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Metallogeny of the Tethyan Orogenic Belt: From Mesozoic Magmatic Arcs to Cenozoic Back-Arc and Postcollisional Settings in Southeast Europe, Anatolia, and the Lesser Caucasus: An Introduction

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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 arc 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; Kuşcu et al., 2019a, b; Voudouris et al., 2019; 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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Mesozoic to Cenozoic Geodynamic and Metallogenic Evolution of the Southeast European-Anatolian-Lesser Caucasian Segment of the Tethyan Orogenic Belt

Mesozoic subduction along the Eurasian margin, progressive closure of the northern branch of the Neotethys, and amalgamation with Gondwana-derived continental blocks

The geodynamic evolution of the segment of the Tethys metallogenic belt including southeast Europe, Anatolia, and the Lesser Caucasus records the convergence, subduction, accretion, and/or collision of Arabia and Gondwana-derived microplates with Eurasia (Fig. 1; Şengör and Yilmaz, 1981; Okay and Tüysüz, 1999; Barrier and Vrielynck, 2008; Rolland et al., 2011; Robertson et al., 2013; Barrier et al., 2018). From the Jurassic until about the end of the Cretaceous, the Timok-Srednogorie belts of southeast Europe, the Pontide belt in Turkey, and the Somkheto-Kabaragh belt of the Lesser Caucasus belonged to a relatively continuous magmatic arc along the southern Eurasian margin, linked to N- to NE-verging subduction of the northern branch of the Neotethys (e.g., Şengör and Yilmaz, 1981; Kazmin et al., 1986; Zonenshain and Le Pichon, 1986; Okay and Şahintürk, 1997; Yilmaz et al., 2000; Adamia et al., 2011; Mederer et al., 2013; Gallhofer et al., 2015; Delibaş et al., 2016; Menant et al., 2018), although S-verging subduction of the Black Sea ocean lithosphere has also been proposed (Eyuboglu, 2010; Eyuboglu et al., 2014, 2017). Magmatism was dominantly medium to high-K calc-alkaline in composition and locally tholeiitic or shoshonitic.

Ore deposits formed during the Jurassic to Cretaceous subduction-related magmatism include mainly porphyry Cu(-Au-Mo), high-sulfidation epithermal Au-Cu, and skarn deposits. They are typically distributed in discrete clusters and ore districts along the magmatic belt (e.g., Ciobanu et al., 2002; von Quadt et al., 2005; Yiğit, 2009; Gallhofer et al., 2015; Delibaş et al., 2016; Moritz et al., 2016a; Kuşcu et al., 2019a, b; Menant et al., 2018). Other ore deposit types include Late Cretaceous sedimentary-hosted deposits—e.g., the Bor

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Fig. 1. Main tectonic zones and mountain ranges of the Tethys belt segment extending from southeast Europe through Turkey to the Caucasus and Iran. The white numbers on a pink background indicate the locations of the study areas included in this special issue: 1 = Baker (2019)—see thick pink lines in the upper right corner inset; 2 = Mederer et al. (2019); 3 = Delibaş et al. (2019); 4 = Hovakimyan et al. (2019); 5 = Rabayrol et al. (2019a)—see stippled area in the upper right corner inset; 6 = Rezeau et al. (2019); 7 = Siron et al. (2019); 8 = Scheffer et al. (2019); and 9 = McFall et al. (2019). The main tectonic zone outlines and locations of suture and subduction zones are from Okay and Tüysüz (1999), Dilek and Altunkaynak (2009), 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 = Izmir-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.

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; Sosson et al., 2010; Rolland et al., 2011; Robertson et al., 2012, 2013) along the Amasia-Sevan-Akera and Izmir-Ankara-Erzincan suture zones (Fig. 1; Hässig et al., 2013, 2017). To the south of the Sakarya zone (Fig. 1), the collage zone with the Tauride-Anatolian platform, the Central Anatolian crystalline complex, and the Pütürge and Bitlis massifs underwent a particularly complex evolution (Robertson et al., 2012), in which Late Cretaceous magmatic rocks and ophiolitic rocks are interpreted as, respectively, subduction-related magmatic arcs (e.g., Rızaoğlu et al., 2009; Schleiffarth et al., 2018) and suture zones related to the closure of small, interconnected oceanic basins, such as the inferred Inner Tauride and Berit oceans (e.g., Şengör and Yilmaz, 1981; Robertson et al., 2006, 2012; Parlak, 2016; Pourteau et al., 2016). Onward from the Late Cretaceous, the complex geometry of the collision and accretion interfaces caused by microplates between the major Eurasian and Arabian plates resulted in significantly different geodynamic evolution in the central part and the extremities of the southeast European-Anatolian-Lesser Caucasian segment of the Tethys belt.

