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Miocene volcanism in the Visegrád Mountains (Hungary): an integrated approach to regional volcanic stratigraphy

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In memoriam late László Korpás

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Abstract: A combined volcanological, petrographical, paleontological, radiometric and paleomagnetic approach to the Middle Miocene volcanism of the Visegrád Mountains, Hungary, constrains their eruptive activity. The volcanic evolution is divided into three stages on the basis of paleomagnetic data. The 1st stage andesitic to dacitic explosive eruptions occurred in a submarine environment ≥16 Ma. Their products show normal polarity and CCW declinations. Scattered extrusive dacitic activity closely followed ≤16 Ma into a reverse polarity stage. A more voluminous, subaerial, andesitic activity (16–15 Ma) produced a large variety of volcaniclastic rocks, mostly block-and-ash- and debris-flow breccias, and lava domes/flows accompanied by subvolcanic bodies. The main eruptive centre was the Keserűs Hill explosive lava dome complex. Within the andesitic activity, that partly overlapped the dacitic extrusive activity, two paleomagnetic stages can be defined. These indicate a CCW rotation within a reverse polarity stage, 15.5–15.3 Ma ago according to K/Ar data. All of the three paleomagnetic stages can also be found in the neighbouring Börzsöny Mts. At the same time, the latter is characterized by a subsequent final stage (with no rotation in the High Börzsöny lava dome complex) that is missing in the Visegrád Mts. With respect to paleomagnetism and the sporadic, uncertain K/Ar data <14.5 Ma, in the Visegrád Mts the main andesitic volcanism may have terminated 15–14.5 Ma. In the Börzsöny Mts, the buildup of the High Börzsöny (14.5–13.5 Ma) may have been coeval with only sporadic late-stage andesitic eruptions in the Visegrád Mts.

Key words: Badenian, paleomagnetism, volcanology, K/Ar geochronology, submarine to emergent activity, lava dome/flow complexes.

1. Introduction and previous work

In the past years, the application of new combined methods (correlation of volcanic units with paleomagnetic, K/Ar geochronological, geochemical as well as structural geological and paleontological data) have contributed to a substantial refinement of the eruptive history and detailed stratigraphy of the Miocene volcanic fields of the North Hungarian Mountains, all belonging to the calc-alkaline Inner Carpathian Volcanic Chain. As a result, the chronological evolution and stratigraphy of volcanism from the Börzsöny Mts (Karátson et al. 2000) through the Cserhát Mts (Póka et al. 2004) to the Bükk Foreland (Márton & Pécskay 1998) could be much more precisely constrained.

The Visegrád Mts are located in North Hungary (Fig. 1: 250 km^2) and belong to the initial calc-alkaline volcanism of the Western Carpathians (e.g. Lexa & Konečný 1974; Konečný & Lexa 1994; Szabó et al. 1992). Together with the northern-lying Börzsöny Mts, they have long been regarded as a single, large Middle Miocene volcanic field (e.g. Korpás (Ed.) 1998 and references therein), composed of a number of lava domes and small stratocones (Karátson 1995; Korpás (Ed.) 1998; Harangi et al. 1999; Karátson et al. 2000; Karátson & Németh 2001). However, whereas the volcanic stratigraphy of the Börzsöny Mts (with an initial explosive submarine stage of 16–16.5 Ma and a late-stage subaerial dome complex of 13.5–14.5 Ma: Karátson et al. 2000) is well-defined, very few and uncertain data have been published about the eruptive activity of the Visegrád Mts. A great number of K/Ar datings were performed in the 1970's by K. Balogh (1977–1979), but they remained unpublished, and were not integrated with coeval paleomagnetic measurements (Balla & Márton-Szalay 1979).

In a historical view, the most important geological contributions to the Visegrád Mts (e.g. Koch 1877; Lengyel 1953; Zelenka 1960; Balla et al. 1977; Korpás (Ed.) 1998; Harangi et al. 1999) agree about the existence of two fundamental rock associations: a garnet-bearing biotite dacite lava and volcaniclastic unit, and a predominantly amphibole andesite mostly volcaniclastic

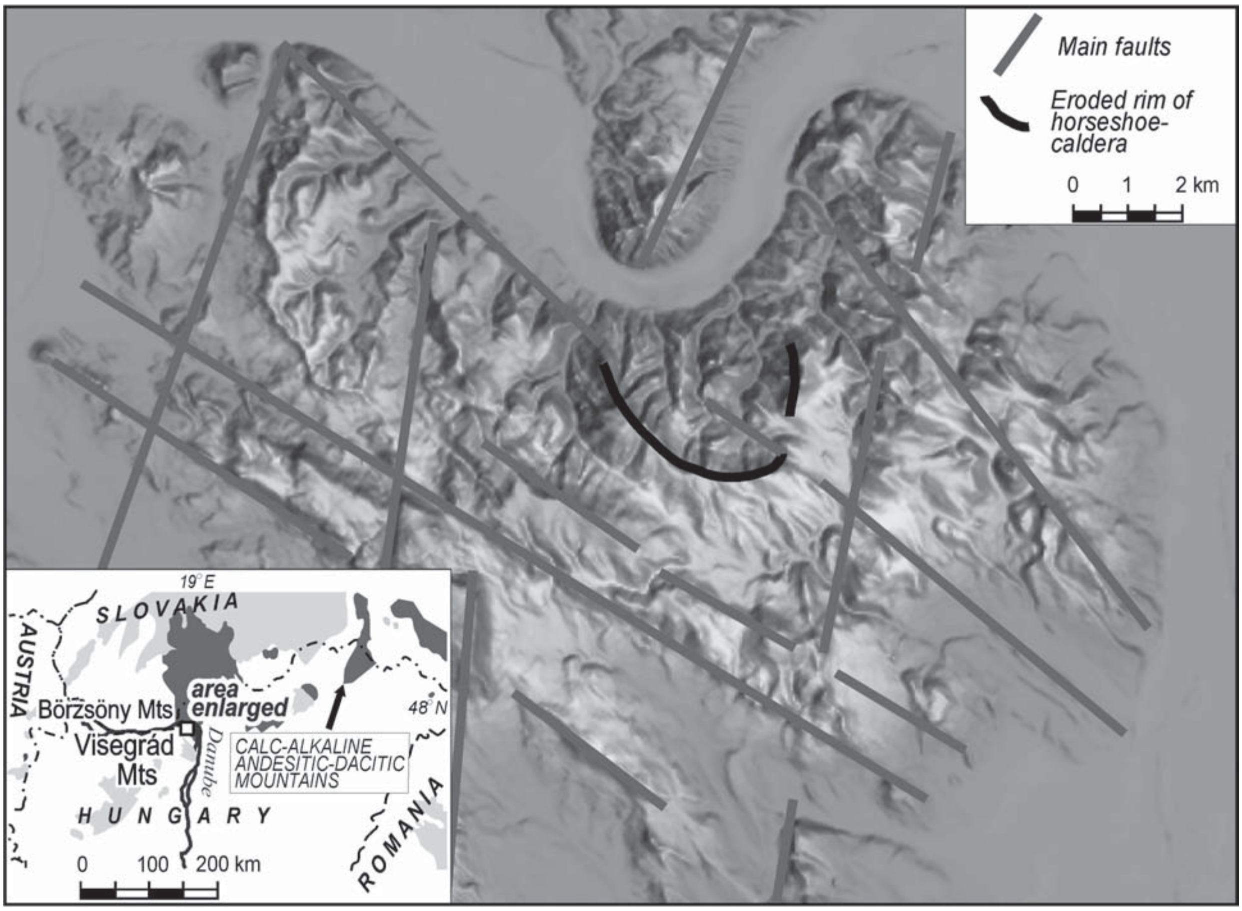


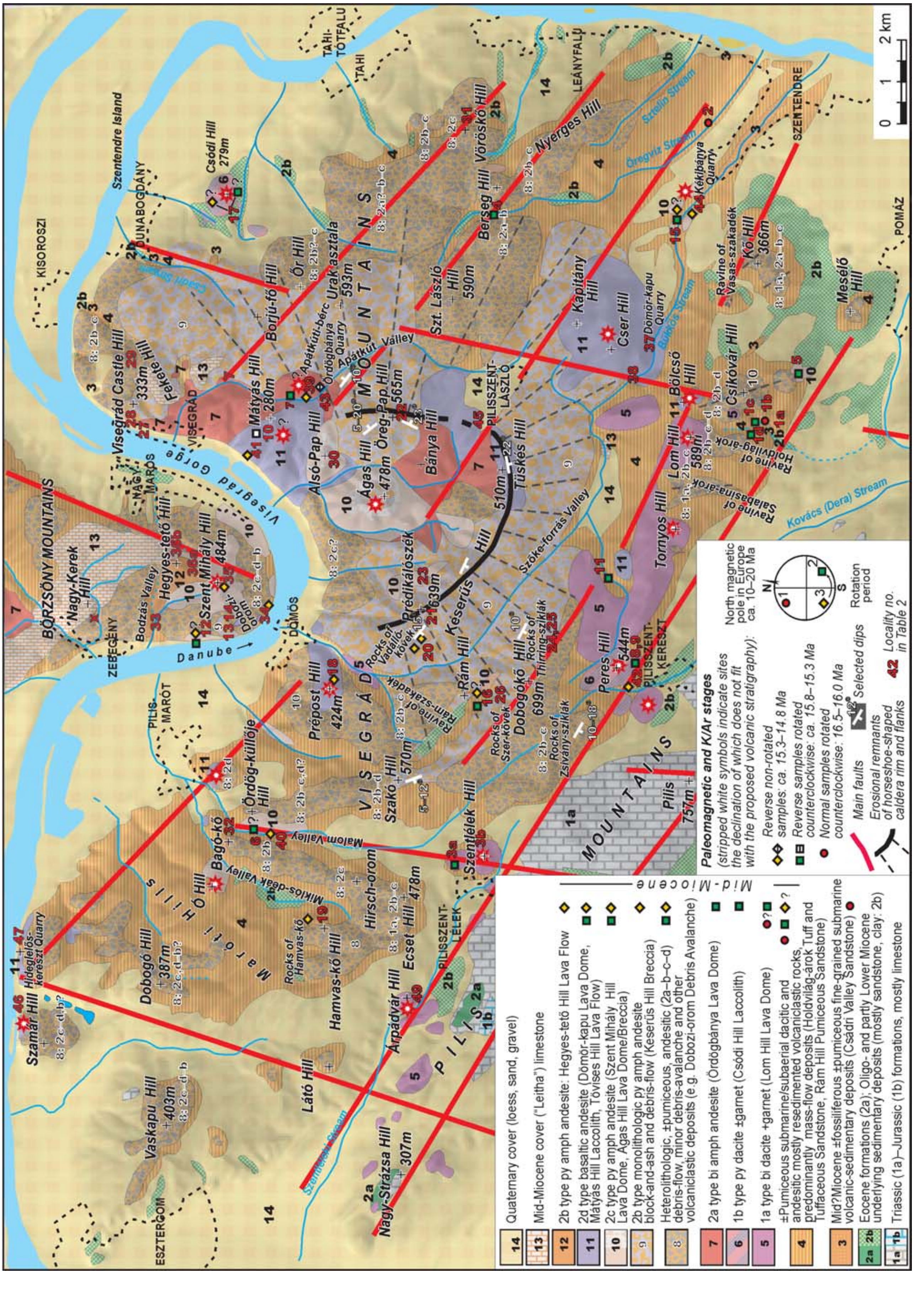
Fig. 1. Shaded relief map (based on the 1:50,000 DEM of Hungary) and geographic setting of the Visegrád Mts.

unit. Stratigraphical constraints (e.g. Zelenka 1960) have long indicated that the former should have preceded the latter. On the other hand, the suggested duration of volcanic activity has been controversial. Pécskay et al. (1995), on the basis of the available K/Ar ages, argued for a 3 Myr long volcanism (16.5–13.5 Ma), whereas Korpás (Ed.) 1998), grouping and averaging the age data, advocated to a much shorter activity (15.2–14.6 Ma).

The first, dacitic/rhyodacitic association can be found mostly in the S periphery of the Visegrád Mts (Zelenka 1960; Balla et al. 1977; Korpás (Ed.) 1998), where it is separated from Triassic limestone hills to the S by a Miocene fault system (e.g. Fodor et al. 1999). The uniform highest elevations of the volcanic and carbonate rocks with flat denudation surfaces (Láng 1955), as well as faults crossing both of them (e.g. Fodor et al. 1999; Székely & Karátson 2004), argue for the intense erosion and Miocene to Pleistocene disintegration of the whole area. The garnet-bearing rock association consists of (1) pumiceous pyroclastic and resedimented volcaniclastic deposits (e.g. in the ravine of Holdvilág-árok, one of the key localities) and (2) exhumed subvolcanic to deeply eroded extrusive bodies (e.g. Csódi Hill, Lom Hill). In some basal strata of the volcaniclastic deposits, the fossil content indicates shallow-marine facies conditions prior to and during the first volcanic eruptions (e.g. Koch 1877; Méhes 1941; Bohn-Havas & Korecz-Laky 1980), similar to the earliest submarine activity of the neighbouring Börzsöny Mts (Karátson et al. 2000; Karátson & Németh 2001). This is in accordance with the early conclusions of Koch (1877), and the observations of Wein (1939), who noted that the tuffs were emplaced firstly in a subaqueous environment, later subaerially.

Shallow submarine volcanism in the Burda (Helemba) Mts of South Slovakia, on the NW periphery of the Visegrád Mts, was also pointed out by Konečný & Lexa (1994). They reconstructed (1) viscous magma extrusion in a submarine environment, accompanied by extensive brecciation, alteration and hyaloclastite formation, (2) explosions resulting in submarine pumice flows, and (3) secondary (reworking) processes such as gravity sliding and slumping of breccias as well as submarine debris

Fig. 2. Simplified volcanological map of the Visegrád Mts, on the basis of the authors' mapping and the maps of Koch (1877), Schafarzik & Vendl (1929), Zelenka (1960), Balla et al. (1977), and Korpás & Csillag-Teplánszky (1999).


