Mineralium Deposita (2002) 37: 541–567
DOI 10.1007/s00126-002-0272-9

ARTICLE

Cristiana L. Ciobanu · Nigel J. Cook · Holly Stein

Regional setting and geochronology of the Late Cretaceous Banatitic Magmatic and Metallogenetic Belt

Received: 7 November 2001 / Accepted: 18 January 2002 / Published online: 8 May 2002

Abstract The 1,500-km-long Banatitic Magmatic and Metallogenetic Belt (BMMB) of Romania, Serbia and Bulgaria is a complex calc-alkaline magmatic arc of Late Cretaceous age. It hosts a variety of magmatic-hydrothermal Cu, Au, Mo, Zn, Pb and Fe deposits, including Europe's only world-class porphyry-copper deposits. Regional metallogeny can be linked to subduction of the Vardar Ocean during the Late Cretaceous, as part of the closure of the Neotethys Ocean that had separated Europe and Africa in the Mesozoic. Porphyry Cu–(Au)–(Mo) and intimately associated epithermal massive sulphides dominate in the central segments of the belt in southernmost Banat (Romania), Serbia and north-west Bulgaria. These districts are the economically most important today, including major active Cu–Au mines at Moldova Nouă in Romania, Majdanpek, Veliki Krivelj and Bor in Serbia, and Elatsite, Assarel and Chelopech in Bulgaria. More numerous (and mostly mined in the past) are Fe, Cu and Zn–Pb skarns, which occur mainly at the two ends of the belt, in Eastern Bulgaria and in Romania. This paper summarises some of the deposit characteristics within the geodynamic framework of terminal Vardar subduction. Heterogeneous terranes of the belt, including the Apuseni Mountains at the western end, are aligned parallel to the Vardar front following continental collision of the Dacia and Tisza blocks. All available geochronological data (numerous K–Ar and some U–Pb and Re–Os ages) are compiled, and are complemented by a new high-precision Re–Os date for the Dognecea skarn deposit, south-west Romania (76.6 ± 0.3 Ma). These data indicate that magmatism extended over at least 25 million years, from about 90 to 65 Ma in each segment of the belt. Within Apuseni Mountains and Banat, where magma emplacement was related to syn-collisional extension in the orogenic belt of Carpathians, ore formation seems to be restricted in time and maybe constrained by a shared tectonic event.

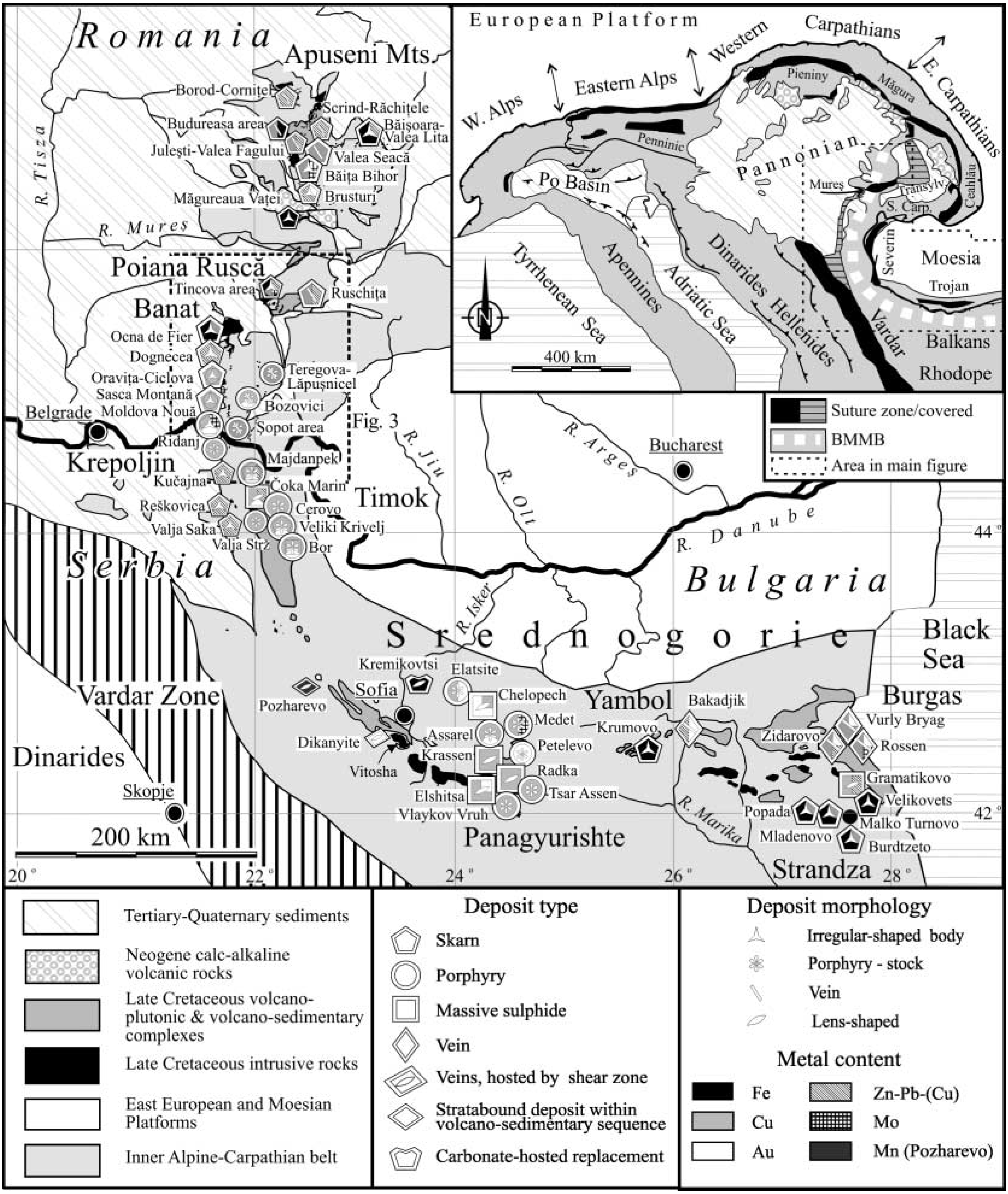
Keywords Banatitic magmatic and metallogenetic belt · Geodynamics · Late Cretaceous · Ore deposit · Re–Os dating

Introduction

The most important ore-bearing igneous belt of calc-alkaline signature within the Alpine–Balkan–Carpathian–Dinaride realm (Mitchell 1996; Janković 1997) has recently been redefined as the Banatitic Magmatic and Metallogenetic Belt, BMMB (Berza et al. 1998; Fig. 1). The BMMB extends through south-eastern central Europe, with a north–south orientation in Romania through Serbia (Yugoslavia), and an east–west-oriented belt in Bulgaria (Fig. 1). Despite gaps in the exposure of magmatic rocks and very irregularly clustered ore deposits, the BMMB can be considered almost continuous along a length of 1,500 km, with a width of 30 to 70 km. The L-shaped belt, and its contained magmatism and metallogeny, have a long-debated history since the connection between 'banatites' and adjacent deposits was first recognised in Banat and Timok in the 19th century (Von Cotta 1864). Banatite, named after the Banat province in south-western Romania, is used as a collective term for these Late Cretaceous intrusive and volcanic rocks including minor tholeiitic and alkaline, but mostly calc-alkaline, high-K calc-alkaline to shoshonitic compositions (Berza et al. 1998, and references therein; Dupont et al. 2002, this issue). The tectonic debate today is focused on the role of subduction and extension in the overall collisional evolution of the Alpine–Carpathian orogen during Late Cretaceous–Tertiary time (e.g. Linzer et al. 1998; Zweigel et al. 1998;

C.L. Ciobanu (✉) · N.J. Cook
Geological Survey of Norway,
7491 Trondheim, Norway
E-mail: Cristiana.Ciobanu@ngu.no

H. Stein
AIRIE Program,
Dept. of Earth Resources,
Colorado State University,
Fort Collins, CO 80523-1482, USA



Hippolyte et al. 1999; Neugebauer et al. 2001; Săndulescu and Visarion 2000). There still are conflicting geodynamic models for micro-plate configuration in the western Tethys (e.g. Săndulescu 1994; Stampfli et al. 1998; Stampfli and Mosar 1999), and for the kinematic reconstruction of the region to a pre-oroclinal configuration of the South Carpathians (e.g. Ratchbacher et al. 1993; Maţenco et al. 1997; Schmid et al. 1998).

Regional metallogeny and its relation to magmatism and geodynamics is unresolved, not least because of a lack

◀

Fig. 1 Geological sketch map of part of south-eastern Europe, showing the distribution and types of main ore deposits and prospects, the principal ore districts and the Late Cretaceous magmatic provinces in the Banatitic Magmatic and Metallogenetic Belt (BMMB). *Inset* shows the geodynamic and structural domains of the belt within the Alpine–Balkan–Carpathian–Dinaride orogenic system, with two principal sutures marked by ophiolites/flysch, interpreted as remnants of basins/segments of the Mesozoic Neotethys Ocean (e.g. Rădulescu and Săndulescu 1973; Săndulescu 1984, 1988; Linzer et al. 1998; Schmid et al. 1998; Stampfli and Mosar 1999)

of reliable geochronological data, both for the magmatic and the hydrothermal events along the entire belt. One aim of this paper, therefore, was to compile the existing geochronological data, in particular numerous K–Ar data in the Romanian, Serbian and Bulgarian literature. This compilation is a first step that may help to guide current and future studies using modern isotopic techniques, such as precise zircon dating of magmatic events by U–Pb, or direct dating of hydrothermal mineralisation by Re–Os on molybdenite or Ar–Ar dating of potassium-bearing minerals in skarn and porphyry deposits.

Geodynamic setting and magmatism

The BMMB is a linkage of magmato-metallogenetic districts that are overall discordant to mid-Cretaceous nappe structures (Cioflica and Vlad 1973). These nappe structures resulted from earlier closures of oceanic basins and collision of continental blocks (e.g. Săndulescu 1984). The main segments are, from north-west to south-east (Fig. 1), the Apuseni Mountains, the Poiana Ruscă and Banat districts (Romania), the strongly north–south-aligned Timok complex and Ridanj–Krepoljin belt (Serbia), which are separated by an apparent gap from the Srednogorie zone of Bulgaria. The complexity of magmato-metallogenetic features in the BMMB is underscored by the spectrum of geodynamic models and by disagreement between different schools of thought. Although rifting mechanisms have found proponents (Antonijević et al. 1974; Bončev 1976; Dabovski 1980; Popov 1981, 1987, 1995), subduction models now prevail.

There are two major sutures within the Carpathian–Balkan orogen, marked by two belts of ophiolites and/or flysch, which are interpreted as remnants of at least two Mesozoic ocean basins (Fig. 1 inset). To the north, remnants of the Severin Ocean are preserved along the Măgura–Ceahlău–Severin–Trojan line (Fig. 1, inset). Further south-west, the Vardar ophiolite records a second larger oceanic basin, which, together with Mureş and Transylvanian branches, may have connected to the Atlantic Ocean (e.g. Săndulescu 1984, 1988, 1994; Fig. 1, inset). Intense debate has centred on whether Late Cretaceous 'banatite' magmatism relates to subduction of Vardar Ocean or the Severin Ocean crust, or a combination of both.

Westward subduction of rocks of the Severin basin has been invoked for banatite generation in the South Carpathians (Rădulescu and Săndulescu 1973; Bleahu 1976; Russo-Săndulescu et al. 1978, 1984; Russo-Săndulescu and Berza 1979; Vlad 1979, 1997; Cioflica 1989). Banatites of the North Apuseni Mountains were ascribed to subduction of rocks of the Transylvanian basin (Rădulescu and Săndulescu 1973; Rădulescu et al. 1993). A model for easterly and northerly-directed subduction during Vardar ocean basin closure has also received favour (Dewey et al. 1973; Hsü et al. 1977; Burchfiel 1980; Janković and Jelenković 1997; Karamata et al. 1999). As a further possibility, Boccaletti et al. (1974) propose consumption of the Vardar Ocean already by the Early Cretaceous, and relate Late Cretaceous magmatism to slab detachment during underthrusting beneath the Rhodopes. Mantle delamination caused by slab break-off is invoked as a possible cause for magmatism in the entire belt (Berza et al. 1998). Early Cretaceous termination of Vardar subduction is consistent with later (Late Cretaceous) magma generation in an extensional regime. Neubauer (2000, 2001) ascribed magma generation to post-collisional I-type magmatism and the abundance of ore deposits within the south-eastern part of Alpine–Balkan–Carpathian–Dinaride realm (ABCD) to slab break-off of subducted lithosphere during Vardar Ocean closure. A key uncertainty remains the precise configuration and timing of Vardar subduction (e.g. Haas et al. 1995; Channell and Kozur 1997; Stampfli et al. 1998; Stampfli and Mosar 1999).

New kinematic and palaeomagnetic data for the South Carpathians (e.g. Pătraşcu et al. 1992; Bojar et al. 1998; Schmid et al. 1998) have facilitated plate reconstructions. Willingshofer (2000) considered subduction of the Severin Ocean crust to have terminated at 80–70 Ma, whereas subduction of Vardar Ocean crust was still going on. Closure of the Western Neotethys Ocean concluded by the oblique collision of the Tisza and Dacia microcontinents and the terminal stages of Vardar subduction (Fig. 2). Tisza, including the present-day Apuseni Mountains, is a block that drifted north-eastwards from the Adriatic promontory of the African continent and became attached to the European margin. In the model suggested in Fig. 2, the Apuseni Mountains are aligned with other segments of the BMMB parallel to the Vardar subduction front. Active subduction extending eastwards to the Black Sea (at that time a newly opened basin; Stampfli et al. 1998) could be the cause for magmatism along the entire belt, intruding and overlying an east–west-oriented collage of terranes along the southern border of the Moesian Platform (Fig. 2). Palaeomagnetic reconstructions support the interpretation that banatites in both the Apuseni Mountains and the South Carpathians, together with the tectonic units that they intrude, were situated within a rigid block (Tisza–Dacia block), south of Europe during the Late Cretaceous (Pătraşcu et al. 1990, 1992; Panaiotu 1998).

Crustal thickening and nappe stacking in the Apuseni Mountains (e.g. Balintoni 1998; Dallmeyer et al. 1999) and South Carpathians (e.g. Berza et al. 1994; Dallmeyer

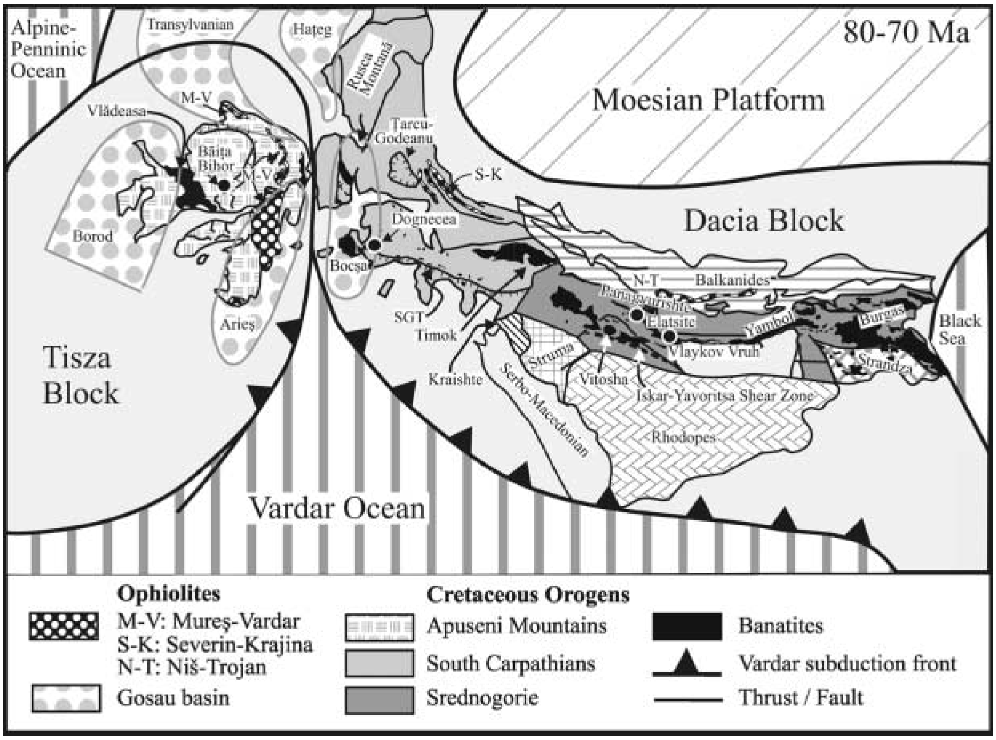


Fig. 2 Schematic reconstruction of BMMB at 80–70 Ma, showing its E–W strike parallel to the Vardar subduction front. The position of banatites is placed on the 80–70-Ma reconstruction of the western Tethys Realm (Willingshofer 2000). 'Gosau' basins formed between the Apuseni Mountains and South Carpathians, adjacent to the collision zone between the two Mid-Cretaceous crustal blocks (Tisza and Dacia), are shown. Structural division in Bulgaria after IGCP Project 369 website http://www-sst.unil.ch/igcp_369/369_maps/moesia/BulgariaTecto_big.GIF. *SGT* Supragetic-Getic Thrust

et al. 1996) resulted from Early to Mid-Cretaceous collision between the Tisza and Dacia crustal blocks. As a result, Vardar subduction was grossly coeval with gravitational collapse and rapid metamorphic core exhumation in the Late Cretaceous. This led to formation of continental 'Gosau-type' collapse basins (Willingshofer et al. 1999, 2001; Willingshofer 2000) in Rusca Montană, Haţeg, Arieş, Borod and Transylvania. The attending extensional regime favoured magma emplacement adjacent to these basins (Fig. 2). Interpretation of aeromagnetic and gravity maps suggests the presence of a large granite pluton beneath Bihor–Vlădeasa, along the border with the Pannonian Basin. Such data also show that magmatic rocks in parallel alignments in north-western Banat and in Poiana Ruscă (Fig. 3) are rooted at depth along the boundaries between mountain ranges and adjacent basins (Andrei et al. 1989). In the Apuseni Mountains, the interaction between pre-existing thrusts and extensional faults related to the onset of Gosau basin development played a major role in controlling emplacement of intrusions. Likewise, in Banat, emplacement was assisted by extensional reactivation of Mid-Cretaceous thrust planes.