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 Rohrmeier et al., 2013; Baker et al., 2016; Sánchez et al., 2016; Siron et al., 2016, 2018; Smith et al., 2016; Delibaş et al., 2017; Melfos 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 Pütürge 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; İmer et al., 2013; Akıncı et al., 2015; Nurlu et al., 2016; Schleiffarth 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 Faccenna, 2000; Rolland et al., 2012; McQuarrie and van Hinsbergen, 2013). This geodynamic setting caused steepening and subsequent break-off of the subducted oceanic slab (Schleiffarth 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; Schleiffarth 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., Faccenna 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; İmer et al., 2013, 2014, 2016; Kuşcu et al., 2013, 2019a, b) and subsidiary iron ore Au-Cu (Kuşcu 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 Şahintürk, 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; Meijers 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; Meijers 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., 1986; Vincent et al., 2005; Moritz et al., 2016a; Rezeau et al., 2016, 2017, 2018). Collision with the Arabian plate and final closure of the Neotethys occurred during the late Eocene-early Oligocene (Vincent et al., 2005; Agard et al., 2011; Ballato et al., 2011; Verdel et al., 2011; McQuarrie and van Hinsberger, 2013). Late Eocene-early Oligocene shoshonitic magmatism and late Oligocene-early Miocene high-K calc-alkaline, partly adakitic-type magmatism are related to the collision to postcollision 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-rock 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 volcaniclastic 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 $^{40}Ar/^{39}Ar$ 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 Ispir-Ulutaş 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 Hovakimyan 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.

Rabayrol 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 southwestward 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 pathfinder for porphyry deposits in prospective metallogenic belts (Rezeau et al., 2019). The composite Cenozoic Meghri-Ordubad 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 Ce^{4+}/Ce^{3+} 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 district- 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 Lavrion 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 on the 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 +8.8‰. This increase in $\delta^{34}S$ values and, by extension, of the Re enrichment of the late molybdenite stage is attributed to ^{34}S-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

Abdioğlu, E., Arslan, M., Kadir, S., and Temizel, İ., 2015, Alteration mineralogy, lithochemistry and stable isotope geochemistry of the Murgul (Artvin, NE Turkey) volcanic hosted massive sulfide deposit: Implications for the alteration age and ore forming fluids: Ore Geology Reviews, v. 66, p. 219–242.

Adamia, S., Zakariadze, G., Chkhotua, T., Sadradze, N., Tsereteli, N., Chabukiani, A., and Gventsdze, A., 2011, Geology of the Caucasus: A review: Turkish Journal of Earth Sciences, v. 20, p. 489–544.

Agard, P., Omrani, J., Jolivet, L., Whitechurch, H., Vrielynck, B., Spakman, W., Monie, P., Meyer, B., and Wortel, R., 2011, Zagros orogeny: A subduction-dominated process: Geological Magazine, v. 148, p. 692–725.

Akıncı, A.C., Robertson, A.H.F., and Ünlügenç, U.C., 2015, Late Cretaceous-Cenozoic subduction-collision history of the southern Neotethys: New evidence from the Çağlayancerit area, SE Turkey: International Journal of Earth Sciences, v. 105, p. 315–337.

Akıncı, Ö.T., 1984, The eastern Pontide volcano-sedimentary belt and associated massive sulphide deposits: Geological Society of London, Special Publication 17, p. 415–428.

Amiryan, S.H., 1984, Gold ore formation of Armenian SSR: Yerevan, Publishing House of the Academy of Sciences Armenian SSR, 304 p. (in Russian).

Babazadeh, V.M., Makhmudov, A.I., and Ramazanov, V.G., 1990, Porphyry-copper and molybdenum deposits: Baku, Azerbaijan Publication, 377 p. (in Russian with German and English abstracts).

Babazadeh, V.M., Musaev, S.D., Nasibov, T.N., and Ramazanov, V.G., 2003, Gold of Azerbaijan: Azerbaijanian National Encyclopaedia: Baku, Azerbaijan, Azerbaijan National Academy of Sciences, 424 p. (in Russian).

Baker, T., 2019, Gold ± copper endowment and deposit diversity in the Western Tethyan magmatic belt, southeast Europe: Implications for exploration: Economic Geology, v. 114, p. 1237–1250.

Baker, T., Bickford, D., Juras, S., Lewis, P., Oztas, Y., Ross, K., Tukac, A., Rabayrol, F., Miskovic, A., Friedman, R., Creaser, R.A., and Spikings, R., 2016, The geology of the Kisladag porphyry gold deposit, Turkey: Society of Economic Geologists, Special Publication 19, p. 57–83.

Ballato, P., Uba, C.E., Landgraf, A., Strecker, M.R., Sudo, M., Stockli, D.F., Friedrich, A., and Tabatabaei, S.H., 2011, Arabia-Eurasia continental collision: Insights from late Tertiary foreland-basin evolution in the Alborz Mountains, northern Iran: Geological Society of America Bulletin, v. 123, p. 106–131.

Barrier, E., and Vrielynck, B., eds., 2008, Palaeotectonic maps of the Middle East; tectono-sedimentary-palinspastic maps from Late Norian to Pliocene: Paris, Commission for the Geological Map of the World (atlas of 14 maps).

Barrier, E., Vrielynck, B., Brouillet, J.F., and Brunet M.F., 2018, Paleotectonic reconstruction of the Central Tethyan realm, tectonono-sedimentary-palinspastic maps from late Permian to Pliocene: Commission for the Geological Map of the World, www.ccgm.org (atlas of 20 maps).

Berger, A., Schneider, D.A., Grasemann, B., and Stockli, D., 2013, Footwall mineralization during late Miocene extension along the West Cycladic detachment system, Lavrion, Greece: Terra Nova, v. 25, p. 181–191.

Bonsall, T.A., Spry, P.G., Voudouris, P.C., Tombros, S., Seymour, K.S., and Melfos, V., 2011, The geochemistry of carbonate-replacement Pb-Zn-Ag mineralization in the Lavrion district, Attica, Greece: Fluid inclusion, stable isotope, and rare earth element studies: Economic Geology, v. 106, p. 619–651.

