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Paleovolcanic reconstruction in the Tokaj Mountains

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The Tokaj Mts, situated in the northeastern part of the inner arc of the Carpathians, forms a part of a Miocene calc-alkaline andesitic-dacitic-rhyolitic volcanic island arc. The ancient volcanic structures were reconstructed on the basis of the 1:50 000-scale and 22 sheets of the 1:25 000-scale geologic-petrologic maps, as well as the revision of the volcanic facies in 150 boreholes. Multispectral and SAR satellite imagery, aerial photos, data and maps of airborne geophysical surveys (magnetic and radiometric), gravity-filtered anomaly maps, geochemical (soil and stream sediment Au, As, Sb, Hg) concentration distribution maps and the K/Ar dating of 132 samples from 80 paleomagnetic measurements were also used.

The anomalies were only taken into consideration in the interpretation if the coincident results of at least 3 methods indicated the presence of any volcanic structure. In consequence, 91 map-scale volcanic structures were identified by morphology – complex calderas, single lava domes, volcanic fissures, subvolcanic intrusions, diatremes, stratovolcanoes and postvolcanic formations. Conclusions were also drawn regarding the link to the volcanic structures and prospective occurrences of the mineral resources of the Tokaj Mts: andesite, dacite, welded zeolitic tuff, K-metasomatite, perlite, pitchstone, pumice, bentonitic, illitic, kaolinitic, diatom-bearing and silicified lacustrine sediments, hydrothermal Au-Ag and Pb-Zn veins, and Hg stockwerks.

Key words: exploration methods, volcanoes, island arc, calc-alkaline, morphology, complex interpretation

Introduction

The subject matter was developed under the leadership of Tibor Zelenka by Pál Gyarmati, János Kiss, László Vértesy, István Horváth, Zoltán Pécskay and Emő Szalay, and was supported by OTKA project T022769. The study aimed at

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establishing an up-to-date approach to the paleovolcanic reconstruction of the Tokaj Mts based on geologic, volcanological, geophysical, geochemical and geomorphologic data.

Exploration history

Reviewing the publications on volcanology concerning the Tokaj Mts from the last 250 years, one can find remarkable statements from almost every author.

The essays of Beudant (1822), Richthofen (1861) and Wolf (1869) are the pioneers of the recognition of geologic formations. The fundamental monograph of Szabó (1867) entitled "Tokaj-Hegyalja és környékének földtani viszonyai" (Geologic features of Tokaj-Hegyalja and its surroundings) provided the basis for the recognition of the volcanic structure of the mountains. Szádeczky (1897) was the first to recognize that the amphibole andesite had broken through the rhyolite.

Pálfy (1927) studied the link between volcanism and ore formation. Rozlozsnik (1937) described rhyolite domes around Mád. The observations of Telegdi Róth (1935) are particularly important: according to him, at Szegi "the andesite rises transected the younger rhyolite tuff series". The monograph on the Szerencs Hills by Hoffer (1928, 1937) is an essay with a volcanological approach, meeting contemporary demands. Liffa (1940) described Tó Hill at Boldogkőváralja as a pyroxene andesite stratovolcano.

Intensive mineral resource prospecting in the middle of the past century also favored basic exploration. Lengyel (1959) specified in several publications the mineralogical and petrologic description of the andesite varieties. Zelenka (1964) recognized five acidic eruption phases in the Szerencs Embayment.

Székyné Fux (1970) linked the formation of the Telkibánya ores to a subvolcanic potassic trachyte body in her genetic model. In our recent view this is a subvolcanic andesite body subjected to potassic metasomatism. The statements of Pantó (1963) have a particular volcanological importance concerning ignimbrite genetics and the distinction between plutonic and volcanic facies (Pantó 1967). Jugovics (1962) recognized several undescribed subvolcanic bodies (Tállya, Erdőbénye) and an eruption center (Tarcal).

The modern geologic mapping of the Tokaj Mts was carried out in the period of 1959 to 1972, resulting in the "Geologic Map of the Tokaj Mts" (Gyarmati et al. 1977). The forerunner of the recent paleovolcanic reconstruction is the map entitled "Structural-volcanotectonic sketch of the Tokaj Mts" (Gyarmati 1977a), published as a supplement to the monograph "Intermediate volcanism in the Tokaj Mts" (Gyarmati 1977b). The author also published the schematic spatial and temporal connections of the volcanism in the "Tokaj Mts" chapter of the "Pannon Enciklopédia" (Pannonian Encyclopedia) (Gyarmati 1997).

The geochemical survey of the area was carried out through Finnish–Hungarian cooperation (Hartikainen et al. 1992, 1993).

Remote sensing was used first at Telkibánya to detect a double andesite caldera structure with rhyolite domes within and andesite parasitic cones at the rim (Horváth et al. 1989). The smaller subsequent tuff volcano structure with its radial and concentric quartz veins was also recognized.

Having collected the geologic, volcanological, geophysical, geochemical data and morphologic analyses made up to then, the modern volcanological map of the Tokaj Mts was drawn in 2000 (Fig. 1) and 2007 (Zelenka 2000; Zelenka et al. 2007). The fluid inclusion studies on samples from the hydrothermal centers of the area (Molnár et al. 1995, 1999) contributed to the determination of the pressure-temperature conditions of the ore generating fluids. Recent studies indicated ancient caldera structures and subvolcanic bodies around every hydrothermal-postvolcanic field (Molnár et al. 1999, 2002).

Spectral depth estimations were made around the centers using gravity and airborne magnetic sections to estimate the thickness of the andesite cover and the supposed depth of the basement (Kiss and Prácser 2000).

Geology of the Tokaj Mountains

In our studies the data on the geology and history of the Tokaj Mountains were revised (Gyarmati and Zelenka 2000; Zelenka 2000), shown in Figure 2.

As far as geology is concerned, the mountains can be divided into a western and an eastern unit. The western unit extends from the Hernád Lineament to the Hercegkút and Hosszúrét Creeks, with Sarmatian and Pannonian volcanic rocks and sediments on the surface. Although the basement is still unexplored, it is assumed to consist of Paleozoic shale on the basis of inclusions in pyroclastics. The eastern unit extends to the Ronyva Creek. In this unit the Proterozoic – Lower Paleozoic metamorphosed basement crops out in the north, while in the south a Mesozoic carbonate-dominated basement is overlain by Badenian volcanics and sediments.

The age of volcanism in the mountains ranges from 15 to 9 Ma BP, i.e. from Late Badenian to Early Pannonian, determined by K/Ar dating (Pécskay et al. 1986; Pécskay et al. 1995; Molnár and Pécskay 2002) and according to paleontological data (Fig. 2).

The character of the volcanism was calc-alkaline based on geochemical analyses of major elements (Fig. 3) and rare earth elements (Fig. 4). The magma possibly originated from the lower crust and the upper mantle.

The volcanism over the basement, originally in NW–SE zones and later during the continuously diminishing depth of the archipelego, shows 3 phases. At first phreatomagmatic eruptions produced large masses of rhyolitic-dacitic pyroclastite during the Early Badenian. In the next phase submarine peperitic, hyaloclastic andesite, andesite lava beds and stratovolcanic andesite continued the succession (according to the Tállya-15 and Füzérkajata-2 boreholes);

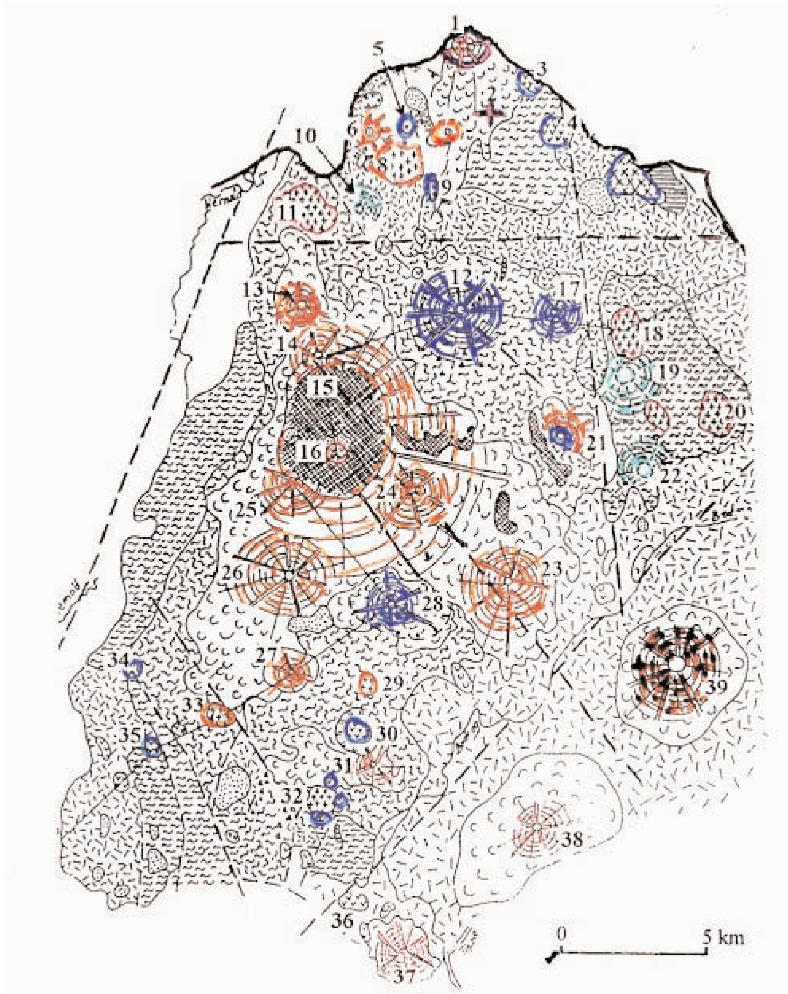

Fig. 1
Geologic-volcanological paleovolcanic reconstruction of 2000 (Gyarmati and Zelenka 2000). 1. Füzér, Remete Hill, dacite; 2. Füzér Castle, dacite; 3. Pusztafalu, Tolvaj Hill, rhyodacite; 4. Pusztafalu, Hársas, rhyodacite; 5. Hollóháza, Pál Hill, rhyolite; 6. Pányok, Nagy Hill, andesite; 7. Hollóháza, Május Hill, andesite; 8. Telkibánya, Kánya and Gyepü Hills, K-metasomatite; 9. Nyíri, Fehér Hill, rhyolite; 10. Telkibánya, Youth Camp, rhyolite tuff; 11. Gönc, Vas and Őr Hills, dacite; 12. Nagybózsva, Fekete Hill, rhyolite stratovolcano; 13. Gönc, Borsó Hill, andesite; 14. Hejce, Gergely Hill, upper laminar andesite; 15. Regéc, andesite caldera; 16. Regéc, Vár Hill, rhyodacite; 17. Kishuta – Pálháza, Som Hill, rhyolite; 18. Vágáshuta, Fekete Hill, dacite subvolcano; 19. Vágáshuta, Nyúl Spring, rhyolite tuff; 20. Sátoraljaújhely, Sátor Hill, dacite subvolcano; 21. Makkoshotyka, Katuska, andesite – rhyolite; 22. Sárospatak, Király Hill, rhyolite tuff; 23. Tolcsva, Fekete Hill, andesite; 24. Óhuta, Zabarla – Hajagos, andesite; 25. Arka, Amgoska, andesite; 26. Baskó, Nagy-Korsós, andesite; 27. Erdőbénye, Szokolya, olivine andesite; 28. Erdőhorváti, Szokolya, Nagy-Páca, rhyolite; 29. Erdőbénye, Mulató Hill, dacite subvolcano; 30. Erdőbénye, Spa, rhyolite; 31. Szegi, Cigány Hill, dacite; 32. Mád, Diós, andesite and rhyolite; 33. Tállya, Kopasz, andesite subvolcano; 34. Abaújszántó, Sátor – Krakkó Hill, rhyolite; 35. Golop, Somos, rhyolite; 36. Tarcal, Terézia Chapel, rhyolite; 37. Tokaj, Nagy Hill, dacite; 38. Zalkod, covered andesite, dacite; 39. Apróhomok, olivine basalt

