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Lithofacies associations of an emerging volcanoclastic apron in a Miocene volcanic complex: an example from the Börzsöny Mountains, Hungary

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Abstract Lithofacies associations of the first-stage volcanic activity of the Miocene Börzsöny Mountains, North Hungary, have been reconstructed in the light of detailed volcanological mapping, volcanic glass geochemistry and evaluation of palaeogeographic data. In the deeply eroded hilly area, near-vent primary and distal/reworked ring-plain volcanoclastics, preserved in a mosaical pattern, have been identified. Facies distribution reveals two probable facies continua: (a) a shallow-marine silicic explosive to resedimented volcanoclastic; and (b) a subaerial debris-flow to fluvial- and shallow-marine debris-flow/turbidite association. Facies characteristics and distribution allow us to (a) substantiate small-sized calderas, the eroded rims or proximal palaeoslopes of which have been preserved by volcanoclastic breccias (mostly debris-flow deposits); (b) reconstruct a well-developed volcanoclastic apron, spread mostly to the north and representing a south-to-north transport direction. Palaeogeographic interpretation of facies successions indicates a shallow-water initial explosive stage and a subsequent, rapidly evolving, emergent ring plain stage fed by different types of volcanoclastic debris flows.

Keywords Volcanic lithofacies associations · Explosive volcanism · Subaqueous pyroclastic flow · Volcanoclastic apron · Debris flow · Carpathians

Introduction

The Börzsöny Mountains situated in the central part of North Hungary are part of the Neogene to Pleistocene Inner Carpathian calc-alkaline volcanic chain (Fig. 1; e.g. Downes and Vaselli 1995). The Middle Miocene dacitic–andesitic volcanism of the region may have been due either to subduction or extensional regimes, or both (Balla 1981; Lexa and Konecny 1974), resulting from complex plate movements in the Tertiary (Szabó et al. 1992; Csontos 1995).

Although there have been many papers on the volcanic activity of the Börzsöny Mountains in general (e.g. Pantó 1970; Balla and Korpás 1980; Karátson 1995; Karátson et al. 2000), the related ore mineralisation (Csillag-Teplánszky et al. 1983; Korpás and Lang 1993) and timing of volcanism (Báldi and Kókay 1970; Korpás and Lang 1993; Karátson et al. 2000), no detailed research deciphering the complex depositional system from a modern volcanological viewpoint has been carried out.

In this paper, we focus on the most problematic initial, dominantly explosive dacitic volcanic activity of the Börzsöny which occurred in the coeval Lower Badenian archipelago (e.g. Báldi and Kókay 1970), a characteristic palaeoenvironment for the majority of calc-alkaline volcanoes of the northern Carpathian region (cf. Konečný and Lexa 1984). Studying the volcanoclastic successions of the first stage (in the sense of Karátson 1995 and Karátson et al. 2000), we describe many exposures, interpret thin sections, analyse the chemical composition of volcanic glasses in detail and re-evaluate previous results. Our main aim was to reconstruct the dominant initial volcanic-sedimentary processes of the Börzsöny which was widespread over the Carpathian volcanic arc in the Middle Miocene. Our objectives were threefold: (a) to define the pre-emergent depositional system of the shallow marine environment; (b) to define the possible emer-

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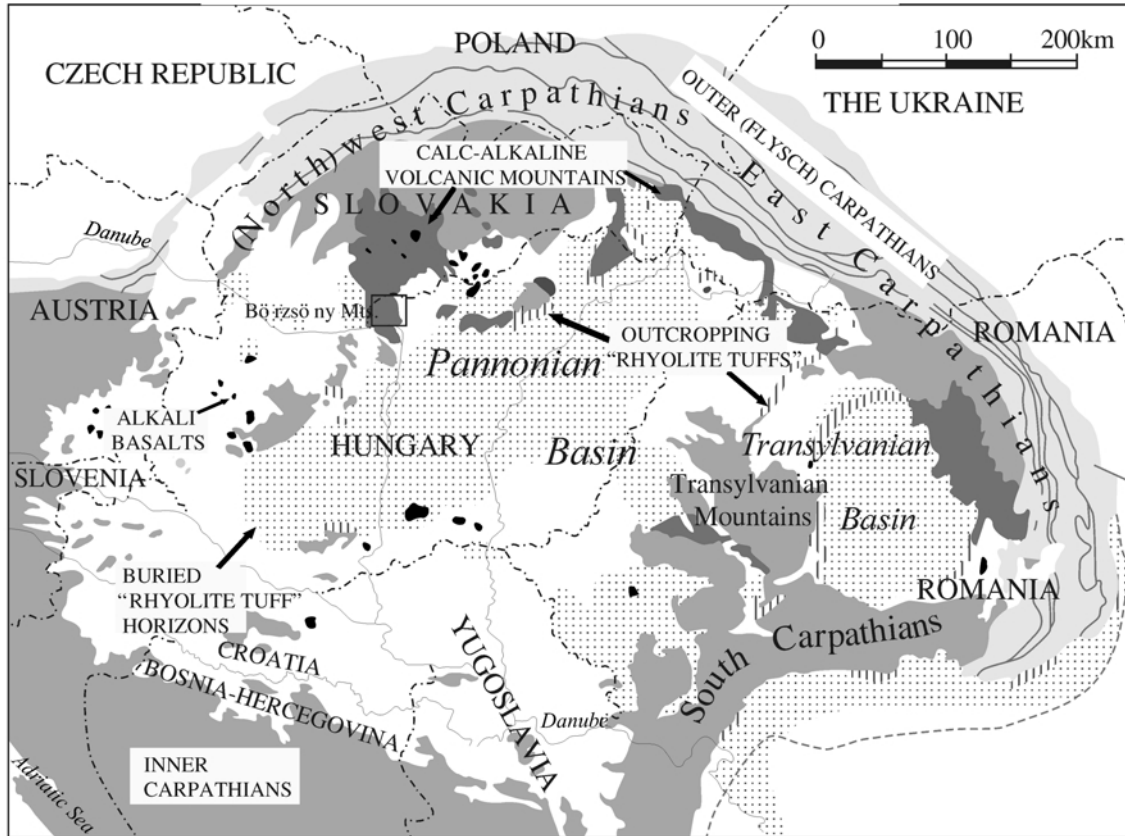


Fig. 1 Geologic setting of the Börzsöny Mountains

gent depositional system; and (c) to interpret the accumulation history in terms of edifice construction and destruction.

Geological setting and palaeogeography

The Börzsöny Mountains overlie a basement of double character: the crystalline Veporids (mostly in Slovakia) to the north and Mesozoic carbonates related to the Transdanubian Mountains (in Hungary) to the south. These rocks are covered by various sedimentary formations of Oligocene (sandstone, clay) and Lower to Middle Miocene age [“schlier” (fine-grained silt), sandstone, gravel; e.g. Korpás et al. 1998]. All these successions were deposited predominantly in normal marine littoral–sublittoral environments.

The direct prevolcanic gravel beds composed of quartzite, metamorphic and locally pumice pebbles (the latter originating from the initial explosive activity) also indicate a shallow marine environment. To the north, these beds reveal traces of rock borer clams and contain *Ostrea* fragments (Karátson et al. 2000). To the south, the initial volcanoclastics at Kismaros village are rich in mollusc fossils, indicating a 30- to 120-m-deep marine environment (Báldi and Kókay 1970; Borza 1973; Karátson et al. 2000). On the other

hand, Báldi and Kókay (1970) also reported fine tuff intercalations with leaf imprints, suggesting dry land in the near vicinity. All these palaeogeographic data, taking the obvious effects of sudden, voluminous, explosive eruptions into account, suggest a rapid volcanic infill, and thus a rapid change in the environment and the sedimentary system.

As the simplified geological map of the Börzsöny Mountains (Fig. 2) shows, the Middle Miocene (predominantly Badenian) volcanic rocks are grouped into three stages (Karátson 1995; Karátson et al. 2000). The deposits of the first stage (“Paleo-Börzsöny”) are widespread, and are found in the low (400–600 m a.s.l.), peripheral terrains; they include garnet-bearing biotite amphibole dacites interpreted as derived from more or less exposed lava domes, and pumice-rich to pumice poor, garnet-bearing dacitic volcanoclastic deposits ranging widely in grain size. The products of the second and third stage are mostly small lava domes and lava flows, among which the “High Börzsöny” dome complex (7–900 m a.s.l.) with its erosional depression is the most prominent (see Fig. 2). Whereas the evolution of the later stages from volcanological, petrographic and geochemical points of view has been clarified (Karátson et al. 2000), the origin of the first-stage volcanoclastic deposits, as well as the volcanic structure they relate to, have remained more obscure.

Traditionally, the pumiceous volcanic successions of the Pannonian Basin were divided into the “lower”,

