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VOLCANIC EVOLUTION AND STRATIGRAPHY OF THE MIOCENE BÖRZSÖNY MOUNTAINS, HUNGARY: AN INTEGRATED STUDY

DÁVID KARÁTSON[1], EMŐ MÁRTON[2], SZABOLCS HARANGI[3], SÁNDOR JÓZSA[3], KADOSA BALOGH[4], ZOLTÁN PÉCSKAY[4], SÁNDOR KOVÁCSVÖLGYI[5], GYÖRGY SZAKMÁNY[3] and ALFRÉD DULAI[6]

[1]Eötvös University, Department of Physical Geography, 1083 Budapest, Ludovika tér 2, Hungary
[2]Eötvös Loránd Geophysical Institute, Paleomagnetic Laboratory, 1145 Budapest, Columbus u. 17–23, Hungary
[3]Eötvös University, Department of Petrology and Geochemistry, 1088 Budapest, Múzeum krt. 4/a, Hungary
[4]Institute of Nuclear Research, Hungarian Academy of Sciences, 4001 Debrecen, Bem József tér 18/c, Hungary
[5]Eötvös Loránd Geophysical Institute of Hungary, 1145 Budapest, Columbus u. 17–23, Hungary
[6]Hungarian Natural History Museum, Department of Geology and Paleontology, H-1431 Budapest, Múzeum krt. 14–16, Hungary

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Abstract: The Middle Miocene volcanic evolution of the Börzsöny Mountains, North Hungary, is presented, correlating new volcanological, petrological, geochemical, geophysical and paleontological data and establishing a detailed stratigraphy on the basis of additional K/Ar radiometric and paleomagnetic measurements. For the earliest volcanic activity, previous biostratigraphy showing an Early Badenian age has been confirmed and precisely defined by paleomagnetic investigations. The first-stage volcanic formations (16.5–16.0 Ma), deposited in a shallow marine environment, include resedimented, syn-eruptive, garnet-bearing dacitic volcaniclastics (originating mostly from small-scale ignimbrite eruptions) and coeval, garnet-bearing dacitic lava domes, sometimes with their volcaniclastic aprons. As the eruptions filled the marine basin, subaerial dacitic-andesitic volcaniclastics, comprising minor ignimbrites and different types of debris-flow deposits were also deposited. A part of the latter may have been related to the formation of two or three medium-sized calderas. The second stage (16.0–14.5 Ma) was characterized by andesitic lava dome activity terminated by a hydrothermal event. During the first half of this stage, a ca. 30° CCW rotation occurred. The third stage produced the most voluminous, moderately explosive, andesitic — basaltic andesitic High Börzsöny subaerial lava dome complex erupting up to the Badenian/Sarmatian boundary (ca. 13.7 Ma). Correlation of K/Ar geochronological and volcanological data shows that lava dome activity of the second and third stage may have been coeval with marine sedimentation in the southern Börzsöny.

Key words: Miocene calc-alkaline volcanism, Börzsöny Mountains, volcanology, geochemistry, paleomagnetism, K/Ar geochronology.

1. Introduction

In the past years, a renewed scientific interest has resulted in a number of publications on the geological history of the Miocene dacitic-andesitic volcanism of the Börzsöny Mountains, North Hungary. However, a synthesis of different scientific approaches to this very complex volcanic area has not been presented, in spite of contributions to the relationship between timing of volcanism and ore mineralization (Korpás & Lang 1993), volcanological aspects related to structure (Karátson 1995, 1997), stratigraphical problems (Korpás et al. 1998) and dividing volcanic formations on maps (Korpás & Csillag-Teplánszky 1999; Karátson et al. 1999a). In this paper, on the basis of an integrated research including field volcanology, paleomagnetic and radiometric measurements, petrology, geochemistry, gravimetry and paleontology, we summarize the volcanic evolution and stratigraphy of the Börzsöny Mountains. Although some open questions have remained, the complexity of our method may serve as an example for studying highly degraded volcanic mountains, like many in the Inner Carpathian calc-alkaline Volcanic Chain.

2. Geologic and geomorphic setting

The Börzsöny Mountains are among the westernmost and oldest members of the Carpathian Neogene to Pleistocene Volcanic Chain (Fig. 1). Xenoliths in the volcanics and partly borehole data show that the basement consists of carbonate rocks related to the Transdanubian Mountains to the S and crystalline schists of the Veporids to the N, separated by the Diósjenő line (Balla 1977). These rocks are overlain mostly by Oligocene and Lower to Middle Miocene sedimentary formations (predominantly clay, sandstone and gravel; e.g. Korpás et al. 1998). Underlying the subsequent Middle Miocene volcanics, these formations crop out mostly along the eastern margin of the Börzsöny Mountains. The volcanic rocks are also covered by Middle Miocene (Badenian) limestone and clay marl mainly along the western margin and in the southern part of the mountains (e.g. Báldi & Kókay 1970; Korpás et al. 1998).

From the geomorphic point of view (Fig. 2), the Börzsöny Mountains are characterized by the contrast of the northern and southern hilly terrain (400–600 m) and the central "High

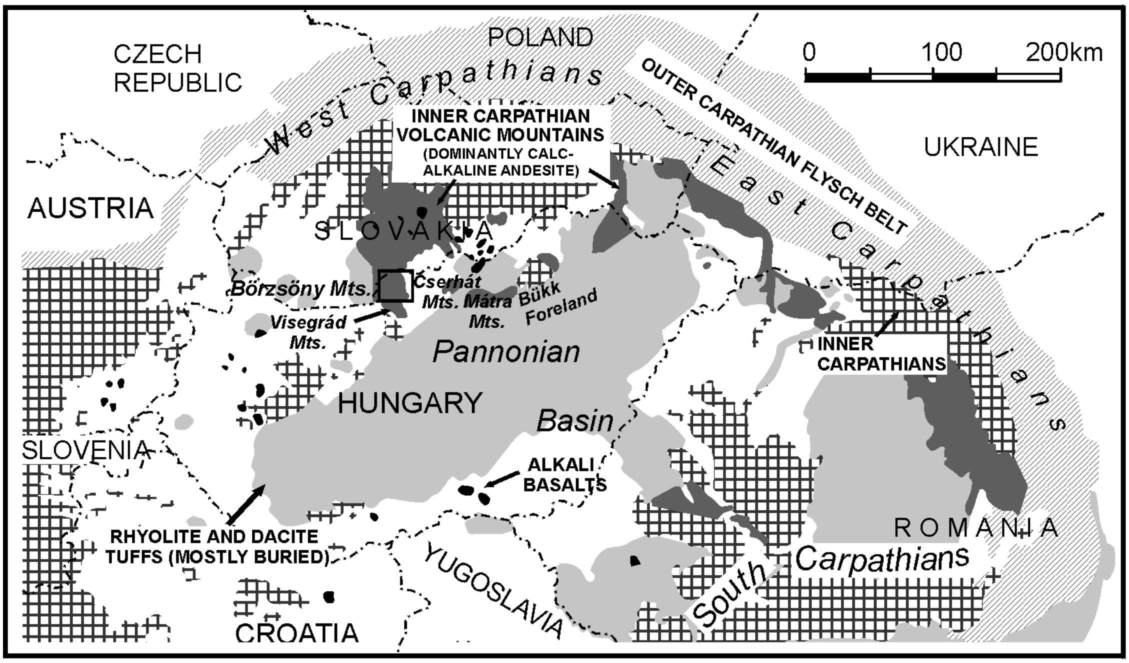

Fig. 1. Geological setting of the Börzsöny Mts.

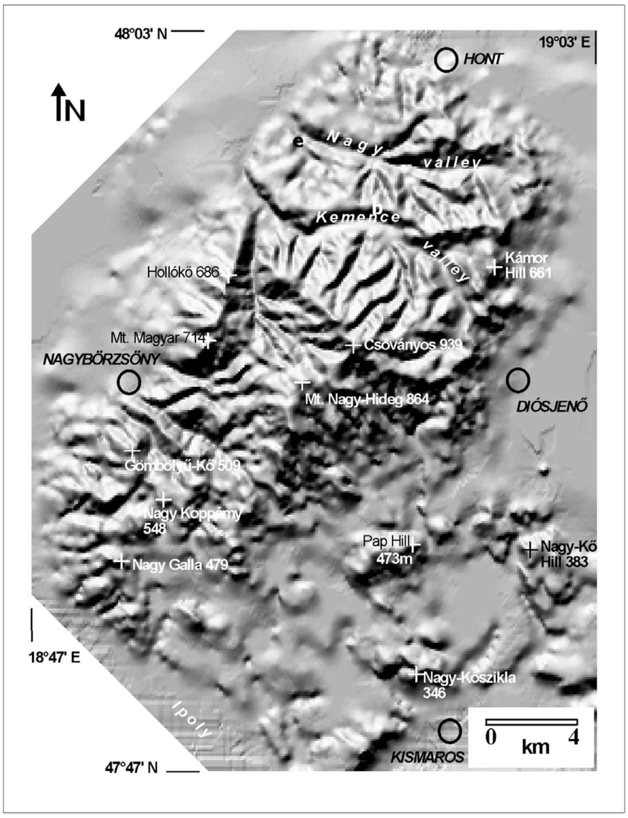

Fig. 2. Shaded relief map of the Börzsöny Mts. Computer-generated image is based on the digitized 1:50,000 topographic map of Hungary. Note the well-preserved cone remnant of the High Börzsöny with its prominent, deeply eroded central depression, the circular shape of Kemence valley, the radial ridges and valleys in the SW Börzsöny, the depression bordered by the Pap, Nagy-Kő and Nagy-Kőszikla hills in the SE, and the rectangular, NW-SE and NE-SW-trending valley network mainly in the S.

Börzsöny", the latter having a medium height (700–900 m; highest point Mt. Csóványos 939 m) and significant relief energy. The northern hills are bordered by the Ipoly (Ipeľ) River; the eastern, elevated margin towards the Nógrád Basin is sharply indicated by a NNE-SSW fault (Czakó & Nagy 1976; Balla 1977); the western part merges in the terraced, alluvial plain of the Ipoly; and the extended southern hills and small intermontane basins are terminated by the distinct Szt. Mihály mountain group (not seen in Fig. 2) facing the Pleistocene Danube Bend.

3. The volcanic formations and their environment

3.1 Deposits underlying the volcanic successions: paleoenvironmental implications

The deposits directly underlying the volcanics belong to the Karpatian-Lower Badenian (Lower-Middle Miocene) Egyházasgerge Formation and Nagyoroszi Pebble Formation of North Hungary. These sedimentary deposits are shallow submarine (littoral-sublittoral) successions consisting of sandstone, schlier and minor gravel beds (Császár 1997; Korpás et al. 1998). Gravel intercalations in the Nagyoroszi Pebble suggest that in the NE, dry land was in the close neighbourhood (Korpás et al. 1998).

As for the character of the initial Middle Miocene volcanic eruptions, the broader paleoenvironment is of great importance. Prior to the volcanism and during the early phase, a littoral-sublittoral bay to the N, a swamp environment to the S and a delta front to the E have been distinguished by Korpás & Lang (1993) and Korpás et al. (1998). On the basis of previously described and newly found surface outcrops, however, *we cannot see evidence for other than a shallow marine environment* (cf. Báldi & Kókay 1970; Borza 1973):

(1) In the S, a rich sublittoral marine fauna (53 taxa) was described from the basal layers of the Kismaros Tuff by Báldi & Kókay (1970). The re-examination of the Kismaros fossil material shows that the preferred water depth is known for 20 species: 85 % points to the infra- and circalittoral depth range, while 15 % can be found in only the infralittoral zone. The preferred Early Badenian age of the fauna was confirmed by Báldi-Beke (1980) on the basis of nannoplankton (NN5) studies. Similar nannoplankton assemblages were also mentioned by Báldi-Beke (1980) from the boreholes Drégelypalánk-2 and Kemence-1. Near Kismaros, at Márianosztra village, Jankovich (1974) described sublittoral marine fauna (molluscs, echinoids, foraminifers) between the initial volcaniclastic layers.

(2) In the E, Badenian tuffitic sand and sandstone were described in borehole Diósjenő-2 between 10 and 39.5 metres (Marczel 1977). The mollusc fauna of the borehole was briefly mentioned by Báldi-Beke et al. (1980). There is a diverse fauna between 10 and 14 metres, similar to the fauna of the Kismaros Tuff (*Chlamys*, *Glycymeris*, *Fusus*, *Anadara*, *Tellina*). The Early Badenian, sublittoral fauna contains exclusively normal marine species. W of Diósjenő village (on the E slope of Boros Hill), we have found a *Chlamys*-bearing coarse sand, overlain with undulating, disturbed contact by pumiceous volcaniclastics. The sand seems to be identical with the Karpatian *Chlamys*-bearing sand at Kismaros village with no described signs of volcanism there (Báldi & Kókay 1970). Therefore, the new exposure implies the possible Karpatian beginning of volcanic activity.

