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Ore Geology Reviews 27 (2005) 95–126

ORE GEOLOGY REVIEWS

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3: Geochronology and geodynamics of Late Cretaceous magmatism and Cu–Au mineralization in the Panagyurishte region of the Apuseni–Banat–Timok–Srednogorie belt, Bulgaria

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Received 30 November 2004; accepted 20 March 2005
Available online 14 October 2005

Abstract

The Apuseni–Banat–Timok–Srednogorie (ABTS) belt, Europe's most extensive belt of calc–alkaline magmatism and Cu–Au mineralization, is related to the subduction of the Tethys ocean beneath the European continental margin during the Late Cretaceous phase of the Alpine–Himalayan orogeny. Economic deposits are restricted to certain segments along the belt, and all major porphyry-style and high-sulphidation ore deposits in Bulgaria are aligned on the Panagyurishte corridor, a narrow zone obliquely crossing the ABTS belt. This paper reviews the geology, geochemistry and geochronology of igneous and hydrothermal events along this corridor, in a profile extending from the European continental basement in the north to the accretionary complex of the Rhodopes in the south. Extensive U–Pb dating of zircons from subvolcanic intrusions and major plutons, supplemented by published age data for magmatic rocks and hydrothermal ore deposits obtained by other methods, reveals a general younging of magmatism from ca. 92 Ma in the north (Elatsite) to ca. 78 Ma in the south (Capitan Dimitrievo). Cu–Au deposits are restricted to the northern and central parts of the profile (ranging in age from ~92 to ~86 Ma), while the southernmost part exposes more deeply eroded mid-crustal plutons devoid of economic mineralization. The age progression correlates with a north-to-south geochemical trend of decreasing crustal input into mantle-derived magmas. Magmatism and ore formation in individual magmatic–hydrothermal complexes along the profile is much shorter lived. For example, subvolcanic intrusions and porphyry Cu–Au mineralization at the Elatsite deposit and andesitic volcanism and high-sulphidation Au–As–Cu mineralization at Chelopech all occurred within a time span of about 1 million years. The age progression of calc–alkaline magmatism within the Panagyurishte region, Bulgaria, from north to south is explained as a consequence of slab retreat during oblique subduction. This led to transtensional block faulting and subsidence, and thus to the preservation of near-surface magmatic–hydrothermal products, including economic Cu–Au deposits. Accretion of continental fragments in the Rhodopes

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doi:10.1016/j.oregeorev.2005.07.024

south of the ABTS belt led to greater uplift of the youngest Late Cretaceous intrusions. This removed any ore deposits that might have been formed in this area.

Keywords: Apuseni–Banat–Timok–Srednogorie (ABTS) belt; Panagyurishte; Bulgaria; U–Pb zircon; Rutile dating; Pb–Sr–Nd isotopes; Cu–Au porphyry; Cu–Au epithermal; Arc magmatism; Subduction retreat

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1. Introduction

As a part of the Alpine–Mediterranean mountain system, the Apuseni–Banat–Timok–Srednogorie (ABTS) belt (Fig. 1) resulted from subduction and obduction of former Mesozoic ocean basins and final collision of Africa with Europe and a number of smaller continental microplates (Jankovic, 1977b, 1997; Sandulescu, 1984, Mitchell, 1996; Berza et al., 1998; Stampfli and Mosar, 1999, Neubauer, 2002). The ABTS belt is part of the Tethyan Eurasian Metallogenic belt (TEMB) and includes some of the best examples of porphyry copper and Cu–Au epithermal ore deposit in Europe, in a broadly similar subduction setting to the circum-Pacific region (e.g., Sillitoe, 1991, 1999; Hedenquist and Lowenstern, 1994; Corbett and Leach, 1998; Tosdal and Richards, 2001, 2002). Active mines include Majdanpek, Bor and Veliki Krivelj in Serbia and Elatsite, Chelopech and Assarel in Bulgaria (see Moritz et al., 2004).

The ABTS belt (Popov and Popov, 2000, Popov et al., 2002) is an L-shaped structure of Late Cretaceous, broadly calc–alkaline, magmatic activity within the Alpine–Carpathian–Balkan orogen of eastern Central Europe. It can be traced from the North Apuseni Mountains and the Banat region in Romania and Serbia through the Serbian Timok and Ridanj–Krepoljin area to the Srednogorie zone in Bulgaria (Figs. 1 and 2), the latter comprising Late Cretaceous rocks from the western border of Bulgaria to the Black Sea. The belt is considered to extend farther to the north in the Western Carpathians, and to the east into northern Turkey, Iran, and south-east Afghanistan, reaching the Himalayas and building the “Tethyan Eurasian Metallogenic Belt” (Jankovic, 1977a,b). A great number of important ore deposits (mainly Cu–Au–Mo) have formed in this belt (Ciobanu et al., 2002).

Several attempts have been made to relate large-scale tectonic processes in the ABTS belt with associated Cu–Au mineralization (Jankovic, 1977a,b; Mitchell, 1996; Berza et al., 1998; Jankovic et al., 1998; Ciobanu et al., 2002; Popov et al., 2002, 2003). Major features of the Late Cretaceous to Tertiary ore deposits of the Alpine–Balkan–Carpathians–Dinaride (ABCD) region were compiled by Heinrich and Neubauer (2002), and a review of the knowledge about age relationships between regional tectonics and Late Cretaceous magmatism and ore formation was published by Ciobanu et al. (2002). Abundant new data on the geodynamic control of magmatic–hydrothermal systems, the geochronology and geochemistry of the Late Cretaceous magmatism, and the characteristics of the Cu–Au deposits have been added during the GEODE programme of the European Science Foundation. The region is well suited to study the time scales of tectonic and magmatic processes at the orogen scale, and to compare the life times of individual magmatic centres and those of single major ore deposits with that of the orogen as a whole.

Previous studies have addressed the question of the duration of hydrothermal systems linked to the genesis of ore deposits (Cathles et al., 1997; Marsh et al., 1997; Ballard et al., 2001). These papers suggest that a single upper crustal intrusion can remain partially molten for at most a few hundred thousand years, and that hydrothermal activity will wane after 100,000 years or less (Cathles et al., 1997). Marsh et al. (1997) showed for the Potrerillos district (Chile) that hydrothermal activity in porphyry-related systems lasted less than 40,000 years, and geochronological methods generally cannot resolve individual hydrothermal events within this short duration. Ballard et al. (2001) state that the giant porphyry copper deposit at Chuquicamata contains porphyries that were emplaced about 1 million years apart, which indicates at least two distinct magmatic–hydrothermal events with a resolvable time difference.

In the present review we first focus on the geological, geochronological and isotope geochemical char-

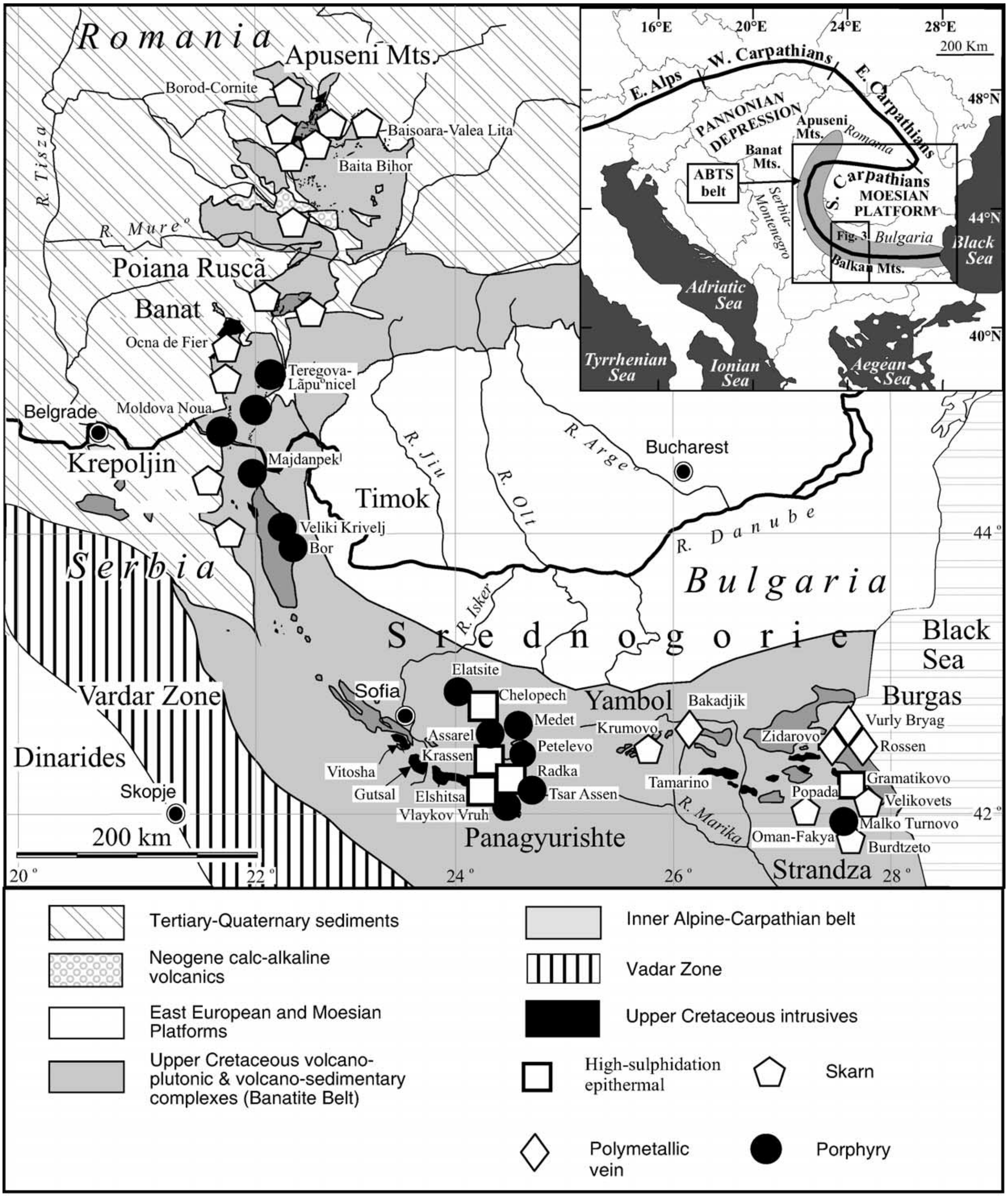

Fig. 1. Locations of the Late Cretaceous ABTS (Apuseni–Banat–Timok–Srednogorie) belt in Eastern Europe, modified after Heinrich and Neubauer (2002), the Serbo–Macedonian metallogenic belt and the Inner Carpathian metallogenic belt (modified after Berza et al., 1998; Ciobanu et al., 2002).

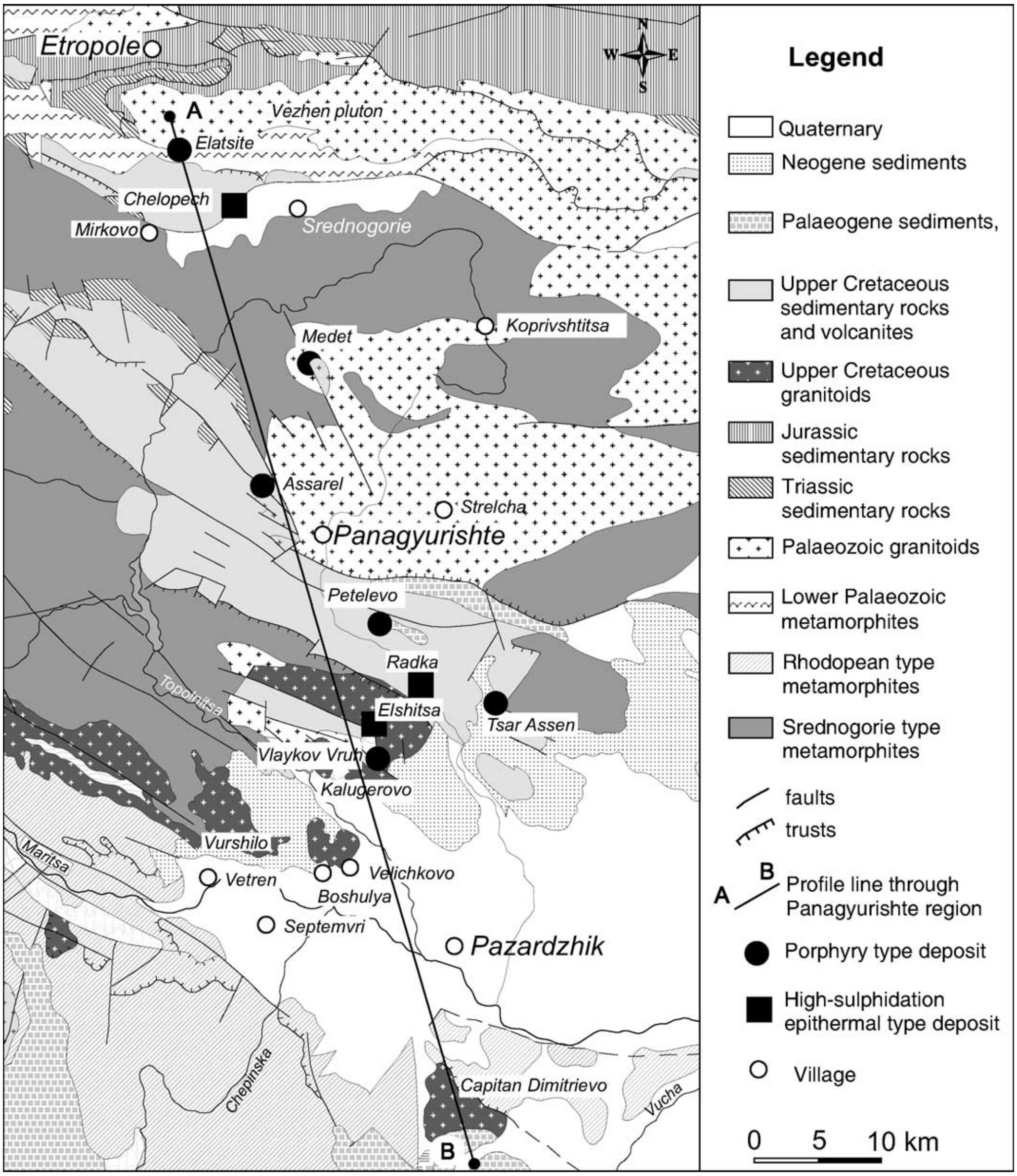

Fig. 2. Simplified geological map of the Etropole–Panagyurishte–Pazardzhik strip including porphyry and epithermal deposits (modified after Cheshitev et al., 1995; Peytcheva et al., 2003) and the profile line (A–B), see Fig. 12.

acteristics of Cretaceous magmatic rocks in the Pangyurishte district of the Central Srednogorie Zone of Bulgaria (Figs. 1 and 2). Fresh volcanic and intrusive igneous rocks are exposed together with Cu–Au porphyry/epithermal deposits at Elatsite, Chelopech, Medet, Assarel, Vlaykov Vruh, Krassen, Radka, Elshitsa and Tsar Assen along a NNE–SSW corridor of ca. 80 km length (Fig. 2). We then consider the changes in the tectonic environment and magmatic style across the belt, and understand why economic deposits were formed in some locations and at specific times. The results show that despite overall similarity in the geochemical features of the magmatic rocks, their location appears to influence the distribution of porphyry systems and epithermal ore deposits. Finally new high precision isotope data for the Panagyurishte transect summarized herein are used to establish the broader context of the evolution of the whole ABTS belt, with the aim of understanding the constraints on the regional geological setting and timing of fertile magmatism and mineralization.