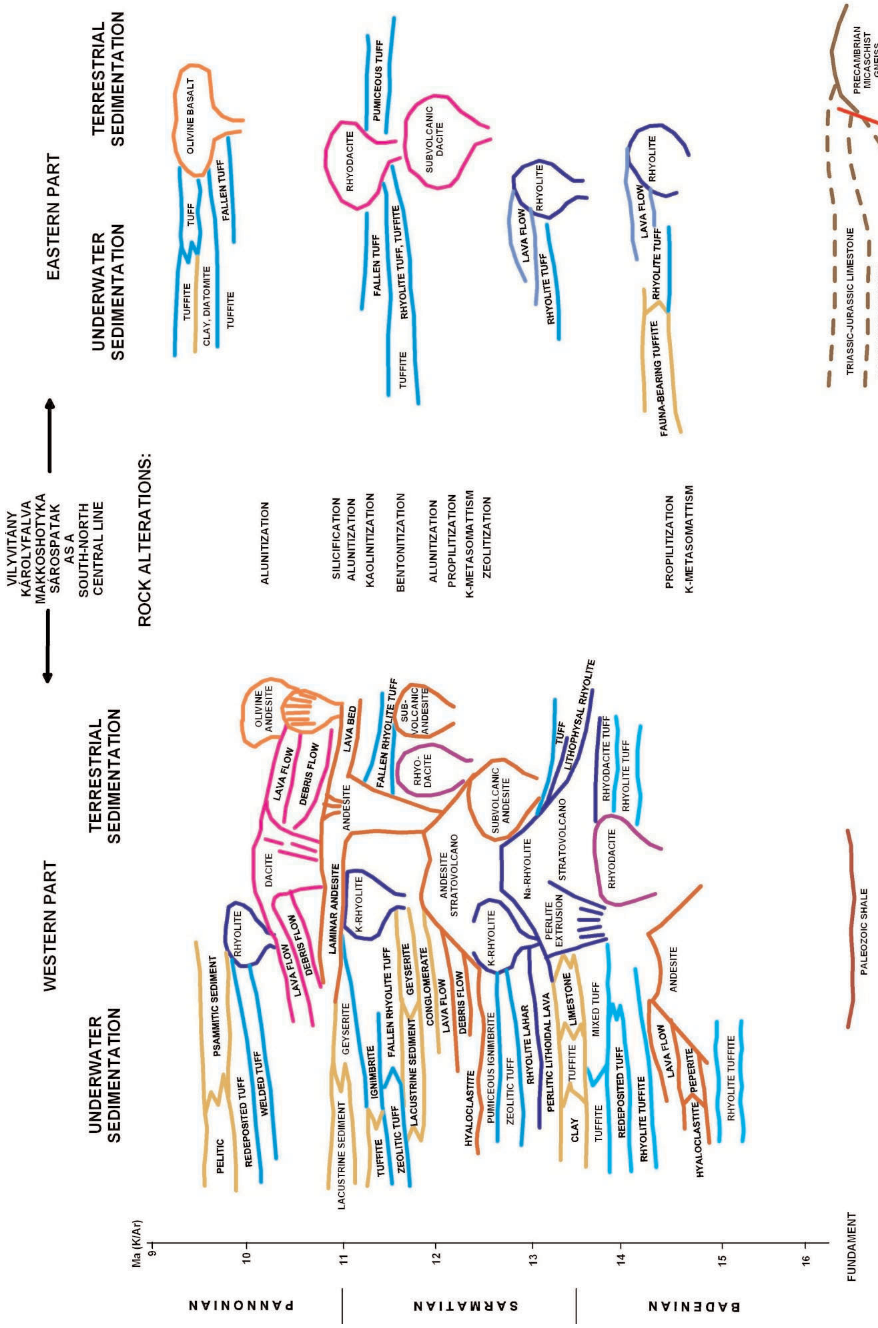

Fig. 2
Sketch of the geologic evolution (T. Zelenka)

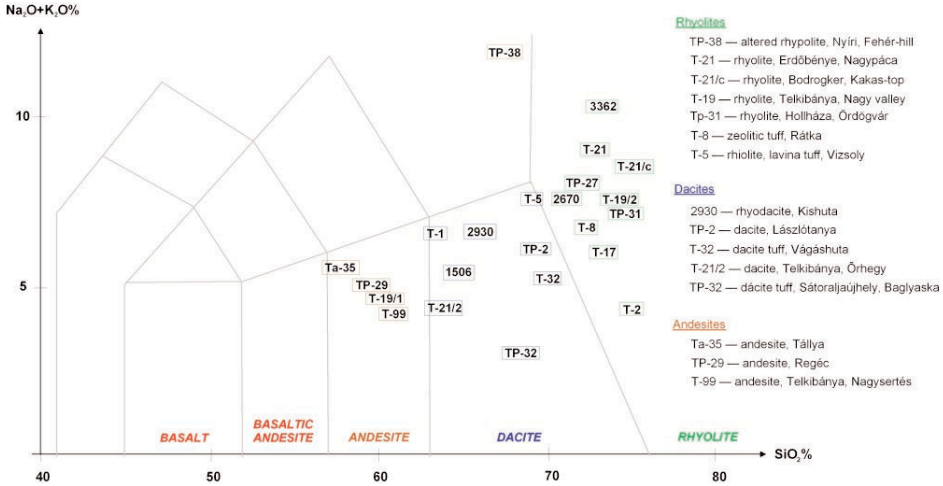

Fig. 3
TAS diagram of the Tokaj Mts volcanic rocks (P. Gyarmati)

thereafter the volcanic cycle was closed by dacitic subvolcanic intrusions (Sátoraljaújhely-8, Kishuta-1, Baskó-3 boreholes).

The phreatomagmatic eruptions, contemporaneously with transgression in the Early Sarmatian stage, produced large volumes of rhyolitic ignimbrite flows and fallen pyroclastics with small lava domes (Erdőhorváti–Szokolya–Nagypáca, Fekete Hill at Kishuta). Several stratovolcanic eruption centers were formed in the central part of the mountains (Hollóháza, Regéc, Mád), producing large masses of andesite and pyroclastics.

The subvolcanic andesite and dacite bodies of this volcanic phase were partly affected by potassic metasomatism (Telkibánya, Óhuta, Sárospatak, Mád). Simultaneous postvolcanic hydrothermal activity produced precious metal ore veins and clay deposits in lacustrine successions (Rátka, Hollóháza, Füzér-radvány, Erdőbénye).

At the Sarmatian–Pannonian boundary ignimbritic and ash-flow tuff originated from several minor rhyolitic centers (Vizsoly, Abaújszántó), bound to N–S striking tectonic zones. In the last phase of volcanism mainly dacite monovolcanoes with lava and debris flows were formed (Nagy Hill at Tokaj, Cigány Hill at Szegi). Olivine andesite domes, dykes (Erdőbénye, Szokolya) and an olivine basalt diatreme (Sárospatak, Apróhomok-10 borehole) indicate the final calc-alkaline volcanic activity.

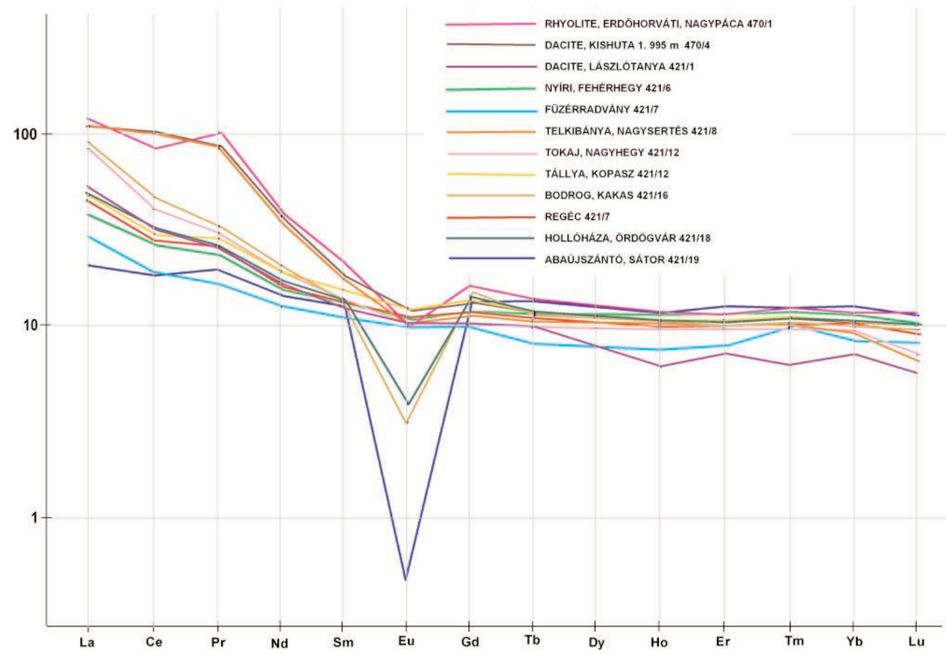

Fig. 4
Rare earth element contents of Tokaj Mts volcanic rocks normalized to chondrite (P. Gyarmati)

Applied exploration methods

Geologic–volcanological analysis

The 1:25 000-scale geologic map series drawn in the Geological Institute of Hungary between 1959 and 1972 under Gábor Pantó's direction, the summarized 1:50 000-scale geologic map depicting the entire Tokaj Mts (Gyarmati et al. 1972) and the above-mentioned tectonic map (Gyarmati 1977a) served as basis of our work.

The geologic work began with revisiting the sites and reviewing the logs of the major boreholes (667 units of mapping or structural exploration and several hundred mineral resource exploration holes). The logs were reinterpreted; the characteristic volcanic facies were identified. In the most important 150 boreholes the facies, the morphology, the genetics and the mutual relationship of the lava flows and pyroclastics were specified. According to geomorphologic observations the erosion of an at least 200–300 m thick section was considered from the end (?) of the Sarmatian, over the area of the entire Tokaj Mts.

Based on the original geologic map and the volcanological field observations in certain areas the modern paleovolcanic map of the Tokaj Mountains was compiled, indicating 39 supposed volcanic eruption centers (Fig. 1).

Morphological analysis based on remote sensing

The morphological criteria applied for identifying volcanic structures were based on the work of Cas and Wright (1988). These analyses were principally aimed at detecting the erosional morphological features, but the major volcanic and tectonic structures were also indicated (Zelenka 1997, 1998, 2000).

The seven channels of Landsat TM-5, the panchromatic Spot-1 scenes, and the data of previous airborne magnetic and radiometric surveys digitized by ELGI (Eötvös Loránd Geophysical Institute) provided the basis of an integrated volcanological interpretation (Kiss and Gulyás 1998; Gulyás et al. 2000).

The ancient ring-shaped escarpments of the tuff volcano at the Telkibánya shooting range, with the radial and concentric quartz vein outcrops, were identified (Horváth et al. 1989; Zelenka 2000). The ancient lava flows, pyroclastics, lava domes and the silicified and argillaceous sediments of the postvolcanic lake basins are well identifiable by stereo aerial photography. The eroded paleoshapes are also well recognizable on digital surface models made using SRTM data.

Based on satellite imagery the andesite calderas, the parasitic cones on their edges, the small rhyolite domes and the subvolcanic bodies within the calderas were reconstructed (Fig. 5). Landsat TM-5 2, 4 and 5 multispectral channel combinations and 5 and 7 single channel scenes proved to be the most appropriate for indicating eroded volcanic structures and volcanological interpretation.

Geophysical data interpretation

In the case of the Tokaj Mts gravimetry method plays an important role in the exploration of basement structures and the overlying high-density lava formations. Magnetic data specifically indicate the position of magnetite-bearing basic volcanic formations, even at some kilometers of penetration depth.

Radiometry (gamma-spectrometry) is limited to the exploration of the top layers to some 10 cm depth and to the indication of secondary alterations; it only indicates the underlying formations in the case of autochthonous soils.

1) Aeromagnetic map

The distribution of andesite and andesitodacite can be estimated from the data of airborne magnetic measurements. This parameter gives the best resolution among geophysical methods because of the variable susceptibility and geometry of the magnetite-bearing rocks.

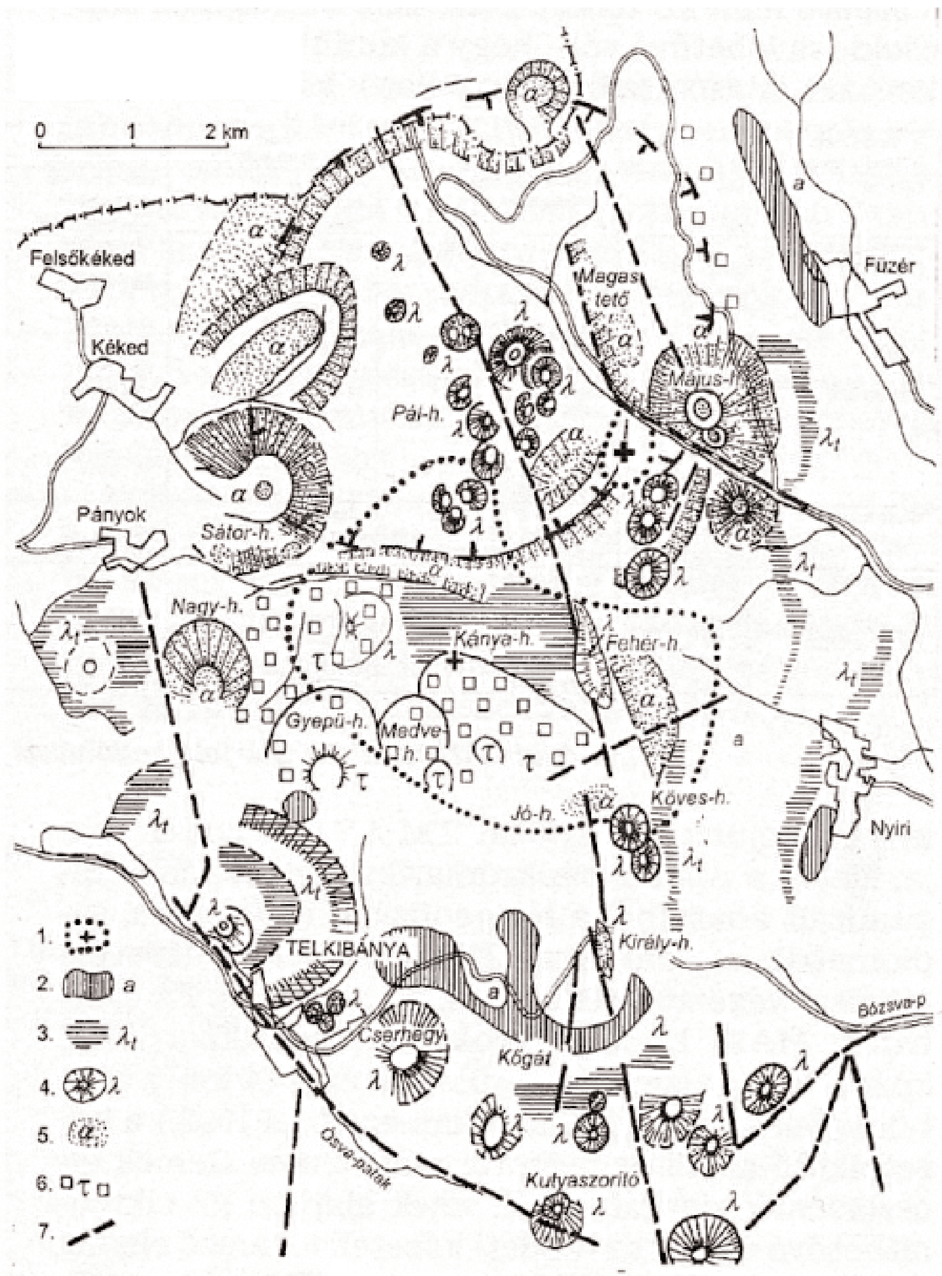

Fig. 5

Andesite caldera, subvolcanic body and rhyolite domes in the vicinity of Telkibánya (T. Zelenka). 1. gravity maximum; 2. sediment; 3. rhyolite tuff; 4. rhyolite dome; 5. andesite; 6. K-metasomatite; 7. tectonic lineament

2) Magnetic total gradient map

The nearest source bodies to the magnetic sensor cause the largest frequency and amplitude anomalies, with the highest gradients. The total magnetic gradient (or analytical signal) is appropriate for the demonstration of these changes (Fig. 6).

