# The youngest volcanic eruptions in East-Central Europe – new findings from the Ciomadul lava dome complex, East Carpathians, Romania

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## Abstract

*Violent explosive eruptions occurred between c. 51 and 29 thousand years ago—during the Last Glacial Maximum in East-Central Europe—at the picturesque volcano of Ciomadul, located at the southernmost tip of the Inner Carpathian Volcanic Range in Romania. Field volcanology, glass geochemistry of tephra, radiocarbon and optically stimulated luminescene* *dating, along with coring the lacustrine infill of the two explosive craters of Ciomadul (St Ana and Mohos), constrain the last volcanic activity to three subsequent eruptive stages. The explosivity was due to the silicic composition of the magma producing Plinian-style eruptions, and the interaction of magma with the underlying, water-rich rocks resulting in violent phreatomagmatic outbursts. Tephra (volcanic ash) from these eruptions are interbedded with contemporaneous loess deposits, which form thick sequences in the vicinity of the volcano. Moreover, tephra layers are also preserved in the older Mohos crater infill, providing an important archive for palaeoclimate studies. Identifying the final phreatomagmatic eruption of Ciomadul at c. 29.6 ka, which shaped the present-day landform of the 1600-m-wide St Ana explosion crater, we were able to correlate related tephra deposits as far as 350 km from the source within a thick loess-palaeosol sequence at the Dniester Delta in Roxolany, Ukraine. A refined tephrostratigraphy, based on a number of newly found exposures in the Ciomadul surrounding region as well as correlation with the distal terrestrial and marine (e.g. Black Sea) volcano-sedimentary record, is expected from ongoing studies.*

The Carpathian Basin, or geologically speaking the Carpatho-Pannonian Region (CPR), is not particularly well known for its volcanic activity. From a geological point of view, its valuable, rare minerals (several of which were described in the 18th century from volcanic mountains), the unusual rock assemblage of the Ditrău Massif in the East Carpathians (that gave input to A. Streckeisen for his famous petrographic classification), or the early 20th century and recently discovered dinosaur fossil findings in Transylvania (Romania) and the Bakony Mountains (Hungary), respectively, are more obvious pieces of international recognition. In addition, the torsion balance developed by the physicist Baron Loránd Eötvös

(1848-1919) to measure fine differences in gravity should also be mentioned, which provided a tool to exploration geophysicists to discover the deep structure of the Carpathian Basin.

The vicinity of Lake Balaton in Hungary, located in the western part of the CPR, is amongst the best known examples of volcanic activity within the CPR. Several tens of volcanic centres constitute the Bakony–Balaton Upland Volcanic Field that consists of maars, tuff rings, and amazing basalt buttes (e.g., Badacsony Hill). However, in contrast to these and other predominantly Pliocene to Early Pleistocene alkali basaltic igneous centres, which are volumetrically insignificant and scattered throughout the basin as monogenetic fields, there is an almost continuous, much more voluminuous Inner Carpathian Volcanic Range. This Range extends from the Northwest to the East Carpathians through present-day Slovakia, Hungary, Ukraine, and Romania. The c. 650 km-long chain of volcanic mountains, up to 1500-2000 m in elevation, was active from Miocene to latest Pleistocene times. Associated, intense hydrothermal ore mineralisation produced rich gold and silver reserves (e.g. Telkibánya in North Hungary) which were used for coinage in medieval times. In addition, extensive rhyolite and dacite tuff sheets (mostly ignimbrites) of Miocene age were also formed throughout the basin, resulting from colossal explosive eruptions in extensional settings. However, with a few exceptions, these latter formations have been subsided in the past millions of years beneath the sedimentary infill of the Hungarian Plain and also in Transylvania due to syn- and post-rift phases of basin formation.

