Deltaic density currents and turbidity deposits related to maar crater rims and their importance for palaeogeographic reconstruction of the Bakony-Balaton Highland Volcanic Field, Hungary

K. NÉMETH

University of Otago, Geology Department, P. O. Box 56., Dunedin, New Zealand

ABSTRACT

The Bakony-Balaton Highland Volcanic Field (BBHVF), active in the late Miocene, is located in the Central Pannonian Basin of Hungary and consists of around 100 mostly alkaline basaltic eruptive centres. After volcanism, deposition took place in lakes inside the maar craters. Above the primary volcaniclastic deposits, thick maar-lake volcaniclastic sediments occur. The steeply dipping (25–35°), 25–30-cm thick, coarse-grained, inverse-to-normal graded beds of reworked tuff represent the foresets of large Gilbert-delta fronts built into the maar crater lakes of the BBHVF. The coarse-grained beds were deposited by low-density granule debris flows and grain flows. Interstratified 10–15-cm thick beds of fine-grained, cross-bedded, reworked volcaniclastic sandstone and mudstone were probably deposited by turbulent sediment gravity flows. The delta fronts generally indicate transportation from north to south, suggesting a strong N–S trending fluvial system, active during or, shortly after volcanism in the BBHVF. The juvenile fragments in the deltaic sediments are often highly vesiculated, rounded/semirounded glassy lapilli. These suggest that the maar volcanism was related to widespread Strombolian-type explosive volcanism that followed the maar-forming phreatomagmatic events. Deposits derived from scoria cones were easily washed into the steep-walled maar basins and deposited by debris flows.

INTRODUCTION

In the Bakony-Balaton Highland Volcanic Field (BBHVF), Hungary (Figs 1, 2 and 3), the formation of large maars and subsequent lake sedimentation (Németh & Martin, 1998) occurred between 7.56 and 2.8 Ma (Balogh *et al.*, 1986; Borsy *et al.*, 1986). The distribution of large hydrovolcanic centres strongly depends on the occurrence of the Pannonian Sandstone Formation in the pre-volcanic stratigraphy. In the west of the area, the Pannonian Sandstone Formation reaches a thickness of 600 m, decreasing eastwards. Where thick Pannonian Sandstone beds are present, normal maar volcanic structures developed, due to the abundant water content of the unconsolidated sand, which led to phreatomagmatic explosions (Lorenz, 1986; White, 1996). With the progressive drying-out of the sand, large lava lakes and Strombolian scoria cones developed in the maar basins, due to the onset of magmatic explosive activity. At the eastern side, the groundwater content of the Mesozoic carbonates (main karst aquifer), Permian Red Sandstones and Silurian schist formations fuelled the initial phreatomagmatic eruptions and produced unusual 'Tihany-type' maars (Németh & Martin, 1998, 1999a,b) with unusually deep maar basins. Similar structures were reported from Mexico by Aranda-Gomez and Luhr (1996). This chapter gives a short summary of the basic characteristics of maar lake deposits and especially the Gilbert-type deltas of the BBHVF, mostly on the Tihany peninsula.

GEOMORPHOLOGY

The BBHVF is a region of low elevation bordered by Mesozoic and Palaeozoic fault ridges with an average height of 250–400 m. Between these ridges are Pannonian lacustrine clastic-filled basins (Fig. 1). The individual eruptive centres show a strong correlation
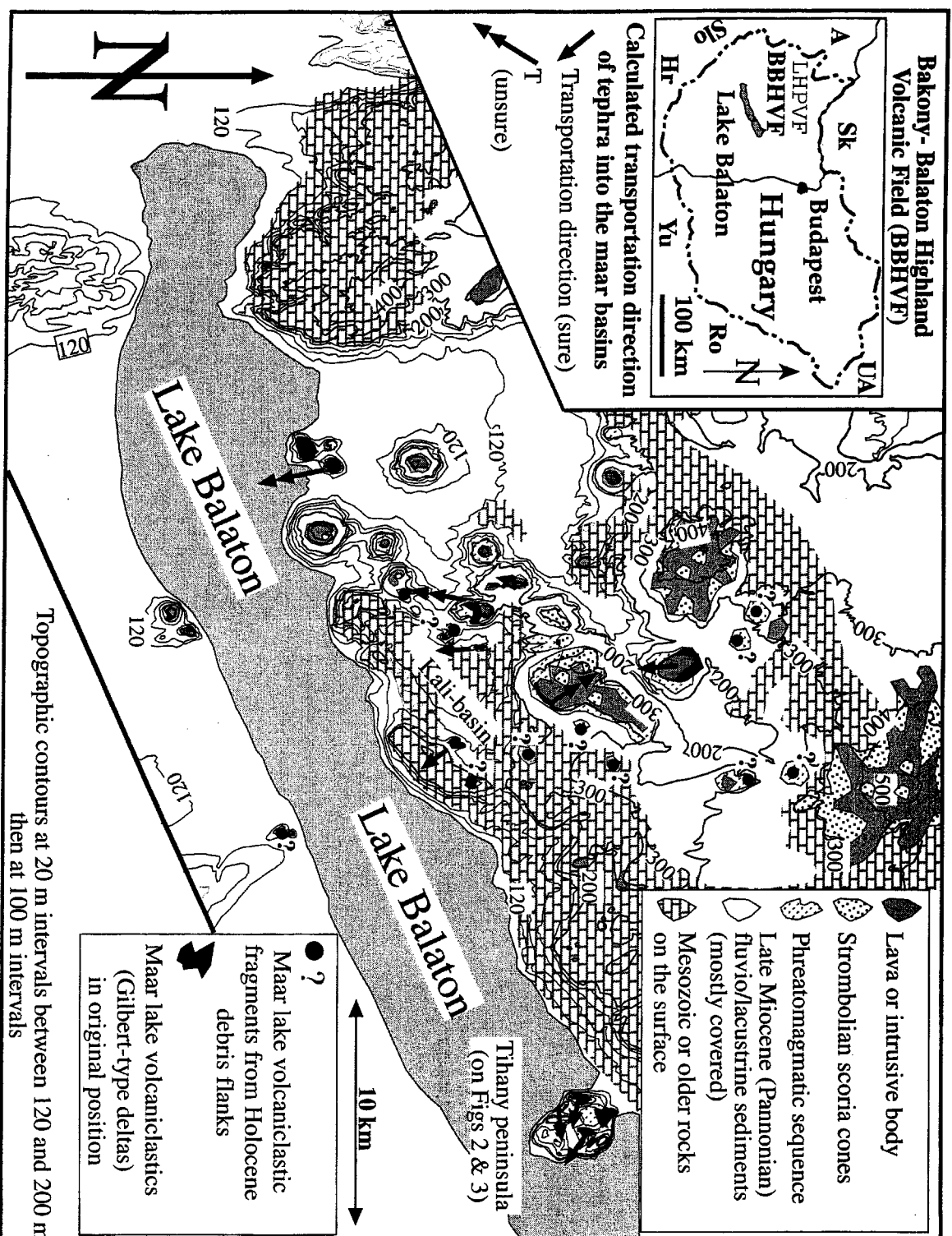
Bakony- Balaton Highland Volcanic Field (BBHVF)

A Sk
LHPVF
Sю BBHVF
BBHVF Lake Balaton Hungary Ro
Hr Yu

Budapest

N

100 km

Calculated transportation direction of tephra into the maar basins

↗ Transportation direction (sure)