Çağatay, M.N., 1993, Hydrothermal alteration associated with volcanogenic sulfide deposits: Examples from Turkey: Economic Geology, v. 88, p. 606–621.

Çiftçi, Y., Dönmez, C., Parlak, O., and Günay, K., 2019, Chromitite deposits of Turkey in Tethyan ophiolites, *in* Pirajno, F., Ünlü, T., Dönmez, C., and Şahin, M.B., eds, Mineral resources of Turkey. Modern approaches in solid earth sciences, v. 16: Cham, Switzerland, Springer, p. 73–157, https://doi.org/10.1007/978-3-030-02950-0_3.

Ciobanu, C.L., Cook, N.J., and Stein, H., 2002, Regional setting and geochronology of the Late Cretaceous Bananitic magmatic and metallogenic belt: Mineralium Deposita, v. 37, p. 541–567.

Çolakoğlu, A.R., Oruç, M., Arehart, G.B., and Poulson, S., 2011, Geology and isotope geochemistry (C-O-S) of the Diyadin gold deposit, eastern Turkey: A newly discovered Carlin like deposit: Ore Geology Reviews, v. 40, p. 27–40.

de Boorder, H., Spakman, W., White, S., and Wortel, M., 1998, Late Cenozoic mineralization, orogenic collapse and slab detachment in the European Alpine belt: Earth and Planetary Science Letters, v. 164, p. 569–575.

Delibaş, O., Moritz, R., Ulianov, A., Chiaradia, M., Saraç, C., Revan, K.M., and Göç, D., 2016, Cretaceous subduction-related magmatism and associated porphyry-type Cu-Mo prospects in the eastern Pontides, Turkey: New constraints from geochronology and geochemistry: Lithos, v. 248, p. 119–137.

Delibaş, O., Moritz, R., Chiaradia, M., Selby, D., Ulianov, A., and Revan, M.K., 2017, Post-collisional magmatism and ore-forming systems in the Menderes massif: New constraints from the Miocene porphyry Mo-Cu Pınarbaşı system, Gediz-Kütahya, western Turkey: Mineralium Deposita, v. 52, p. 1157–1178.

Delibaş, O., Moritz, R., Selby, D., Göç, D., and Revan, M.K., 2019, Multiple porphyry Cu-Mo events in the eastern Pontides metallogenic belt, Turkey: From Early Cretaceous subduction to Eocene postcollision evolution: Economic Geology, v. 114, p. 1285–1300.

Delph, J.R., Abgarmi, B., Ward, K.M., Beck, S.L., Ozacar, A.A., Zandt, G., Sandvol, E., Turkelli, N., and Kalafat, D., 2017, The effects of subduction termination on the continental lithosphere: Linking volcanism, deformation, surface uplift, and slab tearing in central Anatolia: Geosphere, v. 13, p. 1–18.

Dilek, Y., and Altunkaynak, Ş., 2009, Geochemical and temporal evolution of Cenozoic magmatism in western Turkey: Mantle response to collision, slab break-off, and lithospheric tearing in an orogenic belt: Geological Society of London, Special Publication 311, p. 213–233.

Ersoy, E.Y., and Palmer, M.R., 2013, Eocene-Quaternary magmatic activity in the Aegean: Implications for mantle metasomatism and magma genesis in an evolving orogeny: Lithos, v. 180, p. 5–24.

Eyuboglu, Y., 2010, Late Cretaceous high-K volcanism in the eastern Pontides orogenic belt, and its implications for the geodynamic evolution of NE Turkey: International Geological Review, v. 52, p. 142–186.

Eyuboglu, Y., Santosh, M., Yi, K., Tuysuz, N., Korkmaz, S., Akaryali, E., Dudas, F.O., and Bektas, O., 2014, The eastern Black Sea-type volcanogenic massive sulfide deposits: Geochemistry, zircon U-Pb geochronology and an overview of the geodynamics of ore genesis: Ore Geology Reviews, v. 59, p. 29–54.

Eyuboglu, Y., Dudas, F.O., Thorkelson, D., Zhu, D.C., Liu, Z., Chatterjee, N., Yi, K., and Santosh, M., 2017, Eocene granitoids of northern Turkey: Polybaric magmatism in an evolving arc-slab window system: Gondwana Research, v. 50, p. 311–345.

Faccenna, C., Bellier, O., Martinod, J., Piromallo, C., and Regard, V., 2006, Slab detachment beneath eastern Anatolia: A possible cause for the formation of the North Anatolian fault: Earth and Planetary Science Letters, v. 242, p. 85–97.

Gallhofer, D., von Quadt, A., Peytcheva, I., Schmid, S.M., and Heinrich, C.A., 2015, Tectonic, magmatic, and metallogenic evolution of the Late Cretaceous arc in the Carpathian-Balkan orogen: Tectonics, v. 34, p. 1813–1836.

Hanilçi, N., Hüseyin, Ö., and Kasapçı, C., 2019, Carbonate-hosted Pb-Zn deposits of Turkey, *in* Pirajno, F., Ünlü, T., Dönmez, C., and Şahin, M.B., eds., Mineral resources of Turkey. Modern approaches in solid earth sciences, v. 16: Cham, Switzerland, Springer, p. 497–533, https://doi.org/10.1007/978-3-030-02950-0_10.

