

FLUID INCLUSION CHARACTERISTICS AND PALEOTHERMAL STRUCTURE OF THE ADULARIA-SERICITE TYPE EPITHERMAL DEPOSIT AT TELKIBÁNYA TOKAJ MTS., NORTHEAST HUNGARY

FERENC MOLNÁR¹ and TIBOR ZELENKA²

¹Department of Mineralogy, Eötvös L. University, Múzeum krt. 4/A, 1088 Budapest, Hungary

²Geological Survey of Hungary, Stefánia út 14, 1143 Budapest, Hungary

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Abstract: Fluid inclusion data for quartz, adularia, calcite and sphalerite related to mineralization hosted by Neogene volcanic rocks at Telkibánya in northeast Hungary indicate that the temperature varied between 270 °C and 130 °C during hydrothermal activity. Intensive boiling of fluids took place at about 230 °C, and the apparent salinity of the hydrothermal solution was ≤ 5 NaCl equiv. wt. %. The CO₂-content of initial solutions (pre-boiling fluids on 240–250 °C) was about 0.8 mol/kg on the basis of the model calculations. As a consequence of boiling, a vapour-rich, nearly isothermal system developed in the vuggy-brecciated zones of host rocks around ore veins. Euhedral quartz that precipitated in these zones is morphologically different from the vein-filling quartz aggregates. Homogenization temperatures indicate that the quartz veins formed under non-isothermal conditions. The paleotemperature distribution was reconstructed on the basis of the spatial distribution of average homogenization temperatures of quartz vein samples, and taking into account the level differences of sampling. A comparison of the paleotemperature map with the volcanotectonic map indicates that some of the areas of high paleotemperature are located along the major faults mapped in the studied area. The spatial coincidence of some of these thermal centres with the area of the highest residual Bouguer-anomaly values suggests that the heat source of the hydrothermal convection cells was a subvolcanic intrusion. The minimum depth under the paleowater table of the mineralization now exposed at the surface was about 200–440 m.

Key words: epithermal ore deposit, fluid inclusions, boiling, paleotemperature-map, thermal structure, delineation of heat source.

Introduction

Studies of Tertiary epithermal mineralization and active geothermal systems indicate that the mineral deposition processes within these systems can be modelled by the temporal and spatial variation of temperature and fluid chemistry during the hydrothermal activity (Henley et al. 1984; Berger & Bethke 1985). The changes of temperature and fluid composition within active geothermal systems can be directly measured, or at least estimated by means of several geochemical methods. However, in extinct hydrothermal systems these parameters are determined principally by fluid inclusion studies.

Although several microthermometry studies on a variety of epithermal systems have recently been published, there are relatively few documented examples of vertical or horizontal paleotemperature profiles over this type of mineralization (Gatter 1983; Albinson 1988; Vikre 1989; Kwak 1990; Izawa et al. 1992).

According to the genetic models of geothermal systems and epithermal deposits (Henley & Ellis 1983; Hedenquist 1987) abrupt changes in the physicochemical state of fluids most likely occur along principal conduits, such as open fractures. These changes, in particular induced by boiling are favourable for the deposition of precious metals and other elements. Therefore, the delineation of paleothermal centres in areas of epithermal

alteration helps in defining target areas for more detailed geochemical, drilling and other exploration activities.

The objective of this publication is to emphasize how fluid inclusion microthermometry can be utilized in identifying the location of the principal fluid conduits in epithermal ore deposits, based on work undertaken on the Telkibánya deposit in the Tokaj Mts., Hungary.

Geology of the studied deposit

The Telkibánya deposit is located in the Tokaj Mts., northeast Hungary, and is hosted by Neogene volcanic rocks. This region forms part of the Neogene Intra-Carpathian Au-polymetallic zone of mineralization; and is the northern extension of the Carpatho-Balkan Metallogenetic Belt.

The volcanic rocks of the Tokaj Mts. lie within a 1500–3000 m deep volcanotectonic depression which is bounded by two major faults trending NNE–SSW and NNW–SSE. The length of the depression is approximately 100 km, and has a width of 15–20 km (Pantó 1968). The formation of the volcanotectonic depression was probably related to the extensional forces along a strike-slip fault system trending SW–NE (Zagreb–Zemplén Line). The basement beneath the Miocene volcanic and sedimentary rocks consists of pre-Cambrian gneisses and mica

schists; Paleozoic shales, sandstones and volcanic rocks; and Mesozoic limestones (Gyarmati 1977). These basement rocks are also exposed along the margins of the depression.

The thickness of Middle-Upper Miocene (Sarmatian) volcanic rocks in the area of Telkibánya is about 800 m. These rocks are composed of andesites, dacites, rhyolites and rhyolitic

pumice-flow tuffs (Fig. 1). The volcanic rocks are intercalated by sedimentary rocks composed of clay and conglomerate in some places. These Middle-Upper Miocene rocks are underlain by Lower-Middle Miocene (Badenian) volcanic and sedimentary rocks, which also host base metal mineralization. The geochemical and mineralogical characteristics of this deeper min-