Quaternary cover (loess, sand, gravel)
Mid-Miocene cover ("Leitha") limestone
2b type py amph andesite: Hegyes-tető Hill Lava Flow
2d type basaltic andesite (Dömör-kapu Lava Dome, Mátyás Hill Laccolith, Töviskes Hill Lava Flow)
2c type py amph andesite (Szent Mihály Hill Lava Dome, Ágas Hill Lava Dome/Breccia)
2b type monolithologic py amph andesite block-and-ash and debris-flow (Keserűs Hill Breccia)
Heterolithologic, ±pumiceous, andesitic (2a–b–c–d) debris-flow, minor debris-avalanche and other volcaniclastic deposits (e.g. Dobozi-orom Debris Avalanche)
2a type bi amph andesite (Ördögbánya Lava Dome)
1b type py dacite ±garnet (Csódi Hill Laccolith)
1a type bi dacite +garnet (Lom Hill Lava Dome)
±Pumiceous submarine/subaerial dacitic and andesitic mostly resedimented volcaniclastic rocks, predominantly mass-flow deposits (Holdvilág-árok Tuff and Tuffaceous Sandstone, Rám Hill Pumiceous Sandstone)
Mid?Miocene ±fossiliferous ±pumiceous fine-grained submarine volcanic-sedimentary deposits (Csádri Valley Sandstone)
Eocene formations (2a); Oligo- and partly Lower Miocene underlying sedimentary deposits (mostly sandstone, clay: 2b)
Triassic (1a)–Jurassic (1b) formations, mostly limestone
Mid-Miocene
Paleomagnetic and K/Ar stages
(stripped white symbols indicate sites the declination of which does not fit with the proposed volcanic stratigraphy):
Reverse non-rotated samples: ca. 15.3–14.8 Ma
Reverse samples rotated counterclockwise: ca. 15.8–15.3 Ma
Normal samples rotated counterclockwise: 16.5–16.0 Ma
Main faults
Erosional remnants of horseshoe-shaped caldera rim and flanks
Selected dips
42 Locality no. in Table 2
North magnetic pole in Europe ca. 10–20 Ma
Rotation period
VISEGRÁD MOUNTAINS
BÖRZSÖNY MOUNTAINS
PILIS MOUNTAINS
Visegrád Gorge
Danube
Szentendre Island
ESZTERGOM
SZENTENDRE
VISEGRÁD
DÖMÖS
PILISSZENTLÁSZLÓ
PILISSZENTKERESZT
0 1 2 km

flows. Presence of garnet in the Burda rocks suggests an early age in terms of the volcanic activity of the Visegrád Mts.

In some peripheral areas, an andesitic phreatomagmatic series is the initial volcanic product both to the N (Korpás et al. 1967) and the S-SE part of the mountains (Bendő et al. 2001; Karátson et al. 2006). In addition, pumiceous, andesitic lithic-rich volcaniclastic deposits, frequently interbedded with massive volcanogenic sandstone to claystone layers, are also widespread in some basal successions (Karátson et al. 2006 and this paper). The andesitic lithology as well as ca. 16 Ma K/Ar ages of some andesite lavas (see later) indicate that the andesite volcanism started simultaneously with the dacitic one, although more locally.

Traditionally, the second volcanic unit in the Visegrád Mts has been described as a widespread amphibole andesitic association, occurring in the central and northern part. Most rocks are volcaniclastics, but a number of small- to medium-sized lava domes/flows and subvolcanic bodies are also exposed. The termination of the andesitic volcanism is marked by the presence of overlying, calcareous algae- and mollusc-bearing "Leitha" limestone in the N (Fig. 2; Schafarzik & Vendl 1929), and by two small calcareous algae-bearing occurrences of pumiceous "tuffite" in the SE periphery (Koch 1877; Zelenka 1960). The age of the limestone is Early Badenian (Müller 1984; Dulai 1996).

As for volcanic source areas, it has been widely accepted that most of the subvolcanic and/or extrusive rocks correspond to vent areas (e.g. Zelenka 1960; Korpás (Ed.) 1998). In contrast, explanations for the dominant volcaniclastic rocks have been missing or poorly constrained. The lower unit, namely the dacitic pumiceous "stratovolcanic" series has not been connected to any paleovolcanic centres. For the upper unit, that is the amphibole andesitic series, a Somma-type structure was proposed by Schafarzik & Vendl (1929) and Cholnoky (1937), agreed by Balla et al. (1977) and recently by Korpás (Ed.) (1998). Firstly Cholnoky described the "calderas" of the outer, morphologically poorly defined, interrupted Dobogókő Hill and the inner, semicircular Keserűs Hill rims, but no caldera-forming mechanisms (e.g. related pyroclastic deposits or subsidence) have been documented so far.

Karátson et al. (2001, 2006) have identified the Keserűs Hill volcano as the main, central lava dome complex of the andesitic activity, destroyed northward by repeated dome and sector collapse events. It was shown that deposits of high-energy mass flows (debris flows, debris avalanches, e.g. the lower sequences of Szent Mihály Hill and the upper part of Visegrád Castle Hill) can be inferred N of the half-open "caldera", which is a remnant of a deeply eroded horseshoe-shaped depression. In addition, to the S, volcano-sedimentary facies changes (see also in point 3.3) as well as identical lithology to the central part of Keserűs Hill suggest the vicinity of Dobogó-kő to be the distal facies of the Keserűs Hill volcanic edifice, being simply an upthrown segment of a fault. (The fault itself was mentioned first by Láng (1955), and indicated on map by Balla et al. (1977).) Modifying and refining the maps of Balla et al. (1977) and Korpás & Csillag-Teplánszky (1999), Karátson et al. (2006) emphasized the role of NW-SE, N-S and less frequent NE-SW striking faults dissecting the volcanic structures.

From the late 1990's, new research projects on the Visegrád Mts have made it possible to produce a great number of new K/Ar datings and paleomagnetic measurements. Results of new geochemical analyses have also been published (Harangi 1999; Harangi et al. 2001). A paleogeographic study has focused on the Danube Bend and its volcano-geomorphic background (Karátson et al. 2006). In this paper, we present a stratigraphical synthesis based on new volcanological and petrological data, as well as previous and new K/Ar geochronological, paleomagnetic, geochemical and paleontological results. In the light of the newly established stratigraphy of the neighbouring Börzsöny Mts (Karátson et al. 2000), we make a geochronological comparison, and we think that the eruptive activity of both areas can be better revealed due to the integrated approach.

2. Analytical techniques

The rock samples were subjected to regular polarizing microscope investigation with a Nikon Labophot 2 microscope equipped with a Nikon Coolpix 4500. We used standard 30 μm-thick polished thin sections. Major and trace element analysis of 45 samples from the volcanic suite was carried out partly in the Geochemical Laboratories of the Royal Holloway University of London (for analytical details see Harangi et al. 2001) and partly in the ACME Laboratories in Toronto (www.acmelab.com). In the ACME Laboratory, both the major and trace elements were determined by ICP-MS techniques. The two laboratories gave consistent results tested by analysing the same samples at each site.

For K/Ar whole-rock analysis, a piece of rock approximately 2 kg in weight was collected, macroscopically free of xenoliths and obvious alteration, and then inspected by thin-section. These samples were crushed and sieved to 250–100 μm, then washed and dried at 110 °C for 24 h. A portion of the dried fraction was ground resulting in powder which was analysed for potassium. To evaluate the reliability of K/Ar ages, various mineral separates (biotite, hornblende, feldspar, volcanic glass) have also been dated. Incipient weathering of mineral separates was checked for by electronprobe microanalysis and X-ray diffraction. Amphibole, plagioclase and glassy matrix phases were separated by common heavy liquid (Sodium-Politungstite) and magnetic separation techniques from the 0.063–0.125 and 0.0125–0.250 mm fractions after crushing the samples. Final cleansing of the phases was done by handpicking. Rocks containing glass commonly yield rejuvenated ages because glass is normally enriched in potassium and often hydrated and submicroscopically devitrified, which results in the loss of radiogenic argon, even at low temperature. As a consequence, the argon loss may be related to the degree of hydration. On the other hand, it is proven that anhydrous glass in some cases can quantitatively preserve the argon. Therefore, in our work, the dating of pure glass separates aimed to determine the mininum age of the last eruptive event on the study area.

The techniques of argon and potassium measurements were similar to those described in Pécskay & Molnár (2002). To determine potassium content approximately 0.1 g of grounded samples were digested in HF by adding sulphuric and perchloric acids. Potassium concentrations were measured by flame photometer using Li internal standard. Depending on K content of the sample, weights of 0.1–1 g were used for argon extraction. The argon isotopic composition of the purified argon was measured using an isotopic dilution method and ^{38}Ar spike in a sector-type mass spectrometer, operating in a static mode with a single collector system. The result of calibration of the instruments and the details of the applied methods have been described elsewhere (Balogh 1985). Calculation of K/Ar ages was done using the decay constants suggested by Steiger & Jäger (1977). Analytical errors represent one standard deviation. Interlaboratory standards Asia 1/65 LP-6, HD-B1 and GL-0 as well as atmospheric argon were used to control the measurements (Odin 1982). In the stratigraphic evaluation, we refer to the internationally accepted time scale established by Vass & Balogh (1989).

The paleomagnetic laboratory processing of the samples drilled and oriented in situ in the field included measurements of the natural remanent magnetization, stepwise demagnetization by alternating field or thermal method, and measurements of the magnetic susceptibility anisotropy.

3. Petrography and volcanology

In this section, we describe and interpret the petrographic and volcanological features of the mapped volcanic rocks. Petrographically identical rock types may occur as different massive rock bodies and volcaniclastic deposits. In distinguishing genetic rock types, we focused on the assemblage and relative abundance of phenocrysts and accessory minerals as well as structural features of the mineral phases. Glass content and phenocryst versus glass ratio of a rock as well as oxidization state and alteration of minerals have also been considered.

Our groups below are based on petrographic types (Fig. 3) combined with volcanological facies relationships and inferred transport processes. We distinguish between (1) massive rock types of subvolcanic rocks, dykes and lava domes/flows, (2) pumice-bearing volcaniclastic (mostly resedimented) deposits, (3) block-and-ash flow deposits, and (4) other volcaniclastic (epiclastic) mass-flow deposits. It is important that all lithic clasts of groups 2, 3 and 4 are petrographically identical with the subgroups of massive rock types (1), thus help to reveal stratigraphic relationships. The most important petrographic properties are summarized in Table 1. All types are compared to the previously described rocks of the Börzsöny Mts (Karátson et al. 2000). Locality names are given in a simplified volcanological map (Fig. 2), a new compilation of previous data and petrographic and volcanological mapping for the present study. The groups are numbered in agreement with Fig. 2, and for each group an informal lithostratigraphic name (e.g. Lom Hill Lava Dome, Holdvilág-árok Tuffaceous Sandstone) is proposed.

Table 1: Textural parameters and phenocryst modes of the massive rock types of the Visegrád Mountains.

Group	**1/a**	**1/b**	**2/a**	**2/b**	**2/c**	**2/d**
Rock type	**biotite dacite**	**pyroxene**	**biotite amphibole andesite**	**pyroxene amphibole andesite**	**pyroxene amphibole andesite**	**basaltic andesite**
texture	hyalopilitic/trachytic	hyalopilitic/trachytic	hyalopilitic/trachytic	hyalopilitic	hyalopilitic/trachytic	pilotaxitic
totGm (%)	82	77	58	52	53	43
gm crystallinity	hypohyaline	hypohyaline	hypohyaline	hypocrystalline	hypohyaline	hypocrystalline
totPc (%)	18	23	42	48	47	57
plagioclase (%)	14	19	24	27	26.5	39.5
amphibole (%)	–	–	14.5	14.5	12.5	1.5
opx (%)	–	3	<1	4	7	5.5
cpx (%)	–	–	–	–	–	8.5
biotite (%)	3	<1	2	0–1.5	–	–
garnet (%)	1	<1	–	–	–	–
opq (%)	<1	1	1.5	1	1	2
totMafic (%)	4	4	18	21	20.5	17.5
plag/totMafic	3.5	4.75	1.33	1.28	1.29	2.26
amph/pyroxene	–	–	>10	3.63 (1.78–8.55)	1.79 (0.61–1.95)	0.11 (0–0.85)
accessories	garnet, apatite, zircon	garnet, apatite, zircon	apatite	apatite (zircon)	(apatite)	n.o.

totGm — total groundmass content, **totPc** — total phenocryst content, **opx** — orthopyroxene, **cpx** — clinopyroxene, **plag** — plagioclase, **opq** — opaque phase, **totMafic** — total mafic content, **n.o.** — not observed.