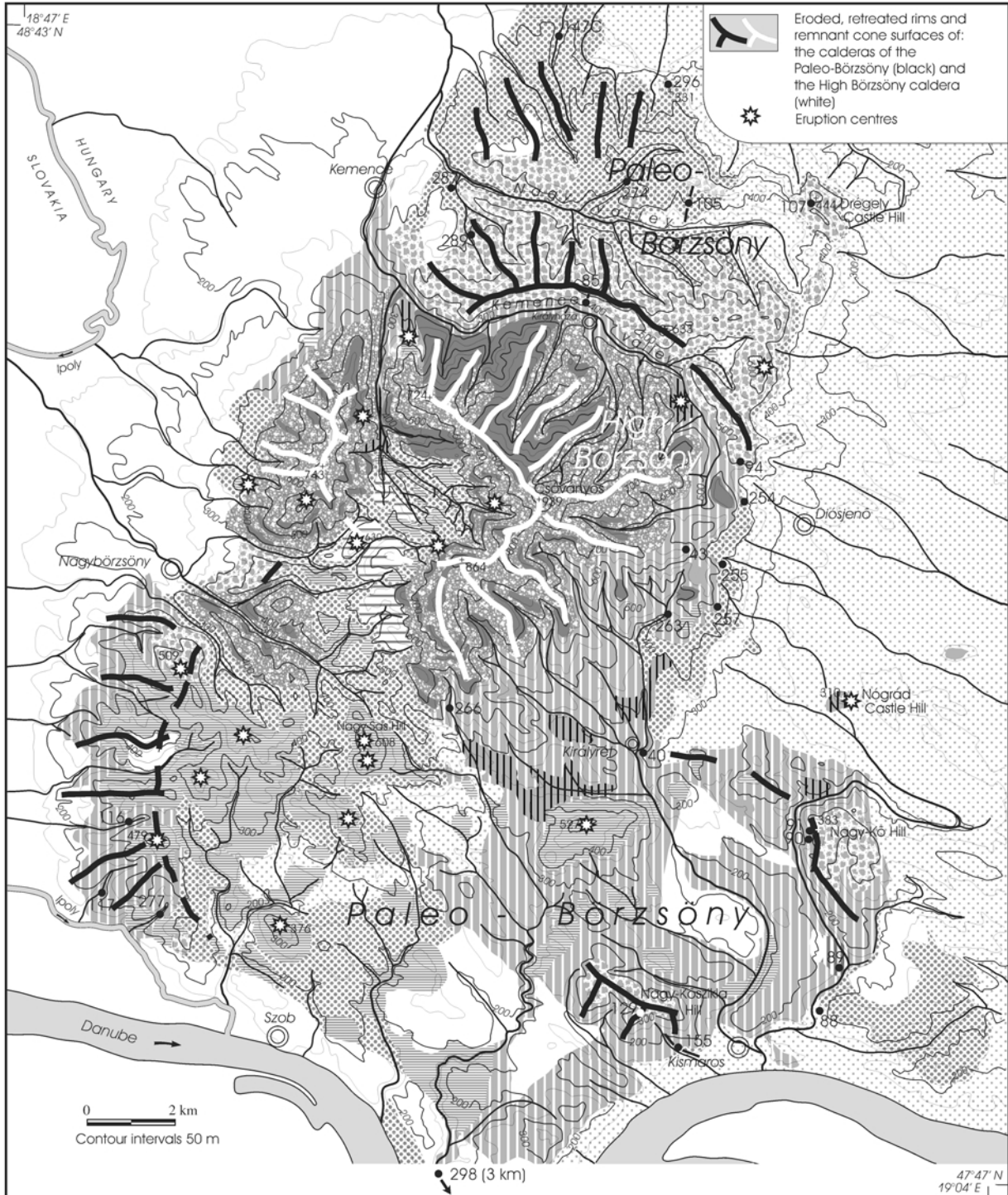


Fig. 2 Geologic sketch map of the Börzsöny Mountains (simplified after Karátson et al. 2000) displaying localities appearing in the text. Contour lines 50 m

“middle” and “upper” rhyolite tuff horizons (Noszky 1930), having average ages of 19, 16.5 and 13 Ma (Hármor et al. 1987). Whereas the “lower” and “upper” tuffs are mostly rhyolitic (cf. Póka 1988), the middle counterpart is dacitic and was named Tar Dacite Tuff (Hármor 1985). The dominant view until recently was that the volcanism of the Börzsöny started at around 15 Ma (e.g. Korpás and Lang 1993), and there are only isolated occurrences of the “middle” tuff in boreholes (e.g. Hont village); however, Karátson et al. (2000) showed that the majority of the first-stage volcanic products were deposited in the Early Badenian, ca. 16.5–16.0 Ma ago, chronologically correlating to the middle tuff. Nevertheless, the few modern geochemical data available have not allowed a larger-scale comparison thus far. On the other hand, the interpretation of the volcanic structure of the first stage has also remained tentative. While Balla and Korpás (1980) and Korpás and Lang (1993) proposed a large number (5–8) of single and overlapping calderas, Karátson (1995) argued for a maximum of three caldera rim segments belonging either to a few smaller or a single compound caldera. The reason for the uncertainty lies partly in the post-tectonic effects (e.g. Czákó and Nagy 1976) that have masked both possible caldera morphology and gravimetry, and partly in the subordinate occurrences of caldera-related deposits, such as lag breccias, mesobreccias and welded or ponded ignimbrites. Given these complications, Karátson et al. (2000) interpreted the reconstructed caldera rims as retreated, eroded topographic margins protected from significant erosion by covering, distal, resedimented breccias related in part to caldera formation. We have tried to clarify the relationship between the proposed caldera rims and the pumiceous volcanoclastic lithofacies associations by collecting detailed field data.

First-stage volcanoclastic successions of the Börzsöny Mountains

Terminology

The ring-plain system is a volcanoclastic apron that consists mostly of resedimented pyroclastics as debris-flow, debris-avalanche and occasionally fluvial deposits that form related lithostratigraphic units (e.g. Cronin and Neall 1997). Ring-plain accumulation occurs during both constructional and destructional phases (e.g. Cas and Wright 1987; Cronin and Neall 1997).

The terms non-welded, pyroclast-rich, submarine mass-flow, probably pyroclastic-flow deposits are used where a shallow subaqueous origin of pyroclast-

dominantly pumice-) bearing mass flow-deposited sediments is relatively well-supported by the fossils and by facies relations to shallow-marine siliciclastic deposits. This conforms to the suggestion of McPhie et al. (1993).

We use the term volcanogenic sand(stone) for fine-grained volcanoclastic sediments where the pyroclastic origin is not well established or supported, due to low content of pumice fragments and high content of volcanic lithic and siliciclastic grains in the beds. This term is chosen to point out the difference between shallow subaqueous deposits related to explosive activity and more distal, more epiclastic products (cf. McPhie et al. 1993).

Volcanoclastic debris flows or lahars are defined as rapidly flowing mixtures of rock debris and more or less muddy water (other than stream flow) from a volcano (e.g. Smith and Lowe 1991). Debris flows are non-Newtonian fluids with high yield strength produced by sediment concentrations much greater than those of stream flows (Pierson and Costa 1987; Costa 1988). Although deposits of debris flows are thought to aggrade progressively (Major and Iverson 1999; Vallance 2000), cross-bedding or horizontal stratification are missing (Smith 1986). The deposits are poorly sorted and composed of particles ranging from clay to large boulder size and showing minor imbrication. Both clast-supported and matrix-supported framework occur, but the former is less frequent (Smith 1986). They are commonly non-graded, with sharp but rarely erosive contacts (Fisher 1971; McPhie et al. 1993). In contrast, inverse to normal grading has been reported from lahar deposits of the Ellensburg Formation, Washington (Schmincke 1967).

Hyperconcentrated stream flows or flood flows contain sediment concentrations intermediate between debris flow and stream flow (Beverage and Culbertson 1964; Smith 1986; Pierson and Costa 1987). Typically clast-supported deposits of hyperconcentrated stream flows are commonly poorly to moderately sorted, composed of horizontal strata, often displaying normal grading. Clast imbrication, if any, is less developed than in stream-flow deposits (Smith 1986). Both debris flow and hyperconcentrated stream flow can occur in a single event at different time and space (e.g. Pierson and Scott 1985; Pierson et al. 1990; Cronin et al. 1997; Lecointre et al. 1998; Cronin et al. 1999).

Debris avalanches are defined as rapid gravity-driven mass flows containing a large volume of incoherent material of unsorted rock and sediment independent of interstitial fluid (e.g. Schuster and Crandell 1984). Debris avalanche deposits may contain both debris derived from the source area and debris eroded during flow, although debris flows and hyperconcentrated stream flows may also have this property (Crandell et al. 1984; Palmer and Neall 1989; Palmer and Walton 1990; Glicken 1991; Palmer and Neall 1991). Volcanic debris-avalanche deposits are commonly non-graded and very poorly sorted, with angular-sub-

angular clasts ranging in grain size from a few centimetres to several tens of metres or larger (Ui 1983; Siebert 1984; McPhie et al. 1993). They often display features characteristic of hydrothermal alteration and contain jigsaw-fit and/or prismatically jointed blocks (e.g. Ruapehu: Turoa diamicton; Lecointre et al. 1998). Syn-eruptive volcanic debris-avalanche deposits may include a small proportion of juvenile magmatic clasts, but these are difficult to distinguish from other volcanic lithics (McPhie et al. 1993).

In the absence of primary deposit morphology, it may be difficult to distinguish between deposits of volcanic debris avalanches and debris flows (lahars). The textural characteristics of these two types of deposits may overlap and, especially in ancient formations, can be very similar. Further complication arises from the fact that subsequent to explosive eruptions, pumiceous material may mix with debris to various extent (e.g. Pierson et al. 1996; Thouret et al. 1998). In this paper, we interpret a debris-flow deposit as having originated from debris avalanche if it exhibits a large number of jigsaw-fit structures on centimetre and even millimetre scale, has no sorting at all, and shows no internal sedimentary features. Where slightly graded character, weak internal stratification and occasionally pumiceous matrix were found, pumiceous pyroclastic-flow-initiated or pyroclastic-flow-related debris-flow/lahar origin has been interpreted. On the other hand, in most cases it is extremely difficult to distinguish between deposits of subaerial and subaqueous (e.g. fan-delta) debris-flow deposits. The interpretation at the current level and exposure conditions in the Börzsöny Mountains has only been supported by larger-scale lithofacies relations.

Our study is based on 26 actual and composite sections in the northern, eastern, southern and southwestern sector of the Börzsöny Mountains (Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12; selected photomicrographs of thin sections in Fig. 13; for locality, see Fig. 2). The reason for making composite logs was the relative lack of large and well-exposed outcrops (typical of the region under temperate continental climate). These logs were produced by careful mapping of valley bottoms up to the top of hillsides. Detailed facies analysis is based on the mapped areas and bed-by-bed descriptions of key outcrops. According to textural and compositional characteristics, the studied deposits are grouped into different lithofacies, which are described below.

Pre-emergent stage

P1., S: Non-volcanic sand(stone), mud(stone) and gravel beds, localities 88, 105, 155, 254 (Figs. 3, 4)

These deposits (Egyházasgerge Formation and Nagyoroszi Pebble; Korpás et al. 1998) directly underlie and are sometimes intercalated with the initial volcanic products. They consist of well-sorted quartzofeldspatic

sand and aleurite, occasionally with biotite and amphibole crystals. Stratified and wavy beds are common. Intercalated, stratified or cross-stratified gravel beds include quartzite, metamorphic, metasedimentary, carbonate, andesite and pumice pebbles (the latter two, up to 5 cm in size, make up 5–8% of the deposit by volume). Mollusc and *Ostrea* fossils are common.