The plate tectonic interpretation of this superb but extinct volcanic activity is rather complex, almost to the same extent as that of Italy. Apart from the alkali basalts that resemble the peri-Alpine occurrences of deep mantle origin, there is a strong calc-alkaline character of many volcanic fields, indicating contemporaneous or inherited subduction. The CPR consists of two continental micro-plates, the so-called Alpine-Carpathian-Pannonian “ALCAPA” and the Tisza-Dacia, which moved to their present position due to the closure of the Tethys by the northward pushing African plate. As a result, subduction of land-locked oceanic basins, collision along the orogen, and extension in internal (e.g. back-arc) areas were responsible for triggering the above-mentioned wide variety of Neogene to Quaternary volcanism. The youngest volcanic segment of the CPR extends along the inner side of the East Carpathians (Fig. 1), from the northern Călimani to the southern Harghita Mountains, where typical calc-alkaline, intermediate (mostly andesitic) volcanic activity shows a well-defined age progression from 10 million to 30 thousand years (ka) ago. This atypical along-arc migration of volcanism was interpreted as a result of oblique subduction that forced the zone of magma genesis to move progressively southward.

## Ciomadul: Late Pleistocene explosive activity within the past 50 ky

The youngest volcanic activity within the East Carpathians, and that of the entire CPR, occurred at the very end of the arc at Ciomadul (or with its original Hungarian name, Csomád) volcano (Fig. 2). At the chain terminus of South Harghita, this touristic, pine-forest covered mountain is a complex of scattered or superimposed 1000–1300 m high lava domes rather than a single volcanic edifice. The highest, amalgamated part of the volcano (1301 m at Ciomadul Mare) hosts scenic twin craters—lake St Ana and Mohos peat bog—the formation of which is interpreted as truncating a central dome complex by late-stage explosive eruptions. The rim of the eastern Mohos crater as well as the southern flanks of St Ana crater are mostly composed of unconsolidated volcaniclastic, mostly pyroclastic deposits (volcanic ash and pumice).

Ciomadul's rock type is porphyritic dacite (Fig. 3), with a mineral assemblage of plagioclase, amphibole, biotite, and occasional clinopyroxene, orthopyroxene, quartz, Kfeldspar and olivine. Geochemically, the dacites belong to the potassium-rich rocks of the South Harghita volcanic segment.

Showing a “youthful” morphology and being rich in gas emanations (mofettes), the relatively young age of the volcano was already noticed in the past centuries. Modern stratigraphic studies based on sedimentary relationships verified this view, but reliable age constraints for an unambigously Late Pleistocene activity have only been provided in the era of radiometric dating. It turned out that, subsequent to predominantly effusive lava dome activity, the last, mostly explosive eruptions of Ciomadul occurred within the past c. 50 ky. Such young volcanism, rather unique in Central Europe, has attracted a growing interest by geoscientists, and, in the past decade, a number of international research teams have have worked in the area with a focus on volcanology, geochronology as well as palaeoenvironmental studies.

Our group, by integrating various interdisciplinary methods, significantly refined the picture of the last eruptive period of Ciomadul. We can now distinguish three major eruptive stages between *c*. 51 and 29 ka, and, in particular, identify the timing of the last violent eruption of the volcano at *c*. 29.6 cal ka bp (calibrated $^{14}$C age in ka bp (before present)). The highly explosive character of these latest volcanic eruptions is explained by the high gas content of the magma, producing so-called Plinian-style eruptions, or the interaction of the magma with underlying water-rich rocks, that resulted in phreatomagmatic activity.

Although the modern landscape is afforested, the pyroclastic deposits of Ciomadul can be studied in steep-sided gullies, slump scars and ‘sand quarries’, which, in fact, are sand-loess deposits with interbedded volcanic ash (tephra) layers (Fig. 4). Moreover, tephra deposits can be recovered from the lacustrine infill of Mohos crater, which turned out to be significantly older than the St Ana crater. The present-day, *c*. 1600 m wide St Ana crater was shaped by the very last *c*. 29.6 ka eruption; its lacustrine succession, therefore, does not contain tephra from previous eruptions.

Out of the three major eruptive stages, we have identified a two-phase Plinian stage that occurred at *c*. 31.5 ka. This eruption, one of the largest and most spectacular, may have been initiated by quiescent lava dome extrusion between *c*. 40 and 32 ka bp in a ‘Proto’ St Ana crater that was probably smaller than now. We suggest that during the 31.5 ka explosive eruption, at first the lava dome was destroyed, and resulting pyroclastic flows were associated with short-lived Vulcanian eruption column (or fountain) collapses. These latter produced pumiceous block-and-ash flows that spread to the southern and south-eastern flanks of Ciomadul. In the final phase, a Plinian column may have emerged from an open vent, possibly tens of kilometres high, generating pumice fallout recognised in distal areas. A classic exposure of this eruption reveals a 0.6 m-thick pumice-fall deposit (with pumice clast diameters up to 5 cm) *c*. 21 km southeast of St Ana crater (Fig. 5).