The value of the total magnetic gradient is high over outcropping volcanics. The anomaly pattern is very complicated, showing the inner complexity of the volcanic formations. In the case of covered lava formations the total gradient anomalies outline the lava bodies.

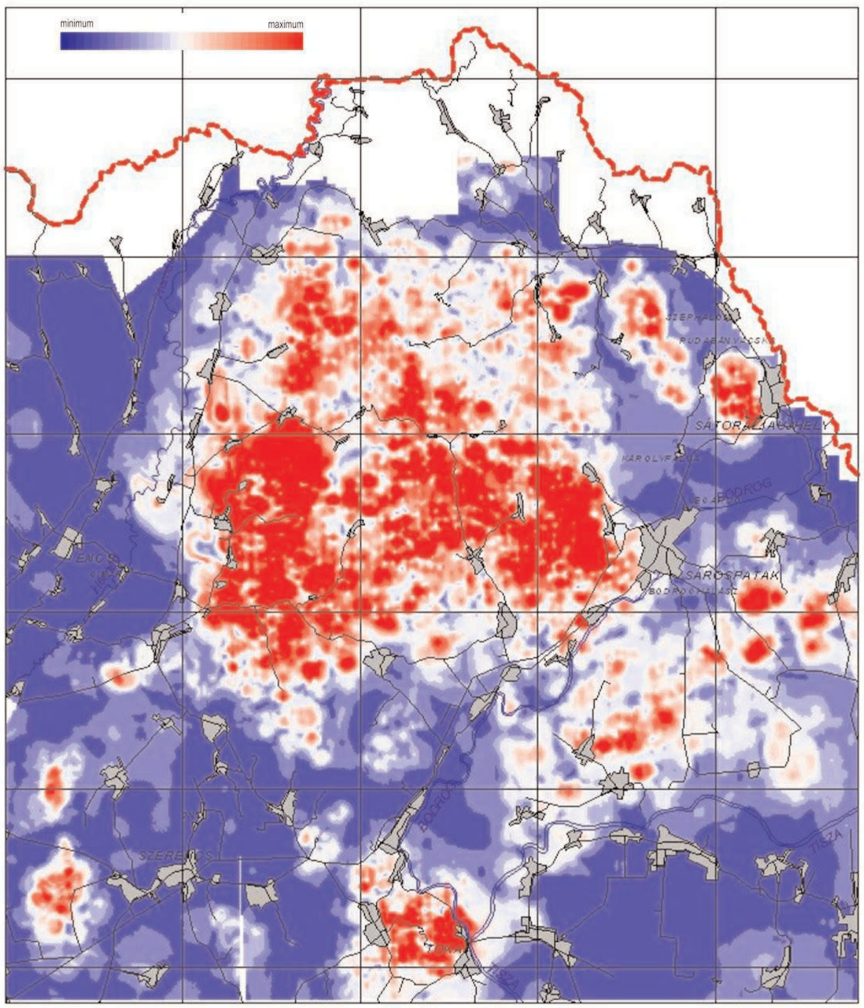

Fig. 6
Total magnetic gradient map from the data of the airborne survey (J. Kiss)

3) Bouguer gravity anomaly map

One of the most apparent gravity anomalies of the area is the large northern gravity minimum, but its origin was not clarified by our interpretation. The pattern of the Bouguer gravity anomaly map (with a reduction density of 2000 kg/m^3) is basically correlated with the basement surface, but the effect of volcanics strongly influenced the gravity field due to the overlapping of the density ranges of volcanic and basement formations. The largest paleovolcanic eruption centers are well recognizable on the Bouguer anomaly map, appearing as gravity maxima.

4) Filtered Bouguer anomaly map

Some eruption centers in the area of the large gravity minimum, which are easy to find at surface or also on satellite scenes, cannot be seen on the original Bouguer anomaly map. The low-frequency effects of deep sources can be filtered out from the Bouguer anomaly map using digital data processing (high-pass filters with 15–30 km wavelength, 1000–1300 m penetration depth), and the effect of the shallow high-density volcanic formations, like andesite and rhyolite, appears (Fig. 7).

The process of edge detection was based on the frequency-filtered Bouguer anomaly maps. The map representation of the results of high-pass filtered data provides a lineament map showing the rock bodies of upper volcanic series, while the low-pass filtered map may give important interpretational help in the construction of the structural geologic map (representing the basement and the volcanic root zones) of the area.

5) Airborne radiometric map (Th, K, U)

The maximum values in the airborne thorium distribution map are apparently associated with the rhyolite ignimbrites, or lava domes (Fig. 8), and these are typical for the Szerencs–Mád ignimbrite and Erdőhorváti rhyolite tuffs as well, which fill in the inner part of rhyolite calderas. The uranium maximum values can be found in the area of rhyolitic hydrothermal volcanic centers.

The largest maximum values (5–8%) of potassium indicate K-metasomatism or alunitization, characteristic for the alterations of subvolcanic andesite rock bodies and for the zones of postvolcanic activity (Telkibánya, Óhuta, Sátoraljaújhely, Mád, Regéc, Szerencs).

6) Seismic measurements

The reason for the scarce availability of seismic data in the Tokaj Mts is the adverse geologic model. Seismic sections are restricted to the edges of the mountains, and these were recorded for exploration of the basement and supposed salt dome structures, so the seismic data are not very useful for paleovolcanic reconstruction. Practically, there was no seismic survey within the mountain range. The only short one, a 1200 m-long reflection seismic section, was

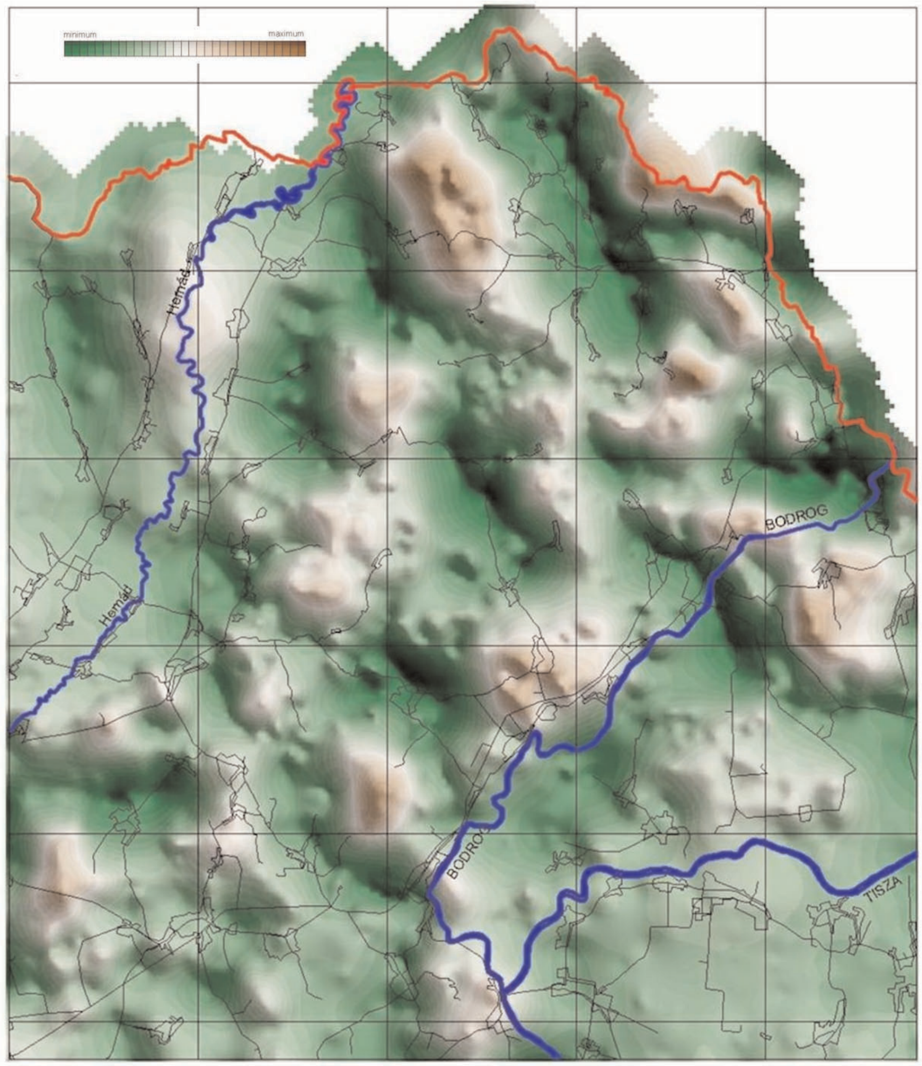

Fig. 7
Filtered Bouguer anomaly map (high-pass, 15 km) with shading (J. Kiss)

recorded S of Mád to explore the thickness and deposition surfaces of volcanic (tuff flow) and marine sediments.

A deep seismic refraction tomography survey (CELEBRATION–2000 project) was carried out in Hungary, yielding a three-dimensional velocity data set. One of the seismic profiles (the CEL4) crossed the southwestern edge of the Tokaj Mts, partly revealing the root zone of the Szerencs caldera structure (there is an upper crust-like velocity anomaly at 8 km of depth, which is presumably caused by the remainders of a magma chamber; Hegedűs et al. 2002).

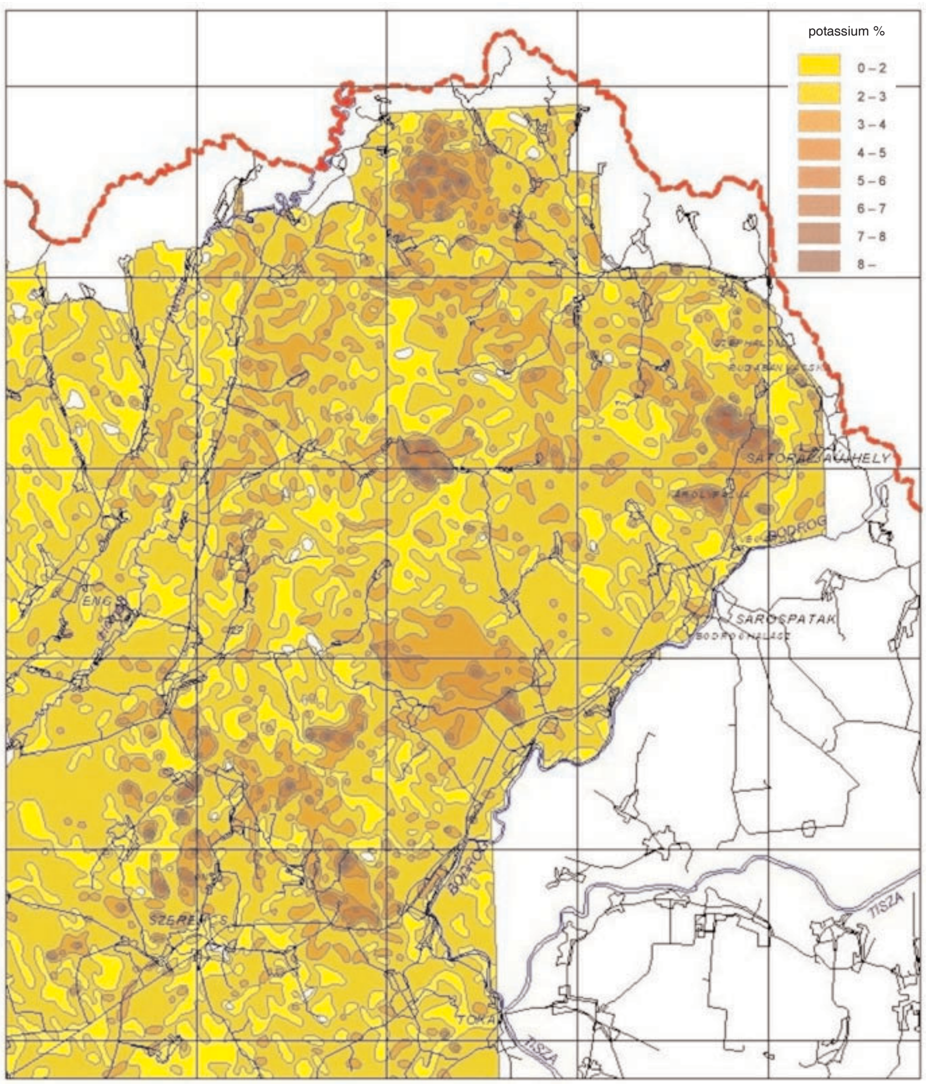

Fig. 8
Airborne radiometric potassium map (J. Kiss)

Geochemical surveys

Stream sediment, soil and rock samples were taken from 0.7 km^2 (on average) water discharge areas in the 1989–1992 period within the framework of a regional geochemical survey of the Hungarian Geological Institute.

Chemical analyses were made using the AAS method on nearly 690 stream sediment and more than 200 rock samples; here only the K, Na, Au, As, Sb and Hg data were considered. The primary aim was precious metal prospecting (Hartikainen et al. 1992, 1993). The secondary migration of the selected 6 elements is typically related to synmagmatic and postvolcanic hydrothermal processes. The Na distribution shows the composition of the volcanic formations in the mountains: the 0.5–2.0% range is characteristic for andesite, the 2.5–3.5% range for rhyolite. K content below 3% also characterizes andesite, in the range of 3–5% acidic volcanites, while K-metasomatized rocks contain more than 5% K.