(3) At Szívszakasztó hillslope in the Nagy Valley (a in Fig. 3: the best outcrop of the contact between the Nagyoroszi Pebble and earliest volcanics), the well-rounded pebbles — mostly quartzite and metamorphics, occasionally pumice clasts — bear the marks of rock borer clams and are intercalated by fine-grained quartzofeldspatic sand with *Ostrea* fragments. This clearly indicates a littoral environment and a rocky seashore in the vicinity. What is more, fossils, most frequently, *Balanus* fragments and marine bivalves (*Isognomon* and *Venerupis*) as well as marine gastropods (*Gibbula* and *Nassa*), have been recovered from the initial, pumiceous volcaniclastic sequences. Although poorly preserved, the identified mollusc and barnacle remains also indicate a shallow, agitated marine environment (shallower, than at Kismaros or Diósjenő-7), without any signs of freshwater influence.

In the northernmost Hont Gorge (see Fig. 3), a thick Karpatian–Lower Badenian sedimentary succession underlying the volcaniclastics crops out (Vass & Marková 1966; Borza 1973). Nearby, beneath the volcaniclastics of the Bába Hill (Fig. 3), pebbles of the underlying conglomerate also show the marks of rock borer clams, and the embedded mollusc fauna shows similarity to the Nagy Valley fauna (*Isognomon [= "Perna"], Ostrea*, *Anomia*, *Venus*, *Venerupis*, *Turritella*, *Balanus*, solitary corals: Borza 1973).

(4) The earliest volcanism also started in a shallow marine environment in the neighbourhood of the Börzsöny Mts. In the Burda (Helemba) range SW of the Börzsöny Mts., Konečný & Lexa (1994) inferred a water depth of ca. 200 m. To the S, in the coeval Visegrád Mts., an Ostrea bed has been discovered recently beneath the first pumiceous volcaniclastics of the Holdvilág Gorge (Badics et al. 2000).

Although the initial volcanism should therefore have been submarine, the calculated shallow water had to be rapidly infilled, if the up to 200 m thickness of the fossiliferous volcaniclastic deposits is considered. This implies that the marine basin rapidly became a changeable coastal environment.

The volcanic formations are discussed below in two groups: volcaniclastic successions and massive rocks (lavas and subvolcanic bodies). These categories largely fit with the early "andesitic-dacitic" and the late "andesitic" petrographical categories of Csillag-Teplánszky & Korpás (1982) and Korpás & Lang (1993), adding that among the earliest formations, there are also massive rocks. Correlating all available data, a three-stage volcanism has been proposed by the present first author (Karátson 1995; Karátson et al. 1999a). As a clue for the following discussion, a simplified volcanological map with such a division is presented (Fig. 3).

3.2 The volcaniclastic successions

The volcaniclastic deposits of the Börzsöny Mts. (without the High Börzsöny breccias) cover roughly 2/3 of the area (see Fig. 3). A general sedimentological feature of them is the succession of stratified and/or graded beds with rapid changes in particle size and type (e.g. juvenile/lithic clast ratio), suggesting complex volcanic-sedimentary processes. Complexity is accentuated by the varied lithology of clasts ranging from andesite to dacite (see Appendix and Section 4). Facies relations of the volcaniclastics in six selected lithological logs are presented in Fig. 4. In the following, we briefly present the proposed stratigraphical units of the volcaniclastic deposits, then discuss their volcanology and time-space evolution.

Nagy Valley Volcanogenic Sandstone

Lithological logs a–c show that the deposits overlying the Karpatian and Lower Badenian sedimentary succession are composed of stratified/cross-stratified sandstone and minor conglomerate beds with normal- to reverse-graded volcanic clasts and minor pumice content. The Szívszakasztó locality in Nagy Valley (Fig. 4a) and the E slopes of Boros Hill, as mentioned previously, expose the nonvolcanic, fossil-bearing underlying sandstone and gravel beds as well. On the basis of these and other scattered outcrops from Kismaros through Márianosztra and Diósjenő to Hont villages, a continuous succession from non-volcanic to volcanogenic deposits can be inferred in the entire Börzsöny. In this paper, the fine-grained volcaniclastic deposits are collectively called *Nagy Valley Volcanogenic Sandstone.* In the marginal parts of the mountains, it may be overlain and/or intercalated by the Kismaros and Kemence Tuffs and the Nagy-Kő Hill Volcaniclastic Breccia (see below and logs a–c), whereas in the central areas, especially in the High Börzsöny, its existence is only inferred by boreholes under thick, subsequent volcanic formations.

Kismaros and Kemence Tuffs

Logs d–f in Fig. 4 have been selected to represent surface outcrops and boreholes that contain moderate to large amount

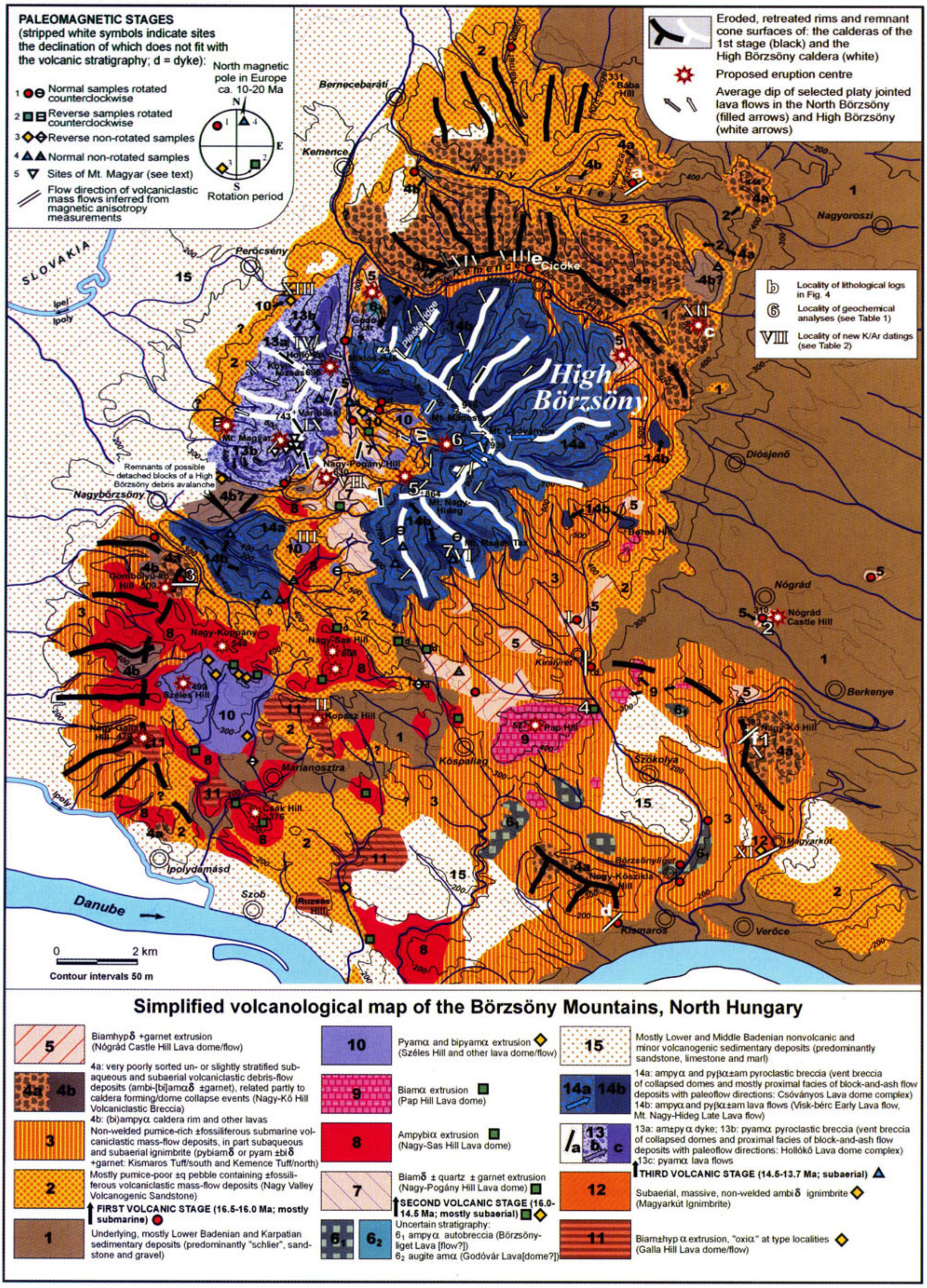

Fig. 3. Simplified volcanological map of the Börzsöny Mts. with paleomagnetic division of volcanic rocks.

(20–30 %) of pumices in successive beds (see Appendix). These deposits — tuffs and lapilli tuffs, 5–10 m thick in individual field exposures and up to 200 m thick in deep boreholes — are characterized by commonly graded/stratified, rarely massive beds, poor sorting of small (mm-cm-sized), subangular to angular pumices and moderate amount (10–20 %) of lithics, lack of thick, well-sorted horizons, presence of cm- and rarely dm-sized prismatically jointed clasts and, in Királyrét (in the heart of the mountains: Fig. 3), the existence of an embedded lag breccia. Welding has been reported (with some uncertainty) only in boreholes (Gyarmati 1976). On the basis of borehole data, the pumiceous volcaniclastic deposits are the thickest and most widespread in the Börzsöny. Characterized by an overall dacitic-rhyodacitic composition (see Section 4 and Karátson & Németh in print), these sequences are ranging in mineral assemblages from garnet-bearing pyroxene biotite amphibole dacite (e.g. at the southern exposures: *Kismaros Tuff*, named first by Báldi & Kókay 1970) to garnet-bearing pyroxene amphibole ± biotite dacite (e.g. in the Kemence Valley: *Kemence Tuff*). However, given the poor exposure conditions and no widespread marker horizons, they are not divided in Fig. 3.

Nagy-Kő Hill Volcaniclastic Breccia

In and around a large number of marginal ridges, the pumiceous deposits give place to, or are interbedded with volcanic breccias totalling 50–100 m in thickness (see logs e and f and upper sections of a, c and d in Fig. 4). These sedimentologically highly variable breccias (see Karátson & Németh in print) consist of dm- to m-sized andesite and minor dacite clasts (occasionally with garnet), are frequently bedded and graded, and have a fine-grained, occasionally stratified/cross-stratified/laminated matrix sometimes with pumice fragments. Not distinguished or named in previous studies, this breccia is collectively called *Nagy-Kő Hill Volcaniclastic Breccia* in this paper.

The three above mentioned formations are proposed to have been deposited in close time-space relationship. As a detailed lithofacies study has pointed out (Karátson & Németh in print), they represent a rapid evolution of a number of small- to medium-sized silicic volcanic centres infilling the shallow submarine environment with pyroclastic and volcaniclastic deposits.

Features of the Kismaros and Kemence Tuffs suggest *small- to moderate-scale ignimbrite eruptions occurring in the close vicinity.* As for the depositional processes, however, the frequent intercalation of pumiceous and volcanogenic sandy-clayey ±fossiliferous material in graded/stratified beds argues for the existence of *resedimented syn-eruptive volcaniclastics* (McPhie et al. 1993). These may have been deposited mostly and initially subaqueously, partly subaerially by gravity-driven and/or water-supported volcaniclastic mass flows (Karátson & Németh in print).

How are these syn-eruptive volcaniclastics related to the proposed, primary ignimbritic origin? In recent literature (e.g. Cas & Wright 1991; White & McPhie 1997), there are three criteria for identifying ignimbrites: 1) presence of pyroclasts; 2) facies characteristics indicating deposition from a density current; 3) evidence for gas-supported (i.e. hot) transport of pyroclasts. Whereas the former two requirements (cf. Fig. 4) are met for the Börzsöny volcaniclastic deposits, the third one (i.e. welding, segregation pipes, fiammes, high-temperature crystallization structures, etc.) is not or is uncertain. Nevertheless, the significant amount of fresh, angular pumice (fragment)s, the radially jointed blocks in many places (see logs in Fig. 4 and the E margin of the Börzsöny), as well as the presence of the mentioned lag breccia at Királyrét, suggest primary (ignimbrite eruption-fed) origin and hot conditions in situ or not too far away. Direct deposition from subaqueous (cf. Cas et al. 1998; Legros & Druitt 2000) and even subaerial pyroclastic flows may also have occurred (e.g. Kismaros [upper section], Királyrét, Magyarkút). Our interpretation is in accordance with the "submarine pumice flows" proposed by Konečný & Lexa (1994) for the neighbouring Burda Mts., but refines it and also all the former views that regarded the first-stage deposits mostly as pyroclastics (e.g. Korpás & Lang 1993; Karátson 1995; Korpás et al. 1998).