## The lacustrine infill of the Mohos and St. Ana craters: tephrostratigraphy and palaeoclimate implications

The Carpathian Mountains have long been known as one of the main refugia for boreal and cool temperate flora during the Last Glacial Maximum (LGM) in East-Central Europe. However, the scarcity of records covering many thousands of years precluded our understanding so far. This situation was recently improved at first through the investigation of lacustrine sediments deposited in the younger St. Ana crater (Fig. 6A). The new record of past vegetation, fire dynamics and lacustrine sedimentation allowed examining in detail the nature of environmental changes in this region during the LGM and the subsequent deglaciation. The vegetation record indicates the persistence of boreal forest steppe vegetation (with Pinus, Betula, Salix, Populus and Picea) in the foreland and low mountain zone of the East Carpathians, and Juniperus shrubland at higher elevations. The sedimentological data also demonstrate intensified aeolian dust accumulation in the lake between 26-20 ka BP and increased regional biomass burning between 23-19 ka BP, suggesting increased continentality in climate (following the deglaciation, the plant macrofossil record indicates establishment of *Betula*, *Pinus* and *Larix* species around the lake up to the Holocene).

The larger and older Mohos crater, which preserves at least 60 m of lacustrine sediments, has only recently been cored down to a depth of 30 m (Figs 6B, 7). Apart from the top 10 metres of peat that covers the last 10 ka (the Holocene), the rest of the record consists of lake sediments. A series of interbedded coarse tephra layers which originated from nearby eruption centres yields an excellent opportunity to link these records to medial and distal occurrences, and to compare past rates of environmental change. In particular the youngest tephra, assigned to the last *c*. 29.6 ka eruption of the St Ana crater, provides a fantastic correlation marker to a distal phreatomagmatic ash that has been identified *c*. 350 km east of Ciomadul in the loess fields of Roxolany at the Dniester river delta in the southern Ukraine. This means that the Late Quaternary Carpathian volcanism had the potential to distribute tephra layers over a large area as far as the Black Sea, which may be used as time-synchronous marker horizons for deposits of Marine Isotope Stage (MIS) 3 and 2 (*c*. 57–14 ka) and, in this way, provides an opportunity to better assess the regional environmental response in the terrestrial environments.

Identification and correlation of proximal and distal tephra layers relies on the determination of the geochemical composition of volcanic glass shards (pumice fragments), which often differ among volcanoes and within individual volcanic eruption histories. Tephra from the last three explosive volcanic stages of Ciomadul are characterised by a uniform dacitic whole rock composition, but significantly differ in their rhyolitic major element glass compositions. The oldest (51 ka) tephra, for example, shows a highly evolved glass composition (high SiO2 concentration of *c*. 78 wt%) which is comparable with that of e.g. Süphan Dagi tephras in eastern Anatolia, Turkey. The younger Ciomadul tephras at *c*. 31.5 ka and 29.6 ka display a less silicic glass composition with mean SiO2 concentrations of *c*. 73 wt% and 76 wt%, respectively. Such compositions can be easily distinguished from those of other rhyolitic tephras from European volcanic sources (e.g. Iceland, southern Italy, Santorini, Nisyros, central and eastern Anatolia). As such, these tephras are unique, well constrained chronostratigraphic correlation markers, allowing the dating and comparison of environmental archives in the Eastern Mediterranean region.

## Summary and hazard assessment

After predominantly effusive lava dome activity in the past, Ciomadul volcano changed its character to explosive activity *c*. 50 kyr ago. The first, violent phreatomagmatic and Plinian eruptions, that were centred at or around the older crater of Mohos, were followed by a quiescent period with likely effusive lava dome growth, possibly in the area of the other present-day crater of St Ana. The latter dome was destroyed explosively *c*. 31.5 kyr ago, producing pyroclastic flows followed by a Plinian phase. Finally, after some 2000 years of quiescence, Ciomadul's last eruption formed the St Ana crater. This violent eruption at *c*. 29.6 ka, again of phreatomagmatic nature, generated tephra deposits as far as 350 km away from the source in the Dniester delta. The interbedded tephra layers in the vicinity of the volcano, and especially coring the *c*. 60 m-thick lacustrine sequence of Mohos, provide an exceptional opportunity for tephrostratigraphical investigations and, at the same time, allow an improved assessment of palaeoenvironmental changes.