The traces of postvolcanic activity in the volcanic formations can be found mainly at the ancient fumaroles, solfataras etc. The Au, Ag and accompanying As, Sb anomalies coincide with the eruption centers, Hg enrichments are at a distance from these. Complex (Au–As–Sb–Hg) anomalies are situated between or around eruption centers, or in areas subjected to K-metasomatism (Fig. 9).

Paleomagnetic surveys

Paleomagnetic surveys were carried out in the Tokaj Mts from 1970 (Fig. 10) on some outcrops of the major rock types (Nairn et al. 1971).

A systematic paleomagnetic survey began from the 1990s by Emőke Márton-Szalay (Hungarian Geophysical Institute). From 1996, aiming to clear up the relationship between geologic, paleomagnetic and radiometric age data, specialists undertook common observations and sampling at outcrops of supposed eruption centers. At present more than 80 paleomagnetic measurements are available. The summarized interpretation of these, together with radiometric age determinations, is the topic of a separate paper (Szalay et al. 2007).

Radiometric age determinations

The K/Ar method was applied already from the 1970s by Kadosa Balogh (ATOMKI). The age data of the most important formations were determined by Zoltán Pécskay (ATOMKI) and his co-workers in the 1980s at the University of Debrecen, following the initiative of Vilma Székyné Fux. In the 1990s a coordinated sampling from outcrops and drill cores provided a large dataset. Up to the publication of this paper more than 132 individual K/Ar method radiometric ages have been provided from the mountains, of which only the ones connected to eruption centers are considered here (Fig. 10). Detailed paleomagnetic and radiometric age data with geologic interpretation were prepared for publication (Szalay et al. 2007).

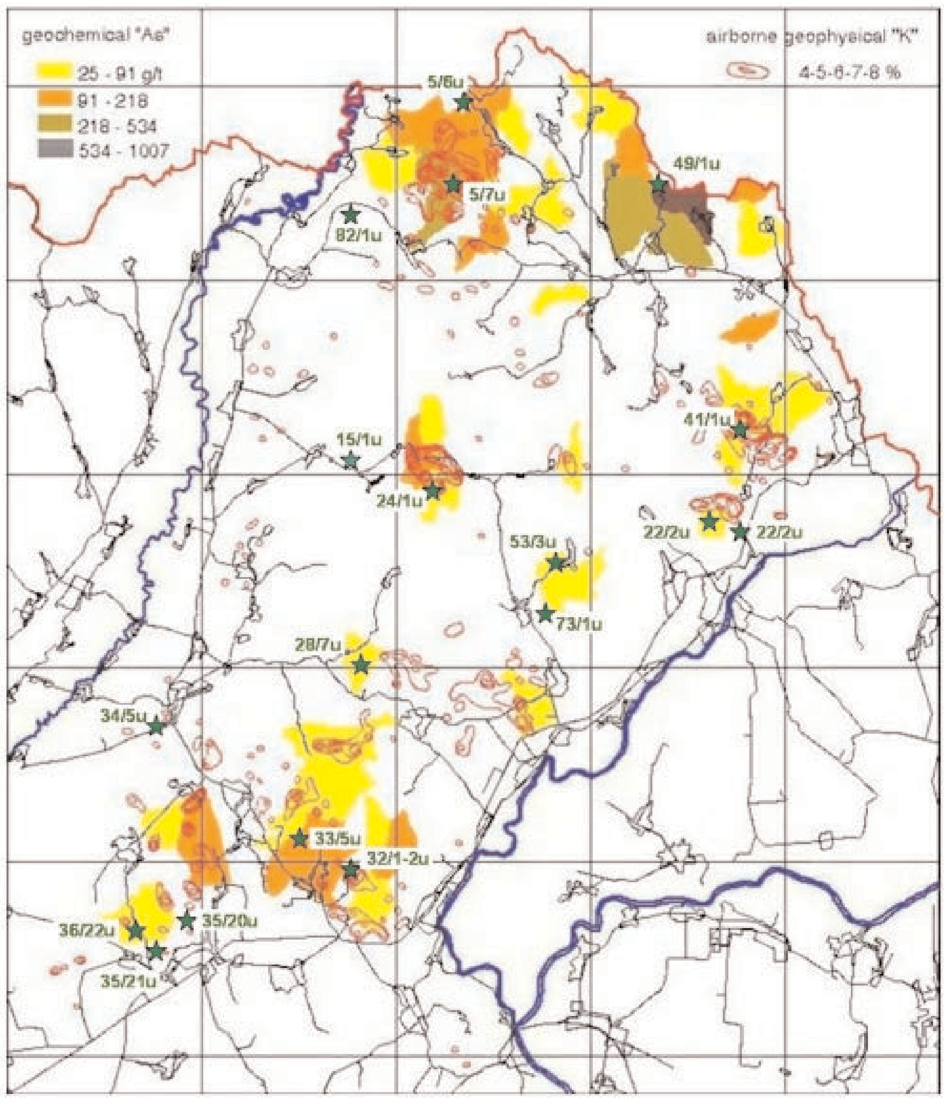

Fig. 9
Geochemical As (I. Horváth) and airborne radiometric K (J. Kiss) distributions with ore and other mineral resource occurrences in the areas of postvolcanic activity (T. Zelenka)

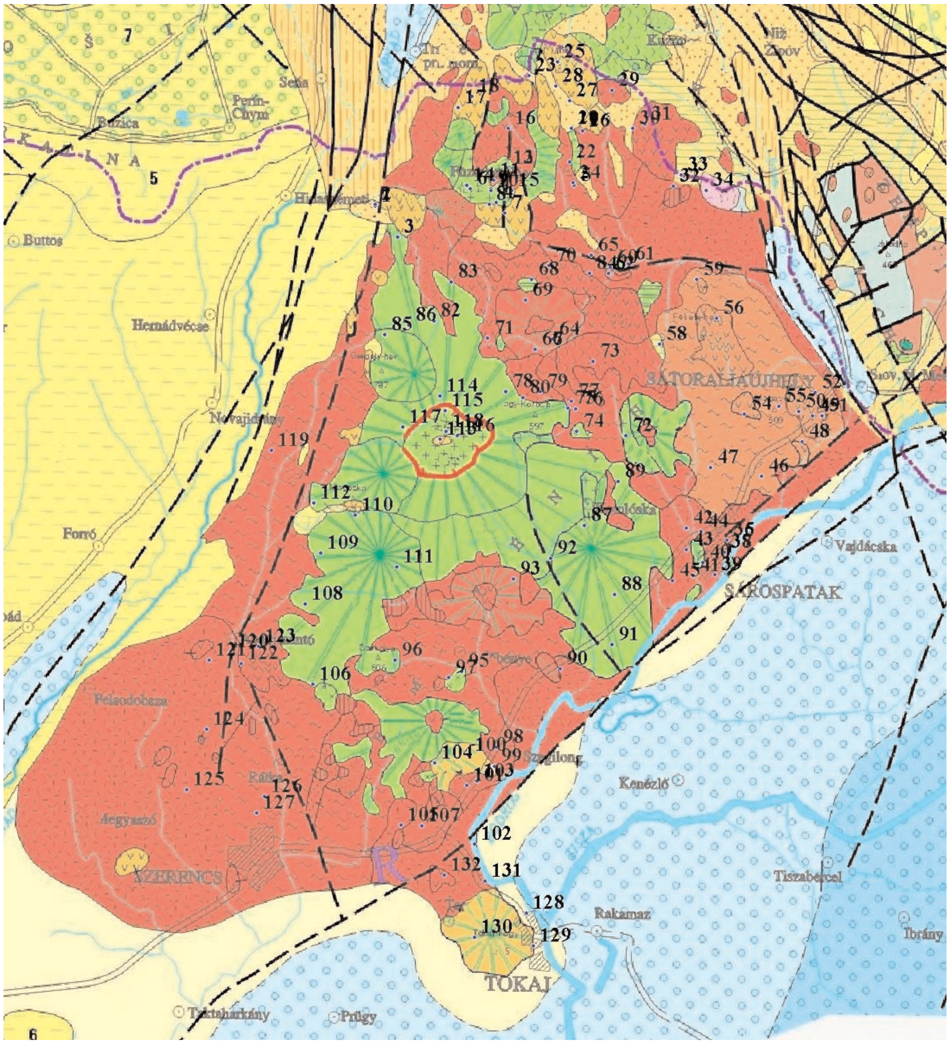

Fig. 10
Sites of paleomagnetic and K/Ar age sampling (Szalay et al. 2007)

Identified volcanic structures of the Tokaj Mountains

Beyond the methods above, our experience, observations and published data on recent volcanic areas were also utilized to identify of Tokaj volcanic structures. Detailed descriptions are given only for the most typical ones of these structures.

The parallel use of several exploration methods allowed us to deduce the eroded location and extension of the eruption centers, but the given datasets do not allow the full reconstruction of the volcanic structures. The data from boreholes in the mountains, which are more than 500 m deep (Ond-19, Mád-23, Tállya-15, Erdőhorváti-13, Baskó-3, Hidasnémeti-1, Telkibánya-2, Füzérkajata-2, Széphalom-1, Rudabányácska-2, Sátoraljaújhely-8, Sárospatak-3, Sárospatak-7), indicate that lava and pyroclastic product sequences of several eruptive phases can be followed up to 1–5 km from the supposed centers (Fig. 2).

The schematic maps (Figs 11 and 12) and Table 1 show the identification number of the sites and the rock names (a=andesite, r=rhyolite, rd=rhyodacite, d=dacite, rf=rhyolite tuff). The positions of the numbered volcanic centers are marked with a dot on the map. The maximum accuracy of the identification of the structures is 10 m, according to the resolution of the applied satellite imagery.

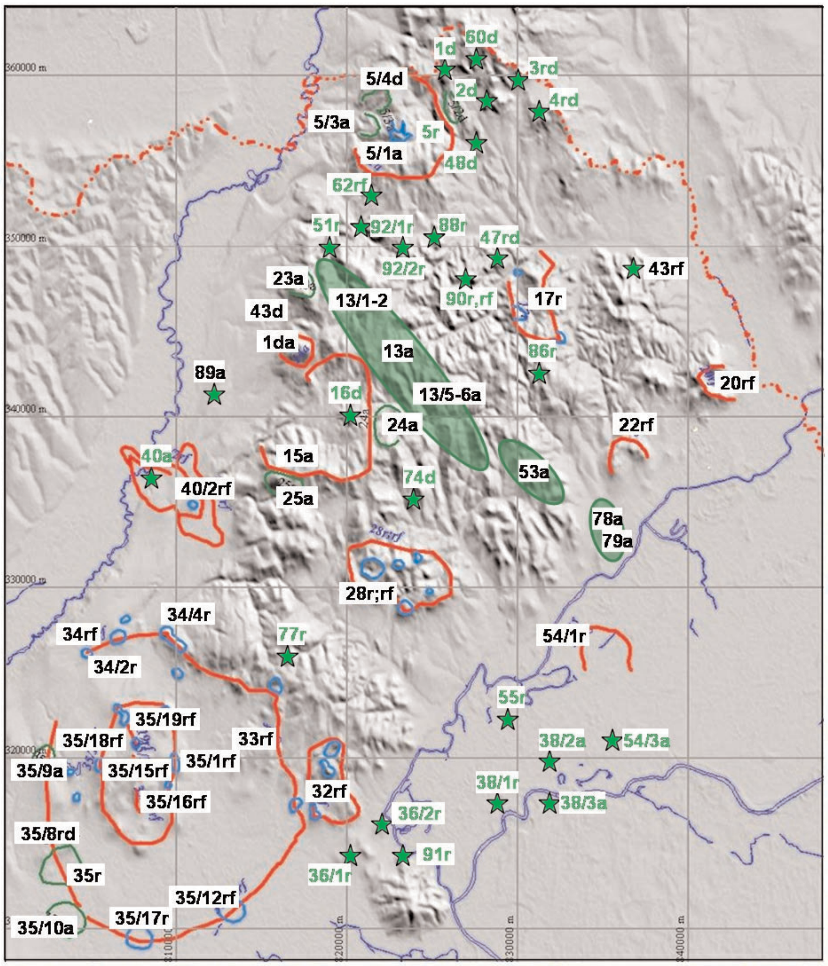

Fig. 11
Caldera structures (red lines), single lava domes (green stars), volcanic fissures (green poligons) (T. Zelenka, J. Kiss)

The text and the attached tables include the rock name and the exploration methods indicating the given volcanic center (geology, remote sensing, gravity, magnetics, radiometry and geochemistry). Generally there were the congruent results of more than one method applied to indicate a supposed center. In the area covered with young sediments (Bodrogköz, Szerencs Creek, Hernád Valley) the buried eruption centers and the type of the lava and pyroclastic bodies in depth were mostly only identified by geophysical data, as outcrops and