2. Regional tectonic evolution and geodynamic setting

The Carpathian–Balkan orogen resulted from the convergence between Africa and Europe during the past 100 Ma (Müller and Roest, 1992; Wortel and Spakman, 2000). Fig. 3 (after Neubauer, 2002) shows a reconstruction of the Late Cretaceous plate configuration, based on palaeomagnetic data and interpretations by Willingshofer (2000) and Neugebauer et al. (2001). The Late Cretaceous units are divided into (1) the ALCAPA (ALpine–CArpathian–PAnnonian) block comprising the Austroalpine units in the Eastern Alps and inner Western Carpathians, (2) the Tisia block extending from Zagreb in Croatia to the Apuseni Mountains in Romania, (3) the Dacia block which includes the Eastern und Southern Carpathians and the Balkans, (4) the Rhodope block and (5) the South-Alpine Dinaric block (Figs. 2 and 3). The Moesian platform represents an indenter that is interpreted to have moved westwards during the Late Cretaceous and the Palaeogene due to the opening of the western Black Sea oceanic basin. The essential result of this restoration is that the ALCAPA, Tisia and Dacia blocks together formed an E–W-trending, straight orogen during the critical time at ca. 80 Ma when extensive magmatism occurred in the ABTS belt. Reconstructions indicate open oceanic tracts, both to the north and south of the Late Cretaceous orogenic belt. According to Neubauer (2002) it was attached to the Moesian platform in the east and to the Adriatic microplate in the west, either by continuous subduction or by collision along segments that are attached to continental blocks (Moesia/Europe) in the east and the Adriatic block in the west. Orogenic polarity of the closure and nappe stacking was, respectively, to the N and NW, rotating units back to their present-day positions (arrows in Fig. 3; e.g., Ratschbacher et al., 1993; Schmid et al., 1998, Neubauer, 2002).

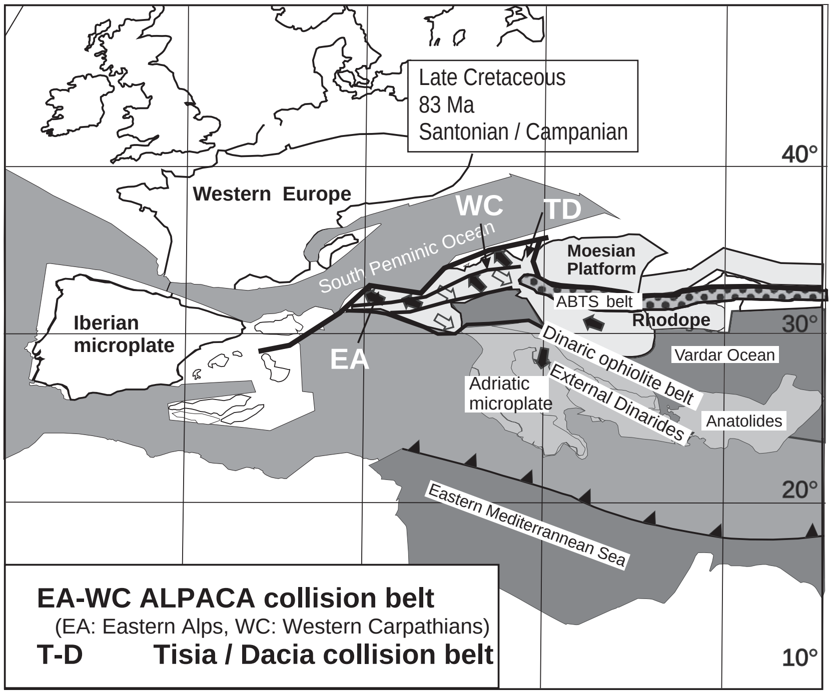

Fig. 3. Palaeogeographic reconstruction of the ABTS belt during Late Cretaceous time (Neugebauer et al., 2001; Neubauer, 2002).

Magmatism in the Srednogorie Zone (Figs. 1 and 2) is broadly related to subduction and has been related to a back-arc tectonic setting (Boccaletti et al., 1978) and associated mineralization. Seismic tomography studies have illustrated the long history (~100 million years) of northward subduction of the lithosphere at the southern margin of Europe (Wortel and Spakman, 2000) persisting to the present day subduction zone south of Crete and the extension of the Aegean back-arc basin. The Srednogorie Zone is the oldest stage of magmatism in this evolution, starting at ca. 90 Ma at the southern passive margin of Europe (Moesian Platform: Lips, 2002).

Hinge retreat (roll-back) has been proposed as an explanation for the long-term evolution for the last 100 million years including the present-day situation as imaged by seismic tomography (Wortel and Spakman, 2000). Magma generation is partly due to the liberation of water from the subducting slab, but may have been enhanced by asthenospheric upwelling attending back-arc extension and possibly by orogen-parallel extension (Neubauer, 2002). Recent geochronological and isotope geochemical data allow us to test this large-scale evolution for the incipient stage in the Late Cretaceous.

3. Late Cretaceous magmatism

Late Cretaceous magmatic products are exposed along most of the ABTS belt (Fig. 2). Some authors (e.g., Berza et al., 1998; Ciobanu et al., 2002; Neubauer, 2002) prefer to use the term “banatites” and BMMB (Banatitic Magmatic and Metallogenetic Belt) as originally proposed by von Cotta (1864). The magmatic products are represented in extrusive as well as intrusive rocks in large volcano–plutonic complexes (Fig. 2: Banat; Timok; Panagyurishte in Central Srednogorie; Zidarovo, Malko Turnovo, Oman Fakya in Burgas-Strandzha region). Four compositional trends are developed in the magmatic rocks of various regions: calc–alkaline, high-K to shoshonitic, tholeiitic, and a peralkaline trend (Dabovski et al., 1972, 1991; Stanisheva-Vassileva, 1980; Karamata et al., 1997; Berza et al., 1998; Kamenov et al., 2002, 2003a,b). Calc–alkaline rocks predominate and peralkaline rocks are restricted to eastern Srednogorie. The rock chemistry varies from gabbroic (basaltic) to granitic (rhyolithic). Intermediate compositions (andesites, diorites, and monzodiorites) prevail in the Timok and the Central Srednogorie regions. Silicic varieties are generally more widespread in the Apuseni–Banat region (in Romania), and mafic rocks are particularly abundant in the Eastern Srednogorie zone (Berza et al., 1998). Across the belt in the Eastern Srednogorie Zone, Stanisheva-Vassileva (1983) observed a zonation of tholeitic through calc–alkaline in the south to high potassium calc–alkaline, shoshonitic and even potassic alkaline products in the north, within the period between 100 and 80 Ma (for the tholeiites), and between 70 and 60 Ma (for the alkaline trachytes) based on K–Ar dating. In the Serbian part of the ABTS belt, Karamata et al. (1997) infer a migration of the Late Cretaceous “subduction-related” andesitic activity in the Timok region in the eastern part of the belt to more silicic and crust-influenced magmas in the Ridanj–Krepoljin region farther west. The north to south younging of magmatism is accompanied by changes in chemical and isotope characteristics in the Central Srednogorie region (von Quadt et al., 2003a,b).

A generally mixed crust and mantle source of the magmas or melted juvenile crust in the ABTS belt are shown by isotope characteristics: $^{87}Sr/^{86}Sr$ varies within the range 0.704 to 0.707 (Kouzmanov et al., 2001; Dupont et al., 2002; von Quadt et al., 2002, 2003a,b; Banjesevic et al., 2004) and ε_{Nd} ranges from $+3.9$ to -3 (Dupont et al., 2002; von Quadt et al., 2002, 2003a,b; this study).

4. Magmatic–hydrothermal ore deposits

The predominant ore-types in the ABTS belt are skarns, porphyry Cu–Mo–Au and high-sulphidation epithermal Au–Ag deposits (Berza et al., 1998; Ciobanu et al., 2002), with subordinate Cu and polymetallic vein deposits (Bogdanov, 1986; Tarkian and Breskovska, 1995). These deposits are distinctly clustered in five regions along the more continuous magmatic belt (Fig. 1): (1) the Apuseni Mountains in Romania, (2) the Poiana Rusca–Banat area in Romania, (3) the Bor–Veliki Krivelj–Majdanpek district of Timok in Serbia, (4) the Panagyurishte mineral district in Bulgaria, and (5) the Burgas district in Eastern Bulgaria.

Iron, copper, and lead–zinc skarns are the major ore-type in the Romanian part of the belt; i.e., the Apuseni Mountains and the Poiana Rusca–Banat areas. Porphyry copper deposits become more predominant in the southern part of Banat, southwards into the Timok region of Serbia, where they are associated with skarns and epithermal replacement deposits, and in the Panagyurishte mineral district in Bulgaria where they are solely associated with epithermal deposits. The Burgas district in the eastern part of the belt is characterized by the presence of Cu to polymetallic veins and skarns close to the Bulgarian–Turkish border. This variation in ore-type along the belt is interpreted to be a function of the types of host rocks, such as the presence or absence of carbonate rocks, the extent of the development of subvolcanic environments, the depth of ore formation, the tectonic setting and the type of magmatism (Berza et al., 1998; Ciobanu et al., 2002; Dupont et al., 2002; Heinrich and Neubauer, 2002).

Porphyry copper deposits are historically the most important and are still mined from Majdanpek, Bor and Veliki Krivelj in Serbia (Jankovic, 1990; Jankovic et al., 1998; Jelenkovic and Kozelj, 2002) and Elatsite and Assarel in Bulgaria (Strashimirov and Popov, 2000; Strashimirov et al., 2002; von Quadt et al., 2002; Moritz et al., 2004). They are hosted by the apical parts of subvolcanic to hypabyssal intrusions, and locally in volcanic and crystalline basement country rocks (Jankovic, 1997; Ciobanu et al., 2002; Strashimirov et al., 2002; von Quadt et al., 2002). The porphyry copper deposits are variably enriched in Au and Mo, which are mined as important by-products (Ciobanu et al., 2002). Compared with the porphyry copper deposits of the Panagyurishte district (Strashimirov et al., 2002), the porphyry copper deposits in the Bor district display a greater vertical zonation of mineralization styles and mineral assemblages (Jankovic et al., 2002). K–silicate alteration, surrounded by propylitic alteration, is recognized in the early hydrothermal stages of most porphyry copper deposits, with local overprints by sericite alteration, and at some localities advanced argillic alteration (e.g., Borska Reka: Jankovic, 1990; Assarel: Strashimirov et al., 2002). Pyrite and chalcopyrite are the most common ore minerals; bornite and magnetite are subsidiary and variable in abundance, and molybdenite, gold and platinum-group minerals are occasional (Bogdanov, 1986; Jankovic, 1990; Dragov and Petrunov, 1996; Strashimirov et al., 2002; Tarkian et al., 2003). Copper grades are generally below 0.4% and gold grades below 0.2 g/t; i.e., rather low compared with world standards (Kesler et al., 2002). There are only a few ages determined for the mineralization in the ABCD region. A Re–Os dating of molybdenite at the Dognecea deposit gave an age of 76.6 ± 0.3 Ma (Ciobanu et al., 2002), which overlaps with the ^{238}U/^{206}Pb zircon age for the Ocna de Fier–Dognecea intrusion (75.5 ± 1.6 Ma, ion-microprobe techniques; Nicolescu et al., 1999). At this location the Re–Os age shows that the skarn mineralization was contemporaneous with the granodiorite intrusion.

Particular chemical characteristics are the significant enrichments in platinum-group elements in the two major porphyry copper deposits at Madjanpek, Bor district, Serbia (Jankovic, 1997; Jankovic et al., 1998, 2002) and Elatsite, Panagyurishte district, Bulgaria (Petrunov and Dragov, 1993; Tarkian et al., 2003). Additionally, Co–Ni mineral assemblages are reported in a few porphyry copper deposits of the Panagyurishte district (Strashimirov et al., 2002). A prominent feature is the elevated Bi concentration in several ore deposits along the belt (e.g., Tarkian and Breskovska, 1995; Cook and Ciobanu, 2001, 2003; Strashimirov et al., 2002; Ciobanu et al., 2003).

