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RELATIONSHIPS BETWEEN VOLCANISM AND HYDROTHERMAL ACTIVITY IN THE TOKAJ MOUNTAINS, NORTHEAST HUNGARY, BASED ON K-Ar AGES

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Abstract: Conventional K-Ar studies of volcanic rocks, rock-forming minerals and hydrothermal adularia and alunite from different volcanic centres of the Tokaj Mts indicate that volcanic activity took place between 15.2 and 9.4 Ma (Badenian–Sarmatian–Pannonian). In the northern part of the Tokaj Mts, ages for the relatively deeply eroded hydrothermal systems (Rudabányácska and Telkibánya Au-Ag deposits and parts of the Regéc caldera), formed mainly by the adularia-bearing low-sulphidation epithermal deposits, are between 13.0 and 12.2 Ma. These systems were developed within andesitic-dacitic volcanic centres with calderas and subvolcanic intrusions. In the southern parts of the Tokaj Mts (near Mád and in the Szerencs Hills region) exposures of hydrothermal systems mainly represent shallow acid-sulphate steam-heated zones of low-sulphidation-type systems, and the K-Ar ages are between 12.1 and 10.4 Ma. Radiometric ages also suggest that in some parts of this latter area, repeated hydrothermal activity occurred, suggesting that hydrothermal circulation developed in relation to different magmatic centres that were active at different times.

Key words: Carpathians, Miocene volcanism, epithermal deposits, K-Ar ages.

Introduction

The Neogene-Quaternary volcanic units of the Carpathians and connected basin areas (Pannonian Basin, Transylvanian Basin) are divided into four major groups (Pécskay et al. 1995; Lexa 1999). The calc-alkaline ignimbrite and felsic tuff units are regionally distributed in the basin areas where they are largely covered by young sediments. K-Ar dating of these units (Pécskay et al. 1995) showed that most deposition took place between 20 and 10 Ma. The low- to high-potassium calc-alkaline intermediate-felsic units are associated with large stratovolcanoes in the Western Carpathians (Central Slovak Volcanic Field, Börzsöny-Dunazug Mts, Mátra Mts, Tokaj Mts, covered volcanics of the Trans-Tisza Region of Hungary) and in the Apuseni Mts were formed in the Miocene, between 16 and 7 Ma (Karpatian–Badenian–Sarmatian–Pannonian). The arc-type, low- to high potassium calc-alkaline andesite, basaltic andesite units are distributed from the Slanské and Vihorlat Mts through the Oas-Gutâi Mts to the Harghita Mts. The major stages of volcanic eruption in this arc occurred from 13 to 0.2 Ma ago. The K-Ar ages for the local alkaline basaltic volcanism developed in the back-arc extensional regime, are between 11.5 and 0.35 Ma.

Among the different volcanic groups only the intermediate-felsic units associated with stratovolcanoes and the andesitic arc-type units are characterized by metallogenetically important hydrothermal activity. Although there is abundant K-Ar data for the various volcanic rocks from these units (Pécskay et al. 1995), systematic radiometric age determination of hydrothermal activity has rarely been conducted (there are some data from the Gutâi Mts and the Central Slovak Volcanic Field; Kovacs et al. 1997; Chernyshev et al. 1995). Thus the age relationships between the various eruption stages and deposition of hydrothermal minerals in volcanic centers has not yet been documented. In this paper we present the results of comparative radiometric dating of volcanic rocks and hydrothermal minerals from various volcanic centers and related mineralized areas of the Tokaj Mts.

General characteristics of volcanism and hydrothermal activity in the Tokaj Mts

The intermediate-felsic calc-alkaline volcanic rocks of Badenian to Pannonian age of the Tokaj Mts were deposited in a N-S trending graben-like structure in northeast Hungary (ca. 100 km long and 25–30 km wide; Pantó 1968; Gyarmati 1977). The basement units consist of various Precambrian and Paleozoic metamorphic rocks, which crop out along the northeastern boundary of the graben (Fig. 1).

Miocene volcanism in the Tokaj Mts took place in two major stages (Gyarmati 1977). The older (Badenian) volcanic stage began with ignimbrite and felsic tuff eruptions along the Szamos Line (Fig. 1). The subsidence of the basement resulted in marine transgression, and the accumulation of thick Badenian andesitic and dacitic lava flows took place under submarine conditions along the axis of the graben. For the late stage of Badenian volcanism, some areas were uplifted and andesitic-dacitic subvolcanic bodies intruded into the earlier volcanic and sedimentary units. The Badenian rocks crop out only in the northeastern part of the Tokaj Mts; they are covered by Sarmatian-Pannonian volcanic and sedimentary accumulations in other parts of the mountains.

The initial stages of the Sarmatian-Pannonian volcanic cycle in the Tokaj Mts started in partly subaqueous and partly subaerial conditions, corresponding to a terrestrial environment