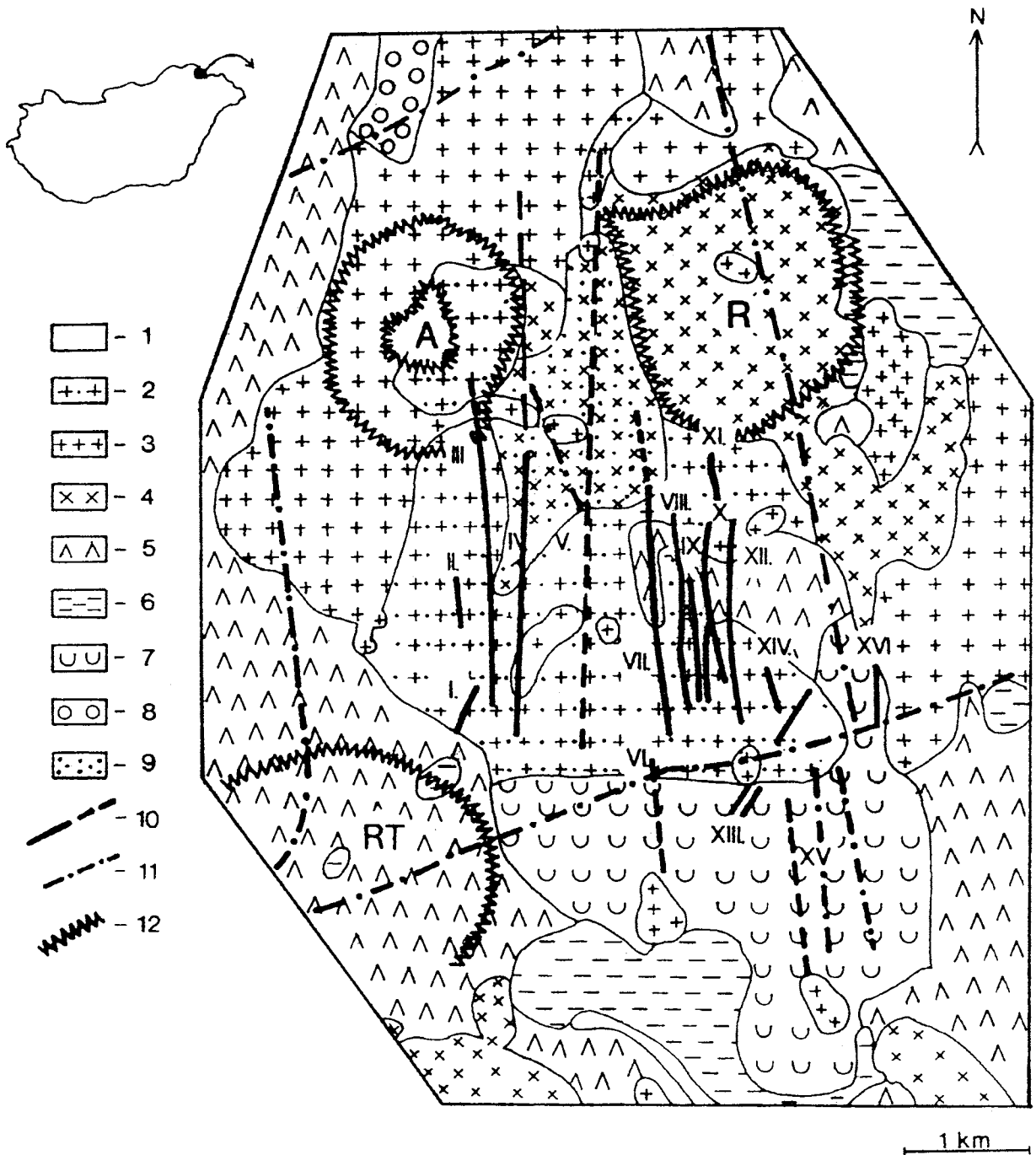


Fig. 1. Geological sketch map of the Telkibánya ore deposit (based on map compiled by Gyarmati et al. 1976). 1 - Holocene sediments. 2 - Pseudotrachyte. 3 - Pyroxene andesite. 4 - Rhyolite. 5 - Rhyolitic pumice-flow tuff. 6 - Clay, tuffite. 7 - Rhyodacite foam-lava. 8 - Dacite. 9 - Potassium metasomatism. 10 - Ore veins: I. Ilona; II. Helén; III. András; IV. János; V. Medve; VI. Sinta; VII. Lobkowitz; VIII. Józserencsét; IX. Brenner I-II.; X. Jupiter; XI. Zsófia; XII. August-Freud; XIII. Glück Auf-Vendelin; XIV. Névtelen; XV. Jó-hegy; XVI. Fehér-hegy. 11 - Major tectonic lines. 12 - Volcanic centres recognized on the surface. RT - Rhyolitic tuff; A - Andesite; R - Rhyolite.

eralization differ significantly from that hosted by the younger volcanic rocks (Széky-Fux 1970).

According to the interpretation of Landsat space photographs of the area and the new results of mapping on the surface, as well as in the reopened old mines (Horváth et al. 1989; Horváth 1990), the early stage of the Sarmatian volcanic activity was characterized by rhyolitic pumice-flow tuffs and caldera collapse in the southwestern part of the mineralized area. Later andesitic volcanic activity occurred along with the formation of a stratovolcano in the central part of the studied area, followed by partial collapse of this volcanic centre. This was accompanied by tectonic movements along NNW-SSW and ENE-WSW trending faults (Fig. 1).

The earlier volcanic rocks were subsequently intruded by a large subvolcanic andesitic body (locally termed "pseudotrachyte"). The marginal zone of this intrusion is highly brecciated. K-metasomatism occurred within the intrusion and locally along its contacts with the country rocks (rhyolitic pumice-flow tuff, andesite, sediments). The K-metasomatised subvolcanic body was later intruded by andesitic dykes. At approximately the same time, rhyolite domes were also emplaced in the vicinity of the mineralization. The majority of the ore veins occur within the subvolcanic body. A few veins also arise along the contact zone of the rhyolite and older andesite (Horváth et al. 1989; Horváth 1990).

The major faults were reactivated several times during and after the volcanism, and the latest event was recorded by the collapse of old mine related to an earthquake in the 17th century (Benke 1988).

Characteristics of mineralization

The subvolcanic body hosting the veins is intensively altered. The most characteristic feature is its high K_2O -content compared with the fresh andesites in the marginal areas to the mineralization. In some places the K_2O -content is greater than 10 wt. % due to the presence of K-feldspar phenocrysts in these rocks (Széky-Fux 1970). The K-feldspars of the "pseudotrachyte" replaced the original plagioclase crystals of andesitic rocks and underwent strong sericitization due to the superimposition of metasomatic-hydrothermal processes. Silicification and pyritization are also characteristic of the "pseudotrachyte". A later fresh adularia occurs in stockworks and quartz veinlets. The K-feldspar-bearing zones which include and surround veins are fringed by propylitic alteration (albite, chlorite, epidote, calcite). The hydrothermal argillic alteration shows vertical zonation. The upper horizons contain kaolinite. Montmorillonite and montmorillonite-chlorite mixed clays become more abundant with depth (Széky-Fux 1970).

The rhyolitic pumice-flow tuff is generally characterized by silicification and weak argillic alteration (kaolinite), though a quartz-alunite assemblage occurs in the upper levels of the eastern and central zone of the ore field, along the August-Freud vein and the Névtelen vein (Fig. 1).

The infillings of various silica phases (quartz, chalcedony, opal) are characteristic of the veins. The quartz infillings often have a vuggy structure due to the hydrothermal dissolution of calcite, and the occurrence of quartz pseudomorphs after platy calcite is also common (Fig. 2a). At depth (in the old mine workings), the veins are known to contain clay (montmorillonite) and carbonate minerals more abundantly. The presence of a base-metal mineral assemblage (sphalerite, galena, chalcopy-

rite, pyrite, acanthite, freibergite and Ag-sulphosalts) has been observed in the deepest levels of the Lobkowitz- and András-veins (Fig. 1). In the eastern part of the deposit (along the Fehér-hegy vein and the Névtelen vein, see Fig. 1) this base-metal mineral assemblage is also known at the surface (Szakáll et al. in press). Gold is believed to occur partly as solid solution in pyrite, though free gold grains (1–10 μm) have also been observed in the quartz. Enrichment with gold occurs in supergene montmorillonite veinlets in the oxidized zone of the mineralization. The Au/Ag ratio is variable, ranging from 1 : 10 to 1 : 100.

Several types of breccias are associated with the veins: polymict and monomict hydrothermal breccias with siliceous or clay matrix, and tectonic breccia. The breccia bodies are generally characterized by enrichment with silver (Horváth 1990).

The preliminary fluid inclusion data (Gatter 1984, 1985; Molnár 1986; Hajdú 1987) indicated two main stages of the hydrothermal activity: boiling at about 230 °C and later deposition of the vein filling minerals at about 200 °C. These earlier data are also included in the present study.

The near-surface oxidation-cementation zone of the Telkibánya ore deposit was almost completely exploited in the Middle Ages. Documentations of mining activity in the 14th, 15th and 17th centuries indicate significant gold production during these periods. Silver ores were largely exploited during the 18th and 19th centuries (Benke 1988).

Results of fluid inclusion studies

The sampling for fluid inclusion study was carried out on the vein outcrops. The most common mineral suitable for fluid inclusion study was quartz, which has a variable morphology and texture in the veins and in the brecciated and vuggy wall rocks. The occurrence of euhedral crystals (often with scepter habit) is restricted to the vuggy or brecciated zones in host rocks (Fig. 2b). The veins are commonly filled with a quartz aggregate that has a banded, brecciated, saccharoidal and stockwork-like texture. Single crystals within these aggregates have a subhedral to anhedral habit.

The euhedral quartz crystals are accompanied by euhedral adularia in some cavities. The adularia crystals (up to 1 mm) suitable for fluid inclusion study are most common in stockwork-like quartz veinlets. The occurrence of calcite is relatively uncommon in the outcropping quartz veins. As a consequence, only two samples were collected for microthermometric study. The sphalerite used here was collected by Széky-Fux (1970) from the deeper horizons of the Lobkowitz-vein.

The microthermometric studies were carried out by means of a Chaixmeca freezing-heating stage (Poty et al. 1976) on 0.1–0.5 mm thick sections of various minerals. The genetic type of the fluid inclusions (e.g. primary, pseudosecondary, secondary) was evaluated on the basis of criteria by Roedder (1984).

Fluid inclusion petrography

The inclusion types recognized at room temperature in the double polished sections of the studied mineral phases are as follows:

Monophase inclusions

a – Solid inclusions. Calcite and adularia inclusions were most commonly observed in various types of quartz (Fig. 2c and 2d).