Many of the *epithermal Cu–Au deposits* have a high-sulphidation character with variably massive development of pyrite as the main sulphide. Mineral assemblages include enargite, covellite, goldfieldite and advanced argillic alteration with vuggy quartz, alunite, kaolinite/dickite and zunyite; diaspore and pyrophyllite are common. High-sulphidation epithermal deposits of the Panagyurishte mineral district share a common paragenetic evolution including an early, massive pyrite stage, an intermediate Au-bearing Cu–As–S stage and a late base-metal stage (Petrunov, 1994, 1995; Strashimirov and Popov, 2000; Kouzmanov, 2001; Kouzmanov et al., 2001; Moritz et al., 2004). The early massive pyrite stage was interpreted by Bogdanov (1986) and Jankovic (1990) as an exhalative submarine product. Recent geological and geochemical studies within the Panagyurishte district demonstrate that the early massive pyrite formed epigenetically by precipitation along fractures, and by progressive replacement of more permeable rock units such as volcanic tuffs and sedimentary rocks without any involvement of seawater (Kouzmanov, 2001; Kouzmanov et al., 2001; Moritz et al., 2001, 2003; Popov et al., 2003; Moritz et al., 2004). Such wall-rock replacement and lithological control by permeable rock units are relatively common in other high-sulphidation deposits (Arribas, 1995; Sillitoe, 1997, 1999; Corbett and Leach, 1998). No volcanogenic massive sulphide scenario is necessary to explain the genesis of the high-sulphidation deposits within the ABTS belt.

A few epithermal deposits in the ABTS belt were described as low- to intermediate sulphidation deposits (Mutafchiev and Petrunov, 1996; Jankovic et al., 1998; Popov et al., 2000b; Ciobanu et al., 2002). The Vozdol deposit in the Panagyurishte district, a polymetallic mineral occurrence, about 1 km from the Chelopech high-sulphidation deposit (Fig. 3), consists of base-metal sulphides, quartz, carbonates, barite and fluorite veins, surrounded by a carbonate, adularia and sericite alteration zone. The spatial association of such polymetallic occurrences in the vicinity of high-sulphidation epithermal and porphyry copper deposits in the Panagyurishte and Bor districts is similar to other base-metal veins at the periphery of high-sulphidation systems (Sillitoe, 1999; Hedenquist et al., 2000, 2001).

The Panagyurishte and Bor districts show typical spatial associations of porphyry and high-sulphidation epithermal deposits (Jankovic, 1990; Jankovic et al., 2002; Strashimirov et al., 2002; Moritz et al., 2004). One of the best examples for a close spatial association is in the southern part of the Panagyurishte district, where the Cu–Au epithermal Elshitsa deposit is located about 1 km NW from the past-producing Vlaykov Vruh Cu-porphyry deposit (Kouzmanov, 2001; Kouzmanov et al., 2003). Cu–Au epithermal occurrences have also been described in the immediate proximity of the Assarel and Petelovo Cu-porphyry deposits (Petrunov et al., 1991; Sillitoe, 1999; Tsonev et al., 2000; Fig. 2). In the northern Panagyurishte district, the Chelopech deposit belongs to a cluster including the Vozdol base-metal veins, the Karlievo Cu-porphyry occurrence, and the producing Elatsite Cu–Au porphyry (Fanger et al., 2001; Fig. 2). This cluster is centred on a major, regional geomagnetic anomaly, interpreted by Popov et al. (2002) as a large upper-crustal magmatic chamber. In the Bor district, epithermal replacement deposits lie above the porphyry copper deposits, with both occurring along the same structures (Jankovic, 1990).

The major *Cu–Au-rich vein systems* in the Burgas district of the eastern Srednogorie belt have quartz and/or carbonate gangue, and carry Cu, Cu–Mo or Cu–Pb–Zn–Ag–Au, including abundant precious metals and bismuth in some places. They are hosted by inferred ring-calderas, centred on volcano–plutonic structures of andesitic, trachyandesitic and trachybasaltic composition (Bogdanov, 1986; Tarkian and Breskovska, 1995).

5. Geology of the Panagyurishte district

The Bulgarian Srednogorie zone (Bonchev, 1930) represents a part of the Carpatho–Balkan Segment (CBS) of the "Tethyan Eurasian Metallogenic Belt" (Jankovic, 1977a) and/or the Late Cretaceous ABTS belt (Popov et al., 2000a). In the new tectonic schemes of Dabovski et al. (2002) and Ivanov (in press), there are some differences concerning the location and extension of the zone, but generally it is located between the Balkan zones to the north, the Rhodope zone and westwards to the adjacent Kraishte (Ivanov, in press) zone, and against the Struma and Morava units (Dabovski et al., 2002) to the south (Figs. 1 and 2). Ivanov (in press) distinguishes an additional Strandzha–Sakar zone (which in former schemes was part of the Eastern Srednogorie zone) based on some characteristic features of the pre-Late Cretaceous basement: metamorphism of the Palaeozoic, Triassic and Jurassic sedimentary rocks that are exposed in the pre-Cenomanian nappe sheets, as well as emplacement of granitic plutons, which become younger to the north-east (Ivanov et al., 2001).

World-class deposits are related to the central parts of the Srednogorie tectonic zone, in a region known as the Panagyurishte district, Panagyurishte strip or Panagyurishte corridor (Mutafchiev and Petrunov, 1996; Bogdanov et al., 1997; Popov et al., 2003), because of its alignment of all major deposits in a zone crossing the Srednogorie magmatic belt (Figs. 1 and 2). The Panagyurishte district has supplied about 95% of Bulgarian copper and gold production up to the present (Mutafchiev and Petrunov, 1996) and a major part of porphyry copper production in Europe. The Panagyurishte district located 60 to 90 km east of Sofia between the towns of Etropole in the north and Pazardzhik in the south (Fig. 3) is characterized by a N–NW-oriented alignment of the ore deposits, a direction that is oblique to the E–W-trending Srednogorie tectonic zone in Bulgaria (Figs. 1 and 2).

The geology of the Panagyurishte district consists of metamorphic and igneous rocks of a pre-Mesozoic basement, crosscut and overlain by abundant Late Cretaceous magmatic and sedimentary rocks, and partly covered by Tertiary sedimentary rocks (Fig. 2). The oldest basement rocks are high-grade metamorphics referred to the so-called pre-Rhodopean Supergroup of possible Precambrian age (Katskov and Iliev, 1993), the Pirdop Group (Dabovski et al., 1972; Dabovski, 1988) or the Srednogorie type metamorphic unit (Cheshitev et al., 1995). They consist of two-mica gneisses, mica schists, ortho-amphibolites, small serpentinite bodies and anatexites. The age of the basement rocks was believed to be Proterozoic (Dimitrov, 1959) or Archaean (Kozhukharov et al., 1974). Ivanov (1988) described them as the “Balkanide type metamorphic complex” and inferred a Palaeozoic age (Fig. 2) on the basis of their field relations with the Late Carboniferous to Permian conglomerates, and U–Pb ages obtained on zircons from the basement gneisses (406 ± 30, 480 ± 30 and 485 ± 50 Ma; Arnaudov et al., 1989). Recently, however, Peytcheva and von Quadt (2004) confirmed Lower Palaeozoic protolithic ages of the metamorphic rocks using the high-precision ID-TIMS U–Pb zircon method. They obtained an age of 502.8 ± 3.2 Ma for a gneiss north of Koprivshitsa (Fig. 2) and found 440 to 460 Ma cores in inherited zircons enclosed in the Cretaceous magmatic rocks. The most recent high-grade metamorphic overprint is late Variscan (Velichkova et al., 2004) but pre-dates the undeformed Variscan granites, whose age is constrained by Rb–Sr isotope dating (Zagorchev and Moorbath, 1987) within the range 342 ± 27 to 238 ± 37 Ma. Recent U–Pb zircon dating on samples from several granitic intrusions yielded 307.7 ± 4.5 Ma for the oldest Smilovene pluton and 285.5 ± 5.2 Ma for the youngest Strelcha pluton (Peytcheva and von Quadt, 2004; Carrigan et al., 2005). Lower grade metamorphic rocks crop out in the northernmost parts of the Panagyurishte corridor. They have a tectonic contact with the high-grade metamorphic rocks and belong to the Berkovitsa Group (Haydoutov et al., 1979) of the Balkan Terrane of north-western Bulgaria (Haydoutov, 2001). The Berkovitsa Group contains a Lower Palaeozoic volcanic–sedimentary sequence that is intruded by calc–alkaline sills and plutons. Phyllites and diabase of the volcanic–sedimentary sequence outcrop in the region of Central Srednogorie (Fig. 3). A diabase sample revealed a U–Pb zircon age of 443 ± 1.5 Ma (Peytcheva and von Quadt, 2004). This sequence was intruded by the granodiorites of the Vejen pluton, dated recently at 314.8 ± 4.9 Ma (Kamenov et al., 2002).

The type and composition of the Late Cretaceous magmatic rocks vary as a function of latitude within the Panagyurishte district (Kamenov et al., 2003b), with subvolcanic and effusive rocks becoming progressively more abundant in the north, while the southernmost parts of the corridor contain holocrystalline intrusive rocks. In terms of composition, andesitic magmas predominate in the northern and central Panagyurishte district, whereas granodioritic intrusions are more abundant in its southern part (Boccaletti et al., 1978; Stanisheva-Vassileva, 1980). Rhyodacites and rhyolites only occur in the central and southern Panagyurishte district (Dimitrov, 1983; Nedialkov and Zartova, 2002; Kamenov et al., 2003a,b). To the south, in the region of the Elshitsa–Vlaykov Vruh deposits, andesites are the earliest volcanic rocks, followed by dacites, before a final stage of dacitic–rhyodacitic subvolcanic intrusions occurred (Bogdanov et al., 1970; Popov et al., 2000a; Moritz et al., 2004). Small, subvolcanic dacite, quartz–monzodiorite and granodiorite intrusions (mostly < 1 km^2 in area), with subsidiary aplites and mafic dykes are co-magmatic with the Late Cretaceous volcanic rocks. Porphyry Cu deposits of the Panagyurishte district are typically centred on such intrusions (Strashimirov et al., 2002; von Quadt et al., 2002; Popov et al., 2003; Tarkian et al., 2003). Larger sized, north-west-elongated, syntectonic, Late Cretaceous granodioritic–granitic intrusions with gabbro to gabbro–diorite sheet-like bodies and enclaves are restricted to the southernmost Panagyurishte district along the Iskar-Yavoritsa Shear Zone (Ivanov et al., 2001; Georgiev and Ivanov, 2003), which corresponds to the transition between the Srednogorie zone and the Rhodope Massif (Figs. 1 and 2).

The Late Cretaceous magmatic rocks are calc–alkaline to high-K calc–alkaline with a local transition to sub-alkaline, and their trace element data are coherent with destructive continental margin and/or volcanic arc-related magmatism (Popov and Popov, 1997; Nedialkov and Zartova, 2002; Stoykov et al., 2002, 2003; Kamenov et al., 2002, 2003a,b).

6. Geochronology of the Panagyurishte transect

6.1. Magmatic evolution along the N–S profile

To constrain the age of the ore forming processes and their relationships to the Late Cretaceous magmatic rock in the Panagyurishte district, we obtained high precision U–Pb zircon and some U–Pb rutile dates that are summarized herein. During the GEODE project Ar–Ar mineral dates of rock-forming and alteration minerals (Handler et al., 2004; Lips et al., 2004; Velichkova et al., 2004) were produced, together with some Re–Os ages of molybdenites (Ciobanu et al., 2002; Zimmerman et al., 2003). Application of these techniques has contributed to a better understanding of the Late Cretaceous evolution of the region.

Apart from field relationships, previously published models were based on K–Ar whole rock and mineral ages and a smaller body of Rb–Sr age data (e.g., Karamata et al., 1997; Berza et al., 1998; Lilov and Chipachkova, 1999; Popov et al., 2000a). In Figs. 4 and 5 we have plotted all available K–Ar and Rb–Sr geochronological data from the Panagyurishte district and the eastern part of the Srednogorie zone. The K–Ar whole rock and different mineral ages are scattered between 50 and 112 Ma. The majority of analyses overlap with the range of our own data (Table 1), but the published ages of 95 to 65 Ma seem to be more widespread in the Srednogorie zone, compared with the other parts of the ABTS belt. In the different single volcano-magmatic–hydrothermal centres the range is smaller (e.g., 78 to 86 Ma for Tamarino Volcano in Eastern Srednogorie). From these data, no clear geochronological trend appears from north to south or from west to east (Figs. 4 and 5), mainly because of the low stability of the K–Ar and Rb–Sr mineral isotope systems to tectonic and thermal/hydrothermal overprint.

6.2. Timing of magmatic activity

High-precision U–Pb zircon data for magmatic rocks associated with (a) the Cu–Au porphyry deposits at Elatsite, Medet, Assarel and Vlaykov Vruh, (b) the epithermal deposits at Chelopech and Elshitsa and (c) the barren intrusions at Velichkovo, Vetren, Capitan Dimitrievo, Vitosha and Gutsal (Fig. 2) all vary with their locations within the NW-trending belt. Considered together, they define a very clear age gradient (Fig. 6a, b).

Cretaceous magmatism started at the northern end of the Panagyurishte district with the intrusion into basement rocks of the Balkan zone (Figs. 2 and 6) of a quartz–monzodiorite at 92.10 ± 0.3 Ma, which is coeval with the beginning of ore formation process at the Elatsite Cu–Au porphyry deposit (von Quadt et al., 2003a, b). The magmatic evolution of the Cretaceous belt then shifted to progressively younger ages towards the southern border of the Srednogorie zone against the Rhodopian zone, where the quartz–monzodiorite of Capitan Dimitrievo has an intrusion age of 78.54 ± 0.15 Ma (Kamenov et al., 2003a,b). In contrast to the published K–Ar data, that scatter over 40 million years (Figs. 4 and 5), our data show that the time span of magmatic activity within the Panagyurishte transect (Figs. 2 and 6) was only ca. 14 million years.