Further away from the eruptive vents, syn- and inter-eruptive resedimentation resulted in deposition of the Nagy Valley Volcanogenic Sandstone. In the N, northward from Kemence Valley, and in the SE, southeastward from Nagy-Kő Hill, field observations show that the fine-grained volcanogenic deposits are progressively better stratified, with pumice decreasing in size and quantity and the strata are thinner and more graded. These sedimentological features fit in with the existence of evolved volcaniclastic aprons. In other words, *the Kismaros and Kemence tuffs and the Nagy Valley sandstone may represent end-member formations of proximal/more primary and distal/more reworked facies, respectively.* This relation is more ambiguous in the central part of the mountains where subsequent massive rocks overlie them.

Proximity of the tuffs seems to be supported by certain types of the Nagy-Kő Hill breccia. This breccia is interpreted as deposited from *high-concentration mass flows* (Karátson & Németh in print), that is debris flows (both submarine/subaerial), lahars and hyperconcentrated streamflows (see Fig. 4; cf. Pierson & Scott 1985; Smith & Lowe 1991). Debris avalanche deposits to the S have also been identified (Karátson & Németh in print). The breccias may have been among the final products of the emerging first-stage paleovolcanic complex. For the primary origin of certain covering breccias in an elevated position — those with monolithological composition and abundant pumices in the matrix — we propose *explosive eruption-associated destructive processes (e.g. dome or sector collapses) resulting in small- to medium-sized calderas* (such as at Mt. Pinatubo, the Philippines, 1991: Newhall & Punongbayan 1996; also see Section 5). In other breccia types, the Nagy Valley sandstone is interbedded upsection by monolithological breccia and the matrix is free of pumices but prismatically jointed blocks are frequent (e.g. at Kámor and Gömbölyű-Kő hills: see c in Fig. 4). These breccias are interpreted as *subaqueous volcaniclastic debris-flow deposit* originating from either minor dome collapses or hyaloclastite formation. A more detailed study may identify many types of syn- and post-eruptive debris flows, although their mapping and correlation are highly complicated by the lack of exposures. A part of the breccias (of more basic lithology) may have originated from, or mixed with, the material of the emerging, subsequent High Börzsöny edifice, for example those exposed on its upper southern slopes (see point 3.3).

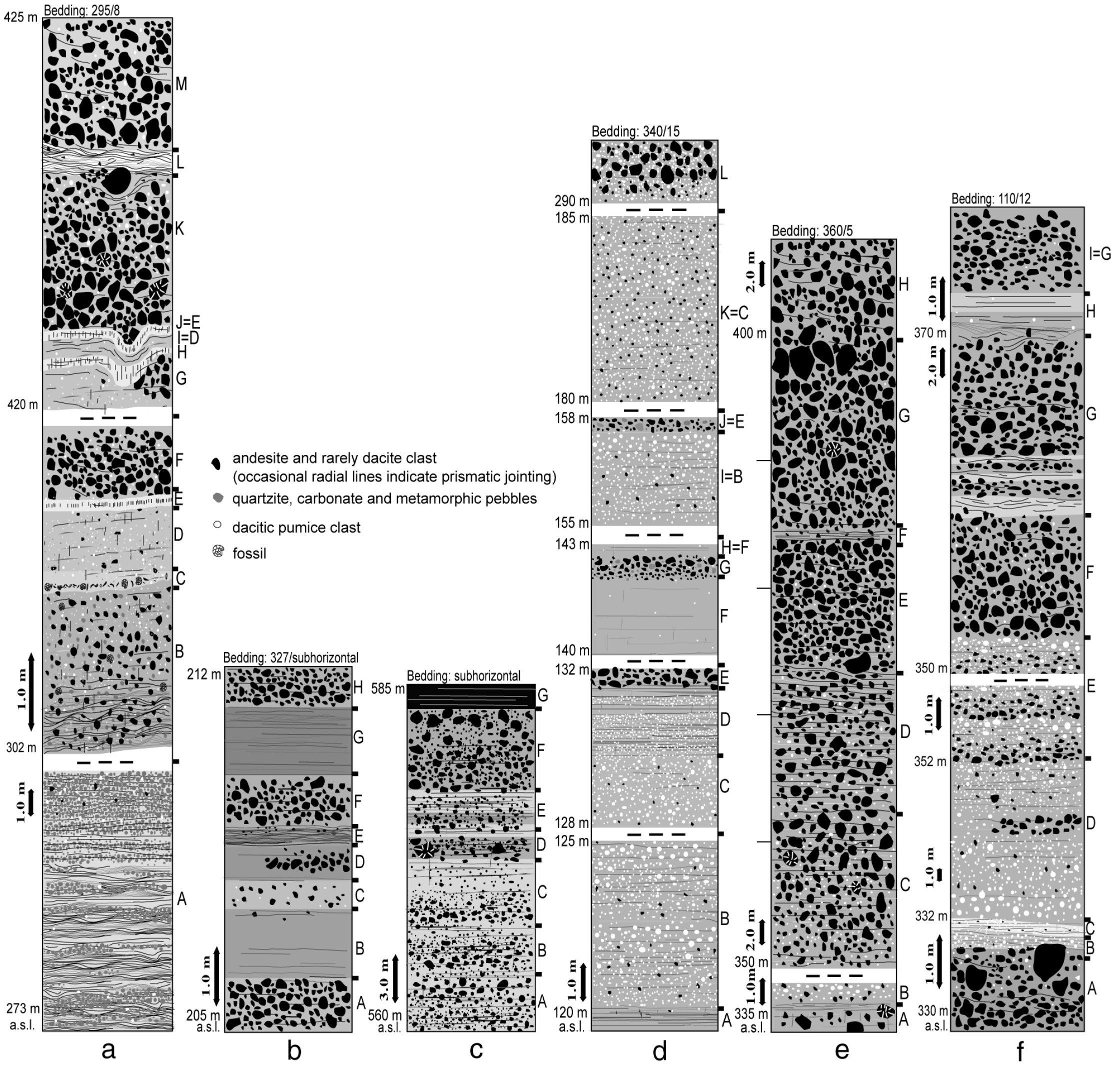

Fig. 4. Selected lithological logs of the first-stage volcaniclastics. Note scale differences. For locality, see Fig. 3. **a:** Szívszakasztó, Nagy Valley (simplified). A — Non-volcanic sand and conglomerate (submarine). B — Mixed volcaniclastic debris-flow deposits developing from A. C — Mollusc-bearing volcanogenic sandstone (submarine). D — As C but without fossils. E — Volcanogenic mudstone (submarine). F — Volcaniclastic debris-flow deposit (submarine? subaerial?). G — Debris-flow scour fill. H — Similar to E but probably subaerial. K — Resedimented syn-eruptive debris-flow deposit (subaerial?) with scour fill. L — Sandy volcaniclastic bed originated probably from fluvial deposition. M — Volcaniclastic debris-flow deposit (subaerial). **b:** Lohanc, Nagy Valley. A — Volcaniclastic debris-flow deposit (submarine?). B — Volcanogenic sandstone (submarine?). C — Volcaniclastic conglomerate (submarine?). D — Hyperconcentrated streamflow deposit. E — Fluvial deposit. G — Hyperconcentrated streamflow deposit. F, H — Volcaniclastic debris-flow deposit (subaerial). **c:** Kámor Hill E slope. A, B, C — Volcanogenic sandstone intercalated with units of submarine volcaniclastic mass-flow deposits. D — Probably resedimented syn-eruptive volcaniclastic debris-flow deposits (submarine). E — Volcanogenic sandstone beds with minor volcaniclastic mass-flow deposits (submarine). F — Syn-eruptive volcaniclastic debris-flow deposits perhaps originated from block-and-ash flow deposits (submarine? subaerial?). G — Amphibole pyroxene andesite lava flow. **d:** NW-SE gully W of Kismaros, the principal exposure of Kismaros Tuff. A — volcanogenic sandstone (submarine). B — Flow units of pumiceous resedimented syn-eruptive volcaniclastics (submarine). C — Pumiceous resedimented syn-eruptive volcaniclastics (submarine). D — Resedimented syn- or inter-eruptive volcaniclastics (submarine). E — Volcaniclastic debris-flow deposit (submarine?). F — Volcanogenic sandstone (submarine). G — Debris-flow deposit (submarine?). L — Pyroclastic-flow deposit or resedimented syn-eruptive volcaniclastics (subaerial?). **e:** Cicőke hillslope in Kemence Valley. A — Resedimented syn-eruptive volcaniclastic mass-flow deposit (submarine). B — Flow unit of pumiceous resedimented syn-eruptive volcaniclastic deposit (submarine). C, D — Volcaniclastic debris-flow deposits (submarine). E — Volcaniclastic debris-flow deposit (submarine? subaerial?). F — Volcanogenic sandstone (lacustrine?). G — Volcaniclastic debris-flow deposit, i.e. lahar (subaerial?). H — Volcaniclastic debris-flow deposit (subaerial). **f:** Nagy-Kő Hill (compiled and simplified from two exposures). A — Volcaniclastic debris-flow deposit (submarine). B, C — Volcanogenic lapillistone and sandstone, respectively, redeposited perhaps from pyroclastic fall. D — Pumiceous resedimented syn-eruptive volcaniclastic mass-flow deposits (submarine? subaerial?). E — Flow units of pumiceous resedimented syn-eruptive volcaniclastics (submarine? subaerial?). F — Volcaniclastic debris-flow deposit (subaerial?). G — Volcaniclastic debris-flow deposit interbedded with fluvial streamflow deposit (subaerial). H — Fluvial and hyperconcentrated streamflow deposit (subaerial).

3.3 Massive rocks

In this point, we distinguish between massive lava- and subvolcanic rocks in the SW, S, SE and in part N Börzsöny and principal constituents of the High Börzsöny.

Dacite and andesite lava domes

Although some early workers already proposed a surficial volcanism for the S and W Börzsöny, resulting in lava domes (e.g. Papp 1933a,b), most later authors (e.g. Balla & Korpás 1980; Korpás & Lang 1993) used the terms "shallow intrusive body" and "vent core" (or "vent infill").

More recently, Korpás et al. (1998) refined the classification describing "subvolcanic bodies and extrusions". The rocks in question crop out mostly in isolated hills, penetrating the volcaniclastics or the underlying sedimentary deposits (see the same stratigraphy in the nearby Burda Hills, Slovakia: Konečný & Lexa 1994). The various alteration of these rocks in the W and central Börzsöny, related to the Nagybörzsöny hydrothermal ore mineralization, is not dealt with here, since detailed works are available (e.g. Csillag-Teplánszky et al. 1983; Korpás & Lang 1993).

According to our thin section studies (see Appendix), all these rocks have porphyric texture. They have either more or less oriented crystals in a glassy groundmass (ca. 2/3 of the samples) or the groundmass is microholocrystalline (ca. 1/3). Intrusive rock types have not been found; rarely, holocrystalline matrix occurs. At the same time, there are field observations suggesting an extrusive origin. These observations include coeval volcaniclastic rocks at same topographic level (e.g. below Gömbölyű-Kő Hill, see before) and glassy groundmass in thin sections around some hills otherwise characterized by microholocrystalline rock texture (e.g. Nagy-Koppány and Nagy-Sas hills). In Pap Hill, one of the samples has microholocrystalline, another (at the top) glassy groundmass. All these data suggest that the majority of these rocks belongs to *more or less eroded extrusions/lava domes* (e.g. *Nógrád Castle Hill, Nagy-Pogány Hill, Nagy-Sas Hill, Pap Hill lava domes:* see Fig. 3). Some holo- and microholocrystalline matrix could, indeed, indicate shallow subvolcanic bodies, but even in these cases we prefer the interpretation of *exposed roots of eroded lava domes* consisting of the more crystallized, resistant basal part. On the other hand, for the majority of the domes, we have no data to give a paleogeographical evaluation. However, as treated in point 3.2, the outer facies of some first-stage domes are volcaniclastic and embedded in volcanic sandstone (see c in Fig. 4). For at least these cases, the paleoenvironment may have been subaqueous.

The High Börzsöny andesitic lava dome complex

In the High Börzsöny, typical facies of a highly eroded subaerial lava dome complex have been identified (Karátson 1995, 1997; Karátson et al. 1999a). These include *(a) coarse pyroclastic breccias being the roots of collapsed domes, (b) proximal facies of block-and-ash flow deposits and (c) horizontal or subhorizontal beds of lava flows.* (It is worth mentioning that a and b have been termed pseudo-agglomerate and agglomerate in some previous Hungarian literature.) The unsorted vent breccias are apparently matrix-free and contain large, rounded boulders due probably to hot, in situ fragmentation (Karátson et al. 1999b). In contrast, the block-and-ash flow deposits have more angular clasts and a significant amount of fine-grained matrix, and show typical features of block-and-ash flows (monolithological composition, slightly vesiculated clasts, interbedded tuff layers, frequent prismatic jointing of blocks, occasional stratification and reverse grading). Their best localities, preserved as small radial paleovalley-filling, now exhumed rock towers, are found mostly on and around the rim of the High Börzsöny central depression (Karátson 1999).

In certain places of these radial exposures, (a) and (b) show *obvious transitions.* Transition between the two facies can be detected well by investigating clast orientation (Karátson et al. 1999b): there is a rapid improvement in orientation from vent breccias to block-and-ash flow deposits.