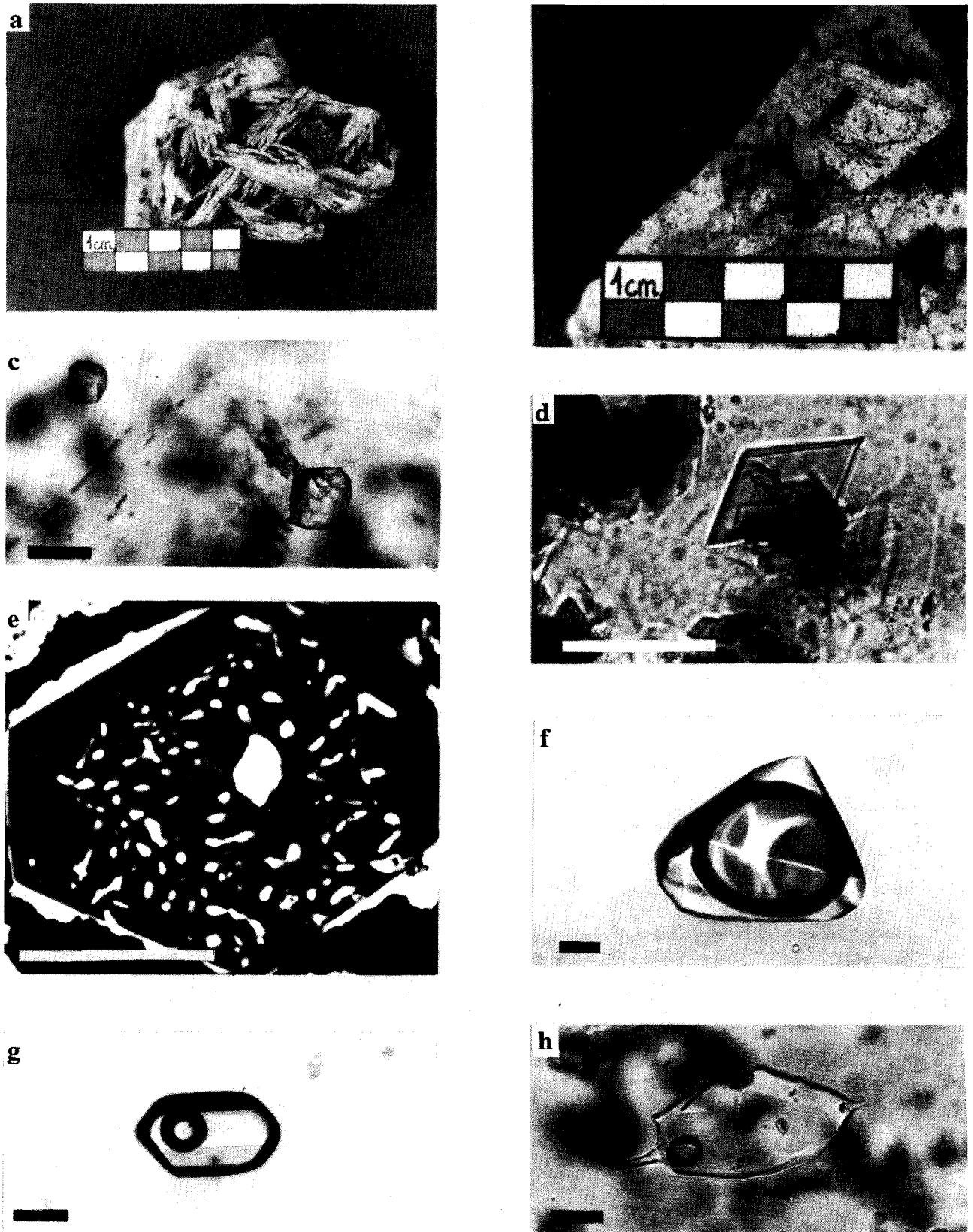


Fig. 2. Photographs of characteristic minerals and their inclusions from the Telkibánya area (scale bars on all photomicrographs are 50 μm). **a** - Vein-filling quartz pseudomorphs after platy calcite. **b** - Euhedral quartz in a vug of slightly brecciated rhyolitic pumice-flow tuff. **c** - Calcite inclusions in euhedral quartz. **d** - Adularia inclusions in vein-filling quartz. **e** - Freibergite inclusions in quartz (backscattered electron image). **f** - Vapour-rich fluid inclusion in euhedral quartz. **g** - Liquid-rich fluid inclusion in vein-filling quartz. **h** - Polyphase inclusion in euhedral quartz.

Less commonly, ore minerals (pyrite, hematite, freibergite; Fig. 2e) were also recorded. The sphalerite contains freibergite, acanthite, chalcopyrite and galena inclusions. The adularia occasionally contains rare calcite inclusions.

b - Liquid inclusions. The secondary monophasic liquid inclusions occur in all the studied minerals. However, some of the single, monophasic inclusions occurring in vein-filling quartz that precipitated at low temperature ($< 180^\circ\text{C}$) could be primary in origin. After freezing the vapour phase usually appeared in these inclusions, thus the original absence of vapour phase at room temperature is related to the metastable state of inclusion liquid.

Two-phase inclusions

a - Inclusions with both liquid and vapour phases, and a L/V ratio less than 30 : 70 (Fig. 2f). These primary inclusions are characteristic of the euhedral quartz crystals occurring in the cavities of host rocks. This type of inclusion is rarely found in the vein-filling quartz.

b - Inclusions with both liquid and vapour phases, and a L/V ratio greater than 70 : 30 (Fig. 2g). These inclusions are most common in the minerals studied. This type of inclusion can be primary, pseudosecondary or secondary. The coexistence of primary, liquid rich, two-phase inclusions with the vapour-rich inclusions suggests the presence of separated liquid and vapour phases (i.e. boiling conditions) during the growth of euhedral quartz.

Polyphase inclusions

a - Inclusions with liquid, vapour and solid phases (Fig. 2h). The solid phases of these primary inclusions are usually irregularly shaped, and show optical anisotropy. During the heating runs, dissolution of these crystallites was not observed, suggesting that the solid phases are randomly trapped minerals rather than representing daughter mineral phases (Roedder 1984).

b - Inclusions with one vapour and two immiscible liquid phases. This type of primary fluid inclusion was observed in a subordinate amount only in two samples of euhedral quartz. The thermometric properties of the immiscible liquid phase coexisting with the aqueous solution (incongruent melting about -20°C and homogenization well above $+31^\circ\text{C}$) are indicative of a liquid hydrocarbon.

Microthermometric data

Tables 1a, 1b and 1c summarize the fluid inclusion data on the studied minerals. The distribution of the homogenization temperatures measured in the II. b.-type primary and pseudosecondary inclusions (Fig. 3) illustrates that the sphalerite, calcite and adularia crystallized during a high temperature ($T > 230^\circ\text{C}$) stage of hydrothermal activity. The deposition of vein-filling quartz may have also started at this stage, though most of the vein formation took place below 230°C . The most common homogenization temperatures measured in euhedral quartz samples are clustered around 230°C .

Apparent salinities of inclusion fluids were calculated from the melting point data (Potter et al. 1978) and almost all are below 5 NaCl equiv. wt. % (Fig. 4). The apparent salinities of inclusions are usually higher in sphalerite, adularia, calcite and vein-filling quartz than in the euhedral quartz.

During the freezing studies, the presence of CO_2 -hydrate ($\text{CO}_2 \cdot 5.75 \text{H}_2\text{O}$) was most commonly observed in inclusions trapped within the euhedral quartz which homogenized at about 230°C (Fig. 5). The frequency of the CO_2 -bearing inclusions also has a maximum in vein quartz samples deposited below 180°C . The small amount of the CO_2 -hydrate within these inclusions did not allow for the accurate observation of the CO_2 -hydrate melting. However, the presence of CO_2 -hydrate was not observed after the final melting of ice. This could suggest a CO_2 -content of the fluid inclusions of about a few tenths of a mole of CO_2/kg solution (Collins 1979).