↖ T (unsure)

UA

Lake Balaton

Lake Balaton

Kali-basin

Tihany peninsula (on Figs 2 & 3)

N

120

120

120

120

120

200 300 400

200 300

300

200

300

500

400

120 m

Topographic contours at 20 m intervals between 120 and 200 m then at 100 m intervals

10 km

Lava or intrusive body

Strombolian scoria cones

Phreatomagmatic sequence

Late Miocene (Pannonian) fluvio/lacustrine sediments (mostly covered)

Mesozoic or older rocks on the surface

●? Maar lake volcaniclastic fragments from Holocene debris flanks

Maar lake volcaniclastics (Gilbert-type deltas) in original position

Fig. 1. Simplified geological map of the Bakony-Balaton Highland Volcanic Field (BBHVF), Hungary.
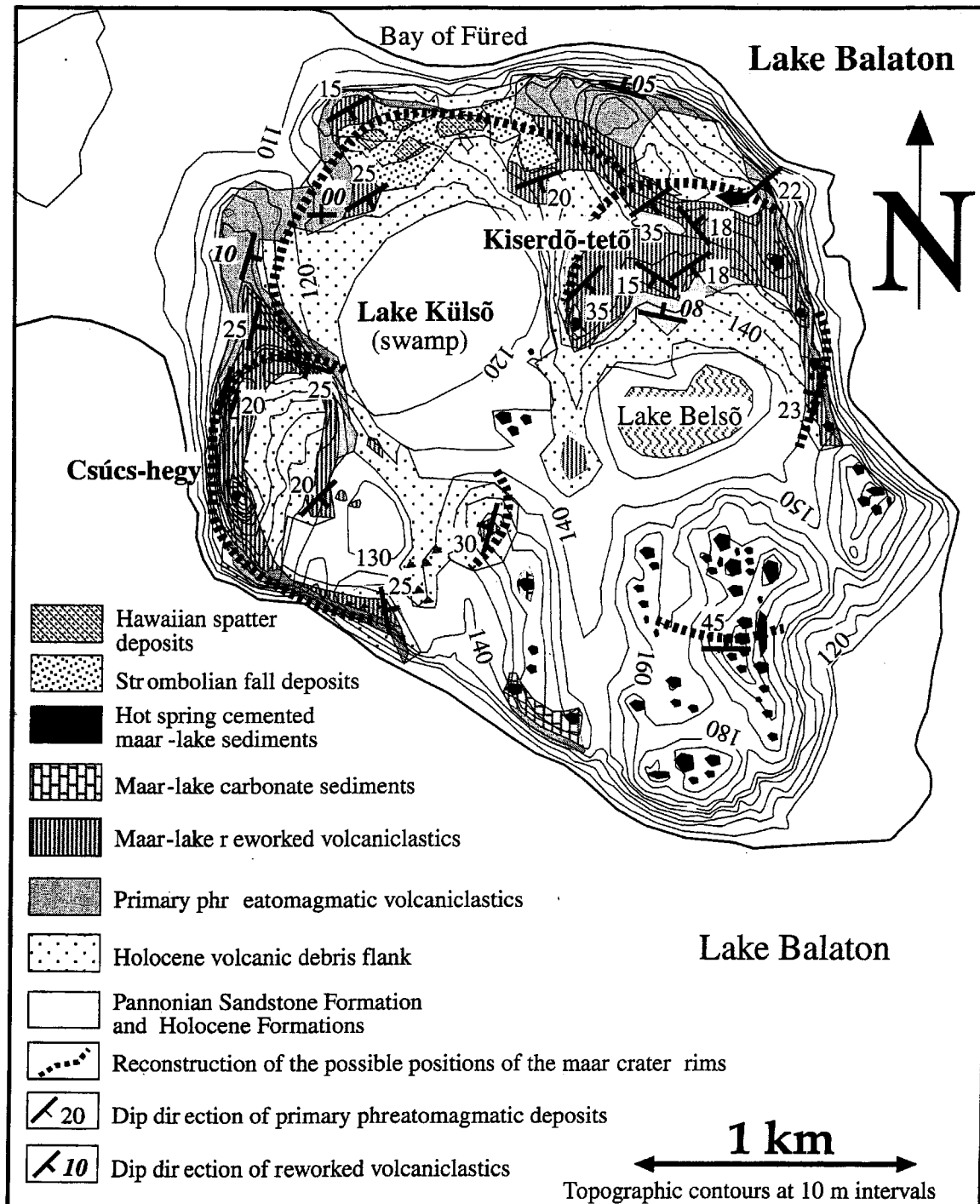
Fig. 2. Geological map of the Tihany peninsula showing the distribution of primary and reworked volcaniclastic deposits in the area.
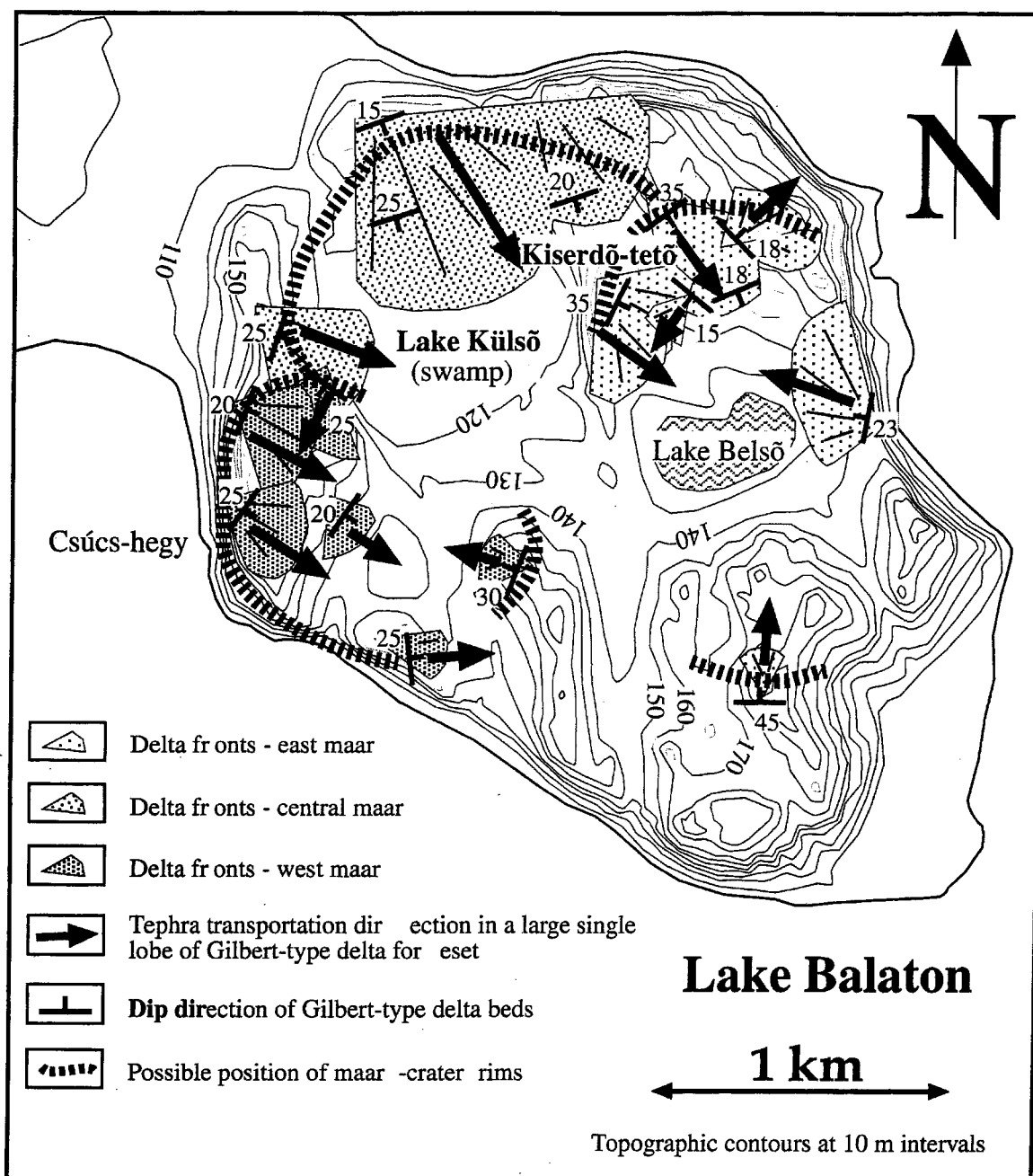
Fig. 3. Reconstruction of large Gilbert-type delta fronts on the Tihany peninsula. Different patterns represent different lobes of large Gilbert-type delta fronts. Delta fronts with similar pattern belong to the same maar crater.
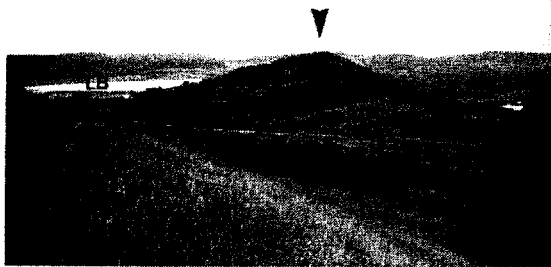
Fig. 4. Overview (E–W) of a hillside of Kiserdő-tető (Tihany peninsula) formed by a remnant of a Gilbert-type delta front. Dashed lines represent dipping of beds (LK, Lake Külső; LB, Lake Belső).

