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Late Cretaceous Cu–Au epithermal deposits of the Panagyurishte district, Srednogorie zone, Bulgaria

Robert Moritz[1], *Kalin Kouzmanov*[2,1] and *Rumen Petrunov*[3]

Abstract

This review compiles geological, mineralogical, and isotopic data from the four largest Cu–Au epithermal deposits of the Late Cretaceous Panagyurishte mineral district, Bulgaria, including from north to south: the producing Chelopech, and the past-producing Krassen, Radka and Elshitsa deposits. Epithermal Cu–Au deposits of the northern and older part of this district are mainly hosted by andesites, whereas those from the southern and younger district are hosted by dacites. Advanced argillic alteration is described in the majority of the deposits, with the most complex alteration assemblage occurring at Chelopech. In all deposits, mineralization is the result of replacement and open-space deposition producing massive sulphide lenses surrounded by disseminated mineralization. Additionally at Chelopech, stockwork vein zones are also an important ore type. At Elshitsa, Radka and Krassen, the mineralized zones are controlled by WNW-oriented faults, and at Chelopech there is a supplementary control by NE-oriented faults. A three-stage paragenesis is recognized in all deposits, including an early disseminated to massive pyrite stage; an intermediate, Au-bearing Cu–As–S stage, which forms the economic ore; and a late Zn–Pb–Ba stage. Sulphur isotopic compositions of sulphide and gangue minerals are consistent with similar data sets from other high-sulphidation deposits. Variations in Sr and Pb isotope data among the deposits are interpreted in terms of fluid interaction with different host-rocks, additionally variability in Pb isotopic compositions can be attributed to differences in composition of the associated magmatism. Throughout the Panagyurishte district, there is a coherent and continuous sequence of events displayed by the epithermal Cu–Au deposits indicating that they result from similar ore forming processes. However, latitudinal differences in ore deposit characteristics are likely related to emplacements at different depths, differences in degrees of preservation as a function of post-ore tectonics and/or sedimentary processes, efficiency of ore formation, and/or modifications of regional controls during the 14 Ma-long geological evolution of the Panagyurishte district, such as magma petrogenesis and/or tectonic regimes.

Keywords: Cu–Au high-sulphidation epithermal deposits, Panagyurishte district, Srednogorie zone, Bulgaria.

Introduction

The Panagyurishte district is a major metallogenic region in Eastern Europe (Fig. 1a), which has supplied about 95% of the recent Bulgarian copper and gold production (Mutafchiev and Petrunov, 1996), and where Late Cretaceous porphyry-Cu and Cu–Au epithermal deposits form the most significant deposits. Within the Tethyan region, the Panagyurishte mineral district displays some of the best examples of the porphyry-Cu and high-sulphidation epithermal ore deposit association recognized in other tectonic settings such as the circum-Pacific region (Sillitoe, 1991, 1999; Hedenquist and Lowenstern, 1994; Corbett and Leach, 1998). The Panagyurishte district is located 60–90 km east of Sofia, between the towns of Etrepole and Pazardzhik (Fig. 1c), and belongs to the Late Cretaceous Banat-Timok-Srednogorie belt extending from Romania through Serbia to Bulgaria (Fig. 1a), a major ore province within the Alpine-Balkan-Carpathian-Dinaride collision belt (Berza et al., 1998; Ciobanu et al., 2002; Heinrich and Neubauer, 2002). While the genesis of porphyry-Cu deposits has been relatively undisputed in the Panagyurishte district (e.g. Strashimirov et al., 2002; von Quadt et al., 2002; Tarkian et al., 2003), the Cu–Au epithermal deposits have remained subject to debate for some time, since they were interpreted as volcanogenic massive sulphide (VMS) deposits in early studies (Bogdanov, 1984), and their high-sulphidation nature has only been recognized in recent years (Petrunov, 1994, 1995; Mutafchiev and Petrunov, 1996).

1 Section des Sciences de la Terre, Université de Genève, rue des Maraîchers 13, CH-1205 Genève, Switzerland. <robert.moritz@terre.unige.ch>
2 Institut für Isotopengeologie und Mineralische Rohstoffe, ETH-Zentrum, CH-8092 Zürich, Switzerland. Present address: (1). <kalin.kouzmanov@terre.unige.ch>
3 Geological Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Street, Bl. 24, 1113 Sofia, Bulgaria. <petrunov@geology.bas.bg>

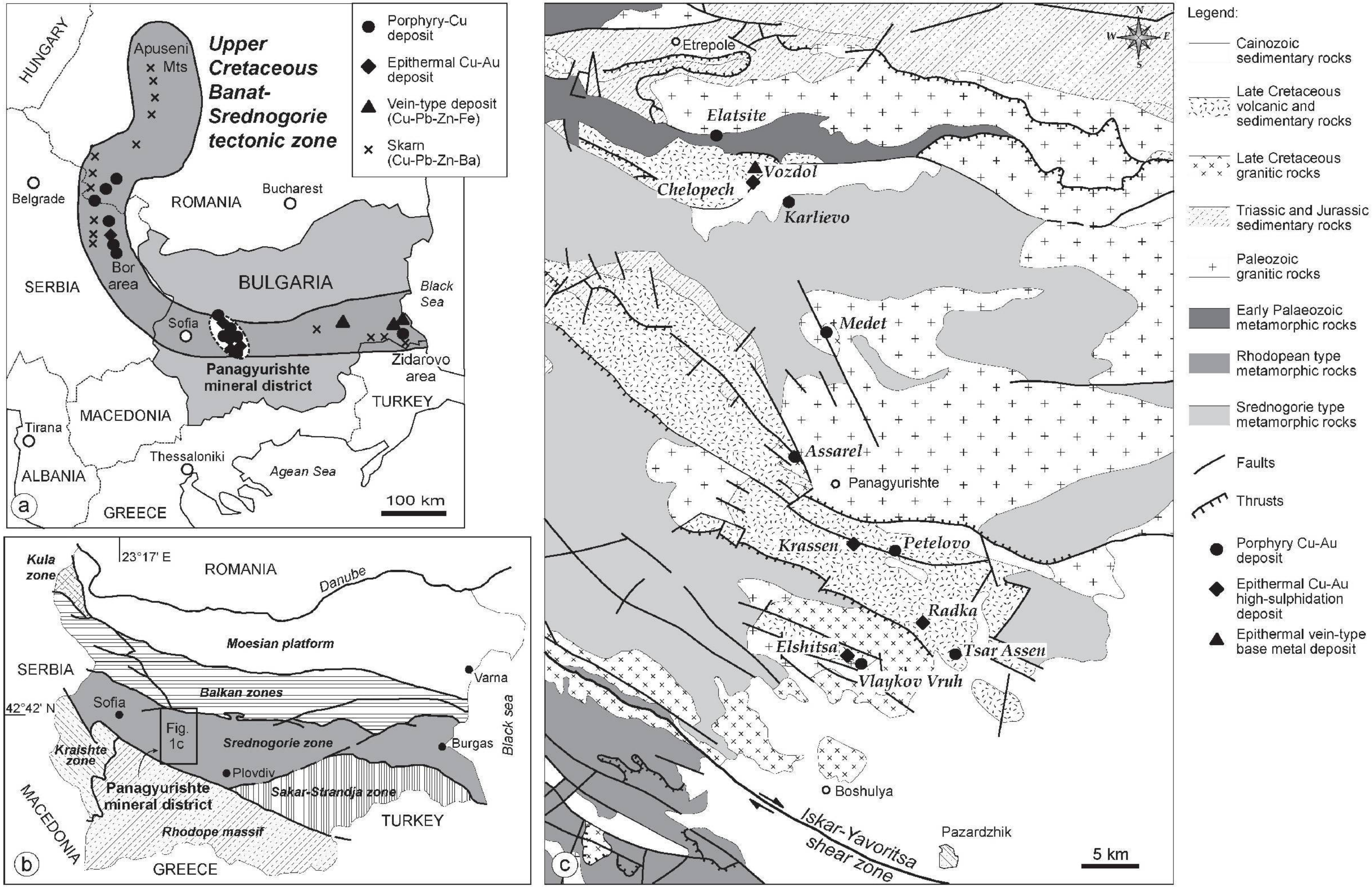


Fig. 1 (a) Location of the Late Cretaceous Banat-Srednogorie Belt in Eastern Europe (after Berza et al., 1998; Ciobanu et al., 2002; Heinrich and Neubauer, 2002). (b) Major tectonic zones of Bulgaria (after Ivanov, 1998). (c) Simplified geology of the Panagyurishte ore district (after Cheshitev et al., 1995).

This review compiles geological, mineralogical, and isotopic information from the four largest Cu–Au epithermal deposits of the Panagyurishte district (Table 1), including Chelopech, Krassen, Radka and Elshitsa (Fig. 1c). It shows that these deposits were formed by similar processes, typical for high-sulphidation epithermal deposits, during the evolution of the Srednogorie belt. However, latitudinal variations of the ore deposit characteristics are recognized, and their significance is discussed as a function of emplacements at different depths, differences in the degree of preservation, efficiency of ore formation processes at the local scale, and fundamental changes in regional geological controls in space and with time.

Regional geological setting

The Srednogorie tectonic zone is an 80 to 100 km wide and east–west oriented zone in Bulgaria, located between the Balkan Zone in the north, and the Rhodopes and the Sakar-Strandja Zone in the south (Fig. 1b; Boncev, 1988; Ivanov, 1988, 1998). The Panagyurishte ore district belongs to the Central Srednogorie zone, and is characterised by a north-northwest oriented alignment of porphyry-Cu and Cu–Au epithermal ore deposits, which is oblique with respect to the east-west trending Srednogorie tectonic zone in Bulgaria (Fig. 1b).

The geology of the Panagyurishte mineral district consists of metamorphic and igneous basement rocks, abundant Late Cretaceous magmatic rocks and subsidiary sedimentary rocks, and subordinate Tertiary sedimentary rocks (Fig. 1c; Popov et al., 2003). The oldest basement rocks are two-mica migmatites, amphibolites and gneisses of uncertain Precambrian age, known as Pirdop Group (Dabovski, 1988), Srednogorie type metamorphic rocks (Cheshitev et al., 1995) or pre-Rhodopean Supergroup (Katskov and Iliev, 1993). Younger metamorphic rocks are Late Precambrian to Cambrian phyllites, chlorite schists and diabases of the Berkovitsa Group (Haydoutov, 2001). Palaeozoic basement intrusions are gabbrodiorites, quartz-diorites, tonalites, and granodiorites-granites (Dabovski et al., 1972; Kamenov et al., 2002).

