Correlating magmatic–hydrothermal ore deposit formation over time with geodynamic processes in SE Europe

ANDOR L. W. LIPS
[1] *Vening Meinesz Research School of Geodynamics, Utrecht University, the Netherlands*
[2] *Present address: BRGM, Mineral Resources Division, REM/VADO, 3 av C. Guillemin, BP 6009, 45060 Orléans cedex 2, France (e-mail: a.lips@brgm.fr)*

Abstract: Numerous magmatic–hydrothermal metal deposits in SE Europe occur in relatively narrow belts of magmatic rocks that have been classically related to subduction. In contrast to the hundred million years of convergence and consumption of lithosphere at the subduction zones in the region, the belts have been produced in discrete time intervals. It has also become recognized that the dominant phases of mineralization in the belts were accompanied by extension. Research focusing on the evolution of the lithosphere at convergent margins identifies secondary thermal and mechanical processes that accompany the primary process of subduction. Such secondary processes have been identified as the possible trigger of the magmatism, regional crustal extension, and enhanced flow of heat and circulation of fluids. The lithosphere dynamics may thus have played a vital role in the formation and localization of the mineralization. Roll-back of the subducted lithosphere, or restoration of the orogenic wedge geometry by changes in internal friction, set by variations in rates of the Africa–Eurasia convergence; and gravitational collapse (e.g. involving slab detachment or root delamination), are the scenarios that favour extension and the transfer of heat to relatively shallow lithospheric levels. Analysis of the temporal and spatial constraints of these geodynamic processes, together with a refining of the timing of the main phases of mineralization is the first step to discriminate between the geodynamic causes, and to determine their effects in relatively short-lived regional igneous and hydrothermal activities and the formation of related mineralization.

The interrelationship between plate tectonics and mineralization was first recognized about 30 years ago, with the appreciation of a strong correlation between plate margins and ore deposit distribution (Pereira & Dixon 1971; Mitchell & Garson 1972; Sillitoe 1972*a*, *b*). The initial correlations were based on the circum-Pacific region but were extended to the Alpine–Himalayan chain by Dixon & Pereira (1974), who showed that the location of a variety of mineral deposits in specific tectonic settings could be related to the development of the Tethyan region. Jankovic (1977) further extended this relationship, emphasizing the genetic link between copper mineralization and a dominantly calc-alkaline volcanic-intrusive belt with volcano-sedimentary intervals.

Mineralization at convergent margins has been seen as part of a continuous process that covers the entire period of convergence. It had become traditional to interpret the convergent margin mineralization in terms of the dip of the subduction zone and the build-up of the orogenic wedge during convergence, which upon reaching maturity then underwent melting and consequently released the fluids assisting in the melting and mineralizing processes (Sillitoe 1991). Whilst such a model broadly explains mineralization in terms of the convergence process, it does not explain why the ore deposits preferentially occur in areas of the convergent margin that are undergoing transtensional or extensional tectonics at the time of mineralization (as originally raised by Izawa & Urashima 1988). More recently, Mitchell (1992, 1996), Mitchell & Carlile (1994) and Jankovic (1997) emphasized the link between the position of the volcanic-intrusive belt and the distribution of dominantly porphyry and epithermal deposits in the Carpathian–Balkan system (Fig. 1). They related the generation of volcanic-intrusive belts at the European convergent margin to the subduction of oceanic lithosphere and associated extension in the related back-arc.

This paper examines the formation of magmatic–hydrothermal deposits, in contrast to the orogenic, or mesothermal, gold deposits (which, for example, have been documented in the nearby Alps by Pettke *et al.* 2000). These two classes of deposits vary significantly in terms of their depth of formation, their fluid source, and their tectonic position with respect to the convergent margin.

From: BLUNDELL, D.J., NEUBAUER, F. & VON QUADT, A. (eds) 2002. *The Timing and Location of Major Ore Deposits in an Evolving Orogen*. Geological Society, London, Special Publications, **204**, 69–79.

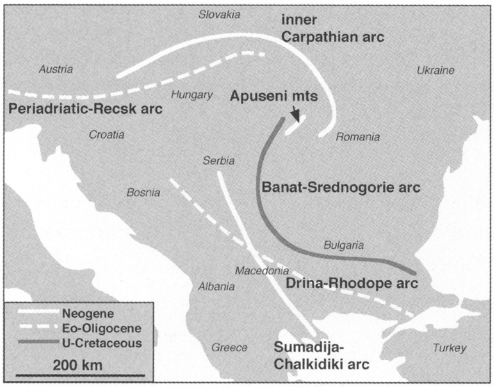

Fig. 1. Post-mid-Cretaceous mineralized volcanic-intrusive belts in the Carpathian–Balkan–Aegean region as presented by Mitchell (1996; after Jankovic 1977).

Magmatic–hydrothermal deposits are commonly associated with a back-arc location, while orogenic gold deposits form at the position of the growing fore-arc (Groves *et al.* 1998). A synthesis of orogenic gold occurrences in the circum-Pacific by Goldfarb *et al.* (2001) summarizes lithosphere-scale scenarios that have resulted in the formation of this class of deposits. Most scenarios involve regional thermal anomalies and extension (Goldfarb *et al.* 2001, fig. 10b–f) in contrast to the traditional view of plate subduction, plate thickening, and formation of a magmatic arc and associated mesothermal deposits (Goldfarb *et al.* 2001, fig. 10a). Despite the marked differences between the two classes of deposits, similar scenarios may have influenced the development of the back-arc, and thus also the formation of the magmatic–hydrothermal deposits.

Together with the presence of regional thermal anomalies and extension during phases of mineralization, the timing of the mineralization has become better constrained, indicating that the mineralizing phases are restricted to narrow time intervals in the convergence process. The refined compilation by Mitchell (1996, following Jankovic 1977, fig. 1) emphasizes that the individual mineralized belts in the Carpathian–Balkan region may have formed within less than 10 million years and indicates the formation of the mineralized belts in SE Europe at latest Cretaceous, Eo-Oligocene, and Neogene times, respectively. It is clear that formation of an entire magmatic belt in a short period of time is in contrast with the continuous consumption of subducted lithosphere and the continuously evolving active margin at the southern edge of Europe associated with over 100 million years of convergence between Africa and Eurasia.

Although academic research and industrially related metal exploration have added substantial data about mineralization in SE Europe in the past decades, two fundamental questions have remained. They form the foundation of the current research, which investigates the potential links between plate-scale geodynamics and mineralization (and forms the backbone of GEODE research).

(1) Why do we observe discrete igneous activity with associated mineralizing events along hundreds of kilometres along the strike of the Tethyan belt, over the past 100 million years?