Whilst there is a regional trend of magmatism in the Panagyurishte transect younging southward, each individual hydrothermally mineralized magmatic centre had a relatively short lifetime of ca. 1 million years or less. The magmatic activity and porphyry copper mineralization at Elatsite are constrained within the age range from 92.10 ± 0.30 to 91.42 ± 0.15 Ma, and at nearby Chelopech from 92.22 ± 0.30 to 91.30 ± 0.30 Ma. After a time gap of ca. 1 million years (or less, considering age uncertainties) the magmatic rocks of the Cu–Au porphyry deposits of Medet and Assarel were formed (Fig. 6a). The age of the pre-ore gabbro–diorite at Medet is 90.36 ± 0.48 Ma (Fig. 6a) whereas the quartz–monzodiorite porphyry (syn-ore?) was formed at 89.63 ± 0.33 Ma. In the adjacent Assarel deposit, the mineralized quartz–diorite porphyry and a subvolcanic hornblende–andesite dyke reveal ages of 90.06 ± 0.22 and 90.00 ± 0.20 Ma, respectively. The host rocks of the southernmost economic copper deposits of Vlaykov Vruh (porphyry

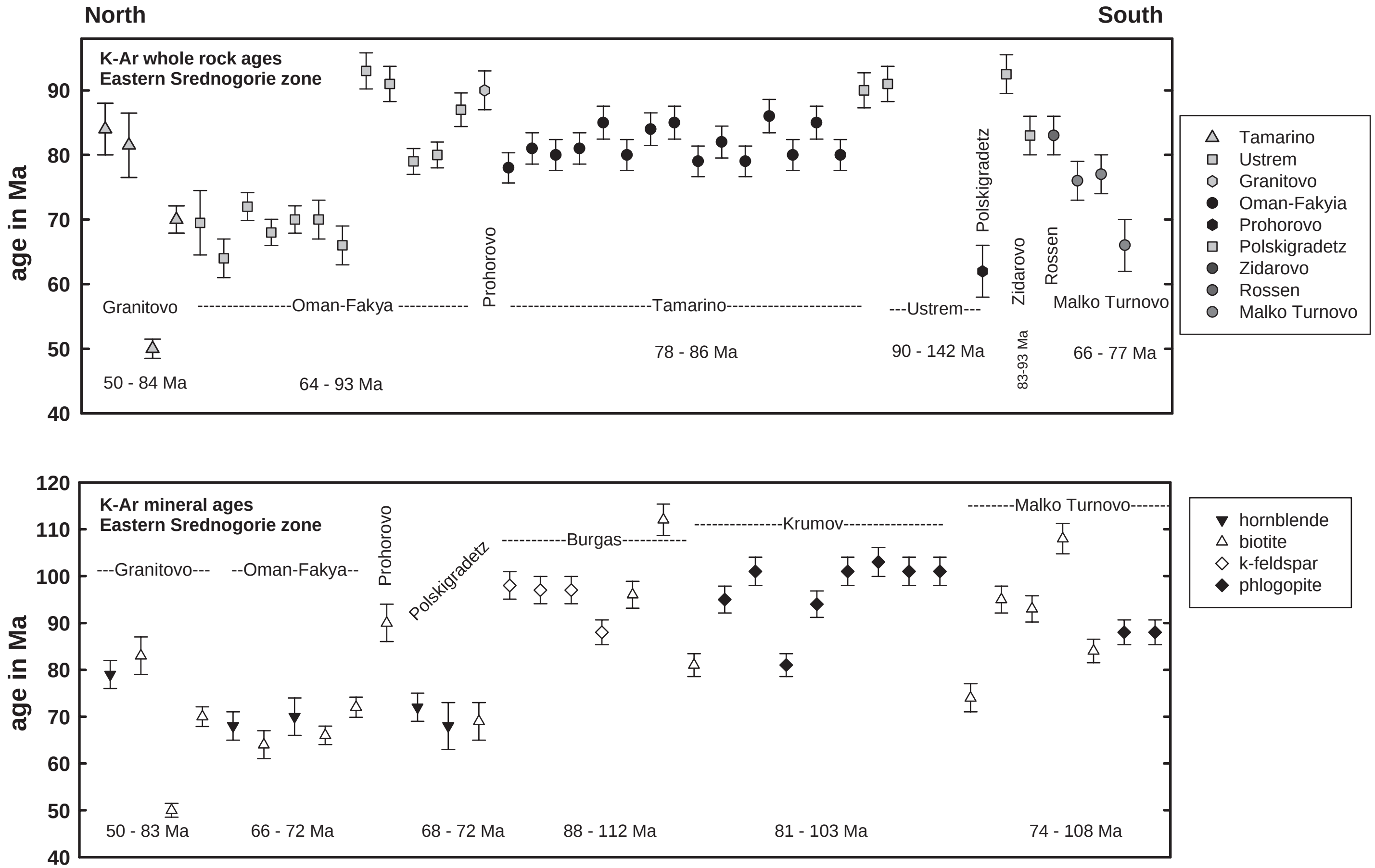

Fig. 4. Summary of the published K–Ar whole rock and mineral ages of the Eastern Srednogorie zone. Localities are shown in Fig. 1. Published data are from Vassilev and Lilov (1970), Chipchakova and Lilov (1976), Zagorchev and Moorbath (1986, 1987), Lilov (1989), Zagorchev et al. (1989), Lilov and Stanisheva-Vassileva (1998) and Lilov and Chipchakova (1999).

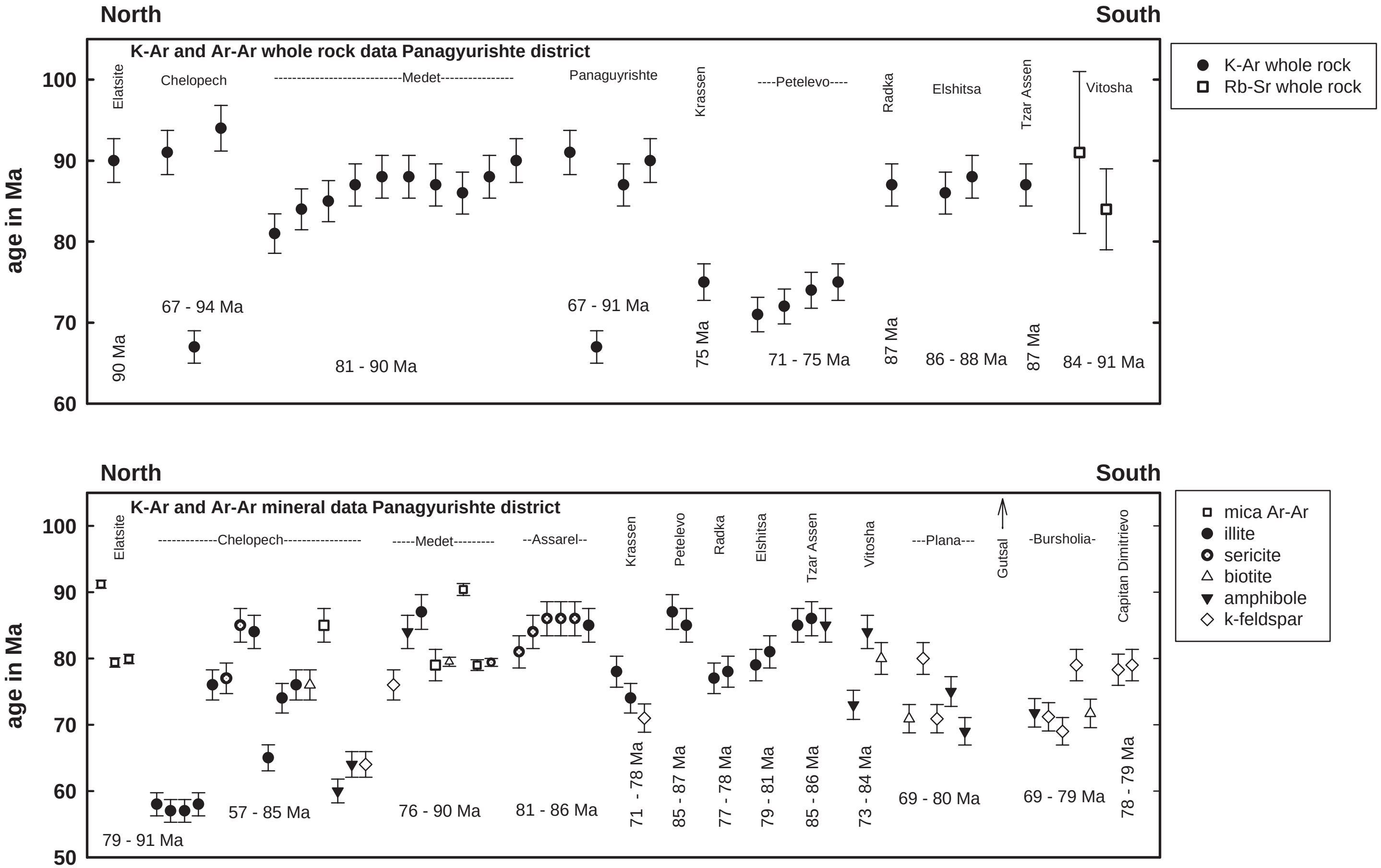

Fig. 5. Summary of the published K–Ar whole rock ages and Ar–Ar mineral ages of the Panagyurishte district. Localities are shown in Figs. 1 and 2. Published data are from Firsov (1975), Boyadjiev (1981), Palskin et al. (1989), Lilov and Stanisheva-Vassileva (1998) and Kamenov et al. (2000).

Table 1
Summary of U–Pb data on zircons and rutile from the Panagyurishte District

Locality	Age in Ma	Error in Ma	Reference
Elatsite			
Pre/syn ore granodiorite	92.10	0.30	von Quadt et al. (2002)
Late mineralization dyke	91.84	0.30	von Quadt et al. (2002)
Post-ore amphibolite–granodiorite dyke	91.42	0.15	von Quadt et al. (2002)
Chelopech			
Pre/syn ore volcanic andesite	91.45	0.15	Moritz et al. (2003), Chambefort et al. (2003)
Syn-ore subvolcanic andesite	92.22	0.30	Stoykov et al. (2004)
Late mineralization trachydacite	91.30	0.30	Stoykov et al. (2004)
Post-ore andesite	91.30	0.30	Stoykov et al. (2004)
Assarel			
Pre/syn ore andesite	90.06	0.22	Unpublished data, von Quadt
Late mineralization granodiorite	90.00	0.20	Unpublished data, von Quadt
Medet			
Pre-ore gabbro	90.36	0.48	Von Quadt et al. (2004)
Syn-ore quartz–monzodiorite	89.61	0.26	Von Quadt et al. (2004)
Elshitsa-granite	86.62	0.11	Peytcheva et al. (2003)
Elshitsa-dacite	86.11	0.23	Peytcheva et al. (2003)
Vlaykov Vruh-rutile, hydrothermal	85.66	0.15	Peytcheva et al. (2003)
Velichkovo-granodiorite	84.60	0.30	Peytcheva and von Quadt (2003)
Velichkovo-gabbro	82.16	0.10	Peytcheva and von Quadt (2003)
Vetren gabbro	84.87	0.13	Peytcheva and von Quadt (2003)
Vurshilo-granite	82.25	0.20	Peytcheva and von Quadt (2003)
Capitan Dimitrievo	78.54	0.13	Kamenov et al. (2003a,b)
Vitosha-gabbro	81.58	0.23	Atanasova-Vladimirova (2004)
Vitosha-syenite	79.67	0.91	Atanasova-Vladimirova (2004)
Vitosha-andesite	80.75	0.40	Atanasova-Vladimirova (2004)
Gudsal	75.64	1.10	Unpublished data, von Quadt

type) and Elshitsa (epithermal) are dated at 86.62 ± 0.11 Ma (Elshitsa granite) and 86.11 ± 0.23 Ma (subvolcanic dacite), respectively (Fig. 6a).

Economic ore deposits in the Panagyurishte district are absent south of the porphyry deposit of Vlaykov Vruh, and the barren intrusive rocks have predominantly coarse equigranular textures. South of the porphyry deposit of Vlaykov Vruh, several Cretaceous non-mineralized intrusive rocks–gabbros, granodiorites, and diorites–intruded between 84.60 ± 0.30 and 82.16 ± 0.10 Ma (Figs. 2 and 6a; Velichkovo, Vetren, Vurshilo). Outside the Panagyurishte district several intrusive complexes (Figs. 1, 2 and 6a), located at the border between the Srednogorie zone and the Rhodope Massif reveal magmatic ages between 81.58 ± 0.23 Ma (Vurshilo granite) and 81.58 to 79.67 Ma (Vitosha pluton). The magmatic evolution in the Cretaceous ended with the intrusion of the Capitan Dimitrievo plutonic rocks at 78.54 ± 0.15 Ma.

6.3. Lifetime of a magmatic–hydrothermal system

The close spatial association of Cu–Au porphyry deposits (Elatsite, Vlaykov Vruh) and epithermal deposits (Chelopech, Elshitsa, Vlaykov Vruh) raises several questions concerning the relative age differences between the two types of deposit and the duration of the Cretaceous magmatism. During the GEODE research programme, additional dating results (Ar–Ar, Rb–Sr mineral, Re–Os) became available to supplement the U–Pb zircon dates.

