Timing of magmatism and mineralization in South Eastern Europe
(Western Branch of the Tethyan Belt)

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Magmatic arcs form above active subduction zones at convergent plate boundaries, where a continental or oceanic plate margin overrides a subducting oceanic plate. Along a subduction zone, continental and oceanic arcs generally form distinct segments (*Kay et al.*, 1982; *Hildreth and Moorbath*, 1988). In continental-margin arcs, the style of tectonic deformation may differ amongst segments along the arc, and may also vary perpendicular to the arc in response to differences in pre-existing geology, convergence rate and direction, or heterogeneities within the subducting plate. The composition of subduction-related mantle magmas varies as a result of heterogeneous source enrichment, and may be modified by mineral fractionation and crustal assimilation processes, which occur primarily in the lower crust and on further ascent through the mature continental crust (*Hildreth and Moorbath*, 1988; *Annen et al.*, 2006). Conversely, igneous geology and geochemistry can be used to identify magma sources and evolution processes and thus serve as geochemical evidence to interpret the large-scale plate-tectonic setting of complex arcs.

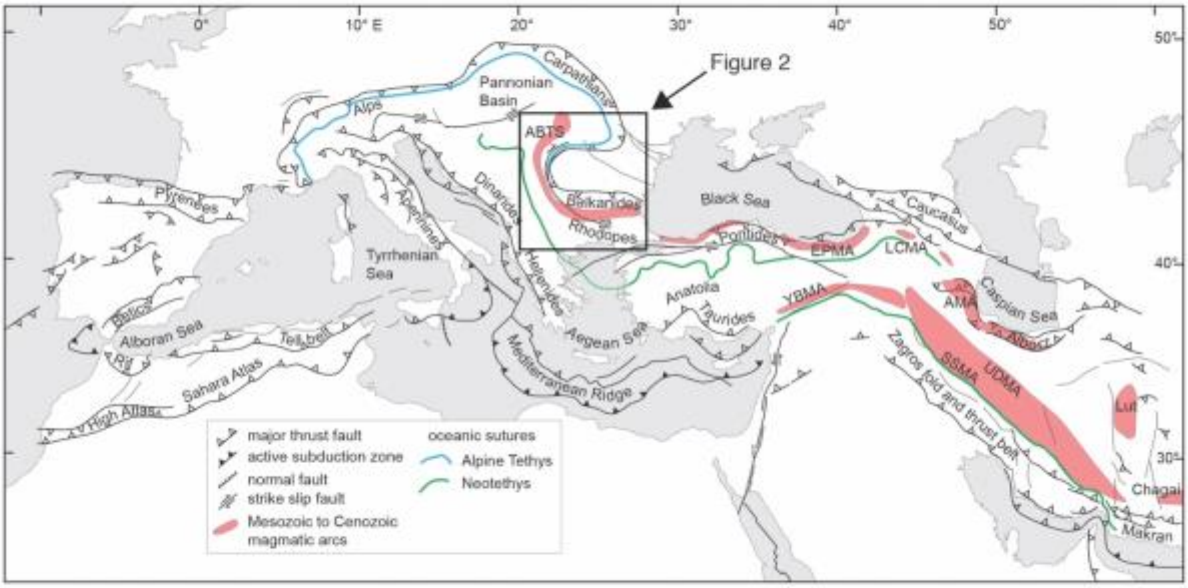

Fig. 1. Tectonic sketch map of western Eurasia (modified from *Morelli and Barrier*, 2004). Major Late-Tertiary to active thrust belts, active subduction zones and recent arc volcanoes are shown in black; older oceanic suture zones and location of Mesozoic to Oligocene magmatic arcs are highlighted by colours. ABTS: Apuseni-Banat-Timok-Srednogorie belt, AMA Alborz magmatic arc, CA Carpathian magmatic arcs, EPMA Eastern Pontide magmatic arc, KB Kerman belt, LCMA Lesser Caucasus magmatic arc, SSMA Sanandaj-Sirjan magmatic arc, UDMA Urumieh-Dokhtar magmatic arc, YBMA Yüksekova-Baskil magmatic arc