At present, the most ‘active’ part of Ciomadul, in terms of sulphurous carbon dioxide emanations (mofettes) and bubbling mud pools, is 4 km away from the St Ana vent at Muntele Puturosu (Büdös Hill). Moreover, recent geophysical studies indicate that there could be partially solidified material, possibly a hot crystal mush, at shallow crustal depths. These findings imply that, similarly to other peri-Alpine Late Quaternary volcanic fields in Germany, France or Bohemia, there is another active volcano farther in East-Central Europe (Fig. 8), where rejuvenated volcanic activity cannot be ruled out.

## Suggestions for further reading

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# Figures

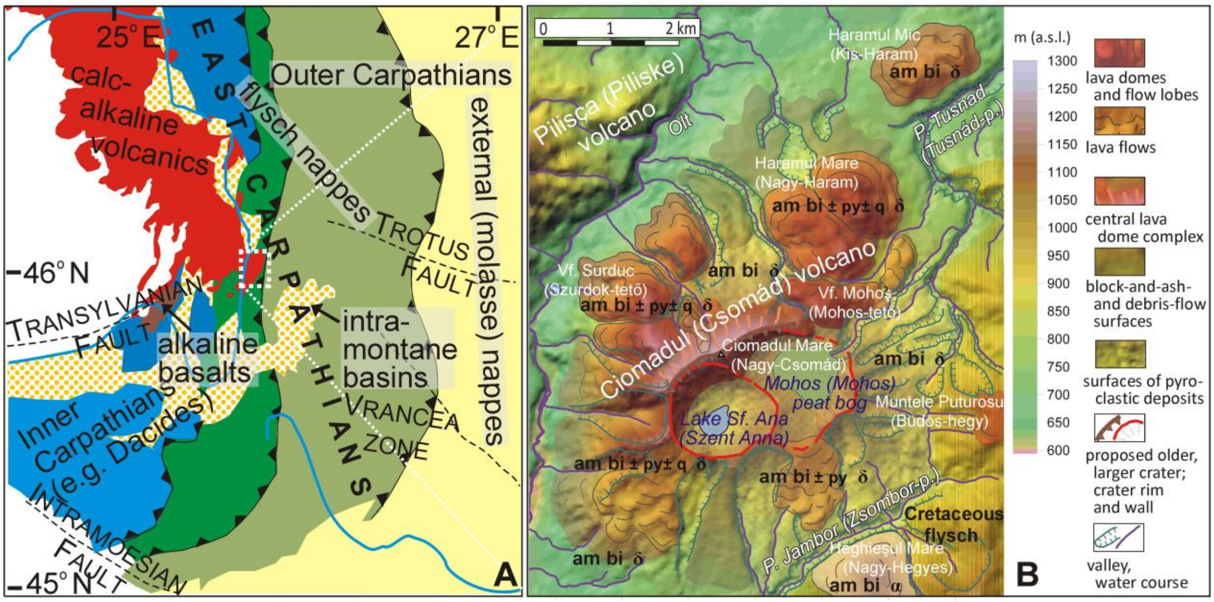

**Fig. 1.** Tectonic and geographic setting of Ciomadul volcano (left) within the East Carpathian Volcanic Range (in red); volcanological sketch map (right). Figure simplified from Karátson et al. (2016) after many authors.

