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Abstract

The Domo de Yauli contains two of the major Zn-Pb±Cu±Ag mining districts of Peru, the Morococha and the San Cristobal districts. They are classical intrusion related ore districts with high temperature, carbonate-hosted base metal deposits and are a typical of the Miocene metallogenic belt of Central Peru. This study is aimed at three main topics, a geochronological, a structural and an isotope and fluid inclusion study. These three different approaches permit us to constrain the factors needed to form world-class deposits. Indeed, formation of such large districts are linked to the conjunction and the right timing among magmatic activity providing heat and fluids, structural stress permitting large fluid circulation and available fluids and elements sources.

The Domo de Yauli is located 100 km east of Lima in the Western Cordillera of Peru. The area is mainly composed of Paleozoic phyllites of the Excelsior Group, Permo-Triassic volcanic and sedimentary rocks of the Mitu Group, Triassic-Jurassic limestones of the Pucará Group, and Cretaceous sedimentary rocks. Incaic compression events of Eocene age have produced isoclinal folds, ramp thrusts in the sedimentary cover rocks and a NE-SW fracture system which crosscuts the entire Domo de Yauli. Major N 120° W oriented lineaments are present in the basement and affect the morphology of the whole area. The positions of these lineaments coincide with the emplacement of the major ore deposits of the district. Outcrops of magmatic rocks are more abundant in the Morococha district, where numerous small stocks of monzogranite intrude the large Anticona diorite. In the San Cristobal district, there are multiple small apophyses of the very altered Chumpe intrusion. The northern monzogranite stocks are related to the formation of four different ore deposit types: Cu-porphyries, Zn-Pb skarns, Zn-Pb±Ag carbonate replacement deposits, and veins. In the south, only polymetallic carbonate replacements and veins are associated to the Chumpe intrusion.

U-Pb dating of zircons from the northern intrusions gives concordant ages of 14.11 ± 0.04 Ma for the Anticona diorite and close to 9 Ma for different monzogranite stocks related to Cu-porphyry style and skarn deposits. Veins of the Cu-porphyry deposit have been dated at 7.9 ± 0.1 Ma by Re-Os on molybdenite and phlogopite from a Zn-Pb skarn gives a $^{40}Ar/^{39}Ar$ plateau age of 7.2 ± 0.2 Ma. U-Pb analyses of zircons from the southern Chumpe intrusion result in discordant points defining a lower intercept age about 6.6 (+1;-3.6) Ma, in agreement with $^{40}Ar/^{39}Ar$ ages of 4.90 ± 0.15 Ma and 4.78 ± 0.16 Ma obtained on sericite from wall rock alteration selvages. U-Pb, Re-Os and $^{40}Ar/^{39}Ar$ age determinations reveal the existence of three distinct magmatic events at 14.1, 9.1 and 6.6 Ma, with the two later ones related to a phase of mineralisation. We therefore conclude that the northern and southern ore deposits bear a different age and that the particularly large abundance of economic ore bodies at Domo de Yauli is the result of successive hydrothermal systems.

A continuous magmatic activity beneath the Morococha district, sustained by repeated injections of new magma and subsequent melting of the host magmatic rock, is documented by numerous concordant U/Pb ages between 9 and 14 Ma and petrological evidences such as reaction rims and plagioclase zonations. The absence of dissolution textures in zircons points out Zr-saturated magmas with temperature as low as 800°C. It implies a rapid cooling and a probable intermediate composition of the successive injections of new magma. Isotopic compositions of the magma ($^{87}Sr/^{86}Sr$ = 0.705627 to 0.707453; $^{143}Nd/^{144}Nd$ = 0.512350 to 0.512510; $^{206}Pb/^{204}Pb$ =18.698 to 18.761; $^{207}Pb/^{204}Pb$ = 15.635 to 15.669; $^{208}Pb/^{204}Pb$ = 38.682 to 38.787) suggest a hybrid melt source of mantle plus crustal origin compatible with zircon ε_{Hf} around zero. Precambrian inheritances in zircons and Hf-depleted mantle model ages of around 1.0 Ga indicate contribution of partial melts from the underlying Arequipa style basement in the generation of the Miocene magmatism.

