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Introduction
The Tethyan mountain ranges stretch from northwestern Africa and western Europe to the southwest Pacific Ocean and constitute the longest continuous orogenic belt on Earth. It is an extremely fertile metallogenic belt, which includes a wide diversity of ore deposit types formed in very different geodynamic settings, which are the source of a wide range of commodities mined for the benefit of society (Janković, 1977, 1997; Richards, 2015, 2016).

This special issue provides a snapshot of recent research projects and the implications for mineral exploration of a short segment of the southeast European, Anatolian, and Lesser Caucasian parts of the Tethyan orogenic belt (Fig. 1). The collection of papers included in this special issue covers a geologic evolution from Mesozoic arc construction and maturation associated with subduction-related magmatism to Cenozoic back-arc and postcollisional magmatism and tectonics. The main ore deposit types that were formed during this geodynamic and metallogenic evolution are porphyry-epithermal systems and associated skarn and carbonate replacement deposits (e.g., Ciobanu et al., 2002; Heinrich and Neubauer, 2002; von Quadt et al., 2005; Yiğit, 2009; Richards, 2015, 2016; Menant et al., 2018; Zürcher et al., 2019). The ore deposits covered in this special issue contain Cu and Au as the dominant commodities, locally accompanied by base metals, i.e., Pb and Zn, and other valuable by-products, such as Mo and Re.

There are other ore deposit types in this segment of the Tethyan metallogenic belt that are not covered in this special issue, such as bauxite and Ni laterite deposits (Herrington et al., 2016), ophiolite-related chromite deposits (Çiftçi et al., 2019), sedimentary exhalative and Mississippi Valley-type deposits (Palinkaš et al., 2008; Hanilçi et al., 2019), or deposits related to surficial brine processes (Helvacı, 2019).

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district of the Timok area, Serbia (Knaak et al., 2016)—and Late Cretaceous volcanogenic massive-hosted deposits—e.g., the eastern Pontides of Turkey (e.g., Akıncı, 1984; Çağatay, 1993; Abdioğlu et al., 2015; Revan et al., 2017)—related to the opening of the Black Sea as a back-arc system.

Between the Late Cretaceous and the Eocene, diachronous collision and accretion of Gondwana-derived continental blocks with the Eurasian margin resulted in progressive closure of the northern branch of the Neotethys (e.g., Okay and Tüysüz, 1999; Jolivet and Faccenna, 2000; Barrier and Vrielynck, 2008; Okay, 2008; Jolivet and Brun, 2010; and Gallhofer et al., 2015). The background topographic relief map is from https://maps-for-free.com. The Lesser Caucasus consists of the Somkheto-Karabagh belt, the Amasia-Sevan-Akera suture zone, and the South Armenian block. The central and eastern Pontides belong to the Sakarya zone. Abbreviations: ASASZ = Amasia-Sevan-Akera suture zone, BM = Bitlis massif, CACC = Central Anatolian crystalline complex, CM = Cyclades massif, CP = central Pontides, EP = eastern Pontides, IAESZ = Iznir-Ankara-Erzincan suture zone, KM = Kazdağ massif, MM = Menderes massif, PM = Pütürge massif, RM = Rhodope massif, SAB = South Armenian block, SK = Somkheto-Karabagh belt, and TAP = Tauride-Anatolian platform.
Late Cretaceous to Cenozoic evolution of the Aegean region, including southeast Europe and western Anatolia

