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A REVIEW OF AGE CONSTRAINTS OF EPITHERMAL PRECIOUS AND BASE METAL DEPOSITS OF THE TERTIARY EASTERN RHODOPES: COINCIDENCE WITH LATE EOCENE-EARLY OLIGOCENE TECTONIC PLATE REORGANIZATION ALONG THE TETHYS

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Abstract: The Tertiary Eastern Rhodopes are a major ore province within the Tethyan metallogenic belt. $^{40}Ar/^{39}Ar$ age data obtained in the past ten years are overviewed and discussed. It allows us to address some of the open questions and shed some new light on the sequence of ore-forming, magmatic and tectonic processes throughout the Eastern Rhodopes. Small to moderately sized ore deposits and prospects in the Rhodope Massif are hosted by high-grade metamorphic, continental sedimentary and igneous rocks. Sedimentary rock-hosted gold epithermal prospects are the earliest hydrothermal systems, hosted by Maastrichtian-Paleocene clastic rocks. Their $^{40}Ar/^{39}Ar$ ages vary between 37.55 ± 0.44 Ma and 34.71 ± 0.16 Ma, with the waning hydrothermal activity overlapping with the start of the oldest volcanism in the Eastern Rhodopes yielding $^{40}Ar/^{39}Ar$ ages ranging between 34.62 ± 0.46 Ma and 32.97 ± 0.23 Ma. Within a very short time between 32.13 ± 0.20 and 31.2 ± 0.4, Pb-Zn-dominated and Cu-Au-dominated epithermal prospects, respectively in the northern and the southern parts, were formed, and coincide with rhyolitic dikes emplaced at about 31.5 Ma. The Late Eocene-Early Oligocene post-orogenic magmatic and ore-forming evolution of the Eastern Rhodopes coincides with the time of collision at about 30-35 Ma of the African and Eurasian plates in the Caucasus and the Rif-Betic belts, when a dominantly subduction-dominated tectonic regime changed to a collision-dominated system, and the northward motion of the African plate slowed down, accompanied by an increasing southward slab retreat velocity in the Aegean Sea.

Keywords : epithermal, Cu-Au and Pb-Zn deposits, $^{40}Ar/^{39}Ar$ dating, Tertiary, Eastern Rhodopes

1. Introduction

The Tertiary Eastern Rhodopes are a major ore province within the Tethyan metallogenic belt (Fig. 1), with mining activities dating back to prehistoric times. Previous contributions (e.g. Arikas and Voudouris, 1998; Marchev et al., 2005) reported the characteristics of the different ore deposits and prospects, analyzed their fundamental relationships with magmatic and tectonic events, and discussed open questions related to ore-forming processes in the Eastern Rhodopes.

Some of the important debates about ore deposit genesis in the Eastern Rhodopes include the chronological relationship of epithermal ore formation between its northern, Bulgarian part, where magmatism has a more shoshonitic to high-K calc-alkaline nature and where epithermal deposits are dominated by Pb and Zn (Fig. 1: Spahievo, Madjarovo, Zvezdel), and its southern, Greek part (Fig. 1: Sappes, Perama, Kirki), where magmatism is predominantly calc-alkaline and the epithermal deposits are dominated by Cu and Au (Arikas and Voudouris, 1998; Marchev et al., 2005). A further debate relates to the nature of sedimentary rock-hosted epithermal gold prospects located in Bulgaria, spatially associated with extensional detachment settings along exhuming gneiss-migmatitic domes (Fig.1: Ada Tepe, Rosino, Stremtsi), in particular whether there was any magmatic link during ore-formation in an area where ore deposits are otherwise typically associated to magmatic activity. Finally, Lescuyer et al. (2003), by comparing the similarity of the Bulgarian sedimentary rock-hosted prospect at Ada Tepe with the one at Perama in Greece along the Aegean Sea, partly hosted by sandstone (Fig. 1), also