The Elatsite porphyry and Chelopech epithermal deposits, located only 6 km apart, have been studied by detailed geology and geochronology using different isotopic systems. Elatsite is connected to multiphase Late Cretaceous monzonitic to dioritic porphyric dykes. The dykes intruded close to the contact of phyllites and diabase of the Berkovitsa Group and the Palaeozoic Vezhen granodiorite. The phyllites

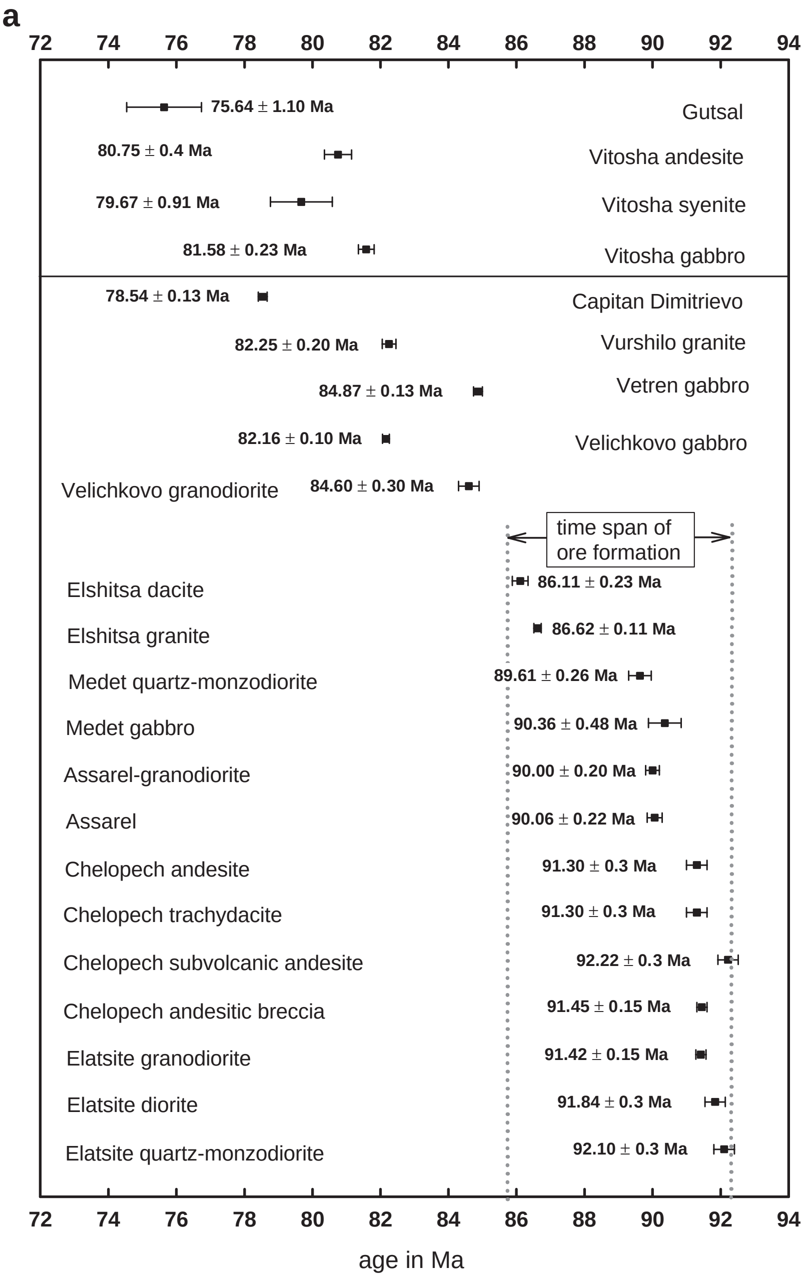

Fig. 6. (a) High precision U–Pb zircon and rutile ages, which have been produced during the GEODE research programme: data are listed in Table 1, localities are shown in Figs. 1 and 2; (b) summary of Ar–Ar, Rb–Sr, Re–Os mineral ages: published data are from Zimmerman et al. (2003), Velichkova et al. (2004) and Atanassova-Vladimirova et al. (2004).

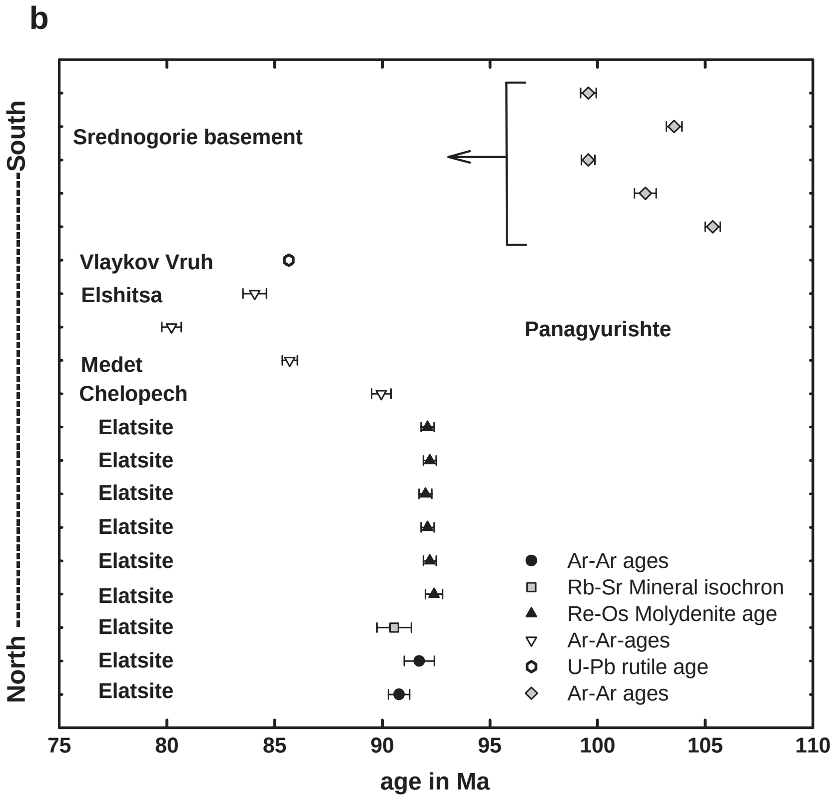

Fig. 6 (*continued*).

show contact metamorphism related to the Vezhen pluton, overprinting the schistosity.

Field evidence shows at least four types of dykes. A major polyphase plagioclase porphyry affected by Cu–sulphide-rich stockwork veining and potassic alteration is cut by multiple phases of amphibole-porphyry dykes, which are pervaded by minor mineralization (veins) and potassic alteration. Aplitic dykes consisting dominantly of quartz and potassium feldspar locally cut amphibole-porphyries, and elsewhere are cut by amphibole-porphyries. A fourth type of dark, fine-grained dyke with a few small amphibole phenocrysts shows no crosscutting relationships with other dyke types, but it is also mineralized and shows some potassic alteration. Mineralization started with magnetite veining accompanied by potassic alteration, mainly in the Palaeozoic granodiorite (Kamenov et al., 2002). The potassic alteration also accompanies the subsequent chalcopyrite + magnetite + bornite paragenesis carrying platinoids and some of the free gold. While the typical stockwork porphyry veining took place, the intensity of potassic alteration decreased and chalcopyrite, pyrite and molybdenite were precipitated. The last dykes were intruded during this stage, cutting earlier veins and showing a reduced degree of potassic alteration and quartz vein density. Subsequently, the deposit was overprinted by a feldspar destructive alteration (mainly sericite and quartz), including massive quartz–pyrite veins up to 30 cm in thickness. Late subvertical, WNW–ESE-striking brittle faults cut and displaced all the lithologies and caused some remobilization of ore. High-precision U–Pb single zircon dating (von Quadt et al., 2004) provided the chance to constrain the time range of the ore-formation process. The main intrusion (quartz–monzodiorite) has a zircon age of 92.10 ± 0.3 Ma and a weakly mineralized amphibole porphyry dyke is dated at 91.42 ± 0.15 Ma. The ore-formation process at the Elatsite Cu-deposit was therefore completed within a time window of 0.9 million years including time-dating uncertainties. This time span is consistent with the results of Zimmerman et al. (2003) using the Re–Os molydenite method. Six published ages range from 92.0 to 92.4 ± 0.3 Ma. A Rb–Sr mineral isochron, based on hydrothermal biotite and potassium feldspar from the early bornite–chalcopyrite–pyrite veins yields an age of 90.55 ± 0.3 Ma. This age lies below the U–Pb and Re–Os ages for ore formation and probably reflects the time of cooling through the closing temperature of the system (<350 °C). Ar–Ar ages on igneous hornblende of 90.78 ± 0.49 Ma are also younger than the magmatic age of the post-ore dyke of 91.42 Ma, and an Ar–Ar biotite result gives an age of 91.72 ± 0.7 Ma (Fig. 6b) with a marginal time overlap considering the dating uncertainties. The published Ar–Ar ages of two mica separates (Lips et al., 2004) from Elatsite at 79.9 ± 0.7 and 79.4 ± 0.7 Ma have no geological connection with the ore-forming process and probably reflect later alteration.

Coherent andesite taken from the Chelopech mine (Figs. 2 and 6a) gives an emplacement age of 91.45 ± 0.15 Ma for a subvolcanic body pre-dating mineralization (Chambefort et al., 2003). Stoykov et al. (2004) dated several volcanic and subvolcanic rocks outside of the Chelopech mine and the ages range from 92.22 to 91.3 Ma (Fig. 6a). The authors interpret the youngest age of a non-mineralized igneous rock, together with field relationships, as the end of ore formation at the Chelopech epithermal deposit. The Ar–Ar biotite age of 89.95 ± 0.45 Ma from the Chelopech area (Fig. 6b) has no geological link either to the time of igneous emplacement or to ore formation and probably reflects an age of later alteration at Chelopech. The protolith ages from the Elatsite porphyries and the emplacement ages of igneous rocks at Chelopech overlap within their uncertainties.

The Vlaykov Vruh porphyry and Elshitsa epithermal deposits are also indicated to be co-magmatic products but here the age dating proved to be less clear cut (von Quadt et al., 2004). The Elshitsa granite intrusion has tectonically reactivated contacts with Late Cretaceous volcano-sedimentary rock in the north and Variscan granites and Precambrian (?) metamorphic rocks in the south. The oldest volcanic rocks are amphibole–pyroxene andesites. They are overlain by dacitic lava flows and ash tuffs and are crosscut by subvolcanic dacitic and porphyritic quartz–granodiorite dykes and bodies (Bogdanov, 1986). Porphyry copper and epithermal Au–Cu deposits are spatially and temporally related to these subvolcanic intrusions (Bogdanov, 1984). Epithermal deposits including Elshitsa and smaller occurrences follow the same structures as the porphyritic dykes, intersecting the volcanic structures. They consist of massive and/or disseminated, steeply dipping sulphide-rich (pyrite–chalcopyrite ± base metals and gold) orebodies. Most of them are hosted by polygenetic breccias of volcanic, phreatomagmatic and hydrothermal origin (Kouzmanov et al., 2003). Mineralization stages in the Vlaykov Vruh porphyry-type and Elshitsa epithermal deposits have several common features, which are summarized by Kouzmanov et al. (2003). The hydrothermal rutile crystallized during the early porphyry mineralization stage at Vlaykov Vruh at a temperature of ca. 635 °C (quartz–rutile oxygen isotopic thermometer; Kouzmanov et al., 2003) and formed euhedral crystals intergrown with quartz, molybdenite and, rarely, chalcopyrite (Peytcheva et al., 2001, 2003) and was formed to be suitable for U–Pb dating.

The Elshitsa granite, representing the plutonic part of the magmatic system, records a zircon age of 86.62 ± 0.02 Ma (Fig. 6a) and has an initial strontium ratio of 0.70514 to 0.70523 (Fig. 10; Peytcheva et al., 2001, 2003). The Elshitsa subvolcanic dacite has a U–Pb zircon age of 86.11 ± 0.23 (Fig. 6a) with similar initial strontium composition (0.70524). Based on overlapping ages (U–Pb zircon) and isotope characteristics (Sr, Nd) of the intrusive and subvolcanic parts of the magmatic system, there are indications of a contemporaneous emplacement and similar petrochemical evolution path of the entire complex and minimal isotopic interaction with the older basement. Unfortunately, zircon from the subvolcanic granodiorite and quartz–diorite at Vlaykov Vruh yielded inherited old-lead components, and thus no precise intrusion age was obtained. The initial strontium ratio of the host Vlaykov Vruh quartz–granodiorite porphyry of 0.70583 is slightly more crustal-influenced than the Elshitsa granite and subvolcanic dacites, and indicates a more pronounced influence of the host rocks—the Palaeozoic granites and metamorphic basement. The zircon population in the Vlaykov Vruh porphyry, which contained over 90% inherited zircons, also supports this conclusion. One possible explanation of this phenomenon is the short life of the chamber (there was no time for dissolving assimilated crustal grains and new growth of zircon from the mixed magma) and rapid cooling of the dykes. The hydrothermal rutiles from the Vlaykov Vruh porphyry copper deposit have a mean ^{206}Pb/^{238}U age of 85.65 ± 0.15 Ma (Figs. 1, 2 and 6b) that is our best estimate for the age of porphyry-type mineralization.

The porphyry deposit Medet and epithermal deposit Elshitsa probably reflect "younger" Ar–Ar ages of 85.7 ± 0.35 and 84.07 ± 0.54 Ma (Fig. 6b). The Ar–Ar age for Elshitsa is around 1.5 million years younger than the U–Pb rutile age (Fig. 6b) and it seems that the Ar–Ar system reflects a closing temperature at ca. 350 °C or a later overprint. Lips et al. (2004) and Handler et al. (2004) have tried to demonstrate that their Ar–Ar ages date the magmatic events or ore formation process.