(2) Why is the mineralization located at a particular place, in a particular geometry (at a particular time)?

In the context of potential plate-scale controls on the mineralization in the Carpathian–Balkan sector of the Alpine–Himalayan chain this paper evaluates relevant geodynamic mechanisms in relationship to the spatial and temporal distributions of the mineralized belts of SE Europe. This paper emphasizes the limits in the timing and duration of various geodynamic mechanisms and highlights their potential contributions (thermally and mechanically) to magmatism, fluid infiltration and extension in the crust. In conclusion, the paper will propose the most likely geodynamic mechanisms that have operated during the formation of the main regional phases of magmatic–hydrothermal mineralization in SE Europe.

Timing: quality, relevance, significance

To examine further the regional crustal features and the geodynamic mechanisms involved, the respective mineralization needs to be placed within the context of the regional tectonic history. A vital factor in this projection is an accurate age determination of the mineralizing event and a temporally well-resolved tectonic history. In principle, the sensitivity of modern age analyses should help to pinpoint any remarkable happening in the evolution of an orogen within a resolution of a few million years. In practice the timing of a combined physical and chemical anomaly like an ore deposit is difficult to establish. To fully appreciate the age information produced it is important to be familiar with the limits of the dating techniques to reduce the potential obscuring effect of misidentified absolute ages. A critical look at dating information shows that, as well as the analytical challenge, three key questions have to be resolved: what is the timing of a specific mineralization, what is the duration of a mineralizing event, and is it possible to identify different stages of mineralization in the same district. The integration of several observations is essential to understand the geological significance of the age information. Ideally this includes temporal information of the mineralization itself (timing of mineralization, timing of host rock deposition, duration of the mineralizing event, duration of associated volcanism, duration of associated hydrothermal activity, spatial variations of temporal information), but also involves information associated with the regional tectonics (e.g. timing of deformation in surrounding basement rocks, timing of basement denudation, timing of basin formation and sedimentation, timing of fault development). To apply the best possible age dataset it is important to have reliable relative age relationships (e.g. to establish overprinting mineralizing events, to discriminate between mineralization which is syn-genetic or epigenetic to the host rock), to appreciate existing age information and carry out strategic absolute age dating, to examine the analytical quality, and to check the geological relevance, before the regional significance can be established (N.B. it is the integration of the above that is currently in progress in the ABCD-GEODE-related Geographical Information System by BRGM http://giseurope.brgm.fr).

The timing of the mineralization in SE Europe has often been derived by interpolation of absolute or stratigraphic ages of host rocks. The most frequently applied age dating techniques do not produce a direct absolute age for the mineralization itself. With the advent of Re–Os dating applied to molybdenite (e.g. Stein *et al.* 1998) or Rb–Sr dating on sphalerite (Nakai *et al.* 1990; Pettke & Diamond 1996), the age information obtained directly for an individual mineral deposit has been greatly improved. Rb–Sr and ^{40}Ar/^{39}Ar isotopic dating techniques consequently help to pinpoint the timing and/or duration of the hydrothermal activity (e.g. Groff *et al.* 1997; Clark *et al.* 1998; Walshaw & Menuge 1998), along with a further refinement of host rock age information (also established by U–Pb dating). The geological relevance of the absolute ages produced is constrained by the effect of post-ore chemical alteration and/or reheating on recrystallization and element diffusion characteristics. Considering this, existing datasets available from K–Ar dating are still applicable for the investigation of the volcanic host-rock deposition, but should be treated with caution when the data are derived from chemically altered samples. The closure temperature ranges of K–Ar, ^{40}Ar/^{39}Ar and Rb–Sr dating allow the investigation of the regional thermal conditions of the crust to project the mineralization and/or host rock in its respective regional crustal environment (e.g. Lips 1998; Lips *et al.* 1998). Re–Os and U–Pb dating are characterized by high closure temperatures and allow the preservation of geologically relevant ages during subsequent thermal disturbances.

Timing of the mineralization in SE Europe

Examining the mineralized belts in SE Europe at Latest Cretaceous, Eo-Oligocene, and Neogene times (Fig. 1) in the light of recently published absolute ages (Fig. 2) shows that they are not equally well resolved. The 12–0.2 Ma Inner Carpathian Arc is best constrained by extensive K–Ar dating programmes (e.g. Pécskay *et al.* 1995*a*, *b*), with mineralization dated around 12–8 Ma (e.g. Lang *et al.* 1994; Kraus *et al.* 1999). K–Ar dating in the Apuseni mountains has indicated the timing of volcanic activity at 15–7 Ma (Pécksay *et al.* 1995*a*; Rosu *et al.* 1997, 2001), whilst the timing of mineralization is poorly constrained by limited 10–11 Ma ^{40}Ar/^{39}Ar laserprobe data on the Valea Morii porphyry alteration (Lips, unpublished). The 25–20 Ma Sumadija–Chalkidiki belt is only constrained in considerable detail at the Kassandra mining area in Greece (Gilg & Frei 1994). The 36–27 Ma Periadriatic–Recsk belt has been confined to a limited extent (e.g.von Blankenburg & Davies 1995) and younger volcanic rocks have been reported along strike (e.g. Pamic & Pécskay 1996). The 40–30 Ma Drina–Rhodope Belt is fairly well constrained in its Bulgarian part (e.g. Harkovska *et al.* 1989; Pécskay *et al.* 1992), and benefits from recent dating campaigns (e.g. Marchev & Singer 1999; Marchev *et al.* 2000). Its extension into Macedonia and Serbia has virtually

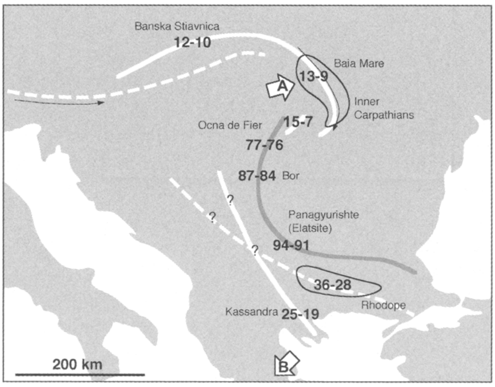

Fig. 2. Recently published absolute age datasets related to ore districts projected on the compilation by Mitchell (1996). Regional dating studies in the Inner Carpathian and Rhodopian domains are indicated by area outlines. White arrows indicate (outward) migration directions of the overriding plate of the subduction systems (A, Carpathian; B, Aegean). Black arrows along the Periadriatic and Inner Carpathian arcs indicate proposed propagation directions of detaching slabs.

no absolute age information. The Banat–Srednogorie arc has been ascribed to the Upper Cretaceous based on limited absolute age information (e.g. see references in *Berza et al.* 1998). Recently obtained age information suggests an heterogeneous set of ages along the arc, as indicated by 76–77 Ma U–Pb and Re–Os ages obtained from SW Romania (Ciobanu *et al.* 2000), by 84–87 Ma ^{40}Ar/^{39}Ar ages (Lips *et al.* unpublished) and similar to slightly younger K–Ar ages (Banjesevic *et al.* 2001) from Serbia, and by 91–94 Ma U–Pb ages from western Bulgaria (von Quadt *et al.* 2001). The above information shows the necessity of an extensive compilation of all the absolute age information produced, along with continued strategic dating campaigns.