The present L-shape of the BMMB mainly relates to post-collisional tectonics within the sutured Tisza-Dacia block, during the Tertiary. The Apuseni Mountains and South Carpathian orogens suffered Tertiary disruption and rotation in the event that generated the sinusoidal shape of the present Carpathian mountain chain (Fig. 1, inset; e.g. Csontos 1995). Palaeomagnetic data for banatites in the two mountain ranges (Pătraşcu et al. 1990, 1992; Panaiotu 1998) show clockwise rotation at different angles because of their relative positions within the Tisza–Dacia block. Orogen-parallel extension, assisted by strike-slip faulting and dextral wrench faulting, is recognised in the South Carpathians and Moesian Platform borders (Ratchbacher et al. 1993; Schmid et al. 1998; Maţenco and Schmid 1999).

The Late Cretaceous igneous rocks of the BMMB are broadly calc-alkaline, with variably high-K to locally shoshonitic character (e.g. Drovenik et al. 1967; Boccaletti et al. 1978; Russo-Săndulescu and Berza 1979; Stanisheva-Vassileva 1980; Gunnesch 1982; Dabovski et al. 1991; Ştefan et al. 1992). Trace-element data and strontium and neodymium isotope data available for banatites support a magma source situated in the upper mantle, yet with variable local crustal contamination (e.g. Downes et al. 1995, Cioflica et al. 1996; Peycheva et al. 2001). The $^{87}Sr/^{86}Sr$ data (summarised from Berza et al. 1998; Janković and Jelenković 1997) are: 0.705–0.709 (Apuseni Mountains), 0.703–0.706 (Banat), 0.706–0.710 (Timok) and 0.704–0.705 (Srednogorie). Dupont et al. (2002, this volume) report geochemical and isotopic data from ore-related, calc-alkaline intrusions from Poiana Ruscă and Banat. They infer partial melting of heterogeneous lithospheric mantle or mafic lower crust, citing typically positive ϵ_{Nd} values (+3.9 to – 0.2), concordant with data obtained by Downes et al. (1995; $\epsilon_{Nd} = +6.9$ to –2.4) and others (e.g. Cioflica et al. 1996; Peycheva et al. 2001). The magmas have all the geochemical characteristics of subduction zone magmas, but Dupont et al. (2002, this volume) speculate that the geochemical signature could also reflect an inherited previous subduction event, based on Nd model ages of about 600 Ma.

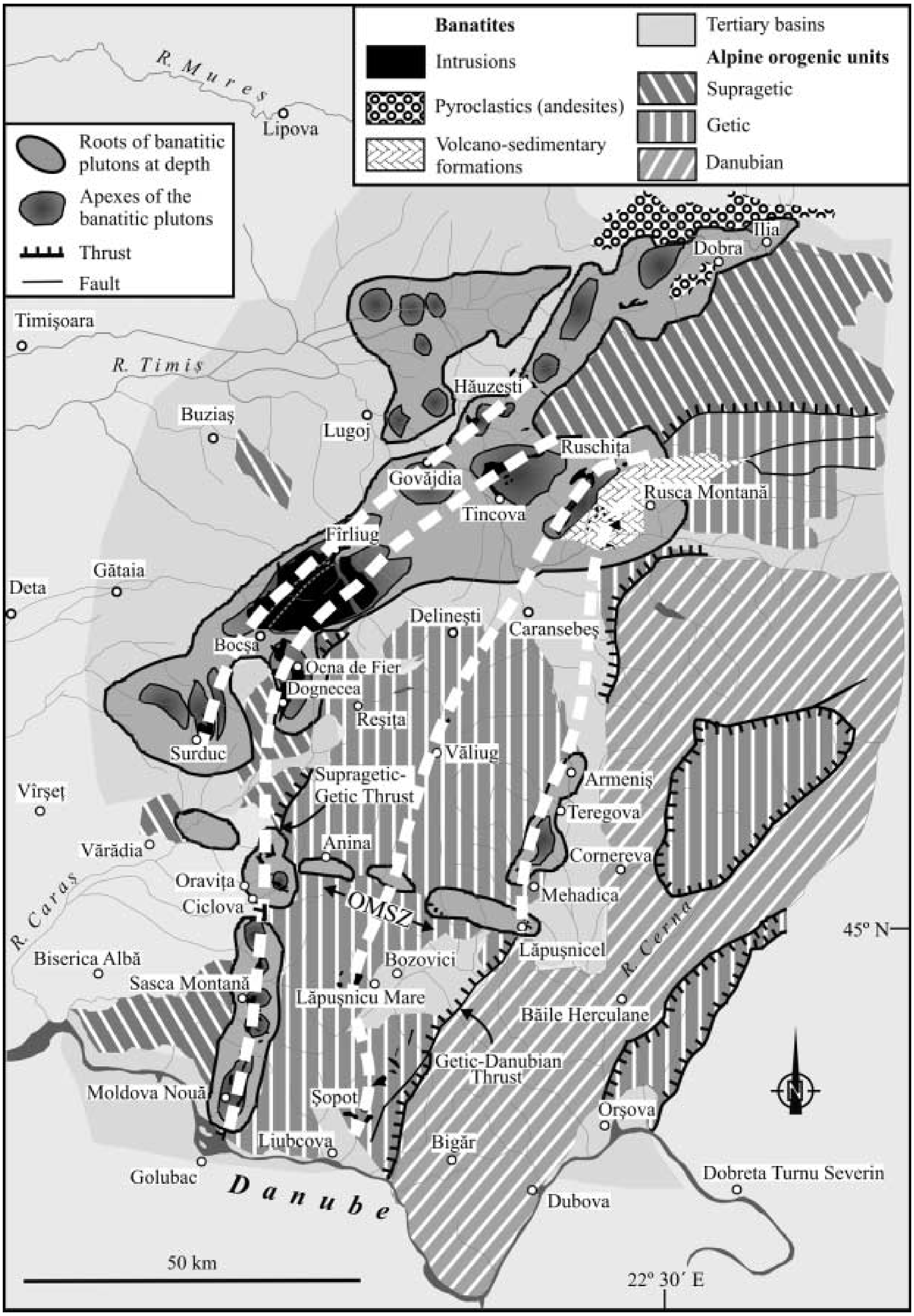


Fig. 3 Outlines of calc-alkaline plutons from Banat and Poiana Ruscă, interpreted from aeromagnetic and gravimetric data (after Andrei et al. 1989), indicating a marked structural control for emplacement of magma chambers at depth. The largest chambers in north-western Banat and in Poiana Ruscă are at the contact of mountain ranges with sedimentary basins. Intrusive rocks in southern Banat are rooted within narrow, elongate magma chambers positioned along tectonic lines including Mid-Cretaceous nappe boundaries (e.g. Supragetic-Getic Thrust, Getic-Danubian Thrust) and Late Cretaceous WNW–ESE-trending cross structures such as the Oraviţa–Mehadica zone (OMSZ). *Dashed white lines* mark the four alignments of intrusions in Banat and Poiana Ruscă (e.g. Cioflica and Vlad 1973a)

Ore deposit distribution and characteristics

Approximately 50 mineral deposits and prospects are spatially and probably genetically associated with calc-alkaline 'banatitic' magmatism along the BMMB (Table 1, Fig. 1), which is the only copper-dominated belt in the ABCD orogenic system (Mitchell 1996; Janković 1997). In many deposits, copper ores are associated with important resources of gold, including at one of Europe's largest gold mines at Chelopech. Anomalous molybdenum is widespread, albeit in generally small amounts, but is rarely recovered. There is a strong correlation between the host rock types (notably volcanic rocks, carbonates) and deposit type, and probably with the depth of magma emplacement. Subvolcanic environments with preserved extrusive rocks are the preferred setting for porphyry-style Cu ± Au ± Mo systems, as exemplified by the large deposits in the Timok and Panagyurishte ore districts. A 'massive

Table 1 Principal mineral deposits and prospects in the BMMB. Deposits given in *italics* are currently active gold exploration areas. Size (category): *1* < 1 Mt; *2* 1–5 Mt; *3* 5–20 Mt; *4* 20–100 Mt; *5* 100–500 Mt; *6* > 500 Mt. Tonnages marked with * are our rough estimates based on published maps and sections. Production figures for Valea Seaca (Pošepny 1874 fide Stoici 1983): 270 t Cu; 373 t Pb; 18.41 t Ag; 13.7 kg Au. Mine production figures for Bulgarian deposits (after Milev et al. 1996): Pozharevo (1907–1976): 0.24 Mt; Kremikovtsi (1951–1994): 41 Mt; Assarel (1976–1995): 52.5 Mt; Medet (1964–1993): 163 Mt; Krassen (1964–1973): 0.3 Mt; Radka (1942–1994): 6.4 Mt; Elshitsa (1952–1995: 2.47 Mt Cu ore; Vlaykov Vruh (1962–1979): 9.8 Mt; Zidarovo (1978–1990): 0.7 Mt; Vurly Bryag (1943–1994): 7.8 Mt; Rossen (1945–1994): 7.5 Mt; Gramatikovo (1960–1990): 1.4 Mt; Burdtzeto (1960–1993): 3.2 Mt; Propada Cu-ore production: 1.7 Mt; Mladenovo: 0.9 Mt. Other sources of information used: Borcos et al. (1984, 1998), Kozelj and Jelenkovic (2001)

	Status	Deposit type	Commodities		Deposit size				Selected references
			Major	Minor	Category	Total (Mt)	Reserves (Mt)	Grades % (g/t Au)	
Romania									
North Apuseni Mts.									
Borod-Cornişel	Prospect	Breccias, veins, skarn features	Zn–Pb–(Cu)	Au, Ag					Berbeleac et al. (1980)
Vlădeasa Massif									
Budureasa area	Prospect	Skarns, irregular	Zn–Pb–(Cu), Fe	Au, Ag					Istrate and Udubaşa (1981)
Scrind-Răchiţele	Prospect	Veins, stratiform sulphide lenses	Zn–Pb–(Cu)	Au, Ag, As					Gheorghiţescu et al. (1980)
Gilau Massif									
Băişoara-Valea Lita	In production	Fe skarn	Fe, Zn–Pb	B	3	ca. 20*	ca. 10*	ca. 30 Fe*	Lazăr and Întorsureanu (1981)
Bihor Massif									
Juleşti-Valea Fagului	Prospect	Veins, skarn features	Cu, Zn–Pb	Au, Ag					Udubaşa et al. (1980)
Valea Seacă	1815–1858	Cu skarn, veins	Cu, Ag, Pb, Au	Bi		< 1*		See footnote	Stoici (1983)
Băiţa Bihor	In production	Cu–(Mo) skarn, pipes	Cu, Mo, Zn–Pb	Au, Bi, W, B, wollastonite	2	5[a]	3[a]	0.56 Cu, 1.06 Zn, 0.46 Pb, 0.09 Mo, 0.064 Bi[a], 1–2 Au (?)	Cioflica et al. (1971), (1977); Stoici (1983)
Brusturi	Prospect	Veins, skarn features	Zn–Pb–(Cu), Au	As					Giuşcă et al. (1976)
South Apuseni Mts.									
Măgureaua Vaţei	Prospect	Skarn, irregular	Fe						Cioflica (1960)
Poiana Ruscă									
Ruschiţa	Closed 1999	Zn–Pb skarn	Zn–Pb		1–2 (?)*		< 5*		Giuşcă and Volanschi (1968)
Tincova area	Prospect	Skarns, porphyry Cu–(Mo)	Fe, Zn–Pb, Cu	Mo, Bi, W					Cioflica et al. (1985, 1987a)
Banat									
Ocna de Fier	Closed 1993	Fe–(Cu) skarn	Fe, Cu	Zn–Pb, B	3	13[b]		30–35 Fe, 0.5 Cu[b]	Kissling (1967); Nicolescu and Cornell (1999); Cook and Ciobanu (2001)

Dognecea	Closed 1989	Zn–Pb skarn	Zn–Pb	Cu, Ag	2	2[b]		3.69 Zn, 1.92 Pb[b]	Vlad (1974)
Oraviţa-Ciclova	Past producer	Cu skarn, porphyry features	Cu, Zn–Pb	Au, Mo, W	2 (?)	5*			Gheorghiţescu (1975); Cioflica and Vlad (1981); Constantinescu et al. (1988)
Sasca Montană	Closed 1998	Cu skarn, porphyry features	Cu, Zn–Pb	Au, Mo	2 (?)	5*			Constantinescu (1980)
Moldova Nouă	In production	Porphyry Cu–(Au)/Mo, skarn features	Cu, Au, Mo	Fe, Zn–Pb, As	5	400–500[a]	300–400[a]	0.35 Cu[a], 0.25 Au (?)	Gheorghiţescu (1972); Gheorghiţă (1974)
	Closed 1998	Cu skarn (Florimunda sector)							
Teregova-Lăpuşnicel	Prospect	Porphyry Cu, veins	Cu, Mo						Gunnesch (1982)
Bozovici	Prospect	Porphyry Cu–(Au), veins	Cu, Au	Mo					Gunnesch (1982)
Sopot area	Prospect	Porphyry Cu, veins	Cu	Au					Gunnesch (1982); Cioflica et al. (1992a)
Serbia									
Ridanj-Krepoljin Belt									
Ridanj	Prospect ?	Porphyry Cu	Cu						
Kučajna	Prospect	Skarns	Zn–Pb, Cu	Ag					Janković (1990); Karamata et al. (1997a)
Reškovica	Prospect	Skarns	Zn–Pb, Cu						
Bor District/Timok Massif									
Valja Saka	Prospect	Zn–Pb skarns	Zn–Pb						Karamata et al. (1997a)
Majdanpek	On standby	LS epithermal, porphyry Cu–(Au)	Cu, Au	Mo, Ag, PGE	6	850–1,000[c]	> 512[d]	0.4 Cu, 0.25 Au[c]	Janković et al. (1998)
	In production	Zn–Pb skarn (Northern sector)	Zn–Pb	Pyrite					
Coka Marin	Prospect	Stratiform sulphide lenses	Zn–Pb, Cu, Au	Ag					Janković (1990); Karamata et al. (1997b)
Valja Strž	Prospect	Porphyry Cu (low grade)	Cu						Janković et al. (1998)
Bor District/Timok Massif									
Cerovo area	In production	Porphyry Cu (7 structures, of which three with cementation zones)	Cu	Ag	5–6	> 500 (?)[d]		< 1 Cu[d]	Janković (1990); Cocić et al. (2001)

Table 1 (Contd.)