The lava flows of the High Börzsöny have already been recognized by Pantó (1970), Balla (1978), Balla & Korpás (1980) and others. They are commonly platy jointed, occasionally with well-developed flowage structures (e.g. at Pléska ridge in the NE High Börzsöny), in accordance with a subaerial emplacement. The lava flows crop out differently in the W and S-E Börzsöny. In the former, all lava flows are interbedded with block-and-ash flow deposits; in the latter, the N-exposed slopes are covered mostly with lavas whose dip is largely identical with that of the slope (cf. Pantó 1970). This implies the northward tilting or faulting of the S-E Börzsöny (also see Section 5). Along the S and E rim of the High Börzsöny, alternating block-and-ash flow deposits and lava flows crop out in similar topographic levels indicating truncated, exposed paleovalley fillings.

Typical thin sections of the High Börzsöny rocks are described in the Appendix. The absence of garnet and biotite as well as their presence as xenoliths cearly indicates the subsequence of High Börzsöny relative to the biotite- and garnet-bearing marginal (and probably underlying) volcanics. The rather uniform rock type — typically amphibole pyroxene andesite — has some differences in the W and S-E parts: in the W High Börzsöny, the andesite samples are more amphibole rich and the hypersthene frequently occurs without augite. This petrographic difference, some dip directions of platy jointed lavas and the too large caldera diameter relative to other simple erosion craters of the Carpathians (Karátson 1995, 1996) suggest *more than one eruptive vent* (also see sections 5 and 6).

In addition to the above, there is a distinct type of massive rocks in the High Börzsöny. These are up to 30 m narrow, some tens–some hundreds metres long *dykes* (Balla 1978; Csillag-Teplánszky et al. 1983; Korpás et al. 1998). Petrographically, they are mostly amphibole andesites. The groundmass in thin sections is more or less glassy so the exposures may represent the near-surface parts of the dykes. Repeated K/Ar dating of the Mt. Várbükk dyke (Fig. 3) has given an older age (14.3–14.7 Ma) than the majority of the High Börzsöny (Table 2). This older age may be explained by an amphibole-rich early "dyke" magma later being completed by pyroxene during the High Börzsöny eruptions. This explanation is in contrast to a previous concept that the amphibole andesite dykes are the final volcanic products (e.g. Balla & Korpás 1980; Csillag-Teplánszky et al. 1983).

4. Geochemistry and petrogenesis

So far, no detailed geochemical work has been published for the Miocene volcanic rocks of the Börzsöny Mts. Downes et al. (1995) used 4 samples from the Börzsöny Mts. in the discussion of the geochemistry and petrogenesis of the Miocene volcanic rocks of the Inner Carpathian arc. Among them, sample #113 from the Nógrád Castle Hill has an unusual composition and deviates from the trends shown by the Börzsöny volcanic rocks. A new sample from the same locality (Table 1) has been analysed and we have got a different geochemical composition than #113 (Table 2 in Downes et al. 1995) that fits better with the geochemical trends of the Börzsöny volcanic rocks.

We have analysed 18 samples selected to cover the petrographical and assumed temporal range of the volcanic activity and to be as fresh as possible. The geochemical analyses were carried out in the Geochemical Laboratories of the Royal Holloway University of London (U.K.) and in the XRAL Laboratories, Toronto (Canada). The major elements and some trace elements (Ni, Cr, V, Rb, Ba, Pb, Sr, Zr, Nb, Y, Th) were determined by XRF spectrometry using fused discs for major elements and pressed pellets for trace elements. The rare earth elements were determined by neutron activation analysis (Canada) and by ICP-AES (U.K.). The major element composition of glasses (pumices and glass shards) was analysed by a JEOL Superprobe JXA-8600 WDS with an accelerating voltage of 15kV at a beam current of 10 nA (beam diameter 5 mm) at the University of Florence (Italy). Data were corrected using the procedure of Bence & Albee (1968). More details about the analytical conditions can be found in Mason et al. (1996) and in Harangi (1999).

The studied samples are usually fresh as shown by the low LOI. The more silicic volcanic rocks of the marginal parts, however, usually have a higher LOI content partly because of the abundance of hydrous minerals, such as biotite and amphibole and partly due to secondary alteration. Nevertheless, their chemical compositions may reflect the original characteristics since no correlation can be observed between the LOI content and the mobile low-field strength element (LFSE, e.g. Rb, Ba, Pb, Sr) concentrations.

Geochemical compositions of representative samples from lava flows and pumiceous volcaniclastics in marginal parts of the mountains and lava flows and clasts from block-and-ash flows of the High Börzsöny are presented in Table 1. As

Table 1: Representative chemical composition of volcanic rocks from the Börzsöny Mts. Numbers of localities are displayed in Fig. 3. α = andesite, $\beta\alpha$ = basaltic andesite, δ = dacite, am = amphibole, py = pyroxene, bi = biotite.

	1st stage			2nd stage	3rd stage			glass composition (Nagy-Kő Hill)		
Locality	1 Nagy-Kő Hill (am α breccia clast)	2 Nógrád Castle Hill (biamhyp δ lava dome)	3 Gömbölyű-kő Hill (biam α breccia clast)	4 Pap Hill (biam α lava dome)	5 Mt. Nagy Hideg (py $\beta\alpha$ lava flow)	6 Visk-bérc (ampyα lava flow)	7 Inóc quarry (ampy α lava flow)	pumice	pumice	glass shard
major elements (wt. %)										
SiO_2	61.96	64.46	60.40	58.29	56.41	56.80	57.20	68.46	68.52	69.74
TiO_2	0.71	0.56	0.768	0.62	0.92	0.81	0.82	0.18	0.15	0.19
Al_2O_3	18.28	18.56	17.90	17.93	18.53	18.70	17.80	13.92	14.01	13.42
Fe_2O_3	5.51	3.82	6.39	7.04	8.19	8.30	7.55	2.36	2.38	1.91
MnO	0.07	0.04	0.11	0.16	0.17	0.14	0.15	0.04	0.08	0.12
MgO	1.92	0.91	2.34	2.60	3.17	2.76	3.09	0.34	0.25	0.24
CaO	5.87	5.64	5.68	6.96	7.75	7.11	7.42	1.91	1.86	1.90
Na_2O	2.89	3.13	2.76	2.88	3.13	2.68	2.92	2.88	2.75	2.89
K_2O	2.49	2.52	2.40	2.69	1.77	2.03	2.25	3.95	4.09	4.16
P_2O_5	0.18	0.16	0.23	0.35	0.23	0.19	0.21			
LOI	1.19	2.48	1.10	1.30	0.48	0.70	0.50			
trace elements (ppm)										
Ni	8	6	7	7	14	9	13			
Cr	17	10	45	19	40	42	63			
Sc	9.70	6.90	17	16.90	19.10	18	22			
Rb	117	113	91	82	70	88	81			
Ba	505	534	1050	1223	549	516	980			
Pb	22.8	24.3	30	22.50	13.50	8	50			
Sr	359	379	460	725	427	361	523			
Zr	142	141	146	127	145	145	141			
Nb	10	10	10	10	8	9	8			
Y	11	5	22	22	29	29	26			
Th	9.00	10.9	16.00	12.60	8.00	10.00	14.00			
La	24.31	31	45	33.70	22.11	28	35			
Ce	52.25	58.7	75	64.80	47.03	53	68			
Nd	23.70	27	32	28.30	21.80	24	25			
Sm	4.84		6.10		4.65	5.00	5.40			
Eu	1.41		1.40		1.39	1.00	1.20			
Gd	3.88				5.01					
Yb	0.82		2.1		2.86	2.8	2.9			
Lu	0.13		0.2		0.48	0.3	0.31			

shown in Fig. 5, the volcanic rocks of the Börzsöny are predominantly *andesites.* Some garnet-bearing samples are classified as *dacite* and, in the High Börzsöny, there are a few *basaltic andesite* occurrences. It is worth comparing these rocks to the similar-aged volcanic rocks of the nearby Visegrád Mts. that are thought to have undergone similar evolution (cf. Korpás et al. 1998). The Börzsöny volcanics have higher total alkali content at a given SiO_2. This difference is more pronounced using the SiO_2 vs. K_2O diagram (Fig. 5 below). The Börzsöny volcanic rocks belong to the *high-K calc-alkaline series* and have systematically higher potassium content than those of the Visegrád Mts. The glass composition of pumices and glass shard from the pumiceous volcaniclastic deposit of Nagy-Kő Hill shows higher SiO_2 and K_2O contents compared to the bulk volcanic rocks (Fig. 6b). They resemble the glasses of the Holdvilág Valley ignimbrite in the

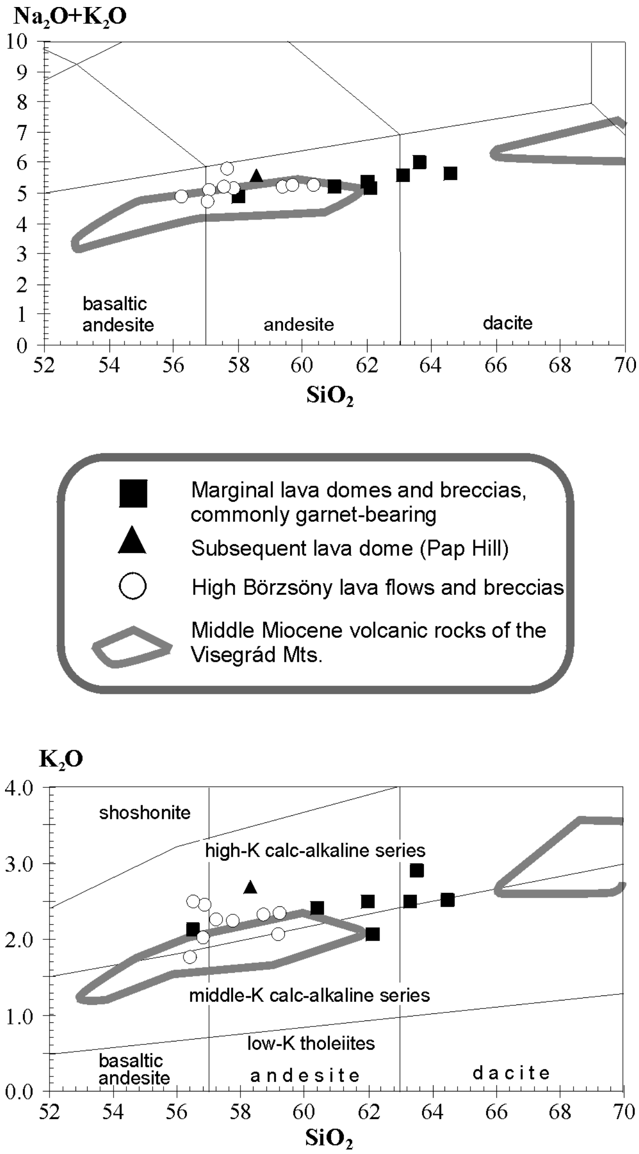

Fig. 5. Classification of the volcanic rocks of Börzsöny Mts. using the TAS scheme (Le Bas et al. 1986) and the SiO_2 vs. K_2O diagram (Gill 1981).

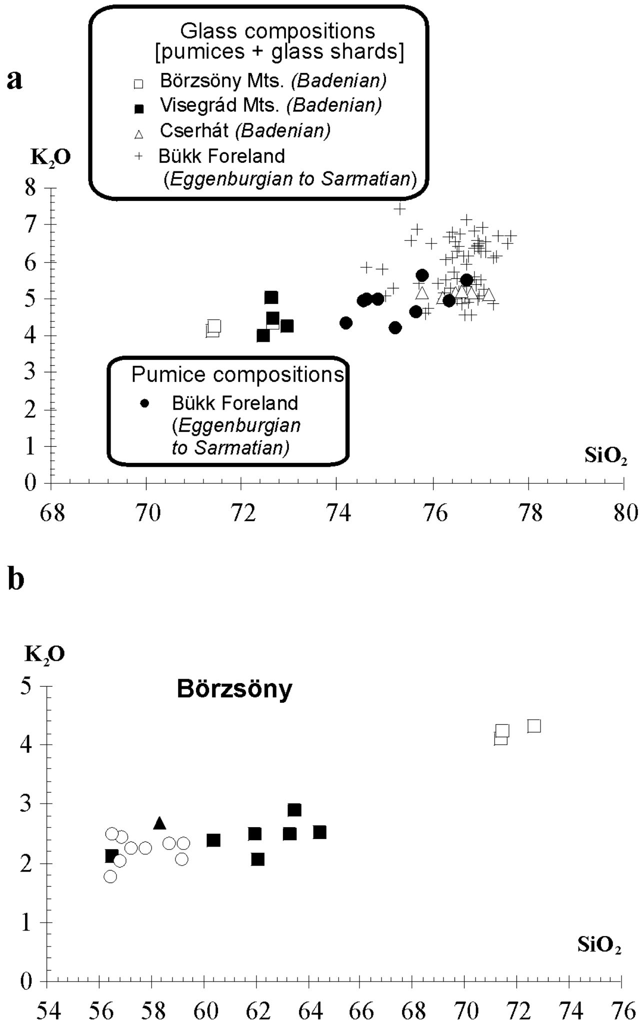

Fig. 6. Comparison of glass composition of pumices and glass shard from the pumiceous volcaniclastic deposit of Nagy-Kő Hill with glass analyses from Early to Middle Miocene ignimbrites of Hungary (a) and with the host volcanic compositions of the Börzsöny Mountains (b). Glass compositions are normalized to 100 wt. % (data from Harangi unpublished). Symbols for b as in Fig. 5.