In summary (Fig. 2), the main phases of magmatism and associated mineralization are temporally best constrained at 95–75 Ma (Banat–Srednogorie), 40–30 Ma (Rhodope), 25–20 Ma (Chalkidiki), and 12–8 Ma (Inner Carpathians). In addition to the periods during which the main phases of mineralization occurred, numerous studies have reported shifts in age of emplacement and chemical characteristics of the magmatism or have related the role of extension to the onset of magmatic activity in the region (e.g. Jones *et al.* 1992; Seyitoglu & Scott 1992; Pirajno 1995; Karamata *et al.* 1997; Berza *et al.* 1998; Rosu *et al.* 2001).

Geodynamic settings

With the periods of mineralization established in the previous section, it is now appropriate to consider the tectono-magmatic evolution of the respective regions during the relevant time periods, in order to determine the geodynamic mechanisms that might have operated. Originally the mechanisms have been put forward as lithosphere-scale causes of extension in the crust and/or the magmatism. In principle, they may have had a control on the timing of the mineralization. This approach aims to identify the geodynamic mechanisms involved in the development of the Carpathian–Balkan region in the past hundred million years, as follows.

Subduction

Classically, the primary process of subduction has been taken to cause the back-arc magmatism and associated mineralization. Examination of the existing dataset on the African–Eurasian convergence (Müller & Roest 1992, fig. 3) shows that for about the past 100 million years convergence between the African and Eurasian plates was active at variable rates, but was slow compared with e.g. Pacific convergence rates. The present Aegean subducting slab appears to be the most western part of the Neo-Tethys subduction (e.g. Wortel & Spakman 2000), as seismic tomography studies have illustrated the long history of northward subduction of lithosphere at the southern margin of Europe (Spakman *et al.* 1988). The Carpathian subduction system appears to be of a similar age (e.g.Wortel & Spakman 2000).

Initiation of back-arc volcanism may have followed the onset of Africa–Eurasia with a time lag of several million years. Based on normal convergence at a constant rate of 20 km Ma^{-1} and a subduction angle of 45°, there is a time lag of more than 7 million years after subduction was initiated before the subducting slab reaches a depth of *c.* 100 km and enters the magma generation window (after Mason *et al.* 1998). This time lag would be greater when subduction is slower, or is oblique to the subduction zone and/or when the angle of subduction is smaller. Calculation shows that although northward subduction commenced around 100 Ma, the associated back-arc volcanism may have initiated since 90 Ma.

Roll-back

A review of the Tertiary subduction history in the Mediterranean and Carpathian region (Wortel & Spakman 2000) concludes that roll-back of subducted lithosphere, set by the Africa–Eurasian convergence, is a primary geodynamic mechanism which has shaped the present-day configuration. It operated from *c.* 30 Ma to the present in the Carpathian and Aegean arcs (e.g. see references in Wortel & Spakman 2000). In detail the Africa–Eurasia convergence rates (Fig. 3) show an alternation of phases of extremely slow convergence (i.e. 6–8 km Ma^{-1}) and relatively faster convergence (i.e. 15–20 km Ma^{-1}) in variable directions. The two phases of extremely slow convergence are identified for the periods around 20–0 Ma, and 75–55 Ma. During the past 30 million years, oceanic lithosphere in the subducting slab has been old (and cold) enough to promote roll-back of the slab (Fig. 4; Royden 1993) and, as a consequence, accentuate the curvature of the arc (Wortel & Spakman 2000). A similar process affecting the region in the 75–55 Ma period is still questionable as the subducted oceanic lithosphere was younger, and thus less dense, at that time and there is no direct evidence from seismic tomography. When roll-back occurs it will enhance extension in the back-arc of the overriding plate and allow upwelling of asthenosphere to shallow mantle levels (becoming a potential source of heat driving melting in the lithosphere),

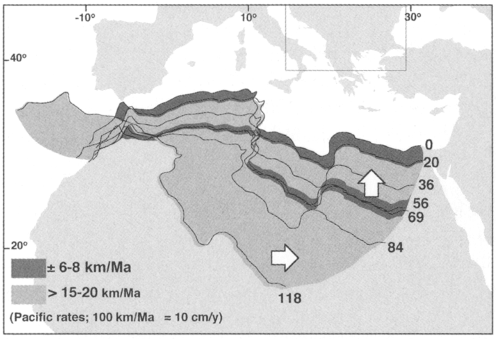

Fig. 3. Summary of overall convergence rates of African and Eurasian plates projected on the present-day outline of Europe and Africa (data extrapolated from Müller & Roest 1992), indicating varying convergence directions and two episodes of slow convergence (*c.* 75–55 Ma and post-20 Ma), alternating with episodes of slightly faster convergence (pre *c.* 75 Ma and *c.* 55–20 Ma). Square in upper part of figure indicates the region considered in this paper.

at which it may induce asthenosphere-dominated magmatism.

Critical wedges

Another process related to plate convergence is caused by associated changes in internal friction of the active margin wedge (based on critical wedge theories of Davis *et al.* 1983 and Dahlen 1990). Drastic changes in the convergence rates, and thus in internal friction of the wedge, can affect the potential energy distribution in the orogenic wedge at the margin of the overriding plate. Faster convergence, causing an increase in friction, leads to a narrower and thicker orogenic wedge. Similarly, when the internal friction in an orogenic wedge is lowered, or lost, the wedge will force the redistribution of material to restore its wider and flatter critical wedge geometry. Such a process has been identified for the 15–5 Ma period in the East Carpathians, where rapid morphological and tectonic changes in the orogenic wedge may be directly related to roll-back (Sanders 1998; Sanders *et al.* 1999). A similar process, but preceding the roll-back, has been interpreted for the Aegean arc (Lips 1998) with the transformation from a high friction wedge to a low friction wedge geometry at *c.* 45 Ma. The additional interaction with the roll-back has caused an accelerated back-arc extension and allowed collapse of the Rhodope region in the internal parts of the orogen (Figs 5 and 6; Lips 1998; Lips *et al.* 2000). It is emphasized that the above scenario is seen as a crustal process, rather than a process operating at the scale of the whole lithosphere, when evaporite horizons are involved as the decollement-forming lithology. Deep-seated low-friction lithologies (e.g. at the base of the crust) may introduce the whole lithosphere to the restoration process. Its potential role in the formation of mineralization is expected in the combined extension and fluid infiltration in the rear of the wedge, generated at elevated thermal gradients.