	Status	Deposit type	Commodities		Deposit size				Selected references
			Major	Minor	Category	Total (Mt)	Reserves (Mt)	Grades % (g/t Au)	
Veliki Krivelj	In production	Porphyry Cu, skarn features	Cu	Au, Ag	6	750^{c}		0.44 Cu^{c}	Jelenković and Vakanjac (1999)
	Past production	HS epithermal Cu, VMS features	Cu, Au	Ag, Se	6				Miličić and Grujičić (1980); Janković et al. (1980), (1998)
Bor	In production	Stockwork Cu–(Au)	Cu, Au			540		0.67 Cu, 0.2 Au^{c}	
	Future reserves	Porphyry Cu (below stockwork)	Cu						
Bulgaria									
Western Srednogorie									
Pozharevo	Past producer	Stratiform	Mn		1	0.24^{e} (prod)		ca. 28 Mn^{e}	Bogdanov (1982)
Kremikovtsi	In production	Replacement or SEDEX type	Fe, barite		4–5	100*		ca. 30 Fe^{e}	Bogdanov (1982)
Dikanyite	Prospect	Shear zone hosted	Au	Base metals					http://www.hereward.com
Panagyurishte District									
Elatsite	In production	Porphyry Cu–Au	Cu, Au	Mo, PGE	5	> 300^{e}		0.33 Cu, 0.25 Au^{e}	See Bogdanov (1987); Strashimirov and Popov (2000) and references therein
Chelopech	In production	HS epithermal Au–Cu, VMS features	Au, Cu	Ag	4	50–60*	33^{f}	1.24 Cu, 3.38 Au^{f}	
Assarel	In production	Porphyry Cu–(Au)	Cu, Au	Ag	5	300^{c}	130^{c}	0.44 Cu, 0.2 Au^{c}	Angelkov and Parvanov (1980); Bogdanov (1987)
Medet	Closed 1993	Porphyry Cu–Mo	Cu, Mo	W	5	200^{c}		0.34 Cu, 0.1 Mo^{c}	See Bogdanov (1987); Strashimirov and Popov (2000) and references therein
Krassen	Closed 1973	HS epithermal Cu, VMS features	Cu	Au, Ag	1	0.3^{e} (prod)			
Petelevo	Prospect	Au cap on low-grade porphyry Cu	Au	Cu					
Radka	Closed 1994	IS epithermal Cu, VMS features	Cu	Au	3	8–10^{e}			
Tsar Assen	Past producer	Porphyry Cu	Cu	Au	3	ca. 10^{e}			
Elshitsa	1952–1995	LS epithermal Cu–(Au), VMS features	Cu, Au, pyrite	Ag	3	6–10^{e}		1.03 Cu^{e}	

Vlaykov Vruh	Closed 1980	Porphyry Cu	Cu	Au	3	ca. 10[e]		
Yambol District								
Krumovo	Past producer	Fe skarn	Fe	B	3	ca. 20[e]	45 Fe[e]	Bogdanov (1982); Ivanova-Panayotova (1974)
Bakadjik	Past producer	Epithermal Au-Zn–Pb veins	Au, Zn–Pb	Cu	2	2[f]	2 Au[e]	Bonev (1974); Bogdanov (1987)
Burgas District								
Zidarovo	Past producer	Cu-Zn–Pb–(Au) veins	Cu, Zn–Pb, Au	Bi	3	ca. 10[e]		Bogdanov et al. (1994); Tarkian and Breskovska (1995)
Vurly Bryag	Past producer	Cu–(Au) veins	Cu	Au	3	ca. 10[e]		Bogdanov (1987)
Rossen	Past producer	Cu–Mo–(Au) veins	Cu, Mo	Au, Bi	3	ca. 10[e]		Bogdanov (1987)
Malko Turnovo District								
Gramatikovo	Past producer	Stratiform sulphide lenses (VMS?)	Cu, Zn–Pb		2	1.4[e] (prod)		Bogdanov (1982, 1987)
Burdtzeto	Past producer	Fe–(Cu) skarn	Fe, Cu	B	2	3.2[e] (prod)		Bogdanov (1982, 1987)
Propada	Past producer	Cu–Fe skarn	Cu, Fe		2	1.7[e] (prod)		Bogdanov (1987)
Mladenovo	Past producer	Cu–Fe skarn	Cu, Fe		1–2	0.9[e] (prod)		Bogdanov (1987)
Velikovets	Past producer	Fe skarn	Fe		2	2[e] (prod)		

[a] Sources of deposit tonnage/grade data: Minvest SA (http://www.toptech.ro/minvest)
[b] Cook and Ciobanu (2001)
[c] Mutschler et al. (1999)
[d] Bor Copper Institute
[e] Milev et al. (1996)
[f] Navan Resources PLC

sulphide' type of epithermal deposit, commonly, but not always, of high-sulphidation affinity, is intimately associated with porphyries in the same parts of the belt, rarely forming a continuum as seen in the Bor and Majdanpek ore fields (Sillitoe 1980; Janković et al. 1998). Several porphyry and epithermal deposits are enriched in platinum-group elements (Majdanpek: Janković et al. 1998; Elatsite: Petrunov et al. 1992; Petrunov and Dragov 1993; Tarkian et al. 1999), and are comparable with some deposits from the western Pacific margin (e.g. Tarkian and Stribrny 1999). Bismuth sulphosalts, conspicuously without antimony-bearing phases, are present in virtually all BMMB deposits, and in some they form significant concentrations (e.g. Băiţa Bihor, Ocna de Fier, Zidarovo; Žák et al. 1994; Tarkian and Breskovska 1995; Bogdanov and Vavelidis 2000; Ciobanu and Cook 2000a).

Skarn deposits

Skarn is the most frequent type of mineralisation along the BMMB (Tables 1 and 2, Fig. 1). Iron skarns are prominent in ore districts at the two ends of the belt, in south-western Romania and in eastern Bulgaria (Fig. 1, Table 1). Significant copper ores were exploited from iron skarns in Malko Turnovo near the Black Sea (Table 1), where early magnesium skarn associated with magnetite is overprinted by garnet pyroxene skarn and later chalcopyrite + pyrite + molybdenite (Bogdanov 1987). Forsterite skarn hosting a magnetite–chalcopyrite–bornite ore assemblage, with a characteristic Fe–Cu–Co–Bi–Ag–Sn–Te–Se–Au geochemical signature, forms an inner Cu–Fe core at the Ocna de Fier deposit. Cook and Ciobanu (2001) considered this to typify fluid plume mineralisation in a proximal skarn setting. Copper and Cu–(Mo) skarn deposits and small prospects, often with peripheral Zn–Pb–(Cu) veins with skarn and breccia features, are characteristic in the western part of Apuseni Mountains. Such spatial variation in metallogeny is interpreted in terms of pluton-derived zonation (Cioflica et al. 1982; Ştefan et al. 1988). Similarly, the Banat district includes the full range of skarn deposits (Table 1), with small copper-rich skarns grading into porphyries or apical porphyries with skarn halos. Several authors (Vlad 1979, 1997; Cioflica et al. 1992a, 1992b) have attempted to correlate deposit types and magmatism in the Banat district to a regional zonation away from a subduction front. Zinc–lead skarns form distal parts of deposits or ore fields (Table 2) and rarely occur as isolated economic deposits (Fig. 1). The skarn affiliation of some of these Zn–Pb lenses in schists has been questioned because they commonly lack spatial relationships to proximal skarns (e.g. Ruschiţa; Kräutner 1996) or even intrusive rocks (e.g. Scrind-Răchiţele; Gheorghiţescu et al. 1980).

Most skarns are located at the immediate contacts with their causative intrusions (Table 2). Highest temperature (~750 °C) skarns are usually barren, but may contain exotic mineral assemblages. Gehlenite-bearing skarns occur at Oraviţa-Ciclova (e.g. Constantinescu et al. 1988) and melilite-bearing-skarns are known at Măgureaua Vaţei (e.g. Marincea et al. 2001; Pascal et al. 2001). Ludwigite (Marincea 1999, 2000) is a common accessory mineral in the magnesian parts of most iron skarns (Table 2). Ludwigite and other boron-rich minerals, such as szaibelyite (Marincea 2001), form significant concentrations in the Cu–(Mo) skarn at Băiţa Bihor. Exploitation of lithological contacts results in laterally extensive skarn ore fields with large-scale metal zonation (Table 2). Cioflica et al. (1977) described Mo → Cu → Zn–Pb deposit zoning in the Băiţa Bihor district, where molybdenum is enriched closest to the magmatic fluid source. Ciobanu and Cook (2000b) considered that metal zoning (Cu–Fe → Fe → Zn–Pb) in the Ocna de Fier-Dognecea ore field is centred surrounding a single subjacent granodiorite in the deepest part of the Ocna de Fier deposit. Fluid infiltration along the contact between Mesozoic limestone and Precambrian schist in the ore field resulted in the distal formation of the Zn–Pb skarn at the Dognecea deposit, 5 km from the igneous source at the Ocna de Fier deposit. Nicolescu and Cornell (1999) derived a 10-km depth for metal deposition in the ore field based on silicate geobarometry of hornfels, but textural observations indicate a maximum depth about 5 km (Ciobanu and Cook 2001).

Porphyry-style and epithermal Cu–(Au–Mo) deposits

The two major metallogenetic districts in the central part of the BMMB (Bor in Serbia; Panagyurishte in Bulgaria) both contain hypabyssal intrusions together with approximately coeval volcanic ore host rocks. Deposits have dominantly porphyry-style characteristics, with associated epithermal deposits of low-, intermediate- and high-sulphidation type (Fig. 1, Tables 1, 3 and 4). Moldova Nouă, a significant porphyry district in southernmost Banat, lacks volcanic rocks and is associated with small copper skarns rather than epithermal veins. Significant differences between the Bor and Panagyurishte districts include the apparently greater vertical extent of mineralisation in Bor, and the exposure of the porphyritic intrusion adjacent or close to mineralisation in Panagyurishte (Strashimirov and Popov 2000). In some of the largest deposits of the Bor district, causative intrusions are only inferred at depth (e.g. Janković et al. 1998).

In the Bor district, porphyry-style mineralisation occurs in a variety of styles and at various locations as stockworks in plutonic cupolas (Valja Strž), at the same level as dyke swarms above intrusions (Veliki Krivelj; Jelenković and Vakanjac 1999), and as stockworks above intrusions, but below high-sulphidation epithermal ores (Bor; Janković 1990). At Majdanpek, the largest-tonnage copper deposit in the BMMB, porphyry-style vein stockworks are fault controlled above an inferred intrusion, with adjacent low-sulphidation epithermal veins and skarn ores (Janković et al. 1998).

The Zn–Pb–Cu–Au–Ag prospect at Čoka Marin in the Bor district (Janković 1990; Karamata et al. 1997b) is not associated with porphyry mineralisation and resembles a syngenetic volcanogenic massive sulphide (VMS) deposit. Large, but, so far, subeconomic porphyry systems extend as far north as Poiana Ruscă. Clusters of prospects in Poiana Ruscă, between Tincova and Ruschiţa at the border to present-day Rusca Montană, and along the Şopot–Teregova–Lăpuşnicel alignment in southern Banat (Fig. 1), have been described as apical porphyries with pyrite halos and/or porphyries with skarn halos (Cioflica et al. 1985, 1995; Cioflica 1989).

In Panagyurishte (Bogdanov 1980, 1987), a pairing of porphyry deposits adjacent to epithermal 'massive sulphide' deposits is characteristic. These include the Elatsite porphyry near Chelopech, Petelevo near Krassen, Tsar Assen near Radka and Vlaykov Vruh near Elshitsa (Tables 3 and 4; Kouzmanov et al. 2002; Bonev et al. 2002, this volume). The sulphidation character, however, is high at Chelopech and Krassen, intermediate at Radka and low at Elshitsa. The Medet–Assarel ore field contains only porphyry deposits (Strashimirov et al. 2002, this volume). Stockworks show a variety of positions relative to causative porphyries, either within the intrusion (Medet), along the contact between intrusion and basement (Elatsite) or volcanic rocks (Assarel), or even distal to the intrusion (Petelevo). The porphyry copper deposit at Elatsite is moderately gold-rich and contains a rare assemblage of Co–Bi–Ag–Sn–Te–Se–Au-bearing minerals, as well as PGM, in massive magnetite–bornite ore at the core of the porphyry system (Dragov and Petrunov 1996; Kouzmanov et al. 2000; Strashimirov et al. 2002, this volume).

Considerable debate has focused on the origin of the 'massive sulphide' character of these epithermal deposits in volcanic settings. Collomorph textures, laminations and the apparent bedding parallel distribution of pyrite observed in Bor and in the Panagyurishte districts have been taken as evidence for the deposition of at least some of the sulphide minerals by submarine exhalative processes within the volcanic–sedimentary pile. This was followed by epithermal overprinting by Cu- and Au-rich fluids related to porphyry systems (e.g. Janković 1990; Petrunov 1995; Bogdanov et al. 1997; Tsonev et al. 2000). Sillitoe et al. (1996) described Bor as an example of a "high sulphidation deposit in the volcanogenic massive sulphide environment". The high sulphidation character with advanced argillic alteration, sulphate minerals and enargite in the largest deposits (Bor, Chelopech, Krassen) encourages comparison with the Pacific Rim (e.g. Lepanto, Philippines; Hedenquist et al. 1998), suggesting a genetic link between porphyries and epithermal deposits. Fluid inclusion and isotope studies at Chelopech (Moritz et al. 2001) and elsewhere in the Panagyurishte district (Kouzmanov et al. 2001a, 2002, this volume) are consistent with such a link, but the presence or the genetic significance of a precursor syngenetic VMS stage is unclear.

Extensive Cu–(Au–Mo) vein systems are known only from the unique alkaline volcanic-hosted setting in the Yambol and Burgas districts in eastern Bulgaria. Large ring-caldera structures are preserved that host small, but rich ores, with considerable enrichment in trace metals, e.g. very high Bi contents of Cu–Au veins at Zidarovo (Tarkian and Breskovska 1995) and high Mo–Co ± W content in Cu–Pb–Zn veins at Rossen.

Geochronology

All available whole rock and mineral ages (mostly K–Ar, with some whole-rock Rb–Sr and U–Pb zircon data) for magmatic rocks of the BMMB have been compiled in order to better understand the timing of magmatism and ore formation across the belt. In addition, we report a new Re–Os age for molybdenite in Zn–Pb skarn from the Dognecea deposit, in an effort to constrain the age of mineralisation and its relationship to the Ocna de Fier-Dognecea intrusion. Our compilation (Table 5, Fig. 4) shows a range between 110 and 38 Ma, with some 80% of the ages falling between 85 and 65 Ma.

Different analytical methods have been used in the isotopic age determinations and it is likely that some of the considerable variation relates to problems with the techniques employed, rather than to real ages of the samples. Consistently narrower age intervals were calculated from data obtained using fast neutron activation for potassium concentrations and thermal neutron activation (NA) for radiogenic argon determination by the Institute of Nuclear Physics and Engineering Laboratory (INPE), Bucharest (e.g. Soroiu et al. 1986; Strutinski et al. 1986). Ages calculated from radiogenic argon data obtained by isotope dilution (ID) determined at the Institute of Geology and Geophysics (IGG), Bucharest (e.g. Kräutner et al. 1986; Russo-Săndulescu et al. 1986), show a shift towards younger and commonly wider age ranges. For Rusca Montană, the NA data of Strutinski et al. (1986) are systematically older than the ID data of Kräutner et al. (1986) for the same intrusions. Because of problems with excess argon, the inclusion of altered rocks in many data sets, and K–Ar resetting well after the time of emplacement, we appreciate that many of the K–Ar ages in our compilation, particularly those determined at IGG, should be used with caution.

