Dávid Karátson · Daniel Veres ·
Ralf Gertisser · Enikő K. Magyari ·
Csaba Jánosi · Ulrich Hambach *Editors*

Ciomadul (Csomád), The Youngest Volcano in the Carpathians

Volcanism, Palaeoenvironment, Human Impact

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Preface

> *"My own guiding principle…is the idea of the brotherhood of peoples – becoming brothers and sisters in spite of all wars and conflicts"*
>
> *(Béla Bartók on his Cantata Profana, 1931)*

During his life, the main aim of Béla Bartók, the greatest Hungarian composer of the twentieth century, was to understand and popularize the folk music of the people living in the Carpathian Basin. As a result of his own field trips, he collected thousands of original Slovakian and Romanian folk songs. While doing so, he was working in the Austro-Hungarian Monarchy, which indeed comprised a diverse range of people, languages and cultures. Bartók's work greatly contributed to recognizing the values of ancient Hungarian, Romanian and Slovakian folk music. Ironically, during the years of his collection work (the first two decades of the twentieth century), instead of building brotherhood, the peoples of the Carpathian Basin were infected by growing nationalism. Eventually, the Monarchy participated in the First World War, at the end of which the Austro-Hungarian empire fell apart and the descendant states (Austria, Hungary, Czechoslovakia, the Ukrainian part of the Soviet Union, Romania and Yugoslavia), each with a significant number of minorities, became enemies. Unfortunately, the hostile and tense relations were conserved, and after the Second World War, the peoples of the Carpathian Basin (except for Austria) lived under communist regimes for four depressing decades of comradely ”friendship”. After the political changes in 1990, with several countries becoming EU member states, these relations have been slightly improving, but are far from satisfying.

Hundreds of years earlier, the situation was completely different, in particular, in the eastern region of the Carpathian Basin called Transylvania (Erdély in Hungarian, Überwalt or later Siebenbürgen in German, and Ardeal in Romanian). There, according to the historical record, Hungarians (represented partly by a specific ethnic group, the Székelys, also known in German-speaking countries as Szeklers), Vlachs (Romanians), and Germans (Transylvanian Saxons) had inhabited the area from at least the twelfth century. These people cooperated in many ways, making Transylvania in the Middle Ages a powerful and rich country of subsequent principalities.

The land of Transylvania, especially its eastern part—the Eastern Carpathians—which was populated mainly by the Székelys, is rich in natural resources and beautiful landscapes. Rising above 1500–2000 metres, the Eastern Carpathians consist of a number of mountain ranges constituting a typical orogen (a so-called thrust-and-fold belt). On the internal side of the orogen, the most common of a huge variety of rocks are andesite and dacite—volcanic rocks that reveal an extended, c. 10 million year-long volcanic history that lasted almost up to today. As a result, well-preserved volcanic landforms, covered by dense forests and divided by breathtaking, smaller to larger basins, dominate the landscape. At the southern end, where volcanism is the youngest, post-volcanic phenomena, such as mofettes, sulphurous precipitations, and precious mineral waters, make the land unique in East-Central Europe.

This southern tip of the volcanic chain is called the Ciomadul-Puturosu Hills (in Romanian), or, in the language of the surrounding Székely Hungarian inhabitants (the largest minority in Romania), the Csomád-Büdös Hills. Puturosu/Büdös means ‘stinky’, the name clearly reflecting the sulphur odour obvious at several localities. This name is known from written sources from the early eighteenth century and its correct interpretation was given at first by the Saxon mineralogist Johann E. Fichtel, who wrote that *der sogenannte Bůdỏsch […] ein von innen noch immer brennender Vulkan ist*, that is, *the so-called Stinky Hill ... is a volcano still burning from within* (Nachricht von den Versteinerungen des Großfürstenthums Siebenbürgen, 1780). Stinky Hill, with its sulphurous caves and therapeutic mofettes (carbon dioxide emanations) became famous Europe-wide, attracting visitors and scholars from remote countries too.

In addition to Stinky Hill, a major attraction of the Ciomadul-Puturosu Hills are its twin craters: the older, larger Mohoş (Mohos), which is already breached and filled by a peat bog, and the younger, deeper and circular-shaped Sf. Ana (Szent Anna), in English St. Anne, which hosts a picturesque crater lake. The mysterious lake with its dark waters was first mentioned on maps in the mid-eighteenth century. It was highly appreciated by the local people, especially in summertime benefitting from its particular location and cold microclimate. Moreover, for more than two centuries, the area has given momentum to scientists from nearby towns to remote countries, eventually leading to international collaborations, studying the peculiarities of the related volcanism—rocks, minerals, raw materials, rare plant species, and archaeological findings.

It has turned out that the history of the land is not less diverse and complex than that of the people who lived or still live there. Due to the unique and continuous research efforts, we do know that Ciomadul was the site of the youngest eruption of the whole Carpathian Basin less than 30 thousand years ago and that its volcanic activity dates back to almost 1 million years. We know that the twin craters were formed by colossal explosive eruptions—first sourced at Mohoş, then at Sf. Ana crater—during the final eruptive phase from c. 50 thousand to less than 30 thousand years ago. We have also learned a lot about the palaeo-environmental history of the latest period of volcanic activity—the Late Quaternary—by studying the unique record of the lacustrine infill of the twin craters.

The idea of this book was born in 2015, when an international research group, including the present editors, started to pursue a complex volcanological project on the eruptive activity of Ciomadul. Several of us, however, had already been working in the area for many years and realized that the scientific results, alongside a large amount of information accumulated in the past decades, are important not only for the research community, but also for the greater public.

In view of this, we believe that the exciting, multidisciplinary research results obtained in this remarkable area and the lessons emerging from Ciomadul's studies should not only be presented to the international professional audience (geologists, volcanologists, botanists, archaeologists, historians, and teachers in natural and human sciences), but also disseminated in the local and regional context for the Székely Hungarians and Romanians, who live together with the volcano, for the thousands of visitors each year arriving from wider areas, and for those planning a trip to the volcanic landscape to support their eco-conscious tourism. Thus, the book aims to serve scientists to get acquainted with the scientific characteristics of Ciomadul from as many aspects as possible and to provide information at a general level for interested laypersons and decision-makers. Fulfilling these objectives, the book presents the state-of-the-art of science in a style that intends to remain reader-friendly, trying to match popular scientific requirements as much as possible.

As the Council of Europe recognized, regional or minority languages are part of Europe's cultural heritage and their protection and promotion contribute to the building of a Europe based on democracy and cultural diversity. In harmony with this, in this book, we follow the European Charter for Regional or Minority Languages (1992) about the use of toponyms: when first mentioned in a chapter, either in the text or in figures/maps, the official (i.e. Romanian) names are always followed (in brackets) by the names used by the minority population (i.e. the Székely Hungarians).

The book is divided into two parts. The first part, after summarizing the research history of Ciomadul, presents the details of the volcanism and related topics in eight chapters; the second part deals with the palaeo-environmental aspects of the larger area, along with its human history in nine chapters.

Chapter 1 (Csaba Jánosi et al.) covers the geoscientific exploration, including the earliest written records along with the origins of names and their map representation, and milestones in geology and volcanology, with an emphasis on dating volcanic rocks, the use of mofettes and mineral waters, as well as botanical research, history, and tourism. Chapter 2 (Liviu Matenco) introduces the reader to plate tectonics and the geological structure of the larger area of Ciomadul, the Southeast Carpathians. Chapter 3 (Dávid Karátson et al.) presents details of the eruptive activity of Ciomadul: how volcanism evolved, what kind of eruptions occurred, and what volcanic landforms and deposits were produced. Chapter 4 (Alexandru Szakács and Ágnes Gál) deciphers the origin of volcanic rocks: their study, their nomenclature, and their formation including magma genesis and differentiation. Chapter 5 (Sabine Wulf et al.) considers the explosive eruptions of Ciomadul in a regional context, presenting how pyroclastic formations can be correlated by using tephrostratigraphy. Chapter 6 (Daniel Veres et al.) presents the details of syn- and post-eruptive landscape evolution, and explains contemporaneous surface processes by investigating sedimentary successions and interbedded pyroclastic layers (tephras) in the larger Ciomadul area. Chapter 7 (Alexandru Szakács) considers the exciting question of the current status of Ciomadul volcano, with emphasis on potential future activity and the media coverage of the topic. Finally, Chapter 8 (Csaba Jánosi et al.) presents the peculiar minerals, mofettes and acidulous mineral waters of Ciomadul, including its famous spa culture.

Part II starts with Chapter 9 (Enikő K. Magyari et al.) that presents the palaeo-environmental changes of Ciomadul in the past 30 thousand years as revealed and deciphered from boreholes drilled into the lake sediments of Sf. Ana. Chapter 10 (Krisztina Buczkó et al.) focuses on the specific history of the lake, showing the limnological changes, also based on the lacustrine infill. Chapter 11 (Ioan Tanţău et al.) presents the Holocene vegetation history of Ciomadul using, again, borehole records, in particular, pollen data from both Mohoş and Sf. Ana, placing the results into the context of the Southeast Carpathians and showing human impact. Chapter 12 (Jack Longman et al.) covers the variations of chemical elements in the Mohos lacustrine infill, presenting how these changes can be related to specific environmental (e.g. climate) events and human-driven metal pollution. Chapter 13 (Zoltán-Róbert Para and Krisztina Tóth) shows the present-day flora and fauna of Ciomadul, ranging from the brown bear through the peat bog communities to rare species such as Siberian ligularia or mouse-eared bats. Chapter 14 (Marian Cosac et al.) presents interesting findings from caves in the karst area of Vârghiş (Vargyas) Gorges, that host Ciomadul ash layers and help with the timing of human appearance and abandonment in Palaeolithic times. Chapter 15 (Sándor-József Sztáncsuj and József Puskás) deals with the long time interval from the Neolithic to the Bronze Age, listing the surprisingly rich archaeological finds of the larger region. Chapter 16 (István Botár) shows the details of the earliest human settlements and human history in the Ciomadul region from the age of migrations (3rd century) to the Middle Ages (15th century). Finally, Chapter 17 (Ágnes Herczeg et al.) provides an account of the landscape history and land use from the Middle Ages to modern times, and the concept of the Ciomadul-Balvanyos Region, along with present-day and future eco-tourism.

The chapters in this book are authored by over fifty colleagues, who have been gathered from local Székely Hungarians through Romanian scientists to researchers from Hungary and all over Europe (France, Germany, United Kingdom, The Netherlands), all recognized in their research field. Hopefully, the diverse author content itself symbolizes the main aim of the book as described above, at least this time exceeding the stressed historical-political past of the Carpathian countries—and in harmony with the Bartókian concept.

Budapest, Hungary
July 2021

Dávid Karátson
on behalf of the editors

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Contents

Part I Volcanic Eruptions, Landscape Evolution and Postvolcanic Phenomena

Part II Palaeoenvironment and Human History

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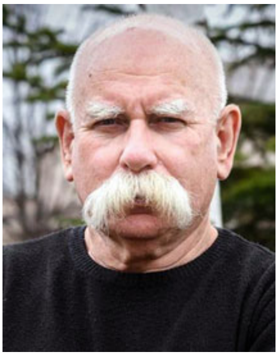

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Part I

Volcanic Eruptions, Landscape Evolution and Postvolcanic Phenomena

1 History of Research: Geoscientific Exploration of the Ciomadul Hills

Csaba Jánosi, Dávid Karátson, and Ferenc Wanek

Abstract

Székelyland in Transylvania (Romania) has few regions as unique as the Ciomadul (Csomád) Hills in their unparalleled beauty. Professionals have been researching this distinctive volcanic region for centuries. Earth scientists study the young volcanic cones, igneous rocks, mineral springs, and mofettas; limnologists probe the waters of Sf. Ana crater lake; botanists roam the peat bog of the Mohoş crater. Ancient fortresses of the region are fascinating subjects for archaeologists, rich folklore and traditional beliefs have inspired many of the greats of Hungarian literature. And research is still on going in recent times.

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1.1 Geographic Setting

The Ciomadul (Csomád) Hills form the southernmost part of the volcanic region of the Călimani-Gurghiu-Harghita (Kelemen-Görgényi-Hargita) mountain range on the east side of the Transylvanian Basin, Romania. It is wedged between the Ciucului (Csíki-havasok) and Bodocului (Bodok) mountains, and the Lower Ciuc (Alcsíki) and Bixad (Sepsibükszád) basins (Fig. 1.1). Nestled in the centre of the volcanic structure, and giving the region its charm and most attractive geographical feature, are the twin craters filled by Lake Sf. Ana (in Hungarian, Szent Anna; in English, St. Anne) and the peat bog of Mohoş (Mohos). Lake Sf. Ana is the site of the last volcanic eruption of the Carpathian-Pannonian region. The somewhat older Mohoş is filled by a peat bog, drained by the Roşu (Veres) stream. In the north, at the edge of the Ciuc (Csíki) Basin, the Ciomadul Hills are bordered by the separate cones of Haramul Mic (Kis-Haram), Haramul Mare (Nagy-Haram), Haramul Ierbos (Fű-Haram), Scaunul Vârghisului (Vargyasszéke), the long ridge of the Ciomadul Mare (Nagy-Csomád), and the truncated cones of Vârful Surduc (Szurduk-tető) and Vârful Cetății (Vár-tető) (Fig. 1.2). On its southern border is the separate eruption centre of Heghieşul Mare (Nagy-hegyes). To the east, on the border of Harghita (Hargita) and Covasna (Kovászna) counties, rise the solitary cones of the Puturosu (Büdös/Stinky) Hill and Balvanyos

D. Karátson et al. (eds.), *Ciomadul (Csomád), The Youngest Volcano in the Carpathians*,
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Fig. 1.1 Located between the Lower Ciuc (Alcsíki) Basin in the north and the enlarging alluvial plain of River Olt leaving the Tuşnad (Tusnád) Gorge to the south, the Ciomadul Hills mostly consist of a group of amalgamated volcanic cones (so-called lava domes) which are truncated by a twin crater: Sf. Ana/Szent Anna (occupied by a crater lake) and Mohoş (Mohos) (already filled by a peat bog). Oblique Google Earth image

Fig. 1.2 The Ciomadul Hills as viewed from the north (*Photo* Dávid Karátson). The flat-topped cone to the left is Haramul Mare (Nagy-Haram); on the right, Vârful Surduc (Szurduk-tető) overlooking the Tuşnad (Tusnad) Gorge

(Bálványos) Hill. Scientific literature often groups these together with Ciomadul itself, referred to as Ciomadul-Puturosu (Csomád-Büdös) Hills (see more in Chap. 3). "*This term was used by Antal Koch a good hundred years ago, and also by Ferenc Herbich—although in a reverse order, since they called the entire area of these mountains as the Stinky (Puturosu/Büdös) massif*" writes András Kristó (1995), a teacher of geology-geomorphology, and a renowned twentieth century naturalist of Székelyland.

1.2 Medieval to Early Modern Written Records of Ciomadul Hills

In this chapter, to review the history of geoscience of the Ciomadul area, the "Land of the Giants and Fairies" as it was known in medieval times, we must recall the earliest legend of the region. The people who inhabited the area explained the mysterious peaks and mountain lakes with an "origin story". The great Hungarian storyteller, Elek Benedek, recounts the tale this way (*A Szent Anna-tó keletkezése*/The origin of Lake Sf. Ana):

"*A long time ago, where the slow waters ripple today, there was a proud castle reaching to the sky on top of a high mountain. Across this castle there was another castle on the mountain peak above the Stinky (Puturosu/Büdös) Cave. These two castles belonged to two brothers who could never see eye to eye and were constantly quarrelling. The only thing they agreed on was to torment their serfs in the villages. Once the lord of the castle above Stinky Cave won an exquisite golden carriage and six magnificent horses by playing cards. He hurried over to his brother to brag about his win, being convinced that no finer horses could be found near or far. He promised his brother his castle and all his possessions if he could come to Stinky Castle with even better horses.—I'm coming with twelve! sneered the brother. He ordered his servants to bring the fairest maidens to him from the countryside. He then selected twelve of them, the most beautiful was Ana. The brother seized the girls, harnessed them up, and—instead of horses—made the girls pull his carriage. He was whipping them mercilessly. As blood was streaming from Ana's back, she cursed the brutal lord wishing the earth would swallow him up. Right then and there the earth shook with thunder and lightning, the tower swayed, and then the entire castle collapsed sinking into deep waters. Where once the proud castle stood, there was a lake with twelve lovely swans swimming in the waves. They swam ashore, shook themselves and became maidens again. Eleven of them fled back to their villages but Ana stayed by the lake. She built a chapel on the shore and lived out her life there in silent prayer. After news of her spread far and wide, pilgrims started to visit the chapel. The people called the lake Sf. Ana in memory of the saintly girl.*"

The first written record of any place names from the Ciomadul Hills is found in the Mikó family's forest survey report, prepared for the Hungarian King, Louis the Great, in 1349. As most of the early written documents in Hungary, this is in Latin as well. "*Prima scilicet meta incipit in campo Bezedmezew uocato, a parte septem-trionali, ubi iuxta metam terream, aliam de nouo similiter terream, in cuiusquidem Campi alia parte uersus partem orientalem, vnam metam terream iuxta antiquam, deinde progrediendo, ad eandem partem orientalem ad toberch kuzberch et Bydushyg peruenitur, abhinc eundo ad partem meridionalem peruenitur ad Somburfw, directe ulterius eundo, uenitur ad Gerebenchfw, et Zaldubuspotakfw, quod declinat ad fluuim Olth (…)*". Boér and Tamás (2018) offer a translation in their book *Szentanna:* "*The first border sign is at a place called Bezedmezew, in its northern parts, where a new earthen mound was erected beside the old one. In this same field, to the east, another earthen mound was built beside an old one. Then travelling further in the same easterly direction, they reached Toberch, Kuzberch, and Bydushyg. From there they headed south towards Somburfw, and from there straight on to Gerebenchfw and Zaldubospotakw, which slopes towards the river Olt.*" Further investigation of the place names makes it probable that Jimbor village (Somborfalva, part of present-day

Bixad/Sepsibükkszád), the Jimbor (Zsombor) stream, and Bója (Boiu), or Bója Hill at Tuşnad (Tusnád), can be linked to Zsombor, the tenth century Transylvanian '*gyula*' (chieftain of the Hungarian tribes), and to his son, Bója. Geographical names ending with the letter '*d*', such as *Csomád* or *Tusnád*, also suggest this early origin.

The lake is first mentioned as Lake Sf. Ana in a Latin manuscript *Siculia* in 1702 by István Lakatos, pastor of the Cozmeni (Csíkkozmás) parish: "*The deepest is Lake Sf. Ana above the mountains of Tuşnad, surrounded by peaks and without an outflow. Near the lake there are ordinary stones suitable for building and carving*". There are two theories about the origin of the name. One is that the lake was named after Saint Anne by the medieval sulphur miners of Turia (Torja), Tuşnad, and Lăzăreşti (Csíkszárfalva) who considered Virgin Mary's mother to be their patron saint. While in another theory, Jesuit inspiration is behind the name. Jesuit monk Ferenc Kunits states in his book *Dacica siculica,* printed in Cluj (Kolozsvár/Klausenburg) in 1731: "*Close to the same place rises Sf. Ana's mountain, the top of which is largely occupied by a lake. It can be walked around in three hours and is so deep that it has refused to give up her secret to anybody trying to measure her depths. (…) Her secrets include that at certain times her waters swell higher than the sea, though no rivers feed her; other times her waters flood the fields below. The storms and intense hail arising from here destroyed the neighbouring countryside so much so that its people, not trusting their own human strength, were forced to seek God's and the saints' intervention. Their hope was not in vain. With unprecedented fear of God, and reverence to Sf. Ana, the mother of Mary, they named the mountain Sf. Ana. God listened to their prayers and yearly supplications and quieted the elements.*"

The chapter *Útiképek Székelyföldről* (Travels in Székelyland), in Lajos Réthi's 1868 volume *Magyarország képekben* (*Hungary in Pictures*), mentions the pilgrimage to Lake Sf. Ana. "*The people feel a certain mystical reverence for the lake (…). Pilgrimages are usually held here twice a year; each time multitudes come from the surrounding Catholic regions: Gheorgheni (Gyergyó), Ciuc (Csík), and the northwestern part of Trei Scaune (Háromszék). The pilgrims walk slowly around the lake and chant holy hymns following their priest. I was told that a long time ago people believed that a monster, the grandson of fairy-tale dragons was living in the lake. So, at the pilgrimages they prayed for the demise of this monster. The priest sang: »The monster living in this lake«; to which the people answered in unison »Drop dead and be lost!« The people got used to chanting this answer so much that when the priest started the litany of the saints, the people still answered the same!*".

Mózes Vitos recalled in one of his *Csíkmegyei Füzetek* (*Notes from Ciuc*) (1894–1902) that these pilgrimages on St. Anna's feast day "*often counted crowds of twenty or thirty thousand. Due to bloody fights and rowdy behaviour of drunkards these pilgrimages were banned. First, by Bishop Ignácz Battyáni on August 13, 1786, then a second time for the same reasons in 1844 by Bishop Miklós Kovács, shortly after the pilgrimages started again in the 1830s.*"

The crater lake of Ciomadul first appeared on a published map around 1720. Johann Baptist Hofmann's map of Transylvania shows the lake with a "*videlt palus*" (certainly a lake) note. The map of the Josephinian Land Survey of Transylvania (compiled between 1763 and 1787) already shows a St. Anna Teich (with the location of the nearby chapel), as well as other locations such as Büdes Hogy, Csomal *[sic]*, Kis Hegyes, Nagy Hegj above Bükszat, Kö Ponk, Fenÿas Ponk, Nagÿ Harrom as well as several streams, like Sombor Patak, Hallasag Patak. An earlier map in Ignaz Müller's manuscript from 1769 shows a "Lacus S. Anna", but this particular document was top secret, so much so it remained unknown to his contemporaries. Anton Wenzely's map, printed in 1789, also shows the crater lake of Ciomadul as *S. Anna See*, accompanied by a geographical place name of *Varteteje* (Vârful Cetăţii). The lake increasingly became a symbol of the Ciomadul region for visitors, and at the same time a major focus of later scientific research (Fig. 1.3).

Fig. 1.3 Crater lake of Sf. Ana (Szent Anna) in winter, from the Belvedere lookout point established near the winding road leading down to the lake. Even with global warming, the ice on the lake freezes tens of centimetres every year and can last until March (*Photo* Dávid Karátson)

1.3 Getting to Know the Geology and Volcanology of Ciomadul

1.3.1 History of Geological and Volcanological Research

The first geological study of the Ciomadul Hills, including the Putorosu Hills and Stinky Cave of Turia, was published by mineralogist Johann Ehrenreich Fichtel of Sibiu (Nagyszeben) in the second volume of his major work, *Beytrag zur Mineralgeschichte von Siebenbürgen* (Contributions to the Mineral History of Transylvania), *Nachricht von den Versteinerungen des Großfürstenthums Siebenbürgen* (Report on the Fossils of the Grand Duchy of Transylvania), published in Nürnberg (Fichtel 1780). In the postscript of the second volume, on p. 122, he wrote: "*...der sogenannte Bůdŏsch (Büdöshegy) [...] ein von innen noch immer brennender Vulkan ist...*", meaning "the so-called Stinky Hill [...] that is still a burning volcano inside". He gave detailed descriptions of the volcanic host rocks of Stinky Cave, which he called "sulphur cave", along with its gas emissions and sulphur precipitations. He even mentioned the sulphur springs of the area that were already known at his time. Relying on scientific literature, he correctly identified Puturosu Hills as a volcanic structure, comparing it to the Solfatara near Naples in Italy. His descriptions greatly contributed to making the Puturosu Hills known throughout Europe and attracting travellers and researchers alike.

There is a description of Puturosu Hills by an unknown author in the 1838 issue of the magazine *Mulattató* (Entertainer), published in

Kronstadt (Brașov/Brassó) and written in Hungarian. In the article titled, *A Torjai Büdös-hegy* (The Stinky Hill of Turia), he said "*I can state with certainty that it was a mountain spewing fire, and then it quieted down—but when did it last explode and when did it fall asleep? Even the oldest legends are silent about that*".

The first comprehensive geological work on Transylvania also discussed the Ciomadul Hills, confirming the earlier writers' hypotheses. This first synthesis of geological observations, *Geologie Siebenbürgens* (Geology of Transylvania), was written by Franz Ritter von Hauer and Guido Stache, published by the *Vereine für Siebenbürgische Landeskunde* (*Association for Transylvanian Heritage [a Transylvanian Saxon organization]*) of Sibiu (Hermannstadt/Nagyszeben), and was printed in Vienna, Austria in 1863. The book was associated with a 1:576,000 scale geological map (Fig. 1.4) edited by von Hauer, with contributions by Albert Bielz, Ferdinand von Richthofen, Guido Stache, and Dionys Štur who divided the territory of Transylvania for geological mapping. The Harghita

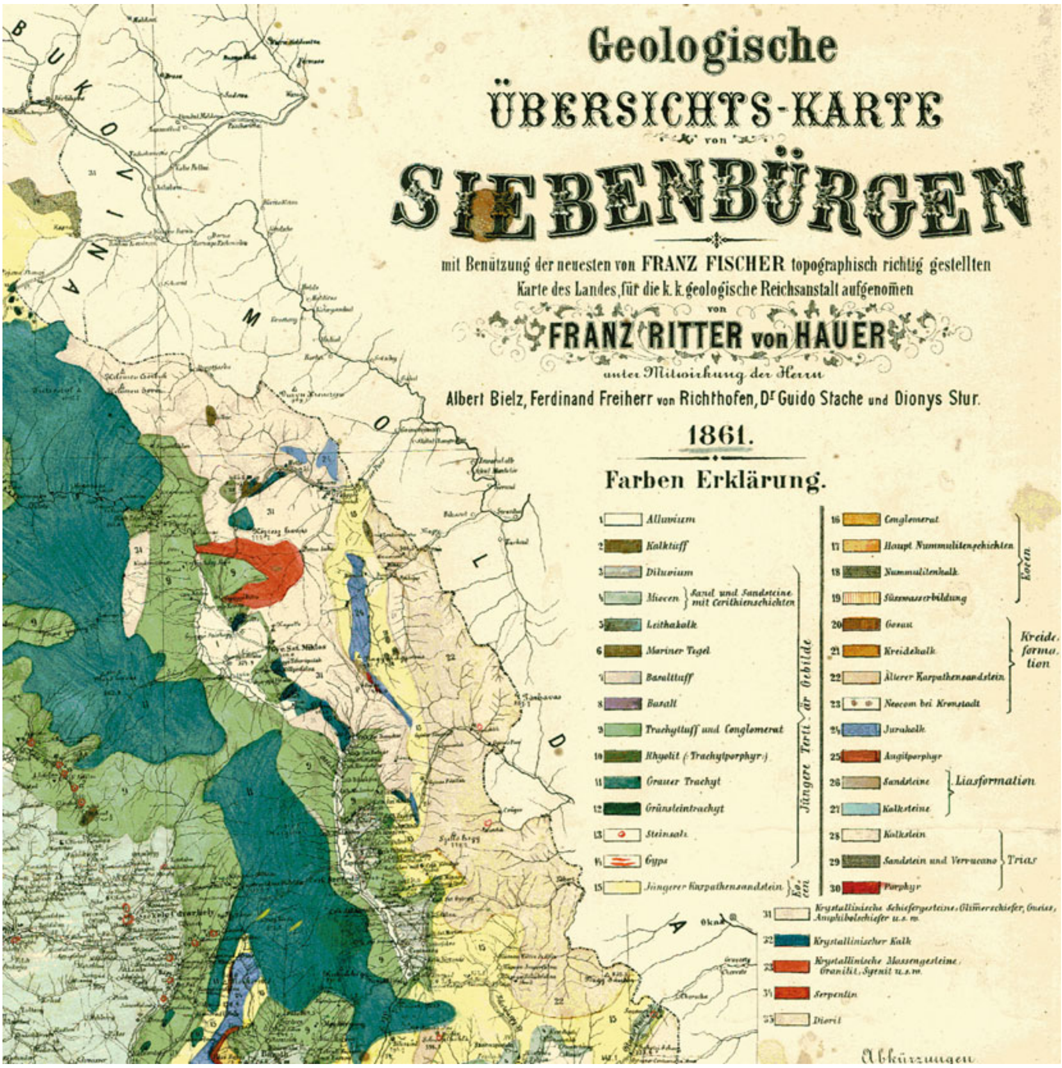


Fig. 1.4 Detail of the first comprehensive geological map of Transylvania (1861) displaying the "trachytes" of the Ciomadul Hills in the context of the Harghita Mountains. Scale 1:576,000

Fig. 1.5 Lake Sf. Ana (Szent Anna). Drawing by Gusztáv Keleti from Balázs Orbán's *A Székelyföld leírása történelmi, régészeti, természetrajzi s népismei szempontból* (History, archaeology, natural history and folklore of Székelyland, 1868), engraved by Károly Russ

Mountains was mapped by Ferdinand Richthofen (Korodi and Hoffmann 2016).

After visiting the Ciomadul Hills, Balázs Orbán, a famous writer, etnographer, photographer of the nineteenth century, interpreted correctly the phenomenon of Lake Sf. Ana. In the third volume of his major work, *A Székelyföld leírása történelmi, régészeti, természetrajzi s népismei szempontból* (History, archaeology, natural history and folklore of Székelyland, 1869), he postulated that "*The funnel shape of the circular ridges it occupies, the red trachytic debris around the lake, and the traces of fire on the nearby hillsides, point to the fact that it is the crater of an enormous volcano, now filled with water*" (Fig. 1.5).

1878 marked a turning point in the study of Lake Sf. Ana and Puturosu Hills, when two papers were published by researchers at the Department of Mineralogy and Geology of the Hungarian Royal University at Cluj. Under the leadership of department chair Antal Koch, chemistry professor Antal Fleischer and assistant Sándor Kürthy analysed the rocks and minerals of the region, as well as the mineral precipitations connected to the volcanic activity. The results were published—almost simultaneously—in two separate papers. One was an important regional assessment, *A Székelyföld földtani és őslénytani leírása* (Geological and palaeontological description of Székelyland) by Ferenc Herbich, included in the *Annales of the Royal Geological Institute of Hungary* (Magyar Királyi Földtani Intézet Évkönyve). The other was a report by Antal Fleischer and Antal Koch: *Jelentés a tórjai Büdös és vidéke földtani viszonyairól, forrásairól, gázkiömléseiről és a Büdös-barlang csepegéséről* (Report on the geology, mineral springs, fumaroles, and the precipitations of Stinky Cave in the region of Puturosu of Turia), published in the *Annales of the Székely Association of Culture and Economy*. Koch published these data again in more detail in his 1900 synthesis, *Az Erdélyrészi-medence* *harmadkori képződményei—Neogén csoport* (The Tertiary Formations of the Transylvanian Basin—The Neogene Group; Koch, 1900).

József Budai recognized the acidic (silica-rich) nature of the rocks of the Ciomadul Hills, describing them as trachyte—using contemporary terminology. Budai published his results, *Adatok a Hargita déli részének petrographiájához* (Contributions to the petrography of southern Harghita), in the *Bulletin of the Hungarian Geological Society* in 1881. Based on Budai's work and on Mór Pálfy's 1895 paper, *A Hargita andezites kőzeteiről* (On the andesitic rocks of the Harghita), published in the *Az EME Orvos–természettudományi Értesítője* (Medical-Natural Science Bulletin of the EME), in 1900, Koch classified the Ciomadul rocks as biotite andesite, noting that they are "really close to dacites".

Károly Papp's excellent work also needs to be mentioned here. His paper, *A futásfalvi Pokolvölgy környéke Háromszék vármegyében* (The region of Pokolvölgy/Devil's valley at Futásfalva/Alungeni in Trei Scaune County), published in 1912 in the *Bulletin of the Hungarian Geological Society*, discussed in detail the post-volcanic activities, mineral springs, and estimated that the volcano last erupted 300,000 years ago. Papp was also the first to notice the volcanic ash layers and pointed to their significance.

János Bányai, probably the best scholar and promoter of the geology of Székelyland in the first half of the twentieth century (Fig. 1.6), published an outstanding study in the *Bulletin of the Hungarian Geological Society* (Bányai, 1917). His paper, Kézdivásárhely vidéke Háromszék vármegyében (The region of Târgu Secuiesc in Trei Scaune County), correctly described the pumiceous layers of the Fehérmartok outcrop near Târgu Secuiesc (Kézdivásárhely) being associated with the activity of the Ciomadul volcano. "*Below the thin topsoil is a yellowish sand which turns light grey in the deeper parts. About 2 m from the surface this sand is divided into upper and lower parts by a 0.2 m thick lapilli layer of amphibole-biotite andesite pumice. / Pieces of this pumice, varying from rice to fist size, form a strikingly bright layer in the sand. On closer examination, the*

Fig. 1.6 János Bányai, geologist, teacher, writer, museologist (1886–1971), at his home desk in Odorheiu Secuiesc (Székelyudvarhely). *Source* collection of Rezső Haáz Museum, Odorheiu Secuiesc, photographer unknown

porous structure is evident to the naked eye. 2–3 mm hexagonal, brown biotite flakes, and 2–3 mm long, glassy amphibole needles can also be observed in the matrix. Under a loupe, the matrix shows silky fibres and plagioclase minerals./[…] So, we can conclude that part of this material is made up of redeposited debris from the andesite around Lake Sf. Ana." We have to point out—in light of recent research—that the pumiceous layer in question is not redeposited debris, but a primary pyroclastic unit from one of the last explosive eruptions of Ciomadul (see Chap. 3 on volcanism).

Lajos Lóczy Sr. (1849–1920), geologist, geographer, director of the Hungarian Geological Institute and the second chair of Geography Department at the University of Science (later Eötvös Loránd) in Budapest, presented a short but to-the-point lecture at the Hungarian Geological Society in 1918. The lecture material was also published as a short communication, *A Szent Anna-tó vulkáni krátere* (The volcanic crater of Lake Sf. Ana) in the *Bulletin of the Hungarian Geological Society* in the same year. Lóczy recognized Sf. Ana and Mohoş as twin craters, the explosive nature of their eruptions, and their young age. He correctly described "*the thick layer of pumice and ash draping the slopes toward Bixad village*", and called contemporary Hungarian geologists to make it their priority to explore and study the volcanic ranges around Sf. Ana lake.

János Bányai, following his 1917 paper, continued to publish about the region of Lake Sf. Ana. In a 1940 supplement to the journal *Székelység* (The Székelys)—which he also edited—he wrote an article, *A Szent Anna tó és környéke* (The district of Lake Sf. Ana), and was the first to describe the geographical features of Ciomadul Hills. He interpreted the crater of Mohoş and its original western part as a caldera of an earlier explosion, in which later the crater of Lake Sf. Ana formed. He also published a comprehensive description of the Ciomadul Hills in a book on local history, *Székelyföld írásban és képben* (Székelyland in words and pictures), printed in Budapest in 1941. He detailed the natural history of the Ciomadul Hills in the chapters *A székelyek és Székelyföld* (The székelys and Székelyland) and the *Székelyföld tájai* (Landscapes of Székelyland).

A study was published in 1956 in the journal of the Romanian Academy of Sciences, *Comunicările Academiei R. P. România* (*Communications of the Academy of P. R. of Romania*) by geologists Dan Slăvoacă and Constantin Avramescu of Bucharest, who questioned the depression of Lake Sf. Ana as a volcanic crater and argued for a structural basin. Similarly, Constantin Privighitoriţa denied the crater nature of the lake in his study published in 1970 in the *Lucrările Colocviului de Limnologie Fizică* (*Reviews of the National Colloquium on Physical Limnology*), basing his opinion on an erroneous geological assessment. He explained the formation of the lake basin as erosional mass wasting of lava layers that were sitting on top of volcanic ash on the Cretaceous basement.

In 1964, Aurelia Lazăr and Adela Arghir published a petrological study of the rocks in the Ciomadul area in the journal of the Romanian Institute of Geology, *Dări de Seamă ale Şedinţelor* (Meeting Reports). They distinguished green hornblende andesite, basaltic hornblende andesite and augite hypersthene andesite, and estimated active volcanism lasting up to the Pleistocene.

Starting from the 1970s, Wilfried E. Schreiber, professor of geology at the Babeş-Bolyai University of Cluj-Napoca, investigated the volcanic morphology of Harghita Mts, including the Ciomadul Hills. In his 1972 study *Incadrarea geografică şi geneza masivului Ciomadu* (Geographical setting and genesis of the Ciomadul massif), published in the *Studia Universitatis Babeş–Bolyai, Geologia-Geographia,* he presented the young volcanic landforms of Ciomadul on a map, including the "cones", interpreting them correctly as distinct eruption centres, and the explosive twin craters (Fig. 1.7). After further works, in 2006 Schreiber and co-author Enikő Unger published this map in the *Földtani Közlöny (Bulletin of the Hungarian Geological Society);* in that paper they also interpreted the erosional volcanic features in the light of the entire Southern Harghita Mountains.

Studying the rocks of the Southern Harghita and Ciomadul, János Treiber, professor of

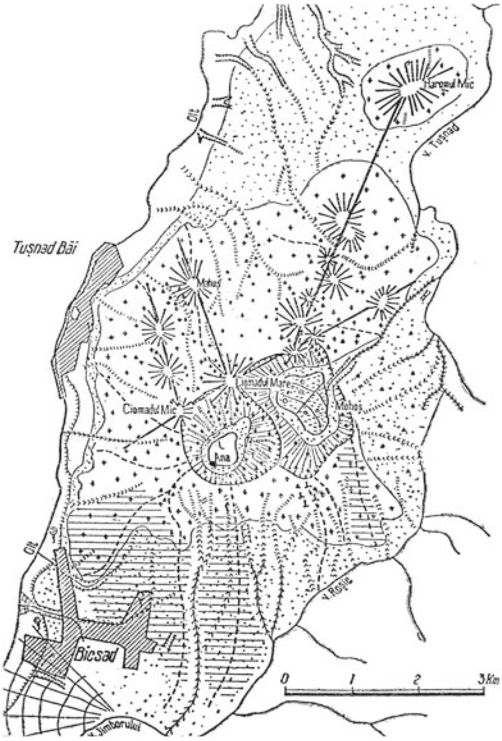
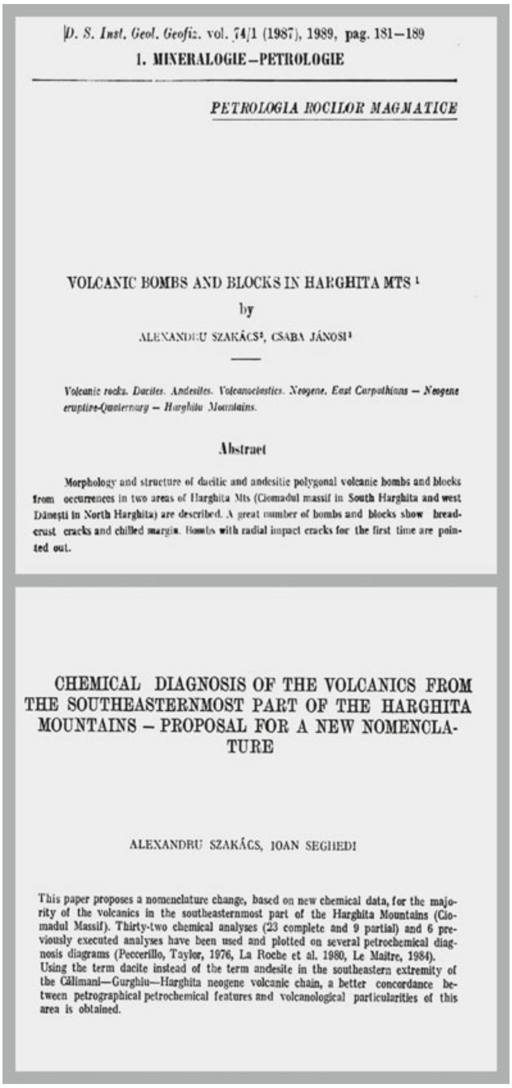


Fig. 1.7 Volcanic geomorphological interpretation of the Ciomadul Hills (Schreiber 1972). For details, see text

petrology at the University of Cluj, concluded that the second biotite andesite phase and the third pyroxene andesite—basalt phase of the volcanic activity of the Pilişca (Piliske) and Ciomadul are contemporary, and their activity ended in the Pleistocene. His study was published in 1974 in the university's publication on geology and mineralogy, *Studia Universitatis Babeş-Bolyai, Geologia-mineralogia*.

In 1982, in connection with his petrological investigations, the first author of this chapter, Csaba Jánosi, geologist, delineated exploitable pumice occurrences on the outer edge of the crater: on the Câmpul Lung (Hosszúmező) of Tuşnad and on the eastern slopes of Coacăze (Kukojzásorka). He also described the "breadcrust bombs" of Ciomadul that were first mentioned in the first part of the twentieth century: in 1922 Jenő Cholnoky discussed the characteristic breadcrust bombs of Ciomadul, and Viktor Zsivny provided mineralogical studies on them in 1929. The Comloş ditch (Komlósárok) below Băile Tuşnad (Tusnádfürdő) was considered as the main occurrence of these volcanic bombs. Jánosi recognized additional locations in the gullys of the Rosu and Disznyó streams on the southern slopes of Muntele Lacului (Tóbérc). In 1989, Alexandru Szakács and Csaba Jánosi published a comprehensive study on these volcanic bombs in the journal, *Dări de seamă ale şedinţelor* (Meeting Reports, Geological and Geophysical Institute of Romania) (Fig. 1.8).



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1. MINERALOGIE–PETROLOGIE

PETROLOGIA ROCILOR MAGMATICE

VOLCANIC BOMBS AND BLOCKS IN HARGHITA MTS [1]

by

ALEXANDRU SZAKÁCS[2], CSABA JÁNOSI[3]

Volcanic rocks. Dacites. Andesites. Volcanoclastics. Neogene. East Carpathians – Neogene eruptive-Quaternary – Harghita Mountains.

Abstract

Morphology and structure of dacitic and andesitic polygonal volcanic bombs and blocks from occurrences in two areas of Harghita Mts (Ciomadul massif in South Harghita and west Dăneşti in North Harghita) are described. A great number of bombs and blocks show bread-crust cracks and chilled margin. Bombs with radial impact cracks for the first time are pointed out.

CHEMICAL DIAGNOSIS OF THE VOLCANICS FROM THE SOUTHEASTERNMOST PART OF THE HARGHITA MOUNTAINS – PROPOSAL FOR A NEW NOMENCLATURE

ALEXANDRU SZAKÁCS, IOAN SEGHEDI

This paper proposes a nomenclature change, based on new chemical data, for the majority of the volcanics in the southeasternmost part of the Harghita Mountains (Ciomadul Massif). Thirty-two chemical analyses (23 complete and 9 partial) and 6 previously executed analyses have been used and plotted on several petrochemical diagnosis diagrams (Peccerillo, Taylor, 1976, La Roche et al. 1980, Le Maitre, 1984). Using the term dacite instead of the term andesite in the southeastern extremity of the Călimani—Gurghiu—Harghita neogene volcanic chain, a better concordance between petrographical petrochemical features and volcanological particularities of this area is obtained.

Fig. 1.8 Front pages of geological-volcanological works published in the 1980s by Alexandru Szakács, Ioan Seghedi and Csaba Jánosi (for details, see text)

Alexandru Szakács and Ioan Seghedi began their state-of-the-art volcanological and volcano-geological studies in the late 1980s. Their petrological analyses confirmed and demonstrated in detail that the previously described high-silica andesite is predominantly dacite. Their investigations shed first light on the lava dome character of Ciomadul volcanism and on the explosive nature of the last eruptions. Zoltán Pécskay and Dávid Karátson joined this work in the early 1990s. Pécskay conducted the first K–Ar radiometric dating of the volcanic rocks. In 2015 Szakács and his colleagues published the results of their comprehensive, decades-long investigations in the paper, *Eruptive history of a low-frequency and low-output rate Pleistocene volcano, Ciomadul, South Harghita Mts., Romania*, in the journal *Bulletin of Volcanology* (Szakács et al. 2015).

Crisan Demetrescu and Maria Andreescu have been examining the geothermal conditions of Romania, including the Eastern Carpathians. In their 1994 study they reported a highly focused heat flux anomaly under the Ciomadul area with temperatures exceeding 800 centigrade at a depth of 20 km. Continuing this line of research, Mihaela Popa and colleagues analysed the earthquakes of the Southeast Carpathians and published their results in *Pure and Applied Geophysics* (Popa et al. 2011). They found that—in addition to the Vrancea zone, which caused the earthquakes of Bucharest—the Ciomadul Hills also present considerable seismic activity with earthquake centres (hypocentres) occurring in a peculiar, vertical arrangement. Based on the reduced velocity of seismic waves, Popa and colleagues inferred the presence of partially molten rock material (magma) between depths of 8–20 km. Balázs Kiss and his colleagues identified two types of amphiboles in the dacites of Ciomadul, and published their data in *Contributions to Mineralogy and Petrology* (Kiss et al. 2014). One type of amphibole can be associated with the silicate-rich magma system of the upper crust at the depth of 8–12 km. The other type of amphibole forms—sometimes with further change of the former—when additional molten mafic material is pushing up from below. Szabolcs Harangi and colleagues published a study in 2015(a) in *Journal and Volcanology and Geothermal Research*, where, based on magnetotelluric investigations (i.e. which examines the electrical resistivity distribution beneath the surface), they confirmed the presence of magma even today, at an estimated depth of 5–20 km. In the deeper regions a partially molten phase is probable. Mickael Laumonier and his team estimated the amount of the magma to be 20–58 cubic kilometres, drawing attention to the fact that this volume is more than one of Ciomadul's entire erupted mass so far (Laumonier et al. 2019).

Examining the evolution of volcanic landforms in his 1996 morphometric study in *Journal and Volcanology and Geothermal Research*, Dávid Karátson explained the relatively large diametre of the Ciomadul twin craters by their explosive origin and the intense frost shattering and related slope processes during the last glacial period. From the late 2000s, Karátson and his colleagues studied the relationship between the volcanic activity and the resultant volcanic landforms. In his 2007 monograph, *A Börzsönytől a Hargitáig* (From the Börzsöny to the Harghita Mts.), Karátson gave detailed descriptions of two key outcrops of the last explosive volcanic activity, the one near Băile Tușnad and another one in the gorge of the Roșu (Veres) stream draining the Mohoş peat bog. Karátson and his co-authors' 2013 article in *Journal and Volcanology and Geothermal Research* identified the lava domes of Ciomadul as Peléan-type and coulée-type (the latter being asymmetrical domes emplaced on a slope). Comparing the domes' morphometric characteristics with other lava domes worldwide, Karátson and colleagues estimated the Ciomadul domes 10–100 thousand years old. This age was also supported by preliminary zircon dating. Using this dating method on zircon grains (separated mainly from pumice clasts), Szabolcs Harangi and his colleagues reported a chronology of the explosive eruptions in *Journal and Volcanology and Geothermal Research* (Harangi et al. 2015b).

The focus of the latest research is the age progression of the eruptions, the development of lava domes, their eruptive rates, and the late-

Fig. 1.9 Geological-volcanological field work at Ciomadul. **a** Geophysical exploration of the lacustrine infill of Lake Sf. Ana (*Photo* Dávid Karátson). **b** Deposit of one of the latest pyroclastic-flows (so-called block-and-ash flow) with an outsized prismatically jointed block (*Photo* Csaba Jánosi). **c** Studying the pyroclastic sequence of one of the latest explosive eruptions, the Târgu Secuiesc ('TGS', Kézdivásárhely) eruption (*Photo* Dávid Karátson). **d** Sampling massive dacite lava boulders for K–Ar radiometric dating (*Photo* Dávid Karátson)

stage explosive activity (Fig. 1.9). Karátson et al. (2016, 2017) and Wulf et al. (2016) published on the late-stage explosive eruptions 50–30 thousand years ago and the related tephrostratigraphy. Most recently, Molnár et al. (2018, 2019) used zircon dating to decipher the development of the lava domes. Pierre Lahitte, Dávid Karátson and their colleagues published a two-part study in *Bulletin of Volcanology* (Lahitte et al. 2019; Karátson et al. 2019), where they presented the Cassignol-Gillot K–Ar technique for dating the lava domes, compared the results of different radiometric methods, and estimated the lava production rates of Ciomadul. Chapter 3 of this book will give more details about the latest research, the problems already solved and the questions still outstanding.

1.3.2 Age of the Last Volcanic Eruptions

After it became obvious in the nineteenth century that the Ciomadul Hills were a—geologically speaking—young volcano, the last two hundred years saw a number of earth scientists trying to estimate the exact timing of the last eruptions. It is no surprise that this question is of interest not just for researchers but also for the general public. While the timing of stages and phases of volcanism cannot be understood without knowing the history of volcanism (see Chaps. 3–6), it is worth tracing how researchers thought about the age of the last eruptions over time (Fig. 1.10).

In his already cited monograph published in 1900, Antal Koch was the first to attempt to

Fig. 1.10 Artist's vision of the youngest eruptions of Ciomadul that may have been witnessed by Palaeolithic Man (*Picture credit* Edvárd Takács)

pinpoint the age of the eruptions when he wrote on p. 325: "*The volcanic activity that produced the pyroxene andesite of the southernmost peaks of the Harghita and the basalts along the Olt river, most probably occurred during, or at the very end of, the last phase of the Tertiary, and perhaps even in the Quaternary*".

Regarding the young age of the eruptions, Jenő Cholnoky's statement, undoubtedly exaggerated, should be quoted from his study published in 1922: "*Barring the lush vegetation cover, one could expect renewed eruptions at any moment*". Around the same time, in 1929, Gyula Szádeczky-Kardoss connected the problem of volcanic activity with human prehistory in his study, *A Székelyföld képződése* (The Formation of Székelyland): "*In the south, Saint Anne mesmerizes everyone with her virginally whole crater and pristine waters within. The pure volcanic sand on the diluvial terraces around Puturosu shows that the eruptions on the southern reaches continued until even humans appeared. These early men made rudimentary stone tools from the opals and other volcanic rocks*". Indeed, knapped stone tools can be collected north of Vârful Cetății (Vártető) on the high terrace of the Olt river at Balinoş (Balinos), and at Lăzărești. Polished stone tools have been found in Tușnad's district called Falumejjéke and in Câmpul Capelei (Kápolnamező), south of Lăzărești. Although exact, radiometric dating was not available at that time, Cholnoky wrote in his 1941 work, *Erdélyi képek* (Images of Transylvania): "*The crater of Lake Sf. Ana is fresh and intact (…) Geologically speaking, the activity of the volcano had only recently ceased. 'Recently' means that it may have been erupting 100,000 years ago.*" As we shall see in later chapters, Cholnoky, who often put forward bolder hypotheses than his contemporaries, could have been even bolder with this suggestion…

Agreeing with Cholnoky's hypothesis, András Székely wrote about the Ciomadul Hills in 1959 in his study published in the *Földrajzi Közlemények (Geographical Review of the Hungarian Geographical Society): "This is the youngest volcanic mass in the entire Carpathian Mountains. (…) It was still active in the Pleistocene. The original volcanic structures are best preserved here. The finest evidence of this is the twin craters of Ciomadul.*"

On the other hand, János Bányai, who was the foremost scholar of the Ciomadul Hills in the middle of the twentieth century, found these ideas unsubstantiated. In his 1964 study, *A Szent Anna-tavi ikerkráterek erupciójának kora* (Eruption age of the twin craters of St. Anna's Lake), published in the Földrajzi Értesítő (*Geographical Bulletin of the Hungarian Scientific Academy*), he doubted that the Ciomadul erupted in the Pleistocene and defended the earlier notion that put the eruptions at the end of the Pliocene. It is interesting to see that one of Bányai's critics, Pál Marosi—professor of hydrogeology at Babes-Bolyai University—'lectured' Bányai by writing in 1957 in the journal *Korunk* (Our Times): "*According to our current knowledge, prehistoric man probably saw smoke rising from the Ciomadul*." Based on data available today, this was the truth…

The first radiometric dating was carried out in 1982 when the first author of this chapter (Csaba Jánosi) and Sándor Szakáll, a mineralogist at the University of Miskolc, sampled a huge dacite block lying on the side of Stinky Hill, next to the Vârghis (Vargyasi) mineral spring. Zoltán Pécskay analysed this sample at the Nuclear Research Institute in Debrecen, Hungary, employing the K–Ar method already in use in Hungary at that time. The dacite proved to be about 200,000 years old. Unfortunately, the political situation of those years made it impossible to incorporate this extremely important measurement into a geological report, so it remained as an often-doubted anecdotal data. It was finally published, together with the radiometric ages of Mt. Cucu (Kakukkhegy) in southern Harghita, in 1992 in the *Bulletin of the Hungarian Geological Society* by Zoltán Pécskay, Alexandru Szakács, Ioan Seghedi and Dávid Karátson.

The 1990s saw an increasing number and larger variety of radiometric dating efforts. This was made possible—beside the political changes—by an ever-expanding cooperation of Transylvanian, Hungarian, and international researchers. The first results already caused quite a surprise. In 1994, Étienne Juvigné of France and his Romanian and Hungarian co-authors used radiocarbon (^{14}C) method on a charcoal sample—gained from charred wood separated from pumice collected south of Băile Tușnad—and determined its age to be only 10,700 years. Because of this early Holocene age was received with scepticism, Alexandru Szakács and Ichio Moriya repeated the measurements in a Japanese laboratory. The same charcoal material now showed a slightly older, Late Pleistocene age of over 36 thousand years. The palaeosol under the pumice layer proved to be 41–45 thousand years old (Moriya et al. 1996). This data was confirmed in 2010 by Szabolcs Harangi and his colleagues who measured the charcoal layer to be 39 thousand years old. (Using the latest international calibration standards, these values have been recalculated to be a couple thousand years older, as published in 2016 by Dávid Karátson and his co-authors.) It needs to be mentioned that radiocarbon dating gives reliable results up to a maximum age of c. 40 thousand years, so in order to get more accurate ages other radiometric dating methods need to be conducted as well. (Chapter 3 has more details on different dating methods that are of huge importance at Ciomadul.)

In their study published in the *Bulletin of the Hungarian Geological Society* in 2007, Anna Paula Vinkler and her colleagues described a new pumiceous layer east of the village of Bixad. Using radiocarbon dating on charcoal gained from the pumice, they determined its age to be 27 thousand years (which was recalibrated to 31.5 thousand years; Fig. 1.11). This age was confirmed by Szabolcs Harangi and his colleagues in 2010 and 2015 using radiocarbon and zircon dating methods. They postulated that the eruption producing that particular pyroclastic layer at Bixad was the very last volcanic activity of Ciomadul.

Fig. 1.11 Charcoal fragments embedded in pyroclastic deposits can be used for radiocarbon (^{14}C) dating, useful to infer the age of the eruption. Example near the village of Bixad (Bükkszád) (*Photo* Dávid Karátson). For more details, see Chap. 3

However, the age of the thick sedimentary layers of Sf. Ana crater did not fully fit into this hypothesis. Enikő Magyari examined core samples from this succession, where samples from 17 m yielded 26 thousand years, while samples from 21 m, 27 thousand years calibrated radiocarbon age. In their 2016 study, Dávid Karátson and his co-authors examined the uppermost tuff layer of Mohoş which they identified in a core sample at a depth of 15 m under 10 m-thick Holocene peat. Karátson et al. suggested that this uppermost layer—above which they measured a c. 29 thousand old radiocarbon age—is the result of the last volcanic eruptive activity of Sf. Ana crater. Whereas radiocarbon ages can only be considered as indirect evidence, in their 2019 study Karátson et al. also measured an age of c. 28 thousand years using K–Ar dating on dacite blocks collected on the southern slopes of Sf. Ana crater. They presumed these blocks to be deposited by the last explosive eruption of Ciomadul that created the present shape of the crater lake.

1.3.3 Exploration of Mofettes and Mineral Waters

The most interesting and exciting phenomena of the Ciomadul Hills are the post-volcanic activities such as dry carbon dioxide emanations (mofettes), popularly referred to as “stinky” pits, and the carbonated mineral water springs. The study of these natural wonders, as mentioned above, dates back to the eighteenth century to the work of Johann E. Fichtel. The results of the latest research are described in Chap. 8.

Fig. 1.12 Student field trip participants approach the Sulphurous/Stinky Cave (Grota Sulfuroasă or Puturosu—Kénes or Büdös-barlang) of Turia (Torja) (*Photo* Szabolcs Kósik)

The first chemical analyses of the gas emissions of the caves of Putorosu Hill: the Small (Peștera/Grota Mică/Kis-barlang), Sulphurous/Stinky (Sulfuroasă/Büdös), Alum (alaun/Timsós), Murder (Ucigașă/Gyilkos), and Bird Cemetery (Cimitirul Păsărilor/Madártemető: Figs. 1.12 and 1.13), were carried out by Lajos Ilosvay who studied them for decades in the latter half of the nineteenth century. Based on his data published in 1895, *A torjai Büdös-barlang levegőjének kémiai és fizikai vizsgálata* (Chemical and physical analysis of the gases of the Puturosu Cave of Turia), the composition of the gas is 95.49% carbon dioxide, 3.64% nitrogen, 0.58% hydrogen sulphide, and 0.01% oxygen. A radiologist-toxicologist couple, Endre Szabó and Zsuzsa Szabó-Selényi, confirmed the measurements of Ilosvay in a 1981 publication. They also found methane in the gas (under 0.5%) as well as radioactivity produced by radon (present in 0.1–0.2%). Ilosvay measured a gas flow rate of about 2000 m^3 per day, Szabó and Szabó-Selény about 3500–4000 m^3 per day. The most recent geochemical and flux studies of the Ciomadul gas emissions are carried out by Boglárka-Mercédesz Kis and her colleagues (see more in Chap. 8). In a 2006 study, *A torjai Büdös-hegy gázasbarlangjainak, mofettáinak denevéráldozatai (1999–2002),* (Bat remains in the gas caves and mofettes of the Stinky Hill of Turia (1999–2002)), Levente Barti and Ágnes Varga published scientific descriptions of the individual caves and of the remains of animals—especially bats—killed by the gases. The *Székelyföldi mofettás könyv* (Mofettes of Széklyland), written in 2017 by Réka Incze, Csaba Jánosi, Zoltán Kisgyörgy and Mária Tatár, discusses in great detail the gas emission and Mofettes of the Ciomadul-Puturosu Hills (Fig. 1.14).

Fig. 1.13 Entrance of Murder (Ucigaşă/Gyilkos) Cave. Unlike the other caves, the rocks here are not stained yellow by the precipitated sulphur, so there is no warning of the carbon dioxide that accumulates near the surface (*Photo* Csaba Jánosi)

Fig. 1.14 In the small area of the Apor Daughters' Bath (Apor-lányok feredője), close to Băile Balvanyos (Bálványosfürdő), there are eight different mineral waters, each with a different pH ranging from 1.82 to 4.28. Their strong acidity is the result of the free sulphuric acid they contain. Tiny ashy or whitish springs bubble up here, a true Central European rarity (*Photo* Dávid Karátson)

Folk traditions related to the “stinking pits” of Turia were elaborated on by Sándor Bosnyák in his 1999 study *A halál országa—Öregek önkéntes halála* (The Land of Death—Voluntary Death of the Elderly). He gave a thorough overview of the legends of those who sought their own death in the cave also called the “gate of hell” or “porch of hell”, sometimes the “bridge to hell”, which had already been included in the literary works of Balázs Orbán and Mór Jókai in the nineteenth century.

The carbonated acidulous mineral waters of Ciomadul (locally called ‘borvíz’, literally wine water) have a library’s worth of literature. The first chemical analysis of the waters of the region date back to the nineteenth century, to András Gergelyffi, Zsigmond Bélteki and Sámuel Pataki. Pataki’s 1820 work, *Descriptio physico-chemica aquarum mineralium Transsylvaniae* (A physical and chemical description of Transylvania’s mineral waters) included data of the Fortyogó Baths in the Jimbor (Zsombor) stream at Bixad. In 1866, Károly Cseh performed the chemical analysis of the acidulous waters of Ivó-spring from Câmpul Sărat (Sósmező), the waters with alum (Timsós or Sós) baths, and the “Várpadi-feredő” (formerly called “Transilvania” Baths) in Balvanyos. The first chemical analysis, *Chemische Analyse der Mineralquellen von Tusnád in Siebenbürgen* (Chemical Analysis of the Mineral Springs of Tuşnad in Transylvania), was published—in German—in 1866 by Gustav H. Dietrich, a chemist from Braşov. Antal Fleischer and Antal Koch also gave important data on mineral water analyses in their already cited study of 1878, especially on the chemical composition of the Katalin, Károl, Borvíz, and the four alum (Alsó timsós, Kis timsós, Befedett timsós, Felső timsós) mineral springs. In 1869, Balázs Orbán gave a detailed account on the mineral and carbonated waters, baths and “stinking” pits around Ciomadul-Puturosu Hills in the chapters entitled Ciuc (Csik-szék) and Trei Scaune (Háromszék) of his book, *A Székelyföld leírása* (Description of Székelyland).

At the turn of the twentieth century, Vilmos Hankó of Praid (Parajd) was the most eminent chemist analysing mineral waters. One of his best-known works is *A Magyar Birodalom ásványvizei és fürdőhelyei* (The Mineral Waters and Baths of the Hungarian Empire), co-written with Samu Papp and published in Budapest in 1907. Băile Tuşnad and its surroundings were given a special and important place in this publication.

Between the two World Wars, the best-known researcher of Székelyland was the already mentioned geologist, János Bányai, who published dozens of scientific and popular papers on the mineral waters of Transylvania. As he wrote: “*Transylvania is the homeland of mineral waters or as the székelys call them borvíz (‘wine waters’). Based on our research so far, we can safely say that the globe does not have another corner that would have such number and variety of mineral waters than this.*” Among his extensive list of works studying mineral waters, a special mention goes to two of his books. One is the *A székelyföldi ásványvizek* (The Mineral Waters of Székelyland), published before World War II in 1934. The other is *A Magyar Autonóm Tartománybeli ásványvizek és gázömlések* (Mineral Waters and Mofettes in the Hungarian Autonomous Province) written with others in 1957. Bányai published his writings as supplements to the journal *Székelység* (The Székelys)—with him as editor—in its 1939–1940 volumes, and later as a separate edition in 1940 with the title *A Szent Anna tó és környéke* (Vicinity of Lake Sf. Ana). Several chapters, such as the *A torjai Büdös barlang* (The Stinky Cave of Turia), *A Szent Anna tó és Mohos tó* (Lake Sf. Ana and Mohos Lake), *Bálványosvár* (Fort Balvanyos Hill), *Ahol a pogányoltárok füstöltek* (Where once the pagan altars smoked), *Fürdőtelep* (Bathing place), *Sepsibükszád ásványvíz sokadalma* (The diversity of mineral waters of Bixad), *Pokolvölgy* (Hell Valley), and *Băile Tuşnad* (Tusnádfürdő) illustrate the mineral waters and mofettes of Ciomadul. His opening sentence alludes to the mysteries of the land: “*We are stepping into the land of fairies where even the old Székely sages bow down*”.

In connection with Bányai’s work, we must remember Gábor Csajághy, researcher at the mineral-chemistry laboratory of Geological

Institute of Hungary. Csajághy worked on the chemistry of mineral waters of those Transylvanian territories that returned to Hungary during the years of 1941–1944. He analyzed 17 mineral water springs in the Ciomadul area. At the presentation of his study, *Az 1941–42 évi erdélyi ásványvízkutatások eredményei* (Results of the 1941–42 mineral water exploration in Transylvania), Ferenc Pávai-Vajna—geologist at the mentioned Institute—, with his family roots in Trei Scaune, commented: "*Either volcanism or tectonic movements are the explanation for the presence of the mineral springs of Székelyland, it is most probable that these waters were of higher temperature in the past. It could be expected that the temperature of these waters should be increasing with greater depths. Thus, drilling deeper wells at the appropriate locations should be a well-founded proposition in order to find and extract mineral waters of higher temperatures. I would like to see hot springs being developed in Székelyland for the benefit of people with heart diseases*".

During the same time period, János Straub also examined the Transylvanian mineral waters. He published his results only after World War II, in the *Magyar Állami Földtani Intézet Évkönyve* (Annals of the Geological Institute of Hungary of 1950). Of the 56 mineral springs he examined, five are in the area of Ciomadul: the Main Well (Főkút) of the baths of Băile Tuşnad, and the springs called Ilona, Mikes, Sf. Ana I. and Sf. Ana II.

Lajos Jugovics, geologist, published an outstanding study in 1947 in the journal *Hidrológiai Közlöny (Bulletin of Hydrology)* on the area of Stinky Hill titled, *A torjai Büdöshegy hidrogeológiai viszonyai és ásványvizei* (The hydrology and mineral waters of Stinky Hill of Turia).

Another important volume, *A Magyar Autonóm Tartománybeli Ásványvizek és Gázömlések* (Mineral Waters and Gas Exhalations in the Hungarian Autonomous Province), was written by Árpád Szabó, Ilona Soós, Árpád Schwartz, János Bányai, Csaba Várhelyi and was published by the Academic Publishers in Bucharest in 1957. Out of the 46 Székelyland mineral springs examined by the authors, ten are located on the western and southern edges of Ciomadul, and in the vicinity of Băile Tuşnad and Bixad. The authors measured the amount of dissolved radon and radium in the waters, as well as the composition of the gases of the mofette in Băile Tuşnad and the Puturosu Cave of Turia. They also published on the radon and hydrogen-sulphide content of the waters of the Transylvania and Csiszár Baths of Balvanyos and of the Bugyogó (Bubbling) spring of Bixad, as well as the radium content of mud of Timsós (Alum) spring of Balvanyos, and of the "Tiszás" springs of Tuşnad (Fig. 1.15).

From the 1950s, staff and researchers from a variety of institutes (the Institute of Geology and Institute of Balneophysiotherapy in Bucharest, the Institute—now University—of Medicine and Pharmacy of Târgu Mureş/Marosvásárhely, and the Mureş County Health Directorate) conducted further studies on the mineral springs, and analysed the chemical composition of the waters and of the gases emitted from the mofettes. Geologist Artemiu Pricăjan described in detail the mineral springs and baths of the region in his books *Apele minerale si termale din România* (Mineral and thermal waters of Romania) in 1972, and *Substantele minerale terapeutice din România* (Therapeutic mineral substances of Romania) in 1985. The 1974 book, *Hargita megye gyógytényezői* (Therapeutical factors of Harghita County) included a chapter by Zoltán Rákosy titled, *A Csomád-Büdös hegycsoport ásványvízforrásai, gyógyfürdői és gázömlései* (The mineral springs, baths, and gas emissions of the Ciomadul-Puturosu Hills), where he inventoried 44 mineral water springs of Lăzăreşti.

Between 1970 and 2000, geologists and chemists from the Harghita Geological Research and Exploration Company carried out detailed mapping and chemical analyses of the acidulous mineral waters and mofettes of the Ciomadul and its wider region. In 2000, Zsolt Berner, Csaba Jánosi and Éva Péter published their results as the *A Kelemen-Görgényi-Hargita vonulat ásványvizei* (The mineral waters of the Căliman-Gurghiului-Harghita mountain range). They presented the chemical analyses of acidulous and sulphur water sources: 16 springs on the northern side and 18 on the southern side of Ciomadul. In

Fig. 1.15 Using acidulous mineral waters (locally called 'borvíz', literally wine water) around Ciomadul has a centuries-long tradition. **a** Bükkszád's largest mineral water spring is the Bugyogó (Bubbling), located under the south-western slope of Ciomadul. **b** The small 'Borvíz' museum, a yurt-shaped building, was created in the centre of Tuşnad (Tusnád) village in 2003. **c** Desk of András Kristó (†1994), a renowned twentieth century geology and geography teacher and naturalist of Székelyland, housed in the Borvíz museum. **d** A variety of contemporary mineral water bottles in the Borvíz museum (*Photos* Csaba Jánosi)

addition to the main cations and anions of the waters, these particular tests, performed at the University of Karlsruhe, also detected varying quantities of 31 trace elements (Ag, As, Al, Ba, Bi, Cd, Ce, Co, Cr, Cs, Cu, Ga, In, La, Li, Mn, Mo, Ni, Pb, Rb, Sb, Sn, Sr, Th, Tl, U, V, W, Y, Zn, B). In 2001, in the 10th Volume of the *Észak- és Kelet-Magyarországi Földrajzi Évkönyv* (Geographical Yearbook of Northern and Eastern Hungary), Csaba Jánosi described and mapped the water types of the Ciomadul region: of Lăzăreşti, Tuşnad, Băile Tuşnad, Bixad, and Turia.

In most recent years, the Csíki Természetjáró és Természetvédő Egyesület (Hiking and Conservation Association of Ciuc), operating in the Ciomadul-Balvanyos micro-region, published three scientific books: *A székelyföldi fürdők és gyógyhelyek* (Mineral spa and therapeutical sites of Székelyland) in 2005; *Székelyföld borvizei*

(Mineral waters of Székelyland) in 2009; and *Székelyföld fürdői* (Baths of Székelyland) in 2013. They gave detailed descriptions of the acidulous, carbonated, salt, and sulphur springs and baths as well as the mofettes of the Ciomadul region. Chapter 8 of this book will give more information on these.

The mineral precipitations of alum and sulphur related to the post-volcanic activities of Ciomadul were first mentioned by János Fridvalszky, a Jesuit educator and naturalist of Cluj, in his book published in 1767, *Minerologia magni principatus Transylvaniae seu metalla, semi-metalla, sulphura, salia, lapides et aquae conscripta* (*Mineralogy of Metallic, Semi-metallic, Sulphur, Salt and Rocks and Waters of the Hungarian Principality of Transylvania*). Nineteenth century literature discussed the sulfidic precipitates of Stinky Hill as alaun or alaunerde (i.e., alum and alumearth). Modern use of state-of-the-art instruments made further mineral discoveries possible in the crater of Lake Sf. Ana and in the gas-emitting fissures of the dacite rocks. In 2003, Olivier Hercot and his colleagues described thenardite, aftitalite, and nahkolite minerals. In most recent years, researchers at University of Miskolc, Sándor Szakáll, Ferenc Kristály and their colleagues were the ones who studied the minerals precipitated from the volcanic gases and mineral waters of Ciomadul (see Chap. 8).

1.4 Limnology, Plant and Animal Geography, Landscape History, and Tourism

1.4.1 Limnology

András Kristó summarized the history of limnological investigations of Lake Sf. Ana, formed in the younger crater of Ciomadul. In his 1994 book, *A Csomád hegycsoport* (The Ciomadul Hills), Kristó recounts the earliest attempts: "*István Lakatos, a Catholic parish priest from Cozmeni (Csíkkozmás), considered it to be a bottomless lake in his 1702 work, Siculia delineata et descripta accuratius quam hactenus… (Székelyland outlined and described in more detail than before…). According to János Fridvaldszky's report from 1767, they could not reach its bottom even with an 1800 feet rope weighted with lead.*" Karl Gottlieb von Windisch of Bratislava (Pozsony) also mentioned in his 1790 work, *Geographie des Grossfürstenthums Siebenbürgen* (Geography of the Grand Duchy of Transylvania), that it was impossible to measure the lake's depth. József Károly Éder wrote in his book, *Erdély Ország Ismertetésének Zengéje* (Echos about Transylvanian Description) published in Cluj and Sibiu in 1796, that the lake was considered to be at least 1800 feet deep. In the 1840 issue of the *Nemzeti Társalkodó* (National Conversations), an informative supplement to the *Erdélyi Híradó* (Transylvanian News) of Cluj, there is already an indication that the depth of the lake was measured a few years earlier when a 42 feet long pole hit the bottom. László Kővány reports in the publication, *Erdélyország statisztikája* (Statistics of Transylvania) that Ferenc Mentovich and Ferenc Jánosi of Nagykőrös measured a depth of 30–35 feet in 1840.

In volume 3 of his seminal work, *A Székelyföld leírása* (Description of Székelyland), Balázs Orbán reported a depth of 40 feet in the year 1869: "*Enjoying the beautiful promenade along the shoreline we walked around the lake that has a regular circular outline. Keeping track of the number of our steps we calculated the circumference to be 2350 steps. (…) This lake has no visible source or outflow; its water is clear, transparent, and good for drinking, although the edges get warm in the summer, but farther from the shore it is ice cold. It is 40 feet deep in the centre.*" In 1894, Mózes Vitos described Lake Sf. Ana in *Csíkmegyei füzetek* (Notes from Ciuc County), relying on facts and figures from Balázs Orbán, mainly from the point of view of village life of the nearby communities. According to János Bányai, the lake was first surveyed at the beginning of September 1907 by a group of civil school teacher candidates from Budapest. They found the maximum depth to be 8 m.

The first detailed scientific survey of Lake Sf. Ana was carried out by József Gelei in 1908. He

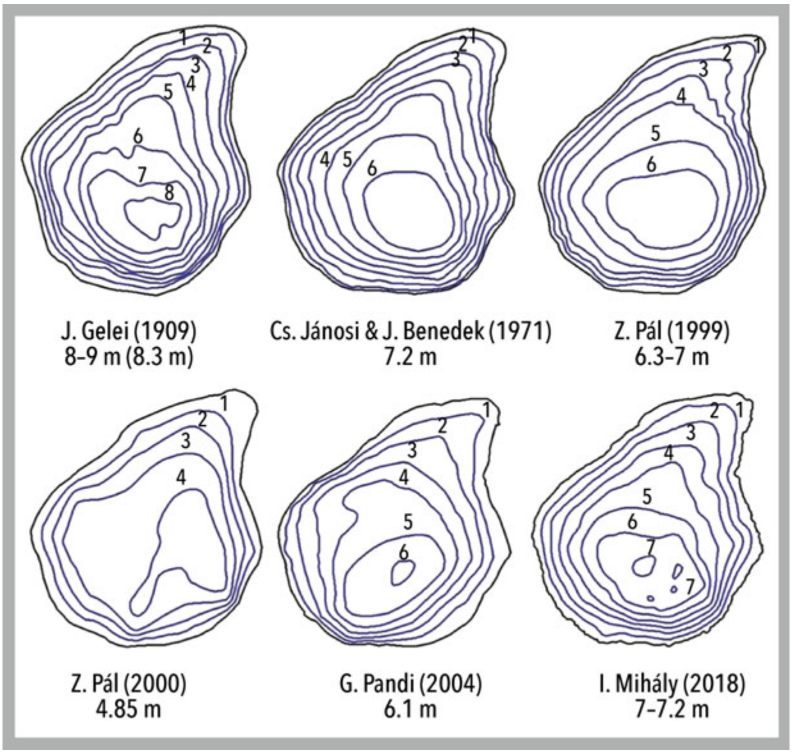

Fig. 1.16 The progression of depth measurement of Lake Sf. Ana over the last hundred years (*Source* István Mihály 2018)

published the first bathymetric (depth) map of the lake as well. According to Gelei, the maximum depth of the lake varies between 8 and 9 m, depending on the amount of precipitation (Fig. 1.16).

The next significant limnological survey was published after World War II, in 1955 by Ion Pisota and Anton Năstase. They determined the depth of the lake at 7 m and its circumference at 1737 m. The water balance of the lake was studied in 1970 by Cristian Privighitoriţa. In 1971, Petre Gâştescu investigated the depth, surface area, the dissolved mineral content and mineral types of the lake water. Since it is fed by precipitation only, the mineral content is very low (50–70 mg/l). Gâştescu classified the water as “unstable sodium sulphate, sodium bicarbonate oligotrophic waters”. Also in 1971, Csaba Jánosi and József Benedek completed another bathymetric map, and like Ion Pisota, they found the deepest point to be over 7 m. The next survey was carried out by Zoltán Pál in 1999. He measured a maximum depth of 6.3 m, but less than 5 m two years later. Gábor Pándi found a maximum depth of 6.1 m in 2004. Octavian G. Duliu and his colleagues measured 7 m as maximum depth in 2008. In 2018, István Mihály published the most current depth map of Lake Sf. Ana, indicating a maximum value of 7.2 m. Beside drawing the bathymetric map, he also analysed the previous measurements. Reviewing over a hundred years’ worth of data and also considering the margin of errors of previous measurements, he calculated an average of half a metre of water level decrease, which he mainly explained by a decrease in rainfall.

1.4.2 Plant and Animal Geography

The beginnings of flora and fauna research of the Ciomadul Hills date back to the early nineteenth century. It is a definite challenge and a unique opportunity for any botanist to describe the flora of the peat bog of Mohoş, or the rare plants—remnants from the last ice age—in the acidulous bogs formed on the edge of the mountain, such as Băile Nadaş (Nádasfürdő), and the bogs of "Közép-patak, Nyírkert, Varsavész" and "Buffogó" (bubbling).

Johann C. G. Baumgarten, a medical botanist from Sighişoara (Segesvár/Schäßburg) was the first to describe—in 1816—the plants in the peat bog of Mohoş and by Lake Sf. Ana. Starting from the 1850s, the Szász Természettudományi Egyesület (Saxon Association for Natural Science) in Sibiu initiated a more systematic research. Ferdinand Schur explored the Ciomadul-Puturosu Hills in 1858 and published a large number of botanical data in his 1866 work *Enumeratio Plantarum Transsilvaniae* (List of Transylvania's Plants). Botanists Lajos Simonkai, István Győrffy, Gyula E. Nyárády, Emil Pop, Rezső Soó and Bálint Zólyomi also contributed with important publications. In 1943, Zólyomi published a vegetation map of the peat bog of Mohoş, showing areas of open water in the swamp as well. In his 1960 book, *Mlaştinile de turbă din Republica Populară Romînă* (Peat bogs in the Romanian People's Republic), Emil Pop described in detail the eutrophic and oligotrophic bogs around Ciomadul, and listed the animal and plant species of the Mohoş described so far. Regarding the swamp, he noted that while Gyula Istvánffy counted 29 open water ponds in 1894, there were only 13 left in 1960. He explained this with the fact that in 1908 the public landlords of Lăzăreşti cut drainage ditches in the bog, attempting to drain it, so grazing cattle would not sink and drown in it, and to enable peat extraction. This drainage, as well as the subsequent deforestation, led to a significant drop in the bog's water level. Fortunately, no peat extraction took place. The peat bog of Mohoş finally became a protected area in 1980.

Palaeo-environmental research of Mohoş and Sf. Ana crater—in particular, via boreholes drilled into the lacustrine sequence of the crater infill—has been done by Ioan Tanţău, Enikő Magyari and their co-workers. Details of this ongoing research, conducted from the 2000s, are provided in the first chapters of the second part of this book.

In the 1995 issue of the *Csíki Zöld Füzetek* (Green Booklets from Ciuc), Ibolya Jánosi published a summary, *A Csomád-Büdös hegy csoport élővilága* (The Wildlife of the Ciomadul-Puturosu Hills). In the same issue, István Tőke gave a description from the forestry point of view in his article, *A Csomád-Büdös hegycsoport erdő és vadgazdálkodása* (Forest and Game Management of the Ciomadul-Puturosu Hills).

1.4.3 Landscape History

Landscape history and landscape architecture is a relatively young discipline. The first such explorations in the Ciomadul-Balvanyos region were carried out at the end of the 1990s by landscape architects Ágnes Herczeg and Gábor Szűcs and horticultural engineer Albert Fekete (in more detail, see Chap. 17). In the landscape history chapter of their 1998/1999 documentation, *Ciomadul-Balvanyos Development Strategy* (Herczeg et al. 1999), the authors emphasized: "*Landscape is a breathing, living organism existing at the intersection of humans and nature, and it continuously changes and evolves. (…) Images of the power of nature and the struggle and faith of the people living here from time immemorial have been kept alive in ancient legends and later in works of literature. The historical past of Ciomadul-Bálványos encompasses all the aspects of the Szekler culture, lifestyle, and destiny*". Analysing and comparing the ordnance survey maps of the Josephinian Survey (1st in 1763–1787), Franciscian Survey (2nd in 1819–1869), Francisco-Josephinian Survey (3rd in 1869–1887) of the Habsburg Empire, the authors illustrated how the forest cover, meadows, available arable land and pastures changed over time, as well as how settlements developed and transportation routes changed.

Architects Zsolt Tusnádi, Ferenc Salamin and Győző Esztány examined several villages such as Lăzăreşti, Tuşnad, Tuşnadu Nou (Újtusnád), Băile Tuşnad, Bixad and Turia. They summarized the history of these villages, presented their layout and architectural imageries, as well as analysed how they fit into and interact with their natural environment. The authors drew attention to the importance and current condition of the villages' architectural heritage assets, like streets, squares, ditches, churches, cemetreies, crosses, fences, or gates. A separate chapter of this *Ciomadul-Balvanyos Development Strategy* is dedicated to the topics of nature conservation, agriculture, population geography, infrastructure, tourism, environmental protection, and also touches on traditional culture, beliefs and folklore.

Archaeological explorations at Ciomadul were reported by András Sófalvi in his book, *Székelyföld középkori várai és a keleti határvédelem* (Medieval fortresses of Székelyland and the Eastern Border Protection) in 2006. Sándor Ferenczi (1938), then Zoltán Székely, Kurt Horedt and István Molnár (1962) worked and published on Balvanyos Hill, the Vapa- (Vápa) and Falcon (Şoimilor/Somkő) Fortresses of Bixad, and the Vârful Cetăţii (Vár-tető) of Tuşnad.

1.4.4 Tourism

After recounting the history of scientific exploration and research of the Ciomadul Hills, we end this chapter with citing the reports of notable early travellers and the tourist guides written for today's naturalists.

The first "travel notes" are from the end of the eighteenth century. From them we learn how noblemen from Transylvania climbed the ruins of Balvanyos (Bálványosvár) Fortress, visited the sulphur caves of Stinky Hill, and went to see Lake Sf. Ana. Count József Teleki went on an excursion to the Ciomadul in 1793, and later in 1799 he published his experiences under the title, *Úti jegyzések* (*Travel Notes*). The Saxon doctor of Medwesch (Mediaş/Medgyes), Daniel G. Schein, recounted his visit to Lake Sf. Ana in his book, *Das Land und Volk der Szeckler in Siebenbürgen* (The Land and People of the Székelys in Transylvania), published in 1833. John Paget visited Stinky Hill in 1835 or 1836. In 1837, Mihály Szentiváni visited Ciuc and Trei Scaune counties while in Transylvania, and wrote about his experiences in *Gyaloglat Erdélyben* (Walking in Transylvania): "*Two truly worthwhile sights of Ciuc are the Lake Sf. Ana and the so-called Puturosu*". In 1841, Ferenc Nagy described the origin of Lake Sf. Ana this way: "*imagine a sugar loaf shaped mountain which, due to volcanic or other forces of nature, collapsed and took the form of a funnel. At the bottom of the funnel, only God knows at what depth, rest the waters of the quiet lake.*" In 1845, Auguste de Gerando, a French landowner, writer, and diplomat (who married Emma Teleki from Transylvania), wrote about Stinky Hill in Chap. 22 of his book, *La Transylvanie et ses habitants* (Transylvania and its people): "*One of Târgu Secuiesc's attractions is a grotto canina, also known as solfatara, where the peasants of the area go to recover from their illnesses.*"

The first real tourist guide was edited by József Sándor and Gyula Merza and published in 1891 by the Hungarian Cultural Society of Transylvania titled, *Uti-Kalauz Magyarország erdélyi részében* (Travel Guide in the Transylvanian part of Hungary). The chapters on Ciuc county were written by Fülöp Jákó Imets and Antal Becze. Imets, who was born in Tuşnad, described in great detail the area of Băile Tuşnad, Balvanyos and Lake Sf. Ana, listing numerous other geographical place names as well. In 1896, Vilmos Hankó, in his "popular natural science" work titled *Székelyföld* (Székelyland), also described in detail the region of Băile Balvanyos, Stinky Cave of Turia, and Lake Sf. Ana. The next tourist guide book—in 1901—was the *Erdélyi Kalauz* (Transylvanian Guide) edited by Dezső Radnóti and published by the Carpathian Association from Transylvania. The association's local chapter in Ciuc County contributed with details on the hiking trails around Lake Sf. Ana (Fig. 1.17).

In the twentieth century, numerous tourist guides, both in Hungarian and Romanian, were published on the baths around Ciomadul (especially Băile Balvanyos, Băile Tuşnad). These books are also great to learn about the natural history of the area. In the most recent decades, Zoltán Kisgyörgy, Enikő Zsigmond and Csaba Jánosi wrote about the tourist attractions of the region. The guide, *A Csomád hegycsoport—Tusnádfürdő és környéke* (The Ciomadul Hills—Băile Tuşnad and its surroundings) was written

Fig. 1.17 All seasons offer unrivalled opportunities for hiking around Lake Sf. Ana (*Photos* Levente Dósa, Dávid Karátson)

by Enikő Zsigmond in 2009. In 2010, Bogdan Florescu (Bucharest) published a topographic map of Ciomadul at a scale of 1:20,000, showing both Romanian and Hungarian place names. This map is perhaps the most accurate available to the general public to date. In 2013, Enikő Zsigmond also drew a tourist map of Lake Sf. Ana and its surroundings at the scale of 1:35,000 with Hungarian, German and Romanian descriptions; it was published by DIMAP in Hungary. The already mentioned Carpathian Association of Transylvania (EKE) published a tourist guide in 2018 as Volume 7 of their series *EKE-Bakancs* (*EKE Hiking Boots*), titled *A Csomád hegység—Barangolás a Szent Anna-tó környékén* (Ciomadul Hills—Wanderings around Lake Sf. Ana).

Those who wish to learn even more about these unique and mystical places in this corner of the world, can turn to the rich literature and read the novels, short stories, or poems of Mór Jókai, Géza Gárdonyi, Elek Benedek, József Nyírő, Ferenc Sántha, and Sándor Kányádi (prominent Hungarian writers and poets of the nineteenth-twentieth centuries).

2 Introduction to the Tectonic Evolution of the Southeast Carpathians

Liviu Matenco

Abstract

The Southeast (SE) Carpathians, together with the larger area of the Ciomadul (Csomád) volcano, is part of the curved Carpathian Mountain chain and orogenic system that has evolved since the Triassic and presently forms a double 180° loop from Vienna in Austria to Sofia in Bulgaria. The mechanisms of forming such an arcuate mountain chain have puzzled researchers for generations. Furthermore, the way in which rocks are brought from depth and exposed at the surface in mountain chains, i.e., exhumation, together with other processes such as associated magmatism, has been a constant topic of tectonic studies for decades. In the area of the SE Carpathians, a marked shift in the tectonic style in the last 8 million years has resulted in a gradual change in magmatism that was ultimately responsible for the most recent volcanic phase (c. 1 Ma–30 ka) at the chain-ending Ciomadul volcano.