Fig. 5. Overview of the Csúcs-hegy outcrop at Tihany. Note the steeply dipping beds of Gilbert-type delta front (GD) covered by silicified maar lake carbonates (ML).

with the occurrence of the Pannonian clastic sediments, indicating the importance of these beds as a water source for the phreatomagmatic explosive activity during the volcanism. The hydrovolcanic landforms were maars with low rims. Strombolian scoria cones and shield volcanoes formed on the more elevated ridges (Fig. 1). In those areas, where the karst aquifer was present in the basement rock, unusual maar volcanic structures (Tihany-type maar volcanoes) developed (Németh & Martin, 1998, 1999a,b). Where thick Pannonian sediments are present, normal maar volcanoes built up. Both types of maar volcanic centres functioned as local basins within which thick maar lake deposits accumulated. The more steeply dipping beds have better preservation potential, due to the strong carbonate and silica cementation, eroding as steep ridges, usually higher than the flat-topped primary volcaniclastic remnants (Fig. 4). The erosional remnants of former Gilbert-type delta fronts are probably the most commonly preserved volcanic landforms in the BBHVF (Figs 4–6).

PRIMARY AND REWORKED VOLCANICLASTIC DEPOSITS RELATED TO MAARS: TEXTURAL DIFFERENCES

Maars are monogenetic volcanic craters, cut into pre-eruptive country rocks and surrounded by a low ring wall (tephra/tuff ring) of pyroclastic material (e.g. Fisher & Schmincke, 1984; Cas & Wright, 1987). Originally the term 'maar' described a topographic feature, consisting of a crater and a tephra/tuff rim. This term incorporates the ring wall, the crater sediments, the diatreme, and the feeder dyke. The syn-eruptive processes

Fig. 6. Overview of the Kiserdő-tető outcrop at Tihany. The lower part of the outcrop represents the crater fill (lower diatreme) deposits (LD), covered by steeply dipping Gilbert-type delta front beds (GD). The dashed line represents the position of a chute structure above the lower diatreme deposits.

are driven by magma/groundwater, Fuel- (Impure) Coolant Interaction (FCI) and produce mostly base surge and phreatomagmatic fallout beds up to a few tens of metres' thick around the excavated maar crater (e.g. Wohletz, 1986; White, 1996). During the post-eruptive processes subsequent to the formation of the maar basin, the undercutting of the groundwater level lead to formation of a lake. The filling of this lake was usually controlled by (i) mass movements (mass flows of any type from the inner crater wall), (ii) delta deposits, (iii) atmospheric loads, mostly ash fall from nearby eruptive sites, (iv) production of organic matter in the lake and (v) intensive mineral-rich spring activity (Büchel, 1993). Especially in ancient maars and their deposits, it is crucial to distinguish primary and secondary volcaniclastic deposits.

Primary volcaniclastic deposits of maar volcanoes are mostly generated by turbulent pyroclastic density currents (base and/or pyroclastic surges). The tephra forming the low rims of tuff rings and maars is usually fine grained, and tends to be consolidated (Moore, 1967; Sheridan & Wohletz, 1983). Abundant fine-grained ash contains a high proportion of fine to medium-grained blocky pyroclasts (Wohletz, 1986). In general the volcanic glass fragments from these primary deposits are non- or weakly vesiculated, and they do not show significant geochemical variation. Maar ejecta contains abundant non-juvenile debris, torn from the pre-eruptive substrate (Lorenz, 1986). Near-vent explosion breccias may show large impact sags but many large blocks, however, are carried by the surge currents and are matrix-supported with no underlying depressions. Beds with abundant accretionary lapilli antidunes and scour-fills are common (e.g. Sheridan & Wohletz, 1983).

Volcaniclastic rocks from reworked volcaniclastic beds, such as the beds of a delta front building into a maar crater, can be separated from primary volcaniclastics by their textural characteristics as well as by the presence of different volcanic glass clast populations in the same beds (tachylitic and sideromelane glasses). Usually the scoriaceous clasts are better rounded and relatively well sorted. Remnants of altered, palagonitized, irregular rims around larger clasts are significant signs that reworking processes produced the deposits. The relatively high percentage of free, broken crystals in the individual rock fragments, especially those rimmed by palagonite, also represent post-eruptive reworking. Importantly the typical bedding characteristics (bomb sags, accretionary lapilli) of individual units are useful features that distinguish primary from reworked deposits in an ancient maar sequence.

GILBERT-TYPE DELTAS

Gilbert-type deltas are produced by progradation of alluvial or fluvial systems into a standing body of water, either lacustrine or marine, usually in a basin with a steeply inclined margin (Gilbert, 1885). They have a very steep depositional surface, i.e. foreset slopes that are inclined near the angle of repose and dominated by gravity-driven processes (e.g. Massari, 1996; Sohn et al., 1997).