Interpretation The well-sorted siliciclastic deposits reflect a dominantly non-volcanic sedimentation in a shallow-marine basin, where substantial sediment influx occurred. Thick sequences of the North Börzsöny interpreted as submarine fan deltas (Korpás et al. 1998) may represent a southeastern prograding sediment infill, which was most likely influenced by the early volcanism since the deposit contains a significant amount of volcanic clasts. The source of the volcanics is uncertain, because the limited maximum size of andesite and pumice pebbles allows not only a local but also a neighbouring origin, in accordance with the widespread areal distribution of the “middle tuff” eruptions of the Pannonian Basin.

P2., PBLT: Pumiceous, block bearing, bedded dacite/rhyodacite lapilli tuff, localities 40, 43, 85, 90, 91, 116, 117, 129, 155, 255, 266, 277 (Figs. 5, 6, 7, 8)

This unit is probably the most widespread (80–100 km²) and comprises unsorted or moderately sorted deposits with fine-grained matrix (<40–60 vol.%) and lapilli- and block-sized pumice and lithic clasts. Pumice clasts are yellowish white to whitish grey, centimetre-sized (up to 15 cm), subangular and subrounded and contain millimetre-sized biotite and quartz phenocrysts. Lithic clasts are brown to dark grey, commonly oxidised, altered, millimetre to centimetre sized (up to 30 cm), subangular and angular and contain amphibole, pyroxene and less frequently biotite phenocrysts. Block-sized lithic clasts with prismatic jointing may occur. The matrix contains abundant millimetre-to-centimetre-sized lithic and pumice clasts and, less frequently, crystal fragments. Garnet phenocrysts are common. The deposit has two facies: massive (e.g. 40, 117, 155, 266) and stratified (e.g. 40, 43, 85, 116, 129, 155); the latter is composed of thin alternating layers of fine ash or volcanogenic sand and pumice (fragment)-rich tuff. In some of the massive beds, up to 2-m-thick flow units with normally graded lithics and reversely graded pumices occur (90, 91, 155, 257; e.g. Fig. 7, 8). At locality 255 there occurs an underlying, undulating volcanogenic sandstone bed rich in centimetre-sized mollusc fossils; in the South Börzsöny, at locality 155 (Kismaros), intercalated mollusc-bearing fine-grained marine volcanoclastic deposits were reported by Báldi and Kóckay (1970).

Interpretation The large number of relatively fresh, stretched pumice fragments both on millimetre and

Fig. 3 Detailed lithological log of 105 locality (Szívskasztó, Nagy Valley). See text for facies symbols

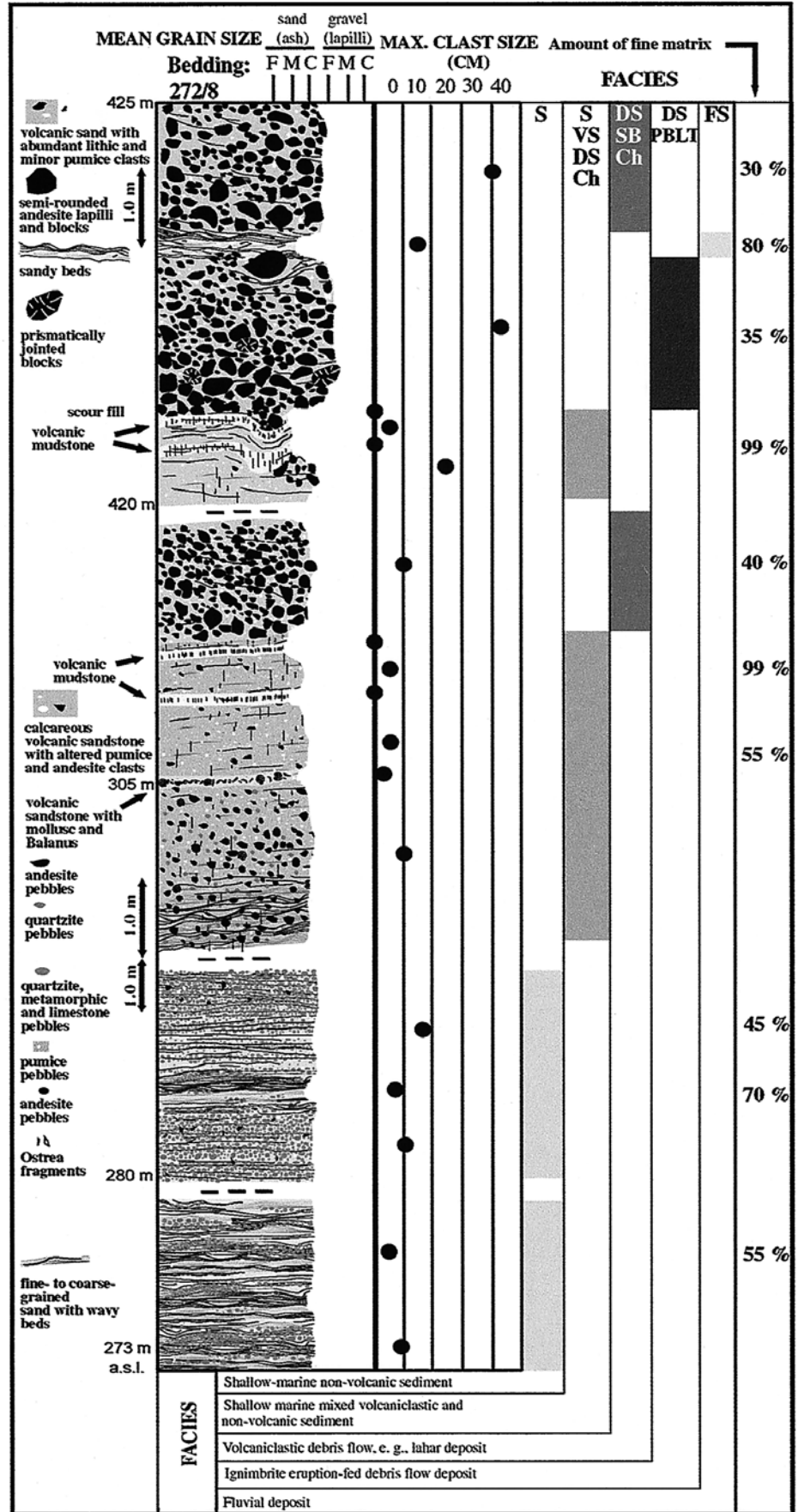
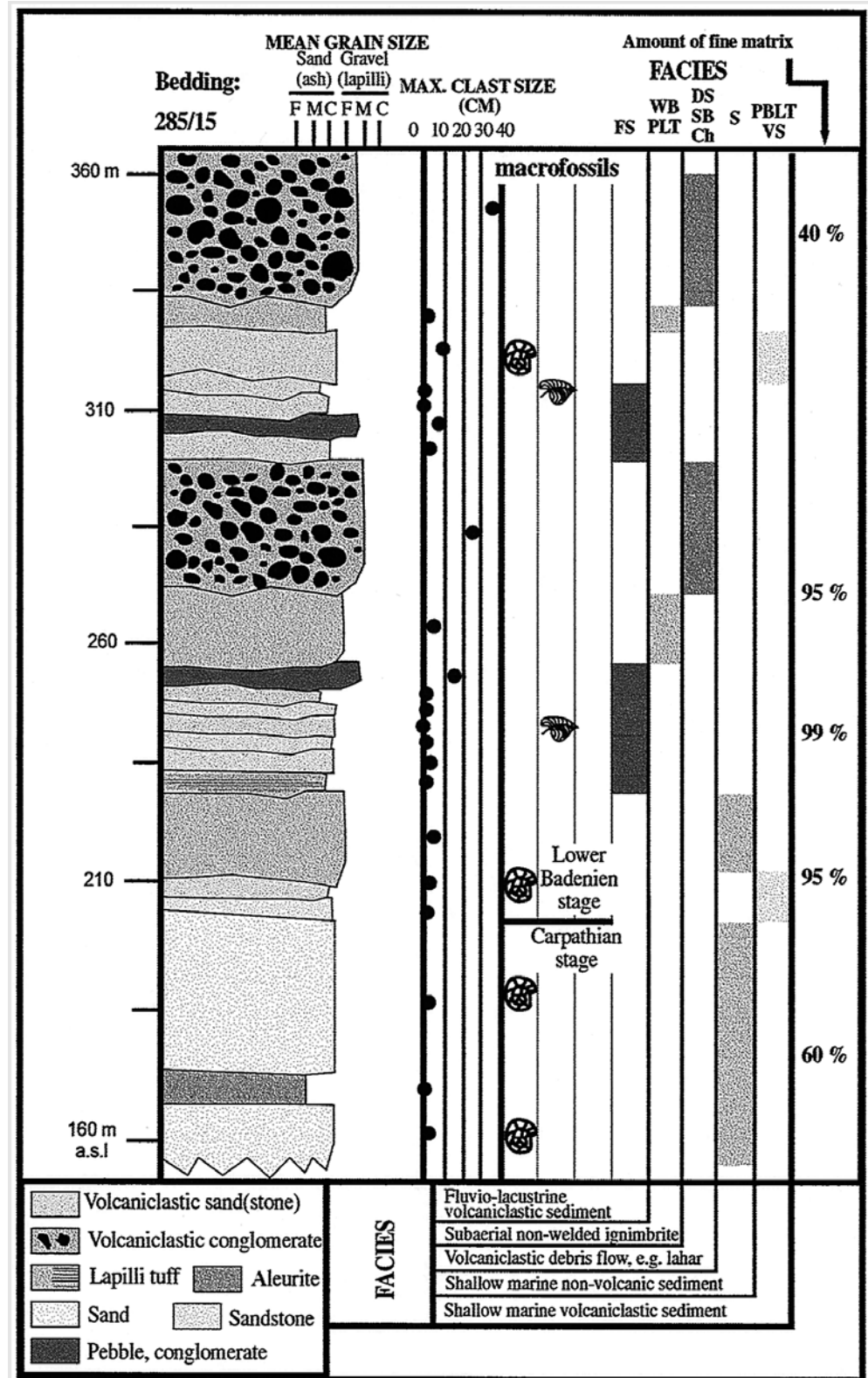