2.1 Introduction

Orogenesis (mountain building) is typically associated with the convergence of plate boundaries (e.g., between oceanic and continental crust). In the case of continent–continent collision—once the denser oceanic plate has subducted beneath the more buoyant continental plate—the similar buoyancies of the continental plates inhibit subduction, causing enhanced exhumation and the formation of the highest topography. Examples are observed in the European intra-continental mountain chains, such as the Pyrenees, Alps and Carpathians (Fig. 2.1a). Continental collision is also the period of orogenesis when compressional stresses are transmitted further outside the mountain chain, with potentially far-reaching consequences (Ziegler et al. 1998). Understanding the mechanics of continental collision is fundamental to unravelling the interplay of topographic uplift and erosion, deformation and metamorphism, and associated volcanism (Doglioni et al. 2007). It is generally thought that the topography of a mountain chain increases until the amount of continental material accreted by convergence equals the amount of continental material removed by erosion. This "steady state" is generally achieved by an enhanced creation of topography in the core of the mountain chain by subduction of continental plates, which is then steadily removed by erosion, i.e., the higher the topography, the higher the rate of erosion,

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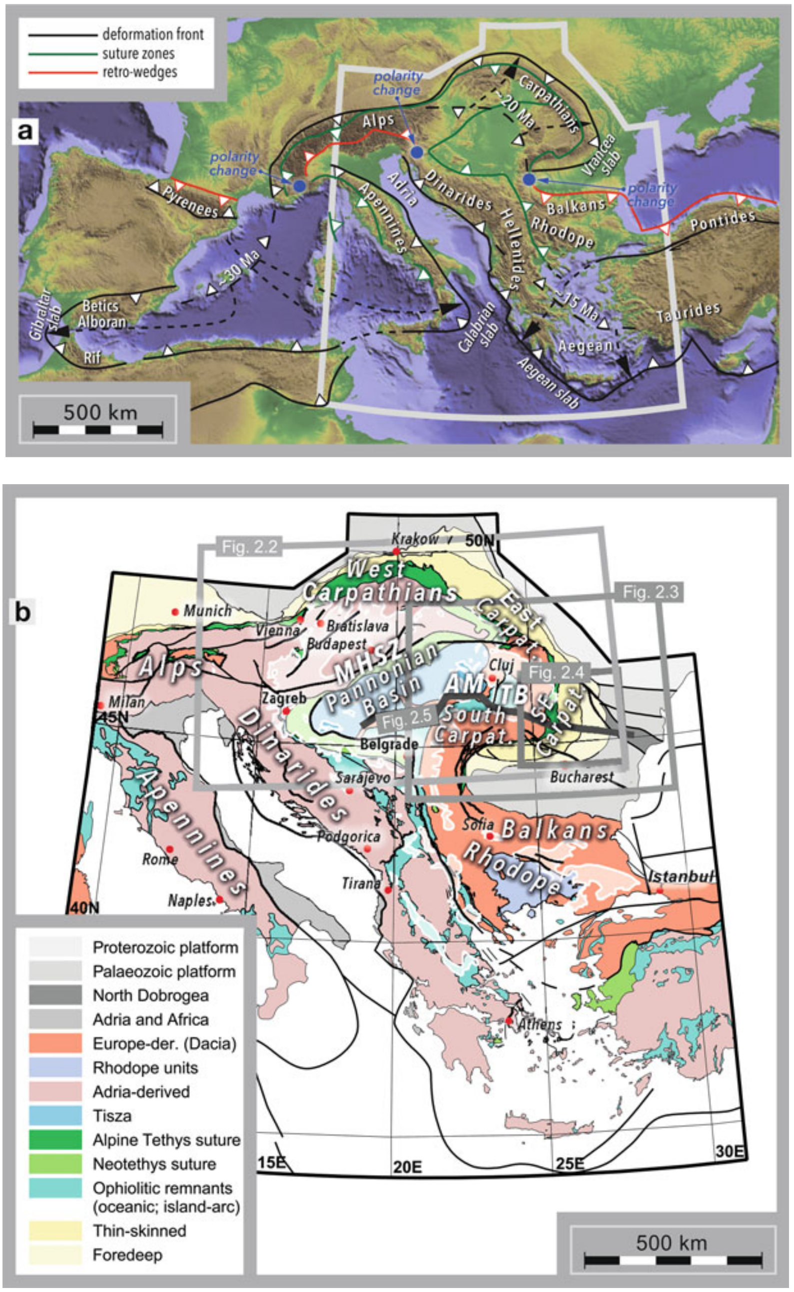

	Proterozoic platform
	Palaeozoic platform
	North Dobrogea
	Adria and Africa
	Europe-der. (Dacia)
	Rhodope units
	Adria-derived
	Tisza
	Alpine Tethys suture
	Neotethys suture
	Ophiolitic remnants (oceanic; island-arc)
	Thin-skinned
	Foredeep

Fig. 2.1 **a** Map in the system of European Mesozoic—Cenozoic orogens. Dashed black line is the position of the orogenic front prior to the onset of extension associated with the retreat of the Calabrian, Aegean and Carpathian slabs; **b** Tectonic map of the Alpine–Carpathians–Dinaridic–Hellenidic system (simplified from Schmid et al. 2020) with the extent of the Pannonian and Transylvanian back-arc basins (white transparent background). The grey rectangles are the locations of Figs. 2.2, 2.3 and 2.4. The grey line is the location of the cross-section in Fig. 2.5. AM = Apuseni Mountains; TB = Transylvanian Basin; MHSZ = Mid-Hungarian Shear Zone

moderated by the local climate. In Europe, this is generally the case of mountain chains that record very high rates of convergence, such as the Alps or the Pyrenees. However, most other European mountain chains were, or still are, affected by much higher rates of subduction, plunging oceanic or continental plates at high depths (100s' to more than 1000 kms) into the Earth's sub-lithospheric mantle. A higher subduction rate can displace and move a mountain chain laterally over millions of years, resulting in the formation of highly arcuated "Mediterranean"-type orogens, such as the Apennines, Carpathians, Hellenides and the Betics-Rif system (Fig. 2.1a, e.g., Faccenna et al. 2004; Jolivet and Faccenna 2000). This arcuated geometry was achieved by the subduction system pulling laterally one part of the orogen during its rapid sink into the mantle (from dashed to continuous black lines in Fig. 2.1a). These Mediterranean-type orogens evolved rapidly in the last ~35 Ma during the retreat of genetically associated slabs (i.e., the Calabrian, the SE Carpathian Vrancea, the Aegean and the Gibraltar slabs) at times that generally peaked during the Miocene (e.g., Ismail-Zadeh et al. 2012; van Hinsbergen et al. 2020). The lateral movement is accommodated by coeval divergent motions (i.e., extension) affecting the opposite side of the orogen relative to the subduction zone. This process forms large basins floored by either continental or oceanic lithosphere (such as the Pannonian and Aegean basins, or the Black Sea), and are generally called extensional back-arcs (e.g., Doglioni et al. 2007; Horváth et al. 2006). Most of these Mediterranean orogens are tectonically active at present, displaying large horizontal and vertical motions (up to centimetres per year) that rapidly change the topography and drainage, while creating significant amounts of societal-relevant natural hazards, such as landslides, flooding events and seismicity (Fig. 2.2, e.g., Rădoane and Vespremeanu-Stroe 2017).

2.2 The Carpathian Mountains and Their SE Bend Zone

The Carpathians are no exception to the typical Mediterranean-type evolution. The Miocene back-arc extension associated with the retreat of the Vrancea slab has created the large intra-continental Pannonian Basin (Fig. 2.1b). Recent studies, such as Tiliţă et al. (2013), have confirmed that the extension of the basin is minor in other areas, such as the eastern Apuseni Mountains (Erdélyi-középhegység), Transylvanian Basin, or the East and South Carpathians (Fig. 2.1b). The Carpathians have gradually migrated over the last 110 million years of evolution from an area located in the present-day Serbia and southern Hungary to their current position by clockwise rotations and eastward translations of microplates that accompanied the retreat of a westward subducting slab, as summarised and well-illustrated recently by van Hinsbergen et al. (2020). Other studies have shown that the eastward movements cannot be accommodated by the dominantly north–south oriented absolute plate motion of Africa relative to Europe, which means that most of the SE Carpathians have rotated and moved independently in such a way that the amount of extension

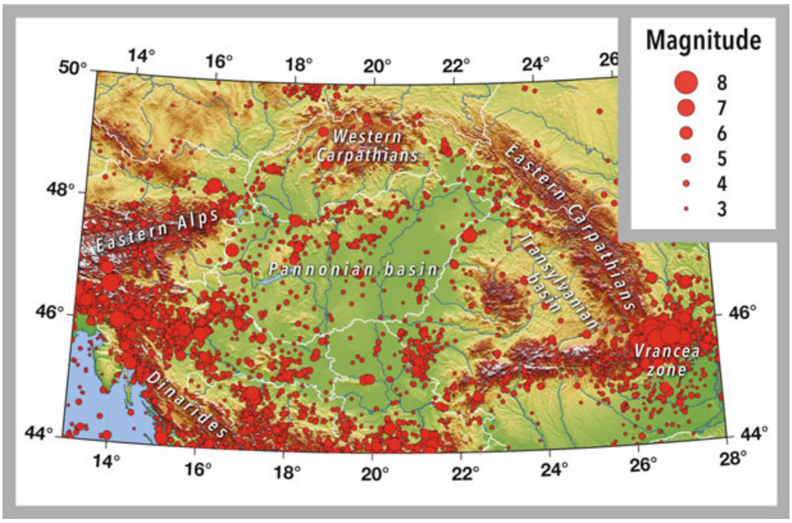

Fig. 2.2 Earthquakes with magnitude larger than 3 on the Richter scale in the Carpatho–Pannonian region occurred between the years 456 and 2015 (modified after Matenco 2018). The location of the map is displayed in Fig. 2.1a

in the Pannonian Basin equals the amount of Carpathians convergence at the tectonic plates contact (e.g., Matenco et al. 2016). These north- to eastwards translations and clockwise rotations have resulted in the formation of the characteristic double loop of the Carpathians around their SE bend and the connection with the Balkan Mountains (Fig. 2.1a). Tectonic and exhumation studies, such as Merten (2011), have demonstrated that the tectonic events responsible for creating the average mountainous topography took place dominantly in the Cretaceous/Palaeogene in the South Carpathians and Apuseni Mountains, and in Miocene times in the East Carpathians (Fig. 2.3). However, the south-eastern corner of the Carpathians is an exception, because here the topography is younger, progressively modified since the Pliocene and presently displays the highest rates of deformation observed in the entire chain (Fig. 2.3, e.g., Necea et al. 2021).

Early researchers, such as Săndulescu (1984), have long established the first order structure, tectonic units and timing of deformation, while in more recent times numerous refinements have been added in local or international literature. In a fairly simplified nomenclature (Fig. 2.4), the European stable foreland is located to the east and south of the SE Carpathians (Scythian and Moesian platforms), which represents the lower unit in a plate tectonic scenario. To the west and north of the SE Carpathians (Fig. 2.4), the thick-skinned nappes (i.e., basement-bearing duplications) of the Dacia Mega-Unit (Bucovinian–Getic system) and their sedimentary cover represent the upper tectonic plate. At their contact, sediments have been scraped off during subduction by forming a number of nappes stacked on top of each other, resulting in a thin-skinned (i.e., made up only by sediments) thrust belt. In addition, two young intra-montane late Miocene/Quaternary sedimentary basins have developed at the interior of the orogen (Brașov/Brassó and Târgu Secuiesc/Kézdivásárhely basins).

The European foreland of the Carpathians is made up of a collage of units underlain by an old Precambrian or Palaeozoic basement, which is overlain by sediments with variable thicknesses and degrees of deformation. These were observed at depth in drill cores or defined by various geophysical studies in the foreland and beneath the thrusting of the Carpathian units (e.g., Visarion et al. 1988). The Dacia Mega-Unit is a piece of the European continent that split off during the Jurassic opening of the so-called Ceahlău-Severin Ocean, which was part of the much larger Alpine Tethys (e.g., Schmid et al. 2020 and references therein). This unit was sutured back to Europe during the Cretaceous/Miocene tectonic plate convergence that created the East Carpathian Mountains and its presently observed nappe geometry. The nappe stack of the Dacia unit (the Getic and Bucovinian nappes system, Fig. 2.4) formed during successive late Early to latest Cretaceous tectonic events (e.g., Schmid et al. 2020). These nappes are largely covered in the SE Carpathians, but their connection has been long inferred by surface observations studies and confirmed by more recent geophysical observations, such as the one of Bocin et al. (2013).

In the thin-skinned thrust belt, the Ceahlău unit (Severin in the lateral prolongation in the South Carpathians) contains relicts of the formerly intervening ocean, being deformed during the same two Cretaceous events that created the three thrusted nappes observed today (Baraolt, Ceahlău, Bobu). To the east and southeast of the Ceahlău-Severin system, a wide zone of other sedimentary nappes forms the remainder of the external Carpathians thin-skinned belt, well exposed to the north and gradually buried to the southwest and west in the area of the South Carpathians referred locally as the Getic Depression (e.g., Krézsek et al. 2013). Surface observations, synthesised in many studies (e.g., Schmid et al. 2020 and references therein) have shown that the various individual nappes (Convolute Flysch, Macla, Audia, Tarcău, Marginal Folds, Fig. 2.4) were emplaced in a Miocene temporal succession that becomes gradually younger eastwards. The combination with exhumation studies has shown more recently that the deformation peaked during the final moments of the Carpathian collision at around 11–8 Ma (e.g., Matenco et al. 2010).

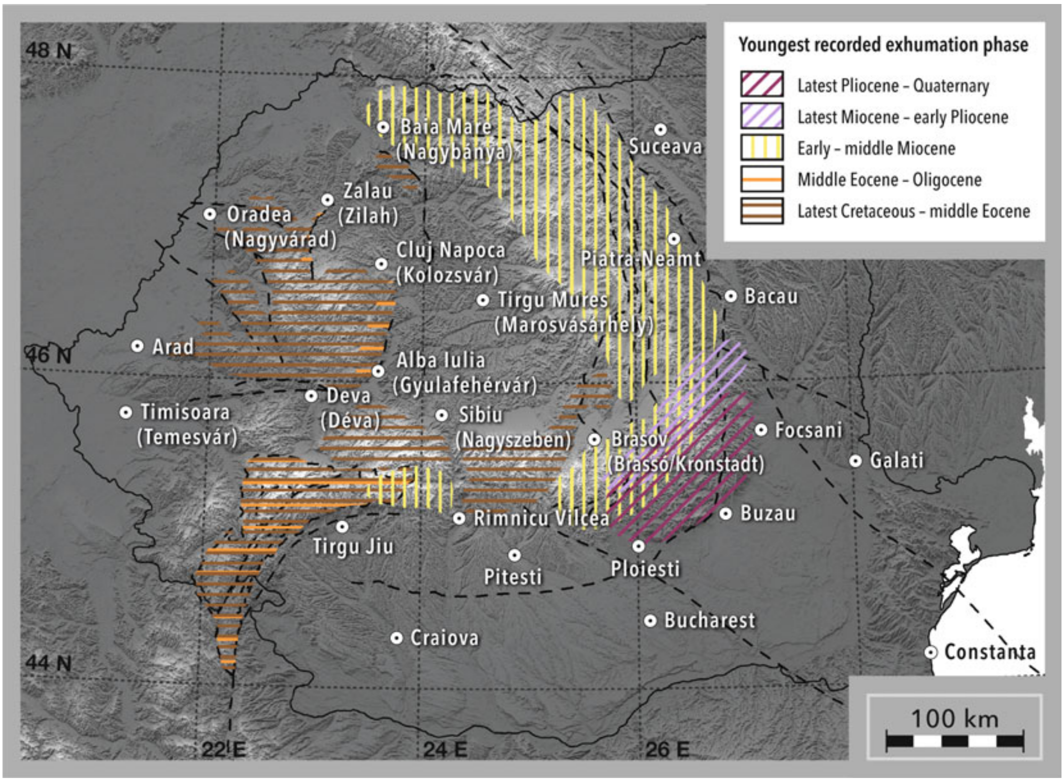

Fig. 2.3 Topographic map of East Carpathians showing the age of the youngest tectonic exhumation phase (after Merten 2011), interpreted as the tectonic age of topographic relief. Most of the present-day topography in the Apuseni Mountains (Erdélyi-középhegység) and South Carpathians was formed during latest Cretaceous/Palaeogene times. Only a small area in the South Carpathians indicates enhanced Miocene exhumation. The present-day topography of the entire East and SE Carpathians is the result of post-Palaeogene exhumation events. The bulk of this exhumation is Miocene, being overprinted by a younger latest Miocene/Quaternary exhumation event restricted to the external South-East Carpathians. The broader location of the map is displayed in Fig. 2.1a

To the northwest, the Miocene evolution of the Transylvanian Basin is one of the most striking European examples of dynamic topography, i.e., topography controlled by deep sub-lithospheric processes. The up to 3.5 km thick Miocene sedimentary cover has an apparent symmetric geometry both in cross-sections and in map view (Figs. 2.4 and 2.5). The subsidence accommodating the observed sedimentation took place during middle-late Miocene times (e.g., Tiliţă et al. 2013). Towards the end of the late Miocene (~8 Ma) the entire Transylvanian Basin was uplifted to the ~600 m maximum present-day topographic elevation, followed by significant erosion and local deposition of Pliocene/Quaternary continental sediments (e.g., Matenco et al. 2010). These substantial Miocene vertical movements were driven by sub-lithospheric processes such as asthenospheric circuits active during the eastern migration of the Vrancea slab, defined by the sinking of the slab.

2.3 Tectonic Processes in the SE Carpathians During the Last 8 Million Years

The sedimentation associated with the gradual nappe emplacement ended somewhere around 8 Ma. Further sedimentation took place in a large basin juxtaposed over the Moesian Platform and parts of the thin-skinned nappes of the SE

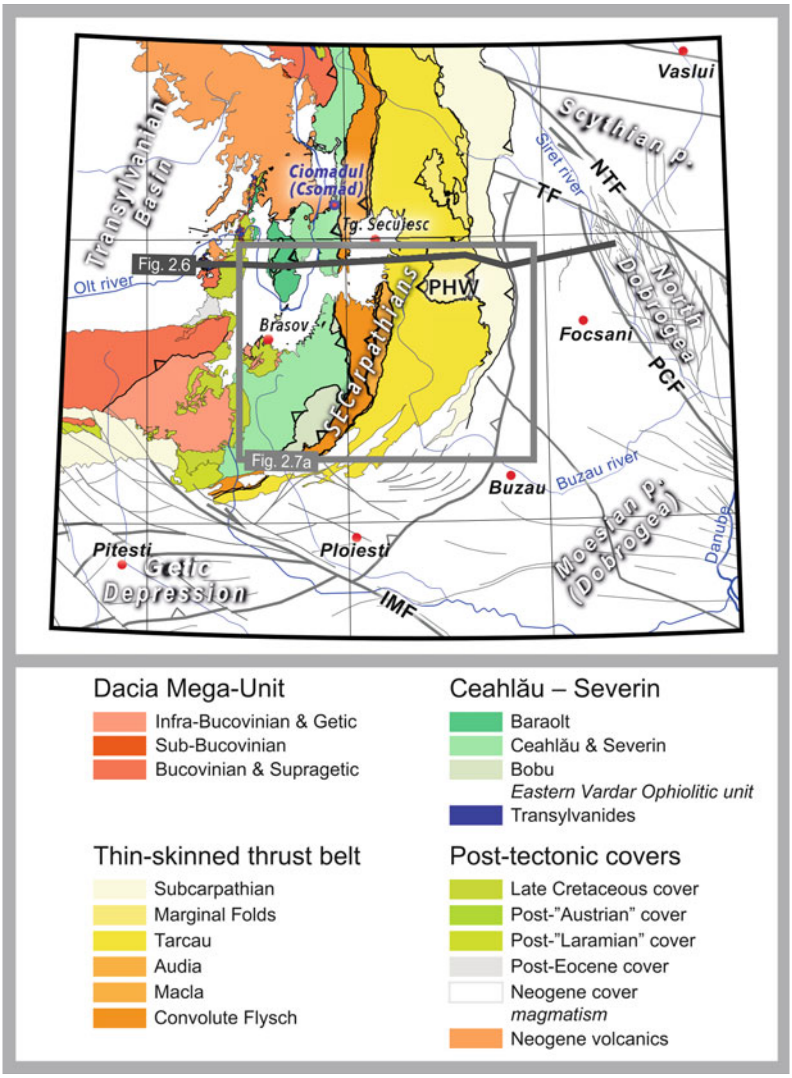

Fig. 2.4 Simplified tectonic map of the South–East Carpathians (modified from Maţenco 2017). The grey line is the locations of geological cross section in Fig. 2.6. IMF = Intramoesian Fault; PCF = Peceneaga - Camena Fault; TF = Trotuş Fault; NTF = New Trotuş Fault; PHW = Putna half-window

Carpathians and Getic Depression, which holds yet another geographically juxtaposed name, the Dacian Basin, well reviewed most recently by Jipa and Olariu (2009), which overlaps most of the SE Carpathians foreland area (white to the E, SE and S in Fig. 2.4). Deposition resulted in a very thick pile of sediments in the area situated around the Focşani city (i.e., the Focşani Basin), where the total thickness of Miocene to recent sediments reaches 13 kms (Tărăpoancă et al. 2003). The deposition is associated with a fast subsidence, interpreted by many studies, such as the one of Ismail-Zadeh et al. (2012), to be driven by the vertical load exerted by the subducted Vrancea slab, a remnant of the lower tectonic plate subducted deep in the mantle, still (barely) attached to the overlying lithosphere only in this particular Focşani area (Fig. 2.5).

The gradually accelerating subsidence in the Focşani area was and still is accompanied in the neighbouring SE Carpathians by a continuous migration of the location of uplift from the internal NW to the external SE units through time (Fig. 2.6). The studies of Merten et al. (2010) and Necea et al. (2021) showed that continuing the long-term orogenic uplift and

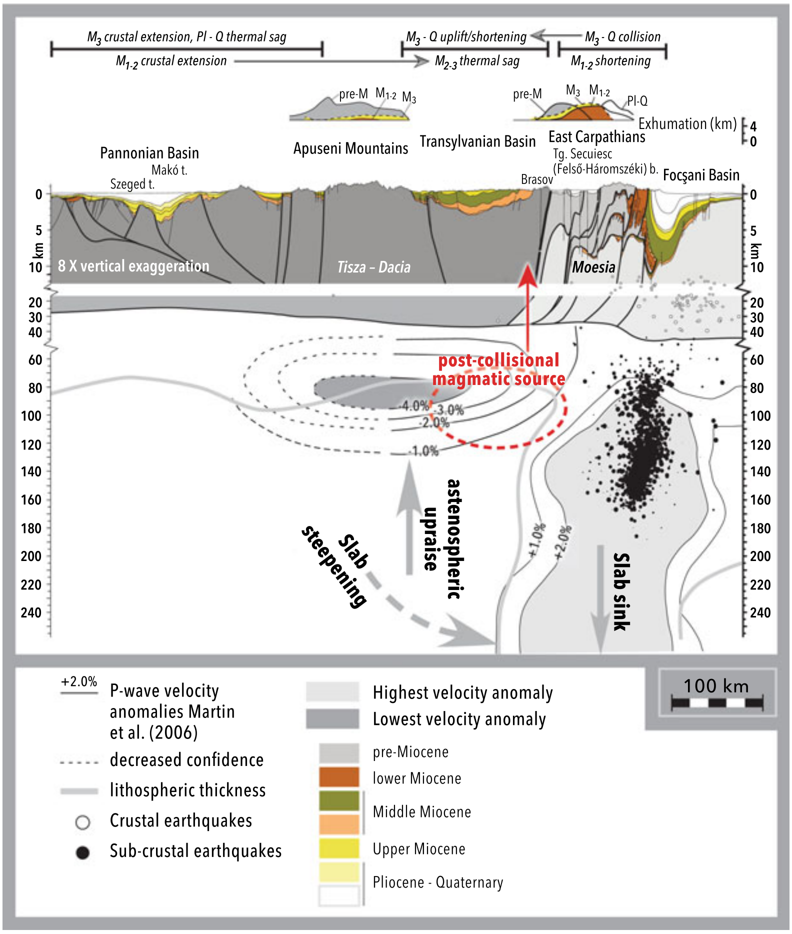

Fig. 2.5 Simplified cross section across the south-east part of the Pannonian Basin, Apuseni Mountains, Transylvanian Basin, and South-East Carpathians, and amounts of exhumation over the Apuseni Mountains and SE Carpathians derived from low-temperature thermochronology (modified from Matenco et al. 2016). The geological cross section displays only Miocene-Quaternary sediment geometries and faults patterns. All pre-Miocene structures are ignored. The location of the cross section is displayed in Fig. 2.1b. pre-M = pre-Miocene; M_1 = early Miocene; M_2 = middle Miocene; M_3 = late Miocene; Pl = Pliocene; Q = Quaternary. The lower part of the figure is the crustal and upper mantle structure beneath the western Pannonian Basin—Carpathian Mountains with underlying the seismicity and the anomalies detected by high resolution, local teleseismic tomography. Note the dynamic topography associated both with the Vrancea slab and with the post-Miocene uplift of the Transylvanian Basin associated with the asthenospheric upraise. The red dotted ellipse is the location of a mantle anomaly reflecting asthenopheric upraise, interpreted to generate the post-subduction magmatism. The Ciomadul (Csomád) volcano is one of the multiple expressions of this magmatism that started ~3 Ma

exhumation of 4–5 km in the Cretaceous/earliest Palaeogene, and of 5 km during the latest Palaeogene/Miocene, with a further 5 km of exhumation taking place in the last ~3 Ma (Figs. 2.5 and 2.6). Because subduction at the contact of the two major tectonic plates had stopped 8 Ma, this uplift and associated exhumation must be related to another process. Depth studies, such as Leever et al. (2006) and Maţenco et al. (2007), have shown that this exhumation is related to higher-angle thick-skinned thrusts cross-cutting the entire crust and internal parts of the orogenic wedge (Fig. 2.6, e.g., Necea et al. 2021).

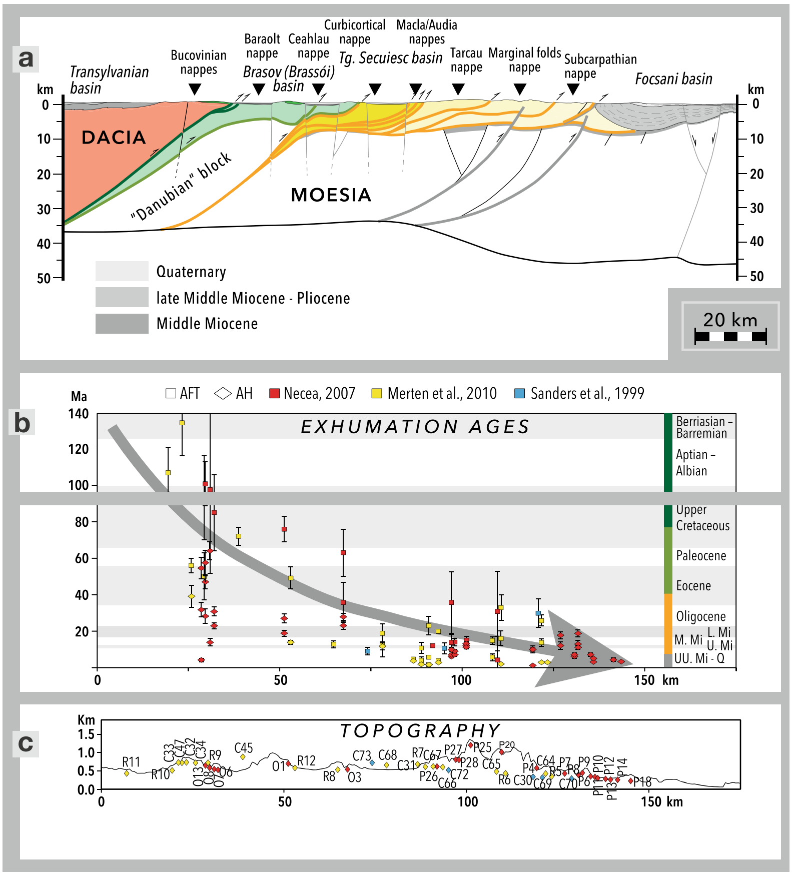

Fig. 2.6 Thermochronological transect in the Southeast Carpathians (simplified from Necea et al. 2021); **a** Crustal scale tectonic cross section along the SE Transylvanian Basin, SE Carpathians and their foreland including the Focșani Basin. The Moho structure at the base is taken from passive and active geophysical experiments. Faults are coloured as a function of their activity following the four main time periods defined in Fig. 2.6b; **b** Exhumation (apatite fission track—AFT and Apatite U-Th/He—Ahe) ages plotted across the geological cross-section and with time. Note the clear pattern of older ages in the western hinterland and gradually younger ages towards the eastern foreland; **c** Sample code and location plotted against topography along the low-temperature thermochronological transect

The combination of enhanced uplift in the SE Carpathians and subsidence of the foreland that took place during the last 3 Ma is thought to be related to the evolution of the locally subducted Vrancea slab (Ismail-Zadeh et al. 2012; Popa et al. 2008). More specifically, the subduction created the steepening and sinking of the slab, associated with an asthenospheric uprise beneath the Transylvanian Basin (Fig. 2.5). The migration of deformation and the asthenospheric uprise is also responsible for the formation of the intramontane Pliocene/Quaternary Brasov and Târgu Secuiesc basins, which are shallow extensional grabens with sediments averaging few hundreds to few tens of metres in thickness (e.g., Fig. 2.6).

2.4 The Link Between Tectonics and Magmatism in the SE Carpathians

The large volume of East Carpathian Călimani-Gurghiu-Harghita (Kelemen-Görgényi-Hargita, CGH: Szakács et al. 2018) volcanic range (southern termination in Fig. 2.4), including Ciomadul and its geomorphic expression in the volcanic edifices, has been studied intensely by researchers (see Chaps. 3 and 4). Based on their extensive publication record, the 13.5 to less than 0.03 Ma volcanism can be grouped into two categories (e.g., Seghedi et al. 2011; Szakács et al. 2018). The majority of the magmatism observed is extrusive, i.e. by the formation of volcanoes and associated sub-volcanic intrusion, deposition of volcaniclastic sediments and manifestations in terms of hydrothermal and epithermal deposition from fluid solutions or gas emanations.

The first category, described as a typical subduction-related magmatism, is observed in areas adjacent to the East Carpathians, and can be generally described as gradually migrating toward the southeast during the time interval from ~13.5–4 Ma. This gradual migration through time was interpreted−first by Mason et al. in 1998−as the result of oblique subduction along the East Carpathians, where subducted oceanic or continental lithosphere would have reached the depth of the magma-generating window gradually from northeast to southwest. The subduction-related origin shows an apparent contradiction with the results of the above described tectonic, structural and geophysical studies, which show that subduction stopped in the east and SE Carpathians 8 Ma ago. In other words, the 8–4 Myr time interval shows emplacement of subduction-related magmas in a period when no subduction took place. This contradiction might be, for instance, explained by the prolonged residence times of such magmas at depth preceding volcanic activities. However, the generation of this magmatism in a collisional setting remains an important question to be further studied, as described later in this book.

The second category includes magma compositions that gradually changed starting around 3 Ma to adakite-like calc-alkaline and to sodium and potassium alkaline volcanism, terms which refer to the geochemical compositions of magma generation. This change is described and interpreted by Seghedi (2011) to be driven initially by processes associated with rapid movement of the asthenospheric mantle and subsequently by direct mantle sourcing with various compositions affected or not by differentiation and temporary residence at crustal levels. This type of magmatism is observed only in areas that are adjacent to the SE Carpathians and continued from 3 Ma until its last expression in the Ciomadul volcanic area. This change in magmatism is in agreement with the change in tectonic style of the past 3 myr, i.e., the accelerating uplift and subsidence in the orogen and its foreland, respectively (Fig. 2.4). The source of this magma (Fig. 2.4) is the asthenospheric uprise and associated circuit around the Vrancea slab (Seghedi et al. 2011), while a genetic link with active crustal magma chambers in the Ciomadul area has been inferred by high-resolution geophysical studies (e.g., Popa et al. 2012).

2.5 Implications for Natural Hazards

The prolonged effects related to the sinking lithospheric slab and its associated asthenospheric upwelling circuit is not only responsible for the recent volcanic activity, but is also associated with a significant crustal deformation characterized by rapid subsidence and uplift (Fig. 2.6), which has an impact on the present-day evolution of topography and natural hazards in the SE Carpathians. GPS studies (e.g., van der Hoeven et al. 2005), have shown that while the SE Carpathian's thin-skinned nappes are uplifting with velocities up to 5 mm/year, the Focșani Basin is subsiding with velocities up to 7 mm/year. Geological and geomorphological studies (e.g., Leever et al. 2006; Necea 2010; ter Borgh 2013), have shown that the combination of differential vertical movements has gradually shifted with time during the last 3 myr towards the southeast with velocities in the similar orders of mm/year. These movements induced rapid topographic changes towards a continuously changing state of the drainage network, as observed in many geomorphological studies (e.g., Rădoane and Vespremeanu-Stroe 2017).

These studies have also shown that given the high rates of vertical and horizontal movements, the landslide risk is probably the highest in continental Europe. Rapid changes in the river network (e.g., capturing, shifting, incision) took place in recent times and are still on-going, as inferred for example from Buzău and Olt rivers (e.g., Necea et al. 2021).

The seismogenic Vrancea zone is well known for its strong and devastating earthquakes reaching magnitudes of around 7, sourced at intermediate (70–220 km) mantle depths, well described by many studies (Fig. 2.2, e.g., Ismail-Zadeh et al. 2012 and references therein). Deformation in the overall sinking slab shows the highest rates observed in continental Europe (e.g., Wenzel et al. 1999). By contrast, much less is known on the mechanisms of the large number of crustal earthquakes that reach magnitudes of around 5, which are of significant societal concern. Existing studies have shown that crustal seismicity correlates with the previously described thick-skinned thrusting beneath the external nappes of the SE Carpathians and with the activation of normal and strike slip faults farther in the foreland, as demonstrated by the 2013 and 2017 seismic events of the Galaţi and north Focsani area (e.g., Bocin et al. 2009; Petrescu et al. 2021).

In the SE Carpathian hinterland, volcanism with its most recent expression in the Ciomadul poses an unknown potential risk, if any (see Chap. 7). At geological time scales, the correlation between the evolution of the adjacent intramontane Pliocene/Quaternary Brasov and Târgu Secuiesc basins and the associated volcanism may show a potential of reactivation, but the recent evolution of these basins indicates that such a process is decelerating (Leever et al. 2006).

2.6 Conclusions

The southeast part of the Carpathians provides an important location for studies aimed at understanding the mechanics of topography building in mountain chains that are in an ultimate stage of evolution of a subducted slab. While evolving as a typical collisional nappe emplacement orogen until 8 million years ago, the tectonic situation changed significantly afterwards when no further absolute plate motions took place. The exhumation and topographic growth pattern changed with time, from enhanced in the core of the mountains to more recently focussed in their south-eastern part, which is rather unusual in classical models of creating orogens. The latter period is characterized by the gradual accretion of sediments or continental basement derived from the lower subducting plate. After tectonic plates convergence has essentially ceased, or reduced to fairly small values, most of the last 3 million years of evolution of the Southeast Carpathian mountain chain has been driven by processes related to the sinking Vrancea slab and its associated asthenospheric circuit, driving differential uplift in the mountain chain and subsidence in its foreland. This tectonic process was associated with a major change of magmatic activity to smaller volcanic volumes, including the chain-ending eruptions of Ciomadul from c. 1 million to less than 30 thousand years ago. These processes conditioned a situation where deformation shows the highest rates in continental Europe, inducing significant topographic changes, and implying a large number of natural hazards, including, potentially, volcanic hazards (see Chap. 7).

3

Evolution of the Ciomadul Volcanic Field—Lava Domes and Explosive Eruptions

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Abstract

Ciomadul (Csomád) is the youngest volcano in the Carpathians and the Carpatho-Pannonian Region whose latest eruptions may have been witnessed by Palaeolithic people. It is the only volcano in the region where, although with little probability, future eruptions may occur. Ciomadul was a lava dome complex, and its volcanic activity included both effusive (lava) and explosive (pumice and ash) eruptions that lasted almost one million years, terminating less than thirty thousand years ago. This makes Ciomadul an important target for future investigation to determine detailed volcanic stratigraphy and eruptive scenarios for long-lived lava domes. Here, we present the state-of-art of the research of this unique volcanic activity and the related volcanic landforms.

3.1 Introduction

Exactly when was the youngest volcano of the Carpathians active? What kind of eruptions took place? Could the Palaeolithic people have witnessed these eruptions? Can we expect any future volcanic activity? These or similar questions related to the young age of volcanism can be put forward mostly in active volcanic regions. However, on the basis of recent research results, which were predicted already at the turn of the twentieth century by some scientists (e.g. Antal Koch, Lajos Lóczy, Jenő Cholnoky—esteemed geologists and geographers in Hungary), they also make sense here, at the southern tip of the volcanic Harghita (Hargita) Mountains. Moreover, such questions may not only be of interest to dedicated researchers, they are also exciting for the public. Volcanic rocks and their formation are presented in Chap. 4; dispersal of explosive

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volcanic ejecta (so-called tephra) in Chap. 5; the activity status of the volcano in Chap. 7. Here, as a summary of Ciomadul's volcanism, the past eruptive processes and resultant landforms are presented, along with geochronology. But before going into detail, let us look at this unique volcanic landscape of East-Central Europe!

3.2 Geographical Setting of Ciomadul Volcano

Ciomadul, located east of the Olt river at the south-eastern edge of the Călimani-Gurghiu-Harghita (Kelemen-Görgényi-Hargita) volcanic range and bordered by the Quaternary Ciuc (Csíki), Bixad (Bükkszád) and Târgu Secuiesc (Felső-háromszéki) basins, looks, at first sight, different from its neighbouring mountains (Figs. 3.1, 3.2) These mountains, the South Harghita Mountains themselves, and the Ciuc and Bodoc (Bodok) mountain ranges to the east, which are composed of Cretaceous flysch deposits, consist of relatively flat, N-S oriented ridges. By contrast, in between them, the volcanic hills of Ciomadul show a more rugged relief. Their elevation is slightly lower than that of the adjacent ranges (e.g., Bodoc Mts.); the highest point is Ciomadul Mare (1301 m a.s.l.), and the elevation of the individual hills relative to the Lower Ciuc Basin to the north is just 600–700 m.

The unique beauty of the volcanic hills is most strikingly seen from the Lower Ciuc Basin (Fig. 3.3a), which forms a wide alluvial plain closed toward the south by the conical or truncated hills of Ciomadul. Between Ciomadul and the adjacent Pilişca (Piliske) volcano, the Olt river finds its way through the narrow, picturesque Tuşnad (Tusnád) Gorge. The landscape is similarly magnificent looking from the south, although without a wide plain; downstream of the Tuşnad Gorge, the valley becomes winding, somewhat elongated at Bixad, and Ciomadul provides a scenic view from here also.

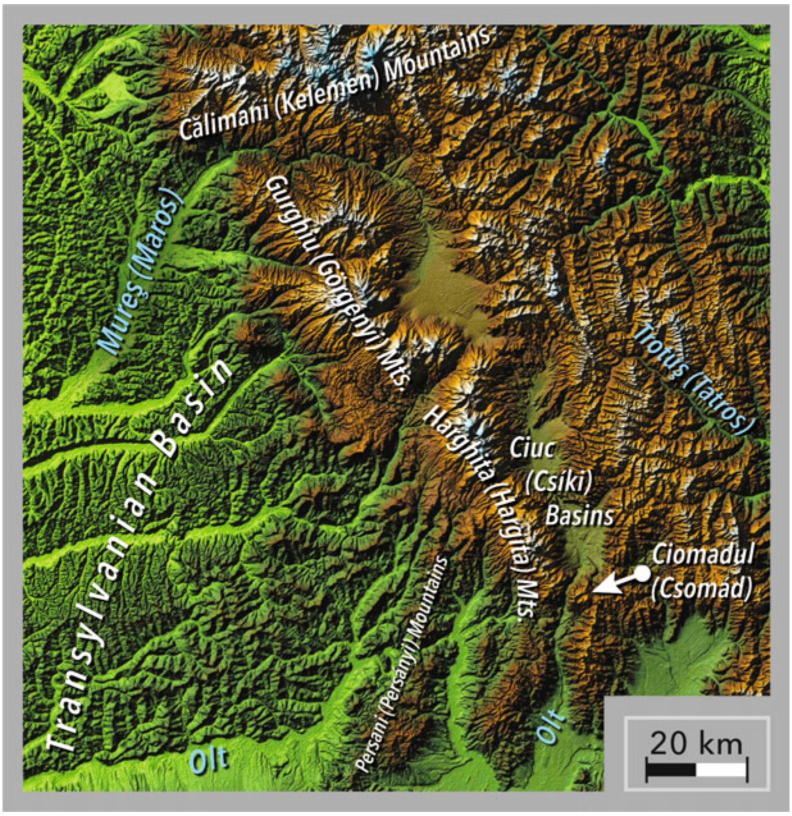


Fig. 3.1 Geographical setting of the Călimani (Kelemen)–Gurghiu (Görgényi)–Harghita (Harghita) Mountains within the East Carpathians (coloured and shaded relief image based on STRM [Shuttle Radar Topography Mission] DEM [Digital Elevation Model] data)

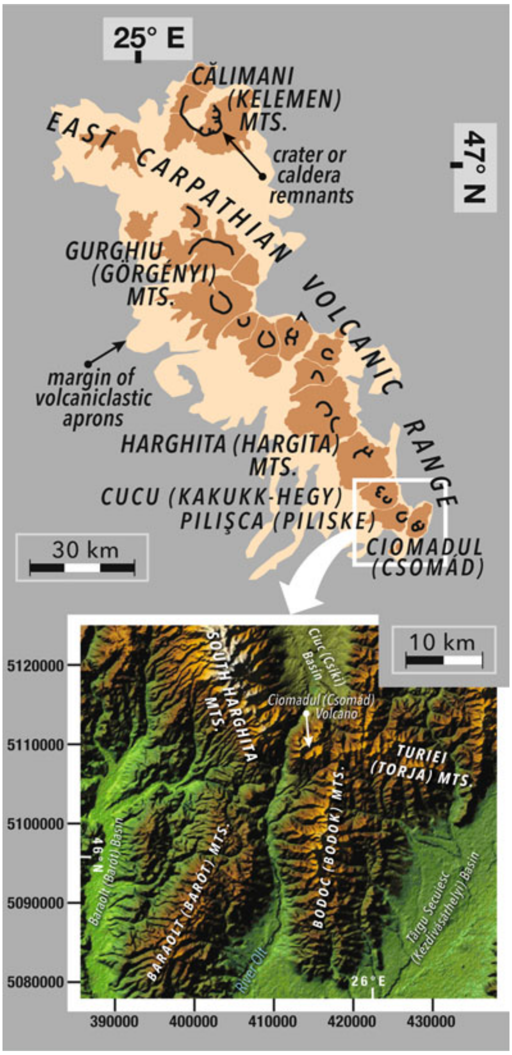


Fig. 3.2 Location map of Ciomadul along the East Carpathian Volcanic Range. White box refers to the vicinity of the volcano (enlarged topography shown on SRTM DEM)

In the geographical literature, Ciomadul is often called the Ciomadul-Puturosu (Csomád-Büdös) Hills. This is because the area can be divided into a much larger western sector, which is a uniform volcanic massif except for the northernmost Haramul Mic, and the eastern hills of Puturosu (Büdös), Balvanyos (Bálványos) and Dealul Mare (Hegyes-tető). Puturosu and Balvanyos are much smaller and protrude the flysch separately. Counter-clockwise, the boundaries of this larger area of Ciomadul-Puturosu are the Tuşnad Gorge to the west, the Bixad Basin and the Jimbor (Zsombor) stream (which runs to the Olt river) to the south, the Balvanyos stream to the southeast, the Tuşnad stream to the northeast and the Lower Ciuc Basin to the north (see Fig. 3.4).

The main geomorphic elements of Ciomadul, showing conical or truncated conical geometries, are lava domes which are shown on the right. However, it should be noted that the final volcanic activity of the Harghita Mts. was represented by lava dome formation not only at Ciomadul. Whereas the lower two-thirds of the 1.5–2 million year-old andesitic Pilişca volcano resembles other edifices of the South Harghita range, Bába Laposa is a peripheral dacitic dome on its northern flanks. Further to the south of Pilişca along the river Olt, the flat-topped lava domes of Murgul Mic (Kis-Murgó) and Lüget-Malnaş (Lüget-Málnás) consist of shoshonite (alkali-rich basaltic trachyandesite), a peculiar rock type distinct from those of Ciomadul. These rocks and the dacite of Bába Laposa have been dated by the zircon (U-Th)/He method at slightly less than 1 Ma (Molnár et al. 2019). Trace element studies to decipher the origin of these magmas are in progress. However, here, on the basis of their position, these occurrences are not considered as part of Ciomadul volcano (cf. Szakács et al. 2015), although their affinity from both volcanological and petrological points of view should be further studied.

3.3 Lava Domes: Formation, Eruptive Activity and Degradation

To the north and southeast, at the periphery of the Ciomadul massif, individual lava domes occur separately, whereas in the central part, domes are adjoining or superimposed, collectively called a lava dome group or lava dome complex. The central domes constitute the majority of the domes, and they host a peculiar twin crater: the younger Sf. Ana (in English, St. Anne; in Hungarian, Szent Anna), filled by a lake, and the older Mohoş (Mohos), which is

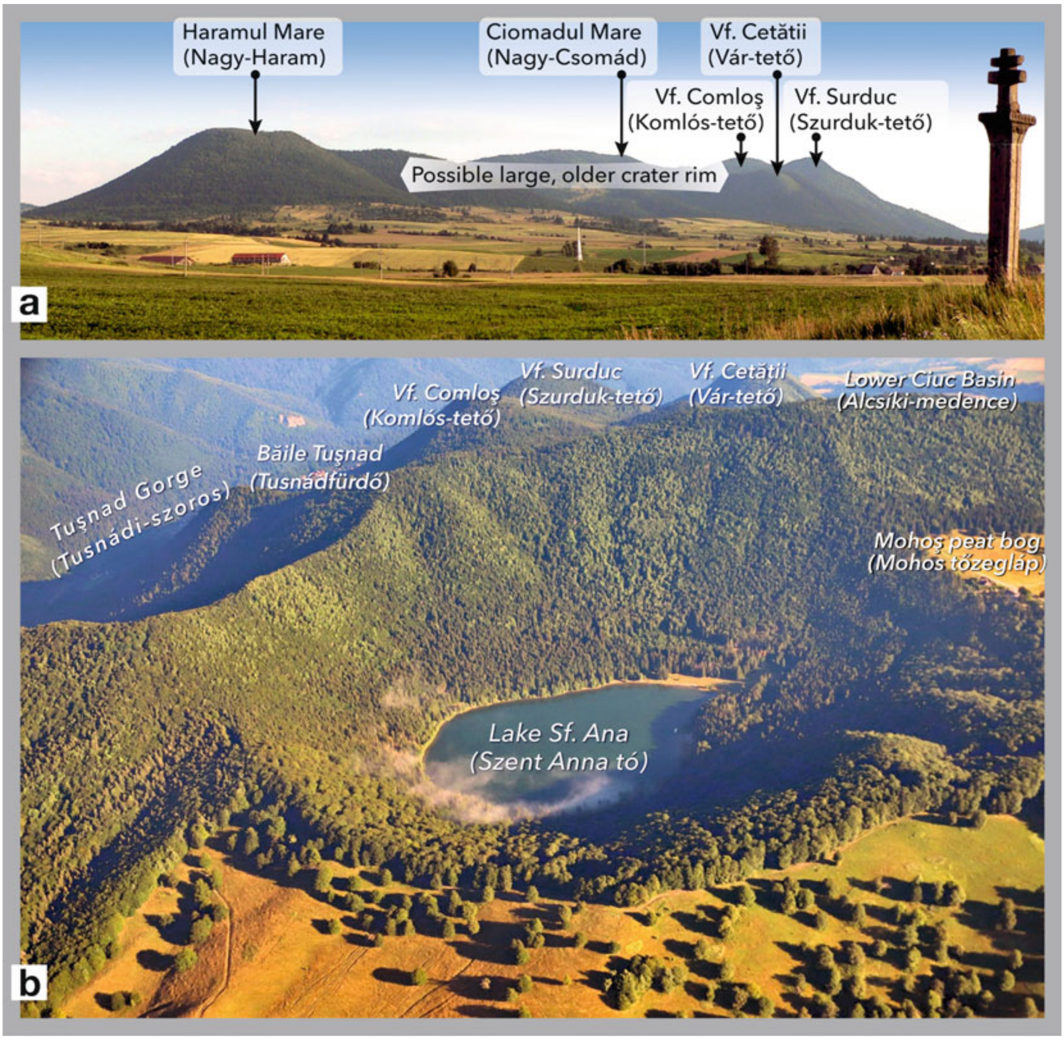


Fig. 3.3 **a** Panoramic view of Ciomadul displaying the general topography of the mountain. Note the reduced height of Ciomadul Mare due to (multiple?) crater formation (*photo credit*: Dávid Karátson); **b** Aerial view of Ciomadul from the south-west, with Lake Sf. Ana (*photo credit*: István Fodor)

now reduced to a peat bog and its crater filled by a thick lacustrine sequence (Figs. 3.3b, 3.4).

LAVA DOMES Lava domes are small- to medium-sized volcanic landforms that develop by the extrusion of viscous, silica (SiO_2)-rich andesitic, dacitic or rhyolitic magmas. They can be distinguished from lava flows (commonly with a less silicic composition) by a height/width ratio >0.1, that is, they grow upward rather than flow away from their source. The high SiO_2-content and other physical properties make such magmas highly viscous. Thus, the slow moving hot lava builds up steep or very steep landforms, which have their own names in many languages. Most commonly, however, lava domes are less steep and have a roundish, conical or truncated cone shape, called Peléan domes

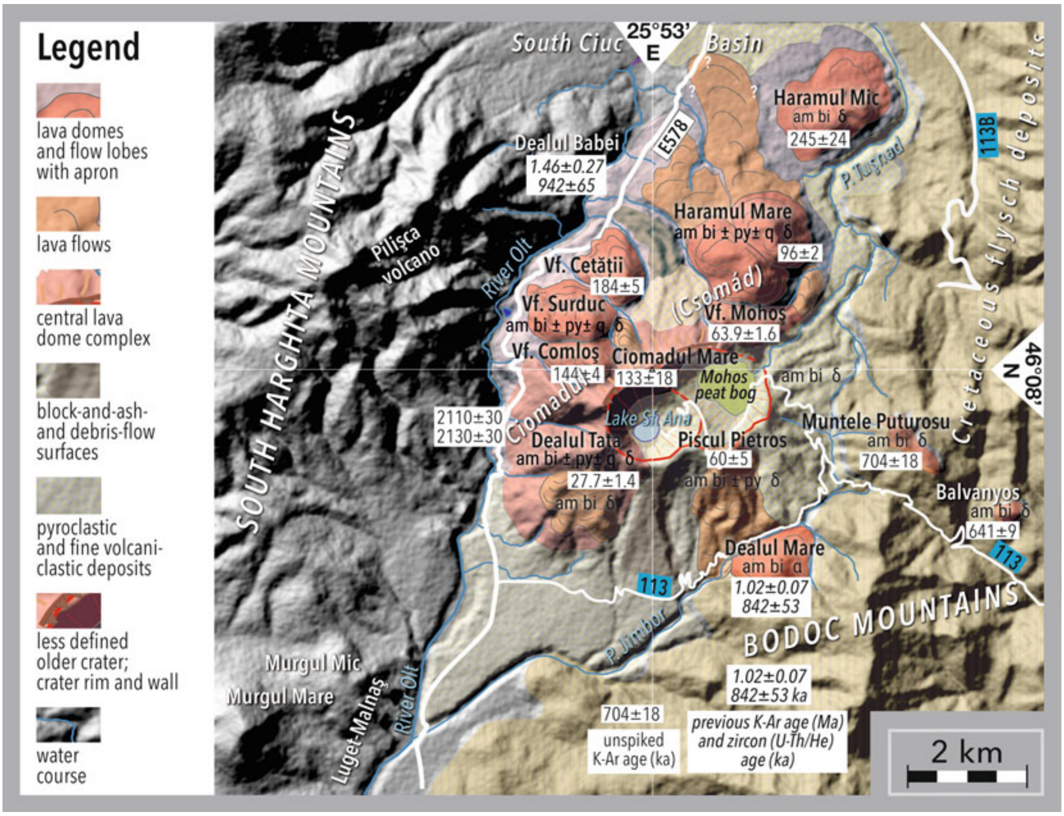


Fig. 3.4 Volcano-geomorphological map of Ciomadul (after Karátson et al. 2016; 2019) with lava dome lithologies based on Szakács et al. (2015). Am = amphibole, bi = biotite, py = pyroxene, q = quartz, α = andesite, δ = dacite

after Mont Pelée on Martinique Island (Lesser Antilles) where this phenomenon has been first described.

Peléan domes typify the majority of Ciomadul's lava domes, the best examples being Haramul Mare (Nagy-Haram), Haramul Ierbos (Fű-Haram), Dealul or Vârful Cetăţii (Vár-tető). The smaller domes can be asymmetric coulées (short lava flows) such as Vârful Comloş (Komlós-tető) and Vârful Surduc (Szurduk-tető); an exception is the flat-topped Haramul Mic (Kis-Haram), which is a so-called low dome. All domes but one are made up of dacitic lava, lithologically speaking, an amphibole- and biotite-bearing dacite often with pyroxene; the exception is the southernmost, isolated Dealul Mare, whose rock type is a slightly less silicic andesite with similar mineral composition (Szakács and Seghedi 1986).

At present, Ciomadul's volume is ~7.8 km^3 in total, comprising the solid rocks of its lava domes; the eroded material from the edifice is estimated at only c. 0.2 km^3 (Karátson et al. 2019) (see Table 3.1). More than half of the volume makes up the central domes: the Ciomadul Mare area and Haramul Mare–Haramul Ierbos. In places where smaller individual domes can be recognised, which formed during a short time period, their volume is just a couple of tens of km^3. The smallest, significantly eroded Puturosu and Balvanyos domes, which are at the same time the oldest, are <0.1 km^3 in volume.

Most of the Ciomadul domes are intact, slightly eroded landforms that in some cases still expose a syn-eruptive breccia envelope at the lower periphery (e.g., Vârful Cetăţii; Szakács

Table 3.1 Volumetry of Ciomadul's lava domes (after Karátson et al. 2019)

	Base level (m asl)	Area (km^2)	Present volume (km^3)	Proportional volume (as % of total)	Erosion since emplacement (km^3)[a]
Dealul Mare (Hegyes-tető)	760	1.52	0.30 ± 0.03	3.9	0.040
Puturosu (Büdös)	900	0.47	0.07 ± 0.01	0.9	0.010
Balvanyos (Bálványos)	870	0.20	0.02 ± 0.00	0.3	0.004
Haramul Mic (Kis-Haram)	690	1.34	0.19 ± 0.03	2.4	0.010
Vf. Cetății (Vár-tető)	684	1.05	0.29 ± 0.02	3.8	0.006
Vf. Surduc (Szurdok-tető)	651	1.28	0.39 ± 0.02	5.0	0.007
Vf. Comloş (Komlós-tető)	660	0.79	0.43 ± 0.03	5.5	0.004
Ciomadul Mare (Nagy-Csomád)	616	7.96	2.90 ± 0.15	37.1	0.033
Haramul Mare (Nagy-Haram)	725	3.86	1.20 ± 0.08	15.4	0.012
Vf. Mohoş (Mohos-tető)	812	1.02	0.10 ± 0.02	1.3	0.002
Piscul Pietros (Köves Ponk)	775	1.14	0.34 ± 0.03	4.3	0.002
Volcaniclastic aprons		53.81	1.57 ± 0.13	20.1	0.044
Total		74.44	7.82 ± 0.55	100	0.175

[a] *calculating with a long-term erosion rate of 31.5 m/My (Karátson 1996) applied to each dome area*

et al. 2015). Effect of post-eruptive erosion is prominent in some places of the upper flanks by stony debris slopes, so-called 'block seas' (e.g., Ciomadul Mare), which were produced by frost shattering of dome rocks during the last (Würm) glacial period. The well-preserved lava dome landforms, along with the relatively intact twin craters with their circular rims, inspired the well-known Hungarian geomorphologist, Jenő Cholnoky (1922), to put forward this exaggerating statement: "*If there was not a vegetation cover, we could expect a future eruption in almost any moment!*" The state and the potential renewal of volcanic activity has also become an important question in modern volcanology (see Chap. 7).

Lava domes can form individual, isolated structures, but it is more typical when they are part of larger volcanic systems such as calderas or composite volcanoes. Moreover, lava dome groups consisting of amalgamated or superimposed domes are considered as a particular type of composite volcanoes. Lava domes commonly erupt effusively, but also explosively, as exemplified by Merapi in Java, Unzen in Japan, or Mont Pelée itself, which produced catastrophic eruptions with a high number of fatalities several times in their recent histories, causing widespread damage in the surrounding regions (Fig. 3.5). At Ciomadul, such explosive eruptions could have been witnessed by the Palaeolithic people in prehistoric times.

Why and how can a lava dome produce explosive eruptions? Lava domes, as mentioned above, are formed due to the extrusion of viscous magma to the surface. However, in case of a large amount of gas (volatiles) in the magma, the process can cause explosive fragmentation of the still hot, ductile lava dome, accompanied by the rapid release of gas. As a result, the explosive disruption and the collapse of the dome is often

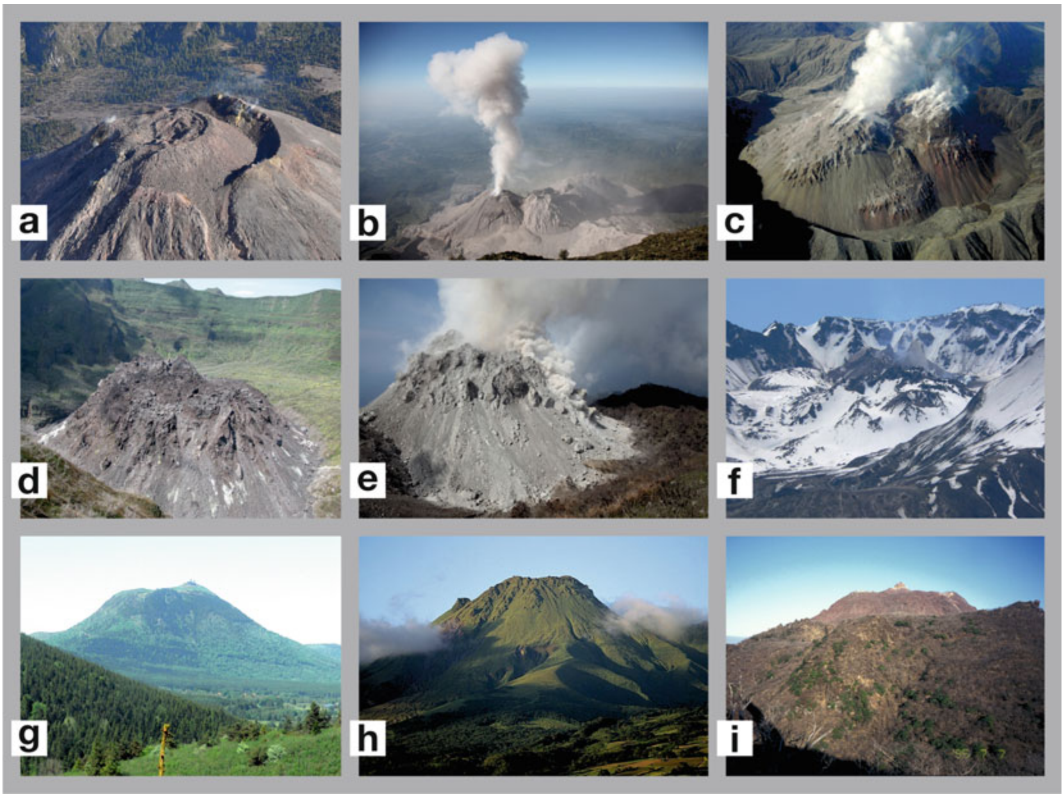


Fig. 3.5 Active and dormant lava domes worldwide. **a** Colima, Mexico, with its 2011 dome (*photo credit*: Jamie I. Farquharson); **b** Santiaguito, Guatemala, 2012 (*photo credit*: Richard Roscoe); **c** Chaiten, Chile, 2010 (*photo credit*: David J. Schneider); **d** Kelud, Java, Indonesia, 2007 (*photo credit*: Shmithsonian Institution) **e** Paluweh, Java, Indonesia, 2012 (*photo credit*: Richard Roscoe) **f** Mt. St. Helens, USA, 2005 (*photo credit*: Dávid Karátson) **g** Puy de Dôme, France, c. 11,000 years old (*photo credit*: Dávid Karátson) **h** Mt. Pelée, Martinique, France, 1932 (*photo credit*: Smithsonian Institution); **i** Unzen, Kyushu, Japan, 1995 (*photo credit*: Dávid Karátson)

accompanied by ash fall. The collapsed material is commonly directed sideway as a peculiar mass movement—this is the notorious 'glowing cloud', or in French, inspired by Mont Pelée's 1902 eruption, *nuée ardente.* Volcanologists call this process a *block-and-ash flow*, which is a particular type of pyroclastic flow. In fact, such a process is one of the most dangerous volcanic phenomena on Earth. The mixed blocks along with the finer-grained rock fragments are mostly confined to, and deposited on, valley floors, while the accompanying ash cloud can reach distances of 10–15 km from the vent, and areas far away from any valley. The temperature of the ash can be up to 300–500 °C, which is certainly lethal for human beings in a moment. One of the most devastating *nuée ardente* catastrophes occurred at Mont Pelée in 1902, when 29,000 people died. In the following, we will show that such high-temperature block-and-ash flows, evidenced by charcoal remains of burned trees that once grew on the slopes of the volcano, have also been identified at Ciomadul from its late-stage eruptive history.

In more detail, the explosive disruption of a lava dome can be associated with falling volcanic particles (i.e., *pyroclastic fall*). At lava dome complexes in particular, short-lived, discrete explosions can also occur without growth of a new lava dome, for instance from a summit crater of an existing dome. Such an explosive process is termed a *vulcanian* eruption, which we have evidence of at Ciomadul (see below). Apart from ash-sized particles (which, after deposition and

Fig. 3.6 Dacite blocks and breadcrust bombs from Ciomadul showing a cracked outer layer and commonly a porphyritic texture (with white plagioclase). Reddish colour marks oxidized lava derived from outer dome/lava flow surface, breadcrust cracks indicate rapid cooling and shrinking. Light grey to whitish colours are due to alteration. Hammer for scale

compaction, are called *tuff*), vulcanian outbursts often produce *lapilli* (2–64 mm) as well as *blocks and bombs* (>64 mm), which may characteristically include so-called *breadcrust bombs* (Fig. 3.6). These characteristic bombs form during ejection from a crater when cooling of the decimetre or even metre-sized rock fragments results in fracturing and jointing on the bomb surface. At Ciomadul, findings of breadcrust bombs have been made particularly on the southern slopes (e.g., Comloş/Komlósárok valley) since the nineteenth century, and they were already considered as early evidence of the volcanic origin of the massif. It should be noted, however, that such blocks can be produced not only during pyroclastic falls, but—typically at Ciomadul—also pumice-rich block-and-ash flows. possibly related to explosive lava dome formation (Szakács and Jánosi 1989; Karátson et al. 2016).

TEPHRA The Greek word tephra (in plural, meaning ash) has been re-introduced into the volcanological literature in 1954 by the Icelandic volcanologist Sigurður Thorarinsson as a specific term to describe all pyroclastic material. With time, it has been used more restrictively. For example, in the classic volcanology textbook of Williams and McBirney (1979) tephra includes only pyroclastic-fall deposits. Nowadays the term tephra is applied mostly to fine-grained, typically unconsolidated material (McPhie et al. 1993), whereas due to its loose definition, the term is less commonly used in volcanic sedimentology. *Tephrochronology* and *tephrostratigraphy,* however, are important research fields dating and correlating medial and distal (fine-grained) pyroclastic deposits.

Craters of composite volcanoes or, more rarely, those of lava dome complexes, can also produce more explosive, sustained eruption columns without dome growth and disruption. At Ciomadul, one can also find evidence of this kind of activity, which is called a *plinian* or when less explosive a *subplinian* eruption, named after Pliny the Younger who witnesses and described the catastrophic eruption of Vesuvius in AD 79. Characterized by pumice fall in proximal and medial settings (i.e., up to several tens of km), these explosions affected the largest area at Ciomadul (see below).

The deposits from plinian or subplinian eruptions typically cover the topographic lows. Their volume is difficult to assess. This is due partly to the small number of exposures, and also to the fact that a portion of the material was deposited farther away during these highly explosive eruptions. With the prevailing winds, pyroclastic material could have travelled great distances, accumulated finally as *tephra* layers in lakes, valleys or oceans (see Chap. 4). Moreover, a significant part of the pyroclastic material has been removed since deposition, especially during the glacial periods when the sparsely vegetated surface was subjected to rapid denudation. Even if the annual precipitation may have been lower than today, most of the pyroclastic material (pumice and ash) were removed by debris flows/mud flows (lahars; see Chap. 6). At present, the redeposited, fine-grained pyroclastic

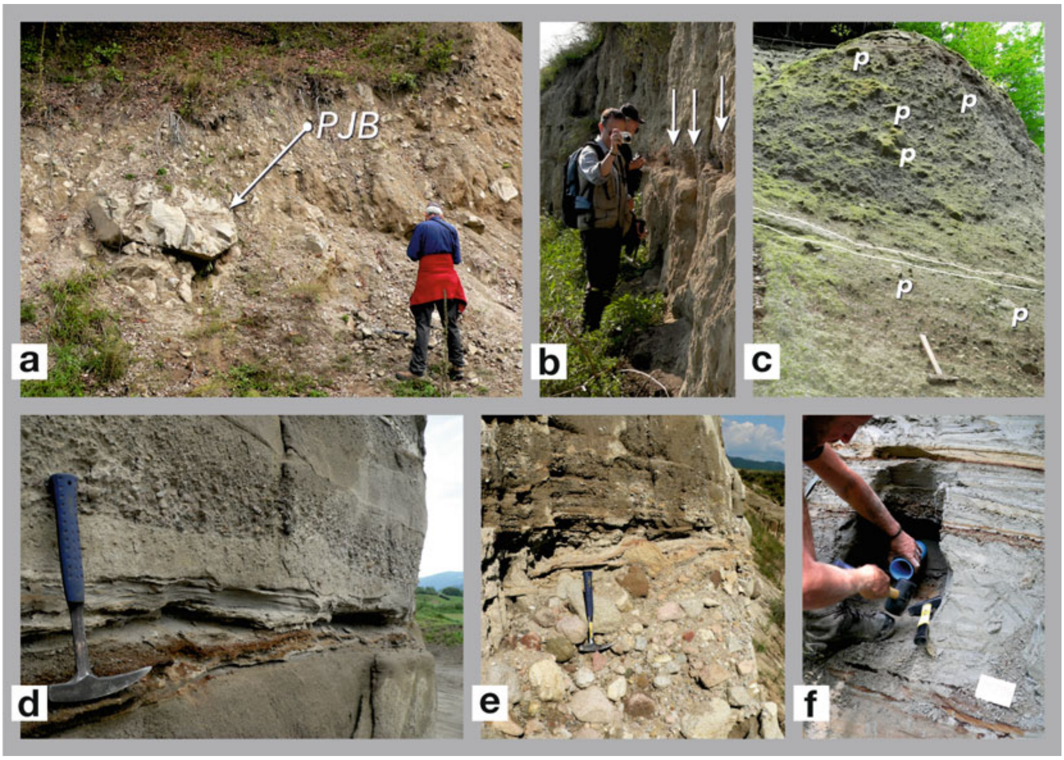


Fig. 3.7 Pyroclastic, syn-eruptive volcaniclastic, and sedimentary deposits at Ciomadul. **a** Block-and-ash flow deposit south of Piscul Pietros (Köves Ponk) with a prismatically jointed block (PJB, arrowed) **b** Pyroclastics from the so-called 'Târgu Secuiesc (TGS) eruption' with sub-plinian distal pumice-fall deposit (arrowed) at Târgu Secuiesc (Kézdivásárhely), representing the first phase of the eruption **c** Pumice (p)-rich pyroclastic-flow units at the outlet of Mohoş (Mohos) peat bog, representing the second phase of the TGS eruption **d** Debris-flow, hyper-concentrated stream-flow and normal fluvial deposits at Tuşnad Nou (Újtusnád) Quarry **e** Very coarse debris-flow deposit (hammer) near Lăzăreşti (Lázárfalva), possibly from the Würm glacial, showing grey (unaltered) and reddish (oxidized) clasts from remobilised lava dome material **f** Alternating sandy and clay-rich sediments, c. 10–20 ka, constituting the palaeo-lacustrine sequence of Mohoş crater

material, up to tens of metres thick, can be found in the Lower Ciuc Basin, downstream of the Tuşnad Gorge along the river Olt, and also to the southeast along the Turia (Torja) stream (e.g., Karátson et al. 2016). Most easily, these deposits can be studied in "sand quarries", excavated by local people and used up to now (e.g. Tuşnadul Nou/Újtusnád, Lăzăreşti/Lázárfalva, Ghidfalău/Gidófalva; for more details, see Chap. 6) (Fig. 3.7).

A considerable part of the explosive products have been preserved near the twin craters, which were their source vents, primarily on the eastern and southern slopes of Mohoş crater (e.g., Hosszúmező, Románpuszta), to the east along the Roşu (Veres) stream which breaches the crater, to the north along the Vârghiş stream, and to the south along the Jimbor stream. The proximal explosive deposits can also be recovered from the lacustrine infill of Mohoş crater (Karátson et al. 2016; Wulf et al. 2016) and also crop out on the north-eastern inner side of Sf. Ana crater (e.g., at the Belvedere lookout point near the winding road down to the lake). Details of these peculiar deposits are presented below.

3.4 Explosive Eruptions and Products

Several authors proposed one or more "dome-building" stages of Ciomadul (e.g., Szakács et al. 2015; Molnár et al. 2019) preceding the latest-stage explosive period. However, explosive eruptions may have also been present throughout the extended periods of lava dome growth, and we will present evidence of this below and the next chapters. Yet, it is well documented that during the last 50–60 thousand years the dome-building episodes were punctuated markedly by highly explosive eruptions. It should be emphasized that, in the densely forested area, the products of these are difficult to trace, and there might have been an even larger number of such eruptions than pointed out and correlated so far. In any case, there is no doubt that violent explosive eruptions occurred at Ciomadul, which, to our knowledge, did not typify the adjacent, older (Plio-Pleistocene) South Harghita volcanoes. These explosions resulted in the formation of the twin craters of Mohoş and Sf. Ana.

As for the style of the explosive activity, the contact and interaction of the uprising magma with the water-rich flysch rock of the basement increased, which occasionally led to so-called *phreatomagmatic* eruptions (e.g., Szakács and Seghedi 1989; Szakács et al. 2015; Karátson et al. 2016). This type of activity characterized the early explosive period at around 50–60 thousand years ago (abbreviated to 50–60 ka = kiloyears ago), then the final eruptions around 30 ka, respectively. The sudden contact between the magma and subsurface water transforms magma into small volcanic particles or ash, which is then deposited as tephra layers.

On the other hand, there were also "dry" magmatic explosions at Ciomadul (Szakács et al. 2015; Karátson et al. 2016). They were related to the explosion of volatile-rich magmas of deep origin, which fragments the magma to small volcanic (ash) particles but also larger pumice clasts (in the latter case, these are the *plinian* or *subplinian* eruptions, see above). 21 km away from Ciomadul, at the outskirts of Târgu Secuiesc town, a tephra layer consisting of cm-sized pumices was already described at the beginning of the twentieth century by the geologist János Bányai (see Chap. 1). The eruption that produced this tephra some 31,500 years ago might have been the largest of the volcano (see later) (Fig. 3.8).

The explosive volcanic products, which crop out in various settings (deep gullies, abandoned fluvial terraces, artificial road cuts, walls of sand quarries etc.), could only be as old as the lowest exposed part of the surrounding topography in a stratigraphic sense. On the basis of the available chronological data, they are usually not older than 50–60 ka (Karátson et al. 2016). As for tephra-bearing localities, exceptions include the lower part of the several tens of metres thick loess sequence at the Dniester River, the base of the Târgu Secuiesc loessy-sandy sequence, and possibly the lower strata of the huge sand quarries south of Sfântu Gheorghe, which may be as old as 100–150 ka according to preliminary luminescence dating (see below, and in Chap. 6).

Apart from these field relationships, little information is available on the early explosive eruptions of Ciomadul. In this regard, Karátson et al. (2013), building on a 70 years-old idea of János Bányai, suggested that the arcuate, flat ridge of Ciomadul Mare could be related to the formation of an early, large explosion crater due to a violent eruption. If so, considering the age of Ciomadul Mare (around 130 ka), it is possible that tephra layers pertaining to such old or even older explosive eruptions of Ciomadul may be identified by future research (also see Chap. 6).

Whereas the ideas discussed above are assumptions, the first well-defined explosive eruptions of Ciomadul are represented by the c. 50–60 ka tephras from the so-called Early Phreatomagmatic and Plinian Activity (EPPA), as outlined in the comprehensive paper of Kará-tson et al. (2016).These tephra layers indicate a predominantly phreatomagmatic eruption sequence. Their best exposures can be found, among others, around Turia village and on the southern flanks of Ciomadul ("Turia tuffs"). The primary pyroclastic units crop out only in some spots, as most were redeposited by fluvial processes and sometimes

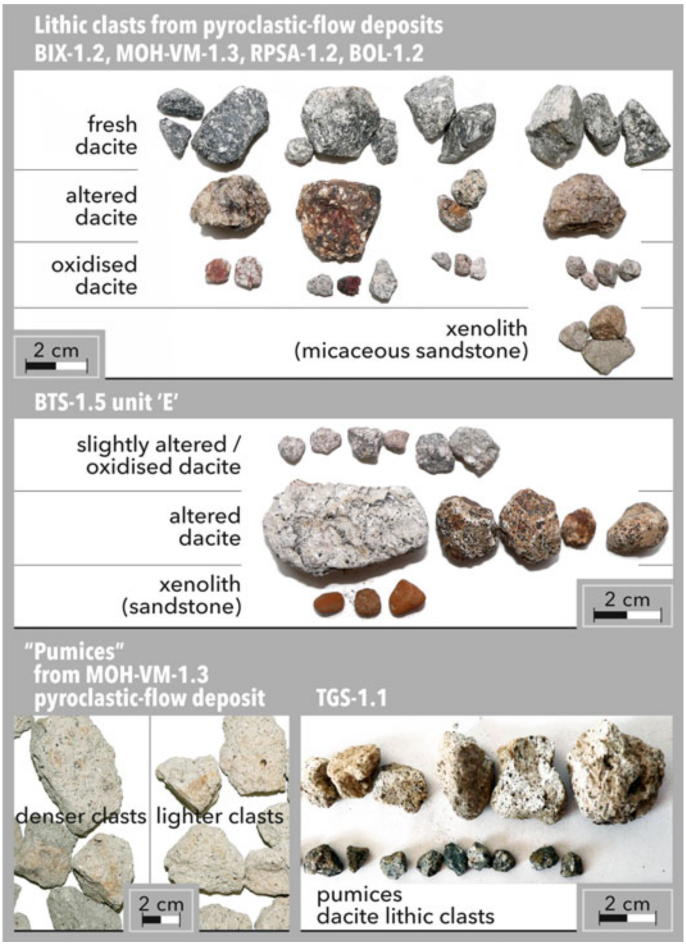


Fig. 3.8 Components of pyroclastic deposits of Ciomadul volcano's late-stage explosive eruptions (after Karátson et al. 2016). Upper panel: lithics (dacite) and xenoliths (sandstone) from the third pyroclastic-flow phase of Târgu Secuiesc ('TGS') eruption (~31.5 ka). Abbreviations (e.g. BIX-1.2) refer to locality and unit number as defined in Karátson et al. (2016). Middle panel: dacite lithics and xenoliths collected at Băile Tuşnad locality ('BTS' eruption, poorly dated at 40–42 ka). Lower panel left: pumices with various density from the second pyroclastic-flow phase of TGS eruption. Lower panel right: pumices and dacite lithics from the first pyroclastic-fall phase of TGS eruption (collected at Târgu Secuiesc)

by volcanic mudflows or lahars (see Chap. 6). The source of these eruptions could have been an early Mohoş crater whose relatively young age of c. 60 ka is suggested by the age of the lava flows of Piscul Pietros (60 ± 5 ka; Lahitte et al. 2019) that are truncated by the crater rim, and the c. 55–70 ka age of the sediments underlying the tephras north of Turia.

The products of one of the most interesting eruptions of the final phases of EPPA can be traced in a small roadside quarry south of Băile Tuşnad along the E 578 highway. Named BTS after the village, the outcropping tephra layers have been dated at around 40–42 ka, but with considerable uncertainty (see below). The lower part of the eruptive sequence comprises a series of plinian/subplinian pumice-fall deposits (Fig. 3.8). Following a time gap, indicated by controversially interpreted, intercalated sediments (Szakács et al. 2015; Karátson et al. 2016), the upper part of the sequence exposes two thick, charcoal-bearing pyroclastic-flow deposits (Moriya et al. 1996; Karátson 2007; Szakács et al. 2015; Karátson et al. 2016). As mentioned in Chap. 1, the charcoal gave first an erroneous radiocarbon age of c. 10,700 years BP, but at the same time successfully called attention to the very young, late Quaternary eruptions of Ciomadul. In addition, to the north at the village of Sânmartin (Csíkszentmárton), two successive tephra layers in a quarry (Karátson et al. 2016), interbedded with fluvially deposited Late Pleistocene flysch gravel originally deposited by rivers flowing from the mountains to the west, may also be from to the BTS eruptions, since they yielded a still unpublished luminescence age of c.

42 ka (see below in the next section). All these deposits seem to have been sourced from a new vent west of Mohoş, a Proto-Sf. Ana crater (Karátson et al. 2016).

This crater, which truncates the western part of the central lava dome complex, may have been transformed several times during its activity. Its eruptions, subsequent to BTS, are summarized under the name MPA (Middle Plinian Activity; Karátson et al. 2016), which refers to the characteristic pumice content of the respective volcanic deposits. The latest, most energetic MPA eruption is represented distally by the abovementioned, widely spread tephra cropping out at Târgu Secuiesc. That deposit is part of a complex but well-defined eruption sequence, called "Târgu Secuiesc" (TGS), dated at c. 31.5 ka (Vinkler et al. 2007; Harangi et al. 2010; Karátson et al. 2016; Wulf et al. 2016).

The successive events of the TGS eruption can be interpreted on the basis of analysis of a number of well-preserved outcrops and similar to worldwide analogues. In particular, after the publication of Karátson et al. (2016), a proximal outcrop labelled by those authors MOH-VM (a road cut beneath Vârful Mohoş), has been further excavated (Fig. 3.9), allowing insight into the whole eruption sequence (Kiss et al. 2021). A lava dome started to grow in or around the coeval Sf. Ana crater many years earlier. In the first phase of the TGS events, this dome was destroyed explosively, associated with pumiceous pyroclastic-fall from a plinian/subplinian eruption column. In the vicinity of the twin craters, this event is represented by several metre-thick pumiceous deposit with explosion breccia containing black and reddish (oxidized) lava clasts up to tens of cm large, probably originating from the disrupted lava dome and/or deeper vent rock (see dacite lava clasts in Fig. 3.8).

The second phase of the eruption was a subplinian eruption, associated with a series of dilute pyroclastic density currents (so-called surges) that left stratified or cross-stratified beds 1–2 m

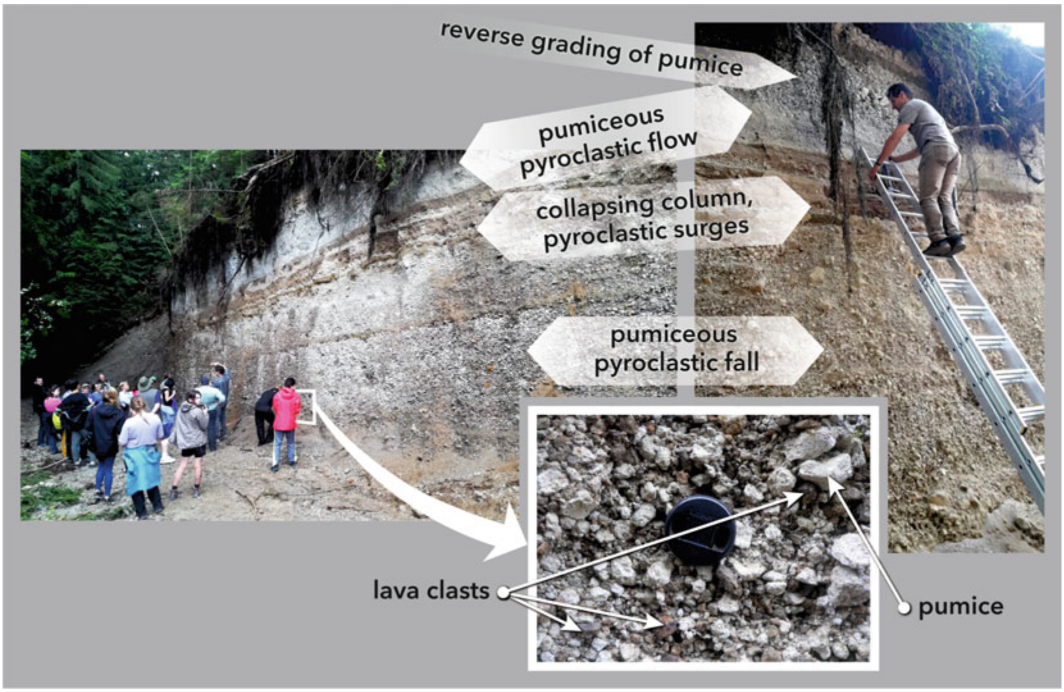


Fig. 3.9 Pyroclastic sequence of Târgu Secuiesc (TGS) eruption near vent (taken at INTAV meeting field trip near Mohoş outlet in 2018). Both photo show the first-phase coarse pumice fall-deposit starting with explosion breccia, covered by the second-phase, stratified pyroclastic-surge deposits, in turn overlain by the third-phase, coarse-grained pumiceous pyroclastic-flow deposit

thick in proximal settings (Szakács and Seghedi 1989; Karátson et al. 2016). 2D textural analyses of several hundred pyroclasts together with 3D tomographic imaging, clast density analysis, and Raman spectroscopy of the groundmass glass, indicate that conduit processes, such as melt degassing and outgassing, changing fragmentation depth, vertical and horizontal heterogeneity in degassing state, and changing crystallinity of the melt had important control on the eruption style, along with changing vent geometry (Kiss et al. 2021). Interaction of magma and external water could have intensified the explosions. It is being examined whether this second eruptive event or the first-phase plinian/sublinian event have deposited the long-known pumice-fallout at the distal location of Târgu Secuiesc, which is 40 cm-thick and contains smaller, cm-sized clasts (also of black and reddish lava).

After some repose time, suggested by an unconformity, the last (third) subplinian and vulcanian eruption phase produced a series of pumice-rich pyroclastic fall and flows, that may have originated from explosion of the partly degassed and frozen magma in the conduit (left from the previous plinian/subplinian phase) due to a newly arriving magma batch (Vinkler et al. 2007; Karátson et al. 2016; Kiss et al. 2021). A quick explosion may have mobilized the conduit material and resulted in vulcanian explosions and pyroclastic flows. These flows rushed down in all directions on the volcano, since the respective deposits, 3–5 m thick, can be found on all flanks except the north, where the high Ciomadul Mare ridge may have acted as a barrier. These pyroclastic-flow deposits are quite characteristic, containing large, whitish grey blocks of pumice with contrasting density (which reflects various degree of degassing and crystallinity), and sometimes bearing charcoal remnants (e.g., near Bixad village).

Spectacular outcrops of pyroclastic surges and flows of the second and third event can be found, for example, on the northeastern flank of Mohoş crater along the trail to Lăzăreşti, nearby in the gorge of Roşu stream at the crater outlet, along Jimbor stream in the south, and east of Bixad village along national road no. 113.

Karátson et al. (2013) raised the hypothesis that there should have been even younger eruption (s) than the TGS, because the c. 27,000 year-old calibrated radiocarbon age obtained on the material from the base of the lacustrine infill of Sf. Ana lake (Karátson et al. 2013, 2016; Magyari et al. 2014) is unambiguously younger than 31.5 ka (with respect to the attached uncertainties of age determinations, see next section). Karátson et al. (2016, 2019) verified this assumption in the field. First, some thin phreatomagmatic layers overlying the second phase units of the Târgu Secuiesc eruption were identified in artificial ravines below Balondoş (Bolondos) Hill and beneath the Belvedere lookout point at Sf. Ana crater. Moreover, the material of the latest tephra has also been recovered from the lacustrine infill of Mohoş (Karátson et al. 2016; Wulf et al. 2016), displaying a different chemical composition relative to the Târgu Secuiesc deposits (see Chap. 5). The sediments overlying the latest tephra obtained from the Mohoş borehole yielded a radiocarbon age of 29.6 ka (29,597 ± 610 cal yr BP). Eventually, Karátson et al. (2019) published a 27.7 ± 1.4 ka K–Ar age obtained on one of the dacite blocks draping the southern rim of Sf. Ana, interpreted to have been ejected from the crater during (one of) the last eruptions.

On this basis, we argue that the final eruption of Ciomadul occurred unambiguously within the past 30 thousand years, i.e., sometime around 28–29 ka. The eruption(s) were once more characterized by lava dome growth followed by its explosive disruption, associated with (or followed by) phreatomagmatic activity. These final eruptive events were summarised as Latest Sf. Ana Phreatomagmatic Activity, LSPA (Karátson et al. 2016). The destroyed dome completely disappeared, and due to the poor preservation of the thin phreatomagmatic tuffs, the eruption s) cannot be reconstructed in more detail at present. However, there can be no doubt that the latest eruption (s) have been violent explosive events, responsible for creating the regular, circular, and quite large crater of Sf. Ana (1600 m in diameter).

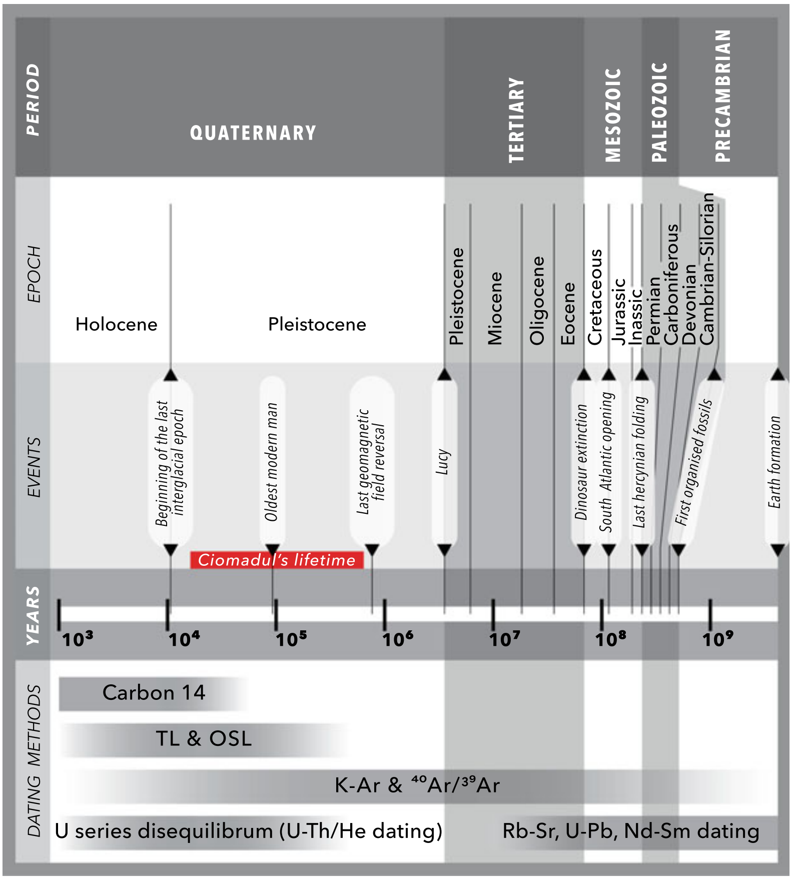
It should also be noted that whereas prior to this final activity several explosive eruptions occurred in a period that lasted for tens of thousands of years or even longer, such activity abruptly stopped at around 28–29 ka. Subsequently, similar to Mohoş, the crater of Sf. Ana went extinct, and since then no eruptions occurred at Ciomadul. In Sf. Ana crater, an extended, continuous history of lacustrine infill has started, which has been lasting up to now and no tephra layers were identified within the sediment column spanning to present day (see Chaps. 9 and 10).

3.5 Dating the Volcanic Rocks—Methods and Results

The geochronological aspects of Ciomadul have already been briefly presented in Chap. 1 due to the gripping research topic that provided exciting, novel results. Here, we think the various methods applied are worth an overview, along with a summary of the specific experience gained at Ciomadul. How does a given dating method work, what materials does it date, under what conditions can it be reliable? Which method should be chosen for a given purpose? Can any results be taken for granted—can any age date obtained be considered indisputable? (Fig. 3.10).

Dating, especially using radiometric methods, yields a unique opportunity to constrain the timing of volcanic activity, even at eruption level. Radiometric dating started at Ciomadul only four decades ago, but even this short time period has been enough to obtain precise age data at hand with relatively low uncertainties in the order of less than tens of thousands of years, and in some cases approaching a thousand-year precision, surpassing previous, poorer, relative (e.g., palaeontological) age estimates with uncertainties of millions of years.

Fig. 3.10 Time-scales of radiometric dating methods indicating Ciomadul's eruptive activity (after Gillot et al. 2009)



When evaluating a single age date we should know that every method is burdened by uncertainties for various reasons. On one hand, there are geological errors (including peculiarities of the collected material, for instance, whether we work with sufficiently fresh, unaltered sample), and analytical errors on the other hand (e.g., issues related to collecting and preparing the sample, separating mineral fractions, and the quality of the applied instrument along with its specification). The latter errors result in a calculated numerical uncertainty. For instance, the Gillot-Cassignol K–Ar age of Haramul Mare, with 1σ (sigma) uncertainty, is 96 ± 2 ka, which means that, if the measured data has a normal (or Gaussian) distribution, the resultant age ranges between 94,000 and 98,000 years with a probability of 68% in any repeat analysis. At 2σ uncertainty, this probability will increase to 95% and, in the given example, to ±4 ka (equalling to a range between 92,000 and 100,000 years).

It is important to note that the analytical uncertainty does not reveal anything about the geological uncertainty, thus a smaller σ value itself does not mean a more "precise" age determination. This statement is to be stressed because a number of studies worldwide show that age dates, depending on the applied method and the quality of the sample, are often controversial—one date does not necessarily overlap with another even with repeated measurements. Therefore, the radiometric methods, which are quite useful in terms of scale with respect to earlier relative methods, can only be applied alongside other investigations, in particular establishing field relationships as well as geomorphological observations, and sedimentological and geochemical correlations.

3.5.1 Morphometric Dating

The morphometric method is mentioned here because it was one of the first used at Ciomadul, with the aim at constraining the ages of the twin craters (Karátson 1996) and later those of lava domes (Karátson et al. 2013). The main point has been the quantification of the 100–150 year-old qualitative statement about the "youthful" shape of Ciomadul landforms (see Chap. 1), by comparing the morphometric features of a given volcanic landform to others with a known age. As an indirect method, the morphometric method is similar to palaeontological (biostratigraphic) dating of sedimentary rocks, which gives the relative age of the bracketing deposits of a volcanic layer mostly on the basis of their fossil content, or using relative stratigraphic correlation, and must be viewed alongside radiometric results. In exceptional cases, there are also fossil-bearing volcanic deposits, which, however, are missing at Ciomadul. Yet, already in the 1970s, biostratigraphic research indicated a likely Late Pleistocene age for Ciomadul (Ghenea et al. 1971).