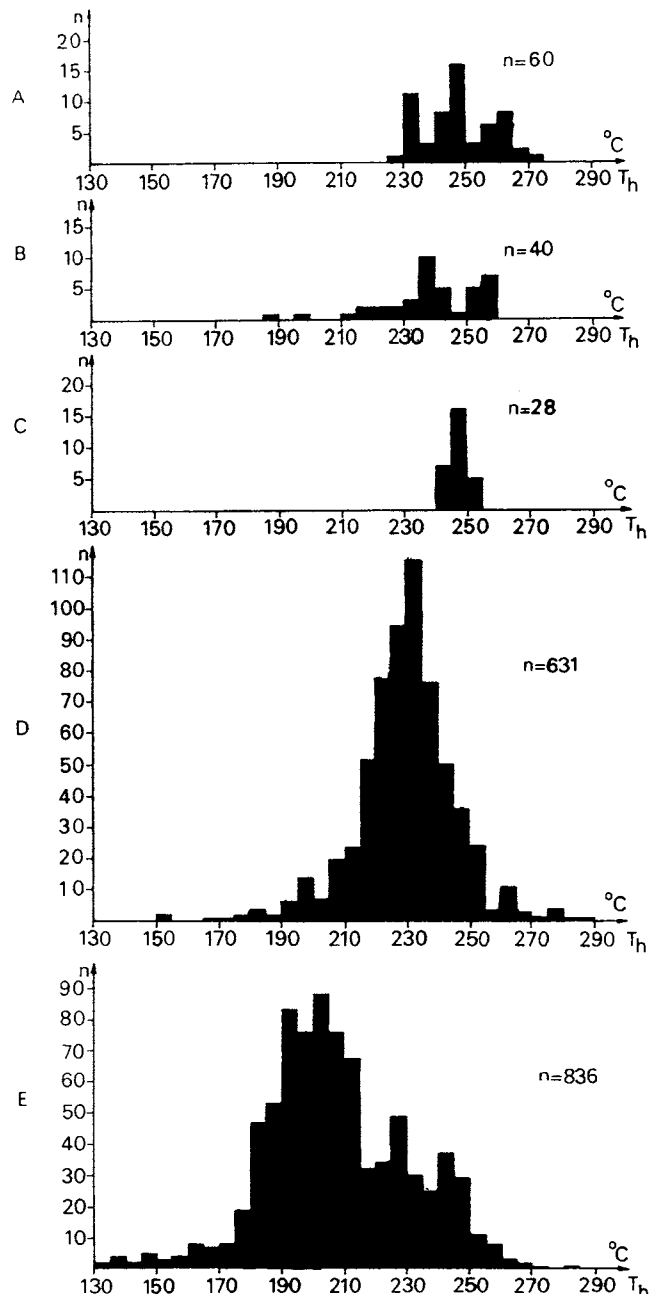


Fig. 3. Distribution diagrams of homogenization temperatures (T_h) measured in fluid inclusions of various minerals from the Telkibánya ore deposit. A - Adularia. B - Calcite. C - Sphalerite. D - Euhedral quartz. E - Vein-filling quartz. n - number of measurements.

Table 1a: Fluid inclusion data of euhedral quartz samples.

Sample locality (*)	Homogenization temperature (°C)					Concentration (NaCl equiv. wt. %)
	n	min.	max.	average ± s.d.	mode	
Telkibánya-East	27	179	267	212±16	214	0.90
Ilona-vein	17	227	252	235±6	236	1.09
Ilona-vein	22	196	263	230±11	234	1.30
János-vein	30	214	299	232±13	228	0.61
János-vein	18	151	243	227±21	231	0.93
János-vein	21	154	267	214±30	220	1.49
János-vein	19	198	250	230±11	232	1.66
Medve-vein	77	191	285	231±16	230	0.82
Medve-vein	25	193	251	230±14	231	1.09
Medve-vein	27	173	250	228±18	231	1.09
Sinta-vein	31	189	270	227±20	224	1.02
Lobkowitz-vein	31	199	243	227±9	229	0.90
Lobkowitz-vein	5	229	240	234±5	233	1.55
Lobkowitz-vein	28	214	267	239±15	233	1.67
August-Freud-vein	29	206	241	232±7	232	-
Jó-hegy-vein	53	216	281	238±13	243	2.00
Jó-hegy-vein	59	197	276	231±16	233	1.36
Névtelen-vein	23	230	254	245±6	244	1.15
Fehér-hegy-vein	35	218	253	228±7	223	3.17
Fehér-hegy-vein	56	192	263	223±13	219	1.39

(*) - the nearest vein; n - number of measurements

Table 1b: Fluid inclusion data of vein quartz samples.

Sample locality	Homogenization temperature (°C)					Concentration (NaCl equiv. wt. %)
	n	min.	max.	average ± s.d.	T _{rec}	
Helén-vein	18	176	193	184±5	193	0.28
Helén-vein	22	182	213	203±7	208	0.43
András-vein	23	186	211	198±7	189	1.64
András-vein	26	207	245	224±5	226	1.17
András-vein	20	215	237	230±5	223	0.97
András-vein	16	181	204	188±5	153	2.98
János-vein	10	188	206	195±5	186	0.86
János-vein	25	207	237	227±9	223	1.38
János-vein	19	238	251	242±4	235	1.17
János-vein	18	180	201	191±7	170	2.39
János-vein	12	204	220	208±4	189	2.11
Ilona-vein	12	210	221	216±3	197	0.30
Medve-vein	10	198	253	228±16	226	3.01
Medve-vein	9	130	145	138±5	137	-
Lobkowitz-vein	16	172	199	182±6	203	1.69
Lobkowitz-vein	15	163	199	179±9	177	4.31
Lobkowitz-vein	12	160	179	170±7	177	2.65
Lobkowitz-vein	20	187	277	211±17	226	0.87
Józerencsét-vein	37	178	238	205±10	235	3.52
Józerencsét-vein	22	150	236	200±8	225	2.89
Brenner-vein	13	191	198	196±1	227	0.91
Brenner-vein	20	195	228	217±8	228	1.06
Jupiter-vein	21	202	232	216±7	248	2.43
Jupiter-vein	20	202	229	213±7	240	3.17
Névtelen-vein	18	228	243	243±4	248	1.82
Névtelen-vein	20	214	233	228±4	237	2.60
Glück-auf-vein	14	241	261	250±5	246	1.13
Glück-auf-vein	18	239	266	248±5	248	2.17
Fehér-hegy-vein	18	223	263	240±10	250	2.59
Fehér-hegy-vein	12	173	220	197±13	193	3.00

n - number of measurements; T_{rec} - average homogenization temperatures recalculated to +450 m elevation**Table 1c:** Fluid inclusion data on adularia, calcite and sphalerite samples.

Mineral	Sample locality	Homogenization temperature (°C)				Concentration (NaCl equiv. wt. %)
		n	min.	max.	average ± s.d.	
Adularia	Glück-Auf vein	17	254	270	260±5	3.53
Adularia	Névtelen-vein	17	239	257	248±4	3.20
Adularia	August-Freud vein	12	227	234	232±2	3.32
Adularia	Lobkowitz vein	13	237	256	245±6	3.08
Calcite	Glück-Auf-vein	20	200	259	248±8	2.56
Calcite	August-Freud-vein	20	187	246	228±10	1.84
Sphalerite	Lobkowitz-vein	14	245	252	248±3	3.85
Sphalerite	Lobkowitz-vein	13	241	250	246±3	4.41

n - number of measurements

Interpretation of microthermometric data

Effect of boiling on the composition of fluids

Fig. 6 shows the correlation between average apparent salinity and average homogenization temperatures. The distribution of the data points suggests that the apparent salinity of the initial, high temperature fluids was about 3–4 NaCl equiv. wt. %. These solutions were trapped mostly in the fluid inclusions of sphalerite and adularia. The euhedral and vein-filling quartz was precipitated from cooler and more dilute solutions.