Duration of magmatic activity

Nevertheless, the dataset (Table 5, Fig. 4) is representative of both the spatial distribution and types of magmatites, and thus can help to characterise the approximate age and lifetime of the belt. The oldest rock is the gabbro at Hăuzeşti, Poiana Ruscă (Cioflica et al. 1994; 110–92 Ma). Opinions differ concerning the youngest ages obtained for banatites. These cluster between 65–60 Ma, and a few are even Eocene. The

Table 2 Characteristics of BMMB skarns. *Pz* Palaeozoic; *T* Triassic; *J* Jurassic; *K1* Early Cretaceous; *Grt* garnet; *Di* diopside; *Px* pyroxene; *Wo* wollastonite; *Ves* vesuvianite; *Ep* epidote; *Hd* hedenbergite; *Tr* tremolite; *Fo* forsterite; *Ser* serpentine; *Lud* ludwigite; *Geh* gehlenite; *Chd* chondrodite; *Chu* clinohumite; *Szb* szaibelyite; *Mt* magnetite; *Py* pyrite; *Po* pyrrhotite; *Hm* haematite; *Bn* bornite; *Cp* chalcopyrite; *Mol* molybdenite; *Sp* sphalerite; *Gn* galena; *Sch* scheelite

Skarn type	Deposit	Carbonaceous protolith		Causative intrusive	Morphology/ characteristics	Skarn mineralogy		Ore mineralogy	Deposit/ore field zoning
		Basement	Sedimentary			Calcic	Magnesian		
Fe	Băişoara			Granodiorite	Irregular bodies, at intrusive contact	Grt, Di	Fo (Ser), Lud	Mt, Py, Po, (Mol)	
Fe–(Cu)	Ocna de Fier		J-K1	Granodiorite	10 km strike, deep-seated, onion-shaped at limestone/schist contact	Grt, Di	Fo (Ser), Lud	Mt, Hm, Bn, Cp	Cu–Fe/Fe/ Zn–Pb
Fe	Krumovo	Precambrian	Pz, T, J	?	At gabbro/diorite contact		Fo (Ser), Lud	Mt	
Fe	Velikovets			?		Grt, Px	Fo (Ser), Lud	Mt	
Fe–(Cu)	Bardtzeto		Carbonate and carbonate/ pelitic sediments	Granodiorite	At limestone/ intrusive contact	Grt, Px	Fo (Ser), Lud	Mt, Cp, Py, (Mol)	
Fe–(Cu)	Popada			Monzodiorite/ diorite	At limestone/ gabbro contact	Grt, Px		Mt, Cp, Py, (Mol)	
Fe–(Cu)	Mladenovo			Monzodiorite/ diorite	Lenses at limestone/ gabbro contact	Grt, Px		Mt, Cp, Py, (Mol)	
Cu	Valea Seacă			Granodiorite	At dike contact, structural control	Grt, Di		Cp, Mt, (Mol)	
Cu–(Mo)-(Zn–Pb)	Băiţa Bihor		T carbonate/ dolomite with siliceous levels	Granite/ granodiorite intersected in deep drill holes	5-km strike, pipes, along siliceous level between carbonate/ dolomite	Grt, Di, Wo, Ves	Fo (Ser), Lud, Chd, Chu, Szb	Cp, Bn, Mol, Sp, Gn, Sch	Mo/Cu/Zn–Pb
Cu	Oraviţa-Ciclova		Pz and J-K1 carbonate and carbonate/ pelitic sediments	Monzodiorite, diorite, gabbro	Lenses at intrusive contacts, porphyry features	Grt, Di, Ves, Geh		Cp, Po, Py, (Mol), Sch	
Cu	Sasca Montană			Monzodiorite, diorite granodiorite	Lenses at intrusive contacts, porphyry features	Grt, Di, Ves		Cp, Po, Py, (Mol)	
Cu	Florimunda (Moldova Nouă)			Granodiorite	Irregular bodies at limestone/ intrusive contact	Grt, Di		Cp, Mt, Py	
Zn–Pb	Valea Lita (Băişoara)	Precambrian		Granodiorite	Lenses in schist, distal to Băişoara	Ep		Sp, Gn, Py	

Zn–Pb-(Fe)	Ruschița	Palaeozoic		Granodiorite/ diorite?	Lenses in schist, breccia-Gt skarn	Ep		Sp, Gn, Hm
Zn–Pb	Dognecea		J-K1	Granodiorite	Amass and chimneys at limestone/ schist contact, distal to Ocna de Fier		Hd, Tr, Wo	Sp, Gn. Hm, Py, (Mol)
Zn–Pb	Majdanpek-Tenka1, Severni River		J-K1	Unknown, at depth (?)	Irregular bodies at limestone/ dacite contact, distal to intrusive	Ep		Sp, Gn. Py

youngest age (38 ± 3 Ma) is from a dyke in the Timok Massif (Janković et al. 1981). Some authors (Soroiu et al. 1986; Strutinski et al. 1986) contend that Late Cretaceous–earliest Palaeocene magmatic activity lasted no longer than 10–15 million years and dismiss the young ages as a consequence of alteration and subsequent rejuvenation. Other authors (e.g. Russo-Săndulescu et al. 1984, 1986; Kräutner et al. 1986; Cioflica et al. 1995) argue for a longer BMMB span of 30 million years or more, extending into the Palaeocene–Eocene.

Apart from questionable evidence for plutonic activity extending into the Palaeogene, there are several datasets for dyke swarms that are distinctly and systematically younger than Late Cretaceous. These represent intermediate composition rocks from the eastern Apuseni Mountains (Lemne et al. 1983) and alkali mafic and lamprophyre dykes from northern and eastern Poiana Ruscă (Kräutner et al. 1986; Downes et al. 1995). Their real significance is supported by the observation that ages of dykes related to older intrusive bodies, e.g. in Bihor (Bleahu et al. 1984) or Tincova-Izvodia (Cioflica et al. 1987a), are similar to those of their parent intrusion. This strongly suggests at least two periods of dyke emplacement, with the younger dyke suites reflecting a separate magmatic pulse recorded most consistently in the Apuseni Mountains or at Poiana Ruscă. This northern segment of the BMMB is characterised by thickened crust and strong Tertiary tectonism, which are related to Pannonian basin evolution. Therefore, the presence of younger dykes could be assigned to re-activation of magmatic activity caused by later tectonics, rather than to a final stage of banatitic magmatism sensu stricto. Late dykes with ages of 61–39 Ma also have been reported from easternmost Serbia (Jovanović et al. 2001) and adjacent parts of Bulgaria (45-42 Ma; Harkovska et al. 2001). These dykes, positioned near the junction of the South Carpathians, Balkans and Serbo-Macedonian Massif (Fig. 2) may have resulted from later tectonic events.

Although both the lower and upper limits remain unresolved, the available K–Ar dataset gives a broad 25-million-year interval (~90 to ~65 Ma), for the main magmatic activity in the BMMB. The uncertainty regarding lower and upper limits is at least partially caused by analytical precision, but also to the inability of the K–Ar method to address specific problems such as excess argon and the cooling history versus time of emplacement and later tectonic rejuvenation.

The dataset shows that the ages for any given mode of magmatism (e.g. intrusions, lavas or dyke suites) across the area tend to overlap for each segment (Table 5, Fig. 4). The data distribution actually shows a similar interval (10–20 million years, sometimes as much as 30 million years) for each massif, ore field or even for clusters of small intrusions (e.g. Poiana Ruscă). This is sustained by field observations, which demonstrate the composite nature of most intrusive bodies and the fact that they are cut and surrounded by dense dyke swarms. There is no obvious correlation between composition

Table 3 Characteristics of BMMB porphyry deposits. *K2* Upper Cretaceous; *Mt* magnetite; *Py* pyrite; *Bn* bornite; *Cp* chalcopyrite; *Mol* molybdenite; *Sp* sphalerite; *Gn* galena; *PGM* platinum group minerals; *En* enargite; *Cov* covellite; Alteration: *X* major or dominant; *x* subordinate

Type	Deposit	Host rock				Causative porphyry Intrusive	Deposit characteristics	Alteration		Ore mineralogy		
		Basement		Volcanics (K2)	Porphyry intrusive			Potassic	Argillic	Stockwork		Related veins
		Schist	Granite							Oreshoots	Disseminations, veinlets, veins	
Cu–(Au)-(Mo)	Suvorov, Valea Mare; Vărad (Moldova Nouă)				X	Granodiorite	Intrusive centred, skarn features and halo	X	X		Cp, Py, Mol, Cp, Py	
Cu–(Au)	Majdanpek-Dolovi 1	X		X		Unknown	Above intrusive, at same level as massive sulphides		X		Cp, Py, PGM, (Mol)	
Cu	Cerovo			X		Unknown	Cementation zone					
Cu	Veliki Krivelj			X		Unknown	At the dyke swarm level, skarn features	X	x		Cp, Py, (Mol)	
Cu–(Au)	Bor			X		Unknown	Above intrusive, below massive sulphides		X		En, Cov, Cp, Py	
Cu–Au	Elatsite	X	X		X	Monzonite/diorite?	At monzonite/diorite dyke level, above intrusive?	X	x	Mt, Bn, PGM	Cp, Py, (Mol)	Sp, Gn, Cp
Cu–Mo	Medet				X	Granodiorite?	Monzo-diorite-centred	X	x		Cp, Mol, Py	
Cu–(Au)	Assarel	X	X		X	Granodiorite	Lateral to intrusive	x	X	Cp	Cp, Py, (Mol)	Sp, Gn, Cp
Cu	Tsar Assen			X	X	Granodiorite	Intrusive-centred		X		Cp, Py	
Cu	Vlaykov Vruh	X		X	X	Granodiorite	Apical	X	x		Cp, Py, (Mol)	Py

Table 4 Characteristics of BMMB epithermal massive sulphide deposits. *Py* pyrite; *Bn* bornite; *Cp* chalcopyrite; *En* enargite; *Gp* gypsum; *Anh* anhydrite. *LS* low-sulphidation; *HS* high-sulphidation; *IS* intermediate-sulphidation; *VMS* volcanogenic seafloor massive sulphide

Type	Deposit	Upper Cretaceous host rock		Relationship to porphyry	Deposit characteristics	Ore mineralogy	Gangue
		Volcano-plutonic	Volcano-sedimentary				
Cu, pyrite	Majdanpek	Within andesite		Adjacent and above porphyry at depth	LS, VMS-features	Cp, Py, Bn	Gp
Cu	Bor	Within andesite lava		Above stockwork and porphyry at depth	HS, VMS-features	Bn, Cp, En, Py	Anh, Gp
Au–Cu	Chelopech		At flysch/andesite lava contact	Unknown porphyry	HS, VMS and breccia features	Cp, Bn, En, Py	Anh, Gp
Cu	Krassen		At flysch/andesite lava contact	Satellite to Petelevo porphyry	HS, VMS-features	Cp, En, Py	Anh
Cu	Radka		At latite/andesite ash and tuff contact	Satellite to Tsar Assen porphyry	IS, VMS-features	Cp, Bn, Py, En	Gp
Cu–(Au)-pyrite	Elshitsa		At sub-volcanic dacite/ dacite lava contact	Satellite to Vlaykov Vruh porphyry (1 km along a fault strike)	LS, VMS-features	Cp, Py	Gp, Anh

(i.e. mafic or felsic) in the dyke suites and age; lamprophyres or aplites can be of similar ages. There is, however, a positive correlation between magmatic evolution and age datasets in individual fields in northwestern Banat (e.g. Russo-Săndulescu et al. 1986). Illustrative of this pattern are the Surduc and Bocşa Massifs, in which older ages are obtained for the primitive, alkali mafic units relative to younger, more evolved granodiorites. A similar trend is shown for the Hăuzeşti intrusion, where an evolution from mafic to intermediate magma is mirrored in the age data (Cioflica et al. 1994).

Soroiu et al. (1986) attempted to prove the temporal-zonal distribution of banatites (Russo-Săndulescu et al. 1986; Cioflica et al. 1994) relative to arc evolution by dating rocks from across southern Banat. Data from the three main lineaments suggest no temporal zoning of banatite distribution, with similar age ranges for each alignment (Figs. 3 and 4).

Timing of hydrothermal ore formation

There are currently very few direct ages for mineralisation in the BMMB. Data are limited to a K–Ar age for hydrothermal phlogopite from the Băiţa Bihor Cu–Mo skarn deposit of 76 ± 3 Ma (Bleahu et al. 1984), a very similar Re–Os molybdenite age for the Dognecea deposit (Table 6), and a provisional Re–Os molybdenite age (ca. 80 Ma) for the Vlaykov Vruh porphyry deposit (Kouzmanov et al. 2001b). Potassic alteration and quartz–chalcopyrite stockwork veining at the Elatsite deposit is hosted in a major dyke, dated by U–Pb on magmatic zircons at 92.3 ± 1.4 and 91.41 ± 0.42 Ma (Fanger et al. 2001; Von Quadt et al. 2001). Ore-related hydrothermal K-feldspar + biotite give a Rb–Sr two-point isochron of 90.55 Ma, bracketing ore deposition at Elatsite between 94 and 90.5 Ma (Von Quadt et al. 2002).

Lilov and Chipchakova (1999), in a detailed K–Ar investigation of fresh igneous rocks and minerals from altered rocks, assuming successive generations of magma emplacement and ore formation, provided a general geochronological framework for the entire Panagyurishte district. Several stages of alteration were proposed for some deposits (e.g. Chelopech; syn-ore alteration at 85–74 and 58–57 Ma). A single stage of alteration was found in others (e.g. Assarel; 86–81 Ma from sericite ages on altered quartz monzodiorite and trachytic andesite). Two stages of intrusion and alteration were recognised at the Medet deposit. The first occurred at 88–87 Ma, following quartz monzodiorite emplacement at 90–88 Ma, and the latter between 85–76 Ma, following granodiorite emplacement at 87–86 Ma. These ages differ from earlier K–Ar data at Medet in which the monzodiorite is suggested to have been emplaced at 92–90 Ma, the granodiorite emplaced at 77–75 Ma, and, using hydrothermal K-feldspar in altered rocks, mineralisation occurred at 77–72 Ma (Bogdanov 1980). In the southern part of the

Table 5 Age determinations of 'banatitic' rocks (K–Ar unless otherwise stated). *Qz* Quartz; *P* porphyry; *Px* pyroxene; *WR* whole rock; *Bt* biotite; *Hb* hornblende; *FM* given in reference as 'femic' minerals. Laboratory/method: *IGG* Institute of Geology and Geophysics, Bucharest; *INPE* Institute of Nuclear Physics, Bucharest; *ATOMKI* Debrecen, Hungary. *NA* Determination of K by fast neutron activation and radiogenic Ar by thermal neutron activation; *ID* radiogenic Ar analysed by isotope dilution (where not stated, this was not given in reference). The asterisks represent features mentioned in the next column to the right (weakly altered samples in one case, drillcore samples in a second case

Location	Rock type	Fraction	Age	Reference	Lab (method)
			(Ma)		
Romania					
Apuseni Mountains					
E Apuseni (Gilău border)					
Băişoara	Granodiorite	Biotite	71.0 ± 7.8	Lemne et al. (1983)	IGG (ID)
Cacova	Granodiorite	Biotite	61.4 ± 2.3		
Maşca	Dacite	Whole rock	63.4 ± 2.4		
	Andesite	Biotite	58.7 ± 2.2		
	Qz-andesite	Whole rock	54.8 ± 2.1		
Someşul Rece	Granodiorite	Whole rock	49.5 ± 1.9		
Valea Ierţii	Granodiorite	Biotite	53.4 ± 2.0		
W Apuseni					
Budureasa*	Granodiorite	FM	74 ± 3	Bleahu et al. (1984)	INPE (NA)
	Granodiorite	FM	73 ± 3	(from drill core)	
Pietroasa*	Granodiorite	Biotite	73 ± 3		
	Granodiorite	Biotite	72 ± 3		
	Granodiorite	Biotite	70 ± 3		
*Stînişoara**	Granodiorite	Biotite	72 ± 3		
	Granodiorite	Biotite	72 ± 3		
Leşu Dam (V. Iadului)	Rhyolite	Whole rock	61 ± 3		
Bihor Massif					
	Basalt dyke	Whole rock	77 ± 3	Bleahu et al. (1984)	INPE (NA)
	Basalt dyke	Whole rock	74 ± 3	(from drill core)	
*Băita Bihor**	Basalt dyke	Whole rock	74 ± 3		
	Skarn	Phlogopite	76 ± 3		
	Granodiorite	FM	67 ± 3		
	Basalt dyke	Whole rock	75 ± 3		
Biharia	Basalt dyke	Whole rock	70 ± 3		
	Andesite dyke	Whole rock	65 ± 3		
Bihor batholith	Granodiorite	Whole rock	70 ± 5	Pavelescu et al. (1985)	Rb–Sr
S Apuseni					
Almăşel	Granodiorite	Biotite	74 ± 3	Bleahu et al. (1984)	INPE (NA)
Birtin (Vaţa)	Granodiorite	Whole rock	75 ± 3	Ştefan et al. (1992)	IGG (ID)
	Granodiorite	Whole rock	68 ± 3	Unpublished	
	Granodiorite	Whole rock	61 ± 3	Bleahu et al. (1984)	INPE (NA)
Băiţa	Porphyrite	FM	66 ± 3		
Ampoita	Andesite	FM	77 ± 3		
Ighiel Valley	Andesite	FM	73 ± 3		
Poieni	Granodiorite	Biotite	70 ± 3		
Bulzul Valley	Granodiorite	FM	68 ± 3		
Mureş Valley					
Roşcani	Andesite	Whole rock	71.7 ± 2.7	Downes et al. (1995)	ATOMKI (ID) and Leeds Univ.