Tephra deltas occur in most of the BBHVF maar craters. In several places, exceptionally good exposures show the structure of the steeply dipping foreset of the individual delta fronts (Figs 4–6). Continuous transitions between the flat-lying deltaic topset and the steep foreset have not yet been described from the BBHVF. Deltaic topset strata have probably been eroded, or are just not well exposed in the studied areas. In several places (mostly on the Tihany Peninsula, Figs 1 and 3) complex geometrical structures of steeply bedded, scoriaceous, coarse-grained lapilli beds intercalated with finer-grained, gently dipping, cross-bedded reworked tuff layers, suggest complex transition zones between topset and foreset zones of Gilbert-type delta fronts, as similar characteristics were reported from the Hopi Butte eruptive centres (White, 1992). The best exposures of deltaic foresets are located in the Tihany Peninsula (Kiserdő-tető, Csúcshegy), with at least four delta fronts (Figs 1–3). The beds of the delta front foresets are usually not covered by other post-maar beds. They have also been eroded in most of the topset settings. Locally, late maar-lake carbonate beds overlie the original foreset beds, representing the late central lacustrine facies in the maar basin.

Volcaniclastic beds, interpreted as foresets of the BBHVF delta fronts, are generally 5–25-cm thick, and dip steeply (20–30°) towards the former crater position, forming a concave geometry controlled by the steep inner morphology of the former maar basin (Figs 5 and 6). The total thickness of the foreset sequences is at least 40 m at Tihany peninsula (Kiserdő-tető and Csúcs-hegy). The individual beds usually have irregular tops and bases (Fig. 7). Coarse-grained beds are usually laterally discontinuous and they grade into fine-grained cross-beds. Scoriaceous, fragment-rich scour-fill structures are common. Locally, carbonate (calcite) enrichment is also common, in several cases forming faint bedding. In several places, the large scoriaceous clasts contain a large amount of probably secondary carbonate (calcite) and the
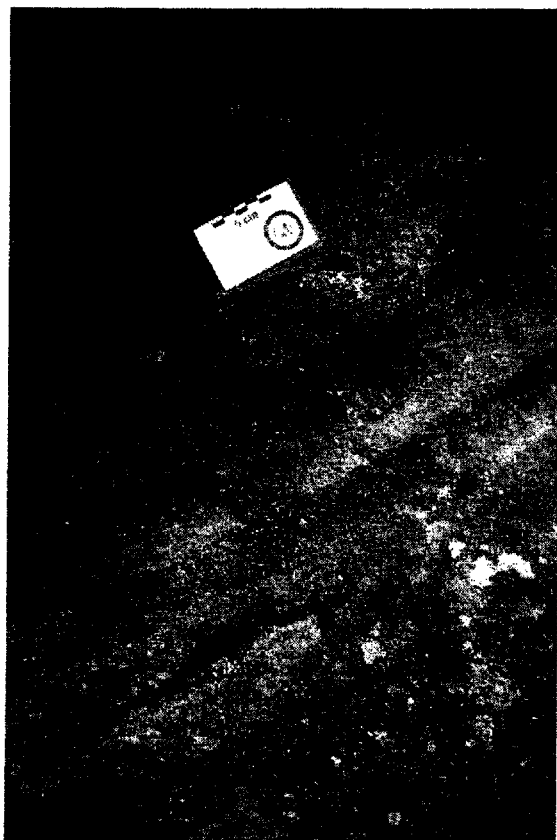
Fig. 7. Irregular base and top in a coarse-grained, grain-supported bed sets from the Kiserdő-tető locality (Tihany).

Fig. 8. Inverse-to-normally graded, coarse-grained beds of Lithofacies 1 (L1) from the Csúcs-hegy locality (Tihany). Note the interbedded fine-grained, low-angle cross-laminated Lithofacies 2 (L2) in the middle of the photo. ML is a maar-lake silicified carbonate lamina set above L1. The coin is 2.5 cm in diameter.

clasts are carbonate-cemented. Fine carbonate-rich beds and laminae are present mostly in the bedded reworked tuff sequences. Bed-specific carbonate alteration probably resulted from both influx of detrital carbonate across the pre-volcanic surface, and alteration of tephra beds by carbonate saturated lake waters during periods of flood or periods of high net evaporation respectively, as White (1989, 1992) described in the Hopi Buttes maar craters. This interpretation for the origin of the carbonate would require revision of our view of the paleoclimatology during the eruptive history of the BBHVF, which is usually considered to be a dry, cold subarctic climate. The evaporative original the carbonate in this interpretation suggests a relatively warm, dry summer and therefore strong seasonality of the region during the period of volcanism. However, the high carbonate content of maar-lake water could also have been derived from runoff from the large Mesozoic carbonate hills or from

subsurface water via new fractures which developed immediately after the phreatomagmatic activity. The carbonate content of these beds could also be explained by substantial hot spring water entering the maar lakes.

Coarse-grained beds show characteristic inverse-to-normal grading (Fig. 8). Isolated outsized basaltic clasts (without any impact craters or folds), usually 5–10 cm in diameter, lie within many beds. Between the coarse-grained foreset beds there are a few fine-grained primary volcaniclastic beds, usually with fall-out characteristics. They usually contain numerous accretionary lapilli, with a maximum diameter of 1 cm. These interbedded primary volcaniclastic beds suggest ongoing volcanic eruptions adjacent to the
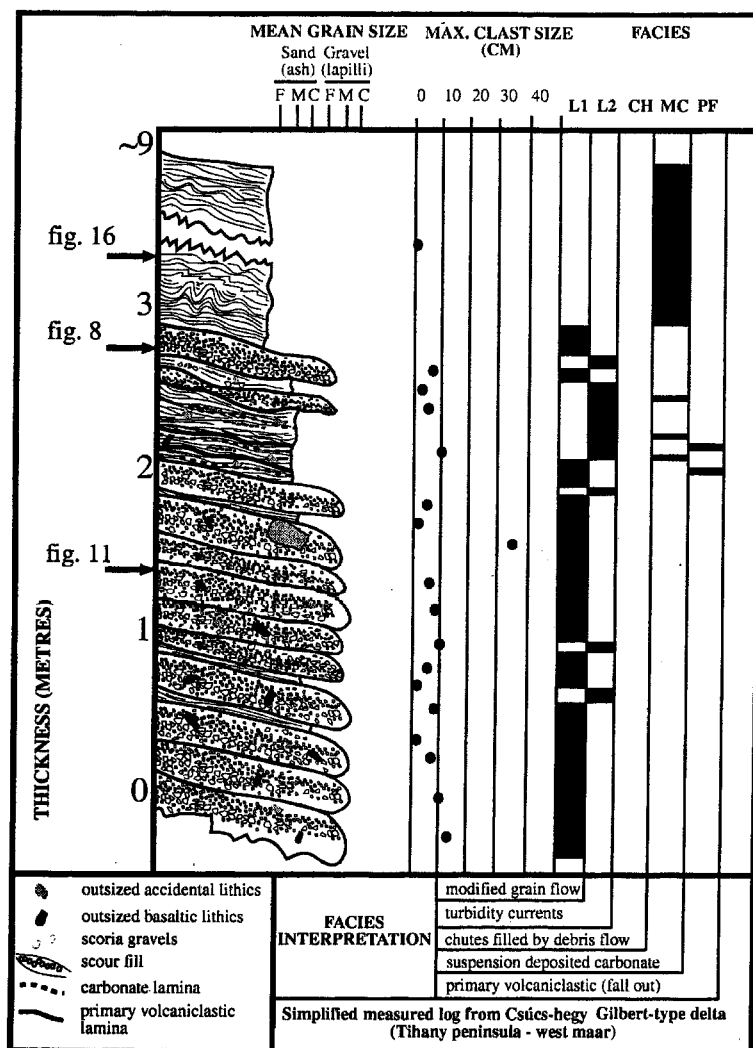
Fig. 9. Simplified log from the Csúcs-hegy (Tihany) locality. Compare with Fig. 5.

earlier-developed maar basins which were already accumulating clastic sediments.