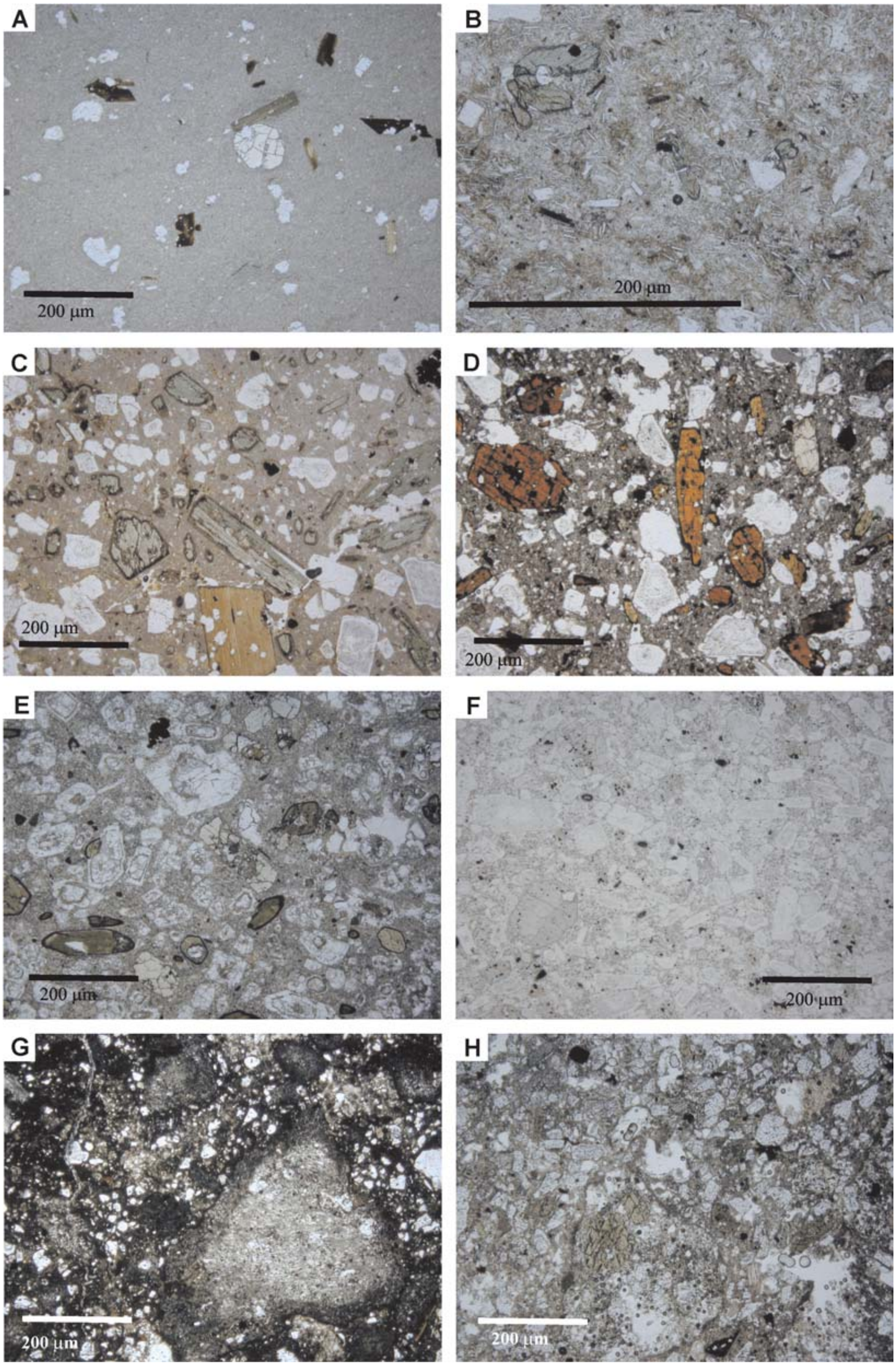


Fig. 3. Photomicrographs of typical textures and phenocrystal assemblages of representative samples from the 6 main massive rock types, and 2 volcaniclastic deposits. **A** — Garnet-bearing biotite dacite (1a, Ravine of Holdvilág-árok). **B** — Pyroxene dacite (1b, Peres Hill). **C** — Biotite amphibole andesite (2a, Kő Hill). **D** — Pyroxene amphibole andesite (opx, oxyamphibole; 2b, Ravine of Salabasina-árok). **E** — Pyroxene amphibole andesite (opx, hbl; 2c, Szent Mihály Hill). **F** — Basaltic andesite (2d, Prépost Hill). **G** — Tuffaceous sandstone with reworked pumices and small claystone clasts (Rám Hill). **H** — Pumiceous resedimented volcaniclastic deposit (Csikóvár Hill) with 2c type phenocrystal assemblage.

3.1 Massive rocks (subvolcanic and extrusive products)

3.1.1 Dacites/rhyodacites

On the basis of whole-rock chemistry (section 4), the two subgroups described here belong to the dacite/rhyodacite rock type in spite of the lack of quartz as free phase.

Garnet-bearing biotite dacite (1a Lom Hill Lava Dome). This is a light grey or pale greenish grey effusive/shallow level subvolcanic rock with hyalopilitic to trachytic texture and commonly flow-band structure and high glass content. The groundmass is generally inhomogeneous: brown, glass-rich hypohyaline patches exist in more transparent, colourless, predominantly hypocrystalline matrix, which is relatively rich in microphenocrysts. In the trachytic textured lava flows the arrangement of these patches in clusters and their alignment in bands cause the common macroscopic flow-band structure of these rocks, well-known for a long time (Zelenka 1960). The groundmass versus phenocryst ratio is much higher compared to the andesites (Table 1). The main phenocrysts are plagioclase (andesine to labradorite) and biotite, while opaque phase (magnetite/titanomagnetite) and almandine garnet occur subordinately. Biotite occurs both as unaltered entire crystals and as partially opacitized and resorbed fragments suggesting comagmatic origin for the former and xenocrystal origin for the latter population. Garnet is a comagmatic (Harangi et al. 2001) and characteristic accessory phase. Biotite and plagioclase as well as zircon and apatite are common inclusions in the garnet. The latter two minerals generally occur in the groundmass too, thus they are characteristic accessory phases of this dacite group, while they are absent or scarce in the andesites.

In the Visegrád Mts, the garnet-bearing biotite dacites occur mainly at the S and SW periphery (including the most voluminous Lom Hill: Fig. 2). High glass content of the rock, as well as roundish, isolated morphology of many hills consisting of this dacite type (Fig. 2), and analogy to the Börzsöny Mts, argue for the existence of small- to moderate-sized extrusive bodies, such as lava domes.

Pyroxene dacite ± garnet (orthopyroxene; 1b Csódi Hill Laccolith). This is a light grey shallow-level subvolcanic and effusive rocks with hyalopilitic texture and rare phenocrysts. The groundmass is hypocrystalline with a high amount of colourless glass, while the needle-shaped plagioclase and orthopyroxene microphenocrysts (up to 50 μm), as well as very few opaque microcrysts, are subordinate (Table 1). Biotite is absent from the groundmass. The phenocryst assemblage is plagioclase (andesine to labradorite), hypersthene with minor opaque phase, and biotite. Unlike in the 1a dacite type, biotite occurs only as small (up to 1 mm) resorbed and fully opacitized crystals suggesting xenocrystal origin, while garnet is less frequent or absent in some localities (e.g. Peres Hill).

This rock type occurs as eroded lava domes in the S periphery of the mountains (e.g. Peres Hill), and as a subvolcanic body (laccolith) of Csódi Hill in the NE (Koch 1871; Harangi 1999).

3.1.2 Andesites

Most of the volcanic rocks in the study area, ca. 90 %, are andesites. We distinguish between four andesite subgroups that represent the majority of the andesitic rocks of the mountains:

Biotite amphibole andesite (biotite, hornblende; 2a Ördögbánya Lava Dome). This is a dark grey or brownish-grey typically effusive rock type. The texture is hyalopilitic with a high amount of glass and high groundmass/phenocryst ratio (Table 1). The opaque phase is almost fully absent in the groundmass, being one of the distinctive features of this rock type. The phenocryst assemblage is plagioclase (andesine to bytownite), amphibole, biotite and magnetite, while orthopyroxene sporadically occurs as trace phase. The majority of the sparse hypersthene crystals (which may be absent) are fragmented and many crystals show resorption rims indicating disequilibria between the magma and the crystals, which suggests a xenocrystal origin of the pyroxene, while the biotite is surely comagmatic.

This rock type occurs in two large bodies (e.g. Ördögbánya Quarry). They may represent deeply eroded, dissected large bodi(es), possibly of lava domes, similar to Pap Hill and Nagy Sas Hill biotite andesites (Karátson et al. 2000) in the Börzsöny Mts, because we found this rock type in heterolithic, epiclastic breccias (e.g. Kő Hill), so it should have originated, at least in part, from an extrusive rock.

Pyroxene amphibole andesite (orthopyroxene, oxyamphibole: 2b Keserűs Hill Breccia). The colour of this rock, changing by locality, depends on the redox condition. The texture is hyalopilitic, but microphenocrysts are relatively abundant in the groundmass (Table 1). In the highly oxidized samples both the amphibole microphenocryst phase and the opaque phase (magnetite, secondary hematite) are red in colour. This alteration was caused by syneffusive oxidation of the hot lava dome surface in a subaerial environment. At other localities amphibole is brown and magnetite is unaltered, so the rock colour is light grey. The phenocryst assemblage is plagioclase (andesine to bytownite), oxyamphibole, and magnetite as minor phase. Orthopyroxene occurs as a minor phase in most samples, but sometimes it exists as a major phase. The amphibole/pyroxene ratio is much higher than in the next group. Biotite is generally absent, but in some samples it can occur as minor phase (Table 1). The biotite-free and biotite-bearing varieties can be found at the same places, thus they may belong to the same group. Apatite occurs as a rare but constantly present accessory phase only in this andesite type. There is an enriched, biotite-bearing subtype of 2b that is a dark red, highly oxidized pyroxene-amphibole andesite and its main phenocryst assemblage is similar to the 2b type but biotite phenocrysts occur as a minor (<1.5 %) phase. All the mafic minerals are fully opacithized and the pristine opaque phase is replaced by hematite. A real peculiarity of this subtype is the high abundance of accessories. Large (up to 300 μm), entire euhedral zircon as well as apatites that are short prismatic euhedral crystals (up to 500 μm) are frequent. In several samples, the amount of this latter phase approaches the minor phase category near to 1 % abundance. The majority of these crystals exist as inclusions in the opacithized amphiboles, but a lot of them occur as a free phase in the groundmass or as inclusions in plagioclases.

The 2b rock type occurs as a local lava flow in the northernmost part of the mountains (vicinity of Hegyestető Hill), and is the dominant constituent of block-and-ash and debris-flow deposits in the upper volcaniclastic unit of the N part of the mountains, dispersed all around Keserűs Hill volcano. At Visegrád Castle Hill it composes the upper monolithic block-and-ash flow breccias, whereas at Szent Mihály Hill middle W part they can be found in mono- and heterolithic debris-flow deposits (Fig. 4, section 4).

Pyroxene amphibole andesite (orthopyroxene, hornblende: 2c Szent Mihály Hill Lava Dome). This is a brown or greyish-brown rock type. Its texture is predominantly hyalopilitic, but in some lava flow units it continuously changes laterally from hyalopilitic to trachytic with decreasing glass content. The phenocryst assemblage is plagioclase (labradorite to bytownite), hornblende and orthopyroxene as major phases, and magnetite as a minor phase (Table 1). In the majority of the samples hornblende is the main mafic mineral, but in a few localities orthopyroxene is predominant. Biotite is absent. The hornblende is frequently opacitized and hypersthene commonly also shows opacite-like alteration. The opaque phase occurs both as microphenocrysts (<20 μm) in the groundmass and euhedral phenocrysts (150–400 μm), while intermediate-sized crystals are lacking. This bimodality of crystal size, which is a characteristic feature of the rock, suggests a two-stage crystallization process (Hibbard 1995).

This rock type constitutes the large bodies of Szent Mihály Hill and Ágas Hill Lava Domes (massive rock, lava breccia and minor block-and-ash flows). Also, it is a subordinate block constituent of block-and-ash flow deposits in the N region of the mountains (Rocks of Vadálló-Kövek, Visegrád Castle Hill) and volcaniclastic mass-flow deposits toward the periphery (Hideglelős kereszt and Basaharc Valley in the NW, Hirsch orom Hill, Rocks of Zsivány-sziklák in the S, Csikóvár Hill, Kő Hill and Ravine of Vasas-szakadék in the SE etc.). Furthermore, 2c type lithic clasts occur in a stratigraphically low position in the phreatomagmatic deposits of the ravine of Holdvilág-árok (Fig. 4 section 1), representing one of the earliest volcanic products of the mountains.

Basaltic andesite (ortho-, clinopyroxene, amphibole) (2d Dömör-kapu Lava Dome). This is a group of grey or brownish-grey shallow level subvolcanic rocks, such as dykes. The texture is generally pilotaxitic. Phenocrysts are abundant, especially plagioclase; the plagioclase/whole mafic phase ratio is the highest in the andesite types (Table 1). The phenocryst assemblage is plagioclase (bytownite to anortite), clinopyroxene and orthopyroxene. In addition to magnetite, amphibole can also be found as a minor phase. The subordinate amphibole is almost completely altered by opacitization. Remnant cores, commonly surrounded by a corona, consist of small hypersthene crystals, which show that both hornblende and oxyamphibole are original phases suggesting inheritance from the preceding andesite types. In some localities the groundmass is modified by subsequent or late-stage syneffusive hydrothermal alteration manifesting itself by small patches of spherulitic saponite, tridimite or opal assemblages.

This rock type is petrologically similar to the late-stage basaltic andesites of the Börzsöny Mts (Karátson et al. 2000). In the Visegrád Mts it occurs either as medium-sized subvolcanic bodies (Mátyás Hill Laccolith) to the deep part of lava domes (Dömör-kapu Lava Dome), or lava flows (Tövises Hill Lava Flow). The lava flows develop striking platy jointing and are characterized by uniform, outward dips (170–180/22°), implying an origin from the Keserűs Hill dome complex. The moderate dip also points to a location on the middle slope of the volcano (Fig. 2). (These platy jointed lava flows are typical in the High Börzsöny dome complex (Karátson et al. 2000) but except for Tövises Hill missing from Keserűs Hill.) Platy jointed basaltic andesite also occurs on Szent Mihály Hill lower part, and a strongly brecciated lava or dyke occurrence on its middle part.

3.2 Pumiceous mostly resedimented volcaniclastic deposits

Pumiceous, fine-grained volcaniclastic deposits (PVD) are exposed in a great number of localities all over the mountains (Fig. 2). They seldom exhibit evidence of hot emplacement, such as segregation pipes (e.g. ravine of Holdvilág-árok upper part, quarry: Fig. 4, layer 1/F) or unbroken crystals in fine ash (fallout deposits at Rocks of Zsivány-sziklák: Kósik 2005). In contrast, most deposits contain abundant, commonly subrounded, cm- (occasionally dm-) sized pumice clasts, typically set in a volcanogenic sand- to claystone matrix occasionally with claystone- and quartzite pebbles (Öregvíz Stream, the Ravines of Salabasina-, Holdvilág-árok and Rám-szakadék, Vaskapu and Ráró Hills, Szakó Hill E, Kő Hill etc.: Fig. 4). In some PVD, subangular to subrounded andesite lithic clasts are also present (e.g. Rocks of Zsivány sziklák, Ravines of Holdvilág-árok and Vasas-szakadék, Öregvíz and Sztelin Streams, Őr Hill, etc.: Fig. 4).

The occasional high pumice content implies a time-space relationship to the original pyroclastic processes. However, (a) the common normal grading of lithic and reverse grading of pumice clasts, (b) the existence of altered and/or subrounded pumice clasts and (c) the frequent non-volcanic xenolith content points to epiclastic reworking. Erosive channels, alternation of pumice-rich lenses with pumice poor laminae, typically <1 m-thick flow units, as well as frequent bedding and grading, imply deposition from volcaniclastic density currents. Reworking by subaqueous to subaerial debris-flows seems to have been the common range of transport processes (cf. Konečný & Lexa 1994; Karátson & Németh 2001; also see point 3.4).

In stratigraphical order, the following types can be distinguished as informal lithostratigraphic units.

