Acta Vulcanologica - Vol. 7 (2) – 1995: 145 - 153

The Călimani-Gurghiu-Harghita volcanic chain, East Carpathians, Romania: volcanological features

A. Szakács, I. Seghedi

Geological Institute of Romania, 1, Caransebes Str., RO-78344 Bucharest, Romania

Abstract

Current volcanological knowledge of the Călimani-Gurghiu-Harghita (CGH) volcanic chain, the southernmost segment of the Carpathian Neogene/Quaternary volcanic arc, is reviewed. The CGH arc is naturally subdivided into four geographically distinct segments: Călimani, Gurghiu, North Harghita and South Harghita, and basically consists of a row of adjacent or partially overlapping composite volcanoes accompanied by their respective peripheral volcaniclastic aprons.

Lava-flow activity and dome extrusions were the main edifice-building events, punctuated by episodic explosive events, some of which produced non-welded pumice and ash flow deposits. Lava dome eruptions, accompanied by gravitational or explosive collapses of the growing domes over steep slopes, generated block-and-ash flows. Edifice failure and related debris avalanche events were common features in several composite volcanoes. Redistribution of loose slope material to topographic lows by debris flows, hyperconcentrated flood flows and normal stream erosion contributed to the accumulation of peripheral volcaniclastic aprons, mostly on land, but also locally in lacustrine environments.

Volcanic edifices are typical medium-sized andesitic composite volcanoes, some of them attaining the caldera stage, complicated by summital or peripheral domes or dome complexes. Dacitic volcanoes are smaller in size and consist of lava dome complexes, in places with associated pyroclastic cones and volcaniclastic aprons.

The volcanic history of CGH lasted ca. 9.5 Ma, with the oldest activity (9.5 Ma) occurring in the northern parts and the youngest at the southern chain-termnus. The last eruption of Ciomadul volcano is only ca 10000yr old. Along-arc migration of volcanism is obvious especially in the southernmost segment.

A new structural model for the CGH, based on volcanic facies distribution («central», «proximal» or «flank», and «distal» or «volcaniclastic» facies) is proposed. It fits the field observations, K-Ar dating and modern structural models of composite volcanoes worldwide better than the previous «two-compartment» model.

1. Introduction

The Călimani-Gurghiu-Harghita (CGH) volcanic chain forms the southeasternmost part and the longest continuous portion of the Carpathian Neogene/Quaternary volcanic arc (Fig. 1). In Romania, Neogene/Quaternary volcanics (mainly of calc-alkaline affinity) developed along the inner part of the Carpathian orogenic belt where they are segmented into a northern volcanic zone (Oaș-Gutâi Mts.), a median zone of shallow intrusions (Țibles, Toroiaga, Rodna and Bârgău Mts.), and a southern volcanic zone (CGH), as well as in the Apuseni Mts. (Fig. 1). Other young volcanic rocks in Romania include small-volume Pliocene-Pleistocene alkali-basaltic occurrences in the Perșani Mts. (southern East Carpathians) and Banat province (eastern Pannonian Basin) (Downes et al., 1995).

The fresh-looking morphology of the CGH volcanic zone allows the recognition of individual volcanic edifices and prominent features including the unique crater lake Sf. Ana at the southern end of the chain. Well preserved, more or less circular depressions, mostly drained by a radial pattern of streams, are considered to be «craters» and formed the starting points in identifying a number of stratovolcanoes along the chain such as Seaca-Tătarca (i.e. Mezohavas in the early, Austro-Hungarian literature), Șumuleu (i.e. Somlyo), Ostoroș (i.e. Osztoros), Luci (i.e. Lucsmelleke), Cucu (i.e. Kakukkhegy) and Sf. Ana (i.e. Szent Anna). Other volcanoes with less obvious morphological features, such as the Călimani caldera (Rădulescu et al., 1973), Fâncel-Lăpușna caldera (Rădulescu et al., 1964b), Vărghiș (or Central Harghita, Rădulescu, 1965) and others, were recognized later. The picture was gradually refined and complicated through the identification of many small-scale volcanic features such as volcanic domes and lava-centers outside the main stratovolcanic edifices (e.g. a number of such small volcanoes have been described in the southern Călimani Mts. by Peltz, 1969).

Generalized structural models of the CGH chain have been proposed by Török (1956) and Rădulescu et al. (1964a; 1973). The former author envisaged stratovolcanic structures built up on a «prevolcanic intrusive basement» all along the chain. This idea was debated later by Rădulescu (1962) who proposed an alternative model (Rădulescu et al., 1964a; 1973) – the two compartment model – that dominated the volcanological conception of the CGH during the past few decades.

Despite continuous research effort, mostly focused on petrological aspects and ore prospecting, volcanological approaches were sparse and localized to limited areas (e.g. Rădulescu et al., 1964a; Rădulescu, 1973; Szakács & Seghedi, 1990) and no larger-scale volcanological investigation was undertaken until very recently. This paper attempts to synthesise, in a modern view, the available data on the volcanology of the CGH chain, based mostly on our own research over the last decade or so.

2. Geotectonic setting

Its general location with respect to the major lithospheric tectonic units of the Carpathian system (i.e. behind the Carpathian accretionary prism) and its calc-alkaline geochemical signatures, led Rădulescu & Săndulescu

