Systematic trends in the evolution of porphyry-related Zn-Pb-(Ag) deposits

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Zinc-Pb mineral deposits in a porphyry system include (i) deposits formed subsequently to a prograde skarn phase, and (ii) replacement bodies and veins that lack skarn assemblages and are best developed in the shallow part of the system, predominantly in the epithermal environment. The latter are frequently called Cordilleran polymetallic deposits, carbonate replacement deposits (CRD), or intermediate-sulfidation (IS) deposits. The term Cordilleran is preferred because these deposits are not restricted to carbonate replacement and often include also low- and/or high-sulfidation mineral assemblages (LS and/or HS).

Based on the study of multiple deposits, an updated model for the evolution of porphyry-related Zn-Pb-(Ag) deposits is presented. It points to a significant overlap between the retrograde stage of Zn-Pb skarns and Cordilleran Zn-Pb deposits. Both mineral deposit groups share characteristics and mineral assemblages that in the ideal case follow systematic trends from low to higher sulfidation state, to subsequently return to lower sulfidation conditions. In Cordilleran polymetallic deposits all or some of the following, frequently telescoped, stages are observed. Repeated events often complicate the picture.

Stage A (LS, Zn-Pb±Cu±Sn, ~350-220°C) is characterized by LS assemblages with pyrrhotite, magnetite, Fe-rich sphalerite (up to 30 mole % FeS), minor galena, chalcopyrite and arsenopyrite. Chalcopyrite and may be also abundant. In deposits with particularly reduced assemblages, siderite and the Sn-bearing minerals cassiterite, stannite, and herzenbergite occur too and sphalerite may have high In content. Main gangue minerals are quartz and chlorite. When well developed, stage A forms pervasive, massive bodies. In some deposits, stage A is absent or only represented by small pyrrhotite inclusions in stage B pyrite.

Stage B (IS, ~280-200°C) consists predominantly of pyrite, often idiomorphic and coarse-grained, and quartz. Minor wolframite and gold may occur too. Widespread sericitization indicates pH decrease compared to stage A. This stage frequently overprints stage A; diagnostic features include the formation of cubic, pyritohedral, and octahedric crystals of pyrite and/or replacement of stage A pyrrhotite and arsenopyrite by marcasite and pyrite.

Stage C (HS/IS, ~280-150°C) may reach up to HS conditions developing Cu-Zn±Au assemblages with enargite/famatinite, covellite, Fe-poor sphalerite, colusite, quartz, alunite and kaolinite that grade outwards to IS Zn-Pb-Ag assemblages with Fe-moderate to Fe-poor sphalerite, galena, tennantite-tetrahedrite, bismuthinite, other sulfosalts, chalcopyrite, rhodochrosite and other Mn-Fe (±Zn) carbonates as well as ± alabandite. Sericite is present mostly intergrown with Mn-Fe carbonates and quartz. In the outermost zone, barite and hematite are frequent, the later locally replaced by magnetite (mushketovite). Stage C mineral assemblages occur in veins that may extend laterally for kilometers in detrital, volcanic, and other poorly-reactive rocks, whereas in
carbonate rocks stage C may form large replacement bodies and dissolution breccias. In distal parts of stage C veins, stibnite, realgar, orpiment and Ag-bearing minerals may occur. Late calcite ± sphalerite ± galena ± arsenopyrite veinlets are common and indicative of further neutralization of the fluid. Anomalous Mn and Fe contents in calcite veinlets are used in exploration as surface and distal expressions of hidden ore bodies. Stage C spans large mineralogical variations; assemblages rich in V, Bi, Ni, Co, In, Ga are also found.

Many Cordilleran Zn-Pb-Ag deposits consist only (or mainly) of stage C with IS mineral assemblages bearing rhodochrosite and other Mn-Fe carbonates. Therefore, in places, they have been termed "intermediate-sulfidation Zn-Pb deposits". However, it has to be considered that these deposits originate by essentially the same processes forming Cordilleran deposits that also display stages A and B and/or those deposits that develop HS mineral assemblages in stage C. Thus, deposits with only IS assemblages in stage C may constitute the "tail" of larger zoned Cordilleran deposits and of porphyry systems.

In the retrograde stage of Zn-Pb skarns, an evolution that parallelizes that of Cordilleran deposits is often recognized. Most of the ore typically consists of Fe-rich sphalerite in LS assemblages with pyrrhotite and magnetite, siderite, and chlorite, formed at ~ < 350°C that are comparable to the LS stage A described above. Occasionally, the LS stage in Zn-Pb skarns is preceded by chalcopyrite-bornite-pyrite assemblages. The LS assemblages are often overprinted by coarse-grained pyrite with a tendency to idiomorphy, like in the Cordilleran stage B. Subsequently, generally minor, veins with Fe-moderate and -poor sphalerite, galena, Ag-bearing sulfosalts, and Mn-Fe carbonates can occur and are equivalent to IS stage C assemblages described above. When these mineral assemblages extend outside the skarn environment, they are indistinguishable from Cordilleran bodies. In other words, the evolution from low to higher sulfidation conditions is also observed in Zn-Pb skarns, although here the LS stage is more widespread than in most Cordilleran deposits.

At several Cordilleran deposits, a "pre-A stage" consisting of Mg exoskarn minerals like talc, serpentine, magnetite, siderite, quartz ± less easily recognizable actinolite and tremolite also supports the transition and overlapping between skarn and Cordilleran Zn-Pb deposits. These magnesium-rich assemblages in protoliths devoid of diagenetic dolomite point to previous hydrothermal dolomitization.

The ore stages of both groups of ore deposits have been formed by low- to moderate-salinity magmatic fluids resulting of the ascent, from the porphyry level, of intermediate-density fluids or of brines diluted by magmatic vapor. Direct ascent of magmatic vapor to the Zn-Pb deposition environment also happens and is probably responsible for the extreme acidic and oxidized conditions yielding the alunite-bearing HS mineral assemblages of certain Cordilleran deposits, in part flanking HS Au mineralization. The common tendency from low to higher sulfidation state is generally explained by decreasing temperature and interaction of the mineralizing fluids with host rock. This evolution, followed by buffering by the host rock, is reminiscent of the classical "looping path through time and space" in the porphyry deposit itself. This summary is largely based on work in collaboration with members of the Mineral Resources and Geofluids Group of the University of Geneva and the geology staff of several mining companies.