Fig. 4 Composite sketch log of 155 locality west of the village of Kismaros (after Báldi and Kókay 1970, strongly modified and completed). See text for facies symbols



centimetre scale suggests that these deposits must have been directly related to silicic eruptive centre(s). The unsorted and commonly massive structure of individual units reflects deposition from mass flows, probably debris flows and/or high-concentration turbidity

currents fed by explosive eruptions. Since there is no clear evidence of welding or any hot emplacement, however, it is very difficult or probably impossible to distinguish between primary pyroclastic-flow deposits and their diluted counterparts in a slightly distal stage,



Fig. 5 Detail of 40 locality (Királyrét): stratified, pumice-rich, resedimented syn-eruptive volcanoclastics

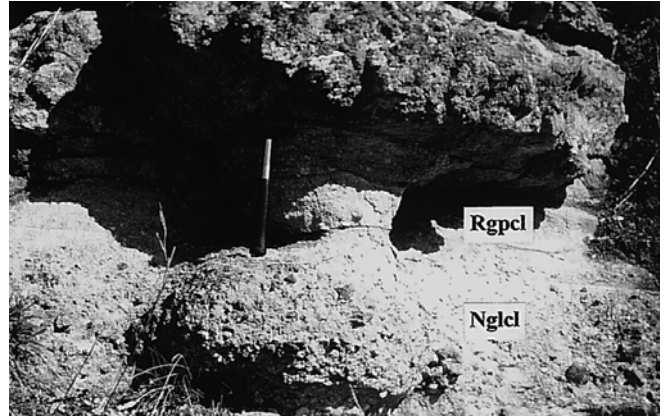


Fig. 7 Close view of the resedimented pumiceous mass-flow deposit in Fig. 6. Normally graded lithic clasts (*Ngcl*) and reversely graded pumice clasts (*Rgpcl*) suggest a flow unit. Note the intense erosion of less resistant pumice-rich horizon (with hammer)

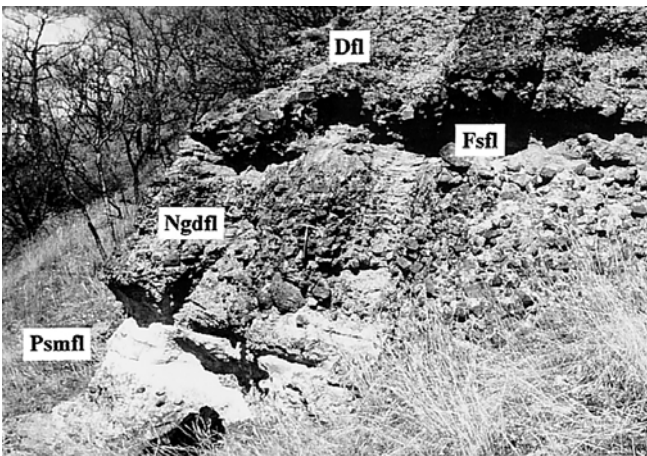


Fig. 6 The Nagy-Kő-Hill eroded, retreated caldera rim (upper part of 91 locality) has been preserved from intense erosion by volcanoclastic debris-flow deposits. *Psmfl* resedimented pumiceous mass-flow deposit; *Ngdfl* flow unit of normally graded debris-flow deposit; *Fssl* interlayered fluvial streamflow bed; *Dfl* slightly graded debris-flow deposit

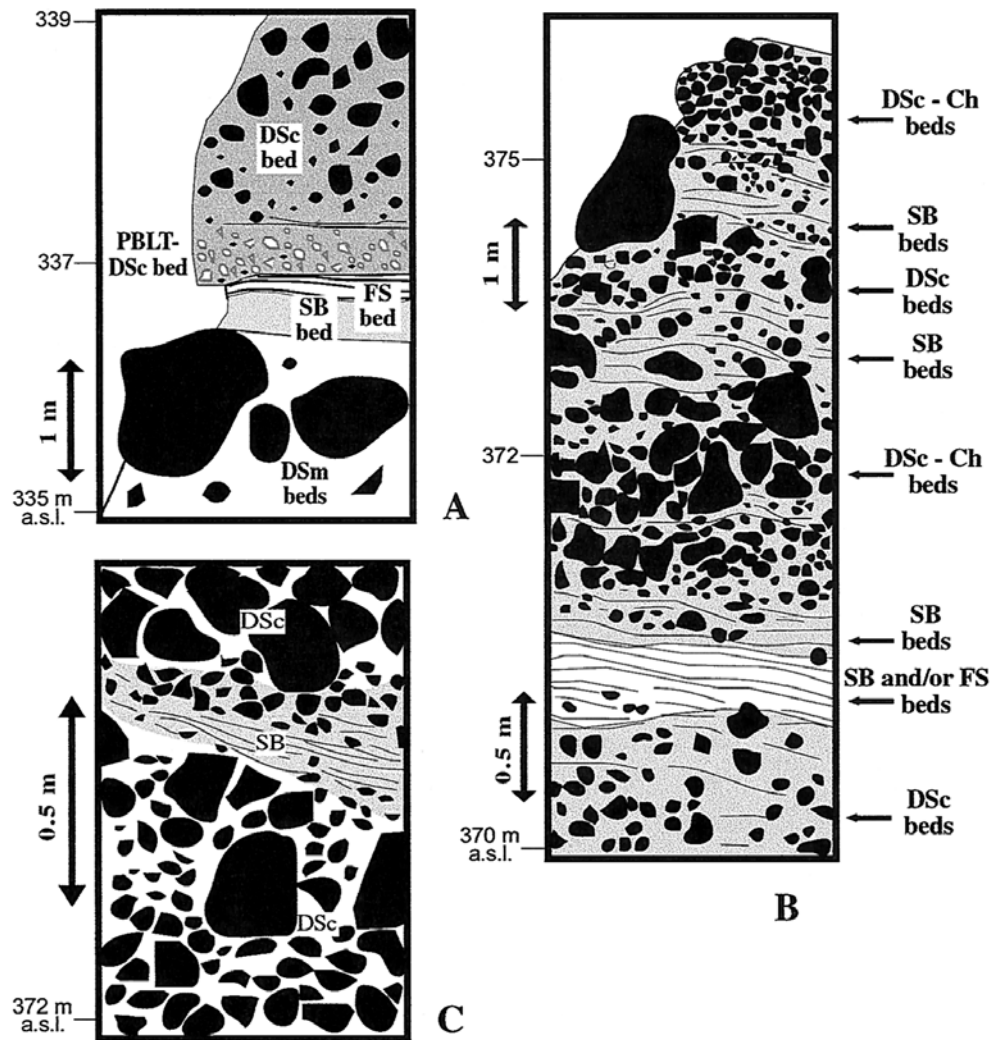
a problem which has been widely addressed recently (e.g. Cas and Wright 1991; Cole and DeCelles 1991; Fritz and Howells 1991; White 2000; Martin and White 2001). The marine fossiliferous sediments, occasionally underlying and interceding with this lithofacies, suggest that this lapilli tuff most likely deposited in subaqueous conditions. Overall, our proposed classification non-welded, pyroclast-rich, submarine mass-flow, probably pyroclastic-flow deposit, corresponds to the term used by McPhie et al. (1993) for deposits where subaqueous and primary (or syn-volcanic) origin is well established.

P3., VS: Volcanogenic, bedded, pumiceous sand, sandstone and gravel, localities 40, 43, 90, 91, 105, 129, 147 C, 155, 255, 264, 287, 296 (Figs. 3, 4, 10, 12)

These are moderately or well-sorted deposits (collectively called Nagy Valley Volcanogenic Sandstone by Karátson et al. 2000) with a dominant fine matrix (<60–80 vol.%) and occasionally lapilli-sized lithic and pumice clasts. Yellowish white to yellow, millimetre-to-centimetre-sized (up to 3 cm), altered, subrounded to rounded pumices with poorly developed texture, make up to 25 vol.% of the deposits. Varicoloured, commonly oxidised, altered subangular and subrounded, millimetre-to-centimetre-sized lithics (up to 5 cm) contain amphibole, pyroxene and less frequently biotite phenocrysts. Quartz pebbles in the North and East Börzsöny are common. Mollusc fossils may occur (localities 105, 155, 255). The deposit exhibits stratification, minor cross-stratification and occasional gradation on a centimetre-to-decimetres scale.

Interpretation The frequent features characteristic of traction transport such as bedding, stratification, low-angle cross-stratification, good sorting as well as rhythmic fine/coarse units suggest deposition from dilute volcanoclastic mass flows in a subaqueous environment. The shallow marine origin is supported by interbedded, fossiliferous volcanogenic sandstone and mudstone as well as fossiliferous character of the lithofacies itself; however, it is hard to reconstruct whether the deposits were directly developed from dilution of eruption-fed volcanoclastic mass flows or reworking of volcanoclastic mass flows during inter-eruption periods. The highly variable pumice content in the deposits as well as the presence of both angular and rounded pumice fragments suggest both direct eruption-related origin and true epiclastic reworking.

Fig. 8A–D Interpretative sketches from the Nagy-Kő Hill caldera rim (90, 91 localities). *Black* andesite/dacite clasts; *white* pumice clasts. **A** Lower part of 90; **B** upper part of 91; **C** detail of the upper part of 91. See text for facies symbols. **D** photo of **B**



Most likely, there was a continuum between these end members as pointed out by several workers (Fritz and Howells 1991; Cole and DeCelles 1991; Cas and Wright 1991). The deposit can be named, according to McPhie et al. (1993), as (reworked?) subaqueous volcanoclastic mass-flow deposit. The relevant mass flows may have been low-density volcanoclastic turbidity currents.

Emergent stage

E1., WB-PLT: Pumiceous, lithic-rich, weakly bedded rhyodacite/dacite lapilli tuff, localities 40, 89, 90, 91, 117(?), 155 (upper part, reported by Báldi and Kókay (1970) (Fig. 5)

Limited mostly to the upper sections of a few exposures, this is an unsorted or moderately sorted deposit with a fine matrix (<40–50 vol.%). White to whitish grey centimetre-sized (up to 12 cm) pumices are dominantly angular and subangular and contain millimetre-

sized biotite and quartz phenocrysts. Brownish to greyish, altered, millimetre-to-centimetre-sized lithic fragments (up to 40 cm) are subangular and angular and contain amphibole, pyroxene and, less frequently, biotite phenocrysts. Block-sized clasts with frequent prismatic jointing may occur. The matrix is rich in pumice-, lithic and, less frequently, crystal fragments including garnet. Stratification is not observed, but, except for 89, weak gradation may occur. At locality 40 (Királyrét), a 1.5-m-thick volcanoclastic breccia which consists of subangular to angular, predominantly cogenetic biotite amphibole dacite clasts up to 30 cm in size is embedded in the deposit.