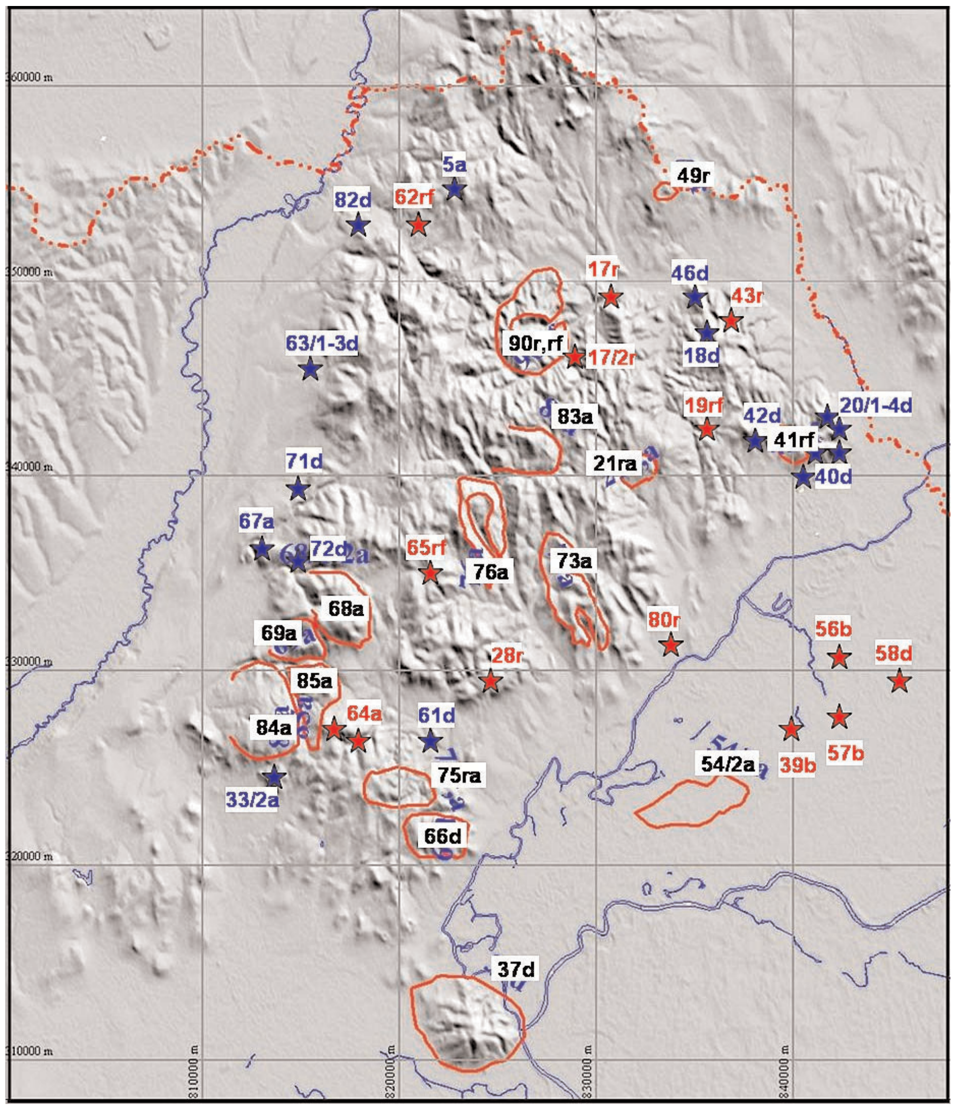

Fig. 12
Subvolcanic bodies (blue stars), diatremes (red stars), stratovolcanoes (red lines) (T. Zelenka, J. Kiss)

boreholes were scarce or lacking. Beyond the 90 centers identified by complex geologic and remote sensing data in this study, we estimate their number to be nearly twice as many based on geophysical interpretation.

Caldera structures

These are oval ring structures with a diameter of several km. Typical features are the escarpments with sharp morphology and the diversified inner parts. Collapsed calderas show a considerable difference of level between the escarpments and the inner part. The escarpments consist typically of multiple bedded, hard pyroclastics, with a series of acidic (rhyolite, dacite) lava domes and intermediate (andesite, andesitic dacite) parasitic cones on the top. In some cases subsequent subvolcanic bodies can be recognized beside the escarpment. More than 100 m-thick pyroclastic flows, ignimbrites, hyaloclastic and peperitic lavas which flowed into water and tuffites with fauna are characteristic of the inner parts of the calderas. In the central zone subsequently intruded lava domes rise above these. Hard silicified 'cap rocks' originating from the hydrothermal water basins of the postvolcanic activity are widely distributed here. In some cases these hydrothermal zones are situated between some rising domes. The zones of different structure and material are easy to distinguish on airborne geophysical maps, satellite imagery and SAR imagery (Fig. 11).

In the following section a list of the caldera structures identified so far is given. Some structures are also introduced in detail.

Szerencs Caldera (34rf, 34/2r, 35rf, 35r and 35d in Fig. 11)

The Szerencs Hills ("Inselbergs") and the Szerencs Creek Valley are regarded as part of a large, recently strongly eroded, partly tectonically subsided caldera, which had never previously been identified. The methods for identification of rhyolitic calderas are demonstrated in detail with this example.

The satellite scene, the total magnetic gradient map (Fig. 6) and the Celebration–2000 CEL–4 deep seismic section and the velocity distribution maps (Hegedős et al. 2002) outline a buried ring structure of approximately 25 km diameter between Abaújszántó and Szerencs. The radar, filtered gravimetry and magnetic total gradient maps also outline the inner and edge zones of the caldera as ring-shaped steps. In the center there is a gravity source body of 1–2 km in diameter at 900–1700 m depth; it is possibly a buried subvolcanic body. On the surface it is surrounded by small, composite rhyolite-dacite domes and their lava flows of 1–2 km in diameter along a circle 3–6 km in diameter at Monok (35/4-5rf, 15-19rf), Golop (35/3r) and Ond (35/1rf), belonging to the inner caldera structure. These are shown as filtered gravimetric and radiometric maxima. Their measured K/Ar age is 11.3–12.2 ± 0.5 Ma (Molnár and Pécskay 2002).

Table 1
Summary of the eruption centers

	Name of the volcanic centre	Coordinates of the center		Size						
		X	Y	m×m	a	b	c	d	e	f
	Szerencs Caldera									
34/1rf	Abaújszántó, Fehér Hill, rhyolite tuff (ignimbrite)	807079	828216	1500x1000	+		+	+	+	+
34/2r	Abaújszántó, Sulyom Hill, rhyolite dome	806438	326949	750x750	+				+	+
34/3r	Abaújszántó, Süveges Hill, rhyolite dome	804745	326183	800x400	+		+			
34/4r	Abaújszántó, Sátor – Krakó Hill, rhyolite dome	809437	327340	2000x1000	+	+			+	
35/1rf	Ond, Kassa Hill, rhyolite tuff (ignimbrite)	807950	318146	1500x1000	+		+		+	+
35/2rf	Szerencs, Fekete Hill, rhyolite tuff flow	807600	317400	500x500	+	+			+	
35/3r	Golop, Somos, rhyolite dome	809357	322883	1500x1000	+	+	+		+	+
35/4r,rf	Monok, Őr Hill – Szőlő Hill, rhyolite dome with ignimbrite	806498	322893	1500X800	+				+	+
35/5r	Monok, Szentes Hill, rhyolite dome	807690	320960	1000x500	+	+			+	+
35/6r	Monok, Ing-vár, rhyolite dome	803804	319177	250x250	+	+1				+
35/7r	Monok, Kaptár – Pipiske, rhyolite dome	803124	317750	1000x1500	+				+	
35/8 rd	Legyesbénye, Majos Hill, rhyodacite dome	803363	215076	500x750	+		+	+	+	+
35/9a	Megyaszó, Nagy-Répás, andesite dome	802602	319868	1500x750	+	+	+	+		
35/10a	Legyesbénye, Dobogó, andesite	803500	310500	500x750	+		+	+		
35/11r	Taktaszada, rhyolite dome (buried)	808000	309550	1500x1500			+	+		
35/12r	Prügy, rhyolite dome (buried)	813000	311500	1500x1500			+	+	+	
35/13d	Monok, Zsebrik, dacite dome	805436	319698	1500X600	+		+		+	
35/14r	Tállya, Patócs Hill – Akasztó Hill, rhyolite dome	805486	319698	1500x600	+		+		+	+
35/15rf	Monok, Kővágótető, rhyolite tuff inside the caldera	807740	319370	1500x1000	+	+				
35/16rf	Monok, Nyíres, rhyolite tuff inside the caldera	807680	317520	2000x1500	+	+				
35/19rf	Monok, Szentes Hill, rhyolite tuff inside the caldera	807370	331350	1500x1000	+	+			+	+
33/1r,rf	Tállya, Dorgó-tető – Fürdős-tető, rhyolite, ignimbrite	815958	323955	2500x2000	+		+		+	
	Hollóháza Caldera									
5a,r	Hollóháza – Telkibánya, andesite with rhyolite dome	821506	357136	7000×8000	+	+	+	+	+	+
5r	Hollóháza, Pál Hill, rhyolite dome	822750	356450	1000x1000	+	+	+		+	
5/2d	Hollóháza, Május Hill, dacite dome with lava flow	826020	357880	1000x250	+	+				
5/3 a	Pányok, Tilalmas, andesite parasitic cone	821510	357140	1000x1000	+	+	+	+		
5/4 d	Kéked, Les Hill, dacite parasitic cone	821570	358590	1000x1000	+	+		+		
5/5 a	Telkibánya, Gyepü Hill, andesite subvolcano	823080	354690	1500x1500	+	+			+	+
	Regéc caldera									
15a	Regéc, andesite caldera	818792	339965	8000×7000	+	+				
16d	Regéc, Castle Hill, dacite (dome)	820184	339844	500×500	+	+	+	+	+	+
14a	Regéc, Gergely Hill, andesite	817480	343881	500x500	+	+		+		
25a	Arka, Magoska, andesite	816118	336239	2000x2000	+	+	+	+		
24a	Óhuta, Zabarla, andesite	802602	319868	1000x500	+	+				
23a	Gönc, Borsó Hill, andesite	817370	347306	1000x1000	+	+		+		
	Boldogkő caldera									
40/1r,rf	Boldogkőváralja, Szentiván Hill, rhyolite caldera	810750	335000	5700x1700	+	+		+	+	
40/2 rf	Boldogkőváralja, Boldogkő Castle, rhyolite tuff dam	811600	335500	1500x250	+	+	+	+	+	
40/4 rf	Vizsoly, quarry, degassed rhyolite tuff, ignimbrite flow	810500	339000	1000x1000	+	+				
40/3 a	Alsócéce, andesite dome (buried)	808610	336090	800x800			+	+		
	Viss caldera									
54/1 rf	Viss, Patkó-zug, rhyolite tuff (buried)	835000	326600	2500x2500			+	+		
54/2 a	Viss, Patkó-zug, andesite dome (buried)	835020	323030	500x500?			+	+		
	Pálháza caldera									
17	Pálháza, Som Hill, rhyolite dome and lava flow	831181	348022	5000×2000	+	+			+	+
17/1r	Pálháza, Gyöngykő Hill, rhyolitic perlite dome, diatreme	830300	349200	1000x1000	+	+			+	
17/2r	Kishuta, Laczkó Hill, rhyolitic perlite dome	829200	346800	600x400	+	+			+	
47rd	Nagybózsva, Páska-tető, rhyodacite dome, diatreme	828868	348864	600x500	+	+			+	
17/3 r	Nagyhuta, Gilevár, rhyolitic perlite dome	828200	346400	500x500	+	+			+	
22	**Sárospatak**, Király Hill, Megyer Hill	836379	338327	3000×1000	+	+			+	
	Erdőhorváti – Erdőbénye caldera									
28 r,rf	Erdőbénye – Tolcsva – Erdőhorváti, rhyolite (with ignimbrite flows)	823019	331471	5000×3000	+	+	+	+	+	
28/6rf	Ránytető, rhyolite ash flow	824721	329353	750x500	+	+	+	+	+	
28/1r	Erdőhorváti, Szokolya, rhyolite dome	823019	331471	750x750	+	+			+	
28/2r	Nagy-Páca, rhyolite dome	824831	330755	500x500	+	+			+	
28/3r	Rakottyás, rhyolite dome	824851	329779	500x500	+	+			+	
28/4r	Peres Hill, rhyolite dome	823479	328852	750x750	+	+			+	
28/5r	Nagy-Mondoha, rhyolite dome	821086	330825	1250x750	+	+			+	
	Mád caldera									
32	Mád, Diósd, andesite and rhyolite (subvolcanic and dome)	818600	320500	2000×2000	+	+			+	+
32/1r,rf	Mád, Király Hill, rhyolite dome, rhyolite tuff, ignimbrite	818950	318210	1000x500	+	+			+	
32/2 rf	Mád, Bomboly, rhyolite tuff, ignimbrite	818170	320330	500x500	+	+			+	+
32!3 r,rf	Mád, Szemere-tető, rhyolite, fallen rhyolite tuff	818600	314800	500x500	+	+			+	
32/4 r,rf	Bodrogkeresztúr, Kakas, rhyolite, rhyolite tuff	820400	317400	1000x500	+	+			+	
	Volcanic fissures									
13/2/ 1a	Telkibánya, Magas-Tér – Hemzső-bérc, andesite	820154	349580	3000×500	+	+		+		
13/2/ 2a	Telkibánya, Holló-kő – Nagy-Sertés Hill, andesite	822388	344982	2000×500	+	+		+		
13/1/ 1a	Gönc, Amádé-vár – Téglás-kő, andesite (3 samples)	818832	347847	1500×1000	+	+		+		
13/1/ 2a	Hejce, Bán Hill – Szár-kő, andesite	819713	344261	1000×1000	+	+		+		
13/6a	Nagyoldal-tető – Nagy-Péter-mennykő, andesite	822830	342200	2000×700	+	+		+		
13/5a	Ilonka Meadow – Sólyom-bérc, andesite	820370	344810	1000×700	+	+		+		
13/2/ 3a	Regéc, Nagy-Bekecs – Tokár-tető, andesite	821707	347607	2500×700	+	+		+		
53a	Komlóska, Nagy-Papaj, andesite	830871	336214	1000x1000	+	+	+	+		

a – Geology, b – Remote sensing, c– Gravity, d – Magnetics, e – Radiometry, f – Geochemistry

Table 1
(Cont.)