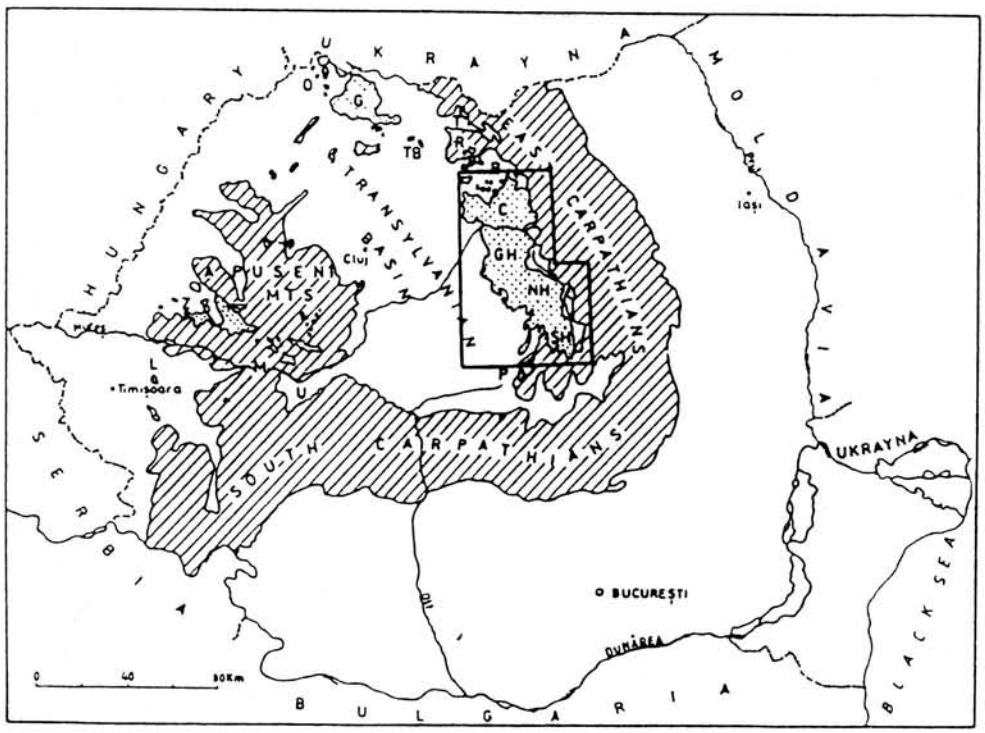

Fig. 1 – Sketch of the Neogene/Quaternary volcanic arc (stipped) in Romania with the location of the Călimani-Gurghiu-Harghita (CHG) volcanic chain (framed); Segments of the arc are labelled as follows: O: Oaş, G: Gutâi, TB: Tibleş, T: Toroiaga, R: Rodna, B: Bârgău, C: Călimani, GH: Gurghiu, NH: North Harghita, SH: South Harghita; Z (Zărand) and M (Metaliferi Mts.) are segments of the Apuseni Neogene volcanic zone, L (Lucareţ) and P (Perşani) are Neogene/Quaternary alkali-basaltic occurrences.

(1973), Boccaletti et al. (1973) and Bleahu et al. (1973) to consider the East Carpathian volcanic arc as being subduction-related in character. Westward subduction of the oceanic crust of an easterly «basin» or ocean whose sparse, obducted remnants are discontinuously recorded within the inner flysch nappes of the East Carpathians, beneath an inferred Transylvanian microplate or an assemblage of several microplates, is inferred. Recently, the subducted crust involved in the generation of the Neogene volcanic arc has been suggested to have belonged to a «marginal basin» of the Eurasian plate with thinned crust or a narrow oceanic-type crust (Rădulescu et al., 1993).

There are, however, some problems with both timing and spatial relationships within the East Carpathians, especially along the CGH portion of the arc. The principal deformational events occurred in the East Carpathians in the Mid-Cretaceous and Early Miocene (Săndulescu, 1984; Rădulescu et al., 1993) without significant volcanism. Most of the calc-alkaline volcanism developed when the compressional structure of the East Carpathians had already been formed, i.e. in a postcollisional environment. The spatial problem is related to the southern segment of the CGH chain (Harghita Mts.) where the parallelism between the Carpathian accretionary prism and the volcanic range breaks down and the South Harghita segment crosscuts the intensely folded inner flysch zone (Szakács et al., 1993). Crustal thickness is typically higher there (c.a 40 km) compared to the other segments (c.a. 30 km) (Stănica et al., 1986; 1990).

These circumstances warn one that no classical subduction model can be routinely applied to explain the peculiar relationships between tectonic processes and magmatism in the East Carpathians, where the subduction signature-bearing volcanic arc developed in a post-collisional tectonic setting, and is apparently a delayed effect of the active subduction processes.

3. General features

With its ca. 160 km length, the CGH chain is the longest continuous volcanic range in the Carpatho-Pannonian Region. Recent K-Ar age determinations (Pécskay et al., 1995) show that the CGH volcanic activity ranges from about 9.5 Ma in the Călimani Mts. to <0.5 Ma in the South Harghita Mts. Age progression is obvious along the whole chain, but is particularly well-developed in the southernmost segment (Szakács et al., 1993).

Most of the volcanics belongs to the calc-alkaline suite, ranging from basalts to dacites, but andesites are certainly the most abundant. Slight tholeiitic trends are shown by some of the earliest products in Călimani Mts., whereas obvious along-arc K-enrichment ending in small volume shoshonitic bodies is found at the southern end of the range (Seghedi et al., 1987; 1995; Szakács et al., 1993; Mason et al., in press). Two pyroxene and pyroxene-amphibole andesites are the most common rock-types. Others include olivine-bearing basalt andesites, frequent in the Călimani Mts., garnet-bearing amphibole andesites as a very rare type (a few small bodies in the Călimani Mts.), aphyric andesites and dacites, amphibole-biotite andesites and dacites, etc. (Seghedi et al., 1995).

The volcanic structure is dominated by adjacent and in places partially overlapping composite volcanoes in the axial part of the chain, with widespread coalesced

volcaniclastic aprons at either side. Within the general NW-SE strike of the range, local N-S and NNE-SSW alignments of volcanoes are also apparent.

The CGH volcanic chain is naturally subdivided in four distinct segments by obvious geographical boundaries such as major valleys and saddles: Călimani, Gurghiu, North Harghita and South Harghita. Except for Călimani, which displays an extremely complex structure, the other segments consist of rows of adjacent composite volcanoes accompanied by their respective volcaniclastic aprons. Small-scale volcanic features, mostly lava domes, are peripheral with respect to the large volcanoes in most of the areas. As a general rule, height, width, volume and complexity decrease from NW to SE along the CGH chain.

4. Volcanic products and inferred activity

A wide range of effusive, explosive and epiclastic products were generated throughout the ca. 9 Ma long volcanic history of the CGH chain by a number of large central or small dispersed volcanic centers. They indicate a corresponding variety of volcanic processes and mechanisms.

Lava flows are the most common volcanic products encountered in, and near, the composite volcanoes. They range from rare short thick dacitic flows such as in Ciomadul (South Harghita) through the most common more or less viscous, variably long and thick andesitic lavas, fluid aphanitic dacitic and andesitic lavas occurring in a number of volcanic structures in the Călimani and North Harghita Mts., to high fluidity basaltic andesite and rare basaltic lavas. Lava flows are easily assignable to their source volcanoes whose flanks they commonly constitute but actual source vents are rarely identified except for near-vent flows such as Harghita Mădăras or Harghita Ciceu in the Virghiș edifice. It is difficult to identify the source of the more distal fluid lavas, especially those interbedded in volcaniclastics, as is the case, for example, in the southern Călimani Mts.