Visegrád Mts. On the other hand, they are less silicic than glasses from Early to Middle Miocene ignimbrites of Cserhát and Bükk Foreland regions (Fig. 6a; the latter regions are named in Fig. 1).

Major and trace element variations with increasing SiO_2 are illustrated in Fig. 7. CaO, Fe_2O_3 and MgO are compatible throughout the series. These trends are consistent with fractional crystallization of olivine and clinopyroxene in the most basic magmas. Al_2O_3 does not show a clear trend, it remains roughly constant suggesting that plagioclase did not fractionate, but accumulated heterogeneously in the Börzsöny volcanics. Among the trace elements, the negative trend of Sc and Y implies a strong control of amphibole and/or garnet during magma evolution. Some scatter can be observed in the distribution of Rb, Ba and Sr. They show positive or constant trends indicating that they behaved incompatible, that is no significant plagioclase and K-feld-

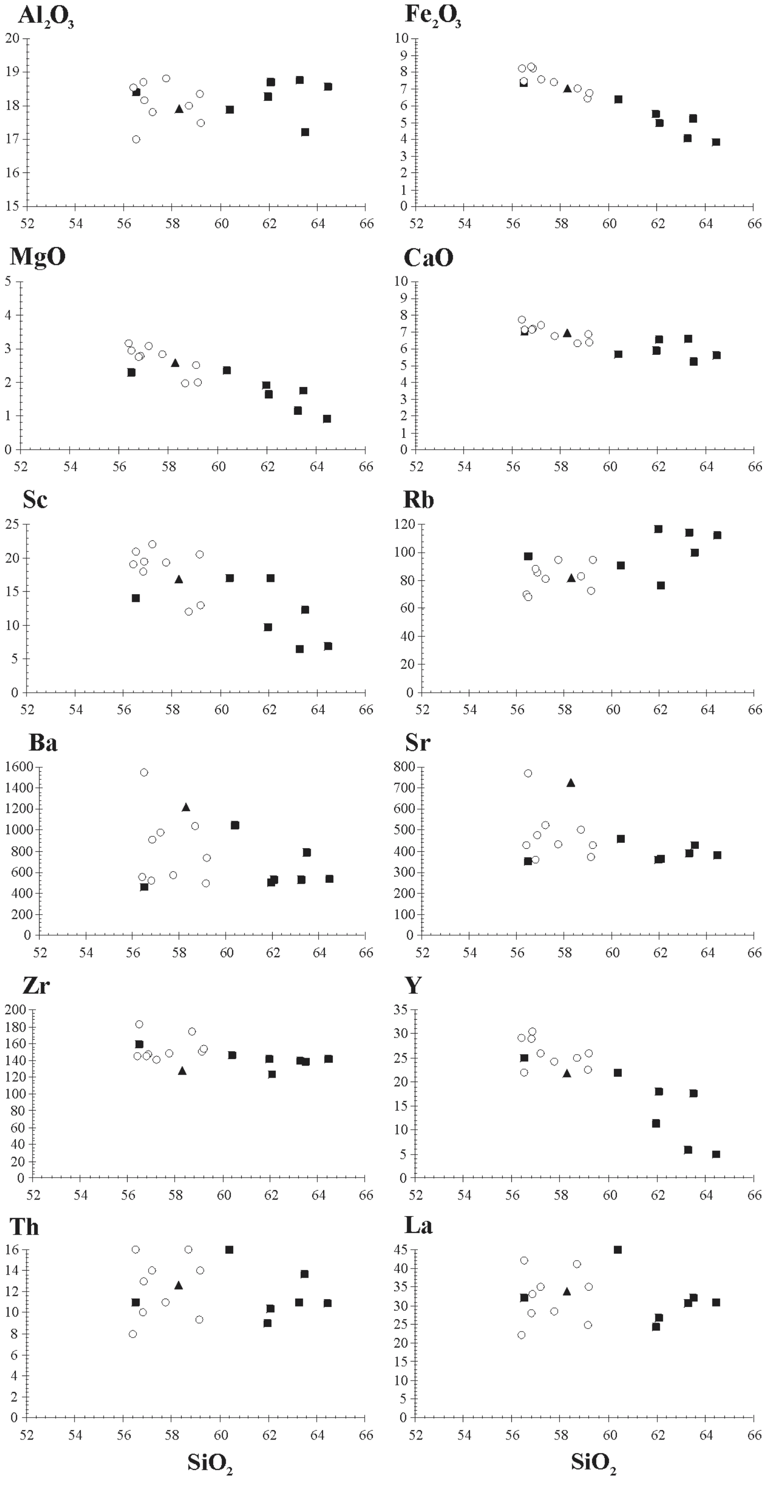

Fig. 7. Variation of some major and trace elements with increasing SiO_2 content. Symbols as in Fig. 5.

spar fractionation occurred. The scatter in the variation of La and Th suggests that other processes than fractional crystallization may have also operated, such as magma mixing and partial melting of heterogeneous source rocks.

N-MORB normalized trace element distribution of the Börzsöny volcanics is presented in Fig. 8. In general, they show fairly uniform trace element patterns characterized by enrichment of LFS elements, negative Nb-anomaly and strong positive Pb anomaly. These features are typical of subduction-related volcanic rocks. The only significant difference can be observed in the Y-Yb-Lu range. The garnet-bearing volcanics show a strong depletion in these elements suggesting early garnet fractionation or residual garnet during partial melting. In contrast, the garnet-free volcanic rocks have very similar trace element signatures.

The geochemical composition of the volcanic rocks from the Börzsöny indicates only *slight differences* between the volcanic products of the petrographically/volcanologically different parts of the mountains, but *they are not cogenetic. The rocks of the volcaniclastic successions as well as the garnet-bearing marginal lava domes are more silicic and characterized by lower Zr/Nb ratio (12–14.6) than the rocks of High Börzsöny and some other domes (Zr/Nb=16–19).*

The Zr/Nb ratio suggests a moderately enriched mantle source for the primary magmas of the Börzsöny volcanics. As far as subduction-related metasomatism is concerned, it is a subject of debate whether the Middle Miocene volcanic activity in the W segment of the Carpathian Neogene Volcanic Chain took place due to the active subduction of the European plate beneath the ALCAPA microplate of the Pannonian Basin (e.g. Balla 1981; Szabó et al. 1992; Downes et al. 1995) or it was a response of the overall extension of the Pannonian Basin (e.g. Lexa & Konečný 1974; Lexa et al. 1993; Harangi et al. 1998; Harangi 1999). In the latter case, melt generation occurred in the metasomatized lithospheric mantle due to the thinning of the lithosphere in the Middle Miocene syn-rift phase of the Pannonian Basin.

5. Volcanic structure and landforms

In this section, we attempt to correlate volcanic structure and gravimetry. Although there have been two relevant contributions to structural geology [a photo-tectonic interpretation by Czakó & Nagy (1976) and a deep-structure investigation on a geophysical basis by Balla (1977)], no modern correlation of tectonic and volcanic structure using the updated gravimetric data base has been carried out. Unfortunately, large-scale postvolcanic tectonic movements (faults, uplifting) of the broad vicinity (e.g. Fodor et al. 1999) obviously overprinted the original situation; in addition, interpretation can hardly be supported in the field due to the general lack of microtectonic features.

Gravitational anomalies of the Börzsöny and its surroundings contain significant regional effects not related to the Miocene volcanic activity. This is due to the high-density Lower Paleozoic crystalline rocks to the N and low-density Mesozoic carbonate rocks to the S, separated by the already mentioned Diósjenő line as a gradient zone. Anomalies are also caused by different depths of the basement.

The regional effects, however, can be moderated by filtering. The *filtered residual gravime-*

Table 2: K/Ar ages from the Börzsöny Mountains measured since the review paper by Korpás & Lang (1993). For locality, see Fig. 3. bi = biotite; am = amphibole; py = pyroxene; w.r. = whole rock.

Locality	Lithology	Dated fraction	K (%)	^{40}Ar(rad) %	Age (Ma)	Reference
I Bajdázó quarry lava dome	bi am dacite	biotite	5.49	28.9	15.4±0.9	Karátson 1995
II Kopasz Hill lava dome	am py bi andesite	w. r.	1.91	23.4	15.2±1.0	Karátson 1995
III Száraz-fa-bérc lava dome	am py andesite	w. r.	2.01	46.9	15.0±0.7	Karátson 1995
IV Mt. Hollókő pyroclastic breccia	am bi andesite	w. r.	1.99	11.8	14.3±1.4	Karátson 1995
V Mt. Csóványos W pyroclastic breccia	am py andesite	w. r.	2.07	53.1	13.9±0.6	Karátson 1995
VI Inóc quarry lava flow	am py andesite	w. r.	2.06	53.5	13.7±0.6	Karátson 1995
VII Rózsa adit, borehole 259 m	-	hydromuscovite	3.14 3.14	33.2 39.6	14.5±0.7 14.6±0.7	Pécskay & Nagy 1993
VIII Kemence Valley central part breccia	py am andesite	w. r.	1.75	26.9	12.5±0.7	this paper
IX Mt. Lófarú dyke	am andesite	w. r.	2.30	58.0	14.7±0.6	this paper
X Nagy-Kő Hill volcaniclastic breccia	bi am andesite	am	0.79	30.6	15.2±0.8	this paper
XI Magyarkút ignimbrite	dacite lapilli tuff	am+bi	1.70	24.4	14.2±0.9	this paper
XII Kámor Hill volcaniclastic breccia	py am andesite	am	0.76	31.4	16.4±0.9	this paper
XIII Perőcsény E lava dome/flow	bi am andesite	am+bi	1.12	42.9	16.8±0.8	this paper
XIV Kemence Valley W lava flow	am py andesite	w.r.	2.13	80.9	15.9±0.8	this paper

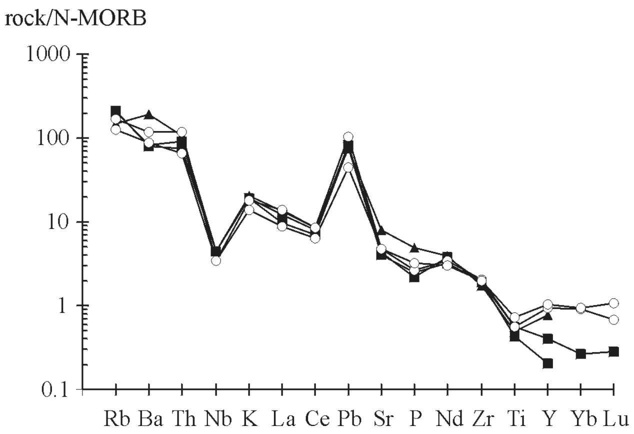

Fig. 8. N-MORB (Pearce & Parkinson 1993) normalized trace element distribution of representative samples from different stages of the volcanism of Börzsöny. Symbols as in Fig. 5.

try map (Fig. 9) is more free from regional effects. The sources of the residual anomalies can be interpreted either as small-scale horizontal changes in the basement (e.g. the maximum of Naszály Hill), or as relatively large, high-density andesite bodies (lavas or subvolcanic rocks). These two factors may conspire in the central and SW part of the Börzsöny where it is obvious that igneous/subvolcanic masses intruded into the host rocks. When investigating the latter area in detail, not only a single but also *several individual bodies can be distinguished.* These bodies largely correspond to topographic elevations located mostly in the SW Börzsöny (Fig. 3: e.g. Sas, Só, Koppány, Csák, Hegyeshegy hills, interpreted as more or less exposed lava domes: Karátson 1995). The topographically most prominent Pap Hill lava dome is located obliquely (northward) above the gravimetric maximum W of Szokolya. Some other, assumed centres in the N and E are not supported so well.

The other large concentric maximum zone can be seen under the High Börzsöny area. *This maximum may be related to subvolcanic bodies under the High Börzsöny edifice.* The edifice itself with a somewhat rectangular-shaped depression (Figs. 2–3) was identified first by Balla (1978) who proposed a stratovolcanic cone with an erosion caldera. As demonstrated in point 3.3, the cone can be termed rather as a lava dome complex with a number of eruptive vents. The large-scale identity of the cone, however, is well supported by gravimetry.