**Fig. 2.** View of Ciomadul lava dome complex from the north.

**Fig. 3.** Fresh dacite of Ciomadul's lava dome rock.

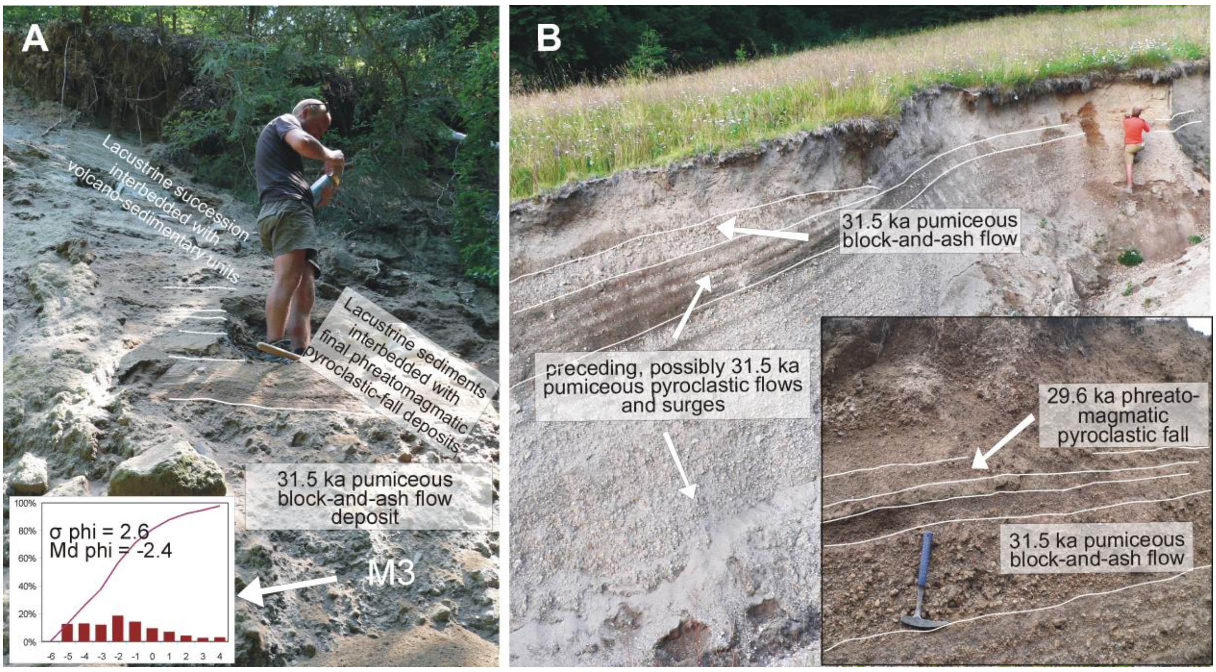

**Fig. 4.** Outcrops showing pyroclastic units from the latest explosive eruptions of Ciomadul: **A**. A proximal gully at the outlet of Mohos crater reveals thick pyroclastic layers overlain by volcano-sedimentary and lacustrine successions. Inset in the lower left corner shows large grain size and poor sorting of clasts from the lowermost ’M3’ pumiceous block-and-ash flow deposit, related to explosive lava dome destruction. **B**. Erosional gully at a medial distance from the source with well-preserved pyroclastic-flow and -surge units, overlain by the latest c. 29.6 ka phreatomagmatic tephra.

**Fig. 5.** Pumice-fall deposit from one of the largest explosive eruptions of Ciomadul c. 31.5 kyr ago.

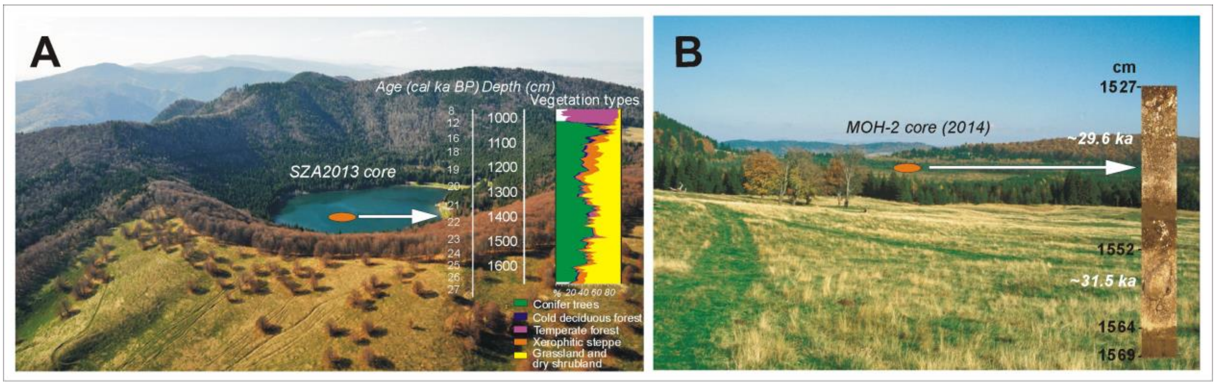

**Fig. 6. A.** The steeper, younger St. Ana crater formed by the latest, c. 29.6 ka, eruption. **B**. The relatively flat Mohos crater is older (c. 50-30 ka) and received tephra from the latest explosive Ciomadul eruptions. Positions of coring in both craters are indicated.