Lava domes, which occur in most of the volcanoes and independently at the peripheries, are a major feature of the chain. Dacitic lava domes or dome complexes are frequent especially in the South Harghita segment (Cucu, Pilișca, Ciomadul volcanoes, Murgul Mare dome) but they are present elsewhere as well (e.g. Răchitiș dome in North Harghita, Pietricelul and Drăgușul domes in the Călimani caldera). Viscous andesitic lava was also frequently extruded as lava domes but is seldom preserved as recognizable morphological-structural entities, except when it formed more voluminous dome complexes such as Bacta (Gurghiu Mts.) or Șumuleu-Ciuc (Harghita Mts.).

Pyroclastic rocks are generally sparsely represented within the central volcanic edifices except for the pyroclastic cone of Ciomadul volcano and some scoria cone remnants in the Călimani and northern Gurghiu Mts. (e.g. Jirca) where they accumulated in significant volumes. They are commonly found as minor local, mostly thin occurrences in the lava piles of the large central «stratovolcanoes» (e.g. Vârghis, Cucu). Pyroclastics are much more widespread beyond the flanks of the composite volcanoes, mostly as parts of the peripheral volcaniclastic aprons.

Genetic types of pyroclastic deposits and corresponding eruptive mechanisms vary largely from Strombolian to Plinian fall, and from phreatomagmatic to pumice-and-ash flow and block-and-ash flow deposits. One Plinian fall deposit has been unambiguously recognized as coming from Ciomadul. This dacitic pumice fall deposit is 4.3 m thick in a proximal area (less than 2 km west of Sf. Ana crater) and c.a. 0.2 m thick at more distal localities c.a. 40 km east of the source. Because of the small number of outcrops, no isopach or isopleth maps have been constructed. Dacitic phreatomagmatic products represented by accretionary lapilli-bearing base surge deposits are present near the Mohoș crater rim in Ciomadul volcano (Szakács & Seghedi, 1989). Four superposed Plinian fall out deposits associated with ash-flow tuffs were recently recognized at the northeastern periphery of Fâncel-Lăpușka caldera.

Small volume basaltic andesite spatter and scoria deposits, diagnostic of Strombolian activity, are found in a number of high-level occurrences within several edifices in the Călimani Mts. (Lucaciul, Tămăul, Pietrele Roșii), Gurghiu Mts. (Jirca) and South Harghita Mts. (Pilișca). We consider them fortunately preserved examples of a much more widespread type of volcanic activity.

Pyroclastic flow and related surge deposits occur frequently in the CGH, exhibiting a large spectrum of features. Pumice-rich or pumice-bearing flows can be recognized in many outcrops. In Ciomadul they form two superposed flow units overlying, and gradually passing from, the Plinian fall deposit of the same dacitic composition. In the southern Călimani Mts. and northern Gurghiu Mts., they display the typical features of non-welded, in places lithic-rich, ignimbrites. Their composition is acid amphibole andesite. Their source has been identified to be related to the Fâncel Lăpușna (northern Gurghiu) caldera. Pumice-rich deposits, presumably of pyroclastic flow origin, are present in other parts of the chain (e.g. North Harghita) as well but no welded ignimbrites have yet been found. The pumice deposits suggest that explosive mechanisms involving large volumes of highly vesiculated dacitic or acid andesitic magmas constituted a significant and characteristic part of the eruptive history of the CGH chain.

Block-and-ash flow deposits of basic andesite or basaltic andesite composition are widespread at the western and southern peripheries of the Călimani Mts. and in northern Gurghiu Mts. Along the Mureș valley, sequences of successive flow-units are well exposed. They consist of 0.5 to 2 m thick reverse to normal graded, otherwise chaotic coarse tuff-breccia-like deposits often with a finer sheared base and another finer level at the top, consisting of unsorted centimetric to decimetric monolithologic andesite blocks and an ash matrix. In places, juvenile blocks displaying evidence of high temperatures (radial cracks, «plastic» shapes) can be seen. Fine, thin, crossbedded ground and/or ash-cloud-surge deposit interbeds can be observed locally. Two types of block-and-ash flow deposits, both of basaltic andesite composition, can be distinguished along the Mureș valley: (1) those with massive juvenile fragments (Lunca Bradului type locality), and (2) those with porous juveniles (Stânceni type locality). They may correspond to different mechanisms of the dome/lava flow collapse events triggering the pyroclastic flow on the steep flanks of the volcanic edifice, gravitational collapse (Merapi type) and explosive collapse (Pelée type), respectively. These types of deposits are frequent, albeit not so well exposed, in many other parts of the CGH pointing to the importance of summit dome building and

lava extrusion and the presence of steep-sloped edifices during volcanic activity.

The peripherally extensive volcanic aprons (Fig. 2) are largely composed of secondary volcaniclastics. Debris avalanche deposits constitute a significant part of them. By their characteristic diagnostic features (megablocks, more or less dispersed jig-saw blocks, etc.) they were recognized recently in almost all of the volcanic aprons. They are thick, chaotic poorly organized deposits that travelled far away from their sources and explain the