Collapse and slab detachment

The terminal collapse of an orogen is classically interpreted to occur following the removal of the thickened lithospheric root of the orogen (Platt &

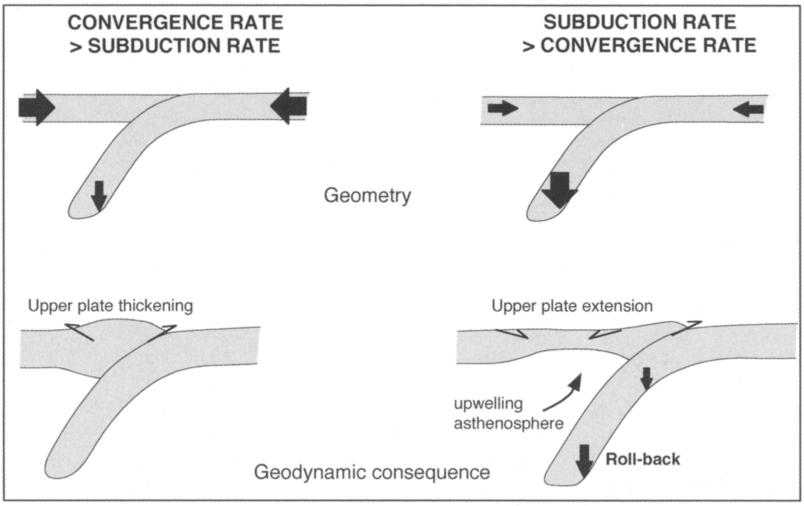

Fig. 4. The concept of roll-back (Royden 1993).

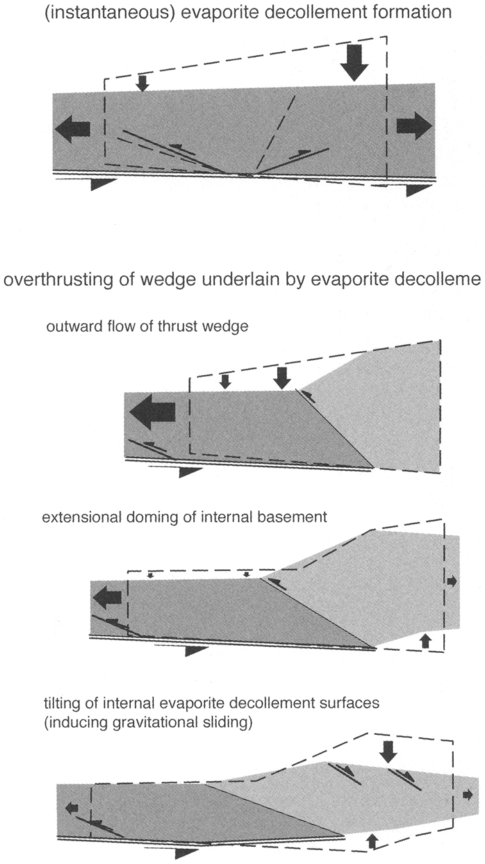

Fig. 5. Schematic representation of the development of a wedge after initiation of a decollement fault in evaporites (double lines in basal fault zone), based on the theoretical critical taper geometries in a non-cohesive wedge as proposed by Davis *et al.* (1983) and Dahlen (1990). Top figure; restoration of the wedge geometry after instantaneous evaporite decollement formation and transformation of a high friction decollement (narrow and high wedge; dashed outline) to a state when the basal decollement experiences no friction (wide and flat wedge). (based on Mohr diagrams of the basal state of effective stress). Lower three figures represent a schematized plausible scenario for the evolution of the Aegean orogenic wedge; restoration of the wedge geometry after accretion of material overlying an evaporite decollement, resulting in internal doming of overthrust material by outward escape of the wedge, and continuing doming and associated tilting of the decollement horizon, which will initiate further gravitational sliding along the decollement.

England 1993). One mechanism for doing this is the process of slab detachment (Wortel & Spakman 1992, 2000). This final state in the subduction history is achieved when tearing of the subducted slab is initiated. This most probably occurs at the point when continental lithosphere in the upper plate reaches the trench and starts to get subducted, following behind denser, stronger oceanic lithosphere or, alternatively, when subduction becomes stagnant (e.g. von Blanckenburg & Davies 1995; Wong a Ton & Wortel 1997; van de Zedde & Wortel 2001). Lateral migration of a tear in a subducted slab along the strike of the subduction zone can enhance slab roll-back and arc migration where the slab is not yet detached, initiate orogenic collapse, and change the signatures of arc volcanism. In the region it has been interpreted to operate along the Periadriatic Lineament from *c.* 45–40 Ma (von Blanckenburg & Davies 1995) and in the Carpathians from 15 Ma onwards (Mason *et al.* 1998), whilst in the Hellenic arc it may be very young (Pliocene) or absent (Wortel & Spakman 2000 and references therein). Slab detachment has been proposed as a possible mechanism involved in the formation of the Neogene mineralized belt (Fig. 7; de Boorder *et al.* 1998). It is very well constrained by independent studies in the inner Carpathian arc (e.g. Mason *et al.* 1998; Nemcok *et al.* 1998), but is not constrained for the Sumadija–Chalkidiki belt. Berza *et al.* (1998) inferred slab detachment to have occurred during the formation of the Banat–Srednogorie arc, although the regional operation of this mechanism in Late Cretaceous times has not been substantiated. A phase of lithospheric delamination is currently considered as likely to have controlled the formation of the Eo-Oligocene mineralized Rhodope belt (Marchev pers. comm.).