As for the lava domes, Karátson et al. (2013) compared the morphometric parameters of Ciomadul's domes with other domes worldwide. The authors concluded that the most useful parameter for constraining their ages is the slope angle, in particular that of the upper dome flanks directly below the summit, which indicated some tens of thousands year-old dome landforms for Ciomadul. However, the authors called attention to the fact that some circumstances, especially the young incision of the river Olt and the related accelerated erosion, have made the westward dome flanks anomalously steep. Therefore, morphometry has been useful only to verify the presence of indeed very young volcanic landforms. Later, K–Ar dating has shown that the youngest lava domes have ages of 100–60 ka (see below).

3.5.2 Conventional K–Ar Dating

K–Ar dating is one of the most widely used radiometric methods, and among the first applied to Ciomadul. It is based on the radioactive decay of one of the potassium isotopes, ^{40}K, to an argon isotope, the so-called radiogenic argon marked as $^{40}\mathrm{Ar}^{*}$. This is a time-proportional process, with a half-life of more than one billion years. In volcanic rocks, the radioactive decay can be used for age determination, because during an eruption the argon content of the magma is diminishing due to degassing to the atmosphere (following the change in pressure). After that, when the volcanic rock cools and solidifies, its argon isotope ratio becomes (ideally) identical to that of the atmosphere (99.6% ^{40}Ar, 0.34% ^{36}Ar, 0.06% ^{38}Ar). In other words, this is the "set up" of the radiometric clock, meaning that, with time, the proportion of ^{40}Ar* (at the expense of the radioactive decay of ^{40} K) begins to increase in the volcanic rock. Using the proportion of these two isotopes, and if we know the absolute quantity of the various argon isotopes, we can calculate the age of the rock and thus the eruption age. With the conventional K–Ar method, the isotope quantity is constrained by adding a known amount of a tracer or "spike" isotope (^{38}Ar) to the gas sample to be dated, then the isotope proportion of the sample relative to the atmosphere (which has constant isotope ratio) is measured.

An important feature, however, is that degassing of argon in certain minerals—or argon extraction—is not always perfect. For example, olivine or pyroxene may contain so-called excess argon of magmatic origin, which will render the calculated age older than it should be. On the other hand, it is essential that the dated volcanic rocks behave as a closed system. For example, with alteration, potassium loss can occur, which also makes the radiometric age too old. By contrast, the addition of potassium makes the calculated age younger, and in a similar way, argon loss (due to, for example, subsequent reheating during rejuvenated magmatic activity) also results in a too young age. Considering all these problems, it is highly important to collect fresh rock samples free of secondary alteration effects, which should also be checked in thin slices of rock samples, so-called thin sections, under a petrological microscope.

The conventional K–Ar method can be used for rocks with an age range from several billion years to exceptionally young ages of hundreds of thousands of years. At Ciomadul, apart from an early attempt when I. Casta determined an age of 850 ka for Haramul Mic in his PhD thesis at the University of Marseille in 1980, the method was used first by Pécskay et al. (1992) on a dacite block at Bene stream. The rock sample, probably derived from the Vârful Cetății dome, was dated at around 200 ka. Subsequently, several other domes have been dated (Pécskay et al. 1995; Szakács et al. 2015). The obtained ages, determined in the Nuclear Research Institute of Hungary in Debrecen, yielded a range from 1 Ma (million years) to 200 ka. For example, one of the oldest domes, Puturosu, was dated at 0.71 ± 0.04 Ma (Pécskay et al. 1995), and one of the youngest, Piscul Pietros, at 0.29 ± 0.11 Ma (Szakács et al. 2015, both with 1σ uncertainty).

It is a basic question, however, which mineral fractions of a rock are used for dating—a problem considered but not solved by the above-mentioned authors. Most of the analyses were performed on so-called "whole rock" samples using representative pieces of the rock containing all of their mineral fractions. However, the various mineral phases constituting the rocks may have crystallized earlier, perhaps much earlier than the eruption. In other words, they did not necessarily originate from the fresh magma they are found in, but were inherited from older magmas or rocks that crystallised from those older magmas. This means that the age of a "whole rock" is a mixed age and is often older than the true age of the eruption. The question of how much this affects the "true" age of a rock was considered and studied in detail by Lahitte et al. (2019), using the advanced technique of the Gillot-Cassignol K–Ar method.

3.5.3 Gillot-Cassignol K–Ar Dating

This technique, named after French scientists Pierre-Yves Gillot and Charles Cassignol who developed it, has been used mainly at the University of Paris-Saclay, Orsay (GEOPS) since the 1980s (Gillot et al. 2006). Its main advantage is that even a tiny quantity as low as 0.1% of radiogenic ^{40}Ar* can be discriminated from atmospheric contamination. This is particularly important for young samples, because in the case of very young samples that are only a couple of thousand years old, ^{40}Ar* is below 1% of the total argon content, and still remains below 10%

for a few tens of thousands-year-old sample. Methodological improvements have made it possible to determine the amount of $^{40}\mathrm{Ar}^{*}$, comparing the argon isotope ratio ($^{40}\mathrm{Ar}_{\mathrm{sample}}/^{36}\mathrm{Ar}_{\mathrm{sample}}$) of the sample with that of the atmosphere directly ($^{40}\mathrm{Ar}_{\mathrm{atm}}/^{36}\mathrm{Ar}_{\mathrm{atm}}$), without adding a spike (i.e. $^{38}\mathrm{Ar}$ isotope). Therefore, this technique is sometimes also called "unspiked" K–Ar dating. As a result of the high precision, rock samples as young as a couple of thousand years were successfully dated worldwide.

Considering that the plagioclase, amphibole and biotite phenocrysts of the dacitic lava dome rocks may have crystallized prior to the eruptions, a group of authors of this chapter—led by Pierre Lahitte—focused on the fine-grained groundmass of the rock (the base or matrix of an igneous rock with crystals of various size). The "radiometric clock" in the groundmass starts in theory coevally with the eruption, when the cooling lava is consolidated. For comparison, the main phenocryst minerals have also been dated, and it was verified that amphibole and plagioclase are older by several hundreds or even more than 1 million years, and that biotite is still a couple of hundred thousand years older, than the age of the groundmass of the lava rock. This finding explains well why early conventional K–Ar ages are systematically older than those obtained more recently. (Notably, uncompleted Ar–Ar dating results obtained on biotite separates from pumices, published by Karátson (2007), yielded similarly too old ages of several hundred thousand years, relative to the real eruptive ages.)

The new Gillot-Cassignol K–Ar results are precise enough for splitting the evolution of the volcano into two main stages (Karátson et al. 2019) (Table 3.2). The geographical name Ciomadul–Puturosu Hills makes chronological sense, since the isolated lava domes or dome remnants (sometimes perhaps "necks", vent rocks) in the eastern periphery are up to two or three times older than Ciomadul sensu stricto, the latter spreading over 80% of the whole volcanic area. One of the oldest volcanic centres is Puturosu Hill, which, perhaps surprisingly, is most affected today by post-volcanic phenomena such as sulphur crystallisation from volcanic gases, bubbling pools,

Table 3.2 Geochronology of Ciomadul's lava domes (after Lahitte et al. 2019; Karátson et al, 2019; Molnár et al. 2018, 2019). Uncertainties given in 1 σ

	Cassignol K–Ar age (ka)	(U-Th)/He age (ka)
Dealul Mare (Hegyes-tető)	–	842 ± 53[3]
Puturosu (Büdös)	704 ± 18[1]	642 ± 44[3]
Balvanyos (Bálványos)	641 ± 9[1]	583 ± 30[3]
Balvanyos vicinity	440 ± 12[1]	–
Turnul Apor (Apor-bástya)		344 ± 33[3]
Haramul Mic (Kis-Haram)	245 ± 24[1]	154 ± 11[3], 163 ± 11[3]
Haramul Ierbos (Fű-Haram)	–	156 ± 18[4], 157 ± 11[4]
Vf. Cetăţii (Vár-tető)	184 ± 5[1]	137 ± 9[4]
Vf. Comloş (Komlós-tető)	144 ± 4[1]	–
Ciomadul Mare (Nagy-Csomád)	133 ± 18[1]	–
Ciomadul Mic (Kis-Csomád)	–	122 ± 12[4], 133 ± 8[4]
Haramul Mare (Nagy-Haram)	96 ± 2[1]	95 ± 14[4]
Vf. Mohoş (Mohos-tető)	63.9 ± 1.6[2] (summit)	97 ± 10[4] (base)
Piscul Pietros (Köves Ponk)	60 ± 5[1]	48 ± 6[4]
Sf. Ana southern crater rim (block)	27.7 ± 1.4[2]	–

[1]*Lahitte et al. (2019)*, [2]*Karátson et al. (2019)*
[3]*Molnár et al. (2018)*, [4]*Molnár et al. (2019)*

and mofettes (CO_2 emanations: see Chap. 8). The new K–Ar ages (all with 1σ uncertainty) of this dome remnant and the nearby Balvanyos dome are 704 ± 18 and 641 ± 9 ka, respectively, and represent an early period of volcanic activity when the dormant magmatic system restarted, following earlier eruptions in the adjacent South Harghita Mts. in Pliocene- to early Pleistocene times. Even older is the andesitic dome of Dealul Mare, dated both with the conventional K–Ar (1.02 ± 0,07 Ma; Szakács et al. 2015) and the zircon (U-Th)/He (842 ± 53 ka; Molnár et al. 2019) method (see below).

Furthermore, based on the new Gillot-Cassignol K–Ar ages, timing of volcanic activity of the main part of Ciomadul confirms the previous finding, suggested by comparative lava dome morphometry. Namely, the activity is much younger than determined by conventional K–Ar dating. The oldest dome in this area, Haramul Mic, was dated at 245 ± 24 ka, but since in this case the dating was performed on groundmass plagioclase, an even younger age was assumed (Lahitte et al. 2019). Indeed, Molnár et al. (2019) determined a zircon (U-Th)/He age of 154 ± 16 ka for the same dome. Young ages were also determined for the dacites of the central lava domes. The oldest, Vârful Cetății, has an age of 184 ± 5 k and Vârful Comloş an age of 144 ± 4 ka, whereas Ciomadul Mare is contemporaneous with an age of 133 ± 18 ka. The latter three ages clearly indicate the timing of the main lava dome growth in the central part of the volcano.

Within the past 100,000 years, further domes formed to the north and south of the main dome complex: Haramul Mare (96 ± 2 ka) in the northeast, Vârful Mohoş north of the Mohoş crater rim (64 ± 2 ka), and Piscul Pietros at the southern crater rim (60 ± 5 ka). As mentioned above, the overlapping ages of the latter two domes that are truncated by the subsequent crater rim landform constrain the onset of the final volcanic explosive phase of Ciomadul. Finally, a number of lava domes may have formed within Sf. Ana crater, destroyed as a result of the MPA eruptions. The youngest age of probably the latest dome, based on new Gillot-Cassignol K–Ar dating on a dome rock fragment collected from Sf. Ana's outer crater slopes, is 27.7 ± 1.4 ka.

3.5.4 Zircon (U-Th)/He Dating

The principle of this dating method, recognized and proposed at first by Nobel Prize winner Ernest Rutherford at the dawn of the twentieth century, is the time-related accumulation of helium from the decay of certain radioactive isotopes of uranium and thorium (e.g. ^{238}U, ^{232}Th). However, the slow natural helium diffusion after rock formation may result in a too young calculated age, which made the method languish compared to other radiometric techniques for a long time. Eventually in the 1970s, helium loss was successfully constrained in relation to the subsequent thermal history of a given mineral and rock after formation. This finding established the so-called field of thermochronology, for which the (U-Th)/He method has been proven to be the most useful technique to constrain, via the thermal history of rocks, aspects such as large-scale tectonic movements and erosional processes.

For its application, a candidate mineral selected for dating should incorporate the radioactive uranium and thorium in a sufficient amount, so that the helium accumulated over time can be reliably assessed. Such minerals include zircon, apatite, hematite and magnetite in volcanic rocks, with the most commonly used mineral being zircon. Accumulation of helium, i.e. the start of the "radiometric clock", begins at a temperature or "closure temperature" of a couple of hundred-degrees (°C), which depends on the properties of any given mineral. For zircon, the closure temperature is 150–220 °C, which means that, in case of a volcanic eruption, the calculated age refers to the cooling of the magma below that temperature. For young ages (younger than c. 380 ka), an additional crucial issue is the so-called disequilibrium in the decay of various radioactive isotopes, which affects the amount of accumulated helium. This can be resolved by using specific corrections.

Zircon (U-Th)/He dating of Ciomadul's volcanic rocks has so far been applied to most of the important lava domes and a few pyroclastic deposits (Kiss 2014; Harangi et al. 2015b, 2020; Molnár et al. 2018, 2019), the method being progressively improved. In short, it can be seen that the zircon ages show a great similarity to the Gillot-Cassignol K–Ar ages, but in some cases there are also differences, which cannot be resolved even with consideration of the given analytical uncertainties (Table 3.2). These differences are negligible for the several hundred thousand-year-long evolution of the lava domes, but with respect to the precise "event stratigraphy" of explosive eruptions, they require caution and call for the application and cross-checking of a number of methods, including foremost the establishment of field stratigraphic relationships.

Considering the frequency of volcanic activity of lava domes, the lengths of the eruptive periods and the lulls in between are fundamental questions, which can be assessed mainly with the Gillot-Cassignol K–Ar and (U-Th)/He dating results, as these are among the only dating methods which can be applied to cover the almost 1 million year-long time span of volcanic eruptions at Ciomadul. Whereas the authors of this chapter (Lahitte et al. 2019; Karátson et al. 2019) divide the activity into two stages separated by a dormancy period between approximately 440 and 200 ka (see the section on magma output rates below), Molnár et al. (2019), based on their zircon (U-Th)/He data, distinguish five eruptive stages, with long repose periods in between (at 780–700, 540–380, 300–180 and 80–60 ka). Using this division, these latter authors propose Ciomadul to be a "long dormant volcano".

However, there are some circumstances and published data, which may modify such a conclusion. First, the last 60 to <30 ka explosive phase, as mentioned above, was characterized by several identified and possibly unidentified eruptions with a frequency of a couple of thousand years or even shorter intervals. Taking this into account, there may have well been explosive eruptions during the long lava dome building period of Ciomadul. Thus, the key issue to understand the extended lava dome activity and its temporal division is the preservation of older pyroclastic deposits. In short, the absence of evidence of older explosive activity punctuating the dome-building episodes does not mean it did not exist.

On the other hand, the frequency of dating and its areal coverage should also be taken into account. So far, roughly two dozen localities of lava dome rocks have been sampled, which hardly provides a complete picture of Ciomadul's volcanic history. For instance, Lahitte et al. (2019) determined a 440 ka age on boulders in the vicinity of Balvanyos without constraining their source, which falls right in the middle of the second repose period of Molnár et al. (2019). Therefore, it can be assumed that an increase in the areal coverage of dating efforts in the future will further refine the lengths of activity and repose periods of volcanic activity and lava-dome emplacement in the area.

3.5.5 Radiocarbon (^{14}C) Dating

One of the best known radiometric methods is the so-called radiocarbon method, which is targeting the dating of organic remains and is based on the measurements of ^{14}C, a radioactive isotope of the element carbon, which occurs in tiny quantity in nature. As its half-life is only 5730 years (meaning that 5730 years after an organism dies, half of its ^{14}C atoms have decayed to nitrogen atoms; similarly, in 11,460 years, only one quarter of the original ^{14}C atoms exist; and so forth), it can be applied reliably only for the past c. 50,000 years. However, due to its precision, it is the most effective dating method in history and archaeology.

Contrarily to the stable isotopes of carbon, i.e., the abundant ^{12}C and the rare ^{13}C, the radioactive ^{14}C (i.e. radiocarbon) is produced in the upper atmosphere from ^{14} N due to cosmic ray action. Although its decay is fast, its production is constant, so its quantity is balanced in the Earth's atmosphere. After production, and bounded into CO_2, it is continuously incorporated into living organisms, and the numerically extremely small ratio of $^{14}C/^{12}C$ is maintained during their lifetimes. However, after death, as organic remains, such as wood, charcoal, seeds, leaves, peat, humus, bone and hair, do not incorporate CO_2 any more, the radioactive decay of ^{14}C begins. Thus, using the $^{14}C/^{12}C$ ratio, the elapsed time can be calculated. The resulting physical age is referred to as "before present", where "present" means AD 1950, and is reported as "years BP".

However, in order to attach a real calendar date to this physical age, it is recalculated with the help of international calibration curves that have been compiled using various data bases, including known historical events or by counting and measuring annual tree rings (so-called dendrochronology). The obtained age date is the "calibrated age" and is expressed in years counted backwards from 1950 (cal yr BP). A major consequence of the decay of ^{14}C through time is that relative uncertainty—the ratio between absolute uncertainty and age—for radiocarbon dating increases with time, while it is the opposite for the K–Ar or (U-Th)/He method described above.

At Ciomadul, dating of volcanism with the radiocarbon method can be helpful in three ways.

Firstly, dating of charred plant remains that have been preserved accidentally in the hot volcanic deposits, which may give a direct age estimate of the eruption. This approach was successful in dating the small BTS quarry and the Bixad roadside outcrop (yielding ages of 40,000–42,000 and 31,500 cal yr BP, respectively: Moriya et al. 1996; Vinkler et al. 2007; Harangi et al. 2010).

Secondly, dating of the organic remains in the lacustrine infill of the twin craters. In the case of Mohoş crater, which after its final eruption was occupied by a lake that periodically received deposits of pyroclastic material (tephra layers) as revealed by boreholes, dating the bracketing organic-rich sediments can yield—and already yielded—indirect but highly useful ages of eruptive events (e.g., a 31,500 and 29,600 cal yr BP age estimate obtained on bulk sediment constraining the TGS and LSPA tephra, respectively). By contrast, only one single age date is important for Sf. Ana crater: the maximum age of its lacustrine infill dated at ~27,000 cal yr BP, which is considered as a time constraint for the closing eruptive activity that shaped the current crater (see Chap. 9 for details).

And thirdly, dating of palaeosols of under- or overlying volcanic deposits (in the case of Ciomadul pyroclastic deposits) can also be performed, if they contain organic remains. In fact, this approach, which is also applicable by luminescence dating (see below), could be used for only one outcrop, BTS, where there is a direct contact between an underlying palaeosol and the BTS pumice fall. The dating of the palaeosol (Moriya et al. 1996) yielded concordant ages with that of the charcoal.

Unfortunately, as mentioned above, radiocarbon dating is limited to around 50,000 years BP, and Ciomadul was highly active between 60–30 ka; even ages over 40,000 yrs might be biased. Here, we recall the case of the BTS tephra. The charcoal from its upper pyroclastic units, confirmed by dating the underlying paleosol, yielded ^{14}C ages of 40,000–42,000 cal yr BP. These ages, close to the maximum limit of the method, are contradicted by zircon (U-Th)/He dates of ~50 ka from the lower pyroclastic-fall unit (Harangi et al. 2015b), and by seemingly too young luminescence dates (see below) of 35–40 ka obtained on the under- and overlying colluvial deposits (unpublished dates of the authors of this chapter) (Fig. 3.11). Without solving the dating problem at this peculiar site, we can conclude that such contradictions not only demonstrate the limits of the radiocarbon method, but also the potential problems in interpreting "high precision" ages resulting from any novel methods applied in a volcanic setting, where the discrepancy from the real eruptive age can be far beyond the analytical uncertainty (e.g., in the order of several thousand years for BTS).

Similarly, whereas the upper part of the lacustrine infill of Mohoş crater down to c. 30 ka was successfully dated by the radiocarbon method (see above), dating of the lower, older succession (with an age of probably 50–60 ka) has proven difficult. This might be partly due to volcanogenic CO_2 leakage, which makes the

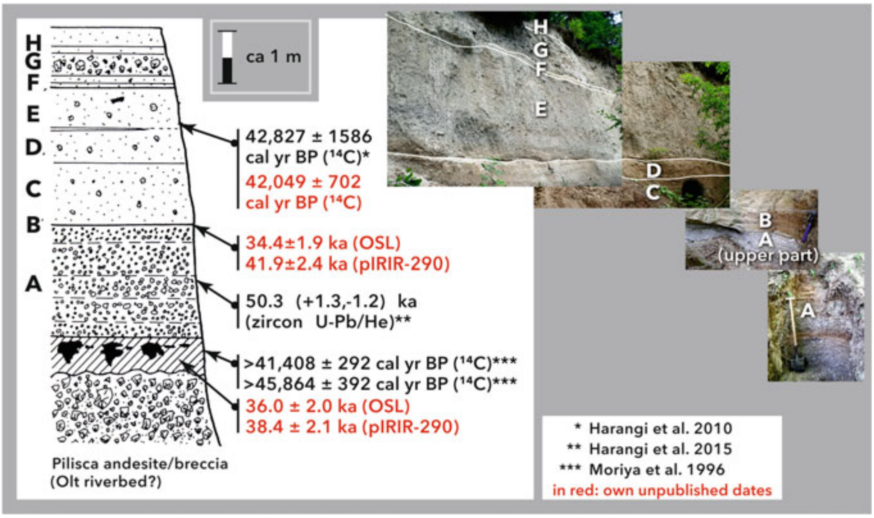


Fig. 3.11 Stratigraphic log and photo-compilation of the pyroclastic sequence of BTS (Băile Tuşnad) eruption, part of the EPPA (Early Phreatomagmatic and Plinian Activity), showing all published (black) and unpublished (red) age estimates. Modified from Moriya et al. (1996), Szakács et al. (2015) and Karátson et al. (2016). A—Plinian pumice-fall sequence, B—reworked colluvium with pumice pebbles, C—finer-grained pumiceous pyroclastic-flow, D, E—coarse-grained pumiceous pyroclastic-flow, F, H—primary or reworked tuff layers from late-stage explosions, G—interbedded debris-flow deposit

radiometric date older than the true age. CO_2 emanation is a frequent phenomenon within active or dormant craters, as can be observed inside Sf. Ana crater even today; the possible methodological treatment of samples affected by volcanogenic CO_2 leakage are dealt with in Chap. 9.

3.5.6 Luminescence Dating

The youngest method of all radiometric-dating techniques is luminescence dating, which has been applied since the 1960s. The method benefits from a peculiarity of certain minerals that, due to the natural ionizing radiation, "trap" electrons in their crystal structure, which are placed in higher energy levels, proportionally with time. If later irradiated artificially, either by heat (thermoluminescence, TL) or light (optical luminescence, OSL) in the lab, the electrons leave their trap and return to the lower energy level, releasing a measurable amount of light (energy).

The best minerals to apply this concept in luminescence dating are quartz and feldspar, and an important prerequisite is that the rock (commonly, a sedimentary rock) to be analysed should not have been exposed to subsequent heat or (sun)light after deposition. Sedimentary deposits (e.g., sand, loess) underlying volcanic rocks, if they contain quartz or feldspar in sufficient quantity, can be good candidates for applying luminescence dating.

So far, the pyroclastic rocks of Ciomadul have been dated by the luminescence method by Harangi et al. (2015b; pumice-fall layer at Târgu Secuiesc) and Karátson et al. (2016; pumice-fall layer at Târgu Secuiesc, and lower tuff and upper pumice unit at Turia). Both TL and OSL techniques have been applied, in all cases on bracketing sediments. Recently, Harangi et al. (2020) published repeated age determinations on samples from some key localities in Karátson et al. (2016). The obtained data show a good agreement, and, as mentioned above, help constrain the Turia tuffs to around 50 ka, and the TGS eruption at 31.5 ka.

Apart from these results, there are also unpublished age estimates obtained by the authors of this chapter, which are worth briefly presenting here. First, some 20 km south of Ciomadul, a large, active sand quarry in the vicinity of Ghidfalau exposes tephra layers, overlain by thick loessy colluvial strata. Dating the sediments right below the tephra yielded a preliminary age of >130 ka, which seems to support the occurrence of early explosive activity of Ciomadul (also see Chap. 6).

The second locality is the Sânmartin quarry, which reveals two tephra layers that were related to the 40–42 ka BTS eruptive sequence based on geochemistry (Karátson et al. 2016). The tephra layers yielded significantly younger ages both with the radiocarbon (34,000–35,000 cal yr BP minimum age of underlying palaeosol) and zircon (U-Th)/He (29.5 ka) method (Harangi et al. 2020), although it should be noted that the dated zircon grains show a large scatter from 60 to 30 ka. By contrast, unpublished luminescence ages obtained by Ágnes Novothny from both the under- and overlying sediments yielded an average age of 42 ka, in good agreement with the BTS age suggested by Karátson et al. (2016). In particular, the identical results of OSL dating on quartz (41 ka) and TL dating on feldspar (43 ka), with an uncertainty of ±2 ky each, should be emphasized.

3.6 Eruptive Activity: Long Term Versus Short Term Eruption Rates

The Gillot-Cassignol K–Ar ages of individual domes, along with zircon (U-Th)/He ages, make it possible to draw conclusions with respect to Ciomadul's long-term volcanic evolution (Karátson et al. 2019) (Fig. 3.12).

The long-term magma output rate of Ciomadul considering its whole life span is 9.7 km^3/Ma (or 0.0097 km^3/ka). Regarding the volume calculations of the lava domes, this average magma output includes two contrasting evolutionary stages. During the first, longer stage (lasting from c. 850 to 440 ka), the south-eastern domes were emplaced, representing only 5% of the total volume. The magma output rate calculated for this period is 0.0012 km^3/ka. After c. 200 ka, however, this low rate changed dramatically, and most of the domes were formed, on average, at a 30-fold rate of 0.0374 km^3/ka. This latter value can be considered very high in a worldwide comparison, since it exceeds the average rate of similar volcanic systems by 10–15 times (e.g., White et al. 2006). At the same time, this intense magmatic period, lasting from 200 to 30 ka, can be considered as the last outburst, making an exception with regard to the long-term

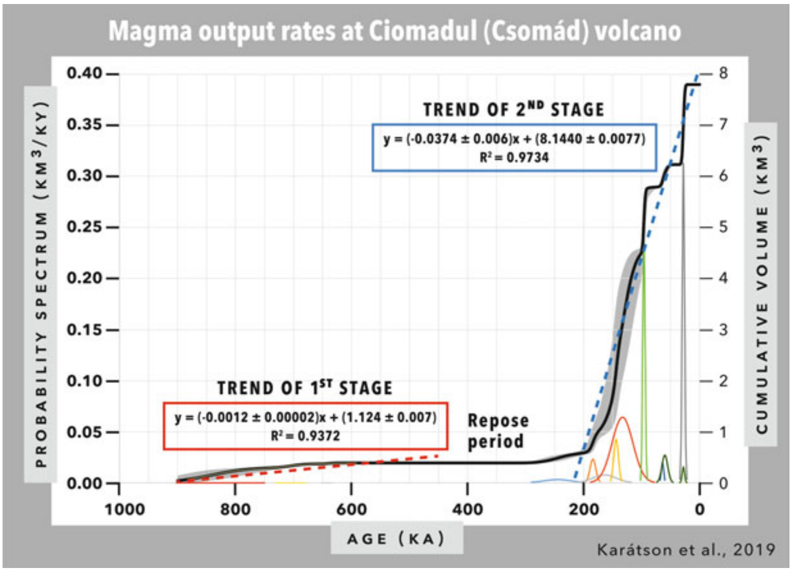


Fig. 3.12 Two stages of Ciomadul's long-term eruptive history as reflected by contrasting magma output rates (Karátson et al. 2019). See text for discussion

decreasing trend in magma production along the East Carpathians along its 10 million year volcanic history (e.g., Dibacto et al. 2020).

Certainly, even a 0.0374 km^3/ka magma output rate is a low value, if individual dome-forming extrusion rates are considered. Considering the observed eruptions of active lava dome volcanoes worldwide, they can be emplaced with a 0.1–0.5 km^3 volume in a few years, tens of years, or no more than one hundred years. For example, Merapi volcano in Java, which has had a persistent eruptive activity since 1786, produced extrusion rates as high as 30 m^3/s during its 2010 eruption (corresponding, theoretically, to 900,000 km^3/ka), while for its last, highly active, one hundred-year-long period, an average rate of 100,000 m^3/month has been calculated (corresponding to 1.2 km^3/ka; Siswowidjoyo et al. 1995).

On this basis, to obtain a rate that typifies the last 200 ka activity of Ciomadul, and assuming the hundred-year average rate of the lava dome complex of Merapi (Java, Indonesia), there were 30 times longer repose periods between the active periods. The reality, however, could have been more diverse, for instance by periods of modest lava dome growth punctuated by low growth and minor to moderate explosive eruptions. At the moment, an even more detailed calculation of Ciomadul's eruptive history is impossible due to the limits of the current dating methods and distinguishing most individual lava domes, although developments in various techniques may result in constraining and dating single eruptions in the future.

3.7 Summary—Volcanic History in the Light of Landscape Evolution

Subsequent to the emplacement of isolated lava domes in the vicinity and that of the late-stage dacites of Pilişca volcano, Ciomadul volcano started to form on the slightly westward-dipping surface of flysch rocks east of the Olt river (Fig. 3.13). Thus, when Ciomadul's eruptions began, the 1.5–2 million year-old main edifice of Pilişca already existed, which may have been coeval with the subsidence of the adjacent, transtensional Lower Ciuc Basin (Fielitz and Seghedi 2005).

Ciomadul's eruptive history is summarised below based on the work of Karátson et al. (2016, 2019) and Lahitte et al. (2019). The first stage of lava dome formation occurred in the east, lasting from c. 850 to 440 ka (Fig. 3.13a). First, the oldest dome, Dealul Mare, then the much smaller domes of Puturosu and Balvanyos were emplaced. Even if long-term erosion since then is considered, their total volume, which remains below 0.5 km^3 at present, could not have been large. The basal lavas of the western part of present-day Ciomadul may also belong to this stage, namely, the lower part of Vârful Surduc, represented by the Turnul Apor lavas dated at 344 ± 33 ka by the (U-Th)/He method (Molnár et al. 2019). Temporarily, the volcanic products of the first stage may have dammed the Lower Ciuc Basin. This Late Quaternary basin already hosted a lake, which had been filled with sediment, and now, due to Ciomadul's new activity, was probably re-created.

The process of formation of a dammed lake may have accelerated when the second volcanic stage began c. 200 ka ago. From north to south, the subsequent lava domes of Haramul Mic, Vârful Cetăţi and Vârful Surduc, then Ciomadul Mare, formed within a hundred thousand year-long period, establishing the main, central Ciomadul dome complex with a total volume of almost 7 km^3. The growing domes completely dammed the Lower Ciuc Basin (Fig. 3.13b), followed by the appearance of the river Olt and the incision of the Tuşnad Gorge. Such a landscape evolution is suggested by describing older terrace gravel underlying the BTS tephra (Szakács et al. 2015) and verified by the 123 ± 11 ka luminescence age of the oldest (fourth) river terrace of Olt, which is only slightly younger than the 180–130 ka lava domes facing the river (the terrace age was obtained some 30 km south of Sfântu Gheorghe by Necea et al. 2013). The main lava dome activity was terminated by the emplacement of the most spectacular, regular-shaped Haramul Mare dome less than 100 ka ago (Fig. 3.13c).

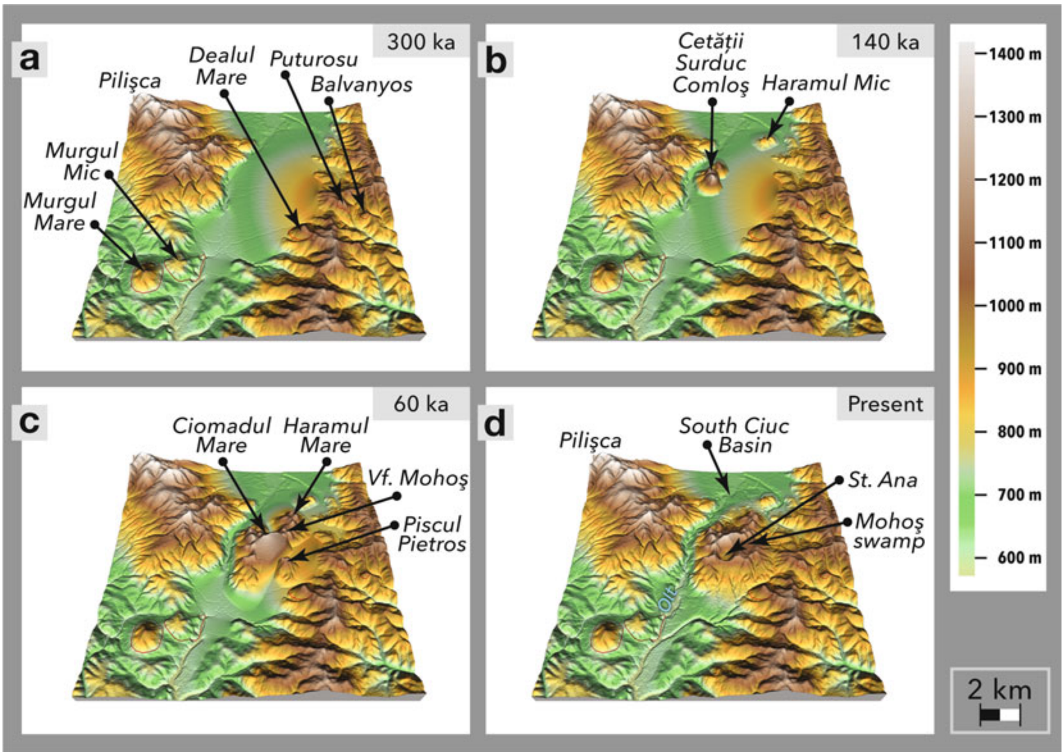


Fig. 3.13 Palaeo-geomorphic evolution (**a**–**d**) of Ciomadul shown by successive DEM reconstructions (Karátson et al. 2019). **a** At ~300 ka: only the southeastern peripheral domes exist, which formed between ~850–440 ka. **b** At ~140 ka: subsequent to the emplacement of Haramul Mic (~200 ka), formation of the western domes takes place. **c** At ~60 ka: subsequent to the emplacement of the central dome complex (Ciomadul Mare, ~130 ka), formation of the small domes of Vf. Mohoş and Piscul Pietros at ~65–60 ka, followed by the early formation of Mohoş crater truncating Piscul Pietros. **d** Final explosive phase (~51–28 ka) which results in the current twin-crater morphology of Mohoş and St. Ana

The lava dome activity spanning hundreds of thousands of years may have been accompanied by explosive activity to an extent which is practically untraceable today. In some cases, supported by a luminescence age obtained in the Ghidfalau sand quarry (see Chap. 6), old tephra layers can be identified over the last c. 150 ka, but even older pyroclastic deposits may frequently lay buried within rivers terraces and basin sediments, thus outside of our reach today. In this respect, formation of the "truncated" northern rim of the twin craters, marked by the Ciomadul Mare dome, may be connected to an early explosive eruption as speculated by Karátson et al. (2013). What is certain, however, is that the explosive activity of Ciomadul increased and became predominant at around 50–60 ka. Phreatomagmatic ("Turia eruptions", ≥50 ka) and magmatic ("BTS eruptions", 40–42 ka) explosive eruptive events closely followed each other. Initially, the source vent of these eruptions may have been the Mohoş crater, probably reshaped several times through the eruptions. Following these eruptions, a new vent opened to the west, the ancient Sf. Ana crater. Final shape of Mohoş crater was formed subsequent to c. 60 ka, as evidenced by the age of the Piscul Pietros dome, which is truncated by the crater rim. The BTS eruptions may have already originated from a Proto-Sf. Ana crater.

During the last tens of thousands of years of activity, intense downcut of the river Olt happened. Geomorphological, sedimentological and stratigraphic observations point to a very energetic fluvial downcut with laharic (debris flow) events, as indicated by the presence of very large boulders weighing several tens of tons in the sand quarries in the south (e.g., at Ghidfalau and Sf. Gheorghe, 20–25 km away from Ciomadul: Chap. 6).

Toward the end of Ciomadul's volcanic activity, at around 31.5 ka, a violent (plinian/subplinian and then vulcanian) eruption occurred, called "TGS". The complex eruption started with the explosive disruption of a lava dome which had possibly been growing for thousands of years in the coeval Sf. Ana crater. The first magmatic explosions resulted in pumice-fallout and explosion breccia near the vent. In a later phase of the eruption, pyroclastic surges and, subsequently, peculiar pyroclastic flows rich in pumiceous blocks and ash rushed down in almost all directions, leaving behind several metre-thick deposits that can be identified on the outer flanks of the twin craters.

The most recent activity of the volcano recognized so far took place a couple of thousand years later, at c. 28–29 ka (Fig. 3.13d). Most likely, this eruption also started with a dome explosion from Sf. Ana crater, followed by phreatomagmatic explosions that deposited thin tephra layers draping the landscape. The latter is covered all around by the recent, Holocene soil.

4

Petrology of Ciomadul Volcano: The Rock Record

Alexandru Szakács and Ágnes Gál

Abstract

The careful study of volcanic rocks can help us understand not only what processes occur with the crust, such as magma evolution and migration, but also surface processes that influence, for example, the violence of volcanic eruptions. In this chapter, we explore the volcanic products of Ciomadul (Csomád), examining their macro- and microscope properties, such as rock-forming minerals, textures, and geochemical composition. Considering this evidence, we present the petrogenetic origin of these rocks, focusing on the succession of natural processes from magma generation to volcanic eruption, as well as on the geodynamic context of these processes.

4.1 Introduction

Ciomadul was subjected to research scrutiny during at least the last two centuries by scholars attracted by the youthful volcanic landscape of the area, suggesting the occurrence of the most recent volcanic activity in the East Carpathians. Petrography—the detailed describing of rocks—was among the earliest-addressed subject in the volcano's research. Before scientists came to examine them, the local Hungarian people realized that the rocks constituting the steep-sloped mountains hosting the Mohoș (Mohos) swamp and the Sf. Ana (Szent Anna) lake were different from those found in the neighbouring area and used particular names to distinguish them. For example, "*darázskő*" (meaning "wasp rock") was used for the coarse-grained, porous, grey to pinkish-coloured, and seemingly useless, volcanic rock, whilst "*köszörűkő*" (meaning "razor rock") was used for the grey, finer grained, homogenous sandstones of the Cretaceous Flysch deposits, used for sharpening their grass-cutting tools. Following the nomenclature of the time, the earliest researchers of the area, such as Hauer and Stache (1863) designated the volcanic rocks of Ciomadul as "*trachytes*" according to a macroscopic examination, revealing a porphyritic texture with phenocrysts of feldspar, biotite, and amphibole. Later, microscopic investigations by Lazăr and Arghir (1964) revealed the composition of the groundmass, composed of much smaller crystals of the same type as the phenocrysts (feldspar, biotite, and amphibole) alongside some subordinate, accessory minerals such as zircon, apatite, Fe-oxides, and occasionally pyroxene and even quartz, besides the glassy component. Such a composition, as well as the lack of alkali-feldspar, led the researchers to identify the Ciomadul rocks as "*andesites*".

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This nomenclature (e.g. *amphibole-biotite andesite*) persisted until the 1980s when statistically significant geochemical data became available, allowing for a composition-based rock identification in accordance with the IUGS Recommendations on igneous rock nomenclature (see Le Bas et al. 1986). Consequently, the nomenclature of the Ciomadul rocks changed from "andesites" to "dacites" (Szakács and Seghedi 1986). However, there is one exception in the case of the Dealul Mare (Hegyes-tető) dome, whose rocks were identified on the basis of their geochemistry as "andesites" (Szakács and Seghedi 1986). Further geochemical studies pointed out that these rocks belong to the high-K calc-alkaline series of volcanic rocks so that "*high-K dacite*" or "*high-K amphibole-biotite dacite*" became the most accurate name for Ciomadul volcanic rocks (Seghedi et al. 1987). It is worth mentioning that, because of the same studies, the nomenclature of the rocks belonging to the two isolated lava domes of Murgul Mic and Lüget, located south of Ciomadul, also changed from "*basaltic andesite*" (e.g. Szőke 1963; Lazăr and Arghir 1964) to "*shoshonite*" (Seghedi et al. 1987).

These findings, together with the recognition of the high-K calc-alkaline nature of some more rocks occurring at nearby volcanic edifices, allowed researchers to contextualize Ciomadul in a regional trend of geochemical changes along the whole Călimani-Gurghiu-Harghita (Kelemen-Görgényi-Hargita range, CGH hereafter), and particularly along its southeasternmost segment, the South Harghita (Szakács et al. 1993). The most recent development in the evolution of rock nomenclature for Ciomadul volcano has been the recognition of an "*adakite-like*" geochemical signature of the South Harghita volcanic rocks, including Ciomadul. This observation is particularly relevant for unravelling magma genesis and evolution not only at Ciomadul but along the whole CGH range and even at a wider, regional scale in the Carpathian-Pannonian Region (Seghedi et al. 2004).

4.2 Petrograpy of the Ciomadul Volcanic Rocks

4.2.1 Macroscopic Description

The macroscopic appearances of volcanic rocks of Ciomadul display various aspects according to their genesis and the type of eruptive product they form: effusive or explosive. Although all of them are of dacitic composition (with one exception), their physical properties (e.g. colour, density, porosity) and general compositional characteristics (e.g. mineral content), which can be observed by naked eye, are variable.

4.2.1.1 Lava Dome Rocks

The dacites of the Ciomadul lava domes are light to dark grey to pinkish-brown with a conspicuous porphyritic texture, where the phenocrysts (and some of the groundmass) are readily distinguishable through macroscopic examination (Fig. 4.1). The dome dacites are generally crystal-rich and medium- to coarse-grained, with phenocrysts up to 2.5–3 cm in size occupying

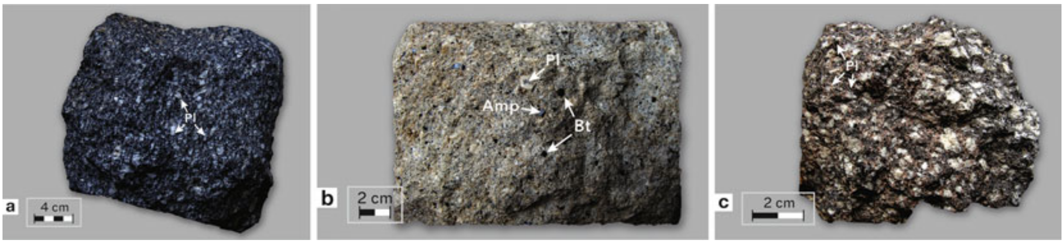

Fig. 4.1 Hand specimens of the Ciomadul dome dacites **a** dark grey dacite with glassy groundmass **b** light-coloured dacite with holocrystalline, light-coloured or felsic groundmass **c** brownish-red dacite with oxidized hyalopilitic groundmass. Large plagioclase (Pl) and small amphibole (Amp) phenocrysts are visible along with a few pseudohexagonal biotite crystals (Bt)

more than 20% of the bulk rock. Some crystal-rich lava dome rocks display a dark-coloured glassy groundmass (Fig. 4.1a). Textures in the Ciomadul dacites vary from slightly porous to compact. In general, the lava dome rocks are much less porous than the pyroclastic ones.

The Ciomadul lava dome rocks are typically massive, showing no oriented fabrics or textures (such as alignment of vesicles). However, in some cases, flow-banding or the alignment of crystals, is present, highlighted by subtle colour changes in the groundmass.

Due to their coarse crystal-size, phenocrysts of feldspar (up to 2.5–3 cm), biotite (up to 6–8 mm), and amphibole (rarely exceeding 5 mm in length) are readily recognizable in the case of almost all Ciomadul dacites (Fig. 4.1). White plagioclase feldspar is the most abundant and largest phenocryst phase of the lava dome dacite, displaying well-formed crystal shapes (Fig. 4.1). The second most readily observable and largest phenocryst are those of biotite, displaying pseudohexagonal, flaky crystals that are black to brownish in colour and moderately shiny. Amphibole is much smaller, showing up as shiny black needles a few mm in length, seen best with a hand lens.

Most Ciomadul dome dacites are fresh (i.e., not altered by hydrothermal activity) except for some surficial alteration visible in places (i.e., weathering). Puturosul Hill, representing the conduct-close remnants of a lava dome, is the only occurrence of strongly altered dacite due to fumarolic transformations rendering the rock a whitish appearance with the original textural, structural and compositional features obscured.

4.2.1.2 Pyroclastic Rocks

Products deposited from explosive eruptions occur either as primary pyroclastic rocks (Chap. 3) or secondary epiclastic (i.e. reworked/resedimented) deposits (Chap. 6). They consist of particles of various size, colour, porosity and composition, which can roughly be grouped into three genetic classes: (1) pumice (light-coloured centimetre- to sub-centimetre-sized, highly porous pieces of degassed magma generated in plinian-type eruptions: see Chap. 3), (2) bread-crust bombs/blocks (decimetre-sized pieces of viscous magma from the partially or totally solidified outer crust of a forming lava dome disrupted by a vulcanian-type explosive episode) and (3) lithic clasts (explosion-disrupted pieces of former lava-dome (or other) rocks entrained in the forming pyroclastic deposit, as presented in Chap. 3).

The pumice-rich dacitic pyroclastic rocks spatially associated to the dome complex are much finer-grained (i.e. smaller-sized minerals) than the dome rocks and their colour is determined by the presence and abundance of white to light-grey pumice clasts.

Pumice—The light-coloured pumices are crystal-poor components of the pyroclastic rocks. Pumice porosity of Ciomadul volcanic rocks was first studied by Lazăr and Arghir (1964), who pointed out porosity values in the range 15–55%. Vinkler et al. (2007) described two macroscopically distinguishable types of pumice: (1) low-density light-coloured, higher-porosity pumice and (2) pumice with a higher-density that is less porous and greyish-coloured. Pumice density was also investigated by Karátson et al. (2016). They found a density range of 1.15–2.50 g/cm^3 showing a continuous variation with most pumice clasts having densities of 1.3–1.8 g/cm^3 (Fig. 4.2).

Bread-crust blocks/bombs—The bread-crust blocks show a fine network of narrow (mm and sub-mm wide) and shallow (mm-deep) surface

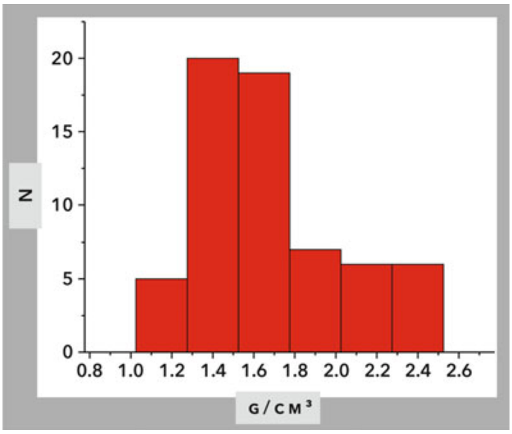

Fig. 4.2 Density distribution histogram of Ciomadul pumice clasts showing a quasi-unimodal distribution with a frequency maximum at 1.3–1.5 g/cm^3. Data from Karátson et al. (2016)

fissures with no textural difference between rim and core. By contrast, the bread-crust bombs display much wider and deeper (cm-sized) surface cracks and contrasting rim and core features (colour, texture and porosity) as described by Szakács and Jánosi (1889). Phenocryst-poor (more glass-rich or even purely glassy) dark-coloured dacite is found in the rim parts of breadcrust bombs (Fig. 4.3). Large porosity variations are recorded across the dm-sized breadcrust bombs displaying highly porous internal structure, sometimes with gradually decreasing pore sizes towards the exterior, and compact non-porous rinds (Fig. 4.3) (Szakács and Jánosi 1989). Both massive and oriented (fluidal) textures were observed in the bread-crust blocks/bombs.

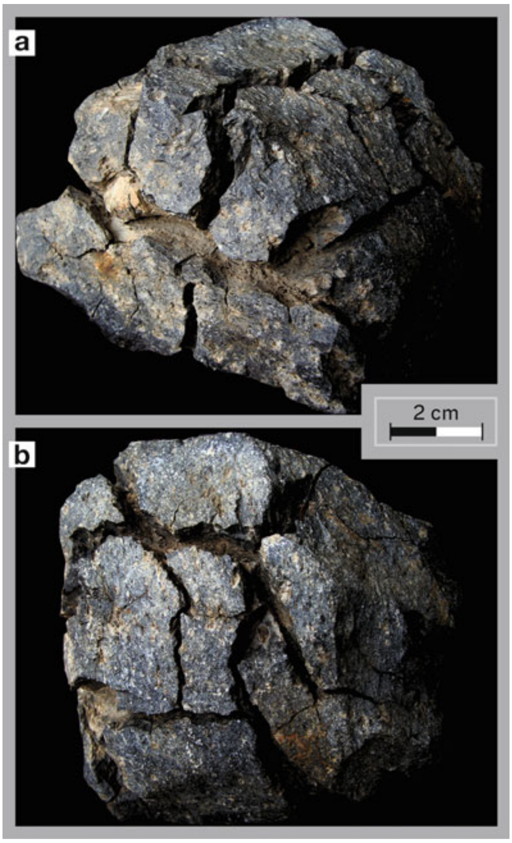

Fig. 4.3 Breadcrust bombs (a, b) showing a dark-coloured compact glassy rind, formed by rapid cooling, and a light-coloured porous interior, formed by slower cooling and degassing. Specimens found in a valley bottom on the southern slopes of Ciomadul volcano

Lithic clasts—These display the macroscopic features of the lava dome rocks as described in the previous section.

4.2.2 Microscopic Description

The microscopic petrographic features of the Ciomadul rocks presented below are compiled from several published papers (Lazăr and Arghir 1964; Szakács and Seghedi 1986, Vinkler et al. 2007; Kiss et al. 2014). The optical microscopic petrography was very much focused on the lava domes, whereas components of pyroclastic rocks, such as pumice clasts, breadcrust bombs and lithic clasts, were studied in much less detail. Based on the recognition of two types of amphiboles, Lazăr and Arghir (1964) distinguished "andesites with green hornblende" and "andesites with basaltic hornblende" and provided detailed descriptions of both types.

4.2.2.1 Phenocrysts

Kiss et al. (2014) described a large spectrum of phenocryst phases in the lava dome rocks, comprising 30–40% of their volume, including plagioclase, amphibole, biotite, clinopyroxene, quartz, alkali-feldspar, and olivine (in the order of their respective abundancies).

Microscopically (Fig. 4.4), **plagioclase** is also the most frequent phenocryst, being represented by two types of crystals, namely larger, frequently aggregated crystals in glomerocrysts, and a population of much smaller, well-formed (euhedral) crystals (Fig. 4.4a–c). Some of the larger plagioclase phenocrysts display sieve-textures due to the presence of abundant volcanic glass inclusions (Fig. 4.4g).

Amphibole is the most common mafic phenocryst phase. Kiss et al. (2014) in their detailed study distinguished two major amphibole types according to their optical features: euhedral to subhedral dark brown-reddish brown amphibole with no zoning, and light brown-yellow zoned amphibole corresponding to the "basaltic hornblende" and "green hornblende", respectively described by Lazăr and Arghir (1964) (Fig. 4.4a–c).

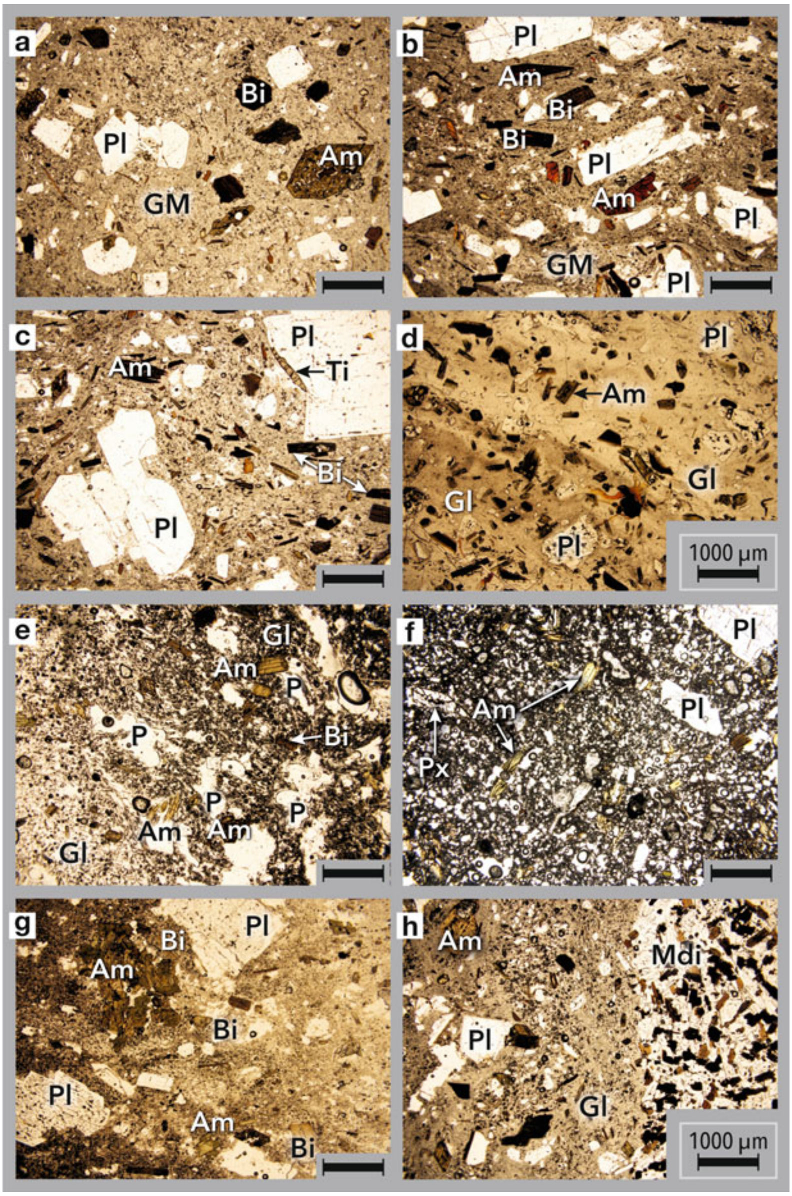

Fig. 4.4 Photomicrographs of typical Ciomadul rocks (lava dome dacites and pumice) viewed with parallel nicols. **a** Typical Ciomadul dome dacite with euhedral amphibole, biotite and euhedral to subhedral plagioclase phenocrysts set in a massive, hyalopilitic groundmass; note the presence of a biotite inclusion in the centre of a euhedral amphibole phenocryst (middle right). **b** Dome dacite with fluidal groundmass draping around a plagioclase phenocryst (lower right). **c** Dome dacite with large plagioclase phenocrysts and small-size, slightly oriented amphibole and biotite crystals. Note the titanite accessory phase adjoining the large plagioclase in the upper right. **d** Finely porphyritic compact bread-crust bomb-rind dacite with fluidal glassy groundmass; the amphibole is of the "green hornblende" type. **e** Highly porous pumice clast with two generations of degassing voids and a porphyritic texture, characterized by small-sized "green hornblende" and biotite microphenocrysts; slight orientation of glass is visible. **f** Uniformly porous pumice clast with microphenocrysts of plagioclase, amphibole, biotite and a single orthopyroxene (lower left corner). **g** "Green hornblende"-type amphibole crystal clot (upper left) in porphyritic dome dacite, sieved-textured plagioclase phenocrysts in the upper middle and lower left, and isolated groundmass amphibole microlites of the "brown hornblende" type. **h** Contact of dome dacite with microdiorite enclave (right third) consisting of equigranular plagioclase, amphibole and biotite crystals. Note the finer porphyritic glassy texture of the dacite close to the contact. Amphibole crystals are of the "brown hornblende" type in both dacite and microdiorite. Abbreviations: Pl—plagioclase feldspar; Amp—amphibole; Bt—biotite; Ttn—titanite; Cpx—clinopyroxene; Gl = volcanic glass; GM—groundmass; P—pore space; Mdi—microdiorite. *Photo credit*: Ralf Gertisser

Euhedral, pseudohexagonal to subhedral **biotite** phenocrysts are the second most abundant mafic phase occurring as yellow to dark brown flakes. The presence of **quartz** phenocrysts in part of the dome rocks was pointed out by Szakács and Seghedi (1986), whereas Kiss et al. (2014) describes them as a ubiquitous component of the Ciomadul dome dacites. They show obvious resorption features such as rounded outlines, embayments and reaction rims. Interestingly, as both authors observed, quartz is present only in samples where pyroxene and, occasionally, olivine, is also present. Some **alkali-feldspar** phenocrysts showing the same resorption features were identified in the lava domes (Kiss et al. 2014). Anhedral **olivine** crystals with reaction rims were also noted by Kiss et al. (2014) in a few samples of dome dacite. **Clinopyroxenes** (augite) usually form crystal aggregates, but they also appear as single crystals. They have euhedral or subhedral habit and show various internal zoning. It is often observed that clinopyroxene crystals have rounded edges and are overgrown by amphibole crystals. The presence of aggregates is a common feature of the Ciomadul dome dacite described in detail as "crystal clots" by Kiss et al. (2014) who distinguished felsic and mafic varieties. The felsic ones are described as a "microdiorite" (plagioclase, amphibole, biotite ± alkali-feldspar ± quartz, and accessories—titanite, zircon, and apatite) (Fig. 4.4g, h). The mafic clots consist of clinopyroxene or olivine or both with minor amounts of plagioclase.

Accessory minerals are mostly represented by apatite, with subordinate zircon and titanite (Fig. 4.4c).

4.2.2.2 Groundmass

The groundmass of the lava dome dacites is typically glassy, with some small crystals (i.e. microlites, commonly <0.1 mm) of plagioclase amphibole and biotite microlites, Fe–Ti oxides, and a silica phase, probably tridymite (a high temperature variant of quartz) (Fig. 4.4a–c). In addition, Mason et al. (1995) noted alkali-feldspar as a groundmass component at Ciomadul volcano. This type of microfabric is known and described as hyalopilitic texture. The glass-microlite ratio is variable. Amphibole is more abundant than biotite in the groundmass (Fig. 4.4b, c). Both massive and oriented groundmass textures were found; needle-shaped amphibole microlites and small biotite flakes are oriented (Fig. 4.4b, c) or, in places, groundmass glass displays flow-orientation features (Fig. 4.4 b). Most of the breadcrust bombs' outer rim display a glassy fluidal texture (Fig. 4.4d).

4.2.2.3 Pumice Petrography

According to Lazăr and Arghir (1964), Ciomadul pumice is composed of 85–95% groundmass (including glass, microlites and pore volumes), 3–7% plagioclase, 1–6% amphibole and 0.2–1.7% biotite. According to these authors, pumice clasts of the pumice-bearing pyroclastic rocks consist of 60–70% volcanic glass besides c. 12% phenocrysts, the difference being represented by microlite and pore volumes (Vinkler et al. 2007). The two pumice types distinguished by Vinkler et al. (2007) (i.e. a more porous and white-coloured, and a denser, light grey-coloured one) are characterized by two generations of degassing voids of bimodal size distribution (Fig. 4.4e), and a single-generation porosity (Fig. 4.4f), respectively.

The phenocryst and microlite assemblage consists of three size-categories of plagioclase, amphibole and, to a lesser extent, biotite (Fig. 4.4e–h). The largest-sized plagioclase phenocrysts are partially resorbed, zoned and sieve-textured with abundant glass (i.e. silicate melt) inclusions indicating partial re-absorption of the mineral. Most amphiboles are greenish-coloured and zoned (Fig. 4.4e, f), with some of them showing resorbed pyroxene cores, while others contain inclusions of tiny plagioclase and biotite crystals as well as glass.

4.3 Geochemistry of Ciomadul Volcanic Rocks

4.3.1 Mineral Chemistry

Information on the chemical composition of rock-forming minerals of the Ciomadul dacites was obtained in the 1990s and presented in various studies addressing broader aspects of the CGH range (e.g. Mason et al. 1995, 1996). However, Ciomadul is represented sparsely and unevenly in those studies. Ciomadul-focused mineral-chemical investigations were performed by Kiss et al. (2014) on dome dacites and Vinkler et al. (2007) on pumice. The following data are compiled from these authors.

4.3.1.1 Lava Dome Dacites

Plagioclase phenocrysts and microlites in the groundmass show a similar compositional range, generally overlapping, but with lower An-content in the cores of the phenocrysts (34 ± 8 mol.% An) than those of the microlites (52 ± 4 mol.% An). Amphibole in the Ciomadul dome dacite shows a large inter-crystalline variability of both major elements (6.4–15 wt.% Al_2O_3; 9.3–17.6 wt.% MgO) and trace elements (20–500 ppm Ba; 100–800 ppm Sr). Two major amphibole phases were identified: hornblende and pargasite, both belonging to the Ca-amphiboles group. The low-Al amphiboles are mostly Mg-hornblendes (although a few edenites also occur), whereas the high-Al varieties are pargasites (with few Mg-hastingsites also identified). Hornblendes show high MnO and low TiO_2 and Na_2O contents, with low Al/Si (0.19 ± 0.02) ratio. They also contain low Ba, Sr, Zr and display a negative Eu anomaly. In contrast, pargasite has high TiO_2, Na_2O, and MnO contents, with high Al/Si ratio (0.33 ± 0.03). They are also rich in Al, Ba, Sr, Zr, and shows no negative Eu anomaly. Intra-crystalline variability of amphibole is also large, in cases as large as the whole variation of the phenocrysts. It should be noted that the same bimodal distribution of amphibole compositions is recognized in both explosive (i.e. pumice) (Vinkler et al. 2007) and effusive (i.e. dome dacite) rocks (Kiss et al. 2014).

4.3.1.2 Pumice

Plagioclase compositions in pumice clasts show a wide range (20–65 mol.% An), but intermediate, andesine compositions (35–55 mol.% An) are by far the most frequent (Vinkler et al. 2007). Based on a larger number of samples, Harangi et al. (2020) published Ciomadul pumice plagioclase compositions in the range 16.3–51 mol % An. The mafic phenocryst assemblage-dominating amphiboles fall, when plotted in the amphibole-diagnostic diagram (Leake et al. 1997), into the fields of edenite, magnesio-hastingsite, magnesio-hornblende and pargasite showing a large compositional variability. For example, Al_2O_3 is in the range 5.59–13.74 wt.%. Similar figures. (6–12 wt.% Al_2O_3) are reported in Harangi et al. (2020). Moreover, important compositional variability of amphibole (in the range of 3–4% Al_2O_3 and 4–6% of MgO) was pointed out even within single crystals. Pumice micas were determined as biotite (<15 wt.% MgO) and phlogopite (16–18 wt.% MgO) (Vinkler et al. 2007). Pyroxenes, mostly Mg-rich orthopyroxene (i.e. ferro-enstatite), appear in pumices only in the nucleus of some amphibole crystals. Rare clinopyroxene overgrowths on orthopyroxene nuclei show Mg-rich augite compositions (Vinkler et al. 2007). Two olivine grains (79–82 mol.% Fo) were also observed in one large pumice clast sample, also in the centre of an amphibole crystal (Vinkler et al. 2007).

4.4 Bulk-Rock Geochemistry of Ciomadul Volcanic Rocks

4.4.1 Major Element Analysis

The available high-quality major element data for Ciomadul, obtained on both dome rocks and pumice, were compiled from Mason et al. (1996), Vinkler et al. (2007), Wulf et al. (2017), Molnár et al. (2018), Lahitte et al. (2019) and Harangi et al. (2020); selected samples are presented in a Total alkali versus SiO_2 (TAS) and a K_2O vs. SiO_2 rock classification diagram (Fig. 4.5). Most of the Ciomadul dome rocks and bulk pumice compositions plot in the trachydacite field of the TAS diagram, plotting in the high-K calc-alkaline series field in the K_2O versus SiO_2 diagram. The two samples that plot in the trachyandesite and high-K andesite fields, respectively, represent the Dealul Mare dome

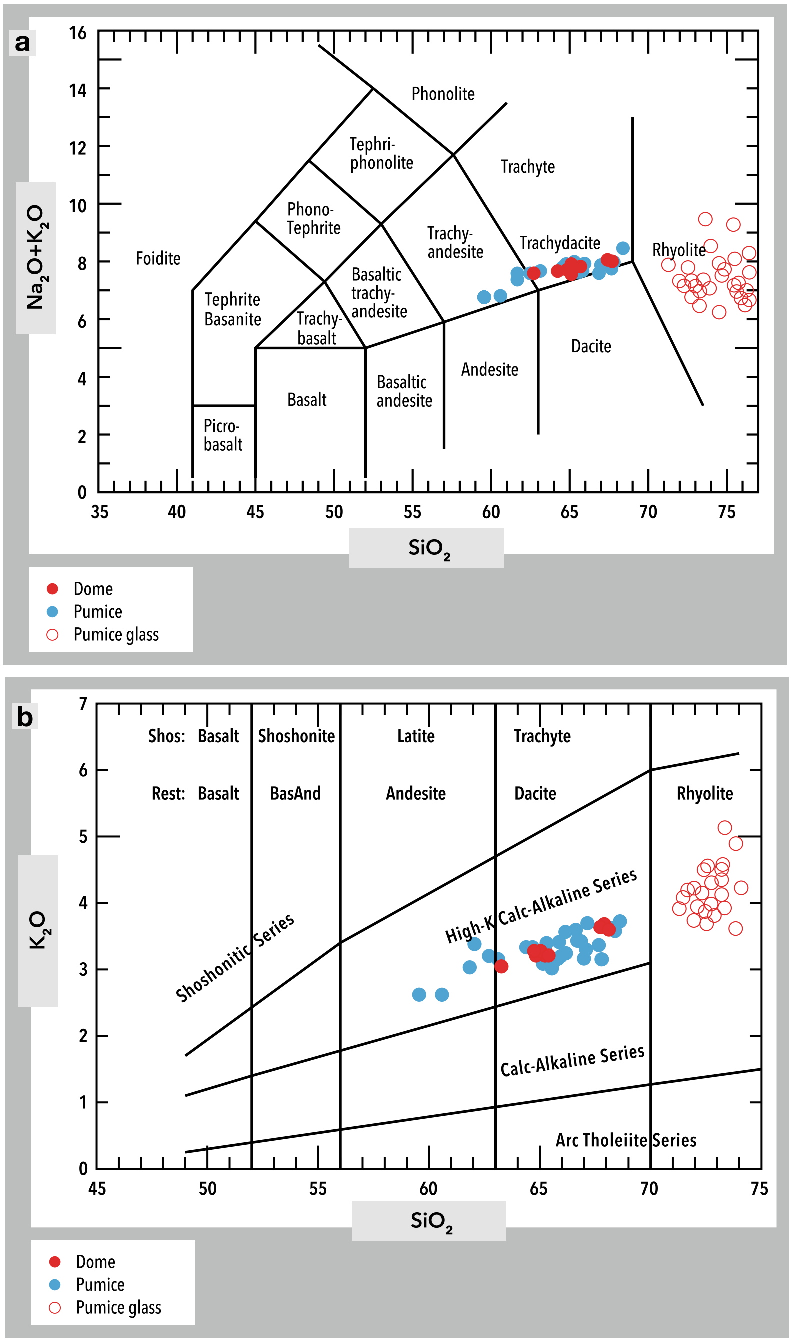

Fig. 4.5 **a** Total Alkali vs. Silica (TAS) diagram of Ciomadul volcanic rocks showing the prevailing trachydacitic composition of lava dome dacite and whole-rock pumice samples and the rhyolitic composition of the pumice glass. **b** K_2O vs. SiO_2 discrimination plots of Ciomadul rocks (dome dacite, pumice whole rock and pumice glass) showing their high-K calc-alkaline chemical signature. Data from Mason et al. (1996), Vinkler et al. (2007), Wulf et al. (2016), Molnár et al. (2018) and Harangi et al. (2020).

rock diagnosed as andesite by Szakács and Seghedi (1986). There is no significant difference between the major element compositions of lava dome dacite and pumice, with both covering the whole trachydacitic SiO_2 range (excepting for the Dealul Mare andesites) (Fig. 4.5). Major element correlations show that MgO, CaO, Al_2O_3, MnO, Fe_2O_3, P_2O_5, and TiO_2 decrease with increasing SiO_2 contents, whereas K_2O and Na_2O slightly increase, just as expected for calc-alkaline series rocks. Apart from these bulk rock pumice analyses, glass chemical compositions of Ciomadul pyroclastic rocks were published by Vinkler et al. (2007) and more recently by Wulf et al. (2017) and Harangi et al. (2020). Pumice glass volatile contents are relatively high (3.5–5 wt.%). Recalculated on a volatile-free basis, the Ciomadul pumice glass compositions fall into the rhyolitic field (70–77 wt.% SiO_2), showing a potassic alkaline character ($K_2O/Na_2O > 1$; Vinkler et al. 2007) (Fig. 4.5). The phenocryst-hosted, glassy silicate melt inclusions are of a similar composition.

4.4.2 Trace Element Analysis

The trace element and rare earth element (REE) distribution of Ciomadul rocks is illustrated in Fig. 4.6. When compared, the trace element distribution (including REE) in pumice clasts shows little variability and it largely mimics that of the dome dacites. The pumice clasts of the pyroclastic rocks are characterized by enrichment in large ion lithophile elements (LILE; e.g. Rb, Sr, Ba), a negative Nb anomaly, and a positive Pb anomaly (Vinkler et al. 2007). The “subduction signature” of the rocks is obvious as it is in the case of other South Harghita rocks and of the whole CGH range. On the other hand, Ciomadul rocks (both lava dome rocks and pumice clasts) show a strong adakitic signature (Fig. 4.7).

4.4.3 Radiogenic Isotopes

A few Sr and Nd isotope data on Ciomadul rocks were published by Mason et al. (1996) as part of a broader study of the whole CGH range. The Nd versus Sr isotope diagram (Fig. 4.8) illustrates the radiogenic isotopic characteristics of the Ciomadul rocks, shared with the other South Harghita volcanics, in contrast to the “normal” calc-alkaline volcanics of the rest of the CGH range: South Harghita as a whole, to which Ciomadul belongs, shows lower values of both Sr and Nd isotope ratios as compared to the rest of the CGH range and form a distinct data plot area on the diagram. In turn, the radiogenic isotope ratios of Ciomadul dacites are among the lowest of those of South Harghita (Fig. 4.8). Two $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ analysis of Ciomadul rocks are presented in Mason et al. (1996).

4.5 Petrogenetic Origin of the Ciomadul Volcanic Rocks

4.5.1 Geodynamic Context

As part of the CGH range, whose volcanic rocks show unequivocal a subduction signature (Fig. 4.6), Ciomadul was implicitly interpreted with the subduction paradigm in mind. Thus subduction-related magma genesis is the most widespread and accepted idea related to the formation of magma causing volcanic activity at Ciomadul. The geodynamic background of the volcanic activity of southern Harghita and Ciomadul (see Chap. 2), within the framework of the subduction related CGH volcanism, is still not unequivocally clarified. Roll-back and gradual break-off of the subducted slab, and lithospheric delamination were invoked to explain the geodynamics of the area (e.g. Mason et al. 1998; Seghedi et al. 2011). Ciomadul rocks share

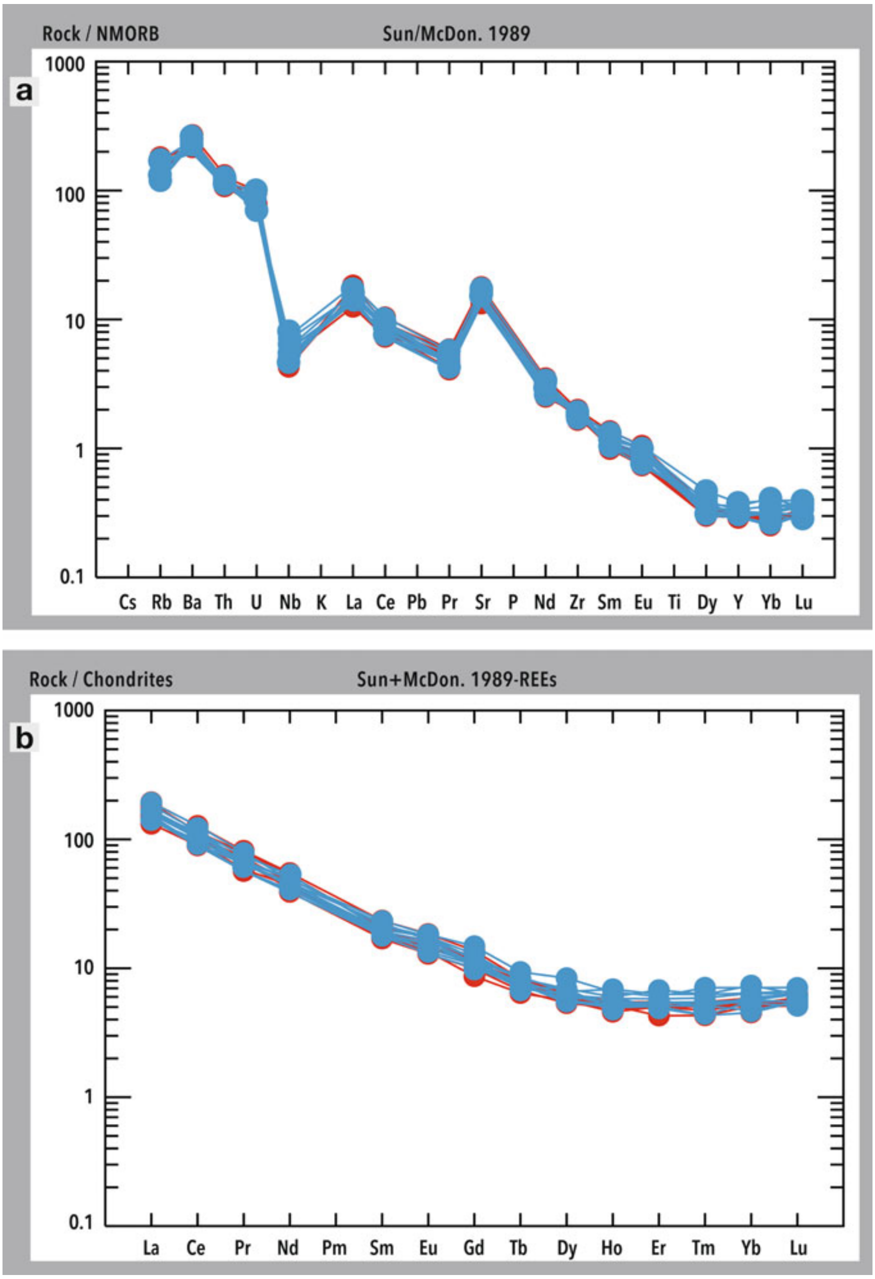

Fig. 4.6 **a** Multi-element or spider diagram, and **b** REE distribution of Ciomadul rocks (blue: dome dacite; red: pumice) illustratinging their “subduction signature” (i.e. enrichment in the large ion lithophile elements Rb, Sr, Ba, a negative Nb anomaly and a positive Pb anomaly). Data from Molnár et al. (2019) and Harangi et al. (2020)

several common petrochemical features with the volcanic rocks of the Neogene andesite-dominated CGH range, such as their broad calc-alkaline character which places them in a subduction-related geodynamic environment. On the other hand, Ciomadul volcanism shares a number of specific geochemical features common to only the South Harghita segment of the

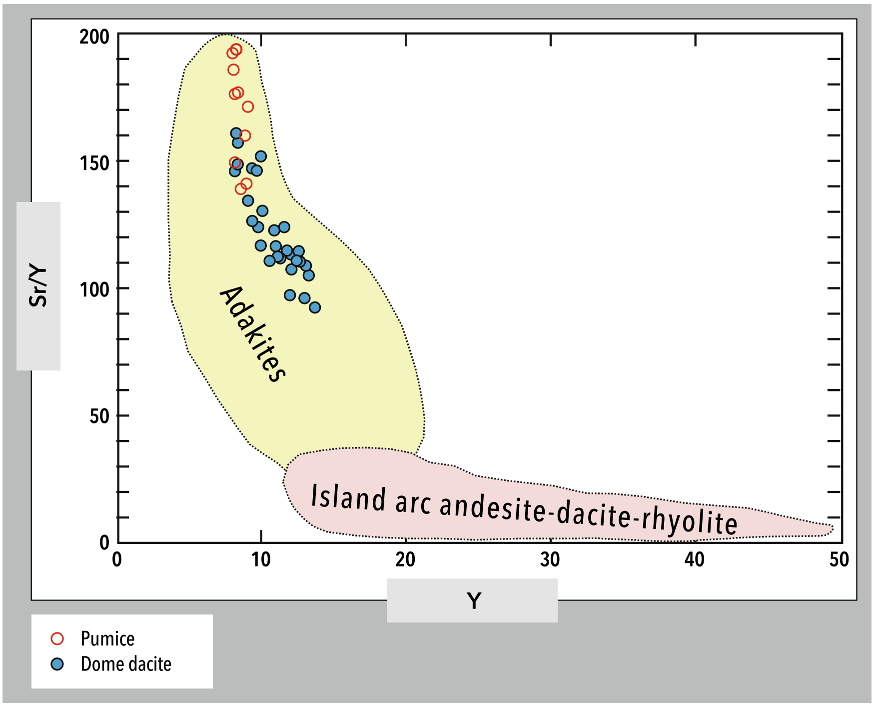

Fig. 4.7 Sr/Y versus Y plot of Ciomadul rocks, illustrating their adakitic signature. Data from Vinkler et al. (2007), Mason et al. (1996), Molnár et al. (2018, 2019) and Harangi et al. (2020)

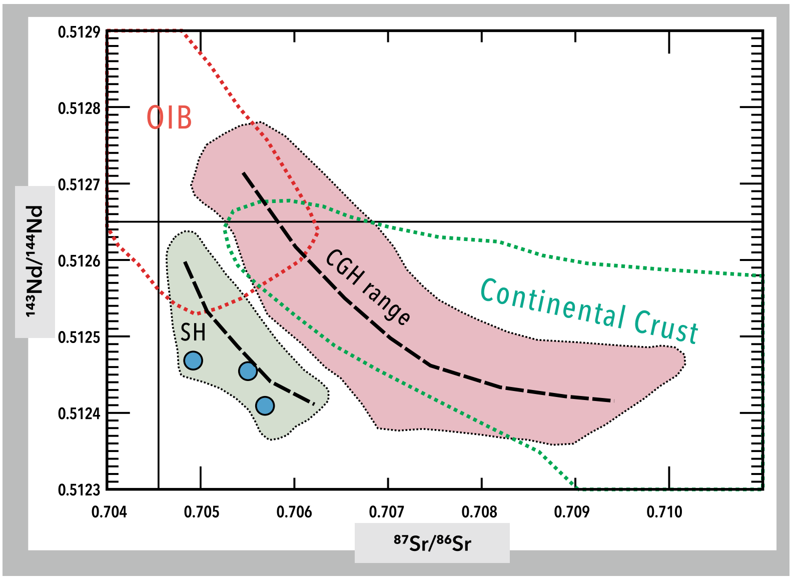

Fig. 4.8 Nd–Sr isotope ratios plot of three Ciomadul dome dacite samples (blue points) as compared with South Harghita (SH) and CGH range domains OIB = ocean island basalts. The black dashed arrows show the contamination trend with continental crustal materials of the mantle-sourced magmas of both CGH and South Harghita, with the notable difference of lower Sr isotope ratios and less amounts of contamination for the South Harghita rocks, including Ciomadul. Data from Mason et al. (1996)

CGH range such as the high-K calc-alkaline character, and comparable Sr and Pb isotopic ratios (Seghedi et al. 1987; Szakács et al. 1993; Mason et al. 1996; Seghedi et al. 2004). Moreover, it is part of a systematically changing geochemical trend in space and time along this segment, consisting of gradually increasing alkalinity concurrent with gradually decreasing erupted magma volumes along the segment from NW to SE (Szakács et al. 1993). These findings strongly suggest that the local (i.e. South-Harghita) geodynamic processes and hence magma generation and evolution processes are somehow different compared to the rest of the CGH range. It was pointed out that the major compositional change from normal calc-alkaline to adakite-like calc-alkaline (including high-K calc-alkaline and shoshonitic) occurred at around 3 Ma in the South Harghita Mts. (Seghedi et al. 2011) probably triggered by post-collisional re-organization of the microplate assemblage in the intra-Carpathian area. This observation enabled Seghedi et al. (2011) to characterize volcanic activity younger than c. 3 Ma, including that at Ciomadul but also the alkali-basaltic volcanism in the nearby Perşani Mts., as being of “post-subduction” (i.e. post-collisional) nature, in contrast to the pre-3 Ma subduction-related volcanism, including part of South-Harghita, characterizing the rest of the CGH range. Therefore, changes in the magma source and melting mechanisms also occurred in front of the Moesian platform triggered by processes such as slab-pull and steepening with opening of a tear window generating the adakite-like calc-alkaline magmas to which Ciomadul magmas also belong (Seghedi et al. 2011; Ferrand and Manea 2021) (Fig. 4.9). Furthermore, Ciomadul is a specific case within the South Harghita segment itself by the uniquely felsic (overwhelmingly dacitic) composition of its rocks. Considering all these geochemical and geodynamic characteristics, it was logical to consider a somewhat particular petrogenesis for this volcano, as discussed below.

4.5.2 Magma Genesis

Reflecting on the advance in knowledge and approach, different ideas on the magma generation processes leading to volcanism at Ciomadul were proposed during the last few decades. Revealing the South-Harghita along-range trend of gradually increasing K content of the volcanic rocks along with the gradually decreasing volumes of erupted magma, Szakács et al. (1993) envisaged gradually decreasing degrees of partial melting of a mantle source interpreted as the effect of gradually decreasing melting temperatures as approaching the subduction-truncating contact with a cold lithospheric block to the south. Vinkler et al. (2007) tentatively proposed a magma generation model involving the hybridization of two melts originating from two magma sources: a primitive mafic magma ponded at the mantle-crust boundary, and a lower crustal felsic magma generated by melting under the heating effect of the underplated mafic magma.

Recognition of the adakitic signature in part of the South Harghita volcanics (Seghedi et al. 2004) led to the refinement of the magma generation models in the area, including Ciomadul. According to the most recent interpretations (Seghedi et al. 2011; Ferrand and Manea 2021), partial melting at the level of the metasomatized lithospheric mantle in the “tear window” created by slab pull and steepening was triggered by the protruding hot asthenosphere. Such a process generated the parental magma of Ciomadul, together with those of the rest of the post-3 Ma South Harghita adakite-like calc-alkaline magmas, in the post-collisional geodynamic setting of the Carpathian bend interior (Fig. 4.9). The adakitic signature is acquired by the low-grade partial melting of the lithospheric mantle superimposed on the dominant calc-alkaline composition imprinted by the same metasomatized lithospheric source inherited from the pre-3 Ma subduction phase. The SE-ward decreasing emplacement ages and magma volumes along

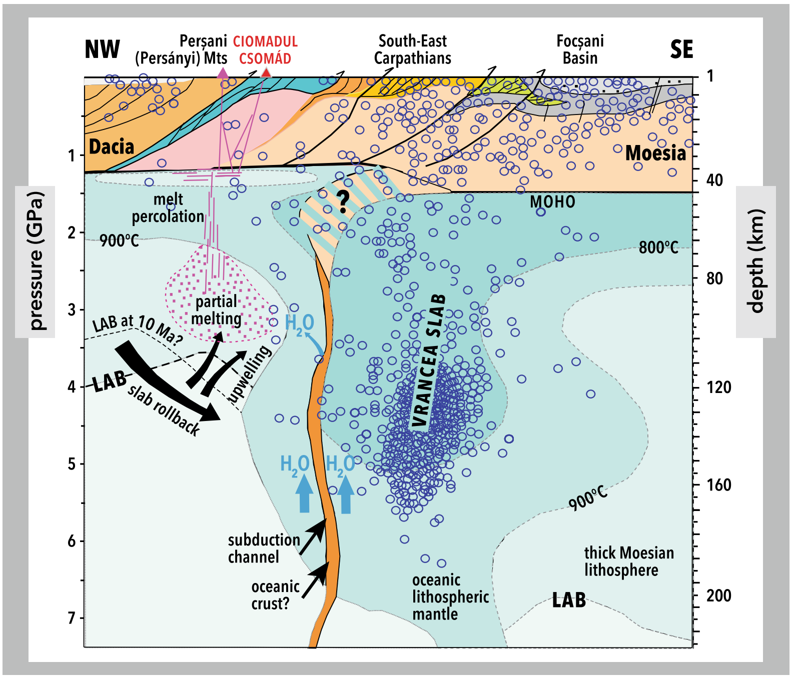

Fig. 4.9 The lithospheric mantle magma source (red point-patterned zone) of the South Harghita and Perşani (Persányi) Mts. volcanism (including Ciomadul) in the broader geodynamic context shown in a NW–SE hypothetical section across the Transylvanian Basin and the East Carpathians bend area including the Vrancea seismic zone (after Ferrand and Manea 2021). Blue circles mark both crustal and subcrustal earthquake foci. MOHO = Mohorovičić discontinuity (crust-mantle boundary); LAB = lithosphere-asthenosphere boundary. The "subduction channel" is the tectonic plate interface zone of a convergent plate boundary

South Harghita (Szakács et al. 1993; Szakács and Seghedi 1995) are explained by the gradual opening of the lithospheric tear during slab steepening (Seghedi et al. 2011).

4.5.3 Magmatic Differentiation

Low-pressure differentiation processes occurring at crustal levels (presumably within upper crustal magma reservoirs) changed the composition of the parental magmas of Ciomadul (see above) through fractional crystallisation, assimilation of country rock and magma mixing.

The primitive mafic (parental) component of the erupted Ciomadul magma was tentatively identified by Kiss et al. (2014) by the presence, in the dome dacites, of pargasitic amphibole whose chemical composition (e.g. the lack of a negative Eu anomaly, as proof of shallow-level magma reservoir processes, among others features) is relevant in this respect.

Magmas change gradually their composition during fractional crystallisation by continuously removing (i.e. fractionating) early crystallized minerals (and their chemical components) from the melt, thus depleting it in those components and enriching it in the remaining ones. According to Mason et al. (1995), plagioclase is the most important fractionating mineral phase as evidenced by, among other features, the presence of a negative Eu anomaly in the bulk rock compositions. Within the mafic mineral assemblage late-stage biotite and amphibole replaced earlier-crystallized pyroxene (or even olivine) during the fractional crystallization (and/or magma-mixing) processes as witnessed by relict pyroxene (or olivine) cores in amphibole phenocrystals (Mason et al. 1995; Vinkler et al. 2007).

Kiss et al. (2014) in their detailed study on Ciomadul dome dacite amphiboles pointed out that the chemical composition of hornblende (one of the two major amphibole types identified) suggests that they originated from a fractionated felsic or silicic magma. According to amphibole thermo-barometrical calculations, the two groups distinguished—low-T amphiboles (the hornblende group) and high-T amphiboles (the pargasite group), respectively—correspond to two different levels of crystallization depths and magma reservoir conditions (Fig. 4.10).

Based on trace element and radiogenic and stable isotope (Sr, Nd, Pb and O) data, Mason et al. (1996) recognized the importance of crustal contamination (i.e. assimilation of crustal material) as a major petrogenetic process in the of the CGH range, South Harghita and Ciomadul included. Contamination with sediments in the upper crust contributed to magma evolution of the South Harghita segment to a higher extent (Mason et al. 1996) probably due to the longer residence time in crustal magma reservoirs located inside a significantly thicker continental crust as compared with other CGH segments (Szakács et al. 1993).

Magma mixing processes (between melts of different compositions) are also important in the petrogenesis of Ciomadul volcanics. Several relevant textural, compositional and mineral chemical features led to the recognition of magma mixing by numerous researchers (e.g. Seghedi et al. 1987; Mason et al. 1995; Vinkler et al. 2007; Kiss et al. 2014). These include the presence of orthopyroxene and olivine nuclei in hornblende phenocrysts, sieve-textured and resorbed plagioclase phenocrysts, and clinopyroxene enveloping orthopyroxene. In particular, the concomitant presence of two generations of amphiboles (hornblende and pargasite) crystallising at contrasting temperature–pressure conditions, implicitly at different depths (Vinkler

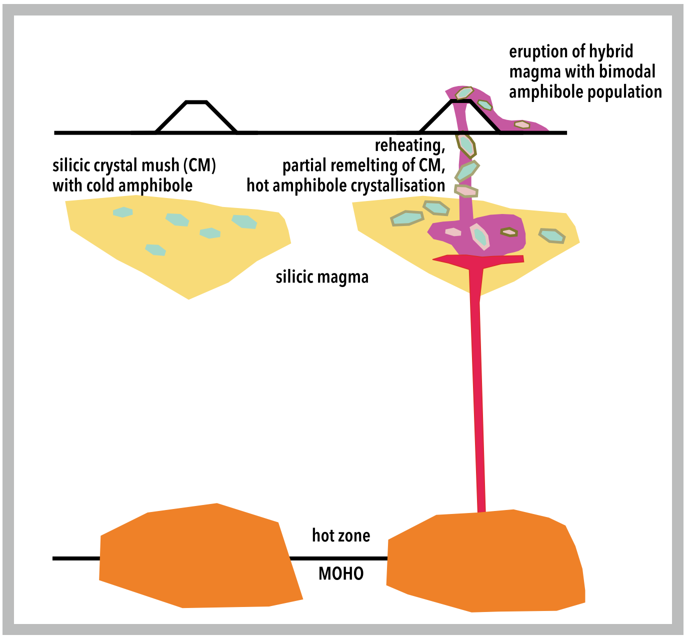

Fig. 4.10 Pre-eruptive (left) and eruption-triggering (right) magma reservoir conditions at Ciomadul based on amphibole mineral chemistry and thermo-barometrical calculations (after Kiss et al. 2014). Arrival of ascending mafic magma into a crystal-mush-containing upper crustal magma reservoir reactivates the otherwise non-eruptible magma leading to eruption. Different crystal colours indicate different compositional amphibole populations (including crystal overgrowth rims). The outermost rim indicates disequilibrium selvages of the amphibole crystals. See text for more details. MOHO = Mohorovičić discontinuity (crust-mantle boundary)

et al. 2007; Kiss et al. 2014), provides compelling evidence of magma mixing at Ciomadul.

