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Gold deposits of the Lesser Caucasus: products of successive Mesozoic and Cenozoic geodynamic settings

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Abstract. Gold deposits were formed during two different geodynamic evolution stages of the Lesser Caucasus, starting with Mesozoic arc construction along the Eurasian margin, and followed by Cenozoic subduction-related to post-collision magmatism and tectonics during final Arabia-Eurasia convergence and accretion. Gold deposits are of the low-, and intermediate- to high-sulfidation type, with the latter ones being associated with porphyry deposits. Some deposits could be analogous to transitional VMS-epithermal systems in the Late Cretaceous Bolnisi district and during nascent Jurassic arc evolution along the Eurasian margin, but require further investigation.

1 Introduction

The Lesser Caucasus extends from the Black Sea to the Caspian Sea, across Georgia, Armenia and Azerbaijan (see inset in Fig.1). It is a central segment of the Tethys orogenic and metallogenic belt, linking the Anatolian and Iranian tectonic zones. The ore deposits and districts can be assigned to two different geodynamic evolution stages, starting with Mesozoic arc construction and evolution along the Eurasian margin, followed by Cenozoic subduction-related to post-collision magmatism and tectonics. Various types of gold deposits were formed during the different stages and are the subject of this review. More details and references about the gold deposits can be found in Moritz et al. (2016a).

2 Geodynamic context

The Lesser Caucasus consists of three tectonic zones: the Jurassic-Cretaceous Eurasian margin, including the Somkheto-Karabagh belt and the Kapan block, the Amasia-Sevan-Akera ophiolite zone, and the Gondwana-derived South Armenian block (Fig. 1). The Somkheto-Karabagh belt and the Kapan block were formed during NE-verging Jurassic-Cretaceous subduction of a northern branch of the Neotethys beneath Eurasia, followed by Late Cretaceous collision with the South Armenian block, and a jump of the Late Cretaceous-Paleogene subduction zone to the SW of the Turkish Bitlis massif. East-verging subduction of the southern Neotethys branch and Cenozoic convergence of Eurasia and Arabia resulted in an Eocene magmatic climax, followed by Neogene collisional to post-collisional magmatism (Sosson et al. 2010; Rolland et al. 2011, 2012; Moritz et al. 2016b; Rezeau et al. 2016). The timing of Arabia-Eurasia collision is still debated, but a majority of authors favor a late Eocene to Oligocene age (40-25 Ma) for initial collision in the Caucasian-Zagros region (see references in Moritz et al. 2016a,b).

3 Ore formation during Jurassic nascent magmatic arc construction along Eurasia

During Middle and Late Jurassic nascent arc construction, the metallogenic evolution was dominated by subaqueous magmatic-hydrothermal systems. Ore deposits in the two representative districts at Alaverdi and Kapan (Fig. 1) include Cu-rich pyrite bodies, polymetallic lenses and veins, and stockwork-type mineralization. Associated hydrothermal alteration varies from chlorite-epidote-carbonate-dominated to silicification and argillie alteration (Khachatryan 1977; Achikgiozyan et al. 1987; Calder 2014; Mederer et al. 2014). The deposits were mainly mined for copper, but gold was an important by-product in the Alaverdi district, and is currently the main commodity mined at the Shahumyan deposit in the Kapan district, where it is intimately associated with tellurides. The Jurassic deposits may represent either coeval hybrid VMS-epithermal-porphyry systems, or the juxtaposition of different mineralization styles with different ages, due to rapid changes in local tectonic, magmatic, sedimentary and ore-forming conditions in a nascent magmatic arc setting. The ages of deposits are bracketed between 162 and 148 Ma (Calder 2014; Mederer et al. 2014).
4 Porphyry-epithermal systems formed during Late Jurassic to Early Cretaceous arc thickening along the Eurasian margin