The decreasing apparent salinity values accompanied by decreasing homogenization temperatures generally indicate the mixing of high temperature saline fluids with low temperature diluted solutions. In contrast to this, boiling usually increases the salinity of fluids (Shepherd et al. 1985). According to the fluid inclusion petrography, there is an evidence suggesting that the euhedral quartz crystals were deposited from boiling solutions. However, the inclusions in euhedral quartz have, in general, lower average salinities than the high temperature, initial fluids (Fig. 6).

The apparent salinity data of fluid inclusions of various minerals from the Telkibánya ore deposit were calculated on the basis of ice melting temperatures. However, the presence of CO₂ was also detected, mostly in the fluid inclusions of euhedral quartz (Fig. 5). The dissolved CO₂ also effects the melting point depression of inclusion liquid (Hedenquist & Henley 1985).

Fig. 6 also shows a "boiling + gas loss curve" which was calculated on the basis of a method suggested by Hedenquist et al. (1992). For the calculation it was assumed that the initial concentration of CO₂ was 0.81 mol/kg at 245 °C in a solution with 0.09 mol/kg (0.5 NaCl equiv. wt. %) of dissolved NaCl. The fitting of this curve with the data points indicates, that degassing of CO₂-bearing boiling fluids occurred in some parts of the paleohydrothermal system of the Telkibánya ore deposit.

Beside the gas-loss trend connected to the boiling of dilute solutions, a simple mixing trend can also be outlined on the Fig. 6. This probably indicates that some of the vein filling quartz precipitated below the boiling horizon of solutions, and the parent fluid of these vein infillings did not lose its minor CO₂-content (see the frequency maximum of vein quartz samples on Fig. 5).

Paleodepth estimations

The saturated vapour pressure of hydrothermal fluids is equal to or larger than the hydrostatic load in boiling conditions. Therefore it is possible to calculate the pressure and paleodepth if the data on temperature, salinity and gas concentration of a boiling fluid are known (Haas 1971, 1976; Bodnar et al. 1985).

Evidence for fluid boiling is based on the coexistence of vapour-rich and liquid-rich inclusions in the euhedral quartz samples. On the other hand, the fitting of the calculated "boiling + gas loss curve" with the inclusion data on Fig. 6 also indicates that the boiling took place in the paleohydrothermal system of the Telkibánya deposit.

Fig. 7 shows the elevation of sampling points as a function of average homogenization temperatures of various quartz samples. Some of the data points are distributed between the boiling point curves for pure water (B.P.C. a and b) calculated with the assumption that the ground water table was situated between 740 m and 800 m elevation. The difference between the boiling point profiles of pure water and very dilute NaCl-solutions can be neglected in this case. Fig. 7 also shows the boiling point curve calculated for a CO₂-bearing fluid with the same composition as the CO₂-bearing model fluid on Fig. 6. This "boiling+gas loss" curve on Fig. 7 (B.P.C. c) also fits in with some of the data points distributed between the boiling curves of pure water. It can thus be concluded that the boiling of fluids occurred 200 to 440 m below the ground water table in the hydrothermal system of the deposit.

Some of the data points on Fig. 7 project below the calculated boiling curves. This indicates that the temperature of the fluids was below the boiling temperature at these sampling points. It can be assumed that within these areas, mostly in the western and marginal areas of the ore field, the paleogeothermal gradient had a linear character - 25 °C/100 m - instead of the non-linear gradient for boiling fluids. Similar distributions of data points were observed on the temperature-depth profiles in the Broadlands, New Zealand (Hedenquist 1990) and Hatchobaru, Japan (Taguchi & Nakamura 1991) geothermal systems.

The reconstruction of the paleotemperature distribution

Fluid inclusions in euhedral quartz collected from various areas of the mineralization display nearly the same mode of homogenization temperatures (Fig. 8; Tab. 1a). This observation suggests that the deposition of euhedral quartz occurred at nearly similar temperatures. The nearly isothermal nature of the CO₂-bearing boiling system in the highly porous (brecciated or miarolitic) zones of wall rocks along or in the upper zones of veins with the temperatures close to the maximum enthalpy of steam (234 °C) suggests that these portions of the system may have been vapour dominated (White et al. 1971). The occurrence of advanced argillic alteration (kaolinite-alunite) along the upper zones of some veins was genetically related to this stage, due to the possibility of the development of an acid sulphate fluid regime during the condensation of gas-rich steam in ground waters (Hedenquist 1987).

The distribution of homogenization temperatures measured in fluid inclusions of vein-filling quartz from various parts of the same vein have several maxima in some cases (Fig. 8) indicating that the isotherms for hydrothermal fluids along the veins were not horizontal. However, the differences between the homogenization temperatures of vein quartz samples are also influenced by the level differences of sampling. This in-

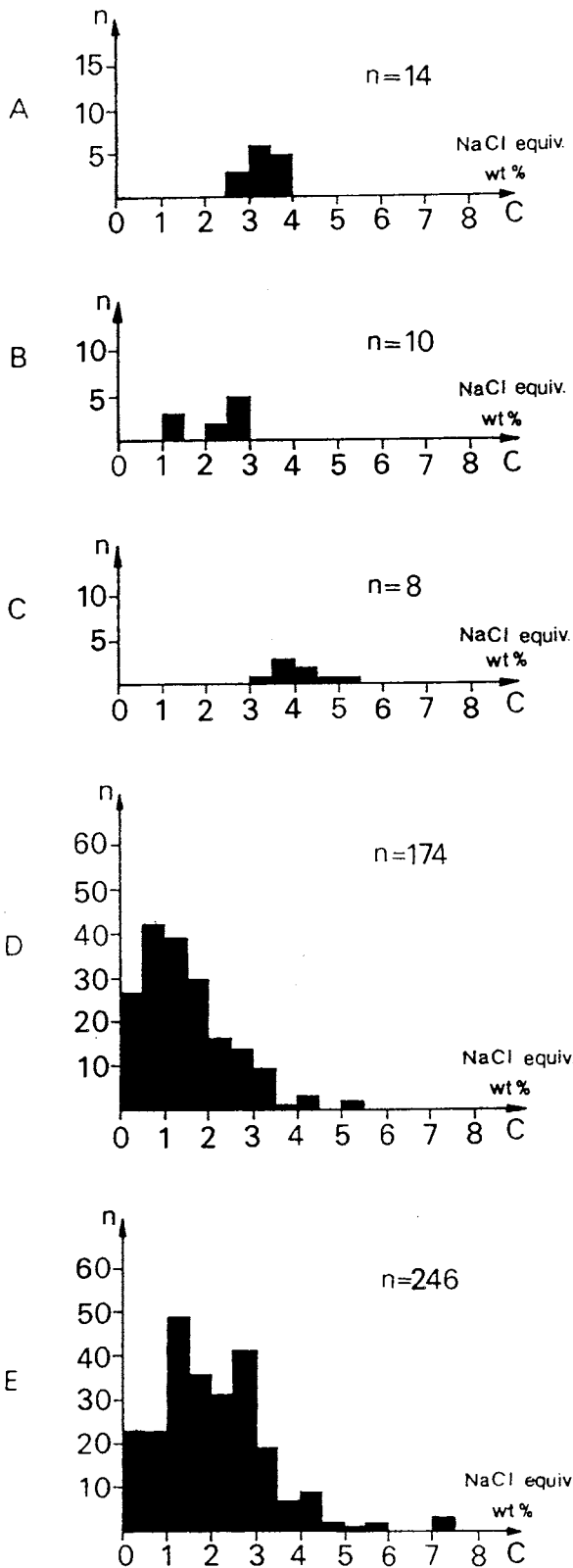


Fig. 4. Distribution diagrams of concentration data (NaCl equiv. wt %) determined in fluid inclusions of various minerals from the Telkibánya ore deposit. A, B, C etc. - see the explanation of Fig. 3.