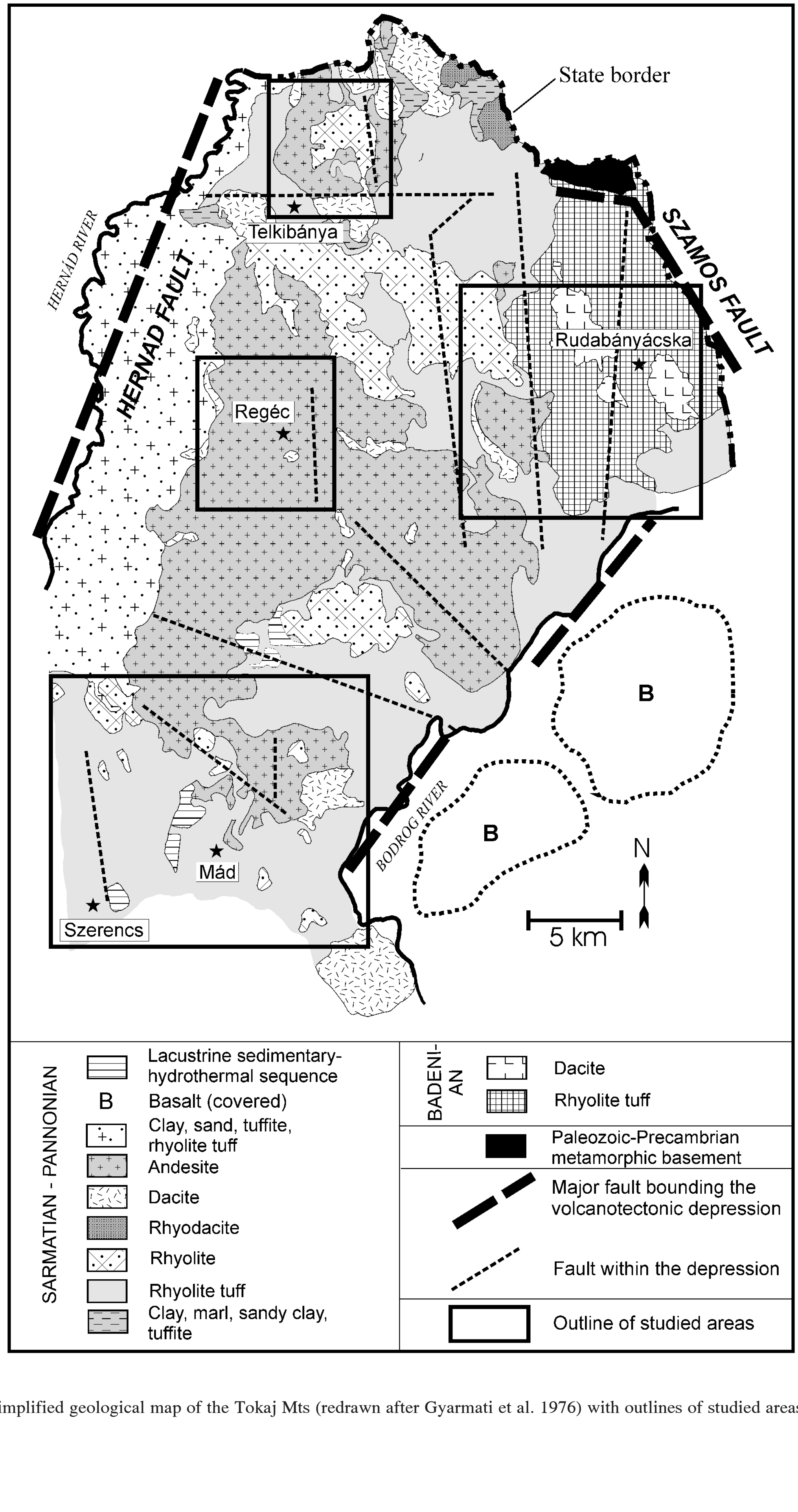

Fig. 1. Simplified geological map of the Tokaj Mts (redrawn after Gyarmati et al. 1976) with outlines of studied areas.

dissected by lagoons and bays. This initial stage was characterized by accumulation of felsic tuff commonly intercalated with shallow marine clay and marl. In the central and northern part of the Tokaj Mts, initial felsic pyroclastic deposition was followed by formation of subaerial andesitic stratovolcanoes (Telkibánya and Regéc; Fig. 1). Synchronous with andesitic volcanism, rhyolite dome-flow complexes were formed in the Mád area as well as southeast of Telkibánya (Fig. 1). In the late stages of Sarmatian-Pannonian volcanism, andesitic dikes and flows related to fissure-volcanism were emplaced in the axial part of the mountains. Dacite extruded along the marginal zones of the graben-structure. The youngest product of volcanism is olivine basalt known from drilling along the eastern boundary of the graben (Fig. 1).

The magmatism related to both Badenian and Sarmatian-Pannonian volcanism generated hydrothermal activity. However, hydrothermal environments in Badenian volcanic rocks are known mostly from deep drilling; their exposures are limited to the northeastern part of the Tokaj Mts. (e.g. the Rudabányácska area; Fig. 1). The mineralized zones in both Badenian and Sarmatian sequences are typical examples of low-sulphidation-type epithermal environments, with different levels of erosion in exposures of various parts of the Tokaj Mts (Molnár et al. 1999). The most deeply eroded zones are characterized by adularia-sericite alteration, which crops out in the vicinity of Rudabányácska, Telkibánya and Regéc (Fig. 1). Remnants of the shallower, acid-sulphate steam-heated alteration zones are also present at Telkibánya and Regéc; however, this type of hydrothermal alteration predominates on the surface at Mád and in the Szerencs Hills, north of Szerencs (Fig. 1). The essentially non-eroded, distal environments of hydrothermal systems are represented by limnic siliceous and clay deposits near Mád and Regéc and in several other parts of the Tokaj Mts.

Detailed K-Ar studies have been conducted on the volcanic rocks and hydrothermal minerals from the following volcanic and hydrothermal centers: Rudabányácska, Telkibánya, Regéc, Mád and the Szerencs Hills.

Method of K-Ar study

The K-Ar age determinations of all samples were carried out at the Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), Debrecen, Hungary, except for some alunite samples (with S35 sample numbers, see Tables 2, 4 and 5) which were analysed at the Okayama University of Science, Japan.

Fresh to highly altered (>8 wt. % K_2O content due to K-metasomatic alteration) volcanic rocks from drillcores and outcrops were crushed, then a sample of the crushed rocks was selected and pulverized. Rock-forming minerals (biotite, amphibole, and sanidine) were separated from the host rocks by a combination of magnetic and heavy-liquid methods. Hydrothermal minerals (adularia and alunite) were handpicked from fractures and cavities of host rocks. Ultrasonic washing in tubes produced clean mineral surfaces. Alunite samples were chemically treated following the method of Itaya et al. (1996) to remove small amounts of contaminant phases such as iron minerals. As a consequence of this treatment, atmospheric argon contamination was significantly reduced.

Potassium determinations were made on about 100 mg portions of the pulverized samples by means of a flame photometer. For Ar analyses, approximately 500 mg of sample were used. Details of analytical procedures (potassium determinations, Ar extraction lines and mass spectrometers) are described by Balogh (1985) and Itaya et al. (1996). All analytical errors in this paper represent one sigma standard deviation (i.e. a 68 % analytical confidence level).

Volcanism, hydrothermal processes and K-Ar ages in different parts of the Tokaj Mts

Rudabányácska

The felsic pyroclastic deposits (ignimbrite, welded ignimbrite, crystal tuff) of Badenian age are only a few hundred meters thick and they cover Triassic-Jurassic carbonate units that are underlain by metamorphic rocks at Rudabányácska (Gyarmati & Pentelényi 1973). K-Ar ages for biotite and sanidine from the pyroclastic deposits are between 15.2 and 13.1 Ma (Fig. 2, Table 1). The eruption centers for ignimbrite are probably along the Szamos Line (Gyarmati 1977); however, there are also small rhyolite domes in the vicinity of Rudabányácska that have similar ages (13.0 Ma, Table 1). The pyroclastic rocks were intruded by dacitic bodies (Száva Hill; Fig. 2), which suffered hydrothermal alteration. Subsequent andesitic dacitic-andesitic lava flows covering ignimbrites are fresh. K-Ar data for whole-rock and amphibole samples suggest a Sarmatian age for intermediate lava flows in this area (12.4–12.2 Ma, Table 1).

The hydrothermally altered rocks of the area occur in a NW-SE oriented zone nearly parallel to the Szamos Line (Fig. 2). The most intense adularia-sericite-pyrite-hematite alteration affected the felsic pyroclastic units of the Bányi Hill and the dacite intrusion of Száva Hill (Fig. 2). The zone with adularia-bearing alteration assemblage is surrounded by regional propylitized rocks (Varga-Máthé 1961). Rocks with adularia-sericite alteration host a siliceous-pyritic disseminated-stockwork gold deposit, which was exploited in medieval times. According to fluid inclusion data, the deeper zones of the gold deposit (Bányi Hill) formed at temperatures of 230–300 °C during boiling of fluids, at a minimum depth of about 300 m below the paleogroundwater table (Molnár 1994).

