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Reconstructing paleoenvironment, eruption mechanism and paleomorphology of the Pliocene Pula maar, (Hungary)

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ABSTRACT

Pula maar is a partially eroded Pliocene maar-diatreme volcano, part of the Mio-Pliocene Bakony-Balaton Highland Volcanic Field. The surficial remnant of the maar-diatreme volcano consists of (1) a distinct depression with a thick post-eruptive lacustrine alginite sediment infill interbedded with coarse-grained volcaniclastic sediments, (2) a narrow marginal zone inside the depression consisting of primary pyroclastic rock units that are interpreted to be partly collapsed and subsided blocks of entire sections from the tephra ring formerly surrounding the maar crater depression, and (3) coarse-grained volcaniclastic debris-flow deposits closely associated with the collapsed primary pyroclastic rock units in the marginal zone. The presence of coherent lava rocks below the crater-fill units, their distribution pattern and their association with scoriaceous beds indicate that, after the maar-diatreme-forming phreatomagmatic explosive activity, small (100 m-scale) scoria and/or spatter cones erupted in the maar crater. These cones are the likely source of the lava flows that partially filled the maar crater basin. The widespread dm-to-m thick basaltic sand and/or silt units at the base of the post-eruptive crater-filling sedimentary succession are interpreted to be reworked volcaniclastic material from the intra-maar scoria/spatter cones as well as from the tephra ring. Based on comparative analyses of 53 core descriptions, this study reveals that the original maar crater basin was larger than previously suggested. The deep level of the maar crater is reconstructed to be a northeast–southwest elongated depression, currently forming a c. 50-m-deep basin. Geomorphological considerations suggest that most of the phreatomagmatic pyroclastic rocks are composed of base surge and tephra fall deposits around the deep maar depression. These allochthonous rock units form a 50–400 m wide zone of proximal tuff-ring sequences. The formation of this zone is inferred to be a result of a combination of syn-eruptive subsidence due to mass deficit in the rigid Triassic dolomite basement caused by the phreatomagmatic explosions as well as post-eruptive subsidence of the crater- and diatreme-filling successions due to diagenetic compaction. The facies in the centre of the maar lake is a soft laminated "alginite" (mainly Botryococcus colonies, diatom frustles, calcium carbonate crystals, clay minerals). In the section exposed in the Pula open cast mine, a single turbiditic layer is present. This layer originated in a landslide, which possibly could have been caused by either syn-eruptive earthquake and/or a sudden post-eruptive subsidence event of the diatreme fill.

1. Introduction

Monogenetic volcanoes are, in general, short-lived (days to years) volcanoes that form scoria cones resulted from mild to violent Strombolian-type of eruptions (Martin and Németh, 2006; Pioli et al., 2008; Valentine and Gregg, in press) and associated lava flows, maar-diatremes, tuff-rings and tuff cones. Maars and tuff-ring s have wide craters surrounded by a circular to oval, rarely crescent-shaped, phreatomagmatic tephra ring (Fisher and Schmincke, 1984; Lorenz, 1986; Cas and Wright, 1987; Vespermann and Schmincke, 2000; Németh and Martin, 2007). The maars are generally characterised by a subsided crater floor, which forms during and after the phreatomagmatic eruptions due to collapse and subsidence of country rocks and pyroclastic deposits in a funnel-shaped volcanic conduit, i.e. in the diatreme (Lorenz, 1986; White, 1991; Lorenz et al., 2003). Crater-floor subsidence continues after the eruption (Suhr et al., 2006) causing collapse of the freshly deposited phreatomagmatic tephra ring, as is commonly recorded in many young and old, eroded maar-diatreme volcanoes (Kienle et al., 1980; Büchel and Lorenz, 1993; Pirrung et al.,

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2003; Grünewald and Büchel, 2004). It has also been observed in recent maar crater rims (Wagner et al., 2003; Moreaux et al., 2004). A tephra ring section that becomes unstable may also form lahars (Giordano et al., 2002; Lorenz, 2007), and in rare cases part of the tephra rings could subside, as has been documented for the lower Permian volcanic pipes of Rödern and Hirschberg in the Rotliegend soft sediments (Germany) and overlying lava flow (Lorenz, 1971).