3.2.1 Csádri Valley Sandstone

At the base of some valleys there is evidence of subaqueous/submarine deposition of fine-grained volcaniclastic mass-flows (e.g. *Ostrea* and *Aequipecten seniensis* fragments embedded in pumiceous and andesite lithic-bearing volcanogenic sandstone), especially in the E periphery of the mountains (e.g. Csádri Stream at Dunabogdány). For further details of these deposits, see section 7 on paleontology.

3.2.2 Holdvilág-árok Tuff and Tuffaceous Sandstone

In the lower position of other localities, tuffs, lapilli tuffs and tuffaceous sandstone (±pumice) were deposited in water-saturated environment (marked by accretionary lapilli, fine lamination, well-developed, contrasting grading of lithic and rounded pumice clasts: ravines of Holdvilág-árok and Vasas-szakadék, Kő Hill, Sztelin Stream, Visegrád Fekete Hill base ("Panorama Road"), Kisvillám Hill, ravine of Rám-szakadék lower part). The earliest volcanic eruptions of the mountains, as revealed in the lowermost units of the ravine of Holdvilág-árok (Fig. 4/1), produced phreatomagmatic deposits (i.e. with accretionary lapilli) and reworked pumiceous epiclastic rocks, directly overlying the basal marine sediments (see section 6 on Paleomagnetic data). There, the bulk chemistry of pumices is andesitic (Bendő et al. 2001). Their lithic clasts and the groundmass contain hornblende and orthopyroxene only, while garnet, biotite and oxyamphibole are absent, suggesting a 2c type andesite. Accretionary lapilli-bearing andesite tuff overlain by dacitic pumiceous lapilli tuff is also exposed at Sztelin Stream (Fig. 4). Korpás et al. (1967) described "andesitic tuffs" in basal position from Malom Valley, the NE part of the mountains, too. There, at Hirsch orom Hill, we have found 2c type andesite lithic clasts in a pumiceous mass-flow unit. In many localities, the shallow-water eruptions gave place to emergent activity, as charcoal or treetrunk remnants show (Kisvillám Hill — Hegedűs 1953; Rocks of Zsivány-sziklák — Kósik 2005; Dobogókő, Ecset and Őr Hills) as well as leaf imprints (Kisvillám Hill — Hegedűs 1953; Dobogókő Hill — Zelenka 1960). This implies a gradual shift from shallow submarine to subaerial deposition (and/or a nearby terrestrial environment). Rhyolitic-dacitic composition has been pointed out from only the ravine of Holdvilág-árok (Bendő et al. 2001) and Öregvíz Stream (i.e. SE part of the mountains) where PVD seem to be related to local lava dome activity (e.g. Zelenka 1960; Höfer 2003). (Without chemical analysis, Koch (1877) and Zelenka (1960) also mention "dacite tuffs" and "tuffites".) In the ravine of Holdvilág-árok, mixed, pumice-poor debris-flow deposits that contain lithic clasts both with andesitic (2c type) and dacitic (1a type) composition as well as pumices both with andesitic (hornblende- and hypersthene-bearing) and dacitic/rhyolitic composition (biotite-bearing) appear in a low stratigraphic position. They are overlain by pumice-rich reworked epiclastics that contain biotite-bearing pumice clasts with rhyolitic composition. A hot emplaced primary ignimbrite unit that is in a higher stratigraphic position contains andesitic pumice clasts and its mineral assemblage is identical with the 2c pyroxene-amphibole andesite, suggesting a concordant magmatic origin. Oxyamphibole fragments as well as andesite lithoclasts of 2b andesite type appear only in the overlying pumice-poor reworked deposits, while augite and 2d basaltic andesite fragments occur in deposits of the uppermost level.

3.2.3 Rám Hill Pumiceous Sandstone

A characteristic PVD occurs in the SW and SE foreground of Keserűs Hill volcano (e.g. valley heads of Rám Hill to upper level of Ravine of Rám-szakadék; Öregvíz Stream) as well as further to the W (valleys of Maróti Hills). This epiclastic rock is full of mm- to cm-sized, 2c type pumice fragments. It also contains claystone, quartzite pebbles and rarely mollusc fragments, and may also have been resedimented directly from explosive eruptions in a shallow water environment.

For all these types of PVD, brecciated lava domes as well as small explosive eruptions can be envisaged as major sources, similar to those inferred in the Burda (Helemba) Mts (Konečný & Lexa 1994) and Börzsöny Mts (Karátson & Németh 2001). Garnet- and dacitic lithoclast-bearing PVD may have been originated from the neighbouring dacite lava domes (e.g. Höfer 2003). Some types of PVD, most typically the Rám Hill Pumiceous Sandstone, may have been originated from Keserűs Hill Lava Dome itself, as indicated by its distribution and its 2c type andesite, which is found as dykes in the source area. The described localities occur both inside and outside the mountains suggesting that transport processes and paleogeography were generally the same all over the mountains. This conclusion is in accordance with scattered, small- or medium-sized volcanic centres.

3.3 Block-and-ash flow deposits

Mostly in the upper levels of the mountains (typically around Keserűs Hill volcano: ca. 35 km^2), a great number of outcrops reveal coarse-grained pyroclastic breccias (clast size up to 5 m) with monolithological composition (Keserűs Hill Breccia: Fig. 4). Petrographically, the main (>95 %) block constituent is the 2b pyroxene amphibole andesite, but there is a unique, zircon and apatite rich biotite-bearing subtype that is a minor (<5 %) but spatially widespread constituent. In some localities the 2c type

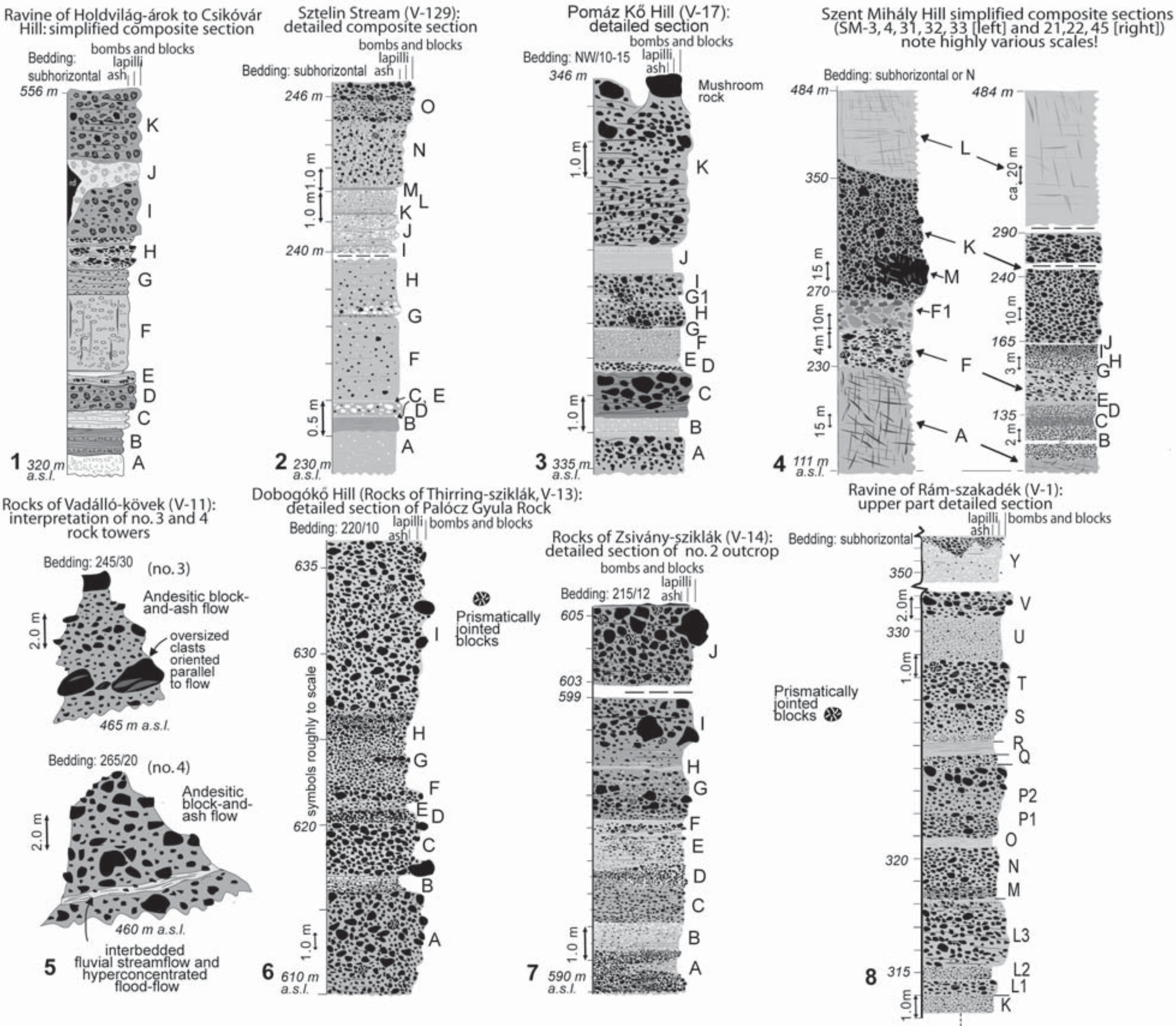


Fig. 4. Selected stratigraphic logs of the dacitic-andesitic volcanism of the Visegrád Mts. For localities, see Fig. 2. **1** — Ravine of Holdvilág-árok (No. 1 in Fig. 2, Table 3): A — *Ostrea*-bearing siltstone, B — Andesitic phreatomagmatic units with accretionary lapilli, C — Garnet-bearing rhyodacitic phreatomagmatic units, D — Andesitic block-and-ash flow, E — Andesitic pumice-bearing hyperconcentrated flood-flow and debris-flow, F — Andesitic ignimbrite, G — Andesitic fall and small-volume pyroclastic-flow, H — Andesitic debris flow, J — Rhyodacitic block-and-ash flow units inferred to be related to coherent rhyodacite bodies, K — Andesitic debris-flow units of block-and-ash flow origin. **2** — Sztelin Stream: A — Submarine (?) siltstone with pumice fragments, B — Siltstone, C, E — Bedded siltstone, D — Pumice-rich tuffaceous sandstone, H — Subaerial (?) dacitic volcaniclastic mass-flow unit with pumice-rich lens at base, I — Pumice-rich lapillistone, J — Pumice-bearing bedded, cross-bedded lapilli tuff with pumice concentration lenses and zones, K — Siltstone (hyperconcentrated flood-flow) with pumice fragments, L — Pumice- and andesitic lithic-rich lapilli tuff, M — Coarse volcanogenic sand (fluvial deposit), N — Andesitic block-and-ash flow with pumice fragments, O — Volcaniclastic debris flow. **3** — Kő Hill: A — Andesitic debris flow, B — Volcanogenic siltstone, C — Debris flow with reverse grading, D — Andesitic lapilli-bearing fine breccia, E — Volcanogenic siltstone, F — Pumiceous lapilli tuff/tuffaceous sandstone, G–G1 — Volcanogenic sandstone (hyperconcentrated flood-flow), H–I — Andesitic debris-flow units with normal and reverse grading and channel fills, J — Silty sandstone (hyperconcentrated flood-flow), K — Andesitic debris flows with normal grading and lithic concentration zones. **4** — Szent Mihály Hill southwestern part (Nos. 34, 14, 35): A — Strongly fractured andesite subvolcanic body, B — Medium-grained breccia (debris flow), C — Densely packed ungraded debris flow, D — Reversely graded debris flow, E — Tuffaceous sandstone, F — Heterolithic, very coarse-grained breccia (small-volume debris avalanche or big debris-flow), F1 — Monolithologic breccia, G — laminated siltstone (hyperconcentrated streamflow), H — Slightly bedded fine-grained breccia, J — Reversely graded debris flow, K — Coarse-grained monolithological debris flow, L — Strongly fractured andesite lava breccia (summit lava dome), M — Basaltic andesite lava breccia (dyke/sill?). **5** — Rocks of Vadálló-kövek (No. 20). **6** — Rocks of Thirring-sziklák (No. 24): A — Andesitic debris flow with reverse grading, B — Fluvial streamflow/debris flow, C — Andesitic debris flow with minor reverse grading, D — Densely packed, reversely graded debris flow, E — Bedded hyperconcentrated flow, F — Normal graded debris flow, G — Debris-flow with double grading, H — Slightly reversely graded debris flow, I — Ungraded debris flow. **7** — Rock of Zsivány-sziklák: A — Erosion channels in pumiceous, lithic-rich debris flow, B — Reversely graded pumiceous volcaniclastic mass-flow, C — Lithoclast-bearing, slightly pumiceous diluted debris-flow, D — Channel fills of lithic- and pumice-rich debris flow. E — Slightly pumiceous debris flow, F, H — hyperconcentrated flood-flow, G, I, J — Andesitic block-and-ash flow-related debris flow sequence. *Continued on next page*

also appears, but it is scarce (< 1 %) and presumably of accidental (picked-up) origin. Poor sorting and stratification, no or minor grading, frequent prismatic jointing and porous texture of clasts are common at the Keserűs Hill–Öreg Pap Hill ridges. Scarcely, small (centimetric) pumice fragments can also be found. These features are consistent with a proximal facies of subaerial block-and-ash flow deposits (BFD). As for the source area of BFD, observations and analogies indicate a single, cone-shaped lava dome group (i.e. the Keserűs Hill edifice): (1) radial pathways inferred from dip data (Karátson et al. 2006, also see Fig. 2), (2) monolithological composition, (3) systematic facies changes from proximal BFD to petrographically identical debris-flow deposits (e.g. Dobogókő Hill 3 km and Csikóvár Hill 7 km to the S, Ecset Hill 5–6 km to the W, Borjúfő Hill 5 km to the E, distances with respect to the Keserűs Hill volcano geometrical centre), and (4) geomorphic, volumetric analogies to worldwide examples (i.e. Unzen, Mont Pelée; see calculations in Karátson et al. 2006). This way, the inferred source area should have been around Ágas Hill, which itself, however, is a post-BFD feature (i.e. another, smaller lava dome of 2c type andesite) that formed subsequent to the proposed sector collapse. On the other hand, the close proximity of BFD to the centre (e.g. Rocks of Vadálló-kövek: 2.5 km) does not mean that the upper part of the Keserűs Hill volcanic cone has been preserved. During the 15 Myr-long degradation, the original horseshoe-caldera of the volcano has been strongly eroded, its rim lowered and retreated (Karátson et al. 2006), which is proven by the fact that these proximal BFD are interbedded with undulating, hyperconcentrated to fluvial streamflow deposits with only 5 to 15° dip, emplaced originally on the lower flanks (Fig. 4; also see point 3.4.3).