Roll-back and detachment: (transient) sources of heat and extension

The above mechanisms have different thermal and mechanical effects, in space and time, on the crust. These differences allow a first order discrimination between the regional scale sources of heat and extension. In both the cases of roll-back and slab detachment, cold mantle lithosphere is replaced by hot mantle asthenosphere and the thermo-mechanical effect on the crust may appear more or less similar. The two processes may differ considerably in their temporal and spatial characteristics. In the case of slab roll-back, the asthenosphere associated source of heat may cover a broad zone parallel to the subduction zone, theoretically migrating over time towards the subduction trench (e.g. Sillitoe 1991) with the induced volcanism following a similar pattern (e.g. Tatsumi *et al.* 1989). Related to the laterally migrating tear in a subducted slab, other heterogeneities in the

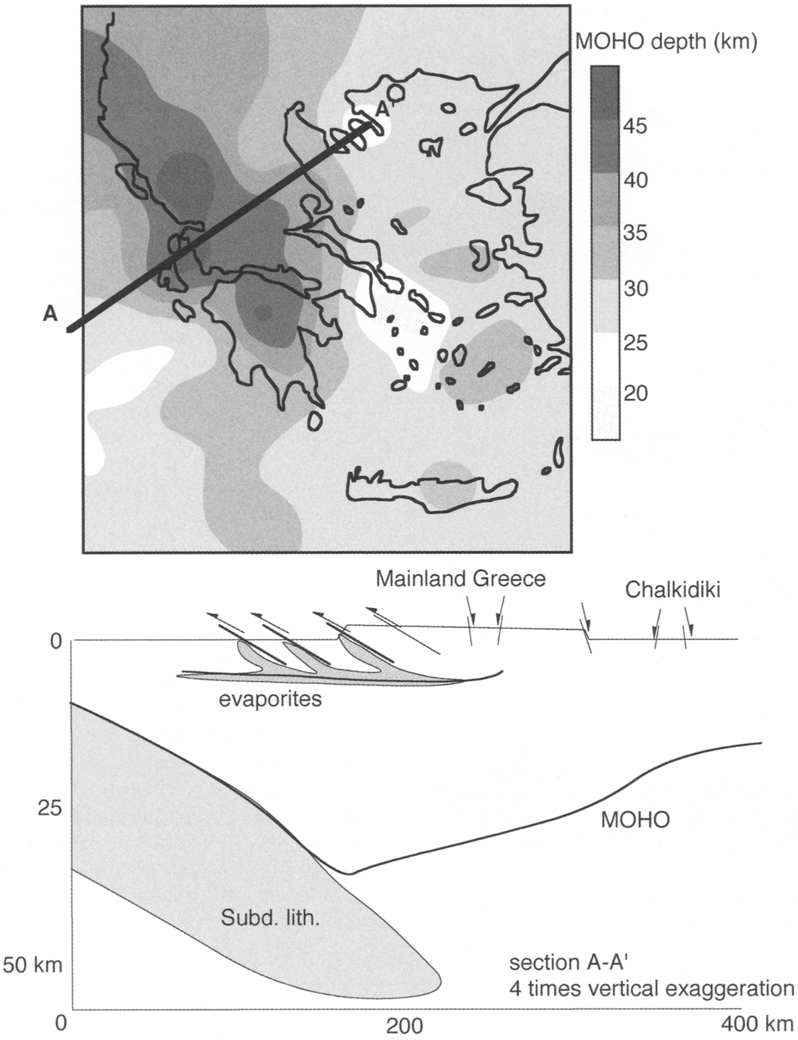

Fig. 6. Present-day configuration of Moho depth in the Aegean system (after Tsokas & Hansen 1997) and cross-section across the Greek mainland, indicating elevated Moho levels in the Aegean back-arc system, initiated by lithospheric delamination or wedge restoration and subsequent roll-back.

subducted lithosphere may become the locus of a rupture generating space for upwelling asthenosphere. The orientation of these ruptures or 'windows' with respect to the subduction direction and their opening/widening characteristics will be reflected in temporal and spatial variations while convergence continued (e.g. Thorkelson & Taylor 1989). Such 'windows' have been recognized in recent studies and have been temporally and genetically associated with back-arc extension, mafic, alkalic, volcanism (Hole *et al.* 1991), migration of igneous activities (Terakado & Nohda 1993), and with different classes of mineralization (Haeussler *et al.* 1995; Goldfarb *et al.* 1998; de Boorder *et al.* 1999; Goldfarb *et al.* 2001).

The lateral detachment of subducted lithosphere as proposed for the Balkan–Carpathian region is likely to have generated a point source of heat propagating with the direction of tearing parallel to the subduction zone (e.g.von Blanckenburg & Davies 1995;Wortel & Spakman 2000). The best recognized example in the region, in the Inner Carpathians, shows the generation of volcanism in the overriding plate with increasing mantle affinities, propagating over 150 km in 10 Ma and affecting individual locations over 2–4 Ma

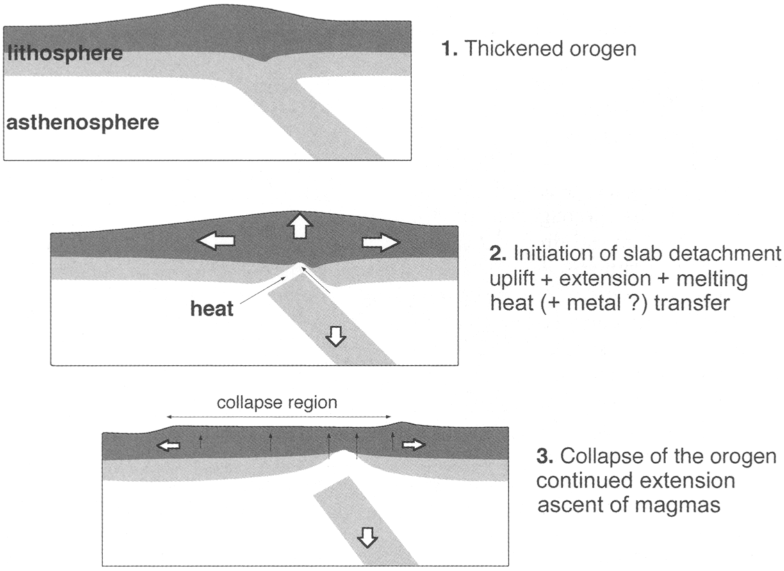

Fig. 7. The hypothetical role of orogenic collapse by slab detachment in the formation of ore deposits (de Boorder *et al.* 1998).

(Mason *et al.* 1998). The thermal implication of shallow slab detachment has been further investigated by van de Zedde & Wortel (2001) and shows that a transient thermal anomaly is created with a temperature increase in the overlying material up to 500 °C, as the rising asthenosphere fills the gap created by the sinking slab. The resulting pulse of heat allows for partial melting of the asthenosphere and the remaining metasomatized lithosphere for several million years.

Conclusions

In summary, the following geodynamic scenarios are proposed for the respective mineralized belts.

