

CHARACTERISTICS OF VARISCAN AND PALAEOGENE FLUID MOBILIZATION AND ORE FORMING PROCESSES IN THE VELENCE MTS., HUNGARY: A COMPARATIVE FLUID INCLUSION STUDY

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ABSTRACT

The Variscan S-type intrusive granite and Palaeogene intermediate subvolcanic-volcanic environment are characterised by intense mineralization in the Velence Mts. Pegmatite, quartz-molybdenite stockwork, and base-metal-fluorite vein mineralization of granite were formed at 1–2.5 kbar pressure at 300–550 °C, around 300 °C and 150–300 °C, respectively. Occasional immiscibility of carbonic aqueous fluids occurred during molybdenite deposition. Cu-porphry, copper bearing breccia and high sulphidation type epithermal mineralization related to Palaeogene igneous activity were formed in low-pressure (20–300 bar) boiling hydrothermal system at 350–450 °C and 250–350 °C. In the Variscan granite-related fluid circulation, early (pegmatitic) fluids had low salinities and late vein-forming solutions had higher salinities with enrichment of Ca. This trend is interpreted as incursion of basin (formational) waters into the granite-related hydrothermal system. Hydrothermal circulation at subvolcanic level in the Palaeogene system was characterised by co-existence of high- and low-salinity fluids due to boiling, and fluids in the low temperature epithermal zones had low salinities. Decrease of salinity with temperature is interpreted as dilution of hydrothermal fluids by meteoric water. Fluid inclusion petrography and microthermometry proved that the eastern zones of the granite body were overprinted by the younger hydrothermal event. Fluid inclusion studies may support the establishment of temporal and spatial evolution of fracture systems not only in the granite of the Velence Mts. but other granitoid areas of Hungary.

Key words: Variscan granite, Palaeogene volcanics, fluid inclusions, fluid evolution, fluid overprint

INTRODUCTION

The Velence Mountains consist of about 200 km² of outcrops of Paleozoic granitoid and Paleogene intermediate volcanic rocks (Fig. 1) in the central part of the Transdanube region of Hungary. The S-type Variscan (280–300 Ma) post-collision biotitic monzogranite intrusion (Buda, 1985) and its granite-porphry and aplite dikes in the western part of the Velence Mts. is hosted by Palaeozoic shales that show contact metamorphism along the igneous body (Jantsky, 1957). The monzogranite crystallized at about 520–700 °C from a water-saturated eutectic melt at an estimated pressure of about 2 kbar (Buda, 1985, 1993). Very few and thin monchiquite-spessartite and carbonatite dikes of Cretaceous age also occur in the granitoid intrusion (Horváth and Ódor, 1984). Calc-alkaline andesitic rocks (lava flows and pyroclastic deposits) of Palaeogene age (Upper Eocene–Lower Oligocene) crop out in the eastern part of the Velence Mts. (Fig. 1). Exposures of the highly altered andesitic rocks form a half circle which probably represents an eroded southern remnant of a caldera-like palaeovolcanic centre. The section of the 1200 m deep Pd-2 drillhole proves the presence of a subvolcanic diorite intrusion beneath the semi-circular structure.

The area of Palaeogene volcanic rocks is separated from the Variscan granitoid intrusion along a NW-striking fault (Nadap–Lovasberény fault); however, dikes and small stocks with andesitic composition of Palaeogene age also transect the granitoid body.

Both the Variscan granitoid and the Alpine volcanic rocks display intense hydrothermal alteration and various ore

mineralization. Therefore the relatively small area of the Velence Mts. is an excellent target for a comparative study of the nature of hydrothermal processes related to Variscan and Alpine magmatic systems developed at different depths. This paper describes the physicochemical state (temperature, pressure, composition) of the magmatic-hydrothermal systems of the Velence Mts. on the basis of fluid inclusion microthermometric analyses. Data are also used to demonstrate that Palaeogene fluid circulation also invaded the Variscan granitoid intrusion.

MINERALIZATION RELATED TO THE VARISCAN MONZOGRANITE

Pegmatite occurs as pocket- and vein-like bodies with up to a few cubic metres volume in all parts of the Variscan monzogranite intrusion (Jantsky, 1957). Their primary mineral assemblage mostly consists of quartz, K-feldspar, plagioclase, biotite and muscovite. Widely distributed miarolitic cavities are also characterised by similar mineralogy, though occurrences of tourmaline, garnet, molybdenite, apatite, epidote, fayalite and grünerite accessories have also been reported at some localities (Nagy, 1967; Buda, 1993).

Quartz-tourmaline metasomatic-stockwork mineralization occurs along the contact zone between the intrusion and Palaeozoic shales (Vendl, 1923; Jantsky, 1957). In those tourmaline-rich zones, veinlets also contain native gold, molybdenite, as well as wolframite and scheelite showings at some places (Böjtös-Varrók, 1966, 1967).

