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Fluid evolution in the Baia Mare epithermal gold/polymetallic district, Inner Carpathians, Romania

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Abstract The Baia Mare district (Romania) represents a complex segment of the Neogene/Quaternary, subduction-related, volcanic chain of the Carpathians. In this province, the calc-alkaline volcanism and associated mineralization are closely related to a major strike-slip fault and an underlying pluton. The ore deposits of the district have many features typical of low-sulfidation (or adularia-sericite) epithermal deposits. The combination of fluid-inclusion microthermometry, Raman spectroscopy, bulk crush-leach analysis, laser ablation-optical emission spectrometry (LA-OES) of individual fluid inclusions and stable isotope data has been used to characterize the ore-forming solutions involved with gold/polymetallic mineralization in three of the largest deposits. Ore fluids at Baia Sprie, Cavnice and Sasar deposits had temperatures of 320 to 150 °C and salinities in the range 0–21 wt% NaCl equiv. During phreatomagmatic activity, fracturing and periods of vein dilation, the pressure fluctuations may have caused boiling. The hydrothermal fluids were Na–K–Li–Ca chloride solutions with lesser amounts of SO₄ and F. The Na/K ratios and the stable isotope compositions are consistent with equilibration of the fluids with country rocks at

progressively lower temperatures. The halogen ratios (Br/Cl) × 10³ in the range 0.13–1.21, together with sulfur isotopic systematics ($\delta^{34}\text{S}$ = 0.3–5.2 per mil), are consistent with a dominantly magmatic origin of the solutes, and probably of the ore fluids themselves.

Keywords Epithermal mineralization · Fluid · Carpathians · Magmatism

Introduction

The Baia Mare district is located in the eastern part of the Carpathian belt, one of Europe's major metallogenic provinces. This subduction-related continental margin arc, which extends from Slovakia, Hungary and Ukraine to Romania, includes some important epithermal gold-polymetallic ore deposits, and has been mined since Roman times. The Baia Mare district, with about 15 mines, provides most of Romania's Pb and Zn and some Au, Ag, Cu and Sb. Extensive mining in the district has resulted in much detailed data on the general geology and mineralogy of the deposits, but most has been published in Romanian journals and a general understanding of the ore fluids is still lacking. The geologic setting of the Baia Mare epithermal province is described in the first part of this paper, on the basis of published information and on our personal observations. This is followed by new investigations on the geochemical features of the mineralization at the Baia Sprie, Sasar and particularly Cavnice vein deposit. A major objective of this study is to understand the origin of the ore-forming fluids and the evolution of the fluid chemistry during multiple mineralizing events specific to the Baia Mare district. A multiple-technique database on fluid inclusions, including microthermometry, Raman spectroscopy, bulk crush-leach analysis and laser ablation-optical emission spectrometry, and stable isotope data provide insights into the relationships between metal deposition and magmatism, tectonics and hydrology.

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Regional geological setting: Carpathian area

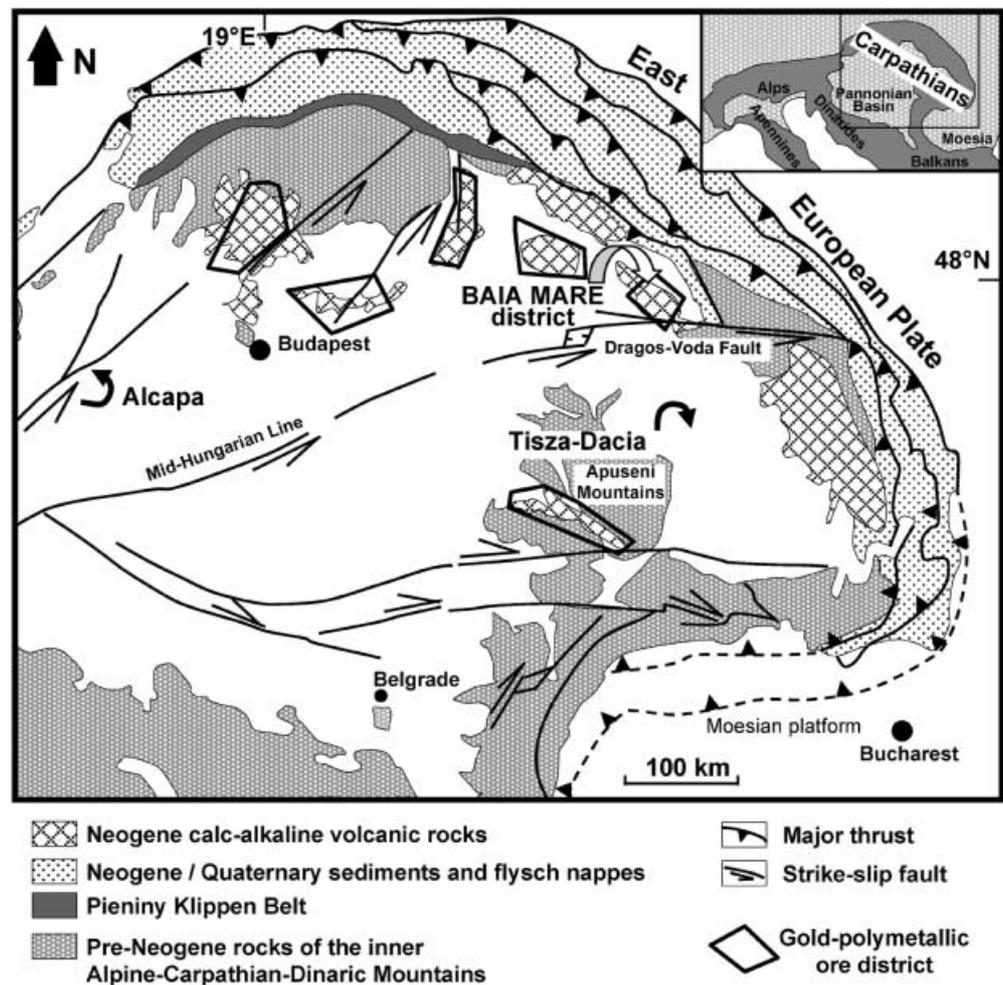
The arcuate belt of the Carpathians is the product of continental collision between the African and European plates, due to the closure of the Mesozoic Tethys Ocean (Royden 1988; Csontos et al. 1992). The Carpatho-Pannonian area straddling the African-European suture includes two continental blocks, Alcapa and Tisza-Dacia (Csontos et al. 1992; Csontos 1995; Seghedi et al. 1998), with different Mesozoic histories and which underwent opposite rotations during the Tertiary (Fig. 1). The boundary between these blocks is represented by the Mid-Hungarian line extending eastwards into the Dragos-Voda fault (Fig. 1). Paleomagnetic data indicate that the Alcapa block shows counterclockwise rotation, whereas the Tisza-Dacia block had a clockwise rotation (Patrascu et al. 1994; Marton and Fodor 1995). Two dynamic processes have been considered to explain the complex microplate movements in the area: the convergence of the Alpine sector expelling the Alcapa block, and a retreating subduction front in the Carpathians (Csontos 1995).

Oceanic crust attached to the East European lithosphere is hypothesized to have been subducted to the

west beneath the Alcapa and Tisza-Dacia blocks (Royden 1988). In an alternative model, Linzer (1996) has proposed that the subducted basin was attached to the Moesian platform (Fig. 1) and subducted to the northwest. Paleomagnetic data suggest that the main subduction event took place in the late Paleogene to middle Miocene (Patrascu et al. 1994; Marton and Fodor 1995), during which all of the ocean basin was consumed. At the end of the Miocene, continent-continent collision occurred between the Tisza-Dacia microplate and the European plate (Royden 1988). Collision was accompanied by calc-alkaline magmatism (Szabo et al. 1992; Linzer et al. 1998) and the formation of a large thrust belt composed of flysch sediments (Sandulescu 1984). Behind the Carpathian arc lies the Pannonian Basin. Its development was controlled by a conjugate system of strike-slip faults connecting areas of extension in the intra-Carpathian domain to areas of coeval shortening within the thrust belt (Royden 1988; Tari et al. 1992; Peresson and Decker 1997).

Calc-alkaline magmatism occurred from the Miocene to the Quaternary (Pecskay et al. 1995). The focus of the volcanic activity shifted, in a general sense, from northwest to southeast through time along the Carpathian arc. The magmatic rocks from the northern sector

Fig. 1 Schematic map showing the main tectonic units of the Carpatho-Pannonian region, including the two continental blocks Alcapa and Tisza-Dacia (with opposite rotations during Tertiary times) and the location of the Carpathian Neogene volcanic belt hosting important ore deposits, and the Baia Mare district in particular (modified after Royden 1988; Csontos et al. 1992; Linzer 1996; Hippolyte et al. 1999). *Inset* map shows the location of the Carpathians within the European Alpine system



(including the Baia Mare district) are thought to have been generated during subduction rollback processes and an almost simultaneous break-off of the descending plate along the entire arc segment (Seghedi et al. 1998). Episodic extrusion of Plio-Pleistocene alkaline basaltic lavas was contemporaneous with the final stages of the volcanic activity, and resulted from asthenospheric mantle upwelling into a slab window (Szabo et al. 1992; Downes et al. 1995; Mason et al. 1998).

Orogenic magmatism was accompanied by widespread hydrothermal activity in the area, producing economic porphyry/skarn copper deposits and both high- and low-sulfidation epithermal mineralization (e.g., Vityk et al. 1994; Borcos 1994; Lexa et al. 1999; Molnar et al. 2000). Metallogenesis seems to be ultimately related to the slab break-off, which provided additional heat to the continental lithosphere and an increased fluid circulation in the crust, due to upwelling of the asthenosphere (Boorder et al. 1998). The strike-slip faults, between which the major blocks moved in the intra-Carpathian area, also appear to be an important control of the mineralization (Neubauer et al. 2000).