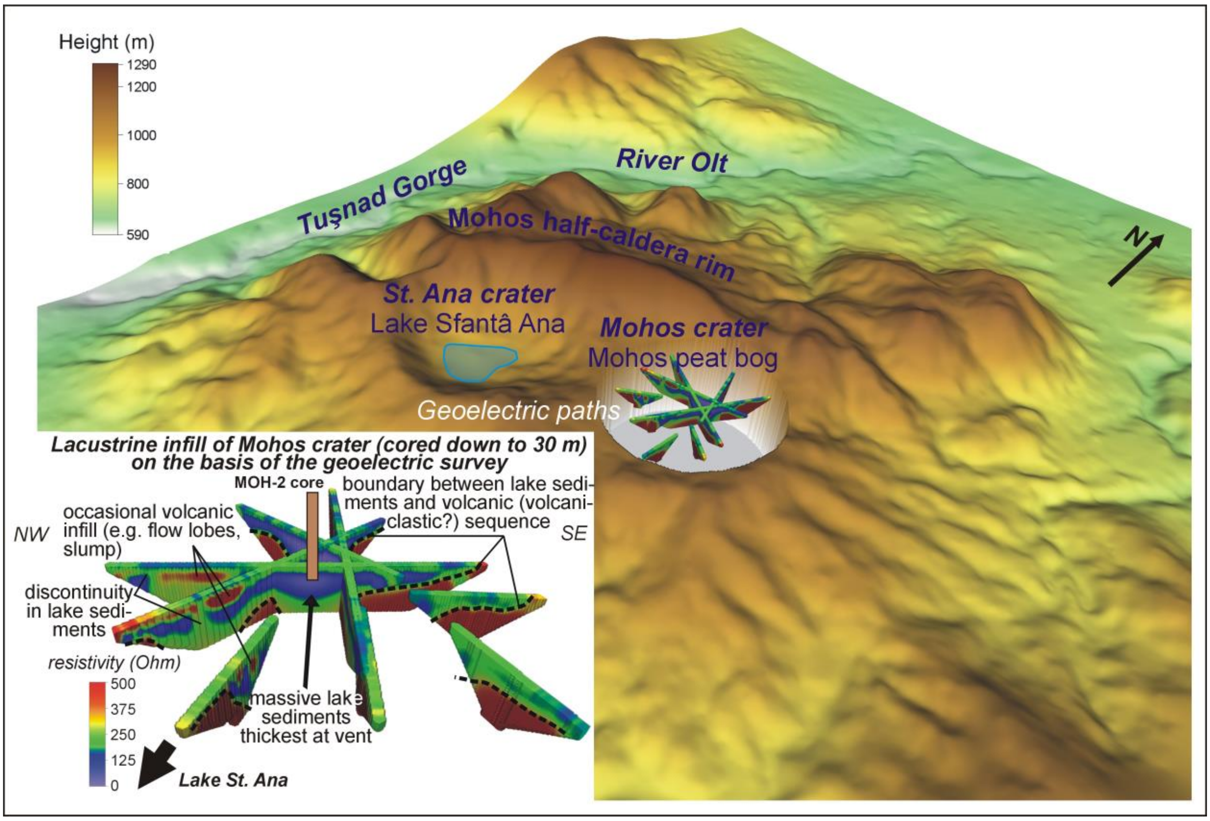

**Fig. 7.** An ongoing geoelectric survey has revealed an, at least, 60 m-thick lacustrine sediment sequence in the Mohos crater infill, cored, at present, down to 30 m.

**Fig. 8.** Artist's vision of the youngest eruptions of Ciomadul that may have been witnessed by Palaeolithic Man. Eruptive activity may potentially reawaken. (Picture credit: Edvárd Takács.)