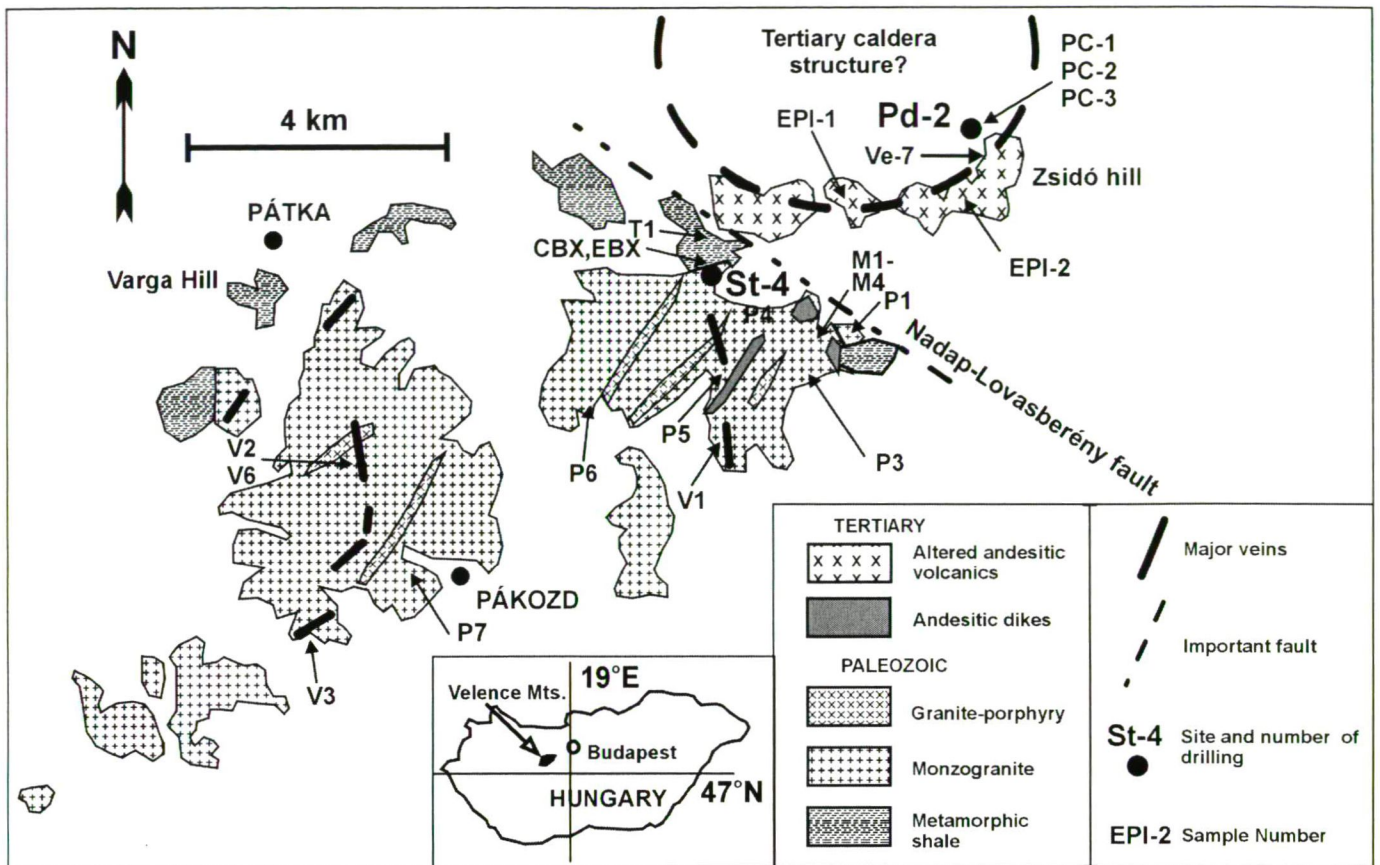


Fig. 1. Geological sketch-map of the Velence Mts. with locations of samples. P1...P7 – samples from pegmatite; M1...M4 – samples from the quartz-molybdenite mineralization; T1 – sample from the quartz-tourmaline mineralization; V1...V6 – samples from the base-metal-fluorite veins; PC1...PC3 – samples from the Cu-porphry mineralization of the Pd-2 drillhole; EPI-1, EPI-2 – samples from the high sulphidation type epithermal mineralization; CBX, EBX – samples from the enargite and chalcopyrite bearing breccia.

Quartz-molybdenite stockwork mineralization occurs along the eastern margin of the monzogranite body (Fig. 1) and it is hosted partly by the intrusion and partly by the metamorphosed shale, the host rock of the Variscan intrusion (Jantsky, 1957). The ore was explored in an inclined adit and results proved that it is non-economic with an average grade of 0.03% Mo (Jantsky, 1957). In the siliceous veinlets, molybdenite is associated with pyrite, pyrrhotite, galena, sphalerite, Zn-rich tetrahedrite, chalcopyrite and marcasite (Tokody, 1944; Jantsky, 1957; Molnár, 1997). Host rocks show weak silicic, kaolinitic, sericitic and chloritic alteration along the veinlets.

Quartz-fluorite-barite-sulphide veins are widely distributed in the monzogranite intrusion (Fig. 1). The width of veins is up to several meters and they can be followed for a few hundred meters along their most typical northeast-southwest and north-south strike-directions. Orientation of veins largely parallels with the strike-direction of granite-porphry and aplite dikes. Outcrops of these veins are leached due to weathering and show vuggy-cellular structure of fine-grained quartz with numerous secondary minerals (Koch, 1985). Below the oxidation zone, the most common sulphide minerals of collomorph-banded and brecciated veins consist of sphalerite, galena, pyrite, chalcopyrite, grey ore minerals and stibnite. Monzogranite along the veins has been subjected to beresitic alteration (intense silicification with sericitic K-feldspar and chloritic biotite; Kiss, 1954).