Geologic overview of the Baia Mare district

The Baia Mare district (Oas-Gutai Mountains) represents a complex segment of the Neogene/Quaternary volcanic belt of the Inner Carpathians and borders the northeastern margin of the Pannonian Basin. This mineral district is located at the northeastern border of the Alcapan and Tisza-Dacia blocks, close to the contact with the European plate.

Geology and control of mineralization

In the Baia Mare area, the volcanic chain cuts Neogene sedimentary molasse deposits, Paleogene sequences belonging to the nappes of Transcarpathian flysch, and metamorphic rocks of early Cambrian age (Sandulescu 1984). The Paleogene flysch sometimes occurs as an uplifted area within the volcanic chain (e.g., Herja area; Fig. 2).

The volcanic events and the associated mineralization are related to a major E–W structure and an underlying 65-km-long and 15-km-wide pluton (inset map, Fig. 2), the boundaries of which define the mineral district (Borcos 1994; Milési et al. 1994; Mitchell 1996). The pluton is not exposed, but geophysical data (magnetic modeling) indicate its presence (Crahmaliuc et al. 1995). The major fault is well-exposed in the eastern part of the district, and its presence beneath the Neogene volcanic rocks was traced using mining and drilling data as well as satellite images and gravity anomalies (Sandulescu et al. 1993). This major tectonic structure (named Dragos-Voda or Carlibaba-Carei fault/lineament) acted as a left-lateral strike-slip fault in the early Miocene, and as a normal fault with a down-dropped southern block dur-

ing the middle and late Miocene (Sandulescu et al. 1993). This change was caused by the major displacement of the Tisza-Dacia block towards the east at the latter time (Morley 1996). The post-Sarmatian (13.6–11.5 Ma) left-lateral movements of the fault are indicated by the paleomagnetic patterns in the lavas. Sarmatian andesites from northern Baia Mare suggest counterclockwise rotations of 30°, whereas within the fracture zone the rotations are as much as 90° (Patrascu 1993). Analysis of fault data along the Dragos-Voda structure indicates, in general, NE- to ENE-oriented contraction directions (Linzer et al. 1998).

Mineralization appears genetically related to this regional structure. Some ore deposits are located on the same E–W regional alignment (Baia Sprie, Suior), some are related to complex collapse areas (Sasar), and others are situated on NW–SE- or NE–SW-trending satellite lineaments (Ilba, Nistru, Cavnic, Herja).

Magmatism

Magmatic activity in the Baia Mare district started in the Badenian (≈ 14 Ma) with deposition of felsic tuffs and ignimbrites. According to K–Ar dating, this event was followed by Sarmatian and Pannonian extrusion (13.4–9.0 Ma) of basaltic andesites, dacites and andesites, and subsequently emplacement of small basaltic intrusions (8.0–6.9 Ma; Edelstein et al. 1992, 1993; Pecsckay et al. 1994, 1995; Kovacs et al. 1997). The predominantly andesitic volcanism (14–7 Ma) in the Baia Mare area belongs to the medium-K, calc-alkaline association which has a high content of incompatible trace elements, including the LILE and LREE. Petrologic and isotope data point to subduction-related, mantle-derived magmas which were strongly crustally contaminated (Kovacs 1998, 1999).

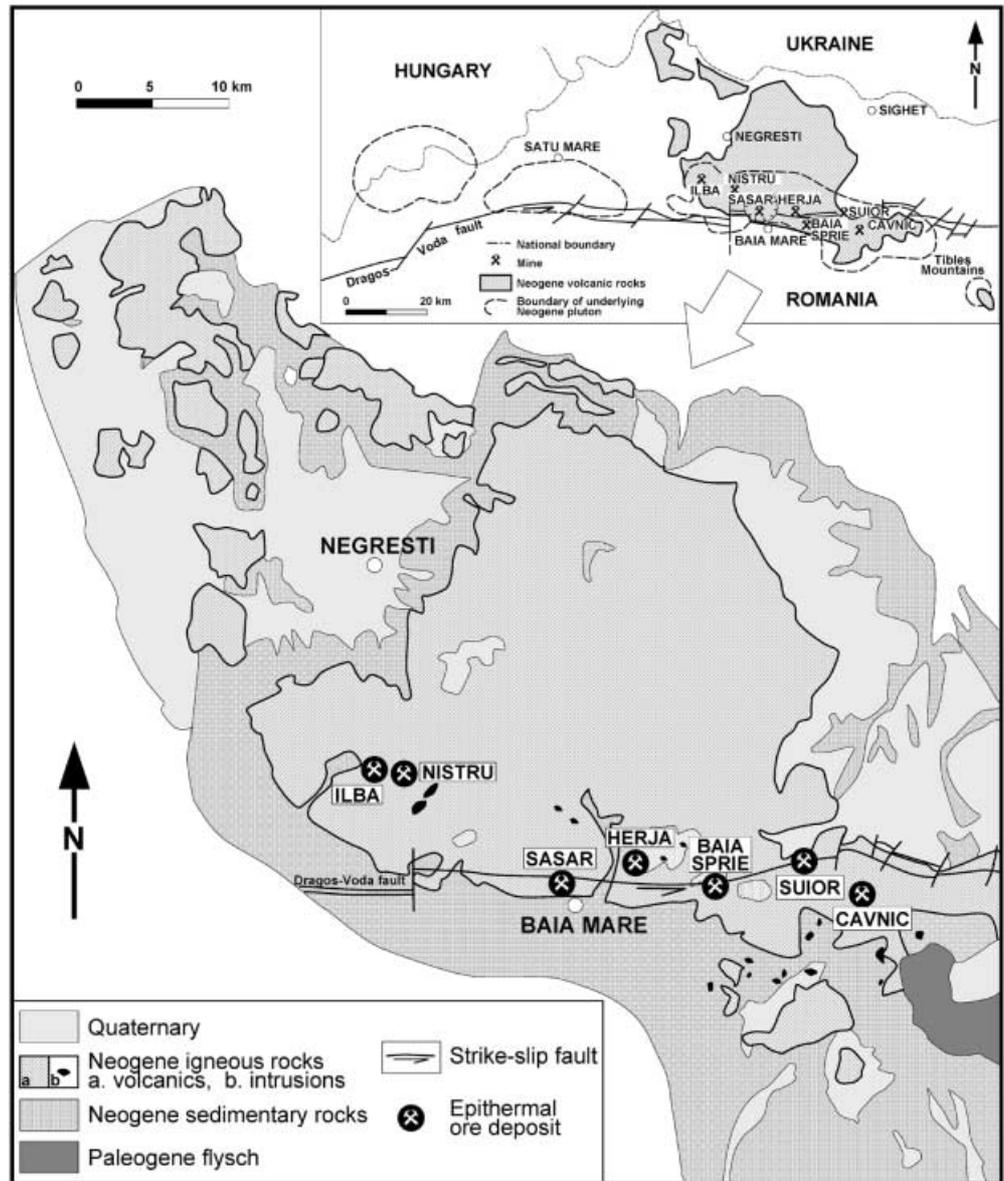
Age of mineralization

Despite the spatial association of mineralization with the volcanic rocks, the hydrothermal activity which has produced the epithermal precious metal- and base metal-bearing deposits in the Baia Mare area followed emplacement of host calc-alkaline rocks by 1.5–0.5 million years (Lang et al. 1994; Kovacs et al. 1997). Mineralization took place only during the Pannonian in two main phases: the first one includes the Ilba-Nistru-Sasar systems (11.5–10.0 Ma), and the second phase is upper Pannonian (9.4–7.9 Ma) and specific to the Herja, Baia Sprie, Suior and Cavnic deposits (Kovacs et al. 1997).

Deposit form, ore minerals and alteration

All deposits of the district have features typical of low sulfidation- or adularia sericite-type epithermal systems (Heald et al. 1987; White and Hedenquist 1995). General

Fig. 2 Simplified geological map of the Baia Mare district, Romania, with the location of the major epithermal deposits. *Inset* map shows the location of the major Dragos Voda fault system and the boundaries of the underlying pluton recognized by geophysical studies (Crahmaliuc et al. 1995)



descriptions of these deposits, summarized below, are provided by Manilici et al. (1965), Borcos et al. (1974), Borcos et al. (1975), Lang (1979), Virsescu et al. (1994), Istvan et al. (1995), Kovacs et al. (1995), Damian et al. (1995), Istvan et al. (1996), Halga et al. (1996), and Marias (1996).

The gold/polymetallic ore deposits show a wide variety of textures, dominantly with veins, cavity filling (bands, druses) and minor disseminations, and stockwork structures (Fig. 3). Spectacular breccia pipes are also present in some mines (Baia Sprie, Cavnica, Sasar, Suior), indicating phreatomagmatic explosions followed by hydrothermal fluid flow (Milési et al. 1994; Genna et al. 1994). The mineral assemblages include native elements (Au, Ag, Cu, As, S), sulfide minerals (pyrite, chalcopyrite, sphalerite, galena, stibnite), sulfosalts (tetrahedrite, jamesonite, bournonite, semseyite, pyrar-

gyrite), and tungstates (wolframite, scheelite), with quartz, adularia, clay minerals, carbonates, rhodonite and barite as gangue minerals. Hydrothermal alteration products adjacent to the veins generally form irregular zones in the host rocks. Propylitic alteration is the most widespread in the area, and consists of andesine, chlorite, epidote and minor calcite, sericite, actinolite and clay minerals (Russo 1971; Stanciu 1973). Where other alteration assemblages are present, the propylitic alteration is further from the veins. The deposits are also characterized by the dominance of adularia-sericite alteration bordering silicified zones near the veins. Also close to the veins, chlorite is sometimes disseminated in the wall rock. The adularia-sericite zone grades outwards into an argillic zone. In detail, the alteration assemblages for each ore deposit are more complex (Russo 1971; Stanciu 1972, 1973).