In the BFD, the described colour change of blocks (2b type) fits the inferred lava dome origin: it represents the contemporaneous oxidation of the fracturing lava domes. This feature, coupled with the pumice content as well as the porous andesite clasts, implies explosive dome collapses rather than simple gravitational ones. It is noteworthy that the High Börzsöny BFD (Karátson 1995) do not show these features, possibly due to the dominant gravitational dome collapses inferred.

The above mentioned facies changes toward debris flows show the extent of the area where the coarse-grained part of the original BFD were still deposited and preserved. The debris-flow counterparts are better sorted and graded and are mostly composed of thinner flow units (e.g. Dobogó-kő Hill: see Fig. 4). The existence of the monolithologic block-and-ash-flow–debris-flow continuum beyond the previously proposed "outer caldera" margin (i.e. Dobogókő or Urak-asztala Hills etc.: Cholnoky 1937; Korpás (Ed.) 1998) excludes the presence of an outer "caldera rim" (see earlier).

3.4 Other volcaniclastic mass-flow deposits

3.4.1 Debris-flow deposits (DFD)

In addition to the diluted, monolithological debris-flows of block-and-ash flow origin, heterolithic DFD crop out at the most distal localities (relative to Keserűs Hill volcano), such as Ráró and Ecset Hills in the W, Csikóvár Hills in the S, Nyerges and Vörös-kő Hills in the E, Szent Mihály Hill lower-central part in the N. There, mostly 2c type andesite blocks and lapilli are mixed with other andesite types (2b > 2d > 2a) and subordinately dacite clasts to various extents, suggesting local depocenter areas at the contemporary erosion base level. Lack of widespread conglomerates (that occur subordinately in the ravines of Rám-szakadék or Holdvilág-árok) implies short transport distances as well as a rapid change from shallow-water to emergent activity. The DFD show thinner and more developed flow units than the diluted block-and-ash flow deposits, and are frequently interbedded with hyperconcentrated to normal streamflow deposits. Sometimes minor pumice content makes a transition towards pumiceous volcaniclastic deposits.

3.4.2 Debris-avalanche deposits (DAD)

The best exposed area of coarse-grained volcaniclastic breccias is the very steep Szent Mihály Hill (exposed by the Late Pleistocene downcut of the Danube Bend: Karátson 2001; Karátson et al. 2006). Especially at its W lower to central part, mono- and heterolithic breccias of 2c–b–d type andesites with block size up to 6–8 m crop out (e.g. Dobozi-orom Debris Avalanche). The presence of large/oversized and cracked blocks, sometimes with jigsaw fit, as well as strongly undulated basal layer point to small-scale debris avalanche or huge debris-flow transport mechanisms. Given the general northward dip of beds, we postulate that most of these breccias originated from the Keserűs Hill volcano, ca. 4 km southward, that is also characterized by 2b–c–d type andesites. Another DAD area is the Visegrád Castle Hill upper part (Karátson 2001; Bendő 2002). There, 2a type brecciated lava is overlain by typical 2b type block-and-ash-flow breccias that show cracked blocks and jigsaw fit, and the matrix is

8 — Ravine of Rám-szakadék: K — Fine-grained volcaniclastic mass-flow, L — Andesitic debris flow–fluvial streamflow sequence (L1 — rounded, medium-sized lithics, L2 — wedging of fine-grained bed, L3 — semirounded cobbles in lenses and zones), M — Stratified andesitic debris flow, N — Ungraded andesitic debris flow, O — Hyperconcentrated flood-flow, P — Andesitic debris-flow sequence (P1 — Ungraded bed, P2 — reverse grading with oversized clasts on top), Q — Andesitic debris flow with undulating (erosive) base, R — Hyperconcentrated flood-flow, S — Reversely graded heterolithic andesitic debris flow, T — Andesitic debris flow from block-and-ash flow, U — Fine lithoclasts in andesitic volcaniclastic mass-flow, V — Monotonous ungraded andesitic debris-flow, Y — Lithic-rich channel fills in pumiceous volcaniclastic mass-flow.

characterized by reddish, fine-grained plastic deformation, typical of debris avalanches. The positive, concentric morphology of the hill might be due to the strongly resistant coarse breccia cover.

3.4.3 Hyperconcentrated flood-flow (HFD) and fluvial streamflow (FSD) deposits

HFD and FSD occur dominantly in the peripheral areas of the mountains (Szent Mihály Hill S part lower sequences, Vaskapu Hill, Ecset and Ráró Hill, Rocks of Zsivány sziklák, Öregvíz and Sztelin Streams etc.), interbedded in particular with fine-grained pumiceous volcaniclastic and debris-flow deposits. Uniquely, they also crop out in the Rocks of Vadálló Kövek (Keserűs Hill: Fig. 4), separating two voluminuous block-and-ash flow units. Their appearance in basal strata (e.g. ravine of Holdvilág-árok, and Őr, Vaskapu and Vöröskő Hills) indicate that the earliest shallow-water environment should have rapidly been replaced by terrestrial environment on the emergent islands. The abundance (widespread preservation) of such deposits, along with various debris-flow deposits, implies long, quiescent inter-eruptive periods, and a relatively low and mosaic-like relief that did not enable reworking processes to deposit their load far away. The emergent archipelago (under subtropical climate), characterized by subaerial debris-flows–hyperconcentrated flood-flow–fluvial streamflow processes, was also pointed out in the time-space related Börzsöny Mts (Karátson & Németh 2001).

4. Geochemistry

In general, the Miocene volcanic rocks of the Visegrád Mts are mostly andesites (Table 2), falling right into the boundary between the medium-K and high-K calc-alkaline series in the SiO_2 versus K_2O diagram (Fig. 5a). Basaltic andesites (2d type) are among the latest rocks and they occur subordinately. The early-stage volcanic rocks have a bimodal character: they are high-K dacites to rhyodacites (1a and 1b) with subordinate andesites (2c: i.e. initial phreatomagmatic activity). The bulk-rock geochemistry of 2c–b–a andesite types overlaps in places, but shows a general trend towards increasing SiO_2 and K_2O content (Fig. 5a). No compositional differences can be observed between the previously mentioned red and light andesite clasts (of 2b) of the same block-and-ash flow deposits. Comparing major element data of the Visegrád andesites with the nearby Börzsöny rocks (Karátson et al. 2000), slight differences can be observed: the Visegrád andesites contain a little bit less K_2O at a given SiO_2 content.

The N-MORB normalized trace element patterns (Fig. 5b) of the basaltic andesites (2d) and the more silicic andesites have very similar character and show typical subduction-related features: enrichment of the large-ion lithophile elements (e.g. Rb, Ba, K), negative Nb-anomaly

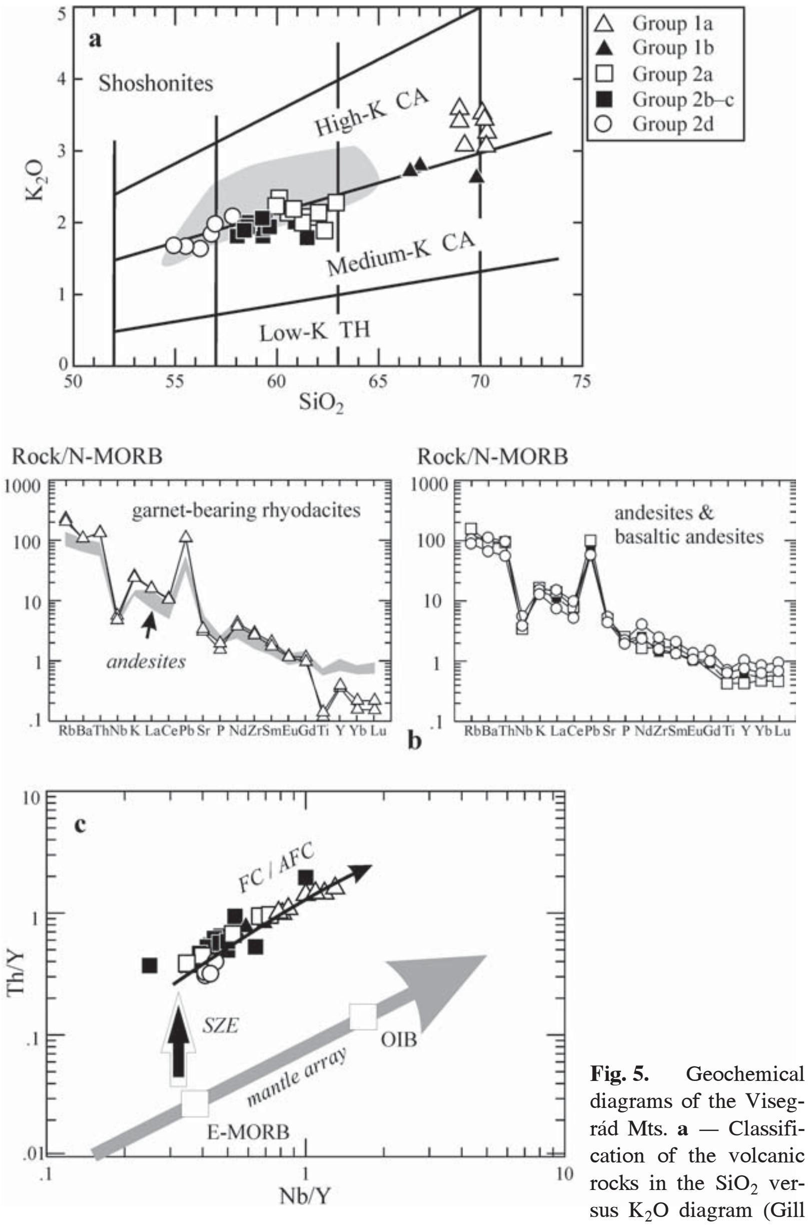


Fig. 5. Geochemical diagrams of the Visegrád Mts. **a** — Classification of the volcanic rocks in the SiO_2 versus K_2O diagram (Gill 1981). The shaded field indicates the Miocene volcanic rocks of the Börzsöny Mts. **b** — N-MORB (Pearce & Parkinson 1993) normalized trace element patterns of representative samples of different groups of the Miocene volcanic rocks of the Visegrád Mts. Symbols are explained in Fig. 5a. **c** — Th/Y versus Nb/Y diagram for the Miocene volcanic rocks of the Visegrád Mts. SZE = subduction zone enrichment; FC = fractional crystallization; AFC = assimilation and fractional crystallization; E-MORB = enriched Mid-Ocean Ridge Basalts; OIB = ocean island basalts.

and positive Pb-anomaly. The garnet-bearing rhyodacites (1a–b) have a similar trace element pattern with slightly higher incompatible trace element abundances, but they show a marked depletion in Y and heavy rare earth elements. A similar feature was also observed in the garnet-bearing dacites of the Börzsöny Mts (Karátson et al. 2000; Harangi et al. 2001). The garnet-free andesites of the Visegrád Mts have fairly similar trace element patterns to the Börzsöny andesites, although the latter ones have characteristically higher Ba concentration.

The basaltic andesite to andesite suite of the Visegrád Mts forms a linear trend in the SiO_2 versus K_2O diagram, suggesting a genetic relationship. The cogenetic relationship is also confirmed by the strong linear correlation between the highly incompatible trace elements, such as La, Th, Nb, Rb, Ba and Pb. The rhyodacites have similar incompatible trace element ratios to the andesites, too, implying that they could have derived from a similar source region. In the Nb/Y versus Th/Y ratio diagram (Fig. 5c), they form a linear trend above the mantle array. It suggests subduction-related enrichment followed by fractional crystallization or assimilation combined by fractional crystallization. Harangi et al. (2001) proposed that contamination by lower crustal metasedimentary rocks could explain the occurrence of the garnet-bearing volcanic rocks. The low Y and heavy REE content indicate either garnet or hornblende fractionation during the early stage of magma evolution.

5. K/Ar geochronology

In Table 3, along with all previous dates (Balogh 1977–1979), analytical results and calculated K/Ar ages are given.

Table 2: Main and trace element geochemistry of selected rock types of the Visegrád Mountains.