The type and composition of the Late Cretaceous magmatic rocks vary as a function of latitude in the Panagyurishte district, with sub-volcanic and effusive rocks becoming progressively more abundant from south to north with respect to intrusive rocks (Fig. 1c). Andesites predominate in the northern and central Panagyurishte district, whereas dacites 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). In the south, andesites are the earliest volcanic rocks, followed by dacites, and a final stage of dacitic-rhyodacitic subvolcanic intrusions (Bogdanov et al., 1970; Popov et al., 2000a). Small, subvolcanic dacite, quartz-monzodiorite and granodiorite intrusions (mostly <1km^2 in size), 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, northwest-elongated, syntectonic, Late Cretaceous granodioritic-granitic intrusions are restricted to the southernmost Panagyurishte district along the Iskar-Yavoritsa Shear Zone (Ivanov et al., 2001; Peytcheva et al., 2001), which corresponds to the transition between the Srednogorie zone and the Rhodope Massif (Fig. 1b,c). The Late Cretaceous magmatic rocks are calc-alkaline to high-K calc-alkaline with a local transition to subalkaline (Fig. 2), 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., 2003a,b).

U–Pb zircon geochronology reveals a 14 Ma-long protracted Cretaceous magmatic and ore-forming activity in the Panagyurishte district (Fig. 1c). The oldest activity is recorded in its northern part, where the age of the Elatsite porphyry-Cu deposit is bracketed by dykes dated at 92.1 ± 0.3 Ma and 91.84 ± 0.3 Ma (von Quadt et al., 2002), in line with recent Re–Os ages of 92 Ma (Zimmerman et al., 2003). At the Chelopech deposit, andesite pre-dating mineralization and latite yield an age of 91.45 ± 0.15 Ma (Chambefort et al., 2003a; Stoykov et al., 2004). Ages decrease southward with 86.62 ± 0.02 and 86.11 ± 0.23 Ma, respectively, for the Elshitsa granite and subvolcanic dacites, and 85 ± 0.15 Ma for the Vlaykov Vruh porphyry-Cu deposit (Peytcheva et al., 2003), 84.6 ± 0.3 and 82.16 ± 0.1 Ma, respectively, for granodiorite and gabbro at Boshulya (Peytcheva and von Quadt, 2003), and 78.54 ± 0.13 Ma for the Capitan-Dimitrievo pluton (Kamenov et al., 2003c).

The Late Cretaceous sedimentary rock succession in the Panagyurishte district starts with Cenomanian-Turonian conglomerate and sandstone, which transgressively overly the basement rocks, contain metamorphic rock fragments and coal-bearing interbeds, and are devoid of volcanic rock fragments. They are postdated by Late Cretaceous intrusive and volcanic rocks, which are interbedded with early Senonian argillaceous limestone, calcarenite and sandstone with abundant volcanic rock fragments. This interbedded rock assemblage is transgressively overlain by Santonian-Campanian red marl of the Mirkovo Formation, and Campanian-Maastrichtian calcarenite and mudstone flysch of the Chugovo Formation (Aiello et al., 1977; Moev and Antonov, 1978; Popov, 2001a; Stoykov and Pavlishina, 2003).

Three predominant fault orientations are recognized in the Panagyurishte district (Fig 1c; Cheshitev et al., 1995; Popov, 2001b; Popov et al., 2003): (1) regional WNW-oriented faults, which are partly thrusts with both northward and southward vergences, and which control the geometry of the distribution of the Late Cretaceous magmatic and sedimentary rocks; (2) shorter NW to NNW-oriented faults, recognized within the entire district, including in the ore centres, and which are parallel to the characteristic ore deposits alignment of the Panagyurishte district; and (3) subordinate NE-oriented faults, also recognized in some deposits (Popov, 2001b; Jelev et al., 2003). According to Dobrev et al. (1967) and Tsvetkov (1976), gravity and magnetic data reveal a regional, deep-seated NNW-oriented fault-zone that coincides with the ore deposit alignment of the district.

Regional tectonic evolution

The Alpine evolution of the Bulgarian tectonic zones is intimately linked to the tectonic evolution and closure of the Tethys (Dabovski et al., 1991; Ricou et al., 1998). Ivanov (1988) interprets the Srednogorie tectonic zone as an island arc that was formed during northward Late Cretaceous subduction of the African Plate beneath the Eurasian Plate. Boccaletti et al. (1974), Berza et al. (1998) and Neubauer (2002) suggest post-collisional detachment of the subducted slab as the trigger for the Late Cretaceous calc-alkaline magmatism and associated ore deposit formation in the Srednogorie zone. In contrast, based on the observation that subduction ceased in the early Cretaceous (Barremian), Popov (1987, 2002) has interpreted the Banat-Timok-Srednogorie zone as a rift. This appears to be in apparent conflict with the subduction-related scenario, but the arguments raised by Popov (1987) could be reconciled with the scenario of Boccaletti et al. (1974), Berza et al. (1998) and Neubauer (2002), if one considers the time lag between cessation of subduction and post-collisional slab break-off. More recently, based on regional lithogeochemical and radiometric age data from magmatic rocks, Kamenov et al. (2003a,b) and von Quadt et al. (2003 a,b) propose a roll-back scenario to explain the geodynamic setting of the Panagyurishte district. However, both slab detachment and roll-back scenarios are disputed by Lips (2002), who argues that conditions for such geodynamic settings were unfavourable in the Late Cretaceous due to the relatively low density and limited length of the young subducted slab, and he favours typical subduction-related calc-alkaline magmatism and associated ore formation processes. A consensus might be difficult to reach, because, as admitted by Neubauer (2002), distinction between subduction-related and slab break-off magmatism remains ambiguous. During the Early to Middle Eocene, continuous tectonic plate convergence resulted in the collision of the Rhodopes with the Srednogorie zone, whereby allochthonous units of the former were thrusted northward on the southern Srednogorie zone (Ivanov, 1988; Ricou et al., 1998).

Evolution of genetic concepts for the Panagyurishte Cu–Au epithermal ore deposits

Early contributions (see Dimitrov, 1960, and references therein) have interpreted the Cu–Au hydrothermal deposits as epithermal to mesothermal deposits genetically linked to porphyry-Cu deposits in the Panagyurishte district. Dimitrov (1960) describes the ore deposits as epigenetic, formed by replacement and open space deposition processes, with a preferential development of alteration zones and ore bodies in volcanic tuffs and sedimentary rocks.

Later, based on the observation that massive pyrite fragments from the early ore paragenesis were set in a matrix of dacitic tuffs in some deposits of the Panagyurishte district, Bogdanov (1984) interpreted the early massive pyrite stage of the Cu–Au hydrothermal deposits as synchronous with volcanic activity and sedimentation in water basins, followed by epigenetic polymetallic ore. Bogdanov (1984) concluded that porphyry-Cu deposits post-dated Cu–Au hydrothermal ores based on K–Ar ages of 90–94 Ma for the volcanic rocks and 75–87 Ma for the intrusions hosting the porphyry-Cu deposits (Chipchakova and Lilov, 1976).

More recently, Petrunov (1995), and Mutafchiev and Petrunov (1996) recognized that the Cu–Au Chelopech deposit of the northern Panagyurishte district (Fig. 1c) shares alteration and opaque mineral associations with typical high-sulphidation epithermal deposits (Hedenquist et al., 2000), also known as acid sulphate or alunite-kaolinite deposits (Heald et al., 1987; Berger and Henley, 1989). Petrunov (1995), and Mutafchiev and Petrunov (1996) proposed a succession of events with submarine formation of early massive sulphide ore, followed by uplift of the volcanic edifice and formation of the high-sulphidation ore in an aerial setting, overprinting the volcanogenic massive sulphide ore. Therefore, they classified the Chelopech deposit as a volcanic-hosted epithermal deposit of high-sulphidation type.

Recent contributions (Popov and Kovachev, 1996; Popov and Popov, 1997; Strashimirov et al., 2002), based on modern genetic concepts (e.g. Hedenquist and Lowenstern, 1994; Hedenquist et al., 2000), interpret the Cu–Au hydrothermal deposits as epithermal high-sulphidation systems genetically linked to porphyry-Cu deposits of the Panagyurishte district, therefore in agreement with the early interpretation by Dimitrov (1960).

Spatial association of the Cu–Au epithermal deposits with porphyry-Cu deposits

The Cu–Au hydrothermal deposit at Elshitsa is located about 1 km to the NW to the past-producing Vlaykov Vruh porphyry-Cu deposit (Fig. 1c). These two neighbouring deposits constitute the best example for the tight spatial association of high-sulphidation epithermal and porphyry-Cu deposits within the Panagyurishte ore district (Kouzmanov, 2001). Such a relationship is not as obvious at the Radka deposit, although granodioritic and quartz-diorite porphyries have been described in its vicinity. Cu–Au epithermal occurrences have also been described in the immediate proximity of the Assarel and Petelovo porphyry-Cu deposits (Petrunov et al., 1991; Sillitoe, 1999; Tsonev et al., 2000a; Fig. 1c). The Chelopech deposit belongs to an ore deposit cluster in the northern Panagyurishte district, which also includes the vein-type Vozdol base metal occurrence, the Karlievo porphyry-Cu occurrence, and the major producing porphyry-Cu Elatsite deposit (Popov et al., 2000b; Fig. 1c). This ore deposit cluster is centred on a major, regional geomagnetic anomaly of the northern Panagyurishte district, interpreted by Popov et al. (2002) as a shallow, large magmatic chamber.