Hässig, M., Rolland, Y., Sosson, M., Galoyan, G., Sahakyan, L., Topuz, G., Celik, O.F., Avagyan, A., and Müller, C., 2013, Linking the NE Anatolian and Lesser Caucasus ophiolites: Evidence for large-scale obduction of oceanic crust and implications for the formation of the Lesser Caucasus-Pontides arc: Geodinamica Acta, v. 26, p. 311–330.

Hässig, M., Rolland, Y., and Sosson, M., 2017, From seafloor spreading to obduction: Jurassic-Cretaceous evolution of the northern branch of the Neotethys in the northeastern Anatolian and Lesser Caucasus regions: Geological Society of London, Special Publication 428, p. 117–143.

Heinrich, C.A., and Neubauer, F., 2002, Cu-Au-Pb-Zn-Ag metallogeny of the Alpine-Balkan-Carpathian-Dinaride geodynamic province: Mineralium Deposita, v. 37, p. 533–540.

Helvacı, C., 2019, Turkish borate deposits: Geological setting, genesis and overview of the deposits, *in* Pirajno, F., Ünlü, T., Dönmez, C., and Şahin, M.B., eds., Mineral resources of Turkey. Modern approaches in solid earth sciences, v. 16: Cham, Switzerland, Springer, p. 535–597, https://doi.org/10.1007/978-3-030-02950-0_11.

Herrington, R., Mondillo, N., Boni, M., Thorne, R., and Tavlan, M., 2016, Bauxite and nickel-cobalt lateritic deposits of the Tethyan belt: Society of Economic Geologists, Special Publication 19, p. 349–387.

Hippolyte, J.-C., Müller, C., Sangu, E., and Kaymack, N., 2017, Stratigraphic comparisons along the Pontides (Turkey) based on new nannoplankton age determinations in the eastern Pontides: Geodynamic implications, *in* Sosson, M., Stephenson, R.A., and Admia, S.A., eds., Tectonic evolution of the eastern Black Sea and Caucasus: Geological Society of London, Special Publication 428, p. 323–358.

Hovakimyan, S., Moritz, R., Tayan, R., Melkonyan, R., and Harutyunyan, M., 2019, Cenozoic strike-slip tectonics and structural controls of porphyry Cu-Mo and epithermal deposits during geodynamic evolution of the southernmost Lesser Caucasus, Tethyan metallogenic belt: Economic Geology, v. 114, p. 1301–1337.

İmer, A., Richards, J.P., and Creaser, R.A., 2013, Age and tectonomagmatic setting of the Eocene Çöpler-Kabataş magmatic complex and porphyry-epithermal Au deposit, east Central Anatolia, Turkey: Mineralium Deposita, v. 48, p. 557–583.

İmer, A., Richards, J.P., Creaser, R.A., and Spell, T.L., 2014, The late Oligocene Cevizlidere Cu-Au-Mo deposit, Tunceli Province, eastern Turkey: Mineralium Deposita, v. 50, p. 245–263.

İmer, A., Richards, J.P., and Muehlenbachs, K., 2016, Hydrothermal evolution of the Çöpler porphyry-epithermal Au deposit, Erzincan Province, central eastern Turkey: Economic Geology, v. 111, p. 1619–1658.

Janković, S., 1977, The copper deposits and geotectonic setting of the Thethyan Eurasian metallogenic belt: Mineralium Deposita, v. 12, p. 37–47.

——1997, The Carpatho-Balkanides and adjacent area: A sector of the Tethyan Eurasian metallogenic belt: Mineralium Deposita, v. 32, p. 426–433.

Jolivet, L., and Brun, J.-P., 2010, Cenozoic geodynamic evolution of the Aegean: International Journal of Earth Sciences, v. 99, p. 109–138.

Jolivet, L., and Faccenna, C., 2000, Mediterranean extension and the Africa-Eurasia collision: Tectonics, v. 19, p. 1095–1106.

Jolivet, L., Faccenna, C., Goffe, B., Burov, E., and Agard, P., 2003, Subduction tectonics and exhumation of high-pressure metamorphic rocks in the Mediterranean orogens: American Journal of Science, v. 303, p. 353–409.

Jolivet, L., Faccenna, C., Huet, B., Labrousse, L., Le Pourhiet, L., Lacombe, O., Lecomte, E., Burov, E., Denele, Y., and Brun, J.-P., 2013, Aegean tectonics: Strain localisation, slab tearing and trench retreat: Tectonophysics, v. 597, p. 1–33.

Jolivet, L., Menant, A., Sternai, P., Rabillard, A., Arbaret, L., Augier, R., Laurent, V., Beaudoin, A., Grasemann, B., and Huet, B., 2015, The geological signature of a slab tear below the Aegean: Tectonophysics, v. 659, p. 166–182.

Kaiser Rohrmeier, M., von Quadt, A., Driesner, T., Heinrich, C.A., Handler, R., Ovtcharova, M., Ivanov, Z., Petrov, P., Sarov, S., and Peytcheva, I., 2013, Post-orogenic extension and hydrothermal ore formation: High-precision geochronology of the central Rhodopian metamorphic core complex (Bulgaria-Greece): Economic Geology, v. 108, p. 691–718.

Karakhanian, A.S., Trifonov, V.G., Philip, H., Avagyan, A., Hessami, K., Jamali, F., Bayraktutan, M.S., Bagdassarian, H., Arakelian, S., Davtian, V., and Adilkhanyan, A., 2004, Active faulting and natural hazards in Armenia, eastern Turkey and northwestern Iran: Tectonophysics, v. 380, p. 189–219.