Locality	Ravine of Holdvilág-árok	Csódi Hill	Peres Hill	Pilisszent-lászló	Panoráma Hill	Öreg-Pap Hill	Prédiká-lószék	Szt. Mihály Hill	Szt. Mihály Hill	Dömör-kapu
Sample	VH-H1	VH-CSH	PS5	VH-18/1	P1A	VH-L84	30/1	SMH298/29	SMH298/4	12/2A
Group	1a	1b	1b	2a	2a	2b	2b	2b	2d	2d
Major elements [wt. %]										
SiO_2	68.90	66.16	69.63	61.53	59.1	58.7	59.06	57.2	55.8	56.68
TiO_2	0.18	0.25	0.27	0.56	0.59	0.61	0.58	0.51	0.73	0.90
Al_2O_3	16.48	17.48	16.25	18.11	17.6	18.35	18.05	18.5	18.5	17.94
Fe_2O_3	3.36	4.13	3.04	5.98	6.24	6.66	6.48	6.3	8.12	7.60
MnO	0.06	0.1	0.07	0.09	0.07	0.12	0.12	0.14	0.13	0.12
MgO	0.38	0.65	0.56	1.96	2.91	3.3	3.23	4.08	3.18	4.06
CaO	3.36	4.24	3.62	6.44	6.67	7.5	7.35	7.23	8.12	7.80
Na_2O	3.60	3.53	3.54	2.93	2.96	2.69	2.88	2.66	2.89	2.26
K_2O	3.06	2.69	2.61	2.08	2.2	2	1.93	1.78	1.63	1.97
P_2O_5	0.14	0.18	0.14	0.19	0.22	0.18	0.16	0.12	0.14	0.16
total	99.52	99.41	99.73	99.87	98.56	100.11	99.84	98.52	99.24	99.49
LOI	0.92	0.97	0.67	1.58	1.5	1.63	1.13	1.55	0.7	0.37
Trace elements [ppm]										
Ni	4	4	5	12	n.d.	11	9	n.d.	n.d.	11
Cr	8	4	5	33	22	29	24	27	14	48
V	17	15	20	126	n.d.	138	128	n.d.	n.d.	189
Sc	2.50	4.4	5.10	18.2	15	21.4	20.60	15	20	30.20
Rb	112	107	100	81	76	73	76	56	54	59
Ba	666	678	502	542	557	497	551	470	432	707
Pb	32.3	28.6	29.0	25.9	n.d.	18.1	20.0	n.d.	n.d.	17.2
Sr	303	340	289	432	415	420	414	311	344	489
Zr	197	187	139	116	121	107	105	109	119	183
Nb	11	10	9	10	10	8	8	7	7	13
Y	11	17	13	24	20	18	17	15	21	29
Th	15.50	13	10.70	12.6	11.7	11.1	11.00	8.5	6.9	11.60
La	39.00	34.51	30.40	35.8	36	28.2	28.10	22	22	37.73
Ce	77.12	67.17	54.00	59.3	61	47.9	52.13	45	45	73.92
Nd	27.10	22.6	20.30	28.5	19	19.1	18.50	20	39	29.70
Sm	4.56	3.6	n.d.	n.d.	4.2	n.d.	3.46	3.2	3.6	5.50
Eu	1.18	1	n.d.	n.d.	2	n.d.	1.02	0.7	2.8	1.39
Gd	3.54	2.96	n.d.	n.d.	n.d.	n.d.	3.33	n.d.	n.d.	5.51
Dy	2.24	2.51	n.d.	n.d.	n.d.	n.d.	2.91	n.d.	n.d.	4.79
Ho	0.37	0.49	n.d.	n.d.	n.d.	n.d.	0.57	n.d.	n.d.	0.97
Er	0.64	1.2	n.d.	n.d.	n.d.	n.d.	1.41	n.d.	n.d.	2.41
Yb	0.67	1.53	n.d.	n.d.	0.6	n.d.	1.63	1.3	2.9	2.59
Lu	0.10	0.26	n.d.	n.d.	0.14	n.d.	0.27	0.05	0.18	0.43

n.d. = non determined

The garnet-bearing dacitic rocks have yielded ca. 16 Ma ages (15.9 Ma average age of biotite separates). The same ages (>16 Ma on whole rock and an amphibole separate) were also obtained from the stratigraphically related earliest andesitic volcaniclastics, from the ravine of Holdvilág-árok. Thus, the 16 Ma age may reflect the beginning of volcanic activity in the Visegrád Mts. According to stratigraphic constraints, the volcanism continued to develop after a short quiescence, and on the basis of all available K/Ar data the peak of the volcanic activity occurred ca. 15.5–15 Ma ago. It should be noted that, in some cases, andesite K/Ar ages older than 16 Ma might be the consequence of the presence of excess argon. Especially andesitic rocks possessing phenochrysts of olivine, pyroxene, hornblende or plagioclase may give anomalously old apparent ages, owing to the incorporation of excess argon from the environment, as the phenochrysts crystallized in the magma prior to its eruption (see K/Ar ages obtained on amphibole separates).

A small number of younger ages obtained on whole-rock samples (i.e. 13–14 Ma) can be related to minor or secondary event(s). However, at least those K/Ar ages determined on volcanic glasses make it likely that the dates younger than about 14.5 Ma can rather be considered "apparent ages" (also see the Discussion).

6. Paleomagnetic data

A great number of paleomagnetic results, reported in Table 3, were obtained in the 1970s (Balla & Márton-Szalay 1979), while another set was produced recently. Since our results are published for the first time, new data are shown with statistical parameters k and α_{95} (Fisher 1953). The scatter of the individual directions within a sample group (consisting of 4–9 independently oriented cores) is expressed by k, while α_{95} gives the radius of the confidence circle (which for the previously published localities varied between 5 and 17).

The newly sampled volcanic rocks are of good quality and yielded statistically excellent results to infer reliable paleomagnetic directions. The single claystone locality from the ravine of Holdvilág-árok (No. 1 in Table 3) is of lower quality, yet its counterclockwise (CCW) rotation (with reverse polarity) obtained is important for the general interpretation of the paleomagnetic data. The claystone is overlain by initial, andesitic biotite-bearing phreatomagmatic deposits, whose declinations are also suggestive of CCW rotation (probably with a successive, normal polarity). The same characteristics typify the initial pumiceous deposit of Öregvíz Stream also in the SE part of the mountains (No. 2). All these biotite-bearing pyro- and volcaniclastic rocks (occasionally with garnet) are among the oldest volcanic products in the area. In the Börzsöny Mts, the basal garnet-bearing dacitic successions also exhibit CCW rotation (with normal polarity). Therefore it stands to reason to seek correlation between the Börzsöny and Visegrád Mts, starting the volcanic evolution with the CCW rotated normal polarity paleomagnetic zone (marked with circle) and proceeding as Table 3 shows.

A striking feature of the paleomagnetic results from the Visegrád Mts is the dominance of reversed polarity. In fact, with the exceptions of the above-mentioned two normal polarity rotated sites of the earliest successions, the other positive inclinations, coupled with uncertain declinations, can be regarded as "anomalous" paleomagnetic directions (Csódi Hill second site, Szamár Hill and Hideglelős-kereszt quarries). This way, subsequent to the oldest volcanic stage with normal polarity, the volcanic activity should have been most intense during a reversed polarity zone. As for Csódi Hill, additional results of M. Lantos (unpublished) complete the picture about a cooling subvolcanic body (e.g. Bendő & Korpás 2005): the fast cooling edge shows reverse polarity, while the slow-cooling near-vent part may have been solidified during a transitional period to normal polarity.

At the same time, in agreement with our conclusion for the Börzsöny (Karátson et al. 2000), this reversed zone is characterized by a marked change from counterclockwise (CCW) rotated declinations to non-rotated ones (with respect to the stable European reference declination). In Table 3, these two groups are marked with squares and rhombs. By analogy with the Börzsöny, the rotation period can be placed within the long reversed polarity zone between 16 and 15 Ma (see point 8.1 in Discussion).

The paleomagnetic data set of Table 3 does not contain evidence for the continuation of the volcanic activity in the Visegrád Mts less than 15 Ma, although we note that the basaltic andesite rocks, among which are the youngest products from stratigraphic constraints, have not been measured with one exception.

The magnetic anisotropy of some sites (i.e. in the ravine of Holdvilág-árok) shows that the volcanic rocks were deposited concordantly with the underlying, largely horizontal sedimentary deposits. This implies that no large-scale tilting has occurred in the mountains. This conclusion is in accordance with the fact that the magnetic foliation planes of the most widespread and measured 1st stage tuffs in the Börzsöny Mts are also near-horizontal.

7. Paleontological constraints

In the Visegrád Mts, fossiliferous sedimentary deposits can be found in smaller areas than in the Börzsöny Mts. However, there are a number of important key localities mainly in the E and N periphery, representing (1) the initial volcanic eruptions, (2) the gap in the volcanic activity following the dacitic eruptions, and (3) the period just after the termination of volcanism.

(1) A fossil-rich assemblage similar to the Kismaros Tuff in the Börzsöny Mts (Báldi & Kókay 1970) is not known in the Visegrád Mts from the beginning of the volcanism. However, some old findings along the E periphery (close to the present Danube: e.g. Öregvíz Stream, Nagy Villám Hill etc.) reported by Koch (1877)

Table 3: Correlation of all previous and new K/Ar ages and paleomagnetic measurements in the Visegrád Mts. ○ = first paleomagnetic stage according to the stratigraphy of the Börzsöny Mts (normal polarity, affected by CCW rotation). Average of biotite K/Ar ages is 15.9 Ma (4 datings). □ = second paleomagnetic stage according to the stratigraphy of the Börzsöny Mts (reverse polarity, affected by CCW rotation). Average of K/Ar ages is 15.57 Ma (10 datings) and 15.48 Ma (without the amphibole and glass ages). ◇ = third paleomagnetic stage according to the stratigraphy of the Börzsöny Mts (reverse polarity, unaffected by rotation). Average of K/Ar ages is 15.06 Ma (36 datings) and 14.90 Ma (without the amphibole and glass ages). (The whole rock ages of the Pilisszentlászló-2 boreholes have been omitted from the calculations, because there is no indication for the paleomagnetic stage, and because they may have been affected by rejuvenation (see text).) In column 3, the quotation marks refer to original lithological description of some rocks (refs 1, 2) not checked in the field. Additions in brackets indicate more precise or more probable lithologies. For rock types (1b, 2a etc), see text.

Locality key (Fig. 2) and sample no.		Locality and stratigraphy	Lithology	Paleomagnetism		K/Ar geochronology						Remarks	Refs	
				D°/I° k; α_{95} *	stage	No. K/Ar lab	dated fract.	K %	$^{40}Ar_{rad}$ %	$^{40}Ar_{rad}$ (ccSTP/g)	Age (Ma)		Paleo	K/Ar
1a	V0	Ravine of Holdvilág-árok underlying dep.	claystone	111/–47 7; 20	(X)							older paleomagnetic stage, possibly with a bigger rotation	3	
2	V127	Öregvíz Stream	“pumiceous (dacite?) tuffite”	354/47	○								1	2
1b	V0	Rav. of Holdvilág-árok lower pyroclastic series	phreatomagmatic biotite-bearing andesitic tuff	348/64 178; 7	○								3	3
1c	V0	Rav. of Holdvilág-árok middle pyroclastic series	pumiceous dacitic tuff with dacite lithic clasts + garnet	155/–70 179; 4	□	5351	biotite	6.68	71.3	4.368×10^{-6}	**16.73±0.65**	B.Zs.	3	3 3
1c	V0	Rav. of Holdvilág-árok middle pyroclastic series	interbedded andesitic tuff andesitic block-and-ash flow deposit			5352 5350	am w. r.	0.66 1.41	56.0 52.8	4.280×10^{-6} 8.989×10^{-6}	**16.58±0.67** **16.36±0.68**	B.Zs.		
1d	V0	Rav. of Holdvilág-árok upper pyr. series	pumiceous andesitic lapilli tuff (ignimbrite)	150/–70 207; 5	□								3	
3a		Pilisszentlélek	1a dacite + garnet			4417	biotite	5.76	76.8	3.524×10^{-6}	**15.67±0.60**	B.K.		3
3b		Pilisszentlélek	“andesite” (1a dacite)	150/–36	□							dyke	1	
4	V42	Öregvíz Stream upper section	“andesite” (dacite) tuff	132/–63	□								1	2
5		Csikóvár Hill SE	2c andesite	141/–60	□							dyke	1	
6	V21	Ördög-küllője Hill W (quarry)	am andesite (2c?)	163/–49	□	412	w. r.				**13.9±1.5**	bi content (Balla & Márton-Szalay 1979) is unlikely	1	2
7	V26a	Apátkút Valley	2a andesite	168/–54	□	422	w. r.				**15.1±1.2**		1	2
8		Cser-forrás Spring (Pilisszentkereszt)	bi andesite (1a dacite)	172/–37	□								1	
9		Peres Hill	1b dacite				w. r.				**14.8±0.8**			2
10		Mátyás Hill quarry	2d andesite	172/–75	□	414	w. r.				**15.8±1.0**		1	2
11	V146	Bükkös Stream upper section	“pumiceous tuffite” (+with biotite)	174/–63	□								1	
12	SM28	Szent Mihály Hill lower lavas	2c andesite	175/–40 175; 4	□ ? ◇ ?	6160 6203	glass am	2.03 0.51	45.5 38.3	1.157×10^{-6} 3.254×10^{-6}	**14.60±0.60** **16.20±0.76**		3	3 3
13	SM30	Szent Mihály Hill lower level	2b andesite breccia			5511	w. r.	1.19	28.6	7.553×10^{-7}	**16.26±0.91**			3

Table 3: *Continued from previous page.*

Locality key (Fig. 2) and sample no.		Locality and stratigraphy	Lithology	Paleomagnetism		K/Ar geochronology						Remarks	Refs	
				D^o/I^o k; α_{95} *	stage	No. K/Ar lab	dated fract.	K %	$^{40}Ar_{rad}$ %	$^{40}Ar_{rad}$ (ccSTP/g)	Age (Ma)		Paleo	K/Ar
14	SM4	Szent Mihály Hill middle level	2d andesite			5510	w. r.	1.32	66.4	8.299×10^{-7}	**16.14±0.64**			3
15		Kékibánya Quarry	2c andesite	175/–50	□ ◇?									
16		Miklós-forrás Spring (Rám Hill)	pumiceous (lapilli) tuff	178/–45	□ ◇?								1	
17		Csódi Hill	1b dacite	193/–52	◇	428	w. r.				**16.5±1.0**		1	3
		„	„	193/3	?								1	
		„	„	198/–67	◇							0 m distances are given	4	
		„	„	217/–25	?							30 m from S quarry edge:	4	
		„	„	164/–19	?							75 m position of vent is	4	
		„	„	169/18	?							300 m located at ~200 m	4	
		„	„	159/19	?							325 m	4	
		„	„	162/–41	□ ?							350 m	4	
18	V7	Prépost Hill	2d andesite	180/–56	◇	5515	w. r.	1.21	19.5	7.213×10^{-7}	**15.32±1.14**		1	3
	V7	Prépost Hill	2d andesite			416	w. r.				**13.5±1.0**			2
19		Hamvas-kő Hill	"pumiceous tuffite"	186/–55	◇								1	
20	V11	Rocks of Vadálló-kövek	2b andesite block-and-ash-flow breccia	189/–59 34;10 189/–64 132; 6	◇ ◇	5771 6156 6157 6202	w. r. plagi glass am	1.56 0.25 2.67 0.49	74.4 13.9 60.0 38.7	9.418×10^{-6} 1.543×10^{-7} 1.422×10^{-6} 3.262×10^{-7}	**15.43±0.59** **15.81±1.59** **13.64±0.54** **17.00±0.80**		3 3	3
21	V11	Prédikálószék Hill	„			4418	am	0.48	59.2	3.308×10^{-7}	**17.10±0.72**	B.K.		3
22	V25	Öreg-Pap Hill	„			5770	w. r.	1.53	52.1	9.996×10^{-7}	**16.69±0.69**			3
23	V66	Prédikálószék Hill E	2b andesite			6155	w. r.	1.42	35.5	8.435×10^{-7}	**15.20±0.70**	dyke		3
24	V13	Dobogókő Hill (Rocks of Thirring-sziklák)	2b andesite breccia			5772	w. r.	1.53	45.5	9.183×10^{-7}	**15.35±0.67**	Rocks of Vadálló-kövek in lithology		3
25	V13	„	py am andesite (2b?)			4419	w. r.	1.65	55.7	9.602×10^{-7}	**14.90±0.60**	dyke; B.K.		3
26	V45	Rocks of Szer-kövek	2b andesite			5773	w. r.	1.47	32.8	7.688×10^{-7}	**13.42±0.68**			3
27	V2c	Visegrád Castle Hill lower level	2a andesite lava breccia			5505	w. r.	1.12	51.8	6.339×10^{-7}	**14.45±0.61**	alteration may have caused rejuvenated age		3
28	V2a	Visegrád Castle Hill upper level	2b andesite breccia			5769	w .r.	1.46	26.6	8.701×10^{-7}	**15.28±1.00**	overlying debris avalanche deposit with Rocks of Vadálló-kövek lithology		3
28	V2a	„	„			5504	w. r.	1.17	62.0	6.995×10^{-7}	**15.29±0.60**	„		3
28	V2a	„	„			6162	glass	2.36	17.7	1.406×10^{-6}	**15.20±1.20**			3
28	V2a	„	„			6201	am	0.52	39.6	3.553×10^{-7}	**17.60±0.80**			3
29	V5	Visegrád "Panorama Road"	2c andesite breccia			5506	w. r.	1.46	40.4	7.655×10^{-7}	**13.47±0.62**			3
30	V29	Alsó Pap Hill	2c andesite breccia			5509	w. r.	1.05	23.6	5.516×10^{-7}	**13.48±0.86**			3
31	V36	Vörös-kő Hill	2c andesite breccia			5518	w. r.	1.23	12.8	6.383×10^{-7}	**13.30±1.40**			3