Dome dacite amphibole compositions were also used by Kiss et al. (2014) to quantify the pre-eruptive thermodynamic conditions during crystallisation in the magma storage system by applying amphibole thermo-barometrical calculations. Two temperature regimes were identified corresponding to the two amphibole populations (hornblende and pargasite, respectively) and to two different storage depths: a shallower and lower temperature (800 ºC) regime, and a deeper and hotter one (900 ºC). Low-Al hornblende was a component of a felsic crystal mush-like magma body formed at c. 8–12 km depth, whereas high-Al pargasite crystallised from a hot mafic magma stalling at greater depths (Fig. 4.10).

To conclude, despite their apparent overall petrographic homogeneity, the Ciomadul volcanics record a complex magma evolution history developed during the time interval between partial melting of the source mantle rocks and eruption at the surface.

4.5.4 Eruption-Triggering Mechanisms

The presence of two amphibole populations formed at different temperatures and depths, disequilibrium features observed in plagioclase, biotite and amphibole phenocrysts, as well as the presence of pyroxene and olivine cores in amphibole (Vinkler et al. 2007; Kiss et al. 2014) led to the hypothesis that interaction occurred between two different magmas by repeated invasion of hotter mafic magma into the colder and shallower magma reservoir beneath Ciomadul (Fig. 4.10). Such a process can reactivate the otherwise non-eruptible crystal-mush-type residual magma eventually leading to eruption (Kiss et al. 2014). Furthermore, this mechanism could develop quickly, days to weeks prior to eruption (Kiss et al. 2014). Considering such precedents in the volcano's evolution, as well as its overall eruptive history and the age of its most recent eruption at only less than 30,000 years ago (Szakács et al. 2015; Karátson et al. 2016; Molnár et al. 2018), as summarized in Chap. 3 of this book, there were speculations concerning possible future activity at Ciomadul, a subject that is addressed in Chap. 7.

4.6 Summary

The Ciomadul volcanic rocks are classified today as adakite-like high-K dacites, except for the Dealul Mare dome rocks that are classified as high-K calc-alkaline andesites. The rock-forming mineral assemblage is quite homogenous across all studied rock samples, consisting of plagioclase, amphibole and biotite as major mineral phases. Rock textures and structures are more variable. The dome dacites are either glomerophyric, holocrystalline or show hyalopilitic groundmass textures, whereas glassy textures dominate in the pumice clasts of the pyroclastic rocks and the outer rinds of bread-crust bombs/blocks. Rock porosity is also highly variable, even in the case of pumice clasts and individual bread-crust bombs/blocks. Optical microscopy investigations revealed the presence of further mineral phases: quartz, alkali-feldspar, pyroxene and even olivine, along with apatite, zircon and titanite. Furthermore, mutual relationships between minerals were observed such as inclusions of pyroxene, olivine and silicate melt in phenocrysts, as well as reaction (and resorption) features relevant for petrogenetic interpretations.

Despite their apparently homogenous overall mineralogical composition, significant compositional variability of the major mineral phases feldspar and amphibole of both dome dacite and pumice clasts were pointed out. Amphibole was found as belonging to two different mineral species: low-Al hornblende and high-Al pargasite that formed under different thermodynamic conditions, corresponding to shallow-level, low-temperature reservoir conditions, and deeper crustal high-temperature reservoir conditions, respectively.

Whole-rock major and trace element chemistry of dome dacite and pumice, as well as of pumice glass, complemented by radiogenic isotope compositions, brought new insights into understanding the petrogenesis of the Ciomadul rocks in the geodynamic context of the youngest (<3 Ma) post-collisional volcanism in the CGH range, in particular its South Harghita segment. The parental magmas of Ciomadul were generated by low-grade partial melting in the lithospheric mantle in the "tear window" created by slab pull and steepening triggered by the protruding hot asthenospheric mantle, a process that may explain the adakitic geochemical signature of the Ciomadul rocks. The original magma then evolved during a complex magma differentiation history involving fractional crystallisation, crustal assimilation and magma mixing processes in shallow crustal magma reservoirs. Petrographic details along with mineral chemical data led to the hypothesis according to which at least the dome dacite eruptions were triggered from the shallower (8–12 km deep) magma reservoir by invasion of hotter mafic magma, ascending from a deeper crustal storage zone, into a cooling (otherwise non-eruptible) felsic crystal mush reactivating the volcanic system.

5

Gone with the Wind: Dispersal of Ciomadul Tephra

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Abstract

Ciomadul's last explosive eruptions produced large volumes of pumice and ash, so-called tephra, which had the potential to be dispersed by wind over wide areas and deposited in geological archives (e.g., lakes and ocean floors). Using the chemical fingerprinting of volcanic glass in tephra deposits, at least four main eruptive events can be distinguished for the last 100 thousand years: the "Turia" (older than 51 ka), the "BTS" (40–42 ka), the "TGS" (31.5 ka), and the latest "St. Ana" eruptions (28–29 ka). Most of these tephras have been found only in proximal (near-vent) and medial-distal (15–30 km) locations around the volcano. One tephra showing a typical Ciomadul chemical fingerprint and correlated preliminarily with the "St. Ana" eruption, but probably much older in age, has proven a much further dispersal as far as 350 km towards the Ukraine, highlighting the violent explosive nature of the Ciomadul volcano and its volcanic ash impact also on distal areas.

5.1 Introduction

Tephra, as defined in Chap. 3, is loose volcanic material of any grain size that is ejected into the atmosphere by an explosive eruption, transported by wind and deposited in geological archives in various distances from the source volcano. The usage of "tephra" is equivalent to "pyroclastic rock", although the latter is commonly used for more compacted deposits too (i.e., volcanic tuff). If detected in sedimentary strata such as old lake deposits or loess sequences, layers of tephra can be valuable event markers for dating and linking these sediments with other strata that contain the same tephra units. If the package of sediments and tephra is situated relatively close to a volcano, a series of tephra layers from past eruptions can provide an important clue to the volcano's eruptive history. Conclusive identification of tephras is crucial for both dating and volcano-

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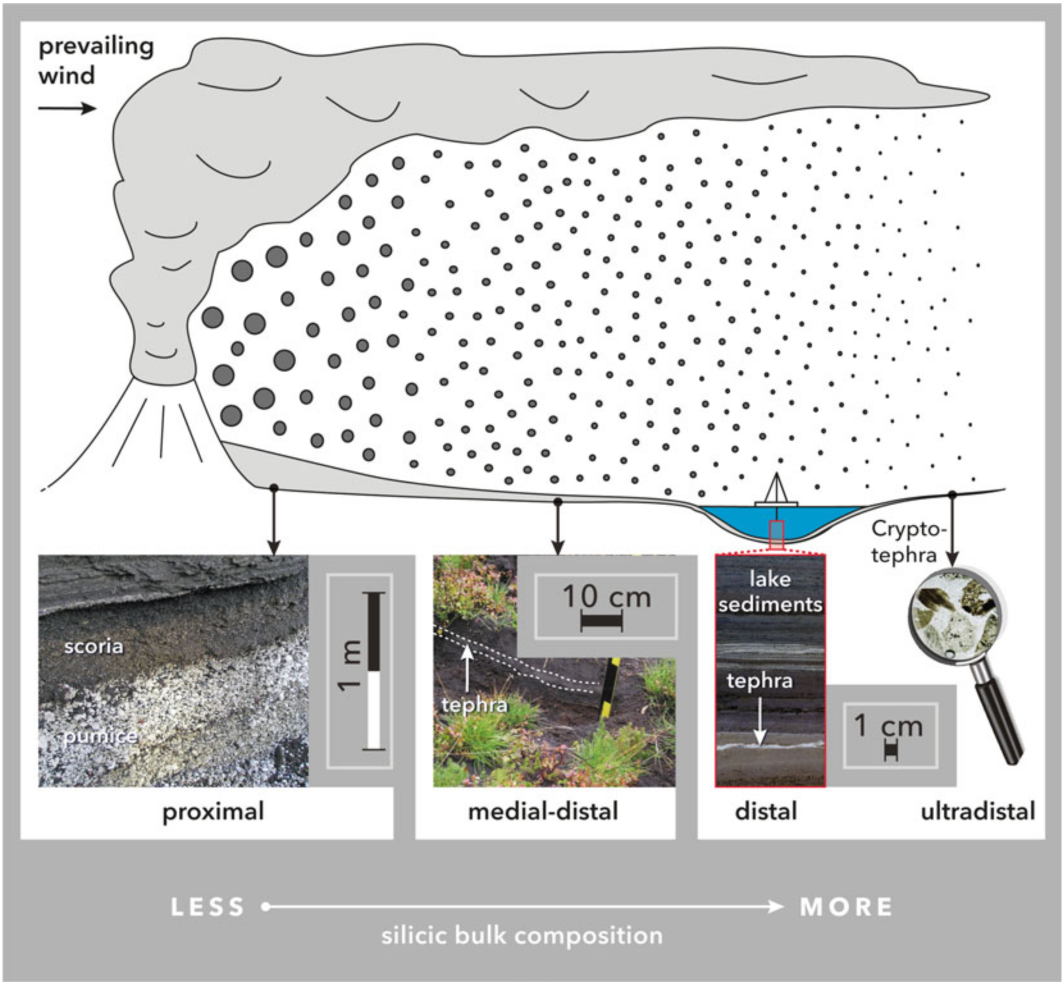


Fig. 5.1 Schematic dispersal of tephra showing changes in grain size, thickness and bulk chemistry with distance from the source volcano. Coarse-grained pumice and scoriae clasts form relatively thick deposits in the proximal (near-source) area. Tephra material transported by wind and deposited in medial-distal, distal and ultradistal sites (e.g., lake or ocean sediments) systematically decreases in grain size and thickness, and sorting of tephra components of different densities leads to a change in the bulk chemistry of the deposit from low-silicic to higher-silicic compositions. In large distances, only macroscopically non-visible tephra layers, so-called cryptotephra layers, are preserved

stratigraphical purposes (Lowe 2011). Tephra consists of three main components that together make up its bulk chemical composition: (1) volcanic glass (pumice or scoria clasts) that forms by rapid cooling of magma during eruption; (2) minerals that already formed in the magma chamber inside the volcano prior to the eruption; and (3) country rock fragments that have been incorporated into the magma prior to or during the eruption (Fig. 5.1). Tephra can be transported within an eruption cloud either by aerial (pyroclastic fall) or flow processes (pyroclastic density currents). Tephra transported by air has the potential to be widely distributed depending on the strength and direction of the prevailing winds that occur during the eruption. Grain size sorting processes during this aerial transport are responsible for larger and denser tephra components such as volcanic blocks and bombs (particles >64 mm), heavy minerals and rock fragments to be deposited nearer to the volcano, and for smaller and lighter fragments such as

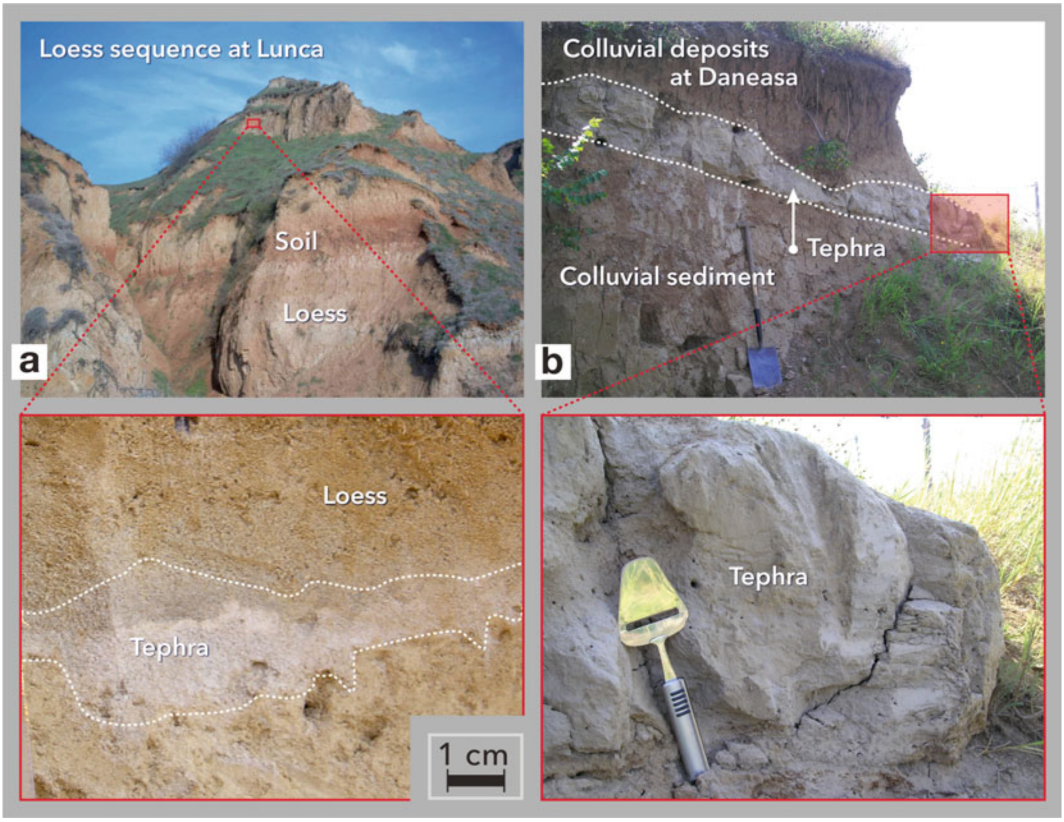


Fig. 5.2 Examples for tephra deposits from the Campanian Ignimbrite eruption (Italy) in **a** loess and **b** in colluvial soils in southern Romania

lapilli (particle size 2–64 mm) and volcanic ash (particles <2 mm) dominated by volcanic glass to be distributed over wider areas. The thickness of a tephra fall deposit also decreases with distance from the volcano, often from several meters in proximal settings to macroscopically non-visible layers, so-called crypto-tephra layers, in ultra-distal settings. The deposition of very fine-grained ash from the eruption cloud in distal areas strongly depends on local precipitation patterns, often explaining the presence and absence of tephras in geological archives that are close to each other. Tephra is best preserved in ice sheets, calm water bodies (lakes) and peat bogs, but it can also be found in ocean sediments, soils, loess, or cave deposits (e.g., Figs. 5.2 and 5.3). In Romania and neighbouring countries, geological archives for recording tephra from Ciomadul are dominated by alluvial (eroded and redeposited) sediments, loess and cave deposits (Figs. 5.2 and 5.3). Preservation in these archives is only possible under certain depositional conditions, for example, if sediment accumulation rates are high and if weathering and erosion are low. Typical examples of important tephra-bearing terrestrial settings at Ciomadul are presented in Chaps. 6 and 14. However, many lakes in Romania are man-made or too young for recording Ciomadul tephra, whereas older natural lakes still lack tephra investigations.

5.2 Principles of Tephrochronology

Geological archives can also be valuable recorders of past climate and environmental change, and tephras in sediments can play essential roles in dating and linking these records. This is

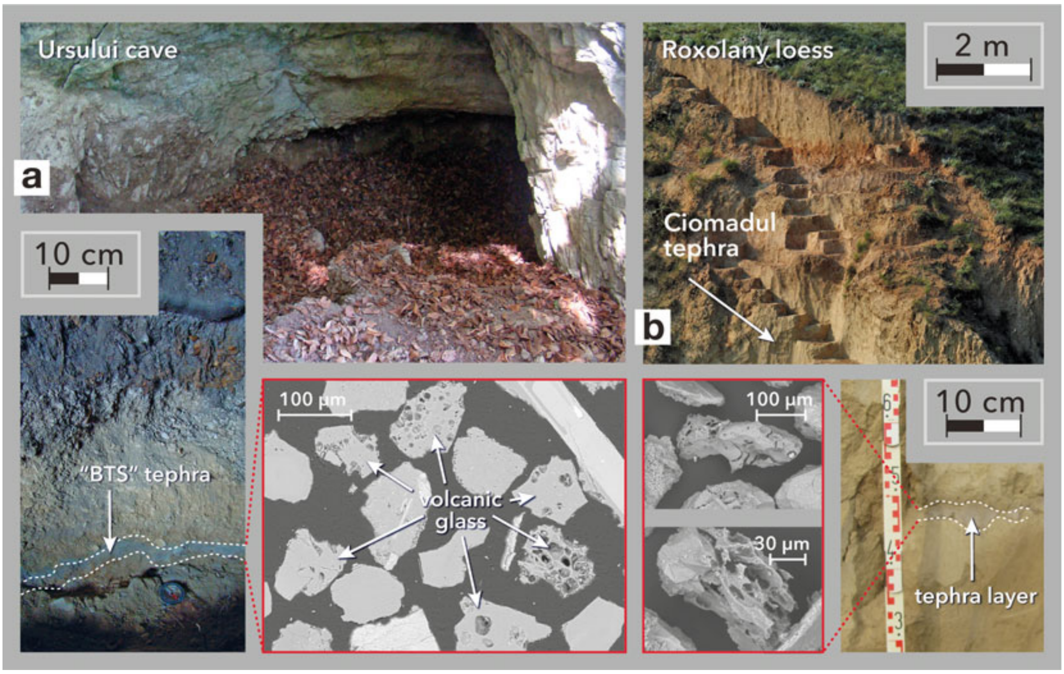


Fig. 5.3 Distal sites with Ciomadul tephra occurrences: **a** Ursului (Medve) cave (Romania) with sedimentary deposits containing the "BTS" tephra and backscattered scanning electron (BSE) microscopic image of tephra components. **b** Roxolany loess and soil sequence (Ukraine) with position of the Ciomadul tephra preliminarly correlated with the "St. Ana" eruption and scanning electron microscopic (SEM) image of volcanic glass

because tephra is deposited almost instantly, and therefore tephra from the same eruption in different geological archives can be used to synchronise the past climatic information, so-called proxy data, on a regional or wider scale. If reliably dated by radiometric (radiocarbon) or radioisotopic techniques (e.g., ^{40}Ar/^{39}Ar, (U-Th)/He; Chap. 3), or by other means of dating such as annual layer counting in ice cores or lake sediments, ages of tephras can be imported into a sediment age model and used as independent time markers to test or improve dating of the palaeoclimate record. This discipline is called *tephrochronology* and has been employed in many archives worldwide. In Europe, tephrochronological studies are long common in regions that were impacted by volcanic ash fall from e.g., Icelandic, Eifel/German and Italian highly explosive eruptions (Fig. 5.4). Tephra studies in the Eastern Mediterranean region, however, including the volcanic islands of the Aegean Arc (e.g., Santorini, Kos, Nisyros, Yali) and the Central and Eastern Anatolian volcanoes (Turkey) are still in their infancies. This holds also true for Ciomadul, although the recent rapid progress in dating and detecting distinct tephra deposits from Ciomadul's latest activity (e.g., Harangi et al. 2015b; Karátson et al. 2016; Wulf et al. 2016; Veres et al. 2018) has opened up the opportunity to use these as valuable time and correlation markers in Romanian geological archives and beyond (Fig. 5.4).

5.3 Detection of Tephra in Geological Archives

Detection of tephra in proximal archives is straightforward if tephra deposits occur as thick visible layers that are dominated by coarse pumice or scoria clasts (Figs. 5.5, 5.6a). Thinner and finer grained tephra layers can often be discovered by magnetic susceptibility or X-ray fluorescence scanning of sediment cores that

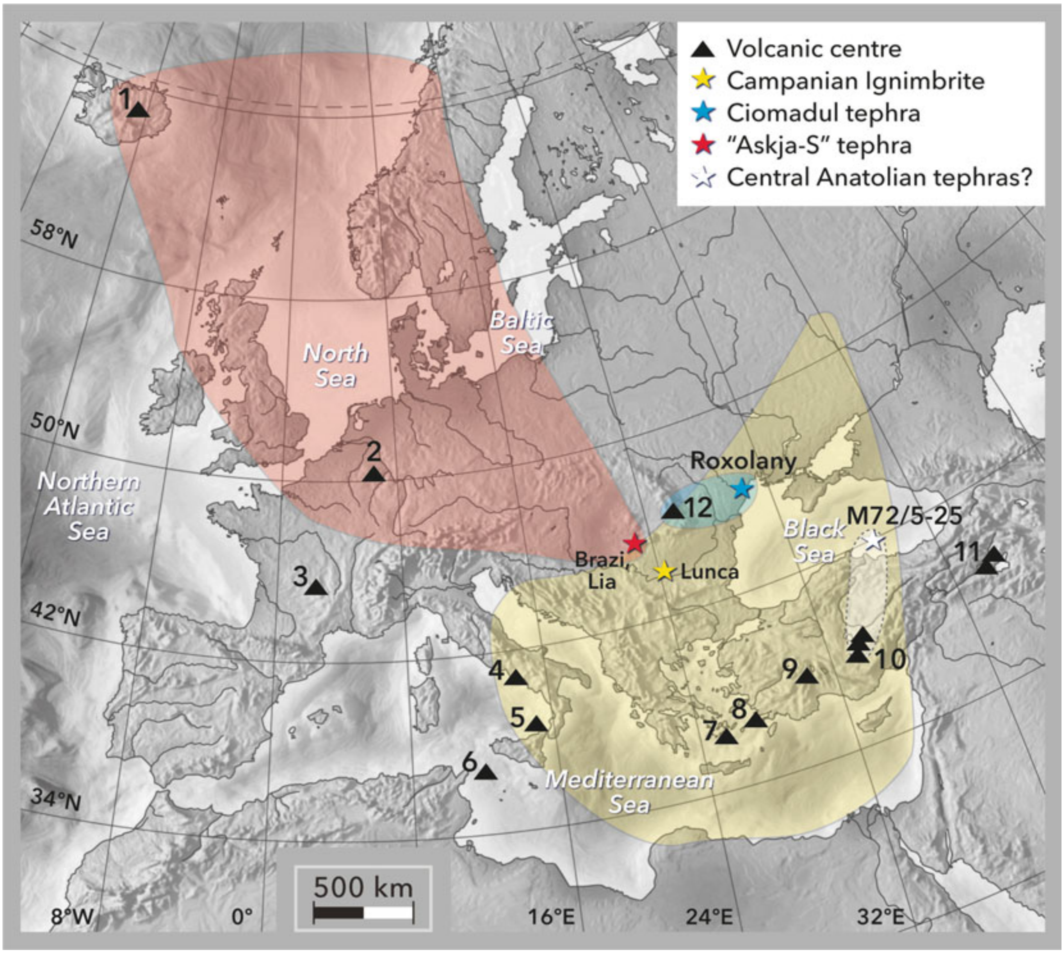


Fig. 5.4 Dispersal fans of tephras from Iceland (light red area = "Askja-S" tephra) and Italy (yellow area = "Campanian Ignimbrite") that have been detected in Romanian lakes and loess sequences (red and yellow stars). Black Sea coring site M72/5-25 (white star), and the locations of Roxolany (Ukraine, blue star) are also shown. Black triangles represent main volcanic centres: 1 Askja, 2 Eifel, 3 Auvergne, 4 Campanian Volcanic Province, 5 Aeolian Islands, 6 Pantelleria, 7 Santorini, 8 Kos-Yali-Nisyros, 9 Western Anatolia, 10 Central Anatolia (Acigöl, Hasan and Ercyes Dagi), 11 Eastern Anatolia (Nemrut and Süphan Dagi), and 12 Ciomadul

have been retrieved from the geological archive (Fig. 5.5). This technique allows identifying differences in the abundances of certain chemical elements such as potassium or titanium between the tephra layer and its embedding sediments. Such scans, however, always require verification of the presence of volcanic glass, which relies on microscopic inspection of sample material (Fig. 5.6b, c). Tephra layers in distal to ultra-distal sites—hundreds to thousands of kilometres away from the source volcano—might not be visible by naked eye anymore; here, the detection of cryptotephra layers that often comprise only a few tiny glass shards requires complex and time-consuming laboratory procedures (Fig. 5.6d).

5.4 Identification of Tephra via Glass Chemical Fingerprinting

Identification of tephra is based on the chemical composition of its volcanic glass, which is generally different for each volcano and each single

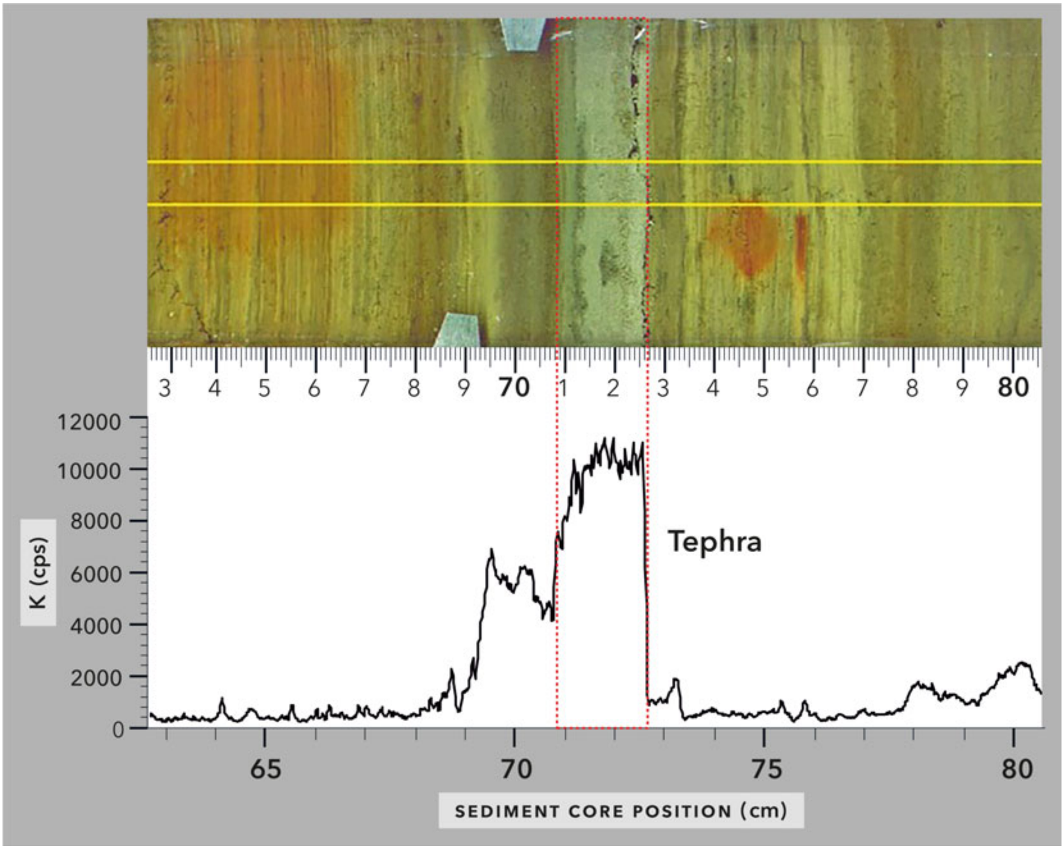


Fig. 5.5 Example of detecting a tephra layer in lake sediments by X-ray fluorescence elemental core scanning data. The high peak in potassium reflects the increased concentration of this element in the tephra layer compared to the sediments. The lower K-peak to the left of the primary tephra indicates sediments that are mixed with redeposited tephra material

eruption. This is unlike traditional volcanological-petrological studies, which determine bulk chemical compositions of proximal tephra deposits to interpret magmatic and tectonic processes. Compared to glass compositions, tephra bulk chemistry changes with distance from the volcano to more silicic compositions due to aerial sorting processes of its components, preventing unambiguous tephra identification. The glass chemical fingerprint is commonly determined by high-precision analytical techniques such as electron probe microanalyses (EPMA) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Usually, the EPMA major and minor elemental composition of several single glass shards is sufficient to assign the tephra to a specific volcanic event, but sometimes additional LA-ICP-MS trace element analyses are required for a more detailed tephra discrimination. Correlation of tephras is based on comparing the chemical data set with available literature data by using bivariate elemental plots and/or statistical analysis (see Lowe et al. 2017).

5.5 Glass Chemical Composition of Ciomadul Tephras

As described in more detail in Chap. 3, at least four distinct explosive eruptions (or eruption series) took place during Ciomadul's last phase (60–30 ka) of activity: the "Turia" eruptions (more than 51 ka), the "BTS" eruption (40–

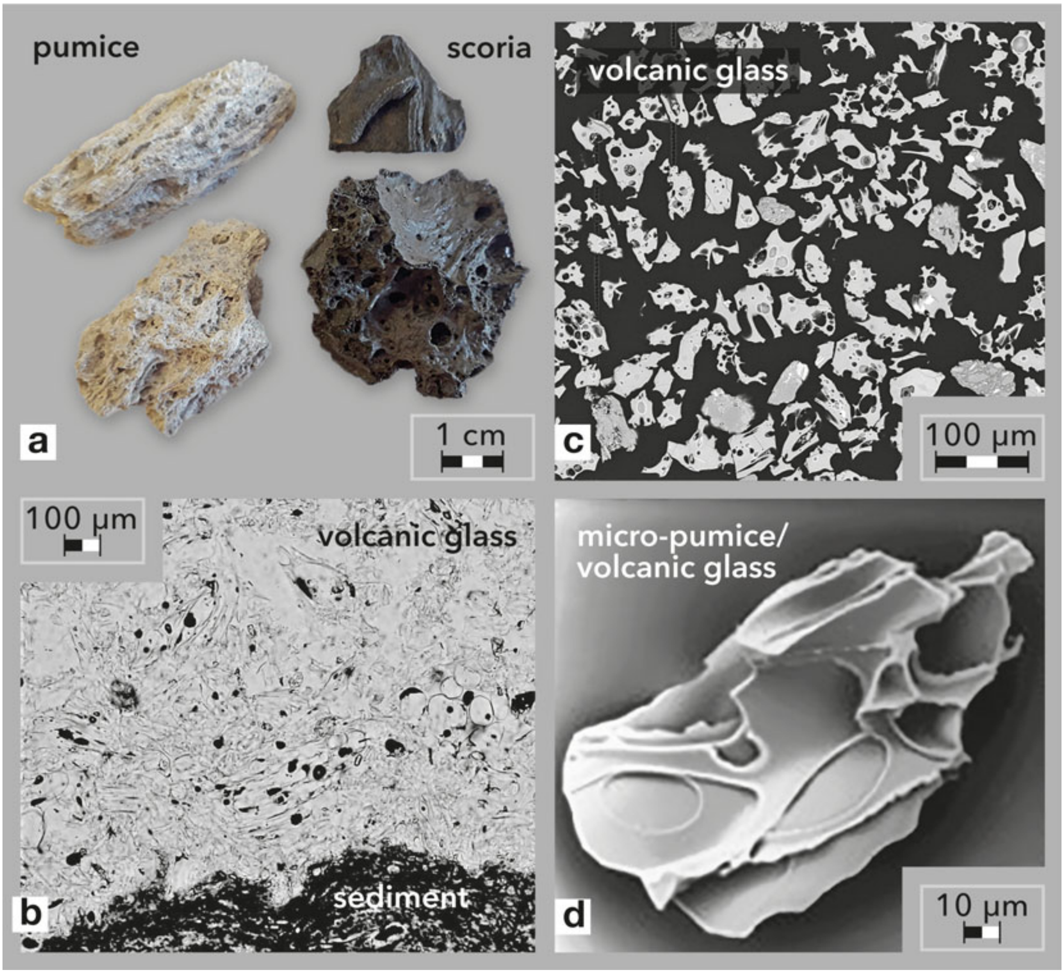


Fig. 5.6 Examples of volcanic glass: **a** Pumice (white) and scoria (black) fragments from proximal deposits. **b** Micro-pumices and volcanic glass shards in a distal tephra layer that is embedded in lake sediments (transmitted light microscopic image), characterised by a transparent colour and high amount of bubbles. **c** Assemblage of micro-pumice fragments from a medial-distal site (scanning electron microscopic image) showing the bubbles and partly angular nature of volcanic glass. **d** A volcanic glass shard in an ultra-distal tephra (backscattered scanning electron microscopic image)

42 ka), the “TGS” eruption (31.5 ka), and the latest phreatomagmatic eruptions from the current St. Ana crater (LSPA, or simply “St. Ana” eruptions: 28–29 ka; Karátson et al. 2016, Wulf et al. 2016). The respective tephras are all dacitic in bulk composition with concentrations in silica (SiO_2) of c. 63–68 wt% (e.g., Szakács and Seghedi 1986), but their volcanic glass chemistry significantly differ from each other by being rhyolitic with overall higher silica concentration ranges between 70 and 80 wt% (Karátson et al. 2016; Wulf et al. 2016) (Fig. 5.7).

Tephra glasses from the “Turia” eruptions show the highest silica concentrations (75–80 wt %), while tephra glasses from the “TGS” eruption are characterised by the lowest silica values (70–74 wt%). The “BTS” and “St. Ana” tephras have intermediate glass compositions that overlap with the above-mentioned silica concentration ranges, with the “BTS” tephra being more homogenous in composition compared to the “St. Ana” tephra. Differences in glass compositions among the Ciomadul tephras are also visible in other major elements, as shown in the bivariate

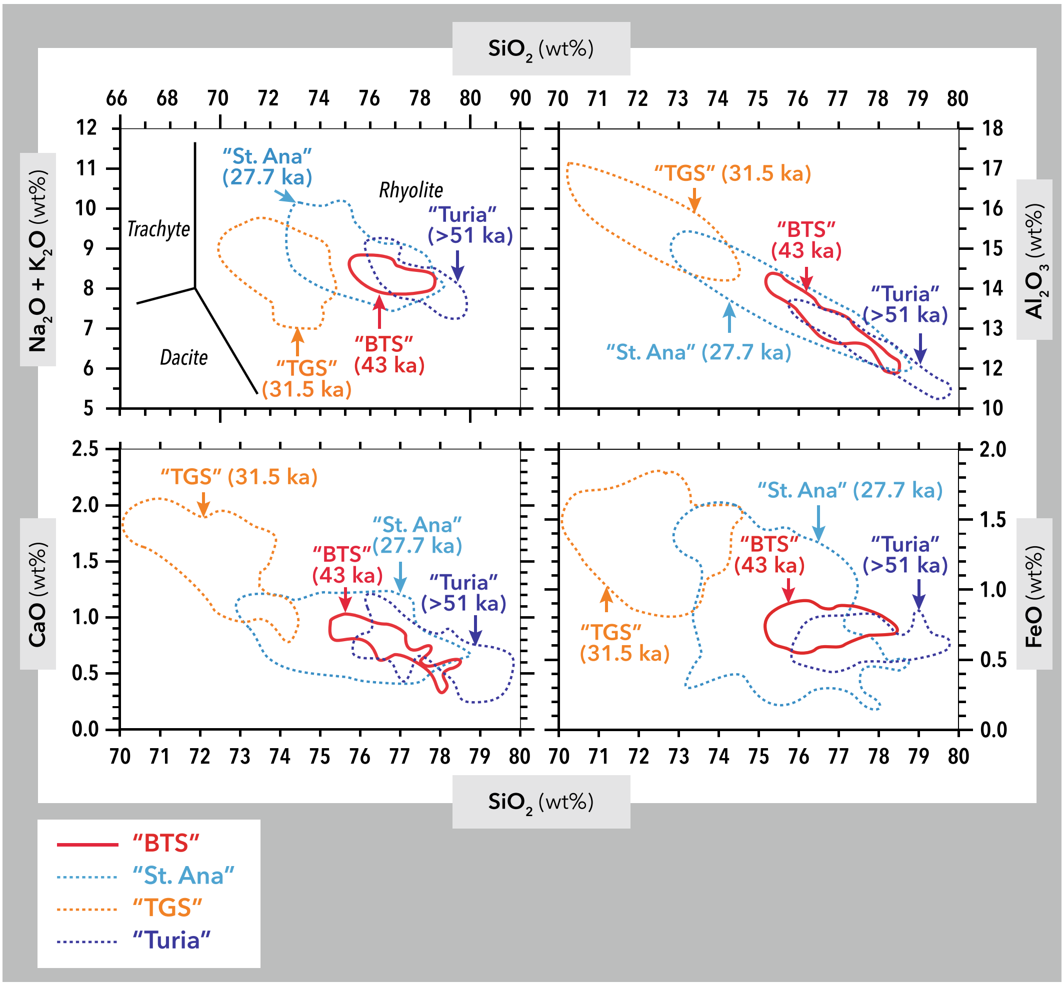
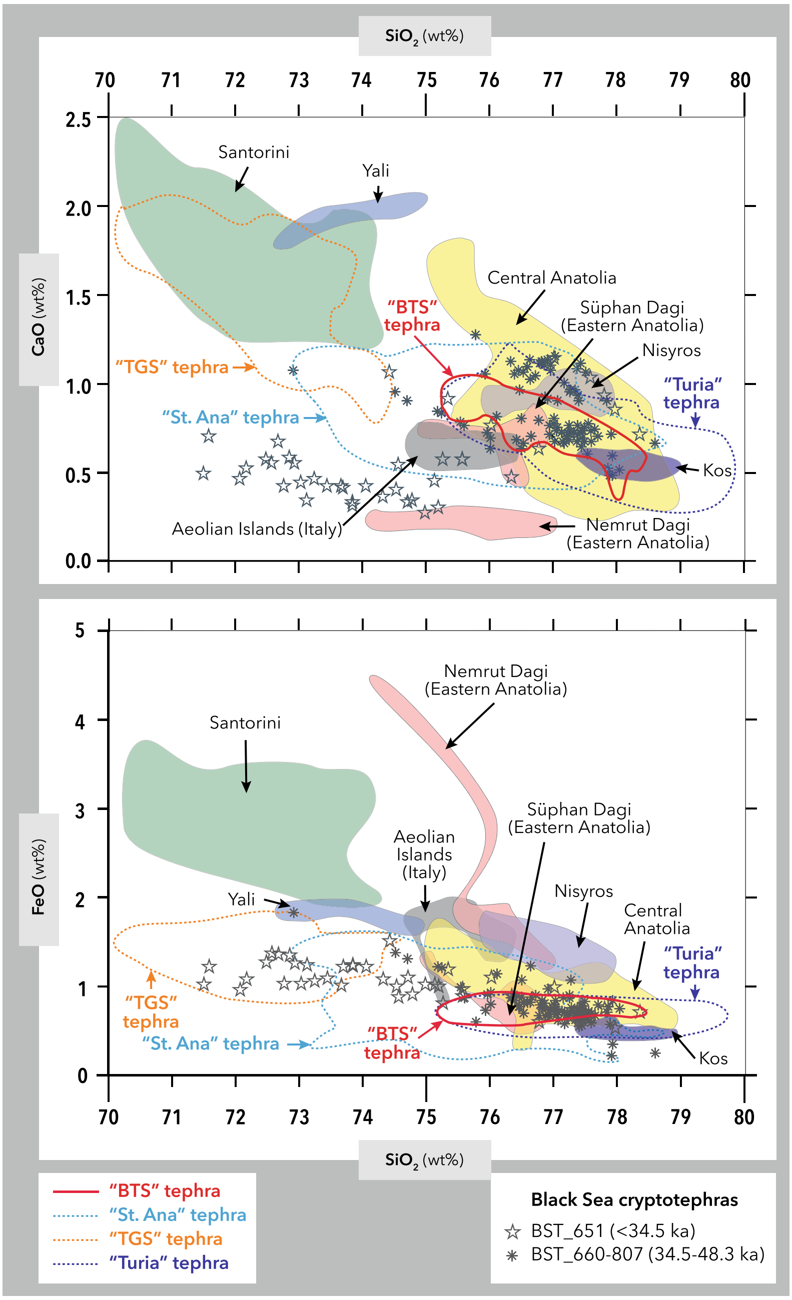


Fig. 5.7 Bivariate elemental plots for geochemically distinguishing tephras from the last Ciomadul volcanic eruptions: Major element glass compositions such as total alkalies ($Na_2O + K_2O$), CaO, Al_2O_3 and FeO are plotted against the silicon oxide compositions of individual glass shards of tephras from the proposed four distinct Ciomadul eruptions. Note that glasses from the "TGS" eruption (yellow envelope) has lower SiO_2 and higher CaO, Al_2O_3 and FeO concentrations than those from the "St. Ana" (light blue envelope) and "BTS" (red envelope) events. Volcanic glasses from the older "Turia" eruption (dark blue envelope) have the highest SiO_2 content but the lowest CaO, Al_2O_3 and FeO concentrations

plots for aluminium (expressed as Al_2O_3), iron (FeO), calcium (CaO), potassium (K_2O) and sodium (Na_2O; see Fig. 5.7); these are pivotal for unambiguous identification.

When comparing the glass major element compositions of Ciomadul tephras with rhyolitic tephras from other adjoining volcanic centres in the Mediterranean region, there are significant differences for Italian and Aegean Arc tephras but astonishing similarities given for Central/Eastern Anatolian and Kos tephras, especially with the "Turia" tephra (Fig. 5.8). However, in order to understand the tephra dispersal and therewith the magnitude of Ciomadul eruptions it is vital to unambiguously distinguish Ciomadul tephra from tephra of other volcanic sources. This can be accomplished by even more detailed chemical analyses of tephra glass shards such as LA-ICP-MS trace element compositions which are currently in progress (e.g., Király et al. 2017).

Fig. 5.8 Comparison of glass chemical data of rhyolitic tephras from Ciomadul and other Eastern Mediterranean volcanoes with cryptotephra data from the Black Sea core M72/5-25. Bivariate plots of CaO and FeO versus the silica content SiO_2 are used to visualise the similarity of major element compositions of Ciomadul tephras (yellow, red, light and dark blue enveloped) with tephras from the Aeolian Islands (Italy), Aegean Arc Islands (Santorini, Kos, Nisyros, Yali), central and eastern Anatolia. Cryptotephra layers found in the sediment core from the south-eastern part of the Black Sea (BST samples) fall into two main time periods—younger than 34.5 ka and in between 34.5 and 48.3 ka—and are plotted as individual symbols (stars, asterix). Note that most cryptotephra data of the Black Sea from the older time interval (Asterix) match the major-element composition of the Ciomadul "BTS" tephra and partly overlap the compositions of the "St. Ana" and "Turia" tephras. For positions of volcanic centres and coring site see Fig. 5.4



5.6 Dispersal of Ciomadul Tephras: Modern and Past Wind Patterns in Romania

5.6.1 Local to Regional Distribution of Ciomadul Tephras

Dispersal of tephra strongly depends on the local to regional wind patterns at the volcano and in more distal areas on the amount of precipitation. Romania in general has a temperate continental to transitional oceanic climate. Prevailing winds in Romania are humid winds from the Northwest (*Westerlies*). Those show lower intensities in the eastern part of the country, where cold-dry north-easterly winds (*Crivăt*) from the Russian Plain dominate. Other local winds include Föhn winds in some foothill depressions and at the base of mountains, hot south-westerly winds (*Austru*) in western Romania, warm-wet winds from the South (*Băltăret*), and sea breezes at the Black Sea coastline (Fig. 5.9).

Ciomadul volcano is located in the Southeast Carpathian mountain range in the central part of Romania, where today mainly westerly and north-easterly wind systems prevail. Therefore, tephra that would erupt today would likely be transported either towards the east into the Black Sea region or towards the south-southwest into the Aegean region. However, wind pattern and resulting tephra dispersal were likely different during the time of the last Ciomadul eruptions, when climate was in general cooler than today. Reconstructions from Romanian loess deposits suggest that the prevailing winds were Westerlies during this period, which would imply a

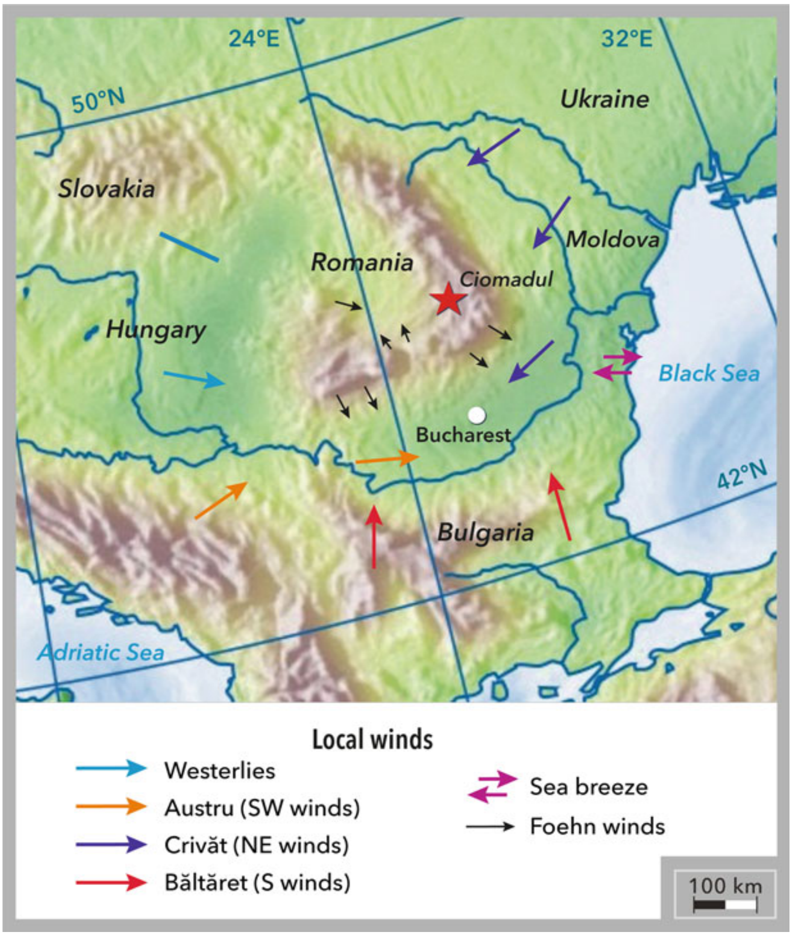


Fig. 5.9 Map of Southeast Europe and Romania with prevailing wind systems, controlling the distribution of tephra from volcanic eruptions

predominately easterly distribution of Ciomadul tephra (e.g., Bokhorst et al. 2011).

Past wind patterns can be best tested by glass chemical fingerprinting of tephra deposits in as many geological archives around the volcano as possible. Such studies have been initiated for the young Ciomadul tephras in proximal and medial-distal locations (Wulf et al. 2016; Veres et al. 2018; Chap. 6). However, detailed information from distal and ultra-distal sites are still rare.

The first results suggest that the four late-phase tephras were dispersed in several directions (Fig. 5.10): the "Turia" tephra, deposited from subsequent, typically phreatomagmatic eruptions, has been found at the proximal site near Bixad (Sepsibükszád) c. 2.6 km southeast of St. Ana, where it is 2–5 m thick and relatively coarse grained. It also occurs in three distal sites up to 21 km southeast of Ciomadul volcano near Turia (Torja) and Târgu Secuiesc (Kézdivásárhely). Here, the tephra is much finer grained and is at least 2 m thick (Karátson et al. 2016). The "BTS" tephra has been identified in two geological archives, both of which are located west of Ciomadul volcano. The first site is the type locality at Băile Tuşnad (Tusnádfürdő), positioned c. 2 km west of Lake St. Ana, which comprises a 4 m thick pumice-fall deposit overlain by c. 5 m thick pyroclastic-flow deposits (Karátson et al. 2016). The second site is the Ursului (Medve) cave in the Varghis Karst area located in ca. 30 km distance west-northwest of the volcano (Fig. 5.3a). Here, the finer grained "BTS" tephra reaches a thickness of 5–15 cm (Veres et al. 2018). The "TGS" tephra which again is result of a complex eruption succession has been detected so far in a number of proximal and three medial-distal sites as far as 21 km southeast of Ciomadul volcano. The proximal sites include the outlet of Mohoş crater (Rosu stream) and Románpuszta c. 2 km northeast of Lake St. Ana, and at Balondoş (Bolondos) Hill ca. 3.5 km in the East of the volcano. Tephra thicknesses at these sites vary between 2 and 5 m. In the medial-distal sites near Turia and Târgu Secuiesc, the "TGS" tephra is 10–40 cm

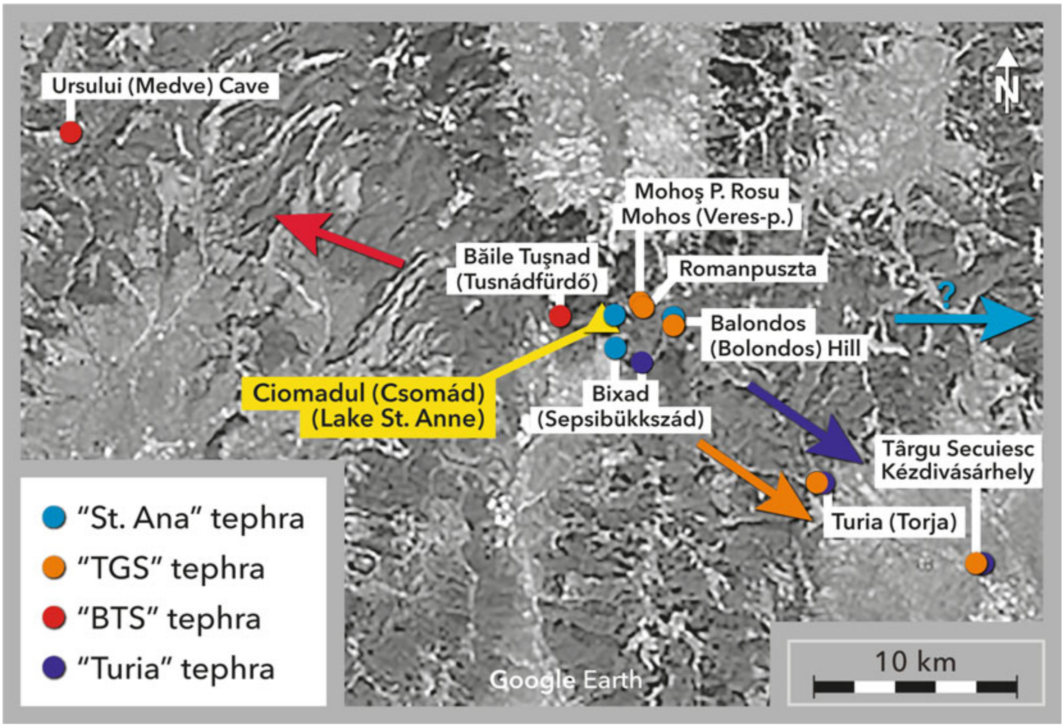


Fig. 5.10 Distribution of Ciomadul tephras in proximal and medial-distal sites

thick and overlies colluvial soil material that separates it from the older "Turia" tephra (Karátson et al. 2016). Tephra from the final "St. Ana" eruptions has been found at the inner slopes of St. Ana crater and in three other proximal sites northeast, east and southeast of the volcano, where it is up to 0.5 m thick. A distal tephra of 2–3 cm thickness with a "St. Ana"-like glass chemical signature has been identified in the loess sequence of Roxolany in the southwestern Ukraine, 350 km east of the volcano (Wulf et al. 2016) (Figs. 5.3b, 5.10). However, the correlation with the youngest eruption phase is currently challenged by evolving chronostratigraphic investigations at the loess site which indicate a much older age of this Ciomadul tephra.

5.6.2 Searching for Ciomadul Tephras in Distal and Ultra-Distal Sites

The distribution patterns of the four studied Ciomadul tephras suggest a predominant dispersal by westerly or north-westerly winds towards the east and southeast, but there are also exceptions as demonstrated by the dispersal of "BTS" tephra towards the west. The relatively large thicknesses of all tephras in distal sites between 21 km and potentially 350 km from the volcano raises the expectation of finding Ciomadul tephras in even further distal to ultra-distal sites in the Black Sea region ("Turia", "TGS" and "St. Ana" tephras) or in the northern Balkans and beyond ("BTS" tephra). However, finding suitable geological archives in those regions that cover the 60–30 ka time interval is not an easy task. Tephras dispersed to the East and Southeast could potentially be found in other loess sequences in the Ukraine or Russia or in the sediments of the Black Sea. The latter have been sampled during multiple scientific drilling campaigns, but most studied cores from the nearer, western part of the Black Sea cover only the last 30,000 years. Sediment core M72/5-25 from an ultra-distal (1000 km from source) site in the south-eastern part of the Black Sea is an exception and extends back to 64,000 years before present. Cullen et al. (2014) have investigated the cryptotephra content of this core in 2014 and identified multiple eruptions from Santorini (Greece), Italy, as well as central and possibly eastern Anatolian volcanic centres. Several cryptotephra layers tentatively attributed to yet unknown eruptions of the relatively nearby (350–500 km) central Anatolian volcanoes show similarities in glass major element composition to both the "Turia" and "St. Ana" tephras. However, ages of cryptotephra layers constrained between 48,300 and 34,500 years before present do not match the "Turia" and "St. Ana" eruption ages and therefore exclude a source from Ciomadul volcano. Other potential Ciomadul tephra archives in the Eastern Mediterranean region are located in the south and southwest of the volcano and include the Tenaghi Philippon peat bog in north-western Greece, and the Lakes Ohrid and Prespa in Albany/Macedonia. However, to date, none of these archives have revealed evidence for containing Ciomadul tephra. The occurrence of the "BTS" tephra at the Ursului site 30 km west of Ciomadul (Veres et al. 2018) indicates dispersal by easterly to north-easterly winds. Hence, further distal findings may be expected in sites in western Romania and potentially in the northern Balkan countries and beyond.

5.7 Findings of Other European Tephras in Romanian Geological Archives

It is noteworthy that not only tephra from Ciomadul volcano can be found in Romania but also widely (ultra-distally) transported tephra from other volcanic centres in Europe. These include Italian and Icelandic volcanic centres (Fig. 5.4). The first example is given by the occurrence of a several tens of centimetre-thick tephra from the "Campanian Ignimbrite" super-eruption in loess and colluvial soils in southern Romania (Veres et al. 2013) (Fig. 5.2a). The "Campanian Ignimbrite" erupted c. 40 ka ago from the Phlegraean Fields in southern Italy and has been dispersed by Westerlies across the Eastern Mediterranean region and towards the northeast as far as Russia, 2000 km east from its volcanic source. The second example derives from Holocene lake sediments in western Romania, where an intense cryptotephra search identified the early Holocene “Askja-S” tephra from Iceland (10.8 ka old; Kearney et al. 2018). The distribution pattern of this tephra was hitherto limited to northern and central Europe; the new finding in Romania implies an ultra-distal transport of more than 3200 km by strong north-westerly winds. Both examples demonstrate that Romania has in the past not only been impacted by volcanic ash fall from Ciomadul eruptions but also from other European volcanic centres, depending on the magnitude and wind patterns of respective eruptions. This needs to be considered for future volcanic risk assessments.

6

Palaeogeography: Syn- and Post-eruptive Landscape Evolution Around Ciomadul

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Abstract

Ciomadul's landscape represents an amalgamation of volcanic edifices that build up a lava dome complex. Spanning almost 1 million years of volcanic and geotectonic evolution, Ciomadul periodically released large amounts of volcaniclastic material that modified the local topography. The volcanic activity constrained the Olt River by carving the narrow and steep gorge at Tuşnad and clogged its alluvial plains with the sudden input of volcanically derived material such as laharic deposits. This geomorphological forcing is best expressed in the landscape we see today along the Olt valley with narrower sectors, and a ribbed and furrowed appearance of the side valleys and their terrace systems. This chapter aims to summarize the recent progress in understanding the syn- and post-eruptive landscape evolution in the area by looking at key sedimentary sequences along the Olt valley and assessing their tephrostratigraphic potential for providing direct evidence for past eruptive and volcanism-related events at Ciomadul.

6.1 Introduction

The stratigraphy and geochronology of sedimentary deposits around Ciomadul (Csomád) volcano are not yet well assessed despite that along the Olt or Turia (Torja) valleys (Fig. 6.1), thick successions of colluvial, fluvial, and aeolian deposits can be found. These Middle to Late Quaternary sedimentary deposits, alongside the wide and relatively flat Ciuc (Csíki) and Braşov (Brassói) Basins, represent a characteristic topography for the area that contrasts with the monotonous flysch mountainous landforms bracketing the Olt valley, such as the Baraolt (Barót) and Bodoc (Bodok) Mountains, and the

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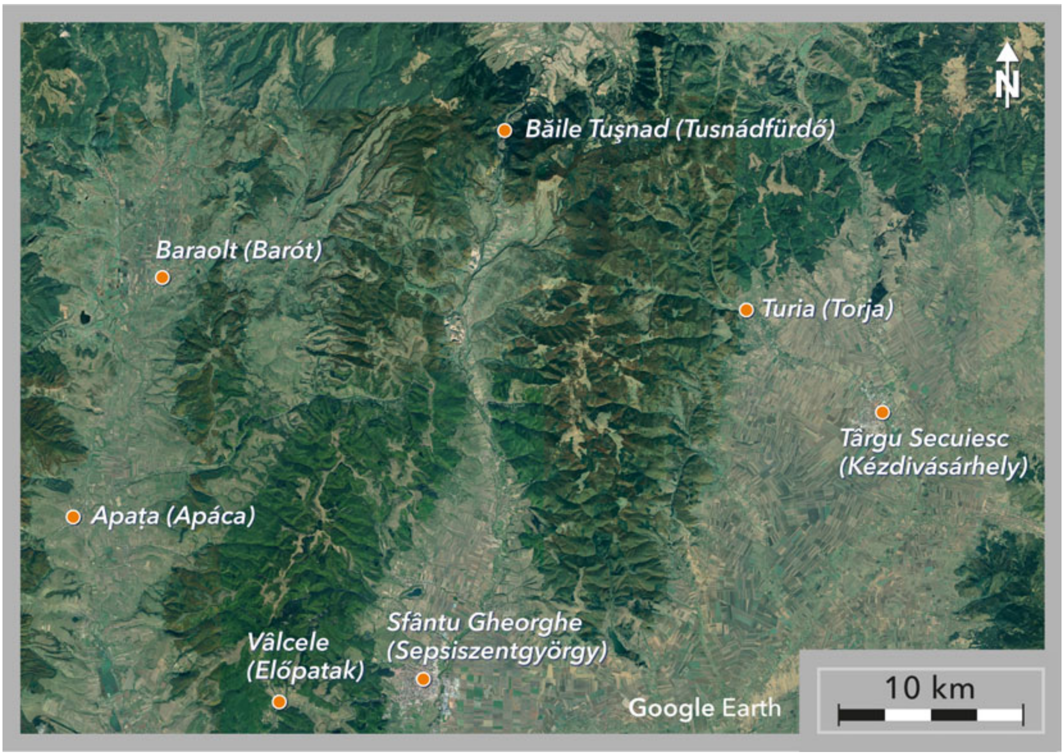


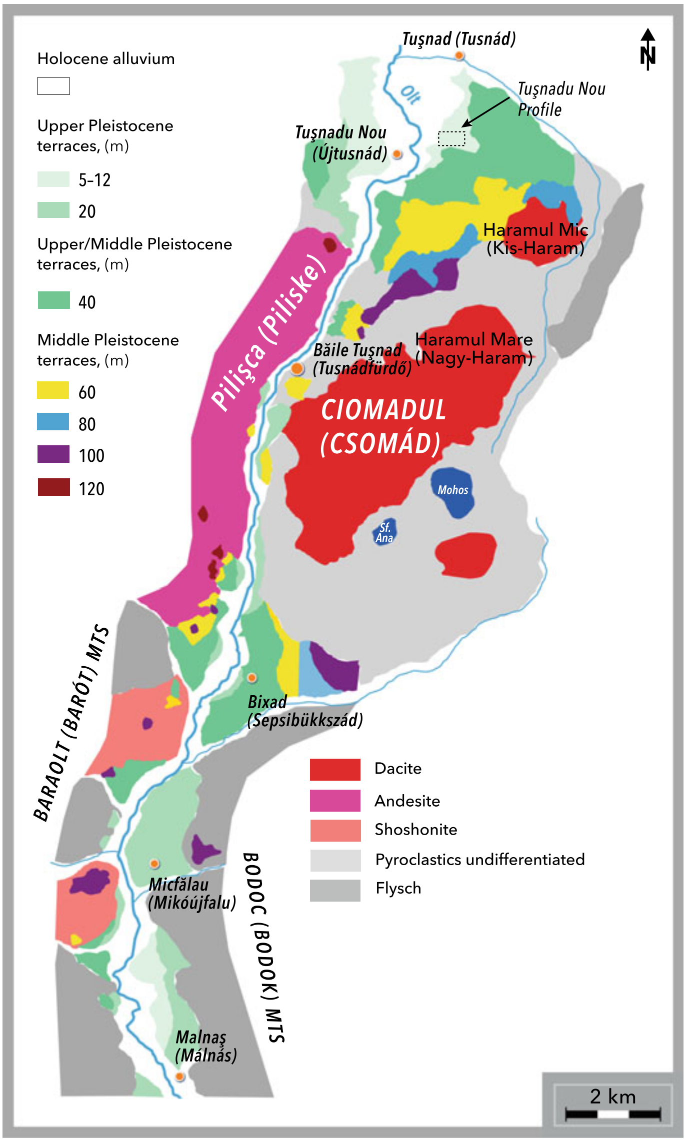
Fig. 6.1 Location of study area along the Olt valley between Tuşnadul Nou and Sfântu Gheorghe

volcanic landscape of Ciomadul and Harghita (Hargita) ranges. Although only a few sedimentary outcrops are available for observation along the Olt valley (Fig. 6.2), we can still employ tephrostratigraphy—the study of volcanic ashes embedded in sedimentary deposits—to characterize the palaeoenvironments, relief dynamics, and the landforms we see today, and use them to better understand the volcanic landscape evolution around Ciomadul volcano.

During the Quaternary period (2.6 Ma—present), river valleys experienced repeated changes caused by significant variability in temperature and precipitation between what are generally regarded as warm-wet interglacial and cold-dry glacial periods. The process is similar to the hydrological cycles we see on a seasonal basis, with large water release during the springtime, often with a risk of flooding and strong erosive power, enhanced sediment-load but also much reduced discharge after warm summer months. In the long term, this global variability in hydroclimate controlled the amount of water available, which in turn influenced the rate of landscape erosion. For example, a reduced vegetation cover during glacial periods resulted in a different water balance and much stronger slope erosion and along the lowest elevation of rivers and creeks. A consequence of this is that even coarse sediments, such as gravels and boulders, could be stripped from the landscape and delivered to the river valleys in larger quantities. This ensured a considerable fluvial sediment load, with rivers building large alluvial systems comprising thick sedimentary fluvial deposits, mainly gravel beds. On the contrary, during warm interglacials, under conditions like those experienced today, the vegetation cover protects the slopes from erosion, which results in river valleys carrying less and mainly finer sediments, and thus, due to the higher water discharge, often cutting channels within their floodplain areas.

In areas experiencing steady land uplift such as the Carpathians (Chap. 2), long-term changes

Fig. 6.2 Simplified thematic map of Tuşnadul Nou—Malnaş area showing the distribution of Olt river terraces, the volcanic rocks, the volcaniclastic deposits and the flysch rocks outcropping around Ciomadul (adapted from Ghenea et al. 1971)



in stream channel morphology and the variable intensity of erosional processes are significantly accelerated during the transitions from glacial to interglacial periods and vice versa (Vandenberghe 2008). The most obvious result of this process are river valleys characterized by a system of terraces, flanking one or both sides of the valley, with the oldest terrace further from the river and at higher elevation. Once formed, the terrace systems may be further impacted by landslides, buried under alluvial fans of small tributaries discharging into the main valley, or covered by mantles of windblown fine-grained sediments (i.e., loess). Therefore, the present-day landscape around Ciomadul and surrounding basins (Fig. 6.1) actually reflects a mosaic of deposits of varying age and characteristics and shaped by various erosional and/or accumulation processes that have been active through time.

As described in Chaps. 2 and 3, and also highlighted in Fielitz and Seghedi (2005) and Necea et al. (2013) for Ciomadul and surrounding areas both tectonic uplift, subsidence, and volcanism played a major role in landscape evolution

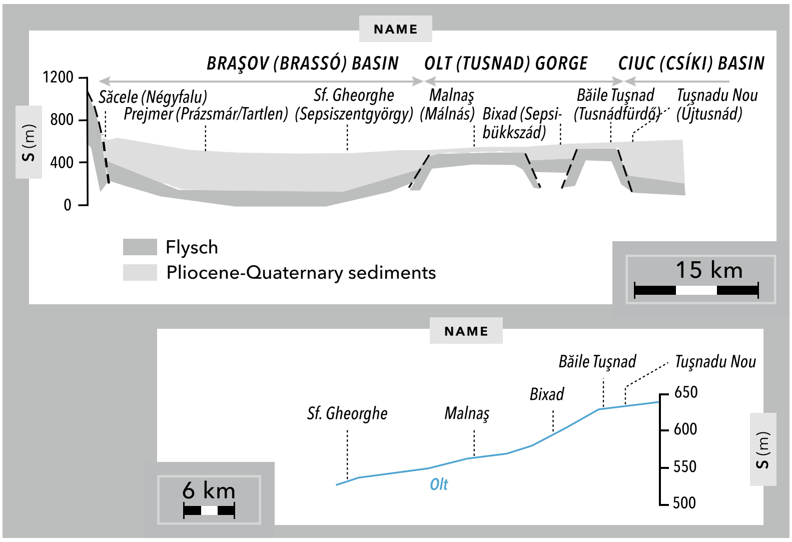


Fig. 6.3 Cross-section between Lower Ciuc Basin in the north and Braşov Basin in the south, highlighting the tectonic forcing on sediment accumulation (upper panel) and its impact on the river longitudinal profile (lower panel) (adapted from Ghenea et al. 1971)

in the larger southeastern Carpathian zone, particularly around the Ciomadul—South Harghita area (Karátson et al. 2019; Lahitte et al. 2019; Molnár et al. 2019). The effect of such tectonic and volcanic processes around Ciomadul has been the formation of laterally discordant landforms (Fig. 6.2) that induced a continuous adaptation of the river systems to cope with changes in the depositional or transport thresholds (Fig. 6.3), often irrespective of hydroclimatic forcing. In this chapter we show that the study of sedimentary volcanic ash layers provide unexpected information on the palaeogeography of syn- and post-eruptive landscape dynamics around Ciomadul for the last 150 thousands years.

6.2 Current Understanding of Ciomadul's Eruptive Activity for the Last 850 ka

Based on new data derived from K–Ar dating of volcanic rocks and digital elevation modelling (DEM)-based volumetrical considerations, Karátson et al. (2019) proposed an up-to-date palaeogeomorphological evolution scheme for the Ciomadul lava dome complex, highlighting also its influence on local landscape dynamics (see Chap. 3). Data show that Ciomadul developed on the erosional surface of Lower Cretaceous flysch and ~2 Ma old andesites from the neighbouring Pilişca volcano. Recent dating constraints indicate that Ciomadul experienced an extended eruptive history from ~850 ka (Lahitte et al. 2019, Karátson et al. 2019), with predominantly effusive activity during the first stage (~850 to ~440 ka) that also produced the isolated, peripheral domes such as Puturosu (Büdös-hegy) and Balvanyos (Bálványos). Subsequently, after possibly a long repose interval, a voluminous central dome cluster developed in the second stage of lava dome building from about ~200 ka. This occurred with well-documented explosive activity that resulted in the formation of the twin craters Mohoş and Sf. Ana during the youngest phase of volcanic evolution between ~60 to <30 ka (Karátson et al. 2016).

Our current understanding of the different stages in the formation of Ciomadul volcanic field holds important clues for interpreting the sedimentary sequences we describe in the following. But before presenting the two key sedimentary sequences discussed in this chapter, let us summarize the four major eruptions/eruptive successions that define the dominantly explosive activity at Ciomadul for the past c. 60 ka (Karátson et al. 2016) and whose tephra products can be found in various sedimentary profiles. These include:

(i) the “Turia” eruption(s) older than 51 ka, likely from the Mohoş crater;
(ii) the complex “BTS” eruption from the Sf. Ana crater at c. 40–42 ka; (i) and (ii) are collectively termed the Early Phreatomagmatic and Plinian Activity (EPPA);
(iii) the Middle Plinian Activity comprising plinian-subplinian successions, of which the best known is the complex “TGS” eruption at 31.5 ka; and
(iv) the final dominantly phreatomagmatic eruptions (Last Sf. Ana Phreatomagmatic Activity, LSPA), in particular the “St. Ana” eruption at c. 28–29 ka.

Although the geochemical composition of glass shards released from all these eruptions is generally rhyolitic, there is significant elemental variability to distinguish between the different eruptions (see details in Chaps. 3 and 5), but stratigraphic considerations must also be taken into account for more comprehensive results.

6.3 The Olt Valley Between the Lower Ciuc and Braşov Basins

Previous chapters already mentioned the volcanic and geotectonic landscape towards the narrow divide at Băile Tuşnad (Tusnádfürdő) called the Tuşnad Gorge (Fig. 6.1). It stretches between the western part of the Ciomadul lava dome complex (comprising peripheral dacitic domes and the Mohoş/Mohos and Sf. Ana/Szent Anna twin craters) to the east, and the southern fringes of the andesitic Pilişca (Piliske) volcano to the west (Fig. 6.2). From Tuşnadul Nou, in the Lower Ciuc Basin, the slope of the terrain towards Băile Tuşnad and the Sfântu Gheorghe Basin becomes steep (Fig. 6.3), pointing to disequilibrium in river flow and morphological dynamics. This is best exemplified by remnants of terrace systems found at different altitudes within and down-valley from the Tuşnad Gorge (Ghenea et al. 1971), as well as by the presence of thick pyroclastic deposits, especially in the Lower Ciuc area and within the Bixad area, south of Ciomadul (Fig. 6.2).

6.3.1 The Sedimentary Profile at Tuşnadul Nou (TSN)

A very interesting sedimentary profile, unstudied so far, is found at the Tuşnadul Nou (Újtusnád) quarry, not far from the northernmost lava domes of Haramul Mic (Kis-Haram, emplaced ~150 ka) and Haramul Mare (Nagy-Haram, formed ~100 ka (Molnár et al. 2019; Lahitte et al. 2019; Karátson et al. 2019). Dacitic lava flows likely related to these domes extend down to the alluvial plains of the Lower Ciuc Basin, with the lava rocks exposed in a few small quarries, as well as on the banks of the Olt river and crossed by the national road no. 12 just south of Tuşnadul Nou village. The regional relief indicates that the dacitic lava flow(s) and the extended pyroclastic talus observed within the Lower Ciuc Basin and towards Băile Tuşnad influenced the Olt river morphodynamics, constraining the river flow to a narrower confine towards the Tuşnad Gorge (Fig. 6.2).

The Tuşnadul Nou sand quarry is a key location for understanding the regional relief dynamics during the last eruptive phase of Ciomadul (~60 to <30 ka), as well as lateral variability in the accumulation of volcaniclastic products in this sector of the Lower Ciuc Basin. The c. 500 m long quarry wall exposes c. 15 m thick volcaniclastic and sedimentary deposits (Figs. 6.4 and 6.5). From top to bottom, the succession reveals c. 0.5 m thick topsoil (Unit A), which overlies a c. 2–3 m thick Unit (B) consisting of sandy loess and volcaniclastic-rich aeolian reworked sediments. Unit C (1–1.5 m thick), rich in 2–5 cm large pumices, is the next, overlying a 3–4 m thick Unit D, consisting of alternating centimetre beds of primary fine ash and reworked sediments, and showing soft-sediment deformation structures, which we interpret as seismites (see below). Massive beds tens of centimetre thick of fine matrix including whitish-to-greyish slightly reworked pyroclastic-flow deposits dominate the lower half of the sequence within Unit E (Figs. 6.4 and 6.5). Thin layers with evidence of water escape structures and channel infills are also visible within Unit E, as well as the remnants of tree

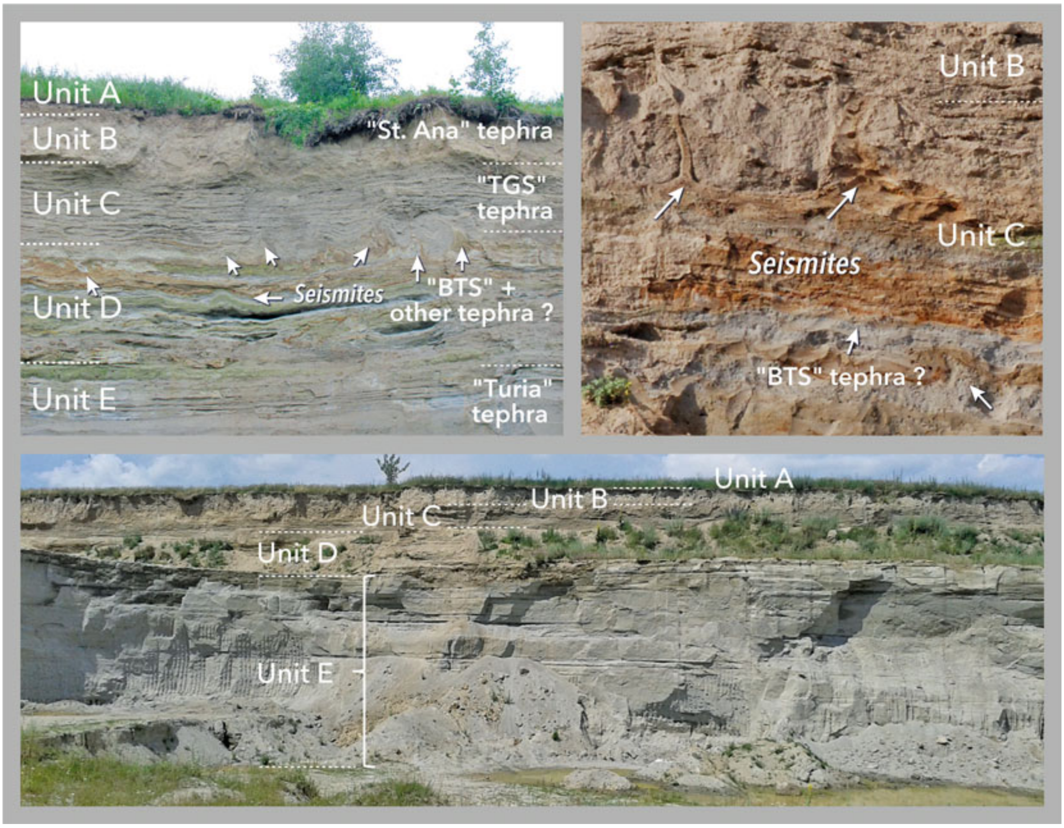


Fig. 6.4 Tuşnadul Nou (TSN) sedimentary and volcaniclastic profile. Left upper panel: the volcaniclastic succession detailed in the upper part of the quarry, with main stratigraphic units identified (A to E) and our tephrostratigraphic interpretation (i.e., St Ana tephra, TGS tepha, BTS tephra, Turia tephra) as discussed in the main text. Right upper panel: details on the seismites structures identified along the profile. Lower panel: the ca. 15 m tall profile at TSN highlighting the consistent thickness of unit E (*photo credit*: Daniel Veres)

trunks that have been dislodged and entrained within the pyroclastic flows (Fig. 6.5).

6.3.2 Tuşnadul Nou—An Unique Profile for Tracing the Most Recent Eruptive Activity of Ciomadul?

Despite the fact that no chronological constraints are yet available, an answer can be provided using existing geochemical data on distal tephra and proximal volcaniclastics as discussed in Karátson et al. (2016) and in Chap. 5. In this respect, we analyzed the glass-shard geochemistry (Fig. 6.6) of representative samples from each major volcaniclastic unit exposed at Tuşnadul Nou, and our preliminary conclusions are:

- Unit E: Two samples from different beds within Unit E labeled TSN-1.1 and TSN-1.2 provided data similar to the “Turia”-type tephra layers and pyroclastic-flow deposits as presented in Karátson et al. (2016) and dated to >51 ka. The internal stratigraphy within this unit is fully concordant with other similar deposits exposed on the flanks of Sf. Ana crater or along the Turia valley (see Chap. 3). In light of these results, it appears that pyroclastic flow layers within Unit E are linked to the Turia-type eruptive succession. Indeed, Turia-type pyroclastic products are widespread regionally (see

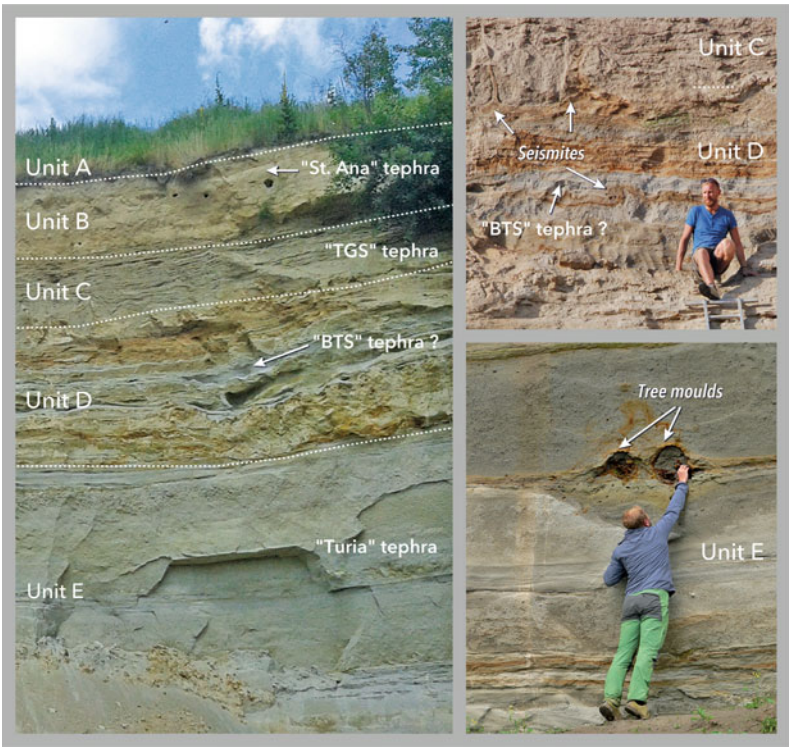


Fig. 6.5 Tuşnadul Nou (TSN) sedimentary and volcaniclastic profile. Left panel: close-up image of units A to E, and their stratigraphic boundaries. Upper right panel: details on the seismites and the BTS tephra; Lower right panel: example of tree moulds casts within Unit E (*photo credit*: Daniel Veres, Ulrich Hambach, Dávid Karátson)

Karátson et al. 2016) and our observations at Tuşnadul Nou further add to the magnitude of these eruptions that were probably sourced from the Mohoş crater.

- Unit D: Although this unit has been strongly impacted by soft-sediment deformation structures, it retains the original depositional facies, in which thin sediment beds separate several primary tephra layers comprising mainly pumices and shattered lava pieces in a sand ash fraction. First, we interpret the soft-sediment deformation structures as *seismites*, which are earthquake-deformed sedimentary layers formed by ground shaking (e.g., liquified sand). The presence of numerous *soft-sediment deformation structures* such as clastic dikes (Fig. 6.4) support our interpretation and indicate a period of enhanced local seismic activity related to eruptions and/or lava dome explosions from Ciomadul. Second, it is very likely that the tephra layers (see for example sample TSN-2.1) observed within Unit D relate to primary depositional events; we base this assertion on field relationships documented at Tuşnadul Nou quarry, but also on a thick sediment sequence exposed on the southern slopes of Sf. Ana crater, the so-called BIX-4 site (Karátson et al. 2016). Furthermore, in correspondence with our findings, a dozen tephra/volcaniclastic layers, some in consistent thicknesses, have been documented in the sediment core recovered from the Mohoş crater in 2014 and which covers the last 40–50 ka.

Even if additional research is necessary to verify these assumptions, we suggest that several (some of minor magnitude) eruptions may have occurred at Ciomadul between the major Turia (>51 ka) and TGS (31.5 ka) eruptive events, including the already established BTS eruption dated to c. 40–42 ka. Notably, this volcanically highly active eruptive period was collectively termed as the EPPA by Karátson et al. (2016). Two superimposed tephra beds exposed in another sand quarry at Sânmartin (Csíkszentmárton), 10 km north of Tuşnadul Nou, likely belong to the EPPA phase (see discussion in Chap. 3).

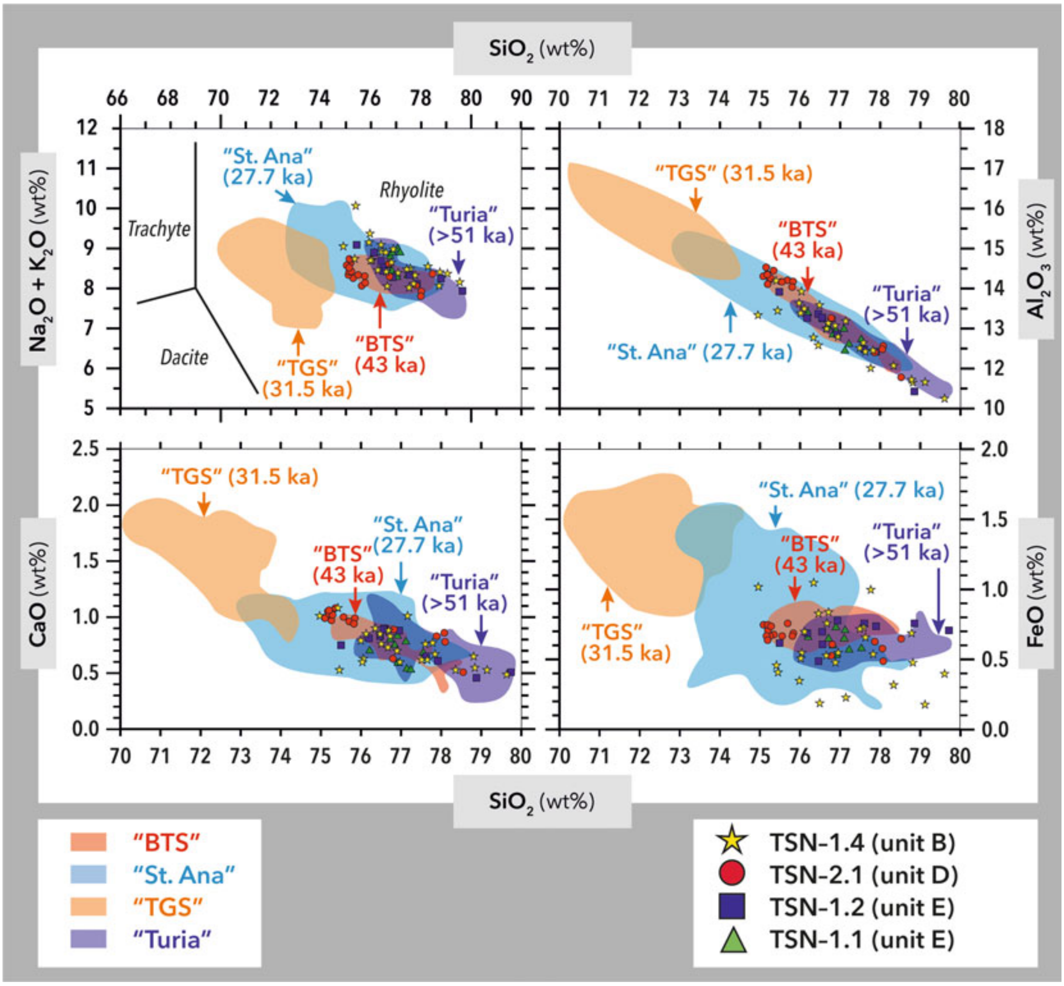


Fig. 6.6 Glass shard chemical data of the Tuşnadul Nou (TSN) profile versus the chemical envelops of glass shard data from the main Ciomadul eruptions for last 51 ka (Karátson et al. 2016; Wulf et al. 2016)

– Unit C: It is very likely that the pumice-rich Unit C relates to the MPA phase, which is linked to eruptions from the Sf. Ana crater at around 31.5 ka. Volcaniclastic products related to this eruption are widespread regionally, from massive pyroclastic-flow and fall deposits on the slopes of Ciomadul (Szakács et al. 2015; Karátson et al. 2016) to pumice-fall deposits found as far as Târgu Secuiesc (Chap. 3). It would be no surprise that such deposits are found at Tuşnadul Nou, but more research is needed to assess whether the undulating bed architecture seen within Unit C reflects the impact of syn or post-eruptive deformational processes (seismites, bed liquefaction, convolution) as documented within Unit D.

– Unit B: Although this unit comprises mainly volcaniclastic sediments and sandy loess-derivates, its lower boundary towards Unit C is clearly visible (Fig. 6.5). A sizable increase in volcaniclastic content, in a fine, whitish powdery fraction is seen in the middle part of the unit. A sample collected from this spot (sample TSN-1.4) returned glass-shard geochemical composition similar to what Karátson et al. (2013, 2016) and Wulf et al. (2016) defined as the St. Ana tephra, linked to the last explosive eruptions at Ciomadul ca. 29–28 ka (Karátson et al. 2019) (Fig. 6.6). This find is exceptional and, alongside data discussed in Karátson et al. (2016), it adds clear evidence for the presence of fine ash from this latest eruption also in proximal settings. The fact that the St. Ana tephra is not preserved in a considerable thickness can be explained perhaps by its emplacement during the Last Glacial Maximum, a time period of strong wind activity that resulted in large-scale wind erosion of exposed landscapes, re-deposition of loose tephra material, and formation of thick loess deposits in more sheltered locations.

6.4 Sedimentary Profiles in the Olt Valley South of Băile Tuşnad

Only a few man-made outcrops exist along the Olt valley between Băile Tuşnad and the Braşov Basin, and the most relevant ones for our understanding of the regional relief dynamics are those exposed at Bodoc (Bodok), and the sand quarries at Zoltan (Étfalvazoltán), Ghidfalău (Gidófalva), Coşeni (Szotyor), and Chichiş (Kökös) in the Olt terrace deposits (Fig. 6.7). Although the profiles are continuously modified by modern sand quarrying, interesting observations have been made in the past concerning the fluvial infill of the Olt valley. For example, Ghenea et al. (1971) discussed the terrace systems (as summarized in Fig. 6.7) along the Olt valley between Malnaş and Sfântu Gheorghe, of which the most extensive is the Upper Pleistocene (last 130 ka) terrace in the step of 10–15 m, situated nearest to the Olt river valley. Remnants of older terraces are preserved only in patches, and at higher elevations and are strongly impacted by both slope erosion and geotectonic processes (Necea et al. 2013).

From our field observations, there is clear stratigraphic evidence of previously unknown eruptions from Ciomadul in the form of tephra layers/pyroclastic deposits preserved within the

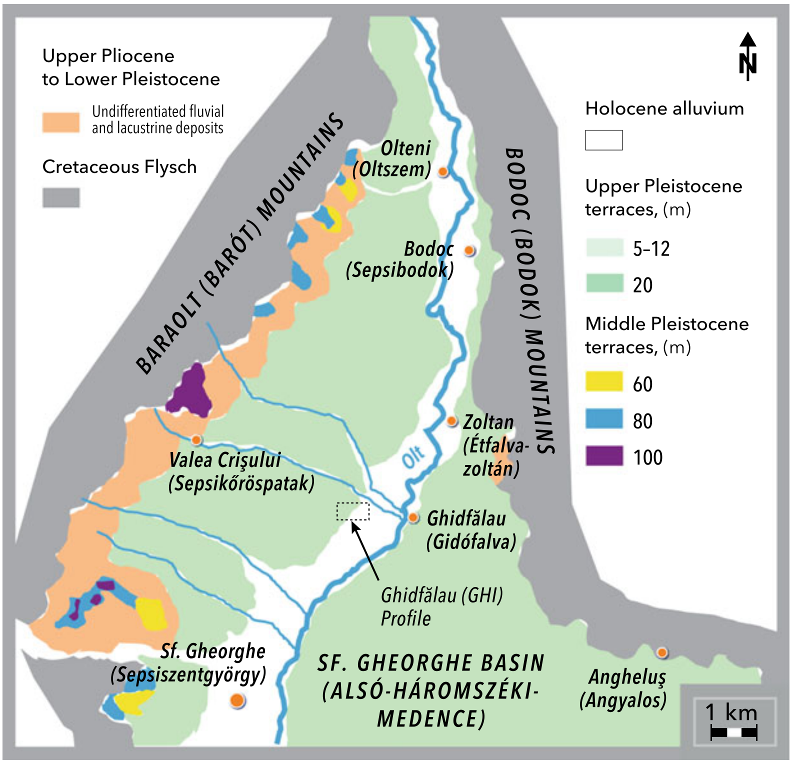


Fig. 6.7 Simplified relief map of the Olt valley between Malnaş and Sfântu Gheorghe area— adapted from Ghenea et al. (1971) showing the distribution of river terraces and location of Ghidfalău (GHI) profile

fluvial sequences along the Olt valley upstream of Sfântu Gheorghe town. For this book chapter, we will focus however only on the observations recently made at the new sand quarry at Ghidfalău.

6.4.1 The Ghidfalău (GHI) Sedimentary and Volcaniclastic Profile

The profile exposed at Ghidfalău, c. 3 km north of Sfântu Gheorghe (Sepsiszentgyörgy) is one of the best examples of the potential catastrophic impact the eruptions from Ciomadul had on the regional landscape evolution in the recent past (Fig. 6.7). Here, the thick volcaniclastic deposits that have been exploited as construction materials for decades provide a most interesting feature, both stratigraphically, but also for their likely interpretation as volcanogenic products, namely *lahars*, (as has long been speculated by Rădulescu and Peltz 1968).