The K-Ar age of intrusive dacite from Száva Hill affected by intense K-metasomatic (K-feldspar-sericite) alteration, is 13.2 Ma (Table 1). The K-Ar age for adularia from the stockwork deposit of Bányi Hill is 13.0 Ma (Table 1). These data suggest that hydrothermal mineralization of the area near Rudabányácska took place at the end of the Badenian rhyolitic-dacitic volcanic stage and may be related to emplacement of shallow intrusions.

Telkibánya

The volcanic and sedimentary sequence of Sarmatian-Pannonian age that is exposed in the vicinity of Telkibánya is

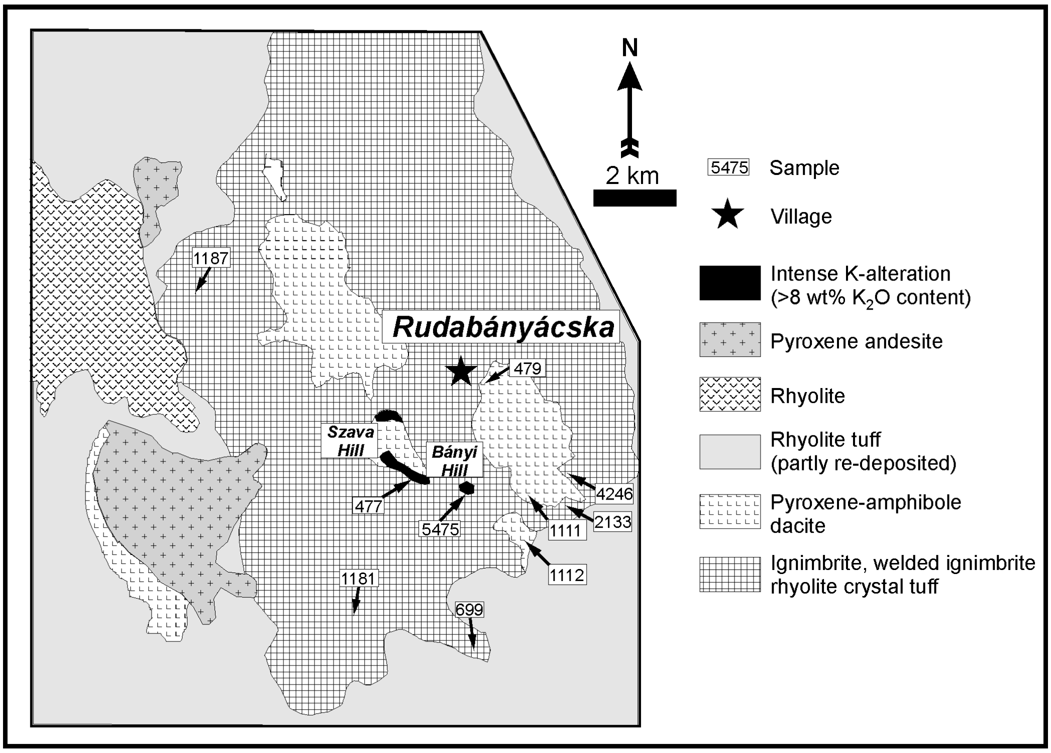

Fig. 2. Simplified geological map of the Rudabányácska area (redrawn after Gyarmati et al. 1976), with the locations of samples for K-Ar dating.

Table 1: K-Ar data for fresh and altered rocks and hydrothermal minerals from the Rudabányácska area. 1 — Pécskay et al. (1986).

Volcanic stage, type of hydro-thermal alteration	Sample No	Location	Type of rock and mineral	K (%)	40Ar rad (%)	40Ar rad (10^{-6}ccSTP/g)	Age (Ma)	Reference
			FRESH ROCKS					
pyroclastic eruptions	1187	Kovácsvágás, Hallós Valley	rhyolite tuff biotite	6.71	68.0	3.966	15.2±0.6	1
	4246	Sátoraljaújhely, Kopaszka Hill	rhyolite tuff biotite	6.19	55.9	3.201	13.3±0.5	this study
	2133	Sátoraljaújhely, Boglyaska Hill	dacite tuff biotite	6.58	23.6	3.374	13.2±0.8	this study
	699	Sárospatak, Somlyód Hill	rhyolite tuff sanidine	5.33	76.0	2.724	13.1±0.5	1
Domes and flows	1181	Sárospatak, Ciróka Hill	rhyolite biotite	5.97	59.0	3.015	13.0±0.5	1
	479	Rudabányácska, Kövespatak	amphibole dacite	2.27	17.0	1.101	12.4±1.0	1
	1112	Sátoraljaújhely, Néma Hill	pyroxene amphibole dacite	2.22	45.0	1.075	12.4±0.5	1
	1111	Sátoraljaújhely, Sátor Hill	pyroxene amphibole dacite,	2.37	52.0	1.123	12.1±0.6	1
			amphibole	0.50	18.0	2.420	12.3±1.0	
			ALTERED ROCKS					
Intrusion, adularia-sericite	477	Rudabányácska, Nagy Szava Hill	K-metasomatized dacite	4.94 5.19	61.0 63.0	2.606 2.656	13.3±0.6 13.1±0.6	1
			HYDROTHERMAL MINERALS					
neutral-alkaline boiling	5475	Rudabányácska, Bányi Hill	adularia	10.49	73.3	5.320	13.0±0.5	this study

about 1 km thick and is underlain by Badenian intermediate volcanic rocks, based on data from the 1240 m deep Telkibánya-2 borehole (Széky-Fux 1970; Gyarmati 1977; Molnár et al. 1999). Interpretation of geophysical data by Zentai (1991) suggests that the depth to the basement is about 2000 m.

Sarmatian volcanism started with ignimbrite and rhyolitic tuff eruptions from a still recognizable volcanic center at the northwestern end of Telkibánya village (Horváth et al. 1989; Fig. 3). The early products of explosive activity accumulated in subaqueous conditions and are interbedded with clay and marl as well as coarse siliciclastic sedimentary rocks. The next stage of volcanic evolution was characterized by the formation of subaerial andesite stratovolcanic and caldera-like structures. Horváth & Zelenka (1997) recognized two caldera structures,

