

**PLIOCENE CRATER LAKE DEPOSITS AND SOFT-SEDIMENT DEFORMATION  
STRUCTURES ASSOCIATED WITH A PHREATOMAGMATIC VOLCANO:  
PULA MAAR, WESTERN HUNGARY**

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**Abstract:** Pula maar is a Pliocene eroded, phreatomagmatic volcano, part of the Mio/Pliocene Bakony-Balaton Highland Volcanic Field. The remnant of the maar consists of a (1) distinct depression with a thick alginite, lacustrine laminite infill interbedded with coarse grained lapilli tuffs, (2) a narrow belt of a primary pyroclastic unit (tuff ring) in the marginal zone of the depression (erosion remnant of the tuff ring) and, (3) a reworked coarse-grained volcanoclastic unit in the marginal zone. . Paleo-earthquakes associated with ongoing nearby volcanic eruptions and/or large volume debris flows initiated by crater wall collapses into the maar crater lake are inferred to be responsible of formation of soft sediment deformation of fine-grained volcanoclastic sediments.

**Keywords:** tuff ring, maar, crater lake, debris flow, turbidite, slumping

### **Introduction**

The intracontinental alkaline basalt volcanism at the Bakony- Balaton Highland Volcanic Field (BBHVF), western Hungary (Fig. 1) was active between 7.56 and 2.3 Ma (Balogh et al. 1986; Borsy et al. 1986; Balogh 1995). During the volcanic activity, short lived (days to month) monogenic volcanoes (Walker 2000) were formed and preserved such as erosional remnants of tuff rings, maars, scoria cones or basaltic mesa flows (Németh & Martin 1999). Maars and tuff rings have wide craters surrounded with often incomplete, crescent-shape phreatomagmatic tephra ring (Vespermann & Schmincke 2000). The maars are generally characterised by subsided crater floor, which form after the phreatomagmatic eruption due to collapse and subsidence of loose country rock and pyroclasts in a funnel shape volcanic conduit (Lorenz 1986). There is no sharp difference between tuff rings and maars in general,

their tephra ring consists of similar accidental lithic clast-rich lapilli tuffs and tuffs rich in fragments of disrupted country rocks. Craters are commonly filled by water relatively quickly (days to months) from the water table disrupted by the phreatomagmatic. These crater lakes function as sedimentary traps in which loose tephra from the surrounding crater rim is transported (White 1992). Due to the steep inner crater wall of these volcanoes, sediment transported by energetic debris flows, (modified) grain flows as well as normal deep water turbidity currents (Smith 1986). In remnant hydrovolcanic fields these crater lakes may preserve a unique sedimentary record of an entire area (Kulbe et al. 2000; Zolitschka et al. 2000). From the BBHVF, alginite (oil-shale) studies in the past decades have characterised laminated sediments formed in closed crater lakes such as Pula or G erce (J ambor & Solti 1976; Hably & Kvacek 1998; Willis et al. 1999; P apay 2001). However, only recently the importance of studies aiming in the description and interpretation of the sedimentary processes that are involved in the formation of these (N emeth 2001) maar pitted basins. We therefore here intend to give a short description of the pyroclastic and maar crater deposits of Pula maar and highlight the importance of distinguishing primary, intra- and extra-crater sedimentary processes that operate in association with a hydrovolcanic field.

### **Volcaniclastic succession of Pula**

The Pula crater is a north-south elongated depression, currently forming a maximum 50 m deep basin (Fig. 1). The volcanic-related rocks have been grouped into four major lithofacies on the basis of their bedding, sorting, grading and compositional characteristics. The central part of the volcanic depression is filled with finely bedded, laminated, normally graded, fine-grained volcanic silt and sandstone with angular quartz and minor (up to 20 vol %) non-to-weakly vesicular, non-abraded tephrite to phonotephrite glass shards (**facies 1 - central laminated**). The mantle bedding, normal grading and the well-bedded characteristics of these beds indicate turbidite sedimentation (Walker 1992; Drohmann & Negendank 1993). Thicker bedded, coarse-grained lapilli tuff beds are predominantly inverse-graded indicative of grain flow deposition (**facies 2 - central juvenile-rich facies**) (White 1992). Tephrite/phonotephrite glass shards in beds of **facies 2** are weakly vesicular, microlite poor and blocky (Fig. 2) suggesting a phreatomagmatic explosive origin during their formation (Heiken 1974). Such glass shards were derived from the crater rim due to slumping and collapsing of part of the loose phreatomagmatic tephra surrounding the crater lake such processes are observed in young maar volcanoes (B uchel & Lorenz 1993). The coarse-grained beds often truncate underlying laminae causing dewatering-structures, soft sediment deformation and