In the Aegean region (Fig. 1), including southeast Europe and western Anatolia, continental accretion from the latest Cretaceous on resulted in building of orogenic belts and progressive southward migration of the subducting slab since the Eocene from the Rhodope massif to its present location along the Hellenic trench (Fig. 1). The southward propagation of the compressional front and an increased velocity of slab retreat resulted in rapid stretching of the upper crust, partial collapse of the orogenic belt, and opening of the wide Aegean back-arc basin (Jolivet et al., 2013). This was accompanied by progressive exhumation of Cenozoic metamorphic core complexes (e.g., Rhodope, Kazdağ, Menderes, and Cyclades massifs, Fig. 1) and migration of contemporaneous postcollisional and back-arc magmatism from north to south (e.g., Jolivet et al., 2003, 2013; Dilek and Altunkaynak, 2009; Jolivet and Brun, 2010). N-trending subvertical slab tear below western Anatolia since the middle-late Miocene (de Boorder et al., 1998; Wortel and Spakman, 2000) resulted in large-scale block rotation, pronounced extensional kinematics (Jolivet et al., 2015; Menant et al., 2016), and major high-K calc-alkaline and shoshonitic magmatism (Dilek and Altunkaynak, 2009; Ersoy and Palmer, 2013; Prelević et al., 2015). 

Ore deposit types formed during the Cenozoic evolution of the Aegean region are more diverse than the ones formed during Jurassic-Cretaceous arc construction along the Eurasian margin. The Cenozoic ore deposits include porphyry Au-Cu-(Mo) deposits, carbonate replacement and skarn deposits, vein-type and breccia-type high- to low-sulfidation epithermal systems with base and/or precious metals, and sedimentary rock-hosted epithermal Au deposits. They are linked to extensional tectonics, particularly exhumation of metamorphic core complexes and low-angle detachment faults, and are preferentially associated with high-K calc-alkaline to shoshonitic magmatism (e.g., Marchev et al., 2005; Márton et al., 2010; Bonsall et al., 2011; Yiğit, 2012; Berger et al., 2013; Kaiser Roehrmeier et al., 2013; Baker et al., 2016; Sánchez et al., 2016; Siron et al., 2016, 2018; Smith et al., 2016; Delibas et al., 2017; Mellös and Voudouris, 2017; Voudouris et al., 2019). The ore deposits become progressively younger from the northern Rhodope massif in Bulgaria and Greece to the southern Aegean region. This trend goes in parallel with the north to south migration of metamorphic core exhumation and magmatism, in line with the protracted retreat of the subduction zone.

Late Cretaceous to Cenozoic evolution of central and eastern Anatolia

During the latest Cretaceous to early Cenozoic, the Central Anatolian crystalline complex and the Tauride-Anatolian block were amalgamated with the Eurasian margin along the Sakarya zone, including the Pontide belt (Fig. 1), during closure of the northern branch of the Neotethys. At the same time, the southern branch of the Neotethys zone was subducting beneath the southern margin of the Bitlis and Fütürge massifs (Fig. 1; Kazmin et al., 1986; Zonenshain and Le Pichon, 1986; Robertson et al., 2012; Rolland et al., 2012). The closure of the northern Neotethys and slab break-off beneath the Pontide belt was accompanied by concomitant opening of the Black Sea as a back-arc basin in the north (Fig. 1; Keskin et al., 2008; Sosson et al., 2016; Hippolyte et al., 2017). Subduction of the southern branch of the Neotethys resulted in late Paleocene to early Eocene arc and back-arc magmatism across Anatolia (e.g., Robertson et al., 2007; Iner et al., 2013; Akbuç et al., 2015; Nurlu et al., 2016; Schleifarth et al., 2018).

Collision of the Arabian plate with the eastern Anatolian segment occurred between the Eocene and the Miocene (Fig. 1; Şengör and Yilmaz, 1981; Jolivet and Facenna, 2000; Rolland et al., 2012; McQuarrie and van Hinsbergen, 2013). This geodynamic setting caused steepening and subsequent break-off of the subducted oceanic slab (Schleifarth et al., 2018), which propagated westward beginning in the late Oligocene (Rabayrol et al., 2019b). By contrast, in central Anatolia, which remained unaffected by the direct collision with the Arabian plate, the magmatic front migrated southward beginning in the early Miocene during tectonic escape and slab rollback/delamination of the subducting Cyprus slab (Fig. 1; Delph et al., 2017; Schleifarth et al., 2018; Rabayrol et al., 2019b). The combined effects of the collision with Arabia in the east and slab retreat and extension in the Aegean region explain westward tectonic escape of the Anatolian plate since the latest Miocene and Pliocene along the northern and eastern Anatolian faults (e.g., Facenna et al., 2006).