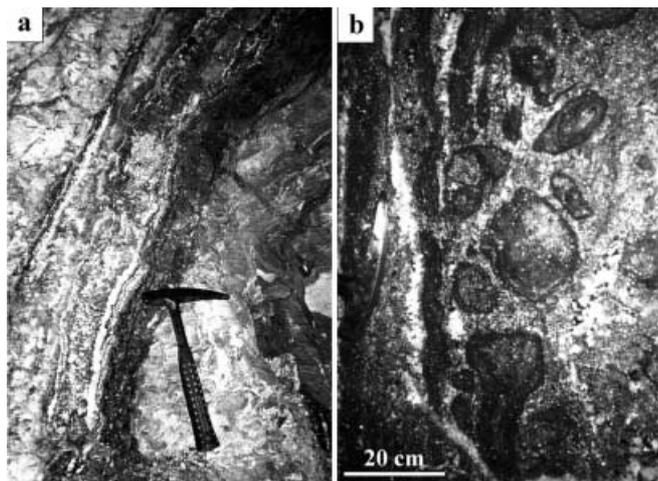


Fig. 3a, b Textural features of epithermal deposits in Baia Mare district (Cavnic deposit). **a** Banded texture in a quartz-sulfide vein. **b** Cockade breccia with magnetite and pyrite

Specific features of ore deposits and fluid-related mineralization

For this study, we focused on the three major deposits in the district to investigate the chemical aspects of the ore fluids: Baia Sprie, Sasar, and particularly Cavnic. The descriptions of these mineral deposits are based on our personal observations and mine mapping data provided by a local exploration company (IPEG Maramures, Romania).

The *Cavnic* deposit is spatially associated with a NE-SW-trending lineament which may be a second-order structure of the major Dragos-Voda fault. It is a polymetallic deposit with local Au–Ag enrichments (generally in the upper part of the system) which were selectively mined out in the past. The Cavnic deposit has a long history of mining, probably beginning in Roman times (Popescu 1995), but the most intense exploitation has occurred during the last 50 years. The deposit has current reserves of 20 million tons of ore with grades of 1 g/t Au, 30 g/t Ag, 1–2% Pb, 1–3% Zn, and 1% Cu. Fourteen low-sulfidation epithermal-type veins (400 to 1,500 m long, 1 to 7 m thick, and with a 900-m vertical extent) are hosted by Neogene volcanic rocks (Fig. 4). In the middle and deeper parts of the deposit, the host rocks are Paleogene-Miocene sedimentary units and middle Miocene dioritic bodies. Vein breccias formed in multiple episodes of hydraulic fracturing host ore minerals. Mineralization has a wide variety of textures, including bands, druses, disseminations and stockwork structures.

On the basis of detailed, mineral assemblage studies in individual veins (successive bands of mineralization, crosscutting relations), we propose a succession of five main alteration and mineralization stages (Fig. 5).

1. M0 corresponds to regional propylitic alteration (epidote, andesine, chlorite) which marks the beginning of the hydrothermal effects.

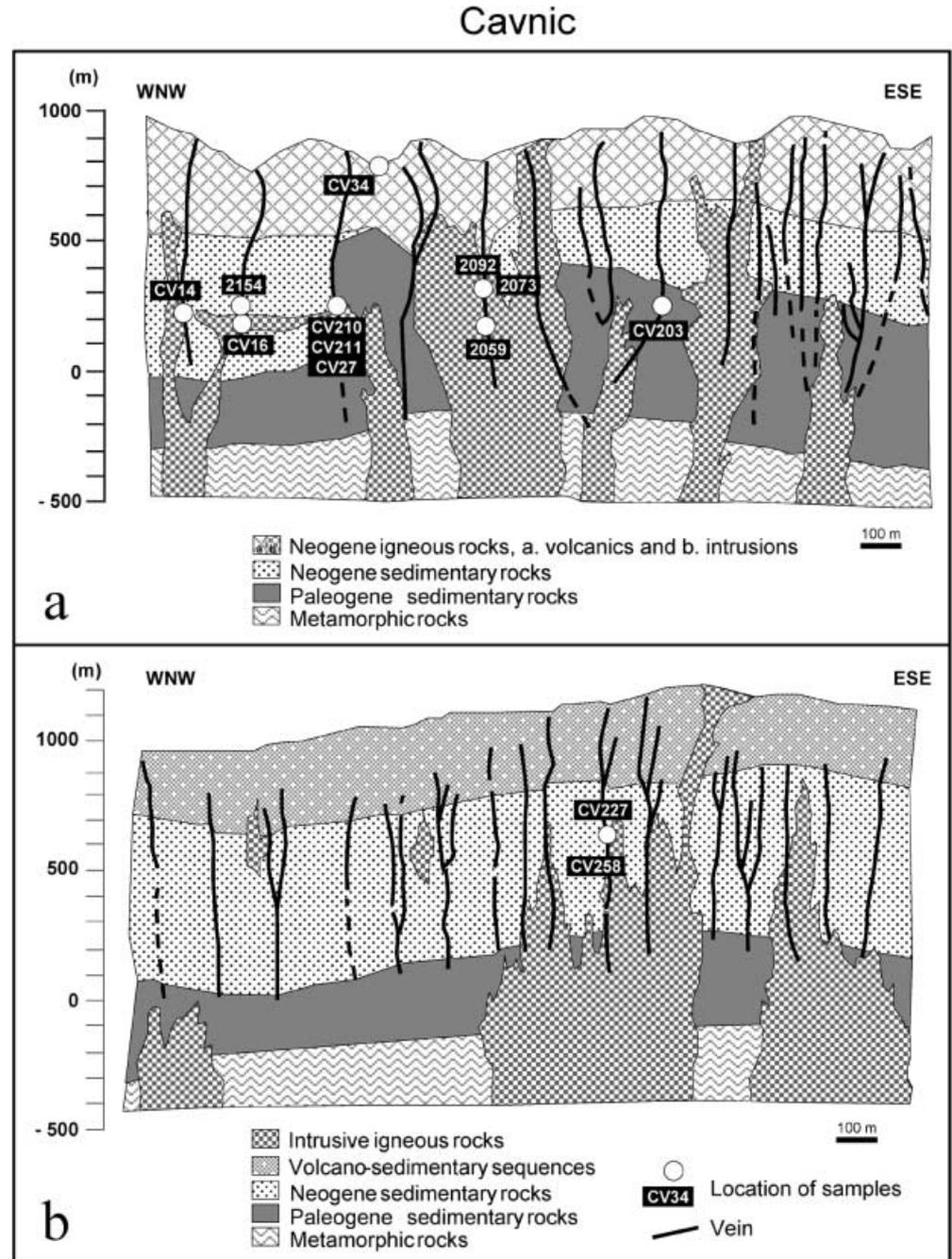
2. M1 is characterized by formation of a quartz, pyrite, magnetite, hematite, scheelite and chlorite mineral assemblage. A potassic alteration event is observed at the end of the stage. The transition from stages M1 to M2 is gradual, with some deposition of M1 minerals during M2.
3. M2 corresponds to a copper-rich event with precipitation of chalcopyrite, pyrite, covellite, chlorite and rare occurrences of gold.
4. M3 marks the deposition of sphalerite, galena and sometimes gold in a gangue of quartz, adularia, argillic minerals (illite/smectite) and carbonates (calcite).
5. M4 represents a lead-, zinc-, and manganese-rich stage with deposition of rhodonite, rhodochrosite and adularia. This assemblage is gradually replaced by kutnahorite and antimony-bearing phases such as bournonite, tetrahedrite and stibnite. Some occurrences of electrum are also observed. The mineral assemblage also includes rare realgar and orpiment.

Generally, not all the stages are present in one single vein, but the crosscutting relations permit the overall reconstruction of the Cavnic mineral paragenesis shown in Fig. 5.

The *Baia Sprie* deposit is located on a E–W regional fault which is considered to be part of the main Dragos-Voda fault. Two main veins (Principal and Nou) are developed on the northern and southern limits of an E–W graben (Fig. 6), with a volcanic sedimentary filling which is cut by several breccia pipes. The Principal vein is 5,250 m long, as much as 22 m wide, and has more than 800 m of vertical extent. Five mineralizing events have been identified for the Baia Sprie deposit, and these are generally similar to those identified in the Cavnic veins. However, some differences were observed. The Baia Sprie deposit is manganese-poor, tungsten-bearing phases occur mainly in the copper-rich ores, and a gold- and silver-rich zone (with 400-m vertical extent) is well-defined. The main stages are iron (stage M1), copper-bismuth-tungsten (stage M2), lead-zinc (stage M3), antimony (stage M4), and gold-silver (stage M5). A well-defined vertical zonation has been observed in the Principal vein, particularly in the western part of the deposit, with copper-rich mineralization at depth, polymetallic (lead, zinc, antimony) mineralization at intermediate levels, and a gold- and silver-rich zone in the upper part. The top of the system is characterized by the presence of realgar, orpiment and native arsenic. A distinctive association was observed between specific alteration types and metallogeny. The copper-rich ore is mainly related to a chloritic alteration, the polymetallic mineralization with sericite-argillic alteration, and the gold- and silver-rich mineralization is widely developed in association with an adularia-quartz assemblage.