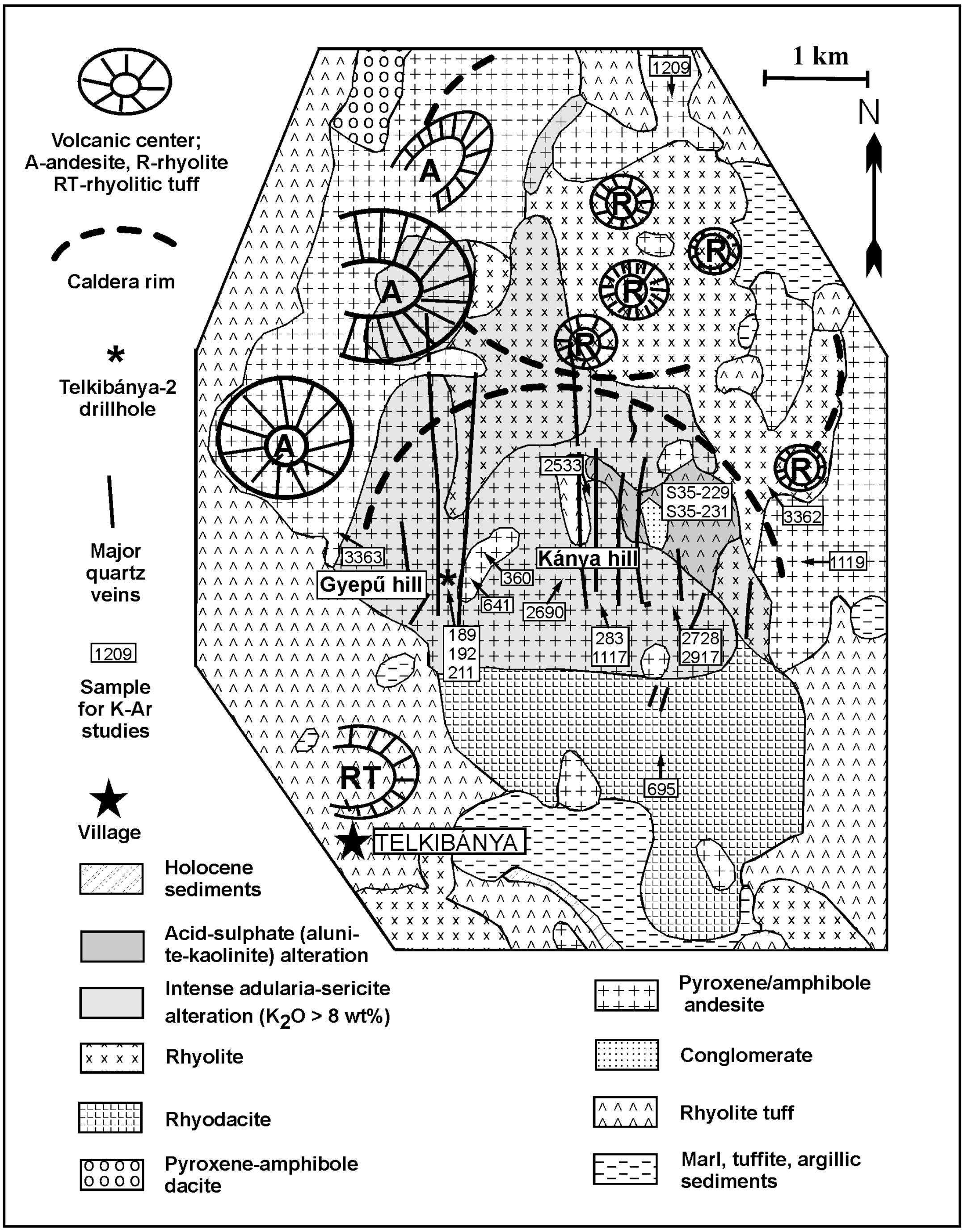

Fig. 3. Geological sketch-map of the Telkibánya ore deposit compiled on the basis of maps from Széky-Fux (1970), Gyarmati (1977), Molnár (1993) and Horváth & Zelenka (1997), and locations of samples for K-Ar dating.

each about 5–7 km in diameter (Fig. 3). The K-Ar ages for stratovolcano pyroxene- and amphibole- andesitic lava flows are between 13.1 and 11.6 Ma (Table 2). Radiometric ages for rhyolite and rhyodacite domes and flows that formed within the calderas are between 12.6 and 11.5 Ma (Table 2). According to data from drillholes and interpretation of geophysical data, a subvolcanic andesite intruded the southern caldera structure during the late stages of volcanic evolution (Horváth & Zelenka 1997; Zelenka et al. 2000).

At the time of the Sarmatian-Pannonian boundary, volcanism was still active in the vicinity of Telkibánya. These youngest volcanic rocks in the area occur as pyroxene andesite lava flows and dikes (the so-called "upper pyroxene andesite" according to Gyarmati 1977). The radiometric ages for these units are between 10.9 and 10.6 Ma (Table 2).

The low-sulphidation type epithermal mineralization of the area near Telkibánya is characterized by the occurrence of N-S striking quartz veins in the central parts of caldera-like struc-

Table 2: K-Ar data for fresh and altered rocks and hydrothermal minerals from Telkibánya. Reference: 1 — Pécskay et al. (1986).

Volcanic stage, type of hydro-thermal alteration	Sample No	Location	Type of rock and mineral	K (%)	40Ar rad (%)	40Ar rad (10^{-6}ccSTP/g)	Age (Ma)	Average age (Ma)	Reference
FRESH ROCKS									
Stratovolcanic lava flows and post-caldera domes and cones	211	Telkibánya-2 drillhole, 173.6 m	amphibole-pyroxene andesite	1.57	15	0.762	12.4±1.8	13.1±1.2	1
					33	0.824	13.5±1.5		
	1119	Telkibánya. Fehér Hill	pyroxene andesite	1.65	28	0.802	12.4±0.7	-	1
	283	Telkibánya. Csengő adit	pyroxene andesite	1.58	36	0.749	12.3±0.8	-	1
	2690	Telkibánya. Kánya Hill	andesite	3.11	53	1.477	12.2±0.5	-	this study
	1209	Hollóháza. Szurok Hill	pyroxene andesite	1.15	40	0.542	12.1±0.6	-	1
	192	Telkibánya-2 drillhole, 182.5-183 m	pyroxene andesite	1.87	20	0.870	12.0±1.3	11.8±1.0	1
					16	0.850	11.6±1.5		
	3363	Telkibánya, Gyepű Hill	pyroxene andesite	1.51	50	0.696	11.8±0.5	-	this study
	1117	Telkibánya, Teréz adit	amphibole andesite	2.51	41	1.132	11.6±0.5	-	1
	695	Telkibánya. Jó Hill	rhyodacite	4.83	40	2.373	12.6±0.6	-	1
	3362	Nyíri Fehér Hill	rhyolite	6.93	75	3.113	11.5±0.4	-	this study
Late dikes	360	Telkibánya, Medve Hill	pyroxene andesite	1.79	47	0.762	10.6±1.4	-	1
	641	Telkibánya, Baglyas Valley	pyroxene andesite	2.46	37	1.43	10.9±0.5	-	1
ALTERED ROCKS									
Adularia-sericite	2533	Telkibánya. Kánya Hill	K-metasomatized andesite	10.68	85.1	5.003	12.0±0.5	-	this study
	189	Telkibánya-2. drillhole 19.2-20.0 m	K-metasomatized andesite	9.03	72	4.165	11.7±0.9	12.4±0.8	1
					91	1.696	13.2±1.3		
HYDROTHERMAL MINERALS									
Neutral-alkaline	2917	Telkibánya. Veresvíz Valley	adularia	12.46	24.4	5.930	12.2±0.7	-	this study
boiling	2728	Telkibánya. Veresvíz Valley	adularia	13.33	95.2	6.442	12.4±0.5	-	this study
Acid-sulphate	S35-229	Telkibánya. Kánya Hill	alunite	5.97	64.6	2.902	12.5±0.5	-	this study
steam-heated	S35-231	Telkibánya. Kánya Hill	alunite	8.16	69.3	3.899	12.3±0.6	-	this study