Economic significance and metal ratios of the Cu–Au epithermal deposits

Chelopech is the largest and, at present, the only producing high-sulphidation deposit in the Panagyurishte mineral district (Table 1). It ranks among the major high-sulphidation deposits of

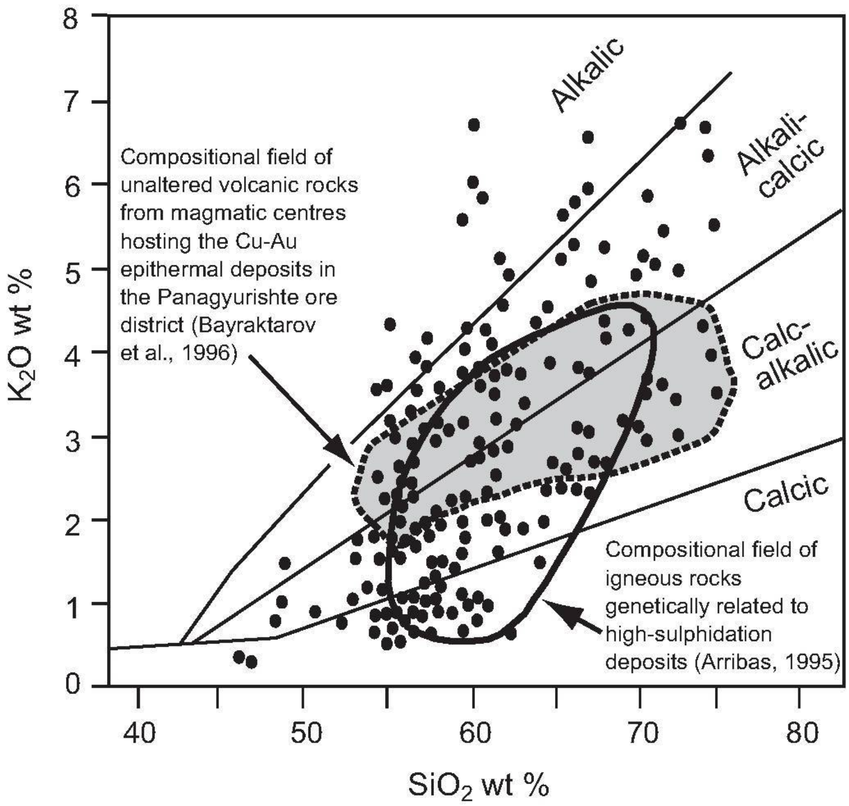


Fig. 2 K_2O vs. SiO_2 diagram for Late Cretaceous igneous rocks from the Panagyurishte ore district (black dots). Data for the Panagyurishte ore district from Bayraktarov et al. (1996), and data compilation of igneous rocks genetically related to high-sulphidation deposits from Arribas (1995).

Table 1 Major characteristics of high-sulphidation deposits from the Panagyurishte ore district.

Ore deposit		Chelopech	Krassen	Radka	Elshitsa
Immediate host rocks		Massive andesites; phreatomagmatic diatreme breccia; sedimentary rocks (oolithic, biodetrital and sandstone layers); volcanic tephra and tuff.	Andesitic breccia tuff, and lava.	Preferentially dacitic breccia (abundant) and dacitic tuff (rare). Subordinate lava flows.	Dacite subvolcanic body, dacitic tuff, volcanic breccia.
Alteration		Proximal to ore bodies: advanced argillic with vuggy silica (innermost part of silicic zone with pyrite and APS minerals*, followed laterally by quartz-kaolinite-dickite-pyrite-APS minerals*). Intermediate: phyllic. Distal: propylitic. At depth: diaspore, pyrophyllite, alunite and zunyite.	Proximal: advanced argillic (quartz-kaolinite/dickite). Intermediate: phyllic. Distal: propylitic (including adularia).	Proximal: phyllic (innermost part with quartz-sericite followed laterally by quartz-sericite-albite). Distal: propylitic.	Proximal to ore bodies: advanced argillic (quartz-sericite +/- diaspore). Intermediate: phyllic. Distal: propylitic
Orebody geometry & texture		Veins, dissemination, massive sulphide lenses with replacement textures, breccia.	Moderately dipping massive sulphide lenses, disseminations.	Mainly steeply dipping massive sulphide lenses surrounded by disseminations, breccia pipes, rare quartz-sulphide veins.	Mainly steeply dipping massive sulphide lenses, surrounded by disseminations, breccia and rare veins.
Ore & alteration control		Fault and lithological control.	Fault control (& lithological?)	Fault and lithological control.	Fault and lithological control.
Mineralogical differences	Enargite	Abundant	Present	Rare, upper levels	Rare, upper levels
	Luzonite	Abundant	Minor	None	None
	Native Ag	None	Minor	Minor	Minor
	Tetrahedrite	Rare	Present	Present	Present
	APS minerals*	Abundant	None	None	None
	Kaolinite/Dickite	Abundant	Present	None	None
	Alunite	At deeper levels	None	None	Rare, upper levels
	Diaspore	At deeper levels		None	Rare
	Pyrophyllite	At deeper levels		None	Rare
	Vuggy silica	Present locally		None	None
	Chalcedony	Abundant		None	None
Tonnage* (Mt)		42.5	0.3	8.9	4.5
Ore grades	*Cu (%)*	1.28	0.76	1.06	1.13
	Au (g/t)	3.4		1.5-2.0	1.5
	Ag (g/t)	8.4 (18)		25-30	15
Metal ratios	*Ag/Au*	2.5		16	10
	Au/Cu	2.7		1.7	1.3
	Ag/Cu	7.8		26	13.3
Production period		1954- ... (still in operation)	1962-1973	1942-1995	1922-1999
Source of information (except tonnage and production mainly from Strashimirov et al., 2002)		Petrunov (1989, 1994, 1995); Moritz et al. (2001, 2003); Chambefort et al. (2002, 2003); Georgieva et al. (2002); Arisanov (pers. comm., 2002).	Radonova (1969, 1970); Radonova and Velinov (1974); Tsonev et al. (2000a).	Radonova (1962); Chipchakova et al. (1981); Tsonev et al. (2000b); Kouzmanov (2001); Kouzmanov et al. (2004).	Radanova (1967, 1970); Chipchakova and Stefanov (1974); Dimitrov (1985); Kouzmanov (2001).

APS minerals*: Aluminium-phosphate-sulphate minerals; Tonnage*: total of past production and remaining resources.

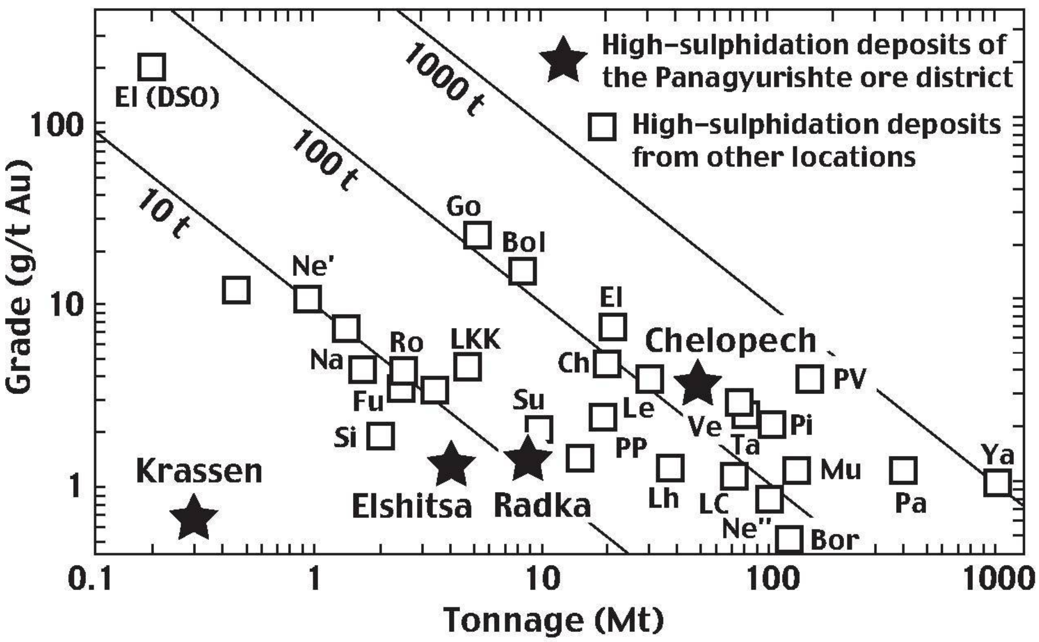


Fig. 3 Grade–tonnage diagram of high-sulphidation deposits from the Panagyurishte ore district in comparison to similar deposits from other localities. Grades and tonnages of the Bulgarian deposits are from Strashimirov et al. (2002). The diagram is modified from Hedenquist et al. (2000) with additional data from Sillitoe (1999) marked with an asterisk (*) in the following list. Bol — Boliden, Sweden; Bor — Bor*, Serbia; Chinkuashih, Taiwan; El — El Indio, Chile; El (DSO) — El Indio direct shipping ore; Fu — Furtei*, Italy; Go — Goldfield: U.S.A.; LC — La Coipa*, Chile; Le — Lepanto, Philippines; Lh — Lahoca, Hungary; LKK — Lerokis and Kali Kuning*, Indonesia; Mu — Mulatos, Mexico; Na — Nansatsu district (including Kasuga), Japan; Ne' and Ne" — Nevados de Famatina*, Argentina (high and low grade ore, respectively); Pa — Pascua, Chile; Pi — Pierina, Peru; PP — Paradise Peak, U.S.A.; PV — Pueblo Viejo, Dominican Republic; Ro — Rodalquilar, Spain; Si — Sipan*, Peru; Su — Summitville, U.S.A.; Ta — Tambo, Chile; Ve — Veladero, Argentina; Ya — Yanacocha, Peru.

the world, with a tonnage and a gold grade comparable to important deposits of the circum-Pacific region such as El Indio in Chile, Lepanto in the Philippines and Pierina in Peru (Fig. 3). By contrast, the past-producing Elshitsa and Radka deposits are on the borderline of economic deposits, and Krassen remains an uneconomic occurrence (Fig. 3).

The northern zone stands out as the more fertile part of the Panagyurishte ore district. Indeed, the location of the major high-sulphidation Chelopech deposit coincides with the geographic position of the economically significant porphyry-Cu deposits of the area (Fig. 1c), including Elatsite (354 Mt at 0.44% Cu and 0.2 g/t Au), Medet (163 Mt at 0.32% Cu and 80 g/t Mo), and Assarel (319 Mt at 0.36% Cu), whereas the southern porphyry-Cu deposits at Tsar Assen (6.6 Mt at 0.47% Cu) and Vlaykov Vruh (9.8 Mt at 0.46% Cu) are much smaller (Porphyry-Cu data from Strashimirov et al., 2002, total of past production and remaining resources), and correlate spatially with the lesser economic Elshitsa, Radka and Krassen epithermal deposits.