The eastern part of the Baia Sprie deposit has a predominantly polymetallic character. The mineralization exhibits a wide variety of textures, including breccia-veins, stockworks, disseminations and numerous vugs filled with antimony-rich minerals. The close

Fig. 4a, b Schematic cross section of the Cavnic deposit, showing two zones of the mine (a Cavnic-Boldut, b Cavnic-Roata; modified from Borcos et al. 1975, and Marias 1996), and the location of samples for microthermometric studies



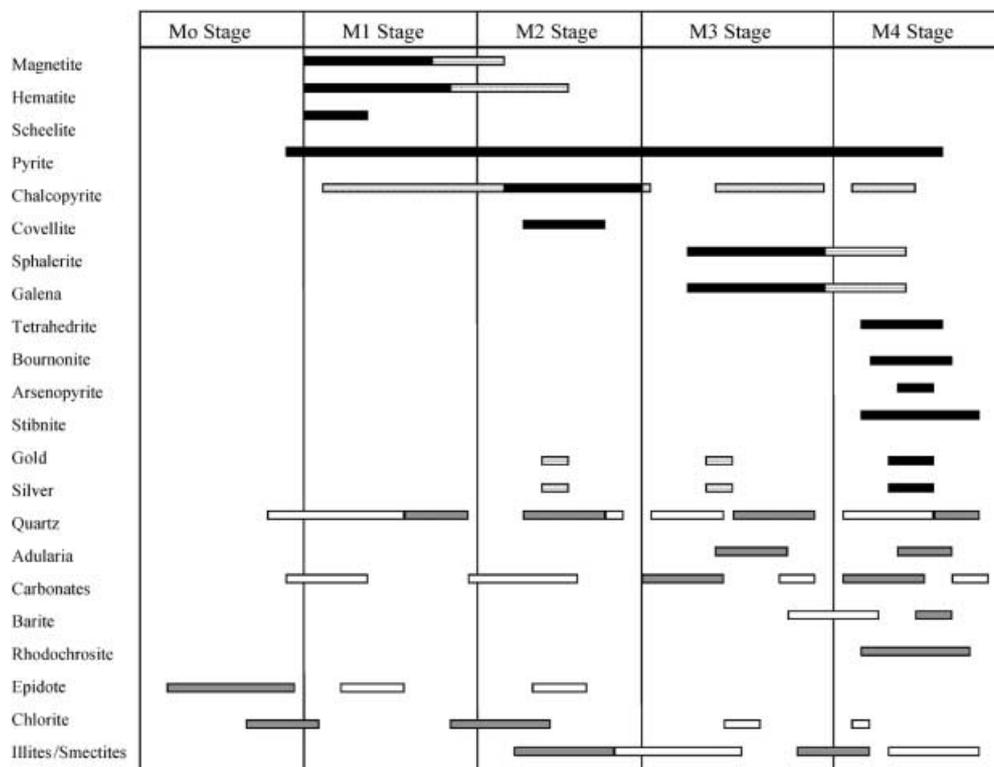
spatial relation between the breccia pipes and mineralized veins indicates a genetic link between hydrothermal events and phreatomagmatic explosions. Breccia veinlets, breccia dikes as wide as 1.5 m, and breccia pipes as wide as 25 m contain a mixture of hydrothermally altered, volcanic and sedimentary rock clasts and a cement containing fragments of sedimentary origin.

In the Minei Hill open pit (Fig. 6), situated in the western and uppermost part of the Baia Sprie deposit, the mineralization is silver-rich (as much as 8,000 g/t Ag and 1 g/t Au). The mineral assemblage is represented by galena, sphalerite, pyrite, chalcopyrite, and sulfosalts, surrounded by widespread quartz-adularia alteration.

The silver-rich character is due to the presence of numerous microscopic silver-bearing sulfosalts (freibergite, pyrargyrite, myargyrite), which are detected mainly within the galena crystals.

At the *Sasar* orefield, magnetic modeling (Crahmaliuc et al. 1995) suggests a collapse structure filled with volcanic debris. Lava flows of quartz-bearing andesites are widespread. The boundaries of this caldera (?) delimit the highest grade gold-silver zone of the Baia Mare district. A complex system of mineralized bodies is found in the *Sasar* orefield, including banded veins with quartz-chalcedony and silver-bearing sulfosalts, different types of breccias, and stockworks.

Fig. 5 Simplified paragenetic sequence of vein-filling (*dark shading*) and alteration minerals (*lighter shading*) in the Cavnic deposit. The dark shade means a higher development of vein-filling or alteration minerals



Extensive potassic alteration (adularia-rich), local silification and/or argillization represent the main hydrothermal alteration styles. The major vein (Principal; Fig. 7) is 900 m long, 2 m wide, and has a vertical extent of 900 m (Sasar-Dealul Crucii deposit). At depth, mineralization has a lead-zinc character whereas in the upper part, the ore-system is gold- and silver-rich.

Fluid-inclusion studies

Sample strategy

Our aim for a subsequent fluid-inclusion reconnaissance was the characterization of the thermal and fluid-compositional evolution which lead to the observed spatial zonations and temporal stages in the Baia Mare ore deposits. We systematically sampled vein and host-rock material which showed, where possible, clear time relations and covered a significant vertical and horizontal extent in the three deposits (Cavnic, Baia Sprie and Sasar). After petrographic study of samples representing all stages from all three deposits, only some were found to contain adequate material for quantitative fluid-inclusion study. Finally, the best samples and data coverage was possible at Cavnic, for the polymetallic mineralization stages M1 to M4. This was complemented by limited information from the precious-metal stage M5 at Sasar (gold-rich; data from Bailly et al. 1998), and from Minei Hill at Baia Sprie (Ag-rich).

Analytical methods

Microthermometric characterization of the fluid inclusions was performed on 30 doubly polished wafers (250 μm thick), using a Chaixmecca heating-freezing stage. The stage was calibrated using the melting point of solid standards at $T > 25\text{ }^\circ\text{C}$, and natural and synthetic fluid inclusions for $T < 0\text{ }^\circ\text{C}$. The accuracy is approximately $\pm 0.2\text{ }^\circ\text{C}$ during freezing, and $\pm 1\text{ }^\circ\text{C}$ when heating over the 25–400 $^\circ\text{C}$ range. Fluid salinities were determined from the last melting temperatures of the ice, using the equation given by Bodnar (1993). Traces of CO_2 were identified in some inclusions by micro-Raman analysis, using the Dilor Labram Raman spectrometer facilities at UMR G2R (Unité Mixte de Recherche, Géologie et Gestion des Ressources Minérales et Energétiques), Nancy.

Bulk crush-leach analysis was performed on five quartz samples from veins collected at the Sasar, Baia Sprie and Cavnic deposits. Samples were prepared using the procedure of Bottrell et al. (1988) and Yardley et al. (1993), in the laboratory of Leeds University. The anions (F, Cl, Br, SO_4) were analyzed by ion chromatography on doubly distilled water leachates, and the cations (Na, K, Li) by atomic emission spectroscopy. The calculated fluid-inclusion compositions from crush-leach analysis are based on the major anion concentration in each sample, which in our case is represented by chlorine. The ion concentrations were calculated using the salinities determined by microthermometric studies. For two samples from the Cavnic deposit (CV16,

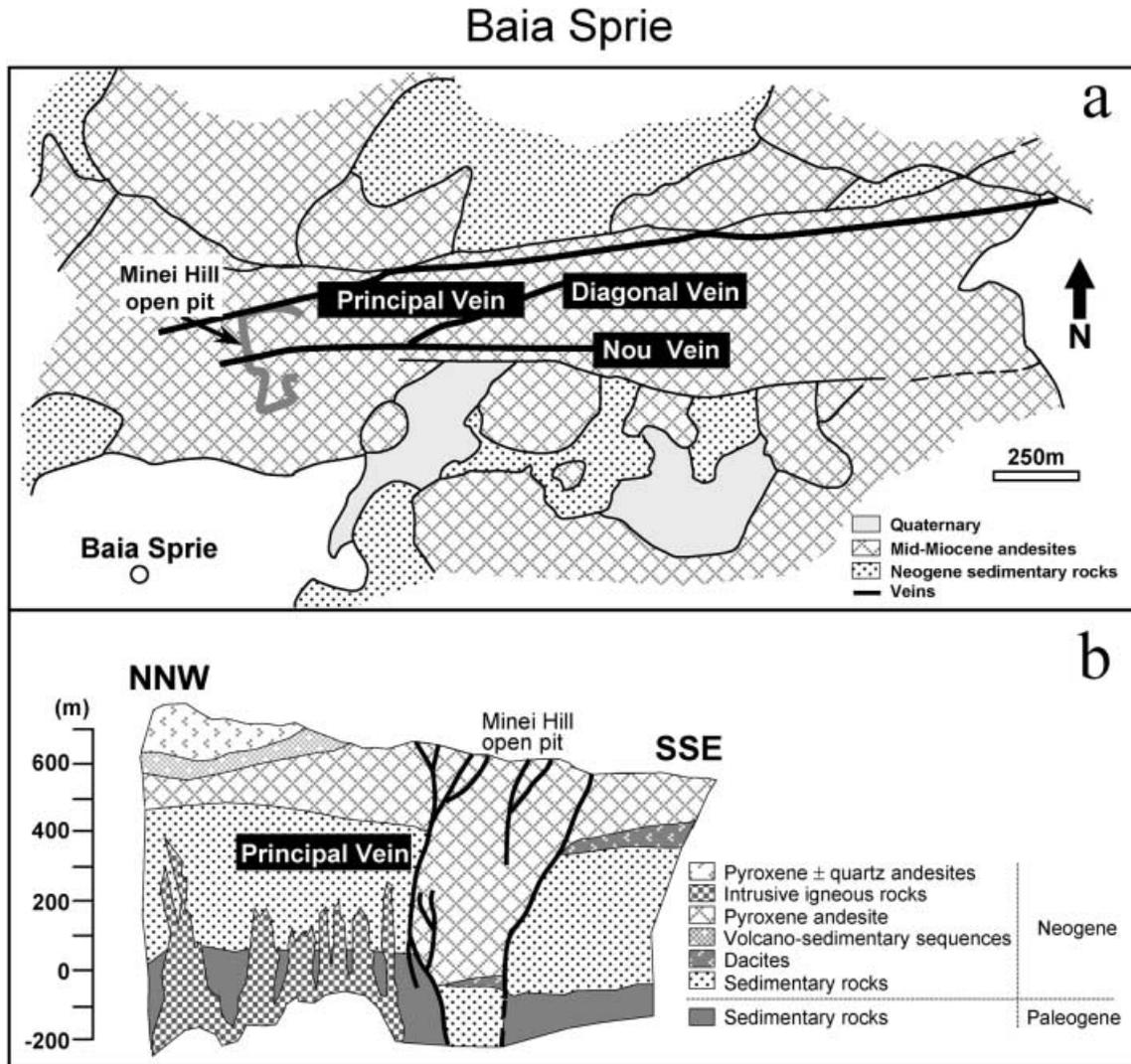


Fig. 6 **a** Simplified geological map of the Baia Sprie zone (modified from Gabor et al. 1984). **b** Schematic cross section of the Baia Sprie deposit (modified from Borcos et al. 1975)

CV211), the fluid chemistry was deduced using two sets of salinities revealed by microthermometric data.