Sulphide ores from the veins were mined near Pátka in the northern parts of the Velence Mts (Fig. 1) where the grade of ore was 1.23% Pb and 4.81% Zn. Barite is a common gangue mineral in some veins only (southern part of the Meleg Hill, Fig. 1; Erdélyi, 1939, 1952), and mostly in their shallow parts. Fluorite forms abundant masses of coarse grained pinkish and greenish aggregates in some veins especially north of Pákozd (Fig. 1); it was exploited during the 1950s. Total production was 8040 tonnes of high grade (92–95% CaF₂) and 10 573 tonnes of low grade (10–20% CaF₂) fluorite (Jantsky, 1966). On the basis of REE content of fluorite Horváth et al. (1989) suggested that its deposition may also be related to a hydrothermal activity during emplacement of monchiquite-spessartite and carbonatite dikes of Cretaceous age. However, those dikes are not widespread and are very thin with no alteration around them in the granite; thus it is unlikely that the weak Mesozoic magmatic event may have generated important hydrothermal activity resulting in formation of several metres thick fluorite veins.

MINERALIZATION RELATED TO PALAEOGENE ANDESITIC VOLCANISM

Porphyry-copper type mineralization occurs at 880 to 1070 m depth in the Pd-2 drillhole (Fig. 1) in a subvolcanic intrusion of diorite composition. The host diorite is characterised by potassium-silicate (K-feldspar, phlogopite,

sericite) and propylitic (epidote, chlorite) alteration (Darida-Tichy, 1987). Quartz stockwork contains pyrite, chalcopyrite and sphalerite. Disseminated ore consists of chalcopyrite, bornite, pyrite, magnetite and ilmenite in strongly silicified zones. Locally, at 670 m depth, minor skarn with andradite, epidote, quartz and pyrite is also present.

High sulphidation type epithermal mineralization is widespread in the outcrops of the remnants of the eroded volcanic sequence in the eastern part of the Velence Mts. (Fig. 1). Hydrothermal centres are characterised by irregular and mushroom-shaped massive and vuggy silica bodies surrounded by alunite-kaolinite and pyrophyllite-dickite-kaolinite-diaspore-alunite alteration (Darida-Tichy, 1987). Occurrences of topaz, zunyite and native sulphur are also known in the alteration zones (Nemecz, 1979). Silica bodies are brecciated and contain abundant secondary iron minerals. Non-weathered silica masses are characterised by abundant pyrite dissemination. Alunite crystals from the alteration zones are sodium-rich and contain phosphorus minerals (schwanbergite-woodhausite) in their cores (Vendl, 1931; Bajnóczi et al., 2002).

Siliceous breccia bodies with copper mineralization also occur along an E–W striking contact zone of granite and shale in the eastern part of the Velence Mts., close to the Tertiary volcanic field (Fig. 1). Typical sulphides in those breccias occurring as several metres wide dike-like bodies on the surface, as well as few centimetre thick veinlets in

drillcores, are pyrite, enargite, chalcopyrite and grey ore minerals. Breccia fragments consist of silicified granite and shale with variable size up to 10–20 centimetres and angular shapes. Fragments are cemented by grey silica, though open vugs between them are also present. Kubovics (1958) related this type of mineralization to the Tertiary volcanism. The occurrence of enargite, that is a typomorphic mineral in high sulphidation type epithermal systems (Hedenquist and Arribas, 1999) and the proximity of the mineralization to the Tertiary hydrothermal fields (Fig. 1) also support that conclusion.

RESULTS OF FLUID INCLUSION STUDIES

Fluid inclusion petrography

Comparative fluid inclusion petrography of quartz and fluorite from various mineralization of the Velence Mts. revealed important differences in the state and composition of fluids during the Variscan and Alpine hydrothermal activities (Fig. 2). The most common type of primary and secondary fluid inclusions from the granite-related mineralization consists of about 5 to 30 vol.% vapour phase in the aqueous liquid phase. In addition to this type of inclusions, the quartz-molybdenite mineralization is also characterised by the presence of carbonic-aqueous fluid inclusions with variable aqueous liquid to carbonic liquid or carbonic vapour ratios. This latter inclusion association suggests phase-separation processes at a relatively high

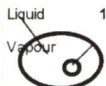




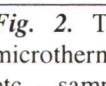
Type of inclusion	Phase composition	Pegmatite in granite	Quartz-molybdenite stockwork in granite and shale	Quartz-tourmaline veinlets in shale	Base metal and fluorite veins in granite	Cu-porphyry showings in subvolcanic diorite	Chalcopyrite bearing breccia vein in granite	Enargite bearing breccia/granite/shale contact	High-sulphidation type alteration zones in andesite
		P1, P2, P3, P4, P5, P6, P7	M1, M2, M3, M4	T1	V1, V2, V3, V6	PC-1, PC-2, PC-3	CBX	EBX	EP-1, EP-2
 1a	L+V V<10%	S 90-180°C 6 - 23 CaCl ₂	-	-	S-P 80-140°C 10 - 25 CaCl ₂ S-P 170-210°C 7 - 21 NaCl F - P 110-160 1 - 10 NaCl	-	-	-	-
 1b	L+V V=10-30%	S-P 90-250°C 2 - 20 NaCl S 320-350°C (*) 0-2 NaCl P 320-370°C 3 - 4 NaCl	S 220-280°C S 280-320°C 1 - 6 NaCl 8 - 14 NaCl	S 240-300°C (*) S 330-390°C (*) 0 - 1 NaCl	-	S 270-370°C 13 NaCl - 24 NaCl+CaCl ₂	S 260-360°C 1 - 21 NaCl	S 210-400°C 1-21 NaCl	S-P 310-380°C S 220-290°C 1 - 13 NaCl
 1c	L+V V=40-60%	S present (*) (sample P1)	-	-	-	-	S-P 400-410°C 3-5 NaCl	S-P 370-450°C 1-8 NaCl	-
 1d	L+V V>80%	S present (*) (sample P1)	-	S 340-380°C (*)	-	S-P 360-500	S-P 400-460°C	S-P 310-440°C	S-P 280-290°C
 2	L+V+H (+Sy+X) V=10-30%	-	-	-	-	S-P 270-520°C 31 NaCl - 79 NaCl+KCl	S-P 410-450°C 26 - 40 NaCl	S-P 260-450°C 26 - 40 NaCl	-
 3	Laq+LCO ₂ (+VCO ₂) LCO ₂ = 40-90%	-	S-P 280-300°C 0-11 NaCl	-	-	-	-	-	-