Subduction-related magmatic arcs are frequently endowed with magmatic-hydrothermal porphyry Cu±Au±Mo and epithermal Au±Ag±Cu deposits, which can themselves be taken as tectonic indicators. These deposits usually occur in discrete belts and do not extend along the entire length of magmatic arcs. Barren and mineralised segments are thought to be due to large-scale variations in tectonic stress of the lithosphere, and well-endowed segments empirically correlate with flat slab subduction, subduction of oceanic ridges or subduction reversals (e.g. *Cooke et al.*, 2005; *Rohrlach and Loucks*, 2005). Major porphyry deposits develop preferentially in arc segments that were subjected to a compressional stress state during ore deposit formation (e.g. *Richards*, 2003). Horizontal compression can trap magmas in a lower crustal magma chamber, where high-pressure magmatic differentiation and cyclic replenishment lead to enrichment in volatiles and metal content. Compression also helps establishing upper-crustal magma chambers, thus preventing volcanic eruption and unfocused loss of volatiles, but favouring focussed fluid release through intensely veined porphyry stocks (*Rohrlach and Loucks*, 2005; *Richards*, 2012).

The Eurasian continental margin includes the world's second-longest magmatic arc system (*Jankovic*, 1997), besides the Circum-Pacific region. Unlike the Circum-Pacific, which is dominated by long-lasting subduction of oceanic plates below continents, the magmatic arcs of Eurasia are embedded in the Alpine-Himalayan intra-continental orogenic system (Fig. 1). Arc magmatism was driven by subduction of the Neotethys ocean in Mesozoic to Tertiary times, but terminated at the time of collision and was subsequently heavily overprinted by major collision-related deformations (e.g. *Schmid et al.*, 2008]. This collisional overprinting makes the reconstruction and interpretation of arc magmatism and the associated geotectonic setting more difficult (*Sosson et al.*, 2010). The Late Cretaceous Apuseni-Banat-Timok-Srednogorie (ABTS) belt in south-eastern Europe is the western-most arc in the Alpine-Himalayan orogenic system related to the subduction of Neotethys (*Berza et al.*, 1998; *Popov et al.*, 2002). This magmatic arc extended over 1000 km length, from the Apuseni Mountains of Romania to the Black Sea (Fig. 1, 2), and was deformed after emplacement on a lithospheric scale (*Neubauer*, 2002). Five segments that show distinct magmatic and mineralisation trends can be distinguished along this arc (Fig. 2). The timing and evolution of the magmatism and its associated ore deposits are well studied in the central and eastern segments (*von Quadt et al.*, 2005; *Georgiev et al.*, 2012; *Kolb et al.*, 2013; Gallhofer et al., 2015, 2016).