Major elements in individual fluid inclusions have been detected using a laser ablation-optical emission spectrometry (LA-OES), a new analytical procedure still under development at UMR G2R, Nancy (Fabre et al. 1999). The Na/Ca and Na/Li (mass) ratios were calculated from calibration curves obtained using different standards (Fabre et al. 1999). Measurements for potassium were below the detection limit (about 750 ppm).

Fluid-inclusion characteristics

Cavnic

Fluid inclusions were studied in quartz, sphalerite and carbonate for samples collected over a wide area from different veins and at various levels of the deposit (Fig. 4).

A detailed chronology of the fluid-inclusion formation with respect to mineral stages was established. Primary inclusions occurring along growth zones in crystals, isolated inclusions, and secondary inclusions delineating short healed fractures within minerals were studied.

The fluid inclusions can be grouped into three types on the basis of their phase relationships at room temperature. They include aqueous inclusions with traces of CO₂ detected by Raman spectroscopy in the vapor phase (type 1), and aqueous two-phase liquid- or vapor-rich inclusions (types 2 and 3, respectively). Type 1 inclusions are restricted to veins of the M0-M1 stages. The CO₂ abundance could not be determined quantitatively due to the low peak/background ratio in Raman spectra. Birefringent solids (carbonates?, sulfates?) were observed in some aqueous inclusions from the same M0-M1 mineral stages, but they are difficult to identify due to their small size. In this study, microthermometric measurements were obtained mostly from type 1 and 2 inclusions. The amount of liquid in vapor-rich inclusions (type 3) is very low, and thus microthermometric data were not obtainable. The range of homogenization

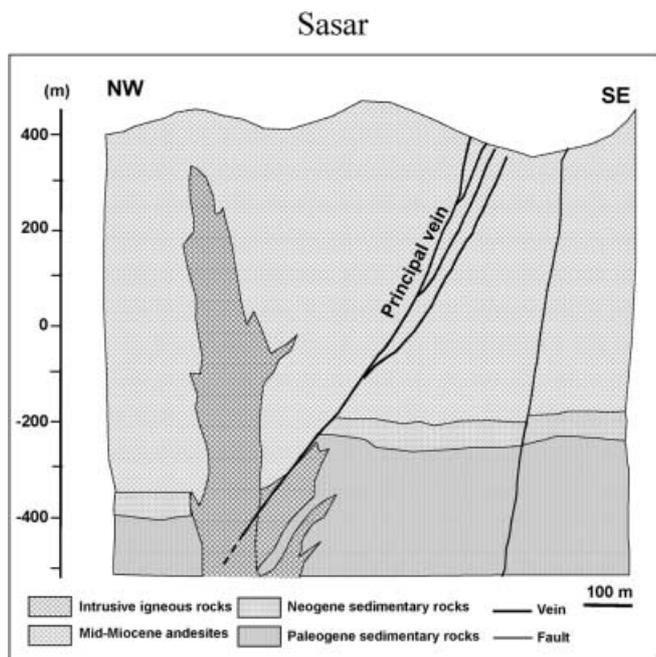


Fig. 7 Simplified cross section of the Sasar deposit (Dealul Crucii area; modified after Borcos et al. 1975)

temperatures (T_h) and salinities are presented in Table 1. The T_h of quartz-hosted inclusions from the early mineralization stages (M0-M1) were in the range of 273–316 °C, and the salinities were between 4.0 and 14.4 wt% NaCl equiv. For the M1-M2 stages, the salinity and T_h ranges are comparable: 3.6–14.4 wt% NaCl equiv and temperatures of 249–315 °C. Lower salinities occurred in fluid inclusions in quartz, sphalerite and carbonates from the M3-M4 stages (1.6 to 5.4 wt% NaCl equiv). The T_h range for these later mineralizing events was from 195 to 370 °C.

Overall, the salinity of hydrothermal solutions varies from 1 to 14 wt% NaCl equiv. and, in the same mineralization stage (or sometimes in one single quartz crystal), the salinity spans a considerable range, for example, 5 to 14 wt% NaCl equiv. (Fig. 8). Some inclusions from the early mineralization stages (M1-M2) record more saline fluids. These could perhaps reflect episodic injections of a brine, as described by Simmons (1991) for the Fresnillo deposit in Mexico. Salinity variations might also appear during extensive fluid boiling processes (Simmons and Browne 1997; Scott and Wanatabe 1998). Evidence for boiling in the Cavnic deposit appears during stage M1. Vapor-rich inclusions within planes or growth zones were considered as evidence of boiling, although the critical evidence, comprising a population of co-existing vapor-rich and liquid-rich inclusions which homogenize over the same temperature range (Ramboz et al. 1982; Bodnar et al. 1985), is missing. In our samples, the majority of vapor-rich inclusions have a thin film of liquid surrounding a large bubble, precluding microthermometric observations.

Lower salinities, which are characteristic of the later mineralizing events (M3, M4), suggest a greater

involvement of meteoric fluids in the hydrothermal system at this time. These fluids may, alternatively, represent the low-salinity vapor phase which resulted from boiling.

The homogenization temperature data (Fig. 8) indicate a general cooling trend in the Cavnic hydrothermal system, from 315 °C in the early Fe-W-rich stage mineralization (M1), to 260–300 °C in the chalcopyrite-rich stage (M2), and to 200 °C in the late base metal event (M3-M4). A wide range in the homogenization temperatures was detected for some inclusion populations of the M3-M4 base metals/gold stage. The spread of T_h values can have several causes, but principally it is due to entrapment of variable proportions of liquid plus vapor and post-entrapment necking. Evidence of boiling is common in many samples of the M3-M4 mineralizing events, but evidence of 'necking' is generally absent although, in few cases, liquid-only inclusions may be due to necking-down (Bodnar et al. 1985). These fluid-inclusion populations were avoided in our microthermometric studies. The distribution of T_h is a definitive test for discriminating inclusion populations which underwent necking (Loucks 2000). Such populations have nearly symmetric T_h histograms, a feature which was not observed in the fluid-inclusion populations observed here. Instead, they are rather skewed to a predominance of measurements near the lower limit, which is characteristic for fluid-inclusion populations sampled during boiling. In boiling systems, as proposed here for Cavnic, the best estimation of true fluid temperature is considered to be the lowest value of the fluid-inclusion T_h interval (stage M3-M4, Fig. 8).

As epithermal ore deposits form at shallow levels (1–2 km) and because we suggest boiling has occurred, pressure corrections are minimal. The pressure regime is assumed to be close to hydrostatic for the Cavnic system, similar to other extinct or active epithermal environments (Hedenquist et al. 1992).

Baia Sprie

Microthermometric data were obtained on samples collected in the upper part of the Baia Sprie deposit (Fig. 6), from different levels in the Minei Hill open pit. Four samples from outcrops of silver-rich veins (stage M5) and two samples of altered country rocks (andesites) were suitable for microthermometric investigations. Fluid inclusions were studied in different growth zones of quartz crystals or in planes related to the microfracturing of quartz and sphalerite. For one sample (25034C-96), it was possible to study fluid features in different stages of the vein-fracture dilation (banded vein; stages I, II and III).

Two types of fluid inclusions are present: two-phase, aqueous, liquid-rich, and a vapor-rich type. The amount of liquid in the vapor-rich inclusions is generally very low (<5 vol% liquid), and thus microthermometric measurements were very rarely possible. Accidentally

Table 1 Summary of the fluid-inclusion data from the Cavnic deposit. Studied fluid inclusions, primary (*P*) or secondary (*S*) are hosted by quartz (*qz*), sphalerite (*sph*) or carbonate (*carb*) samples. The homogenization temperature (*Th*) and the salinity of ore fluids

are presented according to the main mineralization stages (*M0* to *M4*). The measured salinities for the stages *M0*–*M1* may be somewhat high because the presence of CO_2 in solution contributes to the freezing-point depression (Hedenquist and Henley 1985)