Lahar is an Indonesian term, which refers to rapid, usually destructive debris flows or mudflows that occur when pyroclastic deposits released during volcanic eruptions mix with water and travel downslope into adjacent river valleys, incorporating also a mixture of pre-eruptive rocks (i.e. debris). They tend to follow valleys and thus the mudflows are constrained into a narrow space, which, along with the significant (>5%) fine fraction, greatly increases their destructive capacity. Lahars are one of the deadliest volcano hazards with the power of shaping the surrounding relief as well as inducing enormous loss of human life and livestock. There are numerous examples throughout our recent history of lahar disasters (e.g. Nevado del Ruiz, Colombia, 1985, with many fatalities), which make the study of these deposits even more compelling for understanding the past impact of such processes in the Ciomadul area.

Our stratigraphic field observations indicate that apart from other volcaniclastic and sedimentary units two major *lahar* or *lahar-like* units are visible in the quarry at Ghidfalău. This is typically illustrated in Fig. 6.8 by the sharp lateral contact between the two-lahar beds (Units D and H, see discussion below; Fig. 6.9), as well as by the different glass-shard chemical composition of the pumice clasts we collected within these units (Fig. 6.10). Lahars can occur in volcanic areas during an eruption or following heavy rainfall, snow melt, or sudden outbursts of dammed lakes that remobilize unconsolidated pyroclastic and other volcaniclastic deposits. For the sequence at Ghidfalău, given the abundance of pyroclastic material within the lahar units in a relatively uniform grain-size matrix, we consider they have been emplaced more or less syn-genetically with some major eruptions from Ciomadul.

Dating and interpreting such deposits is difficult, and for highlighting the existing age constraints, we need to assess first the stratigraphic relationships visible at Ghidfalău. From top to bottom, the exposed sequence comprises the topmost soil labelled as Unit A (Fig. 6.8). It represents a quiet sedimentation regime for the last 11.7 ka, the time period for the formation of the topsoil cover corresponding to the current interglacial period, the Holocene. The topmost soil caps Unit B that comprises yellowish carbonate-rich sandy loess, which constrains a period of predominantly wind-blown accumulation of finer particles. By analogy with loess deposits in the Lower Danube region, Unit B most likely represents a period of enhanced aeolian sedimentation linked to Marine Isotope Stage (MIS) 2. It overlies Unit C, which consists of loess-derivates but comprises also fining-upwards gravelly slope scree deposits, and pyroclasts reworked from the top of Unit D.

The succession A–C rests upon what we interpret as the *upper lahar* Unit D (Fig. 6.8). This unit comprises mainly pumiceous pyroclasts (i.e., very rich in pumice and pumice lapilli fragments) with grain sizes ranging from sand ash to very fine-gravel fractions. Boulders consisting mainly of andesite and dacite lava rock appear randomly throughout (Fig. 6.9), but a large accumulation of such boulders of various sizes towards the bottom of the unit as seen in some places along the quarry may indicate gravitational accumulation during transport within the laharic flow (Fig. 6.8). Most of these boulders are well

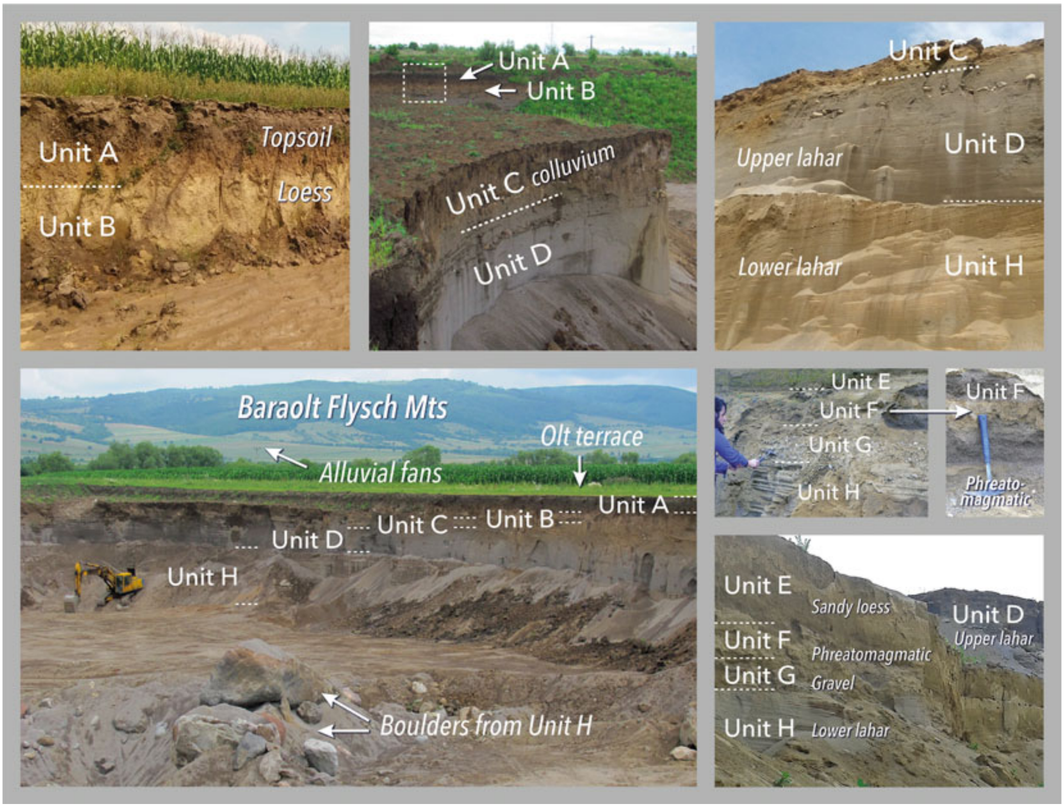


Fig. 6.8 Ghidfalău (GHI) sedimentary and volcaniclastic profile. Upper left panel: details on the topmost stratigraphic succession showing the relationship between the units A and B as discussed in the main text. Upper middle panel highlights the relationship between units C and D, and Upper right panel shows the discordant contact of units D and H. Lower left panel shows the lateral stratigraphic context of GHI profile, and Lower right panel shows the more continuous lateral stratigraphic context between units D and H (*photo credit*: Daniel Veres)

rounded. This is a clear indication of their fluvial transportation, albeit the degree of roundness very likely indicates their remobilization from preexisting fluvial deposits upstream.

In Fig. 6.9 lowermost panel it can be seen that to the side of the quarry, thus parallel to the main river flow direction towards south, the *upper lahar* Unit D overlies a 2–5 m thick yellowish loamy to sandy loess (Unit E). We shall mention that it is not at all clear how much of Unit E has been removed when the upper lahar Unit D was emplaced, but in the middle sector of the quarry (Fig. 6.8), the upper lahar Unit D directly overlies another lahar-type deposit, which we label as the *lower lahar* Unit H. This unit appears much coarser than Unit D, it has a different colour and bed architecture, and is distinguished by the large number of boulders entrained within, some of enormous sizes (up to 10–15 m in size). The presence of the typical Ciomadul dacite, in addition to the frequent oversized boulders suggest remobilized talus breccias from around the lava domes that build up the Ciomadul lava dome complex.

6.4.2 Distinguishing Between the Two Superimposed Lahar Units at Ghidfalău

The sharp contact between the upper lahar Unit D, greyish in colour, with massive layers

Fig. 6.9 Ghidfalău (GHI) sedimentary and volcaniclastic profile. Upper left panel shows a close-up of the discordant contact between units D and H; Upper right panel shows the stratigraphic contact of units D and E. Middle left panel highlights the size and rock type of boulders entrained within unit H, and Middle right panel shows the erosive contact between units D, E and H. Lowermost panel details the lateral stratigraphic succession between units D and H, and existing chronological control (available IRSL, infrared stimulated luminescence ages also indicated) (*photo credit*: Daniel Veres)

predominantly horizontally bedded cuts discordantly into the lower reddish Unit E, which is coarser grained, and shows slightly inclined bed geometries. In places, at the contact between the two-lahar units, large chunks of loess eroded from Unit E (Fig. 6.9) have been entrained adding to the evidence that the upper lahar (Unit D) discordantly cuts into the pre-existing deposits. Second, we collected small pumices (1–2 cm in size) from throughout the lahar Units D and H and had these subjected to geochemical analyses via electron probe microanalysis. Preliminary results indicate that the two units are also clearly geochemically distinguishable from each other, the upper lahar Unit D showing an intermediate chemistry between the "TGS" and the "St. Ana" type compositions, whereas lahar Unit H has a higher silica composition that is rather similar to a "Turia"-type tephra (Fig. 6.10). These chemical data alongside the stratigraphic considerations are strong arguments for distinguishing between the two-lahar

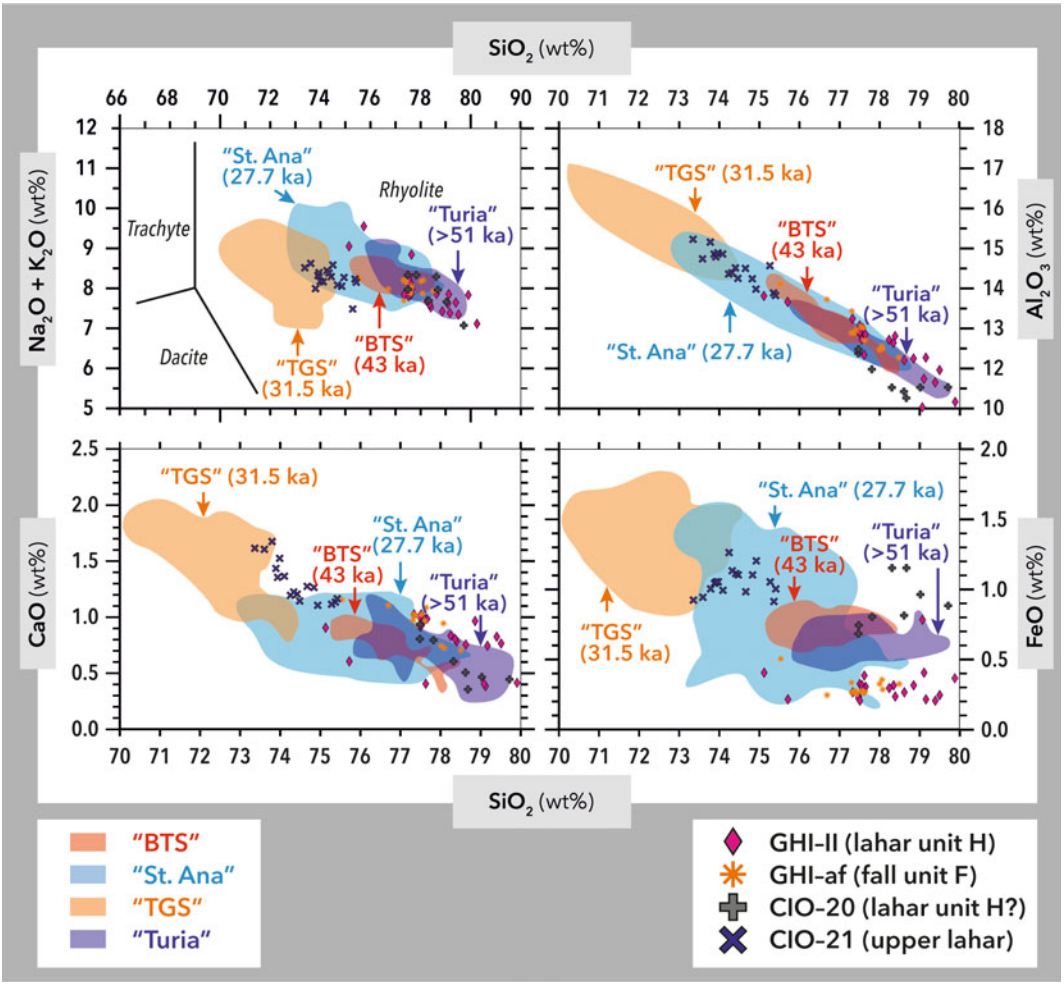


Fig. 6.10 Glass shard chemical data of the Ghidfalău (GHI) profile versus the chemical envelopes of glass shard data from the main Ciomadul eruptions for last 51 ka (Karátson et al. 2016; Wulf et al. 2016)

units, but what can be said about the chronological relationships?

To answer this question, we have to take a closer look in the quarry sector where the lowermost sedimentary succession can be better assessed (Fig. 6.9). Here, below Unit E, the exposed sequence continues with Unit F (sample GHI-af) comprising two subsequent layers of phreatomagmatic ash-fall, first reported here, each around 20 cm thick and separated by a thin sedimentary bed. The two-phreatomagmatic ash layers are coarse, well- sorted, comprise mixed lava clasts and show some upward grading. Maximum clast sizes vary around 2.5 cm, but most of the clasts are in the 0.5 cm range or finer. These characteristics point to a direct ash fall deposition following an explosive eruption of Ciomadul—indeed, as seen in Chap. 3, phreatomagmatic eruptions have already been documented at Ciomadul both for the Turia and the latest St. Ana eruptive phases.

The next in succession is Unit G around 0.5 m thick and comprising mainly flysch gravel; it indicates a period of alluvial fan build-up, probably connected to enhanced detrital input by the nearby Valea Crişului (Sepsikőröspatak) river that drains the Baraolt flysch mountains to the west. The lower laharic Unit H (sample GHI-ll) is the lowermost unit exposed in the quarry, and although it has been available for study for only 3–4 m in thickness at this spot, it shows the same characteristics as the lahar Unit H at the quarry centre (sample CIO-20). Its upper boundary towards Unit G is gradual, but its lower contact is not exposed.

To acquire reliable chronological data, several samples from Unit E were dated by the luminescence method that determines the time elapsed since mineral particles have last been exposed to light, and thus, denotes the age of particle burial and deposit formation (see methodological principles highlighted in Chap. 3). Here, we briefly discuss results of the pIRIR$_{290}$ luminescence dating protocol that focuses on dating the last exposure to light for feldspar mineral grains. By this method, the uppermost dated sample within Unit E yielded an age of 134.4 ± 7.6 ka, whereas the lowermost one gave an age of 153.1 ± 8.5 ka (Fig. 6.9). Altogether, these results suggest that the sedimentation period of the sandy loess represented by Unit E took place during MIS 6. This glacial stage dates back to c. 190–130 ka ago and has been characterized by the deposition of thick accumulations of windblown deposits, such as loess, similar to what we have observed at Ghidfalău within Unit E.

These chronological data imply that the lower lahar Unit H as well as the phreatomagmatic Unit F are most likely either of MIS 6 age, or perhaps even older. Nonetheless, this is the first reliable field stratigraphic assessment, as well as geochemical and chronological data of tephra layers originating from eruptions at Ciomadul likely older than the last interglacial. This implies that by investigating in more detail the distal field stratigraphy combined with radiometric dating, the hypothesis first raised by Karátson et al. (2013) on the likelihood of explosive eruptions from Ciomadul older than the EPPA phase can be better assessed. More work is needed in order to clarify these questions, but as the contact between the two-lahar beds seen in the middle of the quarry at Ghidfalău is clearly discordant, one might expect significant time gap in between at this very spot. This calls for careful field assessment of stratigraphic relationships, highlighting also the utility of glass-shard geochemical data (see Chap. 5) in differentiating between eruptive products from the Ciomadul volcanic field.

6.4.3 The Cause of Laharic Flows at Ciomadul?

The processes generating lahar deposits along the Olt river down-valley from the Tuşnad Gorge were volcanic eruptions from Ciomadul that released large amounts of pyroclastic material from ash fall/flows, followed by rapid transportation of these products to the Olt's drainage network. The limited evidence of fluvial features such as the characteristic staking pattern of fluvial deposits, or the limited sorting observed would indicate that these deposits were emplaced following mass-flow along the palaeo-Olt river valley. Damming of the narrow valley upstream of the Tuşnad Gorge (or between Bixad and Malnaş) may have easily and frequently occurred following eruptions at Ciomadul, with the volcanic products flowing into the narrow divide between Ciomadul and Pilişca volcanoes, and effectively blocking the river discharge. It is thus likely that eruptions from Ciomadul, particularly those that produced significant pyroclastic flows such as already documented for the TGS eruption, led to short-term blockages of drainage at, or upstream of, present-day Băile Tuşnad. Overflows may have then triggered rapid erosion of the loose rock debris that formed the natural dam, resulting in catastrophic overspills entraining not only pyroclastic deposits but also ripping off blocks of rocks from the surrounding volcanic landscape or remobilizing previously deposited fluvial sediments such as gravels and boulders. It is well known that when concentrated river flow occurs alongside a narrow channel such as, for example, the Tuşnad Gorge, it can cause fast and deep incision into the surface by turbulent flows. The presence of very large boulders—several metres in diameter—in different morphologies, from rounded to angular, and especially of different rock types ranging from andesites and dacites to Cretaceous conglomerates, stand proof for the catastrophic emplacement of the lahar deposits alongside the Olt river valley downslope of Tuşnad Gorge (Figs. 6.8 and 6.9). Although similar deposits were documented only in a few other sand quarries southward of Ghidfalău, it is likely they cover a much larger surface area within the Braşov Basin but are currently obscured from view being buried under younger fluvial and aeolian deposits (Fig. 6.7).

6.4.4 Linking Lahars at Ghidfalău to Eruptions from Ciomadul?

Based on the limited age constraints discussed above, it appears that Unit H is older than Marine Isotope Stage (MIS) 6, whereas lahar Unit D that discordantly cuts into the existing sediments must be much younger (i.e., younger than 134 ka). If we consider the geochemical composition of pumices collected from these deposits, lahar Unit D shows a MPA-type composition. Lahar Unit H shows a composition rather similar to the EPPA field, but also with slightly more scatter in the major element oxides that would allow defining a new geochemical envelope for volcanic activity at Ciomadul older than the EPPA (Fig. 6.10).

The MPA activity was characterized proximally by widespread, pumiceous pyroclastic flow deposits, mostly poorly sorted massive lapilli tuffs, and distally by pumiceous pyroclastic-fall deposits. The eruption(s) that led to the formation of these deposits have been defined as the MPA (Middle Plinian Activity: Karátson et al. 2016) and are currently dated to c. 31.5 ka (Harangi et al. 2010; Karátson et al. 2016; Wulf et al. 2016). One of the latest MPA eruptions is represented by the TGS tephra occurrence at Târgu Secuiesc (see Chaps. 3 and 5). It shall be mentioned that deposits linked to this eruption blanket the slopes of Ciomadul in all directions, being visible in several outcrops as discussed in Chap. 3. Large volcaniclastic aprons blanketing the foot of Ciomadul around and south of Bixad village indicate preferential surge directions towards west and south, into the Olt, Valea Rosie, and Jimbor valleys, following eruptions from the Sf. Ana crater (Fig. 6.2). Given the corresponding glass-shard geochemical composition between pumices from the laharic Unit D and these of the TGS tephra, we speculate that there is a genetic link between the two. This assertion is further strengthened if we consider the stratigraphic relationships at Ghidfalău previously discussed between Units A and D, and the fact that the terrace deposits were already considered of Upper Pleistocene age by Ghenea et al. (1971), following biostratigraphic considerations. However, further dating and analyses of the sedimentary deposits exposed at Ghidfalău are necessary for testing these hypotheses.

As for the age and origin of laharic Unit H, at this stage of research we can only state that it is linked to an eruptive phase at Ciomadul dating to or possibly even predating MIS 6. To date however, almost no information is available on the early explosive eruptions of Ciomadul, even though Karátson et al. (2013) suggested that Ciomadul Mare ridge that towers above the rims of Mohoş and Sf. Ana craters could be a crater wall remnant of an older explosive eruption. This possibility was further substantiated by the recent K–Ar dating of lava rock from the Ciomadul Mare ridge to 133 ± 18 ka (see discussion in Chap. 3). Certainly, such an age relates to the dome building activity of the central part of the volcano preceding a (possible) explosive eruption that truncated the Ciomadul Mare, but it is expected that future research will fully clarify the tephrostratigraphic potential of Ciomadul beyond the last 130 ka.

6.5 Summary

We showed that sedimentary profiles along the Olt valley could reveal unexpected information on past landscape dynamics and their tight coupling with volcanic and tectonic activity in the region. By carefully evaluating stratigraphic field relationships, we showed that even in proximal settings a complex evidence of past volcanic activity could be discerned, such as in the new volcaniclastic profile described at Tuşnadul Nou. Apart from the importance of this profile in better assessing the timing and extent of past eruptive activity at Ciomadul, further study of the soft-sediment deformations structures we interpret as seismites will provide us with crucial information on past seismic activity, its timing, and the related hazard.

Furthermore, the existence of older eruption phases throughout the long evolution of Ciomadul have long been speculated, but to date only limited evidence has been provided, and especially no numerical data was available for placing these events more securely in time. We showed that the interesting profile at Ghidfalău preserves unique evidence of catastrophic discharge modulated by sudden input of volcanogenic material from Ciomadul into the Olt river valley. We interpret these deposits as reflecting laharic events, some of the most destructive geomorphological agents, but also potent landform constructive events. Based on careful stratigraphic and geochemical assessments we also highlighted the potential of new tephra layers older than the EPPA phase (dating to >51 ka) for improving our current understanding of the dynamic evolution of the Ciomadul lava dome complex throughout its long life span.

7

Ciomadul Volcano: Dormant or Extinct?

Alexandru Szakács

Abstract

Ciomadul (Csomád) volcano has been subjected to a period of intense research over the past few decades owing to its relatively recent eruption less than 30,000 years ago, raising important questions about possible future activity. The presence of an incompletely frozen upper crustal magma chamber beneath the volcano pointed out by various geophysical investigations and precedents of previous eruptions following long-lasting periods of inactivity are further arguments in favour of a thorough scrutiny of this issue. However, due to sensational media coverage, this question is often exaggerated and distorted by local and international news outlets. This chapter aims to discuss the current status of Ciomadul volcano and its capability for further eruptions in light of all available geological and geophysical data as well as theoretical considerations.

7.1 Introduction

Volcanoes are commonly considered active when there is a credible record of their eruption during "historical times" (Simkin and Siebert 1994). However, this term is quite imprecise because it means different times at different places in the world (Szakács 1994). Furthermore, even if such a definition of "active volcano" is still purely conventional, it says nothing about the actual status of a volcano, and is irrespective of the timing of its most recent eruption, while the capability (and probability) for a further eruption remains unknown. Other terms used to express the current activity status of volcanoes are "dormant" (i.e. "active" in the sense of having documented historical eruptions but currently not erupting), and "extinct" (i.e. without potential for an eruption in the future). The terminology related to the activity status of volcanoes could be, and actually is, further complicated by terms such as "potentially active" volcanoes. De Silva et al. (1990) for example, classified the poorly known Central Andean volcanoes as potentially active if they have, among other features, a well-preserved summit crater, or pristine lava flow textures and morphologies. As for Ciomadul, Harangi et al. (2015a) put forward the term "volcano with potentially active magma storage" to name the current state of the volcano. McBirney et al. (2003) proposed the term "capable volcano" as an alternative for "active volcano" (i.e. with historical eruptions), to name those volcanoes which are able to erupt in the future.

But how can the "capability" of a volcano not listed in the Catalogue of Active Volcanoes (i.e. conventionally not considered "active") be assessed? This question leads to the idea of a

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phenomenological definition of "active volcano" (Szakács 1994), based on in-depth knowledge of the current status of the magma plumbing system of the volcano instead of the currently used conventional definition.

On the other hand, a number of researchers consider more than 10,000 years for a conventional time limit in defining "active volcanoes", in particular when site-safety is at stake such as in the case of nuclear waste repositories, where time intervals of tens of thousands of years are required with no volcanic and/or seismic activity. Such a prudential approach is welcome and meets the idea of a "capable volcano" of McBirney et al. (2003). Ciomadul is a proper case of a volcano whose active/extinct status can be discussed as a relevant example, because its last eruption is too "old" in terms of the conventional active volcano definition (i.e. 10,000 years), but recent enough (c. 30,000 years) to be considered within the range of volcano capability.

7.2 Summary of the Eruptive History of Ciomadul Volcano

Recalling a detailed presentation of the evolution of the volcano (Chap. 3), only the most important information, necessary for understanding the questions related to its activity status, is summarized here. Ciomadul (Fig. 7.1) is a lava dome complex of dacitic composition, the major volume of which is concentrated in a central group of tightly packed domes with two explosion craters (Mohoş/Mohos, and Sfânta Ana/Szent Anna/St. Anne) piercing through it, and a few peripheral domes. Its time–space evolution was unravelled by Szakács et al. (2015), Harangi et al. (2015b) and, in more detail, by Lahitte et al. (2019), Karátson et al. (2019) and Molnár et al. (2019). According to the age data, during the last c. 850 ky, the focus of volcanic activity shifted from peripheral locations (firstly in the south-eastern, later in the northern side) to central areas, and mostly consisted of lava dome-building effusive eruptions of viscous dacitic magma. Smaller or bigger explosive episodes may have occurred in this extended time period too, but these were apparently not preserved in the geological record. The most recent eruptive phase, starting from 100 to 50 ka ago, was dominantly explosive (phreatomagmatic and sub-Plinian eruptions) through the two craters.

The petrological features of the volcano are presented in detail in Chap. 4. Recent petrogenetic investigations (Kiss et al. 2014) revealed magma chamber processes responsible for at least part of the Ciomadul eruptions. The major result is that influx of fresh, more mafic (than dacitic) magma into the cooling magma chamber, which contained remnant dacitic magma (a crystal mush incapable of erupting), re-activated the volcanic activity several times during the eruptive history of the volcano. In other words, a cooling crustal magma chamber being in a "cold storage" state can be converted by new magma or heat influx into a "hot-storage" state (e.g. Bachman and Huber 2016), able to erupt. These findings are strongly relevant when discussing the possibility of further eruptions at Ciomadul.

Particular attention was given to the most recent eruptions of the volcano, their timing and mechanisms. One of the latest, and most intense, explosive events deposited a well-preserved pumice-rich pyroclastic sequence (Szakács et al. 2015; Karátson et al. 2016). Its eruptive mechanism was defined as sub-Plinian or Plinian (Szakács et al. 2015; Karátson et al. 2016). Radiocarbon dating of charcoal fragments found in the pyroclastic deposits (Juvigné et al. 1994; Moriya et al. 1995, 1996; Vinkler et al. 2007; Harangi et al. 2010), pre-eruptive palaeosol organic matter (Moriya et al. 1995, 1996; Szakács et al. 2015) and sediments over- and underlying tephra layers recovered from the Mohos crater palaeo-lacustrine succession (Karátson et al. 2016), which were correlated with biostratigraphic results (Tanţău et al. 2003; Magyari et al. 2006), constrained the age of this eruption to c. 31–32 thousand years. Karátson et al. (2019) identified an even younger eruption c. 28 thousand years ago, possibly associated with the disruption of a lava dome and phreatomagmatic tephra dispersal, which determined the actual topography of Sf. Ana crater. Wulf et al. (2016) pointed out the presence of

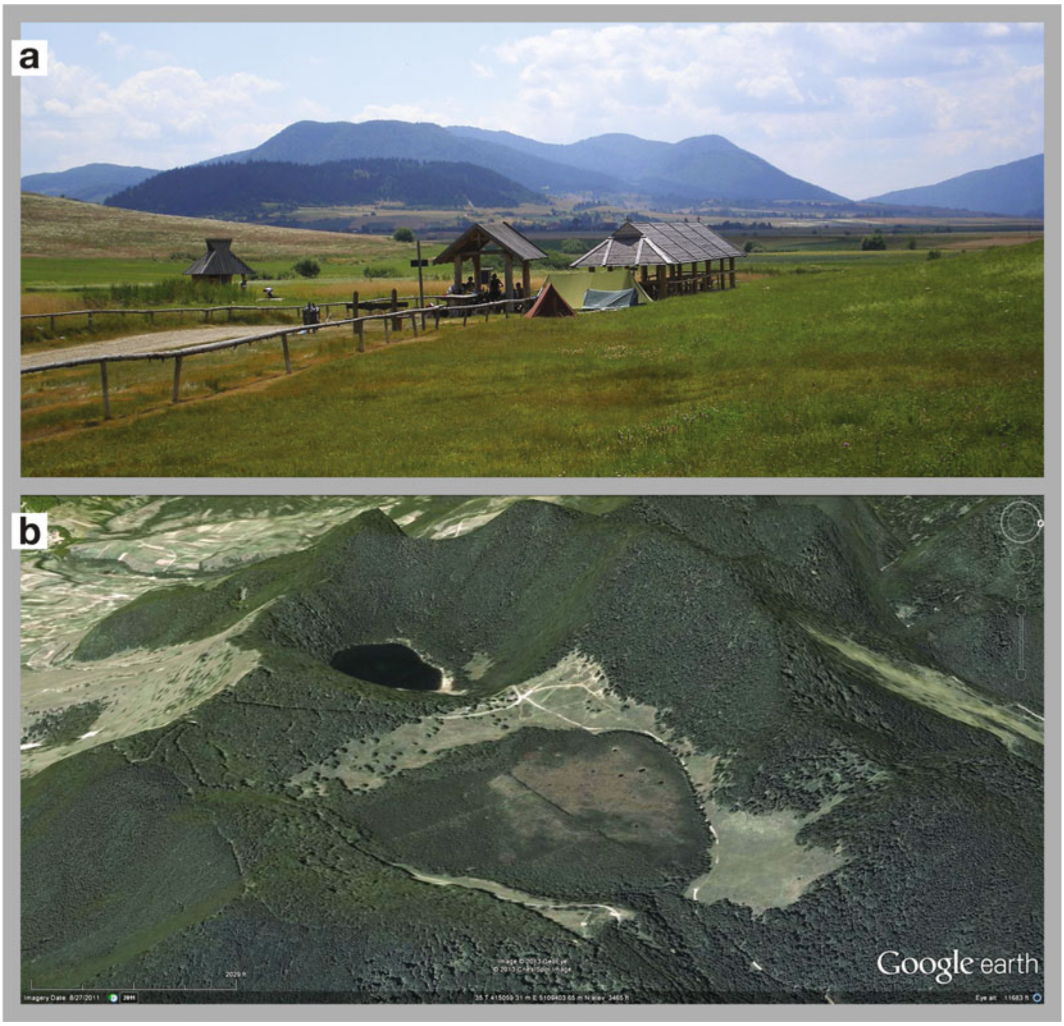

Fig. 7.1 **a** Ciomadul volcano as seen from the North (*Photo credit*: Alexandru Szakács). **b** The central part of Ciomadul captured from Google Earth with its two explosion craters St. Anne (left) and Mohos (right) (Source: Google Earth)

distal ash—called the Roxolany Tephra—deposited from the most powerful eruptions (possibly from older explosive activity; Chap. 5), recovered in loess deposits some 300 km to the east in the delta of Dniester river in the Ukraine.

7.3 Extinct or Dormant? A Short History of the Subject

Chapter 1 of this book on the research history of the Ciomadul region presented in detail how our knowledge on the latest volcanic eruptions evolved trough time. We may remember the statement of Jenő Cholnoky (1922), intending to describe suggestively the undisturbed original topography of the volcano ("*one could expect renewed eruptions at any moment*"), which can be better assessed now in the light of present-day knowledge.

The emergence of the scientifically founded idea that Ciomadul has an unconsolidated magma chamber (i.e. some partially molten material still exists beneath the volcano) dates back to the 1980s. Information gathered by a temporal seismic station installed at the shores of St. Anne lake following the great 4 March 1977 Vrancea earthquake (with a magnitude of 7.2) was analysed by Vasile Lăzărescu (University of Bucharest). Based on the evidence for local crustal microseismicity located beneath the volcano and for attenuation of teleseismic waves, Lăzărescu arrived at the idea that there is a crustal magma chamber beneath Ciomadul with some melt fraction (Vasile Lăzărescu, unpublished data). Unfortunately, Lăzărescu died before publishing his findings. His idea was revisited and confirmed decades later when radioisotopic dates on products of the latest Ciomadul eruptions became available, proving the very young age of the volcano (e.g. Moriya et al. 1995, 1996; Vinkler et al. 2007; Harangi et al. 2010).

The earliest documented interrogation related to whether or not the volcano could erupt again in the future dates back to 1993 (Szakács and Seghedi 1993). Szakács et al. (2002) concluded that future magmatic activity cannot be ruled out completely. The validity of such a statement was reinforced by the results of further research (see Chap. 1). A significant result was the findings of Popa et al. (2012), who suggested the presence of a low-velocity zone beneath the volcano at 8–20 km depth based on seismic tomography, interpreted as the signature of a magma chamber. On the basis of petrological results and knowledge of the behaviour of currently active volcanoes worldwide, Kiss et al. (2014) pointed out that lava dome-building eruptions at Ciomadul might have been triggered a short time (days to weeks) after the injection of fresh mafic magma into the cooling magma chamber containing residual dacitic magma. With these antecedents, and based on further geophysical (magnetotelluric) studies, Harangi et al. (2015b) arrived at a conclusion similar to that of Lăzărescu and Szakács that "*future volcanic activity cannot be ruled out unequivocally because the melt-containing crystal mush can be remobilized*". Recent investigations of e.g. Kis et al. (2019), summarised in Chap. 8 on the carbon dioxide emanations on the Ciomadul area, suggested that a significant part of the gas output originates from a magma body located beneath the volcano as a proof of magma chamber activity, a conclusion questioned in this chapter.

One of the most recent scientific studies on the subject (Laumonier et al. 2019), based on thermal numerical modelling, claims that the Ciomadul subsurface magma plumbing system currently contains 20–58 km^3 of melt, representing 20–58% of the magma-storing reservoir volume, in contradiction with the 5–15% calculated earlier by Harangi et al. (2015a). Such a great amount of melt, according to the authors themselves, is significantly more than twice as much as the total edifice volume (8.74 km^3, Szakács et al. 2015; 7.82 km^3, Karátson et al. 2019), i.e. the minimum amount of magma erupted during the whole eruptive history of the volcano. Since the modelling used a high number of estimated values as input parameters, the output volume figures have large uncertainties. Moreover, the authors started from premises related to the local structure of the crust (assuming 25 km upper-middle crust consisting of amphibole-facies metamorphic rocks and 15 km lower crust consisting of granulite facies metamorphic rocks), strongly influencing the results of the thermal modelling, which are at odds with the known crustal make-up of the area. The current presence of significant amounts of possibly eruptible melts beneath Ciomadul can be questioned based on other reasons as well. The recorded column-like seismic velocity and magnetotelluric anomalies could, for example, also be related to the presence of ascending fluids instead of interstitial magma (Kovács et al. 2021).

7.4 Ciomadul Media Coverage

A Google search on 25 July 2021 yielded 3,910 hits when searching for "Ciomadul eruption" in the Hungarian language.

Unfortunately, the latest scientific results on the activity status of Ciomadul are reflected with increasing distortion in the Hungarian language media in Hungary, and mimicked and further distorted in the Transylvanian Hungarian and Romanian media. On one hand, in the media news, the published scientific results and

Hitte volna? Bármikor kitörhet a magyar vulkán

Ha felébred a Kárpát-medence vulkánja, az pusztító lesz

Dr. Harangi Szabolcs, az ELTE TTK Földrajz- és Földtudományi Intézetének igazgatója kutatótársaival a Kárpát-medence legfiatalabb vulkánjának, a Székelyföldön található Csomád vulkán magmatárolóját és a 30 ezer évvel ezelőtti utolsó kitöréséből származó törmelékanyagait vizsgálja, hogy egy nem teljesen kizárható újabb kitörés esetleges előjeleit idejében felismerhessék.

09:09 Ahogy kijött a börtönből ott folytatta, ahol korábban abbahagyta

09:08 Házi olasz ciabatta kenyér bögrésen, tejtermék nélkül

09:07 Pezsgőfürdő, aranyvonat - 22 éves a Sopron Ronchetti Kupa-győzelme

09:02 Varga Mihály: Életeket menthetünk, ha otthon maradunk - videó

Un vulcan din Romania considerat stins „clocoteste" pana la pragul de eruptie

George-Andrei Cristescu,

O echipa internationala de cercetatori a descoperit depozite de magma in Masivul Ciomatu - Puturosu, din Carpatii Orientali, o structura a Muntilor Harghitei formata recent - un vulcan stins, care a erupt ultima oara acum 30.000 de ani, dar care nu pare cu totul mort.

Magyar kutatók szerint újra kitörhet a székelyföldi vulkán

2017. június 19., hétfő, 18:36 | mta.hu

Magma Lurks Below This 'Extinct' Volcano in Romania

Rocks in the upper crust beneath Ciomadul are, on average, 15 percent molten, with some areas reaching as high as 45 percent

Fig. 7.2 **a**, **c** Assemblage of media news titles as published in Hungary. **b**, **d** Articles in the Romanian media of **b** Romanian and **d** Hungarian language. **e** Articles in international English language media

interpretations related to the "dormant" state of the volcano were presented as new findings (as they referred to the authors themselves who presented that information). On the other hand, the more cautious and only scientifically valid "cannot be completely excluded" formulation was replaced by sensationalist alternatives (Fig. 7.2), suggesting the probability of a future eruption, as the incomplete title list of Hungarian (and one Romanian) language media news (translated in English) presented below eloquently proves.

"*Kitörhet egy vulkán a közelünkben*" (A volcano may erupt in our neighbourhood), Magyar Nemzet: https://magyarnemzet.hu/archivum/tudomany-es-technika/kitorhet-egy-vulkan-a-kozelunkben-4046315/.

"*Hitte volna? Bármikor kitörhet egy vulkán Magyarország területén – ezt a meglepő kijelentést tették a Magyar Tudományos Akadémia szakértői*" (Would you have ever thought? A volcano in Hungary [sic!] may erupt at any time – experts of the Hungarian Academy of Science put out this surprising statement), Blikk: https://www.blikk.hu/aktualis/belfold/hitte-volna-barmikor-kitorhet-a-magyar-vulkan/9dw2pnt.

"*Előjelek nélkül*" (Without warning), Magyar idők: https://www.magyaridok.hu/lugas/elojelek-nelkul-251017.

"*Figyelem: ismét kitörhet a Csomád vulkán*" (Warning: Ciomadul volcano may erupt again), ATV: http://www.atv.hu/belfold/20170619-figyelem-ismet-kitorhet-a-csomad-vulkan.

"*Riadót fújtak a tudósok, ismét kitörhet a csomádi vulkán*" (Scientists alerted: Ciomadul volcano may erupt again), Blikk: https://www.blikk.hu/aktualis/kulfold/kitorhet-a-csomadi-vulkan/peeyd7h.

"*Ijesztő adatok: kitörhet az erdélyi vulkán?*" (Frightening data: may the volcano in Transylvania erupt again?), Civilhetes Független Közéleti Magazin: https://civilhetes.net/ijeszto-adatok-kitorhet-az-erdelyi-vulkan.

"*Vulkánkitörésre figyelmeztetnek Erdélyben: újra működésbe léphet a Csomád; „Kétség sem fér hozzá, hogy a Csomád működik",* Harangi Szabolcs)" (Volcanic eruption is alerted in Transylvania: Ciomadul may reactivate again; There is no question that Ciomadul is active, Szabolcs Harangi), Blikk: .

"*Un vulcan din România considerat stins*" *clocoteşte* "*până la pragul de erupţie*" (in Romanian; A volcano considered extinct is "bubbling" to the edge of an eruption), Adevarul online: https://adevarul.ro/news/eveniment/un-vulcan-romania-considerat-stins–clocoteste-pragul-eruptie-1_5d310c2b892c0bb0c6985384/index.html.

It is obvious nowadays that there is a serious problem with science communication through the social media, not just in Romania and Hungary, but worldwide. As the paper of Laumonier et al. (2019) was published in a prestigious scientific journal, the "active" status of Ciomadul volcano started to gain international media coverage. This was suggested by the "apparently extinct" expression in the article title itself, which may be logically interpreted as "actually active". Accordingly, it is not surprising that the media transmitted this "statement of fact" to the general public. However, whereas high-prestige international media environments such as the website of National Geographic and the Smithsonian Institution (USA) communicated the findings in a somewhat less sensationalist manner, the Hungarian media, and then also the Romanian ones again presented them in a more direct and exaggerated way:

"*Magma found simmering under an 'extinct' volcano. Here's what that means*", National Geographic: https://www.nationalgeographic.com/science/2019/07/magma-found-simmering-under-extinct-volcano-what-that-means/.

"*Magma Lurks Below This 'Extinct' Volcano in Romania*", Smithsonian Magazine: https://www.smithsonianmag.com/smart-news/magma-lurks-below-extinct-romanian-volcano-180972681/.

"*Ha felébred a Kárpát-medence vulkánja, az pusztító lesz*" (If the volcano of the Carpathian Basin awakens it will be devastating), Origo, https://www.origo.hu/tudomany/20200115-a-karpatmedence-legutobbi-vulkankitoreseinek-nyomaban.html.

"*Vulcanul de sub lacul Sfanta Ana si a reluat activitatea dupa aproape 30 000 de ani. 'Lava fierbe si exista semne de activitate, desi l-am considerat stins. E imminent', spun cercetatorii din toata Europea*" (The volcano beneath the Sfanta Ana lake resumed its activity after 30,000 years. 'Lava is boiling and there are signs of activity, although we considered it extinct. It is imminent', say researchers across Europe), Stiristul de Serviciu, http://stiristul.com/vulcanul-de-sub-lacul-sfanta-anasi-a-reluat-activitatea-dupa-aproape-30-000-de-ani-lava-fierbe-si-exista-semne-de-activitate-desi-l-am-considerat-stins-e-iminent-spun-cercetatorii-din-toata-Europa/.

Overall, as a consequence among the media-consuming public—in particular among the local people living in the proximity of the "apparently extinct" volcano— concern has started to emerge based on the scaring but scientifically unproven impression that Ciomadul is on the verge of an impending eruption. Such an irresponsible manner of communicating scientific results to the public by the media is able only to spoil the societal credibility of the scientists involved and makes a significant disservice to the cause of sound science communication. Although in cases beyond their reach, scientists' responsibility may also be considered when the authors, who are cited as a credible source of information, accept media distortion and/or exaggeration of their published research results without being amended or challenged later on, as is the case for Ciomadul.

7.5 Eruptive Capability of Ciomadul

The arguments in favour of a still capable Ciomadul volcano can be summarized as follows:

(1) Magma volumes of 20–58 km^3 are currently present underneath the volcano, as inferred by Laumonier et al. (2019), hence theoretically available to erupt. The amount of melt may locally exceed a volume fraction of >50% in the reservoir. This is important because, according to theoretical reasons, the eruptibility of magma requires a melt fraction of > 50% (Miller 2016); therefore, accepting the existence of melt fractions of 50–58% in the present-day magma reservoir, one may consider the ability of small volumes of magma to erupt in the future, irrespective of new magma supply from below.

(2) In theory, as mentioned, a magma reservoir containing residual magma can be reactivated by a new batch of hotter magma coming from below, as it happened several times during the eruptive history of Ciomadul itself. However, there is no positive evidence that magma is still being generated at deeper levels of the system, and, alongside, that magma chamber reactivation (leading to an eruption) is going on.

(3) There is little doubt, according to the most recent age determinations of the latest-erupted volcanic products (c. 28 ka), that there were repose periods of 10 to 100 thousand years in Ciomadul's evolution (e.g. Molnár et al. 2019) longer than the time passed since its last eruption, hence a future eruption is not out of question in the context of the long-term evolution pattern of the volcano.

(4) There are known worldwide examples of volcanoes reactivated after long-lasting dormancy periods (i.e. in the order of 10,000 years). However, most of them belong to a different category of volcano (caldera-type "supervolcanoes", such as Campi Flegrei or Yellowstone) or to large-sized composite volcanoes, such as Chiliques in Northern Chile (de Silva and Francis 1991) or Bolshaya Udina in Kamchatka (Global Volcanism Program, Smithsonian Institution), both of them showing recent signs of activity, but all unlike Ciomadul.

On the other hand, there are also serious arguments against a capable Ciomadul volcano, other than the negative evidence (or lack of evidence) about the presence of a still active, hence eruption-prone magma plumbing system beneath the volcano:

(1) Ciomadul is geographically and geodynamically located at the very end of a space–time waning and volumetrically decreasing volcanic range belonging to a trend of progressive along-arc extinguishing volcanic activity (Szakács and Seghedi 1993, 1995; Szakács et al. 2018), so its last eruptions may mark the very end-manifestation of that trend. Instead of considering Ciomadul as a still capable volcano, one may assume, considering this time–space evolution pattern, that a new, even smaller-volume volcano could emerge sometime in the unforeseeable future in the SSE extension of the volcanic range.

(2) No other volcano in the volcanic province Ciomadul belongs to (the Călimani-Gurghiu-Harghita range)—including its closest neighbours—has a magma plumbing system containing residual magma, and whose extinct status can be questioned, so that the volcanic range itself can be viewed extinct as a whole. But it is true that the presence of an active volcano in an otherwise extinct volcanic field as a final manifestation of activity cannot be completely excluded.

(3) The assemblage of phenomena collectively termed "post-volcanic", including gas emanations and a focused heat-flux anomaly, shows in fact features typically associated with "post-" rather than "syn-volcanic" processes: cold CO_2 emanations (mofettes) instead of higher-temperature fumarolic activity, while the geothermal anomaly can

be easily explained by the presence of a cooling magma chamber instead of a freshly-supplied hot chamber, especially if one compares these features with those occurring at active volcanoes.

(4) To the best of the author's knowledge, there is worldwide no volcano comparable to the type (dacite dome complex) and size (<9 km^3) of Ciomadul, which erupted during "historical times", hence is catalogued as active, after a dormancy period of 30 thousand years or more.

(5) In the likely case that the source of the geophysical anomalies is not related to the presence of magma in the cooling storage system (e.g. ascending fluids, such as H_2O and CO_2, including dissolved chemical species), as suggested by Kovács et al. (2021), the possibility of future eruptions of the volcano is totally excluded.

One has to admit that these "con" arguments are not less circumstantial than the "pro" are: hypothetical statements without firm evidence. In summary, there is no compelling evidence to support whether Ciomadul is a capable volcano or not. Therefore, the early statement of Szakács and Seghedi (1993), and Szakács et al. (2002) that "*future magmatic activity, including volcanism, cannot be ruled out*", later re-affirmed by others, is still the only valid one until otherwise demonstrated. Nothing else should be communicated with certainty, so this statement reflects our limited knowledge on the real actual status of the volcano.

7.6 Towards Solving the Dilemma

From the above discussion, it is obvious that more focused investigations are needed to soundly answer the question of Ciomadul's eruptive capability. First, the real current status of the magma chamber beneath Ciomadul has to be examined, basically using geophysical tools. The amount (volume and melt fraction) of residual magma has to be estimated with higher precision and in a more reliable manner than the figures published by Laumonier et al. (2019). Then, a more precise location and geometry of parts of the magma storage system possibly containing eruptible magma has to be determined. Finally, based on these findings, the current dynamics of the magma storage system have to be understood: is it currently shrinking because of continuous cooling or is it swelling because new magma is currently added from below? Complex and integrated geophysical research methodologies have to be used to obtain answers to these important questions. Goal-designed and -devised seismic, magnetotelluric and geothermal studies have to be undertaken to obtain a realistic picture of the current state of the magma reservoir below Ciomadul. Second, the deepest part of the magma-plumbing system must also be investigated, aiming at understanding whether new magma is currently produced. This involves further petrogenetic studies focusing mainly on the youngest Ciomadul rocks, and a purposefully devised geophysical investigation on Ciomadul and its surroundings. Finally, alternative hypotheses (other than the current generation and presence of eruptible magma volumes) have to be tested by adequate investigation methods and evaluated, such as that proposed by Kovács et al. (2021).

7.7 Summary

One of the most interesting and most debated issues related to Ciomadul volcano, whose most recent eruption occurred less than 30 thousand years ago, is its activity status (i.e. the capability for future eruptions). According to the widely accepted standard conventional definition of "active volcano", Ciomadul is catalogued as extinct. However, it was credibly hypothesized that its magma storage system at shallow crustal depths still contains a certain amount of unfrozen magma. Furthermore, there is a general consensus that the currently available remnant melt in the last-erupted magma chamber is probably not eruptible anymore. However, according to the recently understood eruptive history of the volcano, and based on worldwide analogies, reactivation of such a magma chamber by input of a new magma batch from below cannot be ruled out. Therefore, any discussion on the activity status of Ciomadul volcano is to be shifted from the current state of its shallow crustal magma chamber to the state of its deeper magma-generating system. Although “pros” and “cons” can be brought into discussion, the actual state of the deepest part of the Ciomadul magmatic system is essentially unknown because of a lack of dedicated geophysical investigations using adequate methodologies. Moreover, in light of recent results and ideas (e.g. Kovács et al. 2021), even the presence of magma beneath the volcano, whether eruptible or not, is questionable. These ambiguities can only be solved by devising a bespoke research project involving a multi- and interdisciplinary approach. Given the uncertainties described, the exaggerated and distorted sensationalist manner in which some media agencies reflect the research results related to the eruption capability of Ciomadul—without being amended or challenged by the media themselves or the cited authors—is unacceptable.

Minerals, Mofettes, Mineral Waters and Spa Culture at Ciomadul

8

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Abstract

The geologically young age of Ciomadul is not only highlighted by the presence of intact volcanic landforms (such as crater lakes), but also through the occurrence of sulphate minerals, gas emissions typically as mofettes, and mineral-rich water springs that occur around the volcano. This volcanic-related activity has played an important role to the local population over time, where the gas emissions, known as mofettes, or 'stinky pits' to locals, were used as healing gas baths. Similarly, the mineral-rich water springs were used, depending on their temperature, as drinking or curing baths.

8.1 Introduction

Due to the sulphurous gas emanations, alum efflorescence, and spring waters, the strong post-volcanic activity of the Ciomadul area has been known since ancient times. A large variety of particular minerals formed by the interaction of rock-forming minerals with the gases of sulphurous mofettes, fluids and solutions, and interference of microbes in the area. Of particular note is the accumulation of native sulphur, a product of hydrogen-sulphide in the mofette emanations and microbial interactions. The mineral-rich water also deposits calcium carbonates, native sulphur, iron and silicon oxides, and sulphates. In some sandstone outcrops, various arsenic sulphur minerals crystallized, supposedly by the reaction of sulphurous gases and dissolved arsenic of the spring waters. Gaseous emanations are not just beneficial to medical recovery, their research is also scientifically important in studying the state of volcanic activity. The strongly mineralized spring waters—named 'wine waters' by the local people—formed the basis for curing baths and drinking cures in the larger Ciomadul area. All these features make Ciomadul an outstanding region on a global scale, and a unique case in East-Central Europe for multiple post-volcanic processes.

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8.2 Getting to Know Ciomadul's Post-volcanic Activity

The first traces of research of post-volcanic processes, most prominently developed around Puturosu Hill, have been present in the literature for centuries, if not for millennia; its sulphurous and alum caverns, mofettes and 'boiling' (degassing) springs are found in written records dating back to the eighteenth century. The alum, a hydrous sulphate mineral, and sulphur precipitations have their first written reference in the work of János Fridvaldszky, naturalist and canon (1767). They were observed as powdery deposits on rock surfaces, known as efflorescences. The sulphate deposits of Puturosu (Büdös) Hill (meaning Stinky Hill) were named in the nineteenth century as 'Alaun' and 'Alaunerde' (meaning alum and alum-earth in German) in work such as that of Foetterle (1854) and Brehm (1855). This may have led to a major misunderstanding of the region's mineralogy, as the similarity of 'Alaun' and alunite led to the inclusion of the latter in some monographies, although its occurrence was never confirmed.

The first detailed chemical and petrographic investigations related to the gas emanations and mineral water springs were done by Fleischer and Koch (1876), who observed the minerals mentioned above in dacite that had been strongly weathered by the action of gaseous emanations at the Büdös ('Stinky'), Timsós ('Alum'), and Gyilkos ('Killer') caverns. Koch (1885) was the first to mention the occurrence of alum in the form of potassium alum as the most common alum mineral, typically forming by efflorescence on rock surfaces. Hercot et al. (2003) reported the formation of thénardite (an orthorhombic sodium sulphate), aphthitalite (a trigonal potassium-sodium sulphate), and nahcolite (a monoclinic sodium carbonate) in degassing cracks of the lava rocks that crop out along the road to the St. Ana crater lake. The sulphate efflorescences of the Alum-cavern were investigated by Szakáll et al. (2006).

The mineral paragenesis found on Puturosu Hill—resulting from the action of hot sulphurous gas emanations (solfataras) and carbon dioxide emanations (mofettes)—is well known from active volcanic environments around the globe such as the famous Solfatara crater in the Phlegraean Fields near Naples. In the wider Ciomadul area, a similar arsenic sulphide paragenesis was described by Kristály et al. (2006) from the vicinity of the Nyír Baths mofette in Lăzărești. Deposits of spring waters were investigated by Bányai (1938) and more recently by Szakáll et al. (2009), as summarised below. Also worth mentioning is the volume 'Mineralogy of Székelyland, Eastern Transylvania, Romania' (in English) created for the World Congress of Mineralogy held in Budapest in 2010 (Szakáll and Kristály 2010). This book, presenting the minerals of Ciomadul, includes a chapter entitled 'Brief geological and mineralogical research history of Székelyland' (Unger et al. 2010).

8.3 The Hydrothermal Mineral Deposits of Ciomadul

8.3.1 Sulphides

From the Nyírfürdő mofette field of Lăzărești at the border of the Ciomadul area, arsenic sulphides were described from the cracks of a poorly consolidated sandstone, originating from the interaction of post-volcanic sulphurous emanations and arsenic-bearing pore fluids. The arsenic sulphides generally occur as <1 mm prismatic crystals and are developed as a cementing phase of the sandstone. Five groups can be distinguished based on their colour and morphology: dark orange to red prismatic crystals of realgar, light orange prismatic crystals of alacránite (Fig. 8.1), fine-grained lemon-yellow aggregates to thin coatings of uzonite (Fig. 8.2), and pale lemon-yellow earthy aggregates of pararealgar (Kristály et al. 2006). Additionally, lemon-yellow orpiment (Fig. 8.3) has been observed as sporadic-rare earthy dull spots. Such a variety in arsenic sulphide paragenesis is unusual even on a global scale. They can appear together in yellow, orange or reddish colours,

Fig. 8.1 Prismatic alacránite crystals from Lăzăresti (Lázárfalva). Width of the picture: 3 mm (*Photo* László Tóth)

earthy masses as well as minute prismatic crystals or needles.

8.3.2 Sulphates

The oxidation of sulphur to sulphuric acid—in the vicinity of widespread hydrogen sulphide bearing gaseous emanations in the region—acidifies the soil fluid and fluid infiltrations of the surface layers, setting off the acid-sulphate alteration of the affected rocks, marked by whitened friable alteration products (Fig. 8.4). A resulting process is the intense leaching of aluminium, potassium, sodium and calcium from the rock-forming plagioclase and alkali-feldspar crystals. Dark minerals, like amphiboles and biotite, are digested to a lesser extent, the reason behind being the scarcity of iron- and magnesium-bearing sulphates. Therefore, aluminium-dominated sulphates are the most widespread in the Ciomadul area. The available water supply strongly delimits the amount and stability of sulphate deposition. Sulphates are more abundant in a strongly acidic environment, while with increasing precipitations, which dilute the acid-sulphate solutions and change the pH, sulphates tend to dissolve and other phases such as kaolinite become enriched. Recently, the most prominent sulphate depositions were found in the Alum cavern and its immediate area, growing as wool-like, fibrous crusts or floury spots 2–3 mm in size. In smaller forms, these are found in numerous outcrops around Ciomadul. Szakáll et al. (2006) identified Ciomadul sulphates, revealing that only alum-(K)—a cubic hydrated potassium-aluminum-sulphate—occurs among the strictly defined alum minerals, forming glassy, colourless, and isometric grains 0.5–1 mm in diameter that occur mostly as loose aggregates (Fig. 8.5). Dissolution by fluids has corroded and rounded the crystal

Fig. 8.2 Crust of uzonite from Lázárfalva. Width of the picture: 4 mm (*Photo* László Tóth)

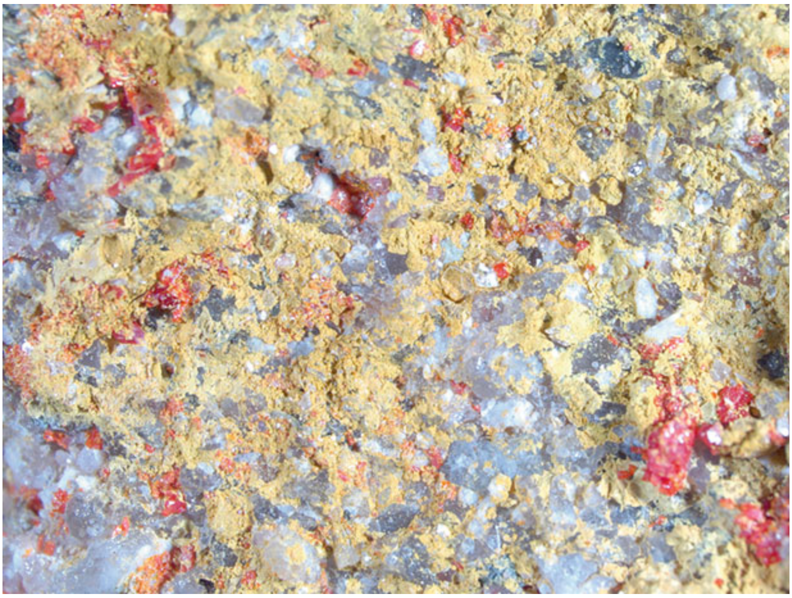

Fig. 8.3 Earthy orpiment with red realgar spots from Lăzăresti. Width of the picture: 3 mm (*Photo* László Tóth)

Fig. 8.4 Entrance of Alum (Alaun/Timsós) Cave with white powdery aluminium sulphates (*Photo* Csaba Jánosi)

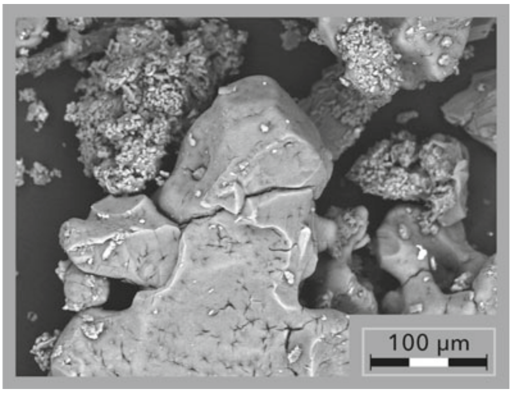

Fig. 8.5 Octahedral alum-(K) with tabular alunogen, Alum Cave. Scanning electron microscopy image (*Photo* Árpád Kovács)

faces of formally octahedral and hexahedral crystals. Alum-(K) tends to occur without any associated phases, but occasionally creates loose porous encrustations together with gypsum which may reach several square metres in size.

Other sulphates are further mentioned in the order of their frequency. Gypsum (a monoclinic hydrated calcium-sulphate) occurs as bundles up to 1–3 mm of colourless prismatic or acicular crystals, mostly as single phase encrustations, but is also observed associated with other sulphates and accompanies, although in minor amounts, the native sulphur depositions of the Puturosu cavern. Halotrichite (a monoclinic, hydrated iron-aluminium-sulphate) (Fig. 8.6) and pickeringite (a monoclinic hydrated magnesium-aluminium-sulphate) (Fig. 8.7) occur as colourless, silky masses of fine needles developed in jumbled aggregates. The two sulphates have a similar crystal structure and only a chemical analysis can differentiate between them. Alunogen (a triclinic hydrated aluminium-sulphate) is found in tabular, glassy and colourless aggregates usually associated with tamarugite (a monoclinic hydrated sodium-aluminium-sulphate), also tabular but in smaller sizes (Fig. 8.8). Celestine (an orthorhombic strontium-sulphate) occurs rarely as colourless short prismatic crystals up to several micrometres, observed only using scanning electron microscopy.

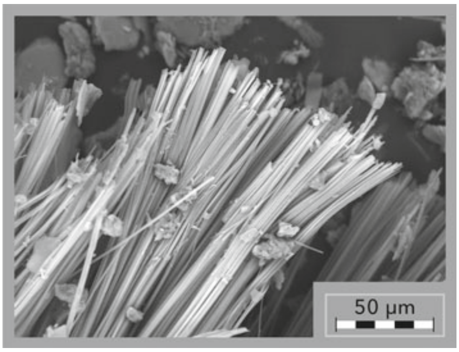

Fig. 8.7 Pickeringite needles from Alum Cave. Scanning electron microscopy image (*Photo* Árpád Kovács)

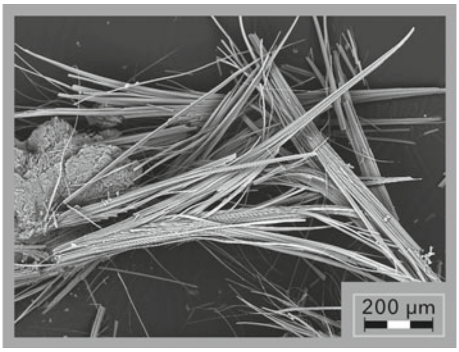

Fig. 8.6 Halotrichite needles from Alum Cave. Scanning electron microscopy image (*Photo* Árpád Kovács)

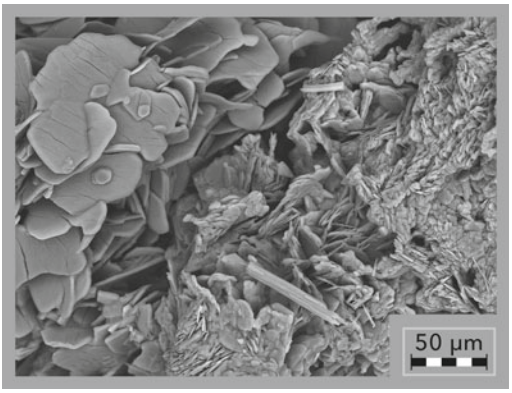

Fig. 8.8 Tabular alunogen and tamarugite, Alum Cave. SEM Scanning electron microscopy (*Photo* Árpád Kovács)

8.3.3 Native Sulphur

Large deposits of native sulphur are found in the Puturosu cavern as yellow to green loose, floury crusts developed from the decomposition of hydrogen sulphide below the gas level of the mofette (Fig. 8.9). Sârbu et al. (2018) investigated the native sulphur deposits from the cavern wall. Their research focused on the microbial biofilm on the boundary of native sulphur formations, which delimits two chemically different zones. From the presence of biofilms, the authors concluded that microbes played an important role in the accumulation of sulphur. According to their observations, the yellow earthy aggregates consist of millimetric orthorhombic crystals of sulphur, especially in the deeper zones of the sulphur crusts. Similar native sulphur precipitations are found in many other locations of Ciomadul (Fig. 8.10), including the Alum and Killer caverns, Puturosu-, Sós ('Salty')-, and Vár ('Fortress')-creeks, Füstösmező ('Smoky-meadow'), Hammasfürdő ('Cinder Baths'), Sóskút ('Salty spring'), Lake St. Ana, and the Nyír Baths (Nyírfürdő). Another type of native sulphur precipitation is related to spring waters containing finely dispersed sulphur in suspension. From this greyish-white solution, also known as sulphur-milk, sulphur crystallises as dark grey, fine-grained aggregates or thin crusts. This type of sulphur is also orthorhombic, similarly to that deposited by gaseous emanations, despite having a different colour. The most important sulphurous springs are Torjahágaja Baths, Büdös/Stinky creeks and Nyír Baths at Lăzărești, Băile Balvanyos (Bálványosfürdő), Stinky Hill, Apor Daughters' Bath (Apor lányok feredője) and the Turia (Torja) eye-baths.

8.3.4 Carbonates and Oxides

The mineral-rich waters emerging from underground reservoirs build up spectacular mineral deposits around their springs. Precipitation of solid products is mainly controlled by the drop in

Fig. 8.9 Powdery native sulphur on the wall of Stinky Cave (*Photo* Sándor Szakáll)

Fig. 8.10 Crust of native sulphur from Lăzăresti (*Photo* Csaba Jánosi)

pressure and temperature, but also by the change in the waters' chemical composition. The dissolved ion content of mineral-rich waters is strongly defined by the chemical properties and mineralogical composition of the rocks serving as their reservoir. However, the spring deposits accumulating today may significantly differ in their mineralogical composition from older deposits that originated from thermal springs heated up by the volcanic activity. Spring deposits are frequently built up as large humps and wide layers of crusts, or just as fine-grained powders or finely crystalline envelopes. Based on their chemical composition, the following types can be found in the Ciomadul area: calcic (calcium carbonate), limonitic (iron oxide, hydroxide), siliceous (silicon dioxide), and sulphatic and sulphurous (described in detail above) deposits.

The mineral forming the calcareous (calcic) deposits is calcite (a trigonal calcium carbonate). It has a porous, spongy texture, and is either fine- or coarse-grained and sometimes finely or coarsely fibrous. Porosity often decreases in larger masses or crusts (Fig. 8.11). The colour of the deposits is dominantly white or, occasionally, yellowish or yellowish-brown, caused by iron oxides. Some occurrences are found at the Nádasfürdő Baths, in Tușnad (Veresvíz/Redwaters) and at Balvanyos ('Stinky Cave of Turia', Csiszár Baths).

The limonitic precipitations of brown, yellowish brown and brown to red coloured masses are diverse in mineralogical composition. Appearance of the formations may be massive, porous or film-like crusts, but also powdery, floury, and ochre-like (Fig. 8.12). Limonite is primarily composed of a mixture of crystalline and amorphous iron oxides. The mineralogical composition of the deposits was investigated by Szakáll et al. (2009). The limonitic deposits were found to be rich in microscopic detrital grains of rock-forming minerals, such as muscovite, feldspars and quartz. The iron oxide components have a predominantly disordered structure or are

Fig. 8.11 Precipitation of calcite from spring water at Băile Balvanyos (Bálványosfürdő) (*Photo* Csaba Jánosi)

Fig. 8.12 Precipitation of iron oxides from spring water at Băile Balvanyos (*Photo* Csaba Jánosi)

amorphous and generally inhomogeneous, not corresponding to any mineral. However, in some rare types, the crystallinity of the iron phases reaches a degree by which goethite (an orthorhombic iron oxide-hydroxide, or, even more rarely, hematite (a trigonal iron oxide) can be identified. Occurrences include Tuşnad Băi (Tópataka), the 'Stinky Cave of Turia', Csiszár and the Balvanyos Baths.

The siliceous spring deposits of contemporary age, or mostly older, thermal spring related formations, are built up by opal-type material (a hydrated silicon dioxide) in glassy or dull aggregates of compact or porous masses. They have characteristic conchoidal fractures and are usually white, creamy, or brown due to iron oxides. The youngest deposits have a poorly developed structure (opal-A), in contrast to older materials that are characterized by increasing atomic ordering (opal-C and opal-CT). A general tendency exists by which the younger, more disordered opals transform into more ordered forms with time, as amorphous solids are unstable, like glass, and crystallise if given enough time. Massive opal deposits are mostly described from the main fountain of Tuşnad Băi. White glassy crusts of opal-C also from encrustations in cracks of Puturosu Hill have also been found.

8.4 Gas Emissions and Mofettes

The last eruption of Ciomadul volcano occurred less than 30 ka ago, yet a significant amount of volcanic gas still comes to the surface today. This happens in different forms. Dry gas emissions, so-called mofettes, can be found mainly in the area of Lăzăreşti, Băile Tuşnad and Băile Bálványos, where the population has used them for medicinal purposes since ancient times (as part of the bathing culture, see below). Dry gas emissions are also connected to the caves and cavities on and around Stinky Hill ('Stinky'—Sulfuroasă/Büdös, Alum—Alaun/Timsós, Small—Mică/Kicsi, Murder—Ucigaşă/Gyilkos, Bird Cemetery

—Cimitirul Păsărilor/Madártemető, and Akna caverns). These are either natural depressions or abandoned sulphur mine cavities that are now partially filled with gas. The gases also appear in solution in the form of carbonated mineral waters. In addition to focused gas emissions, such as mofettes, gas emissions can also diffuse through soil, as indicated by the lack of vegetation, strongly weathered rocks, and the secondary precipitated minerals presented above. The gases in mofettes are mainly composed of carbon dioxide (up to 98%), nitrogen (up to 70%), methane (up to 1.7%), oxygen (up to 18%), hydrogen sulphide (up to 840 ppm) and noble gases, such as helium, neon and radon. Although gas outflow is considered by many to be a post-volcanic activity, it is important to mention that gas outflow is a common phenomenon of active volcanic areas, among other phenomena such as earthquakes, and may indicate that there may still be magma present in the local crust. The role of volcanoes in the global carbon cycle has been studied mainly on the basis of emissions from active volcanoes, but there is growing scientific evidence that significant amounts of carbon dioxide are also released in long-dormant volcanic areas (Burton et al. 2013; Caracausi et al. 2015). Determining the flux (amount of emission projected over a given area) and geochemical properties provides important information about the origin of the gases, and the spatial location of the gas flows can help find a relationship between surface degassing and the magmatic system.

According to a study by Kis et al. (2017), the carbon-dioxide flux in the Ciomadul region shows variable values depending on the type and location of gas leaks (Fig. 8.13). Measurements show that for focused emissions, the carbon dioxide flux varies between 277 and 8172 g per day, which is equivalent to emissions of 0.1 and 2.98 tonnes per year. Higher values were found in the vicinity of Stinky Hill, in the valley of the Jimbor (Zsombor) stream, at the Vallató and Bükkös baths (belonging to the Mikes Baths next to the Grand Hotel) in Bálványos, in the Csiszár Baths in Băile Bálványos, and in Sósmező northwest of it. Unsurprisingly, the highest value was shown by the Stinky Cave, from which 1,920 tonnes of CO_2 are released every year. Diffuse gas leaks occur in many areas, such as in the valley of the Jajdon stream belonging to Turia, around Lăzărești, in the valley of the Stinky (Büdös) stream, and around Stinky Hill. Of these, the above researchers carried out measurements in the two best-known areas: the Apor Daughters' Baths in Balvanyos and the Nyír Baths in Lăzărești. The Apor Baths are a unique part of the southern foot of Stinky Hill because here the mofette gas comes to the surface together with the groundwater. It also has

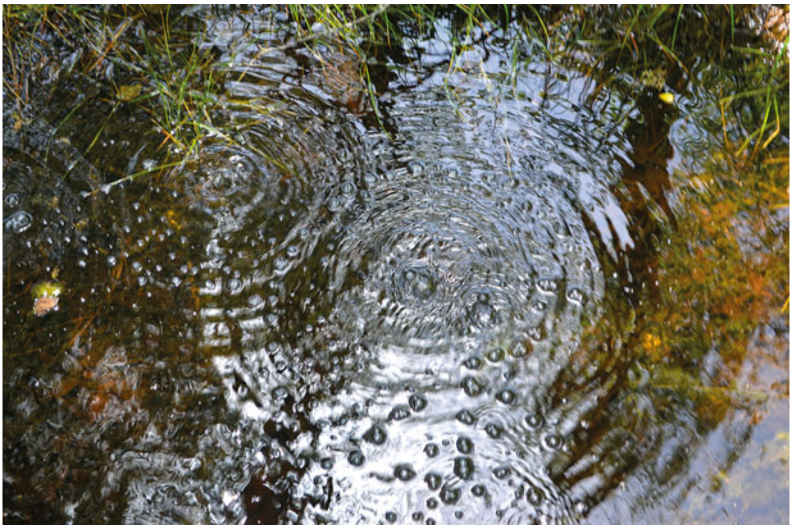

Fig. 8.13 In the mofettes around Ciomadul, gases are released from the slowly cooling magma reservoir either as dry gas emanations (mofettes) or through mineral waters (springs). The gas contains mostly carbon dioxide but also some hydrogen sulphide, which is why one can smell rotten eggs near the occurrences (*Photo* Csaba Jánosi)

bubbling pool beds, locally known as 'baths', but in rainy weather there is intense bubbling all over the area. The valley of the Stinky stream below it presumably lies on a tectonic fault line, and the gas flows—on the heavily altered dacitic lava rocks—are characterized by a lack of soil cover and vegetation, native sulphur deposits, and a strong hydrogen sulphide odour. The area releases 5,290 tonnes of carbon dioxide into the atmosphere each year. In the case of the other study areas, the Lăzărești high gas emissions near the bubbling pools and mofettes emit 1,460 tonnes of carbon dioxide per year.

The largest carbon-emitting areas are located on the edge of the younger volcanic lava dome structures and at the junction of two older domes, Stinky Hill and Balvanyos. The gases usually burst in the line of valleys, presumably along fault lines that help the gases to reach the surface, both in the case of the smaller streams in the Olt and Ciomadul areas. In many cases, carbon dioxide comes to the surface without interacting with groundwater, while in other cases it is the groundwater that brings the gas to the surface in the form of carbonated mineral water (see next section). According to Kis et al. (2017), a total of 8,700 tonnes of carbon dioxide comes to the surface at Ciomadul every year, but this can only be considered as a minimum value, because the researchers have so far managed to survey only some parts of the area. However, the observed discharges are already of similar intensity to those of volcanic areas which were active about ten thousand years ago, such as Vulture, Panarea, Roccamonfina, and Amiata volcano in Italy (Fig. 8.14).

An important tool in the study of the origin of gases is the stable isotope ratio of carbon $(\delta^{13}C_{CO_2})$ and helium ($^3He/^4He$) in the gases. The $\delta^{13}C$ values are given relative to PDB (Pee Dee Belemnite) or more recently the V-PDB (Vienna Pee Dee Belemnite), which is the international standard for relative carbon isotope ratios. Isotopic ratios of $\delta^{13}C$ vary according to the geological reservoirs: in marine carbonates the mean $\delta^{13}C$ content is 0‰, the Earth's mantle carbon has an isotopic composition around −5‰, while organic matters are isotopically light,

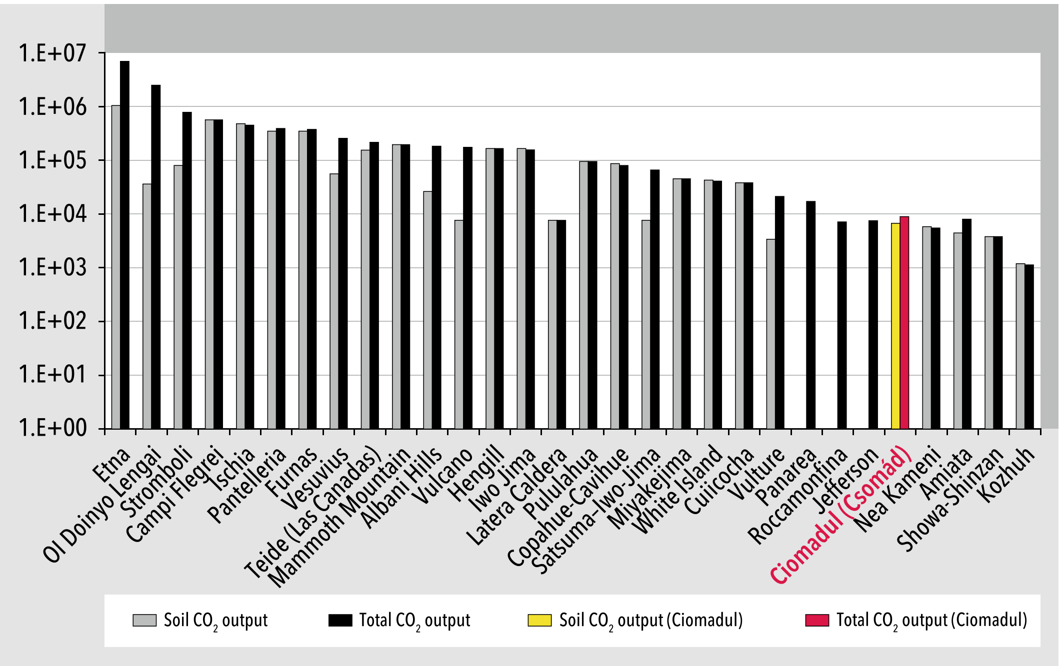

Fig. 8.14 Total CO_2 output and CO_2 output from the soil of various volcanoes worldwide (after Kis et al. 2017 and references therein). Ciomadul is highlighted

having a mean $\delta^{13}C$ content of −25‰ (Hoefs 2018). Concerning the isotopic composition of helium, the ratios are usually reported relative to the atmospheric values, as R/R_a, where R means the $^{3}He/^{4}He$ ratios measured in the sample and R_a the $^{3}He/^{4}He$ ratio of the atmosphere. Crustal rocks usually have a R/R_a value between 0.01 to 0.1, the atmosphere has a ratio of 1, and mantle derived rocks have a value ranging from 5 to 50 (White 2015).

Regarding the origin of the mofettic gas in the South Harghita area, other researchers (e.g. Althaus et al. 2000; Vaselli et al. 2002) have previously suggested a magmatic origin. In a more recent study, Kis et al. (2019) showed that the carbon isotope composition of carbon dioxide gases ranges from $\delta^{13}C_{CO_2}$ −1.40 to −4.61 ‰ V-PDB. The isotopic composition of helium in the gas mixture reaches 3.1 R/R_a, suggesting that the mofettic gas is of magmatic origin and derived from a deep crustal magmatic body. Comparing the Ciomadul data with the gas emissions in the Transylvanian Basin and the Carpathian Foreland (e.g. Sărmăşel, Bazna, Andreiasu de Jos and Berca; Fig. 8.15), where methane-rich gases formed in the crust burst to the surface, the helium isotope ratio of the latter moves around 0.02–0.06 R/R_a (i.e. much lower than at Ciomadul). This confirms that in the case of Ciomadul, a significant part of the gases comes directly from the degassing of the magmatic body. The magmatic component is more evident in areas with the highest carbon flux of the mofettic gas, such as the Apor Baths, the Stinky Cave, the Jimbor (Zsombor) Creek Valley, and the Jajdon Valley.

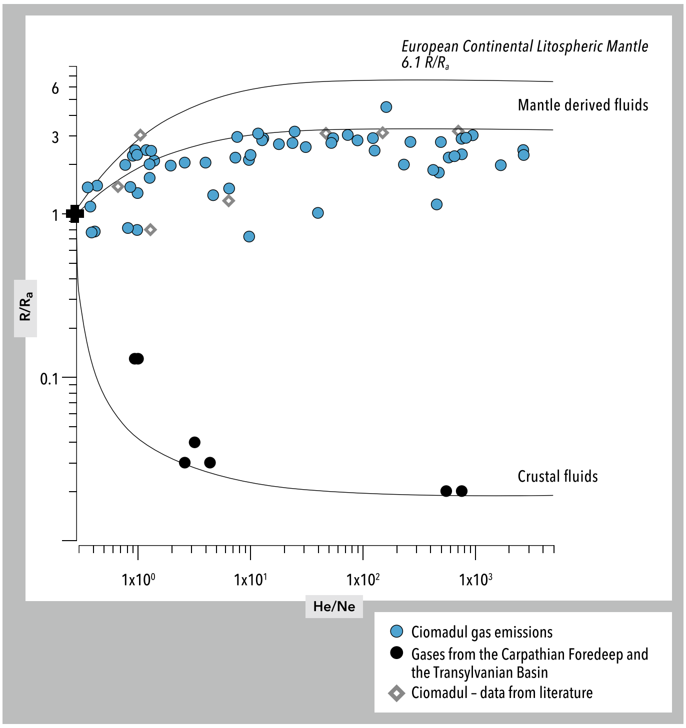

Fig. 8.15 Helium isotopic ratios (R/R_a values) and $^{4}He/^{20}Ne$ relationships for gas samples at Ciomadul vs the Carpathian Foredeep and Transylvanian Basin (after Kis et al. 2019). The theoretical lines represent binary mixing of atmospheric He with mantle-originated and crustal He (Pik and Marty 2008). The assumed endmembers for He-isotopic ratios and $^{4}He/^{20}Ne$ ratios are ATM (1 R_a, $^{4}He/^{20}Ne = 0.318$, Sano and Wakita 1985); subcontinental European lithospheric mantle is 6.1 ± 0.9 R_a and $^{4}He/^{20}Ne = 1{,}000$ (Gautheron and Moreira 2002); typical crustal end member is 0.02 R_a and $^{4}He/^{20}Ne = 1{,}000$ (Sano and Marty 1995). Data from Althaus et al. (2000), Vaselli et al. (2002), Baciu et al. (2007), Frunzeti (2013) and Kis et al. (2019)

The isotope ratios of carbon and helium suggest that the primary, degassing magma was formed during partial melting of the lithospheric mantle. This is because helium isotope ratios are lower than the average European value for a lithosphere mantle, which is 6.1 R/R_a. The slightly lower R_a values obtained can be explained by the fact that the source area of the magma in the mantle was permeated by fluids released from carbonates transported into the mantle by subduction of oceanic crust. Gas emissions of similar origin are also found in many volcanic areas in Italy and Indonesia, where subduction plays an important role in the initiation of volcanism. Considering the fluxes of carbon dioxide in the area of Ciomadul, the quantified 8,700 tonnes representing the annual emission is a minimum value, as only a limited number of degassing areas was investigated. Still the obtained fluxes are comparable to other volcanic systems worldwide.

8.5 Spa Culture at Ciomadul

8.5.1 Tradition of Baths and Mofettes

The gas emissions, known locally for their healing effects—which the locals refer to as ‘stinking’—serve as a common ritual, since the local inhabitants use the mofettes on a daily basis. Residents in the area know exactly which mofette is best for them, which they visit regularly to alleviate or prevent various, mainly cardiovascular, rheumatic complaints. In addition to mofettes found locally around the volcano, CO_2-rich gases also appear in basements or wells in private homes. Gas-containing cellars are referred to by the population as ‘musty’ cellars, known to be fatal if CO_2 concentrations reach high enough levels. Such cellars can be found especially in the vicinity of Lăzărești and Tușnad. Folk observations often associate fluctuations in gas levels in cellars and mofettes with weather and air pressure.

In addition to the dry, mofette-type emissions, the gases passing through aquifers and dissolving in the water under high pressure also created a large number of carbonated mineral water sources, locally called ‘borvíz’, literally ‘wine water’, water that is fizzy like wine.

Most of the carbonated mineral springs burst to the surface along the fault lines delimiting the edge of Ciomadul, or in deep stream valleys cut inside the mountains. Since ancient times, the local population has used the mineral water springs not only for drinking and for possible curative effects, but also for a traditional bathing culture, typical of the Romanian countryside.

The aquifers of the mineral springs are, on the one hand, contained within the rocks of the lower Cretaceous, representing the basement of the volcanic rocks, including calcareous marls, calcareous sandstones, and fragmented assemblages of shale, and, on the other hand, they are contained within fractured dacite lava rocks and eroded volcanic debris. The discharge of mineral water sources in the Cretaceous flysch layers on the eastern edge of Ciomadul is poor. By contrast, there are high-discharge aquifers on the northern edge of the Ciomadul Mountains in the loose, fine-grained volcanic sandstone formations of the Ciuc Basin, and along the fault line marking the Tușnad Gorge. In the Tușnad Gorge and in the Bixad Basin, located on the southern edge of the mountains, the carbonated springs burst to the surface at the border of flysch sediments and loose volcanic debris.

The variation in the chemical composition of the nearly three hundred carbonated, sulphurous mineral water sources in the Ciomadul area is closely related to the diversity of the rocks of the area. Geologist János Bányai was right when he stated that “*there is hardly any mineral water in Europe that has no spitting image in Székelyland… Typical examples of this are the waters of Băile Bálványos and Băile Csiszár. In these places, the ferrous, sulphurous, salty, calcarous, alum-like, alkaline waters vary over an area of a few hundred square meters*” (Székelyföld írásban és képben/Székelyland in words and pictures, 1941). At the turn of the twentieth century, the great Hungarian writer Géza Gárdonyi, who was hiking in the Ciomadul Mountains, wrote about the mineral waters: “*Well, I have drunk many expensive and noble drinks in my life, but only*

> *angels drink these in the heaven. As if it was not even water, it was just a cooling, light-air, celestial good thing that God could only create for himself. My eyes almost shed with tears of pleasure*."

8.5.2 Overview of the Most Famous Occurrences

The most characteristic baths and mofettes of Ciomadul were formed in the area of the Büdös Hill (Fig. 8.16), but baths and mofettes can be found in almost all parts of the hills (Incze et al. 2017).

Lăzărești, located in the northeastern foreland of Ciomadul, has more mineral water sources alone than the whole region. These are usually low-discharge sources, most of them from highly fragmented flysch rocks in the valleys enclosing volcanic debris layers accumulated at the foot of the cones of Haramul Mic and Haramul Mare—Tușnad, Hosszúmező, Súgó and Büdös. The Hí stream, which reaches the settlement of Lăzărești from the southeast, presumably intersects the flysch layers along the main fault line indicating the subsidence of the Ciuc Basin. The mineral waters emerging in this valley are highly mineralized of the magnesium-sodium-bicarbonate-chloride type, and can be classified into the group of mixed waters.

One of the most popular wells of Lăzărești is the Nagyborvíz, and also the calcium-magnesium-carbonated mineral water of the Fortyogó or Nyírfürdő (Nyír Baths), where the water is accompanied also by hydrogen-sulphur and carbon dioxide gas emissions (Fig. 8.17). The Nyír Baths also have an outdoor pool, smaller pools for the feet and a mofette, which are used locally for the treatment of rheumatic, vascular and skin diseases. The water is also heated and used at home. On the ridge of Borvíztető, other mineral water springs can be found that are of the calcium-magnesium bicarbonate-

Fig. 8.16 Major features of the area of Stinky (Sulfuroasă/Büdös) Hill, showing its most important mofettes, draped on a Google Earth image

Fig. 8.17 Today's bath culture at Ciomadul emerged from small civil baths, which were formed mostly in the area of Stinky Hill. Here, the Büdös-gödör (Stinky pit) of Nyírfürdő (Nyír Baths) at Lăzăresti can be seen, where there was already a popular spa in the eighteenth century. At that time, bathers used the pits as gas baths, where they entered in their 'underwear' so that the gas would reach their bodies more easily (*Photo* Csaba Jánosi)

type and often disappear during the dry periods and act as dry gas emissions.

In the small Kápolnamező Basin formed of flysch deposits, several springs of the calcium-magnesium-bicarbonate type emerge, the most well-known being the Fenekbeli or Török, the Nagyveremi, and the Szenes. Along the Kápolnamező stream emerges the Sósborvíz spring, which is of the sodium-magnesium-calcium-bicarbonate-chloride type (the name Sósborvíz is also used for several sources in the area). This spring once functioned as a kind of geyser and formed calcareous precipitates or tufa. A similar, sodium-bicarbonate-chloride type spring, is the Sóskapadi spring, which emerges in the valley of the Tuşnad stream in a small limestone tufa basin, and the Fűrész spring of the magnesium-calcium-bicarbonate-chloride type that emerges in the valley of the Veres stream.

The springs of Kisasszonyok and Fingós that emerge in the valley of the Tuşnad stream, as well as the springs of Erősárok, can be classified into the group of the calcium-magnesium-bicarbonate-sulphate-type of waters. The sulphate springs of Erőssárok are referred to by locals as 'eye water', used locally by some people for treating conjunctivitis. Waters of similar composition are found in the valley of the Büdös (Stinky) stream, in the foreground of the abandoned sulphur mines from the Middle Ages.

In the sandstones that outcrop on the left side of the Stinky stream in the greyish-white, loose sediments, the crystallization and accumulation of sulphur is still persisting from hydrogen sulphur gas. The old extraction site still shows the dams used for sulphur processing and fragments of pottery vessels used to capture sulphur.

Reading the book 'De re metallica' of Georgius Agricola (the German Georg Bauer, who lived in the sixteenth century and was famous for his mining and metallurgical work; Fig. 8.18), we get a picture of the sulphur production from

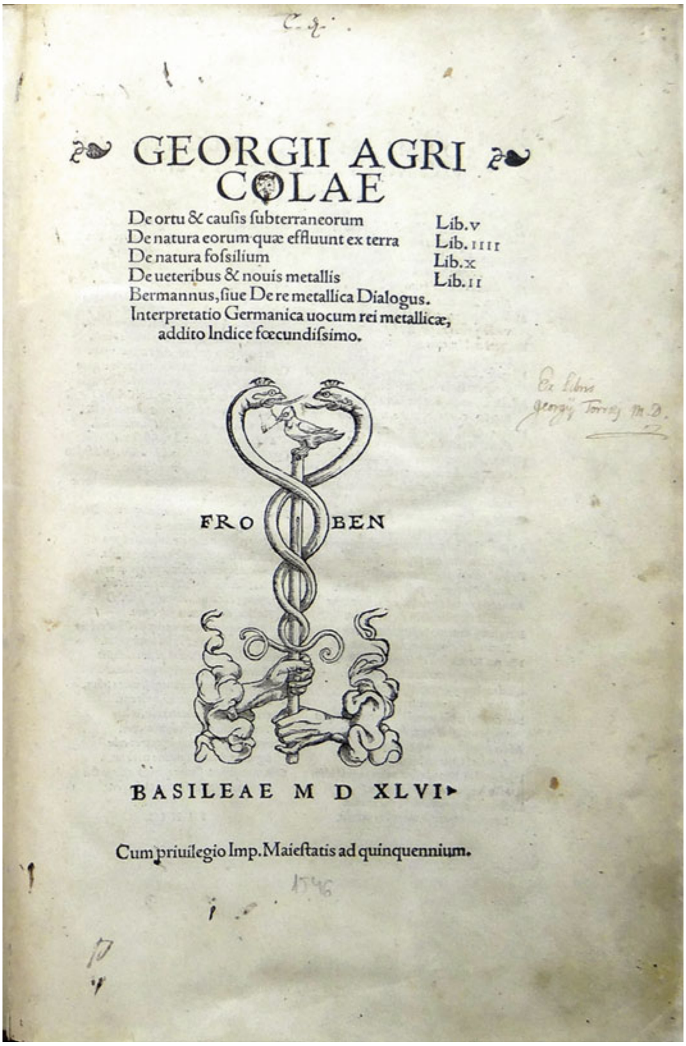

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Fig. 8.18 Front cover of the book 'De re metallica' of Georgius Agricola (Georg Bauer), published by Hieronymus Froben and Nicolaus Episcopius (second edition, printed in Basel in 1561). Its 12th book is about manufacturing salt, soda, alum, vitriol, sulphur, bitumen, and glass, and it contains the first mention of sulphur production at Kápolnamező (south of present-day Lăzăresti/Lázárfalva)

Kápolnamező: "*The pots were plastered with clay to prevent the sulphur from escaping. For the same reason, the sulphur collecting container is also covered with clay. They then gave fire to the wood and heat the ore until the sulphur evaporates. The rising steam enters the collecting vessel through the nose of the vessel and condenses there into sulphur again, which, like the molten wax, settles to the bottom. From here, it flows through the spout, and the worker forms loafers from it, or inserts pipes, rods, or thin wooden sticks into it, and makes sulphur candles.*" In Tușnad, even in the 1940s, the iron corners and locks were fixed with sulphur in the stone gate legs carved from the dacite of Haramul Mic. They poured as heated sulphur into the cavity engraved in the stone in which the iron corner was placed. The sulphur then recrystallized during cooling and solidified the iron structure. The carbonated mineral waters erupting on the border of Lăzărești accumulated a significant amount of mud and limonite around the source. This iron ore was mined in older historical times, as evidenced by the place name Vasláb found in the neighbourings of the village, as well as the slag accumulated around the smelters.