The Banat–Srednogorie belt appears to have been generated by subduction related magmatism (as traditionally proposed) that followed the onset of Africa–Eurasia convergence since *c.* 110 Ma. The relatively low convergence rates caused a time-lag of 10–20 million years before the melting process was initiated. Variations in convergence directions with respect to the geometry of the active margin may have caused the temporal variation in the magmatism (and mineralization), resulting in the occurrence of 95–90 Ma, 85–90 Ma and 75–80 Ma systems in the west Bulgarian (Panagyurishte), east Serbian (Bor) and SW Romanian (Ocna de Fier) parts of the belt, respectively. It is unlikely that the system was affected by detachment of the subducted slab at that time (e.g. Berza *et al.* 1998), as the relatively low density of the young slab proposed, and its limited length, would have offered unfavourable conditions.

The Rhodope mineralized province was most probably controlled by gravitational collapse produced by lithospheric delamination (Marchev pers comm), or by the reconfiguration of the accretionary wedge after the loss of internal friction in its frontal parts (Lips 1998). The spatial and temporal characteristics of both scenarios suggest the introduction of a regional heat source over an area with an unknown geometry. Based on the above scenarios the identification of the Drina–Rhodope arc is premature and a regional extension of the Rhodope province into former Yugoslavia and into Turkey is still unfounded and requires further attention.

The Adriatic–Recsk belt appears to have been controlled by slab detachment following Alpine subduction as proposed by von Blanckenburg & Davies (1995). Although the propagation direction of the heat source from west to east is plausible, the exact timing and propagation rate are not resolved by the geochronological dataset. Further constraints on the timing and localization of individual mineral occurrences requires an improved temporal resolution of the geodynamic process.

The Chalkidiki region suffered from progressive collapse of the Aegean orogenic wedge (Lips 1998), assisted by roll-back of the subducted lithosphere. This initiated around 25–20 Ma and produced extension, magmatism, and mineralization in the rear of the orogenic wedge. Further extension towards the north(west) and (south)east may not concern a single belt but a wide region, trending roughly parallel to the regional outcrop patterns, as the Miocene–Recent collapse has affected the whole region extensively.

Detachment of the subducted slab is the most plausible scenario for magma generation in the Inner Carpathians and the propagation of the magma source from NW to SE from 12 Ma to 0.2 Ma. In the Inner Carpathians it is best constrained by independent studies and techniques. The timing of the mineralization is however still remarkable and its generation should remain under further consideration as the main ore districts (e.g. Banska Stiavnica and Baia Mare) were produced in the same time interval around 12–10 Ma. Also little mineralization appears to be associated with the 10–0 Ma history of the detachment process.

The evolution of the Apuseni Mountains may be partially considered together with the Inner Carpathians as it may well represent a fragment of the proto-Carpathians that has become dismembered by detachment and enhanced roll-back of the southeastern portion of the Carpathian subducted slab. The dominant phase of magmatism and associated mineralization may be similar to the 13–9 Ma mineralized belt of the Inner Carpathians. Supported by the palaeomagnetic and geochemical results of the Apuseni (Rosu *et al.* 2001) and of the Inner Carpathians (Mason *et al.* 1998) it is speculated that a synchronous formation of the mineralization across the Carpathians is controlled by the timing of a regional fragmentation of the crust. The fragmentation may have occurred when the overriding lithosphere responded to a combined ENE-directed roll-back and a gradual SE-directed detachment of the subducted lithosphere. The process caused the development of the present geometry of the Carpathians, thinning of the lithosphere, the dismembering of existing crustal fragments, and magma ascent along the dominant crustal fractures. A careful restoration of the crust and mantle lithosphere around the Carpathians at 13–9 Ma is required to further examine this speculation.

The investigations reported here were supported by the Vening Meinesz Research School of Geodynamics (VMSG). Discussion with Paul Mason, Hugo de Boorder, Rinus Wortel, Stan White and Derek Blundell, and reviews by Wolfgang Frisch and Kurt Stüwe on a previous version have been appreciated. Critical comments from reviews by Thomas Pettke and Robert Handler have helped to improve the manuscript.

References

Banjesevic, M., Cocic, S. & Radovic, M. 2001. Petrology and K/Ar ages of volcanic rocks for widen Bor zone as the part of the Timok magmatic complex (east Serbia). *In: Abstracts of ABCD-GEODE workshop, Vata Bai Romania, Romanian Journal of Mineral Deposits*, **79**, 39–40.

Berza, T., Constantinescu, E. & Vlad, S.-N. 1998. Upper Cretaceous magmatic series and associated mineralzation in the Carpathian-Balkan Orogen. *Resource Geology*, **48**, 291–306.

Ciobanu, C.L., Stein, H. & Cook, N.J. 2000. A Re-Os age for molybdenite, Dognecea skarn deposit, Banat, Romania. *Abstracts of ABCD-GEODE workshop, Borovets Bulgaria*, 19.

Clark, A.H., Archibald, D.A., Lee, A.W., Farrar, E. & Hodgson, C.J. 1998. Laser probe ^{40}Ar/^{39}Ar ages of early- and late-stage alteration assemblages, Rosario porphyry copper-molybdenum deposit, Collahuasi district, I Region, Chile. *Economic Geology*, **93**, 326–337.

Dahlen, F.A. 1990. Critical taper models of fold-and-thrust belts and accretionary wedges. *Annual Review Earth and Planetary Science*, **18**, 55–99.

Davis, D., Suppe, J. & Dahlen, F.A. 1983. Mechanics of fold-and-thrust belts and accretionary wedges. *Journal of Geophysical Research*, **88**, 1153–1172.

de Boorder, H., Spakman, W., White, S.H. & Wortel, M.J.R. 1998. Late Cenozoic mineralisation, orogenic collapse and slab detachment in the European Alpine Belt. *Earth and Planetary Science Letters*, **164**, 569–575.

de Boorder, H., Spakman, W., White, S.H., Lips, A.L.W., Wortel, M.J.R. & Kronemeijer, W.M. 1999. Late orogenic mineralization: tomography and geodynamic setting. *In:* Stanley, C.J. *et al.* (eds) *Mineral Deposits: Processes to Processing*. Balkema, Rotterdam, 1305–1306.

Dixon, C.J. & Pereira, J. 1974. Plate tectonics and mineralization in the Tethyan region. *Mineralium Deposita*, **9**, 185–198.

Gilg, H.A. & Frei, R. 1994. Chronology of magmatism and mineralization in the Kassandra mining area, Greece: the potentials and limitations of dating hydrothermal illites. *Geochimica et Cosmochimica Acta*, **58**, 2107–2122.

Goldfarb, R.J., Phillips, G.N. & Nokleberg, W.J. 1998. Tectonic setting of synorogenic gold deposits of the Pacific Rim. *Ore Geology Reviews*, **13**, 185–218.

Goldfarb, R.J., Groves, D.I. & Gardoll, S. 2001. Orogenic gold and geological time: a global synthesis. *Ore Geology Reviews*, **18**, 1–75.