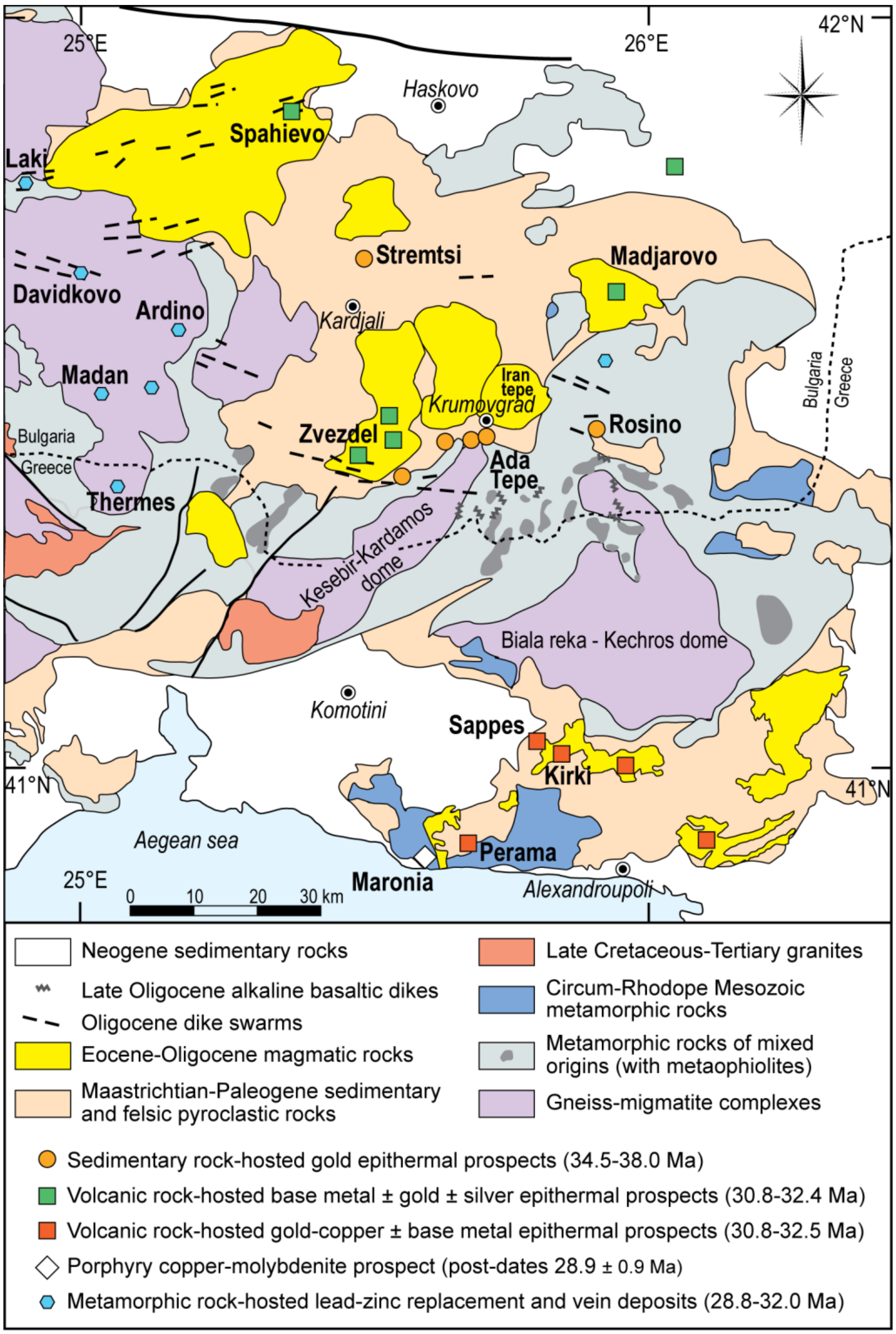

Fig. 1. Simplified geological map of the Eastern Rhodopes showing locations of the main epithermal and porphyry prospects and deposits (After Marchev et al., 2004b with additional information from Melfos et al., 2002, Marchev et al., 2005 and Voudouris, 2006).

opened the question about any possible genetic, temporal relationship among them.