Herepea	Basaltic andesite	Whole rock	66.0 ± 2.7		
	Basaltic andesite	Whole rock	65 ± 2.5	Vâjdea and Tănăsescu (unpublished) IGG (ID)	
South Carpathians					
Poiana Ruscă					
Panc	Alkali basalt		59.7 ± 2.2	Downes et al. (1995)	ATOMKI (ID) and Leeds Univ.
	Alkali basalt		57.7 ± 1.7		
	Cerbal	Alkali basalt	49.7 ± 1.9		
Alkali basalt			47.12 ± 1.4		
Hăuzeşti intrusion	Gabbro	WR remnant	110.0 ± 5.5	Cioflica et al. (1994)	ATOMKI (ID)
	(same sample)	Magnetite	104.2 ± 4.8		
	(same sample)	Feldspar	91.7 ± 3.6		
	Monzonite–diorite	WR remnant	85.3 ± 4.5		
	(same sample)	Magnetite	91.0 ± 4.1		
	(same sample)	Biotite	87.3 ± 3.4		
	(same sample)	Feldspar	79.8 ± 3.1		
	Monzonite–granite	Whole rock	81.1 ± 3.1		
Hăuzeşti intrusion	Spessartite dyke	Whole rock	74.9 ± 2.9	Cioflica et al. (1994)	ATOMKI (ID)
Jureşti	Monzonite–diorite	Whole rock	77.2 ± 3.0		
Drinova	Andesite	Whole rock	77.2 ± 3.1		
Tincova-Izvodia	Granodiorite	Biotite	82 ± 3	Cioflica et al. (1987b)	INPE (NA)
Intrusion	P-granodiorite*	Biotite	81.7 ± 2.5	Strutinski et al. (1986)[a]	
	Granodiorite	Biotite	81 ± 3		
	P-granodiorite*	FM	81.3 ± 2.4		
Dykes	Microgranite	Feldspar	90 ± 5		
	Andesite	Feldspar	81 ± 3		
	Lamprophyre	Whole rock	81 ± 3		
	Rhyolite	Biotite	80 ± 3		
	Microgranite	Feldspar	78 ± 3		
	Microdiorite	Whole rock	77 ± 3		
	P-diorite*	FM	64.4 ± 1.9		
Vălişor intrusion	Monzodiorite enclave	Bt/Hb	91 ± 4	Cioflica et al. (1987b)	INPE (NA)
	Monzodiorite	Bt/Hb	86 ± 3		
	Monzodiorite	Bt/Hb	82 ± 3		
	Microdiorite enclave	Hornblende	78 ± 3		
	Monzonite–diorite	Whole rock	68.0 ± 2.6	Cioflica et al. (1994)	ATOMKI (ID)
Vălişor area	P-diorite	FM	80.9 ± 2.4	Strutinski et al. (1986)	ATOMKI (ID)
	P-diorite	FM	78.1 ± 2.3		
	P-diorite	FM	72.0 ± 3.0		
	P-diorite	FM	72.7 ± 2.2		
	Aplite	Whole rock	72.6 ± 2.2		
	P-diorite	FM	72.7 ± 3.6		
	Basic tuffite	FM	67.8 ± 2.0		
Ruscă Montană volcano-sedimentary basin					
Ruschţta	Camptonite	FM	81.8 ± 2.4		
	P-granodiorite	Biotite	80.3 ± 2.4		
	Qz-P-diorite	Biotite	80.1 ± 2.4		
	Quartz-porphyry	Whole rock	77.4 ± 2.3		
	Latite	Whole rock	76.2 ± 2.3		
	Basaltoid andesite	Whole rock	75.8 ± 2.3		
	Granodiorite	Biotite	75.5 ± 2.3		
	Qz-P-diorite	FM	74.1 ± 2.2		
	Granodiorite	Biotite	70.8 ± 2.1		
	Dacite	Whole rock	69.3 ± 2.1		

Table 5 (Contd.)

Location	Rock type	Fraction	Age	Reference	Lab (method)
			(Ma)		
Glimboca-Ruschiţa	Granodiorite	Whole rock	76.2 ± 3.5	Kräutner et al. (1986)	IGG (ID)
Intrusive rocks	P-granodiorite	Whole rock	72.5 ± 9.8		
	Granodiorite	Biotite	70.8 ± 1.9		
	Granodiorite	?	68.8 ± 2.6		
	P-granodiorite	Whole rock	68.7 ± 2.6		
	Granodiorite	Whole rock	67.5 ± 2.6		
	Granodiorite	Whole rock	65.5 ± 2.5		
	Granodiorite	Whole rock	63.3 ± 2.6		
	Granodiorite	Whole rock	63.0 ± 2.5		
	Granodiorite	Whole rock	60.6 ± 2.7		
	P-granodiorite	Whole rock	60.0 ± 2.6		
	Granodiorite	Biotite	59.9 ± 2.4		
	P-granodiorite	Biotite	56.3 ± 2.1		
	Microdiorite	Whole rock	54.4 ± 2.3		
	Granodiorite	Whole rock	54.1 ± 2.4		
Extrusive rocks	Welded tuff	Whole rock	82.0 ± 3.1	Kräutner et al. (1986)	IGG (ID)
	Andesite fragment	Whole rock	79.3 ± 3.2		
	Welded tuff	Whole rock	70.7 ± 2.7		
	Px-andesitic tuff	Whole rock	66.1 ± 2.5		
Rusca Montană volcano-sedimentary basin					
Extrusive rocks	Welded tuff	Whole rock	54.5 ± 2.1	Kräutner et al. (1986)	IGG (ID)
Lamprophyre dykes	Camptonite	Kataphorite	53.4 ± 3.1		
	Camptonite	Kataphorite	46.4 ± 2.3		
	Camptonite	Whole rock	44.5 ± 2.1		
	Camptonite	Whole rock	38.8 ± 1.9		
Banat					
Surduc Massif					
Surduc 1	Qz-monzonite–diorite	Whole rock	75.56 ± 2.73	Russo-Săndulescu et al. (1986)	IGG (ID)
	Qz-monzonite–diorite	Whole rock	74.25 ± 3.05		
	P-monzonite	Biotite	68.4 ± 2.47		
	Qz-gabbro	Biotite	68.32 ± 2.48		
	Qz-gabbro	Whole rock	68.09 ± 2.8		
Surduc 2	Monzogranite	Biotite	62.23 ± 2.3		
	Monzogranite	Biotite	55.42 ± 2.68		
Bocşa Massif					
Bocşa 1	Monzonite	Biotite	87.94 ± 3.27	Russo-Săndulescu et al. (1986)	IGG (ID)
Bocşa 2	Monzonite–granite	Whole rock	81.17 ± 3.10		
	Monzonite–granite	Biotite	80.01 ± 2.90		
Bocşa 3	Granodiorite	Biotite	65.57 ± 2.47		
	Granodiorite	Biotite	56.79 ± 2.32		
	Granodiorite	Zircon	79.6 ± 2.5 (mean of 8)	Nicolescu et al. (1999)	U–Pb zircon (Stockholm Univ.)
Ocna de Fier-Dognecea intrusion	Granodiorite	Zircon	75.5 ± 1.6 (mean of 9)	Nicolescu et al. (1999)	U–Pb zircon (Stockholm Univ.)
Dognecea		Molybdenite	76.6 ± 0.3	(this paper)	Re–Os (AIRIE)

Ciclova–Oraviţa (CO)	Diorite	Biotite	79 ± 3	Soroiu et al. (1986)	INPE (NA)
	Diorite	Biotite	79 ± 3	Weakly altered sample	
	Diorite	Biotite	77 ± 3		
	P-granodiorite	Biotite	74 ± 3		
CO Brădişorul de Jos	Granodiorite*	Biotite	67 ± 3	Soroiu et al. (1986)	INPE (NA)
Moldova Nouă	P-granodiorite*	Biotite	69 ± 3	Weakly altered sample	
Lăpuşnicu Mare	P-granodiorite	Biotite	76 ± 3		
	P-granodiorite*	Biotite	73 ± 3		
	P-granodiorite*	Biotite	71 ± 3		
Bănia	P-granodiorite*	Biotite	78 ± 3		
Şopotu Vechi	Qz-monzonite–diorite	Hornblende	89 ± 4		
	Qz-P-monzonite	Biotite	83 ± 3		
Mehadica	Granodiorite	Biotite	78 ± 3		
Borlovenii Vechi (Nera)	P-diorite	Hornblende	76 ± 4		
Borlovenii Vechi (Nera)	P-diorite	Hornblende	76 ± 4		
Serbia					
South Carpathians					
Ridanj-Krepoljin belt					
Dykes and shallow intrusions		Various	74–70	Karamata et al. (1997a)	ATOMKI (ID)
Dacites, andesites, rhyolites			(rejuvenated at 60)		
Drill core (Ridanj, Reškovica): Granodiorite, P-Qz-diorite					
Timok Massif					
E Timok (ET)	Hb and Bt–Hb andesite	Various	90–80	Karamata et al. (1997a)	ATOMKI (ID)
ET (Čoka Marin, Bor)	Dacite/Andesite	Various	70–63		
W Timok	Hb–Px-andesite/latite	Various	80–72		
Intrusions/younger lavas	Various	Various	75–62		
Majdanpek	Pegmatite vein	K-feldspar	93 ± 4	Janković et al. (1981)	IGEM Moscow
Čoka Marin	Bt–Hb andesite	Amphibole	85.5 ± 3.4	Karamata et al. (1997b)	ATOMKI (ID)
	(same sample)	Whole rock	58.8 ± 2.5		
	(same sample)	Feldspar	56.3 ± 2.8		
	Px–Hb andesite	Whole rock	83.8 ± 3.8		
	Hb andesite*	Whole rock	82.89		Univ. Geneva
	Dacite–andesite (min)	Whole rock	72.6 ± 3.2		ATOMKI (ID)
	P-diorite	Whole rock	69.6 ± 4.1		
	Qz–P-diorite	Whole rock	69.1 ± 3.5		
	Bt–Hb andesite	Whole rock	63.9 ± 2.4		
	Dacite–andesite	Whole rock	62.92		Univ. Geneva
Zlot	Latite	Whole rock	80 ± 4	Janković et al. (1981)	IGEM Moscow
Valja Strž	Monzonite	Whole rock	78 ± 4	Weakly altered sample	
Crni Vrh	Diorite	Whole rock	71 ± 6		
Velja Pester	Bt–Hb–Qz-diorite	Whole rock	67		
Bogovina	Kajanite	Whole rock	38 ± 3		
Bor area					
Bor	Dacite*	Whole rock	79 ± 4		
Borska Reka	Hb–Bt-andesite*	Whole rock	78 ± 4		
Veliki Krivelj	P-diorite	Whole rock	76 ± 6		
Bor ore deposit zone	Hb-andesite	Hornblende	89.7 ± 3.6	Banjesevic (2001)	
Widen zone SW of Bor	Px-basaltic andesite	Whole rock	76.7 ± 3.0		

Table 5 (Contd.)

Location	Rock type	Fraction	Age (Ma)	Reference	Lab (method)
Bulgaria					
Srednogorie					
Western Srednogorie					
Intrusives			89–73	Dabovski et al. (1991)	
Vitosha Massif	Monzonite		83 ± 6	Lilov (1989)	Rb–Sr
Central Srednogorie					
Panagyurishte	Volcanic rocks		94–64	Dabovski et al. (1991)	
Panagyurishte	Intrusive rocks		80–69		
Elatsite deposit	Monzodiorite porph.	Zircon	92.3 ± 1.4	von Quadt et al. (2001)	U–Pb zircon (ETH Zurich)
		Zircon	91.41 ± 0.42		
	K-feldspar-biotite 2-pt. cooling age		90.55	von Quadt et al. (2002)	Rb–Sr
Elatsite-Chelopech ore field	Stage II magmatites	Whole rock	91–90	Lilov and Chipchakova (1999)	
	Stage IV magmatites	Whole rock	67–65		
Medet–Assarel ore field	Stage II magmatites	Whole rock	91–88		
	Stage III magmatites	Whole rock	87–86		
Medet deposit	Q-monzodiorite		90–92	Bogdanov (1980)	
	Granodiorite porphyry		77–75		
Southern Panagyurishte	Stage II magmatites	Whole rock	90	Lilov and Chipchakova (1999)	
	Stage III magmatites	Whole rock	88–85		
	Stage IV magmatites	Whole rock	75–67		
Vlaykov Vruh deposit		Molybdenite	ca. 80	Kouzmanov et al. (2001b)	Re–Os (Geneva)
Iskar-Yavoritsa shear zone					
Varshilo pluton	Leucogranite	Zircon	82.25 ± 0.4	Peycheva et al. (2001)	U–Pb zircon (ETH Zurich)
Outcrop near Vetren	Gabbro	Zircon	81.3 ± 1.5		
Marika intrusive rocks			91–69	Dabovski et al. (1991)	
Eastern Srednogorie					
Strandza volcanics			84–81	Dabovski et al. (1991)	
Yambol-Burgas	Volcanic rocks		84–73		
Yambol-Burgas	Intrusive rocks		80		
North Burgas	Volcanic rocks		77–70		

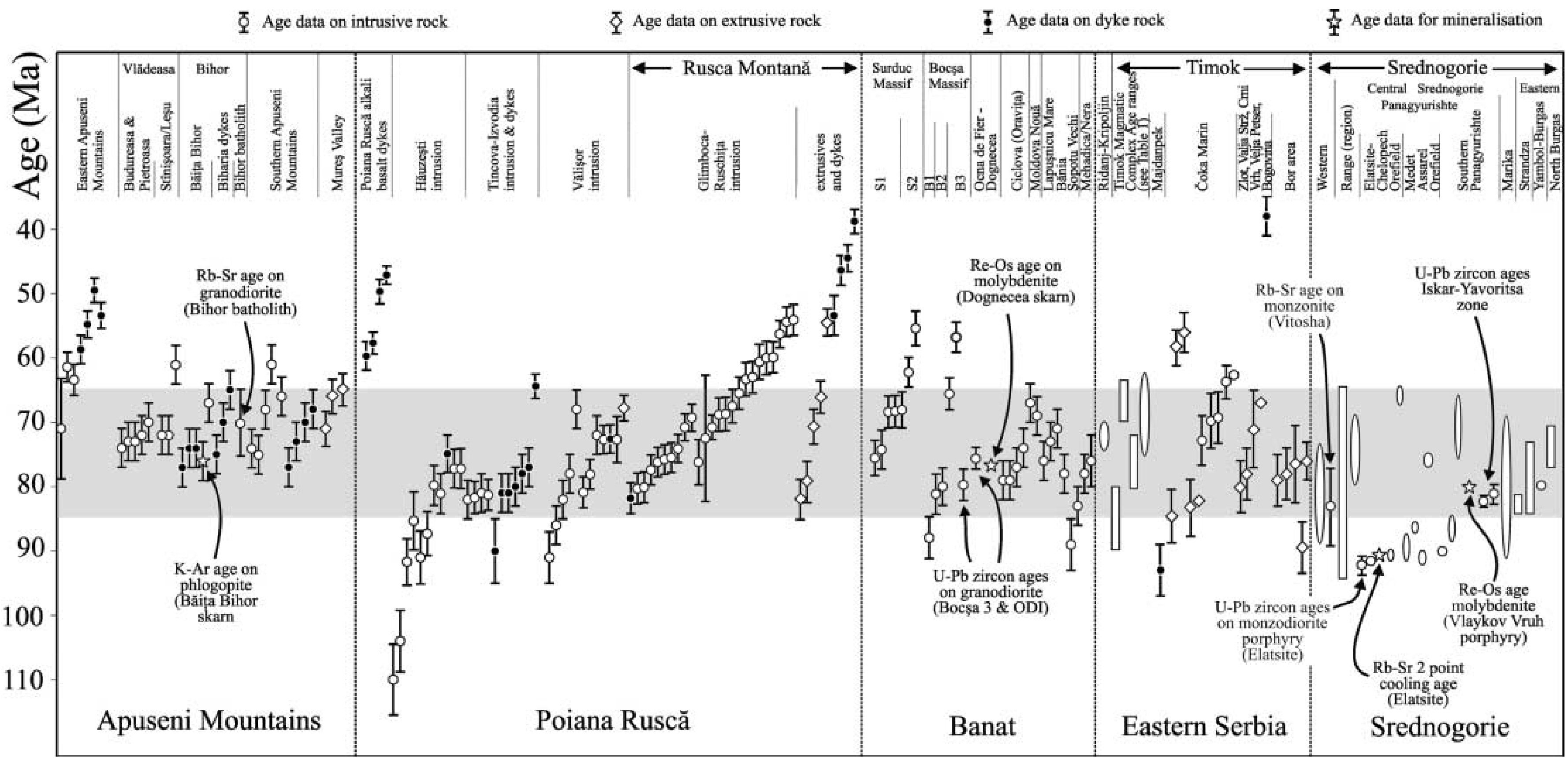


Fig. 4 Graphic summary of radiometric age data, with *error bars* as given by original sources (Table 5). Published age ranges as *ellipses* (intrusive rocks) and *bars* (extrusive rocks). Age data, in the same sequence as Table 5, are arranged from left to right on the diagram. Within each district dataset, ages are sorted by decreasing age. The *central, darker band* shows the main period of magmatic activity (85–65 Ma)

Panagyurishte district, Lilov and Chipchakova (1999) reported K–Ar data for intrusion and related porphyry alteration at the Petelevo, Tsar Assen and Vlaykov Vruh deposits (87–85, 88–86 and 86–85 Ma, respectively), which contrast sharply with ages of alteration minerals in ‘massive sulphides’ at Krassen, Radka and Elshitsa (78–71, 78–77 and 81–79 Ma, respectively). Given the limitations of the K–Ar method in complex, poly-stage porphyry deposits, where barren and mineralisation-related alteration stages may overlap, these data remain to be refined to properly constrain age of mineralisation relative to magmatism. In contrast, the K–Ar method is more reliable to date ore formation using K-bearing minerals in skarn, e.g. phlogopite, given the unequivocal paragenetic relationships.