7. Geochemical and isotopic character of Late Cretaceous magmas

Porphyry copper deposits and epithermal Cu orebodies are the end result of a complex sequence of events initiated by magma genesis at convergent plate margins (e.g., Tosdal and Richards, 2002). Before starting a detailed interpretation of the ABTS belt it is useful to review the mechanisms of magma ascent and emplacement in the lithosphere. Convergent margin magmatism is linked to subduction of an oceanic plate beneath an overriding continental or oceanic plate, upon which the arc is constructed. Geochemical studies have shown that, even in an island-arc environment, the porphyry-related magmas are not a direct product of melting in the mantle wedge above the Benioff zone, but result from significant amounts of fractionation and interaction of this magma with the overlying lithosphere. Isotopic and geochemical evidence for crustal interaction in Central Andean magmas (continental arc system) is clear (Hildreth and Moorbath, 1989; Richards, 2003). A period of intensive MASH (melting, assimilation, storage, and homogenization) processes is implied in the batholithic magma chambers. Before trace element data became available for the Srednogorie zone, small geochemical differences in the K_2O/Na_2O ratio were used to explain a geochemical evolution from more tholeiitic affinities in the eastern part of the belt to calc–alkaline dominated magmas within the central Panagyurishte district (Stanisheva-Vassileva, 1980). New geochemical data (Kamenov et al., 2002, 2003a,b; Atanassova-Vladimirova et al., 2003, 2004) from all major porphyries, Cretaceous magmatic and Variscan intrusive rocks are presented in several discrimination diagrams in order to identify differences in their geotectonic positions. In Figs. 7 and 8, more than 95% of the available analyses, including Variscan basement rocks, show tectonic characteristics of a volcanic arc setting (Fig. 7) and there is no evidence of a syncollisional geotectonic setting. In an extended spider diagram, all the Cretaceous magmatic rocks (Fig. 8) show very similar arc-initiated geochemical characteristics, with an enrichment of Cs, Rb, Ba, Th, U, Pb and a strong depletion in Nb and Ta. The magmatic rocks for Elatsite, Medet, Capitan Dimitrievo, Vitosha, Vetren and Velichkovo have similar patterns between Sr and Lu (Fig. 8), apart from the Elshitsa rock suite. The lower enrichment between Sr and Lu (at Elshitsa) seems to reveal a higher degree of fractionation.

Among the trace element patterns, no obvious differences are discerned between Cretaceous and Variscan magmatic rocks. The Ce content for rocks with SiO_2 values at 57.5% (Hildreth and Moorbath, 1989; Kamenov et al., 2003a,b) shows a north-to-south decrease from Elatsite (Fig. 2) to Elshitsa and a jump to higher values within the barren intrusive rocks (Vurshilo, Capitan Dimitrievo, Vitosha, Fig. 2). The Rb/Cs ratio increases from Elatsite to Elshitsa (Fig. 2) and decreases within the barren intrusive rocks. Hildreth and Moorbath (1989) explain both phenomena by a decrease in the thickness of the continental crust, but the existence of different crustal blocks or different isotopic characteristics could be another explanation. Thus, we have tried to establish whether the isotopic system Pb–Sr–Nd provides evidence of different source components or demonstrates separate evolution trends. In Fig. 9a the initial ε_{Nd} values calculated using intrusion ages (Fig. 6a) increase from around -3 at the northern border of the Pangyurishte district to $+2$ in the southern part. Most of the magmatic rocks lie on this evolutionary line, apart from the Variscan intrusions and two Elatsite samples. Similar observations are reported for the Chilean Andes (Hildreth and Moorbath,

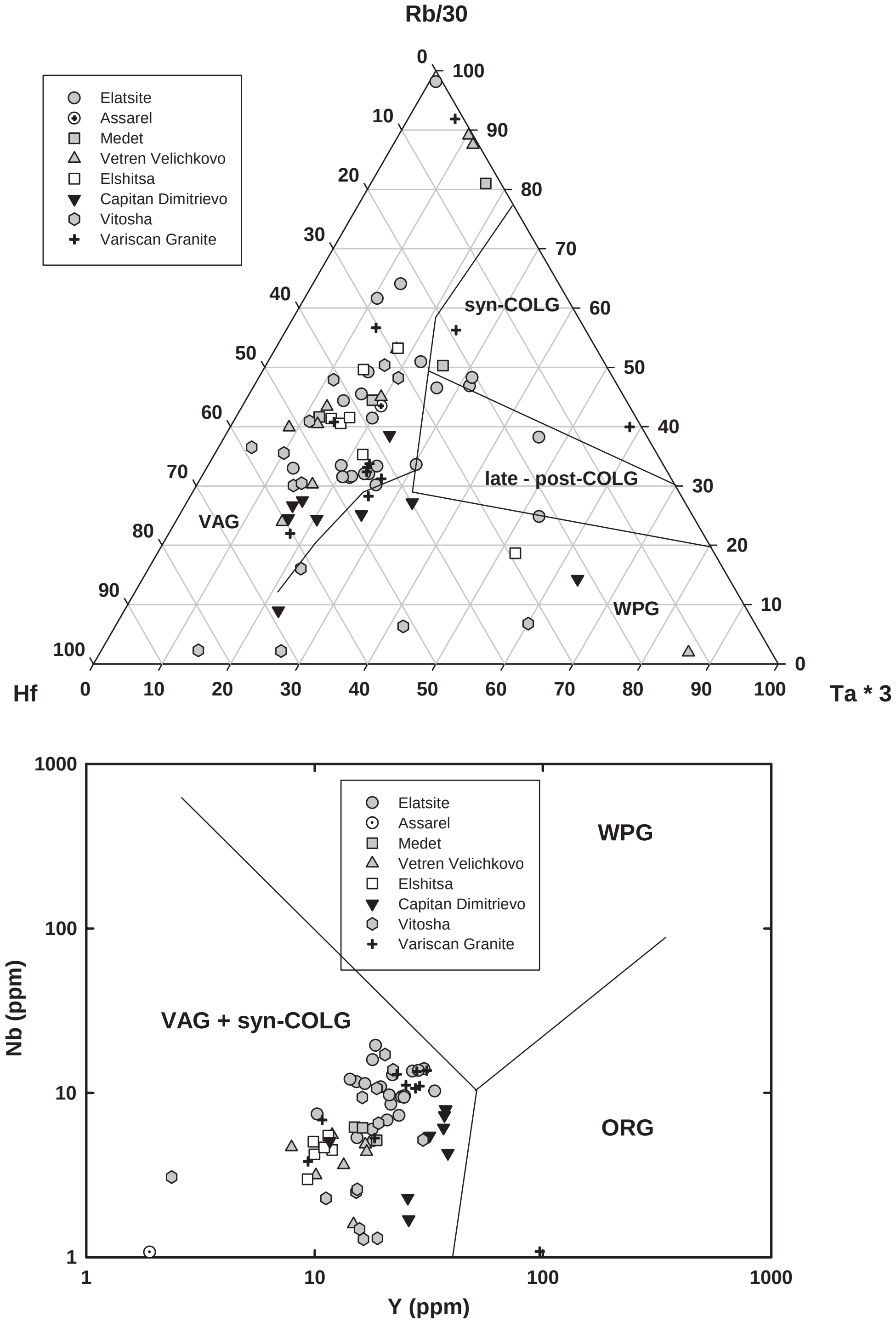

Fig. 7. Geochemical discrimination diagrams, Rb/30-Hf–Ta*3 (Harris et al., 1986) and Nb–Y (Pearce et al., 1984). Abbreviations: WPG—within plate granite, COLG—collision granite, VAG—volcanic arc granite, ORG—ocean ridge granite.

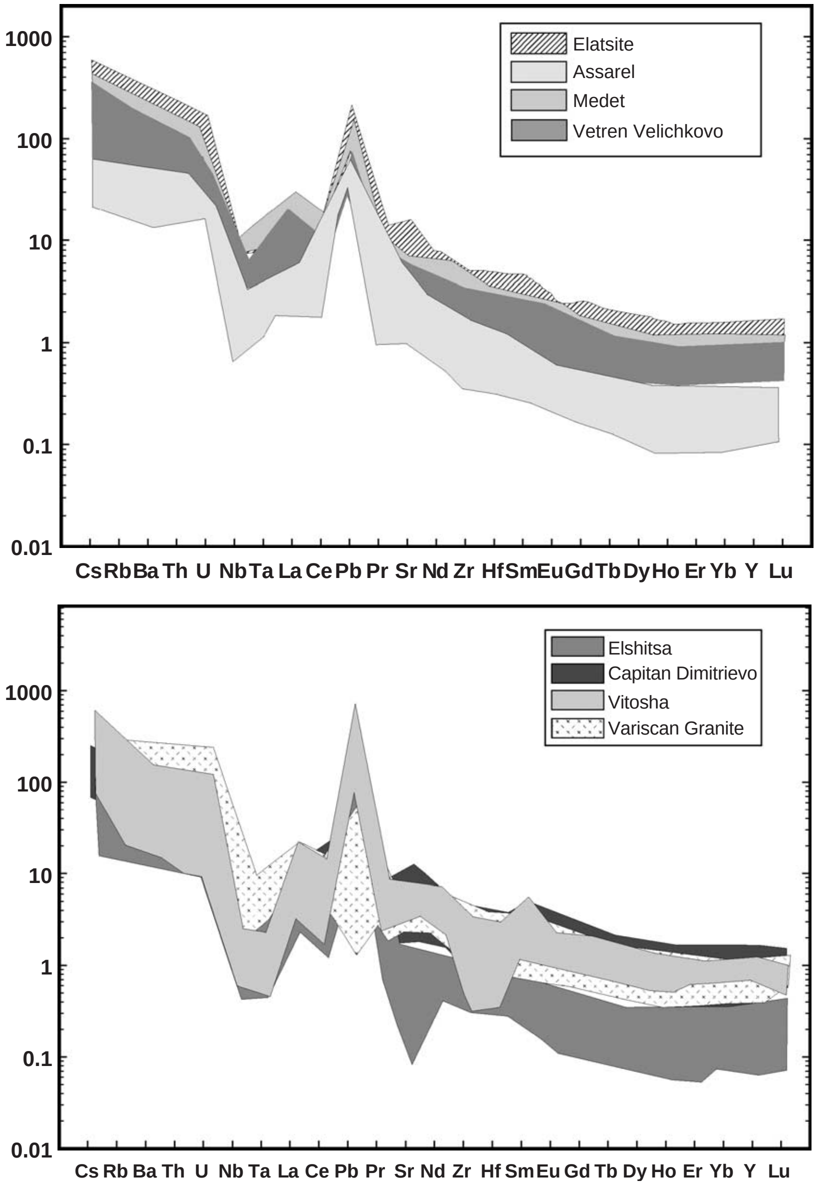

Fig. 8. Trace element variation diagrams for the intrusion centres of the Panagyurishte district: Elatsite, Assarel, Medet, Vetren, Velichkovo, Elshitsa, Capitan Dimitrievo. Vitosha is located south of Sofia at the border between the Srednogorie zone and the Rhodope Massif (Figs. 1 and 2). The Variscan granites are plotted for comparison with the Cretaceous intrusives.

1989) and the increase in the ε_{Nd} values and the decrease of the Sr ratios are correlated with a reduction in the thickness of the continental crust. The question of how many different sources are involved can be answered by using the ε_{Nd} versus 1/Nd ppm diagram (Fig. 9). Based on this diagram, it seems that rocks from both the oldest part (Elatsite) and from the youngest part (Capitan Dimitrievo) of the Panagyurishte district have ε_{Nd} values that can be explained by a two-component mixture including a fractionation trend as an additional parameter; magmatic rocks from the Chelopech–Elatsite area reveal

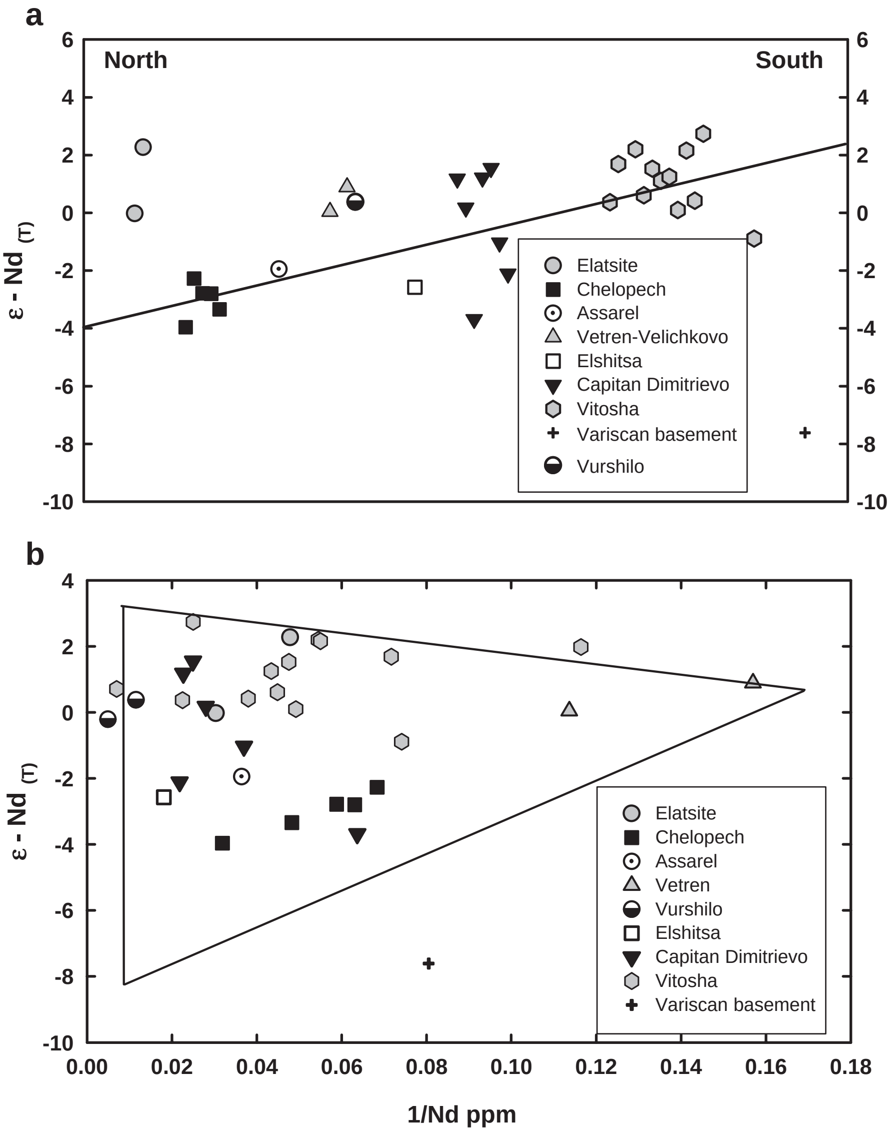

Fig. 9. a) ε_{Nd} values–corrected for their intrusion ages (Table 1)–plotted from north to south across the Panagyurishte district; b) ε_{Nd} values versus 1/Nd demonstrate the contributions of probably different magma sources.

the input of a crustal source, and probably assimilation of the Variscan granite cannot be excluded as a member of the mixing process. It seems that the oldest rocks of the Cretaceous magmatic sequence show the highest input of a crustal component (Fig. 9b) and the youngest rocks from the Vitosha pluton are less contaminated, with ε_{Nd} values up to +2.5 (Fig. 9a, b).