LITHOFACIES OF GILBERT-TYPE DELTA FRONTS

In general, two major lithofacies groups can be identified on BBHVF delta fronts, similar to those described by Massari (1996) on coarse-grained, Gilbert-type progradational wedges in marine environments: (1) massive or graded beds, generally clast-supported; and (2) units with various types of internal lamination, including flat, low-angle, broadly convex-up, and

wavy lamination, and backset cross-lamination. The two lithofacies groups were described from two type localities at Tihany peninsula from the Csúcs-hegy (Fig. 9) and Kiserdő-tető (Fig. 10).

Lithofacies 1 (L1)

The first facies group consists of massive or graded beds, usually with regular, sheet-like geometries. They generally show extensive lateral persistence, although very gradual pinch-outs are common. They are generally a few decimetres thick. Coarse-grained beds consist of pebble and sand (lapilli)-size scoriaceous clasts of average diameter 0.5–1 cm. These beds are
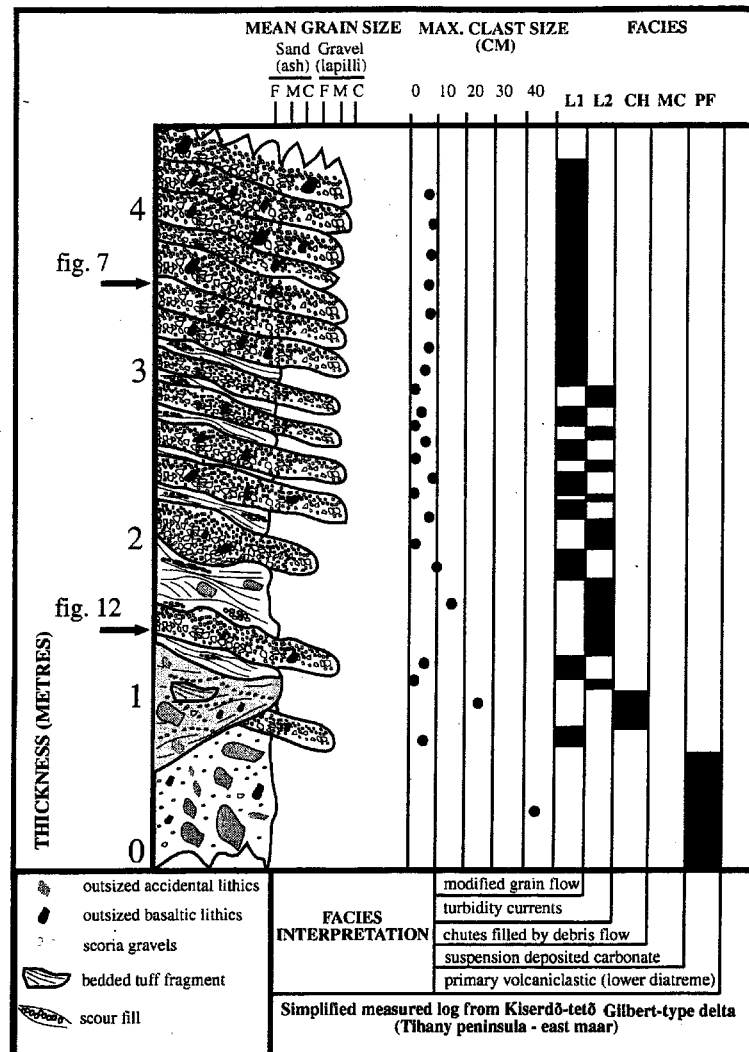
Fig. 10. Simplified log from the Kiserdő-tető (Tihany) locality. Compare with Fig. 6.

predominantly clast-supported (Fig. 11). Most beds are inversely-graded or structureless. Normal grading is always related to inversely graded bottom zones of beds (Figs 8 and 11). Some layers show an upward increase in the packing of the larger clasts, with a transition from matrix-supported (sand matrix) to clast-supported texture. The carbonate filling is characteristic of the upper clast-supported parts of the beds. Imbrication of elongated, platy clasts (mostly schist clasts, Tihany Peninsula) is also common as well as slump scars, and small (1–2-m long, 15–20-cm deep) elongated downslope-running scours (Fig. 12).

From general studies of normal marine and lacustrine environments, it is considered that massive or

Fig. 11. Hand specimen of a coarse-grained, grain-supported lapilli tuff from Csúcs-hegy (Tihany).
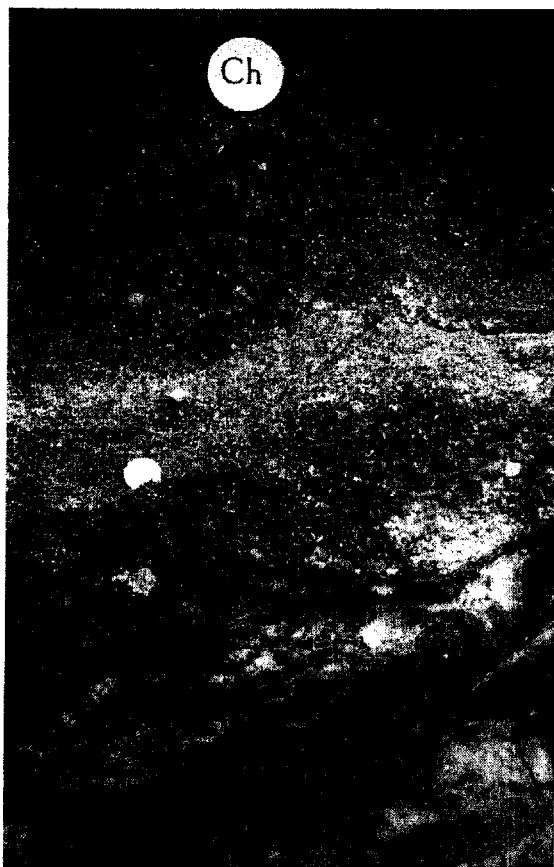
Fig. 12. Small chutes and scours (Ch and arrows with dashed lines) on the lower bed surface of a coarse grained bed (Lithofacies 1) from the Kiserdő-tető (Tihany) outcrop. Their elongation is identical with the bed dip direction. The coin is 2.5 cm in diameter.

graded layers are usually deposited by flows in which a critical value of concentration was exceeded, so that the ability of the bed-load layer to move and sort the sediment particles was suppressed (Lowe, 1988). While normally-graded beds may be the result of the collapse of turbulent, high-concentration suspended sediment clouds, layers showing inverse grading throughout, or within the basal division, and predominant a-axis imbrication, may have been generated by highly concentrated, cohesionless sediment gravity flows dominated by frictional/inertial effects. Such flows are often termed 'modified grain flows' (Lowe, 1976, 1982). Waning flows may also produce inverse-to-normal grading as argued by Hiscott (1994, 1996). In fact, if any traction structures are present, it must be waning flow rather than the result of a 'collapsing

suspension'. This mechanism ('modified grain flow') could be applied to model the transportation and depositional environment of the coarse-grained litho-facies group on the slope of the inner side of the crater wall.