Re–Os dating of molybdenite from Dognecea

To provide a reference point for the timing of skarn formation in Banat, we have dated magmatic-hydrothermal activity at the Dognecea deposit using Re–Os in molybdenite. Unlike in other deposits, molybdenite is restricted to scarce occurrences within uncommon quartz-rich skarn in the Ocna de Fier-Dognecea district, linking it to skarn formation. Our sample consists of well-crystallised, centimetre-sized platelets of molybdenite from underground at Dognecea. General principles and methodology for molybdenite dating are outlined in Stein et al. (1998a, 1998b). Sample-to-sample reproducibility, illustrating the robustness of the chronometer, has been documented (e.g. Watanabe and Stein 2000). Molybdenite presents a unique situation for the Re–Os method of dating in that it usually contains ppm level Re and essentially no initial or common Os, making it a single mineral chronometer. The mineral separate was prepared at AIRIE (Stein et al. 1998a) and Re and Os concentrations were determined at the AIRIE molybdenite laboratory at Colorado State University. For this study, a Carius-tube digestion was used, whereby molybdenite is dissolved and equilibrated with Re and Os spikes in HNO_3–HCl (aqua regia) by sealing in a thick-walled glass ampule and heating for 12 h at 230 °C. Osmium is subsequently recovered by solvent extraction using CCl_4, and Re is recovered by anion exchange. Purified Re and Os are loaded onto platinum filaments and isotopic compositions are determined using NTIMS on a NBS 12-inch radius, 90° sector mass spectrometer. Two molybdenite standards, developed at AIRIE, are run routinely as an internal check (Markey et al. 1998).

The sample gave an age of 76.6 ± 0.3 Ma (Table 6), which overlaps, at the 2σ level, with the U–Pb zircon age given by Nicolescu et al. (1999) for the Ocna de Fier-Dognecea intrusion (75.5 ± 1.6 Ma). The age of intrusion and mineralisation, thus, is younger than that of the barren Bocşa-3 unit (mean U–Pb zircon age, 79.6 ± 2.5 Ma, Nicolescu et al. 1999). The Re–Os age shows that skarn mineralisation is contemporaneous with granodiorite emplacement and links the Dognecea mineralisation conclusively to the Ocna de Fier-Dognecea intrusion. The precise Re–Os age for mineralisation at Dognecea, coupled with the U–Pb zircon data for the granodiorite (Nicolescu et al. 1999), substantiates the centred source model for the entire ore field (Cook and Ciobanu 2001). The data obtained by two reliable precise methods provide a point of reference for discussion of other deposits in the BMMB. In other ore fields (e.g. Oraviţa-Ciclova, Băiţa Bihor), molybdenite is widespread in skarns, hornfels and intrusions. Systematic investigation of Re–Os ages of molybdenite in each of these rock types may be necessary to establish the timing of skarn formation.

Table 6 Re–Os age for a molybdenite from the Dognecea deposit, Romania

Sample number	AIRIE run	Re (ppm)[a]	^{187}Re[a] (ppm)	^{187}Os[a] (ppb)	Age[b,c,d] (Ma)
OdFD.99G1	CT-212	1524 (1)	957.9 (9)	1224 (2)	76.6 ± 0.3

[a] Re and ^{187}Os uncertainties in parentheses are absolute at 2σ uncertainty for the last digit indicated

[b] Uncertainties include error in (1) ^{185}Re and ^{190}Os spike calibrations, 0.05 and 0.15%, respectively, (2) magnification with spiking, (3) mass spectrometric measurement of isotopic ratios, and (4) the ^{187}Re decay constant (0.31%)

[c] Molybdenites rarely require a blank correction. In the AIRIE molybdenite laboratory, blanks are Re = 17–18 pg, Os = 6–8 pg with a variable ^{187}Os/^{188}Os ranging from 0.5 to 8.3

[d] Age is calculated by $^{187}Os = {}^{187}Re\,(e^{\lambda t}-1)$ where $\lambda = {}^{187}$Re decay constant and t = age; ^{187}Re decay constant used is 1.666×10^{-11} yr^{-1} with an uncertainty of 0.31% (Smoliar et al. 1996); uncertainty shown for age is absolute at 2σ

Discussion and conclusions

Formation of the BMMB as a Late Cretaceous magmatic arc in the terminal stages of Vardar subduction was governed by differing types of extensional regimes in the collisional orogens of the Carpathians and Balkans as a consequence, in part, of their inherited Early to Mid-Cretaceous geologies. In the western part of the BMMB (Apuseni Mountains, Poiana Ruscă, Banat), magma emplacement was facilitated by extension subsequent to gravitational collapse and metamorphic core exhumation. This is evidenced by ‘Gosau’-type basins and the deep roots of magma chambers at the borders between mountain ranges and adjacent basins. In contrast, a sustained extensional regime is indicated from trough-graben structures with thick (2–8 km) volcano–plutonic and –sedimentary piles in the central and eastern parts of the belt (Timok and Srednogorie).

The difference in local geodynamics within the same collisional orogen is revealed by comparison of metallogenetic trends in the South Carpathians. A gradational change between ores in the two above extensional settings is emphasised by the transition from dominant skarn to porphyry between Banat and Timok. To emphasise this transition, Moldova Nouă is a porphyry copper deposit with only minor skarn, whereas in both the Oraviţa-Ciclova and Sasca Montană ore fields, copper-skarns are dominant, despite the fact that the three ore fields have comparable settings, i.e. similar relationships between intrusions and carbonate units. In Timok, distal Zn–Pb skarn, rather than copper skarn, occurs peripheral to the porphyry-copper deposits wherever carbonates are present in the ore fields (e.g. at Majdanpek, Veliki Krivelj). Likewise, a comparison between low-grade, sporadic porphyry mineralisation in Poiana Ruscă and the giant tonnages in the Bor district shows the impact of variable extensional regimes on metal concentration.

The role played by tectonics upon magmatism/mineralisation during BMMB formation is further stressed by recent data from the southern Srednogorie, near the boundary with the Rhodopes, within the Iskar Yavoritsa shear zone (IYSZ; Fig. 2). A series of plutons from Elshitsa (southern Panagyurishte) to Vitosha (south-western central Srednogorie) are regarded as broadly coeval with development of this shear zone (Ivanov et al. 2001. Gold mineralisation is hosted within the IYSZ (e.g. the Dikanyite prospect at the southern border of Vitosha). The 83–80-Ma intrusions have comparable isotopic signatures to elsewhere in the belt (Peycheva et al. 2001).

Even though methodologies and relative precisions differ, the available radiometric data indicate that the BMMB was formed by protracted igneous activity, maybe extending for as much as 25–30 million years within each segment of the belt. Dates for hydrothermal ore formation are very sparse, but the Re–Os molybdenite age from the Dognecea deposit and K–Ar phlogopite age from the Băiţa Bihor deposit are remarkably similar (77–76 Ma). This may suggest that skarn mineralisation relates to a broad tectonic event that extended from the Apuseni Mountains to Banat, and that ultimately controlled intrusion emplacement and ore formation in the western part of BMMB. In the BMMB, as in other belts of the ABCD realm, mineralisation events are relatively late in the orogenesis and are characteristically triggered by short-lived events that allow transfer of magma/fluids/metals to shallow structural levels (c.f. Neubauer 2001).

In contrast, dates for porphyry deposits at both ends of Panagyurishte district indicate a narrower range of ~10–14 million years across the district. A provisional Re–Os age of molybdenite in at the Vlaykov Vruh porphyry deposit, southern Panagyurishte (~80 Ma; Kouzmanov et al. 2001a) is comparable with the skarn ages from the Apuseni Mts and Banat. In northern Panagyurishte, a significantly older age-range (between 94 and 90.55 Ma; Von Quadt et al. 2002) has been considered for the mineralisation in the Elatsite porphyry.

These data leave open several questions. How many mineralising events took place along/across the belt? Can different metal sources be identified? Last, but not least, what are the constraints upon the timing of these events relative to overall geodynamics during belt formation? Careful observation of geological relationships between dykes and ore distribution/grades in conjunction with precise geochronometers for igneous (e.g. U–Pb on zircons) and hydrothermal events (e.g. Re–Os on molybdenite) offer a promising avenue for further work, to elucidate the geodynamic evolution of magmatism and ore formation in the BMMB.

Acknowledgements We are grateful to Ion Gheuca, IGR, Bucharest, who greatly assisted us by providing digital versions of published 1:1 million scale geological maps of Romania and adjacent areas of Serbia. We sincerely thank Constantin Gruescu for providing the sample of molybdenite analysed in this study. Helpful, constructive reviews by Tudor Berza and an anonymous referee are gratefully appreciated, as are the insightful and thorough comments of Chris Heinrich and Richard Goldfarb. All the following have assisted us greatly with fieldwork along the BMMB: B. Găbudeanu (NAMR, Bucharest), G. Fodor (Minvest SA, Deva), R. Câmpeanu and O. Kiss (SM Băiţa Bihor), V. Marcu (SM Iara), V. Sereţan and V. Ciocan (Formin SA, Caransebeş), I. Căpriţă (IM Bocşa), S. Boroancă (Formin SA, Oraviţa), E. Nagy (Moldomin SA, Moldova Nouă), D. Balica, (Moldova Nouă), D. Kozelj, B. Vučković and R. Lakota (Bor Copper Institute), K. Bogdanov (University of Sofia) and A. Arisanov (Navan-Chelopech AD).

References

Andrei J, Cristescu T, Calota C, Proca A, Romanescu D, Russo-Săndulescu D, Ştefan A, Suceavă M, Bradu M, Hannich D, Albaiu M (1989) Spatial distribution and structural images of banatites from Romania deduced from gravity and magnetic data. Rev Roum Géol Géophys Géogr Géophys 33:79–85

Angelkov K, Parvanov B (1980) The Assarel porphyry copper deposit, Bulgaria. In: Janković S, Sillitoe RH (eds) European copper deposits. Soc Geol Appl Ore Deposits Spec Publ 1: 59–62

Antonijević I, Grubić A, Djordjević M 11(1974) The Upper Cretaceous palaeorift in Eastern Serbia. In: Karamata S (ed) Metallogeny and concepts of the geotectonic development of Yugoslavia. Belgrade, pp 315–339

Balintoni I (1998) The Apuseni Mountains. In: CEI CERGOP Study Group (eds) Reports on geodesy. Monograph of southern Carpathians. Geotectonic analysis of the region of central Europe, no 8. Warsaw Univ of Technology/Inst of Geodesy and Geodetic Astronomy 7(37), pp 93–101

Banjesevic M (2001) The volcanic rocks petrology and K–Ar areas for Widen Zone Bore ore deposit as the part of the Timok magmatic Complex (East Serbia). J Conf Abstr 6(1):269

Berbeleac I, Lazăr C, Florescu R, Cîmpeanu N, Cîmpeanu S, Constantinescu E, Covrig L, Itu V (1980) The Laramian base metal occurrences from Bucea-Cornişel area (Plopiş Mountains). DS Inst Geol Geofiz 47(2):29–54

Berza T, Balintoni I, Iancu V, Seghedi A, Hann HP (1994) South Carpathians. ALCAPA II. Field guidebook, pp 37–50

Berza T, Constantinescu E, Vlad SN (1998) Upper Cretaceous magmatic series and associated mineralisation in the Carpatho-Balkan Orogen. Resour Geol 48:291–306

Bleahu M (1976) Structural position of the Apuseni Mountains in the Alpine System. Rev Roum Géol Géophys Géogr Géol 20:7–19

Bleahu M, Soroiu M, Catilina R (1984) On the Cretaceous tectonic–magmatic evolution of the Apuseni Mountains as revealed by K–Ar dating. Rev Roum Phys 29:123–130

Boccaletti M, Manetti P, Peccerillo A (1974) The Balkanids as an instance of back-arc thrust belt: possible relation with the Hellenids. Geol Soc Am Bull 85:1077–1084

Boccaletti M, Manetti P, Peccerillo A, Stanisheva-Vassileva G (1978) Late Cretaceous high-potassium volcanism in eastern Srednogorie, Bulgaria. Geol Soc Am Bull 89:439–447

Bogdanov B (1980) Massive sulphide and porphyry copper deposits in the Panagyurishte District, Bulgaria. In: Janković S, Sillitoe RH (eds) European copper deposits. SGA Spec Publ 1:50–58

Bogdanov B (1982) Bulgaria. In: Dunning FW, Mykura W, Slater D (eds) Mineral deposits of Europe, vol 2: Southeast Europe. Mineralogy Society and Institute of Mineralogy and Metallurgy, London, pp 215–232

Bogdanov B (1987) Copper deposits of Bulgaria (in Bulgarian). 'Technica', Sofia

Bogdanov K, Vavelidis M (2000) Bismuth minerals from ore deposits in Bulgaria and Greece. Ann Univ Sofia 'St Kliment Ohroidski', Fac Geol Geogr, Livre 1-Geol 92:75–84

Bogdanov K, Mladenova V, Breskovska V (1994) Mineralization of Zidarovo ore field (in Bulgarian). Ore Form Process Mineral Deposits 35:32–41

Bogdanov K, Tsonev D, Kuzmanov K (1997) Mineralogy of gold in the Elshitsa massive sulphide deposit, Sredna Gora zone, Bulgaria. Miner Deposita 32:219–229

Bojar AV, Neubauer F, Fritz H (1998) Cretaceous to Cenozoic thermal evolution of the southwestern South Carpathians: evidence from fission-track thermochronology. Tectonophysics 297:229–249

Bončev E (1976) Lineament-geosynclinal zones – zones of impermanent riftogenesis. Geol Balcanica 6:85–100

Bonev PK (1974) Ore formation and genesis of the Bakadjik gold-polymetallic deposit, south-eastern Bulgaria. In: Problems of ore deposition. Proceedings of the 4th International Association of the Genesis of Ore Deposits Symp, vol 1, pp 226–232

Bonev IK, Kerestedjian T, Atanassova R, Andrew CJ (2002) Morphogenesis and composition of native gold in the Chelopech volcanic-hosted Au–Cu epithermal deposit, Srednogorie zone, Bulgaria. Miner Deposita (in press) DOI 10.1007/s00126-002-0273-8