Within days to months after the eruption, the craters of maar-diatreme volcanoes are commonly filled by groundwater from aquifers disrupted by the phreatomagmatic explosive eruption. These crater lakes function as sediment traps into which tephra from the surrounding tephra ring is transported (Smith, 1986; White, 1992). Due to the steep inner crater wall of these volcanoes, sediment could be transported by energetic debris flows, (modified) grain flows as well as normal turbidity currents (Smith, 1986; Drohmann and Negendank, 1993; Fisher et al., 2000; Pirrung et al., 2001; Pirrung et al., 2003; Pirrung et al., 2008). Eolian sediment is also a very important component in the crater fill of many maars especially in arid climate such as the SW-USA (White, 1989; White, 1990).

In partially eroded phreatomagmatic volcanic fields such as the Mio-Pliocene alkali basaltic volcanic fields in the western Pannonian Basin, these crater-lake sediments preserve a unique sedimentary record documenting the environmental and climatic history of the surroundings of the maar volcano (Ashton and Schoeman, 1983; Vos et al., 1997; Ramrath et al., 1999; Brauer et al., 2000; Goth and Suhr, 2000; Leroy et al., 2000; Zolitschka et al., 2000a; Zolitschka et al., 2000b; Dimitriadis and Cranston, 2001; Pápay, 2001; Scharf et al., 2001; Hayward et al., 2002; Mingram et al., 2004; Sachse, 2005; Franzen, 2006).

In this paper, we reconstruct the paleoenvironment, eruptive style and paleomorphology of Pula maar from the central part of the Bakony-Balaton Highland Volcanic Field (Martin and Németh, 2004), Hungary (Fig. 1). On the basis of its unique stratigraphic position, Pula became one of the key locations for Neogene stratigraphy studies to demonstrate the coeval timing of Pliocene volcanism in the western Pannonian Basin and with ongoing lacustrine sedimentation within the Pannonian Lake (Jámbor and Solti, 1975, 1976; Jámbor, 1980; Jámbor et al., 1981; Jámbor, 1989). More recently, independent field data demonstrated that extensive lacustrine sedimentation in the extensive Pannonian Lake ceased well before the eruption of the Pula maar-diatreme volcano (Magyar et al., 1999; Sacchi et al., 1999; Sacchi and Horváth, 2002; Magyar et al., 2006; Magyar et al., 2007) and, therefore, a reinterpretation of the Pula maar-diatreme volcano with its volcano-sedimentary stratigraphy as well as its eruption mechanism is necessary. In addition, Pula maar was among the first locations in Europe where maar lake deposits (alginite) were mined commercially for agricultural purposes, having been active since the 1980s (Jámbor and Solti, 1976; Solti, 1986, 1987). The mining operation at Pula generated in a large number of drill-cores that were not studied from a volcanological point of view. Unfortunately the original cores were lost, and therefore the current study relied entirely on the technical descriptions of the drill logs filed in the Data Repository of the Geological Institute of Hungary. The re-evaluation of the technical reports on the lithofacies identified in the 53 drill-cores was accomplished in a comparative way and supported by extrapolation of field observations of volcanic lithofacies exposed in the surface around the depression of Pula. Field experience and research over the past ten years on pyroclastic rocks in western Hungary (Martin and Németh, 2004, 2005, 2007) also helped to identify key textural characteristics in the technical reports. Here we summarize the general field observations and the available drill-core data with the aim to produce a modern model for the eruptive mechanism, paleoenvironmental reconstruction and the erosion history of the Pliocene Pula maar.