Kazmin, V.G., Sbortshikov, I.M., Ricou, L.-E., Zonenshain, L.P., Boulin, J., and Knipper, A.L., 1986, Volcanic belts as markers of the Mesozoic-Cenozoic active margin of Eurasia: Tectonophysics, v. 123, p. 123–152.

Keskin, M., Gen, Ş.C., and Tüysüz, O., 2008, Petrology and geochemistry of post-collisional middle Eocene volcanic units in north-central Turkey—evidence for magma generation by slab breakoff following the closure of the northern Neotethys Ocean: Lithos, v. 104, p. 267–305.

Knaak, M., Márton, I., Tosdal, R.M., van der Toorn, J., Davidović, D., Strmbanović, I., Zdravković, M., Živanović, J., and Hasson, S., 2016, Geologic setting and tectonic evolution of porphyry Cu-Au, polymetallic replacement, and sedimentary rock-hosted Au deposits in the northwest Timok magmatic complex, Serbia: Society of Economic Geologists, Special Publication 19, p. 1–28.

Kuşcu, İ., Yılmazer, E., Güleç, N., Bayir, S., Demirela, G., Gençalioğlu Kuşcu, G.G., Kuru, G.S., and Kaymakçi, N., 2011, U-Pb and ^{40}Ar-^{39}Ar geochronology and isotopic constraints on the genesis of copper-gold–bearing iron oxide deposits in the Hasançelebi district, eastern Turkey: Economic Geology, v. 106, p. 261–288.

Kuşcu, I., Tosdal, R.M., Gencalioğlu-Kuşcu, G., Friedman, R., and Ullrich, T.D., 2013, Late Cretaceous to middle Eocene magmatism and metallogeny of a portion of the southeastern Anatolian orogenic belt, east-central Turkey: Economic Geology, v. 108, p. 641–666.

Kuşcu, İ., Tosdal, R.M., and Gençalioğlu-Kuşcu, G., 2019a, Episodic porphyry Cu(-Mo-Au) formation and associated magmatic evolution in Turkish Tethyan collage: Ore Geology Reviews, v. 107, p. 119–154.

——2019b, Porphyry-Cu deposits of Turkey, *in* Pirajno, F., Ünlü, T., Dönmez, C., and Şahin, M.B., eds, Mineral resources of Turkey. Modern approaches in solid earth sciences, v. 16: Cham, Switzerland, Springer, p. 337–425, https://doi.org/10.1007/978-3-030-02950-0_8.

Marchev, P., Kaiser-Rohrmeier, M., Heinrich, C., Ovtcharova, M., von Quadt, A., and Raicheva, R., 2005, Hydrothermal ore deposits related to post-orogenic extensional magmatism and core complex formation: The Rhodope massif of Bulgaria and Greece: Ore Geology Reviews, v. 27, p. 53–89.

Márton, I., Moritz, R., and Spikings, R., 2010, Application of low-temperature thermochronology to hydrothermal ore deposits. Formation, preservation and exhumation of epithermal gold systems from the eastern Rhodopes, Bulgaria: Tectonophysics, v. 483, p. 240–254.

McFall, K., Roberts, S., McDonald, I., Boyce, A.J., Naden, J., and Teagle, D., 2019, Rhenium enrichment in the Muratdere Cu-Mo (Au-Re) porphyry deposit, Turkey: Evidence from stable isotope analyses ($\delta^{34}S$, $\delta^{18}O$, δD) and laser ablation-inductively coupled plasma-mass spectrometry analysis of sulfides: Economic Geology, v. 114, p. 1443–1466.

McQuarrie, N., and van Hinsbergen, D.J.J., 2013, Retrodeforming the Arabia-Eurasia collision zone: Age of collision versus magnitude of continental subduction: Geology, v. 41, p. 315–318.

Mederer, J., Moritz, R., Ulianov, A., and Chiaradia, M., 2013, Middle Jurassic to Cenozoic evolution of arc magmatism during Neotethys subduction and arc-continent collision in the Kapan zone, southern Armenia: Lithos, v. 177, p. 61–78.

Mederer, J., Moritz, R., Chiaradia, M., Spikings, R., Spangenberg, J.E., and Selby, D., 2019, Ore formation during Jurassic subduction of the Tethys along the Eurasian margin: Constraints from the Kapan district, Lesser Caucasus, southern Armenia: Economic Geology, v. 114, p. 1251–1284.

Meijers, M.J.M., Smith, B., Kirscher, U., Mensink, M., Sosson, M., Rolland, Y., Grigoryan, A., Sahakyan, L., Avagyan, A., Langereis, C., and Müller, C., 2015, A paleolatitude reconstruction of the South Armenian block (Lesser Caucasus) for the Late Cretaceous: Constraints on the Tethyan realm: Tectonophysics, v. 644–645, p. 197–219.

Meijers, M.J.M., Smith, B., Pastor-Galan, D., Degenar, R., Sadradze, N., Adamia, S., Sahakyan, L., Avagyan, A., Sosson, M., Rolland, Y., Langereis, C., and Müller, C., 2017, Progressive orocline formation in the eastern Pontides-Lesser Caucasus: Geological Society of London, Special Publication 428, p. 117–143.