When reconstructing the original form in more detail, it is important that the S-E part of the edifice seems to be tilted northward (see earlier, and Balla 1978, Karátson 1995): the initial, pumiceous volcaniclastics crop out 650–700 m a.s.l. on the S-SE slopes and ca. 300 m a.s.l. along the Kemence Valley. Taking this into account, and according to (1) the calculated 1300–1400 m absolute height (Karátson 1996, 1997), (2) the ca. 800 m inferred relative height and (3) the 5.5 km basal radius, the volume of the (simple) original cone could be some 25 km^3. Because the residual gravimetry map and field observations show no trace of collapse, the erosional origin of the central depression is very likely. On the basis of the classification of Karátson et al. (1999c), we think the present depression has formed from a number of distinct craters/scarps by long-term fluvial erosion, whereas the western sector may have avalanched to the W (Karátson 1995, 1997).

The interpretation of the volcanic structure is much more difficult when trying to infer larger-scale forms, that is *calderas.* Although several caldera-forming mechanisms, such as downsag, plate- or piston-like, chaotic, piecemeal, etc., have been distinguished (e.g. Walker 1984; Scandone 1990; Lipman 1997; Moore & Kokelaar 1998), the resulting gravimetry is largely similar (e.g. Rymer & Brown 1986; Deplus et al. 1995): characteristic minima zones inside and outside the caldera rim, due to shattered rocks of the collapse and/or to the low-density infill (e.g. pumiceous volcaniclastics, lake sediments). In the Börzsöny Mts., Balla & Korpás (1980) and Korpás & Lang (1993) proposed a large number of calderas, whereas Karátson (1995, 1997) argued for a single depression coalesced from three smaller ones.

In the residual gravimetric map of the Börzsöny Mountains, instead of unambiguous caldera structures, *extended, quiet minima areas* can be seen outside the two maxima zones *which should correspond to low-density, pumiceous, volcanogenic material.* However, in the SE Börzsöny around

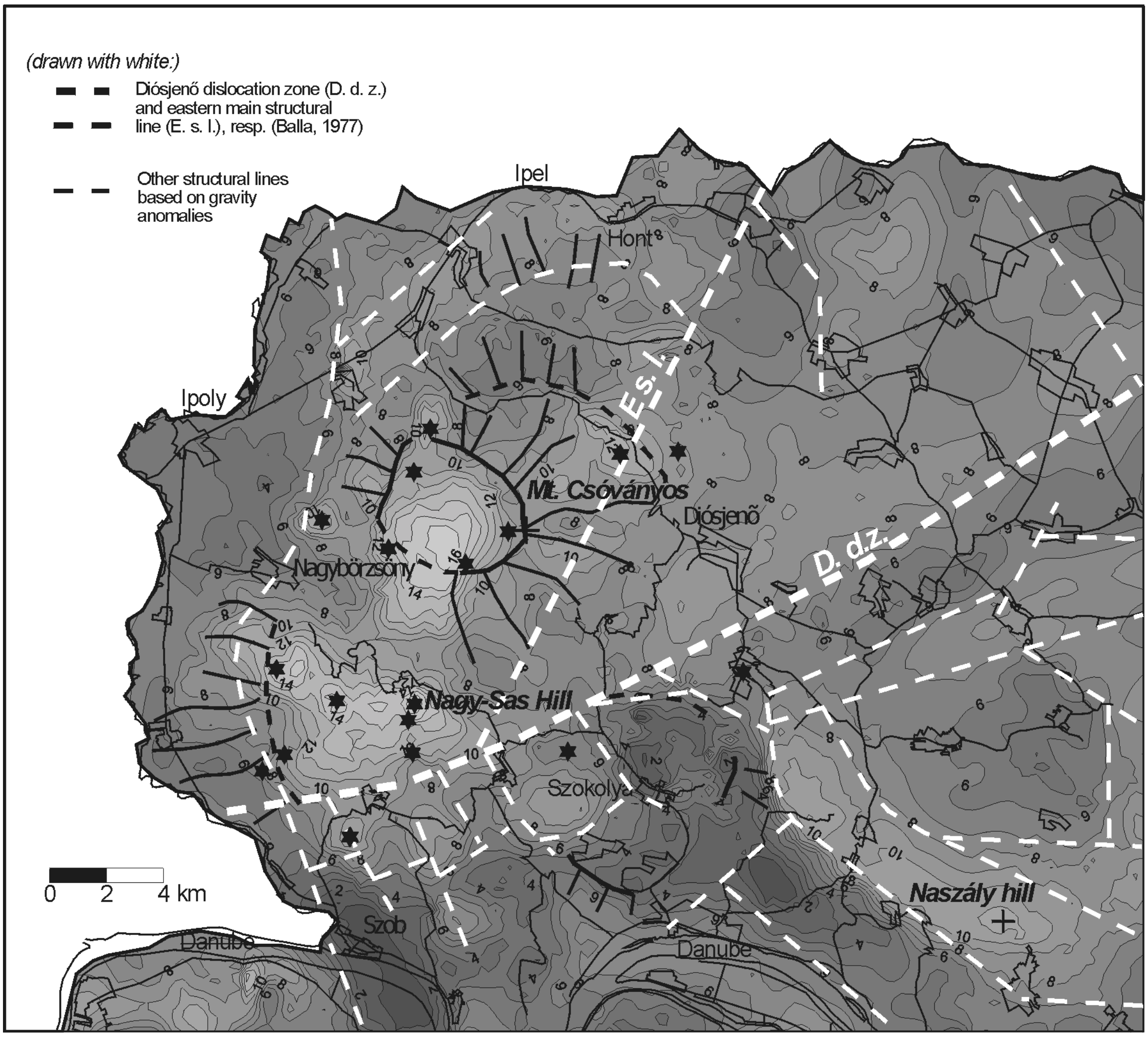

Fig. 9. Residual gravimetry map of the Börzsöny. Gravity anomalies of the Börzsöny Mts. have been filtered to intensify the short wavelenght anomalies (less than 10 km) and to suppress those having longer wavelength (i.e. larger-scale regional effects). This procedure does not mean that only anomalies smaller than 10 km (horizontally) are displayed, because the anomalies of the individual bodies are not sinusoid in character (every anomaly has a Fourier spectrum), therefore the regional anomalies may also have harmonics (i.e. short wavelenght components) that are not filtered. Density for correction: 2400 kg/m^3. Symbols as in Fig. 3.

Szokolya village, *a prominent local depression* appears that may be related to a fault-bounded caldera structure (Nagy-Kő Hill caldera: Karátson 1997; in part corresponding to the 'Szokolyahuta centre' of Ferenczi 1936 and the 'Börzsönyliget stratocone' of Balla & Korpás 1980). Although subsequently formed tectonic lines may have overprinted it, the caldera structure seems to be supported by the presence of (a) concentric, low topographic ridges in the E and S (see Fig 3: Karátson 1995, 1997), (b) resistant, commonly monolithological breccia cover on these ridges interpreted as primarily related to caldera formation (Fig. 4f: Karátson 1997; Karátson & Németh in print), (c) occurrence of lag breccia at Királyrét, (d) radial flow directions of submarine pyroclastic flows at Királyrét, Nagy-Kő Hill and Kismaros obtained from magnetic anisotropy measurements (see Fig. 3) and (e) postvolcanic lake sediment infill in the Szokolya basin (e.g. Ferenczi 1936).

In the N, along the Kemence Valley, the arcuate, flat ridge of the valley (Balla & Korpás 1980) and the presence of similar breccia with pumiceous matrix (Fig. 4e: Karátson 1997) also suggest an (eroded, retreated) caldera rim section. In the SW, in relation to the gravimetric maximum zone, geomorphic features (i.e. radial ridges and valleys, presence of planèzes) as well as pumiceous deposits in radial valleys have been proposed to represent an outer caldera slope (Karátson 1997). These latter (N and SW) caldera rims, however, are not seen or are very uncertain in the gravimetric map, suggesting that dome/sector collapse rather than caldera collapse occurred.

6. Geochronology of the volcanism

6.1 K/Ar datings and their evaluation

During the last decades, over 100 K/Ar determinations have been carried out on whole rock samples and mineral fractions from the Börzsöny Mts. The main purpose of K/Ar dating was to obtain abso-

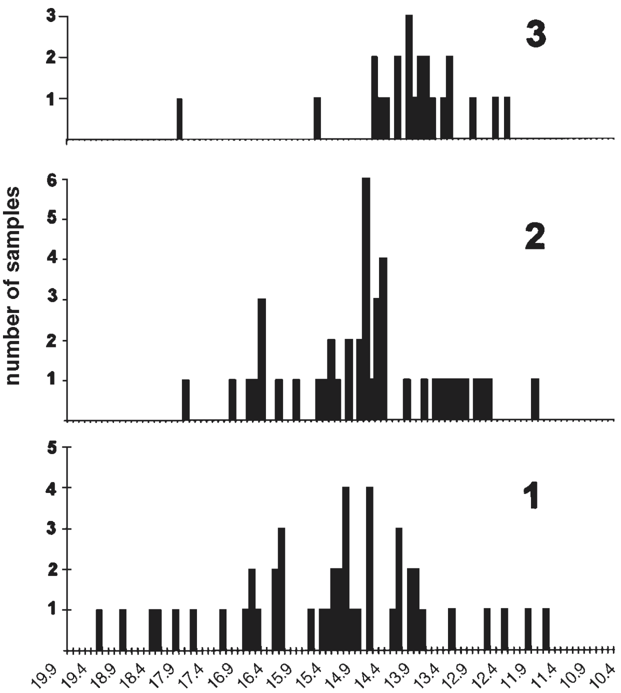

Fig. 10. Summary histogram of K/Ar ages measured on rocks from the Börzsöny Mts. 1, 2, 3: volcanic stages corresponding to Fig. 3.

lute ages for the time and duration of volcanic activity and to date hydrothermal processes and ore mineralization. Dating was carried out mainly in the Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), Debrecen, and partly in the Geological Survey of Israel (GSI), Jerusalem. The first determinations from ATOMKI were published by Balla et al. (1981); a summary with detailed results of both laboratories was presented by Korpás & Lang (1993).

All the available K/Ar data, arranged in three volcanic stages proposed by Karátson (1995), are shown in Fig. 10. The K/Ar ages obtained since the publication of Korpás & Lang (1993) are given in Table 2. Details of instruments and methodology as well as calibration were published by Balogh (1985). Atomic constants suggested by Steiger & Jäger (1977) have been used for calibrating age.

Stratigraphic considerations (e.g. Báldi & Kókay 1970) and paleomagnetic investigations (next point) suggest a Lower Badenian time for the beginning of volcanism. *Many K/Ar ages also show a Lower Badenian earliest activity.* Among those obtained on unaltered rocks are worth mentioning the 16.5 Ma average age of garnet-bearing dacite tuff in Kóspallag-11 borehole (Hámor et al. 1980), fitting with the 16.4 Ma age of the Middle Rhyolite Tuff (Tar Dacite Tuff) of the Pannonian Basin (Hámor et al. 1979) and the 16.4 Ma age of the garnet-bearing volcanic breccia of Kámor Hill embedded in the underlying volcanogenic sandstone (this paper: Table 2, Fig. 4c).

However, a significant part of the K/Ar ages are younger. On one hand, a younger age has been confirmed for the well-known hydrothermal event: 15.1 ± 0.5 Ma was given in the GSI by averaging K/Ar data on hydrothermally altered rocks and 14.6 ± 0.5 Ma in ATOMKI by using hydromuscovite formed in the process (Pécskay & Nagy 1993). On the other hand, the High Börzsöny andesite and basaltic andesite rocks, which are not affected by hydrothermal alteration (cf. Korpás & Lang 1993), systematically give K/Ar ages around or below 14.0 Ma. This Badenian/Sarmatian age poses a major stratigraphic problem because it has been shown that the South Börzsöny cover deposits are also Lower Badenian in age (e.g. Báldi & Kókay 1970; Báldi-Beke et al. 1980; Dulai 1996).

When determining the exact geological age and time span of volcanism, we have to consider the following difficulties of K/Ar dating:

1. The given analytical errors of K and radiogenic Ar determinations are necessarily uncertain, in the best case their values characterize the average accuracy of the laboratory; the real error of individual measurements can be different.

2. K/Ar and real geological ages may be biased. The radiometric age is older, when (i) the rock contains undegassed xenoliths, (ii) the rock contains excess argon, for example in amphibole that crystallized in a magma chamber; in addition, (iii) during hydrothermal processes, radiogenic argon can be incorporated. The radiometric age will be younger, if (i) a long time after rock formation, radiogenic argon is lost in the course of alteration or heat effect, or (ii) when K is incorporated in the rock also a long time after its formation.

Some of the rocks from the assumed first volcanic stage contain excess Ar and show strong rejuvenation (e.g. ages on samples from borehole Perőcsény-26 range from 16.8 Ma to 12.1 Ma). Thus, *the mean age of the first-stage rocks cannot be used for estimating the beginning of volcanic activity;* there is no independent criterion for eliminating overprinted ages from the set of data. In the next section, however, we present paleomagnetic measurements that can better resolve this problem.