Interpretation This deposit significantly differs from the previous ones. It does not contain fossils and has thicker beds. These features are characteristic of sub-aerially emplaced, loose, non-welded pyroclastic-flow deposits. The large number of angular pumice clasts fits with the primary origin. In addition, on a millimetre-to-centimetre scale, the deposit shows little signs of hydrothermal alteration, corresponding to subaerial



Fig. 8D

emplacement where hydrothermal alteration is limited, compared with subaqueously emplaced deposits. At the same time, since there are no gas segregation pipes, nor welding, the interpretation is somewhat ambiguous. Subaqueous deposits which are direct products of silicic ignimbrite-forming eruptions may not be distinguished from subaerial ones. Several workers pointed out that water even few tens of metres deep (that depth was reconstructed for the Börzsöny Mountains: Báldi and Kókay 1970; Karátson et al. 2000) can easily be flashed out by an emplacing pyroclastic mass flow (e.g. Cas and Wright 1991; Legros and Druitt 2000). However, in the Börzsöny Mountains, the WB–PLT deposits do not intercalate with marine units nor do they contain fossils; hence, the interpretation that they were deposited from subaerial pyroclastic flows appears to be most likely. This is in accordance with the Királyrét volcanoclastic breccia which is interpreted as a lag breccia.

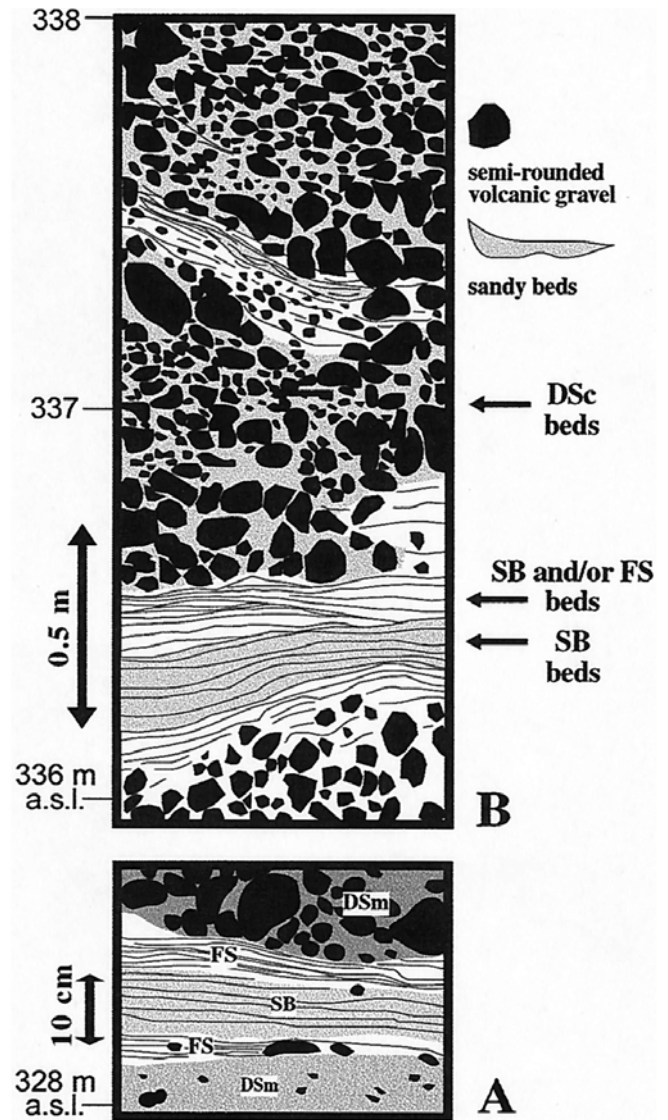


Fig. 9A,B Interpretative sketches from Nagy-Kőszikla Hill (129 locality). **A** Detail of the lower part; **B** upper part. See text for facies symbols

E2., DS: Diamicton sheet, volcanoclastic breccia, localities 85, 90, 91, 94, 105, 107, 129, 147 C, 183, 274, 287, 298, etc. (Figs. 3, 4, 6, 7, 8, 9)

This lithofacies is a widespread, well-exposed breccia (Nagy-Kő Hill Volcanoclastic Breccia; Karátson et al. 2000) in the Börzsöny Mountains. It blankets the higher-elevated marginal areas and their broad vicinity, covering as much as 60 km² in the northern and southeastern sectors. Beds are tabular or lobate with convex upper surfaces. Complete vertical sequences are not known, but various types can be studied in many outcrops (the listed localities indicate the best exposures). The described occurrences are up to a few tens of metres high and extend a few hundreds of

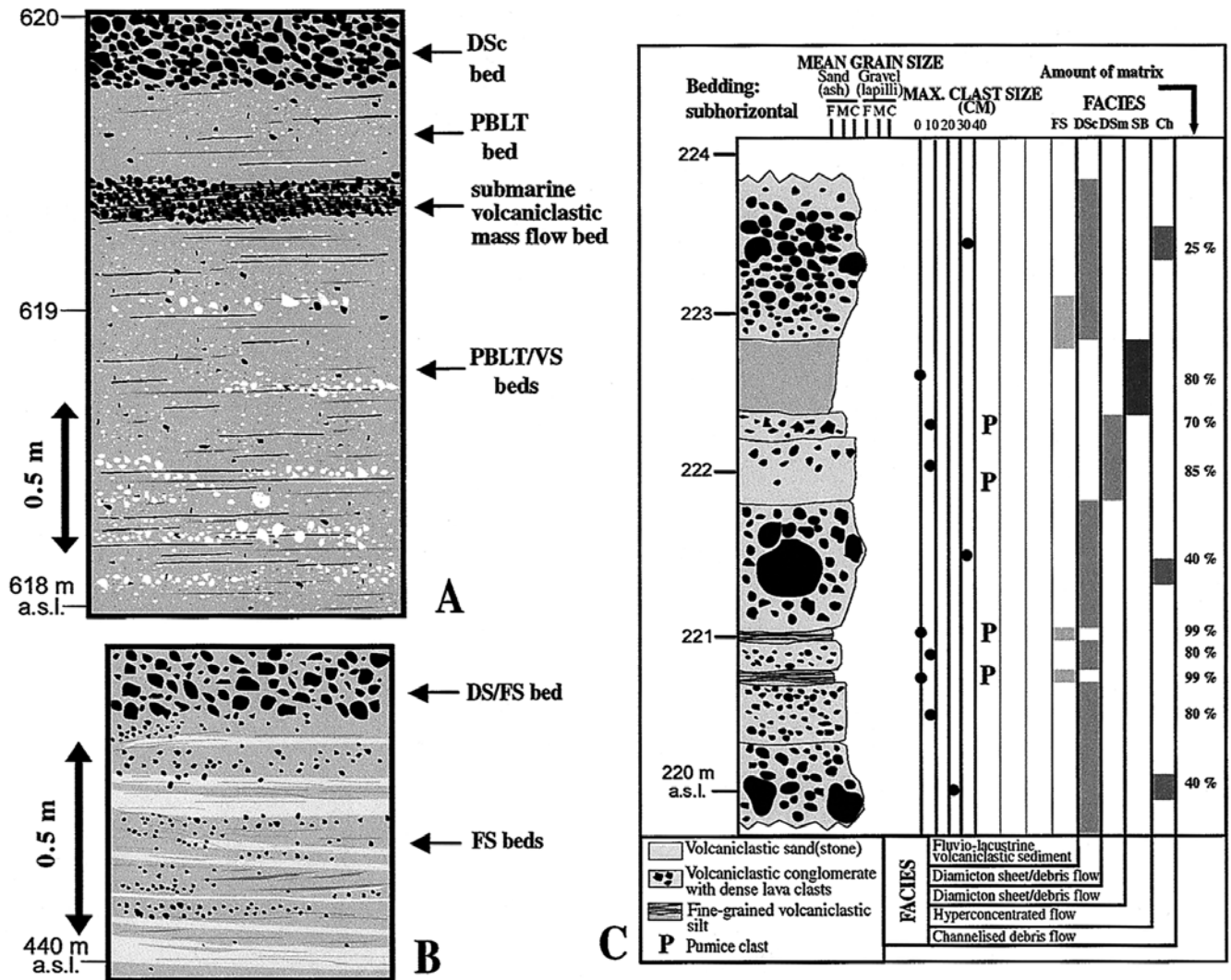


Fig. 10A–C Exposures from the North and East Börzsöny Mountains showing facies variations of Nagy Valley volcanogenic sandstone. *Black* andesite clasts; *white* pumice clasts. **A** Interpretative sketch of Hosszú-bérc hillslope quarry (43 locality); **B** interpretative sketch of Drégely Castle Hill (upper part, detail: 107 locality); **C** composite sketch log of Német Valley stream bed (147 C locality). See text for facies symbols

metres laterally. They contain commonly subrounded and subangular, less frequently angular, dense andesite and subordinate dacite lapilli and decimetre- and millimetre-sized blocks. Hydrothermally altered dense volcanic lithic clasts are found in some cases, forming jigsaw-fit structures on a millimetre-to-centimetre scale, and the matrix is rich in free, broken minerals, mainly feldspars and amphibole. In the matrix, small, subrounded, strongly altered pumice fragments may be present. Reverse and less frequently normal gradation of lithic clasts in 5- to 10-m-thick beds are common. Dense channel fills and sandy bedforms (see below) are frequently intercalated. In many places, two major sublithofacies of DS beds are distinguished:

1. DS_m is a matrix-supported lithofacies with subrounded to subangular dense megablocks up to 3 m in diameter (localities 85, 90, 91, 298). The matrix does not display any internal stratification. In certain beds there are common (up to 10–20 vol.% visual estimation) small, rounded and subrounded pumice clasts up to a few centimetres in diameter (localities 85, 129). The large blocks do not have an oriented distribution in the overall DS_m; instead, they float in the fine-to-coarse-grained sandy matrix.
2. The DS_c lithofacies is a more clast-rich (clast-supported), slightly better sorted, occasionally weakly bedded and graded member of the DS units (e.g. localities 85, 90, 91, 105, 129). The matrix of these beds does not or only occasionally contains pumice fragments.