Fig. 2. Types of fluid inclusions according to their phase compositions observed at room temperature and their microthermometric data in various post-magmatic and hydrothermal mineralization of the Velence Mts. Abbreviations: P1, P2 etc. – sample numbers (see localities of samples on Fig. 1); L – aqueous liquid; LCO₂ – carbonic liquid; V – vapour; VCO₂ – carbonic vapour; H – halite; Sy – sylvite; X – undetermined daughter mineral; P – primary inclusion; S – secondary inclusion; (*) – Palaeogene overprint on the Variscan mineralization; NaCl – salinity in NaCl equiv. wt.%; NaCl+CaCl₂ – salinity in NaCl+CaCl₂ equiv. wt.%; CaCl₂ – salinity in CaCl₂ equiv. wt.%; NaCl+KCl – salinity in NaCl+KCl equiv. wt.%. Salinities were calculated from ice-melting temperatures using data from Bodnar and Vityk (1994) for NaCl-type fluids and data from Oakes et al. (1990) for NaCl+CaCl₂ and CaCl₂ type fluids, both undersaturated at room temperature. Salinities were calculated from clathrate-melting temperatures for aqueous-carbonic fluid inclusions using data from Collins (1979). Salinities were calculated from halite and sylvite dissolution temperatures for NaCl- and NaCl+KCl-type fluids saturated at room temperature using data from Bodnar and Vityk (1994) and Sterner et al. (1988).

pressure in the Variscan post-magmatic fluid system. The hydrothermal systems related to the Palaeogene volcanism are characterised by more variable fluid inclusion associations. In the porphyry and siliceous-breccia related copper mineralization the presence of halite, sylvite and other daughter mineral bearing inclusions is common, and these inclusions are associated with liquid-rich and vapour-rich aqueous fluid inclusions. In the epithermal zones vapour-rich aqueous fluid inclusions are also associated with the liquid-rich ones, but the daughter-mineral bearing fluid inclusions are absent. The associations of fluid inclusions in mineralization related to Tertiary igneous activity indicate relatively low pressure boiling in those hydrothermal systems. Some samples from pegmatite and quartz-tourmaline mineralization of the Variscan granite also contain fracture-related secondary fluid inclusion planes with associations of liquid-rich and vapour-rich fluid inclusions (Fig. 2). This may indicate that the Palaeogene hydrothermal fluid circulation also invaded the Variscan granite in some zones. This is compatible with the occurrence of enargite-bearing mineralization and Palaeogene andesite dikes and stocks in the granite intrusion (Fig. 1).

Microthermometric data for granite-related post-magmatic formations

Two-phase liquid rich inclusions homogenised to a liquid phase most typically between 100 and 300 °C (Fig. 2 and Fig. 3). Eutectic melting occurred below -50 °C in many of these inclusions during freezing runs; these observations together with the observed very low ice-melting temperatures support modelling of their fluid composition in the Ca-rich part of the NaCl-CaCl₂-H₂O ternary (Oakes et al., 1990) in most cases. Calculated salinities are from 2 NaCl equiv. wt.% to 25 CaCl₂ equiv. wt.%. In carbonic-aqueous fluid inclusions of the quartz-molybdenite stockwork mineralization, carbonic phases melted between -60.2 and -56.6 °C suggesting that these phases may also contain a minor amount of CH₄, H₂S and N₂ (Burruss, 1981). Melting temperatures for clathrate phases (Collins, 1979) indicate 0–11 NaCl equiv. wt.% salinities of the aqueous phase in these inclusions. Homogenization of carbonic phase took place to liquid between -5 and +5 °C (for inclusions with high volume of carbonic-phase), as well as between 25 and 30 °C (for inclusions with low volume of carbonic phase). Total homogenisation was rarely observed due to decrepitation of most carbonic-aqueous fluid inclusions at a temperature above 250 °C. Decrepitation occurred both during homogenisation to carbonic and aqueous phases. When homogenisation occurred (in two inclusions) it took place at 284 °C to aqueous liquid and at 302 °C to carbonic liquid (Fig. 3).

Microthermometric data for Palaeogene hydrothermalism

Liquid-vapour inclusions homogenised to liquid or vapour depending on their bulk densities. In some cases, critical homogenisation was also observed in fluid inclusions with liquid/vapour volume ratios near to 50:50. Homogenisation temperatures (both to liquid and vapour) for two-phase inclusions are clustered around 250 and 350 °C. Critical homogenization for two-phase inclusions occurred between 380 and 450 °C (Fig. 2 and Fig. 3). Eutectic melting in some of the two-phase liquid-rich fluid inclusions

occurred below -50 °C during freezing experiments; ice melting temperatures in these inclusions correspond 1 NaCl equiv. wt.% to 24 NaCl+CaCl₂ equiv. wt.%. However, salinities for inclusions from epithermal zones are always lower than 13 NaCl equiv. wt.%. Critical homogenisation temperatures correspond to 1–8 NaCl equiv. wt.% salinities (Bodnar and Vityk, 1994).