The Balondoş (Bolondos) summit, 1,100 m high, consists of flysch rocks south of

Kápolnamező and east of Ciomadul. The Súgó and Hosszúmező streams flow along the slopes facing the Ciuc Basin, along which the calcium-magnesium bicarbonate type mineral water sources called Mélyvápatövi, Súgópatak and Csigolyási emerge. At the source area of the Súgó Creek, several carbon dioxide emissions with high hydrogen-sulphur content occur.

Before 1842—until the formation of today's Băile Tușnad—Nádas Baths, located southeast of Tușnadu Nou (Újtusnád), was the most visited bath in the area. This bath, established on high-discharge ferrous springs, was already mentioned by István Lakatos, parish priest of Cozmeni in the late 1600s, in his Latin manuscript about Szeklerland. The spa is located in a peat bog area between the northern slopes of Haramul Mic and Haramul Mare. The peat bog is soaked in mineral-rich waters of sodium-magnesium-calcium-bicarbonate-chloride type. Sodium chloride is probably derived from the salty clay rocks of the sub-volcanic flysch layers. The mixed mineral-rich water has a mineral content of 4,485 mg/l, a CO_2 content of 2,244 mg/l and a temperature of 14 °C. One of the springs containing hydrogen-sulphide was also used by the locals as 'eye water' here, and to treat various rheumatic and vascular diseases. The mineral water was heated in vats with heated stones, and in the 1950s it was even transported in wooden ponds to the surrounding villages. A sponge-structured tufa bench was deposited from the emerging waters on the northern edge of the bog, which began to be extracted in 1802 and used for limestone burning. It is probable that there were also iron smelters in the vicinity of the spa in the past, as evidenced by the iron deposits in the area.

In the valley of the Olt at Tușnad, on the floodplain of the river, several sources of mineral water occur. In the parts of Tușnad called Szeretszeg and Alszeg, two shallow hydrogeological wells revealed mineral water of the sodium-magnesium-calcium-bicarbonate and bicarbonate-chloride type. A similar type of mineral water source in Tușnad Nou is the Bátordi, in the neighbourhood of which, in the garden of Bátordi, mineral water emerged from several wells in 1956 with artesian character. In 1973, a bottling plant was built in the vicinity of the Tușnad Nou railway station, which still produces sodium-magnesium-calcium-bicarbonate-chloride type mineral water under the name Tușnad. Carbon dioxide was also sold at the factory.

The most significant mineral water springs in the area of Tușnadul Nou and Băile Tușnad are the springs in the foreground of Ciomadul, breaking along a probable fault line in the north-east-southwest direction: the high-discharge springs of Nádas, Vargyaspatak, Tiszáspatak, Várvápa, Rezső and Ilona at Băile Tușnad, Szegények feredeje, Szent Anna, Apor, Mikes, Komlósárok and Ördöglik. Most of these sources are of the sodium-magnesium-calcium-bicarbonate-chloride type. The exceptions are the Szegények Feredeje Baths, which are pure sodium chloride type waters, and the Ördögliki mineral water of magnesium-calcium-sodium-bicarbonate type. The Nádasi and Tiszáspataki springs have accumulated large amounts of tufa and limonite, the former of which was used by the local population for limestone burning. The huge spring cone of the former Főkút is made up of reddish, whitish opal. The water of the Főkút, which was built in the nineteenth century. According to Balázs Orbán, 19th-century writer, etnographer, photographer, "*it is a popular acidic water and in such a the place and countryside it is famous all across the neighbouring Danube principalities*".

Băile Tușnad was developed into a modern spa in 1842 (Fig. 8.19). The resort, formerly known as the Pearl of Transylvania, was established in the Tusnád Gorge of the Olt River, in a place called the Speech Field. Most of the springs in Băile Tușnad come to the surface from strongly fragmented flysch layers that appear at the foot of Szurdok Hill. Waters with temperature of 20–22 °C can be classified as a sodium-chloride-bicarbonate type of springs. The total mineral content of the Ilona spring, which fed the former Rezső bath, now Mesothermal beach, is 6,716 mg/l. The mineral water sources of St. Anna in the indoor Stefania Bath, reminiscent of old times, provide the water needs of today's

Fig. 8.19 View of Băile Tuşnad (Tusnádfürdő). In the foregrond, the artificial Lake Ciucaş (Csukás) that was formed in the early 1900s, and in the background, the rocks of Stânca Şoimilor (Sólyomkő) that belong to the Pilişca (Piliske) edifice can be seen (*Photo* Csaba Jánosi)

treatment centre in Băile Tuşnad. The bathing culture also includes the mofette discovered by Jacob Philip Imets in 1895, which has long been referred to as the ‘Imets sulphur vaporizer’. The development of the baths on the shores of Lake Ciucaș in 1979 was greatly boosted by an exploratory well drilled to 1,140 m in 1979, from which artesian water of 62 °C erupted; the total mineral-content of the pure sodium-bicarbonate water was 12,264 mg/l; however, large amount of calcium carbonate deposition blocked the liner, so another 859-m-deep well was drilled in 2011 to bring to the surface a water with a temperature of 38.8 °C and a total mineral-content of 12,037 mg/l, also of sodium-bicarbonate type. Nowadays, the hot water is utilized by the spa established on the northern shore of Lake Ciucaș. At the northern border of Băile Tușnad, in the vicinity of the Tiszási warm (19–23 °C) springs, under the Vártető, deepened hydrogeological drilling revealed sodium chloride type mineral water at a temperature of 47 °C.

Further north, at the mouth of the Vargyas stream in the Olt River, the Galuskás mineral water, which feeds the peat bog of Középpatak, and the sodium chloride bicarbonate water of the Sósborvíz of Balinoș surface. It should be noted that in the area of Băile Tușnad, several slightly salty mineral water springs emerge under the terrace plain of the settlement. In the Csukás Lake of Băile Tușnad and in the area where the Miners/Bányász stream flows into the Olt river from the west, strong CO_2 springs can be observed. It can be said that Băile Tușnad has been developing since the political changes; in addition to its diverse mineral waters and the spa, the mineral water treatment centres operating in hotels are a great attraction.

To the south, leaving the border of Băile Tușnad, in Bixad village in the Olt Valley, on the slope of the long-known Antalkáék feredője or

Tolvajkő Baths, carbonated, warm mineral water springs are also present, from which, in addition to tufa, pale green opal precipitates. In the nineteenth century there used to be a swimming pool next to the Bugyogó ('Bubbling') mineral water, north of the settlement.

In addition to the north–south fault line marked by the Tușnad Gorge, two other significant structural lines are known in the Bixad area, indicated by mineral water springs.

One is the line on the south side of Ciomadul, running in an east–west direction, marked by springs called Szilvási, Bugyogó, Falu, Tópataki, Verespatak and Disznyópatak, with tufa and limonite cones in places. The chemical characteristics of the waters is calcium-sodium-magnesium-bicarbonate-chloride, which corresponds to the Lower Cretaceous, so-called Sinaia, layers that form the base of the Ciomadul Massif. To the east, in the source region of the Jimbor stream—in the western part of Sósmező presented below—are the Vallató, Hammas, Bükk folk baths and Mariska mineral waters, around which a strong CO_2 outlet can be observed, accompanied by hydrogen sulphide gas and native sulphur depositions. The water in the baths is sulphuric and sulphated. The water of the Szemvíz (Eye-wash) Spring is of the calcium-magnesium-sulphate type. The accumulated large limonite cones in the Mariska mineral water that bursts in the sandstone layers of the flysch is of the calcium-bicarbonate type.

The other occurrences, designated by mineral springs, are located in the valley of the Jimbor stream, which runs along the flysch rocks of the Bodoc (Bodok) Mountains and the volcanic structures of Ciomadul. Starting from the flow of the Tó stream into the Jombor stream until the Jombor mineral water, the springs of Gáspári, Gubás, Keresztes, Sósborvíz and Kőborvíz can be found that are highly mineralized and of the sodium-calcium-magnesium-bicarbonate-chloride type. The sodium-chloride-bicarbonate-type mineral water named Sósborvíz of Lopály has a total mineralisation of 7,401 mg/l and is referred to by the locals as 'medicinal water'. The low-mineral-bearing Jimbor (Zsombor) mineral water, which emerges at the foot of the Nagyhegyes, can be classified into the calcium-magnesium-bicarbonate type. In the pyroclastic deposits located northeast of Bixad, Csaba Jánosi, the first author of this chapter, collected white geyserite-like rock in the 1980s, containing plant imprints, indicating former thermal water activity.

As we presented in the previous section, the southern side of the volcanic cones of Stinky Hill and Balvanyos Hill rising above Băile Balvanyos—in the words of János Bányai "*the area of caves that breathe death*"—is extremely rich in 'dry' mofettes and 'wet', sulphurous, carbonated mineral waters. The watershed on the border of Bixad and Turia, geographically at the confluence of the Büdös and Jombor streams, is called Sósmező, where in the sixteenth century, a popular spa existed. The bath guests, who were accommodated in foliage tents at that time, used the caves on the side of Büdös Hill as a mofette, a gas bath, in which they entered in 'underwear' to make the gas touch their bodies better. Currently, the Grand Hotel Bálványos conference and wellness hotel is located on the northern side of Sósmező (Fig. 8.20). The Bányai, Fidelis and Károly mineral water springs that emerged here once and accumulated large amounts of tufa and limonite, but these springs disappeared during the development of the new spa buildings of recent decades. Their water used to be mixed with the sodium-calcium-magnesium-chloride-bicarbonate-sulphate type. In the lower, southern part of the Sósmező, the Katalin spring and the water of a hydrogeological drilling occur with pure sodium chloride content, 17ºC and a mineralization of 39,969 mg/l, with the latter being used by the former Balvanyoș spa hotel before clogging.

In the cracks of the dacite lava rocks of Stinky Hill, medieval sulphur miners formed the cavities of the Small, Stinky, Alum and Killer Cave, and the Bird Cemetery, whose CO_2 gas flows described in the previous section were used as 'gas baths'. Located on the southern slope of Büdös Hill, the original Alum Bath, later referred to as the 'Valley of Death' and then known as the Apor Daughters' Bath, still has springs with a pH of 1.5 sulphuric acid. The sulphuric acid content of their calcium sulphate-like water is

Fig. 8.20 Northwest of Băile Balvanyos, the Grand Hotel Bálványos or Balvanyos Resort conference and wellness hotel is located on the northern side of Sósmező (*Photo* Csaba Jánosi)

727.5 mg/l. Beneath the bubbling pools are the Szemvíz (Eye Wash) and Lábmosó-fürdő (Foot Wash Bath), whose white coloured sulphuric-water water is of the sodium-calcium-sulphate-chloride type (Fig. 8.21).

Westward of Balvanyos, on the southern slope of Nagy Csoma Hill (Dealul Albinelor), in the strongly fragmented sandstone of the flysch, Dénes Csiszár, at the end of the nineteenth century, founded the Csiszár Baths, in which seven swimming pools containing water with different chemical compositions and mofettes awaited those wishing to recover (Fig. 8.22). These folk-baths were settled on the waters of the Arany (Red), Zöld (Green), Csokoládés (Chocolate), Great Basin, Hammas (or Hamvas), and Jordán (Jordan) and Zsófia (Sophia) spring waters. They are extremely complex chemically. The water of the Chocolate Pool, which also contains free sulphuric acid, is of magnesium-sulphate type, the sulphur-milk-like water of Hammas is of sodium-calcium-bicarbonate-chloride-sulphate type, and the ochre-yellow-coloured water of the Great Pool is classified as calcium-magnesium-sodium-bicarbonate-chloride type. Among the drinking wells, the water of the Jordan spring is of the calcium-magnesium-bicarbonate-sulphate type, while the ferrous water of Sophia is of the calcium-bicarbonate type.

After many decades of decline, the full renovation, management and use of the baths has been undertaken by civil associations and foundations. The so-called Kaláka (voluntary co-operative work) movement is the right way to revitalise the baths, and since 2015 it has proven to be a viable, community-building and result-

Fig. 8.21 The Lábmosó-fürdő (Foot Wash Bath) of Sósmező (*Photo* Csaba Jánosi)

oriented way to maintain the mineral springs. As a cultural heritage, this movement can not only promote the development of a local sustainable tourism industry, but also strengthen local peoples' attachment to their folk traditions.

Opposite the Csiszár Baths, below the ruins of the former castle of Bálványos, the sodium-chloride-bicarbonate type springs of Várpad occur, which were once also known as the Transylvania Baths and today they feed the ruined basins of the Margaret Bath. Adjacent to the basins is the sodium-calcium bicarbonate-type water of the Ibolya mineral water spring in a stone rim. In the valley of the Balvanyos stream, which borders the Várpad Baths to the east—above the former carbonic acid plant Apor next to the now disappeared Szilamér springs—a well brings to the surface the concentrated grey-coloured sodium-cloride type mineral water.

Today's Băile Balvanyos was formed by the merging of the Csiszár and Várpad Baths. At its exit towards Turia is the spring of Vasas or Transylvania, the waters of which can be classified into sodium-calcium-magnesium-bicarbonate chloride waters. South of the centre of Băile Balvanyos, next to the open-air stage, nearly a thousand metres of hydrogeological drilling was made into the flysch layers. From this, concentrated sodium-chloride mineral water periodically bursts to the surface, from which a spectacular red limestone tuff cone has formed. In the northern part of Turia, a pagan folk custom has survived at the Szemmosó (Eye-Wash) well with sulphuric water. After washing the eyes, the rags were hanged on the bushes around the source so that the disease is not taken home.

8.6 Summary

Around Ciomadul, a large variety of minerals can be found that formed by the interaction of rock-forming minerals with the gases from sulphurous mofettes, fluids and solutions. Apart from mofettes, the peculiarity of the area are the acidulous mineral waters locally called 'borvíz' (wine water). The diversity of mineral waters lies in the large number of dissolved minerals, which vary over a wide range. The mineral waters are very acidic (with pH between 1.5 and 4) and contain free sulphuric acid, which is a very rare phenomenon. The volcanic activity has strongly influenced the culture of the people living locally for hundreds of years. In the discovery of the waters, where later the communal curing baths were created, shepherds played a huge role, who, walking on the wine-water meadows and

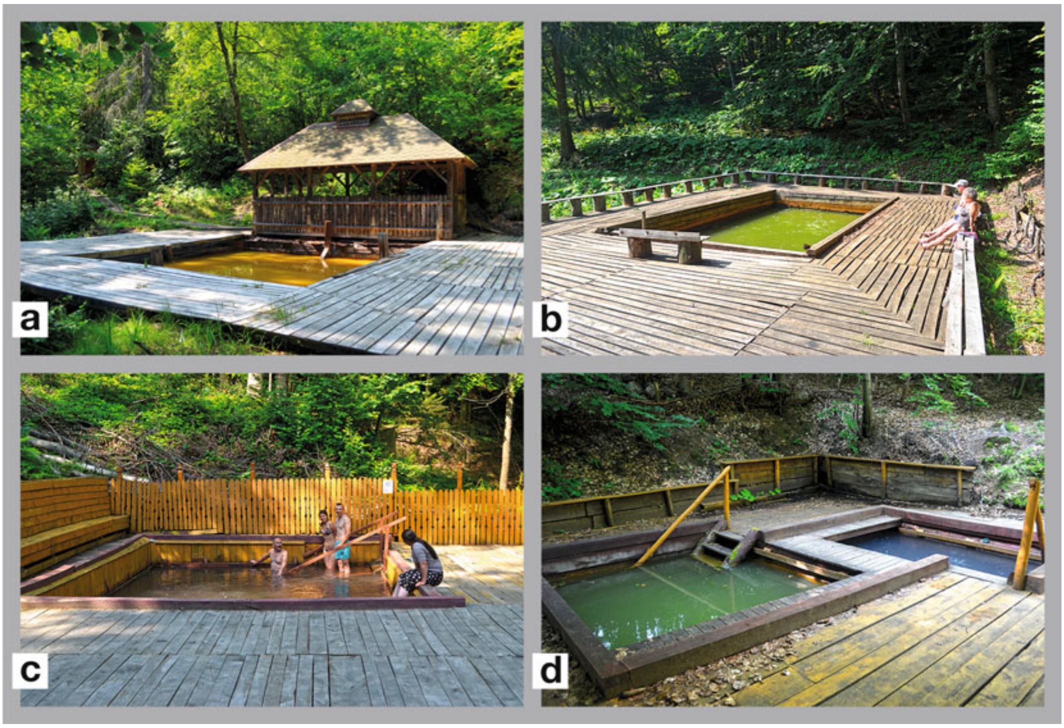

Fig. 8.22 Pools of the Csiszár Baths, in which seven swimming pools containing water with different chemical compositions were created. **a**—Arany (Gold) Basin, in the background the covered Hammas Basin. **b**—Timsós (Alum) Basin. **c**—Csokoládés (Chocolate) Basin. **d**—Twin pools at the Gyöngy (Pearl) and Vér (Blood) Springs (*Photos* Csaba Jánosi)

standing in stinking pits, noticed their healing effects and passed their experiences on to their fellow villagers. In ancient and medieval times, people were more attentive to natural remedies and had long been aware of the beneficial effects of acidulous mineral waters. This experience played a major role in the development of folk baths and the widespread spa culture in the region.

Part II

Palaeoenvironment and Human History

9

Palaeoenvironmental Changes During the Last Glacial Period in the Ciomadul Hills

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Abstract

Continuous lake sediment archives extending back to the coldest stage of the last glaciation (LGM: last glacial maximum) are particularly rare in the Carpathian basin. Of outstanding value is the crater lake of St. Anne (Sf. Ana / Szent Anna), at the bottom of which lake and mire sediments have accumulated and give us insight into the paleoenvironmental conditions of the Ciomadul region since ~27,200 years. In this chapter we report on the environmental history of the mountain group surrounding Lake Sf. Ana since the last glacial using the results of our paleoecological work that have been going on for two decades. We also include some recent findings not reported earlier. In the coldest period of the last glaciation steppe tundra vegetation prevailed on the crater slope, trees were not present. Pollen enclosed in the sediment suggests that pine forests grew at lower altitudes, where deciduous trees also found refuge. Warming in this area occurred spectacularly earlier than

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in the North Atlantic region. Plant macrofossil remains preserved in the lake sediment suggest that Scots pine and European larch settled on the crater slope as early as 16,200 years ago, and summer mean temperatures increased by 4 °C in less than 100 years.

9.1 Introduction—Shelter in Volcanic Craters

The Carpathian Basin in Eastern Europe was an important refuge for the temperate flora and fauna during the Quaternary glaciations. Of these cold periods, the last glacial cycle, known as the Würm or Weichselian glaciation, ended about 11,700 years ago. There is a growing body of direct and indirect evidence that, despite the harsh weather, cold-tolerant temperate species lived inland, where geographical isolation created small differences in their gene pool and thus increased the genetic diversity of these species as a whole (Magri et al. 2006; Varga 2010; Magyari et al. 2014ab; Tzedakis et al. 2013). Species for which Carpathian refugia were proved include European beech (*Fagus sylvatica*) and European hornbeam (*Carpinus betulus*), brown bear (*Ursus arctos*) and hedgehog (*Erinaceus europaeus*), but we can also mention here the yellow and red-bellied toads (*Bombina variegata*, *B. bombina*) or the woodland ringlet (*Erebia medusa*).

Why are Lake Sf. Ana and Mohoş (Mohos) peat bog so important when it comes to refugia during the Ice Age? Continuously formed lake sediments that date back to the LGM are found in very few places in the Carpathian Basin. What's more, along the entire Carpathian mountain range only the lake sediments of these volcanic craters allow the continuous study of the environmental history of the last 30,000 years. The species composition of the terrestrial environment, its changes, and the vegetation dynamics can all be excellently studied by pollen, plant macrofossil and DNA analyses of the sediments filling the bottom of the twin crater that are currently slightly acidic (Fig. 9.1).

The development of the aquatic flora and fauna can be inferred from the study of algae (mainly diatoms and green algae), non-biting midges (Chironomidae) and small crustaceans (Cladocera) (see the next chapter for more details). In addition, we can examine the changes in the chemical and physical parameters of the sediment, from which we can draw conclusions about the vegetation cover of the crater slopes, the strength of mass movements and chemical weathering, the changes of which can ultimately be attributed to climate change.

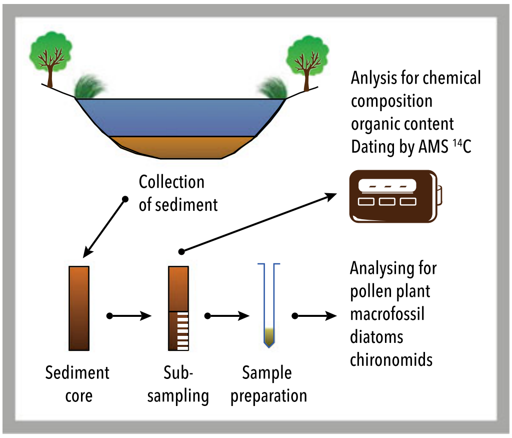

Fig. 9.1 Methods and flowchart of quaternary palaeoecological studies

In this brief summary, we report the nearly 30,000-year history of the mountain range surrounding Lake Sf. Ana, about which the members of our research group have published several international studies over the past two decades.

9.2 Research History

We wrote 1999, the 15th INQUA (International Association of Quaternary Research) Congress was held in Durban, South Africa. This international conference is the main forum for researchers of the Ice Age (Pleistocene), and the 1999 meeting placed special emphasis on rapid climate oscillations from 30 to 60,000 years ago. These climate oscillations were named after their descriptors and are called Dansgaard-Oeschger (D-O) events (Rasmussen et al. 2014). These are high-amplitude climate oscillations lasting about 1,500 years with mild summers and the advancement of conifer trees in Europe. It was found that these events recurred regularly during the indicated period (Fig. 9.2). The reason for these changes is partly unknown, explained by the unevenness of Earth's heat distribution, and the sudden changes in ocean currents. Why did all these climate changes come to the focus of the INQUA conference? Because our species, Homo sapiens, entered the European continent at this time, and this migration was presumably aided by a D-O warm period (D-O interstadial), and then from ~40,000 years onwards our species has become monopolistic on the continent. It is not a question of how curious we are: under what environmental conditions our human being lived at that time? One of the very first *Homo sapiens* sites is known just from the Peștera cu Oase cave in south-western Romania (dated to 37,800 cal yr BP) (Trinkaus et al. 2003; Fu et al. 2015). There was also a discussion at the conference about whether there is a climate archive in our region, a kind of 'inventory' that covers the entire last glacial period (about 100 thousand years).

Returning home from the thought-provoking conference, we began feverishly looking for such a site: where could we study this decisive, exciting time period in the Carpathian region? It soon became apparent that if there were any potential lake sedimentary archives dating back tens of thousands of years, we would have to look for it in the surviving volcanic craters, because only crater lakes can be sufficiently deep to have chance for continuous sedimentation. Only in such lakes can we expect lake sedimentation even in the coldest periods. And this has led us to conversations with Dávid Karátson, who began his volcanological research on Ciomadul at that time: if there is such a place, we must look for it in the youngest volcanic region of the Carpathians, at the southern end of the Harghita Mountains. Moreover, there were not many candidates within this area either, since (as we read in Chap. 3) the crater lakes of the andesite and dacite volcanoes in the area are not long-lived; they recharge and then drain erosively.

In the early 2000s, this is how we got to Lake Sf. Ana in Transylvania with Mihály Braun, who developed his lake sediment sampling device (Livingstone piston corer) with special care. In 2001, the corer was already able to take 1 m long, 7 cm wide cylindrical samples from a boat. Both the significant water depth (about 6 m) and the small weight of the sampling boat (which does not exert sufficient resistance, lowering the corer can lift it) may have contributed to the fact that we only managed to retrieve 4 m sediment in 2001, and for a short time we believed that the lake is relatively young (only 10,000 years old based on the radiocarbon age measured at the bottom of the sediment column). It is "our excuse" that this assumption was also supported by erroneous radiocarbon data, which (as we have already read in the chapter on the history of science) was first measured by French researchers on charcoal found in volcanic tuff layers near Bâile Tuşnad (Tusnádfürdő) (Juvigné et al. 1994). Then in 2009, 2010, and in 2013 we returned to the lake. In the meantime, the drilling technique was also constantly evolving, and we started the drilling from the thickly frozen ice of the lake, so that we could penetrate to much greater depths. Finally, in 2013, we reached the bottom of the crater lake sediment at a depth of 17 m (Fig. 9.3).

In February the average thickness of lake ice is ~30 cm, and since the Ciomadul Hills are the breaking point of the Siberian low-pressure air currents, night temperatures of -15 °C are not uncommon even at the beginning of March, which we had several times. In this cold weather we could drill only with making fire on the ice to warm our freezing hands (Fig. 3). It was a gigantic fight, but it was worth it!

In summary, the 2001 borehole resulted in a 4-metre-long sediment, the 2009 borehole length was 9 m, and the 2010 borehole was 12 m, which was extended by another 5 m from the 2013 borehole. Analysis of the 2013 sediment sequence showed that below 15 m sediment depth biological remains are no more present, only coarse pumice debris, silt and clay, so we reached the bottom of the crater fill. From the point of view of lake history, the significance of the 2013 drilling is given by the fact that its age model confirms the correctness of our age-depth model for the 2010 core: lake sediment accumulation most likely started 27,200 years ago.

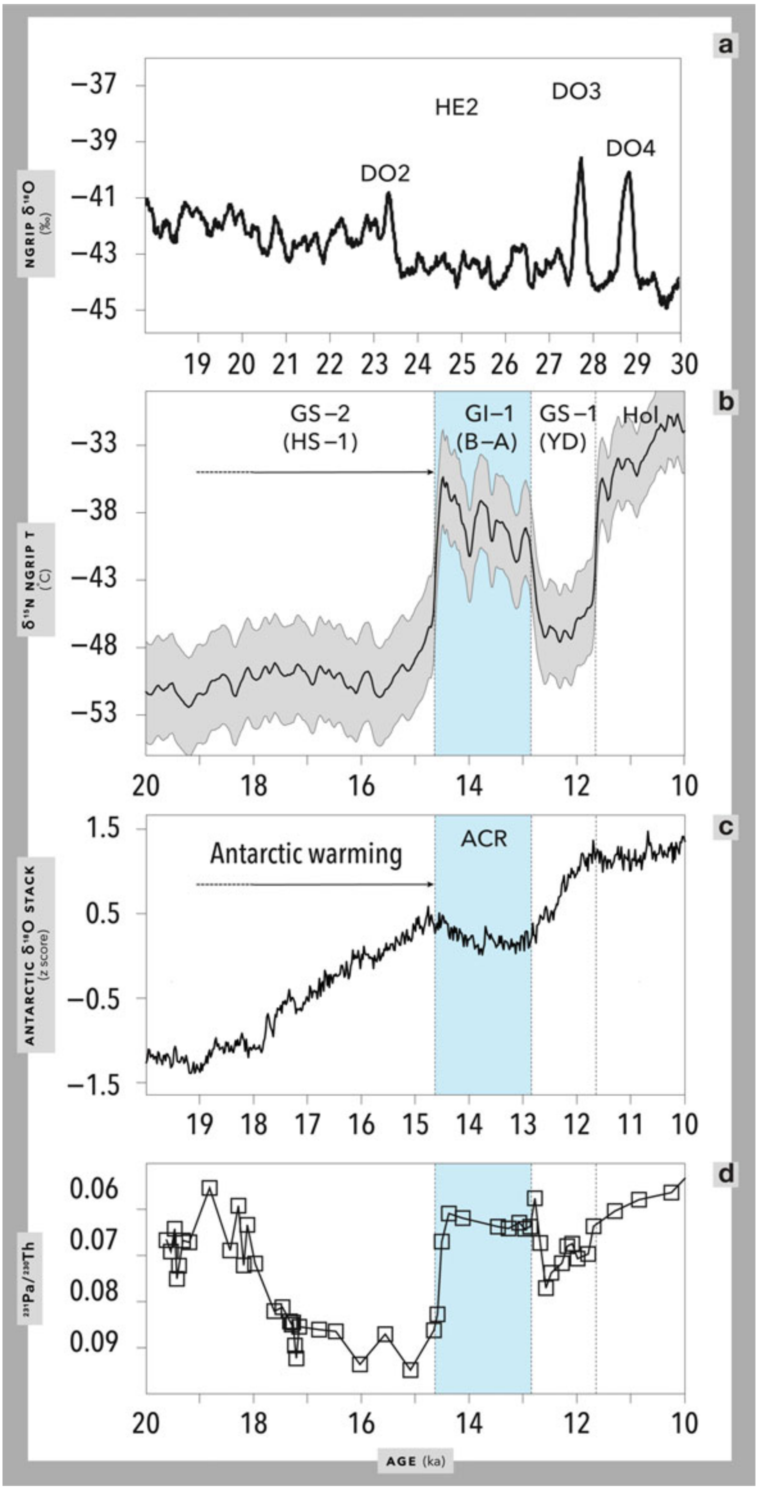

Fig. 9.2 δ^{18}O record **a–b** from the Greenland NGRIP ice core between 30–19 thousand years with Dansgaard-Oeschger (DO2–4) and Heinrich (1–2) events, NGRIP surface-air temperature (δ^{15}N and diffusion-based reconstruction) with 1-sigma uncertainty between 19–11 thousand years showing Heinrich stadial 1 (HS-1), the Bølling/Allerød Interstadial (B-A), the Younger Dryas cold reversal (YD) and Holocene periods (Ho) **c** a stack of Antarctic ice core δ^{18}O records (z-scores) with the Antarctic Cold Reversal (ACR) **d** Atlantic Meridional Overturning Circulation (AMOC) strength (^{231}Pa/^{230}Th) from the Bermuda Rise shown on its published 14C-dated timescale

Fig. 9.3 Examples of lake sediment sampling in Lake Sf. Ana in **a** 2001 **b–c** 2009 **d** 2010 and **e** 2013 (inset shows drilled sample)

Taking into account measurement and calibration errors, the calibrated age can be up to 460 years younger or older.

Most of the analyses were done on the 2001 and 2010 cores, the results presented below are largely based on these two cores, as is the lake history in the next chapter. In both cores we tried to analyse and measure most parameters (multi-proxy approach). However, the analyses had a number of limitations. For example, there were not enough organic residues in the deeper layers, or simply due to recent methodological developments, properties that were still unavailable at the time of the analysis are already measurable on newer cores. The sediment core, however, were perfectly suited for making well-founded palaeoenvironmental inferences.

Pollen grains, diatoms and cysts of yellow-brown algae (Chrysophyta) were examined at high resolution in both the 2001 and 2010 cores, and organic matter content measurements and geochemical analyses were performed on both cores as well (Magyari et al. 2006, 2009 2014ab). Non-biting midge larval head capsules (Chironomidae) were also studied in the late glacial (14,700–11,700 cal yr BP) section of the 2010 core (Tóth et al. 2021). Based on this, we reconstructed July mean temperatures between 17,000 and 9,000 cal yr BP. In addition, we reconstructed regional and local fire histories. Where possible, we also made inference on the local lakeshore vegetation using plant macrofossils.

9.3 The Sf. Ana Crater Lake

Lake Sf. Ana is located at an altitude of 946 m above sea level. At present, the average annual temperature in the area is 6–7 ºC, the warmest month is July (15 ºC), and the annual rainfall is currently around 800 mm. The slopes of the crater are covered with forest. Norway spruce (*Picea abies*) dominates on the lake shore, while European beech is frequent a little higher (Fig. 9.4). The primary reason for this particular vegetation zonation is temperature inversion, whereby cold air settles in the valley bottom resulting in a reverse vegetation zonation; cold-tolerant spruce forests are at the bottom, while moderately warm, humid climate preferring beech forests are in the middle, and warm-preferring oak forests at the top of exposed hilltops. This zonation is apparent in the crater and in the Tuşnad Gorge of the nearby Olt River. Presently, the pH of the lake water is acidic in winter (pH ~5), but it can move to the slightly alkaline range (pH ~>7.5) in summer due to the growth of algae and bathing. Unfortunately, the increasing tourist pressure of the last two decades resulted in strong water quality deterioration, as shown in the next chapter.

Phytogeographically we are in the Eastern Carpathian floristic region, where more than 200 endemic and relict plant species live. Pollen from flowering plants arrive from large distance into Lake Sf. Ana, whose size (average radius of the lake basin is 310 m) suggests that about half of the pollen assemblages arrive from within 10 km, while the other half can come from a distance of up to 100–200 km and travel mainly to the area with westerly wind currents.

9.4 Radiometric Dating of the Sf. Ana Lake Sediments

One important question of the research was the age of the deepest lake sediment, from which we can also infer the formation age of the Sf. Ana Crater (it obviously precedes the age of the oldest sediment somewhat). The most common method for dating late Quaternary lake sediments is radiocarbon dating (carbon-14, ^{14}C hereafter; also see Chap. 3). This unstable form of carbon reacts with oxygen to form carbon dioxide, which is then incorporated into living organisms (e.g., by respiration). Once the creature dies, the amount of carbon can then only decrease, decaying naturally due to radioactivity. Therefore, the lower the measured ^{14}C, the older the sediment (up to a maximum of ~50,000 years). The older the sample, the less ^{14}C, generally increasing the margin of error during analysis. The shells or preserved bodies of organised trapped in the sediments can therefore be used as proxies to date the sediments. However, for Lake Sf. Ana, we know that there is an upwelling of old carbon dioxide in crater (see Chaps. 3 and 7). There is no ^{14}C in this upwelling carbon dioxide because it is too old, meaning that direct ^{14}C dating of the bulk sediment is not possible, as is the remains of aquatic organisms, because we would get unrealistically old ages since aquatic organisms take

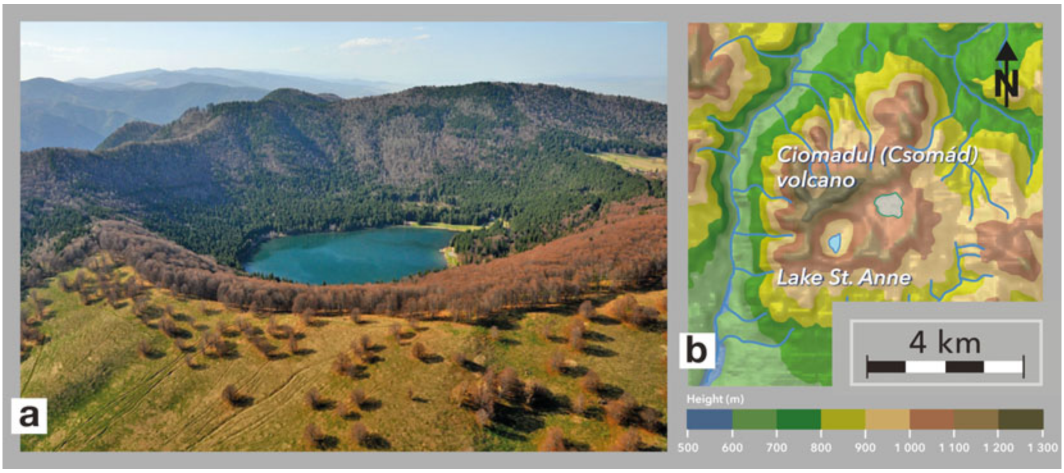

Fig. 9.4 Aerial **a** photograph of Lake Sf. Ana showing the Norway spruce stand on the lakeshore (*photo credit*: Dragos Asaftei), deciduous forest further uphill with beech dominance and grazing meadows at lower altitudes **b** Topographic map of the area

up an build in their bodies this old ^{14}C-free carbon dioxide. As such, analysis must be undertaken on organisms that have incorporated in their body atmospheric CO_2. These are the remains of terrestrial plants living on the crater slopes like terrestrial remains (i.e., seeds, pine and spruce needles, and plant remains). However, from the last glacial maximum it is nearly impossible to find such terrestrial plant macrofossils, since organic matter production and preservation was limited at that time. By filtering the sediment, some terrestrial plant remains were found, but not in the deepest layers.

Another option is to select airborne pollen grains for dating. Sisyphus work, but in the case of such a unique sediment, everything must be done to set up a more reliable age scale. Further complicating the age modelling is that the rate of sediment formation is highly variable. When only a few centimetres of sediment are formed over millennia (such as in the late glacial period immediately preceding the Holocene), it is almost impossible to assign accurate ages to the depth.

A large amount of radiocarbon dates (accelerated mass spectrometer, AMS ^{14}C) was measured on the 2010 and 2013 cores. We determined 16 AMS ^{14}C date from the 2010 and 76 from the 2013 core so far (Annex 1). Based on these, we can say that Lake Sf. Ana was formed approx. 27,200 years ago, which, however, does not correspond to the age of the crater formation, as the lake begins to form after the eruption, and blocking of the crater bottom and rainwater accumulation can take hundreds or even thousands of years. The onset of calm sediment formation is also highly dependent on post-volcanic activity.

9.5 Ice Age Tundra, Permafrost and Taiga Forests of Ciomadul

By examining pollen and plant macrofossils in all three long cores directly after the formation of the lake we inferred that no contiguous vegetation cover was present on the crater slopes directly after the formation of the lake. It was then—between about 27,200 and 16,200 years ago—that the coldest period of the last glaciation occurred, with the English abbreviation LGM (Last Glacial Maximum). There were no plant macrofossils in the sediment deposited during this period, the pollen composition suggested a mixture of tundra and steppe vegetation. The filling of the crater took place at an extremely fast rate, as indicated by the coarse debris and sand layers supplied by turbidites in the sediment (Figs. 9.5 and 9.6). Dropstones, which often reach 2–4 centimetres in diameter were also abundant in the sediment. With the help of geochemical and geophysical studies, we can draw conclusions about the composition of the air and even the prevailing winds. For example, the magnetic susceptibility of a sediment shows the amount of minerals with magnetic properties. This was very high in the lake between 27,000 and 20,000 years ago, however, it did not show a close correlation with changes in sediment iron content, suggesting that the magnetic minerals did not enter the water directly from the crater slope, but were transported by air. Their concentration increase marks the period of dust deposition (loess formation) in the area, which only declined towards the end of the LGM, approximately 20,000 years ago. Magnetic susceptibility analysis has shown that increased susceptibility values are mainly associated with magnetite and hematite minerals. Also indicative is the behaviour of titanium in the sediment. The enrichment of this element occurs in lake sediments when erosional processes produce and bring into the lake inorganic derbies that is produced by frost shattering for example. Titanium (Ti) was abundant in the sediment until 16,150 years ago, after this date it decreases, and its final decrease took place only towards the end of the Pleistocene, during the late glacial when the crater lake became forested (around 12,400 cal yr BP).

What can we tell about the sparse vegetation of the crater slope during the LGM? For this we have to turn to the pollen diagram (Fig. 9.7). This is dominated by chenopods (Chenopodiaceae) and wormwoods (*Artemisia*) together with juniper (*Juniperus*) and alpine cushion herbs belonging to the genera *Saxifraga, Minuratia, Helianthemum* and *Armeria*. Although trees were not present on the crater slope during the LGM,

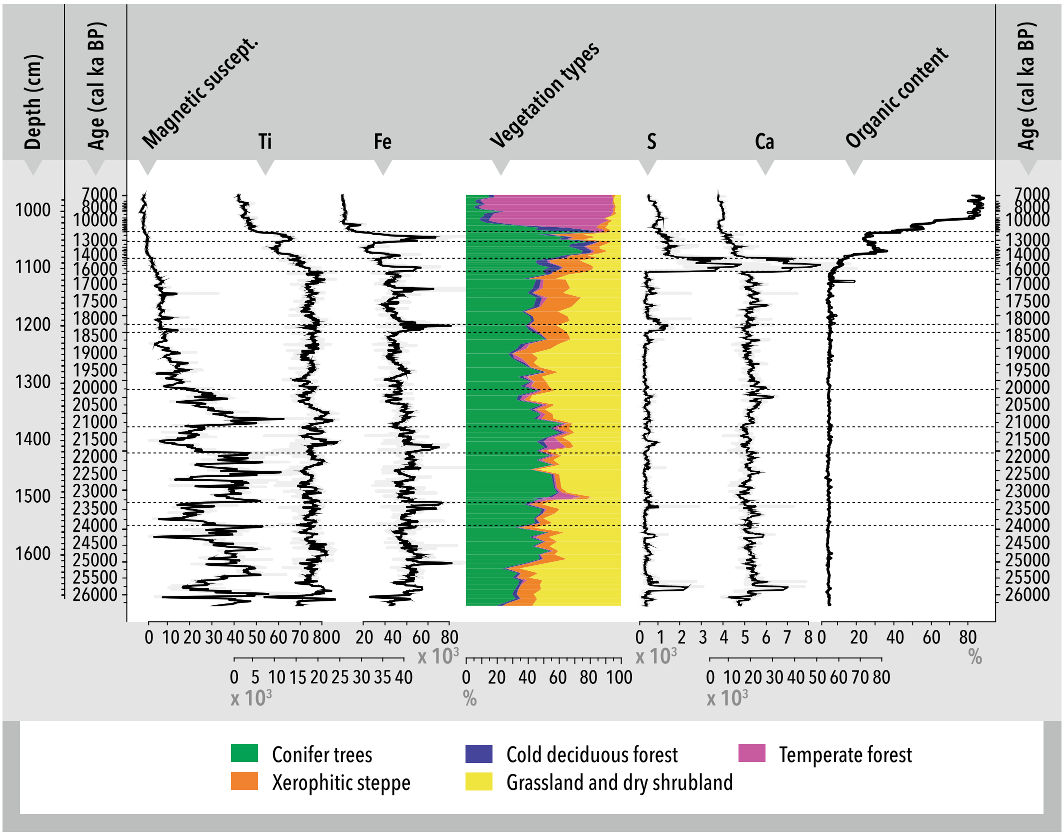

Fig. 9.5 Magnetic susceptibility (MS), titanium (Ti), iron (Fe), sulphur (S) and calcium (Ca) intensities (103 counts), organic content (LOI%), major vegetation types (% pollen data), depth and age (cal yr BP) of core SZA-2010 from Lake Sf. Ana (1682–970 cm depth). Dashed lines in the figure mark major changes in the MS and XRF element data. In the summary percentage pollen diagram each pollen type was assigned to a major vegetation type following a simple biome scheme (Feurdean et al. 2014).

Fig. 9.6 Turbidite layer in core SZA-2010 of Lake Sf. Ana between 1327 and 1343 cm depth suggesting high energy sediment relocation/transport

the diversity of the terrestrial herbs was remarkably high. The highest pollen diversity was found between 20–22 thousand years. Interestingly, the composition of tundra and steppic plants, the lake level changed several times suggesting that the climate was variable even within the coldest phase of the last glaciation. The first is exemplified by the different herb pollen composition between the 23,000 and 19,000 years. It is also interesting that the vegetation compositional change starting at 19,000 years brought the expansion of several semi-desert and steppic plants suggesting that in the warming landscape

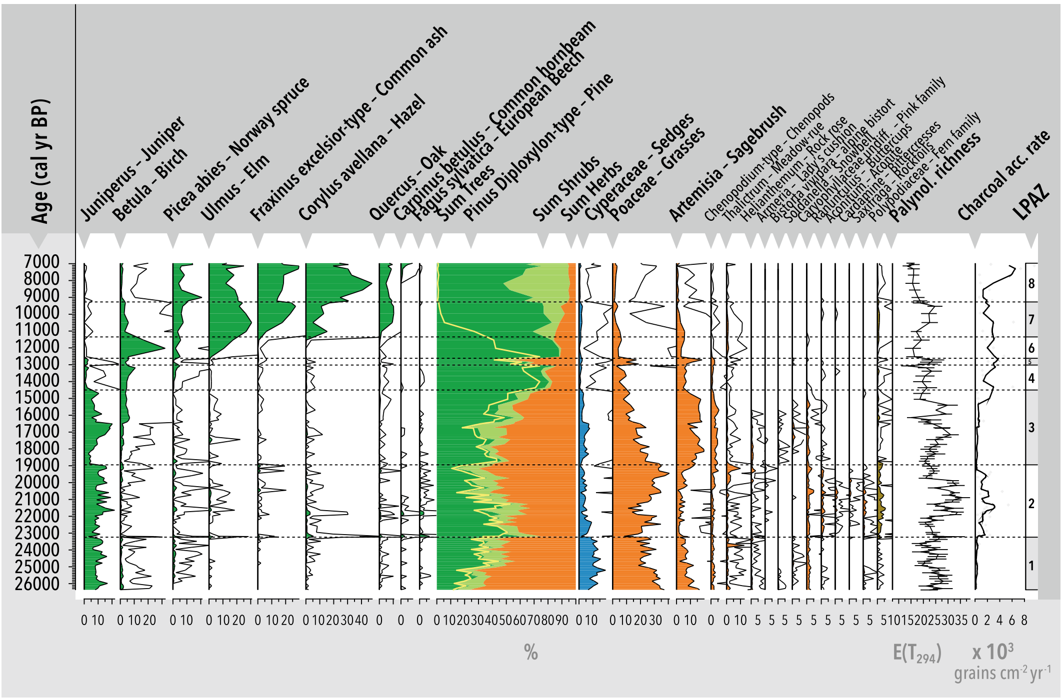

Fig. 9.7 Percentage pollen diagram of Lake Sf. Ana, core SZA-2010, for the last glacial and Early Holocene period with palynological richness and microcharcoal accumulation rates; LPAZ: local pollen assemblage zones

available moisture was a very important limiting factor for plant dispersal.

It is surprising for a first sight that even though trees were not growing on the crater slope during the LGM (tree plant macrofossils were not found), tree and shrub pollen was abundant, they reached 45%. Taking into account, however, the dispersal characteristics of pollen, we can say that this tree pollen abundance can be well explained by the abundant pollen production and dispersal capacity of the bisaccate pine pollen type (*Pinus* Subgenus *Diploxylon*) that arrived from larger distance to the lake. We should not forget about junipers (Juniperus sp.) either, the pollen of which was also abundant (its pollen production is less than pine). This pollen composition suggests that at lower elevation (likely below 600 m) the Ciomadul landscape was similar to the modern boreal forests, particularly to its South Siberian dry zone, where boreal forest steppe predominates for example in the northern, partially rain shadow slopes of the Altai-Sayan Mountains.

9.6 Afforestation of the Crater Slope

Let's turn our attention to the late Pleistocene warming again! In Western Europe, and in particular in Greenland, the first marked warming (inferred from the $\delta^{18}O$ records of the Greenland ice cores) and vegetation compositional change (inferred from terrestrial pollen and plant macrofossil records) was detected about 14,700 years ago (Rasmussen et al. 2014). This so-called late glacial period was characterised by warming that was intermingled by several short or longer term cold episodes, each representing a negative feedback in the climate system driven by melting ice and freshwater burst into the North Atlantic Ocean. In contrast to NW Europe, in the area of the Black Sea and in the Great Hungarian Plain climatic amelioration and rapid vegetation change can be detected earlier, around 16,200 years ago that resulted in the disappearance of steppe tundra habitats and the expansion of boreal and cold temperate mixed forests.

In order to understand the reasons of this difference between NW and East-Central Europe, we have to know the history of sea ice and ocean currents in the North Atlantic as briefly mentioned above. Even though the melting of the polar ice started already 19 thousand years ago, and accordingly oxygen isotope ratios indicate marked warming in the Antarctic ice cores from ~18 thousand years, in the North Atlantic meridional overturning circulation was different from today until 14,700 years ago. The warm currents moving towards the north were slower than today, and the submerging point where south moving cold current starts was displaced southward due to the larger extent of the North Atlantic sea ice. This prevented warming in this area. The Eastern Carpathians are located far away from the norther basin of the Atlantic Ocean, a major influence of European climate, and its climate was influenced also by the territories located to the east and north, and in the watershed of Black Sea. In this latter area warming was pointed out since 19,000 years. Alkenones (cell wall lipids) in the sediment of Black Sea suggest that in the watershed of the Dnester and Dneper rivers extensive peat (*Sphagnum*) bogs developed 17,000 years ago and large permafrost areas melted away. Looking at the pollen and plant macrofossil compositional changes, physical and chemical records of the Lake Sf. Ana sediment, we see that the main change was the expansion of coniferous trees from 16,300 years, and in parallel with it the sulphur (S), calcium (Ca) and organic content increased. These indicators suggest organic matter decomposition in oxygen depleted environment and paludification (mire development).

It is evident that we witness a rapid warming here, that is also supported by the increasing presence of plant macrofossils in the sediment (Fig. 9.8). First to settle on the crater slope was Scots pine (*Pinus sylvestris*) at ~16,200 years, while Norway spruce (*Picea abies*) appeared at 15,900 years ago. This was followed by downy birch (*Betula pubescens*) and dwarf birch (*Betula nana*). All these inferences are based on the finding of their bud and bract scales, whole buds, fruits and nuts. Macroscopic charcoal remains (macrocharcoal) became abundant 17,000 years ago pointing to the recurring burnt down of the local woody vegetation. The lakeshore was covered by sedges at this time (*Carex rostrata, C. nigra*), and from 16,300 years aquatic macro zoo-benthos appeared and was dominated by the larvae of non-biting midges (chrionomids). The community composition of these insects is very sensitive to air temperature during the flight period (July and August), therefore they are good indicators of summer mean temperatures.

9.7 Mosses and Peat

Brown mosses and *Sphagnum* peat mosses were also among the first to appear. Particularly species of the latter group acidify their environment, and their presence thus indicates decreasing pH of the lake water. This change was likely also amplified by the appearance of the acidic coniferous litter, and was also signalled by very rapid changes in the algal flora (particularly diatoms, see next chapter). From among the green algae, colonial algal groups, such as *Pediastrum* and *Scenedesmus* species disappeared suggesting that the nutrient content of the water column likely decreased at 14,700 years. This initial warming phase of the late glacial is called the Bølling/Allerød interstadial named after its type localities in the Netherlands. It was followed by the last cold reversal of the Pleistocene, the Younger Dryas stadial. Surprisingly, this 1000-year long cold period had little impact on the local vegetation; plant macrofossil composition of the sediment did not change. On the other hand, the pollen diagram shows a clear expansion of steppic forbs and herbs that likely reflects vegetation change at lower altitude, and overall we can say that regional forest cover decreased suggesting that available moisture decreased remarkably in this period (between ca. 12,850–11,700 years). This was followed by the expansion of birches in the pollen record suggesting reforestation. Pine-birch forests were widespread in this region in the Early Holocene, including the crater slope. A similar phenomenon,

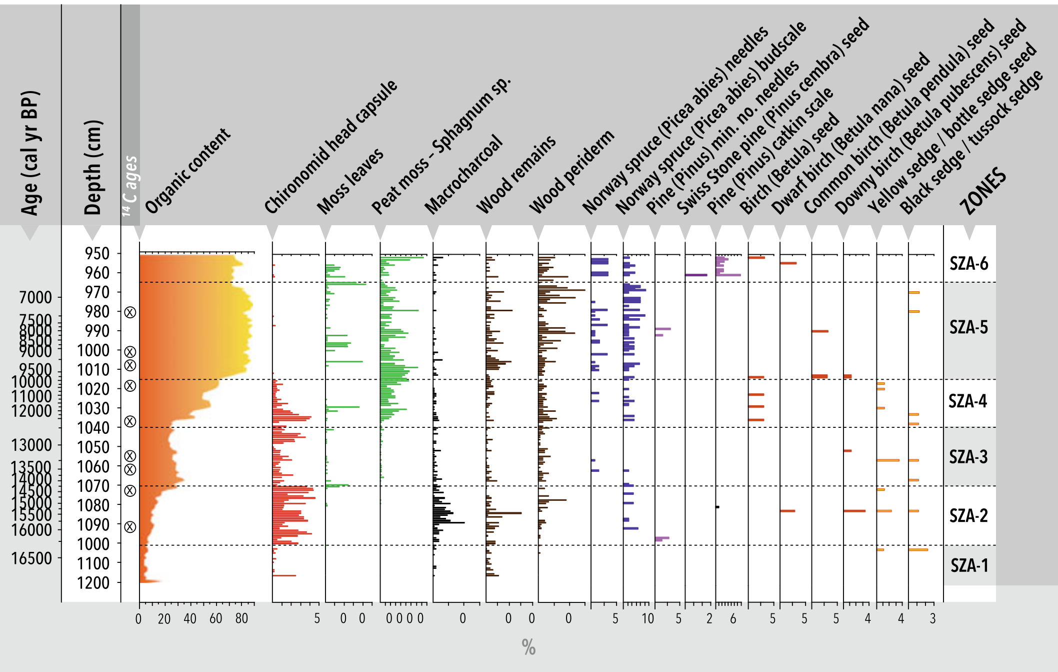

Fig. 9.8 Plant macrofossil concentration diagram of Lake Sf. Ana, core SZA-2010

i.e. that above 1000 m a.s.l. the Younger Dryas cold reversal had minimal impact on the local vegetation, was also detected in the Southern Carpathians. The reason for this is likely similar to the regional climatic differences in Europe during the Younger Dryas, similarly to the late LGM. Namely, the Younger Dryas climatic reversal was caused by a large volume freshwater burst into the North Atlantic Ocean, to our best knowledge, that caused the southward displacement of Atlantic Meridional Overturning Circulation (AMOC) and its decreasing flow intensity.

In the meantime, warming continued at the southern pole, and even intensified showing that heat distribution was controlled by the oceanic current at this time, with the incoming solar radiation staying the same. Our data demonstrate that the major impact of this cold reversal was precipitation decrease in the Lake Sf. Ana region. Although we have no winter proxy in our studied biotic proxies, it is likely that winters became colder, while summers remained warm due to the increasing incoming solar radiation at this time. Even though *Sphagnum* moss concentration increased in the sediment of Lake Sf. Ana during the Younger Dryas suggesting further acidification (non-biting midges likely reacted to this negatively). The algal flora showed a very different change, however. Green algae that disappeared during the Bølling/Allerød warm period (interstadial) appeared again during the Younger Dryas, we found their remains in very large quantity in the sediment. Knowing that the environment became more acidic this phenomenon is hard to interpret: green algae indicate increasing nutrient availability in the lake water, the source of which can be dust fallout or enhanced soil erosion. We cannot exclude that even though precipitation overall decreased, its seasonal distribution also changed, with occasional heavy rainfalls and associated stronger erosion events bringing in nutrients into the lake.

The last major change in the terrestrial vegetation described in this chapter took place at the Holocene onset, about 11,700 years ago. In the Early Holocene pollen and plant macrofossil assemblages suggested that all three birch species living in the area today were already present (downy birch, common birch, dwarf birch), and the pollen and plant macrofossil composition suggested the presence of pine-birch forests in the region. Taking into account climatic inversion in the crater today, the deciduous tree species detected in the pollen and plant macrofossil records, e.g. Norway maple (*Acer platanoides*), elm (*Ulmus sp.*), common ash (*Fraxinus excelsior*) and deciduous oak (*Quercus sp.*) were likely present on the crater rim and in the surrounding warm mesoclimate mountain slopes. We wrote about the Holocene vegetation dynamics of the area in the previous chapter.

9.8 Non-Biting Midge (Chironomid) Remains in Lake Sf. Ana

Non-biting midges (Chironomidae) are a family within the Diptera ordo of insects. Their larvae live in water, and only a short part of their life cycle is spent outside the aquatic habitats during the imago phase, when they fly off, mate and lay eggs. Subsequently they perish. Chitinous head capsules of the larvae fossilize well in organic lake sediments and can be identified to species or species group level using light microscopic analysis. Their communities are very sensitive to environmental change, and in oligotrophic environments they are particularly sensitive to summer mean temperature changes. Using this characteristic, they can be used for quantitative reconstruction of past summer mean temperature changes. One important condition of the chironomid analysis is to find at least 50 identifiable chironomid head capsules in the analysed sediment layer that is the minimum for statistical analyses (Tóth et al. 2012, 2021). This condition was met in the sediment of Lake Sf. Ana between 17,100 and 9,100 years, thus our summer mean temperature reconstruction covers this time period (Fig. 9.9). So far we identified 16 chironomid taxa in Lake Sf. Ana and the reconstructed July mean temperatures range is between 7.1 and 15.5 ºC (the modern value is ~15 ºC). The largest amplitude increase in mean July temperatures was detected at 16,300 years, when July temperatures increased by 4.9–5.0 ºC. This finding agrees well with the amplitude of warming found in the Black Sea and at Antarctica, but differs from NW Europe (Pedro et al. 2015). The second largest amplitude warming was reconstructed at the late glacial onset (around 14,600 years in our record); the reconstructed amplitude was 1 ºC warming. This is much lower than similar reconstructions show for NW Europe, and can most likely be explained by earlier warming in the Lake Sf. Ana region, at 16,300 years. Reconstructed July mean temperatures were between 13.4–15.5 ºC during the late glacial. Finally, reconstructed air temperatures at the Holocene onset did not increase at Lake Sf. Ana, even though the terrestrial vegetation clearly indicated warming. This likely erroneous reconstruction can most likely be explained by other environmental factors that drove the species composition change of the chironomid fauna. The water pH also decreased in the early Holocene, with the plant macrofossil composition of the sediment suggesting that the lake turned into a peat bog at this time (i.e., water depth decreased considerably).

9.9 Ice Age Refugia in the Eastern Carpathians

In the LGM pollen record of Lake Sf. Ana several deciduous tree species/genera were present, such as beech (*Fagus* sp.), European hornbeam (*Carpinus betulus*), ash (*Fraxinus sp.*). elm (*Ulmus sp.*), lime (*Tilia*), oak (*Quercus*) and hazel (*Corylus sp.*), and we found short time periods during the LGM when the overall pollen frequency of temperate deciduous tree pollen reached 5%. Even though pollen does not prove local presence, and so we can only infer a possible regional presence of these tree taxa, if we take into account LGM climate model based species distribution models and the results of population genetic analyses in phylogeographical surveys for European beech and European hornbeam that record refugial habitats via area specific alleles, then we can surmise that most temperate deciduous tree species typical in the area today likely survived the LGM in the Carpathian Mountains. The most probable location of these microrefugia were in the slopes of the Apuseni Mountains in warm micro- and mesoclimate shelters. Identifying these localities is however impossible with classical

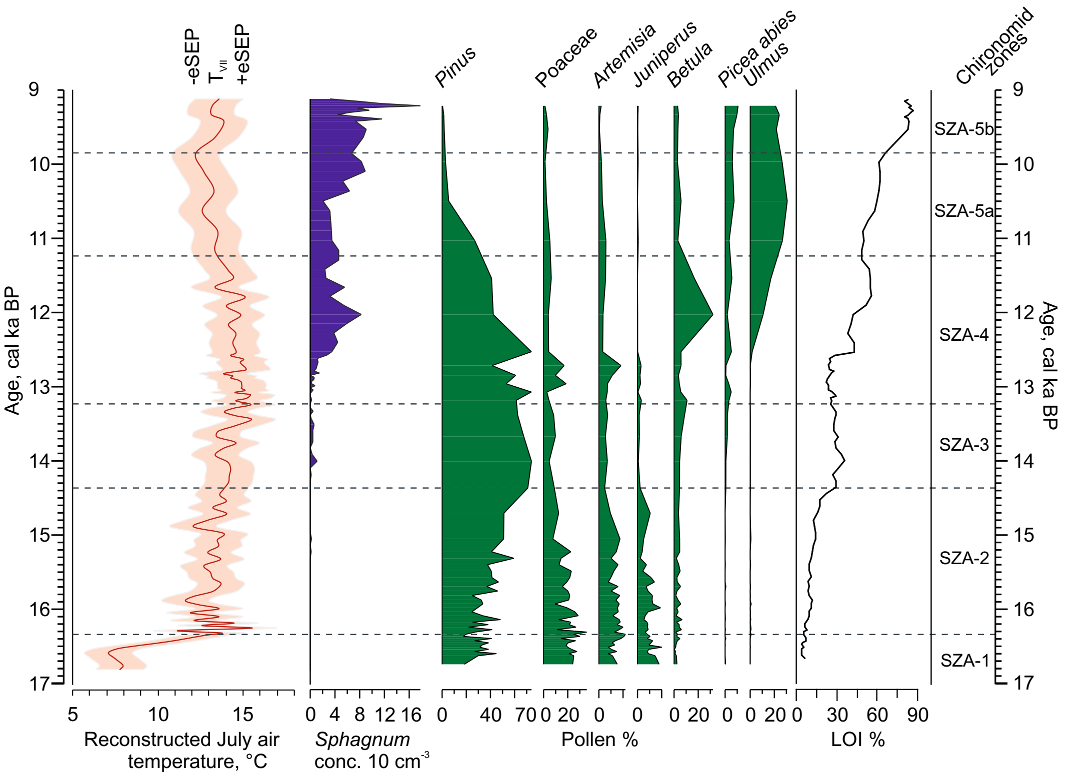

Fig. 9.9 Chironomid inferred temperature estimates (T_{VII}) and sample-specific standard errors of prediction (eSPE), *Sphagnum* leaves concentration (per 10 cm^{-3}), percentage abundance of selected pollen types (Pollen %) and loss-on-ignition (LOI, %) values from core SZA-2010, Lake Sf. Ana (East Carpathians) with zones for the chironomid stratigraphy (SZA-). Redrawn and modified from Tóth et al. (2022)

palaeoecological techniques. Protection of this unique genetic diversity is our responsibility that can be reached by leaving at least part of the forests unmanaged. This way we can preserve local, area-specific genetic variants that in many case provide the possibility for climate change adaptation via their slightly different genome.

9.10 Summary

The Carpathian Mountains were one of the main mountain reserves of the boreal and cool temperate flora during the Last Glacial Maximum (LGM) in East-Central Europe. In this chapter we presented a record of vegetation, fire and lacustrine sedimentation from the youngest volcanic crater of the Carpathians (Lake Sf. Ana) to examine environmental change in this region during the LGM and the subsequent deglaciation. Our record indicates the persistence of boreal forest steppe vegetation in the foreland and low mountain zone of the East Carpathians and juniper scrubland at higher elevation. We demonstrated attenuated response of the regional vegetation to maximum global cooling. Between ~22,870 and 19,150 years we found increased regional biomass burning that is antagonistic with the global trend. Increased regional fire activity suggests extreme continentality likely with relatively warm and dry summers. We also demonstrated xerophytic steppe expansion directly after the LGM and regional increase in boreal woodland cover from 16,300 years together with a 4.9–5.0 ºC increase in July mean temperatures inferred by changes in the non-biting midge larval communities. Pollen data furthermore hinted at the regional presence of some mesic deciduous trees during the LGM. Our sedimentological data also demonstrated intensified aeolian dust accumulation between 26,000 and 20,000 years.

Annex 9.1 Results of the AMS ^{14}C measurements from core SZA-2010 Lake Sf. Ana

Depth (cm)	Dated material	Conv. age (yr BP)	±	Cal. age range BP (2σ)	Age (cal BP) used in linear model	±	Carbon content (mg)	Comment
980–982	*Sphagnum* sp. leaves, *Picea abies* needles, bud scales	6246	26	7155–7258	7206.5	51.5	1	
1000–1002	moss leaves and shoot, bud and bract scales, periderms	8216	28	9082–9286	9184	102	1	
1008–1009	*Picea abies* bud scales & needle leaf bases	8293	54				0.38	
1018–1019	*Carex rostrata* achene, *Picea abies* bud and bract scales, moss leaves	9261	93				micrographite measurement, 0.14 mg C	
1036–1038	macrocharcoal, moss leaves, periderm, bract scales	10,739	42	12,562–12,742	12,652	90	0.58	
1055–1056	cf. *Carex* sp. seed, *Picea abies* needles	11,097	150	12,712-13,222			0.09	
1060–1061	*Picea abies* needle base, bud	11,374	490	12,040-14,708			0.01	
1072–1073	micro- and macrocharcoal	14,038	38	16,830–17,263	17,046.5	216.5	1	outlier in linear model
1091–1092	Cyperaceae leaves	15,400	44	18,556–18,784	18,670	114	1	outlier in linear model
1085–1086	Bud and bract scales	14,118	339				0.05	
1095–1096	*Picea* sp. needle leaf base and bud	14,196	111				0.25	
1126–1127	Cyperaceae leaf fragments	14,541	67	17,371–17,976	17,673.5	302.5	0.26	
1340–1342	macrocharcoal, Cyperaceae leaf fragments, chironomid head capsules, Cladocera ephippa	17,338	84	20,290–21,138	20,714	424	0.28	
1365–1366	Cyperaceae leaf fragments, chironomid head capsules, Cladocera ephippa	17,626	96	20,523–21,387	20,955	432	0.18	
1538–1540	Moss leaves, shoot, chironomid head capsules, Cladocera ephippa	19,717	122	23,133–23,953	23,543	410	0.13	
1661–1662	Cladocera ephippa	21,685	163	25,400–26,713	26,056.5	656	0.09	

Limnological Changes in Lake Sf. Ana

10

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Abstract

Lake Sf. Ana at the top of Ciomadul volcano is one of the only open water crater lakes in the Carpathian Mountains, and has been providing a habitat to bacteria, algae, and microscopic animals in the pelagic zone, as well as rich lakeshore wildlife for 27,000 thousand years. The water of the lake is considered to be clean even today, although plenty of signs denote that the once oligotrophic lake becomes mesotrophic at least in the summers. In this chapter, we describe the response of lake and lakeshore wildlife to climate fluctuations through time, as well as some transformations induced by more recent human activity. The processes taking place in the lake are reconstructed based on palaeoecological methods via the analysis of core samples obtained from the lacustrine sediment.

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10.1 Introduction

The number of lakes with a considerable surface size of over one square kilometre amounts to more than one million on Earth. Of them, Lake Sf. Ana (Lake Saint Anne, Szent Anna-tó), even if its surface is smaller (with an area of 0.2 km^2, i.e. 20 hectares), is a peculiar occurrence and is deemed to be one of the most exceptional lakes. It is the "highlight" of the volcanic range of the Eastern Carpathians, which are unparalleled for other reasons too. What makes it so unique?

10.2 The Uniqueness of Lake Sf. Ana

Being a crater lake, itself makes it so special. The majority of such lakes are characterized by a small catchment area and the crater rim protects the water from being stirred (Fig. 10.1). If the crater is deep enough, it may even lead to anoxic conditions on the bottom. In this case the life activities of living organisms residing there, i.e., bioturbation, will not prevent the deposition of sediment either; hence the substance accumulating and settling here continuously (since the formation of the lake) becomes suitable for high-resolution (yearly or even seasonal) analyses. Provided that the crater is not too deep—only some tens of metres—the crater is rapidly filled via sedimentation, and water level decreases in a short while. However, if the depth of the crater is several tens or hundreds of metres and it was formed thousands or millions of years ago, the remaining sediment may be used for retaining long and unique data sequences. The lacustrine sediment of Lake Sf. Ana is an example of the former case. Usually, the analysis of lake sediment may as well be used to infer even the movement of planets (see the so-called Milanković-Bacsák Cycle on the cyclical changes of the orbital elements of Earth), which affects numerous climatic factors (temperature and the change thereof, precipitation conditions, source of precipitation, seasonality), the wildlife of adjacent and more distant areas; furthermore, it has an impact on the changes of water quality, too. This is also valid when the lake disappears: lakes

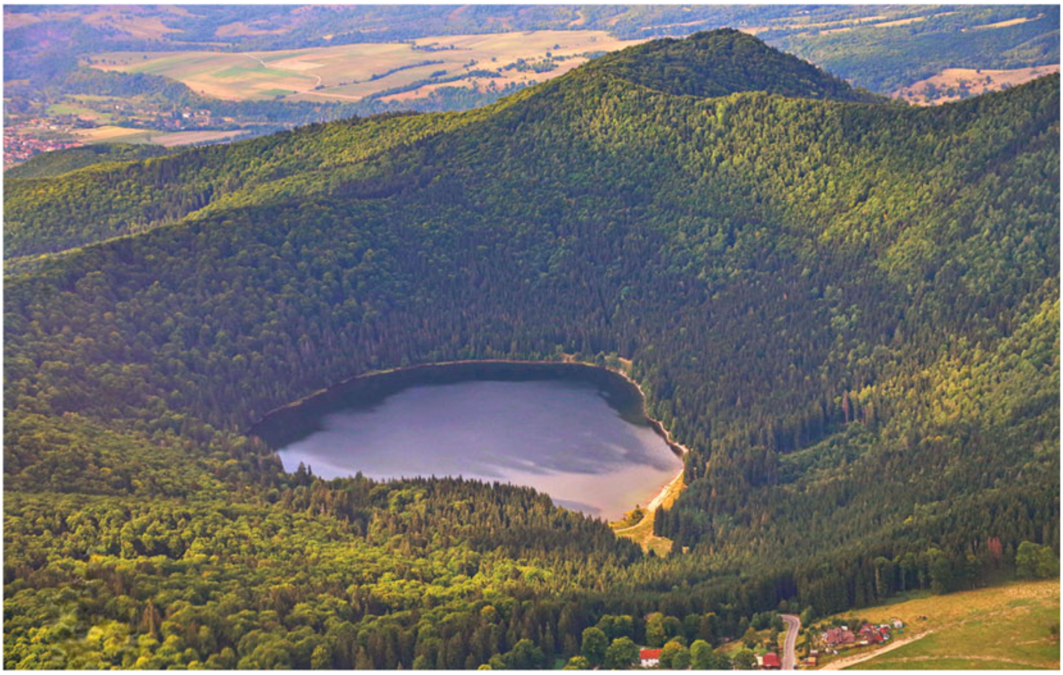

Fig. 10.1 View of Lake Sf. Ana; *Photo credit*: István Fodor (Miercurea Ciuc)

in-filled by sediment (so called “palaeo-lakes”) prove in many cases to be the only reliable evidence of the ancient environment. Lake Sf. Ana is one of the few places in the Carpathian Mountains where climatic fluctuations can be studied from the Last Glacial Maximum (LGM) due to it’s unique location, and general rarity.

Secondly, Lake Sf. Ana is considered to be extraordinary since it is the last and only still open-water, primary crater lake along the Carpathians. Since craters tend to be filled up sooner or later or get drained via natural erosion, the fact that visitors can nowadays enjoy the view of a glimmering water surface is attributable specifically to the relatively young age of the last eruptions of Ciomadul (Csomád) that created Sf. Ana crater. As far as similar lakes or bogs situated in the Carpathians are concerned, going backward chronologically, Luci (Lucs) Peat Bog which was formed in the Pliocene caldera of Luci-Lazu (Nagykőbükk) volcano in the Hargita is worth mentioning; yet this feature is most probably of secondary origin (created by a landslide in the Ice Age). Likewise, a natural damming caused by a Pleistocene slide might have created Lake Szinna (Morské Oko, Slovakia) within the Late Miocene volcanic crater or caldera of the Vihorlat (Vihorlát) Mountains. Consequently, we do not know any other primary crater lake apart from Lake Sf. Ana in the whole Carpathian Basin.

Finally, Lake Sf. Ana is unique because it is described as the lake with the clearest water in the Carpathians. Crater lakes are predominantly fed by rainwater, and only ground water and hydrothermal solutions may contribute to their water balance. Water loss takes place mainly through evaporation and leakage (as long as water finds a way to break through by breaching the crater rim as a result of natural erosion processes). Initially, there is also no permanent water courses that would carry sediment load into the crater lake, until it remains intact, and this is the reason for the bright, clean water. Since the quantity of nutrients to take is low and there is hardly any life present in open waters, these lakes are characterized by low biotic activity. As Tibor Hortobágyi, the famous Hungarian algologist put it in 1943 when writing about Lake Sf. Ana: water quality *“rivals distilled water”*.

10.3 Formation of Lake Sf. Ana

Depressions forced on the Earth’s surface are filled with water relatively quickly provided suitable hydrological conditions are met (e.g. an impermeable layer and adequate rainfall). Even the smallest pond ensures habitable conditions to plenty of microscopic organisms until it dries up, typically dominated by similar, wide-spread, and wide tolerance creatures. Water that is present for much longer (for decades, centuries or even millions of years) may result in the evolution of a community of organisms unique to that particular water body. The closed nature of lakes and the long-time interval can result in the speciation of new species, that is, real evolutional processes occur in the lake. Accordingly, Lake Sf. Ana is characterized by a unique and special flora and fauna including endemic species—such as some representatives of the diatom genus *Kobayasiella,* which resides in this lake only (Fig. 10.2).

The lake formed from a catastrophic eruption of Ciomadul volcano, leaving a significant and isolated depression atop the mountain. The bedrock of the lake is Cretaceous sediments and dacitic lava domes and pyroclastics (ash and pumice; see Chap. 3). The bottom of Lake Sf. Ana consists predominantly of eruptive products, which altogether, form an impermeable layer around the depression, allowing for water to collect and form the lake as it is seen now, likely forming shortly after the last eruption ~30 000 yrs. Not only has the volcanic activity made the lake’s formation unique, but it will also have influenced localised weather patterns from the eruption of volcanic ash and gas, ultimately determining rates of precipitation, lake acidity, and biodiversity of the newly formed lake. More recently, CO_2 degassing continues to occur across the lake sediment and lake water, but we have no information as to how the intensity of degassing alternated across the history of the lake.

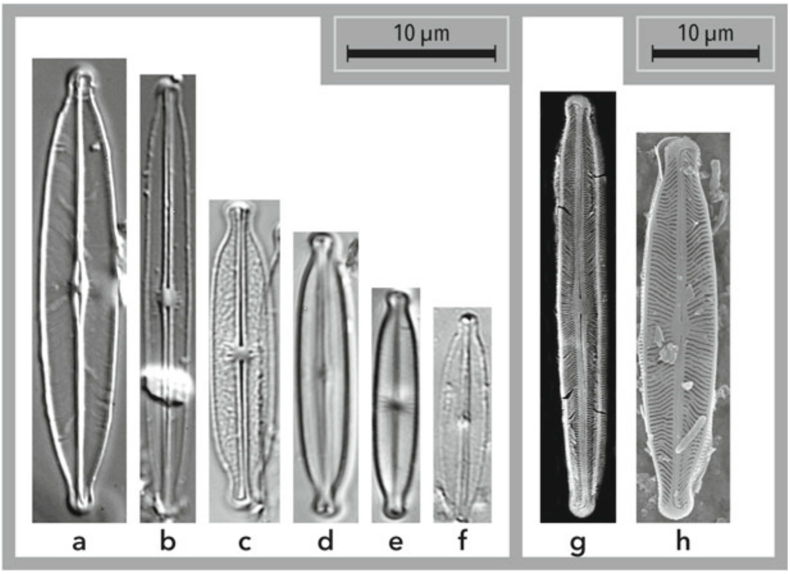

Fig. 10.2 Species of the *Kobayasiella* genus are indicators of very good water quality and are typical in acidic waters. We described two taxa new to science from the Holocene (*K. elongata* ***b-g***, *K. tintinnus* ***f, h***.). *Credit* Krisztina Buczkó

10.4 Water Quality and Biodiversity

What is the quality of the lake today? In brief: it is clean, acidic with high dissolved oxygen level. Regular water-chemical, bacteriological as well as algological investigations have been conducted since 2011 under the supervision of the Sapientia Hungarian University of Transylvania. According to these studies, the available nutrient content in the pelagic of the lake is rather low. One of the most significant features characterizing the life of lakes is whether thermal stratification can develop. Shallow lakes are frequently stirred by wind, hence these waters are not stratified, whereas deep lakes often undergo permanent thermal stratification. In this case the water temperature of deeper sections in the lake is 4 °C (as water of 4 °C has the highest density). The upper layer of the lake follows the thermal fluctuation of the lake surface and there is a thermocline between the two layers. The water of the lake can be mixed down to the bottom only in case the temperature of the whole water body drops below 4 °C. The mixing of water layers normally increases the access to nutrients, which has an impact on the reproduction of organisms dwelling in open waters. Recently no permanent stratification has evolved in Lake Sf. Ana, likely due to its relatively shallowness. Furthermore, the water is rich in oxygen and there is no anoxic condition (oxygen depleted) close to the lake bottom.

In the wintertime the water of Lake Sf. Ana gets frozen, and thick ice cover develops in the cold crater every year. Scientists from the Babeş-Bolyai University at Cluj-Napoca measured, under the leadership of Zoltán Pál, an average of 70 cm in 1999; nevertheless, at certain locations, ice thickness reached 1 m. (In recent years, however, due to global and regional warming, the ice cover has generally been thinner and existed for a shorter period.) Frequent snowfalls build further layers of the ice. Thick ice, nevertheless, is very favourable for carrying out palaeolimnological studies because it makes camping on ice possible, and small drilling platforms can be built offering stable working conditions (see Chap. 9).

According to studies carried out by Tibor Hortobágyi (1943), the phytoplankton of Lake Sf. Ana is poor in species. He highlighted the dominance of *Parvodinium inconspicuum* (previously known as *Peridinium inconspicuum*; Dinophyta) (Fig. 10.3). This dinoflagellate is known to be good at tolerating the acidification of water and is able to reside even under low pH conditions; therefore, it can frequently be collected in acidic lakes. It can be generally established that the more

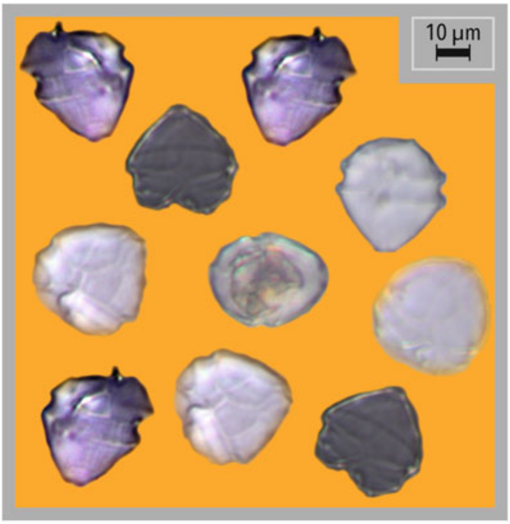

Fig. 10.3 *Parvodinium inconspicuum*, which has been a typical dinoflagellate of Lake Sf. Ana for decades. *Credit* Krisztina Buczkó

we divert from neutrality, the lower species abundance is in the biome. From Hortobágyi's work we know that according to previous data, *P. inconspicuum* was the most typical alga in the lake already in the late nineteenth century. (It should be noted, however, that these results were based on the analysis of samples collected mainly with a plankton net, which implies that organisms smaller than 25 microns were not included in the samples.) The pH value of the lake has increased significantly in the 2000s with values between 4.5–8.5. This pH increase is attributed to the increased abundance of algae and their life activities (photosynthetic absorption of CO_2). The available nutrients (mainly phosphorus and nitrogen) getting into the lake increase as a result of the more and more intensive tourism and have become responsible for the increase of algal biomass.

Microlife, nevertheless, is far more abundant in the lakeshore zone but, unfortunately, has not attracted much attention yet. Tibor Hortobágyi revealed 48 algal taxa here including predominantly filamentous conjugating green microalgae and desmids (Zygnematophyceae/Closterium), but there is no doubt that plenty more algal species dwell here.

10.5 Lake Level Changes

Lake Sf. Ana is a closed system, with no drainage and fed mainly by rainwater. According to meteorological data, the amount of water (and snow) draining onto the lake (~600–700 mm/yr annually, and twice/three times higher amount of water flowing into the lake annually (including the runoffs from the slopes) is far more than evaporation (~500 mm/yr); therefore, theoretically, water level should be increasing. On the contrary, measurements going back to nearly one and a half century reflect the opposite. As presented in Chap. 1 on research history, Balázs Orbán reported a water depth 40 feet, i.e. approximately 12 m, in 1870 (he had pushed down a 12-m-long log through the ice cover of the lake, which implies that water depth was minimum the aforementioned figure and might have been even more). The first professional measurement was published by József Gelei in 1909 at 8.3 m. This measurement was followed by a modern reading of 7.2 m at the deepest point of the lake in 1971 (Csaba Jánosi), and 6.3 m in 1999, and 6.1 m in 2004 (Zoltán Pál, Gábor Pándi). The latest readings, measured at the deepest point of the lake were 6.4 m in 2012 and 7.2 m in 2018 (István Máthé, István Mihály). At the time of our investigations conducted between 2001 and 2013, the water depth was between 6 and 6.2 m in the summer months according to measurements performed by Enikő Magyari and her team.

Notwithstanding the uncertainties, which may as well be explained by the application of different measurement methods, the data suggest that water level in the lake is characterized by considerable fluctuation. Underground leakage—the extent of which is unknown—also contributes to the negative annual water balance (water lost this way appears in the form of springs on the external slopes of the crater). Dry or extremely dry years, as well as increasing water temperatures in the summer, which intensify evaporation, are also among the reasons. The effect is even more dramatic when the duration of hot, dry time periods increases. In addition, a significant difference may be detected seasonally as water levels may be nearly half a metre higher after the melting of snow compared to water levels on hot summer days. Consequently, the fluctuation of water level is reasonable on the long term (even if, in contrast to the permanently dry or wet periods, the level has most likely decreased over the past one hundred years); however, high-resolution water level reconstructions on a yearly or decade scale are not reliable.

10.6 Palaeolimnological Reconstruction

Quantitative palaeoecology is aimed at quantifying past environmental changes. The principle is simple: organisms found in samples taken currently (modern samples) can be analysed regarding the environmental and ecological circumstances in which they occur. By collecting organisms from many different locations and measuring background variables in parallel, we can determine the environmental needs of each species. Using this knowledge and the assistance of transfer functions, we can make conclusions as to the climate of the past based on the composition of former communities of organisms.

We studied the siliceous algae for revealing the limnological changes of the Lake Sf. Ana in detail. Two types of algae were analysed, diatoms (Bacillariophyta), that are unicellular aquatic photoautotrophs and chrysphytes cysts. Diatom valves, due to the siliceous cell walls, are usually well preserved in lacustrine sediments; they are extensively used proxies in palaeolimnological studies as being an abundant, ecologically diverse, sensitive biological group. Most of the diatoms have specific ecological preferences, exhibit a variety of life strategies, and their short life spans enable them to respond fast to environmental changes; and they are often used for quantitative phosphorous and pH reconstructions. Another algal group, a subject of frequent palaeolimnological investigations, is the golden-brown algae (Chrysophyta division). Some of these form roundish siliceous cysts under unfavourable circumstances (Fig. 10.4). The ratio of diatoms and Chrysophyta cysts show a strong correlation with trophic level change; nevertheless, water depth and pH are proven to be the main impacts. Chironomid-based temperature reconstruction (see Chap. 9), as well as diatom-based pH- and total phosphorus reconstructions, have been carried out in Lake Sf. Ana up to date.

10.6.1 Aquatic Life During the Last Glacial Maximum (LGM)

According to the radiocarbon dating of SZA-2010 core (obtained in 2010), the first diatom-bearing sample age has an age of approximately 26,400 cal yrs BP, so the autochton sedimentation began not later than this time. It might be surprising, however, that the richness and variability of both diatoms and chrysophyte cysts indicate the existence of a diverse aquatic life at that time already (Figs. 10.5 and 10.6). Sporadically though, green algae (*Pediastrum*) also dwelled in the water, (Fig. 10.7) and the lakeshore was settled by sedge. We have no information about the intensity of post volcanic activity in the crater at that time, and whether warm water inflow was in place, that could serve a good explanation for the high biodiversity at the early stage of the lake development.

Throughout the period of the following nearly ten thousand years (up to the period 16,700 cal yrs BP), the obtained sediments point to the presence of primarily ferns and moss dwelling in the crater on which diatoms resided, too. In the crater, which was undergoing constant sedimentation, most of the material deposited from inorganic inwash, erosion, and the organic matter content therefore could barely reach 3–4%. By virtue of our investigations, this 3–4% organic matter content comprises the remains of lake-dwelling organisms, aeolian particle sedimentation (mainly pollens), as well as organic debris washed in from the shore. Volcanic ash particles (which were washed in or transported by wind erosion) can also be studied under the microscope in this period. The diatom composition denotes intense erosion from the crater, and the high prevalence of species capable of active

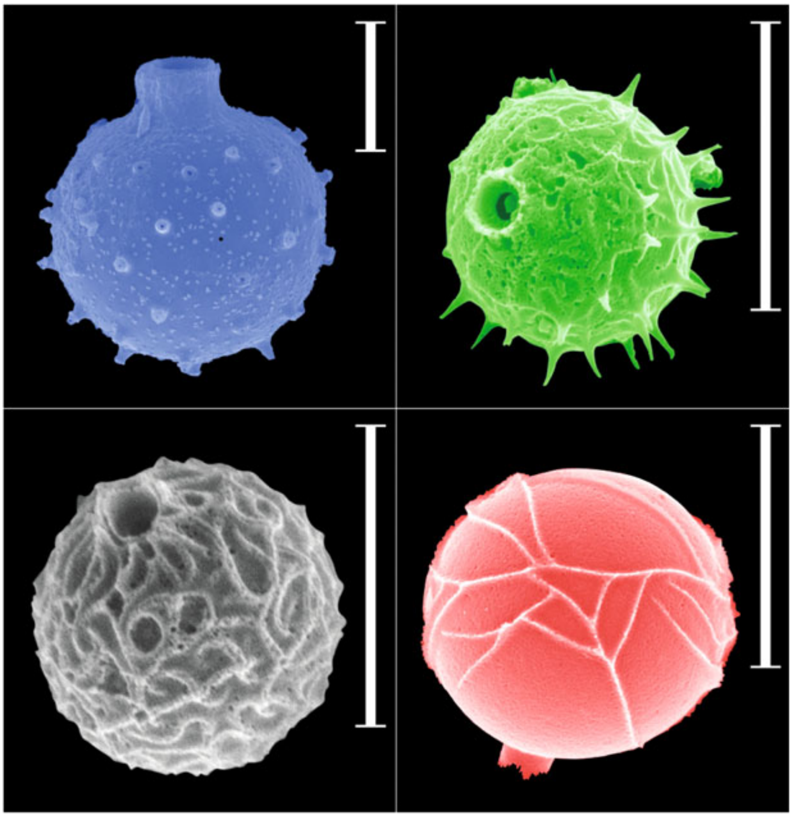

Fig. 10.4 A multitude of cysts can be detected in Lake Sf. Ana. *Credit* Krisztina Buczkó

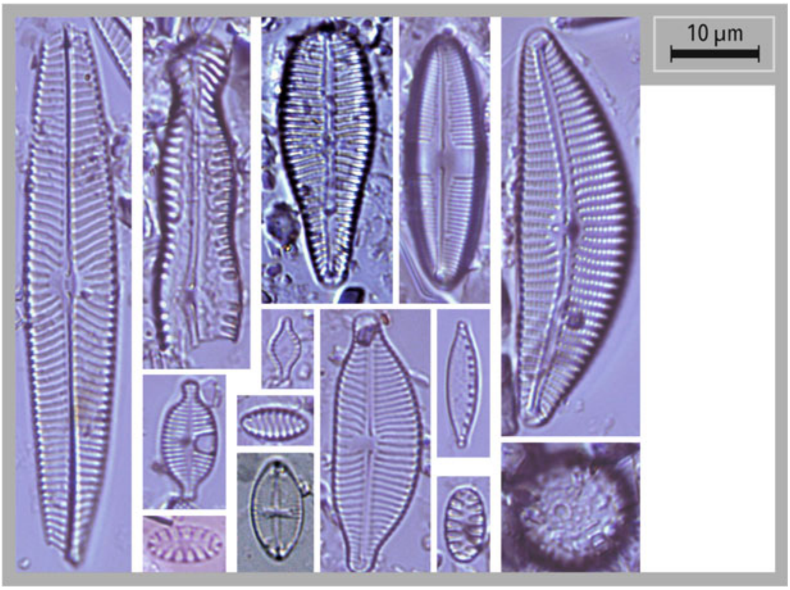

Fig. 10.5 Plenty of species were found in the bottommost samples taken from the 7-m-long core obtained in 2010. *Credit* Krisztina Buczkó

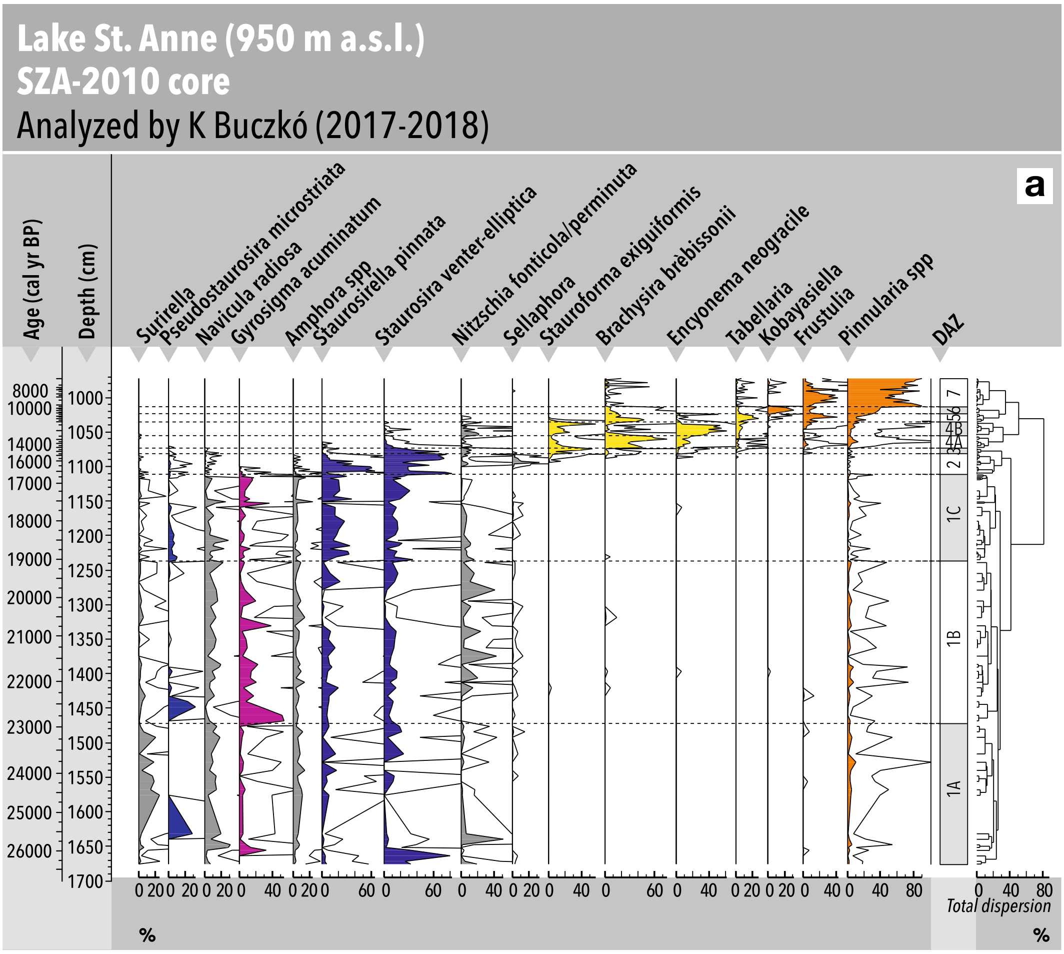

Fig. 10.6 Changes in the rate of the diatom taxa between 26,400 and 7000 calibrated BP years

movement attests to the existence of an unstable environment. These diatoms can move to the surface of the sediment after being buried under the alluvium washed in from the shore. In addition, plenty of desiccation-tolerant species have been recovered from this period. These are the so-called aerophytic algae, which dwelled near the water-plane, on barren rock surfaces, dense green clumps, or mats of mosses from where the diatoms were washed out from time to time. Regarding the alkalinity of the lake the water was slightly alkaline or circumneutral at this period (Fig. 10.8).