Interpretation The DS lithofacies displays features typical of debris-flow deposits: poor sorting, lack of stratification, graded to non-graded beds with erosive contacts in some places and tabular beds without erosive contact in other places (Nemec and Steel 1984;



Fig. 11 Detail of the 298 locality: basal zone of a small-scale debris avalanche with angular blocks and abundant varicoloured, altered lapilli in the matrix. Note lack of stratification

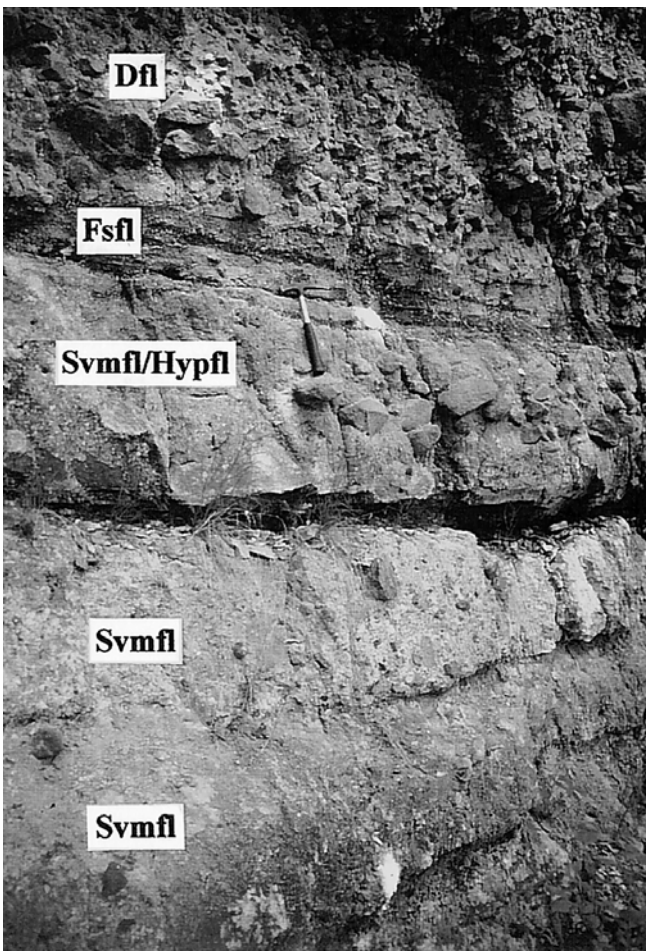


Fig. 12 Submarine volcaniclastic mass-flow beds (*Svmfl*) and subsequent hyperconcentrated-flow (*Hypfl*), fluvial stream flow (*Fsfl*) and debris-flow (*Dfl*) deposits at 287 locality near the Nagy Valley

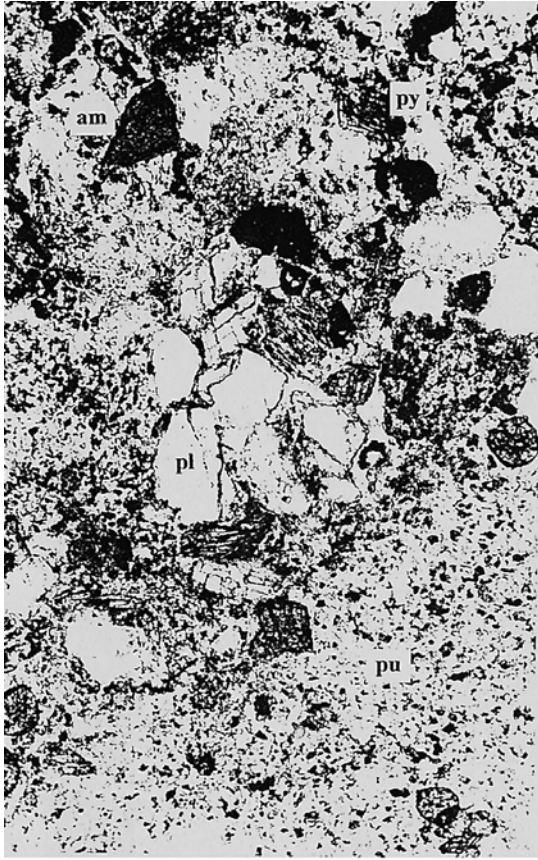
Smith 1988; Walton and Palmer 1988; Palmer and Neal 1991; Cronin et al. 1997; Lecointre et al. 1998). Thickness of beds and large clasts indicate deposition from large, high-competence debris flows.

The common association of such deposits is a distal (re)deposition of pyroclastic-flow material by debris flows that are generated on a broad, terrestrial ring plain around a large silicic eruptive centre during mostly inter-eruptive periods. Pumice-rich DS_m beds suggest direct or indirect relations to ignimbrite-forming eruptions, where either diluting pyroclastic flows are transformed into debris flows, or pyroclastic-flow deposits are subsequently mobilized into debris-flow then hyperconcentrated stream-flow systems in valleys that drain the volcano slopes (Pierson et al. 1996; Major and Iverson 1999; Cronin et al. 2000).

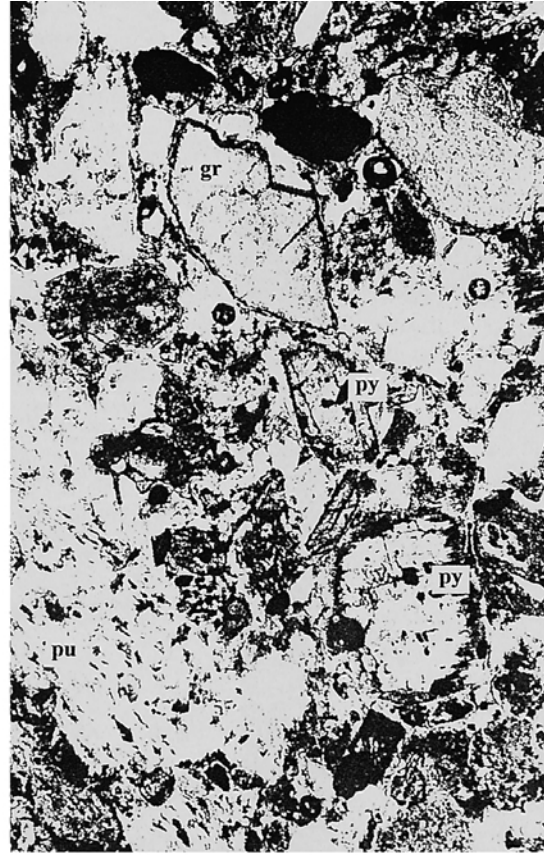
This transformation could be facilitated in the Börzsöny Mountains by frequent heavy rains under the coeval, Middle Miocene climate. On the basis of palaeoecological and palaeobotanical data, Andreánszky (1951), Báldi (1960) and Pálfalvy (1974) proposed a balanced subtropical climate with ca. 19–20°C annual mean temperature and ca. 1000-mm annual rainfall for the South Börzsöny. Pyroclastic flow transformation into debris flows/lahars occurred most likely along the marginal, coastal areas of the emerging volcanic island, where lagoons and wide river mouths gave a substantial source of water to either dilute the passing pyroclastic flows or remobilize loose pyroclastic-flow deposits in inter-eruptive periods. Syn- and inter-eruptive debris-flow deposits, however, cannot be distinguished at the present outcrop conditions. DS_m beds, having a large amount of matrix and unbroken pumices, are thought to be more directly related to eruptive activity than DS_c beds (especially beds that display better sorting and more rounded clasts).

The large number of dense, angular, monolithological lava rock fragments in some DS beds (localities 85, 90, 129, 298) suggest relations to small-scale dome collapses after/during silicic ignimbrite-forming eruptions. On the other hand, in some beds, jig-saw fit structures, broken minerals and angular-subangular rock fragments can be explained by debris avalanche-generated debris-flow origin. Large debris-avalanche deposits are not found, but in one case (locality 298; Fig. 11), angular, broken, varicoloured but largely monolithological clasts suggest small-scale avalanche originating from rockslide or rockfall (cf. Kerle and van Wyk de Vries, in press). All these events may have been associated with small- to medium-sized caldera formation during the eruptive periods (cf. Pinatubo: Newhall and Punongbayan 1996; Shiveluch: Belousov et al. 1999), a problem which is discussed in detail later.

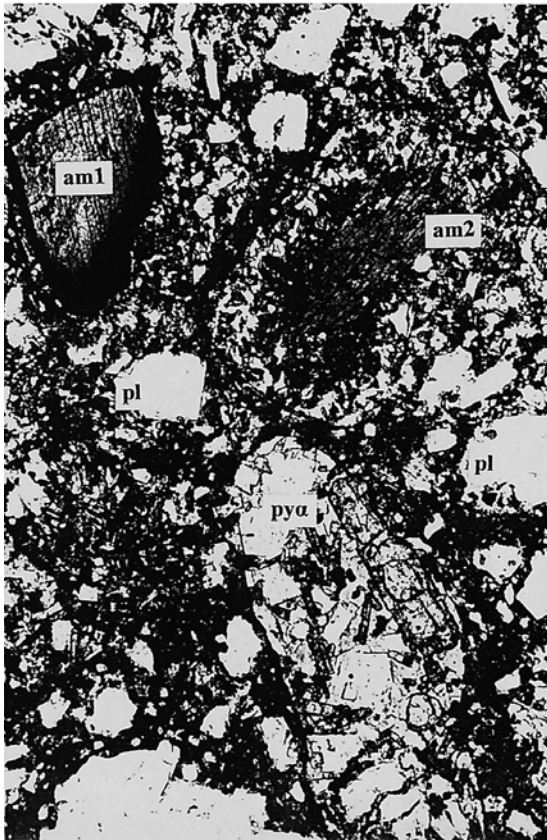
Progressive deposition from diluted block-and-ash flows and small avalanches, and disaggregation of larger, brecciated clasts, together with erosion and incorporation of rip-up clasts, resulted in the transfor-