Several new studies were undertaken recently in order to constrain some of the debates associated to the ore-forming processes in this province. In this contribution, we present an overview and discuss ^{40}Ar/^{39}Ar age data obtained over the past ten years, including data gathered more recently by a multidisciplinary research group focused on tectonics, magmatism, and ore deposit geology and geochemistry in the Eastern Rhodopes. This data set allows us to tackle the open questions mentioned above and permits to shed some new light on the sequence of ore-forming, magmatic and tectonic processes throughout the Eastern Rhodopes. In addition, we investigate the link of ore-formation in the Eastern Rhodopes with geodynamic changes, which occurred along the Tethys during the Late Eocene and Early Oligocene.

2. Regional geological and geodynamic setting

The Tertiary Eastern Rhodope Massif belongs to the Alpine-Himalayan orogenic belt and is interpreted as an accretionary complex, formed during Alpine convergence between the Adriatic-Apulian continental promontory of African affinity and the European Mosean plateform, within a north-dipping subduction system (Ricou et al., 1998). The evolution of the Rhodope Massif is commonly subdivided in two stages, including (1) a compressional stage, with thrusting and progressive thickening of the crust starting during Late Jurassic times (Bonev et al., in press), and culminating during the Middle Cretaceous (Burg et al., 1990), followed by (2) Late Cretaceous-Early Tertiary, syn-to post-orogenic collapse, as a result of unstability of the overthickened crust, which finally resulted in exhumation of deep metamorphic rocks along detachment faults (e.g. Bonev et al., 2006a), the formation of Late Eocene to Oligocene sedimentary basins filled with continental clastic rocks (e.g. Goranov and Atanasov, 1992), and widespread Late Eocene to Early Miocene basic to felsic magmatism (e.g. Arikas and Voudouris, 1998; Marchev et al., 2004a). The Palaeogene magmatism of the Central and Eastern Rhodopes culminated at about 30-35 Ma, and was accompanied by abundant ore-forming hydrothermal activity (Arikas and Voudouris, 1998; Marchev et al., 2005).

3. Major types of ore deposits and prospects of the Eastern Rhodopes

Small to moderately sized ore deposits and prospects in the Rhodope Massif are hosted by high-grade metamorphic, continental sedimentary and igneous rocks (Arikas and Voudouris, 1998; Marchev et al., 2005). The economically most significant ore deposits are Pb-Zn-Ag vein and marble-hosted replacement deposits of the Central Rhodopes within the Laki, Davidkovo, Ardino, Madan and Thermes ore fields (Fig. 1). They were formed between about 28.8 and 32.0 Ma, and are contemporaneous with the emplacement of felsic dike swarms, and are related to rapid tectonic and erosional denudation of metamorphic core complexes during late-orogenic collapse (Kaiser-Rohrmeier et al., 2004).

In the Eastern Rhodopes, epithermal deposits are hosted by volcanic centres of calc-alkaline, high-K calc-alkaline and shoshonitic composition. In the northern, Bulgarian part of the Eastern Rhodopes, epithermal deposits are Pb- and Zn-rich, with subsidiary Cu, Au and Ag, with predominantly intermediate-sulfidation fluid state characteristics, and are locally associated with low-grade Cu-Mo porphyry occurrences (Singer and Marchev, 2000; Marchev and Singer, 2002; Rice et al., 2007). The main ore districts are Spahievo, Madjarovo and Zvezdel (Fig. 1), which produced about 16.5 Mt of Pb-Zn ore during about 50 years (Marchev et al. 2005). A small gold mine remains in operation near Spahievo (Fig. 1). The epithermal deposits from the southern part of the Eastern Rhodopes located in Greece are characterized by Cu- and Au-enrichments with respect to the Bulgarian ones, and display gangue and ore paragenetic associations revealing high-sulfidation fluid states evolving progressively to later stage intermediate/low-sulfidation fluid states (Voudouris, 2006; Voudouris et al., 2006; Ortelli, 2009; Ortelli et al., 2009). They include the recently discovered Perama and Sappes prospects (Fig. 1; Michael et al., 1995; McAlister et al., 1999; Lescuyer et al., 2003).