Groff, J.A., Heitzler, M.T., McIntosh, W.C. & Norman, D.I. 1997. 40Ar/39Ar dating and mineral paragenesis for Carlin-type gold deposits along the Getchell trend, Nevada: Evidence for Cretaceous and Tertiary gold mineralization. *Economic Geology*, **92**, 601–622.

Groves, D.I., Goldfarb, R.J., Gebre-Mariam, M., Hagemann, S.G. & Robert, F. 1998. Orogenic gold deposits: a proposed classification in the context of their crustal distribution and relationship to other gold deposit types. *Ore Geology Reviews*, **13**, 7–27.

Haeussler, P.J., Bradley, D., Goldfarb, R.J., Snee, L. & Taylor, C. 1995. Link between ridge subduction and gold mineralization in southern Alaska. *Geology*, **23**, 995–998.

HARKOVSKA, A., YANEV, Y. & MARCHEV, P. 1989. General features of the Paleogene orogenic magmatism in Bulgaria. *Geologica Balcanica*, **19**, 37–72.

HOLE, M.J., ROGERS, G., SAUNDERS, A.D. & STOREY, M. 1991. Relation between alkalic volcanism and slab-window formation. *Geology*, **19**, 657–660.

IZAWA, E. & URASHIMA, Y. 1988. Quaternary gold mineralization and its geological environment in Kyushu, Japan. *In: Bicentennial gold, Geological Society Australia Abstracts*, **22**, 177–182.

JANKOVIC, S. 1977. The copper deposits and geotectonic setting of the Tethyan Eurasian metallogenic belt. *Mineralium Deposita*, **12**, 37–47.

JANKOVIC, S. 1997. The Carpatho-Balkanides and adjacent area: a sector of the Tethyan Eurasian metalogenic belt. *Mineralium Deposita*, **32**, 426–433.

JONES, C.E., TARNEY, J., BAKER, J.H. & GEROUKI, F. 1992. Tertiary granitoids of Rhodope, northern Greece: magmatism related to extensional collapse of the Hellenic Orogen? *Tectonophysics*, **210**, 295–314.

KARAMATA, S., KNEZEVIC, V., PÉCKSAY, Z. & DJORDJEVIC, M. 1997. Magmatism and metallogeny of the Ridanj-Krepoljin belt (eastern Serbia) and their correlation with northern and eastern analogues. *Mineralium Deposita*, **32**, 452–458.

KRAUS, I., CHERNYSHEV, I.V., SUCHA, V., KOVALENKER, V.A., LEBEDEV, V.A. & SAMAJOVA, E. 1999. Use of illite for K/Ar dating of hydrothermal precious and base metal mineralization in central Slovak Neogene volcanic rocks. *Geologica Carpathica*, **50**, 353–364.

LANG, B., EDELSTEIN, O., STEINITZ, G., KOVACS, M. & HALGA, S. 1994. Ar-Ar dating of adularia - A tool in understanding relations between volcanism and mineralization: Baia Mare area (Gutii Mountains) Northwestern Romania. *Economic Geology*, **89**, 174–180.

LIPS, A.L.W. 1998. Temporal constraints on the kinematics of the destabilization of an orogen; syn- to post-orogenic extensional collapse of the Northern Aegean region. *Geologica Ultraiectina*, **166**, 1–224.

LIPS, A.L.W., WHITE, S.H. & WIJBRANS, J.R. 1998. 40Ar/39Ar laserprobe direct dating of discrete deformational events, a continuous record of Early Alpine tectonics in the Pelagonian Zone, NW Aegean area, Greece. *Tectonophysics*, **298**, 133–153.

LIPS, A.L.W., WHITE, S.H. & WIJBRANS, J.R. 2000. Middle-Late Alpine thermotectonic evolution of the southern Rhodope Massif, Greece. *Geodynamica Acta*, **13**, 281–292.

MARCHEV, P. & SINGER, B. 1999. Timing of magmatism, alteration-mineralization, and caldera evolution in the Spahievo ore field, Bulgaria, from laser-fusion 40Ar/39Ar dating. *In:* STANLEY, C.J. ET AL (eds) *Mineral Deposits: Processes to Processing*. Balkema, Rotterdam, 1271–1274.

MARCHEV, P., RAICHEVA, R., SINGER, B., DOWNES, H., AMOV, B. & MORITZ, R. 2000. Isotopic evidence for the origin of Palaeogene magmatism and epithermal ore deposits of the Rhodope Massif. *In: Abstracts of ABCD-GEODE workshop, Borovets Bulgaria*, 47.

MASON, P.R.D., SEGHEDI, I., SZÁKACS, A. & DOWNES, H. 1998. Magmatic constraints on geodynamic models of subduction in the East Carpathians, Romania. *Tectonophysics*, **297**, 157–176.

MITCHELL, A.H.G. 1992. Andesitic arcs, epithermal gold and porphyry-type mineralization in the western Pacific and eastern Europe. *Institution of Mining and Metallurgy Transactions*, **B101**, 125–138.

MITCHELL, A.H.G. 1996. Distribution and genesis of some epizonal Zn-Pb and Au provinces in the Carpathian-Balkan region. *Institution of Mining and Metallurgy Transactions*, **B105**, 127–138.

MITCHELL, A.H.G. & CARLILE, J.C. 1994. Mineralization, antiforms and crustal extension in andesitic arcs. *Geological Magazine*, **131**, 231–242.

MITCHELL, A.H.G. & GARSON, M.S. 1972. Relationship of porphyry copper and circum-Pacific tin deposits to palaeo-Benioff zones. *Institution of Mining and Metallurgy Transactions*, **B81**, 10–25.

MÜLLER, R.D. & ROEST, W.K. 1992. Fracture zones from combined Geosat and Seasat data. *Journal of Geophysical Research*, **97**, 3337–3350.

NAKAI, S., HALLIDAY, A.N., KESLER, S.E. & JONES, H.D. 1990. Rb-Sr dating of sphalerites from Tennessee and the genesis of Mississippi Valley type ore deposits. *Nature*, **346**, 354–357.

NEMCOK, M., POSPISIL, L., LEXA, J. & DONELICK, R.A. 1998. Tertiary subduction and slab break-off model of the Carpathian-Pannonian region. *Tectonophysics*, **295**, 307–340.

PAMIC, J. & PÉCSKAY, Z. 1996. Geological and K-Ar ages of Tertiary volcanic formations from the southern part of the Pannonian Basin in Croatia - based on surface and subsurface data. *Nafta*, **47**, 195–202.