Slump scars, and small elongated downslope-running scours (chutes) are common features (Fig. 12), and abound in many modern (Prior et al., 1981; Kostaschuk & McCann, 1987; Prior & Bornhold, 1988; Syvitski & Farrow, 1989) and ancient (Postma, 1984; Postma & Roep, 1985; Postma & Cruickshank, 1988; Colella et al., 1987) deltas. Possibly due to lack of exposure, large-scale chutes have not yet been satisfactorily identified in the BBHVF. Despite its significant depth (up to 300 m), the maar lake itself is not a large basin, and its length is not adequate to develop large chute structures as is common in normal marine environments (e.g. width from 10 to 200 m; depths from 2 to 20 m). The only large chute-type channel identified from the Tihany peninsula was at the Kiserdő-tető outcrop, where a feature measuring 7–10-m wide and 1.5–2-m deep is filled with matrix-rich debris flow deposits. However the chutes on delta-fronts in the maar basin are generally infilled either by deposits of smaller, less-robust turbidity currents, or by debris flows spawned by slumping of the chute walls, or by suspension settling related to the stream channel mouths, from which the chutes often emanate (Nemec, 1990).

Lithofacies 2 (L2)

The second facies group shows diffuse, planar, crude to very regular lamination with an average grain size of 1 mm (Fig. 13). Individual beds are few centimetres thick (up to 20 cm). The laminae may grade laterally into flat lenses or pebble-sized scoria clasts (average of 1 cm in diameter). Outsized pebbles (up to 15 cm in diameter) mostly of scoria or juvenile lithics are relatively common. Often, large (mostly) pyroxene crystals (up to 1 cm in diameter) form small lenses (5–10-cm long). Individual laminae are ungraded, but faint normal grading can be identified in thicker (>3 cm) beds. This lithofacies contains a high proportion of lenticular units, with 10–25-cm thick planar or shallow concave-up scoured bases and broadly convex-up tops. This lithofacies group is well represented in sequences in Tihany (Kiserdő-tető), but in other places they represent only a small proportion of the total thickness (Káli Basin) (Fig. 1).

Diffuse planar lamination on the foreset slopes of Gilbert-type deltas has commonly been modelled as

Fig. 13. Lithofacies 2 (L2) from Csúcs-hegy (Tihany). Dashed line represents the border between Gilbert-type delta front beds and silicified maar-lake carbonates (ML). Note the light-coloured, carbonate-rich lamina (arrow) in the fine-grained lithofacies (L2).

resulting from freezing of successive traction carpets at the bases of highly concentrated flows (Colella *et al.*, 1987; Postma & Cruickshank, 1988; Nemec, 1990). Lowe (1982) argued that traction carpets may develop under the influence of dispersive pressure and under upper-stage plane bed conditions, in relatively coarse-grained materials under high-density turbidity currents during their evolution from relatively steady, non-depositing flows to highly unsteady, rapidly sedimenting flows. It is suggested that, even in the case of bed materials coarser than sand, lamination may reflect temporal and spatial variations in bed shear stress and lift forces acting on sediment particles in motion over the bed, related to strongly fluctuating conditions such as burst and sweep cycles (Hiscott, 1994, 1996; Massari, 1996).

In the planar bedded, mostly fine-grained volcaniclastic facies, large lenticular units with highly rounded, well-sorted scoriaceous fragments, averaging 1–2 cm in diameter are common. These lenses are elongated and have a faint inner structure with diffuse bedding.

Lenticular units similar in geometry and internal structure to those described in the BBHVF delta fronts have been reported from (1) the foreset, toeset and bottomsets of Gilbert-type deltas and other delta fronts in marine or lacustrine environments (Colella *et al.*, 1987; Postma & Cruikshank, 1988), (2) coarse-grained deposits of high-density turbidity currents (Hendry & Middleton, 1982; Surlyk, 1984), (3) deposits of hyperconcentrated flood flows at points of flow expansion in subglacial eskers (Brennand, 1994) and (4) alluvial-fan deposits related to unconfined sheet-floods (Blair, 1987). The first two of these are most

likely to occur in the BBHVF maar-lake sediments. High-sphericity rollable clasts are concentrated in the lenses probably because they are more mobile than clasts of other shapes (Massari, 1996).

SCORIA-CONE-DERIVED CLASTS RELATED TO LARGE HYDROMAGMATIC VOLCANIC FIELD

While studying the texturally distinctive beds of the Gilbert-type delta fronts, a large proportion of scoriaceous lapilli was found within individual beds (Figs 14 and 15). The lapilli grains are usually tachylite and are microvesiculated (10–50% – visual estimation), with elongated, often calcite- or zeolite-filled vesicles. Usually the beds are well sorted and the lapilli are subrounded to well rounded. Around the individual lapilli there are often thin, altered, usually palagonitized rims (Fig. 14). These kinds of rims do not always entirely cover the lapilli. Sideromelane clasts are usually rare, small and broken, with a wide range of grain sizes within the same bed. Large crystals, usually pyroxenes, olivines or quartz crystals of metamorphic origin, are also represented in the beds but in relatively low proportions. A wide range of chemical compositions of the sideromelane glasses are present, even in the same beds. All of these characters suggest that the the clasts originated from Strombolian eruptions. In several beds, thick algae rims on individual grains indicate repeated algal blooms in the maar lake (Fig. 15). Most of the reworked tephra which makes up the delta fronts in the maar basins was not supplied
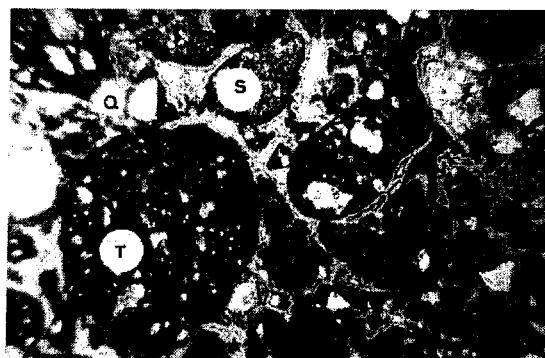

Fig. 14. Reworked tuff from fine-grained lithofacies (L2, Kiserdő-tető, Tihany) in thin section. Note the roundness of the grains as well as their dark colour rim (mostly altered glass). S, sideromelane; T, tachylite, Q, quartz. The shorter side of the picture is 4 mm.
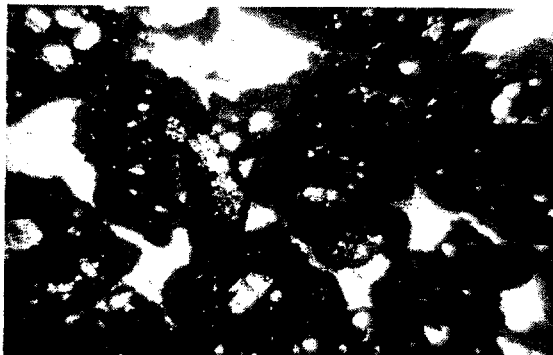
Fig. 15. Algae-rimmed scoria lapilli from reworked volcaniclastic deposits (L1, Csúcs-hegy, Tihany). The shorter side of the picture is 4 mm.

from the phreatomagmatic ejecta wall of that crater. The maar volcanoes own ejecta are usually of base surge and phreatomagmatic fallout origin, with a large amount of disrupted accidental lithics from the pre-eruptive rock formations. In contrast, the deltaic tephra in almost all locations in the BBHVF is dominantly composed of variably vesiculated tachylitic juvenile glass and lithic fragments. Sideromelane glasses of phreatomagmatic origin are usually rare and small. Thus, the Gilbert-type delta fronts represent reworked remnants of a widespread Strombolian scoria cone field on the BBHVF.