	Name of the volcanic centre	Coordinates of the center		Size						
		X	Y	m×m	a	b	c	d	e	f
78/1- 3a	Sárospatak, Szent Vince Hill – Páncél Hill, andesite – Hercegkút, Gombos	834717	334671	3000×200	+	+	+	+		
79/1- 2a	Sárospatak, Mandulás – Kutya Hill – Bodroghalász andesite	835198	334176	3000×200	+	+	+	+		
	Subvolcanic bodies, intrusions									
46d	Kovácsvágás, Baradla, dacite subvolcano	831141	342514	1000×200	+	+		+	+	
20/1-3d	Sátoraljaújhegy, Magas Hill, Szár Hill, Vár Hill, Sátor Hill, dacite subvolcanoes	841948	342243	3000×3000	+	+	+	+		
20/4d	Sátoraljaújhely, Vár Hill, dacite subvolcano	841397	341372	250X250						
40d	Sátoraljaújhely, Néma Hill, dacite subvolcano	840836	339885	2000×1000	+	+		+		
42d	Rudabányácska, Száva Hill, dacite subvolcano	838252	342043	2000×1000	+	+	+	+	+	+
18d	Kovácsvágás – Vágáshuta, Fekete Hill – Osztra Hill NE, dacite subvolcano	836109	346911	1500×600	+	+	+	+		
17/2r	Pálháza– Kishuta, Gilevár, perlite extrusion	831181	348022	500×500	+	+	+		+	
33/2a	Tállya, Gomboska – Kopasz Hill, pyroxene andesite subvolcano	813704	324536	800×800	+	+		+		
61d	Erdőbénye, Mulató Hill, pyroxene andesite subvolcano	821677	326143	2000×500	+	+	+	+		
63d	Hejce, Tilalmas, 3 samples of N-S dacite subvolcanoes	815236	345593	2000×1000	+	+	+	+	+	
67a	Boldogkőváralja, Tó Hill, andesite	812803	336439	2000×1000	+	+	+	+		
71d	Korlát, Répás, dacite	814736	339594	250x250	+	+		+	+	
82d	Gönc, Vas Hill, dacite	817650	353055	1000x1000	+	+	+	+	+	+
	Diatremes									
64a	Erdőbénye, Szokolya, andesite	817360	326894	500x500	+	+		+		
65a	Baskó, Horváthkút Meadow, rhyolite tuff	821596	334842	500x500	+	63	+			
62rf	Telkibánya, Youth camp, rhyolite tuff	820595	352695	1500x1000	+	+			+	
19rf	Sárospatak, Nyilazólyuk (Nyílkút), rhyolite tuff	835889	341983	500x500	+		+			
39b	Sárospatak, Apróhomok, basalt	840000	327000	500x500	+			+		
28/6rf	Erdőbénye, Kőgát, rhyolite tuff	824721	329353	250x250	+	+			+	
43rf	Mikóháza, Baradla, rhyolite tuff	837051	347962	500x500	+	+			+	+
56b	Vajdácska, Várhomok, basalt? (buried)	842410	330650	500x500?			+	+		
57b	Dorkó, Cseredűlő, basalt? (buried)	842250	327810	500X500?			+	+		
58d	Bodroghalom, Nyírtanya, dacite (buried)	845630	329520	500x500?			+	+		
80ba	Sárazsadány, Mancsalka, andesite	833680	331370	1000x1000			+	+		
	Stratovolcanoes									
37d	Tokaj, Nagy Hill, dacite stratovolcano	823925	311375	6000x6000	+	+		+		
66 d	Szegi, Cigány Hill, dacite stratovolcano	821570	321780	3500x2000	+	+		+		
41rf	Sátoraljaújhely, Fekete Hill – Rudabányácska, Bánya Hill	840406	341121	2000×1000	+				+	+
73a	Tolcsva, Fekete Hill, andesite stratovolcano	828527	333670	6500x2000	+	+				
21d,a,r	Makkoshotyka, Katuska Hill, dacite – andesite – rhyolite	831993	340621	2000x2000	+	+	+	+	+	+
75a,rf,r	Erdőbényefürdő, Hollóstető, andesite – rhyolite tuff, rhyolite	819653	323684	3500x2100	+			+	+	+
76a	Óhuta, Magas Hill, andesite	823910	338497	4000x2000	+	+		+		
83a	Háromhuta, Nagy Kőrös Hill – Nagykirályos, andesite	826660	341790	3500x2200	+	+	+	+		
84a	Abaújszántó, Molyvás, andesite	813500	328000	5000x3000	+	+	+	+		
85a	Abaújkér, Bánya Hill, andesite	815680	328730	4500x2000	+	+		+		
68a	Sima, Nagykorsós-Somberek, andesite	816789	332528	3000x3500	+	+	+	+		
54/2a	Viss, Fazekas-zug, andesite (buried)	835020	323030	6000x2500			+	+		
90rf,r	Nagybózsva, Fekete Hill – Csattantyú Hill, rhyolite tuff, rhyolite	827000	347500	5000x5000	+	+	+		+	
	Single lava domes									
51r	Telkibánya, Varga Hill – Nagy Valley, rhyolite dome	819400	349990	500x500	+		+	+		
46r	Nagyhuta, Jakabvár Hill, Nagyfulón, rhyolite domes	835238	348934	500x500			+	+		+
3rd	Pusztafalu,Tolvaj Hill, rhyodacite dome	830110	360031	1000×1000	+		+			+
4rd	Füzérkajata, Hársas Hill, rhyodacite dome	831832	357587	800×800	+		+			
48a	Füzérkomlós, Akasztó Hill, andesite dome	827776	355564	500×500 2000×2000	+					
1d	Hollóháza, Vágott Hill, dacite dome	825690	360650	1000x500	+	+	+			
2d	Füzér Castle, dacite neck	828144	358246	500x500	+	+	+			+
49r	Füzérradvány, Korom Hill, rhyolite dome	833645	354557	2000×2000 500×500	+		+			+
60d	Pusztafalu, Tolvaj Hill, dacite dome	827520	360480	750x750	+	+	+			
63d	Hejce, Tilalmas, dacite dome	815236	345593	500x250	+	+	+	+	+	+
74d	Erdőhorváti, Eperjeske, dacite dome	823790	334970	700x500	+	+				
77r	Erdőbénye, Faragványos, rhyolite	816660	326030	1200x1500	+	+			+	+
47rd	Nagybózsva, Páska Hill, rhyolite dome	828868	348864	500×500	+	+			+	
91r	Tokaj, Lebuj Inn, rhyolite dome	823400	314200	250x250	+				+	
92/1r	Telkibánya, Cser Hill, rhyolite-perlite dome	821600	350600	1200x400	+	+			+	
92/2r	Telkibánya, Ork – Ógönc, rhyolite-perlite domes	823600	349400	1500x700	+	+			+	
36/2 r	Bodrogkeresztúr, Dereszla, rhyolite dome	822110	316240	500x500	+	+			+	
36/1r	Tarcal, Terézia Hill, rhyolite dome	820150	324140	500x500	+	+	+		+	
38/1r	Zalkod, Lukató, rhyolite? dome (buried)	828710	317540	?		+	+			
38/2a	Zalkod, Jakab Hill, andesite (buried)	831770	319930	?			+	+		
38/3a	Szabolcs, Földvár (motte), andesite lava dome (drillhole)	831710	317220	500x500?	+		+	+		
54/3a	Viss, Fazekas-zug, andesite lava dome (buried)	835660	320900	500x500?			+	+		
54/1r	Viss, Patkó-zug, rhyolite dome (buried)	834430	326470	500x500?			+		+	
55r	Szegi, Kásod Meadow, rhyolite dome (buried)	829920	321980	500x500?		+	+			

a – Geology, b – Remote sensing, c – Gravity, d – Magnetics, e – Radiometry, **f** – Geochemistry

According to the geologic mapping (Gyarmati and Zelenka 1968a and b) and structural and mineral resource exploration boreholes, there is ignimbrite as well as fallen and redeposited tuff of 200–350 m thickness inside the caldera, between the lava domes. These indicate five horizons of eruptions (Zelenka 1964).

Andesite domes (Megyaszó 35/9a, Legyesbénye 35/10a) and subvolcanoes (Tállya 33/2a) showing local magnetic and gravity maxima are uplifted at the edges of the outer circle of the large caldera. Rhyolite volcanoes (Monok 35/6–7r, Abaújszántó 34/1–4r,rf, Tállya 33/1rf, Mád 33/3r, rf, Prügy 35/17r) can be outlined with filtered gravimetric and radiometric total intensity maxima. The determined K/Ar age of these volcanic formations is 11.6 ± 0.4 Ma (Molnár and Pécskay 2002).

In the thermal water-charged geyser basins of the postvolcanic centers limnoquartzite, bentonite and diatomite were deposited (Rátka: Koldu, Kerektölgyes, Hercegköves, Új Hill (33/5u); Szerencs: Aranka-tető (35/20u); Bekecs: Kis Hill (35/21u); Monok: Zsebrik). In these basins As and Hg were enriched. Low sulfidization (LS) type, Au-bearing quartz veins (ore indications) can be found on Fuló Hill at Legyesbénye (35/22u) and on Bomboly at Mád (32/2u) in areas subjected to potassic metasomatism. Postvolcanic activity was accompanied by kaolinitization and alunitization. The K/Ar age of the latter is 10.4–12.1 ± 0.7 Ma (Molnár and Pécskay 2002). Diatomite deposits were formed in fallen, bedded rhyolite tuff deposited in water (Zelenka 1967).

The bulk of ignimbritic ash-flow tuffs was also deposited in water. The glassy material of the tuffs is strongly zeolitized. At Rátka the welded pumiceous tuff contains spherical bombs of 20–40 cm diameter, formed from the same material, originating from the ignimbritic flow of the Fürdős-tető eruption center. At Abaújszántó and Bánya Hill submarine exhalative Pb–Zn–Sb ore lenses were formed in the rhyolite tuff or tuffite and in the accompanying Sarmatian sediments (Pentelényi 1967).

Boldogkővár Caldera (40rf, 40a in Fig. 11)
Viss Caldera (54a, 54r in Fig. 11)
Hollóháza Caldera (5r, 5a in Fig. 11)

A double ring of a caldera of 7–8 km in diameter was recognized on a satellite image between Hollóháza and Telkibánya (Fig. 11). At the edge of the caldera a series of andesitic and dacitic parasitic volcanic cones can be found (Liffa 1953). On the northern part of the caldera there are rhyolite domes and their lava flows with large K, Th and U anomalies, which broke through Sarmatian rhyolite tuff and argillaceous sediments (Kiss and Zelenka 2009). On the southern part, at the gravity maximum of Telkibánya Kánya Hill and Gyepü Hill (5/3a, 5/7a) the 2.5×2.0 km-sized caldera structure, open in V-shape to the S, can be traced down to a depth of 1500–1600 m, accompanied by K, As, Au, Ag and Sb enrichment on the surface with 20 nearly N–S and NNE–SSW-striking, LS-type epithermal precious metal ore veins (5/7u). The K/Ar age is 11.8–13.1 Ma (Pécskay et al. 1986; Molnár and Pécskay 2002).

The Telkibánya-2 structural borehole found rhyolitic and dacitic tuff complex over the Badenian clay marl (Székyné Fux 1970). The original stratovolcanic amphibole andesite was propylitized and intruded by the K-metasomatic subvolcanic andesite on the caldera edge (Molnár and Zelenka 1995).

Regéc Caldera (15a, 15d in Fig. 11)
Pálháza Caldera (17r in Fig. 11)
Erdőbénye Caldera (28r in Fig. 11)
Mád Caldera (30a, 30r, 32rf in Fig. 11)
Sárospatak Caldera (22rf in Fig. 11)
Sátoraljaújhely Caldera (20rf in Fig. 11)

Volcanic fissures

The hard, standing dykes form elevated crests and ridges on the surface. Near to the upstreaming zone the rock is steeply banded, while around the channels the pyroxene andesite lava beds dip 10–30°. The following occurrences were grouped here:

Telkibánya, Magastér – Resztelt-bérc – Hemzső-bérc (13-3a in Fig. 11)
Telkibánya, Hollókő – Nagy-Sertés Hill (13-2a in Fig. 11)
Gönc, Amádévár – Téglás-kő – Bán Hill (13a in Fig. 11)

A nearly NNW–SSE striking pair of bands of gravity maximum and minimum in the direction Gönc, Amádévár – Téglás-kő – Bán Hill indicates a nearly 10 km-long tectonic lineament (Fig. 11). This is also outlined on the satellite image along the Kis Creek. Three spots of magnetic ΔT anomalies and total gradient maxima can be found at Amádévár, Téglás-kő and Bán Hill, each 1–1.5 km in diameter (Fig. 6). The lava beds show 60° dip around the eruption centers and 10–35° in the distal region. The ring structure at Téglás-kő on the satellite scene indicates a small-sized eruption centre. The K/Ar age of the lava cover (pyroxene andesite) at Sólyom Rock, belonging to this zone, is 11.9 ± 0.52 Ma (Pécskay in Zelenka et al. 2007).

Regéc, Kis-Bekecs – Nagy-bekecs – Pengő-kő – Tokár-tető and Nagyoldal-tető – Nagy-Péter-mennykő (13-5, 6/a in Fig. 11)
Komlóska, Nagy-Papaj (53/a in Fig. 11)
Sárospatak, W and SW part (78a/79/a in Fig. 11)

The pyroxene andesite lava bodies of two parallel, N–S striking, several km long and some 10 m wide series of volcanic fissures appear along the Hotyka Creek Fault, W and SW of Sárospatak, as weak magnetic and gravity anomalies. The K/Ar age of Páncél Hill and Szent Vince Hill (78/1–3a) on the western side is 12.5 ± 0.9 Ma, while the age of the bodies along Hercegkút Gombos, Sárospatak Mandulás, Sárospatak Kutya Hill (79/1–2a), Sárospatak Vár Hill on the eastern side is 11.63 ± 0.45 Ma (Pécskay in Zelenka et al. 2007).

Subvolcanic bodies, intrusions

These bodies consist of microholocrystalline or porphyry rocks with sharp morphological boundaries and often with columnar joints. On the gravity map these are denser bodies than their surroundings, extending to depth. Their texture changes downward; according to mining exploration data it becomes coarsely crystalline.