Chelopech is characterised by higher Cu and Au grades (1.28% and 3.4 g/t) relative to Krassen (0.76% and 0.69 g/t), Radka (1.06% and 1.5–2.0 g/t) and Elshitsa (1.13% and 1.5 g/t). Silver grades are on average lower at Chelopech (8.4 g/t) than at Radka (25–30 g/t) and Elshitsa (15 g/t), which is reflected by a low Ag/Au ratio of 2.5 at Chelopech in contrast to 16 and 10, respectively, at Radka and Elshitsa. The Chelopech deposit has a higher Au/Cu ratio of 2.7 than the Radka and Elshitsa deposits, respectively, with 1.7 and 1.3 (Table 1). Additionally, Chelopech is characterised by elevated contents of S, Ga and Ge that have been by-products during ore dressing (Popov and Kovachev, 1996).

Host rocks of the Cu–Au epithermal deposits in the Panagyurishte ore district

At Elshitsa, the ore bodies are hosted by an about 100 m wide breccia zone within a WNW-elongated and steeply dipping Late Cretaceous subvolcanic dacite body (Fig. 4c). This subvolcanic rhyodacite body crosscuts a belt of andesitic-dacitic volcanic rocks located between Palaeozoic granitoids to the south and the Late Cretaceous Elshitsa intrusion to the north (Fig. 1c). Dacitic volcanic rocks and breccia form the preferential rock environment for metasomatic replacement and hy-

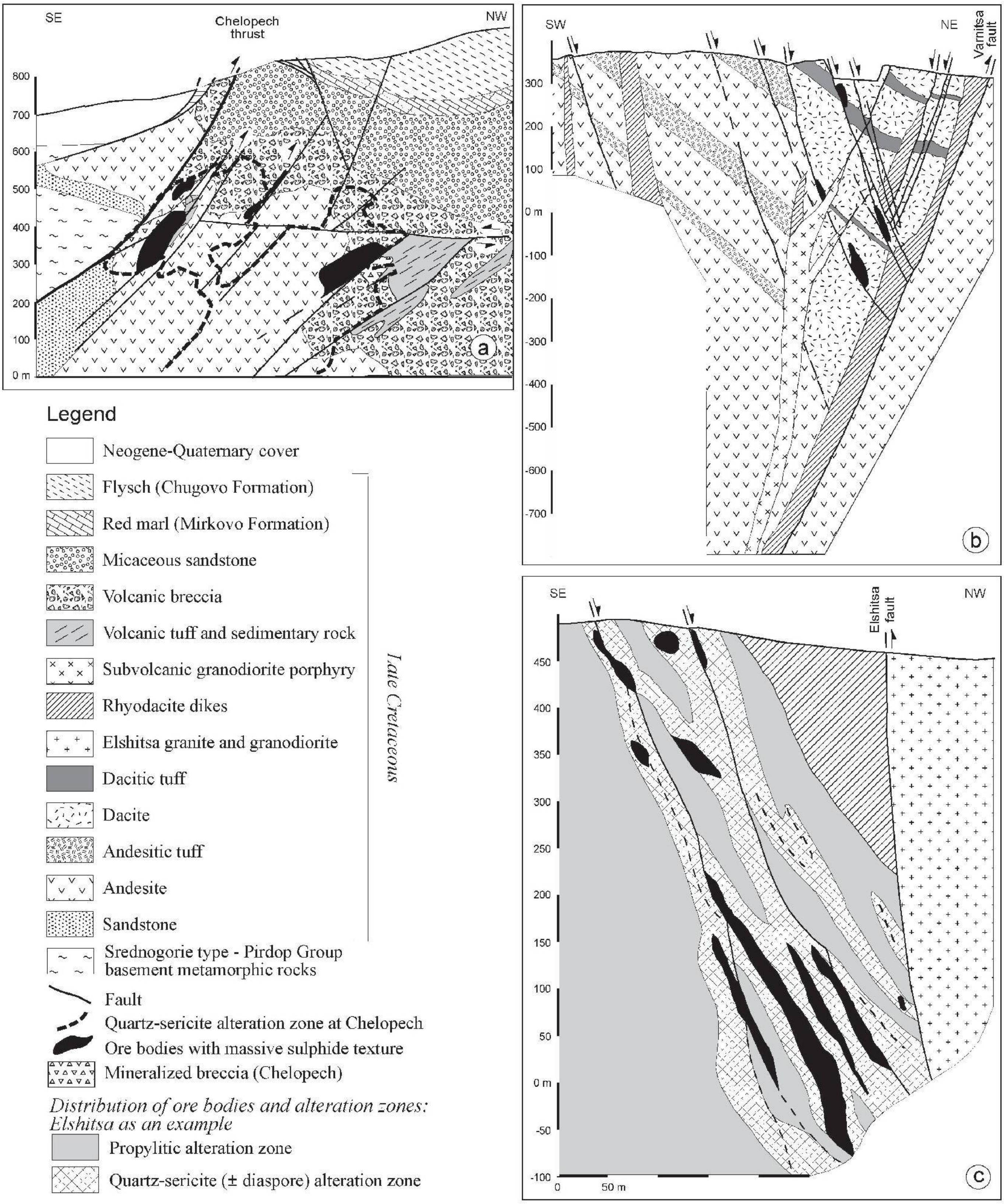


Fig. 4 (a) Cross sections of the Chelopech (after Chambefort, 2005), (b) Radka (after Popov and Popov, 1997; Tsonev et al., 2000b; Kouzmanov et al., 2002) and (c) Elshitsa deposits (after Chipchakova and Stefanov, 1974).

drothermal precipitation (Fig. 4c; Kouzmanov, 2001).

The Radka deposit occurs in an andesitic-dacitic volcanic belt, with subordinate rhyodacitic dykes and granodioritic and quartz dioritic porphyries (Fig. 4b), immediately to the northeast of the Late Cretaceous Elshitsa intrusion (Fig. 1c). The immediate host rocks of the mineralized zones are exclusively Late Cretaceous dacitic lava flows, volcanic breccia and tuffs (Fig. 4b). The latter two are preferential hosts to the mineralization (Bogdanov and Bogdanova, 1974; Kouzmanov, 2001; Kouzmanov et al., 2004).

In the Krassen deposit (Fig. 1c), the host rocks of the mineralized zones are andesitic breccia, tuffs and lava flows that have been overthrusted along the Krassen fault on the sedimentary rocks of the Chugovo Formation (Tsonev et al., 2000a).

The Chelopech deposit is hosted by a Late Cretaceous volcanic and volcano-sedimentary complex, transgressively overlaying Precambrian and Palaeozoic metamorphic rocks (Fig. 1c, Table 1; Popov et al., 2000b). The Late Cretaceous rock sequence consists of detrital sedimentary rocks derived from the basement, and andesitic, dacitic to trachyandesitic subvolcanic bodies, lava flows, agglomerate flows, tuffs and epiclastic rocks. They are transgressively covered by sandstone, argillaceous limestone, and the terrigenous flysch sequence of the Chugovo Formation (Fig. 4). The ore bodies are hosted by (1) an andesitic subvolcanic body, associated with phreatomagmatic, diatreme breccias, and (2) sedimentary rocks with oolithic, biodetrital and sandstone layers interbedded with (3) volcanic tephra-tuff containing accretionary lapilli and pumices (Chambefort et al., 2003b; Jacquat, 2003).

Unaltered volcanic rocks from the magmatic centres hosting the Cu–Au epithermal and porphyry-Cu deposits are enriched in K with respect to equivalent rock types in barren areas (Bayraktarov et al., 1996). Figure 2 shows that the K_2O vs. SiO_2 field of the volcanic host rocks of the ore deposits in the Panagyurishte district overlaps with the upper part of the field typical for volcanic rocks genetically related to high-sulphidation deposits (Arribas, 1995).

Wall rock alteration of the Cu–Au epithermal deposits in the Panagyurishte district

Alteration assemblages are variable among the different Cu–Au epithermal deposits of the Panagyurishte ore district (Fig. 5). Chelopech displays laterally and vertically the most complex alteration assemblages among these deposits (Fig. 5a). Laterally outward from the ore bodies, there are four alteration assemblages: (1) a silicic zone with massive silica, sparsely developed vuggy silica, disseminated pyrite and aluminium–phosphate–sulphate (APS) minerals; (2) a quartz–kaolinite–dickite zone with pyrite, APS minerals, and anatase; (3) a widespread quartz–sericite alteration zone; and (4) a propylitic zone. Below the present mining level (405 level, about 400 m below surface), samples from 2 km deep drill cores (from the surface) reveal that the alteration evolves into a diaspore, pyrophyllite, alunite, zunyite, rutile, and APS mineral assemblage (Petrunov, 1989, 1995; Georgieva et al., 2002).

Radonova (1970), Radonova and Velinov (1974), and Tsonev et al. (2000a) report an advanced argillic assemblage (quartz–kaolinite/dickite) in the immediate wall rocks of the mineralized zones at Krassen, followed laterally by a phyllic and propylitic alteration (Fig. 5b). At Elshitsa and Radka, the wall rock alteration of the mineralization consists predominantly of a phyllic assemblage (quartz–sericite in the immediate host rock of the sulphide bodies followed laterally by quartz–sericite–albite) and grades outwards into a propylitic alteration assemblage (Fig. 5). In addition at Elshitsa, subordinate diaspore and dumortierite have been recognized in the quartz–sericite alteration immediately next to the mineralized zones (Radonova, 1967, 1970), and alunite has been documented at shallow mining levels by Dimitrov (1985), thus revealing the occurrence of advanced argillic alteration in this deposit (Figs. 4 and 5). In contrast to the Chelopech deposit, neither vuggy silica, nor any hypogene kaolinite/dickite and APS minerals have been recorded at Elshitsa and Radka (Table 1, Figs. 5 and 6). Illite is the predominant clay mineral in the two later deposits.

Ore body geometry of the Cu–Au epithermal deposits in the Panagyurishte ore district

In all three deposits of the southern Panagyurishte ore district, i.e. Elshitsa, Radka and Krassen, the mineralized zones consist predominantly of massive sulphide lenses surrounded by a halo of disseminated mineralization (Tsonev et al., 2000a,b; Kouzmanov, 2001). In addition, at the Elshitsa and Radka deposits there is also subordinate veinlet-type ore (Kouzmanov, 2001). At the Chelopech deposit stockwork ore is also abundant, and in contrast to the high-sulphidation deposits of the southern Panagyurishte district, vein-type ore is volumetrically and economically as important as massive sulphide ore surrounded by disseminated ore (Petrunov, 1994; Jacquat, 2003).