On the whole, in the period 26,400–17,000 cal yrs BP, the lake gave home to a surprisingly diverse algal community of high species abundance, of which many species have only been detected in arctic fields recently. So far, we have identified 260–270 diatom taxa throughout the history of Lake Sf. Ana, and this number may become higher. Diatoms were widespread especially in waters of lower temperature, whereas with the increase of water temperature other taxa became more competitive. Individual samples often showed the co-existence of 50 diatom taxa in the LGM period.

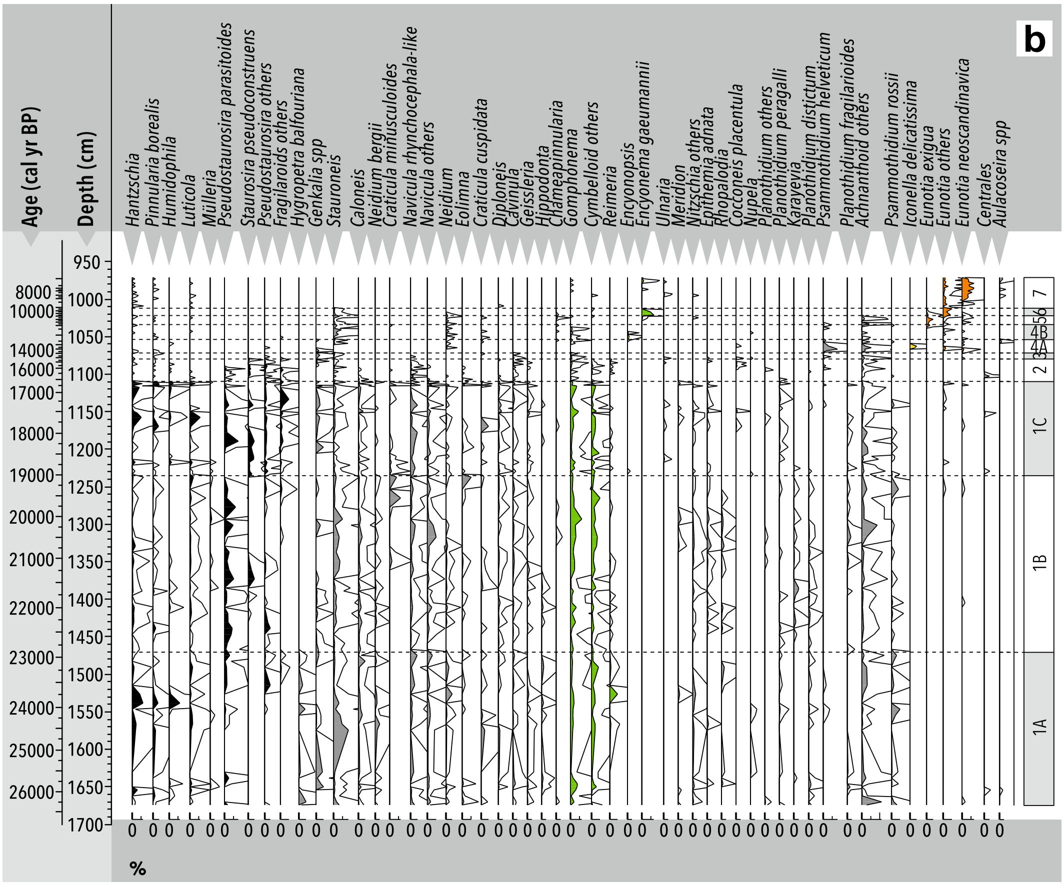

Fig. 10.6 (continued)

10.6.2 Accelerated, Subsequent Changes Following the LGM

Following the LGM a wide range of changes started to take place in the lake. These changes usually occurred in parallel with the development of the vegetation in the crater and/or on more remote areas; however, in some cases, it seems as if the lake had not been directly affected by the prevailing climate. There was a considerable change in the life of the lake around 16,700 years ago as the ratio of the formerly dominant and relatively larger (80 to 100-µm-long) diatoms, which were capable of moving, plummeted. Of them the disappearance of *Gyrosigma acuminatum* (an erosion indicator species) is the most conspicuous change. (The reasons for this change are described in detail in the Chap. 9.) After 16,200 cal yrs BP both air temperature and the available nutrients level in the water rose. Pollens of aquatic plants indicate the presence of an extensive macrophyte community, whereas green algae typical of warm waters and higher nutrient concentration dwelled in the water (species of the *Pediastrum* and *Scenedesmus* genus) (Fig. 10.5). These green algae may refer to the rise in water level at the same time. The organic matter content of the sediment nearly doubled during this period (from 5 to 10% of the bulk composition). Diatoms were represented by tiny species unable to move, and their species number was also rather low in this time. In addition, pH was lower, and the water became progressively more acidic. This entailed a drop in the number of species, as well as the replacement

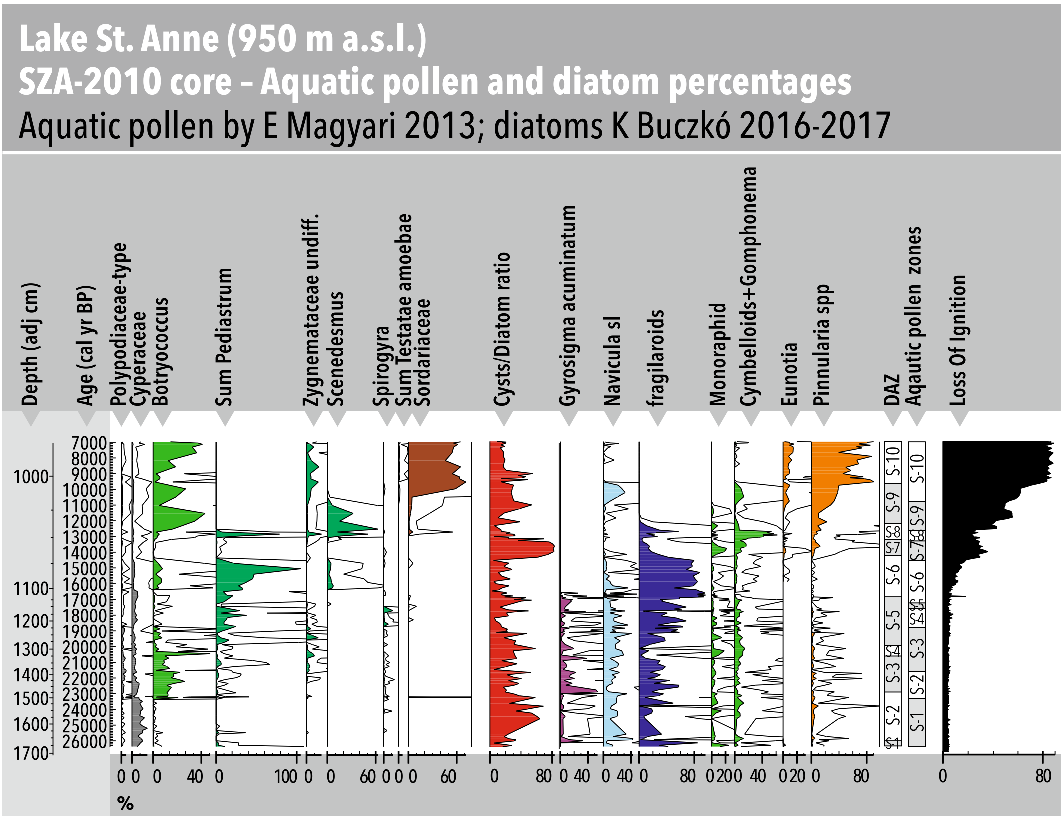

Fig. 10.7 Change in the relative frequency of aquatic plants and diatoms between 26,400 and 7000 calibrated BP years

of species, which ultimately led to the complete reorganisation of the diatom community.

According to one of the most surprising results of our study,—as our diatom-based quantitative reconstruction proves—the pH of lake water in the period between the lake formation and 16,700 cal yrs BP—during the first ten thousands of years of the lake history—was not acidic as it would be expected based on the base rock and current water-chemical measurements; instead, it was slightly alkaline or minimum circumneutral. The modern diatom training set, which consists of 622 samples and covers a pH range of 4.3–8.4, was used for diatom-based pH reconstruction. (This large dataset provides the robustness and reliability of the reconstruction). After 16,700 cal yrs BP the alkalinity of lake water changed, the pH began decrease, the lake water turn to acidic direction.

An explanation might be for this pH change, that following the LGM, diatoms reacted to the acidizing effect caused by CO_2 degassing inside the carter induced by post volcanic activity; however, podzolic (acidic) soil formation going hand in hand with the spread of pine forest that appeared on the crater slopes at that time, and the pH-reducing effect of *Sphagnum* (peatbog-mosses) developing on the lake shore may have resulted in the acidification of the lake water.

As shown in detail in the previous chapter, a global warming commenced 14,700 years ago. The ratio of chrysophyte cysts soared compared to that of diatoms, which may imply the sudden, considerable increase in water level but may as well indicate that the nutrient content of the water decreased; hence, the water became oligotrophic. The proportion of acidophilic diatoms proliferating in acidic water (*Stauroforma exiguiformis, Brachysira brébissonii, Encyonema neogracile*) was rising.

With the passing of time both the temperature and nutrient content of the lake were increasing

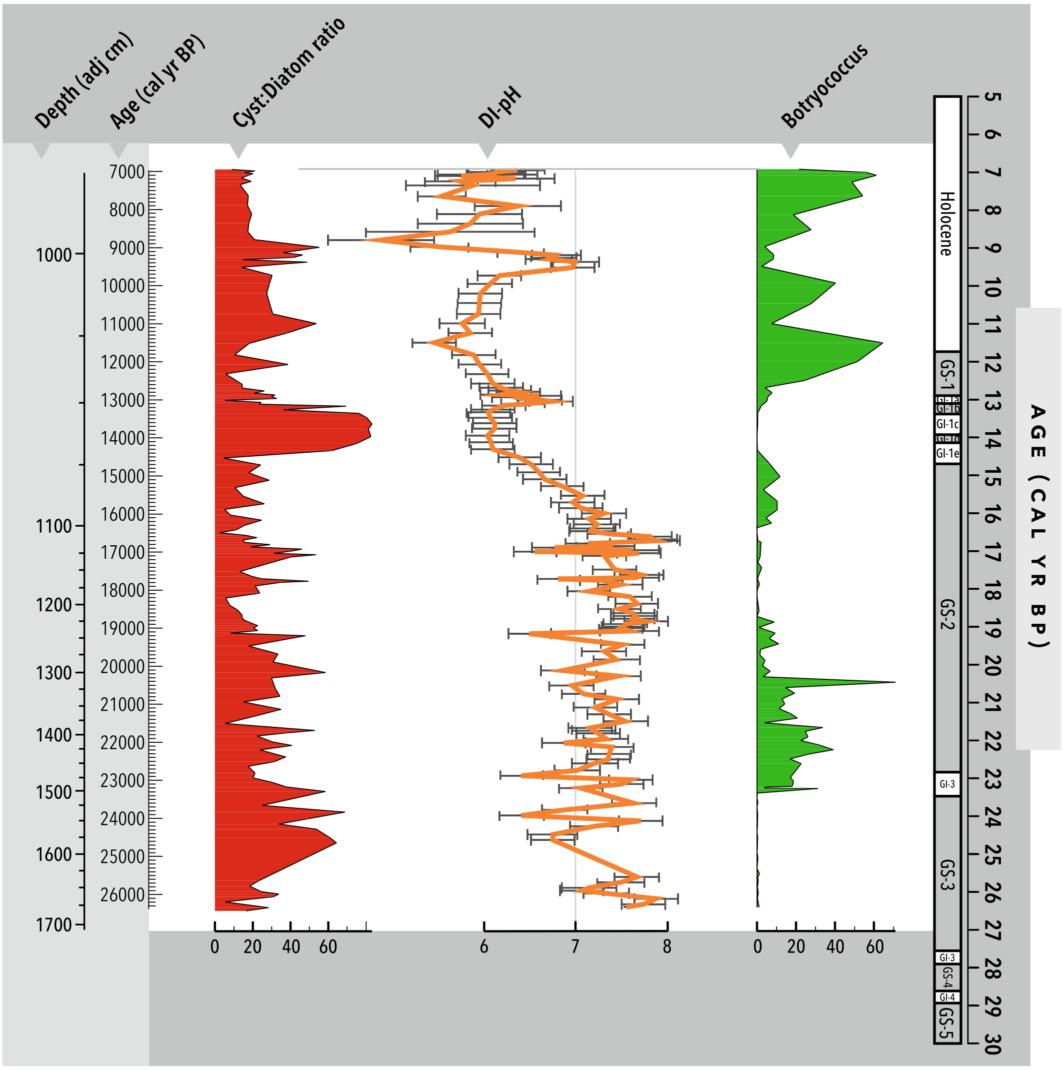

Fig. 10.8 Important conclusions pertaining to change in lake level and trophic status can be drawn in light of the ratio of chrysophytes cysts and diatoms. Quantitative pH reconstruction, fluctuation in the C/D ratio and *Botryococcus pila* in the lake section between 26,400 and 7000 calibrated BP years. The diatom-based pH reconstruction was carried out using the "combined training set" which can be found in the European diatom database and contains the data of 622 lakes

gradually, along with the trophic level. It has already been described that the crater around the lake started to be covered with forest during that period, whereas the quantity of green algae in the water fell and the organic matter content of the sediment grew. These changes account for the decrease of water level.

In the Younger Dryas, i.e. the dry and cold period which interrupted general warming on a global scale from 12,900 to 11,700 cal yr BP, out of the diatoms dwelling in Lake Sf. Ana taxa typical of bogs and preferring acidic water became predominant. The ratio of aquatic plant pollens rose, *Sphagnum* remnants could be detected in the sediment; furthermore, the organic matter content of the sediment increased. All in all, the aforementioned period was characterized by decreasing water level, the advance of the *Sphagnum* bog, and the acidification of lake water.

10.6.3 The Holocene

11,700 cal yr BP represents another major milestone in time. It is the onset of the Holocene, the current geological epoch. Temperature started to increase intensely on a global scale with all the consequences thereof, such as sea level rising by 60 m due to the melting of ice caps, which altered the coastline of continents to a great extent. In the course of the Holocene terrestrial vegetation also experienced a rapid transformation, the slopes of Sf. Ana crater became more extensively covered by forests and witnessed the appearance of deciduous trees. Nonetheless, aquatic organisms in the lake reacted with some delay (ca. 500–600 years) on the basis of radiocarbon data (Fig. 10.9). As for diatoms, the dominant species are still the ones preferring acidic water and inhabiting bogs, especially representatives of the *Eunotia* and *Pinnularia* genus. In the early Holocene, Lake Sf. Ana continues to have low water level and pH < 7 (Fig. 10.8).

All sediment features (macroscopic investigation, geochemistry, evaluation of cladoceras and siliceous algae) denote the existence of only a small-sized pond in the crater surrounded by an extensive peat bog from 9000 cal yrs BP. What is more, even this small pond disappeared in the period 9000 and 7400 cal yrs BP; the open water became overgrown with vegetation and the lake turned into a *Sphagnum* bog. The poor preservation of diatom valves (made up of a high proportion of broken, corroded forms), the disappearance of cladoceras (water fleas) and, most of all, the overwhelming prevalence of peat moss species in the sediment, indicate the intermittent drying of the lake. A bog-specific green alga, *Botryococcus pila*, was recovered in vast

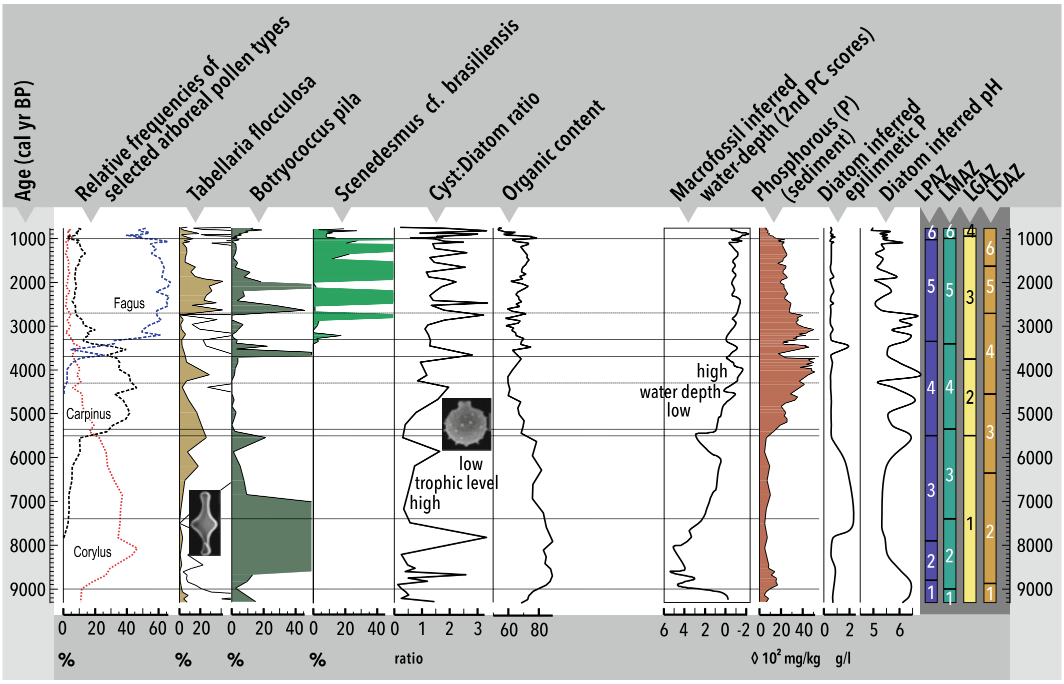

Fig. 10.9 Summary of the main organisms preserved in the Holocene sediment of Lake Sf. Ana and used for palaeoenvironmental reconstruction, as well as results inferred therefrom. Terrestrial vegetation, common algae (*Tabellaria, Pediastrum, Scenedesmus, Botryococcus*), fungal spore (Type 169), result of the principal component analysis (PCA) of the plant macrofossil analysis. Organic matter content. Phosphorus content of the sediment measured directly on the sediment as well as diatom-based phosphorus content reconstruction. Quantitative pH reconstruction. LPAZ indicates pollen zones, LMAZ refers to plant macrofossils zones, LGAZ shows geochemical zones, LDAZ represents diatom zones

numbers in the sediment. Taken all these together, the early Holocene should have been an extremely dry period in the Eastern Carpathians.

7400 years ago, however, the climate became wetter, indicated by the mass occurrence of an aquatic moss, *Warnstorfia fluitans*. The diatom-based pH reconstruction reveals that water became more acidic (pH < 5.5), and macrofossil analysis proves that the lakeshore was occupied by pine forest, whereas a mixed deciduous forest covered the area close to the upper rim of the crater. This is important because the vegetation surrounding the lake itself has a significant acidifying impact on water (not only in Lake Sf. Ana but everywhere).

With around another two thousand years passing, 5300 years ago, the crater was characterized by real lake conditions with an increased water level. Also, cladoceras appeared in the sediment 4300 years ago, which implies high lake level and lower acidity.

A green alga, *Desmodesmus* cf. *brasiliensis* (previously called *Scenedesmus brasiliensis*) begun to proliferate in the open water 2700 years ago; its intense spreading was most likely linked to the increased nutrient—especially phosphorus—supply. The members of the *Scenedesmus* genus are planktic, tend to be typical in eutrophic lakes, fishponds; therefore, the overwhelming prevalence of *Desmodesmus brasiliensis* is a good indication of trophic level. Considering crater morphology, we concluded that as a result of a wetter climate water level rose to the extent which made permanent thermal stratification in the lake possible. (To put it simply, it means that water of 4 °C characterized by the highest density can be found on the bottom; yet, when the temperature of the whole water body becomes 4 °C, the water of the lake gets mixed, and nutrients get into the water from the sediment.) This would explain the proliferation of *D. brasiliensis*. Core samples provide another interesting evidence for increased water level; that is the mass occurrence of the so-called Type 169 ascospores. This fungus may have taken part in the decomposition of tree trunks having submerged under water as a result of a sudden increase in water level.

The past thousand years of the lake were influenced primarily by the human being. The sediment shows traces of forest clearance and burning, fly-ash falling into the water, as well as those of a more intense erosion. The spread of poor-fen and *Sphagnum*-bog species along the north-east lakeshore can be seen even today. Nevertheless, the vegetation of this floating moors is also undergoing a transformation today; its rapid and permanent change is an obvious sign of human impacts. Nowadays we can witness water level decrease linked to anthropogenic eutrophication in Lake Sf. Ana.

10.6.4 Changing pH Levels of Lake Sf. Ana

Acidity has always played an important role in the diversity of life in the lake. A drastic pH change occurred 17,000–16,000 thousand years ago, which may have been caused by the simultaneous change of plenty of variables or because of the commencement/intensification of internal processes. The following factors may have played key roles, (1) during the LGM the pH of rain water was neutral, the carbon-dioxide level in the atmosphere was low; therefore, the pH of water filling up the crater was neutral, (2) no significant degassing could take place from the crater, (3) weathering was poor due to the cold climate, (4) there was no significant biological acidification effect in place due to the absence of vegetation, (5) pH is also highly dependent on temperature (it is higher at lower temperatures; for example, pH is 7.5 at 0 ºC; 7.0 at 25 ºC and 6.6 at 50 ºC)—consequently, lower water temperatures led to higher pH; (6) vegetation evolved both in water and on the crater rim and consumed the carbon-dioxide content of water; hence, it had an alkalinizing effect. These six factors together must have been sufficient enough to maintain a slightly alkaline environment.

The level of pH started to fall in the period 17,000 to 16,000 cal yrs BP. Its decrease suggests that the reasons were complex, included processes that strengthened each other, and the combined results thereof have eventually led to a profound change in the wildlife of Lake Sf. Ana. The region was characterized by general and constant warming, which resulted in the melting of permafrost (permanent ground ice; see previous chapter), and this could have induced CO_2 degassing from the vent. The CO_2 content of the atmosphere was constantly increasing; therefore, in lieu of previous rain waters of neutral pH, water flowing into the crater may have reached pH level 6 (today the pH of rainwater is around pH 5.6). It is also important to note that with rising temperatures the process of weathering also accelerated; the buffer capacity of the system was low due to the underlying acidic volcanic rocks unable to neutralize the acidity of rainwater. This period was characterized by the afforestation of the crater and, most significantly, the spread of pine trees must have considerably contributed to the drop in pH (for details, see previous chapter). Rising temperature itself could have also contributed to the acidification of water, as explained in the previous chapter; temperature was up 4.1–4.2 °C in a short while at around 16,200 cal yrs BP as the chiromonid-based temperature reconstruction suggests. Finally, these processes may have been further intensified as vegetation activity became less intense in the open water, which benefitted the proliferation of dinoflagellates. This is clearly indicated by the dominance of *Parvodinium inconspicuum* until recently.

Probably the most exciting question arising in relation to Lake Sf. Ana is how and to what extent gases released from the crater have contributed to water pH changes in the lake. To answer this question, analysis of sediments from the same period acquired from water bodies other than crater lakes would be required. Unfortunately, such lakes can hardly be found in our region (they should be ancient lakes, such as Lake Ohrid).

10.7 Open Questions Related to the History of Lake Sf. Ana

Several intriguing questions have remained unanswered even after nearly two decades of investigation focusing on Lake Sf. Ana. One of these questions pertains to the change in the spread of cladocerans (water fleas) over time. These organisms made up the main portion of the sediment base in the early Holocene; however, they are completely missing from the water today. When and how did they disappear? Or is it possible that these cladocerans can still be found in the lakeshore zone?

During the classical aging process of mountain lakes, they tend the disappear as a result of the lake surface being gradually covered by the poor-fen and bogs and reaching a status when no open water surface is left, hence the lake disappears. The same process took place in Lake Sf. Ana in the past: the lake, which is extremely susceptible to changes in water balance, was characterized by low lake level in the Early or Middle Holocene. This is a clear evidence that the central part of the Eastern Carpathians—similarly to the Southern Carpathians—was characterized by a dry continental climate with warm summers until hornbeams started to spread around 6600 cal yrs BP. This climate did not allow the formation of a permanent water surface (open water lake) like the current one in the crater owing to evaporation (which was far more intense than today). What made this process reverse and how could an open water surface reappear and remain there? Does it have anything to do with the post volcanic activity?

10.8 Perspectives for the Future

The process is caused by the sedimentation in the lake bottom as well as the proliferation of vegetation. As Tibor Hortobágyi wrote in the 1940s *"the bottom is not funnel like"*, that is the vent of the crater has been already filled up to the lakebed level. According to the seismic investigation of lake sediment layers, the upper part of the sediment consists of soft, unconsolidated mud; hence, there is an almost continuous transition between the sediment and open water. Lake St Ana—if its natural aging continues—will soon share the fate of the late Lake Mohos under the increasingly drier and warmer climatic conditions and will be replaced by nothing else but a mire. As for the study published by Begy et al. (2011), samples taken from various locations show that if the current trends continue, the lake will transform into a peatbog in no more than 300 years. (As explained in the chapter on research history, at Mohos, this process was also accelerated by human activity in the early twentieth century.) Mohos, the area of which is four times larger compared to Lake Sf. Ana—almost 80 hectares—and also situated in the twin craters of Csomád on its north-eastern part, is lying at an altitude 100 m higher above than Lake Sf. Ana. The third chapter on volcanology has already described that it is about twice as old as the crater of Sf. Ana (i.e., it may have formed 50–60 thousand years ago) and, therefore, underwent the aging process earlier. Today, only the irregular round shape and the 15 tiny pools of the peat bog (a number which was 24 in 1963) refer to the once open water, with an area, again, four times larger than the surface of Lake Sf. Ana (Fig. 10.10). The peaty soil of Lake Mohos is characterized by low nutrient level, whereas the pH level is highly acidic (pH = 3.8–4.1). Nevertheless, it is also true that natural tendencies may be altered by the anthropogenic activities of humans.

Estimations related to the aging and filling of the lake can be done based on the quantity of sediment accumulating during a time unit. As for Lake Sf. Ana, the rate of sedimentation has increased over the past 100 years. According to data published by Hutchinson et al. (2016), while the amount of accumulated sediments was 0.012 g per cm^2 per year in the 1900s, this figure became sixfold by the 1970s (0.07 g/cm^2/year). This can be attributed to increased lake production, forest clearance, occasional heavy rains, floods, as well as fires. In addition to fly-ash preserved in the sediment, photos captured that forest fire had destroyed the catchment area of the lake between 1940 and 1950. Our own measurements also show that sediment accumulation has become nearly tenfold since the beginning of the Holocene: merely 0.1 mm sediment was generated per year around ten

Fig. 10.10 The filling up of Mohos crater has been practically completed, open water glitters in few bog pools only. The same fate awaits the crater of Lake Sf. Ana. *Photo credit*: István Fodor (Miercurea Ciuc)

thousand years ago, whereas an average of 1 mm was produced annually about 700 years ago (Magyari et al. 2009).

Factors disturbing the vegetation tend to intensify erosion, i.e. more substances are being washed into the lake. The increasing organic content of the sediment indicates that the amount of sediment generated by the internal production of the lake is also rising, the once oligotrophic lake becomes mesotrophic at least in summertime. Likewise, another process associated with the aging of the lake is the prevalence of the moss ring at the lake. It is vital regarding the nature conservation aspect—also justified by palaeoecological results—that the ecosystem of the lake is very susceptible to deforestation and the changes of forest cover on the surrounding mountain slopes. Disturbance to the forest cover leads to planktic eutrophication via an increasing nutrient influx, which increases the rate of sediment accumulation. In relation to this, swimming in the lake has been forbidden since April 2018 in order to protect the lake.

11 Vegetation History and Human Impact in the Ciomadul Area During the Holocene

Ioan Tanţău, Roxana Grindean,
and Enikő K. Magyari

Abstract

Plant biodiversity is very sensitive to environmental changes, especially changes in climate. The study of vegetation history helps us understand the evolutionary history of plant life, the relationships between different groups of plants and, maybe the most important, how our world has changed through time. Pollen analysis (palynology) is one of the most important and efficient scientific method used in Quaternary palaeoecology and palaeoclimatology. Its main purpose is to reconstruct the past spatial and temporal evolution of vegetation from local and regional environments. In short, it is a method for investigating changes in the vegetation composition by means of the pollen grains and spores that plants produce. The long-term impact of human activities on natural habitats, such as forest clearance, animal husbandry and plant cultivation, can also be described from pollen data, using the anthropogenic pollen indicators. The vegetation history and human impact from the Ciomadul area were reconstructed from two sequences located in the twin craters: Mohoş peat bog and Lake Sf. Ana. These provide fossil pollen records which extend from ca. 11,300 BC to the present and represent an important source of information on changes in the vegetation composition and dynamics for this period.

11.1 Introduction

Palynological studies are a rich source of information of changes in the vegetation composition and dynamics over long time scales. The most valuable palaeoecological archives for these studies are the peat bogs and lake sediments because pollen and spores typically accumulate over time and provide excellent conditions for preservation. Pollen and spores can provide clues about the source plants and the characteristics of the environments in which these plants lived. Their usefulness is due to their abundance, dispersal mechanisms, resistance to mechanical and

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chemical destruction, microscopic size, and often distinct morphology. However, pollen analysis is a complex and time consuming method. After the extraction and chemical treatment of samples, an important step is the microscopic identification and counting of all pollen and spore type from each sample. The results should be presented in pollen diagrams as percentages of the total sum, which consists of the total pollen and spores count, generally excluding pollen of aquatic plants, moss spores, and grains that are not identifiable, because the taxa that produce them do not represent terrestrial vegetation. In Romania, broad-scale vegetation dynamics and diversity from the Holocene (since ca. 9700 BC) have been reconstructed by high-resolution pollen analyses and supported by 14C geochronology. According to these investigations, vegetation distribution and diversity patterns during the early to mid-Holocene (ca. 9700–2200 BC) were primarily influenced by climate and location of glacial refugia (see Chap. 9), whereas vegetation dynamics throughout the late Holocene (ca. 2200 BC to present) were more driven by human impact (Feurdean and Tanţău 2017). Thus, the current composition and proportion of various types of land cover (forest, arable land, pastures) are considerably different from other periods of the Holocene.

The current vegetation in the Ciomadul Massif is characterized in many areas by reverse stratification of the vegetation belts due to the effect of basin climate that leads into reversed climatic gradients from the mountain peaks to the basins. As such, conifers can be found at elevations as low as 650 m where the climate is cooler and deciduous mesothermophilous (warmth-loving) trees are frequently found at elevations above 800 m (Fig. 11.1). The history of

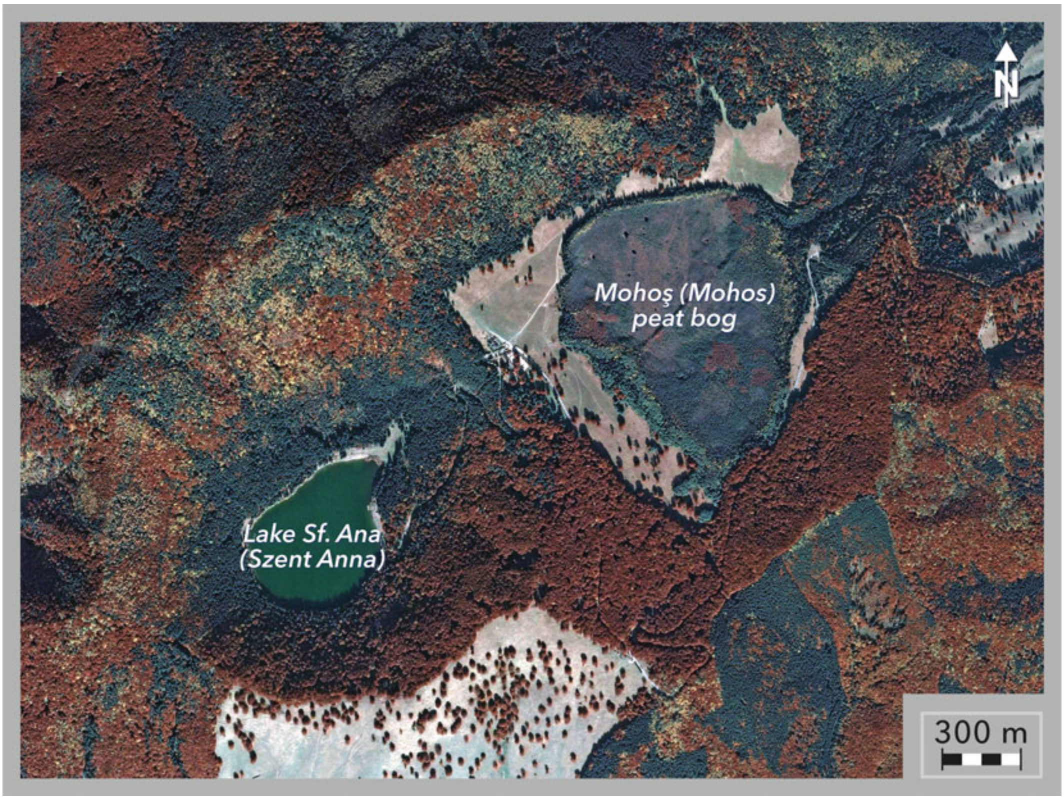

Fig. 11.1 Aerial photo of the Mohoş peat bog and Lake Sf. Ana (modified after Google Earth). Reverse stratification of vegetation causes conifers (dark green) to colonise the lake shore, while deciduous trees (rusty brown) dominate higher slopes. The straight line on Mohoş peat bog surface represents an old drainage channel.

vegetation changes in the Ciomadul Massif has been previously presented by Tanțău et al. (2003; Mohoș peat bog) and by Magyari et al. (2009; Lake Sf. Ana). The Mohoș peat bog, in particular, is found in the twin circular crater of Lake Sf. Ana in the Ciomadul Massif. It occupies an area of 80 ha and has often piqued the interest of various researchers over time due to its rich and unique geographical and phytogeographical features. However, human activities on the peat bog over the last century, including artificial draining channels, deforestation and fire, have led to a significantly different picture of the peat bog we see today (Fig. 11.1). In this chapter, we compare results from the Mohoș peat bog and Lake Sf. Ana with a synthesis of vegetation dynamics from other areas of the Romanian Carpathians published by Feurdean and Tanțău (2017) and with other studies. The name of plants included in the present study are listed in Table 11.1.

Table 11.1 **a** List of plants included in the study grouped into ecological types and **b** human impact indicators types

a

Plant categories	Scientific name	Common name
Conifers	*Pinus* *Picea abies* *Abies alba*	pine spruce silver fir
Cold deciduous trees	*Alnus* *Betula*	alder birch
Temperate deciduous trees	*Ulmus* *Quercus* *Tilia* *Corylus avellana* *Acer* *Fraxinus* *Carpinus betulus* *Fagus sylvatica*	elm oak lime hazel maple ash hornbeam beech
Grass and shrubs	Poaceae *Artemisia* Cyperaceae Ericaceae *Verbascum* Asteraceae Apiaceae *Plantago lanceolata* Rosaceae *Urtica* Cerealia *Secale cereale* *Cannabis sativa* Brassicaceae *Rumex* Fabaceae Ranunculaceae	grass family sagebrush sedges heaths mullein daisy family parsley family ribwort plantain rose family nettle cereals rye hemp mustard family sorrel pea/bean family buttercup family
Xerophytic herbs	*Artemisia* Chenopodiaceae	sagebrush goosefoot family

b

Land use category	Taxa
Cultivated land (crops)	Cerealia, *Secale cereale*, *Cannabis sativa*
Fallow land (ruderals)	Brassicaceae, *Rumex*, *Urtica*, *Artemisia*, Chenopodiaceae
Grasslands/Pastures	Apiaceae, Asteraceae, Poaceae, Rosaceae, *Plantago lanceolata*
Secondary forest (early successional trees)	*Pinus*, *Betula*, *Alnus*, *Fraxinus*

11.2 Vegetation History of the Ciomadul Massif

11.2.1 Changes in Forest Cover and the Composition of Primeval Forests

At the end of the Pleistocene, the vegetation in the Romanian Carpathians was strongly affected by the cold and dry Younger Dryas period (YD; ca. 10,900–9700 BC), when a strong decrease in arboreal pollen (AP) was observed, hinting at the withdrawal of mainly coniferous forests (Tanţău et al. 2006). Based on pollen analysis from Mohoş peat bog (Tanţău et al. 2003) we were able to reconstruct the vegetation in the Ciomadul area. Between 11300 and 9700 BC this was composed of open forests dominated by Scots pine (*Pinus sylvestris*), European larch (*Larix decidua*), Norway spruce (*Picea abies*) and Downy birch (*Betula pubescens*), with few Stone pine (*Pinus cembra*) and alder (*Alnus*) trees and grass steppe communities (sagebrush—*Artemisia*, chenopods—*Chenopodiaceae* and grasses—*Poaceae*) along with sedges (*Cyperaceae*) (Figs. 11.2a and 11.3a). Following the dry and cold YD period, pollen records from the Romanian Carpathians indicate a marked vegetation response to the temperature and precipitation increase at the YD/Holocene transition (ca. 9700 BC). This was manifested as a retreat of the steppe vegetation and a rapid expansion of forests, as observed in pollen diagrams by decreasing percentages of herbaceous pollen and increasing percentages of tree pollen (Feurdean and Tanţău

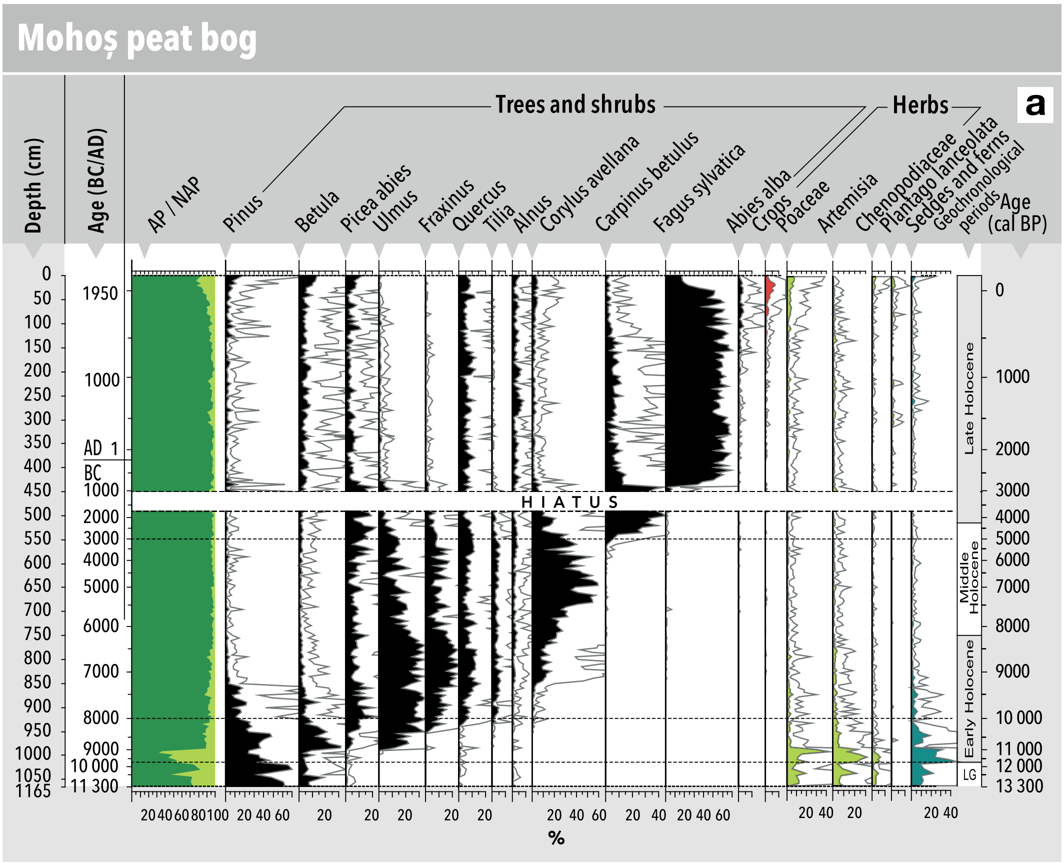

Fig. 11.2 Percentages of selected pollen and spores from **a** Mohoş peat bog and **b** Lake Sf. Ana; AP = arboreal pollen, NAP = non-arboreal pollen. The dashed lines are used to separate the important phases of vegetation changes described in the text at Sects. 11.2.1–11.2.4

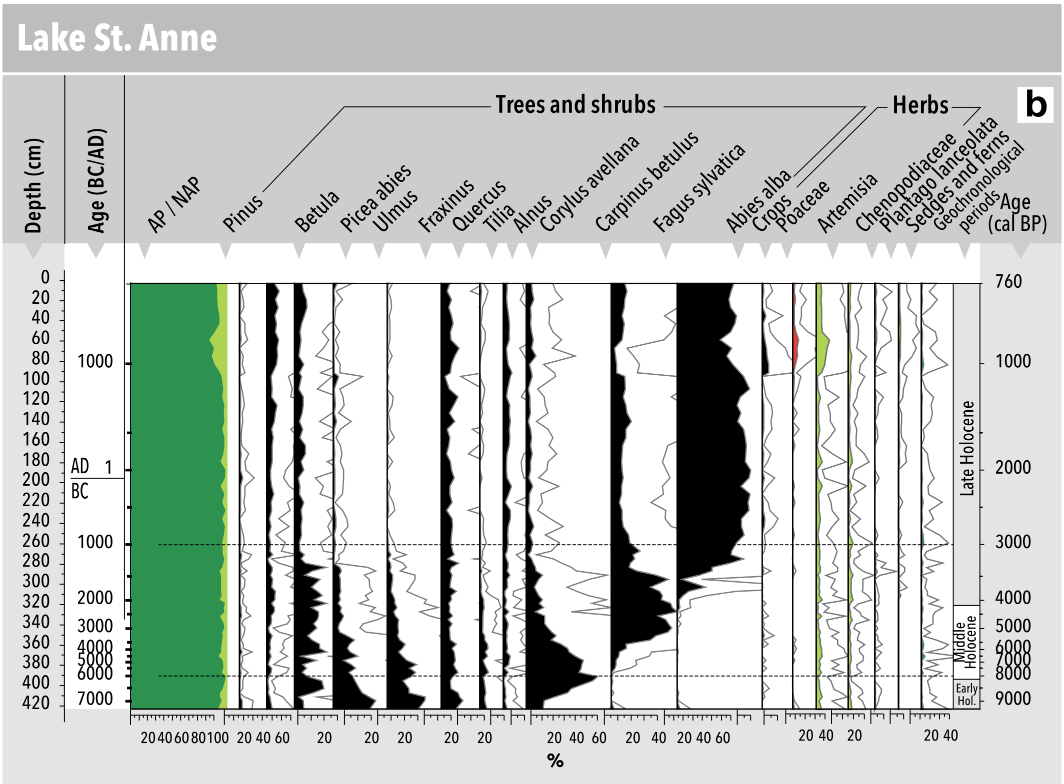

Fig. 11.2 (continued)

2017). Initially the open woodlands were primary composed of cold deciduous trees (alder, birch, and willow). This was followed (ca. 9300 BC) by the expansion of temperate deciduous forests dominated by elm (*Ulmus*), and from ca. 8700 BC included oak (Quercus), lime (*Tilia*), maple (*Acer*), ash (*Fraxinus*) and hazel (*Corylus avellana*). Analyses on plant macroremains from several sites in the Romanian Carpathians indicate that larch was also a significant component of the very early Holocene forests (Feurdean and Tanţău 2017).

11.2.2 Rapid Expansion of Deciduous Tree Species (9700–8000 BC)

The pollen data from the Mohoş peat sequence indicate the presence of an open boreal forest with pine, and birch, and an extensive cold continental steppe in the Ciomadul area at 9700 BC, corresponding to the YD/Holocene transition (Figs. 11.2a and 11.3b). A very rapid change in vegetation composition manifested as a decline in pine and steppe elements, and an increase in birch, elm, and spruce at ca. 9000 BC (Fig. 11.2a). This abrupt change could be due to a drier climate episode, which generated a hiatus of several centuries in the accumulation of peat and thus, lack of pollen data. The abundant presence of montane tree types in this period (including pine, birch and spruce) is concurrent with other pollen records from the Harghita Mountains (Luci peat bog; Tanţău et al. 2014), and also corresponds well with general vegetation development in the Romanian Carpathians (Tanţău et al. 2006, 2011; Feurdean et al. 2009; Fărcaş et al. 2013; Magyari et al. 2018; Grindean et al. 2019). The early Holocene forested landscapes also contained a diverse herbaceous vegetation (alpine grassland) and shrubs suggesting a more open character of these forests, in

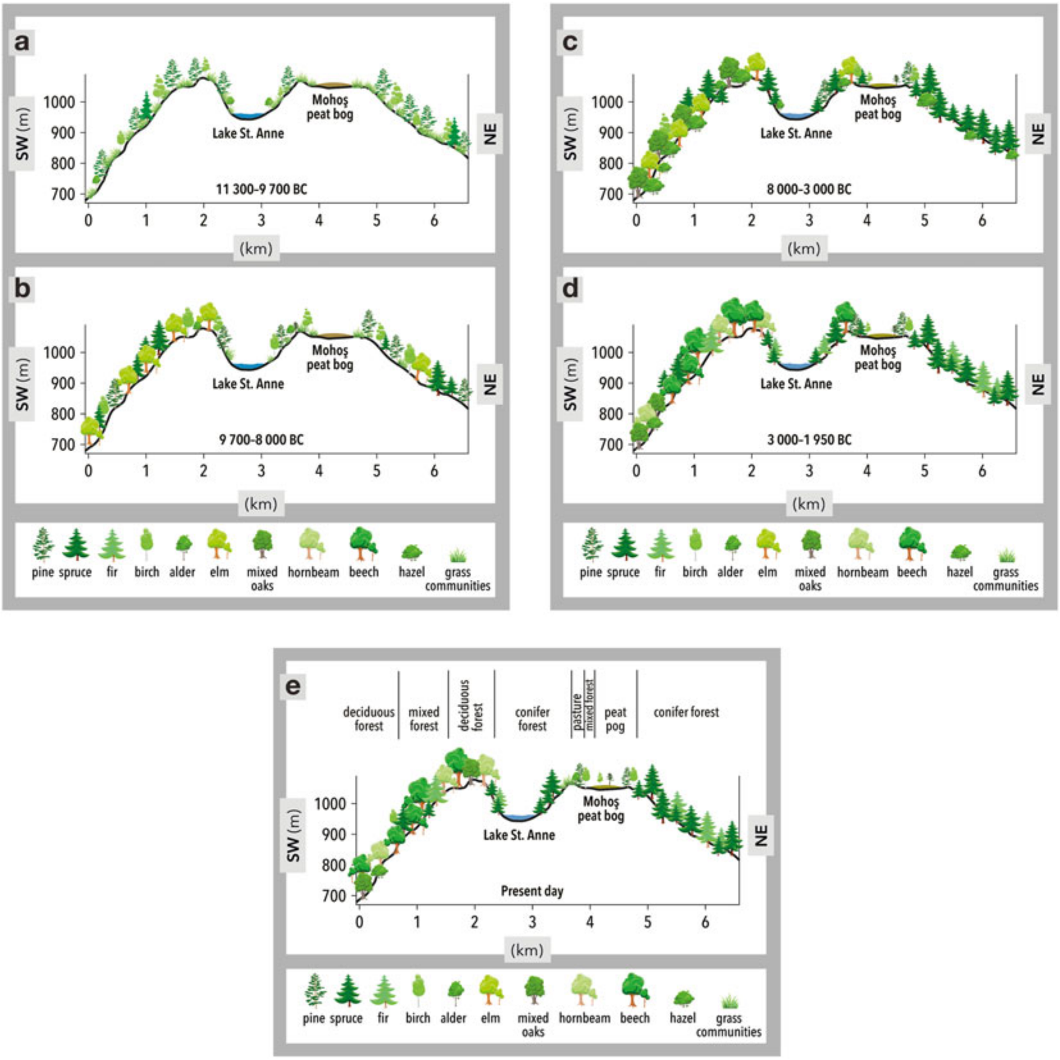

Fig. 11.3 SW-NE transect showing the changes in vegetation composition and distribution in Ciomadul Massif since the end of the Pleistocene and until present. Each panel/drawing (**a**-**e**) depicts the vegetation/land cover composition described in Sects. 11.2.1–11.2.4

agreement with the general inference of the prevalence of more open forests in Romania prior to 7000 BC. At this mid-altitude (ca. 1000 m) site, the forest dynamics of mesothermophilous (warmth-loving) deciduous trees are clearly recorded. It is one of the regions in Europe where elm played a pioneer role competing with birch. The forests also contained other deciduous species, such as ash, and oak (*Quercus*), maple, lime, and hazel (*Corylus avellana*) (Fig. 11.2a). Based on the climatic requirements of these taxa, such a shift in vegetation likely indicates an increase in temperature and moisture availability in the early Holocene. The observed forest succession, beginning with birch and then immediately followed by the mesothermophilous deciduous trees is typical for the Carpathian region (Feurdean and Tanţău 2017). As a specific feature of the vegetation dynamics in the Ciomadul area, oak, lime, maple and hazel expanded from ca. 8000 BC, later than ash (from ca. 8300 BC).

11.2.3 Dominance of Deciduous Trees and Spruce (ca. 8000–3000 BC)

An important change in the vegetation composition occurred at approximately 8000 BC when a decline in birch and pine and a marked rise in spruce and elm could be observed (Figs. 11.2a and 11.3c). The spruce maximum in the Ciomadul massif began at around 8000 BC (Tanţău et al. 2003), which was ca. 1000 years earlier than in the northern part of the Harghita Mountains (Tanţău et al. 2014), but synchronous with other areas of the Eastern Romanian Carpathians (Rodna Mountains) (Tanţău et al. 2011; Grindean et al. 2019). Spruce was a significant taxon in the Holocene forests of many regions in Romania indicating the strong competitive abilities of this tree compared to all other tree species at this altitude (Feurdean and Tanţău 2017). Elm, lime, oak and ash were the main components of the mountain mixed deciduous forests until 6000 BC, and began to decline from about 3000 BC, never regaining their former importance in the forests of this region (Fig. 11.2a, b). However, oak has been able to maintain its abundance throughout the Holocene. This is in agreement with many other pollen records from Romania in which elm, lime, ash and maple can be seen to have declined at around 2000 BC, while oak maintained its abundance until the present day. Hazel occurred in the Ciomadul area at ca. 8000 BC, and expanded from ca. 7300 BC, with a maximum abundance recorded between 6500 and 3000 BC (Fig. 11.2a, b). The hazel expansion was an asynchronous process within Romania, occurring from about 8300 BC at western sites and around 7300 BC in the Eastern Carpathians (Feurdean and Tanţău 2017). It has declined from around 3000 BC, being largely replaced by hornbeam (*Carpinus betulus*). The dominance of deciduous trees and spruce in the Harghita Mountains was affected by two short-term cooling events at 7300 and 6200 BC. Short-term changes in the vegetation composition have been noticed in north western and south eastern Romania and connected to rapid climate changes from the Holocene (Feurdean et al. 2009; Magyari et al. 2012, 2018).

11.2.4 Dominance of Hornbeam and Beech (3000 BC–present)

In the Ciomadul area, as in other parts of Romania, the pollen records show that the spread of hornbeam preceded that of beech. The evolution of hornbeam (*Carpinus betulus*) in the Ciomadul area is better recorded in the Lake Sf. Ana sequence than at Mohoş, where the continuity of the sequence was probably interrupted by several hiatuses probably caused by an abrupt cold and wet period (Piora Oscillation) Figs. 11.2a, b and 11.3d). The expansion of hornbeam is recorded between ca. 5600 and 3500 BC, with higher percentages at Lake Sf. Ana than at Mohoş (Tanţău et al. 2003; Magyari et al. 2009). The beginning of the hornbeam spread coincided with a decline in elm, ash and hazel, and a minor rise in light-demanding tree taxa, such as birch and alder (*Alnus*). Pollen diagrams show that hornbeam was an important canopy constituent in the area between 3000 and 800 BC (Fig. 11.2a, b). There is considerable regional distinction in the proportion of past hornbeam forests, which were much greater in eastern than in the northern or north western parts of Romania (Fărcaş et al. 2013). Hornbeam expanded much earlier in the southern Romanian Carpathians (5700 BC on the southern slopes of Retezat Mountains) in comparison to the northern part of the Eastern Romanian Carpathians (Magyari et al. 2012, 2018). The abundance of hornbeam in the Ciomadul area and in the Romanian forests was of rather short duration, as the tree was mainly replaced by beech as a dominant species, first in the western parts of Romania (ca. 3000 BC), and then in the eastern parts of the country (ca. 1000 BC). A plausible explanation is that dry climatic conditions induced increased wildfire occurrence, thus creating openings in the forest and allowing the rapid spread of hornbeam.

Beech, a shade tolerant species, has been continuously present in the sub-mountain and mid-altitudinal forest belts of Romania from ca. 3000 BC onwards. The expansion of beech in the Eastern Carpathians took place between ca. 1700-1000 BC (Fig. 11.2a, b). This spread is concurrent with a decline in spruce and hornbeam. The expansion of beech occurred asynchronously in Romania, with an earlier advancement (5000 BC) in the Apuseni Mountains (Feurdean et al. 2009), and then a later advancement at about 3500 BC and 2500 BC in the southwestern (Magyari et al. 2012, 2018) and northern Romanian Carpathians (Tanţău et al. 2011; Fărcaş et al. 2013). The expansion of beech in Europe is thought to be associated with either climate changes or a combination of fire, human impact and inter-specific competition (competition between different taxa of the same ecological area).

Silver fir (*Abies alba*), a slow growing species, is the latest advancing tree species in the Romanian forests. It has low pollen productivity and heavy pollen grains that are deposited in the proximity of the parental trees and thus the low pollen percentages of this tree are a good indicator of local tree presence. Silver fir first expanded in the Retezat Mountains and in Apuseni Mountains (ca. 3600–3000 BC) then in the Eastern Carpathians (ca. 1000 BC). Isolated pollen grains of silver fir were recorded at Lake Sf. Ana between 6500 and 1000 BC (Magyari et al. 2009), and at Mohoş between 6000 BC and 1 AD (Fig. 11.2a, b) (Tanţău et al. 2003). Fir pollen has been found abundantly in the Ciomadul area during the late Holocene, as well as other pollen records from Romania, at elevations between 900 and 1500 m, but in contrast to results from neighbouring sequences, such as Luci peat bog (Harghita Mountains; Tanţău et al. 2014), where fir had a modest pollen occurrence until the present day. Based on the pollen percentages of fir, we assume that this species was more important in the forest cover surrounding the Mohoş and Sf. Ana craters than in the northern part of the Harghita Mountains (Luci peat bog), during the late Holocene (Tanţău et al. 2003, 2014; Magyari et al. 2009).

A slight deforestation trend was recorded at Mohoș starting at ca. 1300 AD, probably due to an increase in the local human population during the early Middle Ages, as suggested by the rise in open herbaceous communities (grasslands), especially in grazing indicator pollen types (grasses—*Poaceae* and ribwort plantain—*Plantago lanceolata*). Interestingly, the timing of the first human deforestation around Lake Sf. Ana appears slightly earlier, around 900 AD (Fig. 11.2b) when a ca. 300 years decrease in the local beech-hornbeam forest was detected accompanied by the expansion of pastures and crops indicating the establishment of cultivated fields in the valleys of the Ciomadul Massif (Magyari et al. 2009). This timing broadly agrees with the Hungarian Conquest time. From about 1950 AD, there was a marked reduction in the proportion of beech, coinciding with the increase of light-demanding and early-successional trees (spruce, pine, birch, and oak), and of human impact indicators (cultivated plants—*Cerealia*, chenopods—*Chenopodiaceae* and ribwort plantain) in the Mohoș pollen record, signs of open-forest conditions (Fig. 11.2a). The vegetation composition shown by the pollen in the topmost part of the Mohoș sequence fits with the present day vegetation cover, where pine and birch occur on the surface of the peat bog (Fig. 11.3e), whereas spruce is found around the peat bog and on the slopes of the crater, along with beech. Also notable is that this vegetation transformation from 1950 AD with the spread of Scots pine (*Pinus sylvestris*) trees on the peat surface took place about 40 years after several channels were made on the Mohoș peat bog, an attempt that served the drainage of the peat bog and its utilization as pasture (Pop 1960).

11.3 Human Impact on Vegetation in Ciomadul

The pollen types that reflect human occupation and land-use are usually grouped as presented in Table 11.1b. The development of different agricultural practices changed the floristic composition and richness of the vegetation over the

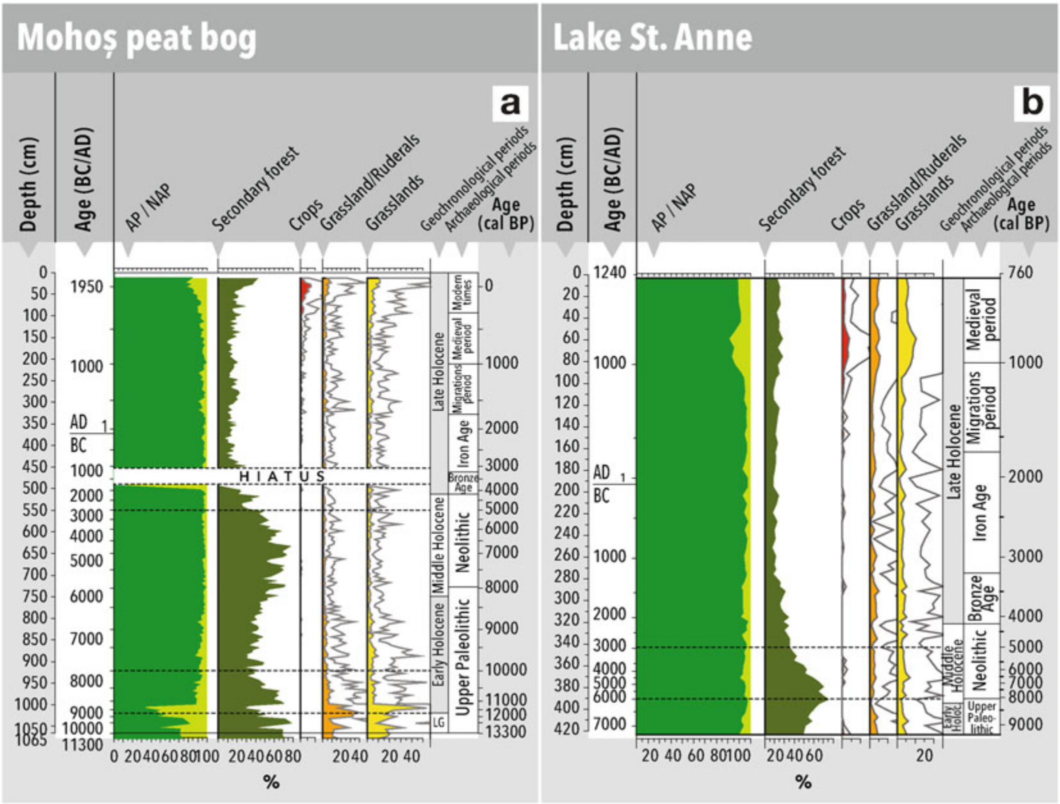

Fig. 11.4 Pollen percentages of selected plants categories according to Table 11.1b from **a** Mohoş peat bog and **b** Lake Sf. Ana; AP = arboreal pollen, NAP = non-arboreal pollen. The dashed lines are used to separate the important phases of vegetation changes described in the text at Sects. 11.2.1–11.2.4

Holocene (from ca. 9700 BC to present). The pollen analyses from the Mohoş peat bog and Lake Sf. Ana encompass a history of vegetation dynamics since the upper Palaeolithic (since c. 11,300 BC) (Fig. 11.4a, b). Although major changes in the land cover during the Paleolithic are mainly associated with natural driving forces (e.g., climate, wildfire, inter-specific competition), the first occurrences of cereals (*Cerealia*) and hemp (*Cannabis sativa*) pollen grains at ca. 7000 BC likely indicate a change in the lifestyle of the prehistoric communities towards the end of the period; from nomadic hunter-gatherer to semi-nomadic and settled farming. The extent to which this change can also be associated with deforestation (for creating arable fields) cannot be clearly derived, as arboreal pollen percentage values (AP) do not visibly decline (Fig. 11.4a) suggesting that the area was poorly populated and human impact was likely far-distance.

During the Neolithic (ca. 6000–2200 BC), the landscape dynamic was mainly characterized by the development of dense and extensive thickets of hazel alongside increasing proportions of spruce in the area (Fig. 11.2a, b). Although widely believed to have natural causes (i.e., climate, wildfires), these changes could also be somewhat related to human exploitation of the natural resources. Coppicing of hazel for example might have contributed to its high abundance, while it was also an important food source for both humans (hazelnuts) and livestock (fodder for cattle). The occurrence of pollen grains from cultivated plants (cereals and hemp), ruderal weeds (e.g., nettle—*Urtica* and mullein—*Verbascum*) and pasturage-related herbs (e.g., ribwort plantain—*Plantago lanceolata*) support the presence of settled farming communities in the surrounding lowlands, using a primitive ploughing system and herding practices (Fig. 11.4a, b).

In the Bronze Age (ca. 2200–1200 BC) the fallow system of farming (primitive crop rotation system) was introduced, which favoured the diversification of ruderal weeds and grassland taxa. Both climate changes and land clearing by man could have been factors in the forest vegetation changes, which mainly favoured the rapid expansion of hornbeam below the spruce vegetation zone (Fig. 11.2a, b). Large quantities of timber (mainly mixed oaks) could have also been harvested for developing large defensive systems characteristic of the time (hillforts). However, the local surroundings of the mire and lake were still covered by closed forest at this time, and only a small scale opening of the forest is inferable with distant crop fields on the basis of the Lake Sf. Ana pollen record (Fig. 11.4b).

In the Iron Age period (ca. 1200 BC–271 AD) the forests were dominated by spruce and beech (Fig. 11.2a, b). The initial low percentages of cereals pollen suggest that local communities temporarily reverted from crop farming, as a method of subsistence, to a pasturage approach as their primary means of food production (Fig. 11.4a, b). However, by the end of the period, both farming methods appear to have been in an equilibrium following the development of the iron plough. Our pollen study does not record important deforestation phases (no decline in the arboreal pollen), although elm, ash, and lime pollen percentages are significantly reduced (Fig. 11.2a, b).

The second half of the Migrations Period (ca. 271–900 AD) is generally associated with deforestations on a large scale and high fire abundance (Feurdean et al. 2013). The noticeable pollen percentage decline of the main tree taxa (beech and spruce) and the increase of those of alder and birch indicate deforestation followed by colonization of early successional taxa (Figs. 11.2a, b and 11.4a, b). Moreover, continuous occurrences of pollen indicators for crops, ruderals and grassland suggest the expansion of agricultural land (arable terrain, managed pastures) (Fig. 11.4a, b).

The Medieval Period (ca. 900–1700 AD) marked the beginning of the decline of trees pollen and increasing pollen percentages of taxa associated with human impact on the landscape (crops, ruderals and grasslands) (Fig. 11.4a, b). Most affected forest species were hornbeam, oak, elm, and ash (Fig. 11.2a, b). All these changes indicate the establishment of large agricultural fields and open landscape to accommodate the growing population. Rye (*Secale cereale*) became an important addition to crop farming. Human impact on the vegetation as recorded in the Mohoş peat bog seems to have been more intense during the Migrations Period (higher abundance of ruderals and grasses) than during the Medieval Period (Fig. 11.4a).

Over the last several centuries, the proportion of forest tree taxa has become visibly reduced (mainly beech) in favour of early successional trees (pine and birch) and herbaceous taxa linked to human impact (Figs. 11.2a, b and 11.4a, b). Current protective management measures for this biodiversity-rich area include the interdiction of deforestation, pastoral activities and artificial draining channels on the Mohoş peat bog.

11.4 Summary

Pollen analysis is a powerful tool not only to demonstrate changes in plant communities through time but also to investigate changes in past climate and human exploitation of the landscape. Our palynological-based study from two sequences (Mohoş peat bog and Lake Sf. Ana) has provided important features of the vegetation history from the Ciomadul massif. Thus, at the end of the Pleistocene, the vegetation was strongly affected by the cold and dry Younger Dryas period, when a strong decrease in arboreal pollen was observed, hinting at the withdrawal of mainly coniferous forests. Following this period, pollen records indicate a marked vegetation response to the temperature and precipitation increase at the YD/Holocene transition (ca. 9700 BC). This was manifested as a retreat of the steppe vegetation and a rapid expansion of forests. Initially the open woodlands were primary composed of cold deciduous trees (alder, birch, and willow). This was followed by the expansion of temperate deciduous forests dominated by elm, and from ca. 8700 BC included oak, lime, maple, ash and hazel. Spruce was a significant taxon in the Holocene forests indicating the strong competitive abilities of this tree compared to all other tree species at this altitude. Elm, lime, oak and ash were the main components of the mountain mixed deciduous forests until 6000 BC, and began to decline from about 3000 BC, being largely replaced by hornbeam. The expansion of hornbeam is recorded between ca. 5600 and 3500 BC, followed by that of beech between ca. 1700-1000 BC. Traces of human impact on the natural land cover from the Ciomadul massif were mainly recorded through shifts of the AP/NAP (trees/herbs) ratio and the occurrence of cultivated plants and weeds, and grassland species. Although noted since the Palaeolithic (since ca. 11,300 BC), anthropogenic influence on the environment was more apparent starting with the Bronze Age (expansion of arable fields through deforestation and fire) and intensified considerably over the last several centuries.

Glossary of Terms. AD – Anno Domini (after the birth of Christ). 1 AD = 2000 years Before Present.

BC—Before Christ; indicating years numbered back from the supposed year of the birth of Christ. In this paper BC years are based on radiocarbon dating and expressed as calibrated years BC.

Boreal forest—Large area in the northern hemisphere that is covered with coniferous forests consisting mostly of pines, spruces, and larches.

^{14}C chronologies (radiocarbon dating)—The age of organic material determined by the amounts of isotope carbon-14. Radiocarbon dating is a method that provides objective age estimates (for the last 40,000 years) for carbon-based materials that originated from living organisms. An age could be estimated by measuring the amount of carbon-14 present in the sample and comparing this against an internationally used reference standard. Carbon 14 (^{14}C) is an isotope of the element carbon that is unstable and weakly radioactive. The stable isotopes are carbon-12 and carbon-13 (also see Chap. 3).

Glacial refugia—A geographic region which made possible the survival of flora and fauna in times of ice ages and allowed for post-glacial re-colonization.

Holocene—An epoch of the Quaternary Period beginning 11,700 years ago and continuing today.

Mixed oaks—A deciduous forest or woodland community dominated by species of tree oak and other mesothermophilous (warmth-loving) trees (elm, ash, lime).

Palynology—The study of pollen and spores produced by plants.

Paleoclimatology—The study of climate changes from the past.

Paleoecology—A branch of ecology that studies the characteristics of past environments and their relationships with ancient plants and animals.

Peat bog—A swamp in which a compact brownish deposit of partially decomposed vegetable matter has accumulated.

Pollen—Microscopic body that contains the male reproductive cell of flowering plants/ the fertilizing element of flowering plants, consisting of fine, powdery, yellowish grains.

Primeval forests—A forest unaffected by humans, typically containing large live trees, large dead trees, and large logs.

Quaternary—The most recent Period of the most recent Era (Cenozoic) on the geologic time scale that spans from 2.588 million years ago to the present and is divided into two epochs: the Pleistocene (2.588 million years ago to 11,700 years ago) and the Holocene (11,700 years ago to today).

Short-term cooling events—Abrupt climate changes which occur when the climate system is forced to transition to a new climate state at a rate that is determined by the climate system energy-balance, and which is more rapid than the rate of change of the external forcing.

Spore—Reproductive cell capable of giving rise to a new individual without sexual fusion, characteristic of lower plants, fungi, and protozoans.

Vegetation belts—Vegetation zone with specific characteristics, determined by the changes of the thermal and water regime in altitude.

Xerophyte—Plant adapted to survive in dry environments.

Younger Dryas—Cold and short period between ca. 12,900 and 11,700 years ago that disrupted the prevailing warming trend occurring at the end of the Pleistocene.

12

Hydroclimate Variability and Pollution History of the Mohoş Peatbog

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and Vasile Ersek

Abstract

Mohoş (Mohos) peat bog, located in the crater of Ciomadul (Csomád) volcano, contains peat dating back nearly 12,000 years. By analysing the chemical composition of peat layers, we can infer the paleoenvironmental conditions recorded in the bog, such as the input of atmospheric dust, providing important information about prevailing wind changes and other climatic changes through time. The Mohoş bog dust record clearly captures the formation of the Sahara desert ~6000 years ago, regularly bringing significant quantities of dust into the area. It also shows the concentration of industrial pollutants captured from the atmosphere, indicating the development of local populations from the Roman Empire, Medieval Period, to the highly polluting Industrial Revolution. Such a study clearly demonstrates the applicability of geochemical analysis of peat archives to studies of human history and palaeoenvironments.

12.1 Introduction

In the Ciomadul region, the twin craters associated with explosive volcanic activity stand out in the landscape. Lake Sf. Ana (Szent Anna), the only crater lake in Romania, is one of the most beautiful lakes in the region and is a popular tourist destination. Less prominent, however, is the larger, shallower and older crater located northeast of Sf. Ana, Mohoş. Over the course of thousands of years, the Mohoş crater, formed from one of Ciomadul's explosive volcanic eruptions ~60,000 years ago, has slowly filled with up with sediment. With no stream inflow, and a breach in the crater rim draining any water, what was originally a lake similar to Sf. Ana has slowly filled-in and become a crater peat bog. The ~70–100 m deep crater is now filled with lake sediments and 10 m of *Sphagnum* peat remains, comprising as much as 3 million m^3 of peat (Tanţău et al. 2003; Longman et al. 2017). The Mohoş peat bog forms a nature reserve that preserves numerous ecological rarities nestled in pine forests, *Sphagnum*-dominated bogs, and small ponds, such as carnivorous plants (e.g.,

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sundews; *Droseraceae*), bog rosemary, and ubiquitous marsh berry.

The slow filling up of the crater lake by peat occurred autogenically, where each new layer of peat bog growth occurred directly on top of a previous layer, effectively burying the previous layer, locking it in place and helping to preserve it. Over time, the deep crater has built up thousands of such peat layers. Each of these layers is unique, having been formed in a specific environment and under specific climatic conditions, subtly altering the chemical signature of the peat. This signature will be recorded in a bog via the relative abundance of a wide variety of elements. Since the bog has been formed in a crater, there are no streams leading into the site. As such, water and moisture for peat growth has to come from precipitation alone, and any chemical elements dissolved or suspended in the rainwater are directly deposited onto the bog surface. This means that each layer of the bog contains distinct chemical signatures, unique to the environment in which the given layer formed.

Particularly dry and dusty periods will be identifiable by their high levels of elements relating to dust deposition (e.g., elements such as titanium, potassium and silicon), whilst wet periods will stand out as more depleted in these elements (e.g., Allan et al. 2013; Chambers et al. 2012; Longman et al. 2017; Le Roux et al. 2012). Changing elemental compositions may also record the impact of human societal development and periods of industrialisation, via their input of heavy metals (e.g., lead, copper and nickel) into the bog sediment (e.g. Kylander et al. 2005; Veron et al. 2014; Longman et al. 2018; De Vleeschouwer et al. 2020). By taking a core from the top to the bottom of the bog, many ancient layers may be recovered and analysed. We can find the age of the layers via radiocarbon dating, and sophisticated age modelling techniques, which allows us to reliably date each individual layer, to ascertain exactly when changes in elemental concentrations occurred (Shotyk et al. 1998; Kylander et al. 2005; Hansson et al. 2015; Longman et al. 2020). Using this approach it is possible to see when wet or dry periods have occurred in the past in the region and to trace the activity of humans or natural phenomena, like volcanic eruptions or desert formation (Allan et al. 2013; Longman et al. 2017; Ratcliffe et al. 2020; Le Roux et al. 2012). Looking at the heavy metal content of the peat, and in particular at lead, it may be possible to see when humans polluted the atmosphere in the region (Longman et al. 2018). Lead is released into the atmosphere from a wide range of activities. These include mining, which causes great quantities of dust to be released, and metal smelting, where the lead-containing ores are exposed to high temperatures to extract their precious metallic contents (Killick and Fenn 2012), causing large quantities of soot and ash to be formed, much of which contains high levels of lead (Csavina et al. 2012; Dudka and Adriano 1997). More recently, large-scale industry, power generation and especially transportation has begun to significantly pollute the atmosphere. All these activities burn fossil fuels, and so release metal-rich smoke and fumes, which enter the atmosphere and subsequently become trapped in the bog.

12.2 Investigating the History of a Peat Bog

To reach the oldest and deepest parts of the peat bog, a corer is needed to retrieve the peat. Once a complete core is retrieved, it is important to establish an accurate chronology in order to investigate how the elemental content has changed over time. This means that the age of each peat layer must be determined. As the peat is naturally carbon-rich, the approach used here relies upon radiocarbon dating, with samples of peat precisely dated via the analysis of radiocarbon content (see also Chap. 3). Computer modelling software is then used to interpolate the age between each of these discrete dated layers and provide an estimated age for each peat layer. For Mohoș, this method showed that the peat is 10,800 year old, which means it covers almost the entire Holocene period, the most recent geological epoch stretching back to 11,650 years ago (Longman et al. 2017). In order to determine the concentration of heavy-metals, quantitative geochemical analysis is employed. Discrete

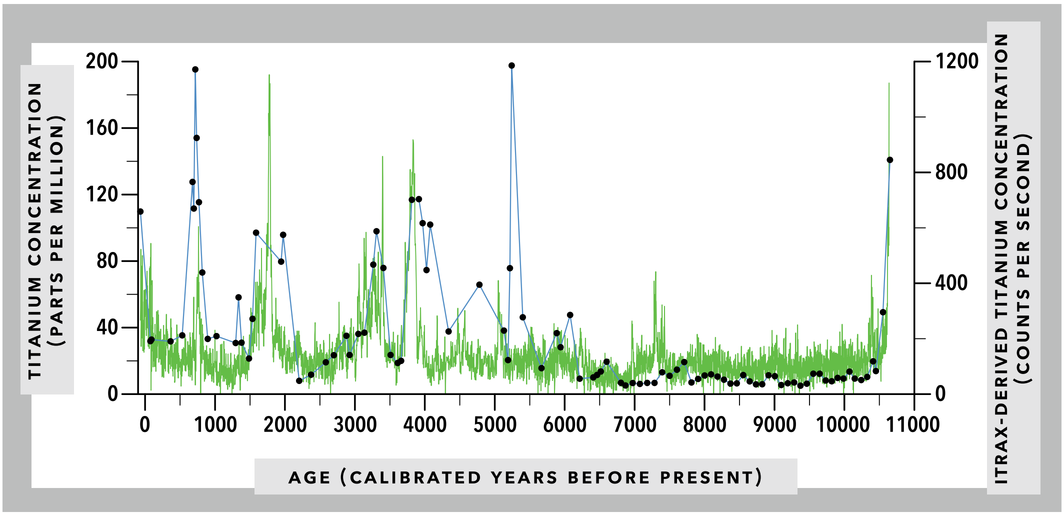

Fig. 12.1 Variations in titanium concentrations in Mohoş peat core. In blue is the data acquired via ICP-OES, whilst the green is ITRAX-derived data (core scanning XRF). Increases in Titanium content are representative of increased dustiness

samples are taken throughout the core, correlating with dated peat layers, and prepared for analysis, typically using Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) and X-ray Fluorescence (XRF). In this case, XRF was carried out using a core scanner (ITRAX), which allows for very detailed analysis of the peat layers. To determine the influence of climatic processes, or the input of pollutants caused by human activity, particular elements are used. By estimating the amount of titanium (Ti), which is a primary constituent of crustal rocks and atmospheric dust, it is possible to reconstruct past periods when the region was anomalously dusty, and therefore, much drier. Ti is used as it is generally not supplied to the bog via other mechanisms, such as local processes or anthropogenic pollution (Longman et al. 2017; Sharifi et al. 2015). Conversely, periods with low Ti concentrations may be related to wetter climates, which inhibits dust formation (Fig. 12.1). The amount of dust entering the bog (in centimetres per year) can also be determined from Ti concentration in each layer, providing insight into the intensity of regionally dry conditions (Fig. 12.2). Another method of inferring the environmental conditions of the bog is the study of the evolving populations of tiny single-celled species called testate amoeba. With this, we can quantify how the local wetness of the bog changed over time and determine if dust events are connected to local droughts by comparing the two factors. Certain species of testate amoeba thrive when the local environment is waterlogged, whilst others are favoured by dry environments. Counting the numbers of these species, it is possible to estimate how wet the surface of the bog was (Longman et al. 2017). To investigate the impact of human activity on the region, elements like lead (Pb) are useful, as they are primarily produced by mining, smelting, and the burning of fossil fuel. These activities produce Pb-rich dust by mining or smoke via smelting, and burning of fossil fuels, which then enter the atmosphere and settle onto the surface of bog, becoming part of the palaeoenvironmental record (Shotyk et al. 1998).

12.3 Saharan Dust in the Mohoş Peat Bog

For the first 4700 years of the Mohoş bog peat record, from 10,800 yr BP (calibrated years before present, where present is considered the year 1950) to 6100 yr BP, dust flux was low

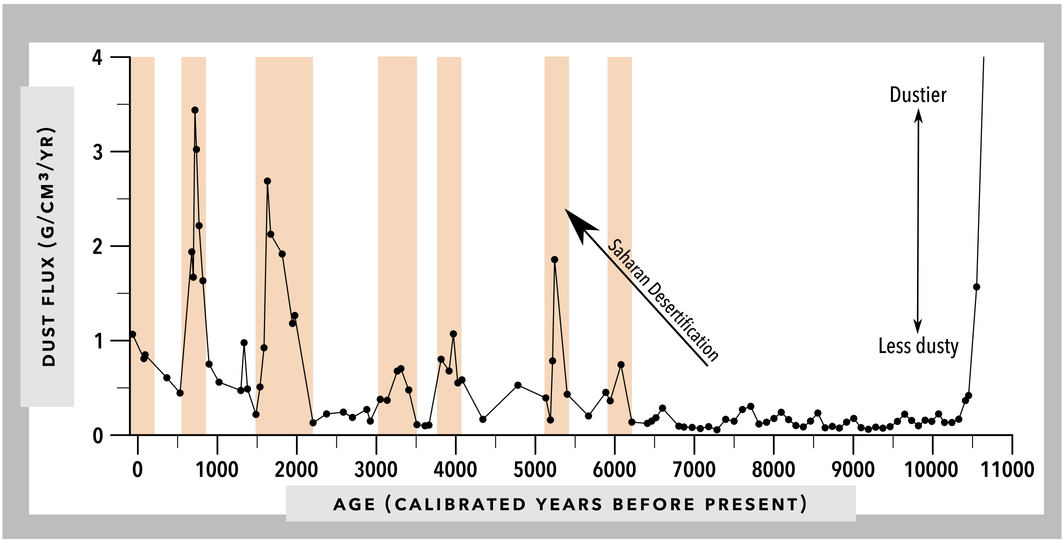

Fig. 12.2 Reconstructed dust flux from Mohoş peat bog. Dust flux is a measure of how much dust was deposited every year into the bog. The uncoloured periods are those of low dust flux, whilst the orange ones are dusty. The timing of Saharan desertification, identifiable as a rise in dust flux after 6000 yr BP is highlighted with an arrow

(Fig. 12.2). This suggests the environment was not favourable for dust emission and it is more likely that wet conditions prevailed regionally (Longman et al. 2017). After 6100 yr BP, there is a clear shift in the levels of dustiness with regular periods of higher dust flux, as shown by increasing Ti content. Two peaks are visible in dust flux data around 5400 and 5000 yr BP (Fig. 12.2). But where is this dust coming from? Is it from a nearby source or transported by winds from further afield? The timing of this change to dustier conditions is intriguing, since it occurs right after a time in history known as the African Humid Period (AHP), characterized by higher humidity in northern Africa (DeMenocal and Tierney 2012), which implies that the Sahara Desert was at the time not as large as it is today. Instead, a green grassland punctuated by large rivers and an occasional large lake, stood in its place (Armitage et al. 2015; DeMenocal et al. 2000). The main reason for this is the variation of the Earth's orbit around the sun (i.e., Milanković cycles). During the AHP, incoming solar radiation to northern Africa was 7% higher than present (DeMenocal et al. 2000). As the African continent was warmer than the Atlantic Ocean, a low-pressure system formed over the present-day Sahara. This low-pressure system pulled moist Atlantic air into the area and caused an intensification of the summer monsoon and enhanced rainfall over North Africa (DeMenocal et al. 2012). The two dust peaks in the Mohoş peat bog record happened at the end of the AHP as the solar radiation was decreasing (Longman et al. 2017). The change caused a slow decline of monsoonal rains, leading to a general drying effect, and formation of the Sahara Desert as seen today, via gradual desertification. The desertification of North Africa led to higher dust production; one study indicates a dust increase of 140% around 5500 yr BP relative to previous levels (Adkins et al. 2006), while another study documents around 4900 years ago a rise in dust production by a factor of five (McGee et al. 2013). It is reasonable to assume that Saharan desertification, the largest variation in dust production in the Northern Hemisphere at this time, is the main source of dust reaching Mohoş. High levels of Ti (relative to Si and K) are typical of dust from the Bodélé depression on the southern edge of the desert, the single largest dust source in the Sahara. Analysis of older Mohoş dust—before 6100 yr BP—shows higher potassium concentrations as a result of local volcanic rock (dacite) erosion, further supporting the link with North African desertification during this time (Longman et al. 2017).

After 5500 yr BP, the dust fluxes vary greatly. Periods of higher dust fluxes persist for a few hundred years and are followed by less dusty periods (Fig. 12.2). This suggests regular cycles of increased and decreased dust production in the Sahara. This is confirmed by spectral analysis, a statistical method which allows for the identification of cycles. It indicates that over the last 6000 years the dust influx indeed follows precise cycles. The clearest cycle is identifiable every ~1200–2000 years, which means that every 1500 years or so there is a period of high dust input at Mohoş. Furthermore, this shows evidence of millennial-scale cycles of Saharan dust influx, similar to a well-documented 1750-year climate cycle observed in the Saharan dust production in several locations close to the desert (McGee et al. 2013).

The findings at Mohoş clearly demonstrate that changes in North African climate, monsoons and general atmospheric circulation patterns impact the Carpathian-Balkan region. These results are the first clear evidence that these forcing mechanisms had a great effect on the regional climate, validating climate models and modern observations. Today, in Romania and Hungary, it is common to see reddish Saharan dust coating car windscreens. This is caused by the same meteorological process which led to dust first arriving at Mohoş thousands of years ago and implies that air masses from the Sahara desert travel periodically northwards and bring with them dust-rich (and very warm) air. The most recent period of the Mohoş dust record (75 yr BP, or 1875 AD to present) is a little different. For the first time in the past 6000 years, there is an indication of a predominant local dust source. Chemically, the dust contains both high-Ti Saharan signature but also high-K from local sources. This recent period covers the interval with higher human impact. Around this time, pollen-based records document a clear decrease in the percentage of tree species, suggesting local deforestation, as trees were cut to use the land for agriculture (see Chap. 11). It appears that deforestation, identifiable by the widespread hay meadows surrounding the bog, increased the erodibility of local soils and increasing the availability of dust in the local environment (Longman et al. 2017).

12.4 Heavy-Metal Pollution in the Ciomadul Region

The analysis of heavy-metals pollution has been used frequently over the past 20 years to effectively reconstruct human resource exploitation (i.e., mining), but until recently there was no such record published from natural Romanian archives, like sediments or peat bogs. The closest palaeo-pollution archive is a peat bog from Serbia (Longman et al. 2018). By focusing on the last 5000 years recorded in the Mohoş peat bog, the metallurgical and pollution-related history of the region can be reconstructed. Unsurprisingly, there is very little evidence of Pb pollution for the period >3000 years BP (Fig. 12.3). As such, aside from trace amounts of Pb found in the Saharan dust described previously, these low-Pb signatures can be used as background, regional pre-anthropogenic Pb values to compare with later signals.

12.4.1 Metal Pollution in Antiquity

The first period of high Pb deposition dates to between 630–450 BC (before common era), which falls within the first part of the Iron Age in the region. Among the various tribal groups populating the area, the Dacians are known to have had an affinity to metals and smelting, particularly of iron and silver (MacKendrick 1975; Taylor 1994). There is archaeological evidence that gold was mined from placers in the Apuseni Mountains (Erdélyi-középhegységh) and iron from Trascăului Massif (Torockói-havasok), in the same region, located far west of Ciomadul (Baron et al. 2011; Borcoş and Udubaşa 2012). The major smelting and metal working centres were closer to these mines of western Transylvania, and one of them was

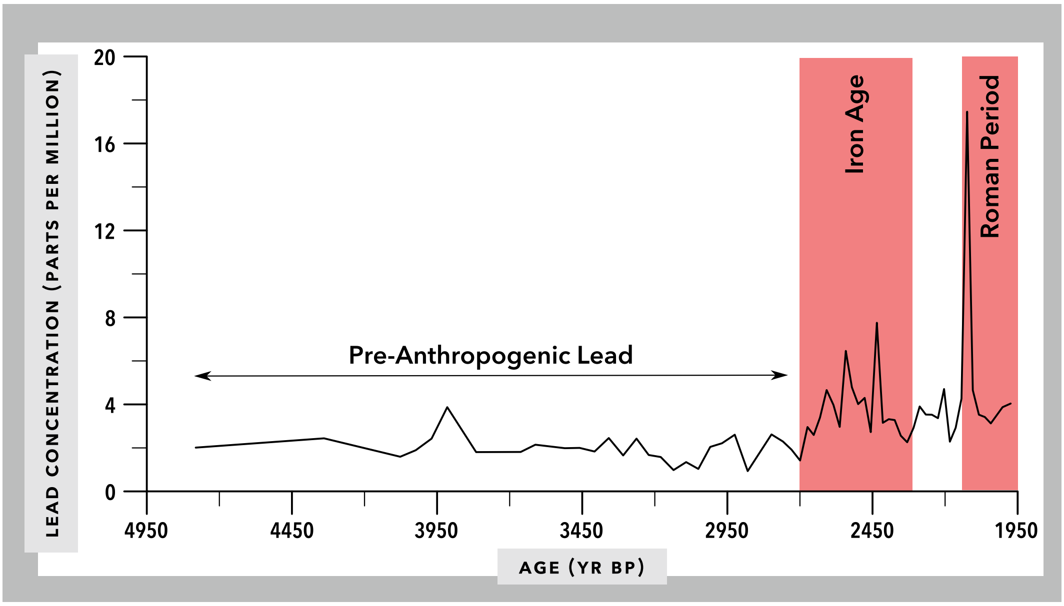

Fig. 12.3 Lead content of Mohoş peat bog for the period 5000 BC to 2000 yr BP. Highlighted in red are the two periods of enrichment, and therefore raised pollution, observed during this time, the Iron Age and the Roman Period

Sarmizegetusa Regia, the capital of Dacia in the Southern Carpathians, which explains the low levels of Pb pollution in Mohoş and perhaps local smelting. However, there is peak in Pb concentration at ~150 BC (Fig. 12.3). It is unclear what caused this peak, but it may be linked to the establishment of a local, short-lived smelting site as the first iron casting in Transylvania is found in the larger Ciomadul area. It seems that the conquering of the Dacians by the Romans in 106 AD (Anno Domini) had no influence on Pb pollution recorded at Mohoş, the Iron Age pollution having ceased prior to the wars between Dacia and Rome. This is interesting as one of Emperor Trajan's primary reasons for conquering Dacia was to exploit its mineral wealth and extensive evidence of such exploitation is present across Romania (Baron et al. 2011; Petković 2009; Rossi and Toynbee 1971). This is especially true in the Apuseni Mountains, where Rosia Montana, or Alburnus Maior, become one of Rome's primary sources of gold and silver. It appears that Roman mining and smelting occurred too far west of Ciomadul to have had an impact on the levels of atmospheric Pb pollution. There is little evidence of pollution at the site until 360 AD, but this is followed by ~100 years of high Pb deposition. This period is known as the Migration Period with intensification of people migration as a result of Roman Empire collapse. For this period, there is quite a lot of archaeological evidence showing metallurgical activity ceased (Longman et al. 2020), and reconstructions from central Europe do not show a period of pollution (e.g. Le Roux et al. 2004; Shotyk et al. 1998). As people migrated across the area, to what is now Romania, some temporary and local mining and smelting operations might potentially explain this small Pb peak.