PÉCSKAY, Z., BALOGH, K. & HARKOVSKA, A. 1992. K-Ar dating of the Perelik volcanic massif (central Rhodopes, Bulgaria) . *Acta Geologica Hungarica*, **34**, 101–110.

PÉCSKAY, Z., LEXA, J., SZAKÁCS, A., BALOGH, K., SEGHEDI, I., KONECNY, V., KOVACS, M., MARTON, E., KALICIAK, M., SZEKY-FUX, V., POKA, T., GYARMATI, P., EDELSTEIN, O., ROSU, E. & ZEC, B. 1995*a*. Space and time distribution of Neogene-Quaternary volcanism in the Carpatho-Pannonian region. *Acta Vulcanologica*, **7**, 15–28.

PÉCSKAY, Z., EDELSTEIN, O., SEGHEDI, I., SZAKÁCS, A., KOVACS, M., CRIHAN, M. & BERNAD, A. 1995*b*. Recent K-Ar datings of Neogene-Quaternary calc-alkaline volcanic rocks in Romania. *Acta Vulcanologica*, **7**, 53–61.

PEREIRA, J. & DIXON, C.J. 1971. Mineralization and plate tectonics. *Mineralium Deposita*, **6**, 404–405.

PETTKE, T. & DIAMOND, L.W. 1996. Rb-Sr dating of sphalerite based on fluid inclusion-host mineral isochrons: a clarification why it works. *Economic Geology*, **91**, 951–956.

PETTKE, T., DIAMOND, L.W. & KRAMERS, J.D. 2000. Mesothermal gold lodes in the north-western Alps: a review of genetic constraints from radiogenic isotopes. *European Journal of Mineralogy*, **12**, 213–230.

PIRAJNO, F. 1995. Volcanic-hosted epithermal systems in northwest Turkey. *South African Journal of Geology*, **98**, 13–24.

Platt, J.P. & England, P.C. 1993. Convective removal of lithosphere beneath mountain belts: thermal and mechanical consequences. *American Journal of Science*, **293**, 307–336.

Rosu, E., Pécskay, Z., Stefan, A., Popescu, G., Panaiotu, C. & Panaiotu, C.E. 1997. The evolution of the Neogene volcanism in the Apuseni Mountains (Rumania): constraints from new K-Ar data. *Geologica Carpathica*, **48**, 353–359.

Rosu, E., Szakacs, A., Downes, H., Seghedi, I., Pécskay, Z. & Panaiotu, C. 2001. The origin of Neogene calc-alkaline and alkaline magmas in the Apuseni Mountains, Romania: the adakite connection. *Romanian Journal of Mineral Deposits*, **79**, 3–23.

Royden, L.H. 1993. Evolution of retreating subduction boundaries formed during continental collision. *Tectonics*, **12**, 629–638.

Sanders, C.A.E. 1998. *Tectonics and erosion; Competitive forces in a compressive orogen - A fission track study of the Romanian Carpathians*. PhD thesis, Vrije Universiteit Amsterdam.

Sanders, C.A.E., Andriessen, P.A.M. & Cloetingh, S.A.P.L. 1999. Life cycle of the East Carpathian orogen: Erosion history of a doubly vergent critical wedge assessed by fission track thermochronology. *Journal of Geophysical Research*, **104**, 29095–29112.

Seyitoglu, G. & Scott, B.C. 1992. Late Cenozoic volcanic evolution of the northeastern Aegean region. *Journal of Volcanological and Geothermal Research*, **54**, 157–176.

Sillitoe, R.H. 1972a. Formation of certain massive sulphide deposits at sites of sea-floor spreading. *Institution of Mining and Metallurgy Transactions*, **B81**, 141–148.

Sillitoe, R.H. 1972b. A plate tectonic model for the origin of porphyry copper deposits. *Economic Geology*, **67**, 184–197.

Sillitoe, R.H. 1991. Gold metallogeny of Chile - an introduction. *Economic Geology*, **86**, 1187–1205.

Spakman, W., Wortel, M.J.R. & Vlaar, N. 1988. The Hellenic subduction zone: a tomographic image and its geodynamic implications. *Geophysical Research Letters*, **15**, 60–63.

Stein, H.J., Morgan, J.W., Markey, R.J. & Hannah, J.L. 1998. An introduction to Re-Os - what's in it for the mineral industry? *SEG Newsletter*, **32**, 7–15.

Tatsumi, Y., Otofuji, Y., Matsuda, T. & Nohda, S. 1989. Opening of the Sea of Japan back-arc basin by asthenospheric injection. *Tectonophysics*, **166**, 317–329.

Terakado, Y. & Nohda, S. 1993. Rb-Sr dating of acidic rocks from the middle part of the Inner Zone of southwst Japan: tectonic implications for the migration of the Cretaceous to Paleogene igneous activity. *Chemical Geology*, **109**, 69–87.

Thorkelson, D.J. & Taylor, R.P. 1989. Cordilleran slab windows. *Geology*, **17**, 833–836.

Tsokas, G.N. & Hansen, R.O. 1997. Study of the crustal thickness and the subducting lithosphere in Greece from gravity data. *Journal of Geophysical Research*, **102**, 20585–20597.

von Blanckenburg, F. & Davies, J.H. 1995. Slab break-off: A model for syncollisional magmatism and tectonics in the Alps. *Tectonics*, **14**, 120–131.

van de Zedde, D.M.A. & Wortel, M.J.R. 2001. Shallow slab detachment as a transient source of heat at midlithospheric depths. *Tectonics*, **20**, 868–882.

von Quadt, A., Peycheva, I. & Kamenov, B. 2001. The Elatsite porphyry copper metal deposit of the Panagyurishte corridor, Srednogorie zone, Bulgaria: U-Pb zircon and isotopic investigations for timing and ore genesis. *Journal of Conference Abstracts*, **6**, 000–001.

Walshaw, R.D. & Menuge, J.F. 1998. Dating crustal fluid flow by the Rb-Sr isotopic analysis of sphalerite: a review. *In:* Parnell, J. (ed.) *Dating and duration of fluid flow and fluid-rock interaction*. Geological Society, London, Special Publications, **144**, 137–143.

Wong a Ton, S.Y.M. & Wortel, M.J.R. 1997. Slab detachment in continental collision zones; an analysis of controlling parameters. *Geophysical Research Letters*, **24**, 2095–2098.

Wortel, M.J.R. & Spakman, W. 1992. Structure and dynamics of subducted lithosphere in the Mediterranean region. *Proceedings of the Koninklijke Nederlandse Akademie voor Wetenschappen*, **95**, 325–347.

Wortel, M.J.R. & Spakman, W. 2000. Subduction and slab detachment in the Mediterranean–Carpathian region. *Science*, **290**, 1910–1917.