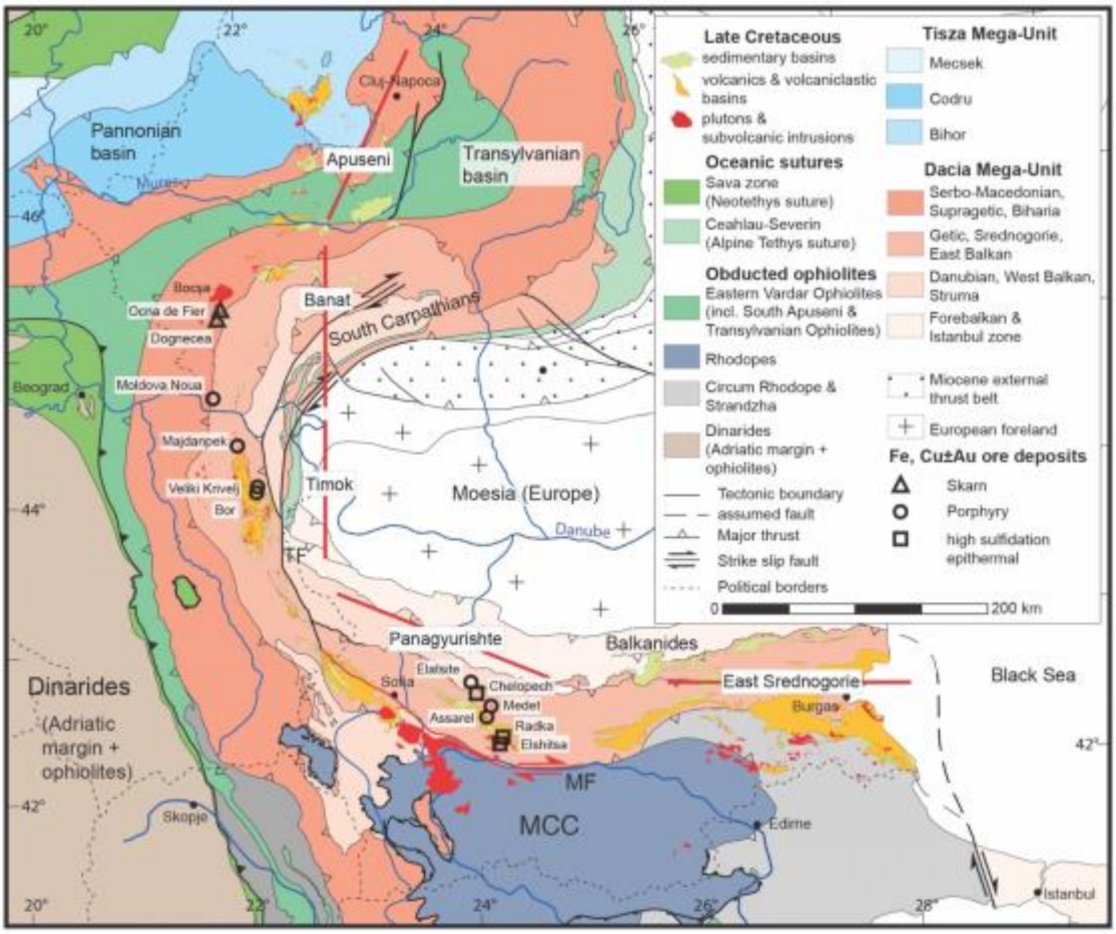

Fig. 2. Geological map of the Carpathian-Balkan orogen, modified from Schmid et al. (2008), showing major tectonic units and the occurrences of Late Cretaceous igneous rocks and sedimentary basins grouped into five segments of ABTS belt. These are, from NW to SE: the Apuseni, Banat, Timok, Panagyurishte and Eastern Srednogorie segments. Red bars are reference lines approximating the present-day orientation of the arc front in each of the five segments, based on geochronological data derived in this and previous studies. MF = Maritsa fault system and TF = Timok fault are major transverse structures used to separate the segments; MCC = Metamorphic ore Complex.

The *Apuseni-Banat-Timok-Srednogorie* (ABTS) belt is one of the world's oldest mining areas and played a major role in the history of European civilizations until the present day. Today, it is Europe's premier Cu-Au (-Pb-Zn-Ag) province, especially for gold-rich deposits associated with calc-alkaline magmatism. The ABTS magmatic arc in the Carpathian-Balkan orogen formed on the European margin during closure of the Neotethys Ocean. Trace element and isotopic signatures of the magmas indicate a subduction-enriched source and variable contamination by continental crust. Extensive U-Pb zircon dating combined with reliable published data suggest magmatic activity at a continental margin for 25 Ma (~92–67 Ma) related to oblique subduction and slab steepening. Ore mineralization is related to porphyry systems (Majdanpek, Bor, Veliki-Krivelj (Serbia), Elatsite, Assarel (Bulgaria)) and includes world-class porphyry Cu-Au-Mo deposits, proximal and distal intermediate and high-sulphidation epithermal (Chelopech (Bulgaria), as well as sediment-hosted and carbonate-replacement deposits that are formed during an economically important window of 6-8 Ma (92-86 Ma or 86-78 Ma in the different segments). Predating tectonics and stratigraphy played particularly important role for the location and grade of mineralization.