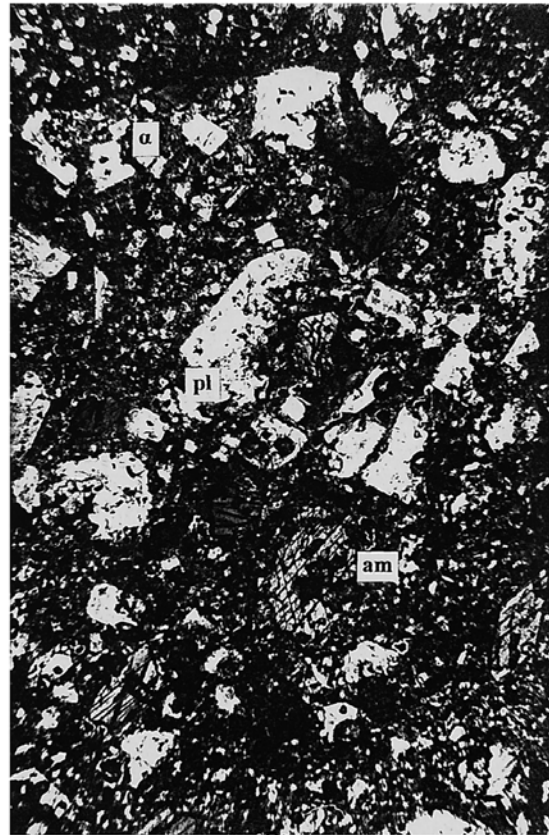
A



B



C



D

Fig. 13A–D Selected photomicrographs of thin sections of the first-stage volcanoclastics of the Börzsöny Mountains. **A** 155 lower part (W of the village of Kismaros): massive pumiceous lapilli tuff (PBLT). *Pu* pumice; *am* amphibole; *pl* plagioclase; *py* pyroxene. Note pumiceous matrix. 1 N; short picture size 2.3 mm. **B** 85 lower part (Kemence valley): graded pumiceous lapilli tuff (PBLT). *Pu* pumice; *gr* garnet; *py* pyroxene (mostly hypersthene). Note clastic matrix. 1 N; short picture size 2.3 mm. **C** 100 (Nagy valley): lithic-rich volcanic sandstone (*VS*). *Pyx* andesite lithic clast with pyroxene and plagioclase crystals in a glassy groundmass; *am1* opacitised amphibole; *am2* amphibole with plagioclase+pyroxene transformation zone; *pl* plagioclase fragments. Note crystal-rich clastic texture. 1 N; shorter picture size 2.3 mm. **D** 129 (Nagy-Kőszikla Hill): clast-rich debris-flow deposit (*DSc*). α indicates hydrothermally altered andesite lithic clast; *am* amphibole; *pl* plagioclase. Note jigsaw-fit texture of broken plagioclase crystals. 1 N; shorter picture size 2 mm

mation to normal debris flows. As flow continued, underlying sediment was completely mixed with the primary components of the debris flows, producing deposits that are homogeneous sandy silt or even mud (northern part of the field area, e.g. localities 147 C, 274, 287). In this way, the eruption-associated hot flows could be transformed to debris flows then fluvial stream flows or shallow-water turbidites in more distal areas (e.g. Lecointre et al. 1998; Cronin et al. 2000). Unconsolidated, loose pyroclastic material was also transformed in this way during inter-eruptive periods. In the North Börzsöny, the transformed DS (and SB, see below) deposits have a northern geographic position relative to the more primary ones (e.g. at locality 85) and the region has a northward-descending slope. Consequently, a transport direction from the southernly source areas (calderas) to the northern volcanic apron is inferred.

E3., SB: Sandy bedforms with fine- to coarse-grained volcanic material, localities 90, 91, 129, 147 C, 274, 287 (Figs. 8, 9)

This deposit can be found mostly interlayered between DS beds. It is a weakly bedded, occasionally pumiceous, fine- to coarse-grained, mostly clast-supported sandstone frequently with larger oversized, subangular and subrounded clasts (up to 10 cm in diameter). Small (up to a few centimetres in diameter) pumice fragments may form stringers which pinch out in a few tens of metres of distance.

Interpretation Poorly developed stratification, clast-supported texture, significant debris content with small clast size, pumice stringers, inverse grading and lack of internal scour surfaces, as well as lack of any marine fossils, indicate deposition from hyperconcentrated stream flows rather than submarine volcanogenic sand deposition (e.g. Smith 1986; Scott 1988;

Palmer and Neall 1991; Cronin et al. 1997; Lecointre et al. 1998).

E4., Ch: Channel fills, localities 90, 91, 129 (Figs. 3, 9)

This deposit is a lenticular, unsorted, coarse-grained conglomerate and can also be found mostly interlayered between DS beds. It laterally pinches out in short distances (few tens of metres). The clasts are large (up to 1 m), dense volcanic fragments with a minor component of sandy matrix between.

Interpretation Fluvial channel fills and channelised debris-flow deposits represent main drainage pathways in the ring plain. Unfortunately, their orientation is not significant, probably because of the small number of exposures.

E5., FS: Fluvial sandstone, mudstone, localities 91, 105, 107, 129, 147 C, 289 (Figs. 3, 4, 9, 10B, C, 12)

This is a volcanogenic to non-volcanogenic sandstone and mudstone series with well-bedded structure. Laminated beds 5–15 cm thick frequently showing cross-stratification are common. The mostly centimetre-sized clasts are subrounded to rounded and heterolithic. Plant fossils were reported at Kismaros village from the southern part of the mountains (Báldi and Kókay 1970). The deposits may be interbedded with DS beds or develop from volcanogenic, shallow subaqueous sandy beds.

Interpretation The well-bedded, cross-stratified, graded beds of sand- and mudstones containing semi-rounded, heterolithic, volcanogenic clasts are characteristic of terrestrial fluvial sedimentary environments. The fluvial deposits seem to correspond to normal terrestrial sedimentation on a broad ring plain during inter-eruptive stages.

Geochemistry of volcanic glasses

On polished thin sections, a large number of volcanic glass shards were studied from the volcanoclastic units (both from primary and reworked deposits). In general, the volcanic glasses are pumice shards with elongated, stretched, woody appearance. They often show oriented texture determined by small feldspar laths. Alteration processes have gradually changed the composition of glass shards from outside to inside and along cracks.

For determining the chemical composition of the volcanic glasses, JEOL 8600 Superprobe electron microprobe was used on oxide 9 standard with ZAF correction method and with 5–20 beam diameter, on polished thin sections. In general, the occasional fresh

Table 1 Major element compositions (microprobe) of selected pumiceous glass shards (individual measurements)

Sample no. ^a	B-90 1	B-90 2	B-43 3	B-129 4	B-105u 5	B-105u 6	B-155u 7	B-155u 8
SiO ₂	70.59	70.67	76.02	68.53	66.26	63.15	67.12	68.26
TiO ₂	0.25	0.25	0.18	0.12	0.37	0.43	0.31	0.43
Al ₂ O ₃	14.24	13.71	11.22	12.75	15.95	14.02	15.26	13.89
FeO _{total}	1.88	2.33	1.70	1.29	5.08	5.64	2.67	2.84
MnO	0.03	0.04	0.06	0.00	0.13	0.14	0.06	0.08
MgO	0.22	0.27	0.08	0.02	1.41	1.42	0.57	0.61
CaO	2.52	1.87	0.87	1.52	4.24	3.72	3.36	2.44
Na ₂ O	2.31	0.76	1.30	2.34	2.85	1.76	3.45	2.64
K ₂ O	3.47	3.22	5.86	5.18	2.46	2.60	2.97	3.64
Total	95.52	93.11	97.29	91.77	98.74	92.87	95.76	94.83
Rock type	Rhyo-dacite, rhyolite	Rhyo-dacite, rhyolite	Rhyolite	Rhyo-dacite	Rhyo-dacite	Dacite, rhyo-dacite	Rhyo-dacite	Rhyo-dacite

Measurements carried out on JEOL 8600 Superprobe with oxide 9 standard, 15 kV acceleration voltage, ZAF correction method and 10- to 25- μ m beam diameter

^aFor locality, see Fig. 2. Samples 1, 2 Nagy-Kő Hill; 3 Hosszú-bérc; 4 Nagy-Kőszikla Hill; 5, 6 Szívzakasztó (Nagy Valley); 7, 8 West Kismaros

pumice glass shards (90–95 vol.% of total) have composition varying predominantly between dacite and rhyodacite (average SiO₂ content 68.8 wt.%; Table 1).

As far as individual sites are concerned, the SiO₂ content of the Nagy-Kő Hill pumiceous deposits (localities 90, 91) fits with the recently determined data from the same locality (68–70 wt.%; Karátson et al. 2000). In addition, we have obtained rhyolitic composition (>75 wt.% SiO₂) at Hosszú-bérc (locality 43). These data first imply that careful searches for fresh pumices can yield much more silica-rich composition than the typical “middle tuff” (i.e. Tar Dacite Tuff) of the Pannonian Basin (67%) and even the “lower” and “upper” rhyolite tuffs (71 and 72% on average, respectively: data from Póka 1988). In other words, chemical composition cannot be associated with simple, uniform events. Secondly, since these rhyodacitic–rhyolitic compositions were measured in the highest (400–600 m a. s. l.) levels of the Paleo-Börzsöny, it is obvious that the rhyolite tuff horizons (Fig. 1) are not confined to the buried part of the Pannonian Basin or the margins of the Carpathian Volcanic Chain, as suggested by many (Póka 1988; Korpás et al. 1998; Hámor 1998). Instead, during the Middle Miocene, a diverse explosive activity, various both volcanologically and geochemically, took place in the Carpatho-Pannonian region, building up a significant part of the calc-alkaline volcanic mountains.

Depositional systems

Shallow subaqueous stage

The initial volcanic products of the Börzsöny Mountains were deposited in a shallow marine basin (e.g. Báldi and Kóky 1970; Korpás and Lang 1993) as successive beds of voluminous submarine pumiceous vol-

caniclastic mass-flow deposits. The shallow-water environment appears to have been maintained for the volcanic activity over a significant time interval according to palaeomagnetic results (16.5–16.0 Ma for the PBLT; see above). The volcanic eruptions, in the light of interbedded, volcanogenic, pumice-containing sandstone layers, were coeval with ongoing marine sedimentation. The unchanged environment is witnessed by common fossil record (mollusc, *Balanus*) in the first volcanoclastic units (Karátson et al. 2000).