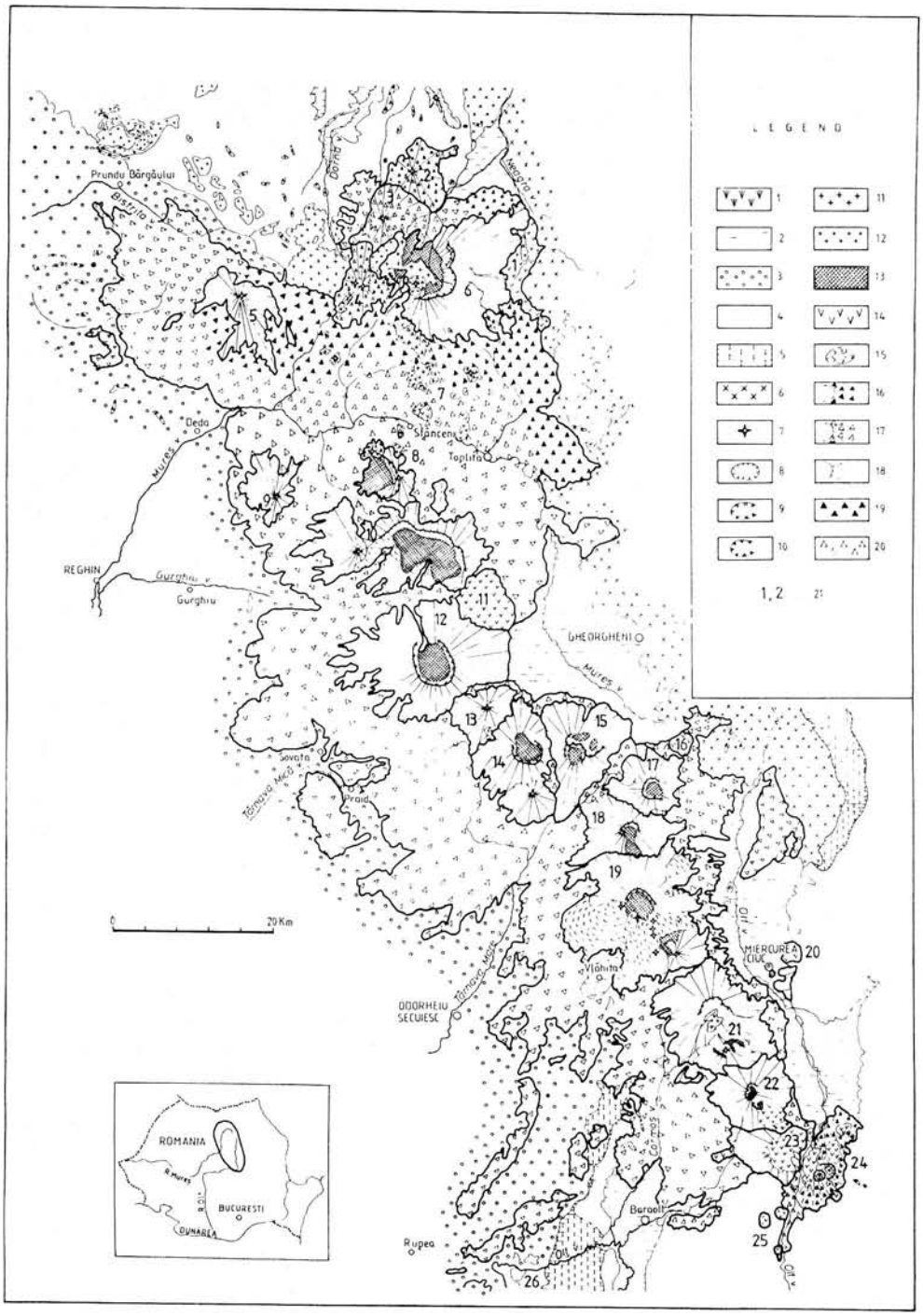

Fig. 2 – Volcanologic map of Călimani-Gurghiu-Harghita volcanic chain, East Carpathians, Romania.
Legend: 1. Quaternary swamp or lake deposits; 2. Tertiary postvolcanic and synvolcanic sediments; 3. Tertiary prevolcanic molasse sediments of Transylvanian basin; 4. Cretaceous-Tertiary sediments of the Flysch zone of East Carpathians; 5. Late Paleozoic-Cretaceous sediments of East Carpathians; 6. Precambrian-Paleozoic metamorphic and plutonic rocks of Crystalline-Mesozoic Zone of East Carpathians; 7. Neck; 8. Crater; 9. Caldera-like depressions; 10. Collapse calderas (caldera fault); 11. Porphyritic intrusive rocks; 12. Fine porphyritic intrusive rock; 13. Volcanic core complexes; 14. Extrusive domes; 15. Lava flows; 16. Pyroclastic cone; 17. Stratovolcanic cone; 18. Effusive cone; 19. Coarse pyroclastic rocks-proximal facies; 20. Mudflow, debris avalanche, debris flow and ephemeral stream epiclastic volcanic rocks; 21. Volcanic edifices and areas: CĂLIMANI MTS. 1. Drăgoiasa; 2. Lucaciul; 3. Tămăul; 4. Rusca-Tihu; 5. Moldovanul; 6. Călimani; 7. South Călimani volcanic field; GURGHIU MTS. 8. Jirca; 9. Obarșia; 10. Fâncel-Lăpușna; 11. Bacta; 12. Seaca-Tătarca; 13. Borzont; 14. Șumuleu; 15. Ciumani-Fierăstraie; NORTH HARGHITA MTS. 16. Râchitiș; 17. Ostoroș; 18. Ivo-Cocoizaș; 19. Vârghiș; SOUTH HARGHITA MTS. 20. Șumuleu Ciuc; 21. Luci-Lazu; 22. Pilișca; 24. Ciomadul; 25. Bicsad-Malnaș volcanic field.

steep front of the volcaniclastic apron in many localities. Although their sources are difficult to localize, in two cases we have found criteria which link debris avalanche deposits to their inferred source. First, the presence of large augite-bearing basaltic andesite blocks was taken as a petrographic criterion to assign widespread debris avalanche (and flow) deposits found in the north west Gurghiu Mts. to a likely source in the western part of the Fâncel-Lăpușna caldera (Fig. 2). Secondly, the SW trending paleotopography controlled by the graben-horst structure of the present-day Perșani Mts. and its northerly structural extension, channelized large volumes of debris avalanche and related debris-flow material coming from «Varghiș caldera» as a very likely source (Fig. 2).

Debris flow/lahar deposits are an essential part of the volcaniclastic aprons occurring in many peripheral outcrops. They often form sequences of successive thin heterolithologic flow units often with erosional base and channels. Such features are well exposed along the Mureș Valley and Budacu valley (western Călimani). Hyperconcentrated flood-flow deposits and less frequent normal stream flow/fluvial deposits and locally developed lacustrine deposits including silt and clay and diatomites (Toplița basin, Eastern North Harghita, western South Harghita/Baraolt Basin) complete the picture of the variety of genetic types in the CGH volcaniclastic deposits.

The types of massive volcanics and volcaniclastic deposits point to a characteristically arc-type volcanism consisting of both effusive and explosive activity with lava flows and domes building up composite volcanic edifices. At the same time, the loose fragmental material coming from both explosive activity and fragmentation of effusive/extrusive products, accumulated as volcaniclastic aprons on low topography through various eruptive and non-eruptive processes.

5. Volcanic edifices, structures and environments

The axial part of the CGH chain consists of a number of adjoining and partially overlapping volcanoes of various size, structure and composition. Most of them can be characterized as composite volcanoes. The term «stratovolcano» is not suitable because most of these structures lack pyroclastics as significant cone-building components. They are the result of complex eruptive histories including several cone-buinding phases interrupted by destruction phases (either caldera-formation, edifice failure or normal erosion).