Sample no.	Vein name	Mineral	Inclusion type	Tm ice range (°C)	Salinity (wt% NaCl equiv.)	Th range (°C)	Number of inclusions
Stage M0–M1							
CV14	Cristofor	Qz	P, S	–2.4 to –3.9	4–6.3	292–316	20
Stage M1							
CV16	Gutin	Qz	P, S	–8.1 to –10.4	11.8–14.4	274–291	16
			S	–4.8 to –5.0	7.6–7.9	285–287	5
CV27	Kelemen	Qz	P	–5.7 to –5.8	8.8–9	288–290	5
			S	–3.0 to –5.0	5–7.9	283–304	10
2059	Gheorghe	Qz	S	–8.1 to –8.4	11.8–12.2	275–277	5
			S	–4.9 to –5.1	7.7–8	273–275	10
			S	–2.9 to –3.0	4.8–5	276–279	4
Stage M1–M2							
CV211	Kelemen	Qz	P	–7.4 to –7.5	11–11.1	270–274	5
			P	–3.2 to –3.3	5.2–5.4	260–269	4
			S	–10.4	14.3	295	2
			S	–7.9 to –8.1	11.6–11.8	291	2
			S	–4.3 to –4.4	6.9–7.0	290–296	6
CV210	Kelemen	Qz	S	–2.5 to –2.7	4.2–4.5	278–315	7
Stage M2							
2073	Gheorghe	Qz	P	–5.8 to –6.1	9–9.3	258–270	4
			S	–9.7 to –10.2	12.5–14.1	263–280	10
2092	Gheorghe	Qz	P, S	–2.1 to –3.3	3.6–5.4	249–294	22
Stage M3							
CV227	Ana-Nicolae	Qz	P	–2.6 to –2.8	4.3–4.7	225–240	4
			S	–2.4 to –3.3	4–5.4	207–272	11
Stage M4							
CV203	Ungarn	Sph	P, S	–2.7 to –3.0	4.5–5	253–290	10
		Qz	S	–2.1 to –2.2	3.6–3.7	271–302	3
CV34	69	Qz	P	–2.3 to –2.5	3.9–4.2	267–271	3
			S	–0.9 to –1.8	1.6–3.1	246–370	15
CV258	Ana-Nicolae	Carb	P, S	–2.5 to –2.7	4.2–4.5	214–230	4
2154	Gutin	Qz	S	–2.7 to –3.2	4.5–5.3	195–370	17

trapped solid phases are present in some samples, but are difficult to identify due to their small size. Clathrates were not observed upon cooling, and CO_2 was not detected by Raman spectroscopy. Low eutectic temperatures (approximately -50°C) suggest the presence of divalent cations (Ca, Mg, Fe) in the hydrothermal solutions. The majority of homogenization temperatures (*Th*) of fluid inclusions in the veins ranges from 176 to 254°C (Table 2). The rare inclusions which homogenize into the vapor state have relatively high temperatures (340 – 380°C), probably due to some incorporation of liquid during trapping.

Salinities in fluid inclusions are in the range of 5 to 15 wt% NaCl equiv. Only for one vapor-rich inclusion was it possible to observe the final ice-melting temperature (with a value of -3.3°C), corresponding to 5.4 wt% NaCl equiv. salinity. In samples from all the pit levels, several groups of fluid inclusions with different salinities are seen. This feature suggests significant

salinity variations during hydrothermal episodes at the Baia Sprie deposit (Fig. 9). Locally, salinity variations may be related to water-vapor loss through boiling. Boiling conditions are indicated by the presence of coeval liquid-rich and vapor-rich inclusions, and vapor-rich inclusions occurring in the quartz growth zones. The abundance of adularia in some samples is also indicative of a boiling fluid. Boiling releases CO_2 to the vapor, resulting in an increase in the solution pH, shifting it from the stability field of illite to that of adularia (Browne and Ellis 1970). The altered country rocks, with a quartz-sericite (adularia, rare sulfides) paragenetic stage, appear to contain more dilute fluids (with about 6 wt% NaCl equiv. and $\text{Th} = 174^\circ\text{C}$). Most fluid inclusions in veins from the Minei Hill open pit have moderate salinities (5–15 wt% NaCl equiv.), similar to other silver-rich epithermal deposits such as Fresnillo, Mexico (Simmons 1991) or Creede, Colorado (Barton et al. 1977; Hayba et al. 1985).

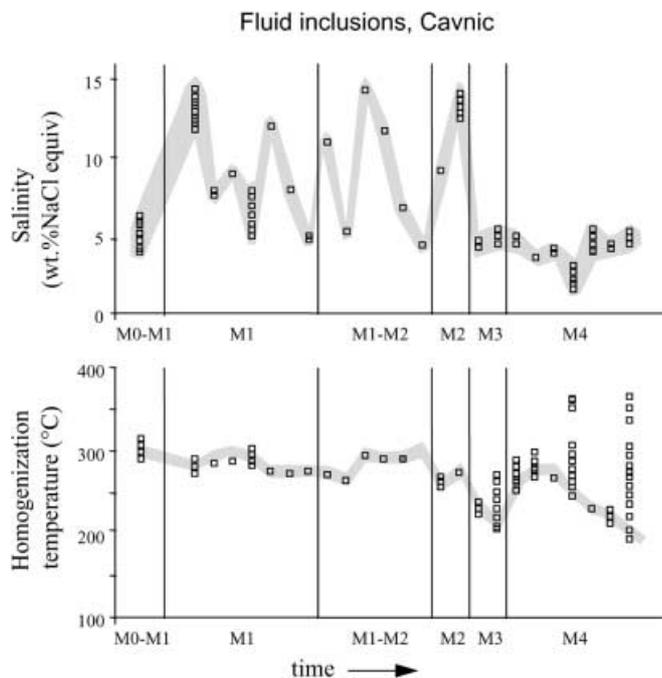


Fig. 8 Fluid evolution during ore deposition of the main mineralization stages (M0 to M4) in the Cavnic deposit. Within the same stage, different fluid-inclusion populations were distinguished on the basis of their salinities. Large variations in salinity are seen between and within samples, which may be explained by occasional input of saline fluids and/or extensive fluid boiling

Previous microthermometric data related to ore deposition in the Baia Sprie deposit are reported by Manilici et al. (1965), Lang (1979), Pomarleanu et al.

Table 2 Summary of microthermometric features of the samples from Minei Hill open pit, Baia Sprie. Primary (P) and secondary (S) aqueous liquid- or vapor-rich (V) inclusions were studied in quartz (qz) and sphalerite (sph). Four samples were from veins and

Sample no.	Location	Mineral	Inclusion type	Tm-ice range (°C)	Salinity (wt% NaCl equiv.)	Th range (°C)	Number of inclusions	
25034A-96	Base level (+ 550 m)	Qz	S	-9.4 to -9.8	13.2-13.7	231-241	10	
			S	-3.0 to -3.1	5-5.1	187-222	5	
			S (V)	-3.3	5.4	341-379	2	
25034C-96	Base level	Qz	S	Stage I	-4.9 to -8.2	7.7-11.9	206-254	5
				S (V)			365	2
			S	Stage II	-9.9 to -10.1	13.8-14	208-219	4
				Stage III	-7.5 to -7.6	11.1-11.2	205-223	4
			P?	-6.0 to -6.6	9.2-10	224-229	5	
			S	-7.2 to -8.5	10.7-12.3	189-244	9	
I/17A	Level I (+ 600 m)	Qz	S	-4.1 to -4.2	6.6-6.7	217-247	7	
			P, S	-2.9 to -4.0	4.8-6.4	157-159	6	
25035C-96	Level III (+ 650 m)	Sph	P	-10.1 to -10.4	14-14.4	231-232	5	
			P, S	-7 to -8.4	10.5-12.3	176-205	9	
III/2	Level III	Qz	P, S	-3.3 to -5.3	5.4-8.3	179-202	6	
			P	-9.6 to -10.0	13.5-13.9	181-198	6	
V/18B	Level V (+ 729 m)	Qz	S (V)			338	2	
			S	-10.9 to -11.2	14.9-15.2	205-215	5	

(1985). They noted homogenization temperatures ranging from 200 to 300 °C for the main stage of sulfide minerals and gold deposition. Nedelcu and Pintea (1993) also provide some data on fluid inclusions in quartz crystals from various paragenetic sequences collected from different levels of the Baia Sprie mine. They report homogenization temperatures ranging from 147 to 359 °C, and the salinities between 3.6 and 20.0 wt% NaCl equiv. Boiling was also suggested to have occurred. More recently, Bailly et al. (1998) note quartz and sphalerite from different ore stages (M1 to M4) of the Baia Sprie deposit (eastern part) containing fluid inclusions which are similar to those in the Cavnic mineral deposit, with salinities of 0.2 to 21 wt% NaCl equiv. and temperatures ranging from 150 to 300 °C.

Sasar

Microthermometric results on quartz crystals from the Au-Ag-rich stage (V) of the Sasar deposit were reported by Bailly et al. (1998). The different quartz generations reveal the presence of dilute fluids. The salinity varies from 0.0 to 4.2 wt% NaCl equiv., and the homogenization temperatures are mainly 150-200 °C.

Ion content

Bulk crush-leach analysis on quartz samples from the Sasar, Baia Sprie and Cavnic veins, and calculated ion concentrations (Table 3) reveal the presence of dominantly Na-K-Li chloride solutions in the Baia Mare

two were from altered wall rocks (I/17A and III/2). For one sample (25034C-96), it was possible to study fluid features in different stages of the vein-fracture dilation (banded vein; stages I, II, III)

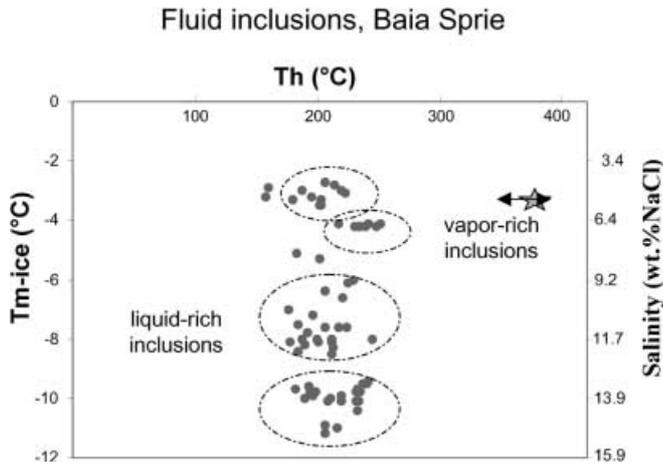


Fig. 9 Melting temperature of ice (T_{m-ice}) versus homogenization temperature (T_h) for aqueous fluids from silver-rich mineralization of the Minei Hill open pit, Baia Sprie

orefield. Sodium is the major cation, and the Na/K (molal ratios) varies from 3 to 19. Both the sodium and potassium concentrations are low in gold-bearing quartz veins from Sasar. For the Cavnic deposit the Na/K ratio decreases from 19 in the iron- and tungsten-rich M1 stage to 3 in the M3 base metal event. This variation in chemistry may have been caused by reactions between the fluid and host rocks (Giggenbach 1988). Preferential leaching of potassium-rich minerals (argillic minerals, K-feldspar) may have occurred in stage M3 compared to stage M1. This variation in chemistry may be also due to the fact that the bulk crush-leach method analyzes a number of different fluid-inclusion types as a single fluid. Lithium is also present, with highest concentrations in the Cavnic polymetallic veins (as much as 689 mmol/kg).