Structural control of the ore bodies and the alteration zones

The Elshitsa and Radka deposits share similar structural controls on each side of the Elshitsa intrusion (Fig. 1). In both deposits, the ore bodies are steeply dipping and, together with the wall rock alteration, they are controlled by WNW-ori-

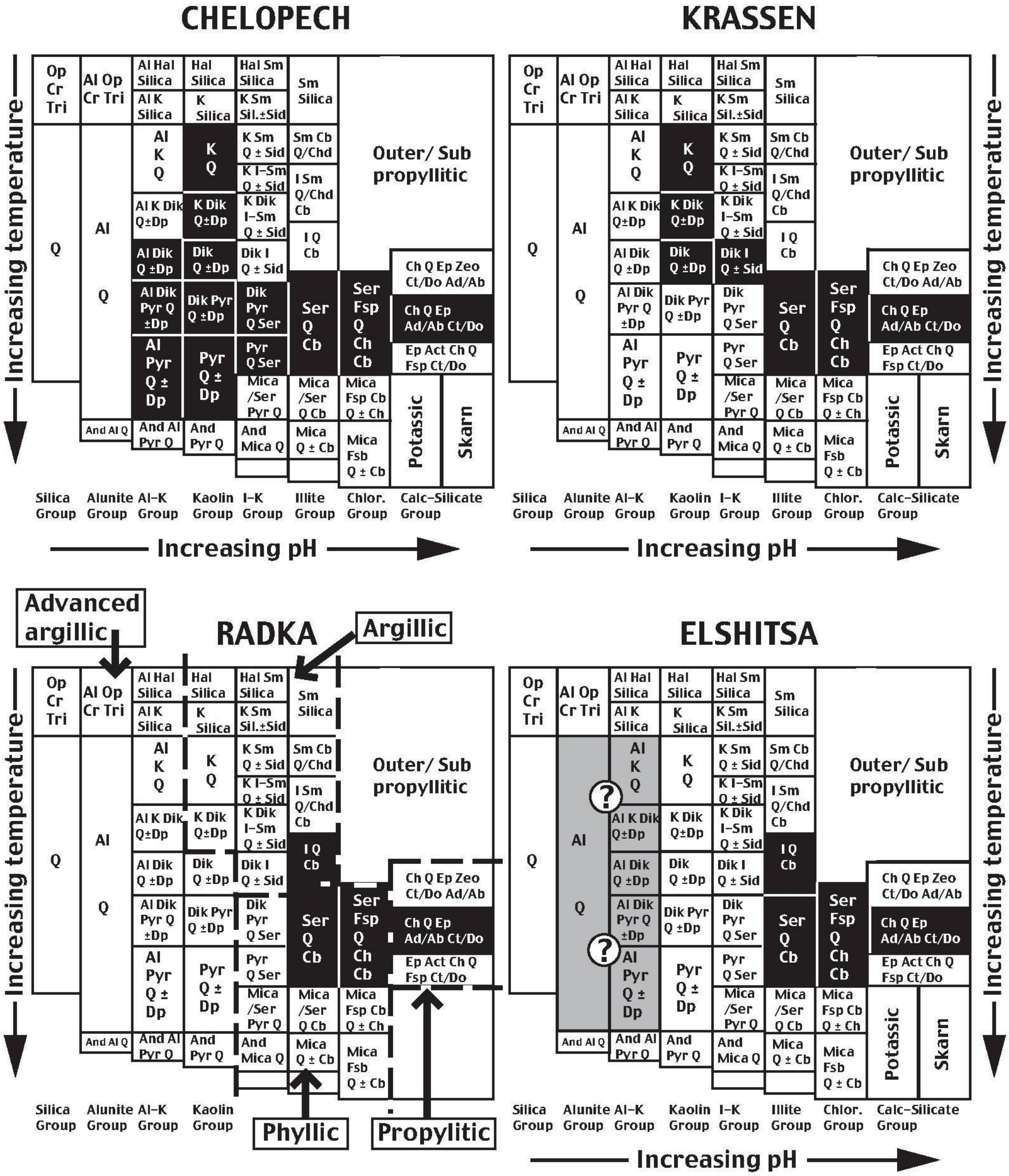
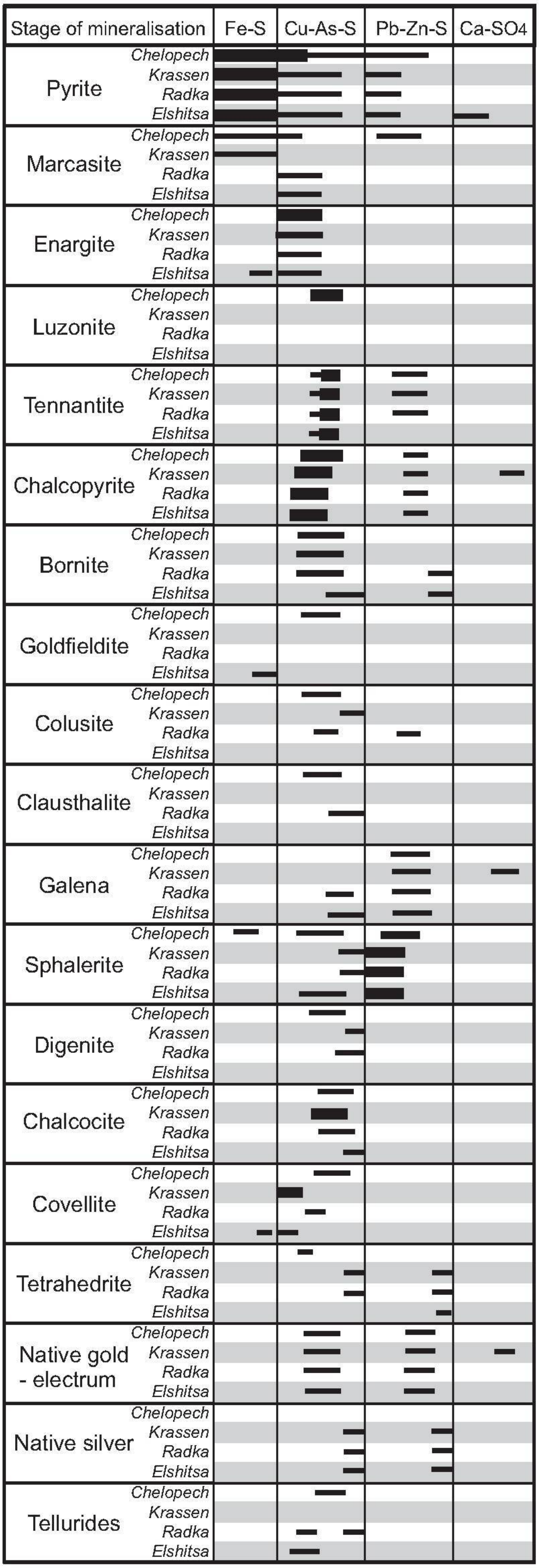


Fig. 5 Hydrothermal alteration assemblages described in the Chelopech (Petrunov, 1989, 1995; Georgieva et al., 2002), Krassen (Tsonev et al., 2000a), Radka (Tsonev et al., 2000b; Kouzmanov, 2001) and Elshitsa deposits (Radonova, 1967, 1970; Chipchakova and Stefanov, 1974; Dimitrov, 1985; Popov et al., 2000a; Kouzmanov, 2001) represented on diagrams after Corbett and Leach (Fig. 4.1, p. 71, 1998) showing the relative stability ranges of alteration mineral assemblages as a function of temperature and pH. The alteration zones (advanced argillic, argillic, phyllic, propylitic) defined in hydrothermal systems (Corbett and Leach, p. 73, 1998) are only represented for the Radka deposit, for the sake of clarity. The characteristic alteration assemblages of each deposit are highlighted with white letters on a black background. For Elshitsa, there is an additional grey background with questions marks, because Dimitrov (1985) reports an alunite facies without mentioning the other alteration minerals present in the same facies, therefore the alteration assemblage remains uncertain. Ab—albite; Act—actinolite; Ad—adularia; Al—alunite; And—andalusite; Bio—biotite; Cb—carbonate; Ch—chlorite; Chab—chabazite; Chd—chalcedony; Ch—chlorite; Cr—cristobalite; Ct—calcite; Do—dolomite; Dik—dickite; Dp—diaspore; Ep—epidote; Fsp—feldspar; Hal—halloysite; I—illite; K—kaolinite; Op—opaline silica; Pyr—pyrophyllite; Q—quartz; Ser—sericite; Sid—siderite; Sm—smectite; Tri—tridymite.



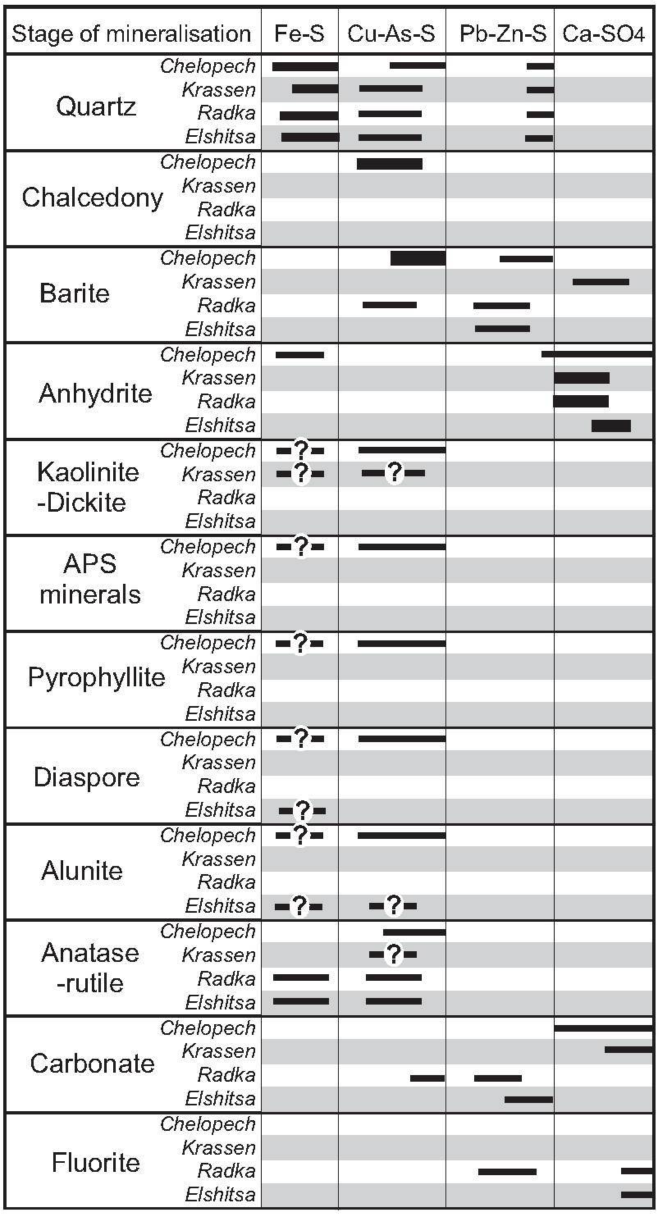


Fig. 6 Principal opaque and gangue mineral paragenesis of the Chelopech (Petrunov, 1989, 1994, 1995; Simova, 2000; Jacquat, 2003), Krassen (Tsonev et al., 2000a), Radka (Tsonev et al., 2000b; Kouzmanov, 2001) and Elshitsa deposits (Popov et al., 2000; Kouzmanov, 2001).