Typical porphyry Cu and intermediate-to-high-sulfidation epithermal systems were emplaced in the Somkheta-Karabagh belt during the Late Jurassic to Early Cretaceous, when the arc reached a more mature stage with a thicker crust, and sufficient amounts of fertile magmas were generated by magma storage and MASH processes. Porphyry Cu formation started at 146 Ma at Teghout in the Alaverdi district (Amiryan et al. 1987), and was followed by a major cluster of porphyry Cu and epithermal systems at ~133 Ma in the Gedabek district (Babazadeh et al. 1990; Hemon et al. 2012), laterally extending to the Gosh and Chovdar epithermal deposits (Fig. 1; Moritz et al. 2016a). The epithermal deposits are characterized by argillic alteration, intense silicification, local vuggy silica, and opaque assemblages, including enargite, chalcocite, covellite, tellurides, sulfosalts and base metal sulfides. The deposits are both structurally and lithologically controlled (Moritz et al. 2016a). The Gedabek district experienced major uplift and denudation during the Early Cretaceous (Sosson et al. 2010). It is still unclear how the epithermal deposits were preserved during this tectonic evolution, since such ore deposits are particularly vulnerable to erosion. Porphyry Cu and epithermal style mineralization reported in the Mehmana district (Fig. 1; Mederer et al. 2014) could possibly be roughly contemporaneous with the porphyry-epithermal systems at Teghout and Gedabek. However, because of poor age constraints, further studies will be necessary to verify this.

5 Epithermal and transitional-type ore formation during final Late Cretaceous subduction of the northern Neotethys

The Late Cretaceous Bolnisi district (~87-71 Ma) is the last major metallogenic event before the South Armenian block accreted with the Eurasian margin (Fig. 1). It documents hinterland migration of the active magmatic arc, attributed to a flatter subduction geometry (Rolland et al. 2011). Mineralization is stratigraphically controlled, one group is hosted by Turonian to early Santonian volcanic and volcano-sedimentary rocks (Madneuli deposit; Tsetli Sopeli, Kvemo Bolnisi and David Gareji prospects), and a second group (Sakdrisi deposit; Darbazi, Imedi, Beqtakari, Bnelikhevi and Samgreti prospects) is hosted by Campanian volcanic and volcano-sedimentary rocks (Gugushvili et al. 2014). Genetic models are consistent with a submarine magmatic-hydrothermal system (i.e., transitional VMS-epithermal setting with a potential porphyry system at depth; Migineishvili 2005; Gialli et al. 2012; Gugushvili et al. 2014). A vertical distribution of mineralization styles is recognized in several ore centers (e.g., Madneuli, Sakdrisi, Kvemo Bolnisi, David Gareji) with Cu-rich ore bodies at depth grading upwards into sphalerite, galena and barite veins, vertical breccia and stratiform ore-bodies, and gold-bearing epithermal mineralization at shallow levels (Gialli et al. 2012; Gugushvili et al. 2014). The low-sulfidation Beqtakari precious and base metal system is controlled by a stratiform breccia sequence (Lavoie et al. 2015).

6 Cenozoic gold deposits: witnesses of final subduction of the southern Neotethys and collision between Arabia and Eurasia

Abundant Cenozoic magmatic rocks outline the accretionary boundary and suture zone between the Gondwana-derived South Armenian block and the Jurassic-Cretaceous Eurasian margin. This major collision zone coincides with the dextral Pambak-Sevan-Sunik fault system, and controls a number of significant epithermal-porphyry mining districts described below (Fig. 1).

The Zangezur-Ordubad district is a major ore producer of the Lesser Caucasus (Fig. 1). Spatially associated porphyry and epithermal systems are hosted by the major Meghri-Ordubad pluton (Fig. 1) and associated volcanic rocks (Karamyan 1978; Amiryan 1984; Babazadeh et al. 1990; Moritz et al. 2016a, b). Dextral strike-slip tectonics initiated during oblique Arabia-Eurasia plate convergence controlled Eocene ore deposition and magma emplacement. This tectonic system was repeatedly reactivated during Neogene collision and post-collision ore formation and magmatism (Hovakimyan et al. 2017). The Meghri-Ordubad pluton was incrementally assembled during middle Eocene calc-alkaline subduction magmatism, late Eocene-middle Oligocene post-subduction shoshonitic magmatism, and late Oligocene-early Miocene adakitic, shoshonitic to high-K calc-alkaline magmatism (Rezeau et al. 2016). Porphyry Cu-Mo deposits were formed at the end of the middle Eocene subduction event (~44-40 Ma; e.g. Agarak), and the late Eocene-middle Oligocene post-subduction event (~27-26 Ma; e.g. Kadjaran; Moritz et al., 2016a; Rezeau et al., 2016). Precious and base metal epithermal mineralization accompanied late Eocene and late Oligocene magmatism as evidenced by K-Ar ages (37.5 ± 0.5 and 38.0 ± 2.5 Ma at Tey-Lichkvaz; 24 ± 1 Ma at Atkis near Kadjaran; Bagdasaryan et al. 1969). The epithermal systems consist of veins and stockworks hosted by volcanic and intrusive rocks affected by silicification and sericite-carbonate-argillic (kaolinite) alteration (Moritz et al. 2016a). An early Miocene epithermal event is documented by 20.5 Ma Cu veins overprinting the ~27-26 Ma Kadjaran porphyry deposit (Re-Os molybdenite age; Rezeau et al. 2016).