In-situ analyses of fluid inclusions were carried out using the new LA-OES technique. Major-ion ratios were

determined for individual fluid inclusions in quartz samples from different stages of the Cavnic deposit (stages M1, M1-M2 and M4). For this study, we focussed on the spectral ranges of some major elements commonly found in hydrothermal fluids (Na, Ca, Li, K, Mg). For the 580–780 nm spectral range selected here, the following emission lines were detected: Na (589 nm; stages M1, M2 and M4), Li (670 nm; stages M1, M2), and Ca (790 nm; stage M1-M2; Fig. 10). The analyzed inclusions show Na/Ca (molal) ratios which range from 3.4 to 13 (M1-M2 stage), and Na/Li ratios which vary from 4.6 (stage M0-M1) to 14.5 (stage M1-M2). The elemental ratios for sodium and lithium are in good agreement with those obtained by bulk crush-leach analysis. The LA-OES investigations suggest that early, moderate saline Na-Li-rich fluids (M1 stage) were succeeded by Na–Li–Ca solutions (M1-M2 stage), and finally by lower-temperature and lower-salinity ore fluids enriched in sodium (stage M4; Fig. 10).

Chloride, fluoride, sulfate and bromide contents were detected by the bulk crush-leach method. The fluids in the M1-M2 mineralization stages of the Cavnic system are richer in chloride compared to the later ore stages in Baia Sprie and Sasar (Table 3), consistent with the T_{m-ice} data. High fluoride concentrations (as much as 1,257 mmol/kg) were also detected in early fluids from the Kelemen vein in the Cavnic deposit (e.g., sample CV211). It is notable that fluorite is sometimes present in the mineral assemblage. In other samples from Cavnic, fluoride was below the analytical detection level (0.5 mmol/kg).

Chloride and bromide are useful tracers of fluid source and evolution due to their general conservative behavior in solution (Banks et al. 1991; Bohlke and Irwin 1992). The values of $Br/Cl \times 10^3$ (molar ratios) lie in the range 0.13 to 1.21 (Fig. 11). They are comparable to the Br/Cl ratio of the greisen-related Sn-W deposits of the Cligga Head, England (Smith et al. 1996), and those

Table 3 Reconstructed compositions of ore fluids from the Baia Mare district, including Cavnic, Baia Sprie and Sasar deposits, determined after crush-leach analysis (*nd* not detected)

Ore deposit	Cavnic					Baia Sprie	Sasar
	CV16(a)	CV16(b)	CV211(a)	CV211(b)	CV227	BS19	Sa209
Sample no.	M1	M1	M1-M2	M1-M2	M3	M2-M3	M5
Mineralization stage							
Mean salinity (wt% NaCl equiv.)	7.6	14.4	5.2	14.3	4.7	4.6	2.2
Na (mmol/kg)	3,526	6,681	1,645	4,524	796	758	209
K	188	356	169	466	265	861	33
Li	364	689	171	470	382	260	17
F	nd	nd	457	1,257	nd	36	1
Cl	1,213	2,298	559	1,538	748	767	276
Br	0.57	1.09	0.13	0.37	0.90	0.23	0.04
SO ₄	32	60	31	87	20	nd	37
Na/K (mole ratio)	19	19	10	10	3	1	6
Na/Li	9.7	9.7	9.7	9.7	2	3	12.3
Cl/SO ₄	38	38	18	18	37		7
Br/Cl $\times 10^3$	0.47	0.47	0.24	0.24	1.21	0.30	0.13

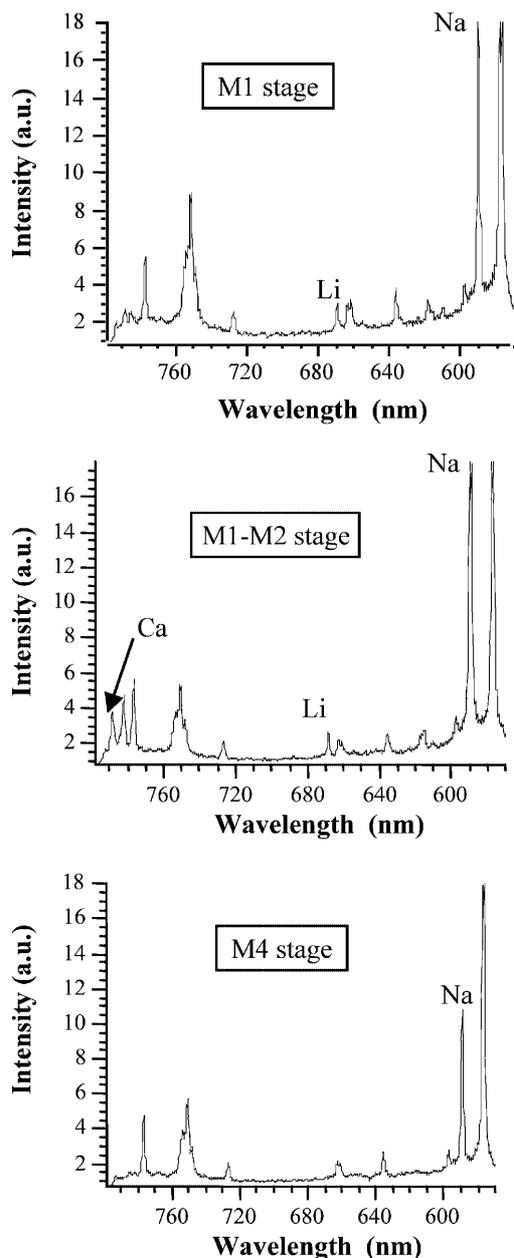


Fig. 10 Optical emission spectra obtained by LA-OES on individual fluid inclusions in quartz samples from different mineralization stages of the Cavnic deposit. The *unlabeled peaks* are related to silica (quartz matrix)

of the quartz topaz-tourmaline rock from the St. Mevan's Beacon, St. Austell, England (Bohlke and Irwin 1992). Such ratios are also typical of many volcanic fumaroles and might be considered to characterize magmatic waters (Bohlke and Irwin 1992). Similar $\text{Br}/\text{Cl} \times 10^3$ values were also reported by Irwin and Roedder (1995) for the fluids associated with porphyry mineralization at Butte, Montana, USA (0.94–1.15). The $\text{Br}/\text{Cl} \times 10^3$ ratio in all these examples is significantly lower than those of seawater (1.54). The halogen ratios are distinct from those of gold-bearing veins in metamorphic

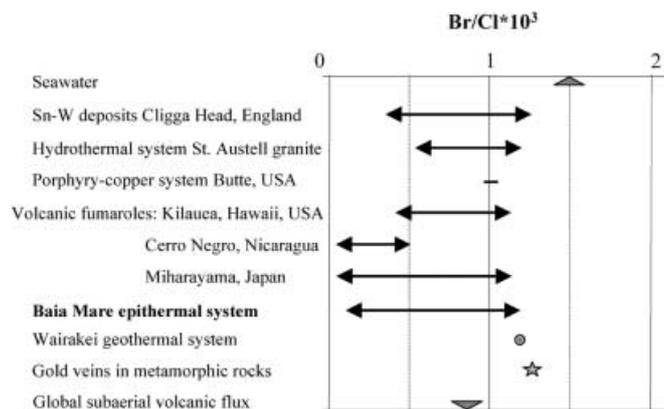


Fig. 11 $\text{Br}/\text{Cl} \times 10^3$ ratio of the Baia Mare orefield-related fluids compared with selected volcanic fumarole condensates, porphyry-copper deposits of Butte, Montana, USA, hydrothermal fluids of St. Austell granite and Cligga Head Sn-W deposit, England, gold-bearing veins in metamorphic rocks, Brazil and Wairakei geothermal system, New Zealand. Sources of data are Bohlke and Irwin (1992), Irwin and Roedder (1995), Bottrell et al. (1988), Smith et al. (1996), Boiron et al. (1999), and Ellis and Mahon (1977)

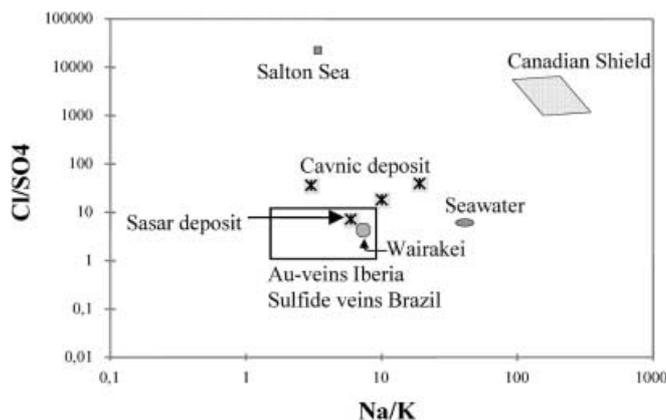


Fig. 12 Na/K versus Cl/SO_4 (molal ratios) determined from crush-leach analysis of fluid inclusions from the Baia Mare district (Cavnic and Sasar deposits), and compared with other reference fluids: gold-bearing veins, Iberia, sulfide veins, Minas Gerais, Brazil (Boiron et al. 1996, 1999), seawater, acid-sulfate waters of the Canadian Shield (Frape and Fritz 1987), the Saltion Sea, USA (Helgeson 1968; McKibben et al. 1987), and the Wairakei geothermal system, New Zealand (Hedenquist and Henley 1985)

rocks (Boiron et al. 1999), and from neutral-pH geothermal waters at Wairakei, New Zealand (Ellis and Mahon 1977). The fluids from Wairakei have an N_2/Ar ratio typical of air-saturated groundwater, indicating no significant magmatic contribution to the system (Giggenbach 1992).