The Late Cretaceous and Cenozoic ore deposits mainly include porphyry Au-Cu-Mo deposits, skarn, and high- to intermediate-sulfidation epithermal systems with primarily gold and associated base metals (e.g., Yiğit, 2009; Iner et al., 2013, 2014, 2016; Kusçu et al., 2013, 2019a, b) and subsidiary iron ore Au-Cu (Kusçu et al., 2011) and Carlin-type deposits (Çolakoğlu et al., 2011). The associated magmatism is dominantly calc-alkaline and locally shoshonitic or adakitic in composition.

Late Cretaceous to Cenozoic evolution of the Lesser Caucasus

The Lesser Caucasus constitutes the eastern frontier of the Anatolian belts, where (1) the Jurassic-Cretaceous Somkheto-Karabagh belt of the Lesser Caucasus is the eastern extension of the Pontide belt along the Eurasian margin (Fig. 1; Okay and Sağıntürk, 1997; Yilmaz et al., 2000; Adamia et al., 2011) and (2) the Gondwana-derived South Armenian block, which collided with the Eurasian margin during the Late Cretaceous (Rolland et al., 2009a, b), is correlated with the Tauride-Anatolian platform (Fig. 1; Sosson et al., 2010; Robertson et al., 2013; Mejiers et al., 2015). The arcuate shape of the eastern Pontide-Somkheto-Karabagh belt is inherited from the preexisting geometry of the Eurasian margin, and its curvature was accentuated by indentation tectonics during collision with the South Armenian block (Fig. 1; Philip et al., 1989; Mejiers et al., 2017). This geometry controlled the Cenozoic evolution of the Lesser Caucasus during convergence and collision with Arabia (Fig. 1), resulting in regional NW-oriented, dextral strike-slip fault tectonics since at least the Eocene in the South Armenian block (Philip et al., 2001; Karakhanian et al., 2004).

Moderate to high-K calc-alkaline Eocene magmatism was related to final subduction of the Neotethys (Kazmin et al.,
eral assemblages and are hosted by volcanic rocks affected by propylitic alteration. By contrast, the polymetallic vein deposits deposited under subaqueous conditions and surrounded by alkaline, andesitic to dacitic volcanic and volcaniclastic rocks dated at ~162 Ma by 40Ar/39Ar geochronology, is hosted by alkaline, partly adakitic-type magmatism related to collision to postcollisional evolution of the Lesser Caucasus (Moritz et al., 2016b; Rezeau et al., 2016, 2017, 2018).

By contrast to the Aegean and the Anatolian regions, the Cenozoic ore types are less diverse in the Lesser Caucasus and consist of porphyry Cu-Mo deposits and high- to low-sulfidation epithermal systems with both precious and base metals. The Cenozoic porphyry deposits of the Lesser Caucasus are significantly enriched in Mo with respect to the Cretaceous porphyry systems of the same belt (Amiryan, 1984; Babazadeh et al., 1990, 2003; Moritz et al., 2016a). On a regional scale, the Cenozoic ore deposits are controlled by the regional NW-oriented, dextral strike-slip fault system affecting the South Armenian block (Philip et al., 2001; Karakhanian et al., 2004).