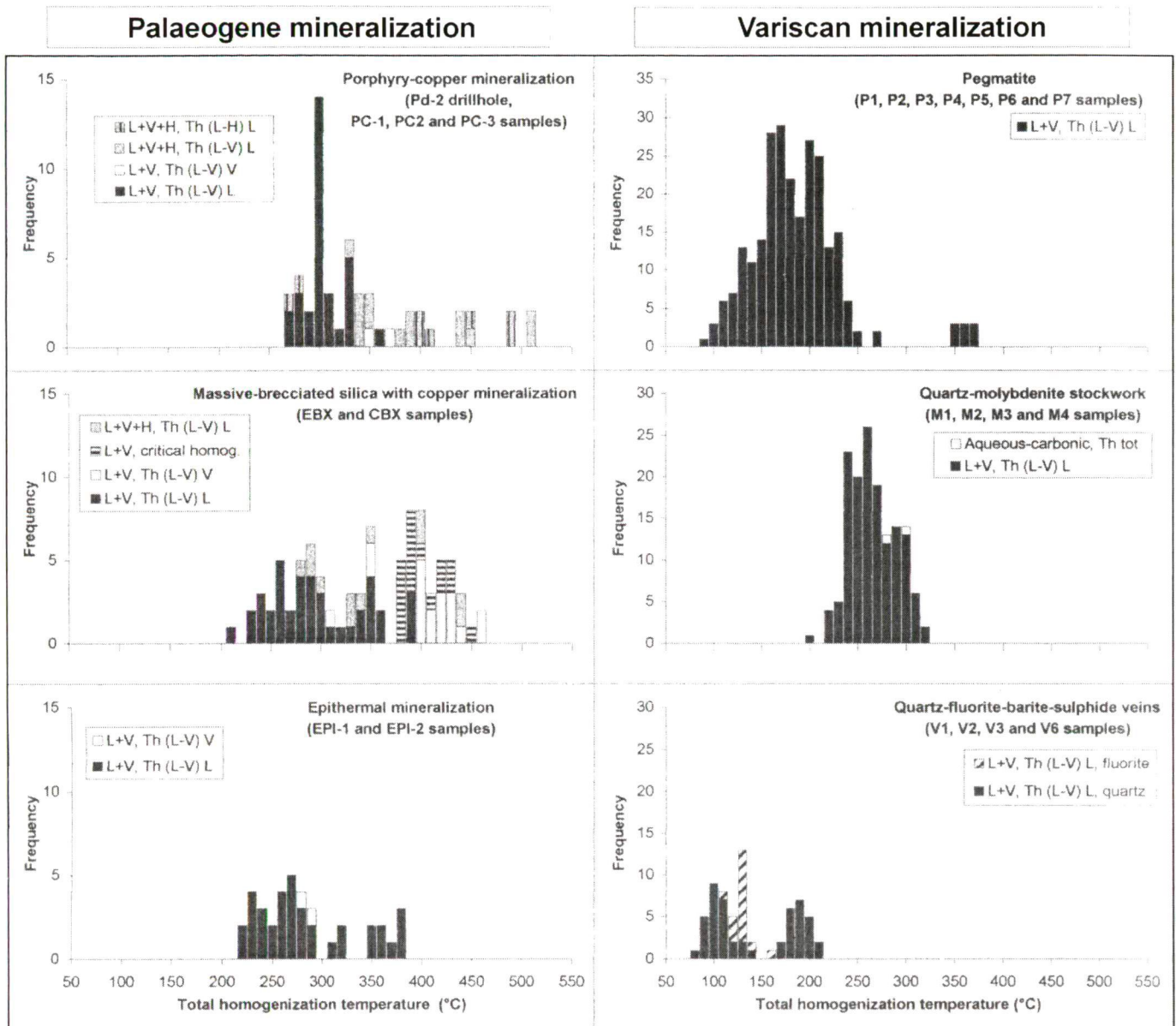
Daughter-mineral bearing fluid inclusions displayed total homogenisation to liquid either by halite dissolution or by vapour phase disappearance. Total homogenisation temperatures for daughter mineral bearing inclusions are widely distributed between 250 and 500 °C (Fig. 3). Salinities calculated from dissolution temperatures of halite and sylvite are from 26 NaCl equiv. wt.% to 79 NaCl+KCl equiv. wt.%. Eutectic temperatures as low as around -55 °C and the presence of other undetermined daughter minerals suggest more complex compositions for those fluid inclusions, therefore salinities may be slightly over- or underestimated (Bodnar, 1994).

Microthermometric analyses from some pegmatite and quartz-tourmaline mineralization of the Variscan granite revealed that homogenisation temperatures and composition of co-existing liquid-rich and vapour-rich two phase inclusions trapped along secondary planes of quartz are identical to those for two-phase fluid inclusion assemblages found in epithermal formations of Palaeogene volcanism (Fig. 2 and Fig. 3). The most common homogenisation temperatures for these inclusions are also clustered around 250 and 350 °C and salinities are from 0 to 2 NaCl equiv. wt.%.