development of dish structures (Fig. 3). All these features suggest active syn-sedimentary slumping and shaking, and are interpreted as debris flow and/or turbidity current emplacement from the crater rim accompanied by paleo-earthquakes (Pirrung et al. 2001). The marginal area of the depression are formed by a narrow belt of phreatomagmatic lapilli tuff and tuff beds (**facies 3 – tuff ring facies**; ~ 30 m thick). This lithofacies consists of rim-type accretionary lapilli bearing (Schumacher & Schmincke 1991), accidental lithic clast-rich, cross- and dune bedded lapilli tuffs/tuffs, which are inferred to be primary in origin (Bull & Cas 2000). They dip toward the centre of the basin or are subhorizontal. Flow indicators suggest that their source was in the centre of the depression. The fourth facies (**facies 4 – volcanoclastic debris flow facies**), a pyroclastic (~20 m) is related to the marginal primary pyroclastic facies (facies 3), which dips at 20-30° towards the centre of the depression. Sedimentary features of the volcanoclastic beds of facies 4, such as 1) presence of large (dm-scale), semi-rounded lapilli tuff fragments in the volcanoclastic beds, 2) high percentage of carbonate cement, 3) larger proportion of broken, angular pyrogenic and/or xenocrystals (mostly olivine and clinopyroxene) and the lack of primary origin indicators (e.g. lack of accretionary lapilli) suggest a reworked origin by debris flows, which are generated on the inner wall of the crater (White 1992; Fisher et al. 2000). The large (dm-scale) floating lumps of lapilli tuff fragments in these beds, the unsorted, matrix-supported texture and disoriented fabric of the rock all support to interpret that the material was transported then deposited by energetic debris flows in the inner wall of the crater by similar way how it was reconstructed from Hopi Butte (White 1992). The common presence of abraded pyroclastic fragments in these beds show that already diagenised pyroclastic rocks existed prior to their disruption, however their origin is inconclusive and either could represent 1) pyroclastic rock fragments that were disrupted by the phreatomagmatic eruption of the Pula maar and incorporated into its own tephra as accidental lithic fragments or 2) an already diagenised part of the Pula maar's own tephra ring that was eroded into the maar crater. The large number of coherent lava clasts in reworked volcanoclastic beds (facies 4), their diverse shape and textural characteristics (microcrystalline to aphanitic) indicates that older lava units were disrupted by the phreatomagmatic volcanic eruption(s) of Pula and subsequently reworked in form of debris flows that developed on the collapsing inner wall of a phreatomagmatic volcano. In this study clear sedimentological evidences show that monogenetic volcanism in western Hungary had different phases as well as significant time span (in comparison to the length of a usual monogenetic phreatomagmatic volcano life span – days to weeks) between eruptions allowing disruption of earlier emplaced lava flows and pyroclastic units.

## Conclusion

Paleogeographical reconstruction focused on the crater lake deposition and their implication in understanding monogenetic volcanism in the region. This study suggests that the original maar basin at Pula was larger than previously suggested, showing the complexity of different depositional processes involved in the formation of such crater lake deposits. a well exposed example. The pyroclastic sequence of Pula is interpreted to be a typical accidental lithic clast-rich lapilli tuff and tuff unit, showing indications that suggest a „damp and sticky” depositional environment. The preserved pyroclastic units record near-vent depositional environment, presumably close to the crater depression. In dissected outcrops, volcanoclastic debris flow deposits have been identified and interpreted to represent energetic debris flows which transported volcanic detritus into the crater lake from the tephra rim. This deposits were rich in intact pyroclastic rock fragments inferred to be a signature of the existence of already consolidated pyroclastic rocks that were recycled into the crater lake. The central lacustrine facies consists of laminated deposits (e.g. alginite) inferred to represent long, quite, intermittent depositional (thousands of years) period.