The low-sulfidation epithermal Zod/Sotk gold deposit is hosted by the Jurassic-Cretaceous Sevan-Akera opholite complex along the easternmost part of the South Armenian block (Fig. 1). Local felsic dikes and stocks, overprinted by ore-related hydrothermal alteration, are interpreted as late Eocene, Oligocene and Miocene (e.g., Levrani 2008).
Therefore, mineralization is reported as Oligocene to Miocene in age, which is at variance with respect to a K-Ar whole rock alteration age of $43 \pm 1.5$ Ma (Bagdasaryan et al. 1969). Thus, it is open to question whether the Zod/Sotk deposit coincides with Eocene subduction-related magmatism or with Neogene collision to post-collision tectonic and magmatic evolution.

The recently discovered Amulsar prospect (Fig. 1) is hosted by late Eocene to early Oligocene volcano-sedimentary rocks affected by silicification and argillic alteration, including alunite. Mineralization is lithologically and structurally controlled. The main ore structure consists of a multiply folded central zone, segmented by late oblique normal faults (Lydian International 2016). Small magmatic intrusions yielded a $34-33$ Ma K-Ar age (Bagdasaryan and Ghukasian 1985), which suggests a link with Neogene collision evolution.

The Meghradzor-Hanqavan ore district occurs along the northern part of the Pambak-Sevan-Sunik fault system (Fig. 1). The Meghradzor low-sulfidation epithermal deposit is hosted by middle Eocene andesite and tuff, and consists of ~EW-oriented quartz-chalcedony-carbonate-sericite veins and breccia zones containing sulfides, tellurides and native gold (Amiryan 1984). K-Ar dating on sericite from altered host rocks yielded an age of $41.5 \pm 1.0$ Ma (Bagdasaryan et al. 1969). The adjacent Hanqavan porphyry Cu-Mo prospect dated at $29.34 \pm 0.12$ Ma by Re-Os molybdenite geochronology (Moritz et al. 2016a) is hosted by a $33.3 \pm 3$ Ma old tonalite (K-Ar whole rock dating, Bagdasaryan et al. 1969). The Eocene to Oligocene ore-forming and magmatic events are reminiscent of the long-lasting metallogenic evolution of the Meghri-Ordubad region (see above). Therefore, the ore deposit potential of this district merits further attention.

7 Intrusion-related deposit in the South Armenian block: witness of south-verging subduction of the northern Neotethys?

The Toukhmanouk prospect occurs in the Tsaghkuniat massif along the easternmost part of the Gondwana-derived South Armenian block, next to the Meghradzor-Hanqavan district (Fig. 1). The Toukhmanouk prospect consists of ~NE-oriented, subvertical quartz-carbonate-sulfide vein swarms crosscutting Jurassic and Cretaceous volcanic and intrusive rocks (Wheatley and Acheson 2011), and a Proterozoic trondhjemite. The main sulfides are sphalerite, galena, pyrite and arsenopyrite, and the

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valuable commodities are gold and silver. Re-Os molybdenite dating yielded an age of 146 Ma (Moritz et al., 2016a). Recently, Hässig et al. (2015) suggested the existence of a SW-verging Jurassic-Cretaceous subduction zone along the eastern margin of the South Armenian block. If we accept such a geodynamic setting, it could explain the particular location of the Toukhmanouk deposit, and it would open up new exploration avenues.

8 Conclusions

The Lesser Caucasus offers an excellent potential for high-sulfidation epithermal deposits associated with porphyry Cu systems in the Late Jurassic to Early Cretaceous subduction setting of the Somkheto-Karabagh belt. Abundant low- to high-sulfidation epithermal deposits and prospects were formed during the Cenozoic evolution of the Lesser Caucasus, and can be locally associated with porphyry Cu-Mo deposits. Their link with either Eocene subduction or Neogene collision to post-collision settings is still open to question. The transitional nature of epithermal systems with VMS-type mineralization in the Late Cretaceous Bolnisi district and during nascent Jurassic arc evolution along the Eurasian margin requires further investigation.

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