Pressure and palaeodepth estimations derived from fluid inclusion data

Pegmatite and miarolitic cavities of the Variscan granitoid intrusion formed at temperatures between 300–400 °C and around 500–550 °C, based on two-feldspar thermometry, and these temperature ranges correspond to from 1.5 to 2.5 kbar pressures along the isochores of primary fluid inclusions (Buda, 1985; Molnár et al., 1995). Similarly high pressure conditions between 1.0 and 2.4 kbar can be inferred from the occurrence of inclusions trapped during immiscibility of carbonic-aqueous fluids during the formation of the quartz-molybdenite stockwork mineralization (Molnár, 1997). These data are in agreement with conclusions of petrological studies suggesting 6–8 km palaeodepth for emplacement of the granite (Buda, 1985). Based on pressure data for pegmatite and quartz-molybdenite mineralization, the formation of base-metal and fluorite veins may have also occurred between 1 and 2 kbars. This pressure range corresponds to 250–300 °C as well as 150–200 °C along the isochores of fluid inclusions from those formations. These low temperature fluids were also trapped in secondary fluid inclusions of quartz from pegmatite.

Petrography and homogenisation behaviour of the two-phase liquid-rich and some daughter mineral bearing inclusions, as well as the associated vapour-rich fluid inclusions from the porphyry-copper type mineralisation of the Palaeogene subvolcanic unit (Fig. 2 and Fig. 3) suggest that boiling of fluids occurred during hydrothermal activity. However, total homogenisation to liquid by halite (or by other daughter mineral) dissolution in some polyphase fluid inclusions indicates that high pressure conditions excluding



Palaeogene overprint in Variscan mineralization

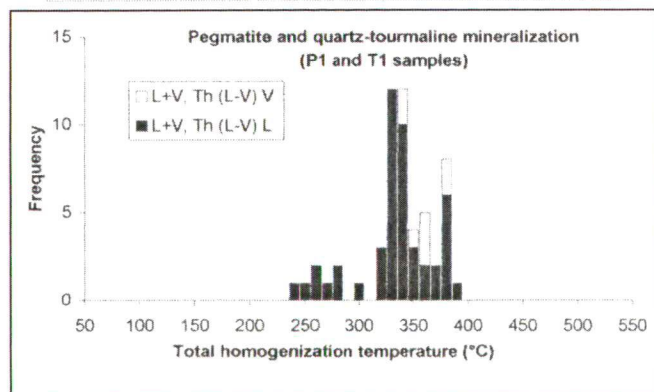


Fig. 3. Frequency distribution diagrams for homogenization temperatures of fluid inclusions from the Velence Mts. Abbreviations: L – liquid; V – vapour; H – halite; Th (L-V) L – homogenization to liquid by vapour-phase disappearance; Th (L-V) V – homogenization to vapour by liquid-phase disappearance; Th (L-H) L – homogenization to liquid by halite dissolution.

boiling of fluids (Bodnar, 1994) may have also occurred periodically. The minimum range of total homogenisation temperatures is between 340 and 390 °C for those inclusions which displayed dissolution of halite at a lower temperature than the homogenisation of vapour phase (Fig. 3). Following a method described by Bodnar and Vityk (1994) for inclusions with this type of homogenisation, the minimum pressure of boiling is from 100 to 280 bars; the latter pressure corresponds to 1100 m depth under lithostatic conditions assuming 2.6 g/cm³ rock density. This depth corresponds to approximately 100 bars pressure under hydrostatic load. Thus fluid inclusion data suggest that the porphyry-copper type mineralization of the Palaeogene volcanic unit formed at a depth around 1000 m during pressure variations between litho- and hydrostatic conditions.

Some assemblages of fluid inclusions and their homogenisation behaviour in the breccia zone along the granite-shale contact are comparable with the fluid inclusion characteristics of porphyry-type mineralisation in the Palaeogene intrusion. Data of halite-bearing inclusions suggest 50–310 bar minimum pressure range for boiling

according to a calculation procedure from Bodnar and Vityk (1994). Boiling of fluids in the high-sulphidation type epithermal zones outcropping above the porphyry intrusion is also indicated by petrography. Due to possible inhomogeneous trapping (Bodnar et al., 1985), it is assumed that homogenisation temperatures around 220–260 °C (Fig. 3) represent the most likely temperature of boiling. This temperature range corresponds to 21–46 bars pressure (Haas, 1976) which indicates 260–590 m palaeodepth under hydrostatic conditions with 0.80–0.95 density of fluids. Similar pressure estimations can be inferred from data for those secondary fluid inclusion assemblages of pegmatite and quartz-tourmaline zones of Variscan age which are very similar to the assemblages of inclusions found in epithermal zones (Fig. 3). Presence of a small amount of carbon dioxide undetectable by microthermometric analyses in fluid inclusions trapped during boiling in epithermal zones (Hedenquist and Henley, 1985; Bodnar et al., 1985) may significantly influence results of pressure and palaeodepth calculations; therefore, the data can only be accepted as the best estimations.

DISCUSSION

The Variscan hydrothermal system was characterised by relatively low salinity fluids during the deposition of mineral assemblages in pegmatites and quartz-molybdenite stockwork mineralization (Fig. 4). Late stage fluids associated with the vein systems hosting base-metal mineralization had high salinities and microthermometric behaviour of their inclusions suggests Ca-rich compositions. The parent fluids of the porphyry-copper type mineralization of the Paleogene intrusive body, as well as the associated breccia ores are characterised by the presence of coexisting high- and low-salinity fluids (Fig. 4). In the lower temperature epithermal zones only low salinity fluids are present.