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**Fig. 1**

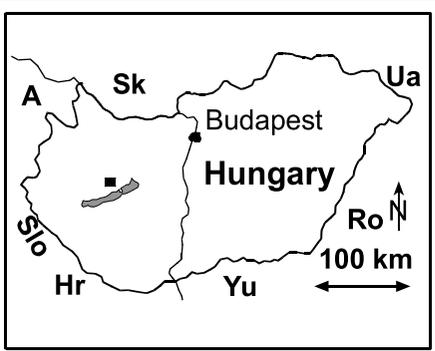
Simplified geological map of the Pula maar.

**Fig. 2**

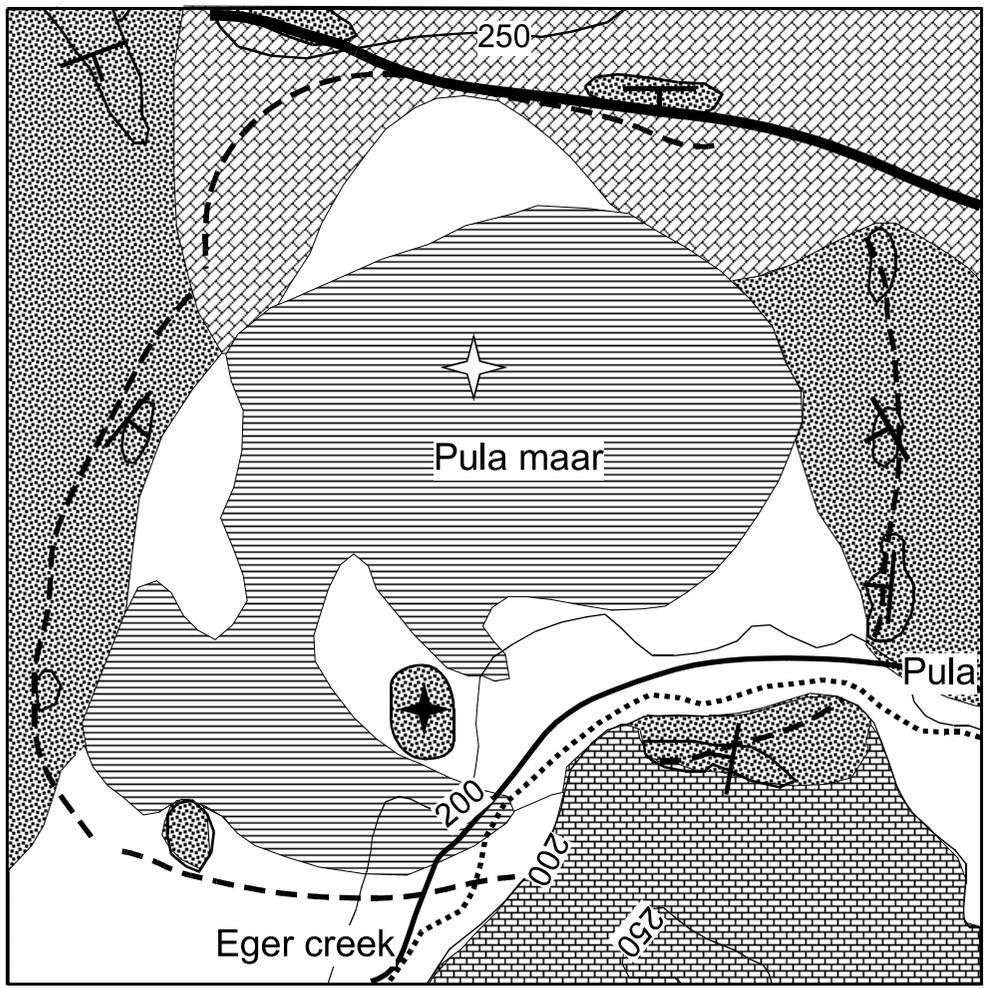
Sideromelane glass shards (microcrystalline angular clasts) forming inverse graded lamina in facies 2 in the central part of the preserved maar lacustrine units. Note the large amount of quartz (white, angular clasts). Paralell polarized light. Shorter side of view is ~ 4 mm.