In contrast*, unbiased radiometric age can be calculated for the end of volcanic activity* by averaging K/Ar data from rocks of the High Börzsöny, unaffected by hydrothermal alteration (Table 3). On the basis of volcanological and petrographical considerations (see before), samples from the W and S-E part of High Börzsöny have been treated separately.

Six ages are available from the W High Börzsöny, all obtained in the ATOMKI. The 14.08 ± 0.81 Ma mean age shows that the estimated average age in any further measurements would fall within the ± 0.81 Ma range in a 95 % confidence interval. On the other hand, the weighted mean and its standard deviation is *14.41± 0.71 Ma. This can be regarded as the geological age for the W High Börzsöny.*

Seventeen ages are available from the S-E part of High Börzsöny, of which 3 were dated in the GSI. Of the 14 ages of ATOMKI, 2 data are omitted: the amphibole from Godóvár

Table 3: Statistical evaluation of K/Ar ages from the High Börzsöny. Values in Ma. In brackets the number of performed datings.

	western part	eastern part	
	ATOMKI (6)	ATOMKI (14)	GSI (3)
Mean age (± confidence interval)	14.08±0.81	13.83±0.12	13.43±2.61
		weighted average: 13.75±0.32	
Mean error	1.22	0.70	0.30
Standard deviation	0.77	0.42	1.05
Weighted mean	**14.41**	**13.88**	**13.54**
		average: 13.71±0.24	
Standard deviation of the weighted mean	0.71	0.44	1.10

(17.8 Ma) contains excess Ar; the age of Mt. Magas-Tax (15.7 Ma) is too old both on the basis of petrography and locality of the sample and statistical considerations. Error assessment is different in the two laboratories, but the 2 mean ages and the weighted means agree acceptably well. The (unweighted) mean of the weighted means, *13.71 ± 0.24 Ma, can be accepted as the time when volcanic activity most likely ceased in the Börzsöny Mts.* Can we distinguish geochronologically between older and younger parts of the High Börzsöny? The several hundred ka lifetime of a dome complex is realistic (cf. Davidson & de Silva 2000) and, as we presented, there are both petrographical and volcanological differences. However, the mean age errors overlap, and the Kolmogorov-Smirnov tests show that the two data populations are statistically not different, so further radiometric datings are necessary.

It is more certain that the *K/Ar ages support the view that volcanic activity did not finish in the Early Badenian.* It occurred more or less continuously and lasted up to the Badenian/Sarmatian boundary. We think that this duration of volcanic activity does not necessarily contradict the existence of the above-mentioned Lower and Middle Badenian cover sediments in the S and W Börzsöny. As we presented in point 3.3, the volcanic activity of both the S and High Börzsöny was characterized by lava dome extrusions. *Their effusive or low-explosivity eruptions at around 15–14 Ma, producing no widespread pyroclastics, may have allowed a coeval, non-volcanic shallow-marine sedimentation in the Badenian archipelago.*

6.2 Paleomagnetic measurements and their evaluation

The paleomagnetic results we are using in this synthesis come from different sources. A substantial amount of data were obtained in the sixties and finally published by Andó et al. (1977). Another set was measured in the late seventies and published by Balla & Márton (1978, 1980). In the latter papers, the earlier data were also tabulated and the interpretation of all the available data led to the following conclusions:

(1) The overall mean paleomagnetic direction (based on the site-mean directions) indicates that, at the time of volcanic activity, the Börzsöny Mts. were at the present latitude and in the same orientation as today.

(2) The Börzsöny Mts. are the product of brief volcanic activity that took place during three magnetic polarity intervals (normal–reverse–normal).

In recent years, systematic paleomagnetic studies of the ignimbrites of the Bükk Foreland, the area N of the Mátra Mts. and the Salgótarján Basin have revealed that rotations must have occurred in the named areas after the emplacement of ignimbrites (Márton & Márton 1995).

On the basis of volcanological and K/Ar radiometric considerations, the pumiceous volcaniclastic deposits in the Börzsöny, overlying the Karpatian-Lower Badenian sedimentary formations, have been assumed to belong to the Middle Rhyolite Tuff or Tar Dacite Tuff (more or less equivalent in age to the Upper Ignimbrite of the Bükk Foreland: Márton & Pécskay 1998). This volcanic complex exhibits about 30° counterclockwise (CCW) rotation. For this reason, and because K/Ar ages have been found inappropriate to define the exact beginning of volcanism, we performed additional paleomagnetic measurements on the volcaniclastic deposits (Kismaros and Kemence tuffs and Nagy Valley sandstone).

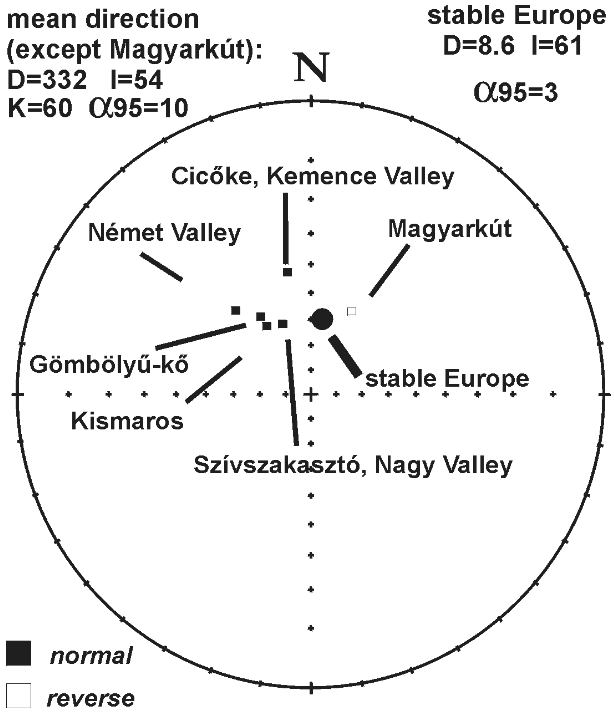

Fig. 11. New paleomagnetic site-mean directions with confidence circles for volcaniclastic rocks of the Börzsöny Mts. For localities, see Fig. 3. Coeval paleomagnetic direction in a stable European framework is shown for comparison. Stereographic projection.

Although the number of suitable new outcrops of the volcaniclastic deposits is limited, the results obtained on them are significant (Fig. 11). *All but one site exhibit moderately CCW rotated declinations with normal polarity.* These sites, along with previous data also showing CCW rotation and normal polarity, are indicated with red circle in the volcanological map (Fig. 3). One site (Magyarkút) is characterized by easternly declination and reversed polarity. The former rock group of sites is interpreted as deposited mostly subaqueously, but that of Magyarkút subaerially, thus the latter must be younger. This is supported by K/Ar dating (Table 2).

The new results call for the reconsideration of the earlier interpretation concerning conclusion (1): *the volcaniclastics were affected by a CCW rotation which necessarily postdates their deposition, so the rotation should occur before or during the emplacement of the subsequent massive andesitic rocks.* Indeed, some of the individual site means of massive rocks of the previous measurements possess westernly, while others have easternly declinations; declinations close to the present N also occur. The earlier treatment of data, that is the combination of all data (Balla & Márton 1980), averaged out the differences. This treatment implied that the differences in individual site mean directions are all due to secular variations of the Earth magnetic field, since there was no reason to split the data into different groups.

In both groups that have westernly and easternly declinations, there are sites with normal and with reversed polarity.

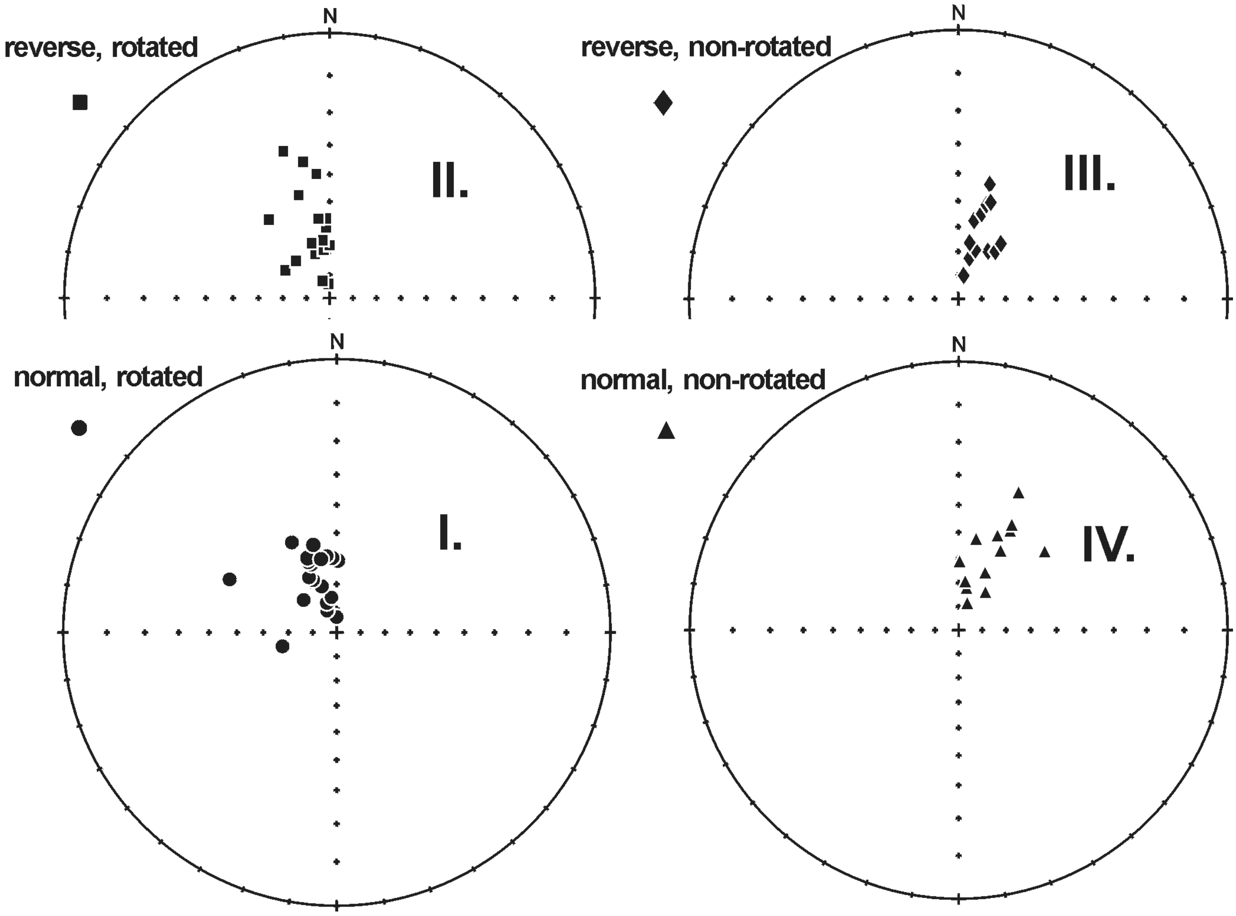

Fig. 12. Paleomagnetic groups in the Börzsöny Mts. (displaying all existing data) with CCW rotated declinations + normal polarity (I), CCW rotated declinations + reversed polarity (II), CW rotated declinations + reversed polarity (III) and CW rotated declinations + normal polarity (IV). Symbols as in Fig. 3. Stereographic projections.

Thus *four paleomagnetic groups can be defined* (Fig. 12): 1. CCW declination + normal polarity (including new results), 2. CCW declination + reversed polarity, 3. CW declination + reversed polarity, 4. CW declination + normal polarity. *Since the garnet-bearing subaqueous volcaniclastics overlying the Karpatian-Lower Badenian sedimentary deposits are definitely among the oldest volcanics, group 1 exhibiting CCW rotation + normal polarity must be the oldest.* What is more, group 1 also includes massive garnet-bearing dacitic rocks suggesting that this rock composition is indicative for age. *Groups 2, 3, 4 are proposed to be successively younger.* Although such a subdivision of the paleomagnetic directions may seem arbitrary, volcanology and K/Ar data broadly agree with the above succession of the volcanic formations.

Naturally, there are a few problematic sites. The problems, from the paleomagnetic side, arise from the fact that some of the magmatic bodies, for example narrow dykes and thin lava flows, may be the point readings of the magnetic field, thus their directions are influenced more by the secular variation of the Earth magnetic field than the post-cooling large-scale tectonic movement of the area itself. Another problem may be that the sampled site is not strictly in situ. Both mechanisms may be invoked to explain the paleomagnetic outliners in the W High Börzsöny, where apart from non-rotated samples, two earlier data suggested CCW rotation. "Repeated experiment", that is sampling and measuring four new sites in a limited area near Mt. Magyar (see Fig. 3), has shown that two of the sites exhibit no rotation, one is characterized by about 30° westernly declination, the last (this one with very poor statistical parameters) with easternly rotated declination: that is the average rotation is zero. Moreover, the last one has reversed polarity, while the others have normal polarity, indicating that *in this part of the Börzsöny, we have to calculate with a number of small fast-cooling magmatic bodies (lava flows),* each of them being point readings of the magnetic field rather than individually useful for tectonic interpretation.