Melfos, V., and Voudouris, P., 2017, Cenozoic metallogeny of Greece and potential for precious, critical and rare metals exploration: Ore Geology Reviews, v. 89, p. 1030–1057.

Menant, A., Jolivet, L., and Vrielynck, B., 2016, Kinematic reconstructions and magmatic evolution illuminating crustal and mantle dynamics of the eastern Mediterranean region since the Late Cretaceous: Tectonophysics, v. 675, p. 103–140.

Menant, A., Jolivet, L., Tuduri, J., Loiselet, C., Bertrand, G., and Guillou-Frottier, L., 2018, 3D subduction dynamics: A first-order parameter of the transition from copper- to gold-rich deposits in the eastern Mediterranean region: Ore Geology Reviews, v. 94, p. 118–135.

Moritz, R., Melkonyan, R., Selby, D., Popkhadze, N., Gugushvili, V., Tayan, R., and Ramazanov, V., 2016a, Metallogeny of the Lesser Caucasus: From arc construction to postcollision evolution: Society of Economic Geologists, Special Publication 19, p. 157–192.

Moritz, R., Rezeau, H., Ovtcharova, M., Tayan, R.N., Melkonyan, R., Hovamkimyan, S.E., Ramazanov, V., Selby, D., Ulianov, A., Chiaradia, M., and Putlitz, B., 2016b, Long-lived, stationary magmatism and pulsed porphyry systems during Tethyan subduction to post-collision evolution in the southernmost Lesser Caucasus, Armenia and Nakhitchevan: Gondwana Research, v. 37, p. 465–503.

Nurlu, N., Parlak, O., Robertson, A., and von Quadt, A., 2016, Implications of Late Cretaceous U-Pb zircon ages of granitic intrusions cutting ophiolitic and volcanogenic rocks for the assembly of the Tauride allochthon in SE Anatolia (Helete area, Kahramanmaraş region, SE Turkey): International Journal of Earth Sciences, v. 105, p. 283–314.

Okay, A.I., 2008, Geology of Turkey: A synopsis: Anschnitt, v. 21, p. 19–42.

Okay, A.I., and Şahintürk, Ö., 1997, Geology of the eastern Pontides: American Association of Petroleum Geologists Memoir, v. 68, p. 291–311.

Okay, A.I., and Tüysüz, O., 1999, Tethyan sutures of northern Turkey: Geological Society of London, Special Publication 156, p. 475–515.

Palinkaš, L.A., Šoštariç, S.B., and Palinkaš, S.S., 2008, Metallogeny of the northwestern and central Dinarides and southern Tisia: Ore Geology Reviews, v. 34, p. 501–520.

Parlak, O., 2016, The Tauride ophiolites of Anatolia (Turkey): A review: Journal of Earth Science, v. 27, p. 901–934.

Philip, H., Cisternus, A., Gvishiani, A., and Gorshkov, A., 1989, The Caucasus: An actual example of the initial stages of a continental collision: Tectonophysics, v. 161, p. 1–21.

Philip, H., Avagyan, A., Karakhanian, A., Ritz, J.-F., and Rebai, S., 2001, Estimating slip rates and recurrence intervals for strong earthquakes along an intracontinental fault; example of the Pambak-Sevan-Sunik fault (Armenia): Tectonophysics, v. 343, p. 205–232.

Pourteau, A., Oberhänsli, R., Candan, O., Barrier, E., and Vrielynck, B., 2016, Neotethyan closure history of western Anatolia: A geodynamic discussion: International Journal of Earth Sciences, v. 105, p. 203–224.

Prelević, D., Akal, C., Romer, R.L., Mertz-Kraus, R., and Helvacı, C., 2015, Magmatic response to slab tearing: Constraints from the Afyon alkaline volcanic complex, western Turkey: Journal of Petrology, v. 56, p. 527–562.

Rabayrol, F., Hart, C.J.R., and Creaser, R.A., 2019a, Tectonic triggers for postsubduction magmatic-hydrothermal gold metallogeny in the late Cenozoic Anatolian metallogenic trend, Turkey: Economic Geology, v. 114, p. 1339–1363.

Rabayrol, F., Hart, C.J.R., and Thorkelson, D.J., 2019b, Temporal, spatial and geochemical evolution of late Cenozoic post-subduction magmatism in central and eastern Anatolia, Turkey: Lithos, v. 336–337, p. 67–96.

Revan, M.K., Hisatani, K., Myamoto, H., Delibaş, O., Hanilçi, N., Aysal, N., Özkan, M., Çolak, T., Karsli, Ş., and Peytcheva, I., 2017, Geology, U-Pb geochronology, and stable isotope geochemistry of the Tunca semi-massive sulfide mineralization, Black Sea region, NE Turkey: Implications for ore genesis: Ore Geology Reviews, v. 89, p. 369–389.

Rezeau, H., Moritz, R., Wotzlaw, J.F., Tayan, R., Melkonyan, R., Ulianov, A., Selby, D., d'Abzac, F.X., and Stern, R.A., 2016, Temporal and genetic link between incremental pluton assembly and pulsed porphyry Cu-Mo formation in accretionary orogens: Geology, v. 44, p. 627–630.

Rezeau, H., Moritz, R., Leuthold, J., Hovakimyan, S., Tayan, R., and Chiaradia, M., 2017, 30 Myr of Cenozoic magmatism along the Tethyan margin during Arabia-Eurasia accretionary orogenesis (Meghri-Ordubad pluton, southernmost Lesser Caucasus): Lithos, v. 288–289, p. 108–124.