The largest and most complex volcano is Călimani which occupies the northern two thirds of the Călimani Mts. (Seghedi, 1982; 1987). In the western half it is built up on a basement of partially uncovered intrusive complex belonging to the southern extension of the East Carpathian «subvolcanic zone». A series of NNE trending older stratocones (Lucaciul, Tămăul, Rusca-Tihu) (Fig. 1) with their corresponding volcaniclastic aprons form at least the western half of the structure. The younger Călimani caldera partially overlaps both these edifices and the higly elevated intrusive basement (over 1900 m high in the Bistriciorul-Struniorul summit). It is topped by a ca. 8 km wide collapse caldera formed on a mostly lava-constructed volcano. Intracaldera stratocones (e.g. Negoiul Românesc), dykes, caldera-rim (Pietricelul) and flank (Drăgușul) domes are post-caldera features as well as a large monzodioritic resurgent central intrusion, exposed in an area about 11 km^2 in the interior of the caldera (Fig. 2).

The southern third of the Călimani Mts. consists of a field of small-scale fracture-controlled edifices (mostly lava domes) dispersed among volcaniclastics that represent the southern peripheral volcaniclastic aprons of the main volcanoes. An effusive lava center is located far west of these structures with fluid andesitic lava flows overtopping volcaniclastics, well exposed on the Scaunul (God's Chair) summit.

The northern part of the Gurghiu Mts. is dominated by the large amphitheater-shaped Fâncel-Lăpușna caldera structure (Fig. 2) ca. 10 km across (Rădulescu et al., 1964b), whose origin has not yet been fully clarified. On its northern flank the remnants of an older volcano displaying an unroofed intrusive core-complex, lava flows and a Strombolian cone (Jirca, Fig. 2) are found. The very large size of the caldera is not accounted for by the volume of the surrounding massive volcanics as is the case with the Călimani caldera. Therefore, widespread pyroclastics have to be taken into account. Possible candidates are the large volume non-welded amphibole andesite/dacite pumice and ash flow deposits occurring over large areas in both southern Călimani and northeastern Gurghiu Mts., including the internal caldera rim. An andesitic dome complex (Bacta) adjoins the southeastern part of the caldera. In the western part an unnamed lava volcano overlies the peripheral volcaniclastics of northern Gurghiu Mts., but even its lava field extension has not been outlined accurately.

Other composite volcanic structures in the southern part of Gurghiu Mts. include Seaca-Tătarca with its quasicircular «caldera» rim and relatively simple structure and shape suggesting rather a shield, Șumuleu with some crater-rim domes and well-exposed intrusive core-complex and a large southern flank lava center, and the double-cratered Ciumani-Fierăstraie edifice. All are typically lava-built composite volcanoes with insignificant pyroclastics in their cone structures. They are surrounded by coalesced volcaniclastic aprons that, due to their similar ages, cannot be separated according to their particular source volcanoes.

The North Harghita volcanoes form a NNE trending row of partially overlapping edifices. The northernmost one (Răchitiș) is a simple aphanitic dacitic dome. Ostoroș, the next, is a small volcano with an erosionally enlarged «crater», intrusive core-complex, rim domes, consisting of andesitic lavas and very minor pyroclastics. Aphanitic lava flows, similar to Răchitiș rocks, are present on the northern flank and at the southeastern foot. It is uncertain whether this latter belongs to Ostoroș or the adjoining Ivo-Cocoizaș structure. Ivo-Cocoizaș is a strongly eroded volcano with a well-exposed intrusive core complex, a morphologically less obvious central amphitheater and with shield-like outer topography. Its lavas range from basaltic andesites to acid andesites, but rhyodacitic rocks are found in boreholes (Stanciu et al., 1985). The southern half of the edifice is overlain by lavas of the next volcano (Vârghiș) to a considerable extent.

The rest of North Harghita is occupied by the large and complex Vârghiș volcano. Its oldest parts are exposed in the caldera interior and in the Harghita Băi area (southeast of the main summit) where we assume the presence of an independent but later partially buried smaller edifice, only the intrusive core complex and its

eastern flank of which are still visible. A large, mostly lava-built cone with a ca. 4 km wide southward-opened caldera-like depression forms the major part of the edifice. Fluid, aphanitic andesitic-dacitic lava flows with well-preserved surface pressure ridges (visible on aerial photos) occur on the eastern flank as well as a small amphibole-biotite-pyroxene andesite lava dome.

«Caldera» formation at Vârghiș is related neither to huge lava outpouring nor to a large ash-flow eruption. It is likely to be the result of one (or more) edifice failures and related debris avalanche event(s); therefore it is not a true caldera but a «horseshoe depression». Postfailure activity concentrated along a north-south fracture where several lava-centers such as Harghita Ciceu and Szilas Vesze, built up a range of late-stage acid andesite lavas whose southward oriented flows and tongues have obvious topographic expressions (Fig. 2). Small volume pyroxene andesite pyroclastics are found in the «caldera» interior, whereas a thin intercalation of amphibole-biotite pyroclastic rocks is found below the western «caldera»-rim. A well-developed core complex with intrusive bodies and related hydrothermal activity is an obvious feature of the «caldera» interior.

A peripheral dome complex of amphibole-biotite-pyroxene andesite composition constitutes the craterless Șumuleu-Ciuc volcano at the southeastern margin of the Middle Ciuc Basin near Miercurea Ciuc. Luci-Lazu is the northernmost South Harghita volcano, with a typical shield morphology of its upper parts. Some andesitic domes complicate the eastern flank whereas a younger-phase effusive center (Lazu) overlaps the structure in the south. An amphitheater-shaped depression hosting the Luci swamp is open southward. The andesite-dominated volcaniclastic apron developed to the southwest forms the basal part of the western South Harghita volcaniclastic assemblage and is tentatively assignable to Luci-Lazu volcano, suggesting that it experienced an early steeper composite cone stage, despite its present-day shield morphology. The Cucu volcano consists of a «primitive» amphibole-pyroxene andesite lava pile surmounted by more acid biotite-bearing lava flows and lava domes, some of them reaching dacitic composition.

Three crater remnants (Karátson et al., 1992), together with the internal flanks of the domes form an unusual rectangular-shaped depression containing the common core-complex assemblage. Pilișca volcano is formed of a steep amphibole-biotite lava dome complex built up over the erosional remnants of a pyroxene andesite and basaltic andesite older cone on which Strombolian spatter is recognized. No obvious crater-like depression is present.

The best preserved volcano is Ciomadul consisting of a viscous dacitic lava dome and lava flow complex and a twin-cratered pyroclastic cone. The lava domes are clustered in the northern and western part of the edifice whereas isolated domes are present to the south (Köves Ponk), southeast (Dealul Mare) and northwest (Baba Laposa) (Szakács & Seghedi, 1986). The remnants of two other isolated domes (Puturosul and Balvanyos) are found farther to the east. The volcanic chain-terminus is marked by three volcanic bodies of which one is an amphibole-biotite-pyroxene andesite lava dome (Murgul Mare) and the others are shoshonitic near-surface intrusions (Murgul Mic and Luget).