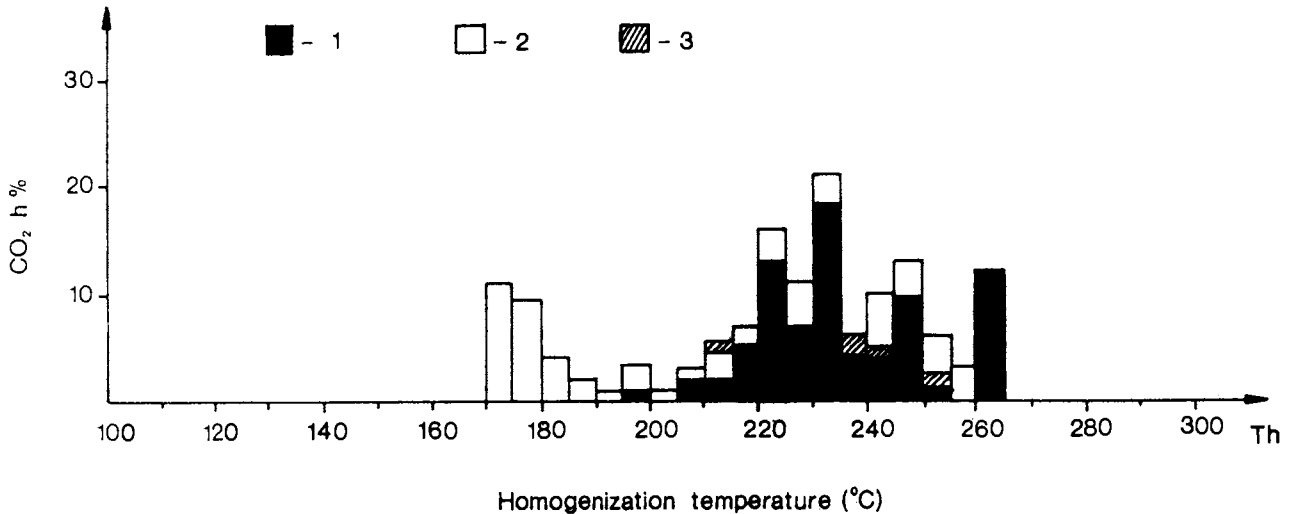


Fig. 5. Homogenization temperatures of CO_2 -bearing inclusions. CO_2 h % - percentage of inclusions characterised by the occurrence of a CO_2 -hydrate phase during freezing measurements. 1 - Euhedral quartz. 2 - Vein-filling quartz. 3 - Calcite.

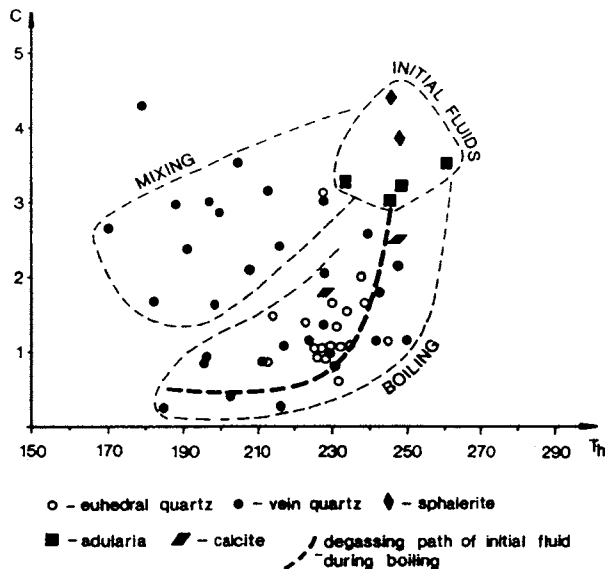


Fig. 6. Distribution of average apparent salinity data (C, NaCl equiv. wt. %) as a function of average homogenization temperatures (T_h , °C). Bold dashed line: the calculated "boiling + gas loss" curve (see text).

fluence can be corrected by the recalculation of temperature data for a nominated level through the mineralization using the boiling curves for the samples deposited from boiling fluids, and a linear paleogeothermal gradient value - $25^\circ\text{C}/100\text{ m}$ - for other samples (Fig. 7).

The average homogenization temperatures of vein-filling quartz samples recalculated to 450 m elevation are also seen in Tab. 1b. In most cases the standard deviation from the average homogenization temperatures are less than $\pm 10^\circ\text{C}$. It is therefore reasonable to construct an isothermal map using a 20°C interval.

The paleotemperature map of the 450 m elevation reconstructed by the method outlined above is shown on Fig. 9, which also shows the positions of volcanic centres and fault systems. The paleohydrothermal system of the Telkibánya ore deposit was probably not related to the volcanic centres as recognized

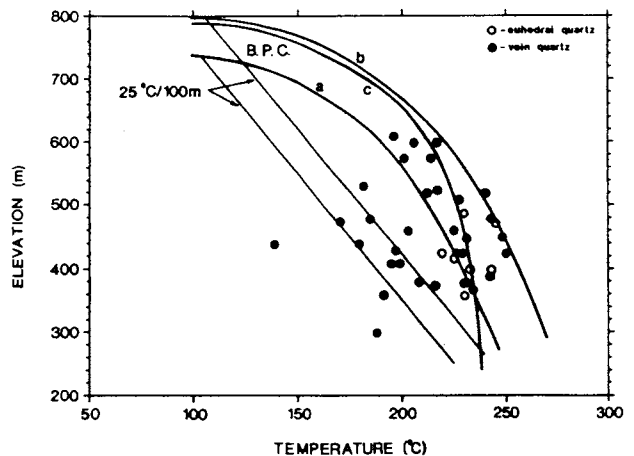


Fig. 7. Average homogenization temperatures of vein and euhedral quartz samples versus its elevation. B.P.C. - Bubble point curves for pure water (a and b) and CO_2 -bearing dilute solution (c) with the same composition as the model fluid on Fig. 6. The distribution of the majority of sample points between or along the bubble point curves suggests that the paleodepth of hydrothermal activity was between 200 and 400 m below the water table at the Telkibánya ore deposit.

on the surface. Some of the thermal anomalies however are aligned along major faults and the largest high paleotemperature area ($T > 220^\circ\text{C}$) occurs close to the intersection of faults trending NNW-SSW and ENE-WSW. On the other hand, this high paleotemperature area is situated above a slight positive gravity anomaly (Fig. 10), probably indicating a subvolcanic mass. The spatial coincidence between the paleotemperature and gravity anomalies suggests that the heat source of the hydrothermal system may have been a subvolcanic intrusion situated below the eastern part of the ore field.