Fluid inclusions in gold-rich veins from the Sasar deposit have low Na/K and Cl/SO_4 molal ratios, similar to neutral-pH geothermal waters of the Wairakei hydrothermal system (Ellis and Mahon 1977; Henley and Ellis 1983) and many gold-bearing veins in metamorphic rocks (Boiron et al. 1996, 1999; Fig. 12). Ratios are very distinct from those of basinal brines.

Isotopic data

The oxygen, hydrogen, sulfur, and carbon isotopic composition of ore-forming fluids from the Cavnic deposit were reported by Piantone et al. (1999). The range for $\delta^{18}\text{O}$ values of quartz from stages M1 to M4 was +6.7 to +11.0 per mil. There were no major differences between the different stages. The $\delta^{18}\text{O}$ values of the coexisting hydrothermal fluids were obtained using the equation of Matsuhisa et al. (1979) and calculated as -2.6 to +3.6 per mil. The δD values measured for fluid-inclusion waters in the same samples vary from -71 to -109 per mil. The hydrothermal fluids involved at Cavnic appear to have a composition resulting from isotopic exchange between water and country rocks (igneous and sedimentary rocks) at temperatures of 200–300 °C. Meteoric water seems to be dominant, although the participation of magmatic carbon cannot be excluded.

Carbon isotope values ($\delta^{13}\text{C}$) for rhodochrosite, dolomite, ankerite and kutnahorite vary from -7.2 to +0.4 per mil relative to PDB. Carbon isotope systematics do not permit us to discriminate between a deep-seated and a crustal source for the hydrothermal carbon at Cavnic.

The $\delta^{34}\text{S}$ values obtained on sphalerite and galena from the main base metal-sulfide stage (M3-M4), and on pyrite crystals from stages M1 to M4 indicate a narrow range extending from +0.3 to +5.2 per mil. Assuming average temperatures of about 300 °C and an H_2S -dominated hydrothermal system, the original $\delta^{34}\text{S}$ composition appears to be close to +3.4 per mil and suggests a magmatic sulfur source (Ohmoto and Rye 1979; Field and Fifarek 1985).

Overall, the hydrothermal fluids at Cavnic appear to have an isotopic composition similar to other, zoned polymetallic veins and epithermal precious-metal deposits in the Baia Mare area (Nedelcu et al. 1992; Cook and Damian 1997; Damian et al. 1998) and elsewhere in the world. These include deposits from the Inner Carpathian chain such as Beregovo, Ukraine (Vityk et al. 1994) and Banska Stiavnica, Slovakia (Lexa et al. 1999).

Discussion and conclusions

Geologic setting

Miocene calc-alkaline volcanic rocks which host the epithermal mineralization were generated in a subduction-related environment during the final stages of the closure of the Tethys ocean between Africa and Eurasia. A period of 0.5 to 1.5 million years elapsed between the emplacement of the intermediate calc-alkalic volcanic rocks and the mineralization, as is commonly observed in other epithermal deposits from North America and the western Pacific (Mitchell 1996). This relationship may reflect the presence of buried

intrusions being slightly younger than the exposed volcanic units. The host igneous rocks are frequently cut by dikes and other intrusive bodies of similar composition, but precise dating of these bodies is not available.

Mineralization

The mineralization and the hydrothermal alteration assemblages are typical of adularia-sericite (low sulfidation) epithermal deposits. One notable feature of the Baia Mare orefield is the chemical and mineralogical complexity of the veins. On the basis of detailed mineral-assemblage studies of individual veins from several mineral deposits, we propose a succession of five main mineralization stages dominated by the following metals: (1) Fe-W, (2) Cu-Bi (W), (3) Pb-Zn-Mn, (4) Sb, and (5) Au-Ag. The top of the system is marked by the presence of realgar and native arsenic.

Ore fluids

The homogenization temperatures of fluid inclusions in three major deposits (Cavnic, Baia Sprie and Sasar) can be interpreted to suggest a general cooling of the Baia Mare ore-forming system, from 320 °C in the early Fe-W stage to 150 °C in the Au-Ag-rich stage, with salinities varying from very dilute to 21 wt% NaCl equiv. Veins with the more saline fluid inclusions are widespread, extending over distances of hundreds of meters (several veins at Cavnic), and occur within different mineralization stages. These features suggest that at discrete times there was an influx of saline fluids from a deep reservoir. Locally, salinity variations may be related to water-vapor loss through boiling and may have aided metal deposition.

The fluid-inclusion data in the Cavnic, Baia Sprie and Sasar deposits document changes in salinities and temperature of the Baia Mare epithermal system which can be correlated with time, explosive volcanism events (phreatomagmatic breccias), fracturing, and mixing of saline fluids with meteoric waters. Direct analyses of fluid inclusions from the Cavnic deposit suggest that moderate- to low-salinity fluids evolved from Na-Li-Ca-rich to Na-rich compositions during cooling, and that they were diluted by meteoric fluids to variable extents.

Metal transport

The relatively high-salinity fluids (up to 21 wt% NaCl equiv.), which are typical of the Baia Mare district, may have a bearing on the polymetallic character of the mineral deposits because chloride complexes are effective means of transporting base metals (Barnes 1979). Furthermore, the difference between the high grades of gold characterizing the Sasar deposit and the high grades of silver, specific to Minei Hill (Baia Sprie

deposit), could be related to different ore-forming fluids. The moderate-salinity fluids at the Baia Sprie open pit (5–15 wt% NaCl equiv.) could be linked to silver transport in chloride-rich solutions, whereas the low-salinity fluids at Sasar (≤ 4.2 wt% NaCl equiv.) could have transported gold as bisulfide complexes (Seward 1973; Giggenbach 1997). At Cavnic, the salinities of the M3-M4 stage, rich in base metals, are not particularly high (ca. 5 wt% NaCl equiv.), possibly the consequence of a dominance of meteoric water.

Origin of fluids

Chloride and bromide are useful tracers of fluid source due to their generally conservative behavior in solution. The Br/Cl ratios in the Baia Mare orefield (Baia Sprie, Cavnic, Sasar) are similar to many volcanic fumaroles (Bohlke and Irwin 1992), and to the porphyry at Butte, Montana (Irwin and Roedder 1995) or other Laramide porphyry-copper deposits (Kendrick et al. 1999). The Br/Cl values are consistent with the degassing of magmatic volatiles as the source of salinity. Sulfur isotopic data also suggest a magmatic reservoir for the hydrothermal sulfur in the Cavnic mineral deposit. The magmatic signature indicated by the halogen ratios and sulfur isotopic composition suggests that there is a stronger genetic relationship between low-sulfidation epithermal deposits and magmatism than previously accepted. More recent studies on geothermal systems and a few low-sulfidation epithermal deposits (Simmons 1995) indicated that magmatic contributions do exist and are possibly important to ore formation. Other studies on low-sulfidation epithermal deposits containing high tellurium concentrations also invoked magmatic fluids as cause of mineralization (Spry et al. 1996; Alderton and Fallick 2000). Some Au-Ag tellurides were also mentioned in the Baia Mare district (Butucescu et al. 1963; Istvan et al. 1995), but they are not as abundant as in the Apuseni Mountains host of the other major epithermal gold province in Romania. Stable-isotope data from the gold-rich deposits of the Apuseni Mountains district show the presence of a dominant magmatic fluid (Alderton and Fallick 2000). Other similar epithermal deposits from the western Pacific (e.g., Kelian, Porgera) have been explained in terms of the input of saline fluids from an underlying porphyry copper system (Leach and Corbett 1993). At the drill depths of 1–1.5 km, porphyry-copper deposits are absent or scarce in the Baia Mare area. Nevertheless, the existence of a porphyry system associated with a monzo-dioritic or monzo-granodioritic magmatic complex is suggested by Udubasa et al. (1983) and Pintea et al. (1999) in the southeastern part of the Baia Mare orefield in the Tibles Mountains (Fig. 2).

Stable-isotope data from the Cavnic deposit suggest a significant contribution of meteoric waters into the hydrothermal system. The meteoric circulation was probably due to a convective hydrothermal system

induced by the underlying pluton. The meteoric component is dominant in epithermal systems related to voluminous magmatism, which induces large and long-lived convection cells which may erase the original magmatic signature of a hydrothermal system (Taylor 1979; Hedenquist and Lowenstern 1994). However, the incorporation of meteoric waters is not incompatible with the conservation of the Br/Cl magmatic signature recorded here, because these meteoric waters are likely to have low halogen concentrations and may not significantly alter the Br/Cl ratios.

Furthermore, recent investigations on lead isotopic compositions of ore deposits and volcanic rocks in the Baia Mare district (Marcoux et al. 2002) demonstrate the genetic link between volcanism and epithermal activity. These results emphasize a magmatic signature for the lead (and possible other metals) in the hydrothermal fluids.

The data discussed above suggest that the fluids related to Cavnic, Baia Sprie and Sasar ore deposits have a complex composition, which may reflect the combined effects of initial magmatic origin, extensive fluid-rock interaction, boiling, and dilution by mixing with meteoric water. The magmatic component may have been acquired by the hydrothermal system during intense water-rock interaction along an advancing front of brittle fracturing, allowing deep-circulating groundwaters to invade the cooling underlying pluton. Such a process might permit the transfer of the magmatic volatiles to waters of the hydrothermal system (Giggenbach 1992).

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