MAAR LAKE CARBONATES

In a few places in the BBHVF a thick, silicified, freshwater carbonate succession covers the volcaniclastic beds. In the Tihany Peninsula the most extensive silicified freshwater carbonate unit was deposited in a maar lake. The carbonate beds are very fine grained and well bedded (Fig. 16). The beds contain a low proportion of volcanic ash which forms dark-coloured laminae. The individual laminae are 0.1–0.7-mm thick, with each lamina representing approximately half-year deposition length, assuming that dark (autumn, winter) and light (spring, summer) laminae couplets represent a full-year depositional cycle due to effects of strong seasonality on lake deposition, similar to varvic (rhythmite) deposits in glacier lakes or other young maar lakes (e.g. Heinz *et al.*, 1993; Talbot & Allen, 1996). The total thickness of carbonate beds in Tihany reaches 10 m, which suggests a minimum of 7150 years and a maximum of 50 000 years of relatively quiet lake sedimentation. Since this calculation is

Fig. 16. Silicified maar-lake carbonate beds (ML, Csúcs-hegy, Tihany). Note the soft-sediment slumping in the lower part of the photo.

based on the current (post-erosion) thickness of the maar-lake carbonates, these estimates probably represent minimum time spans since it is unknown what thickness of sediment has been eroded in the last few million years. It is, however, noteworthy that this calculation is consistent with other calculations based on alginite and oil shale deposits which fill maar craters of the nearby Late Miocene volcanic field at the Little Hungarian Plain Volcanic Field (140 000 years – Gérce) and in the central part of the BBHVF (50 000 years – Pula) (Jámbor & Solti, 1976).

The thinly laminated carbonate deposits formed in isolated crater lakes. The laminite beds that represent lacustrine sequences were deposited by fallout from suspension, and consist of biogenic and chemically produced carbonate, together with a small amount of quartzo-feldspathic silt. The thinly laminated beds lack any signs of bioturbation, which suggests that

the bottom water was unsuitable for aquatic life (e.g. White, 1989, 1992). Thermally stratified water with only seasonal overturn, and alkali-rich crater lake water may together have been responsible for the lack of benthic organisms. The carbonate beds contain a large number of soft-sediment structures such as slumps, folds, water escape and fluidization structures (Fig. 16). The large number of hot spring pipes suggest that they played an important role in forming these sedimentary structures. Another possibility, especially in the Tihany region, is that maar eruptive centers and late Strombolian scoria cones were still active, while maar-lake sedimentation was occurring in nearby maar craters. Thus each explosion could have caused an earthquake in the region and shaken the unconsolidated sediment in the maar lake bottom nearby. Large (1-m high, 30–50 cm in diameter), ovoid shaped structures could also be interpreted as rhizoliths, as reported by Jones *et al.* (1998) from recent hot spring pools from thermal areas of New Zealand.

CONCLUSION: GENERAL MODEL

The relative abundance of the sedimentary structures and textures described above suggests that maar-lake sedimentation was an important process at the BBHVF. The higher preservation potential of maar-lake deposits as Gilbert-type delta fronts or maar-lake carbonates is probably the reason why this type of sediment is one of the most common in the BBHVF. The steeply-dipping Gilbert-type delta front beds form characteristic hills, in contrast to the usually flat-topped primary volcaniclastics. The large proportion of scoriaceous fragments in the Gilbert-type delta foreset beds is a sign of widespread Strombolian activity in the BBHVF during volcanism and maar-lake sedimentation. In recent times these eruptive centers were deeply eroded, and are now only represented by a few feeder dikes or isolated, scoriaceous outcrops. The usually N–S elongation of the individual eruptive centers and the development of the Gilbert-type deltas mainly on the north sides of the maars, suggest that the maar-forming explosions took place in a N–S-oriented fluvial system (Fig. 17).

Processes generally claimed in the literature to be responsible for sediment dispersal on the foresets and toesets of Gilbert-type bodies in normal sedimentary environments are as follows:

1 direct underflows generated by river floods;
2 basinward-flowing river plumes carrying suspended load;

3 flows related to slope failures; and (4) storm-driven seaward-directed flows, which may remove sediments from the nearshore zone and contribute gravity-driven sediment surges to the foreset slope (Massari & Parea, 1990). Of these possibilities, (2) is not relevant to freshwater deposits and (4) is unlikely since the maar basin itself is usually no more than a few kilometres (0.5–3 km) in diameter, and therefore real storm-driven flows cannot develop.

Features thought to be characteristic of fluvial-dominated Gilbert-type deltas, such as radiating, steep-walled chutes cutting foreset slopes, and the frequency of debris flows (e.g. Prior & Bornhold, 1988), have not been clearly identified on the delta fronts of crater lake deposits of the BBHVF. However small downslope-running scours (chutes) are abundant, suggesting intensive small-scale sudden mass movements on the delta flanks, which were probably generated by continuous small stream-induced underflows. Thus large fluvial systems probably did not operate during the formation of the Gilbert-type deltas, but small streams were probably common. Small debris flow deposits and erosion of channels are described. Slope failures played an exceptionally important role in the mass transfer of sediments, as is usually the case in other steep crater lakes (e.g. Büchel & Lorenz, 1993). A general model is proposed, invoking small stream systems through the former volcanic field as was modelled on the Hopi Buttes in Arizona (White, 1992) but due to lack of exposure no better reconstruction can be suggested.

In other Gilbert-type delta fronts from lacustrine or marine environments, sand-dominated foreset deposits are generally thin-bedded, graded to planar-laminated or ripple-cross-laminated, and are commonly intercalated with silt layers similarly to Lithofacies 2 (L2) in the BBHVF. These features suggest deposition by dilute underflows or turbidity currents (Jopling & Walker, 1968; Gustavson *et al.*, 1975; Stanley & Surdam, 1978; Dunne & Hempton, 1984; Flores, 1990). These processes were probably responsible for producing L2 deposits in the BBHVF.