The orientation of the San Cristobal veins are highly variable and rotate from N 30º W easterly to N 90º W westerly. Veins present a paragenesis that can be subdivided into 3 phases: (a) an early wolframite-quartz-pyrite stage, (b) a quartz-base metal stage and, (c) a late quartz-carbonate-barite stage. The carbonate replacement ore bodies are generally stratiform but show clear features of discordance with respect to the carbonate host rocks. Three-dimensional representations of ore bodies and associated veins show that these discordant features and the highest grades are related to the prolongation of veins into the carbonate rocks. Their mineralogical assemblage is similar to that of the veins, with the only difference that the early wolframite-quartz-pyrite stage is absent and an important iron oxide stage is observed early in the paragenetic sequence.

Orientation data were collected for dilatant veins, Miocene dykes and altered striated faults in order to define the paleostress associated with the mineralisation event. In this study, the inverse method was applied to determine the local stress tensors of different parts of the Domo de Yauli area. Determination of paleostress related to the Miocene magmatic event indicates a heterogeneous compression field shifting from E-W to N-S from east to west. The rotation of the main compression orientation occurred across a N 120° W oriented basement lineament. It reveals the active role of strike-slip movement along such lineaments as a control for the formation of ore deposits in the Domo de Yauli area. The origin of these lineaments are difficult to define, nonetheless, numerous structural features of the same orientation in the Mitu Group indicate that their origin date back to the Permian rifting.

Fluid inclusions in sphalerite and quartz homogenise to the liquid phase between 140 and 330°C and are two-phase (0.4 and 6.7wt% NaCl) at room temperature; rare inclusions contain an additional crystal of halite in the early stage (28 to 50wt% NaCl). The vein data show a decrease in homogenisation temperatures concomitant with a diminishing salinity. Contrary to the veins, the data from the carbonate replacement ores show a wide variation in salinity (3.3 to 14wt% NaCl) at constant homogenisation temperature. This can be explained either by mixing of the fluid related to the vein system and a hot brine, or by boiling of the fluid migrating out of the veins into the carbonate. Wolframite, galena and sphalerite from each ore type yield similar lead isotopic compositions ($^{206}Pb/^{204}Pb$ = 18.676 to 18.840; $^{207}Pb/^{204}Pb$ = 15.615 to 15.649; $^{208}Pb/^{204}Pb$ = 38.704 to 38.827) and overlap with those of the Miocene intrusions ($^{206}Pb/^{204}Pb$ = 18.698 to 18.761; $^{207}Pb/^{204}Pb$ = 15.635 to 15.669; $^{208}Pb/^{204}Pb$ = 38.682 to 38.787). On the contrary, strontium isotopic compositions of carbonate and barite are highly variable and too radiogenic to be explained by magmatic input only ($^{87}Sr/^{86}Sr$ = 0.712187 to 0.722782). It may correspond to a predominantly magmatic fluid followed by incoming of ^{87}Sr-enriched fluids. This evolution in two steps is consistent with hydrogen and oxygen isotope data. Isotopic compositions of the fluid associated to the first stages reveal a trend with constant $\delta^{18}O$ values with decreasing δD values ($\delta^{18}O$ = 3.2 to 5.0 ‰ SMOW and δD = -60 to –112 ‰ SMOW), which is interpreted as mixing of a dominantly magmatic component with minor meteoric water equilibrated with the host rocks. On the contrary, ending stages bear isotopic characteristics that define a trend with a conjugated decrease of

$\delta^{18}O$ and δD ($\delta^{18}O$ = -8.1 to 2.5 ‰ SMOW and δD = -57 to –91 ‰ SMOW) and is rather explained by large admixture of meteoric water in the system and subsequent mixing with the magmatic component.

Their different origins are confirmed by laser ablation ICP-MS analyses of the three- and two-phase primary inclusions. The concentrations of the major ore elements, i.e. W, Cu, Zn and Pb, decrease through the paragenesis and, W, and to a lesser extent Cu, show high variations, associated to a steep decrease in concentration with time. The decreasing concentrations can be explained by mineral deposition and differences in the speed of decrease indicate selective precipitation. On the contrary, fluid inclusions of the last stages show an abrupt increase of Ba and Sr concentrations. It points out a higher volume of silicate alteration, probably due to the larger size of the fluid flow cell and is explained by the input of a fluid from a different origin. LA-ICP-MS analyses show that the fluids were totally depleted in W and Cu before reaching the carbonates, whereas Zn and Pb were still present in considerable amounts. This is again due to the selective precipitation and tells us that the economically interesting metals were dominantly introduced by magmatic fluids.