The magmatic evolution of the ABTS belt in Late Cretaceous times can be subdivided into the following stages:

1) *Active continental margin at ~110 Ma:* The north-dipping subduction of the Neotethys ocean along the Sava trench must have started some time before the onset of arc magmatic activity, most likely during the Albian. The formation of strike-slip and pull-apart basins in the Panagyurishte segment indicates that the dextral Maritsa fault system has already been active at that time. Towards the end of this stage the mantle source was geochemically enriched by subduction fluids, to generate the characteristic subduction-like signature of arc magmas.

2) *Initiation of magmatic activity, steepening of the subduction zone and ore deposit formation (~92 to 75 Ma):* The earliest upper-crustal magmatism is recorded by intrusive rocks from the northern Panagyurishte segment and indirectly by co-magmatic sediments preserved in the Eastern Srednogorie segment (~92 Ma). The onset of magmatic activity systematically became younger towards the west (~89 to 72 Ma) in the other segments of ABTS belt. The ascent of magmas to the upper crust might have been facilitated by the steepening of the subduction zone and was partly focussed by pull-apart structures, e.g., along the Panagyurishte lineament associated with strike-slip faulting along the Maritsa shear zone. At the same time, magmatic activity shifted continuously to the south in all the arc segments except for the Apuseni segment, as is evidenced by progressively younger magmatic ages towards south. Economic porphyry Cu and epithermal Cu±Au deposits coincide with early stages of magmatism in the Panagyurishte and Timok segments.

3) End of active subduction and arc magmatism by continental collision (~72 to 67 Ma): Arc magmatism within or near to the intra-arc basins ceased at ~72 Ma in all the segments, but younger plutons occur further south within the Rhodopes and Strandzha unit (Figure 2) south of the Panagyurishte and Eastern Srednogorie segments (69-67 Ma). These latest plutons probably reflect the termination of active subduction of the Sava branch of Neotethys ocean and likely mark the collision between Adria and Europe at the end of Maastrichtian (~66 Ma; *Schmid et al.*, 2008). Younger plutons intruded the Rhodopes only after a significant gap of some 10 Ma (~55 Ma; *Soldatos et al.*, 2008; *Jahn-Awe et al.*, 2010; *Marchev et al.*, 2013).

After the ceasing of subduction, the magmatism shifted to south in the *Serbo-Macedonian-Rhodope* belt (Fig. 2). There, it is directly connected to post-collisional episodes of back-arc extension related to slab break-off and asthenospheric upwelling and delamination (60-40 Ma) and the formation of metamorphic core complexes (MCC) - the North Rhodope MCC (38-25 Ma) and South Rhodope MCC (after 23-22 Ma). The magmatism preserves largely subduction-related features as sourced in the subcontinental mantle lithosphere and lower crust that were enriched during previous subduction. Several isolated time windows of ore forming processes are obtained (U/Pb zircon data, Ar-Ar, K-Ar data): 43-39 Ma (Au-Ag to Au-W deposits in the western Rhodopes); 38-32 Ma (Pb-Zn/ -Ag-Au) vein and carbonate replacement deposits, Bosnia (e.g. Trepca) through Serbia - Macedonia - Greece and southern Bulgaria; 32-24 Ma and 23-18 Ma (porphyry Cu-Au-(Mo) connected with the extensional magmatism following the MCC formation and finally at 12 - 1.8 Ma several epithermal and Carlin-type Au deposits; e.g. Alchar deposit (Macedonia).

In the Miocene, a main segment of ore-formation is the '*gold quadrilateral' of the Apuseni Mountains* (also known as the Transylvanian gold province). It includes a cluster of large, low-sulfidation epithermal Au-Te vein deposits including Sacarimb and Rosia Montana, which is probably Europe's largest gold resource. The epithermal veins are spatially and temporally associated with small to medium-sized porphyry-style Cu (-Au) deposits in calc-alkaline intrusive centers of Miocene age. Magma generation and the emplacement of numerous intrusive stocks are probably related to extensional accommodation of major strike-slip motions, associated with the north-eastward incursion of the Adriatic-Pannonian micro-continent.

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