Overview of the Special Issue

The overview paper by Baker (2019) addresses the differences of metal endowment and styles of major Cu and Au deposits of the Cretaceous and Cenozoic western Tethyan magmatic belt extending from southeast Europe to eastern Turkey (Fig. 1). The Cretaceous ore deposits were formed in subduction-related arc environments dominated by calc-alkaline magmatism and consist dominantly of Cu-Au porphyry, high-sulfidation epithermal, and volcanogenic massive sulfide deposits. By contrast, the Cenozoic setting is dominated by high-K calc-alkaline to shoshonitic magmatism, mostly related to collisional to postcollisional geodynamic environments. Cenozoic ore deposits are characterized by a significant Au endowment and a great deposit style variety, including porphyry Au-Cu and Au-only deposits, the full range of epithermal Au systems ranging from high to low sulfidation types, and Au-rich carbonate replacement deposits and sediment-hosted systems. In the Cenozoic deposits, Cu is only significant in the porphyry systems. Historic workings, geology, and geochemistry were the best initial vectors for the majority of discoveries, and porphyry-epithermal ore deposit models provide excellent guides for exploration.

In the Armenian Kapan ore district located in the southernmost Lesser Caucasus (Fig. 1), Mederer et al. (2019) document that subduction-related Jurassic magmatic arcs of the Tethyan metallogenic belt also provide good targets for mineral exploration. Indeed, Middle Jurassic tholeiitic to transitional calc-alkaline, andesitic to dacitic volcanic and volcanioclastic rocks host ore deposits with different metal endowments, orebody geometries, and hydrothermal alteration and opaque mineral assemblages. The Cu-dominated Centralni West ore deposit, dated at ~162 Ma by 40Ar/39Ar geochronology, is hosted by rocks deposited under subaqueous conditions and surrounded by propylitic alteration. By contrast, the polymetallic vein-type Shahumyan and the Cu-Au-dominated, stockwork-type Centralni East deposits, predating a late Oxfordian unconformity, contain intermediate- to high-sulfidation opaque mineral assemblages and are hosted by volcanic rocks affected by advanced argillic alteration. This study interprets the three deposits as being broadly coeval or being formed in a short time interval in a nascent volcanic arc during Tethys subduction along the Eurasian margin. Their metallogenic setting is compared to similar hybrid or juxtaposed volcanogenic massive sulfide and epithermal-porphyry systems of island-arc environments of the Pacific and Australia.

The eastern Pontides of northeastern Turkey is a major metallogenic segment of the Tethyan orogenic belt (Fig. 1), which has recorded subduction of the Neotethys followed by accretion of the Tauride-Anatolian block with the Eurasian margin. Based on Re-Os molybdenite geochronology, Delibaş et al. (2019) demonstrate episodic porphyry Cu-Mo deposit formation during the entire geodynamic evolution of the eastern Pontides. Indeed, porphyry Cu-Mo deposits were emplaced during Early Cretaceous subduction-related calc-alkaline magmatism, as evidenced by a 131.0 ± 0.7 Ma Re-Os molybdenite age at the İspir-Ühitaq deposit. A second porphyry stage coincides with Late Cretaceous high-K calc-alkaline to shoshonitic magmatism and the final stages of Neotethys subduction, as documented by Re-Os molybdenite ages between 77.2 ± 1.0 and 75.7 ± 0.4 Ma at the Elbeyli and Emeksen prospects. Finally, Eocene porphyry Cu-Mo ore formation took place during postcollisional evolution and adakitic magmatism of the eastern Pontides, based on an Re-Os molybdenite age of 50.7 ± 0.3 Ma obtained for the Güzelyayla deposit. Rhenium enrichment of the porphyry systems is correlated with Eocene adakitic postcollisional and Late Cretaceous subduction-related shoshonitic magmatism.