In general, gravel-dominated foreset deposits, like Lithofacies 1 (L1) of the BBHVF, are crudely stratified, and their individual beds are difficult to discern because of abrupt lateral changes in bed thickness, grading patterns and grain fabrics. Although these features have hampered detailed facies analysis, several characteristics have been recognised in gravelly foreset deposits, such as a predominance of inverse grading, lack of mud matrix, abundance of well-sorted or openwork gravel layers and lenses, and coarsening
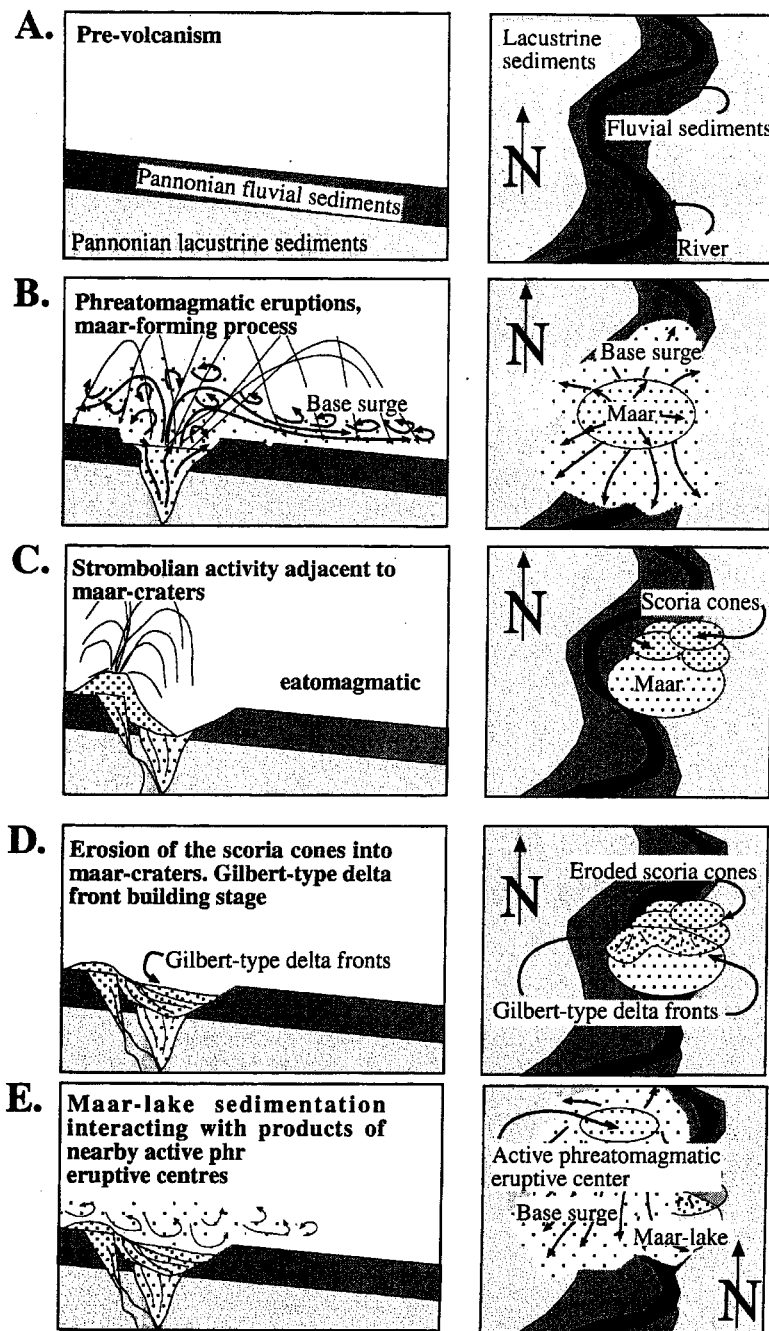
Fig. 17. Phreatomagmatic explosive activity and maar-lake sedimentation in a small stream fluvial system with Strombolian-type scoria cones, and its relation with maar-lake sedimentation. (A) Pre-volcanic shallow lacustrine and fluvial sedimentation. (B) Phreatomagmatic explosive maar-forming volcanic activity in active hydrogeological zones. (C) Strombolian activity due to the lack of water supply. (D) Intensive erosion of the maar-crater walls as well as the scoria cones into the maar basins. (E) Base surge and phreatomagmatic fallout tephra from nearby active vents depositing into a maar crater, intercalated with different type of maar-lake deposits.

of clast size towards the down-dip margin of a bed or the base of foreset slopes. Most of these features have been interpreted mainly in terms of the grain-flow theory described by Bagnold (1954), i.e. as cohesionless debris flows, modified grain flows and grain avalanches (Postma, 1984; Postma & Roep, 1985; Colella *et al.*, 1987; Massari & Parea, 1990; Mastalerz, 1990; Nemec, 1990; White, 1992). Other workers have inferred turbulent flow processes (e.g. Postma & Cruickshank, 1988).

The observed cyclic facies changes from L1 to L2 (i.e. from graded or massive (mostly coarse) beds to some kind of laminated facies), suggests an increase in flow turbulence which was probably due to a decrease in flow concentration (e.g. Postma, 1984). Highly concentrated flows dominated by frictional forces, existing as such, or segregated near the flow base by a process of 'gravity transformation' (Fisher, 1983), can 'freeze' on relatively steep slopes such as a maar-crater inner slope (20–70°), whereas more dilute flows may accelerate downslope, incorporate water, and became more mobile and turbulent (Postma & Roep, 1985). In this way the relative abundance of a particular lithofacies (L1 or L2) is related to the position of the remnant of a delta front. In the west at Tihany peninsula (Csúcs-hegy), L1 is dominant, thus this area must represent a medial position on the delta slope. The eastern delta front remnants contain progressively increasing amounts of L2, and thus represent medial to distal position on the delta slope.

A generalized schematic model is shown in Fig. 17, showing the evolution of the depositional environment of the BBHVF maar craters. Figure 17(A) and (B) shows the hydrovolcanic activity in the fluvial basin, and in Fig. 17(C) the development of the widespread Strombolian scoria cone field is shown. In Fig. 17(D) the mostly N–S Gilbert-type delta front development is reconstructed. Figure 17(E) shows the possibility of intercalated primary volcaniclastics with the ongoing maar-lake deposition. The asymmetric nature of the preserved Gilbert-type delta fronts, suggest that stream systems entrained the tephra from the northern side of the lakes.

The sediment load was probably transported and deposited in the maar lake by underflows depending on the density difference between river/stream and lake water, as was reported in a recent analogue from the Eifel District, Germany (Drohman & Negendank, 1993). Sediment-laden stream water flowed down the delta-front from N–NW to S–SE, derived probably from spring runoffs. Another possibility is that delivery of fluvial sediments to the BBHVF maar craters could have resulted in simple slope instability on the steep inner side of the maar craters, a process which is also common and well reported in the recent maar craters e.g. Ukinrek Maar, Alaska (Büchel & Lorenz, 1993).

In general, the nature of the reworked volcaniclastic beds of Gilbert-type delta fronts from the BBHVF suggest that the processes that formed these beds are similar to those described for fjord deltas and other large, coarse grained, deep water deltaic systems (e.g.

Prior & Bornhold, 1988; Kazanci, 1990; Kazanci & Varol, 1990). The striking difference between these and maar lake-evolved Gilbert-type delta fronts is that maar craters of the BBHVF were probably fed by a freely migrating small stream system transporting mostly scoriaceous tephra to the entire northern halves of the semicircular lakes. The result in most cases was a crescent-shape delta foreset that prograded directly inward from the crater wall, rather than building outward from a single, constricted point source (e.g. as in fjords), such as that described by White (1992) from maar lakes of Hopi Buttes, Arizona. The fact that all the deltaic foresets studied at Tihany are onlapped by all other crater-filling sediments (silicified maar-lake carbonates), indicates that the deltas developed relatively early in the craters' history, which is similar to what White (1992) reported from the maar lakes of Hopi Buttes, Arizona.

Another striking similarity to the Hopi Buttes maar craters is that deposits within these craters show very limited input of their own ejecta (e.g. phreatomagmatic ash – sideromelane). This emphasizes that maar-crater deposits are largely insensitive to their own eruptive processes, but are more sensitive to the sedimentary environment into which the volcanoes erupted and the post-eruptive sedimentary environment of the surrounding area.

According to the reconstructed N–S small stream systems during the volcanism, the paleogeomorphology of the region was probably very similar to that seen at the present day, with small stream systems and large swampy areas between gentle hill sides, as it has been since the Pleistocene (e.g. Cserny, 1997).

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Nemeth K

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