Borcoş M, Kräutner HG, Udubaşa G, Săndulescu M, Năstăseanu S, Biţoianu C (1984) Geological Atlas 1:1,000,000, map of the mineral resources. Explanatory note. Ministry of Geology, Inst Geol Geophys, Bucharest

Borcoş M, Vlad Ş, Udubaşa G, Găbudeanu B (1998) Qualitative and quantitative metallogenetic analysis of the ore genetic units in Romania. Rom J Mineral Deposits Spec Issue 78:1–158

Burchfiel BC (1980) Eastern European Alpine system and the Carpathian orocline as an example of collision tectonics. Tectonophysics 63:31–61

Channell JET, Kozur HW (1997) How many oceans? Meliata, Vardar, and Pindos oceans in Mesozoic Alpine palaeogeography. Geology 25:183–186

Ciobanu CL, Cook NJ (2000a) Intergrowths of bismuth sulphosalts from the Ocna de Fier Fe-skarn deposit, Banat, Southwest Romania. Eur J Mineral 12:899–917

Ciobanu CL, Cook NJ (2000b) Ore genesis and zoning in the Ocna de Fier-Dognecea orefield, Banat, Romania. In: Geodynamics and ore deposits evolution of the Alpine–Balkan–Carpathian–Dinaride Province, ABCD-GEODE Workshop, Borovets, Bulgaria, Abstr vol 18

Ciobanu CL, Cook NJ (2001) Retrograde carbo-fracturing and resulting textures from Fe-skarn ores, Ocna de Fier-Dognecea, SW Romania. In: Piestrzynski A et al. (eds) Mineral deposits at the beginning of the 21st century. Balkema, Lisse, pp 885–888

Cioflica G (1960) Contribution to the understanding of contact phenomenon at the Măgureaua Vaţei contact (Drocea Mts). Stud Cerc Geol 5:509–518

Cioflica G (1989) Copper mineralizations related to Upper Cretaceous–Palaeogene magmatites in Romania. Rev Roum Géol Géophys Géogr Géol 33:13–26

Cioflica G, Vlad ŞN (1973) The correlation of Laramian metallogenic events belonging to the Carpatho-Balkan area. Rev Roum Géol Géophys Géogr Ser Géol 17:217–224

Cioflica G, Vlad Ş (1981) Cupriferous mineralization at Ciclova (in Romanian). An Univ Bucureşti Ser Geol 30:1–17

Cioflica G, Vlad Ş, Stoici S (1971) Répartition de la minéralisation dans les skarns de Băiţa Bihorului. Rev Roum Géol Géophys Géogr Ser Géol 15:43–58

Cioflica G, Vlad Ş, Volanschi E, Stoici S (1977) Magnesian skarns and associated mineralization at Băiţa Bihor (in Romanian). St Cerc Geol Geofiz Geogr, Ser Geol 22:39–57

Cioflica G, Berbelac I, Lazăr C, Ştefan A, Vlad Ş (1982) Metallogeny related to Laramian magmatism in the Bihor Mountains (northern Apusenides, Romania). An Univ Bucureşti 31:3–12

Cioflica G, Jude R, Jude L, Lupulescu M (1985) Contributions on the knowledge of copper–molybdenum–bismuth mineralisation associated with banatites in the Tincova region (Poiana Ruscă Mountains) (in Romanian). St Cerc Geol Geofiz Geogr Ser Geol 30:27–42

Cioflica G, Jude R, Jude L, Lupulescu M (1987a) Contributions to the study of contact phenomena in the Tincova area (Poiana Ruscă Mts.). Rev Roum Géol Géophys Géogr Ser Géol 31:3–14

Cioflica G, Jude R, Jude L, Lupulescu M, Catilina R, Soroiu M (1987b) New K–Ar Ages of Banatitic Magmatites in the Tincova Area (Poiana Ruscă Mountains). An Univ Bucureşti 36:3-10

Cioflica G, Jude R, Lupulescu M (1992a) Evidence of porphyry copper mineralizations and additional remobilisation phenomena in the Lilieci-Purcaru area (Banat, Romania). Rev Roum Géol Géophys Géogr Ser Géol 36:3–14

Cioflica G, Jude R, Lupulescu M (1992b) Cupriferous metallization processes associated with Upper Cretaceous–Eocene magmatites from Romania. Rom J Mineral 76:1–16

Cioflica G, Pécskay Z, Jude R, Lupulescu M (1994) K–Ar ages of Alpine granitoids in the Hăuzeşti–Drinova area (Poiana Ruscă Mountains, Romania). Rev Roum Géol 38:3–8

Cioflica G, Jude R, Lupulescu M (1995) Petrometallogenetic models in the areas with the end Maastrichtian–Palaeocene granitoid intrusions of Romania. Stud Univ Babeş-Bolyai Geol 40:41–54

Cioflica G, Jude R, Lupulescu M, Ducea M (1996) Lower crustal origin of the Late Cretaceous–Eocene arc magmatism in the western part of the South Carpathians, Romania. In: Knežević V, Krstić B (eds) Terranes of Serbia. Belgrade, pp 103–107

Cocić S, Petrović, Cocić M (2001) Geological characteristics of the copper deposit Cementacija-3 – Kraku Bugaresku (in Serbo-Croat). Bakar-Copper 26:31–44

Constantinescu E (1980) Mineralogy and genesis of the skarn deposit at Sasca Montană (in Romanian). Ed Acad Rep Soc România, Bucharest

Constantinescu E, Ilinca G, Ilinca A (1988) Laramian hydrothermal alteration and ore deposition in the Oraviţa-Ciclova area. Southwestern Banat. DS Inst Geol Geofiz 72–73(2):13–26

Cook NJ, Ciobanu CL (2001) Paragenesis of Cu–Fe ores from Ocna de Fier-Dognecea (Romania), typifying fluid plume mineralisation in a proximal skarn setting. Mineral Mag 65:351–372

Csontos L (1995) Tertiary tectonic evolution of the Intra-Carpathian area: a review. Acta Volcanol 7:1–13

Dabovski C (1980) Magmatotectonic features of Upper Cretaceous intrusives in the Srednogorie zone: field and experimental evidence for a rift model. Geol Balcanica 10(1):15–29

Dabovski C, Harkovska A, Kamenov B, Mavrudchiev B, Stanisheva-Vassileva G, Yanev Y (1991) A geodynamic model of the Alpine magmatism in Bulgaria. Geol Balcanica 21(4):3–15

Dallmeyer RD, Neubauer F, Handler R, Fritz H, Müller W, Pană D, Putis M (1996) Tectonothermal evolution of the internal Alps and Carpathians: evidence from $^{40}Ar/^{39}Ar$ mineral and whole-rock data. Eclogae Geol Helv 89:203–227

Dallmeyer RD, Pană DI, Neubauer F, Erdmer P (1999) Tectonothermal evolution of the Apuseni Mountains, Romania: resolution of Variscan versus Alpine events. J Geol 107:329–352

Dewey J, Pitman W, Bonnin J (1973) Plate tectonics and evolution of the Alpine system. Geol Soc Am Bull 85:1429–1440

Downes H, Vaselli O, Seghedi I, Ingram G, Rex D, Coradossi N, Pécskay Z, Pinarelli L (1995) Geochemistry of late Cretaceous–early Tertiary magmatism in Poiana Ruscă (Romania). Acta Vulcanol 7:209–217

Dragov P, Petrunov R (1996) Elazite porphyry copper–precious metals (Au and PGE) deposit. Proc Annu Meeting IGCP Project 356, Sofia, pp 171–175

Drovenik M, Djordjević M, Antonijević I, Mičić I (1967) Les roches magmatiques de la region éruptive de Timok. Acta Geol Acad Sci Hung 11:115–129

Dupont A, Vander Auwera J, Pin C, Marincea Ş, Berza T (2002) Trace element and isotope (Sr, Nd) geochemistry of Upper Cretaceous intrusions from Banat, western South Carpathians, Romania. Miner Deposita (in press) DOI 10.1007/s00126-002-0274-7

Fanger L, Driesner T, Heinrich CA, Von Quadt A (2001) Elatsite porphyry Cu deposit, Bulgaria: mineralisation, alteration and structures. In: Piestrzynski A et al. (eds) Mineral deposits at the beginning of the 21st century. Balkema, Lisse, pp 527–529

Gheorghiţă I (1974) Geological and petrographic study of the Moldova Nouă region (Suvorov-Valea Mare zone) (in Romanian). St Tehn Econ Inst Geol 11:7-188

Gheorghiţescu D (1972) Considerations on the skarn mineralogy and cupriferous mineralisation of Varad (in Romanian). St Cerc Geol Geogr Geofiz Ser Geol 17:49–66

Gheorghiţescu D (1975) Mineralogical and geochemical study of formations in the thermal, metasomatic contact at Oraviţa (Cosoviţa) (in Romanian). DS Inst Geol Geofiz 61:59–103

Gheorghiţescu D, Papp A, Andăr P (1980) Metamorphosed base metal mineralizations of Răchiţele, Vlădeasa Massif, Apuseni Mountains (in Romanian). DS Inst Geol Geofiz 63(2):57–90

Giuşcă D, Volanschi E (1968) Geochemistry of polymetallic sulphide deposits of Ruschiţa, Poiana-Ruscă (in Romanian). Stud Cerc Geol Geofiz, Ser Geol 13:33–42

Giuşcă D, Berbeleac I, Lazăr C, Întorsureanu I (1976) The zonality of hydrometasomatic metamorphism and Laramian metallogenesis from the Brusturi-Luncşoara region (Bihor Mts.) (in Romanian). Stud Cerc Geol Geofiz Geograf Ser Geol 21:31–44

Gunnesch RA (1982) Laramide igneous rocks and related porphyry copper occurrences of Southwest Romania. In: Amstutz GC, El-Goresy A, Frenzel G, Kluth C, Moh GH, Wauschkuhn, Zimmermann RA (eds) Ore genesis; the state of the art. Springer, Berlin Heidelberg New York, pp 319–335

Haas J, Kovács S, Krystyn L, Lein R (1995) Significance of Late Permian–Triassic facies zones in terrane reconstructions in the Alpine-North Pannonian domain. Tectonophysics 242:19–40

Harkovska A, Cvetković V, Pécskay Z (2001) Kraishte magmatotectonic zone (KMTZ – Western Bulgaria) and Ridanj-Krepoljin belt (RKB – East Serbia) – a comparative review of the calc-alkaline magmatism. Pancardi 2001 abstr vol, Geodetic Geophys Res Inst, Hung Acad Sci, Sopron, CP-10

Hedenquist JW, Arribas A Jr, Reynolds TJ (1998) Evolution of an intrusion-centered hydrothermal system: far southeast-Lepanto porphyry and epithermal Cu–Au deposits, Philippines. Econ Geol 93:373–404

Hippolyte JC, Bădescu D, Constantin P (1999) Evolution of the transport direction of the Carpathian belt during its collision with the east European Platform. Tectonics 18:1120–1138

Hsü KJ, Nachev IK, Vuchev VT (1977) Geologic evolution of Bulgaria in light of plate tectonics. Tectonophysics 40:245–256

Istrate G, Udubaşa G (1981) Metallogeny of the banatitic massif from Budureasa, Apuseni Mountains (in Romanian). DS Inst Geol Geofiz 65(2):5–19

Ivanov Z, Henry B, Dimov D, Georgiev N, Jordanova D, Jordanova N (2001) New model for upper Cretaceous magma emplacement in the southwestern parts of Central Srednogorie – petrostructural and AMS data. Rom J Mineral Deposits 79(Suppl 2):60–61

Ivanova-Panayotova V (1974) The Krumovo iron deposit. In: Dragov P, Kolkovski B (eds) Twelve ore deposits of Bulgaria. International Association of the Genesis of Ore Deposits, Sofia, pp 182–191

Janković S (1990) Types of copper deposits related to volcanic environment in the Bor district, Yugoslavia. Geol Rundsch 79:467–478

Janković S (1997) The Carpatho-Balkanides and adjacent area: a sector of the Tethyan Eurasian metallogenic belt. Miner Deposita 32:426–433

Janković S, Jelenković R (1997) Correlation between the Oraviţa-Krepoljin and the Bor-Srednjegorie metallogenic zones. Rom J Mineral Deposits 78:57–70

Janković S, Terzić M, Aleksić D, Karamata S, Spasov T, Jovanović M, Miličić M, Mišcović V, Brubić A, Antonijević I (1980) Metallogenic features of copper deposits in the volcano-intrusive complexes of the Bor District, Yugoslavia. In: Janković S, Sillitoe RH (eds) European copper deposits. SGA Spec Publ 1:42–49

Janković S, Jovanović S, Karamata S, Lovrić A (1981) The isotopic age of some rocks from the Timok eruptive area (in Serbo-Croat). Acad Serbe Sci Arts, Classe Sci Naturelles Math 48:87–94

Janković S, Herrington RJ, Kozelj D (1998) The Bor and Majdanpek copper–gold deposits in the context of the Bor metallogenic zone (Serbia, Yugoslavia). In: Porter TM (ed) Porphyry and hydrothermal copper and gold deposits; a global perspective; conference proceedings. Australian Mineral Foundation, Glenside, South Australia, pp 169–178

Jelenković R, Vakanjac B (1999) Paragenetic features and model of development of the Veliki Krivelj copper deposit (Serbia). Geol Macedonica 13:23–30

Jovanović M, Downes H, Vaselli O, Cvetković V, Prelević D, Pécskay Z (2001) Palaeogene mafic alkaline volcanic rocks of East Serbia. Acta Vulcanol 13(1)

Karamata S, Knežević V, Pécskay Z, Djordjević M (1997a) Magmatism and metallogeny of the Ridanj–Krepoljin belt (eastern Serbia) and their correlation with northern and eastern analogues. Miner Deposita 32:452–458

Karamata S, Živković P, Pécskay Z, Knežević V, Cvetković V (1997b) Geological setting and age of the Coka Marin polymetallic ore deposit (Eastern Serbia). Rom J Miner Deposits 78:79–84

Karamata S, Dimitrijević NM, Dimitrijević DM (1999) Oceanic realms in the central part of the Balkan Peninsula during the Mesozoic. Slovak Geol Mag 5:173–177

Kissling A (1967) Mineralogical and petrographic studies of the exoskarn zone at Ocna de Fier (Banat) (in Romanian). Ed Acad Rep Soc România, Bucharest

Kouzmanov K, Bogdanov K, Ramboz C (2000) Cu–Bi–Pb–Te mineral assemblage in the Elshitsa and Radka deposits, Sredna Gora zone, Bulgaria. In: Geodynamics and ore deposits evolution of the Alpine–Balkan–Carpathian–Dinaride Province. ABCD-GEODE Workshop, Borovets, Bulgaria, Abstr vol 39

Kouzmanov K, Moritz R, Chiaradia M, Fontignie D, Ramboz C (2001a) Sr and Pb isotope study of Au–Cu epithermal and porphyry-Cu deposits from the southern part of the Panagyurishte district, Sredna Gora zone, Bulgaria. In: Piestrzynski A et al. (eds) Mineral deposits at the beginning of the 21st century. Balkema, Lisse, pp 539–542

Kouzmanov K, Moritz R, Chiaradia M, Ramboz C (2001b) Mineralogy, fluid inclusion study, and Re–Os dating of Mo-bearing mineralisation from the Vlaikoiv Vrah porphyry copper deposit, Panagyurishte district, Bulgaria: preliminary results. J Conf Abstr 6(1):557

Kouzmanov K, Bailly L, Ramboz C, Rouer O, Bény JM (2002) Morphology, origin and IR-light microthermometry of fluid inclusions in pyrite from the Radka copper deposit, Bulgaria. Miner Deposita (in press). DOI 10.1007/s00126-002-0270-y

Kozelj DI, Jelenkovic (2001) Ore forming environments of epithermal gold mineralisation in the Bor metallogenetic zone, Serbia, Yugoslavia. In: Piestrzynski A et al. (eds) Mineral deposits at the beginning of the 21st century, Balkema, Lisse, pp 535–538

Kräutner HG (1996) Genetic models for Variscan ore deposits in the Romanian Carpathians. In: Grecula P (ed) Variscan metallogeny in the Alpine orogenic belt. Mineralia Slovaca Monograph, Bratislava, pp 109–128

Kräutner HG, Vâjdea E, Romanescu O (1986) K–Ar dating of the banatitic magmatites from the southern Poiana Ruscă Mountains (Rusca Montană sedimentary basin). DS Inst Geol Geofiz 70-71(1):373–388