Structural controls explain the geometry and distribution of ore deposits and associated magmatism in orogenic belts. They are key elements to consider during regional mineral exploration programs and are linked to the geodynamic evolution of metallogenic belts. This is documented by the regional-to orebody-scale study of Hovakinyan et al. (2019), which is focused on the tectonic evolution of the composite Cenozoic Meghri-Ordubad pluton located in the southernmost Lesser Caucasus (Fig. 1). Dextral strike-slip tectonics was initiated during Eocene Neotethys subduction along the Eurasian margin and controlled the emplacement of small-tonnage porphyry Cu-Mo and epithermal systems. The same Eocene structures were repeatedly reactivated during Neogene postsubduction geodynamic evolution and controlled the emplacement of Oligocene and Miocene porphyry Cu-Mo and epithermal systems, including the world-class Kadjaran deposit. At the tectonic plate scale, the Cenozoic strike-slip tectonic and metallogenic evolution of the Meghri-Ordubad pluton was controlled by NE-oriented Arabia-Eurasia convergence and collision. Miocene NS-oriented compression due to the motion of the Arabian plate explains the geometry of late epithermal overprints and left-lateral reactivation of faults and ore deposits.

Rubayrol et al. (2019a) have examined the geodynamic and magmatic framework of postsubduction porphyry-epithermal systems in Anatolia (Fig. 1). Based on their regional study, they have defined a roughly E-W oriented and 1,500-km-long, late Cenozoic metallogenic belt, which postdates subduction and cuts across the different Anatolian tectonomagmatic zones. Oligocene and Miocene igneous units recognized in three distinct segments of this belt are highly prospective for...
postsubduction Au-rich porphyry and epithermal systems that are grouped into nine mineral districts. Transtensional to transpressional conditions were predominant in the eastern and central segments. Westward migration of ore formation from eastern Anatolia at 25 to 17 Ma to central Anatolia at 10 to 3 Ma is attributed to slab break-off initiation, propagation, and gap opening after the onset of collision with Arabia. By contrast, extensional tectonics controlled magmatism and ore formation in the western Anatolian segment, and their south-westward migration between 21 and 9 Ma is linked to slab rollback of the Aegean and Cyprus plates and slab tearing in the middle Miocene.

Zircon chemistry is one of the vectoring tools that has been proposed as an exploration pathway for porphyry deposits in prospective metallogenic belts (Rezeau et al., 2019). The composite Cenozoic Meghri-Orchubad pluton, located in the southernmost Lesser Caucasus (Fig. 1), provides an ideal location for evaluating zircon chemistry as a reliable tool for magma fertility. Indeed, this pluton consists of three successive and compositionally distinct magmatic cycles emplaced over 30 m.y. in a geodynamic setting evolving from Eocene subduction to Oligo-Miocene postcollision, accompanied by pulsed porphyry and epithermal deposit emplacement. Based on a comprehensive and representative data set, Rezeau et al. (2019) demonstrate that variations in zircon trace element compositions are a function of the chemical evolution of the magmatic suites over time and are significantly impacted by the amount of co-crystallizing titanite and apatite. By contrast, no systematic correlation is recognized between episodes of porphyry deposit formation and variations of zircon composition, i.e., magnitude of Eu and Ce anomalies, and Ce²⁺/Ce³⁺ ratios. Therefore, the reliability of zircon trace element composition as an indicator of magma fertility is put into question, and it is considered as a high risk factor for decision-making in mineral exploration programs.

Next to porphyry and epithermal deposits, intrusion-related, high-temperature carbonate-hosted replacement systems are an important ore deposit type of the Cenozoic part of the Tethyan belt in the Aegean region. Siron et al. (2019) provide new geologic and geochemical knowledge about such ore deposit types belonging to the Kassandra mining district located in the Greek Rhodope metamorphic terrane (Fig. 1). The fault-controlled ore deposits include the past-producing Madem Lakkos deposit and the presently producing Mavres Petres and Olympias deposits. Based on their metal grades and high Au endowment, they are compared to skarn and carbonate-hosted sulfide ore deposits of the southwestern United States of America. Temperature and solubility changes explain distinct-to-ore deposit-scale metal zoning with respect to a concealed late Oligocene magmatic intrusion. Stable isotope and microthermometric fluid inclusion data are consistent with formation from a fluid of magmatic origin accompanied by late dilution with a meteoric fluid, and local fluid-rock interaction and decarbonation. Based on fluid inclusion data, the mineralization depth is estimated at between 1.5 and 5.9 km, assuming hydrostatic conditions.