A distinct group of epithermal gold-silver prospects, already mined during ancient times, are hosted by Maastrichtian to Paleocene syn-detachment, clastic sedimentary rocks overlying metamorphic basement rocks, located along the hanging-wall of detachment faults (Fig. 1: Ada Tepe, Rosino, Stremtsi; Marchev et al., 2004b; Bonev et al., 2006b; Noverraz et al., 2007; Márton 2009; Márton et al., 2010, submitted). The geometry of the epithermal prospects reveals both a lithological and a structural control. Ore formation was clearly associated with extensional tectonics and with on-going supradetachment sedimentation. Ore deposition occurred variably as a consequence of boiling, fluid-rock interaction (fluid desulfidation) and fluid mixing, and explains the variation of paragenesis, geometry and other ore features among the sedimentary rock-hosted prospects. The sedimentary rock-hosted gold prospects display textural and mineralogical features characteristic of low-sulfidation deposits, although intermediate-sulfidation characteristics are also observed (Márton, 2009; Márton et al., submitted).

4. Overview of ages of major hydrothermal, tectonic and magmatic events since the Late Eocene

Figure 2 summarizes hydrothermal ore-forming, tectonic and magmatic events in the Eastern Rhodopes since the Late Eocene. Exhumation of gneiss-migmatite domes during crustal extension is the important process, which dominated the geological evolution of the Eastern Rhodopes during the Late Eocene, immediately before the onset of a sequence of diverse hydrothermal and magmatic events (Fig. 2). Retrograde metamorphism during exhumation with cooling muscovite ages were dated between 39.66 ± 0.47 and 39.28 ± 0.24 Ma in the Biala reka – Kechros dome, and between 38.13 ± 0.36 and 36.90 ± 0.36 Ma in the Keebir-Kardamos dome (Fig. 1; Bonev et al., 2006b, in press; Márton et al., 2010).

Sedimentary rock-hosted gold epithermal prospects are the earliest ore-forming events in various locations across the Eastern Rhodopes, and are hosted by Maastrichtian-Paleocene clastic sedimentary rocks at or close to the contact with underlying metamorphic basement rocks. Stremtsi (Fig. 1) yielded the oldest $^{40}Ar/^{39}Ar$ adularia age at 37.55 ± 0.44 Ma (Moritz et al. unpublished), and the youngest age was recorded for adularia from Ada Tepe, Bulgaria (Fig. 1) at 34.71 ± 0.16 Ma (Marchev et al., 2004b; Márton et al., 2010). The oldest volcanic event in the Eastern Rhodopes started at Iran Tepe, north of the town of Krumovgrad, Bulgaria (Fig. 1), and yields $^{40}Ar/^{39}Ar$ ages ranging between 34.62 ± 0.46 Ma and 32.97 ± 0.23 Ma, which overlap with one U-Pb zircon age obtained from the same location (Márton et al., 2010; Marchev et al., submitted).

Extensive shoshonitic and high-K calc-alkaline magmatic activity occurred at about 32 Ma (not shown in Fig. 2; see Singer and Marchev, 2000; Marchev and Singer 2002) throughout the northern Eastern Rhodopes and resulted in the formation of Pb-Zn dominated epithermal deposits at Madjarovo, Spahievo and Zvezdel, Bulgaria (Fig. 1), with $^{40}Ar/^{39}Ar$ ages between 32.13 ± 0.20 and 31.12 ± 0.35 Ma for epithermal ore formation (Singer and Marchev, 2000; Marchev and Singer, 2002; Marchev et al., 2005). At Spahievo (Fig. 1), an early, deeper porphyry Cu-Mo event yielded ages between 32.82 ± 1.06 and 32.61 ± 0.32 Ma (Singer and Marchev 2000). In the southern Eastern Rhodopes, near the Aegean Sea, porphyry-type Cu-Mo mineralization and Au-Cu±Pb±Zn epithermal ore formation in the Sappes-Kassiteres area, Greece (Fig. 1) occurred also during the Early Oligocene between 32.0 ± 0.5 and 31.2 ± 0.4 Ma (Ortelli, 2009) in an area dominated by calc-alkaline magmatism.