tures (Fig. 3). Gold and silver from these veins was exploited during the midle ages. The intermediate and felsic volcanic rocks related to the caldera-like structures are characterized by strong K-metasomatic (adularia-sericite) alteration along these veins (Fig. 3) with >8 wt. % K_2O content in the rocks (Széky-Fux 1970; Molnár et al. 1999; Molnár & Pécskay 2000). The K-metasomatic alteration pinches out at depth and is surrounded by a propylitic alteration halo. In some rhyolitic tuff and ignimbrite units situated above the adularia-bearing alteration zones, an acid-sulphate type steam-heated alteration zone with kaolinite-alunite assemblage is also present (Molnár 1993; Molnár et al. 1999). The formation of the quartz veins and hydrothermal wall rock alteration occurred at temperatures of 250 to 180 °C, during boiling of hydrothermal fluids. The minimum paleodepth of hydrothermal activity was around 200 to 500 m below the groundwater table (Molnár & Zelenka 1995).

The youngest pyroxene andesite dikes of the mineralized area do not show hydrothermal alteration. This suggests that the age of hydrothermal activity is older than the 10.9–10.6 Ma. K-Ar ages of the very strongly altered rocks with >8 wt. % K_2O are between 12.4 and 11.5 Ma, and for adularia and alunite from quartz veinlets and steam-heated alteration zones, respectively, ages are between 12.5–12.2 Ma (Table 2). These data reveal that hydrothermal activity immediately followed the formation of the host rocks related to the caldera-like structures. The identical K-Ar ages of adularia and alunite indicate that precipitation of alunite in the steam-heated alteration zones was synchronous with the deposition of adularia in veins formed during boiling within the same hydrothermal system.

Regéc

In the central part of the Tokaj Mts, around Regéc, there is a caldera-like circular structure, about 4 km in diameter (Bajnóczi et al. 2000). Data from the Baskó-3 drillhole (Fig. 4) shows that a subaerial stratovolcanic sequence consisting of andesitic lava and pyroclastic units approximately 850 m thick, as well as subvolcanic andesite bodies, accumulated over the Badenian subaqueous intermediate lava flows during the Lower Sarmatian. The K-Ar ages for the stratovolcanic andesite lava flows and subvolcanic units are between 13.6 and 12.1 Ma (Table 3). The average of whole rock and biotite K-Ar data from the dacitic dome situated in the center of the caldera structure (Fig. 4) is 11.6 Ma (Table 3). The late-stage pyroxene andesite flows related to fissure volcanism in the vicinity of the caldera have K-Ar ages between 10.4 and 10.7 Ma (Table 3).

In the area of the caldera at Regéc, there are several hydrothermal centers hosted by regionally propylitized stratovolcanic andesite units. K-metasomatic (adularia-sericite) alteration occurs along the quartz veins (Fig. 4). These veins formed at a temperature between 170 and 190 °C. Boiling hydrothermal fluids of mainly meteoric origin reacted with igneous rocks at a minimum depth of 90–150 meters below the paleogroundwater table (Bajnóczi et al. 2000). In the tuffaceous units of the stratovolcanic sequence, shallow steam-heated alteration zones with alunite-argillite alteration assemblages are also present. At some places in the caldera, the paleosurface of hydrothermal activity is still preserved with hydrothermal eruption breccia and related layered siliceous deposits (Fig. 4).

Table 3: K-Ar data for fresh and altered rocks and hydrothermal minerals from the Regéc area. Reference: 1 — Pécskay et al. (1986).

Volcanic stage, type of hydro-thermal alteration	Sample No	Location	Type of rock and mineral	K (%)	40Ar rad (%)	40Ar rad (10^{-6}ccSTP/g)	Age (Ma)	Average age (Ma)	Reference
FRESH ROCKS									
Stratovolcanic lava flows and subvolcanic bodies	4244	Regéc brook	pyroxene andesite	1.65	54	0.833	13.0±0.5	-	this study
	4058	Regéc	pyroxene andesite	2.02	31	1.068	13.6±0.7	-	this study
	4409	Regéc	pyroxene andesite	1.99	45	1.017	13.1±1.2	-	this study
	4134	Regéc, Soltész Valley	pyroxene andesite	1.89	25	9.324	12.6±0.8	-	this study
	1196	Baskó-3 drillhole, 879.3-885.3 m	pyroxene andesite	3.29	67	1.571	12.1±0.5	-	1
	481	Baskó-3 drillhole, 782.4 m	pyroxene andesite	1.69	43	0.810	12.3±0.6	-	1
	1217	Baskó-3 drillhole, 660.4-664 m	pyroxene andesite	2.24	42	1.061	12.1±0.5	-	1
	1199	Baskó-3 drillhole, 522.1-524.6 m	pyroxene andesite	1.87	50	0.907	12.4±0.5	-	1
Post-caldera dome	814	Regéc, Vár Hill	dacite	3.33	10	1.550	11.9±1.6	11.6±0.6	1
			biotite	4.26	58	1.897	11.4±0.5		
			biotite	4.1	67	1.848	11.5±0.5		
			biotite	4.38	29	1.949	11.4±0.6		
			biotite	6.07	62	2.849	12.0±0.5		
Late dikes and lava flows	1198	Baskó-3 drillhole, 158.6-162.6 m	pyroxene andesite	1.99	43	0.807	10.4±0.5	-	1
	642	Regéc, Tokár Hill	pyroxene andesite	2.00	24	0.836	10.7±0.6	-	1
ALTERED ROCKS									
Adularia-sericite	4031	Regéc, east of the Vár Hill	K-metasomatized andesite	7.8	70	3.747	12.3±0.5	-	this study
	4032	Regéc, east of the Vár Hill	K-metasomatized andesite	8.78	79	4.105	12.0±0.5	-	this study
	4133	Regéc, Csonkás Hill	K-metasomatized andesite	6.73	62	3.103	11.8±0.5	-	this study
HYDROTHERMAL MINERALS									
acid-sulphate steam-heated	4030	Regéc, southern caldera rim	alunite	6.98	67	3.315	12.2±0.5	-	this study