The salinity of fluids fractionated from a crystallising melt is determined by the water content of the melt and the pressure (depth) conditions of crystallization. For example a water saturated granodioritic magma

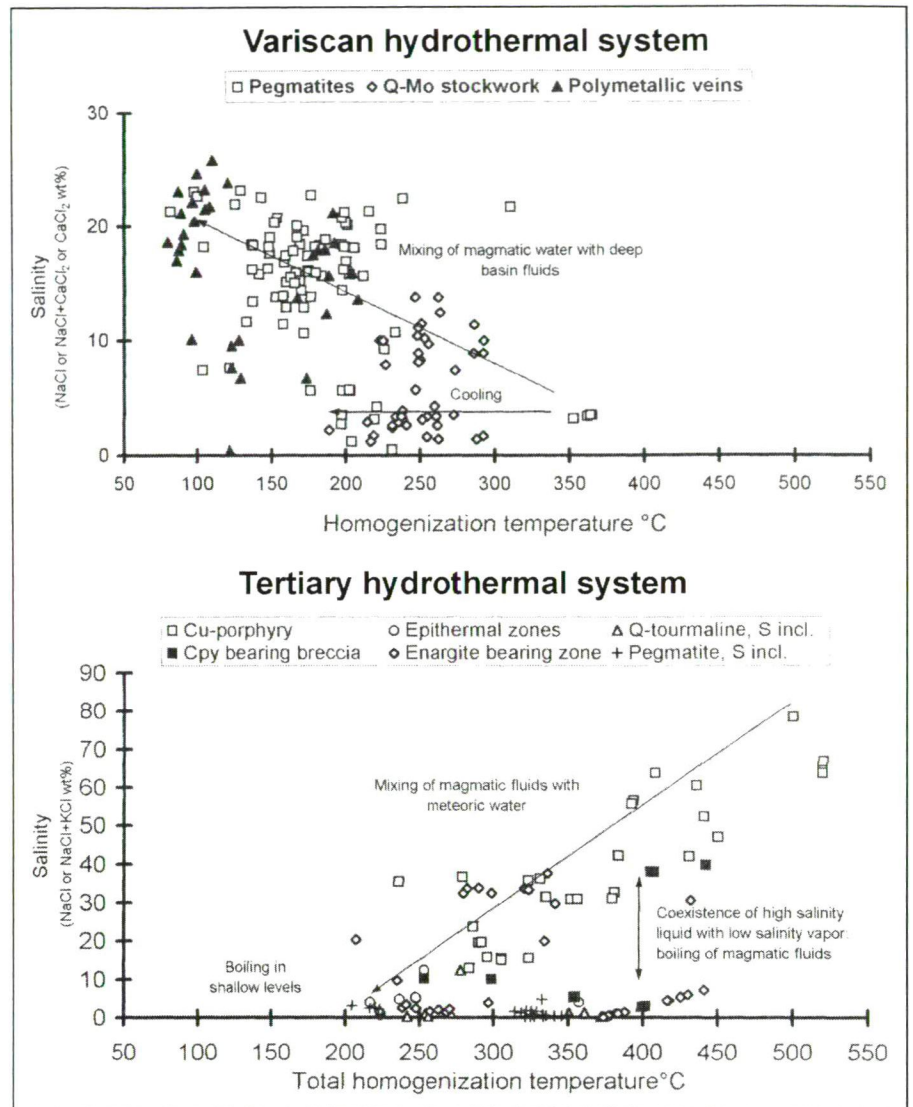


Fig. 4. Variation of salinities of fluid inclusions as a function of homogenization temperatures and interpretation of the observed trends in the various hydrothermal systems of the Velence Mts.

crystallizing at 2.1 kbar pressure may segregate an aqueous phase with salinity of about 12 wt% NaCl equiv. wt.% (Burnham, 1979). This value is close to the salinities of the early fluids in pegmatite of the Variscan granite of the Velence Mts that was water-saturated at the final stage of its crystallization at about 2 kbar pressure (Buda, 1985). Taylor et al. (1979) Weisbrod (1981), Chaumakos et al. (1982) and London (1986a, 1986b) also documented formation of pegmatite from relatively low salinity (around or lower than 10 NaCl equiv. wt.%) fluids. However, in other areas (e.g., Volnyn pegmatite, Weisbrod, 1981; Cathelineau et al., 1981) fluid inclusion studies revealed occurrences of very saline fluids related to the formation of pegmatite. The

differences in the composition of pegmatite related fluids can be explained taking into account the pressure conditions of crystallization. The critical curve of the NaCl-H₂O system intersects the vapour-saturated granite solidus at about 1.4 kbar pressure and 730 °C (Burnham, 1979). If the separation of a fluid phase occurs at a lower pressure than 1.4 kbar then the conditions correspond to the two-phase field of the NaCl-H₂O system and the separated fluid will undergo a further phase separation (boiling) which results in the coexistence of high density (high salinity) and low density (low salinity) fluids. Trapping of the high density fluid phase in minerals yields inclusions which contain halite (and other daughter minerals) at room temperature, while the low density

phase may form vapour-rich inclusions (Bodnar, 1995). These inclusions homogenise at the same temperature but with different modes (e.g. into the liquid and vapor phase).