Rhyolitic dikes crosscutting the Kesebir-Kardamos dome (Fig. 1) yielded sanidine $^{40}Ar/^{39}Ar$ ages of 31.82 ± 0.20 and 31.27 ± 0.16 Ma (Marchev et al. 2004b; Marchev and Moritz unpublished), which overlap with epithermal ore-formation in the northern Madjarovo, Spahievo and Zvezdel and the southern Sappes-Kassiteres districts (Fig. 2). Magmatism is not so well constrained in the southern Eastern Rhodopes of the Greek territory. Rb-Sr and K-Ar geochronological data by Del Moro et al. (1988), Pècskay et al. (2003) and Christofides et al. (2004) show that magmatism also started during the Early Oligocene and continued until the Early Miocene (Fig. 2). A magmatic biotite $^{40}Ar/^{39}Ar$ age of a monzodiorite-diorite from Sappes-Kassiteres (Fig. 1) of 32.6 ± 0.5 Ma reported by Ortelli (2009; not shown in Fig. 2) confirms the Early Oligocene ages published by Del Moro et al. (1988), Pècskay et al. (2003) and Christofides et al. (2004).

5. Discussion and conclusions

The new $^{40}Ar/^{39}Ar$ age data obtained for the epithermal-porphyry system at Sappes-Kassiteres by Ortelli (2009) show that high- to intermediate/low sulfidation epithermal ore formation in Thrace, Greece was contemporaneous with epithermal ore-formation in Bulgaria at Spahievo, Madjarovo and Zvezdel (Fig. 2). The northern Pb-Zn-dominated epithermal prospects associated with shoshonitic to high-K calc-alkaline magmatism and the southern Cu-Au epithermal prospects located in a dominantly calc-alkaline magmatic area formed within a very short time interval between 32.13 ± 0.20 and 31.2 ± 0.4 Ma, and coincide with the emplacement of rhyolitic dikes within the Kesebir-Kardamos dome at about 31.5 Ma (Fig. 2).

Marchev et al. (2005) already discussed the genetic relationship of evolved silicic dikes and epithermal systems in the Bulgarian Eastern Rhodopes. The new age data for Sappes-Kassiteres (Ortelli, 2009) reveal that this genetic relationship is likely also the case for the epithermal deposits within the southern part of the Eastern Rhodopes, where rhyolitic dikes are spatially associated with a number