Table 3: *Continued from previous pages.*

32	V50	Bagó-kő Hill	2b andesite breccia			5775	w. r.	0.97	41.4	5.535×10^{-7}	**14.56±0.66**			3
33	SM36	Szent Mihály Hill, Bodzás Valley	2b andesite			5774	w. r.	1.21	47.8	7.348×10^{-7}	**15.50±0.66**			3
34	SM23	Szent Mihály Hill lower level	2c andesite tuffaceous sandstone	182/–48 132; 6	◇								3	
35	SM33	Szent Mihály Hill summit	2c andesite lava breccia	203/–43 75; 8	◇								3	
36a	SM40	Hegyes Hill summit	2b andesite lava breccia			5768	w. r.	1.29	27.7	7.062×10^{-7}	**14.03±0.80**			3
36b	SM38					6159	glass	2.13	44.7	1.207×10^{-6}	**14.60±0.60**			3
37		Dömör-kapu Quarry	2d andesite			5517	w. r.	1.39	67.8	8.574×10^{-7}	**15.79±0.62**			3
38		Bükkös Stream (near Dömörkapu Quarry)	am andesite (?)			424	w. r.				**13.9±0.9**			2
39		Apátkút Valley	2d andesite	193/–48	◇	418	w. r.				**15.2±1.0**		1	2
40		Malom Valley N	am andesite (2c?)	196/–69	◇	423	w. r.				**15.2±1.7**	may be confused with No. 6	1	2
41		Dömös-Visegrád, roadside quarry	2d andesite	200/–74	◇	415	w. r.				**15.9±1.0**		1	2
42		Kanyargós Stream (Pilisszentkereszt)	"pumiceous tuff"	200/–47	◇							locality may belong to the andesite series based on Balla & Márton's (1977) index map	1	
43	V26	Ördögbánya Quarry	2a andesite	206/–54	◇	5508	w. r.	1.66	75.5	1.050×10^{-6}	**16.18±0.62**			3
44		Bükkös Stream (near Kékibánya Quarry)	"andesite" (2c?)	222/–47	◇								1	
45		Pilisszentlászló NW Quarry	2d andesite			411	w. r.				**15.4±1.2**			2
46	V62	Szamár Hill	2d andesite	126/33	?								1	
47	S4	Hideglelős-kereszt Quarry	2d andesite	105/15	?	417	w. r.				**15.7±1.0**		1	2
						5514	w. r.	1.27	60.9	7.311×10^{-7}	**14.79±0.59**			3
48		Szőke-forrás Valley	"am andesite"			4525	w. r.	1.74	36.0	8.533×10^{-6}	**12.60±0.60**	B.K.: precise locality unknown		3
49		Pilisszentlélek (Árpádvár Hill)	"andesite" (2a dacite)	20/44	?							Uncertain paleomagnetism; probably allochthonous	1	
X		Kerek Hill quarry	"andesite"	143/–50	□							Börzsöny Mts survey; coeval with the Börzsöny 2nd stage	1	

* = k; α_{95} values are given for only the new data published in this paper

1 = Balla Z. & Márton-Szalay E. (1979), 2 = Balogh K. (1977–1979) (unpublished), 3 = present paper, 4 = Lantos M. (unpublished),
w. r. = whole rock, am = amphibole. B.Zs., B.K. = sample collected and described by Bendő Zs. et al. (2001) and Benedek K. (1998), resp.

K/Ar ages of the Pilisszentlászló-2 borehole.

Segment (m)	Lithology	K/Ar geochronology						Ref
		No. K/Ar lab	Dated fraction	K %	$^{40}Ar_{rad}$ %	$^{40}Ar_{rad}$ (ccSTP/g)	Age (Ma)	
65.7–75.8	"andesite" (2d?)	762	w. r.	1.77	49	0.864×10^{-6}	**12.5**	2
130.5–160.7	"andesite" „	763	w. r.	1.64	48	0.858×10^{-6}	**13.4**	2
249.5–260.5	"andesite" „	764	w. r.	1.05	48	0.516×10^{-6}	**12.6**	2
346.6–378.7	"andesite" „	765	w. r.	1.54	67	0.787×10^{-6}	**13.1**	2
503.6–512.2	1a dacite	766	w. r.	2.81	82	1.505×10^{-6}	**13.7**	2
503.6–512.2	1a dacite	„	biotite	6.04	76	3.758×10^{-6}	**15.9**	2
553.0–554.7	1a dacite	767	w. r.	3.95	88	2.219×10^{-6}	**14.4**	2
553.0–554.7	1a dacite	„	biotite	6.08	65	3.619×10^{-6}	**15.3**	2

and Wein (1939), as well as those of the W mountain margin (Vaskapu Hill at Esztergom: Peters 1869) imply shallow-marine environments with signs of volcanic activity. In our field work, one of the classical localities of Koch has been reambulated in the Csádri Stream at Dunabogdány. There, a *Chlamys gigas*-bearing Lower Miocene (Eggenburgian) sand- and claystone (Méhes 1941; Bohn-Havas & Korecz-Laky 1980) is overlain by a pumiceous, andesite lithic clast- and quartz pebble-bearing mass-flow deposit with *Aequipecten seniensis* (previously *Chlamys scabrella*) fragments. This species is known from the Burdigalian to the Pliocene in the Mediterranean region. It also has a long range in the Central Paratethys, from the Ottnangian to the Badenian, which at the same time confirms the post-Eggenburgian beginning of volcanic activity. The described fossil-bearing deposit is directly overlain by pumiceous as well as lithic-rich, fossil-free volcaniclastic layers.

(2) The end of the dacitic volcanism is indicated by a short sedimentary episode, which can be traced on the S slopes of Tornyos Hill at Pilisszentkereszt (Zelenka 1960). The existence of the greyish-white conglomerate containing quartzite, metamorphic and volcanic (dacite and andesite) pebbles was confirmed recently by the present authors. The rock contains lots of fossils, but original shell materials can be identified for only *Crassostrea*, *Balanus* and tube worm specimens, while the other mollusc species show external and/or internal moulds. The composition of the fauna is similar to that described by Zelenka (1960), with the most frequent fossils *Crassostrea, Turritella*, *Balanus* and *Cerithium.* Besides these taxa, our preliminary fauna list contains *Barbatia*, *Natica*, *Cardium*, *Cypraea*, venerid bivalves, trochid gastropods and tube worms. The *Crassostrea* and *Balanus* shells always show strong erosion and rounding. The quantity and roundness of pebbles, the significant erosion of shells, the composition of the fauna, as well as the presence of herbivorous gastropods unequivocally refer to shallow, near-shore, well-agitated normal marine environment. The very poor preservation of the fossils, however, generally makes it difficult to identify the fauna at species level. The composition of the fauna is largely similar to the mollusc assemblages known from Middle Miocene Leitha Limestone localities.

(3) The first fossiliferous sediments deposited after the termination of volcanism have been recovered in the N part of the Visegrád Mts (Fekete Hill at Visegrád). Scholz (1970) identified 9 coral species from the outcropping Leitha Limestone, which unambiguously indicate a shallow, (sub)tropical, normal marine environment. Müller (1984) described several decapod species there, and referred to the locality as Early Badenian in age. Recently, the bryozoan fauna of several Hungarian Badenian localities, including that of Fekete Hill, has been investigated by Moissette et al. (2006, 2007). The most frequent bryozoan morphology types are the encrusting memraniporiform colonies on the surfaces of the coral colonies and calcareous algae, and small roundish celleporiform colonies. Besides these forms, several cellariiform and reteporiform colonies and only a few vinculariform and adeoniform ones have been found in the surrounding sediments. Such a composition of the colony morphologies refers to a very shallow marine environment (0–20 m water depth).

8. Discussion: stratigraphy and volcanic evolution with respect to the Börzsöny Mountains

8.1 Volcanic stratigraphy

1st volcanic stage. Paleontological and volcanological evidence suggests that just before the volcanic activity the main area of the Visegrád Mts was characterized by a shallow subaqueous environment (e.g. Csádri Valley Sandstone) which rapidly became subaerial. The first voluminous volcanic products, distributed at the S and SE margin, are garnet-bearing volcaniclastic and massive rocks of dacitic-rhyodacitic composition. These are preceded by small-volume 2c type andesitic pyroclastic (in some cases phreatomagmatic) deposits both in the S-SE (ravine of Holdvilág-árok, Sztelin Stream) and the N (vicinity of Malom Valley). These deposits are collectively called the Holdvilág-árok Tuff and Tuffaceous Sandstone. The volcanic centres may have been small-scale edifices, preferably lava domes (e.g. Lom Hill Lava Dome, biotite dacite) and subvolcanic bodies (e.g. Csódi Hill Laccolith, pyroxene dacite), as suggested by identical lithologies of massive and volcaniclastic rocks in some places. Due to volcanological constraints (e.g. no or minor ignimbrites, small pumice sizes, mostly reworked pumiceous deposits, no recognized caldera morphology etc.), large explosive eruptions and related calderas can be excluded.

In the Börzsöny Mts, a great number of garnet-bearing dacitic-rhyolitic volcaniclastic as well as massive rocks have been determined older than 16 Ma by combined K/Ar geochronology and magnetostratigraphy (Karátson et al. 2000). These rocks have normal polarity with a typical CCW rotated declination. Two localities of the initial volcaniclastic rocks of the Visegrád Mts show the same paleomagnetic features. Of them, the ravine of Holdvilág-árok seems to be highly reliable for (a) its three successive paleomagnetic stages pointed out from the underlying sedimentary deposits through the volcanic pile; (b) within the analytical errors, its ≥16.0 Ma K/Ar age obtained fits the proposed 1st stage (16.0–16.5 Ma) and early 2nd stage (<16 Ma) activity of the Börzsöny Mts. The average age (15.9 Ma) of the biotite fractions of all Visegrád garnet-bearing dacite samples (see Table 3) is also in accordance. On the contrary, measurements on massive garnet-bearing dacites are subordinate, and they show different paleomagnetic characteristics (most fall into the 2nd stage with CCW declination but with reverse polarity: 1a type dacite of Szentlélek Hill and 1b type dacite of Csódi and Peres Hills). The emplacement of the Csódi Hill Laccolith before or even after the rotation clearly shows that the 1b type dacite may have been younger than the most voluminous 1a type dacites. One of the Börzsöny dacites, the Nagy Pogány Hill Lava Dome, also shows the 2nd stage (CCW declination, reverse polarity) and, similarly to the

Visegrád 1b dacites, garnet is absent or accidental. Although these sites should be investigated in more detail, we can conclude that (1) the initial (biotite- and garnet-bearing andesitic and dacitic) explosive period started simultaneously with the well-defined 1st paleomagnetic stage of the Börzsöny (i.e. ≥ 16 Ma), and (2) at least part of the related dacitic extrusive activity in the Visegrád side (i.e. the 1b type dacites) seems to have lasted longer (≤ 16 Ma), during the 2nd paleomagnetic stage with reverse polarity. Toward the end of the dacitic volcanism, a quiescent period may have taken place at least in the S, as proven by interbedded submarine deposits and fossils at Tornyos Hill.

2nd volcanic stage. A number of the Visegrád paleomagnetic sites (12) shows CCW declination with reverse polarity. The rocks of this group are various andesite types as well as pyroclastic and epiclastic breccias (e.g. Ördögbánya Lava Dome, Rám Hill Pumiceous Sandstone). The rocks are garnet-free. The average of the K/Ar ages (10 datings) is 15.57 Ma (all datings) and 15.48 Ma (without amphibole and glass ages), that is, ca. 15.5 Ma. However, due to the limited number and partly the earlier datings (with >1 Myr error), the real geological age should be considered with caution.

3rd volcanic stage. The next group comprises sites with reverse polarity and no rotation (13 measurements). The much bigger number of K/Ar datings (36, of which 29 are new measurements) makes the average age reliable: 15.06 Ma (all datings), 14.90 Ma (without 6 amphibole and glass ages), that is, ca. 15.0 Ma. The 2b type andesites (Keserűs Hill Breccia, Hegyes-tető Hill Lava Flow), most of the 2c type andesites (Szent Mihály Hill Lava Dome, Ágas Hill Lava Dome), and most of the 2d type basaltic andesites (e.g. Tövises Hill Lava Flow) were formed during this paleomagnetic stage.