Conclusions

The fluid inclusion characteristics of the Telkibánya ore deposit are similar to those of other adularia-sericite type epither-

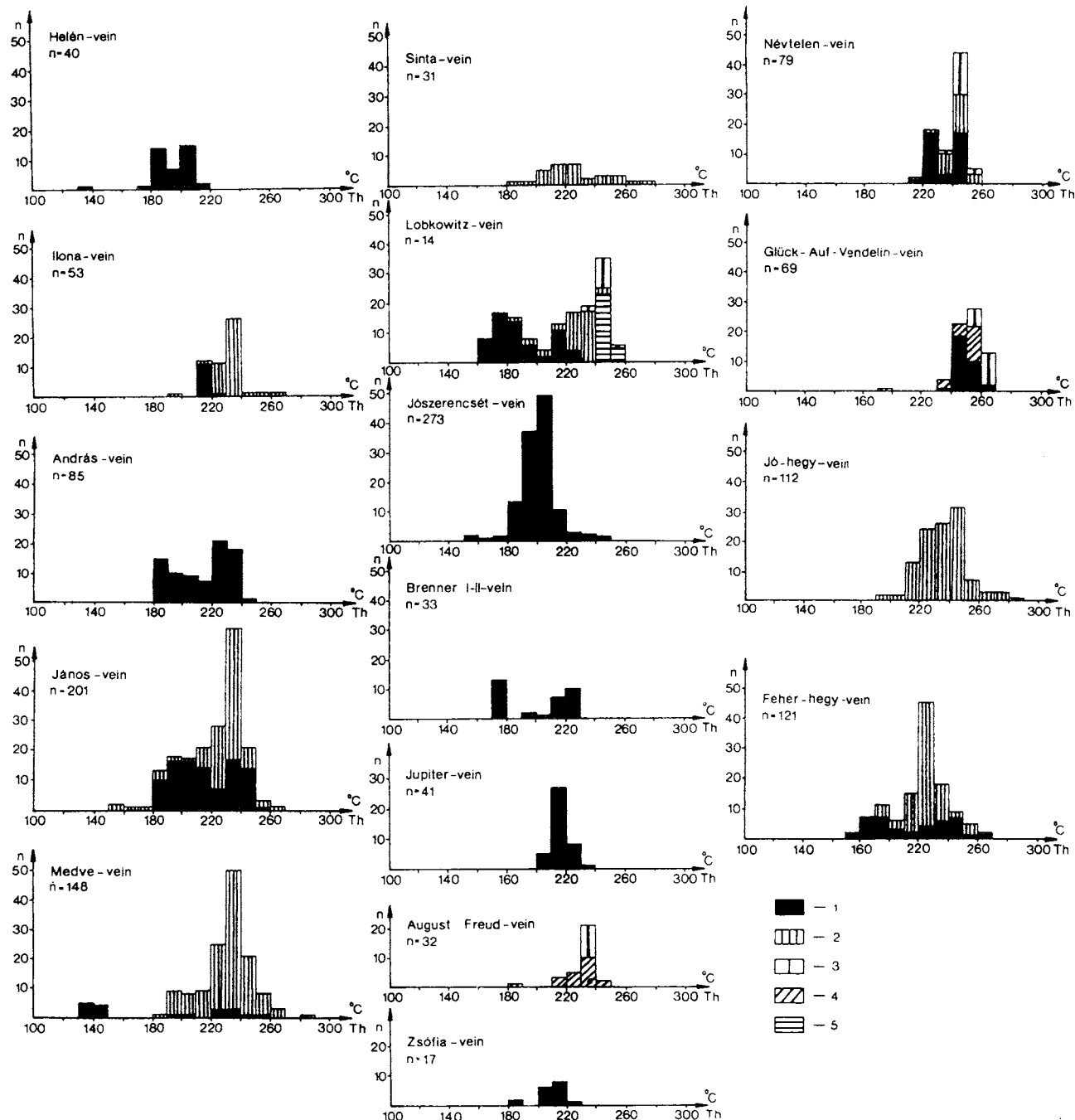


Fig. 8. Distribution diagrams of homogenization temperatures (T_h) measured in various veins. 1 - Vein filling quartz. 2 - Euhedral quartz. 3 - Adularia. 4 - Calcite. 5 - Sphalerite. n - number of measurements.

mal deposits (Hayba 1983; Hayba et al. 1985; Hedenquist & Henley 1985). The temperature of the diluted hydrothermal solutions varied between 270 and 130 °C. The apparent salinity of fluids was below 5 NaCl equiv. wt. %, and the calculated CO₂-content of the initial (high temperature) solutions was about 0.8 mol/kg. The intensive boiling of CO₂-rich fluids may have led to the development of a vapour-dominated system with a temperature about 230 °C. The estimated depth of this system was about 200–440 m below the paleowater table.

The deposition of the euhedral quartz crystals in the vugs of intensively altered rocks and breccias was genetically related to the boiling, vapour-dominated stage. The majority of vein-filling quartz aggregates were deposited later (at lower

temperatures), though some were crystallized together with adularia, calcite and sphalerite before the development of vapour-dominated system.

In contrast with the vapour-dominated system in the highly permeable wall rocks and breccias which had a temperature about 230 °C, the temperature of the liquid responsible for the vein deposition was variable. On the basis of the spatial distribution of average homogenization temperatures of vein-filling quartz recalculated to the 450 m elevation, there appears to have been one major and two smaller thermal maxima within the mineralized area. Combining the paleotemperature and volcano-tectonic maps it may be concluded, that the main conduits of the hydrothermal solutions were the major tectonic lines. The

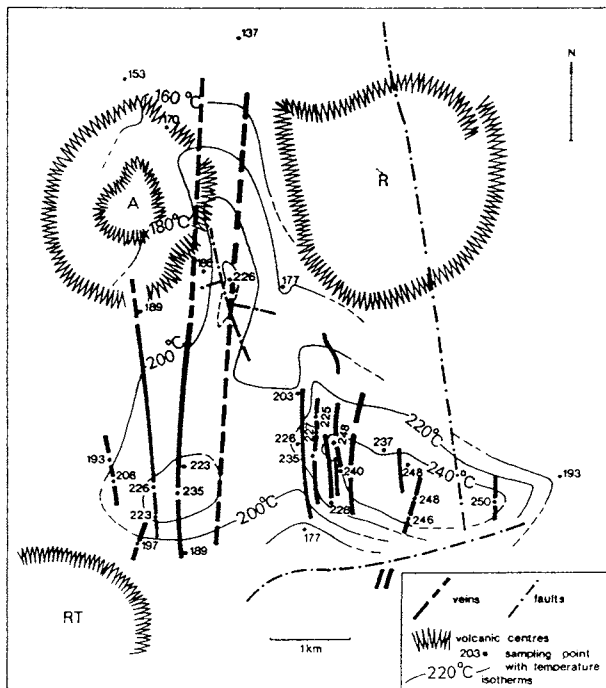


Fig. 9. Position of the paleothermal field in relationship to the volcanic centers and major faults (also see Fig. 1.) in the area of Telkibánya. The isotherms were drawn by the use of the average homogenization temperature data of vein filling quartz samples recalculated to +450 m elevation.

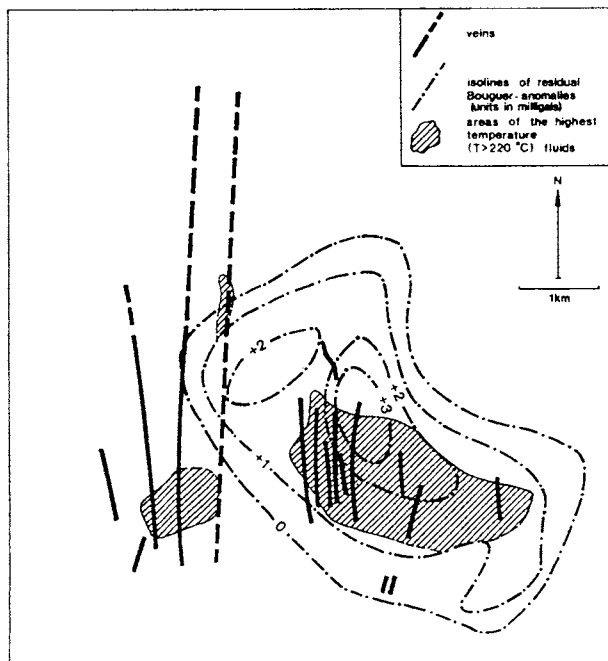


Fig. 10. Superimposition of the residual Bouguer-anomalies (only the positive values are drawn) onto the highest temperature area ($T > 220^\circ\text{C}$, shaded area) shown in Fig. 9. The gravity anomaly map was compiled by the Eötvös Loránd Geophysical Institute, Budapest ($d = 2\text{ g/cm}^3$, radius = 2.5 km).

heat source of the hydrothermal convection was most likely generated by a subvolcanic intrusion indicated by the slight positive gravity anomaly below the largest high temperature area in the eastern part of the ore field.