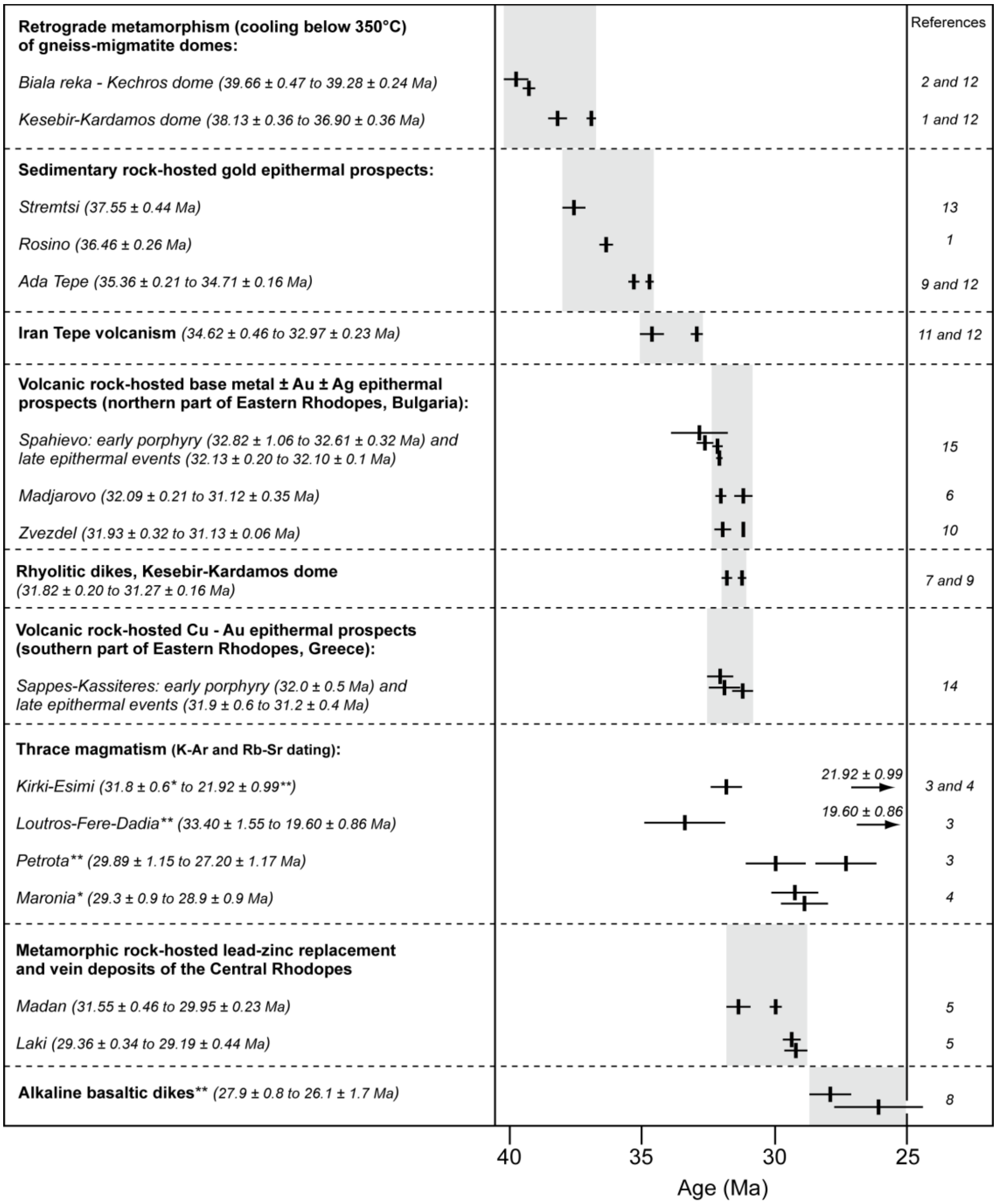

Fig. 2. Summary of the major tectonic, magmatic and ore-forming events in the Eastern Rhodopes since the Late Eocene. The data compilation shows absolute ages obtained by $^{40}Ar/^{39}Ar$ geochronology including 2s analytical errors, except when noted otherwise (see Thrace magmatism, Greece); *: Rb-Sr geochronology; **: K-Ar geochronology. For the sake of simplicity, if more than one age is available for a given location, then only the maximum and minimum ages are included in the figure. All ages are Ma. References: 1 – Bonev et al., 2006b; 2 – Bonev et al., in press; 3 – Christofides et al., 2004; 4 – Del Moro et al., 1988; 5 – Kaiser-Rohrmeier et al., 2004; 6 – Marchev and Singer, 2002; 7 – Marchev and Moritz, unpublished; 8 – Marchev et al., 1997; 9 – Marchev et al., 2004b; 10 – Marchev et al., 2005; 11 – Marchev et al., submitted; 12 – Márton et al., 2010; 13 – Moritz et al., unpublished; 14 - Ortelli, 2009; 15 – Singer and Marchev, 2000. See Figure 1 for locations.

of epithermal occurrences (e.g. Arikas and Voudouris, 1998; Voudouris et al., 2006; Ortelli, 2009; Ortelli et al., 2009). If one includes the ages of the early porphyry events in localities such as Spahievo, Bulgaria and Sappes-Kassiteres, Greece (Fig.1), it shows that ore-forming events started as early as 32.82 ± 1.06 Ma and 32.0 ± 0.5 Ma, respectively, thus yielding an overall ore-forming duration of about 3.5 m.y. throughout the entire Eastern Rhodopes for the volcanic-hosted Pb-Zn and Cu-Au epithermal and associated porphyry deposits. The long ore-forming time intervals recorded in each locality (e.g. Spahievo, Sappes-Kassiteres) reveal pulsed intrusive/volcanic and hydrothermal systems linked to the emplacement of multiple magmatic batches, because single porphyry-epithermal systems typically form only within 30 000 to 100 000 years (e.g. Harris et al., 2009).