Kovácsvágás, Baradla (46/d in Fig. 12)
Sátoraljaújhely (20/rf 20/d in Fig. 12)

At Sátoraljaújhely, on the western edge of the uplifted (outcropping) basement there are andesitic–dacitic subvolcanic bodies in a pincer-shaped caldera, intruded into and affecting the Badenian faunal clay marl by contact. The location of the subvolcanoes on the satellite image is along the edge of the rhyolite tuff and tuffite caldera, in the line of Magas Hill, Szár Hill, Vár Hill, Sátor Hill and Kecskehát, corresponding to an oval magnetic and gravity anomaly. The K/Ar age (11.9 ± 0.5 Ma) and the paleomagnetic results (reverse polarization, minor W rotation) indicate Sarmatian age.

Sátoraljaújhely, Néma Hill (20/d in Fig. 12)
Rudabányácska, Száva Hill (42/d in Fig. 12)
Kovácsvágás (E), Fekete Hill – Osztra Hill (18/d in Fig. 12)
Pálháza – Kishuta (17/r in Fig. 12)
Tállya, Kopasz Hill (33/a in Fig. 12)

The andesite of the subvolcanic body at Tállya – Kopasz Hill was intruded into loose pumiceous rhyolite tuff. The intrusion is supposed to have proceeded in two phases, based on the two kinds of pyroxene andesite. The light grey andesite with vertical columnar joints and sporadic sulfide dissemination was formed first. The K/Ar age of this intrusion is 11.7 ± 1.1 Ma (Pécskay et al. 1986). Later this cooled andesite was again intruded by a black, olivine-rich pyroxene andesite with folded columnar joints, partly along earlier joints, partly on the edge contact. The latest K/Ar measurements show 9.6 Ma age for the olivine-rich andesite (Pécskay, pers. comm).

Hejce, Tilalmas (63/d in Fig. 12)
Boldogkőváralja, Tekeres Valley (72/d in Fig. 12)
Boldogkőváralja, Tó Hill (69/a in Fig. 12)
Telkibánya, Kánya Hill – Gyepü Hill (5/a in Fig. 12)
Erdőbénye, Mulató Hill (61/d in Fig. 12)

The olivine-bearing hypersthene-augite dacite laccolith of Barnamáj (Kulcsár and Bartha 1971) was intruded into micro- and macrofaunal argillaceous tuffite and pumiceous, unwelded rhyolite tuff, metamorphosing these by contact. The body shows weak gravity and strong magnetic anomaly, indicating no extension in depth. The K/Ar age is 11.3 ± 0.5 Ma.

Korlát (71/d in Fig. 12)
Gönc, Hársas Hill – Vas Hill (82d in Fig. 12)

The pyroxene-amphibole dacite subvolcanic body of Hársas Hill and Vas Hill was intruded into Sarmatian faunal clay and pumiceous rhyolite tuff, leading to contact metamorphism. The Telkibánya-VIII borehole crossed this subvolcanic body in more than 100 m length (Ilkeyné Perlaki 1967, 1978). The K/Ar age is 11.6 ± 0.7 Ma.

Bodroghalom (58/d in Fig. 12)

Diatremes

Diatremes originated mainly from deeply rooted, highly explosive phreatomagmatic eruptions. A circular or ring-shaped local gravity minimum indicates the center of a diatreme within the basement regional gravity maximum. Andesite and andesitic dacite cause a weak magnetic total gradient maximum (Fig. 6).

In those sites where the basement or older volcanic bodies are crosscut by a rhyolite tuff vent, circular gravity minima can be observed as well. Some 10 cm-scale rhyolite blocks, pumice lapilli and xenoliths of basement origin (limestone, micaschist, gneiss) prove the proximity of the explosive center. The expelled debris of the rhyolite tuff is unsorted; its cement is in most cases pumiceous, fresh volcanic glass.

S of Vágáshuta, Nyúl Spring (19/rf in Fig. 12)

A circular gravity minimum of 1 km diameter was observed on the top of a maximum at Nyúl Spring, S of Vágáshuta. Large (20–40 cm) xenoliths from basement rocks (carbonates and micaschist) are embedded in welded ignimbritic ash-flow tuff, indicating vent-proximal eruptive facies.

Quarries exploited the material of repeated lava breakthroughs younger than the surrounding explosion vents of pyroclastic flows and hyaloclastite breccia inside the calderae. For example, there is fresh pyroxene andesite in the K-metasomatized andesite of the Kánya and Gyepü Hills at Telkibánya (5/7; Horváth and Zelenka 1997) and a perlite lava extrusion in the hyaloclastite breccia of the Gyöngykő Hill at Pálháza (17/1r; Zelenka 2008).

Telkibánya, Youth Camp (5/rf in Fig. 12)
Bodrogolaszi, Mancsalka (80/a in Fig. 12)
Erdőbénye, Szokolya (64-1-2/a in Fig. 12)

There are diatremes covered by Pannonian sediments in Bodrogköz, indicated by gravity and airborne magnetic surveys:

Apróhomok basalt (39b in Fig. 12)
Vajdácska, Várhomok (57/b in Fig. 12)

Bodroghalom, Nyírtanya (58d in Fig. 12)

Stratovolcanoes

These volcanoes alternatively produced lava and pyroclastics (ash-flow tuff, fallen tuff). The result is a "cakelike" bedded structure, often with outwedging beds. In certain cases the same vent produced a sequence of dacitic, andesitic and rhyolitic lava and pyroclastics (Makkoshotyka Katuska, Erdőbénye Spa), lying over each other. Lava domes were also formed at these stratovolcanoes (Nagybózsva, Fekete Hill in Fig. 12).

Tokaj, Nagy Hill (Kopasz Hill (Bald Hill)) (37/d in Fig. 12)

The pyroxene dacite cone of Nagy Hill at Tokaj is characterized by massive and vesicular lava flows as well as block and ash flows with strongly oxidized lava clasts, alternating at multiple levels. There are steeply dipping, vent facies lava bodies with fluidal texture crosscutting the lava flows, partly beneath the ancient central cone, partly beneath parasitic cones. The diatremes are specific spots of different magnetism on the magnetic map. The satellite scene outlines the outcropping surface of the ancient lava flows, which are curved clockwise. The radiometric age of the repeated, mixed rhyolite-andesite lava explosions (Rózsa 1994) is 10.3–10.5 Ma (Pécskay et al. 1986).

Sátoraljaújhely, Fekete Hill (41/d in Fig. 12)
S from Mikóháza, Ritka Hill – Szénégető Hill (43/rf in Fig. 12)
Makkoshotyka, Katuska Hill (21/r, 21/a in Fig. 12)

Katuska Hill at Makkoshotyka is an extrusive-effusive polyvolcano, which produced a sequence of multiply differentiated dacite-andesite-rhyolite lava. The object causes a gravity minimum, the oldest pyroxene andesite a medium magnetic anomaly, the crosscutting rhyolite complex a high total radiometric and potassium anomaly. The latter is also connected with medium Hg enrichment demonstrated in stream sediment samples.

Füzér, Remete Hill – Milic (1/d in Fig. 12)
Nagybózsva, Fekete Hill – Csattantyú (90/r, 90/rf in Fig. 12)
Tolcsva – Fekete Hill (73/a in Fig. 12)
Erdőbényefürdő (64/a, 64/r in Fig. 12)

Single lava domes

The single lava domes belong to no major caldera or stratovolcano, according to our present knowledge. These are morphologically and petrologically well-outlined objects, with a prominent gravity maximum in their mostly pyroclastic vicinity. Magnetite-bearing dacite and andesite bodies can cause magnetic maxima and rhyolite volcanics radiometric maxima, respectively.

The K content of rhyolite lava bodies is medium (6–8%), while that of rhyolite tuffs is lower (4–5%). The Th content is regionally high (20–30 ppm), and a pointwise hydrothermal U enrichment can be observed in vent zones of rhyolite lava domes (6–10 ppm). From the centers of lava domes the lava flow facies can be followed laterally: massive, fluidal, lithophysal, spheroidal, spherolithic, perlitic (Fig. 12).

Telkibánya, Varga Hill and Nagy Valley (52/r, 52/rf in Fig. 12)

The rhyolite domes of Varga Hill and Nagy Valley at Telkibánya have nearly vertical, perlitic, fluidal texture (gray, white, red bands), and lava and debris flows with 10–30° dip branch off from these. The borehole Tb-7 crossed the covering laminar pyroxene andesite lava flow of 50 m thickness, reaching the underlying welded rhyolite ash-flow tuff. The domes appear as weak maxima on the total gradient map, maxima in radiometric total intensity, and Th and U content as well. The K/Ar age of the laminar, fluidal rhyolite is 13.11 ± 0.53 Ma (Pécskay et al. 1986).

Nagyhuta, Jakabvára Hill, Nagy-Fuló (46/r in Fig. 12)
Pusztafalu, Tolvaj Hill (3/rd in Fig. 12).

The rhyodacite lava of Tolvaj Hill at Pusztafalu broke through Sarmatian sediments. It is indicated by a relative gravity maximum of 1×1 km in diameter. The K/Ar age of the rock is 12.6 ± 0.5 Ma (Pécskay et al. 1986), characterized by a large geochemical Hg anomaly.

Füzérkajata, Hársas Hill (4/rd in Fig. 12)
Füzérkomlós, Akasztó Hill (48/a in Fig. 12)
Füzér, Castle Hill (2/d in Fig. 12)

The dacite neck structure and morphology of Castle Hill is well visible within a 300×300 m area with its more than 60 m-high columns.

Füzérradvány, Korom Hill (49/r, 49/rf in Figure 12)

The maximum of the 10 km HP filtered gravity map at Korom Hill, Füzérradvány, indicates the 50–100 m-thick, silicified upper tuff and the sediments of the geyser basin. The geochemical anomalies (Hg, Au, As, Sb, Ag) accompany the subsequent hydrothermal breccia zones (Fig. 9). There is a K-metasomatized rhyolite dome in the center of the area, at Ember Rock, which was not previously recognized. The K/Ar age of the rhyolite alteration is 12.36 ± 0.47 Ma (Pécskay et al. 1986). The airborne geophysical (radiometric) surveys did not cover this area. The dacite neck shows a medium magnetic anomaly, and its deep source can be recognized on the 20 km HP filtered gravity map. Its K/Ar age is 11.0 ± 0.4 Ma (Pécskay et al. 1986; Pécskay et al. 2005).

Areas of postvolcanic activity

The products of postvolcanic activity can be recognized around the eruption centers, partly inside the major ancient calderas and beside the vents and domes, according to geochemical anomalies. These can be placed into two major groups:

1. Epithermal polymetallic and precious metal mineralizations (K, Au, Ag enrichment).

2. Silicic and argillitic sediments of hot water basins, in some cases with As and Hg mineralization.

Some of these are quartzite veins and limnoquartzite covers exposed by erosion, easy to detect, partly by remote sensing and partly through geochemical anomalies. These formations are attached to ancient eruption centers (Fig. 9), but their K/Ar ages are always younger (Molnár and Pécskay 2002).

Telkibánya, Kánya Hill – Gyepü Hill: Au-Ag quartz veins (5/7u in Fig. 9)
Rudabányácska, Bánya Hill: Au quartz vein (41/1u in Fig. 9)
Füzérradvány, Korom-tető: Au-Ag quartzite breccia (49/1 ru in Fig. 9)
Mád, Diós – Bomboly: gold, quartz and siderite veins (32/2u in Fig. 9)
Tolcsva, Fekete Hill – Kopaszka: Pb-Zn quartz vein (73/1u in Fig. 9)
Abaújszántó, Bányi Hill: Kuroko-type Pb, Zn, Sb (34/5u in Fig. 9)
Sárospatak, Király Hill: Hg quartzite vein (22/2u in Fig. 9)
Sárospatak, Bot-kő: limnoquartzite, bentonite + Hg (22/1u in Fig. 9)
Regéc, Castle Hill: limnoquartzite (15/1au in Fig. 9)
Óhuta, Soltész Valley: quartz vein (24/1u in Fig. 9)
Erdőbénye, Ligetmajor: limnoquartzite and diatomite (28/7u in Fig. 9)
Rátka, Nemesagyag-medence: limnoquartzite, bentonite, kaolinite (33/5u in Fig. 9)
Hollóháza, Szurok Meadow: limnoquartzite, kaolinite, diatomite (5/6u in Fig. 9)
Legyesbénye, Fuló Hill: Au quartzite vein (35/22u in Fig. 9)
Szerencs, Aranka-tető: limnoquartzite, kaolinite (35/20u in Fig. 9)
Bekecs, Nagy Hill: limnoquartzite (35/21u in Fig. 9)
Komlóska, Bolhás: quartz and calcite veins with bentonite (53/3u in Fig. 9)
Gönc, Vas Hill – Or Hill: limnoquartzite (82/1du in Fig. 9)

Eruption centers and mineral resource formation

The epithermal polymetallic and precious metal mineralizations are primarily attached to hydrothermal zones of subvolcanic intrusions, detected partly within the volcanic bodies, in their fissures, crushed zones, and partly in country rocks of the cap region, mainly in the form of veins (Telkibánya, Rudabányácska, Füzérradvány, Komlóska, Tolcsva, Sárospatak, Mád). The potassic metasomatism is characterized by adularia and feldspar formation; hydrothermal alteration by propylitic, quartz-sericite-argillitic and zeolitic zonation. In the ancient postvolcanic, hydrothermal geyser and thermal spring basins attached to the eruption centers, volcanosedimentary silica deposits, diatomite, kaolinite, illite, bentonite, and alunite deposits were formed (Szerencs, Rátka, Monok, Arka, Regéc, Telkibánya, Hollóháza, Füzérradvány, Sárospatak, Erdőbénye – Fig. 9). These show As, Sb, Hg enrichment as a geochemical anomaly.

The ore and other deposit-forming processes and their products are listed at the volcanic structures, volcanic bodies and areas of postvolcanic activities above.

The magmatic rocks solidified from lavas; pyroclastics of the volcanoes are used as building stone. The lava plugs of the subvolcanic rock bodies and the diatremes provide large resources; they contain subsurface lamination or columnar joints, formed perpendicular to the cooling surface by slow cooling. In the shallow levels the rocks are glassy and fine-grained, in the depth becoming gradually coarse crystalline, partly diorite porphyry. These rocks are exploited in quarries (Kopasz Hill 33/a at Tállya, Mulató Hill 61/a at Erdőbénye).