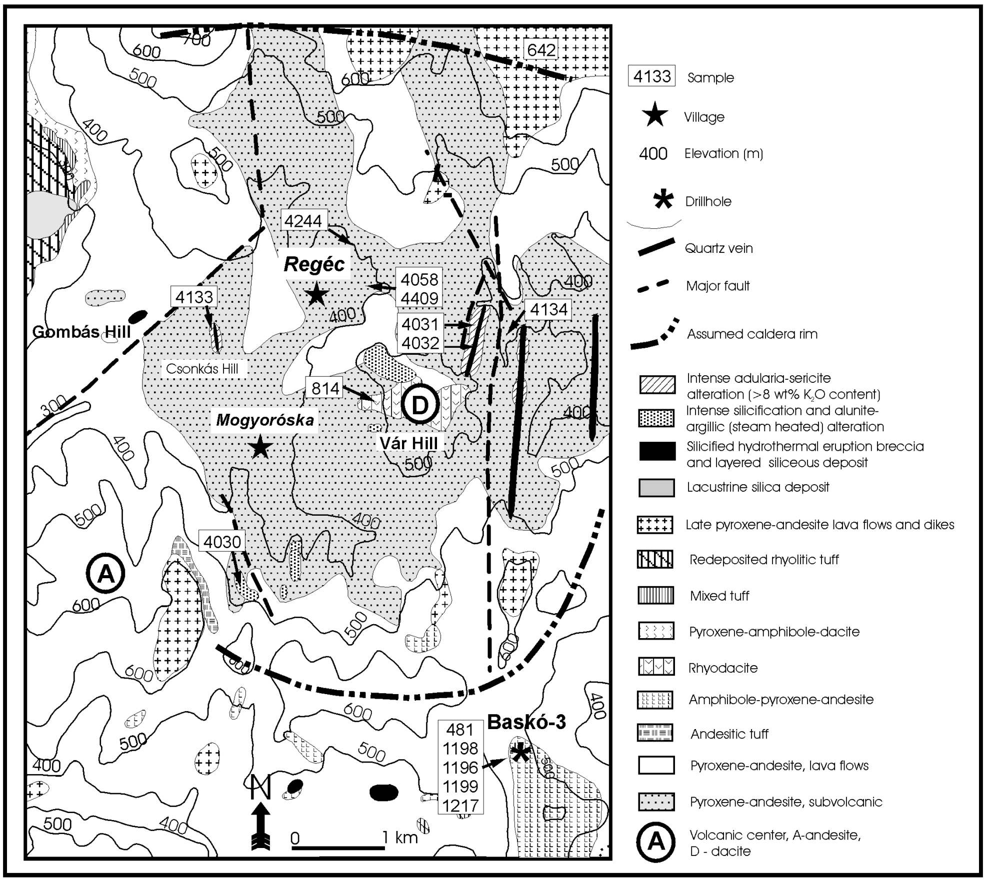

Fig. 4. Simplified geological map of the Regéc area (modified from Bajnóczi et al. 2000), with the locations of samples for K-Ar dating.

The dacite dome in the center of the caldera, as well as the late-stage andesitic lava flows do not show the hydrothermal alteration. This suggests that the age of the hydrothermal activity is older than 11.6 Ma. In agreement with this, the K-Ar ages for the rocks enriched in potassium due to adularia-sericite alteration along the veins are between 12.3 and 11.8 Ma and the age of alunite from a steam-heated alteration zone is 12.2 Ma.

The results of K-Ar age determinations in the vicinity of Regéc confirm that hydrothermal activity was related to the formation of the stratovolcanic and caldera structures and preceded the last stages of volcanism within the caldera and its surroundings.

Mád

In the southern part of the Tokaj Mts, near Mád, volcanic rocks of Sarmatian-Pannonian age are exposed. Igneous rocks of Badenian age are known only from the Tállya-15 drillhole (Fig. 5) below 1000 m depth (Gyarmati 1977); K-Ar data for a submarine andesite flow of the Badenian sequence is 14.2 Ma (Table 4).

The major part of the Sarmatian-Pannonian volcanic sequence consists of pumiceous glass tuff, pumiceous tuff, rhyolite crystal tuff and ignimbrite. These pyroclastic rocks accumulated both under subaqueous and subaerial conditions and are interbedded and intercalated with shallow marine clay and marl beds, as well as lacustrine clay and silica deposits. Zelenka (1964) recognized five major periods of accumulation of pyroclastic rocks. The eruption centres are marked by rhyolitic-dacitic domes and associated pumiceous lava flows (Fig. 5).

The most intensive hydrothermally altered zone is situated northeast of Mád. In this area, the exposures of volcanic rocks consist of felsic pyroclastic deposits and dacitic-rhyolitic extrusions and lava flows of the fourth major eruptive period of the volcanic evolution (Zelenka 1964). K-Ar ages for dacitic and rhyolitic rocks from the fourth volcanic period are between 12.8 and 11.1 Ma (Table 4). Accumulation of andesitic lava flows, agglomerates and tuffs followed this stage. The centre of the andesitic volcanism may be related to the location of the subvolcanic andesitic intrusions found in the Mád 23 drillhole (Fig. 5). Radiometric ages for the subvolcanic andesite and andesitic lava flows are between 11.8 and 11.5 Ma (Table 4). K-Ar data for the rhyolite domes and dacitic extrusions of the fifth volcanic period of the area range from 10.8 to 9.8 Ma (Table 4).

In the area northeast of Mád, the hydrothermal alteration of rhyolitic tuffs of the fourth and fifth volcanic stages represents shallow acid-sulphate steam-heated zones of low sulphidation type epithermal systems (Molnár et al. 1999). The typical alteration minerals are kaolinite and alunite associated with silicification. However, the steam-heated alteration zones also contain N-S and NE-SW oriented quartz veins containing 1.7–2.4 g/t Au in some places (Csongrádi & Zelenka 1995). Some of these veins have quartz pseudomorphs after bladed calcite suggesting that they were formed in a deeper position compared to a steam-heated alteration level, during boiling of near-neutral hydrothermal solutions (at around 180–200 °C, at a depth of 100–160 m below the paleogroundwater table; Molnár & Bajnóczi 1997). Field and paragenetic observations support a shallow steam-heated alteration which overprinted the earlier wall rock alteration and vein formation. Thus we con-

Table 4: K-Ar ages of volcanic rocks and hydrothermal minerals from the Mád area. Reference: 1 — Pécskay et al. (1986); 2 — Itaya et al. (1996).

