics, often mylonitic), which are overlain by metasediments, mainly phyllites and phyllonites. Fabrics are frequently banded and mostly fine-grained. Typical lepidoblastic or granolepidoblastic textures may be preserved, but they are very often overprinted by deformation of a mostly ductile character, and may become mylonitic to ultramylonitic, sometimes blastomylonitic. Porphyroclasts and microclasts of pyrite, albite, sphalerite, epidote, amphibole, as well as mica and chlorite fishes and rock fragments (including vein-quartz fragments) are frequently observed. The post-mylonitic blastesis is most spectacular in the sulphides. The metasediments (phyllites to phyllonites), as

well as the sulphide layers, may preserve the original bedding, but only as a transposed S-surface parallel to the main (mylonitic) schistosity (S2), which may be locally deformed by a later crenulation (S3). The age of S2 and of the corresponding metamorphism has been dated in the chlorite schists as 364 Ma (Upper Devonian, 8).

The ores occur in the Moeche Unit, as lenses in the interface between the metavolcanics and the metasediments or as strongly sheared stockwork bodies in the metavolcanics. The geology, mineralogy, and geochemistry (including  $\delta^{34}\text{S}$  values of sulphides from  $-0.6$  to  $+4.5$  ‰, mean  $+2.5$  ‰) of the orebodies correspond closely to VMS of the Cu-Zn (Cyprus) type, although their complex post-mineralization history and the very strong dynamic metamorphic overprint due to Hercynian collisional tectonics may obscure some of the typical features. The stratigraphy is overturned in the Piquitos mine, and nearly vertical and strongly deformed in the Barqueira mine. Contact metamorphism, attributed to minor, younger intrusives, is still superimposed on some of the Maruxa mine ores, producing granoblastic and diablastic textures. Although the ores are metamorphosed and strongly deformed, their textures are often apparently postdeformational, due to very common solution-transfer processes; the ores are composed mostly of pyrite and chalcopyrite, with subordinate to trace amounts of sphalerite, pyrrhotite, galena, magnetite, hematite, marcasite, linneite, mackinawite, cubanite (*i*), native gold and silver; and, as secondary minerals, covellite, goethite / limonite, chalcocite, malachite, etc. The deformation occurred under brittle conditions for pyrite and sphalerite, but chalcopyrite shows a ductile behaviour. This puts an upper temperature limit for the dynamic metamorphism far below  $450^\circ\text{C}$  (7, 11, 12, discussion in 3).

No primary fluid inclusions related to ore deposition under sea floor could be measured, due to ubiquitous deformation or overprinting; detailed FI petrography shows that the measurable FI present are mostly secondary and consistent with a relatively deep (metamorphic) environment, although some remnants of tiny primary fluid inclusions can be occasionally observed in some phenoclasts of vein (stockwork) quartz crystals. Preliminary fluid inclusion studies (3) on the metamorphic fluids trapped in microfissures in quartz allowed an insight into the epizonal metamorphic conditions ( $P_f \approx 2/2.5$  kb and  $T \approx 325/350^\circ\text{C}$ ). Dense ( $F \approx 0.8$ ), aqueous metamorphic fluids with moderate salinities ( $\approx 8$  wt% NaCl eq.; no  $\text{CO}_2$  detected) produced continuous pressure-solution mobilization of the ores, thus enhancing deformation by small scale solution transfer. This mobilization occurred, however, only over very short distances, so that the original geometric/stratigraphic relationships are still locally preserved or can be inferred.

To check P-T estimations, chlorite geothermometry was performed on selected chlorite samples from the pyrite-quartz-chlorite schists from the main accessible mines, Piquito II and Barqueira, applying five different geothermometric equations (5, 6, 9, 10, 15). Most of the results range from  $\approx 280$  to  $350^\circ\text{C}$ , with the higher values in the Barqueira mine. These preliminary values, centered around  $320^\circ\text{C}$ , approach closely the previous ones (3), but they widen slightly downwards the temperature range assumed, suggesting a slightly lower (down to  $280^\circ\text{C}$ ) limit. The  $280^\circ\text{C}$  value, projected in the P-T field on the isochore graph, would also descend the corresponding lower pressure threshold to  $\approx 1.7$  kb, instead of the 2 kb assumed. This is still to be critically confirmed (work in progress).

Pb and Sr isotope analysis were also performed on various selected pyrite samples from the Piquito II mine. Pre-tectonic massive pyrite and post-tectonic pyrite porphyroblasts (recrystallized or mobilized by solution transfer) were selectively concentrated for that purpose. The Pb isotope compositions found in pyrite are homogeneous and scarcely radiogenic. According to the plumbotectonic model (16), the  $^{207}\text{Pb}/^{204}\text{Pb}$  vs.  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios projected in the graph showing the Pb isotope evolution curves plot in a field between the

mantle and the orogenic environment; in the thoriogenic diagram, the  $^{208}\text{Pb}/^{204}\text{Pb}$  vs.  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios plot between the mantle and the upper crust. This suggests that Pb contained in the analyzed pyrites is a product of mixing from mantle derived Pb (main source) and from Pb related to upper crustal rocks, a result which is in agreement with recently published geochemical data for the Moeche Unit pointing to remnants of a thinned crust (13, 1).

This interpretation is also sustained by the Sr isotope results. Calculated initial values for  $^{87}\text{Sr}/^{86}\text{Sr}$  range between 0'7049 and 0'7056, and 0'7110, for an age assumption of 400 Ma. Two of the samples show  $^{87}\text{Sr}/^{86}\text{Sr}$  analytical ratios of 0'71097 and 0'7078, which produce unreasonable initial values when calculated for 400 Ma: this suggests that these pyrites were the result of mobilization by solution transfer in an open system for Rb-Sr.

If the analytical results for pyrite are plotted in the uranogenic  $^{207}\text{Pb}/^{204}\text{Pb}$  vs.  $^{206}\text{Pb}/^{204}\text{Pb}$  diagram and compared with the lead isotope evolution (14), the projection of their line intercepts the SK curve at 480 Ma, a value that could perhaps approach the age at which Pb was extracted from the mantle and incorporated into the crust, before the mineralisation was formed.

It can be concluded that the various Moeche deposits share a common geologic history, as volcanogenic massive sulphide bodies of the Cu-Zn (Cyprus) type, obducted on the Iberian margin of Gondwana during the variscan collision, and subjected to an intensive metamorphic overprint in epizonal conditions (between  $\approx 300$  to  $350$  °C and 2 to 2.5 kb; the lowermost limit of these values could descend to some 280 °C and 1.7 kb, according to new preliminary results based on chlorite geothermometry, still to be confirmed). Deformation plays an important role in the geologic evolution of the orebodies, and is enhanced by solution transfer and partly concealed by recrystallization of the sulphides. These conditions are reflected in the Pb and Sr isotope signatures of the pyrite, which suggest a mixing of mantle and crustal sources, but also an open system for Rb/Sr which is evident in some of the samples. A value of 480 Ma, certainly older than the ores, might suggest the age of Pb extraction from the mantle.

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