Scheffer et al. (2019) have studied late ore systems belonging to the famous Lavorion mineral district in Greece, which was formed during Miocene postorogenic exhumation of the Hellenic-Aegean belt (Fig. 1). Their study provides new evidence that low-angle detachment faults associated with the exhumation of metamorphic core complexes are major locations of fluid circulation and have a potential for ore formation during the late postorogenic evolution of metallogenic belts. Early low-grade porphyry, skarn, and high-temperature systems in this district were formed by magmatic fluids. A younger ore stage consists of Pb-Zn-Ag vein- and breccia-type ore, with a fluorite and carbonate matrix, which is hosted by late low-angle detachment faults formed during progressive exhumation through the ductile-brittle transition. Based on microthermometric fluid inclusion data, halogen chemistry of fluid inclusions, and stable isotopic compositions of the fluorite and carbonate gangue minerals, Scheffer et al. (2019) conclude that the late Pb-Zn-Ag vein- and breccia-type ore was deposited by surface-derived fluids, devoid of any magmatic component. The surface-dominated hydrothermal system consisted of meteoric fluids, which mixed with evaporated seawater during brittle deformation in a shallow crustal environment.

Porphyry deposits not only provide Cu, Mo, and Au to society, but they also are the predominant source of the world's Re production (McFall et al., 2019). The source and the mechanisms of the pronounced Re enrichment in porphyry deposits are still poorly understood. McFall et al. (2019) have addressed this topic through a study of a postcollisional Muratdere porphyry Cu-Mo deposit of western Turkey (Fig. 1), which is characterized by a particularly high Re enrichment. This deposit contains several stages of mineralization, including two generations of molybdenite hosted by early microfractures and late-stage veins with significantly different Re concentrations. Molybdenite of the late-stage veins has higher Re concentrations (with an average of 1,124 ppm) than early microfracture-hosted molybdenite (with an Re concentration average of 566 ppm). Sulfur isotope compositions of early microfracture-hosted sulfides are consistent with a magmatic source and range between –2.2 and +4.6‰, whereas those of late vein-hosted sulfides are higher and vary between +5.6 and +8.5‰. This increase in δ³⁴S values and, by extension, of the Re enrichment of the late molybdenite stage is attributed to δ³⁴S-enriched sulfur and Re sourced by fluid interaction with surrounding ophiolitic country rocks or to changing redox conditions during late ore formation.

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REFERENCES


METALLOGENY OF THE TETHYAN OROCENIC BELT: AN INTRODUCTION


Robert Moritz has been based at the University of Geneva in Switzerland since 1991, where he is a professor, teaching and leading research projects in economic geology and geochemistry. Robert holds a Ph.D. in geology from McMaster University, Ontario, Canada, and was a research associate at the Institut National de Recherche Scientifique in Quebec City, Canada, from 1988 to 1991. His current research activity is focused on the metallogenic, geodynamic, and magmatic evolution of the Tethyan orogenic belt, with projects in the Lesser Caucasus, Turkey, and southeast Europe, and mainly on porphyry and epithermal systems.

Tim Baker has been chief geoscientist for Eldorado Gold Corporation since 2012. Tim is a graduate of the University of Cardiff, Wales, and holds a doctorate in geology from James Cook University in Australia. He has over 20 years of experience working in industry, academia, and government, including research and academic positions at the Mineral Deposit Research Unit, University of British Columbia, and James Cook University, as well as director of the Geological Survey of South Australia and exploration manager of Sovereign Metals. In 2002, Tim received the Society of Economic Geologists Waldemar Lindgren Award.