The thick andesitic or dacitic lava flows of the stratovolcanoes are fine-grained and high-strength materials as well, but the inhomogeneous material of tuff, agglomerate and debris flows between the lava beds produced by periodical volcanic activity are inappropriate for exploitation (Nagy Hill 37/d at Tokaj).

The central zones of volcanic fissures are good-quality but low-volume building stone occurrences (Gombos 78/a at Hercegkút, Páncél Hill 78/2a and Szent Vince Hill 78/3a at Sárospatak).

The single rhyolite extrusive domes produced perlitic lava bodies and in some sites lava flows, mainly at underwater extrusions as pumiceous lava facies. The extrusive perlite with columnar joints of Pálháza (17/1r), the pitchstone and pumice breccia of Páskatető (47/r) at Nagybózsva and the perlitic bodies of the Ósva Valley between Telkibánya and Pálháza belong to this type. This rock material is appropriate for insulation purposes. The exploitation is restricted by natural protection of the occurrence areas.

The acidic volcanic glass (fallen ash) produced loose pumiceous tuff (pumicite), which can also swell, but its strength is low (Szegi).

The facies of ignimbritic flow tuff, deposited mostly in water, was transformed into zeolite (clinoptilolite, mordenite) in the matrix and on the edges of pumice lapilli as well, forming economic zeolitic rhyolite tuff deposits (Rátka–Koldu, Bodrogkeresztúr, Mezozombor, Mád).

Identified tectonic lineaments of the Tokaj Mountains

Based on satellite imagery covering the entire range (Landsat, radar SRTM), on stereo-aerial photography and on geophysical gravity and airborne magnetic surveys the major tectonic zones drawn in Figure 13 were constructed. These are partly visible on the surface, partly buried structures detected by geophysical methods; however, their strike can be identified unambiguously. The short characteristics of the structures are listed in Table 2.

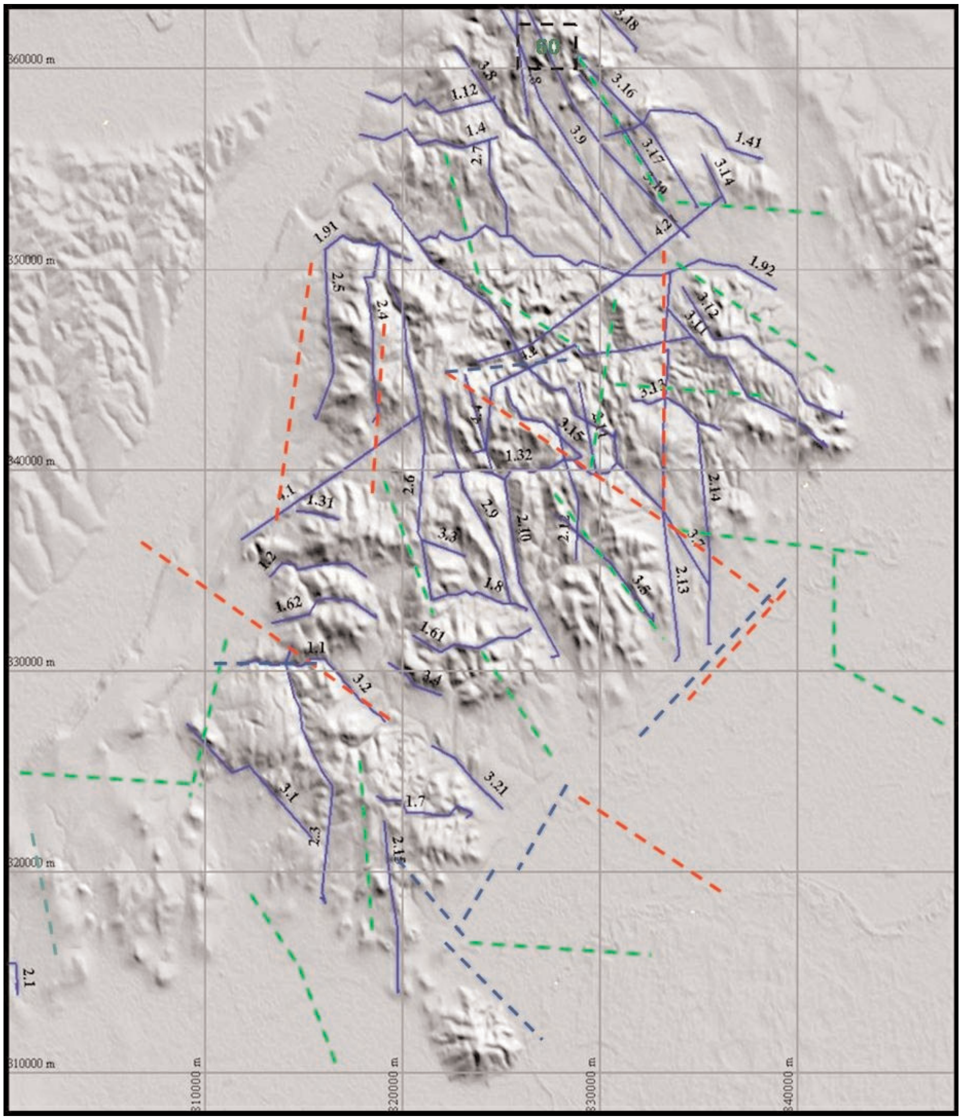

Fig. 13
Structural scheme based on SRTM topography (blue lines), gravimetric (green lines) and magnetic (red lines) surveys (T. Zelenka, J. Kiss). E–W striking: strike-slip and normal faults with downthrow to S (e.g. Bózsva Creek Valley 1.92).
N–S (NNW–SSE) striking: volcanotectonic extension faults along the boundary of volcanics and at veins (e.g. Telkibánya 2.7).
NW–SE striking: faults with large-scale downthrow along the boundary of the mountains, in different rock masses and volcanic fissures.
NE–SW (NNE–SSW) striking: faults with small-scale downthrow or strike-slip sense on the boundary of the mountains and at different rock masses (e.g. Hernád Valley, Kemence Creek).

Table 2
Tectonic structures of the Tokaj Mountains

Tectonic structure, site	Structure type	Geology	Remote sensing	Gravity	Magnetics	Magnetic total gradient	Radiometry	Geochemistry	Length (km)
1. E–W (ESE–WNW) structures									
1.1 Abaújkér, Aranyos Valley	zigzag fault	+	+	+			+		4.76
1.2 Boldogkőváralja, Tekeres Valley	zigzag fault, S downthrow		+	+	+		+		5.74
1.3 Óhuta – Újhuta, Hutai Valley	zigzag fault, S downthrow	+	+	+	+	+		+	10.6
1.4 Pányok, Hasdád Valley	zigzag fault	+		+				+	7.78
1.5 Erdőbénye, Faragványos	zigzag fault, S downthrow	+		+				+	6.78
1.6 Erdőhorváti, Szokolya	zigzag fault, S downthrow		+	+	+			+	6.28
1.7 Szegilong, Cigány Hill – Meszes	formation boundary, fault	+	+	+		+			6.05
1.8 Erdőhorváti, Hárskút Tolcsva Creek	formation boundary	+	+	+					5.3
1.9 Nagybózsva, Bózsva Valley	formation boundary, fault, N downthrow	+	+	+	+	+	+		5.03
1.10 Újhuta, Szpalanyica Valley	formation boundary	+		+			+	+	
1.11 Nagyhuta, Hallás Valley	formation boundary, zigzag fault	+		+			+	+	
1.12 Kéked, Hosszú Valley	formation boundary	+	+	+			+		
2. N–S (NNW–SSE) structures									
2.1 Monok, Nyíres	fault, W downthrow		+	+	+				9.87
2.2 Monok, Nagyrépás – Majos Hill	volcanotectonic				+	+	+		5.35
2.3 Tállya, Hideg Valley		+	+	+	+	+			14.8
2.4 Gönc (Amádévár), Kis Creek	volcanotectonic		+	+					9.57
2.5 Gönc – Hejce – Fony, W border of the Mts.	formation boundary, fault, W downthrow	+	+	+	+	+	+	+	9.1
2.6 Telkibánya – Regéc, Nagy Creek	volcanotectonic, formation boundary, quartz veins	+	+	+			+	+	17.8
2.7 Telkibánya, Kánya Hill Veresvíz Valley	volcanotectonic, fault, E downthrow, ore vein	+	+	+				+	5.18
2.8 Füzér, Bisó Creek	formation boundary, fault, W downthrow	+	+	+					7.38
2.9 Erdőhorváti, Tolcsva Creek		+	+	+		+		+	13.9
2.10 Erdőhorváti – Középhuta, Egres Creek	formation boundary	+	+	+	+			+	15.8
2.11 Komlóska	formation boundary, fault, ore vein	+		+			+		4.67
2.12 Újhuta, Komlóska Creek				+					7.17
2.13 Kovácsvágás, Hosszú Creek	formation boundary, fault, W downthrow	+	+	+		+			20.0
2.14 Hercegkút – Sárospatak, Hercegkút Creek	formation boundary fault, W downthrow, andesite dykes	+	+	+		+	+		11.3
2.15 Bodrogkeresztúr Kakas-nyereg	formation boundary, rhyolite, andesite dyke	+	+	+			+		8.76
2.16 Sima – Baskó, Sás Creek	formation boundary	+	+	+	+				
3. NW–SE structures									
3.1 Abaújszántó, Krakó Hill – Sátor Hill	formation boundary, fault, SW downthrow	+	+	+		+		+	9.14
3.2 Erdőbénye, Aranyos Creek – Mélyvíz	formation boundary, fault, E downthrow	+	+	+	+		+		4.37
3.3 Erdőhorváti, Hajagos Valley	formation boundary	+	+	+	+		+		2.35
3.4 Erdőbénye, Nagy-Mondoha	formation boundary, fault, SE downthrow	+	+	+	+	+	+		3.35
3.5 Komlóska – Tolcsva, Hideg Valley	formation boundary	+	+	+	+	+	+		7.84
3.6 Makkoshotyka, Hotyka Creek Valley	formation boundary	+	+	+	+	+	+	+	
3.7 Telkibánya, Ósva Valley	strike-slip fault	+		+	+	+	+		28.2
3.8 Nyíri, Nyíri Creek Valley	formation boundary, strike-slip fault	+	+	+					13.1
3.9 Hollóháza, Török Creek Valley	formation boundary, fault	+	+	+	+	+			14.7
3.10 Füzér – Füzérradvány, Bisó Creek	formation boundary, fault, SW downthrow	+	+	+	+				14.4
3.11 Kovácsvágás, Gyékényes-árok	formation boundary, fault, SW downthrow			+	+	+		+	11.4
3.12 Rudabányácska, Magas Creek – Hármaskúti Valley				+			+	+	11.6
3.13 Vágáshuta, Fehér Creek Valley	formation boundary	+	+	+	+	+	+		5.11
3.14 Vilyvitány, Gödölye-árok	formation boundary, fault, SW downthrow, breccia, dykes	+	+	+	+	+			2.82
3.15 Óhuta, Nagy-Oldal Valley	formation boundary	+	+	+	+				5.89
3.16 Füzérkajata, Hársas – Korom Hill	formation boundary, fault, NE downthrow	+	+	+	+			+	10.3
3.17 Füzér, Remete Hill – Őr Hill	formation boundary, fault, SW downthrow	+	+	+	+			+	7.14
4. NE–SW (NNE–SSW) structures									
4.1 Arka, Boldogkőváralja Creek	formation boundary, zigzag	+	+	+				+	11.0
4.2 Kőkapu – Pálháza, Kemence Creek	strike-slip fault		+	+		+			11.1
4.3 Nagybózsva, Senyő Valley	formation boundary	+	+	+		+			
4.4 Kőkapu, Ördög Valley	formation boundary	+	+	+	+	+			3.9

Summary

The nearly N–S striking Tokaj Mountains are situated in the northeastern part of the Miocene ALCAPA microplate, between the Pannonian Basin and the inner side of the Carpathian Arc. The range extends into the Slanské Mts in Slovakia. The mountains were formed in the Middle and Late Miocene during subduction, with the calc-alkaline bimodal, intermediate and felsic volcanism of the ancient inner island arc. The mountains are bordered by tectonic zones in a triangle shape. The basement and the Miocene volcanics become thicker to the W, indicating back-arc basin character. In the northeastern part of the Tokaj Mts there are Lower Paleozoic and Proterozoic metamorphic rocks at surface; in the southeastern part of the basement Mesozoic, predominantly carbonate rocks were encountered in boreholes. In the W shale is indicated by xenoliths in pyroclastics. The eastern part of the mountains comprises Upper Badenian – Sarmatian shallow-lagoon sediments and nearly 1000 m thick pyroclastics (produced by phreatomagmatic eruptions) with dacite subvolcanic bodies. In the western part of the Tokaj Mts three volcanic cycles produced nearly 2500 m thick successions in the descending lagoon:

1. Upper Badenian (14–15 Ma) rhyolite-dacite pyroclastic flows, then subaqueous peperitic, hyaloclastitic, stratovolcanic andesite with lava beds and rhyodacite subvolcanoes.

2. Lower Sarmatian (12–13 Ma) large volumes of phreatomagmatic ignimbrite flows from rhyolite calderae, fallen pyroclastics and single rhyolite domes. In the central zone of the mountains there are several large andesite stratovolcanoes and subvolcanoes, with attached hydrothermal epithermal precious metal mineralization and less well-known Pb-Zn enrichment.

3. At the Sarmatian – Pannonian boundary (10–11 Ma): phreatomagmatic rhyolitic ignimbrites, rhyolite domes and andesitic-dacitic stratovolcanoes; finally (9–10 Ma) olivine andesite domes, dykes and calc-alkaline olivine basalt shield volcanoes as final products.

Since then, on average 200–300 m of material was eroded from the uplifted area.

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