Rezeau, H., Leuthold, J., Tayan, R., Hovakimyan, S., Ulianov, A., Kouzmanov, K., and Moritz, R., 2018, Petrological characterization of subduction- and collision-related magmatism in the composite Meghri-Ordubad pluton, southernmost Lesser Caucasus, Tethyan orogenic belt: Journal of Petrology, v. 59, p. 931–966.

Rezeau, H., Moritz, R., Wotzlaw, J.-F., Hovakimyan, S., and Tayan, R., 2019, Zircon petrochronology of the Meghri-Ordubad pluton, Lesser Caucasus: Fingerprinting igneous processes and implications for the exploration of porphyry Cu-Mo deposits: Economic Geology, v. 114, p. 1365–1388.

Richards, J.P., 2015, Tectonic, magmatic, and metallogenic evolution of the Tethyan orogen: From subduction to collision: Ore Geology Reviews, v. 70, p. 323–345.

——ed., 2016, Tectonics and metallogeny of the Tethyan orogenic belt: Society of Economic Geologists, Special Publication 19, 387 p.

Rızaoğlu, T., Parlak, O., Höck, V., Koller, F., Hames, W.E., and Billor, Z., 2009, Andean type active margin formation in the eastern Taurides: Geochemical and geochronogical evidence from the Baskil granitoid (Elazığ, SE Turkey): Tectonophysics, v. 473, p. 188–207.

Robertson, A.H.F., Ustaömer, T., Parlak, O., Ünlügenç, Ü.C., Taslı, K., and İnan, N., 2006, The Berit transect of the Tauride thrust belt, S. Turkey: Late Cretaceous-early Cenozoic accretionary/collisional processes related to closure of the southern Neotethys: Journal of Asian Earth Sciences, v. 27, p. 108–145.

Robertson, A.H.F., Parlak, O., Rızaoğlu, T., Ünlügenç, Ü., İnan, N., Tasli, K., and Ustaömer, T., 2007, Tectonic evolution of the South Tethyan ocean: Evidence from the eastern Taurus Mountains (Elaziğ region, SE Turkey): Geological Society of London, Special Publication 272, p. 231–270.

Robertson, A.H.F., Parlak, O., and Ustaömer, T., 2012, Overview of the Palaeozoic-Neogene evolution of Neotethys in the Eastern Mediterranean region (southern Turkey, Cyprus, Syria): Petroleum Geoscience, v. 18, p. 381–404.

——2013, Late Palaeozoic-early Cenozoic tectonic development of southern Turkey and the easternmost Mediterranean region: Evidence from the inter-relations of continental and oceanic units: Geological Society of London, Special Publication 372, p. 9–48.

Rolland, Y., Billo, S., Corsini, M., Sosson, M., and Galoyan, G., 2009a, Blueschists of the Amassia-Stepanavan suture zone (Armenia): Linking Tethys subduction history from E-Turkey to W-Iran: International Journal of Earth Sciences, v. 98, p. 533–550.

Rolland, Y., Galoyan, G., Bosch, D., Sosson, M., Corsini, M., Fornari, M., and Vérati, C., 2009b, Jurassic back-arc and hot-spot related series in the Armenian ophiolites—implications for the obduction process: Lithos, v. 112, p. 163–187.

Rolland, Y., Sosson, M., Adamia, S., and Sadradze, N., 2011, Prolonged Variscan to Alpine history of an active Eurasian margin (Georgia, Armenia) revealed by $^{40}Ar/^{39}Ar$ dating: Gondwana Research, v. 20, p. 798–815.

Rolland, Y., Perincek, D., Kaymakci, N., Sosson, M., Barrier, E., and Avagyan, A., 2012, Evidence for ~80–75 Ma subduction jump during Anatolide-Tauride-Armenian block accretion and ~48 Ma Arabia-Eurasia collision in Lesser Caucasus-east Anatolia: Journal of Geodynamics, v. 56–57, p. 76–85.

Sánchez, M.G., McClay, K.R., King, A.R., and Wijbrams, J.R., 2016, Cenozoic crustal extension and its relationship to porphyry Cu-Au-(Mo) and epithermal Au-(Ag) mineralization in the Biga peninsula, northwestern Turkey: Society of Economic Geologists, Special Publication 19, p. 113–156.

Scheffer, C., Tarantola, A., Vanderhaeghe, O., Voudouris, P., Spry, P.G., Rigaudier, T., and Photiades, A., 2019, The Lavrion Pb-Zn-Ag–rich vein and breccia detachment-related deposits (Greece): Involvement of evaporated seawater and meteoric fluids during postorogenic exhumation: Economic Geology, v. 114, p. 1415–1442.

Schleiffarth, W.K., Darin, M.H., Reid, M.R., and Umhoefer, P.J., 2018, Dynamics of episodic Late Cretaceous-Cenozoic magmatism across central to eastern Anatolia: New insights from an extensive geochronology compilation: Geosphere, v. 14, p. 1990–2008.

Şengör, A.M.C., and Yilmaz, Y., 1981, Tethyan evolution of Turkey: A plate tectonic approach: Tectonophysics, v. 75, p. 181–241.

Siron, C.R., Thompson, J.F.H., Baker, T., Friedman, R., Tsitsanis, P., Russell, S., Randall, S., and Mortensen, J., 2016, Magmatic and metallogenic framework of Au-Cu porphyry and polymetallic carbonate-hosted replacement deposits of the Kassandra mining district, northern Greece: Society of Economic Geologists, Special Publication 19, p. 29–55.