ented, sub-parallel normal faults dipping 65°–70° to the north (Fig. 4, Table 1). The mineralized faults merge with major, regional faults at depth, i.e. the Elshitsa fault in the homonymous deposit, and the Varnitsa fault at Radka (Fig. 4). At Elshitsa, there is a subsidiary set of NW-oriented strike-slip faults. The Krassen deposit shows a similar setting to these two deposits, where the mineralization is hosted by about an 80 to 100 m wide, and WNW-oriented breccia zone with a moderate dip of about 50° to the NE, and which is sub-parallel to the Krassen fault. Part of the massive sulphide bodies has been brecciated and overprinted by later tectonic movements along the latter (Tsonev et al., 2000a). This late tectonic overprint was already noted by Dimitrov (1960) for the entire Panagyurishte district.

At the Chelopech deposit, two predominant fault orientations are recognized: (1) steeply dipping, WNW to NW-oriented strike-slip faults, and (2) NE-oriented thrusts dipping to the SE. Ore formation is overprinted by tectonic movements along both fault types (Antonov and Jelev, 2001; Jelev et al., 2003; Chambefort, 2005). The breccia zones hosting the ore bodies are elongated parallel to the NE-oriented faults, and the trend of the advanced argillic alteration in this deposit follows partly both fault orientations. These observations also reveal a structural control on both ore formation and alteration in this deposit. The Chelopech fault immediately to the southeast of the deposit is a major NE-oriented thrust (Fig. 4), where rocks of various ages have been thrusted on the Late Cretaceous host rocks of the Cu–Au deposit (Antonov and Jelev, 2001; Stoykov et al., 2002; Jelev et al., 2003; Chambefort, 2005).

Ore stages and paragenesis

The epithermal deposits of the Panagyurishte district share a number of paragenetic features including (Fig. 6): (1) an early disseminated to massive pyrite stage, followed by (2) an intermediate Au-bearing Cu–As–S stage and (3) a late base-metal stage (predominantly Zn, Pb and Ba). A last sulphate stage ends the mineral paragenesis with subordinate sulphides and native gold at Krassen and Radka according to Tsonev et al. (2000a,b; see Fig. 6).

In all four deposits, the first ore stage consists of pyrite with subordinate fine-grained quartz and marcasite, referred to as Fe–S ore stage and as massive sulphide ore (Fig. 6). Pyrite of this stage has a colloform, globular, fine-grained and fine-layered texture. On a macroscopic scale, the massive ore can be locally banded with centimetric alternations of massive pyrite layers and altered rock (Petrunov, 1994, 1995; Bogdanov et al., 1997; Simova, 2000; Tsonev et al., 2000a; Kouzmanov, 2001; Jacquat, 2003). The massive sulphide ore bodies are discordant with respect to the host rocks (Kouzmanov, 2001; Popov et al., 2003). At Elshitsa, the massive ore bodies and the alteration zones are controlled by faults (Fig. 4), and veins with colloform pyrite crosscut the host dacites (Kouzmanov, 2001). At Chelopech, sedimentary rocks and volcanic tuffs are the preferential host rocks of massive pyrite ore. Accretionary lapilli, oolithes, and microfossils are replaced by pyrite in these rocks (Chambefort et al., 2003b; Jacquat, 2003). Massive sulphide ore is typically surrounded by a halo of disseminated pyrite (Tsonev et al., 2000 a,b; Kouzmanov, 2001), and mapping at Chelopech reveals in places a progressive transition from disseminated to massive pyrite ore (Jacquat, 2003).

Early massive pyrite is postdated by sulphides and sulphosalts of the Cu–As–S ore stage (Fig. 6). This second ore stage is the Au-bearing and economic ore mined in all deposits. It is typically subdivided into mineral associations (Petrunov, 1994; Simova, 2000; Tsonev et al., 2000a,b; Kouzmanov, 2001; Jacquat, 2003; Kouzmanov et al., 2004), which are not shown in Figure 6 for the sake of clarity. These mineral associations constitute discrete, recurrent depositional events, which overprint each other (Jacquat, 2003). They occur as veins, cavity fillings, breccia matrix, and replacement of early pyrite. In general, enargite and covellite belong to an early depositional event, followed by a tennantite-chalcopyrite-bornite association. Gold of the second ore stage occurs as native metal and tellurides, but the native mineral is the main gold carrier (Bogdanov et al., 1997; Bonev et al., 2002). Micro- to cryptocrystalline quartz is a ubiquitous gangue mineral of this ore stage (Fig. 6).

A third uneconomic Pb–Zn–S ore stage (Fig. 6) consists of a polymetallic assemblage, including galena, sphalerite, pyrite, chalcopyrite, and barite veins. Calcite has also been reported at Elshitsa at this stage (Kouzmanov, 2001). Gold of this stage occurs as the native metal, and also as electrum at Chelopech. At the Chelopech deposit, a large part of the late polymetallic ore stage is developed below and at the periphery of the economic gold-bearing pyrite–enargite–chalcopyrite ore bodies, that is beyond the advanced argillic alteration zone (Petrunov, 1994, 1995; Jacquat, 2003). The Vozdol occurrence is such a physically separate, polymetallic mineralization about 1 km NNE to the Chelopech high-sulphidation ore bodies (Fig. 1). The gangue of the base metal sulphide veins at Vozdol consists of quartz, ankerite, calcite, dolomite, barite and fluorite, and the veins are surrounded by a carbonate, adularia and sericite alteration zone. This occurrence is considered by Mutafchiev and Petrunov (1995) and Popov et al. (2000b) as a low-sulphidation system, and would be reclassified as an intermediate-sulphidation occurrence according to the new terminology of Hedenquist et al. (2000). The spatial association of the polymetallic Vozdol occurrence and the Chelopech deposit is analogous to other base-metal veins at the periphery of high-sulphidation systems (Sillitoe, 1999; Hedenquist et al., 2000, 2001).

There are a number of major mineralogical differences among the Cu–Au epithermal deposits of the Panagyurishte district (Fig. 6; Table 1). Enargite is abundant at Chelopech (Petrunov, 1994; Simova, 2000; Jacquat, 2003) and predominant at Krassen (Tsonev et al., 2000a), but it is only a minor phase and restricted to the upper mine levels at Radka and Elshitsa (Tsonev et al., 2000b; Kouzmanov, 2001). Luzonite, the low-temperature dimorph of enargite, has only been reported at Chelopech, where it is a common mineral, and as a minor phase at Krassen. By contrast, native silver is absent at Chelopech, but present at Krassen, Radka and Elshitsa, and tetrahedrite is rare at Chelopech and more abundant in the three other deposits. This explains the distinctly lower Ag/Au ratios at Chelopech relative to Radka and Elshitsa (Table 1). Chelopech also stands out with its predominant gangue mineralogy, with chalcedony and barite being major to abundant phases during the Cu–As–S stage (Petrunov, 1994; Simova, 2000; Jacquat, 2003), whereas barite is only reported as a minor phase at Radka during this ore stage (Tsonev et al., 2000b; Kouzmanov, 2001; Kouzmanov et al., 2004; Fig. 6, Table 1).

Isotopic data

The sulphur isotopic compositions of sulphides and enargite from the high-sulphidation deposits of the Panagyurishte ore district fall between –9 and +1 ‰ (CDT), and sulphates yield higher $\delta^{34}S$ values between +15 and +28 ‰ (CDT) (Fig. 7a). Such isotopic compositions are consistent with similar data sets from other high-sulphidation epithermal deposits (see Arribas, 1995), and are typically interpreted in terms of sulphur isotope fractionation during hydrolysis of magmatic SO_2 and fluid oxidation with decreasing temperature (Rye, 1993). Temperatures obtained by sulphur isotope geothermometry in the deposits of the Panagyurishte district are typical for high-sulphidation epithermal systems (Arribas, 1995). At Chelopech, two pyrite-anhydrite pairs from deep drilling samples below the main mining level yield temperatures of 302° and 314°C (Jacquat, 2003), and one enargite–barite pair from the main Cu–As–S ore stage gives a temperature of 240°C (Moritz et al., unpublished data). One galena–barite pair at Chelopech and one chalcopyrite–barite at Elshitsa from the third base metal ore stage yield temperatures of 226° and 250°C, respectively (Jacquat, 2003; Kouzmanov et al., 2003).