2. Geological setting

Pula is a Pliocene maar-diatreme volcano in the eastern part of the Bakony-Balaton Highland Volcanic Field (BBHVF) (Martin and Németh, 2004) (Fig. 1). A succession of Upper Triassic carbonates more than 1000 m thick forms the basement of Pula (Budai and Vörös, 1992; Budai and Haas, 1997; Budai and Csillag, 1999; Budai et al., 1999). This unit is topped by a c. 300-m-thick shallow marine to lacustrine siliciclastic succession (Jámbor, 1980, 1989; Budai and Csillag, 1999; Budai et al., 1999). The volcanic structure of Pula is sandwiched between two NE–SW trending strike-slip faults that were active during the syn-rift phase of the Pannonian Basin about 18–11 million years ago (Budai et al., 1999; Dudkó, 1999; Fodor et al., 2005). The intracontinental alkaline basalt volcanism at the BBHVF, western Hungary (Fig. 1) was active between 7.92 and 2.3 Ma (Balogh et al., 1982, 1986; Borsy et al., 1986; Balogh and Pécskay, 2001; Balogh and Németh, 2005; Wijbrans et al., 2007). Age determination on alkaline basaltic lava rocks just south of the Pula volcanic depression (Tálodi-erdő) (Fig. 1) gave a whole rock K–Ar age of 5.02 +/− 0.39 Ma, from lava rocks in the 3.0 to 7.3 m interval below the surface from the Put-2 core (Fig. 1) (Balogh et al., 1982). Samples collected from surface exposures of the same lava flow just south of the Put-2 location yielded 5.06 ± 0.22 Ma K–Ar dates (Balogh et al., 1982). Many lava flows from the southern flank of the nearby shield volcano Kab-hegy, just north of the Pula depression (Fig. 1) range in age from 4.65 +/− 0.23 to 4.79 +/− 0.39 Ma (Balogh et al., 1982). Few K–Ar age data are available from the coherent lava rocks derived from the volcanic succession of the Pula maar-diatreme volcano. A rock sample of the lava flow recovered from the 40.0–40.5 m depth interval from the Put-1 drill-core in the centre of the Pula depression (Fig. 1) gave a K–Ar age of 4.23 +/− 0.32 Ma (Balogh et al., 1982). Lava samples from the same drill-core but from a deeper level (144.5–147.0 m) gave a K–Ar age of 3.92 +/− 0.96 Ma (Balogh et al., 1982). Other K–Ar age data are 4.28 +/− 0.26 Ma from Put-8 and 4.16 +/− 0.27 Ma from Put-14 (for their locations see Fig. 1). These age data from the surrounding lava fields of Kab-hegy and Tálodi-erdő as well as from the drill-cores of Pula are of similar age as they lie within the error of the measurements, indicating largely coeval volcanism in the region. Textural similarity of volcanic lithic fragments in the phreatomagmatic pyroclastic succession of Pula to the texture of the lava flow of the Kab-hegy–Tálodi-erdő suggests that the explosive eruptions disrupted lava flows once connected to the nearby Kab-hegy and Tálodi-erdő (Fig. 1), therefore Pula is inferred to post-date these lava flow fields. The accumulated laminated lacustrine sediments in the Pula maar lake are inferred to be annually

Fig. 1. Overview map of the Carpathian–Balkan–Pannonian region shows the western Hungarian Late Miocene–Pliocene intracontinental volcanic fields in the centre part of the region (rectangular on inlet map on "A"). A) Late Miocene to Pliocene intracontinental volcanic fields form group of eroded monogenetic volcanic edifices, predominantly phreatomagmatic volcanoes (diatremes, dyke and sill swarms, plugs, lava flows). In the territory of Hungary the volcanic erosion remnants are grouped into two fields (BBHVF—Bakony-Balaton Highland Volcanic Field, LHPVF—Little Hungarian Plain Volcanic Field). Pula maar is located in the centre part of the BBHVF (red rectangular field). B). The Pula maar has been drilled by shallow exploration wells (numbers s.b.) to define the total volume of the accumulated crater-lake sediments (alginate) that has economic interest in the region. Dashed lines: cross section transects of Fig. 3. Violet line: alginate quarry. Red Line: contour of the maar crater wall on the basis of the drill core. This area represents the locations where drill-cores encountered volcaniclastic units. Blue line: area where drill-cores encountered maar lake sediments (alginite). 1—PULA-2; 2—PULA-11; 3—Öcs-12; 4—PULA-7; 5—PULA-3; 6—PULA-5; 7—Put-10; 8—PULA-6; 9—Put-19; 10—Put-7; 11—Put-32; 12—O-17; 13—PULA-4; 14—Put-20; 15—Put-18; 16—Put-17; 17—Put-16; 18—Put-28; 19—Put-35; 20—Put-34; 21—Put-27; 22—Put-8; 23—Put-33; 24—Put-30; 25—Put-9; 26—Put-31; 27—Put-29; 28—Put-23; 29—Put-11; 30—PULA-9; 31—Put-38; 32—Put-24; 33—Put-25; 34—Put-3; 35—Put-1; 36—Put-37; 37—Put-12; 38—Put-36; 39—Put-39; 40—PULA-8; 41—PULA K-2; 42—Put-22; 43—Put-6; 44—Put-26; 45—Put21; 46-Put—5; 47-Put—13; 48-Öcs—11; 49-Put—15; 50-Put—14; 51-PULA—10; 52-PULA—1; 53-PULA—12; 54-Öcs—14; 55-Öcs—18; 56-Öcs—34; 57—Put-2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)