The lithologic, structural and morphologic features of both volcanic structures and deposits are typical of subaerial continental arc-type calc-alkaline volcanism. No obvious feature suggesting subaqueous activity has yet been encountered. Deposition of the volcanic products – effusive and volcaniclastic – was also subaerial, except for very localised lacustrine environments.

6. Eruptive history

The eruptive history of CGH is summarized here based on a large number of K-Ar age determinations (Pécskay et al., 1995). The volcanic activity started with the eruption of the Drăgoiasa dacites ca. 9.3-9 Ma ago in the eastern Călimani Mts. after a preceding intrusive stage (12-9.5 Ma), coeval along the Bârgău subvolcanic zone that extends beneath the Călimani Mts. Intense uplift of the western half of the Călimani Mts. occurred prior the inception of volcanism. Ages as old as 9 Ma are sporadically recorded in Călimani and northern Gurghiu among lithics in andesitic volcaniclastics, suggesting that inception of both dacitic and andesitic volcanism began at about the same time at several locations in the northern CGH.

Basaltic-andesitic stratovolcanoes (e.g. Lucaciul, Tămăul) were built up 9-8 Ma ago. Basaltic-andesite volcaniclastics and several andesitic domes of the same age are also present in southeastern Călimani. A strongly eroded volcano in the northern Gurghiu Mts. (Jirca) yielded similar K-Ar ages. Caldera collapse around 7.2-7.1 Ma ended a stage of evolved andesitic lava-cone building in the central part of Călimani, partially overlapping the older edifices. Post-caldera volcanism and resurgent intrusive magmatism occurred until ca. 6.8 Ma in both intra- and extracaldera areas.

In the northern Gurghiu Mts. the huge Fâncel-Lăpușna composite volcano was built up between ca. 8.6-7.5 Ma, culminating in caldera formation at a still poorly constrained time, perhaps during a longer interval (such as 7.5-7.0 Ma) including both voluminous ash-flow eruptions and related caldera collapse, and edifice failure events. The Bacta dome complex formed at 7.5-7.3 Ma. No apparent post-caldera eruptive events have been as yet confirmed by K-Ar dating. Seaca-Tătarca, Șumuleu and Ciumani-Fierăstraie volcanoes were roughly simultaneously active (ca. 7.2-5.8 Ma) in the southern half of Gurghiu.

Volcanic activity started in North Harghita (ca. 6.3 Ma) when Gurghiu volcanoes were still erupting, and several volcanic edifices (Ràchitiș, Ostoroș, Ivo-Cocoizaș) were built up in roughly the same time interval, lasting less than 1 Ma each. The southernmost North Harghita volcano (Vârghiș) displays a more complex and longer-lasting history, being overall younger than its northerly neighbours. An intense volcano-building stage (5.5-5 Ma) was followed by a large edifice failure/debris avalanche event and second-stage effusive activity whose youngest products were dated ca. 4 Ma.

Proceeding southward, the Luci-Lazu volcano was active between 5.1-3.6 Ma. Its evolution, which apparently includes a cone-building stage, perhaps ended with an edifice failure event leaving behind a southward-open horseshoe depression and a post-failure lava-shield building stage (Lazu). The next volcano (Cucu) started to grow after an apparent age gap of ca. 0.8 Ma. During its relatively short eruptive history (2.8-2.2 Ma), an andesitic cone-building stage was followed by viscous dome-lava eruptions. Pilișca was active between 2.4-1.5 Ma, roughly contemporaneously with the Malnaș group

of shoshonitic and andesitic domes, whereas eruptions in the Ciomadul massif span from ca. 1 Ma to <0.1 Ma. The youngest Ciomadul eruption – subplinian dacitic pumice fall accompanied by pyroclastic flows and debris flows – is constrained by a ^{14}C age of 10,700 + 280 y (Juvigne et al., 1994) obtained on a charcoal piece engulfed in a pyroclastic flow deposit, and a ^{14}C age of ca. 43 ka (Moriya, personal communication) obtained on a paleosoil underlying the pumice fall deposit.

Along-arc age progression of volcanism is obvious for CGH as a whole (Fig. 3). The average migration rate is ca. 17.5 km/Ma but along the chain-terminus South Harghita segment is ca. 7.8 km/Ma. No obvious across-arc migration of the volcanic front has been pointed out.

The difference between the northern half of CGH and its southen part, especially the southern third, is obvious in terms of volcanic evolution. The Călimani, Gurghiu and, partly, North Harghita segments display a slight along-arc migration of volcanism, including a time interval (ca. 7-6.8 Ma) when simultaneously active volcanoes defined a volcanic front covering more than half the length of the chain. In contrast, volcanoes along the southern third, especially its terminal segment, were successively rather than simultaneously actve (Fig. 3). These different patterns of volcanic behaviour along the chain correspond to higher output rates and more intense volcanicity in the case of the northern CGH, and to waning stage of volcanism and progressively lower eruption rates along the chain-terminus segment.

7. Discussion and concluding remarks

The volcanological features point to a typical arc volcanism occurring along the CGH segment of the Carpantian Neogene/Quaternary volcanic arc, located behind the Carpathian accretionary prism. A calc-alkaline (mostly andesitic-dacitic) volcanic arc built up through the eruption of a row of closely spaced juxtaposed or partially overlapping composite volcanoes, some of them evolving to the caldera stage. However, both large-scale ignimbritic volcanism and large-volume basaltic volcanism are missing in the CGH. The volcanic arc is relatively narrow, actually consisting of a single volcanic front displaying along-arc migration of activity.

Eruption styles are also typical of intermediate arc volcanism. Prevailing effusive activity alternated with short explosive pulses, dome extrusions and related phenomena. Explosive activity varies in range from Strombolian to Plinian types. Generation of block-and-ash flows related to dome emplacement on, or above, steep slopes is common. Widespread volcaniclastic aprons, partially merged and/or overlapped were constructed from neighboring active volcanoes. They accumulated peripherally, especially toward the western base of the composite cones, by mass wastage processes including debris flows, and debris avalanches.