The Sr-isotopic trend from north to south gives a similar picture as for the ε_{Nd} values. The Cretaceous magmatic rocks plot on a single trend that is far from the data field for the Variscan intrusive rocks (Fig. 10a). The latter rocks formed from a quite different source type (old continental crust, meta-sedimentary gneiss). In contrast to the Nd data (Fig. 9), the Sr evolution in an $^{87}Sr/^{86}Sr$ versus 1/Sr ppm diagram

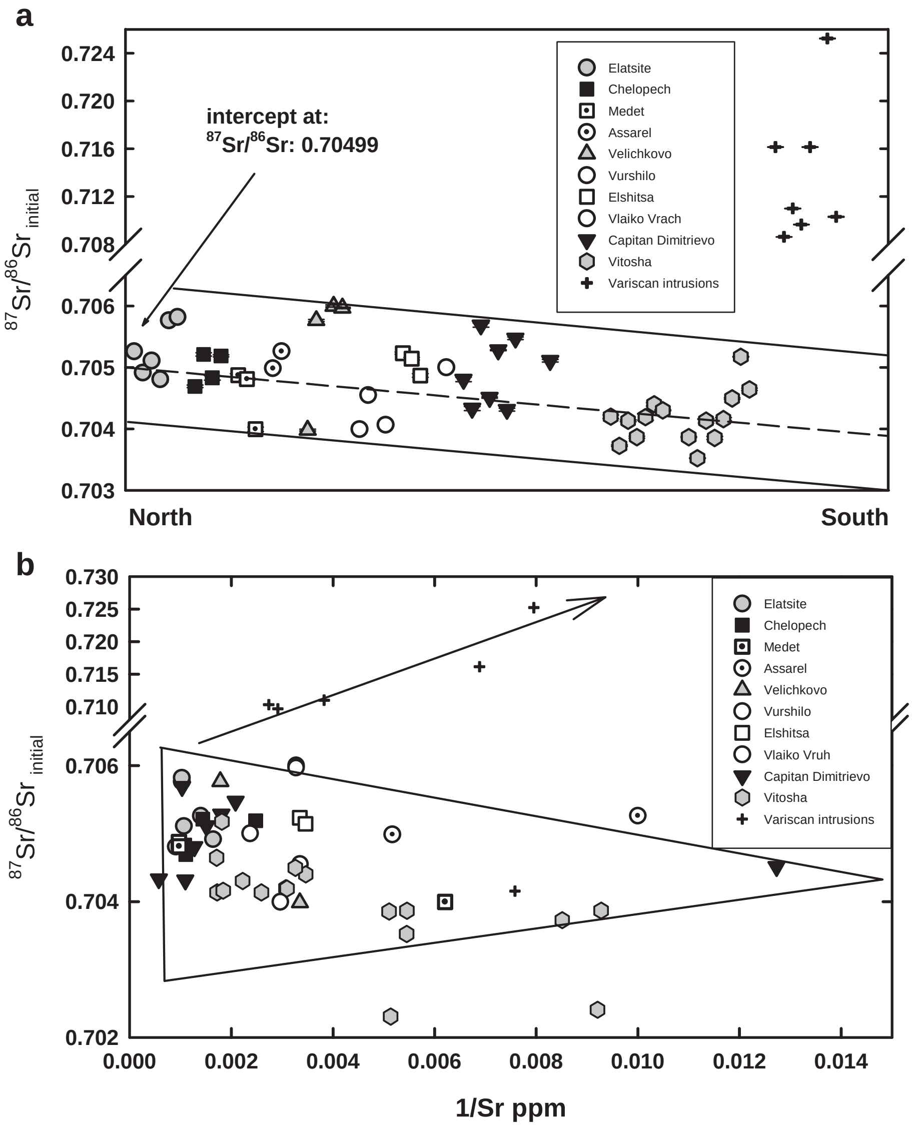

Fig. 10. (a) $^{87}Sr/^{86}Sr_{initial}$ values for all Cretaceous intrusive centres and Variscan granitoids are plotted from north to south across the Panagyurishte district; (b) $^{87}Sr/^{86}Sr$ initial ratios versus 1/Sr demonstrate the evolution of the Cretaceous and Variscan intrusive rocks.

shows two different lines for the Cretaceous and Variscan rocks (Fig. 10b). The scatter of the $^{87}Sr/^{86}Sr_{intial}$ data (Fig. 10b) may be affected by normal fractionation as well as a minor input of metasedimentary rocks, but a Variscan crustal source cannot be excluded. Hf isotope data are available from zircons. These provide a data set with greater confidence (Kamenov et al., 2002; von Quadt et al., 2002, 2003a,b, 2004; Peytcheva and von Quadt, 2003; Stoykov et al., 2004) than whole-rock Hf data, because they represent a clearly confined, dated system (U–Pb zircon: ε_{Hf} values (Fig. 11) increase from the northern part at Elatsite (+2.5 to +7) and Chelopech (+1 to +5), to the centre of Medet-Assarel (+0.0 to +2.5;+0.24 to +2.42), to the southern part of the Panagyurishte at Capitan Dimitrievo (+8 to +10) and the Vitosha pluton

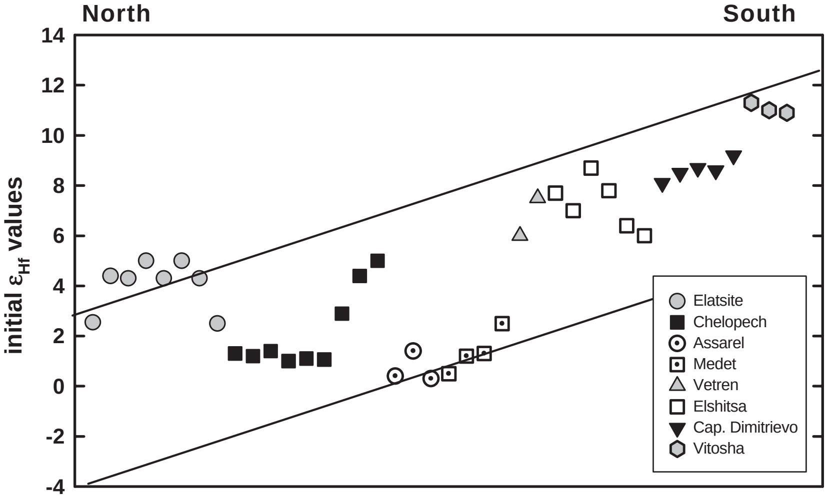

Fig. 11. Initial ϵ_{Hf} values for all Cretaceous intrusive centres are plotted from north to south across the Panagyurishte district: data from von Quadt et al. (2002), Kamenov et al. (2002), von Quadt et al. (2003a,b), Peytcheva and von Quadt (2003) and von Quadt et al. (2004); localities are shown in Fig. 2.

(+10 to +11.5), and reflect the similar geochemical trend in the Sr or Nd systems. The $\varepsilon_{\mathrm{Hf}}$ data of the earliest intrusions at Elatsite (+2 to +5; Fig. 11) are scattered and plot on the upper part of the Cretaceous evolutionary trend.

The Pb isotopes are very sensitive to crustal contamination (<5%) or inputs from sources with different μ-values. In the ^{206}Pb/^{204}Pb versus ^{207}Pb/^{204}Pb diagram (Fig. 12a, Table 2), two distinct fields separate the Variscan intrusive rocks with higher ^{207}Pb/^{204}Pb ratios from the Cretaceous magmatic rocks: the ^{207}Pb/^{204}Pb ratios can reflect the existence of an old-lead component or the assimilation of continental crustal material, probably during the intrusion of magmatic rocks. The youngest rocks from Capitan Dimitrievo have the lowest ^{207}Pb/^{204}Pb ratios or, in other words, are the least contaminated by old crustal sources. To identify different sources we used the ^{206}Pb/^{204}Pb versus 1/Pb ppm plot (Fig. 12b): the database is limited because published Pb isotope data have no concentration values (Table 2). The results clearly demonstrate two evolution lines, one for the Cretaceous magmatic rocks and one for the basement rocks. The detection of such different evolutionary trends in the Pb and Sr isotope systematics leads to the conclusion that the magmatic rocks of the Cretaceous magmatism cannot be explained by a single model of assimilation of the Variscan basement.

8. Variation in ore deposit characteristics across the Central Panagyurishte district

All large-tonnage Cu–Au–Mo deposits are restricted to the northern and geologically older part of the Panagyurishte mineral district, north of the town of Panagyurishte (Figs. 1 and 2), including the producing high-sulphidation deposit at Chelopech (42.5 Mt @ 1.28% Cu and 3.4 g/t Au), the Cu-porphyry deposits at Elatsite (354 Mt @ 0.44% Cu and 0.2 g/t Au) and Assarel (319 Mt @ 0.36% Cu), and the past-producing Cu-porphyry Medet deposit (163 Mt @ 0.32% Cu and 80 g/t Mo). In contrast, the central to southern and geologically younger part of the district only hosts low-tonnage deposits, including the small Cu–Au epithermal deposits at Elshitsa (4.5 Mt @ 1.13% Cu and 1.5 g/t Au), Radka (8.9 Mt @ 1.06% Cu and1.5 to 2.0 g/t Au) and Krassen (0.3 Mt @ 0.76% Cu), and Cu-porphyry deposits at Tsar Assen (6.6 Mt @ 0.47% Cu) and Vlaykov Vruh (9.8 Mt @ 0.46% Cu; resource data for all deposits and occurrences from Strashimirov et al., 2002; Moritz et al., 2004). The younger and southernmost intrusions

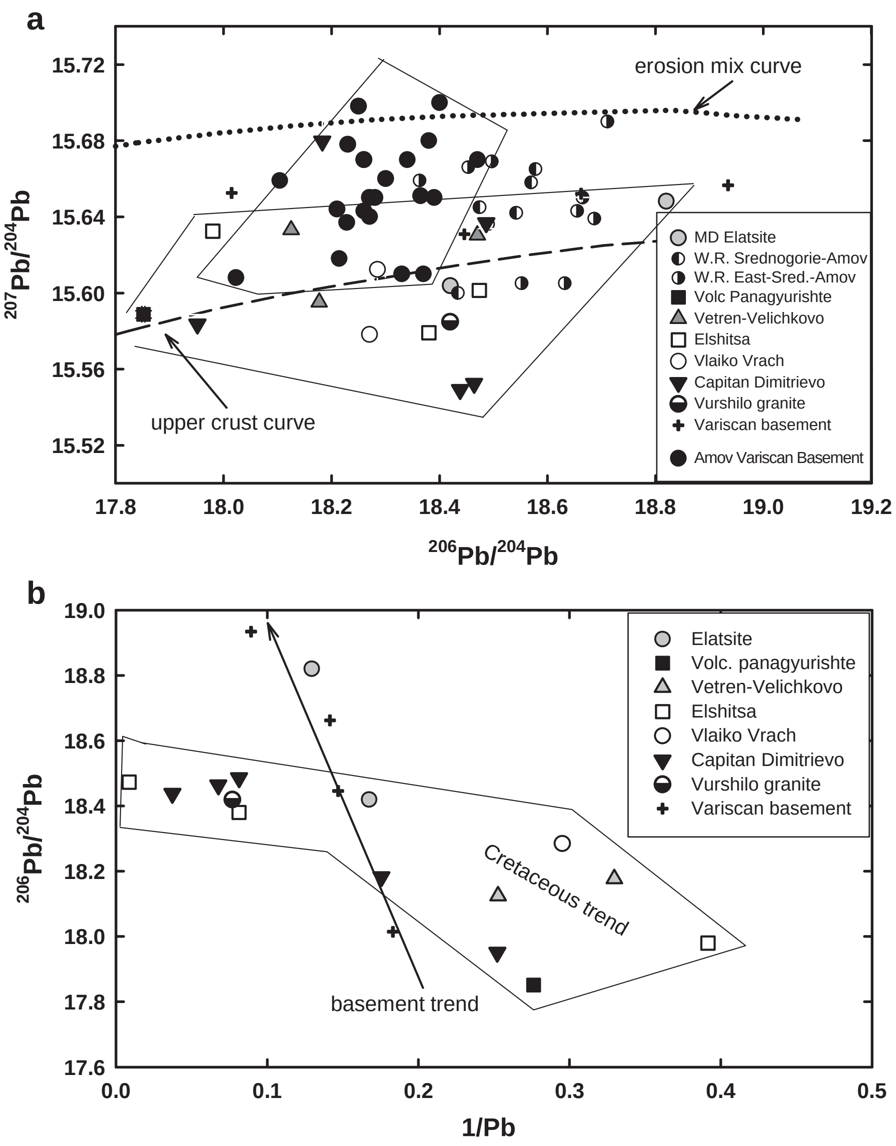

Fig. 12. (a) $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ whole rock plot for the Cretaceous intrusives and the Variscan basement: published data of the western and eastern Srednogorie zone (Amov, 1999) are presented within the same diagram; all Pb isotope data have been age corrected (90 Ma) except the Pb data of Amov (1999); Pb evolution curves, erosion mix and upper crust, from Kramers and Tolstikhin (1997). (b) $^{206}Pb/^{204}Pb$ versus 1/Pb plot explains the different evolution trends of the Cretaceous and Variscan rock suites.

in the corridor (e.g., Capitan Dimitrievo) are totally devoid of ore deposits.