**Fig. 3**

Truncated load cast and dewatering structures cause by the sudden input of volcanic glass shard laden tephra into the Pula crater lake. It is inferred to be transported by turbidity currents. The twisted load casts may be dirrect results of paleoearthquackes, however, this interpretation still needs more work to be prooven. Long side of view is ~ 35 cm.

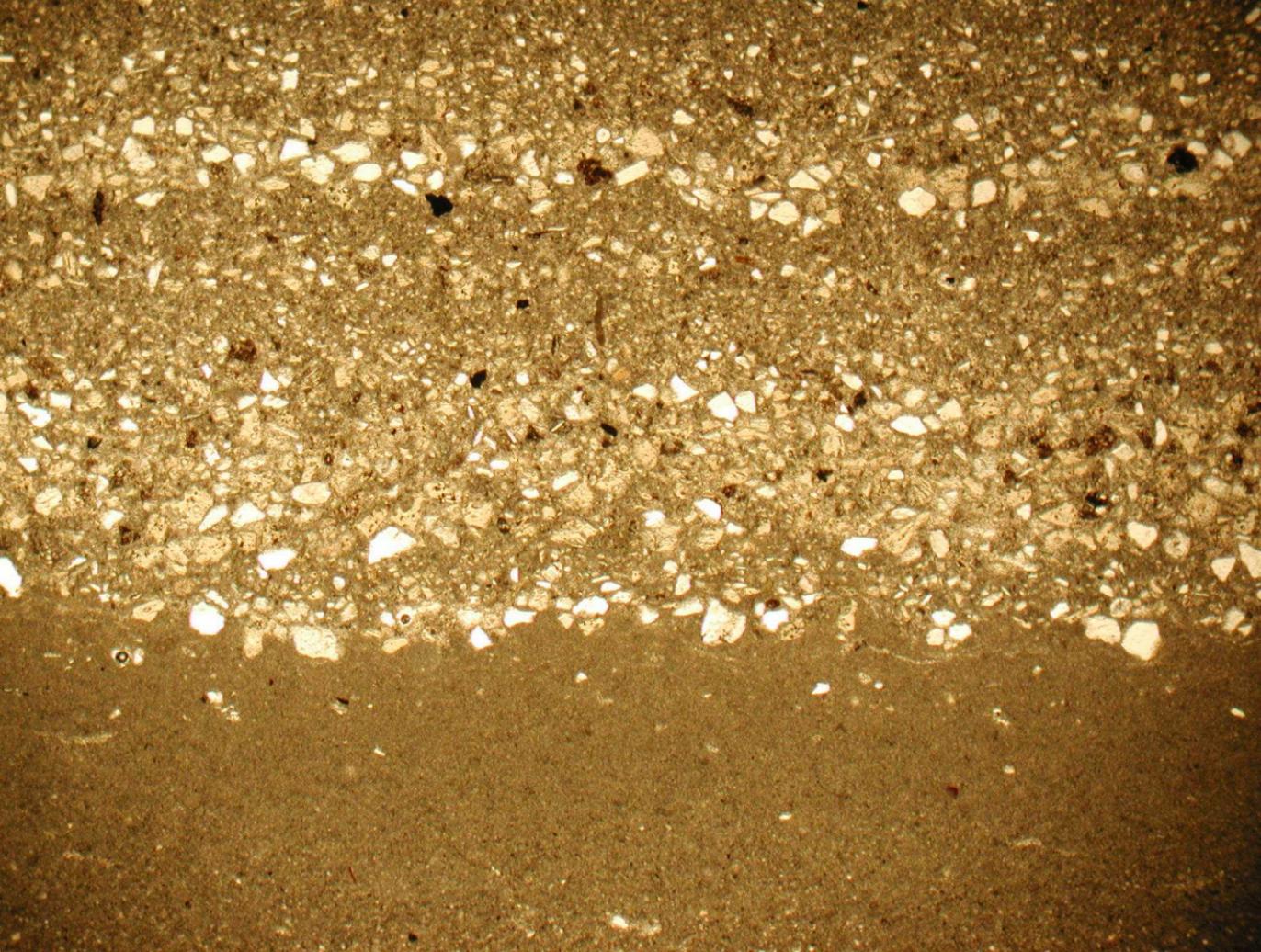


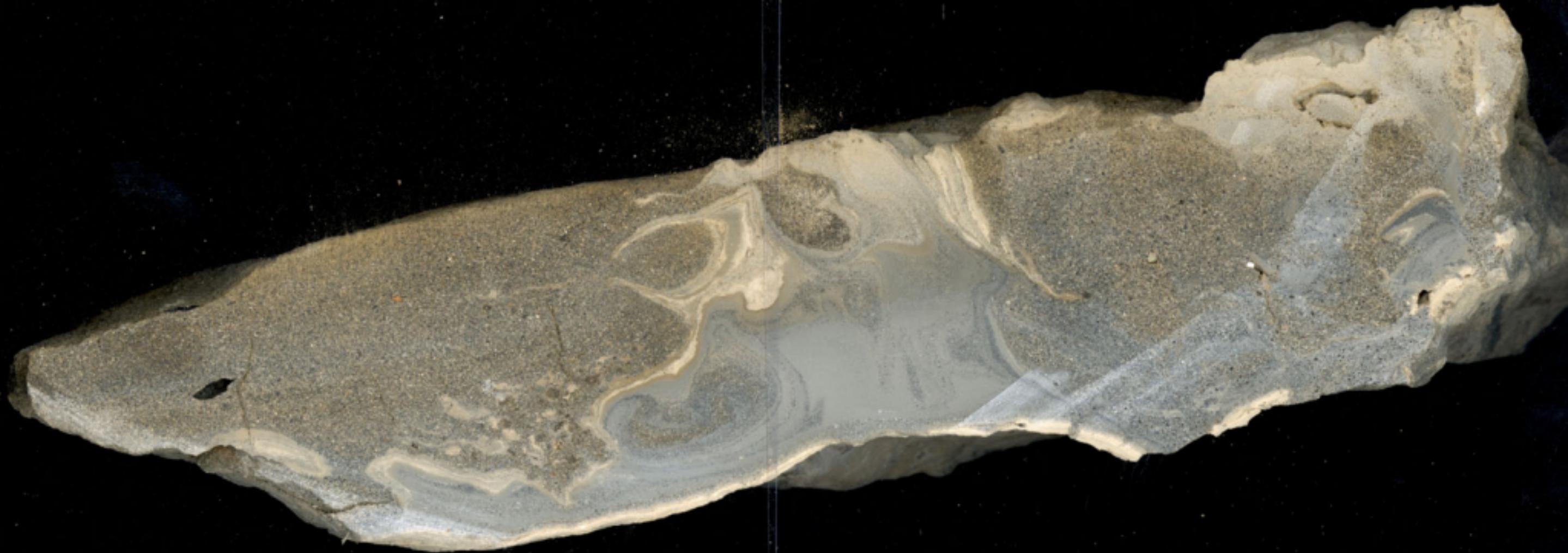
-  Quaternary deposits
-  Central lacustrine crater lake facies
-  Volcaniclastic rocks
-  Miocene freshwater carbonate
-  Triassic carbonate
-  Outcrops in original position
-  Bedding
-  Geyserite
-  Proposed position of crater rim



-  Highway
-  Quarry

500 m





Pliocene crater lake deposits and soft  
sediment deformation structures associated  
with a phreatomagmatic volcano, Pula  
maar, western Hungary.

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