K-Ar age determinations of both axial volcanic rocks and peripheral volcaniclastics basically point out their contemporary emplacement and make it possible to envisage a new structural model for the CGH instead of the «two compartment» model (Fig. 4). The broad volcanic structure of CGH, as viewed in a W-E cross section, reflects the spatial distribution of specific volcanic facies with respect to distance from the inferred center of the axial composite volcanoes. A «central (or core) facies», roughly bounded by the present-day topographic rim of the erosionally enlarged central volcanic depressions, consists of the most eroded central-summit part of the volcanoes including the more or less unroofed intrusive core complexes and related hydrothermal alteration halos, the crater and/or caldera remnants,

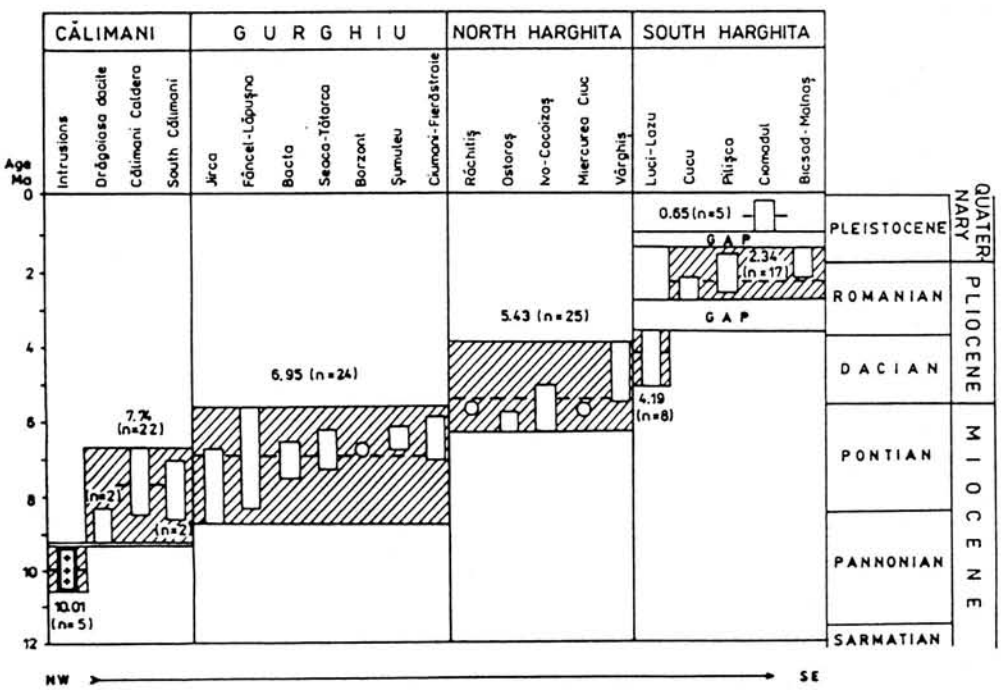

Fig. 3 – Sketch of the time-space evolution of volcanism along the Călimani-Gurghiu-Harghita volcanic chain, based on K-Ar datings. Age ranges for both CGH segments (hatched areas, with average age shown as interrupted lines) and individual volcanic edifices are displayed. The age range of the prevolcanic intrusive activity in the Călimani Mts. is shown separately (crosses). Arrow at the bottom of the figure suggests migration of the volcanic activity.

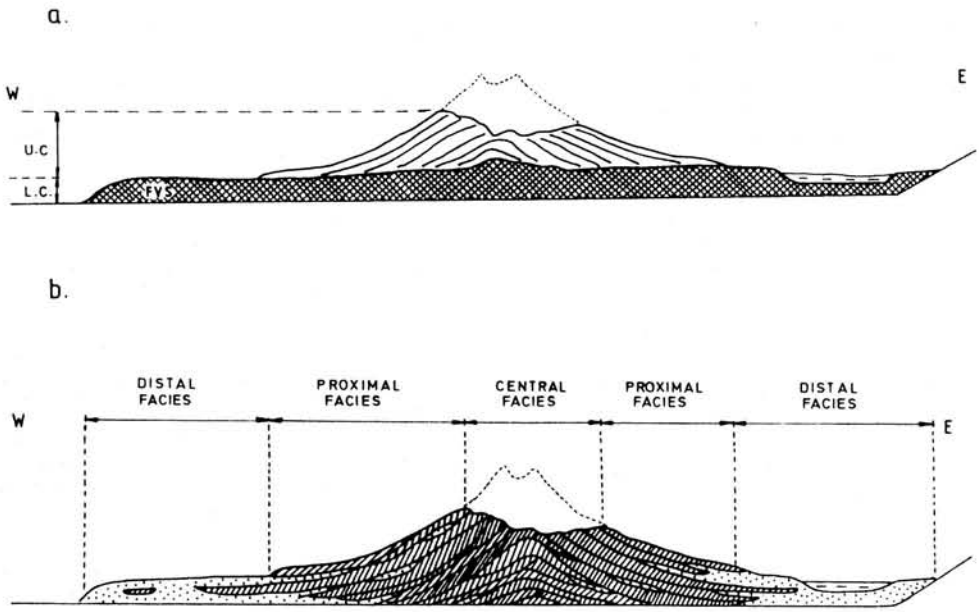

Fig. 4 – Structural models envisaged as W-E transversal sections for the Călimani-Gurghiu-Harghita volcanic chain; a) the «two compartment» model (after Rădulescu et al., 1973) (U.C. upper compartment, L.C. Lower compartment, FVS volcano-sedimentary formation); b) the «facies model» (this paper) (hatched: lavas; stippled: volcaniclastics).

eruptive vents (necks) and other summit-specific features. The «proximal (or flank) facies» corresponds to the erosionally much less modified outer slopes of the edifices bounded by the topographic rim of the central depression and the lower slope break in topography at the base of the conical edifice. Lava flow piles with subordinate pyroclastic interbeds represent the typical composition of this facies. A peripheral «distal (or volcaniclastic) facies» surrounds the base of the volcanoes. Often these volcaniclastic aprons of adjacent volcanoes cannot be distinguished from each other, being complexly interfingered and merged. The geometry and spatial distribution of the distal facies deposits are often controlled by the local topography.

The «facies model» is much more consistent with modern views on composite volcanic edifices, their structures and evolution (e.g. Williams & McBirney, 1979, Fig. 3-43 within).

Acknowledgments

The Geological Institute of Romania has strongly supported our research in recent years. We are also grateful to H. Downes for thoughtful comments on the manuscript and improvements to the final version.

REFERENCES

Bleahu, M., Boccaletti, M., Manetti, P. & Peltz, S. (1973): The Carpathian arc: A continental arc displaying the features of an «island arc». J. Geophys. Res., 78, 5025-5032.

Boccaletti, M., Manetti, P., Peccerillo, A. & Peltz, S. (1973): Young volcanism in the Călimani-Harghita Mountains (East Carpathian): evidence of paleoseismic zone. Tectonophysics, 19, 299-313.