According to the data discussed above, fluid inclusion characteristics of the porphyry-type mineralization related to the Paleogene volcanic activity of the Velence Mts. can be explained by boiling of fluids separated from diorite magma under low pressure (a few hundred bars). However, the occurrence of halite-bearing inclusions showing homogenization with dissolution of halite suggests that even at this relatively low pressure the variation of local pressure between lithostatic and hydrostatic conditions may have occurred resulting in temporary cessation of boiling. In contrast with this, the granite-related magmatic fluids separated at high pressure (around 2 kbars) which prevented their boiling and therefore the appearance of high salinity fluids.

The pressure-temperature boundaries of the two-phase (boiling) field of an aqueous fluid is highly influenced by the presence of additional volatiles. CO₂ sufficiently stretches the two-phase field of fluids (Bowers and Helgeson, 1983) and phase separation may occur at a relatively high pressure. Boiling of carbon dioxide rich fluids was detected in the Variscan granite related molybdenite bearing mineralization of the Velence Mts. However, this phase separation only resulted in the appearance of carbon-dioxide rich and carbon-dioxide poor aqueous fluid phases and important distinction in the salinities of these phases did not occur due to the high pressure conditions of the process.

The above models explain the differences found in the high temperature fluid inclusions from various formations of the Velence Mts. The differences between fluid inclusions characteristics for the Variscan and the Palaeogene low temperature fluid circulation stages can also be explained by the differences in the palaeodepth settings. The shallow levels of the Palaeogene hydrothermal activity resulted in typical high-sulfidation type epithermal processes with relatively low salinity fluids (Fig. 3). Although magmatic fluids may also be present in this part of a magmatic-hydrothermal system, low salinities reveal penetration of meteoric waters into the hydrothermal convection (Hedenquist and Arribas, 1999). The elevated salinity and Ca-rich character of hydrothermal fluids in the late stages of the Variscan granite-related system (Fig. 3) may be explained by mixing of magmatic fluids with deep basin waters. According to data from Roedder (1984), these latter fluids are characterised by salinities often higher than 20 wt% and high Ca-content.

Outcrops of the high sulphidation type epithermal zones in volcanic rocks east of the Nadap–Lovasberény fault (Fig. 1) are approximately at the same elevation as those for the enargite and chalcopyrite bearing breccia zones west of that fault. Both types of mineralization are characterized by associations of liquid-rich and vapour-rich two phase inclusions with similar conditions of entrapment. The occurrence of secondary fluid inclusion planes of quartz from some Variscan pegmatite and tourmalinized zones west of the Nadap–Lovasberény fault also have assemblages and microthermometric data similar to those from the epithermal zones (Fig. 3). Thus observations support the model that epithermal fluids penetrated the eastern zones of the Variscan

granite intrusion. However, enargite and chalcopyrite bearing breccia zones are also characterised by the presence of halite-bearing fluid inclusions that have similar microthermometric data to those from porphyry-copper type mineralization at subvolcanic levels in the Pd-2 drillhole (Fig. 3). Outcrops of andesitic dikes and stocks of Palaeogene age in the Variscan granite also indicate the existence of subvolcanic depths at the present level of erosion west of the Nadap–Lovasberény fault during Palaeogene volcanic activity (Darida-Tichy, 1987). Thus data indicate that fluid circulation along the brecciated contact zone between granite and shale repeatedly occurred at different palaeodepths during the Palaeogene hydrothermalism and therefore significant vertical faulting may have occurred along the Nadap–Lovasberény line.

CONCLUSIONS

The Velence Mts. area is characterised by the occurrence of various mineralization events with different origins in close spatial and sometimes overlapping distributions. The Variscan granite-related pegmatite, quartz-molybdenite stockwork, and vein type base-metal-fluorite veins show significant differences regarding fluid inclusion characteristics in comparison to the high-sulfidation type epithermal, breccia-hosted copper and Cu-porphyry type mineralisation of the Paleogene volcanic rocks. Pegmatite, quartz-molybdenite and base-metal-fluorite veins were formed in a high pressure (1–2.5 kbar) fluid system at 300–550 °C, around 300 °C, and at 150–300 °C, respectively. Occasional immiscibility involving carbonic-aqueous fluids occurred in the Variscan hydrothermal system. The Paleogene hydrothermal system was characterised by boiling of fluids at low pressures (20–300 bars). Temperature for subvolcanic-level hydrothermal activity was between 350 and 450 °C and for epithermal zones it was between 250 and 350 °C. In the Variscan system, salinities of fluids increase from the early pegmatite stage to the late vein-stage, whereas subvolcanic levels were characterised by co-existence of high- and low-salinity fluids and epithermal zones by low salinity fluids. Late stage (low temperature) fluids in the granite-related system show the influence of Ca-rich basin brines on the composition of hydrothermal waters, whereas the low salinity of Palaeogene epithermal hydrothermalism may indicate involvement of meteoric waters in the circulation of fluids. Both porphyry-type and epithermal fluids penetrated into the eastern zones of the Variscan granite.

Results of this study also demonstrate that more detailed fluid inclusion petrography and mapping may be useful to delineate those fractured zones of granite which were affected by Palaeogene fluid circulation. Interpretation of fluid inclusion data together with field evidence also indicate that tectonic events that occurred during the Palaeogene hydrothermal activity may also be recognisable. Using the data base presented in this study, observations on secondary fluid inclusion planes in rock-forming quartz of granite may reveal several fluid circulation events and thus may support the establishment of a model for the temporal and spatial evolution of fracturation in the Velence Mts. This approach may have importance not only in mineral exploration, but also in various environmental projects analysing development of fracturation of granite not only in the Velence Mts., but in other granitoid areas of Hungary.

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