Volcanic stage, type of hydrothermal alteration	Sample No	Location	Type of rock and mineral	K (%)	40Ar rad (%)	40Ar rad (10^{-6}ccSTP/g)	Age (Ma)	Average age (Ma)	Reference
FRESH ROCKS									
submarine flows	1191	Tállya-15 drillhole, 1195-1200 m	pyroxene andesite	0.65	16	0.363	14.2±1.3	-	1
4th volcanic stage, domes and flows	1189	Tállya-15 drillhole, 899-904 m	dacite	0.85	24	0.367	11.1±0.7	-	1
	1197	Tállya-15 drillhole, 518.6-556.7 m	rhyolite	1.29	21	0.604	12.0±0.8	-	1
	1008	Mád-24 drillhole, 17.2 m	rhyolite	3.95	25	0.187	12.2±0.7	-	1
	879	Bodrogszegi, Cigány Hill	pyroxene dacite	2.83	12 35	1.331 1.278	12.1±1.4 11.6±0.9	11.8±0.5	1
	4238	Bodrogkeresztúr Kakas quarry	rhyolite	4.27	55	2.124	12.8±0.5		this study
4th volcanic stage, intrusions and flows	1147	Mád-23 drillhole, 189.3-192 m	pyroxene andesite	1.44	14	0.645	11.5±1.2	-	1
	1137	Tállya, Kopasz Hill	pyroxene andesite	1.92	16	0.873	11.7±1.1	-	1
5th volcanic stage domes and flows	897	Mád, Harcsa Hill	rhyolite	4.16	72	1.761	10.8±0.8	-	1
	832	Bodrogszegi, Cigány Hill	pyroxene dacite	2.89	52 58	1.163 1.071	10.3±0.5 9.5±0.4	9.8±0.5	1
	880	Bodrogszegi, Cigány Hill	dacite	3.07	15	1.214	10.1±0.8	-	1
HYDROTHERMAL MINERALS									
acid-sulphate steam-heated	S35-134	Mád, Király Hill	alunite	8.7	25.4	3.705	10.9±0.3	-	this study
	S35-232	Mád, Mogyorós Hill	alunite	7.0	67.8	3.194	11.7±0.5	-	this study
	MAD FM	Mád, Mogyorós Hill	alunite	8.4	30.5	3.822	11.7±0.3	-	2

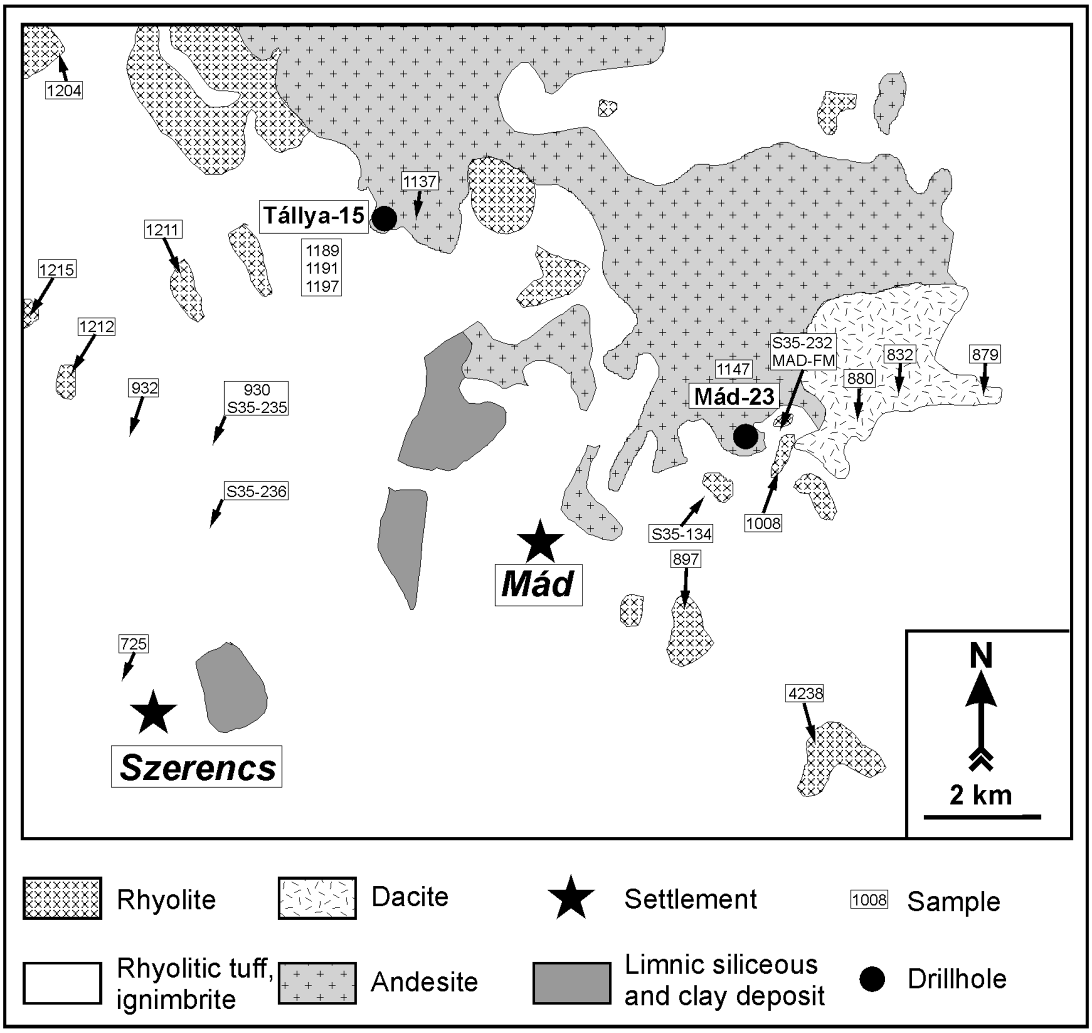

Fig. 5. Geological sketch-map of the southern part of the Tokaj Mts (redrawn after Gyarmati et al. 1976), with the location of samples for K-Ar dating from the Mád and Szerencs areas.

clude that hydrothermal activity was extensive and had multiple stages in the area northeast of Mád. In addition, between the major mineralization stages the level of paleogroundwater table changed significantly due to erosion and/or tectonic uplift.

K-Ar ages for alunite samples from various localities show a rather wide range, between 11.7 and 10.9 Ma (Table 4). The differences of these ages extend beyond the range of their standard deviation; therefore, radiometric ages also indicate the multiple and extended nature of hydrothermal activity in the area. Comparison of ages from alunite with those of volcanic rocks supports the idea that each volcanic period generated its own hydrothermal activity, and that this occurred in different paleorelief settings. However, the youngest dacitic volcanic rocks exposed on the Cigány Hil (Fig. 5, samples 832 and 880) are post-mineral.

Szerencs Hills

In the area of Szerencs Hills, felsic pyroclastic rocks and rhyolitic-dacitic domes and lava flows occur at the surface (Fig. 5). The oldest radiometric date is 12.2 Ma from a biotite sample of a dacitic lava flow (Table 5). The K-Ar ages for the rhyolitic lava flows in the uppermost levels of the volcanic sequence are between 11.7 and 11.3 Ma (Table 5).

The ignimbrite, rhyolitic tuff and re-deposited felsic tuff units of the area are the host rocks of several acid-sulphate steam-heated alteration zones. These are characterized by strong silicification in their centre surrounded by an alunite-kaolinite alteration halo (Molnár & Pécskay 2000). The K-Ar ages from alunite samples of these alteration centres have essentially the same range, between 12.4 and 10.4 Ma, as those for the volcanic rocks of the area (Table 5). This indicates that hydrothermal activity occurred at different periods of time in different localities, most probably related to different eruptions from the felsic volcanic centres.

Summary and conclusions

The results of detailed K-Ar dating indicate that polystage volcanism of the Tokaj Mts took place between 15.2 and 9.4

Table 5: K-Ar data for fresh rocks and hydrothermal mineral from the Szerencs area. Reference: 1 — Pécskay et al. (1986).