Lazăr C, Întorsureanu I (1981) The Maşca-Băişoara iron deposit, Apuseni Mountains (in Romanian). DS Inst Geol Geofiz 66(2):45–69

Lemne M, Vâjdea E, Borcoş M, Tănăsescu A, Romanescu O (1983) Des datations K–Ar concernant surtout les magmatites subséquentes Alpines des Monts Apuseni. An Inst Geol Geofiz 61:1–12

Lilov P (1989) Rubidium–strontium dating of the Vitosha Pluton (in Bulgarian). Rev Bulg Geol Soc 50(1):100–105

Lilov P, Chipchakova S (1999) K–Ar dating of the Upper Cretaceous magmatic rocks and hydrothermal metasomatic rocks from the Central Srednogorie (in Bulgarian). Geochem Mineral Petrol 36:77–91

Linzer HG, Frisch W, Zweigel P, Girbavea R, Hann HP, Moser F (1998) Kinematic evolution of the Romanian Carpathians. Tectonophysics 297:133–156

Marincea S (1999) Ludwigite from the type locality, Ocna de Fier, Romania; new data and review. Can Mineral 37:1343–1362

Marincea S (2000) The influence of Al on the physical and crystallographic properties of ludwigite in three Romanian occurrences. Eur J Mineral 12:809–823

Marincea S (2001) New data on szaibelyite from the type locality, Băiţa Bihor, Romania. Can Mineral 39:111–127

Marincea S, Bilal E, Verkaeren J, Pascal M-L, Fonteilles L (2001) Superposed parageneses in the spurrite, tilleyite- and gehlenite-bearing skarns from Cornet Hill, Apuseni Mountains, Romania. Can Mineral 39:1435–1453

Markey RJ, Stein HJ, Morgan JW (1998) Highly precise Re–Os dating of molybdenite using alkaline fusion and NTIMS. Talanta 45:935–946

Maţenco L, Schmid S (1999) Exhumation of the Danubian nappes system (South Carpathians) during the Early Tertiary: inferences from kinematic and palaeostress analysis at the Getic/Danubian nappes contact. Tectonophysics 314:401–422

Maţenco L, Bertotti G, Dinu C, Cloetingh S (1997) Tertiary tectonic evolution of the external South Carpathians and the adjacent Moesian platform (Romania). Tectonics 16:896–911

Milev VR, Stanev VB, Ivanov VH (1996) Statistical manual of the ore production in Bulgaria during 1878–1995 (in Bulgarian). Zemia, Sofia

Miličić M, Grujičić B (1980) Metallogenic features of the Bor ore district. Guide for field excursions, European copper deposits, Belgrade. Bakar Printing House, Bor, pp 15–38

Mitchell AHG (1996) Distribution and genesis of some epizonal Zn–Pb and Au provinces in the Carpathian–Balkan region. Trans Inst Min Metall B105:127–138

Moritz R, Chambefort I, Chiaradia M, Fontignie D, Petrunov R, Simova S, Arisanov A, Doychev P (2001) The Late Cretaceous high-sulfidation Au–Cu Chelopech deposit, Bulgaria: geological setting, paragenesis, fluid inclusion microthermometry of enargite, and isotope study (Pb, Sr, S). In: Piestrzynski A et al. (eds) Mineral deposits at the beginning of the 21st century, Balkema, Lisse, pp 547–550

Mutschler FE, Ludington S, Bookstrom AA (1999) Giant porphyry-related metal camps of the world – a database. US Geol Survey Open File Report 99-556, Online Version 1.0

Neubauer F (2000) Cretaceous geodynamics and mineralisations along the Alpine–Carpathian–Balkan–Dinaride belt: why are the ore deposits mainly in southeastern sectors? In: Geodynamics and ore deposits evolution of the Alpine–Balkan–Carpathian–Dinaride Province. ABCD-GEODE Workshop, Borovets, Bulgaria, abstract vol 60

Neubauer F (2001) Geodynamic control of late-stage orogenic mineralisation in young orogenic belts: the Alpine–Carpathian–Balkan–Dinaride Mountain belt. J Conf Abstr 6(1):262

Neugebauer J, Greiner B, Appel E (2001) Kinematics of the Alpine–West Carpathian orogen and palaeogeographic implications. J Geol Soc Lond 158:97–110

Nicolescu S, Cornell DH (1999) P–T conditions during skarn formation in the Ocna de Fier ore district, Romania. Miner Deposita 34:730–742

Nicolescu S, Cornell DH, Bojar AV (1999) Age and tectonic setting of Bocşa and Ocna de Fier–Dognecea granodiorites (southwest Romania) and of associated skarn mineralisation. Miner Deposita 34:743–753

Panaiotu C (1998) Paleomagnetic constraints on the geodynamic history of Romania. In: Reports on geodesy. Monograph of southern Carpathians. CEI CERGOP study group no 8, geotectonic analysis of the region of Central Europe. Warsaw Univ of Technology/Inst of Geodesy and Geodetic Astronomy 7(37), pp 205–216

Pascal M-L Fonteilles M, Verkaeren J, Piret R, Marincea S (2001) The melilite-bearing high-temperature skarns of the Apuseni Mountains, Carpathians, Romania. Can Mineral 39:1405–1434

Pătraşcu S, Bleahu M, Panaiotu C (1990) Tectonic implications of paleomagnetic research into Upper Cretaceous magmatic rocks in the Apuseni Mountains, Romania. Tectonophysics 180:309–311

Pătraşcu S, Bleahu M, Panaiotu C, Panaiotu CE (1992) The palaeomagmatism of the Upper Cretaceous magmatic rocks in the Banat area of South Carpathians: tectonic implications. Tectonophysics 213:314–352

Pavelescu L, Pop GO, Weisz E, Popescu G (1985) La nature et l'âge du batholite banatique de Bihor. Report 12th Carpatho-Balkan Geological Association Congress, Krakow, pp 98–101

Petrunov R (1995) Ore mineral parageneses and zoning in the deposit of Chelopech (in Bulgarian). Geochem Mineral Petrol 30:89–98

Petrunov R, Dragov P (1993) PGE and gold in the Elacite porphyry copper deposit, Bulgaria. In: Fenoll Hach-Ali P, Torres-Ruiz J, Gervilla F (eds) Current research in geology applied to ore deposits. Univ Granada, Granada, pp 543–546

Petrunov R, Dragov P, Ignatov G, Neykov H, Iliev T, Vasileva N, Tsatsov V, Djunakov S, Doncheva K (1992) Hydrothermal PGE mineralization in the Elatsite porphyry-copper deposit (Sredna Gora metallogenic zone, Bulgaria). C R Acad Bulg Sci 45:37–40

Peycheva I, Von Quadt A, Kamenov B, Ivanov Z, Georgiev N (2001) New isotope data for Upper Cretaceous magma emplacement in the southern and south-western parts of Central Srednogorie. Rom J Miner Deposits 79(suppl 2):82–83

Popov PN (1981) Magmatectonic features of the Banat–Srednogorie Belt. Geol Balcanica 11(2):42–73

Popov PN (1987) Tectonics of the Banat–Srednogorie Rift. Tectonophysics 143:209–216

Popov PN (1995) Postsubduction Alpine metallogenic zones in the Balkan Peninsula. Geol Macedonica 9:97–101

Rădulescu D, Săndulescu M (1973) The plate-tectonics concept and the geological structure of the Carpathians. Tectonophysics 16:155–166

Rădulescu D, Săndulescu M, Borcoş M (1993) Alpine magmatogenetic map of Romania; an approach to the systematization of the igneous activity. Rev Roum Géol Géophys Géogr Ser Géol 37(2):3–8

Ratchbacher L, Linzer HG, Strusievicz RO (1993) Cretaceous to Miocene thrusting and wrenching along the central South Carpathians due to a corner effect during collision and orocline formation. Tectonics 12:855–873

Russo-Săndulescu D, Berza T (1979) Banatites from the Western part of the Southern Carpathians (Banat). Rev Roum Géol Géophys Géogr Ser Géol 23(2):143–158

Russo-Săndulescu D, Berza T, Bratosin I, Ianc R (1978) Petrological study of the Bocşa banatitic massif (Banat). DS Inst Geol Geofiz 64(1):105–172

Russo-Săndulescu D, Vâjdea E, Tănăsescu A (1984) Neocretaceous–Paleogene subduction igneous rocks in the Romanian Carpathians – mutual relationships, succession and areal distribution. An Inst Geol Geofiz 64:111–119

Russo-Săndulescu D, Vâjdea E, Tănăsescu A (1986) Significance of K–Ar radiometric ages obtained in the banatitic plutonic area of Banat. DS Inst Geol Geofiz 70-71(1):405–417

Săndulescu M (1984) Geotectonics of Romania (in Romanian). Ed Tehnică, Bucureşti

Săndulescu M (1988) Cenozoic tectonic history of the Carpathians. Am Assoc Petrol Geol Mem 45:17–25

Săndulescu M (1994) Overview on Romanian geology. Rom J Tect Reg Geol 75(suppl 2):3–15

Săndulescu M, Visarion M (2000) Crustal structure and evolution of the Carpathian–western Black Sea areas. First Break 18:103–108

Schmid SM, Berza T, Diaconescu V, Froitzheim N, Fuegenschuh B (1998) Orogen-parallel extension in the southern Carpathians. Tectonophysics 297:209–228

Sillitoe RH (1980) The Carpathian-Balkan porphyry copper belt – a Cordilleran perspective. In: Janković S, Sillitoe RH (eds) European copper deposits. SGA Spec Publ 1:26–35

Sillitoe RH, Hannington MD, Thompson JFH (1996) High sulfidation deposits in the volcanogenic massive sulfide environment. Econ Geol 91:204–212

Smoliar MI, Walker RJ, Morgan JW (1996) Re–Os isotope constraints on the age of Group IIA, IIIA, IVA, and IVB iron meteorites. Science 271:1099–1102

Soroiu M, Catilina R, Strutinski C (1986) K–Ar ages on some igneous rocks from the southwestern end of the South Carpathians (Banat Hills). Rev Roum Phys 31(3):849–854

Stampfli GM, Mosar J (1999) The making and becoming of Apulia. In: Gosso G, Jadoul F, Sella M, Spalla MI (eds) 3rd Workshop on Alpine Geological Studies. Mem Sci Geol Padova 51(1):141–154

Stampfli GM, Mosar J, De Bono A, Vavasis I (1998) Late Paleozoic, early Mesozoic plate tectonics of the Western Tethys. Bull Geol Soc Greece 32(1):113–120

Stanisheva-Vasslileva G (1980) The Upper Cretaceous magmatism in Srednogorie Zone, Bulgaria: a classification attempt and some implications. Geol Balcanica 10(2):15–36

Ştefan A, Lazăr C, Berbelac I, Udubaşa G (1988) Evolution of banatitic magmatism in the Apuseni Mountains and associated metallogenesis. DS Inst Geol Geofiz 62–73(2):195–213

Ştefan A, Roşu E, Andăr A, Robu L, Robu N, Bratosin I, Grabari G, Stoian M, Vâjdea E, Colios E (1992) Petrological and geochemical features of banatitic magmatites in Northern Apuseni Mountains. Rom J Petrol 75:97–110

Stein HJ, Morgan JW, Markey RJ, Hannah JL (1998a) An introduction to Re–Os: what's in it for the mineral industry? Soc Econ Geol Newslett 32(1):8–15

Stein HJ, Sundblad K, Markey RJ, Morgan JW, Motuza G (1998b) Re–Os ages for Archean molybdenite and pyrite, Kuittila-Kivisuo, Finland and Proterozoic molybdenite, Kabeliai, Lithuania: testing the chronometer in a metamorphic and metasomatic setting. Miner Deposita 33:329–345

Stoici SD (1983) Districtul metalogenetic Băiţa Bihorului (in Romanian). Ed Acad Rep Soc România, Bucharest

Strashimirov S, Popov P (eds) (2000) Geology and metallogeny of the Panagyurishte Ore region (Srednogorie Zone, Bulgaria). Geodynamics and ore deposits evolution of the Alpine–Balkan–Carpathian–Dinaride Province. ABCD-GEODE Workshop, Borovets, Bulgaria, Guide to excursions A and C. Publishing House St Ivan Rilski, Sofia

Strashimirov S, Petrunov R, Kanazirski M (2002) Mineral associations and evolution of hydrothermal systems in porphyry copper deposits from the Central Srednogorie zone (Bulgaria). Miner Deposita (in press). DOI 10.1007/s00126-002-0275-6

Strutinski C, Soroiu M, Paica M, Todros C, Catilina R (1986) Preliminary data on the K–Ar ages of the Alpine magmatites between Tincova and Ruschiţa (south-western Poiana Ruscă). DS Inst Geol Geofiz 70–71(1):493–503

Tarkian M, Breskovska V (1995) Mineralogy and fluid inclusion study of the Zidarovo copper polymetallic deposit, eastern Bulgaria. N Jahrb Mineral Abh 168:283–298

Tarkian M, Stribrny B (1999) Platinum-group elements in porphyry copper deposits: a reconnaissance study. Mineral Petrol 65:161–183

Tarkian M, Hünken U, Tokmakchieva M, Bogdanov K (1999) Palladium, Platin, Gold und Fluide Einschlüsse in der Porphyry Kupfer Lagerstätte Elacit (Bulgarien). Eur J Mineral 11(Beiheft 1):226

Tsonev D, Bogdanov K, Popov K (2000) The volcanic-hosted sulphide (VHS) deposits from the southern part of the Panagyurishte ore region, Bulgaria. In: Geodynamics and ore deposits evolution of the Alpine–Balkan–Carpathian–Dinaride Province. ABCD-GEODE Workshop, Borovets, Bulgaria, Abstract vol 85

Udubaşa G, Istrate G, Popa C (1980) Mineralizations of the Juleşti-Fagului Valley, Apuseni Mountains (in Romanian). DS Inst Geol Geofiz 63(2):185–211

Vlad ŞN (1974) Skarn mineral genesis at Dognecea (in Romanian). Ed Acad Rep Soc România, Bucharest

Vlad ŞN (1979) A survey of banatitic (Laramian) metallogeny in the Banat Region. Rev Roum Géol Géophys Géogr Ser Géol 23(1):39–44

Vlad ŞN (1997) Calcic skarns and transversal zoning in the Banat Mountains, Romania: indicators of an Andean-type setting. Miner Deposita 32:446–451

Von Cotta B (1864) Erzlagerstätten im Banat und in Serbien. W Braumüller, Vienna

Von Quadt A, Ivanov Z, Peycheva I (2001) The Central Srednogorie (Bulgaria) part of the Cu (Au–Mo) belt of Europe: a review of the geochronological data and the geodynamical models in the light of the new structural and isotopic studies.). In: Piestrzynski A et al. (eds) Mineral deposits at the beginning of the 21st century. Balkema, Lisse, pp 555–558

Von Quadt A, Peycheva I, Kamenov B, Fanger L, Heinrich CA (2002) The Elatsite porphyry-copper deposit in the Panagyurishte ore district (Srednegorei Zone, Bulgaria): U–PB zircon geochronology and isotope geochemical investigations of ore genesis. J Geol Soc Lond (in press)

Watanabe Y, Stein HJ (2000) Re–Os ages for the Erdenet and Tsagaan Suvarga porphyry Cu–Mo deposits, Mongolia, and tectonic implications. Econ Geol 95:1537–1542

Willingshofer E (2000) Extension in collisional orogenic belts: the Late Cretaceous evolution of the Alps and Carpathians. PhD Thesis, Netherlands Research School of Sedimentary Geology, publ 20000301

Willingshofer EF, Neubauer F, Cloetingh S (1999) The significance of Gosau-type basins for the Late Cretaceous tectonic history of the Alpine–Carpathian Belt. Phys Chem Earth 24:687–695

Willingshofer EF, Andriessen P, Cloetingh S, Neubauer F (2001) Detrital fission track thermochronology of Upper Cretaceous syn-orogenic sediments in the South Carpathians (Romania): inferences on the tectonic evolution of a collisional hinterland. Basin Res 13:379–395

Žák L, Frýda J, Mumme WG, Paar WH (1994) Makovickyite, $Ag_{1.5}Bi_{5.5}S_9$, from Băiţa Bihorului, Romania: The ^4P natural mineral member of the pavonite series. N Jahrb Mineral Abh 168:147–169

Zweigel P, Ratchbacher L, Frisch W (1998) Kinematics of an arcuate fold-thrust belt: the southern Eastern Carpathians (Romania). Tectonophysics 297:177–207