As for the mode of deposition of volcanoclastic mass flows in general, recent discussion calls attention to the fact that, in a subaqueous environment, the lack of sedimentary features characteristic of hot deposition during emplacement does not necessarily imply a reworked origin (e.g. Wright and Mutti 1981; Cas and Wright 1991). However, since in the Börzsöny Mountains no hard evidence has been found to support hot, gas-rich state of pumiceous volcanoclastic mass flows, we conclude that most of the deposits represent either a dilute state of a passing volcanoclastic flow, or the eruptions that produced them were characterised originally by low particle concentration. Interbedded volcanogenic, stratified, pumiceous sand and sandstone beds seem to represent deposition by even more dilute volcanoclastic mass flows, i.e. low-concentration turbidity currents (cf. White 2000).

The problem is more complex when eruptive centres of the original pyroclastic flows are to be defined and localised. Since there are no welded and ponded ignimbrites, no distinct ignimbrite beds or flow units thicker than 15 m, no pumices larger than 15 cm in diameter and there are complications in the gravimetric maps (Karátson et al. 2000), we cannot infer definitively the source vents. However, given the subsequent lag breccia at the upper part of locality 40 (Királyrét), the probable caldera structures in a later phase (see below) and segregation pipes in similar and coeval deposits of the Holdvilág valley in the neigh-

bouring Visegrád Mountains (ca. 15 km southward of the Börzsöny), a near-source origin of the submarine products is very likely.

A rapid volcanic infill in the Börzsöny Mountains is indicated by the appearance of subsequent, several tens-of-metres-thick subaerial successions in many exposures and the disappearance of marine fossils, replaced in places by leaf imprints. This change in palaeoenvironment can also be inferred by comparing the total thickness of pumiceous deposits to the proposed <120-m water depth (Báldi and Kókay 1970). In the south, the level difference of lowest (locality 155) and highest (locality 129) occurrence of pumiceous beds is 180 m, whereas in the east, between localities 255 and 43, it is 220 m. The distance between the two sections is 12 km (see Fig. 2). The deposit thickness, despite absolute height data differences (due to the tectonic tilting or faulting of the High Börzsöny; Karátson 1995; Karátson et al. 2000), is conspicuously consistent and exceeds the calculated water depth, supporting the conclusion of an upfilled marine basin and replacing subaerial conditions.

Emergent ring-plain stage in relation to edifice construction and destruction

The upfill of the shallow-marine environment is also shown by facies characteristics (e.g. fluvial deposits, wavy, sandy bedforms, channel and scour fills) typical of a subaerial ring-plain system. The emerged, subaerial environment was probably composed of a number of silicic centres and their aprons. Given the similar lithology and age (cf. Karátson et al. 2000), the volcanic complex is proposed to have evolved continuously from the submarine to the subaerial stage.

How can the coeval palaeovolcanoes of the eruptions be reconstructed? Apart from early-stage dacitic lava domes (see Geological setting and palaeogeography and Fig. 2), there are no direct evidence for larger-scale structures of the volcanoclastic sequences (i.e. unambiguous caldera morphology, concentric, negative gravimetry, well-developed horizons of lag and caldera collapse breccia); therefore, indirect evidence in the area would be more important. As mentioned previously, there are some ridge sections in the periphery of the mountains that can be considered as caldera rim fragments (cf. Fig. 2). Karátson et al. (2000) proposed these sections to belong to a few medium-sized calderas (6–8 km in individual diameter). Since caldera rims are strikingly incomplete (half or even shorter sections) and face the interior of the mountains, a tectonic or erosional coalescence of calderas was assumed (Karátson 1995, 1999). Although this scenario may be correct, it can hardly be substantiated due to strong post-eruptive tectonic movements in the North Hungarian Mountains (cf. Fodor et al. 1999) and 5- to 700-m-deep erosion in the area (Karátson 1996). Thus, it is better to focus on the proposed

caldera rim deposits which are the only clue in the field to be related to palaeovolcano destruction processes.

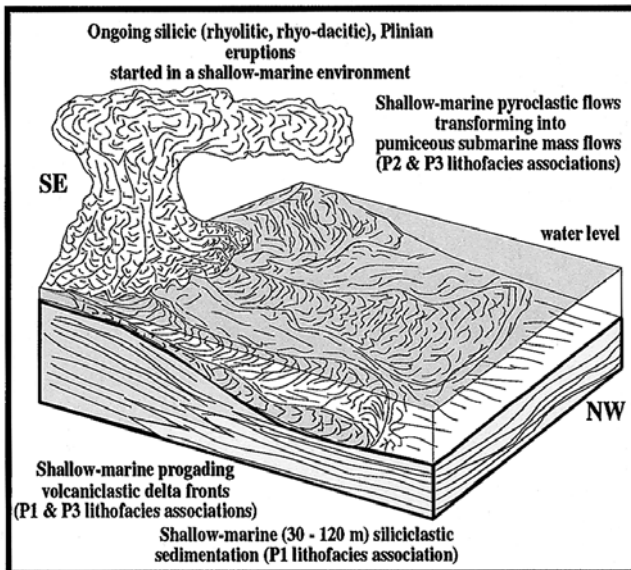
Features of these deposits (Fig. 2) that suggest relations to explosive eruptions and possible caldera formation are: (a) moderate to high pumice content in the DS_m matrix; (b) intercalation of pumiceous volcanoclastic mass-flow deposits (WB-PLT) between breccia horizons (the latter having clast diameter up to 3–4 m); (c) frequent monolithological breccia composition; and (d) frequent prismatic jointing of clasts indicating hot primary origin. Since all or some of these features are found both on the northern (locality 85) and southeastern (localities 90, 91, 129) proposed caldera rims, and since these rims are the highest elevations in the Paleo-Börzsöny (see Fig. 2), they should be the remnants of eroded caldera rims or proximal palaeovolcano slopes. On the other hand, since the rim breccia exposures represent valley filling debris-flow deposits, the actual 6- to 8-km caldera diameters should have been much smaller (some kilometres) at the time of volcanic activity. This implies small caldera or explosive crater origin (and erosion calderas/erosion craters at present: for terminology, see Karátson et al. 1999). In other words, when using the term calderas, we cannot associate large-scale caldera-forming processes.

In summary, the emergent stage can be reconstructed as a volcano complex that consists of a few medium-sized subaerially erupting silicic centres which underwent minor or moderate edifice destruction generating various types of debris-flow deposits. These deposits, subsequent to upfilling the marine basin(s), accumulated (a) on a well-developed (ca. 15×15 km²) ring-plain (including mostly the northern and also the southern occurrences in Fig. 2), (b) along marginal marsh- and lagoon-system and (c) in the surrounding shallow-marine environment.

Conclusion: general features

During the first volcanic stage of the Börzsöny Mountains, the initial eruptions, occurring in a shallow-marine environment, produced subaqueous eruption-fed pumiceous volcanoclastic mass flows transforming into more dilute volcanoclastic mass flows in distal areas (1 in Fig. 14). Eruptive centres may have been located inside the mountains as developing silicic volcanoes. Subsequently, the infilled shallow marine basin(s) continuously evolved to a rugged volcanic archipelago. Subaerially erupted pyroclastic-flow-generated debris flows rapidly built up an emergent ring-plain system (2 in Fig. 14; e.g. Turbeville et al. 1989; Turbeville 1991; Cole and Ridgway 1993; Bahk and Chough 1996). Debris flows (lahars) were frequently generated also in the inter-eruptive periods under the reconstructed subtropical climate. In the nearby, submarine environment, pyroclastic flows and debris flows most

1 Shallow-marine stage



2 Subaerial stage

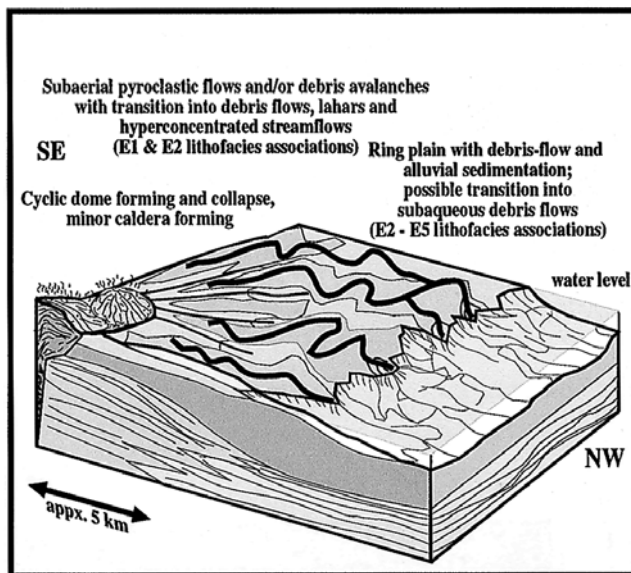


Fig. 14 Proposed palaeogeography for the first volcanic stage of the Börzsöny Mountains (modified after Martin 2000)

likely transformed into subaqueous volcanoclastic debris flows, then turbidity currents (e. g. Whitham 1989; Cole and DeCelles 1991).

Despite the reconstructed palaeogeographic change, which, although geologically brief, may have been continuous and transitional in individual places, the deposits transformed from subaerial eruptions display appearance similar to that developed directly from shallow-marine eruptions. Theoretically, there could be two end-member sequences: (a) subaqueous pumiceous volcanoclastic mass flow–redeposited pumiceous volcanoclastic mass flow–subaqueous reworked volcan-

iclastic debris flow continuum; (b) pyroclastic flow–debris flow (lahar, hyperconcentrated stream flow)–normal fluvial stream flow–subaqueous debris-flow continuum (e.g. Brantley and Waitt 1988; Waresback and Turbeville 1990). These two sequences which represent different palaeogeographic conditions may have mixed with each other and are difficult to distinguish. On the basis of the Börzsöny example, we conclude that in similar, poorly exposed areas displaying transitional facies conditions, it may be the large-scale facies relations rather than individual outcrop features that help reconstruct palaeogeography.

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