Radiogenic isotopes show marked differences among the epithermal deposits of the ore district. The Sr and Pb isotopic compositions of gangue and ore minerals are more radiogenic in Chelopech than at Elshitsa and Radka (Figs. 7b and c). In the case of Sr, this difference cannot be explained by different magmatic sources, since Late Cretaceous magmatic rocks have similar Sr isotopic compositions throughout the Panagyurishte district (Fig. 7b). In all deposits, gangue minerals yield systematically higher $^{87}Sr/^{86}Sr$ ratios than the immediate Late Cretaceous volcanic host rocks (Fig. 7b). This reveals that the ore-forming fluid with a low $^{87}Sr/^{86}Sr$ ratio (~0.7045–0.7060; Fig. 7b), either of direct magmatic origin or equilibrated with the Late Cretaceous volcanic rocks, interacted with ^{87}Sr-enriched rocks such as Palaeozoic granites ($^{87}Sr/^{86}Sr \approx 0.708$–0.712; Fig. 7b) and metamorphic basement rocks or their sedimentary products, i.e. Turonian sandstones ($^{87}Sr/^{86}Sr >$ 0.715; Fig. 7b). The higher $^{87}Sr/^{86}Sr$ ratios of sulphates at Chelopech reveal a more intense interaction of the ore-forming hydrothermal fluids with radiogenic metamorphic basement rocks and their detrital sedimentary products. The role of Late Cretaceous seawater during ore formation remains ambiguous, because its $^{87}Sr/^{86}Sr$ ratio (Koepnick et al., 1985) lies in-between the Sr isotopic compositions of Late Cretaceous magmatic rocks, and of Turonian detrital sedimentary rocks, Palaeozoic granites and metamorphic basement rocks (Fig. 7b).

Interpretation of the more radiogenic Pb isotopic composition of ore minerals from Chelopech relative to deposits of the southern Panagyurishte district (Fig. 7c) remains equivocal. Metamorphic basement rocks and Turonian sandstones contain more radiogenic Pb than Late Cretaceous magmatic rocks and Palaeozoic intrusions of the Panagyurishte district (Kouzmanov, 2001; Kouzmanov et al., 2001). Thus, akin to the Sr isotope data, a more intense leaching of metamorphic rocks and their detrital products by ore-forming hydrothermal fluids could explain the radiogenic nature of ore minerals at Chelopech. Alternatively, the variable Pb isotopic compositions of the epithermal ore minerals might be linked to differences in the composition of the genetically associated magmatism. Although the database is still fragmentary, sulphides from porphyry-Cu deposits of the northern Panagyurishte district apparently yield more radiogenic Pb isotopic compositions than the ones from the southern district (Fig. 7c: Elatsite-Medet-Assarel porphyries vs. Vlaykov Vruh porphyry). Safely assuming that Pb in the porphyry-Cu sulphides is totally to predominantly of magmatic origin, it must be concluded that the Pb isotopic composition of the magmatism is different in both areas, and that there is a larger crustal assimilation in the melts related to the Elatsite, Medet and Assarel porphyry-Cu deposits, and by extension to the Chelopech epither-

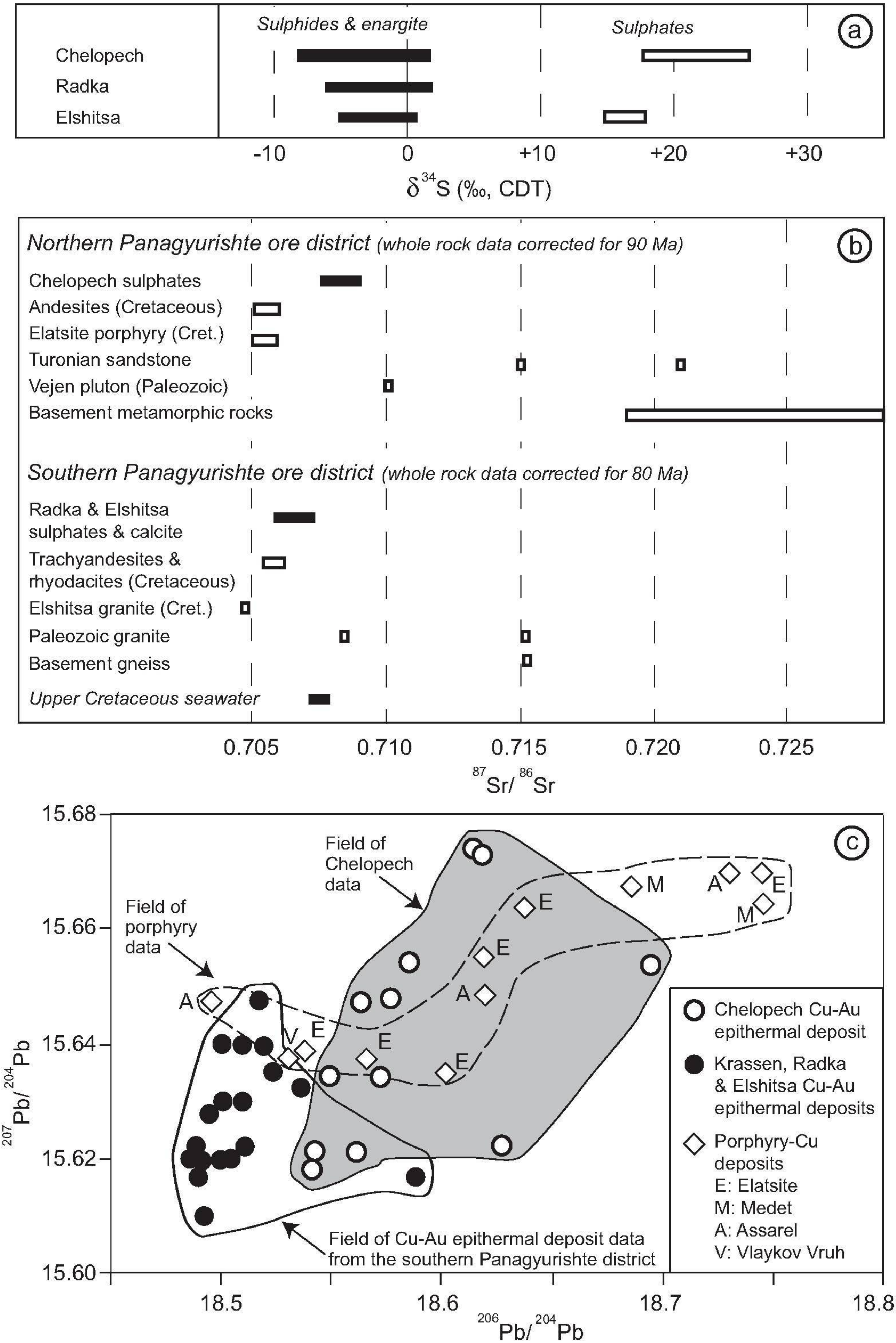

Sulphides & enargite
Sulphates
a
Chelopech
Radka
Elshitsa
-10
0
+10
+20
+30
δ34S (‰, CDT)
Northern Panagyurishte ore district (whole rock data corrected for 90 Ma)
b
Chelopech sulphates
Andesites (Cretaceous)
Elatsite porphyry (Cret.)
Turonian sandstone
Vejen pluton (Paleozoic)
Basement metamorphic rocks
Southern Panagyurishte ore district (whole rock data corrected for 80 Ma)
Radka & Elshitsa sulphates & calcite
Trachyandesites & rhyodacites (Cretaceous)
Elshitsa granite (Cret.)
Paleozoic granite
Basement gneiss
Upper Cretaceous seawater
0.705
0.710
0.715
0.720
0.725
87Sr/86Sr
c
Field of Chelopech data
Field of porphyry data
Field of Cu-Au epithermal deposit data from the southern Panagyurishte district
Chelopech Cu-Au epithermal deposit
Krassen, Radka & Elshitsa Cu-Au epithermal deposits
Porphyry-Cu deposits
E: Elatsite
M: Medet
A: Assarel
V: Vlaykov Vruh
15.68
15.66
15.64
15.62
15.60
207Pb/204Pb
18.5
18.6
18.7
18.8
206Pb/204Pb

Fig. 7

mal deposit. This is in line with Kamenov et al. (2003a,b), who concluded that magmatism varies in composition from north to south in this district. However, even with additional Pb isotope data for whole rocks, it might be difficult to determine ultimately whether the more radiogenic Pb at Chelopech was leached from metamorphic basement rocks by the ore-forming fluid or if it was introduced into the ore deposit by a hydrothermal fluid of magmatic origin, where the magma has assimilated metamorphic basement rocks.

Discussion

The Panagyurishte Cu–Au epithermal deposits: witnesses of similar ore formation processes in space and time during the evolution of the Srednogorie belt

The epithermal Cu–Au deposits of the Panagyurishte district reveal a coherent and continuous sequence of events resulting from similar ore forming processes, typical for high-sulphidation epithermal deposits (Arribas, 1995; Cooke and Simmons, 2000; Hedenquist et al., 2000). Indeed, they share a common paragenesis including an early, massive pyrite stage, an intermediate Au-bearing Cu–As–S stage and a late base metal stage (Fig. 6). The textural and geometrical characteristics of the early, massive pyrite stage document its epigenetic nature, including both structural and lithological controls (Tsonev et al., 2000 a,b; Kouzmanov, 2001; Chambefort et al., 2003b; Jacquat, 2003; Popov et al., 2003). Early massive pyrite ore was formed by precipitation along fractures from a hydrothermal fluid, and by progressive replacement of more permeable rock units such as volcanic tuffs and sedimentary rocks. Such wallrock replacement and lithological control by permeable rock units and bedding planes are relatively common in high-sulphidation deposits (Arribas, 1995; White et al., 1995; Sillitoe, 1997, 1999; Corbett and Leach, 1998). Thus, it is not necessary to invoke profound changes in the geological environment with time, such as a transition from a submarine to an aerial setting, and early syngenetic processes (Bogdanov, 1984; Petrunov, 1995; Mutafchiev and Petrunov, 1996) to explain the genesis of the Cu–Au epithermal deposits of the Panagyurishte ore district. The economic and Au-bearing Cu–As–S stage shows an evolution from an early enargite event to a later tennantite-chalcopyrite-bornite event reflecting a temporal evolution from high to intermediate sulphidation states of the hydrothermal fluid during ore formation, and a low sulphidation state during the subsequent base metal stage (Einaudi et al., 2003). The sulphur isotopic compositions of ore and gangue minerals are coherent with disproportionation of magmatic SO_2 during ore formation (Rye, 1993).

The high ore grade - large tonnage Chelopech deposit: A giant amongst dwarfs in the Panagyurishte district

Despite descriptive and genetic similarities among the Cu–Au epithermal deposits of the Panagyurishte ore district, Chelopech clearly stands out as a giant and as the economically most attractive deposit in this area. The question about fundamental controls leading to the formation of large Cu–Au high-sulphidation epithermal deposits has been addressed in several contributions (e.g. Sillitoe, 1997, 1999; Hedenquist et al., 2000; Tosdal and Richards, 2002). The peculiarities of the Chelopech deposit in contrast to the southern Panagyurishte epithermal deposits are discussed below and may be explained by: (1) an emplacement in a shallower crustal environment, (2) its better preservation, (3) more efficient, local ore-formation processes, and (4) fundamental differences in regional geological controls.