Siron, C.R., Rhys, D., Thompson, J.F.H., Baker, T., Veligrakis, T., Camacho, A., and Dalampiras, L., 2018, Structural controls on porphyry Au-Cu and Au-rich polymetallic carbonate-hosted replacement deposits of the Kassandra mining district, northern Greece: Economic Geology, v. 113, p. 309–345.

Siron, C.R., Thompson, J.F.H., Baker, T., Darling, R., and Dipple, G., 2019, Origin of Au-rich carbonate-hosted replacement deposits of the Kassandra mining district, northern Greece: Evidence for late Oligocene, structurally controlled, and zoned hydrothermal systems: Economic Geology, v. 114, p. 1389–1414.

Smith, M.T., Lepore, W.A., Incekaraoglu, T., Boran, H., Barrios, A., Leroux, G., Ross, K., Büyüksolak, A., Sevimli, A., and Raabe, K., 2016, High-sulfidation epithermal Au and porphyry Cu-Au mineralization at the Karaayi target, Biga peninsula, northwestern Turkey: Society of Economic Geologists, Special Publication 19, p. 85–112.

Sosson, M., Rolland, Y., Müller, C., Danelian, T., Melkonyan, R., Kekelia, S., Adamia, S., Babzadeh, V., Kangarli, T., Avagyan, A., Galoyan, G., and Mosar, J., 2010, Subductions, obduction and collision in the Lesser Caucasus (Armenia, Azerbaijan, Georgia), new insights: Geological Society of London, Special Publication 340, p. 329–352.

Sosson, M., Stephenson, R., Sheremet, Y., Rolland, Y., Adamia, S., Melkonian, R., Kangarli, T., Yegorova, T., Avagyan, A., Galoyan, G., Danelian, T., Hässig, M., Meijers, M., Müller, C., Sahakyan, L., Sadradze, N., Alania, V., Enukidze, O., and Mosar, J., 2016, The eastern Black Sea-Caucasus region during the Cretaceous: New evidence to constrain its tectonic evolution: Comptes Rendus Geosciences, v. 348, p. 181–241.

Verdel, C., Wernicke, B.P., Hassanzadeh, J., and Guest, B., 2011, A Paleogene extensional arc flare-up in Iran: Tectonics, v. 30, TC3008.

Vincent, S.J., Allen, M.B., Ismail-Zadeh, A.D., Flecker, R., Foland, K.A., and Simmons, M.D., 2005, Insights from the Talysh of Azerbaijan into the Paleogene evolution of the South Caspian region: Geological Society of America Bulletin, v. 117, p. 1513–1533.

von Quadt, A., Moritz, R., Peytcheva, I., and Heinrich, C.A., 2005, Geochronology and geodynamics of Upper Cretaceous magmatism and Cu-Au mineralization in the Panagyurishte region of the Apuseni-Banat-Timok-Srednogorie belt (Bulgaria): Ore Geology Reviews, v. 27, p. 95–126.

Voudouris, P., Mavrogonatos, C., Spry, P., Baker, T., Melfos, V., Klemd, R., Haase, K., Repstock, A., Djiba, A., Bismayer, U., Tarantola, A., Scheffer, C., Moritz, R., Kouzmanov, K., Alfieris, D., Papavassiliou, A., Schaarschmidt, A., Galanopoulos, E., Galanos, E., Kolodziejczyk, J., Stergiou, C., and Melfou, M., 2019, Porphyry and epithermal deposits in Greece: An overview, new discoveries, and mineralogical constraints on their genesis: Ore Geology Reviews, v. 107, p. 654–691.

Wortel, M.J.R., and Spakman, W., 2000, Subduction and slab detachment in the Mediterranean-Carpathian region: Science, v. 290, p. 1910–1917.

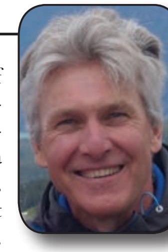
Yiğit, Ö., 2009, Mineral deposits of Turkey in relation to Tethyan metallogeny: Implications for future mineral exploration: Economic Geology, v. 104, p. 19–51.

——2012, A prospective sector in the Tethyan metallogenic belt: Geology and geochronology of mineral deposits in the Biga Peninsula, NW Turkey: Ore Geology Reviews, v. 46, p. 118–148.

Yilmaz, A., Adamia, S., Chabukiani, A., Chkhotua, T., Erdogan, K., Tuzcu, S., and Karabilykoglu, M., 2000, Structural correlation of the southern Transcaucasus (Georgia)-eastern Pontides (Turkey): Geological Society of London, Special Publication 173, p. 171–182.

Zonenshain, L.P., and Le Pichon, X., 1986, Deep basins of the Black Sea and Caspian Sea as remnants of Mesozoic back-arc basins: Tectonophysics, v. 123, p. 181–211.

Zürcher, L., Bookstrom, A.A., Hammarstrom, J.M., Mars, J.C., Ludington, S.D., Zientek, M.L., Dunlap, P., and Wallis, J.C., 2019, Tectono-magmatic evolution of porphyry belts in the central Tethys region of Turkey, the Caucasus, Iran, western Pakistan, and southern Afghanistan: Ore Geology Reviews, v. 111, doi.org/10.1016/j.oregeorev.2019.02.034.



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