Downes, H., Seghedi, I., Szakács, A., Dobosi, G., James, D.E., Vaselli, O., Rigby, I.J., Ingram, G.A., Rex, D. & Pécskay, Z., (1995): Petrology and geochemistry of late Tertiary/Quaternary mafic alkaline volcanism in Romania. Lithos, 35, 65-81.

Juvigne, E., Gewelt, M., Gilot, M., Hurtgen, Ch., Seghedi, I., Szakács, A., Hadnagy, A., Gabris, G. & Horvath, E. (1994): Une eruption vieille d'environ 10.700 ans (^{14}C) dans le Carpathes Orientales (Roumanie). C.R. Acad. Sci. Paris, 318, 1233-1238.

Mason, P.R.D., Downes, H., Thirlwall, M.F., Seghedi, I., Szakács, A. (in press): Crustal assimilation as a major petrogenetic process in East Carpathian Neogene and Quaternary continental margin magmas. J. Petrol.

Karátson, D., Pécskay, Z., Szakács, S. & Seghedi, I. (1992): An extinct volcano in the Harghita Mts.: Mt. Cucu. Tudomány (Hungarian version of Scientific American), 1, 70-79.

Pécskay, Z., Edelstein, O., Seghedi, I., Szakács, A., Kovacs, M., Crihan, M. & Bernad, A. (1995): K-Ar datings of Neogene-Quaternary calc-alkaline volcanic rocks in Romania. In: «Neogene and related magmatism in the Carpatho-Pannonian Region». H. Downes & O. Vaselli (Eds.), Acta Vulcanol., 7, 53-61.

Peltz, S. (1969): Studiul petrografic a părtii de sud-est a muntilor Călimani. St. Tehn. Econ. Bucuresti, 14, 206 pp.

Rădulescu, D. (1962): Asupra existentei formatiunilor subvulcanice in lanțul Călimani-Gurghiu-Harghita, Ann. Univ. C.I. Parhon, ser. St. Nat., Geologie-Geografie, București, 23, 17-21.

Rădulescu, D. (1965): Contribuții la cunoașterea structurii geologice a munților Harghita. D.S. Com. Geol., București 50, 57-68.

Rădulescu, D. (1973): Le volcanisme explosive dans la partie sud-est de Monts Harghita. Ann. Univ. București, ser. Geol., 22, 7-16.

Rădulescu, D. & Săndulescu, M. (1973): The plate-tectonic concept and the geological structure of the Carpathians. Tectonophysics, 16, 155-161.

Rădulescu, D., Vasilescu, A. & Peltz, S. (1964a): Contribuții la cunoașterea structurii geologice a munților Gurghiu. Ann. Com. Geol. București, 33, 87-151.

Rădulescu, D., Vasilescu, A. & Peltz, S. (1964b): Marea calderă Fâncel-Lăpuşna din Munţii Gurghiu. D.S. Inst. Geol., Bucureşti, 49 (1), (1961-1962), 383-386.

Rădulescu, D., Peltz, S. & Stanciu, C. (1973): Neogene volcanism in the East Carpathians (Călimani-Gurghiu-Harghita Mts.) Guide to excursion 2AB. Symposium Volcanism and Metallogenesis, Bucharest.

Rădulescu, D., Săndulescu, M. & Borcoş, M. (1993): Alpine magmatogenetic map of Romania: an approach to the systematization of the igneous activity. Rev. Roum. de Geologie, 37, 3-8.

Săndulescu, M. (1984): Geotectonica României. Ed. Tehn. Bucureşti, 334 pp.

Seghedi, I. (1982): Contribuţii la studiul petrologic al Calderei Călimani. D.S. Inst. Geol. Geofiz., Bucureşti, 67 (1), 87-126.

Seghedi, I. (1987): Studiul petrologic al Calderei Călimani. Doctoral Thesis. Univ. Bucureşti, 161 pp.

Seghedi, I., Szakács, A., Udrescu, C., Stoian, M. & Grabari, G. (1987): Trace element geochemistry of the South Harghita volcanics (East Carpathians). Calc-alkaline and shoshonitic association D.S. Inst. Geol. Geofiz., Bucureşti, 72-73 (1), 381-397.

Seghedi, I., Szakács, A. & Mason, P.R.D. (1995): Petrogenesis and magmatic evolution in the East Carpathian Neogene volcanic arc (Romania). In: «Neogene and related magmatism in the Carpatho-Pannonian Region». H. Downes & O. Vaselli (Eds.), Acta Vulcanol., 7, 135-143.

Stanciu, C., Udrescu, C. & David, M. (1985): The Mădăraşul Mare rhyodacite (Harghita Mountains). D.S. Inst. Geol. Geofiz., Bucureşti, 69, 199-215.

Stănica, D., Stănica, M. & Visarion, M. (1986): The structure of the crust and upper mantle in Romania as deduced from magnetotelluric data. Rev. Geol. Geophys. Geogr., Geophys., Bucharest, 30, 25-35.

Stănica, D., Stănica, M. & Pinna, E. (1990): Magnetotelluric sounding in the East Carpathian-Harghita area. Rev. Roum. Geophys., 30, 25-35.

Szakács, A., & Seghedi, I. (1986): Chemical diagnosis of the volcanics from the most southernmost part of the Harghita Mountains-Proposal for a new nomenclature. Rev. Roum. Geol. Geophys. Geograf., Geologie, 30, 41-48.

Szakács, A. & Seghedi, I. (1989): Base surge deposits in the Ciomadul Massif (South Harghita Mountains). D.S. Inst. Geol. Geofiz., Bucureşti, 74 (1), 175-180.

Szakács, A. & Seghedi, I. (1990): Quaternary dacitic volcanism in the Ciomadul Massif (South Harghita Mountains). Abstract, Inter. Volcanol. Congress, Mainz, 3-8 September 1990, Abstr. Vol.

Szakács, A., Seghedi, I. & Pécskay, Z. (1993): Pecularities of South Harghita Mts. as the terminal segment of the Carpathian Neogene to Quaternary volcanic chain. Rev. Roum. Geol., 37, 21-36.

Török, Z. (1956): A Kelemen havasokban valamint a Görgeny-Hargita vulkáni lánc teruletén található fiatal eruptivum geologiai kutátásanak módszertani kérdései (Methodological problems of the geological research of the young volcanics in the Călimani and Gurghiu-Harghita volcanic chain). Bolyai University, Cluj, 10th Anniversary volume (in Hungarian).

Williams, H. & McBirney, A.R. (1979): Volcanology. Freeman, Cooper & Co. San Francisco, 397 pp.