Despite the large-scale trends in ages, there is no obvious N–S zonation in deposit characteristics at the district scale, with the possible exception of the Ag/Au ratio in the epithermal deposits, which is lower at Chelopech (2.5) than at Radka (16) and Elshitsa (10) further south. This is also reflected in the mineralogical assemblage, since native silver (hypogene) is absent at Chelopech but present at Krassen, Radka and Elshitsa, and tetrahedrite is rare at Chelopech and more abundant in the other

Table 2
Pb–Pb isotope data for igneous rocks of the Panagyurishte district

Locality	$^{206}Pb/^{204}Pb^{a}$		$^{207}Pb/^{204}Pb^{a}$		$^{208}Pb/^{204}Pb^{a}$		U in ppm	Th in ppm	Pb in ppm
Monzodiorite—Elatsite	19.161	0.002	15.664	0.002	38.846	0.006	2.53	9.91	7.73
Syenite—Elatsite	18.857	0.003	15.624	0.003	38.796	0.011	2.52	9.84	5.97
Andesite—Panagyurishte	18.586	0.003	15.623	0.002	38.678	0.007	2.58	7.77	3.62
Gabbro—Velichkovo	18.632	0.008	15.616	0.004	38.640	0.016	1.34	3.32	3.03
Gabbro—Vetren	18.821	0.011	15.647	0.011	38.664	0.012	0.19	0.72	0.56
Basaltic dyke—Vetren	18.716	0.003	15.661	0.003	38.851	0.011	2.26	1.45	3.96
Quartz–Monzodiorite—Vlaykov Vruh	18.493	0.004	15.602	0.004	38.488	0.014	2.24	2.45	115.2
Quartz–Granodiorite—Elshitsa	18.585	0.014	15.588	0.013	38.642	0.017	2.45	9.01	12.29
Dacite–Elshitsa	18.739	0.006	15.668	0.005	38.895	0.018	1.87	8.09	2.56
Quartz–diorite—Vlaykov Vruh	18.892	0.015	15.641	0.013	38.992	0.021	1.98	11.25	3.38
Granodiorite—Vlaykov Vruh	18.563	0.006	15.592	0.005	38.576	0.012	1.4	7.77	4.92
Granodiorite—Capitan Dimitrievo	18.693	0.004	15.646	0.003	38.680	0.009	2.47	18.28	12.29
Gabbro—Capitan Dimitrievo	18.665	0.005	15.560	0.005	38.434	0.014	5.96	2.12	26.89
Gabbro—Capitan Dimitrievo	18.627	0.018	15.701	0.019	38.772	0.045	2.45	1.42	5.69
Monzogabbro—Capitan Dimitrievo	18.537	0.005	15.611	0.005	38.535	0.014	2.26	10.9	3.96
Gabbro—Capitan Dimitrievo	18.542	0.005	15.556	0.007	38.329	0.012	1.13	1.68	14.8
Granite—Vurshilo	18.625	0.007	15.594	0.005	38.685	0.014	2.6	11.16	13
Gabbro—Medet	18.497	0.014	15.675	0.013	38.591	0.036	2.56	2.12	5.46
Quartz–Monzodiorite—Vezhen	18.841	0.005	15.649	0.004	38.912	0.017	2.59	11.26	6.81
Granodiorite—Vezhen	19.164	0.002	15.667	0.002	38.856	0.011	2.47	20.74	11.2
Granodiorite—Vezhen	18.953	0.002	15.666	0.002	38.883	0.006	1.98	16.38	7.07

[a] Pb isotope data are corrected for mass fractionation, errors are 1 sigma standard error.

three deposits. This ratio has previously been correlated with magma chemistry (Sillitoe, 1999) and may relate to the predominance of more acid intrusions in the central to southern Panagyurishte belt. Apart from the difference in Ag/Au, the differences in arc style and compositions within a single magmatic centre are larger than those across the regional transect, probably reflecting local differences in exposed mineralization depths accentuated by differential uplift and erosion after ore formation. Thus, Elatsite, a relatively deep porphyry deposit that is hosted by basements is juxtaposed, by likely late normal faults, to the shallow subvolcanic epithermal deposits at Chelopech. The distribution of deposit types in the Panagyurishte corridor and the absence of any economic mineralization in the south of the transect probably relates more to erosional preservation than to processes that varied systematically from north to south.

9. Discussion and conclusions

Fig. 13 summarizes the available geochemical, tectonic and geochronological data and suggests a possible geodynamic interpretation of the magmatic to hydrothermal evolution of the ABTS belt along the Panagyurishte transect during Late Cretaceous times. Closure of the Vardar Ocean against the E–W-oriented southern continental margin of Europe

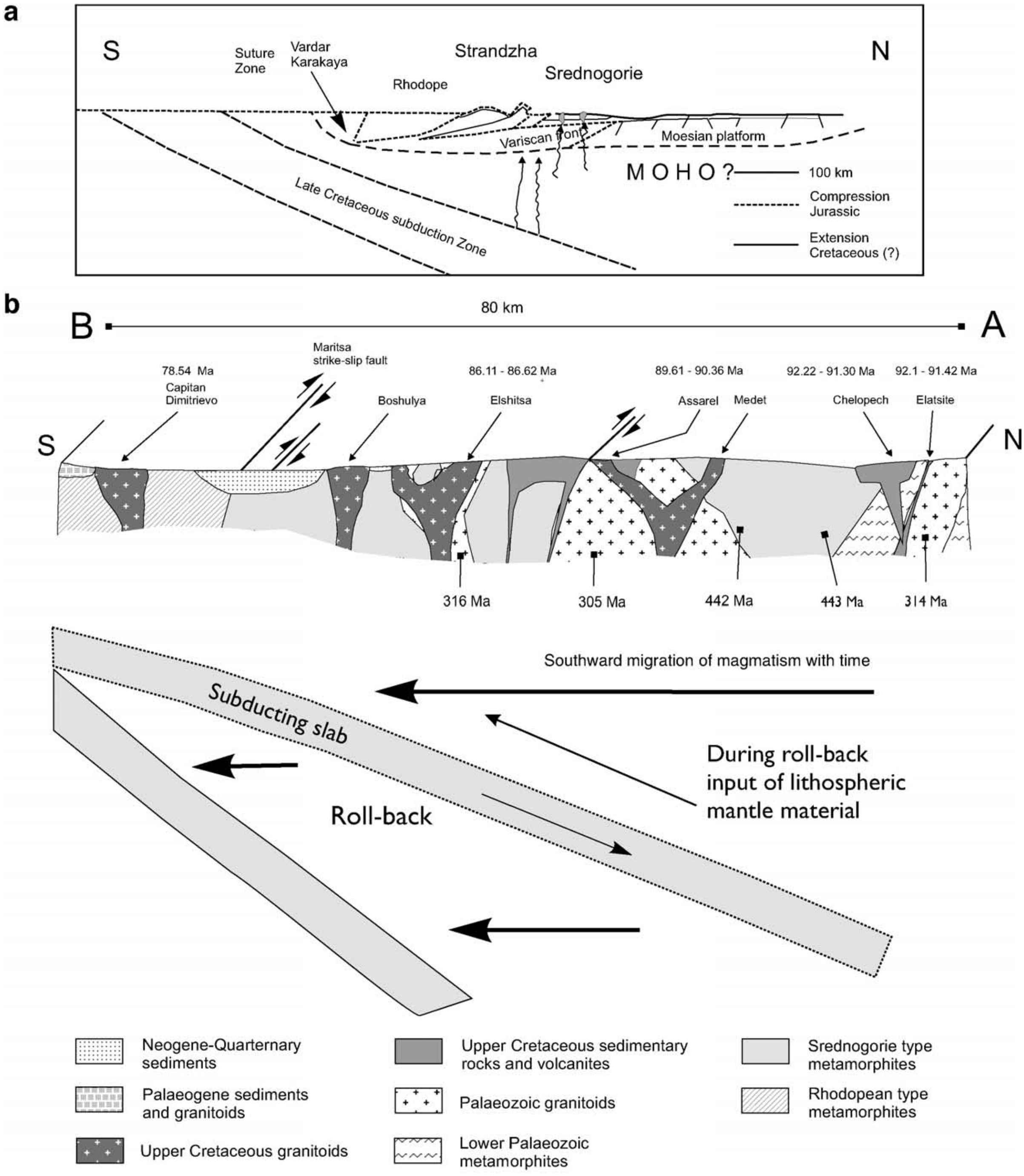

Fig. 13. (a) Modified profile from the Moesian platform to the Vardar–Karakaya zone, after Banks and Robinson (1997); (b) Schematic profile (line A–B, see Fig. 3) through the Panagyurishte district during Cretaceous time; for the U–Pb zircon ages see Table 1, additional age information about the metamorphites and Variscan intrusives are given by Kamenov et al. (2002), Peytcheva and von Quadt (2004) and Peytcheva et al. (2004).

(the present Moesian platform) led to the initiation of an arc environment, starting with calc–alkaline magma emplacement into pre-Mesozoic basement rocks at the northern border of the belt. Oblique (~NW-directed) subduction generated horst and graben structures with subbasins bounded by faults with a dominant dextral strike-slip component, which became filled by volcanic products and co-magmatic shallow intrusions. Magmatism is oldest in the north (~92 Ma at Elatsite and Chelopech) and becomes progressively younger towards the south (~90 Ma at Medet, 86 Ma at Elshitsa and Vlaykov Vruh), ending with mid-crustal plutons in the southernmost part of the belt (~78 Ma at Capitan Dimitrievo) in the transition to the Rhodope domain further south (Ricou et al., 1998). We interpret the ca. 14 million years of age progression from north to south as the result of a gradual southward retreat of the subducting slab, which is consistent with the transtensional structures hosting the magmatic products. At least locally, crustal stress fields must have been near neutral to compressive, allowing the development of upper-crustal hydrous magma chambers for porphyry copper mineralization (Tosdal and Richards, 2001). However, hinge retreat (roll-back) and accompanying extension leads to overall crustal thinning in this arc to back-arc environment, which is not optimal for the formation of giant porphyry deposits, but favours the preservation of near-surface magmatic and hydrothermal products, including volcanic rocks and medium-sized porphyry and epithermal Cu–Au deposits. At the southern border of the calc–alkaline magmatic belt, the youngest products of Cretaceous magmatism are exposed as large mid-crustal plutons, such as the Boshulya complex, which were emplaced into a ductile and actively deforming strike-slip environment (Ivanov et al., 2001). Subsequent uplift and erosion, at least in part as a consequence of the accretion of continental basement material in the Rhodope complex farther south, removed any upper-crustal equivalents of the youngest Late Cretaceous magmatism in this area.

The geochemical signatures (major, trace and REE elements) of all Late Cretaceous igneous rocks are typical for island-arc magmas of subduction-related origin. A fertile MORB-type mantle component (Kamenov et al., 2003b) is indicated by geochemical data (Nb, Zr, Ti) from the Panagyurishte transect, with involvement of hornblende, phlogopite, apatite, rutile and spinel, as well as being in a lherzolitic source. Field relations, petrographic and geochemical data are consistent with a combination of magma-mixing and fractional crystallization in the crust. Field, petrological and mineralogical evidence for magma mixing is observed across the whole transect, but the dominant role of magma mixing is most strongly expressed in the southern part of the Panagyurishte district (Elshitsa and Capitan Dimitrievo). Sr, Nd and Pb whole-rocks isotope compositions of the Cretaceous magmatic rocks are clearly different from those of the exposed pre-Mesozoic basement rocks. Contamination of Cretaceous mantle magmas by this crustal signature is greatest in the north, diminishing towards the magmatic rocks emplaced later in the southern part of the transect. Hinge retreat would enhance the incursion of asthenospheric material into the mantle wedge above the subducting slab, and is therefore consistent with the geochemical trend towards less crustally contaminated mantle melts in the southern part of the Panagyurishte transect in young rocks.

In contrast to the distinct age progression and chemical variation in the magmatic rocks, the associated ore deposits show only small and possibly insignificant differences in composition and deposit style along the Panagyurishte transect. The most prominent regional feature is the alignment of all significant deposits along a narrow NNW–SSE corridor, which may be caused by an old zone of weakness in the pre-existing basement, similar to lineaments localizing ore-forming calc–alkaline centres in back-arc settings elsewhere (e.g., Andes; Coughlin et al., 1998). In the northern to central part of the Panagyurishte transect, porphyry-style Cu–Mo–Au and high-sulphidation epithermal Au–As–Cu deposits are spatially associated with each other in smaller volcano–plutonic centres, whose life span was much shorter than the total duration of magmatism in the belt. Thus, in the northernmost magmatic–hydrothermal centre, where extensive geochronological data from different isotopic systems are available, the emplacement of subvolcanic dykes, andesitic to dacitic volcanism, porphyry-style mineralization at Elatsite and epithermal ore mineralization at Chelopech were all essentially coeval. A maximum duration of magmatic–hydrothermal activity of ca. 1 million years is shown by U–Pb (zircon) and Re–Os (molybdenite) geochronological data, whereas Rb–Sr and K–Ar data include later cooling and hydrothermal resetting ages that are difficult to interpret. Differences in ore style within each mineralized centre are mainly due to different erosion levels in blocks affected by differential uplift and erosion, although some variations in ore composition (e.g., significant variations in the Au/Ag ratio of the epithermal deposits) may relate to local differences in magmatic fluid source (Sillitoe, 1999).

Acknowledgments

This work was supported by the Swiss National Science Foundation through the SCOPES Joint Research Project 7BUPJ062276, 7BUPJ062396 and research grants 21-59041.99, 2000-59544.99, 200020-101853 and 200020-100735. This is a contribution to the ABCD-GEODE research programme supported by the European Science Foundation. Urs Schaltegger and Richard Tosdal are thanked for their excellent reviews and helpful comments, and we thank Derek Blundell and Nick Arndt for their editorial handling of this manuscript. The manuscript benefited from abundant discussions and common field trips with Stanislav Stoykov, Borislav Kamenov, Rossen Nedialkov, Zivko Ivanov, Yotzo Yanev, Rumen Petrunov, Kalin Kouzmanov, Isabelle Chambefort, Lorenz Fanger and Franz Neubauer.

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