The combined $^{40}Ar/^{39}Ar$ age data from the sedimentary rock-hosted gold epithermal prospects show that they constitute an independent hydrothermal system with respect to the volcanic rock-hosted epithermal deposits discussed above (Fig. 2). Based on the age data, formation of these hydrothermal systems also took place during an extended time of about 3.5 m.y., starting at Stremtsi at 37.55 ± 0.44 Ma and ending in Ada Tepe at 34.71 ± 0.16 Ma (Fig. 2). These deposits formed during on-going burial by supra-detachment, clastic sedimentary rocks, which was a process which could have supplied additional heat in addition to the one released from high geothermal gradients, typical for metamorphic core complex exhumation, necessary to sustain extensive ore-forming hydrothermal fluid circulation throughout the Maastrichtian-Paleocene sedimentary basins. The recent $^{40}Ar/^{39}Ar$ age data obtained by Márton et al. (2010) and Marchev et al. (submitted) reveal that the waning hydrothermal activity at Ada Tepe overlapped with starting volcanic activity at the Iran tepe centre (Fig. 2), located north of Krumovgrad (Fig. 1). This suggests that magmatism may have supplied heat, and possibly fluids and gold to the hydrothermal system as well. Nevertheless, this link is still not totally understood, because at other prospects, such as Rosino and Stremtsi (Fig. 1), contemporaneous magmatic activity remains to be demonstrated (Fig. 2). The absolute ages obtained so far (Fig. 2) indicate that the Bulgarian sedimentary rock-hosted systems at Ada Tepe, Rosino and Stremtsi (Fig. 1) have no genetic link with the partly sedimentary rock-hosted epithermal system of the Perama prospect, Greece (Fig. 1), as might be suggested by the comparison of Lescuyer et al. (2003), since the later prospect would be at least 3 m.y. younger than the Bulgarian ones.

The Late Eocene-Oligocene post-orogenic evolution of the Eastern Rhodopes coincides with the time of collision at about 30-35 Ma of the African and Eurasian plates in the Caucasus to the east and the Rif-Betic belts to the west, when a dominantly subduction-dominated tectonic regime changed to a collision-dominated system, and the northward motion of the African plate suddenly slowed down. In this locked subduction system, the southward slab retreat velocity increased in the Aegean Sea (Jolivet and Faccenna, 2000), from the Late Eocene trench position along the Eastern Rhodopes to the present-day position of the Hellenic Trench south of Crete (Jolivet et al., 2003 ; Jolivet and Brun, 2010). Thus, the roughly coeval, widespread formation over the entire Eastern Rhodopes of volcanic rock-hosted precious and base metal epithermal deposits, accompanied by minor porphyry mineralization at about 32 Ma, and preceded by sedimentary rock-hosted gold epithermal ore-formation in supra-detachment basins during exhumation of metamorphic core complexes, between about 38 and 34.5 Ma, coincides with major tectonic plate reorganization at the scale of the Tethys. The coincidence of ore formation in a short time interval in the Eastern Rhodopes and rapid geodynamic changes along the Tethys is analogous to other examples, where tectonic plate reorganization triggered major ore forming events (e.g. Cenosoic settings of southeast Asia and the West Pacific, Garvin et al., 2005). The prevailing extensional setting and geodynamic regime with a southward hinge retreat of the subducting plate also explains the small size of the porphyry systems in the Eastern Rhodopes, because formation of large porphyry systems is favoured in geodynamic settings characterized by slab flattening, contraction and crustal thickening (Cook et al., 2005; Sillitoe, 2008).

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