In the Börzsöny Mts, rocks belonging to the latter two above-mentioned paleomagnetic stages are also widely distributed. They were interpreted as successive stages representing an intense volcanic period, during which a 30° CCW rotation occurred (Karátson et al. 2000). The rotation was part of a general Middle Miocene rotation period in North Hungary (Márton & Márton 1995). The exact timing of the rotation movement could not be determined in the Börzsöny Mts, but on the basis of K/Ar ages and magnetostratigraphic considerations, the 16.0–14.5 Ma interval for the total duration of the two stages was proposed (Karátson et al. 2000). Now, in the light of our results in the Visegrád Mts, average K/Ar ages of rocks emplaced before and after the rotation constrain the rotation between 15.0–15.5 (± 0.5) Ma. Moreover, given the well-defined emplacement of the Keserűs-Hill breccias (15.3 Ma) that do not have a westerly declination, the rotation movement should have occurred between 15.5–15.3 (± 0.5) Ma.

Apart from massive rocks, there are pumiceous epiclastic and rarely pyroclastic deposits that belong to the 2nd and 3rd volcanic (paleomagnetic) stage. In contrast, pumiceous deposits are missing from the 2nd and 3rd stage in the Börzsöny Mts (except a single, uncertain locality of Magyarkút in the SE periphery). This difference indicates a longer-lasting explosive activity in the Visegrád Mts, which is in accordance with the explosive lava dome character of the Keserűs Hill volcano.

The age of the Keserűs Hill Lava Dome complex, the largest, dominant edifice of 2b type andesites (block-and-ash flow breccias), additional 2c type andesites (subvolcanic bodies, lava domes) and subordinate 2d type basaltic andesites (lava flows), can be well constrained by combined paleomagnetic and K/Ar data. Two new sites at Rocks of Vadálló-kövek, that is the highest preserved part of the volcano, have yielded identical paleomagnetism — reverse polarity with non-rotated declination — and the same characteristics have been pointed out for the related Szent Mihály Hill epiclastic breccias and summit lava dome as well. Paleomagnetism of the basaltic andesite of Prépost Hill lava flow is also the same. K/Ar ages obtained on whole rock samples from the Vadálló-kövek area show 15.2–15.4 Ma, well supported by other dates of petrographically identical rocks in the vicinity (e.g. Visegrád Castle Hill upper level — 15.3 Ma; Dobogókő Hill — 15.35 Ma; etc. Table 3). The 2b–c type andesite volcanism of ≥ 15 Ma age was coeval with a widespread effusive lava dome activity in the S Börzsöny (Karátson et al. 2000). As mentioned above, in the latter mountains it was a longer lasting eruptive stage (16.0 to 14.5 Ma). In contrast, on the basis of our volcanological and geochronological data, the dominant 2b–c type andesite volcanism of the Visegrád Mts (actually that of Keserűs Hill) was much shorter. It should have terminated most likely 15 Ma or no later than 14.5 Ma ago, at end of a reverse polarity zone.

On the other hand there is some uncertainty regarding the very extinction of the volcanism. There are a few K/Ar ages younger than 14 Ma, most of them obtained on 2c andesites and limited to the NE-E margin of the mountains. Another group of young ages on 2d? basaltic andesites comes from the Pilisszentlászló borehole, which seem to be slightly rejuvenated. However, some other, typical occurrences of the 2d basaltic andesite (which is otherwise subordinate in the mountains), namely the Tövises and Prépost Hill lava flows, are related to the Keserűs Hill volcano and fall into the 3rd paleomagnetic stage. Moreover, none of the paleomagnetic sites have shown normal polarity without rotation, which is the successive, final paleomagnetic stage (14.5–13.7 Ma) in the High Börzsöny Lava Dome complex (Karátson et al. 2000). Therefore, although some young eruptions, such as a small-scale 2c or 2d type andesitic activity, could have occurred, this should have been very limited. In contrast, given the widespread non-rotated normal polarity paleomagnetism of the High Börzsöny, a voluminous late-stage activity in the Börzsöny Mts lasted considerably longer.

8.2 Magmatic evolution

In the magmatic evolution of the Visegrád Mts there is a systematic change from a more (early stage dacites) to a less silicic (late stage 2d type basaltic andesite) magma, similarly to the Börzsöny Mountains. During the early stage magmatism, mostly dacites and rhyodacites were formed, usually containing garnet phenocrysts (Harangi et al. 2001). These rocks show a marked depletion in the Y and heavy rare earth elements (Fig. 5b) suggesting early crystallization and fractionation of garnets.

In the main (2nd and 3rd) volcanic phase mostly andesites were formed with variable phenocryst contents. In general, amphibole is dominant in most of the rock types accompanied by variable amounts and types of pyroxenes. In the late stage basaltic andesites, however, amphibole is lacking, or occurs as subordinate inherited phase. This indicates that during the evolution of the Visegrád volcanic complex, magmas with decreasing water content were erupted. Within the amphiboles different groups were identified in the four different andesite types mostly on the basis of their oxidization state. In addition, they show a wide range of composition (from Mg-hastingsite in 2a type biotite amphibole andesite and 2c type pyroxene amphibole andesite to tschermakite in 2b type pyroxene amphibole andesite) suggesting crystallization at different temperatures and pressures. The incompatible trace element ratios of the andesites form linear trends suggesting cogenetic relationships, that is a common source region and variable degrees of magmatic differentiation. In addition to the fractional crystallization processes, mixing of magmas formed at different stages of evolution could also occur as shown by the petrographic observations. Finally, Harangi (2001) showed that these rocks also have wide variation of isotopic composition suggesting that various degrees of assimilation of crustal material could have been taken place as well. In summary, the magmatic evolution of the Visegrád volcanism can be described by erupting of magma batches deriving from the same source region, but they underwent variable degrees of magmatic differentiation processes, such as assimilation combined with fractional crystallization and occasionally mixing of magmas.

On the basis of textural properties and mineralogical composition, we assume a continuous change in magma generation processes from 2c type andesites to 2d type basaltic andesites. This is also supported by the geochemical analysis (see Fig. 5).

The generation of late stage basaltic andesite (2d) magma indicates the end of the volcanic activity. However, we cannot find a clear magmagenetic succession between the 2a–b–c andesite types. While successive petrographic features suggest a 2a–b–c–d magmatic evolution, the 2c andesite, as seen in the above, may occur in volcaniclastic deposits of basal stratigraphic position too, and the majority of this andesite type occurs up to the highest stratigraphic levels (i.e. Ágas Hill post-BFD lava dome). The exact stratigraphic position of the 2a andesite type is also ambiguous, although most paleomagnetic and K/Ar data indicate an early stage (see above).

9. Conclusions

The Middle Miocene volcanic stratigraphy of the Visegrád Mts and its relationship to the neighbouring, coeval Börzsöny Mts have been investigated by a combined approach. According to our new stratigraphic model, the Visegrád volcanism was a three-stage eruptive activity lasting from ≥16 to 15.0/14.5 Ma. During the volcanic period, the initial, shallow submarine eruptions gave place to an emergent activity in an archipelago. A comparative drawing about the main volcanic episodes, indicative K/Ar ages, characteristic fossils, and proposed informal lithostratigraphic units of the Visegrád Mountains, with respect to main events and geochronology of the Börzsöny Mountains, is presented in Fig. 6.

Combining field volcanological data with a great number of new and previous K/Ar ages as well as paleomagnetic characters, we propose that the 1st volcanic stage was a short-lived (some hundred kyr) dacitic-rhyodacitic activity, started in the S periphery ≥16 Ma ago. Mostly in peripheral areas, this activity was preceded by andesitic (±dacitic) phreatomagmatic eruptions too. Within the dacitic volcanism, less significant, possibly lava dome-related explosive eruptions occurred earlier, whereas extrusive and subvolcanic activities may have lasted somewhat longer (≤16 Ma). The period (ca. 16.5–≤16 Ma) proposed for the 1st stage is significantly older than 15.2–14.8 Ma in a recent model (Korpás (Ed.) 1998), and largely corresponds to the 1st volcanic stage of the Börzsöny Mts (16.5–16.0 Ma, Karátson et al. 2000). The dacitic pyro- and mostly epiclastic rocks emplaced during this stage exhibit normal polarity with ca. 30° CCW rotation, whereas the dacitic lava dome activity should have continued into a reverse polarity zone.

The much more widespread exlusively andesitic volcanism of the Visegrád Mts may have followed after a time gap, at least in the S where interbedded fossil-bearing sediments indicate a shallow submarine environment. The renewed activity could have been more or less continuous, but can be divided into two stages on the basis of paleomagnetic characters: 2nd stage with reverse polarity and ca. 30° CCW declination, and 3rd stage with reverse polarity and no rotation. The products of these two stages can be found in the Börzsöny Mts as well, where the volcanic period was inferred to represent a significant rotation event (Karátson et al. 2000). In the Visegrád Mts, the timing of the rotation, during the main andesitic activity, can be better constrained by the K/Ar method: 15.5–15.3 (±0.5) Ma. Accordingly, we propose that the rotation period (that occurred toward the end of the 16–15 Ma reverse paleomagnetic zone) divides the 2nd and 3rd paleomagnetic stage both in the Börzsöny and Visegrád Mts.

The rocks of these latter stages have a great variety of massive (1) and volcaniclastic (2) rocks. (1) Biotite amphibole andesites to pyroxene amphibole andesites and basaltic andesites occur as subvolcanic bodies (including sills and dykes), deeply eroded, scattered lava domes, and lava flows. (2) The petrographically identical volcaniclastic rocks include block-and-ash flow breccias and their reworked counterparts (being the most widespread) as well as deposits of the debris-flow/flood-flow/fluvial streamflow continuum. All of these rocks were emplaced

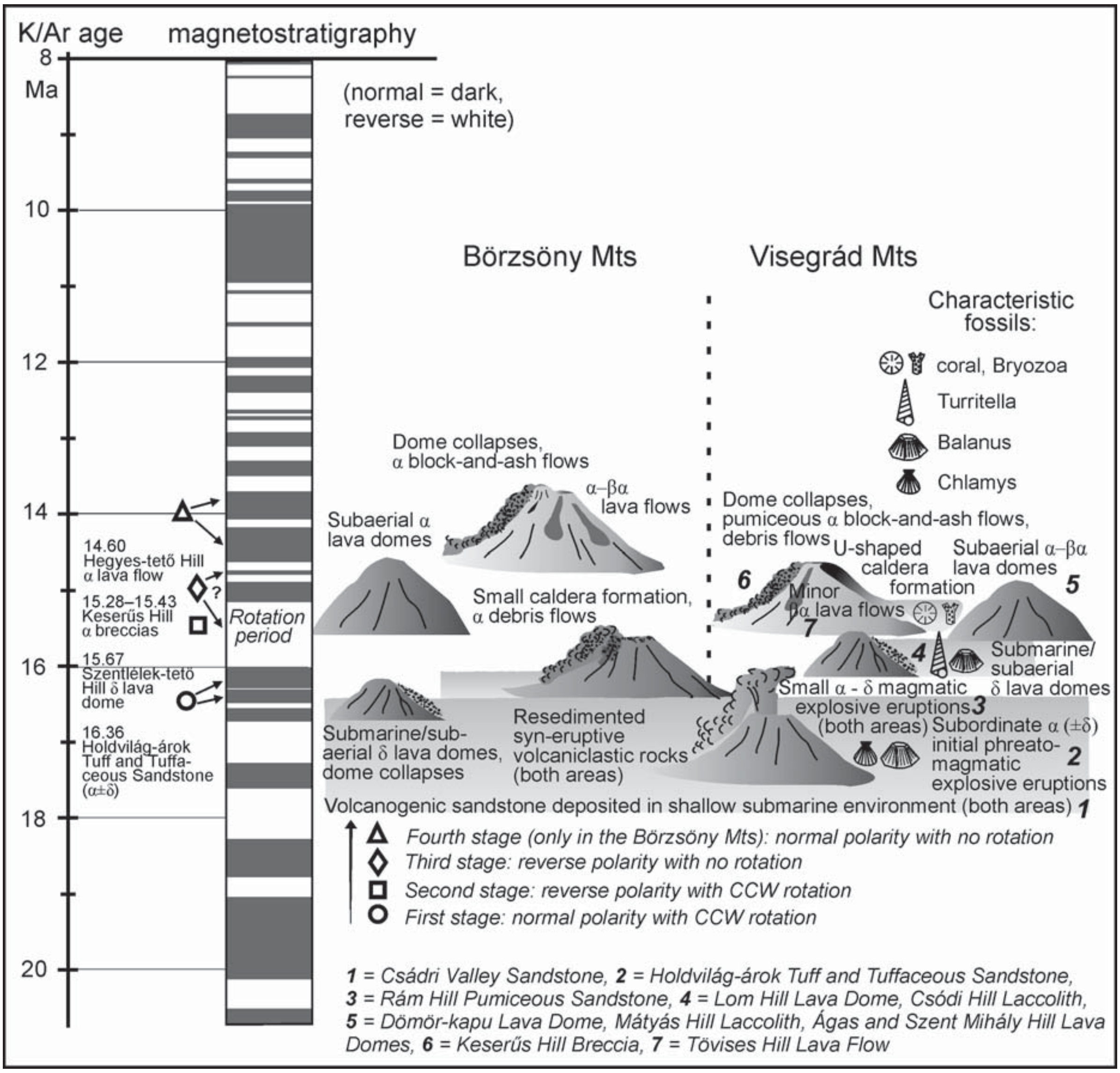


Fig. 6. Geochronology, main volcanic events and proposed lithostratigraphic units of the Visegrád Mts in comparison to the Börzsöny Mts (Karátson et al. 2000).

subaerially. The main eruptive centre was the Keserűs Hill amphibole andesite lava dome complex (Karátson et al. 2006) with a relatively explosive character and minor lava flows. It underwent a horseshoe-shaped caldera formation toward the N; an outer caldera (Dobogó-Kő Hill) suggested in the previous literature is not supported. Around the volcano the volcaniclastic deposits show systematic changes from proximal to distal facies (e.g. from pyroclastic breccias to debris-flow deposits etc.).

In the Visegrád Mts there are no indications for a 4th paleomagnetic stage as is the case with the Börzsöny Mts. However, with respect to sporadic K/Ar ages, a younger than 14.5 Ma volcanic activity is likely, but it should have been very limited in area. In fact, this activity is constrained in time by the deposition of the Langhian (in terms of Central Paratethys, Lower Badenian) "Leitha" limestone. In accordance with this, we propose that the main eruptive period of the Visegrád Mts terminated at 15(–14.5) Ma. This final activity may have been coeval with the buildup of the High Börzsöny basaltic andesite lava dome complex.

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