Another problematic area is the Kemence Valley. Similarly to other N Börzsöny locations, the base of Cicőke locality (Fig. 3) shows a CCW rotation. This is in accordance with the pumiceous matrix of the proposed Kemence caldera wall and the 15.9 Ma K/Ar age of a caldera rim lava flow (see Fig. 4e and Table 2). On the other hand, we obtained a 12.5 Ma exceptionally young K/Ar age from an embedded andesite block at Cicőke and, in addition, some of the cover breccias and lava flows along the Kemence Valley are pyroxene andesites similar to the S-E High Börzsöny lavas. If the young age is right, it can only be explained by assuming an old caldera in the N that subsequently became buried by the High Börzsöny distal products; later on, the caldera rim could be exhumed by postvolcanic tectonism and normal erosion that have revealed the original structure again.

To summarize, the recently obtained and previously published paleomagnetic results suggest that *the older suites of the Börzsöny (group 1 and 2) were formed prior to the CCW rota-*

tion that affected the Middle Rhyolite Tuff Complex in the northern part of the Pannonian Basin. The rotation must have occurred during a reversed polarity interval (= end of group 2).

Prior to this reversed polarity zone, the CCW rotated sites of the Börzsöny Mts. are of normal polarity. What is their exact age? The Upper Ignimbrites of the Bükk Mts. (K/Ar ages 17.5–16.0 Ma), which are the products of more than one volcanic pulse (Szakács et al. 1998), are all reversely magnetized. Thus, they cannot be strictly of the same age as the initial volcaniclastics of the Börzsöny Mts. We think that the latter are younger and so must have formed during the dominantly normal polarity zone ending at 16 Ma (Fig. 13). The reversely magnetized paleomagnetic groups 2 and 3 may have erupted between ca. 16 and 14.5 Ma. The age of group 4 (with normal polarity) cannot be placed with certainty in any of the younger than 15 Ma polarity zones, thus the termination of the volcanism is more constrained by K/Ar than paleomagnetic data.

7. Summary: volcanic evolution and stratigraphy

The volcanic evolution and stratigraphy of the Börzsöny Mountains can be well established correlating volcanology, petrology and geochemistry with K/Ar and paleomagnetic results (Fig. 13). Whereas for the beginning of the eruptive activity, paleomagnetism could yield reliable information, the termination of volcanism could only be dated by the K/Ar method.

Products of the first volcanic stage, garnet-bearing predominantly dacitic rocks, were deposited in a shallow submarine environment ca. 16.5–16.0 Ma ago, as part of the Middle Rhyolite Tuff (Tar Dacite Tuff) of the Pannonian Basin. This stage was dominated (1) by explosive dacitic eruptions originating probably from a small number of silicic, medium-sized paleovolcanoes located in, and emerging from, the coeval archipelago, and (2) by shallow submarine lava-dome extrusions. As for the volcanic-sedimentary processes, resedimented syn-eruptive volcaniclastic mass-flow deposits, in part shallow submarine pyroclastic-flow deposits, have been identified. We propose to divide the resulting volcaniclastics into more proximal and more distal facies. The near-source origin of the former deposits (directly related to explosive eruptions) is suggested by (a) abundant lithic content, (b) dm-sized clasts showing frequent prismatic jointing, (c) a lag breccia occurrence and (d) quasi-radial flow directions (relative to supposed calderas) obtained from magnetic anisotropy measurements.

Later on, when the submarine basin gradually infilled, sedimentation became more complex resulting also in a small volume of subaerial ignimbrites and different genetic types of mostly subaerial debris-flow deposits. One type of the latter may have been related primarily to destructional processes resulting in small- to medium-sized calderas.

In the second stage (ca. 16.0–14.5 Ma based on paleomagnetism and K/Ar datings), lava dome formation was going on. During the first half of this period, a major ca. 30° CCW rotation event occurred. The commonly andesitic rocks formed at this stage have varied lithology, but do not contain garnet. At present, due to selective erosion, the more crystal-

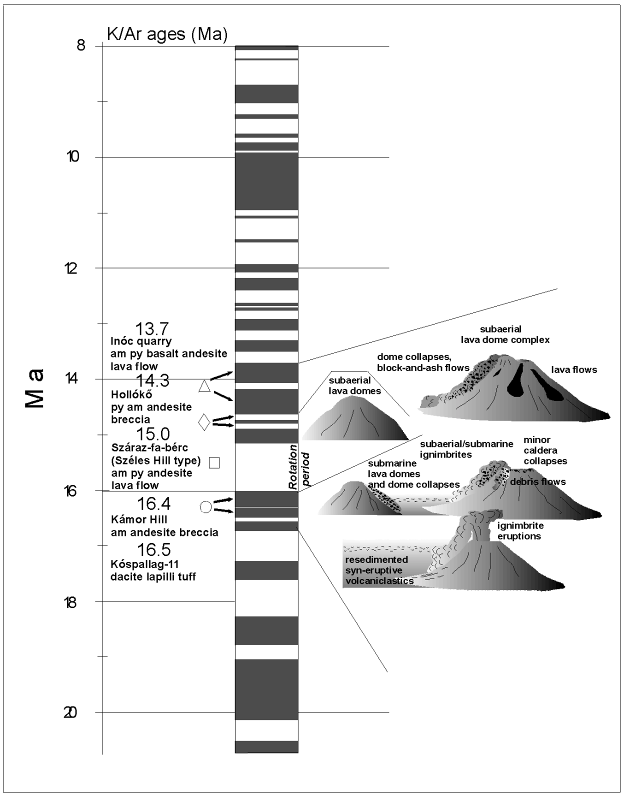

Fig. 13. Proposed stratigraphy of the volcanic activity of the Börzsöny Mts. with the magnetic polarity time scale (adopted from Cande & Kent 1995) displaying suggested positions of the four paleomagnetic groups in Fig. 12 (symbols the same as in Fig. 3), selected, representative K/Ar data and major volcanic events.

lized basal parts of lava domes are often exposed forming inverse morphology. The K/Ar age and paleomagnetic data of the Magyarkút ignimbrite exposure imply that explosive activity may have been rejuvenated and taken place on land. The source of this ignimbrite, due to limited ocurrence, is uncertain. A major, late event of the second stage was a hydrothermal polymetallic ore mineralization in the W that resulted in intense alteration of the coeval and older rocks.

The final, third stage was the build-up of the High Börzsöny andesitic edifice erupted during a normal polarity zone up to the Badenian/Sarmatian boundary (ca. 13.7 Ma based on K/Ar data). In fact, the reverse polarity of a single site at Mt. Magyar indicates that the normal polarity zone was interrupted by a reverse zone (see Fig. 13). The High Börzsöny volcano was a subaerial dome complex producing block-and-ash flows and lava flows probably from a few craters. At present, however, due to intense erosion, the exposed near-vent facies of collapsed domes are more common than real block-and-ash flow deposits. A proposed distinction between the older W and the younger S-E parts of the edifice is supported by volcanology, petrography and in part K/Ar geochronology. Mostly in the S and W Börzsöny, nonvolcanic marine sedimentation (that may have been continuous in places) was simultaneous with the final stage.

Due to tectonic movements and erosion, the majority of the original volcanic successions and primary landforms have degraded (Karátson 1995, 1997). Given their resistant texture, the massive rocks and breccias are those forming the majority of cover strata at present. The fine matrix of debris-flow and block-and-ash flow deposits prevents significant erosion, so they frequently form inverse morphology (Karátson 1999). In contrast, the massive rocks, especially the hydrothermally altered subvolcanic levels and the platy-jointed lava rocks, have experienced more intense weathering and frost shattering. The probable pyroclastic-fall deposits of the first stage, except for local accumulation pods, have been degraded.

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Appendix

Petrography of rocks from the Börzsöny Mts.

A) 1st stage: pumiceous volcaniclastics

Emphasizing the limits of petrography in classifying volcaniclastic rocks, 25 selected thin sections of pumiceous volcaniclastics are summarized below. Approximate rock compositions are shown in Fig. 3.

The rock texture is moderately to highly *clastic.* Mm-sized *pumices and pumice fragments* have a proportion up to 20–30 %. Their margins are not sharp, their shape is commonly irregular, isometric, subangular or subrounded. Pore size is constant. In some samples, the matrix also has a pumiceous character. *Lithics,* similar to pumices in size, include *porphyric andesite* and, rarely, *dacite* clasts. Groundmass of the lithics contains usually more than 50 % *glass.* Infrequently, holocrystalline rocks also occur. The crystals include, first of all, small, thin, sometimes oriented *plagioclases. Amphibole* (brown or green), sometimes with hypersthene and plagioclase transformation zone, is frequently opacitized. Typically large crystals of fresh *biotite* are also abundant, often adjoining fragments or phenocrysts of *garnet*. The latter mineral, that is found in ca. 1/2 of samples but due to large crystal size, the occurrence is naturally accidental, can be regarded common. *Hypersthen*e is more frequent than *augite* that is missing from many samples.

B) 1st and 2nd stage: massive rocks

A summary of 20 selected, representative thin sections is given below. Rock compositions are shown in Fig. 3.

The rock texture is *porphyric.* 1/3 of the samples have *microholocrystalline* groundmass (e.g. Nógrád Castle, Pap, Kis-Sas, Széles, Kopasz hills), the remaining 2/3 (e.g. Nagy-Pogány, Nagy-Sas, Ruzsás, Galla hills, Rustok saddle) has 5–80 % *glass* in the matrix. Crystal size, 1–2 mm in average, is predominatly uniform. Definite crystal orientation is limited (e.g. Széles Hill, Rustok saddle, E of Perőcsény quarry). Mineral assemblages and mineral distribution in the matrix vary to a great extent. The most abundant mineral is *plagioclase:* its single or compound crystals are cyclically zoned. Mostly opacitized, *amphibole (hornblende)* is also abundant; unaltered crystals occur mostly in garnet-bearing samples. Commonly unaltered *biotite* of significant quantity (10–30 %) is missing from only the Börzsönyliget and Széles Hill types. In turn, *augite* occurs in only these latter biotite-free types. *Hypersthene* is always associated with augite, but also occurs alone; it is missing from Nagy-Pogány and Pap hill types and also from some samples of the combined Nagy-Sas Hill group. Various *endogenic xenoliths* can be found, mostly in garnet-bearing rocks.

Representative thin section descriptions:

1st stage. *Bajdázó quarry:* garnet-bearing bi am δ (quartz-free; "dacite" classification based on geochemistry). Groundmass is microholocrystalline and contains apatite. Crystals of 2 mm in average size are relatively scattered. They include plagioclase (45 %), biotite (33 %), amphibole (22 %) and garnet (few crystals). Amphibole is opacitized (25 %). An endogenous xenolith with holocrystalline texture containing plagioclase and totally opacitized amphibole occurs.

2nd stage. *Kis-Sas Hill:* bi am α. Fine-grained groundmass contains ca. 70 % glass, frequent zeolithic vesicles and banded apatite. Moderately abundant crystals, 1 mm in average size, include plagioclase (60 %), opacitized amphibole and biotite (together 40 %).

C) 3rd stage: lava rocks and clasts from block-and-ash flow deposits of the High Börzsöny dome complex

Summary of 17 selected, representative thin sections is given below. Rock compositions are shown in Fig. 3.

The rock texture is *porphyric,* the groundmass contains 40–100 % glass, except for one sample (10 %). Abundant crystals have 1–2 mm average size. Some samples have two size populations. Roughly 1/2 of the samples shows strong crystal orientation. The most abundant mineral is *plagioclase,* then — mostly opacitized — *amphibole* (hornblende; more than 10 %). In the W High Börzsöny samples, except for one, amphibole content well exceeds pyroxene content and may equal plagioclase content. *Hypersthene* occurs in all samples but one; *augite* is missing from 1/2 of the samples. Hypersthene is frequent without augite in the W High Börzsöny, and occurs both alone and with augite in the E and S part. It is common that hypersthene has augite overgrowth. *Biotite* is present in only xenoliths in vent breccias of collapsed domes (W part: Mt. Hollókő, along with *garnet*; SE part: Vilma-pihenő rock tower). (The xenolith origin of the Hollókő biotite, however, is questionable and the rock type needs a more detailed study.) Garnet has also been found as xenolith in lava flows (Inóc quarry).

Representative thin section descriptions:

Mt. Kövirózsás S (W part, platy jointed lava flow): hyp am α. Groundmass is totally glassy and contains some large opaque minerals. Crystals, 1.5 mm in average size, are slightly oriented and include plagioclase (60 %) brown amphibole (25 %), and hypersthene (15 %).

Mt. Csóványos W (SE part, clast from proximal facies of block-and-ash flow deposit): am py α. Fine-grained groundmass contains ca. 70 % glass. Smaller crystals are densely, while larger (1 mm in average size) are rarely spaced. They are plagioclase (55 %), hypersthene (30 %), totally opacitized amphibole (10 %) and augite (5 %).