The results of fluid inclusion studies in the Telkibánya area also demonstrate that paleotemperature mapping is useful to delineate the thermal centres in an epithermal system. The combination of the temperature map with the volcanotectonic and geophysical data helps to outline the role of the fault systems in the circulation of hydrothermal fluids and points to the location of the heat source. Thermal centres are the most favourable areas for further exploration activity.

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References

- Albinson T.F., 1988: Geologic reconstruction of paleosurfaces in the Sombrerete, Colorado and Fresnillo districts, Zacatecas State, Mexico. *Econ. Geol.*, 83, 1647-1667.
- Benke I., 1988: Mining history of Telkibánya. *Közlemények a magyarországi ásványi nyersanyagok történetéből* III. Miskolc, NME Kiadvány, 97-128.
- Berger B.R. & Bethke P.M. (Eds.), 1985: Geology and geochemistry of epithermal systems. *Reviews in Econ. Geol.*, 2, 1-298.
- Bodnar R.J., Reynolds T.J. & Kuehn C.A., 1985: Fluid inclusion systematics in epithermal systems. In: Berger B.R. & Bethke P.M. (Eds.): *Geology and geochemistry of epithermal systems. Reviews in Econ. Geol.*, 2, 73-88.
- Collins P.L.F., 1979: Gas hydrates in CO_2 -bearing fluid inclusions and the use of freezing data for estimation of salinity. *Econ. Geol.*, 74, 1435-1444.
- Gatter I., 1983: Fluid inclusion studies of ore mineralizations in W-Mátra Mts. *Unpubl. Univ. Doct. Thesis, Eötvös L. Univ.*, Budapest, 1-85 (in Hungarian).
- Gatter I., 1984: Ore prospecting and genetical evaluation of mineralizations of Hungary based on fluid inclusion studies. *Unpubl. Research Report, Dept. of Mineralogy, Eötvös L. Univ.*, Budapest, (in Hungarian).
- Gatter I., 1985: Ore prospecting and genetical evaluation of mineralizations of Hungary based on fluid inclusion studies. *Unpubl. Research Report, Dept. of Mineralogy, Eötvös L. Univ.*, Budapest (in Hungarian).
- Gyarmati P., Perlaki E. & Pentélnyi L., 1976: Geological map of the Tokaj Mts. *Published by The Hung. Geol. Inst.*, Budapest.
- Gyarmati P., 1977: Intermediate volcanism in the Tokaj Mts. *Annals of the Hung. Geol. Inst.*, LVIII, 1-196.
- Haas J.L., 1971: The effect of salinity in the maximum thermal gradient of a hydrothermal system at hydrostatic pressure. *Econ. Geol.*, 66, 940-946.
- Haas J.L., 1976: Physical properties of the coexisting phases and thermochemical properties of the H_2O component in boiling NaCl solutions. *U.S. Geol. Surv. Bull.*, 1421-A, 73.
- Hajdú L., 1987: Studies on the Telkibánya ore deposit by means of modern methods. *Unpubl. MSc Thesis, Eötvös L. Univ.*, Budapest, 1-87 (in Hungarian).
- Hayba D.O., 1983: A compilation of fluid inclusion and stable isotope

- data on selected precious- and base-metal deposits. *U.S. Geol. Surv. Open-File Report*, 83-450, 24.
- Hayba D.O., Bethke P.M., Heald P. & Foley N.K., 1985: Geologic, mineralogic, and geochemical characteristics of volcanics-hosted epithermal precious-metal deposits. In: Berger B.R. & Bethke P.M. (Eds.): *Geology and geochemistry of epithermal systems. Reviews in Econ. Geol.*, 2, 129-168.
- Hedenquist J.W., 1987: Mineralizations associated with volcanic-related hydrothermal systems in the Circum-Pacific basin. *Transactions of the 4th Circum-Pacific Energy and Mineral Resources Conference*, Singapore, Honkong, 513-524.
- Hedenquist J.W., 1990: The thermal and geochemical structure of the Broadlands-Ohaaki geothermal system, New-Zealand. *Geothermics*, 19, 151-185.
- Hedenquist J.W. & Henley R.W., 1985: The importance of CO₂ on freezing point measurements in fluid inclusions: evidence from active geothermal systems and implications for epithermal ore deposition. *Econ. Geol.*, 80, 1379-1406.
- Hedenquist J.W., Reyes A.G., Simmons S.F. & Taguchi S., 1992: The thermal and geochemical structure of geothermal and epithermal systems: A framework for interpreting fluid inclusion data. *Europ. J. Mineral.*, 4, 989-1015.
- Henley R.W. & Ellis A.J., 1983: Geothermal systems ancient and modern: a geochemical review. *Earth-Sci. Reviews*, 1, 1-50.
- Henley R.W., Truesdell A.H., Barton Jr., P.B. & Whitney A.J. (Eds.), 1984: Fluid-mineral equilibria in hydrothermal systems. *Reviews in Econ. Geol.*, 1, 267.
- Horváth J., 1990: Research report about the studies of the old mines and their geological characteristics in the surroundings of Telkibánya. *Unpubl. Research Report. Central Geol. Office of Hungary* (in Hungarian).
- Horváth J., Zelenka T. & Fegyvári T., 1989: Paleovolcanic structures in the North-Tokaj Mountains interpreted on the basis of satellite imagery and aerial photography. *Acta Geol. Hung.*, 32, 1-2, 183-190.
- Izawa E., Taguchi S., Kobayashi T. & Watanabe K., 1992: Gold mineralization in volcano-geothermal areas of Kyushu. *Guide to 29th Internat. Geol. Congr. Field Trip C33*, 143-172.
- Kwak A.P.T., 1990: Geochemical and temperature controls on ore mineralization at the Emperor gold mine, Vatukoula, Fiji. *Journ. of Geochem. Explor.*, 36, 297-337.
- Molnár F., 1986: Morphological-genetical studies of quartz crystals occurring in Paleogene-Neogene ore mineralizations of Hungary. *Unpubl. MSc.Thesis. Dept. of Mineralogy, Eötvös L. Univ., Budapest*, 1-85 (in Hungarian).
- Pantó G., 1968: Structural-volcanological relationship between the Tokaji Mts. and its surroundings. *Annual Report of the Hungarian Geol. Inst. of 1964*, 215-225.
- Potter R.W., Clynne M.A. & Brown D.L., 1978: Freezing point depression of aqueous sodium chloride solutions. *Econ. Geol.*, 73, 284-285.
- Poty B., Leroy J. & Jachimowitz L., 1976: A new device for measuring temperatures under the microscope: the Chaixmeca microthermometry apparatus. *Fluid. Incl. Research Proc. of COFFI*, 9, 173-178.
- Roedder E., 1984: Fluid inclusion. *Reviews in Mineralogy*, 12, 1-644.
- Shepherd T., Rankin A.H. & Alderton D.H.M., 1985: A practical guide to fluid inclusion studies. *Blackie and Son Ltd.*, Glasgow, 1-239.
- Szakáll S., Molnár F., Kovács Á. & Dódy I., in press: Sulphide minerals of the Telkibánya ore deposit. *Topographia Mineralogica Hungariae*, II (in Hungarian).
- Székely-Fux V., 1970: The Telkibánya mineralization and its Intra-Carpathian connections. *Akadémiai Kiadó*, Budapest, 1-266 (in Hungarian).
- Taguchi S. & Nakamura M., 1991: Subsurface thermal structure of the Hatchobaru geothermal system, Japan, determined by fluid inclusion study. *Geochemical J.*, 25, 301-314.
- Vikre P.G., 1989: Fluid-mineral relations in the Comstock Lode. *Econ. Geol.*, 84, 1574-1613.
- White D.E., Muffler L.J.P. & Truesdell A.H., 1971: Vapor-dominated hydrothermal systems compared with hot-water systems. *Econ. Geol.*, 66, 75-97.