Volcanic stage, type of hydro-thermal alteration	Sample No	Location	Type of rock and mineral	K (%)	40Ar rad (%)	40Ar rad (10^{-6}ccSTP/g)	Age (Ma)	Reference
			FRESH ROCKS					
Domes and flows with pyroclastics	1204	Abaújszántó Sulyom Hill	rhyolite	3.80	75.0	1.717	11.6±0.4	1
	1211	Golop, drillhole 51.2-52.0 m (Somos Hill)	rhyolite, biotite	5.13	39.0	2.337	11.7±0.5	this study
	1212	Monok Őr Hill	rhyolite	3.86	30.0	1.697	11.3±0.5	this study
	1215	Monok Zsebrik	dacite, biotite	5.76	46.0	2.749	12.2±0.5	this study
			HYDROTHERMAL MINERALS					
acid-sulphate steam-heated	725	Legyesbénye, quarry	alunite	7.96 8.11	43 51	3.423 3.422	11.0±0.5 10.9±0.5	1
	930	Monok, Kassa Hill	alunite	8.79	40	3.677	10.7±0.7	1
	932	Megyaszó, Pipiske	alunite	2.75	27	1.112	10.4±0.7	1
	S35-235	Monok, Kassa Hill	alunite	8.52	59.3	3.760	11.3±0.4	this study
	S35-236	Szerencs, Fekete Hill	alunite	3.93	43.1	1.846	12.1±0.3	this study

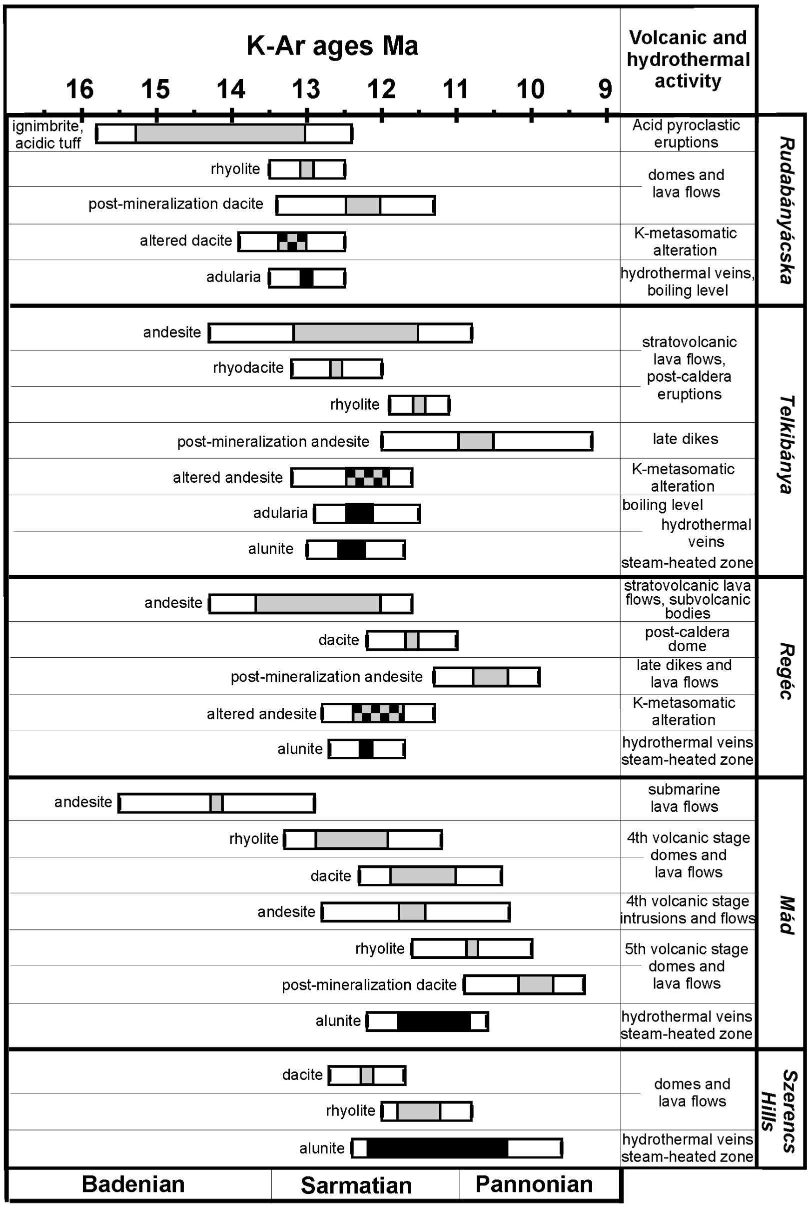

Fig. 6. Summary of K-Ar data from the various volcanic and hydrothermal centres of the Tokaj Mts. Shaded boxes: range of K-Ar data; Empty boxes: range of K-Ar data +/- standard deviations.

Ma (Fig. 6). This extended magmatism generated several hydrothermal systems in different parts of the region and there was repeated hydrothermal activity in some areas.

The K-Ar ages for the oldest hydrothermal systems are between 13.0 and 12.2 Ma (Fig. 6). These systems are related to intermediate (andesitic-dacitic) eruption centres characterized by subvolcanic bodies which locally intruded into stratovolcano and caldera-like structures in the northern part of the Tokaj Mts. Among these volcanic centres, the hydrothermal activity may be connected to the emplacement of dacitic intrusions at Rudabányácska. However, in the caldera-like structure near Regéc, hydrothermal alteration can be related to the evolution of an andesitic volcanism and extrusion of the dacite occurred after the hydrothermal mineralization. At Telkibánya, hydrothermal activity appears to be contemporaneous with andesitic and rhyolitic magmatism. The identical K-Ar ages for strongly altered (K-metasomatized) rocks with greater than 8 wt. % K_2O content and hydrothermal minerals from the same areas, indicate that such datings of completely altered rocks can be used to determine the ages of hydrothermal activity with a high confidence. The same ages for strongly altered (K-metasomatized) rocks, adularia, and alunite from some of these occurrences indicate that acid-sulphate steam-heated alteration at shallow levels was contemporaneous with adularia-sericite mineralization in the deeper levels of the same hydrothermal system.

In the southern part of the Tokaj Mts (in the vicinity of Mád and in the Szerencs Hills area), the ages of hydrothermal alunite are between 12.1 and 10.4 Ma; thus, the hydrothermal systems of this area are slightly younger compared to those of the northern part of the Tokaj Mts (Fig. 6). In agreement with this, hydrothermally altered areas in the southern Tokaj Mts are also less eroded in comparison to the northern Tokaj Mts. In the southern Tokaj Mts, the hydrothermal activity had an extended and polystage nature, suggesting that the felsic eruption centres that were active at different times generated several independent hydrothermal systems. Succeeding hydrothermal pulses at some localities are also recognized on the basis of an overprint of contrasting mineral assemblages.

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