Styles and characteristics of high-sulphidation epithermal systems vary with depth and temperature (Corbett and Leach, 1998; Sillitoe, 1999; Hedenquist et al., 2000). Collectively, several fea-

Fig. 7 Isotope data of epithermal deposits from the Panagyurishte ore district. (a) Sulphur isotope data for the Chelopech (Petrunov, 1994; Moritz et al., 2001; Jacquat, 2003), Radka (Angelkov, 1975; Velinov et al., 1978; Kouzmanov, 2001), and Elshitsa deposits (Kouzmanov, 2001; Kouzmanov et al., 2003). (b) Strontium isotope data for Chelopech sulphates (Moritz et al, 2001, 2003; Jacquat, 2003), Late Cretaceous andesites (Stoykov et al., 2003, 2004), the Vejen pluton and the Elatsite porphyry (von Quadt et al., 2002), Turonian sandstone and metamorphic basement rocks (Jacquat, 2003; Moritz et al., 2003), Radka and Elshitsa sulphates and calcite, and whole rocks from the southern Panagyurishte district (Kouzmanov, 2001; Kouzmanov et al., 2001), and Late Cretaceous seawater (Koepnick et al., 1985). (c) Lead isotope data of the Chelopech Cu–Au epithermal deposit (Moritz et al., 2001), the Elshitsa, Radka and Krassen Cu–Au epithermal deposits (Amov et al., 1974; Kouzmanov, 2001; Kouzmanov et al., 2001; except two data points from Moritz et al., 2001), and the porphyry-Cu deposits, including Vlaykov Vruh (Kouzmanov, 2001; Kouzmanov et al., 2001), Assarel (Amov et al., 1974; Moritz et al., 2001), Medet (Moritz et al., 2001) and Elatsite (von Quadt et al., 2002, except one data point from Moritz et al., 2001).

tures indicate a shallower depth and temperature environment of ore formation at Chelopech than for the other Cu–Au epithermal deposits of the Panagyurishte district (Table 1): (1) low temperature mineral polymorphs, such as chalcedony and luzonite, are confined to the Chelopech deposit, and luzonite is a subsidiary phase at Krassen, (2) vuggy silica is also restricted to the Chelopech deposit, and (3) the presence of enargite is only rarely reported at the Radka and Elshitsa deposits, and only in the upper mining levels. In addition, volcanic rocks are predominant in the northern part of the Panagyurishte district, whereas intrusive rocks become more abundant to the south (Fig. 1c), therefore revealing a progressively deeper crustal environment in the southern part. As reviewed by Sillitoe (1999), the largest high-sulphidation Au deposits are typically located in the shallow epithermal parts of high-sulphidation systems, where lithological permeability is more favourable.

Alternatively, the differences noted among the Cu–Au epithermal deposits of the Panagyurishte district might be related to different erosion levels, with Chelopech being the deposit with the better preservation. Typically, epithermal deposits have a poor preservation potential due to their shallow depth of formation, and the likelihood of their erosion increases with their age (Cooke and Simmons, 2000; Hedenquist et al., 2000). Thus, it appears as paradoxical that Chelopech, as the oldest epithermal deposit of the study area, had the best preservation potential, but this can be explained by local, late tectonics in each deposit. The overthrust on the Chelopech deposit, postdating ore formation, together with the late transgressive deposition of sandstone, limestone and a flysch sequence on top of the volcanic host rocks (Fig. 4a), were certainly key factors for its better degree of preservation. By contrast, the faults controlling the ore bodies at Elshitsa and Radka display a normal sense of movement (Figs. 4b,c), therefore an extensional tectonic setting, clearly less favourable for the preservation of epithermal deposits, possibly resulting in the loss of the upper parts of the Elshitsa and Radka deposits. Higher uplift and erosion rates in the southern Panagyurishte district could be due to the continuous, Tertiary plate tectonic convergence of the Rhodopes with the Srednogorie zone (Ivanov, 1988; Ricou et al., 1998). The subordinate presence or absence of advanced argillic mineral assemblages at Elshitsa and Radka, respectively (Fig. 5), may reflect the deeper erosion level of the epithermal deposits, thus preserving only their bottom parts (Hedenquist et al., 2000). In addition to erosion alone, catastrophic gravitational sector collapse of volcanic edifices, during or following ore formation may also explain the loss of the upper epithermal ore environment at Elshitsa and Radka (e.g. Sillitoe, 1991, 1995).

The formation of large epithermal Au deposits is the result of the confluence of magmatic and hydrothermal factors, the production of large volumes of Au-rich fluids, and an efficient hydrologic system for a focussed fluid flow to the ore site (White et al., 1995; Sillitoe, 1997; Hedenquist et al., 2000). The higher grade and tonnage of the Chelopech deposit reveal that such ore forming processes were particularly favourable in the northern part of the Panagyurishte district. Chelopech is also characterised by major lithological permeability contrasts, with the presence of a diatreme, a location close to a major discordance with basement rocks and a high abundance of sedimentary rocks in its environment (Fig. 4a). Such settings with major lithological permeability contrasts are favourable for the generation of large epithermal Au deposits (Sillitoe, 1997; Hedenquist et al., 2000). The laterally and vertically extensive advanced argillic alteration zone at Chelopech (Fig. 5) documents that the hydrology of its environment has been particularly propitious for the development of acidic conditions due to a large absorption of magmatic vapour by groundwater (Hedenquist et al., 2000).

The higher metallogenic fertility of the northern and older part of the Panagyurishte district reveals a temporal evolution in the ore formation environment on a regional scale. Fundamental variations in space and time of the regional geological context must have occurred between early porphyry-Cu and Cu–Au epithermal ore formation at about 92–90 Ma at Elatsite-Chelopech, Medet and Assarel, and later at about 86 Ma in the Krassen and Elshitsa-Vlaykov Vruh areas (Fig. 1c). The transition from predominantly andesitic volcanism in the northern Panagyurishte district to dacitic in the southern part, with subordinate rhyodacite and rhyolite, reveals a variation in space and time of magma petrogenesis, including a more important crustal input and/or higher degree of fractional crystallisation with time in the southern Panagyurishte district. Major and trace element data support a latitudinal variation in magma petrogenesis (Kamenov et al., 2003a,b), as well as the Pb isotope data of the ore deposits (Fig. 7c, see above). Chelopech has a distinctly lower Ag/Au ratio in comparison to the Cu–Au epithermal deposits of the southern Panagyurishte district (Table 1). According to Sillitoe (1999), magma chemistry is one of the basic controls on Ag/Au ratios in high-sulphidation epithermal deposits. Thus, the variable Ag/Au ratios of the Panagyurishte epithermal deposits are possibly linked to the spatial and temporal variation of the magma chemistry throughout this ore district.

Although the regional tectonic evolution of the Panagyurishte ore district is not fully understood, one may speculate about the favourable tectonic environments that could explain the higher economic potential of its northern part. According to Tosdal and Richards (2002), the formation of porphyry-Cu and high-sulphidation epithermal deposits is favoured in a geological environment characterised by a near-neutral regional stress field, during transient periods of stress relaxation within a magmatic arc. In the Chelopech area, Jelev et al. (2003) suggest from their field studies a switch from a transtensional to a transpressional regime during the Late Cretaceous. Thus, the formation of the Chelopech deposit and, by geographical association, the Elatsite porphyry-Cu deposit may coincide with such a stress relaxation period. Although there is considerable tectonic overprint, the two predominant sets of fault orientations at Chelopech are nearly orthogonal (WNW–NW and NE), and maybe the relic of a regional stress field close to near-neutral during ore formation. Despite the fragmentary tectonic data, the southern Panagyurishte ore district appears to be essentially characterised by strike-slip tectonics along the dextral Iskar-Yavoritsa shear zone (Ivanov et al., 2001; Fig. 1c) that is a geological setting with a pronounced differential regional stress. The smaller Cu–Au epithermal deposits from the southern Panagyurishte district are essentially controlled by WNW-oriented subparallel faults (Figs. 4b–c), therefore consistent with the differential regional stress field. According to Tosdal and Richards (2002), the later tectonic environment is less propitious for the formation of high-sulphidation epithermal deposits, and may explain the lower economic potential of the southern Panagyurishte district.

Conclusions

Ore deposits are markers of specific tectonic, magmatic and fluid circulation events within the evolution of an orogen. The epithermal Cu–Au deposits of the Panagyurishte ore district are no exception to it. These deposits reveal a coherent and continuous sequence of similar ore forming processes, typical for high-sulphidation deposits throughout the regional geological evolution of the Srednogorie belt, characterised by a north to south younging of magmatic and tectonic events.

The variation in the composition of the dominant magmatism, the exposed structural level of the crust, and possibly the variation in tectonics from the northern to the southern part of the Panagyurishte ore district are paralleled by a latitudinal change in the characteristics of the epithermal Cu–Au deposits. Most notably, the northern Panagyurishte ore district appears as the economically fertile part of the Central Srednogorie belt. At this stage of knowledge, no unique explanation can be offered for this latitudinal change in ore deposit characteristics, but they are likely related to emplacements at different depths of the deposits, differences in degrees of preservation as a function of post-ore tectonics and/or sedimentary processes, efficiency of ore formation, and fundamental modifications of regional controls, such as magma petrogenesis and/or tectonic regimes. This study on the epithermal Cu–Au deposits clearly reveals that ore deposit genesis and their characteristics, in particular tonnage and grade, are very sensitive to variations of regional geological processes.

Further studies should try to understand why epithermal Cu–Au deposits in the northern Panagyurishte ore district, such as Chelopech and Krassen, are linked to a dominantly andesitic volcanism, whereas the same deposits in the southern Panagyurishte district are linked to or postdate dacitic magmatism, which itself postdates andesitic magmatism. An additional, open question is linked to the observation that a majority of the ore bodies within the Cu–Au epithermal deposits are controlled by WNW-oriented faults on a local scale, but that the ore deposit alignment on a regional scale has a NNW orientation. Paradoxically, it appears that, despite the north to south variation of geological and ore deposit characteristics within the Panagyurishte ore district, the deep crustal, fundamental control on episodic ore formation remained constant throughout its 14 Ma-long protracted Late Cretaceous magmatic and tectonic evolution.

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