12.4.2 The Middle Ages

A longer period of low Pb pollution is recorded between fifth and twelfth century, corresponding to the Dark Ages known as a period of low technological advancement in most of Europe. Interestingly, a palaeo-pollution record from western Serbia, at the time under the Byzantine rule that extended north up to Danube, shows no decrease in pollution during this period

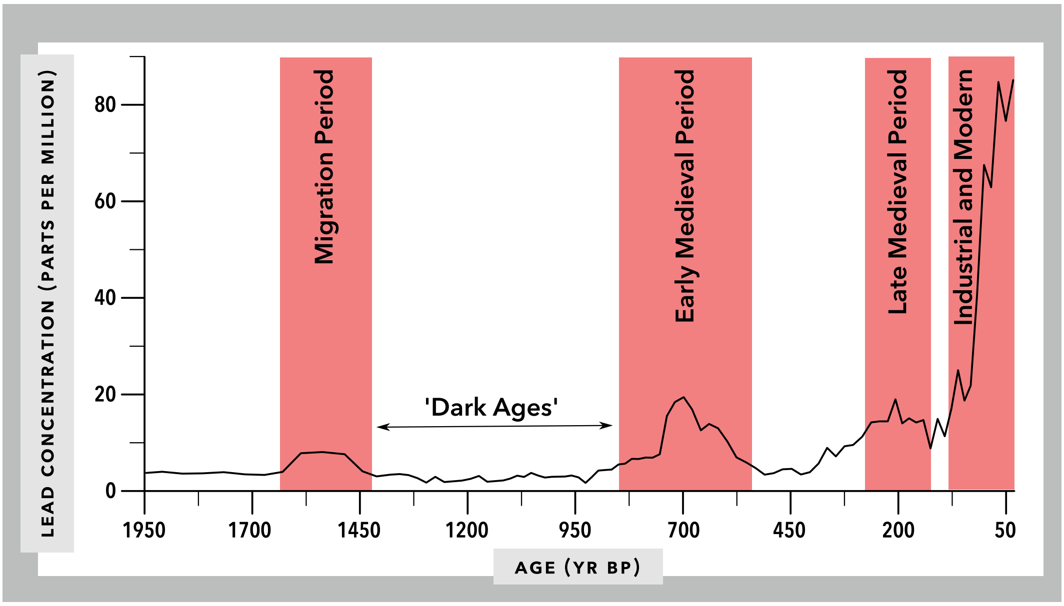

Fig. 12.4 Lead content of Mohoş peat bog for the period 2000 yr BP to the present day. Highlighted in red are the four periods of enrichment, and therefore raised pollution, observed during this time. These are the Migration period, the early and late medieval period, and the industrial to modern period

(Longman et al. 2018). However, the clear decrease in pollution observed at Mohoş suggests a clear east–west divide in Balkan metallurgy. At Mohoş there is a sharp transition from the unpolluted Dark Ages to the pollution of the Early Medieval period at around 1050 AD when old (Roman) mines were re-used. Saxon miners were settled east by Hungarian kings (as Transylvania by this time was part of the Hungarian Kingdom), who brought new technologies which allowed large scale extraction of silver (Ag) from Transylvanian ores (Petković 2009). Estimates indicate that by 1350 AD the yearly production reached 10,000 kg of silver (Borcoş and Udubaşa 2012). This regional boom in mining and smelting is well recorded at Mohoş (Fig. 12.4). The exploitation of silver is a polluting activity as Ag ores also contain large quantities of Pb. Furthermore, *cupellation*, the process by which Ag is separated from the base metals, such as Pb, involves heating the rock to a very high temperature, releasing large quantitates of metal-rich dust (Merkel 2007; Nriagu 1985). By 1450 AD, however, it appears that the Medieval metallurgy declined and in the following 100 years Pb pollution returned to pre-Medieval levels (Fig. 12.4). This decline may be attributed to the arrival of the Ottoman Empire in the local geopolitical stage (Miljkovic 2014). Their expansionist policies lead to successive wars and slowdown of the economic development in the area. By mid-fifteenth century, after a series of military defeats, Wallachia, in the Southern Carpathians, became an Ottoman vassal state and thus, was subject to oppressive Ottoman rules and taxes. It appears this played a role in the regional economic collapse and decrease of metal pollution as observed at Mohoş at the time (Longman et al. 2018; Miljkovic 2014).

Pollution at Mohoş started to increase again around 1580 AD, likely due to scientific and technical progress which allowed the exploitation of deeper ores (Borcoş and Udubaşa 2012). At Mohoş, the Pb pollution continues to increase until 1750 AD (Fig. 12.4) This rise echoes the technological developments at the beginning of industrial revolution that took place in the region, based on metallurgical techniques developed in Central Europe and Britain (Day and Tylecote 1991). These new techniques, including new methods for extracting deep deposits and mechanisation of labour-intensive tasks, greatly improved the productivity. As a result, Transylvanian miners were able to process larger quantity of ores and smelt more metal. The size of the operations in the middle of the eighteenth century is confirmed by official documents from that period. According to these documents, between the 1773 and 1778, Moldova Nouă deposit from the historical Banat (Bánság), the southwestern part of Transylvania, produced alone 4427 tonnes of copper, 225 tonnes of lead and 124 tonnes of silver (Borcoş and Udubaşa 2012).

12.4.3 The Industrial Revolution and Modern Pollution

There is a slight decrease in Pb pollution during the early nineteenth century, but it does not reach the pre-industrial levels. At the end of the nineteenth century, pollution reach levels previously unseen in the record. This significant increase in environmental pollution is linked to technical developments for metal extraction which made possible more mining and smelting activities (i.e., the Industrial Revolution). For example, the installation of railways reduced the time needed to transport the ore from mountain mining sites to smelters, located in valleys and allowed the transport of large amounts of ore resulting in higher productions. The first railway was built in 1855 between Oravița (in Banat) and Baziaș, a port on the Danube. It was specially constructed for coal transport and for the first year it was not open to passenger traffic (Borcoş and Udubaşa 2012). The activity of trains burning fossils fuels likely had an effect on atmospheric pollution, too.

Administrative changes also supported the metal production. During the second half of the nineteenth century, most mines in Transylvania were transferred from private to state ownership. In 1885, the Mining Law was issued, which served to stimulate mining and activities related to mining in the wider region. This period covers one of most prosperous times for mining in the region. The Mining Law ensured that mining-related activities were harmonised, ultimately increasing heavy-metal pollution in the area (Fig. 12.4). National research programmes were also intensified and the systematic exploration of the ore deposits was carried out (Borcoş and Udubaşa 2012). In addition to mining of traditional ores, the identification of deposits containing metals useful to modern industry (e.g., aluminium, zinc and chromium), opened a wide variety of mines, leading to increased export. In addition, the processing of imported ores was regulated and streamlined and thus greater amounts of metals could be smelted. At this time the Mohoş record shows the most intense period of pollution. Between 1900 and 1950, except for a rapid decrease during the first world war, the Mohoș record documents a rapid eightfold increase in Pb pollution (Fig. 12.4).

The rise in the use of leaded gasoline certainly contributed to the high levels of pollution recorded in the early twentieth century in Mohoș. From 1920s onwards, tetraethyl lead was added to the majority of petrol fuels, primarily to boost octane rating and secondly as an anti-knock mechanism. This addition had a pollution impact visible across the globe, with spikes in Pb pollution present in records from Europe, Americas, Asia, and even in isolated locations such as Antarctica and Greenland (Eichler et al. 2015; Longman et al. 2020; Rosman 2000; Weiss et al. 1999). It is clear that pollution increased at Mohoş in the first half of the twentieth century is partly due to leaded fuels and also to increased local mining, smelting and industrial activity.

The Mohoş record shows increasing Pb pollution up to the 1980s which likely reflect Romania's strong post-war industrial economy. In Romania, the period between 1945 and 1990 was characterised by large-scale exploitation using sophisticated geological and geophysical methods, which led to the discovery and exploitation of a wide variety of deposits. The exploitation of uranium-rich deposits from Apuseni Mountains was one of the greatest achievements. The Communist regime pursued a policy with minimal raw materials imports as such local deposits were mined to exhaustion and, sometimes, at low economic rates. These intense activities were carried out with little or no environmental consideration, increasing the metal emissions released into atmosphere. The scale of this activity is clear in official documents which show that between 1945 and 1990, more than 1 billion cubic metres of mining waste was accumulated in the country, covering an area of more than 3000 hectares (Borcoş and Udubaşa 2012; Zobrist et al. 2009).

The most recent two samples from the Mohoş record document a decrease in pollution levels with no increases after 1982. This may be explained by two factors. The first is the collapse of communism in 1989, which had a severe detrimental effect on the funding available for mining and geological exploration. This led to the collapse of Romania's ore mining industry, with only 4 mining regions compared with 49 previously (Borcoş and Udubaşa 2012). Non-metalliferous mining activities were unaffected and so the mining of commodities such as bentonite and kaolinite clays continued. The other significant factor in the pollution decrease was the phasing out of leaded petrol. From 1970s onwards, after concerns raised by the levels of lead in air and soil and its neurotoxicity, leaded petrol was periodically banned across the globe. The ban in Romania came into action in 2005, and if Mohoş peat bog would be cored today the top samples would contain considerably lower lead levels than the ones analysed for this work.

12.5 Summary

The Mohoş peat bog, and the way it developed in the crater over thousands of years, means that it is an ideal location to study the pollution history of the Ciomadul region. By analysing the elemental composition of peat layers, a variety of climatic and pollution-related information have been reconstructed. The bog receives heavy-metal elements through atmospheric deposition, which means that changes in their concentration in peat is related to changes in atmospheric dust input. It is possible to reconstruct changes in dust input in the region by analysing the concentration of elements which compose the dust. High quantities of elements such as Ti, K and Si show that the local environment is very dusty and dry. Over the past 10,800 years, the Mohoş record documents a number of dust events, with the most recent 6000 years considerably more dusty than the preceding 4800 years. This shift is linked to the development of the Sahara desert and the transport of desert dust towards south-eastern Europe during periods when it was moved northwards by atmospheric circulation processes. Another element analysed throughout the core is lead. Lead is a toxic element which enters the bog system via fallout from the atmosphere. Thus, changes in lead concentration can be used to reconstruct pollution and therefore levels of industrial activity. The Mohoş lead record clearly tracks changes in mining and smelting activity from the Roman period to the Medieval Period. The clearest pollution signal is recorded in the twentieth century when the exploitation of the ores in the area of Romania reached its peak and leaded petrol was introduced. The most recent peat layers show a decrease in lead pollution, which trace the transition to more environmentally-friendly activities and better environmental protection.

Modern Flora and Fauna of the Ciomadul Region

13

Zoltán-Róbert Para and Krisztina Tóth

Abstract

The Ciomadul (Csomád) region hosts a diverse array of flora and fauna. Many of these species are typical of the Eastern Carpathians, but several species are unique, like the carnivorous sundew (*Drosera)* or Siberian lingularia (*Ligularia sibirica*) that have existed in the peatbog since the last ice age. Among the protected animal species in the area, those that still have stable populations are the brown bear or yellow-bellied toad. Other, rarer species require special attention, such as the Transylvanian dark bush-cricket or the Carpathian newt, unique to the region and whose population is considered endangered.

13.1 Introduction

In addition to diverse post-volcanic activity, such as mofettes, sulphur caves, and mineral-rich spring waters, the area of Ciomadul-Puturosu (Csomád-Büdös) has just as diverse flora and fauna, strongly influenced by these natural processes. The CO_2 emissions are so intense in some areas that vegetation is absent (e.g., mofettes, see Chap. 8). Conversely, peatbogs formed in the crater of Ciomadul volcano occur alongside forest vegetation (Tinovul Răbufnitoarea/ Buffogó-láp). These habitats are rare throughout Central Europe, but make up an import biome for endemic, residual species, located in the saddle north of Muntele Puturosu (Büdös-hegy, Stinky Mountain).

In 2007, the Ciomadul-Balvanyos (Csomád-Bálványos) area was declared a site of community importance, the so-called Natura 2000 site, as part of the European ecological network for the protection and sustainability of biodiversity, protected species and habitats (Para and Tóth 2006). In February 2010, the Vinca Minor Association won custody of the Ciomadul-Balvanyos Natura 2000 protected area (ROSCI0037). The main task of the supervisor is to protect and maintain natural values, protected species and habitats and, in some cases, to improve the state of the environment. Therefore, detailed assessments were carried out in 2011 and 2012 and then in 2015. However, an important task of the tutelage is to promote the concept of Natura 2000, the natural values of the area, the species and habitats protected by plants and animals, and to draw attention to their importance (Fig. 13.1).

13.2 The Flora of Ciomadul

The flora of Ciomadul belongs to the Euro-Siberian region in the Central European province. The presence of volcanic landforms, stream valleys, water springs and peat bogs results in a wide

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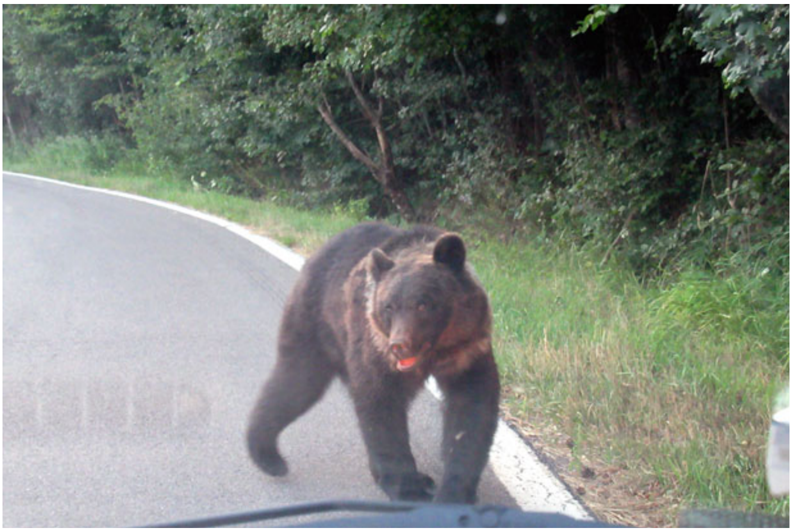

Fig. 13.1 The brown bear is strictly protected in Europe. Its hunting was also banned in Romania (2016), which has led to a significant overpopulation, especially in mountainous areas, including the Ciomadul Hills (*photo credit:* Miklós Kázmér)

range of plant species. This botanical diversity has been shaped by climate and vegetation changes through geological time, flora migrations, and the direct and indirect effects of humans, who also influenced the appearance of today's vegetation (by farming and deforestation). In addition to the species constituting the canopy, the undergrowth contributes to the different types of forest and habitat types, such as; Luzulo-Fagetum beech forests, with spruce (*Abies alba*) and fir (*Picea abies*), and an undergrowth made of hawkweed (*Hieracium rotundatum*), fescue (*Festuca drymeia*) and European blueberry (*Vaccinium myrtillus*); Asperulo-Fagetum beech forests with hornbeam (*Carpinus betulus*), European bittercress (*Dentaria bulbifera*) and sedge species (*Carex pilosa* and *Carex brevicollis*); oak and hornbeam forests of the Galio-Carpinetum type, containing beech, sessile oak and sedge; Symphyto-Fagion dacian beech forests, where besides beech (*Fagus sylvatica*) we can find fir and spruce, and where the grassy layer consists of red lungwort (*Pulmonaria rubra*), oxeye daisy (*Leucanthemum waldsteinii*), comfrey (*Symphytum cordatum*) and hart's-tongue fern (*Phyllitis scolopendrium*), and lastly; peat bogs with forest vegetation including spruce, Scots pine (*Pinus sylvestris*), mountain pine (*Pinus mugo*), downy birch (*Betula pubescens*) and oligotrophic peat bogs with moss (Fig. 13.2).

From the direction of the Olt valley, the forest covering the slopes is made of spruce in the mountains (Jánosi 1995; Fig. 13.3). During winter or on foggy days the cold air reaches the valley floor while warm air stays at the top of the mountains (i.e., vegetation inversion). As such, the spruce varies from the general rule of division of vegetation into altitude levels, and grows below the beech level down to the valley of Olt. The grassy layer here is also poorly developed, composed of great wood-rush (*Luzula sylvatica*), mouse-ear hawkweed (*Hieracium transsylvanicum*), wood-sorrel (*Oxalis acetosella*), European blueberry, and deer fern (*Blechnum spicant*). In some places mosses are common and bulky. Instead of cut spruce forests, there appear red raspberry (*Rubus idaeus*), woodland groundsel (*Senecio sylvaticus*), red elderberry (*Sambucus racemosa*) and diamond grass (*Calamagrostis arundinacea*). The reforestation process begins with the willow tree (*Salix silesiaca*), silver birch (*Betula pendula*), the European aspen (*Populus tremula*), and spruce seedlings.

In the beech (*Fagus sylvatica*) forests we rarely find mountain ash (*Sorbus*), hornbeam (*Carpinus*), birch (*Betula*) and maple (*Acer*). The variety of shrubs includes fly honeysuckle (*Lonicera xylosteum*), gooseberry (*Ribes uva-crispa*), germander meadowsweet (*Spiraea ulmifolia*), common hazel (*Corylus avellana*)

Fig. 13.2 Example of a peat bog habitat with forest vegetation at Ciomadul

and the grassy layer of windflower (*Anemone sylvestris*), asarabacca (*Asarum europaeum*), wood spurge (*Euphorbia sylvestris*), spring vetchling (*Lathyrus vernus*), bittercress (*Cardamine bulbifera*), lungwort (*Pulmonaria officinalis*), and yellow archangel (*Lamium galeobdolon*). In the first phase after clear-cutting, new species occur, including woodland ragworth (*Senecio sylvaticus*), belladonna (*Atropa belladonna*), species of *Scrophulariaceae* and *Polygonaceae*, respectively, the sprout of the cut species (fern; *Pterophyta*), wood bluegrass (*Poa nemoralis*) and red robin (*Geranium robertianum*).

In contrast to the beech forests, oak does not form a united population, with examples of sessile oak also found in other forest associations. Next to the oak, we find common hazel (*Corylus*), common juniper (*Juniperus communis*), common hawthorn (*Crataegus monogyna*), great wood-rush (*Luzula sylvatica*), soft-leaved sedge (*Carex montana*), european blueberry and purple hellebore (*Helleborus purpurascens*).

Along the brooks, the most frequent species of vegetation is the butterbur (*Petasites hybridus*). In some places, for example near the Zsombor brook, we can find a butterbur-heartleaf oxeye association (*Petasitetum-Telekietum speciosae*), which are species adapted to diffuse light and high humidity.

In areas with a fresh water supply, such as in the spring area of brooks, marshland plant associations have emerged, such as marsh-marigold (*Caltha palustris*), cotton sedge (*Eriophorum*), bittercress (*Cardamine*), wood club-rush (*Scirpus sylvaticus*), and various species of sedges (e.g., *Carex*). The flat and permanently wet areas are characterized by yellow sedge (*Carex flava*) and broad-leaved cotton-grass (*Eriophorum latifolium*).

Typical hydrographic formations are wetlands, such as peat bogs, which may be oligotrophic or eutrophic depending on the groundwater level. At a national scale, these habitats occupy only a few thousand hectares at altitudes between 900 and 1600 m. At the Ciomadul-Balvanyos site, such habitats have formed in three places, totalling 1.14 hectares. The most famous of these is the Răbufnitoarea peat bog, to the north of Mount Puturosu, surrounded by beech trees. The other two habitats are Hammas Bath and Turia Bath in the Jajdon valley. These habitats are characterized by specific plants of eutrophic peat bogs, such as the grey alder (*Alnus incana*), European aspen, common cotton grass (*Eriophorum angustifolium*), marsh horsetail (*Equisetum palustre*),

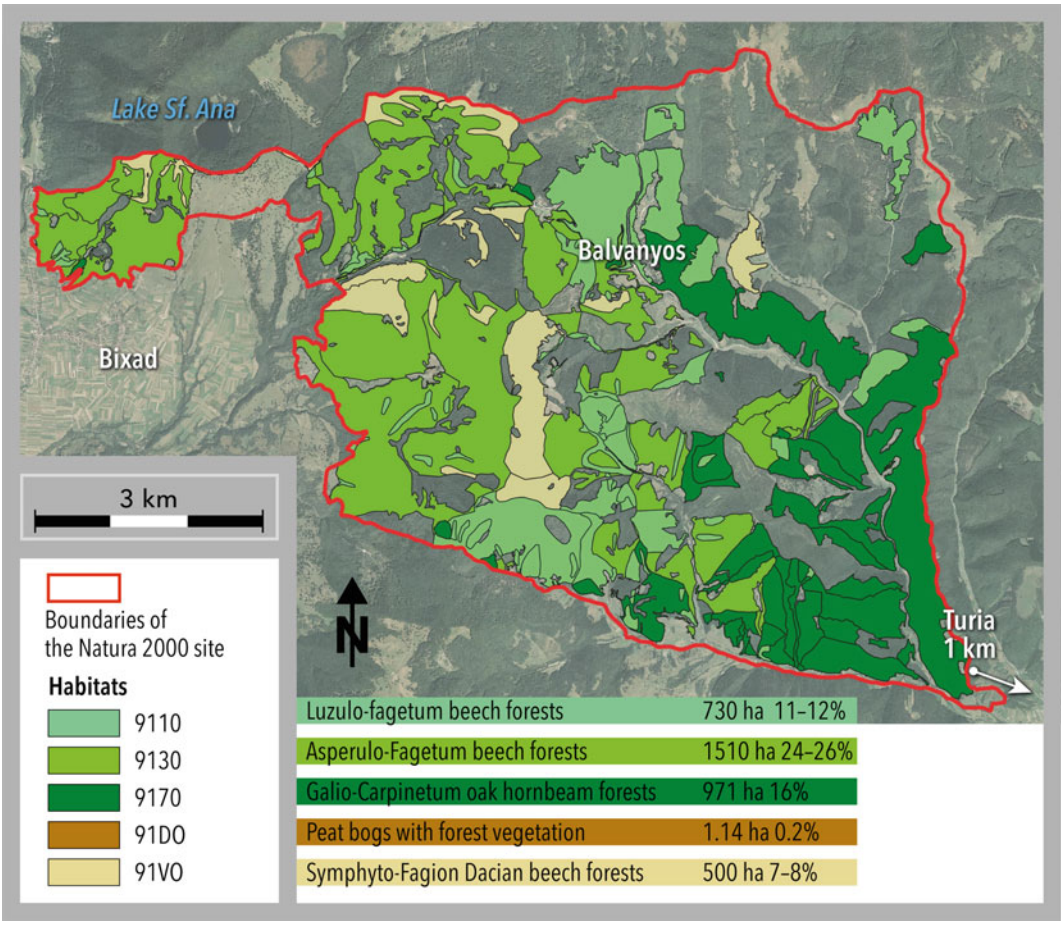

Fig. 13.3 Map of different forest habitats in the Ciomadul-Balvanyos Hills, which includes a 5977 hectare nature conservation area of community importance (Natura 2000)

heat spotted-orchid (*Dactylorhiza maculata*), Siberian ligularia (*Ligularia sibirica*), and other rare plants such as carnivorous round-leaved sundew (*Drosera rotundifolia*) (Fig. 13.4), bog cranberry (*Vaccinium oxycoccos*), black crowberry (*Empetrum nigrum*) and various peat moss species. The Siberian ligularia is the main protected plant of this site. This plant has existed even in the Ice Age in this territory, and is also called a residual species. In Romania it is found in upland peat bogs; at the Ciomadul-Balvanyos site it is present in six places (Fig. 13.5) that are characterized by wet soil, rich in organic matter and with low oxygen content.

13.3 The Fauna of Ciomadul

The fauna of the Ciomadul-Puturosu Hills is similar to the fauna of the middle altitudes of the Carpathians. The brown bear (*Ursus arctos*) is a frequent guest in these forests, while the Asian black bear (*Ursus thibetanus*) appears only occasionally. Species that have proliferated and become more tolerant to human presence have also entered in inhabited area, searching for food in domestic refuse. These include deer and wild boar, especially where they can find acorns. In the Puturosu Mountain forests there are martens, squirrels, foxes and rabbits. The Eurasian lynx

Fig. 13.4 Round-leaved sundew (*Drosera rotundifolia*)

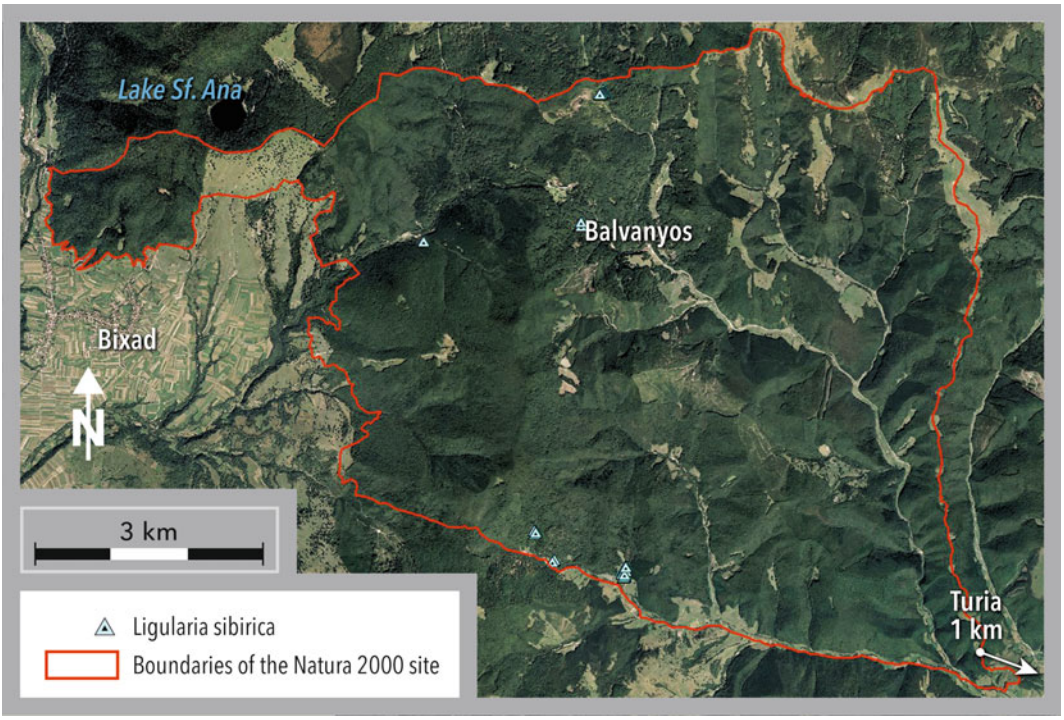

Fig. 13.5 Spread of Siberian ligularia (*Ligularia sibirica*) in the Ciomadul Hills area

(*Lynx lynx*) or wildcat is rarely seen because of its hiding lifestyle, while wolves (*Canis lupus*) hunt near the sheepfolds. The results of the monitoring of the large carnivores show that the brown bear, wolf and Eurasian lynx are not only present at the site, they also have stable populations, with their density across Europe exceeding the average numbers.

Among the countless species of forest birds, the most common are the Eurasian jay (*Garrulus glandarius*), the fieldfare (*Turdus pilaris*), the European turtle dove (*Streptopelia turtur*) and the black woodpecker (*Dryocopus martius*).

The protected species of the Ciomadul-Balvanyos site include fire salamander (*Salamandra salamandra*), northern crested newt (*Triturus cristatus*) and slow worm (*Anguis fragilis*). Among the most common snakes are the Aesculapian snake (*Elaphe longissima*) and, in rocky places, the meadow viper (*Vipera ursini*). Studies made by the Association Vinca Minor, custodian of the protected area Natura 2000 Ciomadul-Balvanyos, since 2015, show that the least endangered species is the yellow-bellied toad (*Bombina variegata*), which, as a highly adaptable species to habitat or weather changes, and is present in almost every water hole and pond along the forest roads (Fig. 13.6). The northern crested newt (*Triturus cristatus*) is found in temporary water holes in the valley of the Jimbor (Zsombor) stream, with a smaller number of the Carpathian newt (*Lissotriton montandoni*), which has a much lower tolerance to human activities. At this site we can also find species such as smooth newt (*Triturus vulgaris*), alpine newt (*Triturus alpestris*), European grass frog (*Rana temporaria*), common toad (*Bufo bufo*) and European green toad (*Bufo viridis*) (Fig. 13.7).

Bats studies of the Association Vinca Minor focused on four species: barbastelle (*Barbastella barbastellus*), Bechstein’s bat (*Myotis bechsteinii*), lesser mouse-eared bat (*Myotis blythii*), and the greater mouse-eared bat (*Myotis myotis*) (Fig. 13.8). The number of the greater mouse-eared bat has fallen sharply in recent years, but due to the monitoring efforts, new species were discovered, such as the lesser horseshoe bat (*Rhinolophus hipposideros*), whiskered bat (*Myotis mystacinus*), Brandt's bat (*Myotis brandtii*), alcathoe bat (*Myotis alcathoe*), Natterer's bat (*Myotis nattereri*), Daubenton’s bat (*Myotis daubentonii*), parti-coloured bat (*Vespertilio murinus*), serotin bat (*Eptesicus serotinus*), northern bat (*Eptesicus nilssonii*), common

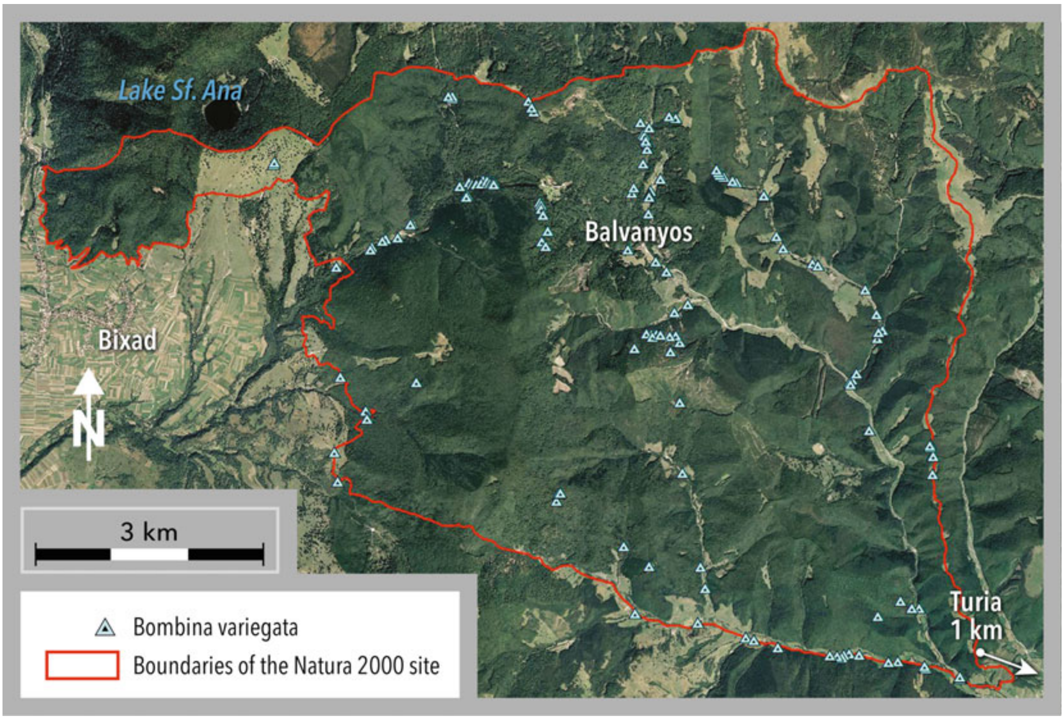

Fig. 13.6 Spread of yellow-bellied toad (*Bombina variegata*) in the Ciomadul Hills area

Fig. 13.7 Female crested newt (*Triturus cristatus*)

Fig. 13.8 The greater mouse-eared bat (*Myotis myotis*)

noctule (*Nyctalus noctula*), common pipistrelle (*Pipistrellus pipistrellus*), Nathusius's pipistrelle (*Pipistrellus nathusii*) and brown long-eared bat (*Plecotus auritus*). The Transylvanian dark bush-cricket (*Pholidoptera transsylvanica*) is another protected species at the Ciomadul-Puturosu Hills (Fig. 13.9). It is found in three habitats in the northern part of the site. The only common feature of these habitats is the lack of grazing.

13.4 Animal Victims of Mofette Gas Emissions

The caves and mofettes on Puturosu Mountain are natural release points for volcanic gases (e.g., CO_2), which are dangerous for animals looking for shelter, unwittingly resting in low oxygen zones. A study was undertaken in 1982–1983 to focus on the bird and mammal victims of these natural gas outlets (Molnár 1983), with a more recent study focusing on bat victims of the CO_2-rich mofettes and caves on Puturosu Mountain (Barti and Varga 2006). Additionally, since monitoring started in 1997, other corpses were recorded, including Eurasian pygmy shrew (*Sorex minutus*), common shrew (*Sorex araneus*), European mole (*Talpa europaea*),

Fig. 13.9 The Transylvanian dark bush-cricket (*Pholidoptera transsylvanica*)

European water vole (*Arvicola terrestris*), bank vole (Clethrionomys glareolus), field vole (Microtus agrestis), wood mouse (*Apodemus sylvaticus*), edible dormouse (*Glis glis*), hazel dormouse (*Muscardinus avellanarius*) and least weasel (*Mustela nivalis*). Different species of amphibians and reptiles were also discovered, such as the agile frog (*Rana dalmatina*), the viviparous lizard (*Zootoca vivipara*), the sand lizard (*Lacerta agilis*), the grass snake (*Natrix natrix*) and several bird species, including the tawny owl (*Strix aluco*), white-backed woodpecker (*Dendrocopos leucotos*), goldcrest (*Regulus regulus*), European robin (*Erithacus rubecula*), song thrush (*Turdus philomelos*), Eurasian blue tit (*Parus caeruleus*), long-tailed tit (*Aegithalos caudatus*), yellowhammer (*Emberiza citrinella*), hazel grouse (*Tetrastes bonasi*) and Eurasian siskin (*Carduelis spinus*).

13.5 Summary

The Ciomadul region in the Carpathian Mountains is a unique location for flora and fauna, heavily influenced by volcanic and post-volcanic activity, which actively shaped the landscape today, and continued to influence the climate of the area. As a Natura 2000 site, Ciomadul-Balvanyos enjoys the protection of many species and habitats, but some species require more special protection, as their numbers have decreased and because they live and survive in only a few places. Therefore, it is of utmost importance to find methods and adopt appropriate measures that better protect the habitats than the species itself. Crucially also, the custodian of the site, the Association Vinca Minor, continues to take care of this special place.

The Palaeolithic in the Karst Area of Vârghiș (Vargyas) Gorges

14

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Abstract

The deposition of tephra, such as volcanic ash and other pyroclastics, can provide important chronological context in archaeological records where standard geochronometers are ambiguous. An example of this are the caves in the Vârghiș (Vargyas) Gorges, close to the volcanic massif of Ciomadul (Csomád) where human presence has been documented since the Middle Palaeolithic. Here, the chronology offered by tephra occurrences can be corroborated with archaeological, archaeozoological, and radiometric dating efforts to outline not only time spans of human presence, but also potential scenarios for the Palaeolithic human abandonment of the area.

14.1 Introduction

The history of ancient humans is often linked to caves that not only provided shelter but preserved traces of their activities such as tools, hearths, cave paintings, and even human remains. The Carpathian area, encompassing both the mountain range and the widespread lowlands drained by the Danube likely acted as migration corridors for Palaeolithic humans and animals in and out of Europe (Hublin 2015). Numerous traces of past human presence and especially a significant number of human remains have been identified in caves such as Pestera cu Oase (Csontok barlangja/Cave of bones), Muierilor or Cioclovina (Asszonyok barlangja/Womens' Cave: Anghelinu et al. 2012). This inventory makes the South Carpathians the region with the most numerous examples of Palaeolithic occupations. Archaeological research deployed mainly in the 1950's exhausted the biggest part of the sedimentary units preserved within the investigated caves; unfortunately, identifying regionally representative tie-points such as tephra occurrences in such contexts is no longer possible, even though it might have been probable. For example, Hoților (Rabló/Robber) Cave (Băile Herculane),

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https://doi.org/10.1007/978-3-030-89140-4_14

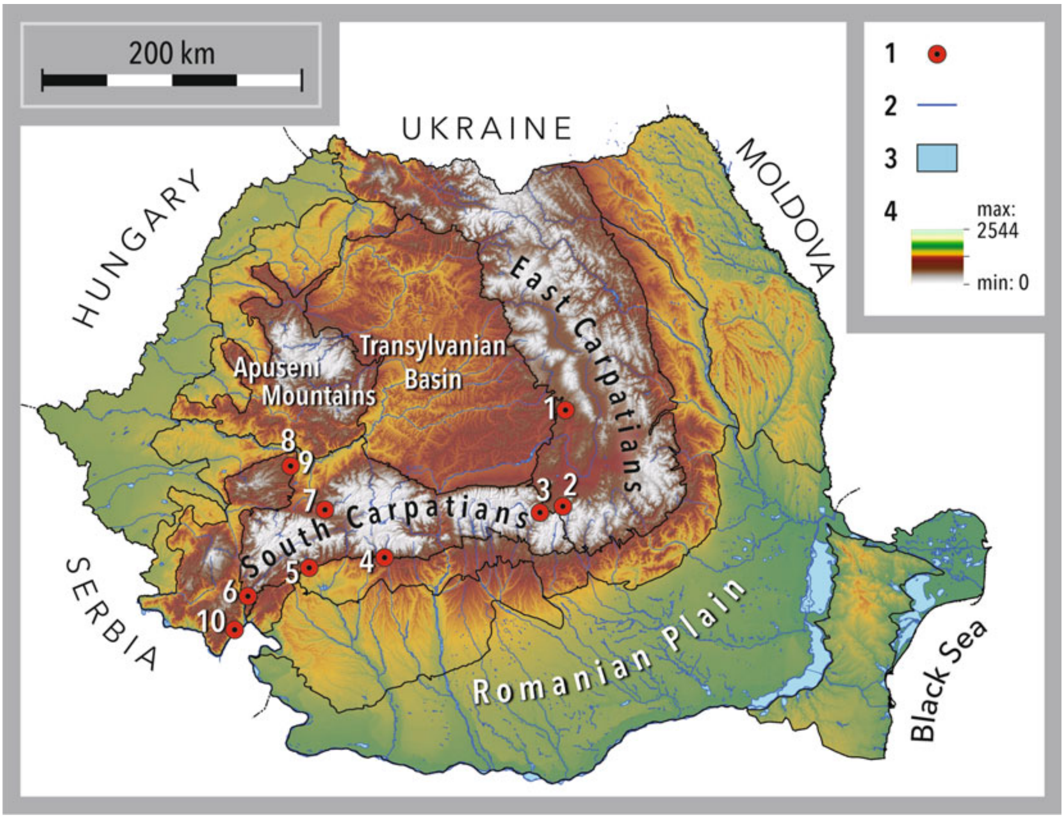

Fig. 14.1 The main caves in Romania with documented Palaeolithic cultural layers: 1. Caves; 2. Rivers; 3. Lakes, river surfaces; 5. Digital Elevation Model (DEM) with colour codes according to elevation. Caves on the map: 1. Abri 122; 2. Gura Cheii—Râşnov (Barcarozsnyó); 3. Liliecilor (Denevér) Cave (Peştera village); 4. Muierii (Asszonyok) Cave; 5. Cioarei (Varjú)—Boroşteni Cave; 6. Hoţilor (Rabló)—Herculane Cave; 7. Bordul Mare—Ohaba Ponor (Ohábaponor) Cave; 8. Spurcată—Nandru (Nándor) Cave; 9. Curată—Nandru Cave; 10. Tabula Traiana Cave

with Palaeolithic cultural layers, is close to the Tabula Traiana Cave (Serbia), where the Campanian Ignimbrite tephra, separating the Middle and Upper Palaeolithic layers, was recovered (Fig. 14.1).

14.2 The Karst System in the Eastern Carpathians

The Vârghiş Gorges is a karst area ~30 km away from Ciomadul with more than 124 caves exposed on four different altitude levels (Fig. 14.2). In some of the caves, the sedimentary archives recorded volcanic ashes as evidence from Ciomadul's eruptive events (Veres et al. 2018), in addition to preserving Palaeolithic archaeological material (Cosac et al. 2018). The gorges are placed at the contact between the Perşani (Persányi) and Harghita (Hargita) Mts. along the Vârghiş stream flowing from northwest to southeast. The karst system was created by the Vârghiş stream, right-side tributary of Cormoş (Kormos) river. The latter is a right-side tributary of the river Olt, north of Augustin (Ágostonfalva), in the Baraolt (Barót) depression (Orghidan and Dumitrescu 1963). The Vârghiş riverbed eroded the Triassic (Anisian)—Jurassic (Callovian) limestone massif for 3.5 km (1.9 km in the Vârghişului Mts and 1.6 km in the Harghita Mts). In the southern part, the gorges are incised 570 m deep, their highest area being Tiva Peak

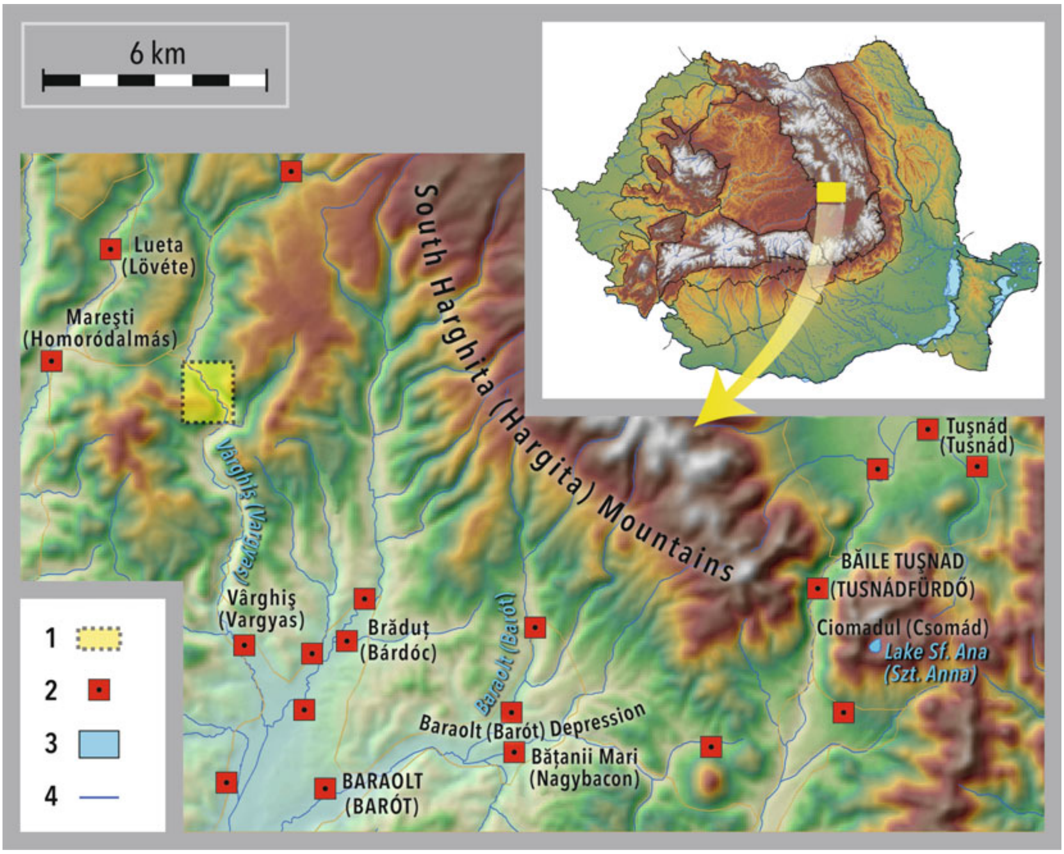

Fig. 14.2 Location of the Vârghiș (Vargyas) Gorges location within the East Carpathians: 1. Vârghiș Gorges area; 2. Settlements; 3. Lakes; 4. Rivers

(935 m) (Murătoreanu et al. 2015). The karst system of more than 124 fossil caves that formed during the Quaternary, starting during Middle Pleistocene times (ca. 1.8 million years ago). The active karst level is currently being formed by several permanent or temporary inundated karst conduits, which discharge at the river level. Speleological research highlighted the complexity and the archaeological potential of the Vârghiș Gorges.

14.3 Palaeolithic Cave Evidence

14.3.1 Cave Locations

In 2014, our team initiated modern archaeological excavations in the area: Abri 122, Gabor (Gábor) Cave, Ursului (Medve) no. 18 and no. 36 caves (Fig. 14.3). In the first two caves, the stratigraphical columns include Palaeolithic lithic and faunal material, while in the last two which unfortunately lack Palaeolithic cultural layers volcanic ash deposits were identified (Figs. 14.4, 14.5, 14.6 and 14.7).

14.3.2 Lithic Material

Excavations in Abri 122 and Gabor Cave revealed a consistent collection of 1087 stone tools made of a diverse array of raw materials, such as quartzite, volcanic rocks (basalt, diorite, and andesite), lydite (black opal), and, to a lesser extent, flint, chalcedony, radiolarite, argillite, jasper.

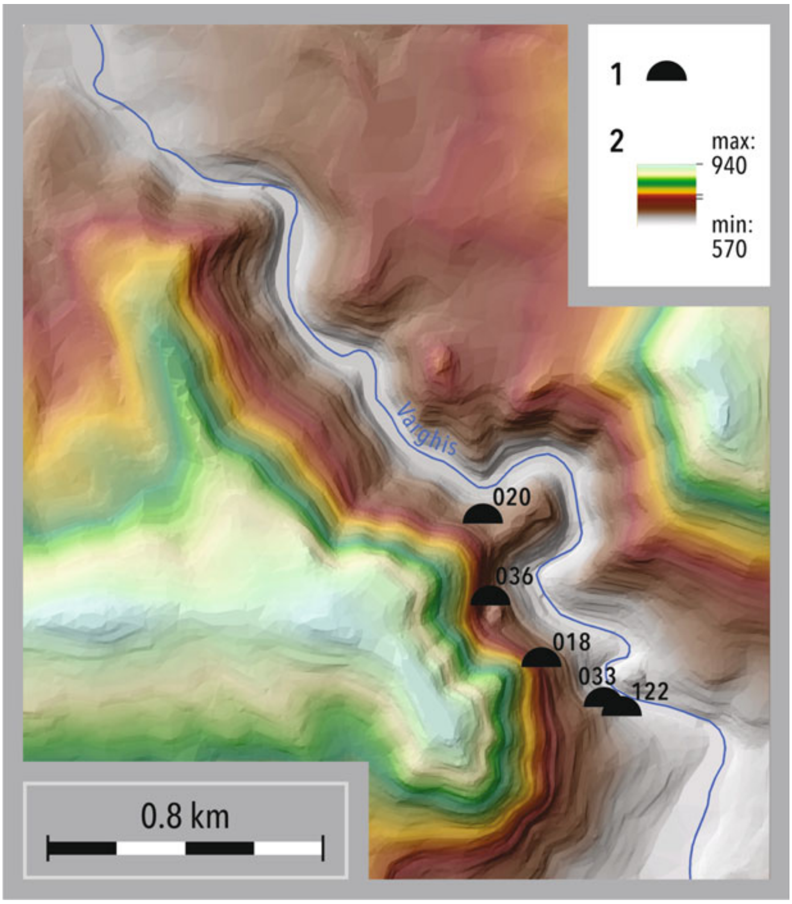

Fig. 14.3 Location of the Vârghiș Caves where post-2014 archaeological research is on-going. 1. Cave; 2. Colour code for different altitudes of digital elevation model (DEM)

The quartzite of local origin is the main (45.3%) raw material employed in producing stone tools, presenting several colour varieties, from blackish and smoky grey to yellowish white or milky white; its cortical surfaces are smooth, while the grain varies from coarse to fine. Other than flakes and indefinite fragments, the most numerous quartzite items are the cortical products, while cores, laminar products and retouched items are less than 3% each. The volcanic rocks (29.4%) probably entered the debitage process as blocks lacking cortical surfaces, fairly homogenous, with relatively coarse grainsize. Although they provided, largely, the same technological category representation as the quartzite, apparently basalt was the raw material of choice for most of the formal tools (i. e. intentionally modified/retouched lithic items).

The last of the well-represented raw materials are the lydite (black opal) and the argillite, making up 13.7% of the assemblage, having provided slightly more cores and laminar products than the quartzite and the basalt. Still, even if they show an obvious homogeneity, due to the lack of structural flaws and the fine texture, the blanks, either flakes or blades, did not represent the preferred choice for formal tools making or bifacial retouching.

The flint, jasper, radiolarite, and chalcedony (11.4% of the assemblage) are, to our knowledge, allogenous raw materials, since a securely located source of origin is still unknown. Their

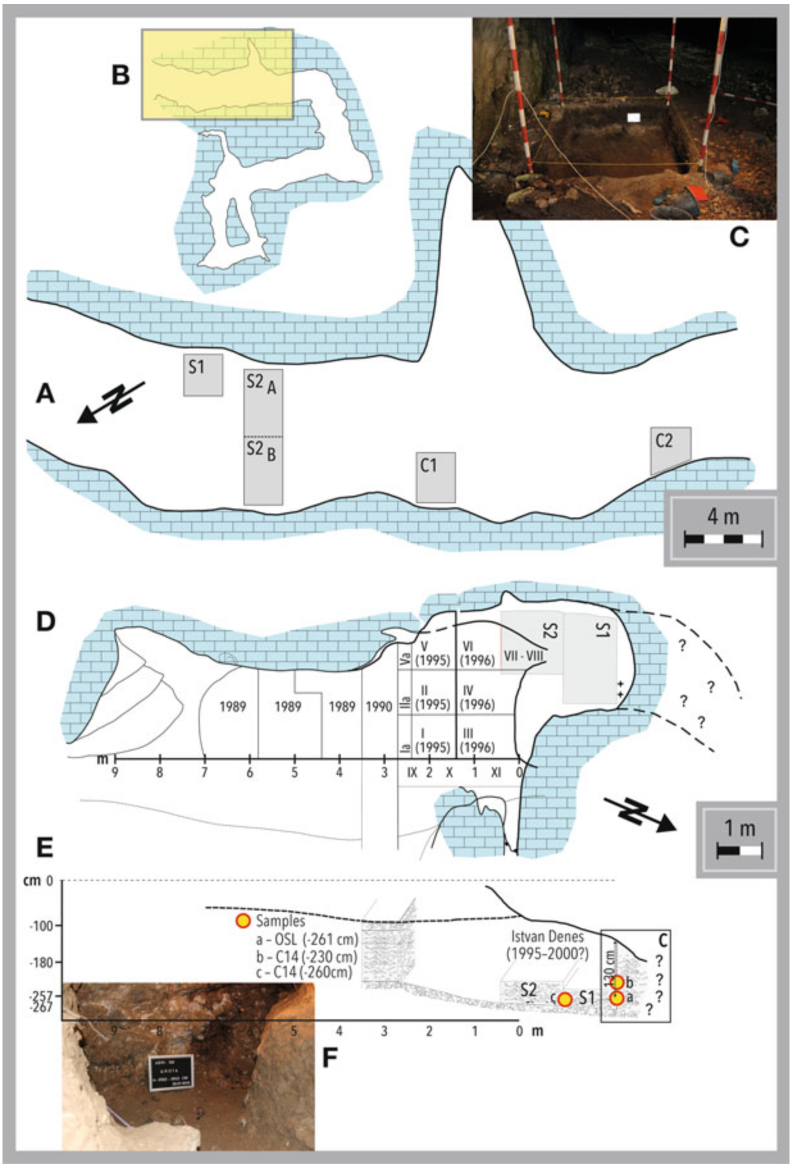

Fig. 14.4 Gabor (Gábor) Cave (no. 20) and Abri 122. **a** The portal area on the caves general layout (after Orghidan and Dumitrescu, 1963). **b** Layout of Gabor Cave from the portal area. **c** S1 trench. **d** Abri 122's layout (modified after Dénes 2003). **e** Abri 122 profiles. **f** Abri 122 profile, July 2016

exploitation, as is the case with the previous raw material types, aimed at obtaining flakes; nevertheless, they also provided a fairly bigger number of laminar blanks, abandoned exhausted cores and retouched items.

Within the technological groups (see Inizan et al. 1995; Boëda 2013), the main products are the flakes, issued from hard-hammer percussion practiced mainly during centripetal debitage. Some of the few laminar products show the isolated use of unipolar debitage. Given the large number of flakes and indefinite items for each raw material type, the recovered fragmented cores are surprisingly few (3.1% of the

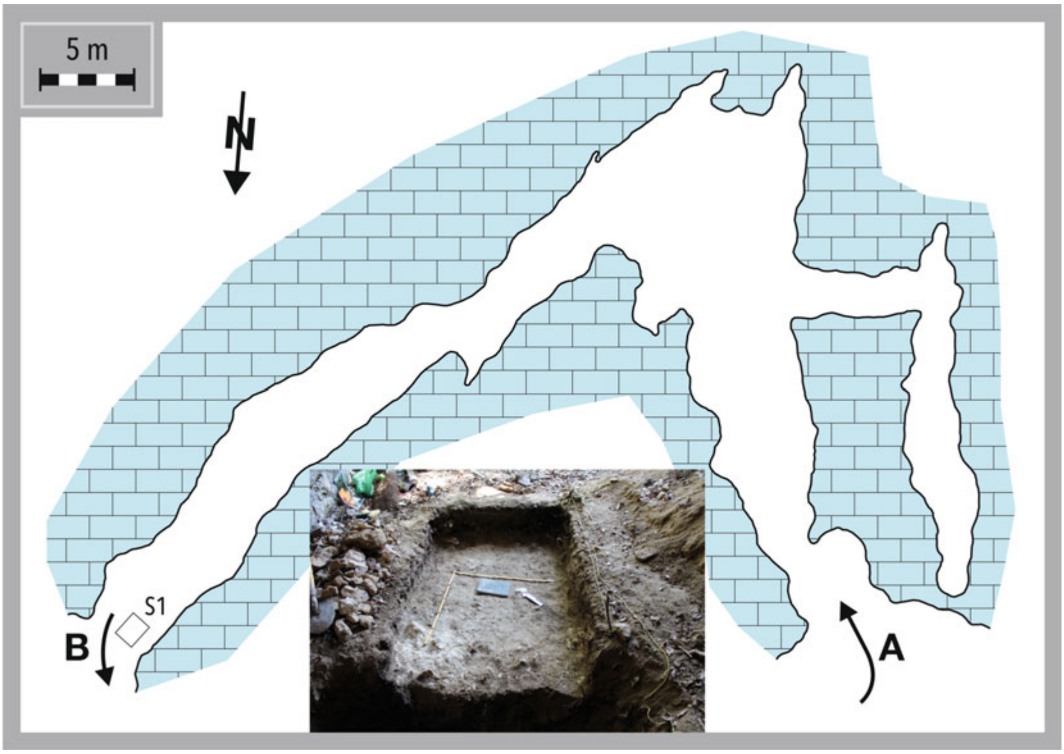

Fig. 14.5 Cave no. 33's layout (modified after Orghidan and Dumitrescu 1963)

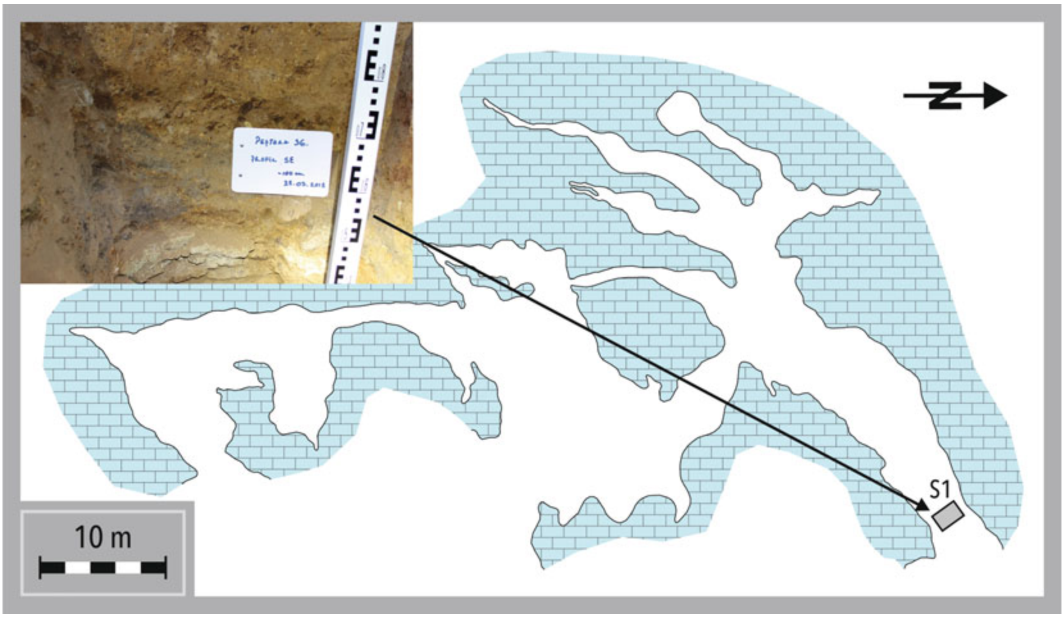

Fig. 14.6 Cave no. 36's layout (modified after Orghidan and Dumitrescu 1963). *Photo* S1 trench, March, 2018, with the tephra deposit

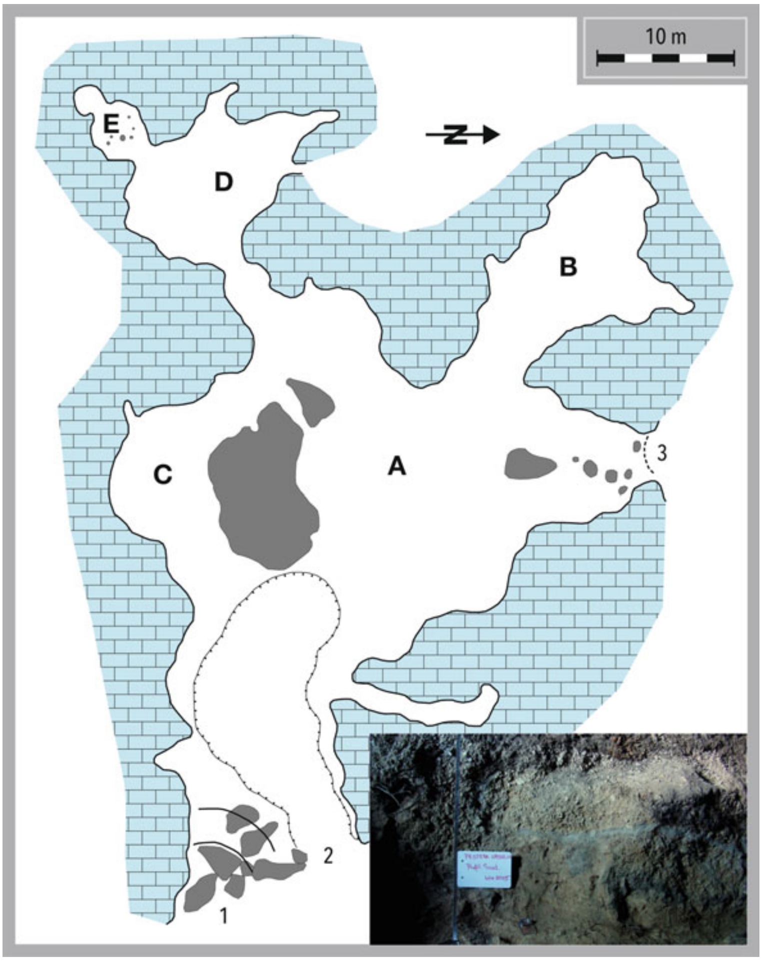

Fig. 14.7 Ursului (no. 18) Cave's layout (modified after Orghidan and Dumitrescu 1963): **1–3** entrances, **a** main chamber, **b** diverticulum, **c** gallery, **d** and **e** small chambers. *Photo* Entry no. 2 trench—profile with tephra deposit

assemblage). Among the intentionally modified lithic products, the most numerous are the flakes with lateral or distal semi steep retouch (lateral and transverse scrapers), as well as notched and denticulated flakes; occasionally, laterally retouched blades also appear. For the bifacially modified tools, the chosen debitage products are wide blades and laminar flakes of quartzite, basalt, and in one case, chalcedony. They exhibit plano-convex or biconvex profiles, slightly asymmetrical long edges, and fractures or accidental removals, probably due to partial rejuvenation attempts (Figs. 14.4, 14.5, 14.6 and 14.7).

14.3.3 Macro- and Microfauna

Recent archaeological excavations yielded numerous fossil bone remains belonging to animals that inhabited the area during the Middle Palaeolithic (from 300,000 to 40,000 years ago). These remains can provide information on the possible, or direct, interactions between ancient humans and local fauna. Discerning the types of fauna can also offer insights into the climate and landscape where ancient humans lived and potentially hunted. The numerous caves in the Vârghiş Gorges have provided shelter not only

Fig. 14.8 Middle Palaeolithic lithic items from Vârghiș Gorges

for Palaeolithic humans, but also for other animals living in the area during the late Pleistocene (e.g., bears, wolves, owls, and bats). Numerous bones were excavated from cave deposits adding information about the local fauna present in the area during the Middle Palaeolithic (Fig. 14.8).

14.3.3.1 Large Mammals

Although not all vertebrate fossil remains bear signs of human interaction and they were not necessarily accumulated in caves as a result of human activity, their occurrence in association with lithic artifacts (stone tools and weapons) is a clear indication that the humans and vertebrates found in the same sediment layers lived at the same time in and around the Vârghiș Gorges. Faunal remains were recovered from many caves of the Vârghiș Gorges, and are continually found in recent excavations, such as those from Abri 122 rock shelter (the most intensely studied and, therefore, best known), Gabor Cave, and Ursului Cave. In the former two sites, the vertebrate remains were found alongside lithic artifacts, whereas in the latter, no lithic artifacts appeared as yet.

The best piece of evidence showing direct interaction between Palaeolithic humans and the local fauna is a fragment of a large bovid tibia from Abri 122 that preserves clear cut marks. The fine parallel lines, made with a sharp stone blade, are partially covered by a carbonate crust, which is clear evidence that the cuts were made before the bone was buried by sediment. Such cuts are left by stone blades when stripping the meat off the bone, when cutting the tendons connecting the muscle to the bone, or, when they are present at bone ends, when butchering a large carcass for easier transportation. Large bovid bones were found in Abri 122, but are too fragmentary to tell if they belonged to the steppe bison (*Bison priscus*—the ancestor of the modern European and American bison) or the aurochs (*Bos primigenius*—the ancestor of modern cattle), both animals that were common part of the fauna at that time. Either way, none of the two bovids naturally used caves for shelter, so the presence of their bones in such places involves transport by either human hunters or natural predators. Since both were very large animals, weighing up to 1500 kg, it is unlikely that a natural predator would carry parts of their carcasses to the caves, making it more probable that they were dismembered by Palaeolithic hunters and transported to the caves the latter used as shelter. Fragments of charcoal indicate that some of the game was cooked and eaten in those temporary shelters.

The case might be different for smaller herbivores, like the ibex (*Capra ibex*) or the boar (*Sus scrofa*), that could be transported to caves not only by humans, but also by large carnivores, like wolves or bears. Boar and ibex teeth and bone fragments are more common than large bovids, but since there are no cut marks or tooth marks on their bones, it is not clear how they ended up inside the caves. The case is even more complicated for the ibex, since this species also uses caves or overhanging rocks for shelter, and can reach even the more remote caves on abrupt cliffs naturally, without implying transport by human or other natural predators.

Large carnivores, such as the cave bear (*Ursus spelaeus*) or the wolf (*Canis lupus*), use caves as dens, and are often the main accumulators of herbivore bone fragments in cave deposits. Although there is no direct evidence (e.g., bite marks or gnawing traces on herbivore bones), such large carnivores might have contributed to accumulating at least middle-sized herbivore bones in caves. Cave bear fossil remains are the most common findings in the faunal assemblages from the late Pleistocene deposits in the Vârghiș Gorges, with wolf remains occurring more rarely. Both animals might have been revered by Palaeolithic hunters for their strength and hunting abilities, but there is no evidence their bones were in any way deposited by humans in the three caves mentioned above. Most probably, their occurrence in these caves is a natural one, as present-day bears and wolves also use caves as shelter or den.

14.3.3.2 Small Vertebrates

Remains of large mammals are not the only ones found in the same deposits as the Palaeolithic artifacts from the caves of Vârghiș Gorges. Sieving of the sediment using 2 mm mesh size yields remains of small mammals, amphibians, and small reptiles. The most abundant small mammal remains are those belonging to rodents, useful in reconstructing past environments. The European water vole (*Arvicola amphibius*) is a rodent that always builds nests in the vicinity of water, with underwater entrances protecting their galleries from predators. The presence of water vole teeth shows that permanent rivers or lakes with sandy or muddy banks were present near or within the gorges. Other rodents, like the European snow vole (*Chionomys nivalis*), inhabit rocky terrain characterized by colder climate, and show that cliffs were present in the area during the Palaeolithic with a climate similar to what we encounter today on the Carpathian heights. On the contrary, the European hamster (*Cricetus cricetus*) avoids rocky terrain, and digs its burrows in the thick soil of steppes and forested steppes. The steppe lemming (*Lagurus lagurus*), and the gray dwarf hamster (*Cricetulus migratorius*) also prefer steppe environments, and support the presence of open fields in the vicinity of the gorges. Some other species, like the common vole (*Microtus arvalis*) and the bank vole (*Clethrionomys glareolus*), inhabit mountain and hill forests, whereas other small mammals, like the narrow-headed vole (*Microtus gregalis*), or the common shrew (*Sorex araneus*), an insectivore, living in forests that have open areas with grass (e.g. large pastures). This rich small mammal assemblage found in the late Pleistocene deposits, account for the presence of many different habitats around the Vârghiș Gorges. Finding their remains within the Palaeolithic sedimentary sequences indicates that they have been brought in by predator accumulation:

several owl species that hunt various small mammals from across a few square kilometres, find shelter in such caves and abris, where they regurgitate pellets containing the bones of the eaten mammals, besides those of other small animals. The presence of birds is clear at least in Abri 122, where small fragments of bird eggshells were also recovered from the sediment.

The diversity of habitats around the gorges is also evident by the amphibian and reptilian faunal remains found in the sediment. Bones of a tree frog (similar to the modern *Hyla arborea* or *Hyla orientalis*) as well as bones of a brown frog (similar to the modern *Rana temporaria*) show that trees were present, whereas the presence of a marsh frog (*Pelophylax sp.*) is another clear indicator of permanent water (Fuhn and Vancea 1961; Murariu 2000; Popescu and Murariu 2001). Reptile bones are more fragmentary and the species they belonged to cannot be clearly identified. However, at least two types of snakes (belonging to the genera *Natrix* and *Zamenis*, but a viper might have also been present), and at least two kinds of lizards (*Lacerta agilis* and *Lacerta viridis*), clearly inhabited the area of Vârghiș Gorges.

14.3.4 The Geomorphology and Climate of Palaeolithic Ciomadul Area

The vertebrates found in the late Pleistocene deposits of the three caves mentioned from the Vârghiș Gorges (Table 14.1, Fig. 14.9), in the same layers with Palaeolithic artifacts, help us understand the natural environment that Palaeolithic humans lived in, and how the surrounding landscape looked like, characterized by steep rocky walls, surrounded by forests, but not very far from grasslands either with a permanent water source, most probably the same river that cut the gorges in limestone and helped form the plethora of caves in the Vârghiș karst system. Such an environment provided humans with large herbivores to hunt, but also held large predators that might have attacked them at any time, in a daily struggle of survival for the Palaeolithic hunters (Petculescu 2013).

14.4 Radiometric Age Estimations

So far, there are several issues regarding the age estimations for the archaeological material discovered in Abri 122 (Cosac et al. 2018; Veres et al. 2018). The recent dating applying the radiocarbon technique were close to the reliable limit of the method. One sample, collected at 227–237 m depth, provided an age of >42,200 uncal (uncalibrated) years before present (BP), while another, at 260 m depth, returned ages of 37,325–35,800 cal (calibrated) years BP and 45,073–41,467 cal years BP, respectively. All charcoal and bone sample were retrieved from areas with archaeological material accumulation. At 260 m depth, optically and infrared stimulated (OSL and IRSL) ages of 141 ± 12 ka and 173 ± 41 ka respectively were also obtained. For the archaeological layer in Gabor Cave, similar analyses are on-going. The volcanic ash deposits identified in Ursului Cave and Cave no. 38 provides a macroscopic accumulation of volcanic ash resulted from an eruption at Ciomadul, probably one of the significant explosive events that occurred during Marine Isotope Stage (MIS) 3, around 40–45 ka BP (see Chap. 3). If so, the findings recovered from the Vârghiș Gorges serve as direct evidence of former speculations that Palaeolithic humans witnessed the late-stage eruptions of Ciomadul. Similar ash traces were also identified in Cave no. 36; unlike the compact deposit in Ursului Cave, here the ash is scattered within a 15–20 cm thick horizon. The collected sample is undergoing age determination analysis. Notably, the two caves are situated on different karst levels—Ursului Cave at 107 m and Cave no. 36 at 85 m, on the same slope, with three differently oriented entrances

Table 14.1 Vertebrates found in the recent excavations of Palaeolithic layers from Vârghiș Gorges (“+” shows the animal was found in the respective cave, “−” shows the animal was not found yet; ? shows fragmentary specimens might belong to the inferred animal)

Colloquial name	Scientific name	Abri 122	Gabor Cave	Ursului Cave
Cave bear	*Ursus spelaeus*	+	+	+
Wolf	*Canis lupus*	+	+	+
Ibex	*Capra ibex*	+	+	+
Boar	*Sus scrofa*	+	−	+
Steppe bison or Aurochs	*Bison priscus* or *Bos primigenius*	+	−	−
European water vole	*Arvicola amphibius*	+		−
European snow vole	*Chionomys nivalis*	+		−
European hamster	*Cricetus cricetus*	+		−
Steppe lemming	*Lagurus lagurus*	+		−
Common vole	*Microtus arvalis*	+		−
Bank vole	*Clethrionomys glareolus*	+		−
Narrow-headed vole	*Microtus gregalis*	+		−
Gray dwarf hamster	*Cricetulus migratorius*	+		−
Common shrew	*Sorex araneus*	+		−
Indeterminate birds	Aves indet	+	−	−
Sand lizard	*Lacerta agilis*	?	+	−
Grass lizard	*Lacerta viridis*	−	+	−
Grass snake or dice snake	*Natrix* sp. (*Natrix natrix* or *Natrix tessellata*)	+	+	−
Colubrid snake (possibly the Aesculapian snake)	Colubridae indet. (possibly *Zamenis longissimus*)	+	−	−
Viper	*Vipera* sp.	−	?	−
European brown frog	*Rana* sp. (possibly *Rana temporaria*)	+	+	−
Marsh frog	*Pelophylax* sp.	+	−	−
Tree frog	*Hyla* sp.	+	−	−
Indeterminate bony fishes	Osteichthyes indet	+	−	−

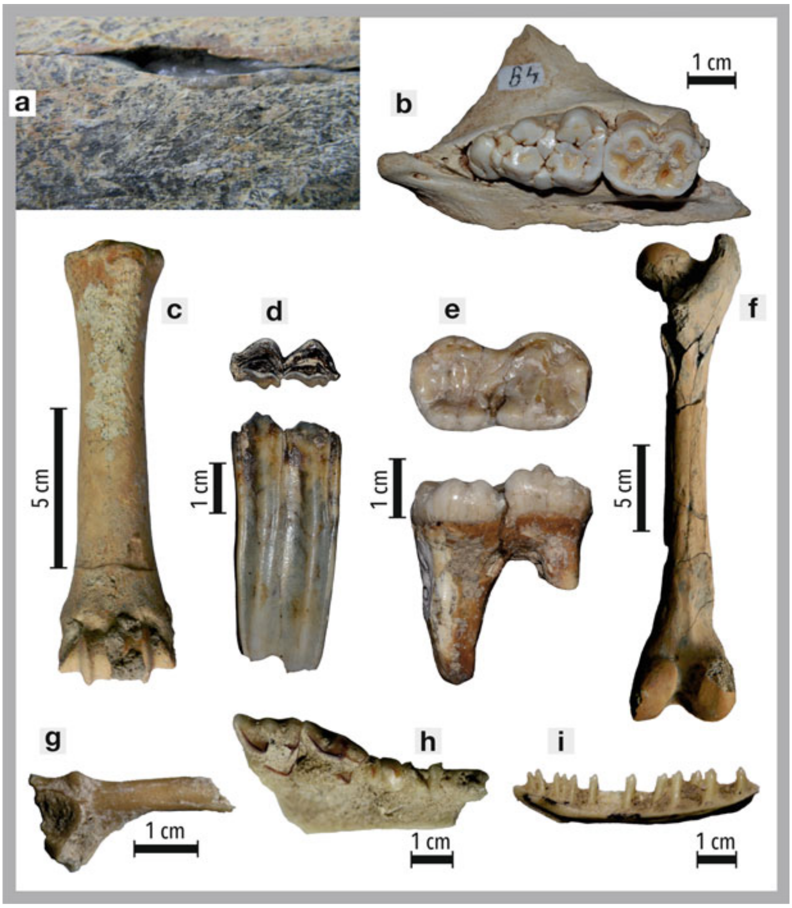

Fig. 14.9 Vertebrate remains from the Palaeolithic sites of Vârghiș Gorges. **a** Cut marks on bovid tibia. **b** Boar upper 2nd and 3rd molars. **c** Ibex metatarsal. **d** Ibex 1st lower molar. **e** Cave bear lower 2nd molar. **f** Wolf femur. **g** Tree frog ilium. **h** Common shrew upper tooth row. **i** Sand lizard lower tooth row

each and strong air flow. Hopefully, future research will be able to better correlate the timing of volcanic events and human activity, in order to better pinpoint the chronology of the hunter-gatherer communities' presence in the Vârghiș Gorges karst area for the last several hundred thousands years.

15 Prehistory of the Ciomadul Region from the Neolithic to the Late Iron Age

Sándor-József Sztáncsuj and József Puskás

Abstract

Volcanoes have always been explained with various superstitions over human history. People of the Antiquity thought volcanoes had a divine origin. In medieval times they were thought to belong to the underworld, and were looked at with curiosity and fear. Volcanism affected, directly or indirectly, human history itself; the destruction of Pompeii in Roman times, the eruption of Samalas in the early Middle Ages, or the explosion of the Krakatau in the nineteenth century are good examples of how volcanoes can influence or even reverse historical destiny. The brilliant civilization of the Minoan Culture flourishing on the island of Santorini in the Aegean Sea was halted for a long period of time by the catastrophic eruption of Thira in the Late Bronze Age (seventeenth century BC). At that time the Quaternary volcanoes of the Carpathian Basin had long been dormant. As stated in earlier chapters, even the youngest of them, the Ciomadul (Csomád), last erupted almost 30,000 years ago. Archaeological and historical sources, however, suggest that with its indirect and multifaceted effects, Ciomadul may have influenced the lives of prehistoric people lived in the area. In this chapter we provide a short, comprehensive overview of the prehistory of the Ciomadul Region from the Neolithic to the end of the Iron Age.

15.1 Introduction

Thousands of years have passed between the last eruption of Ciomadul volcano toward the end of the Ice Age c. 30,000 years ago and the appearance of the earliest farming communities in the area (the beginning of the Neolithic, about the 7th millennium BC). Volcanic activity, however, has left behind many signs in the form of post-volcanic activity. The mineral waters, acidulous waters, mofettes, sulphur gas caves, and peat bogs have always been well known to people living in the area, who exploited them for medicinal, economic, and cultural reasons. Prehistoric (palaeolithic) people might have even witnessed and remembered Ciomadul's volcanic activity, and probably developed complicated superstitions about the eruptions, slowly changing with time. Although these ancient beliefs will never be known due to the lack of written records, archaeological research can go a long way in documenting the utilisation and understanding of natural resources associated with, or produced by, volcanism.

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There are relatively few archaeological finds in the immediate region of the Ciomadul Hills which include the Tușnad (Tusnád) Gorge, the southern part of the Ciuc (Csíki) Basin and the Stinky (Puturosu/Büdös) Hill in the vicinity of Turia (Torja) (see Cavruc 1998, 2000; Puskás 2012, 2013). Only a few systematic excavations were carried out in these regions in the last two hundred years. Even the large, Early Iron Age fortification of Vártető at Băile Tușnad (Tusnádfürdő), in spite of its importance, has only seen preliminary field surveys—apart from a small-scale excavation in the middle of the twentieth century. The lack of archaeological finds from the Ciomadul area can be attributed primarily to its specific geographical location, environmental setting, and economic potential related to its climate and remoteness. Due to the cool and extreme climate, the area was sparsely populated up to the nineteenth century. Thereafter, the population was either under the administration of the historical Székelyland, or lived on large private land holdings of noble families that were administered by the royal county system (see Chap. 16).

Human settlements, both in prehistoric and in later times, were established mainly in the valley of the Olt river and in the fertile, lower valleys of the streams coming from the mountains, mainly on the southern and eastern sides of the volcanic range (Fig. 15.1). The mountainous parts of the land were difficult to cross and were not conducive to a life based on farming because they were—and still are—covered with thick forests, and have narrow valleys between the ranges. The climate of the Ciuc and Cașin (Kászon) Basins north of Ciomadul was equally severe, which contributed to a sparse settlement network in the region, especially in prehistoric times. Pollen analysis of the Mohoș (Mohos) peat bog suggests that until the Middle Ages there was no considerable human activity in the area of the twin craters (Tanțău et al. 2003; Magyari et al. 2006; Daróczi 2012; Chap. 11).

Fig. 15.1 Aerial photo of Lake Sf. Ana, with the Olt valley in the background (*Photo credit*: Zoltán Czajlik, ELTE, Institute of Archaeological Sciences, 2010)

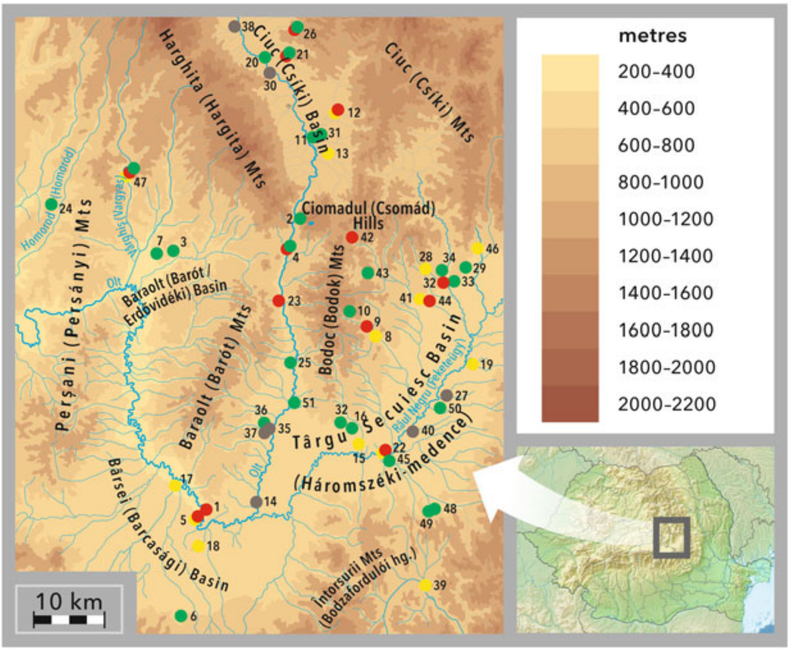

Fig. 15.2 Map of the most important archaeological sites and discoveries. Yellow: Neolitihic; Red: Copper Age; Green: Bronze Age; Grey: Iron Age. 1. Ariușd-Tyiszk-hegy; 2. Băile Tușnad-Vártető; 3. Biborțeni-Kerekdomb; 4. Bixad-Vápa-vára; 5. Bod-Priesterhügel; 6. Brașov-Schneckenberg; 7. Brăduț-Tortoma; 8. Cernatul de Jos-Aranyos-hegy; 9. Cernatul de Jos-Templomdomb; 10. Cernatul de Sus-Hegyes-tető; 11. Cetățuia; 12. Ciucsângiorgiu-Potovszky-kert; 13. Cozmeni-Egeresvölgy; 14. Dobolii de Jos; 15. Eresteghin-Lencséskút; 16. Eresteghin-Zádogostető; 17. Feldioara-Marienburg; 18. Hărman; 19. Imeni-Szentegyház-dombja; 20. Jigodin-Csereoldal; 21. Leliceni-Kőhegy; 22. Leț-Várhegy; 23. Malnaș-Băi-Füvenyestető; 24. Ocland-Kövesbérc; 25. Olteni; 26. Păuleni-Várdomb; 27. Peteni; 28. Petriceni; 29. Poian; 30. Sâncrăieni; 31. Sânmartin; 32. Sânzieni-Köszörükő; 33. Sânzieni-Perkő; 34. Sânzieni-Polyvár; 35. Sfântu Gheorghe-Árnyas Street; 36. Sfântu Gheorghe-Őrkő; 37. Sfântu Gheorghe-Szemerja; 38. Siculeni; 39. Sita Buzăului-Malul Dinu Buzea; 40. Surcea; 41. Turia-Apor kúria kertje; 42. Turia-Bálványos-vár; 43. Turia-Torja-vára; 44. Turia-Vármegye; 45. Țufalău; 46. Valea Scurtă; 47. Vârghiș Gorge; 48. Zagon-Cseremás; 49. Zagon-Mete-hegy; 50. Zăbala-Tatárhalom; 51. Zoltan-Oldalramenő

In spite of all these factors, the Ciomadul region was not entirely uninhabited, even in prehistoric times. Ancient routes connecting the Brașov (Brassói) Basin with the Ciuc Basin through the Tușnad Gorge of the Olt river, or through the Pass of Balvanyos (Bálványos) were used already in the Neolithic Age. Because of its intermediary role and position, the Ciomadul region does not form a distinct archaeological unit, but is organically integrated into the wider area of Southeast Transylvania. The entire area of Southeast Transylvania, covering the upper reaches of the Olt and the watershed of its main tributary, the Râul Negru (Feketeügy), is extremely rich in variegated prehistoric archaeological finds (Fig. 15.2). The early history of Ciomadul, therefore, needs to be reviewed within the broader framework of this region.

15.2 The Neolithic (7th–5th Millennium BC)

After the last Ice Age, at the beginning of the Holocene, the climatic, botanical, and zoological conditions of Central and Eastern Europe gradually changed to the point that they provided favourable conditions for the first farming human settlements. Similar to the entire Carpathian Basin, people of the first Neolithic communities of Southeast Transylvania came from the South Balkans. Their archaeological legacy reveals their southern origins and strong connections to the Karanovo I–Kremikovci–Starčevo–Criș–Körös Cultural Group. The northern member of this group is the Starčevo–Criș Culture, which included the northern part of the Balkan Peninsula and the Danube Basin, extended to the north as far as the Great Hungarian Plain, Transylvania, and the Moldavian Plateau.

There is a relatively large number of Early Neolithic settlements in Southeast Transylvania (Ciută 1997). They are usually found on low-lying terraces or on erosional hills adjacent to the floodplains of the Olt and Râul Negru, such as Leț (Lécfalva)-Várhegy, Bod (Botfalu)-Priesterhügel or Imeni (Imecsfalva)-Szentegyházdombja. Other Early Neolithic site of the Ciuc Basin in the area of the Ciomadul Hills is Cozmeni (Csíkkozmás)-Egeresvölgy. In the northern part of the Râul Negru Basin are Cernatul de Jos (Alsócsernáton)-Aranyos-hegy and Turia (Torja)-Apor-kúria kertje. Excavations revealed that Early Neolithic people lived in small villages, in wattle and daub houses, some of which were semisubterranean. During his excavations in the 1980s, Zoltán Székely uncovered several such dwellings at Turia-Apor-kúria kertje. These houses had a rectangular, 3 × 3 m or 5.5 × 5 m floorplan and had a circular clay fireplace in their centre. In addition to open settlements, several cave sites are also known from the Vârghiș Gorge (Lublinit Cave, Kőcsűr, Cseppköves Cave, Albert Cave). Leț is particularly important of the above-mentioned sites, where Zoltán Székely, Ion Nestor and Eugenia Zaharia carried out large-scale excavations in the middle of the twentieth century. They discovered a site rich in artefacts from different successive levels of the Starčevo–Criș Culture, that proves that the Várhegy site has been inhabited in a number of different time periods (Zaharia 1962). Apart from the cave settlements (which probably also served as temporary shelters), the distribution of these early agricultural villages reflect the climatic and phytogeographical conditions of the area, which can also be reconstructed by environmental history studies. In the increasingly warmer and wetter conditions of the climate optimum of the Atlantic era, most of the area was covered by extensive forests. Neolithic communities gradually expanded their territory to the north-northeast in search of floodplains suitable for agriculture.

The Starčevo-Criș Culture in present-day Romania can be classified into two basic chronological horizons (see Luca et al. 2011). The few available ^{14}C (radiocarbon) chronological data also confirm these horizons. The early period (represented by Phases I and II) dates back to the first half of 6th millennium BC, while the later period (Phases III and IV) can be dated to the second half of the 6th millennium. Although there are no radiocarbon data for these periods from Southeast Transylvania, the sites there—mainly on the basis of the pottery characteristics—can be assigned to Phases III and IV. The valleys of the Olt and Râul Negru thus seem to have been settled relatively late, at the end of the 6th millennium BC. Exploration of raw material sources might have been the reason for this north-northeast expansion.

The Starčevo–Criș communities can be characterised with sedentary lifestyle, based on cereal cultivation and sheep and goat breeding (which did not originate in the Carpathian Basin). Beside the settled lifestyle and agriculture, these early societies still relied heavily on hunting, fishing, and gathering. Raw materials needed for everyday life were obtained partly from distant locations, such as the obsidian from the Tokaj–Eperjes Mountains, but geological resources close to their settlements were also explored. It cannot be ruled out that the Starčevo–Criș people had some connections with the late Mesolithic communities of the area and the two were interacting in this exploration process. Some sites show evidence of seasonal use—these are rich in rocks needed for toolmaking of stone but unsuitable for farming. One such site is Sita Buzăului (Szitabodza)-Malul Dinu Buzea, which has been used for millennia by peoples of the Palaeolithic and Mesolithic Eras (Păunescu 2001).

Early Neolithic period saw the appearance of pottery and some knapped and polished stone tools (e.g., blades, scrapers, and axes), as well as bone and antler tools typical of the early farming lifestyle. Pottery was made locally with the necessary clay extracted from sites within the settlements. If needed, sand and organic materials like cereal bran were added as temper to the clay. The pots then were burned in pits under an open fire. The simple, rounded or slightly biconical (double truncated cone) shape of the pots mimicked the shape of vessels carved from gourds or wood (Fig. 15.4a–e). The ornamentation of the vessels is distinctive for this era and of this culture. Patterns were impressed into the surface with pinching, wheat heads, barbotine, or ribs. In addition to small cups, bowls, and pots, larger storage vessels were also made (Fig. 15.3). Beside the tools and objects of everyday use, items indicating spiritual or religious beliefs are also found in these settlements. Such items are fired clay figurines with human shapes or altars.

There is little information regarding how or what these early farming communities believed. The burial of the dead within the settlements, often directly under the dwellings or in waste pits, suggests that their superstitions regarding death, and the burials themselves, have not yet taken a canonized form. At the same time, human remains buried in a constricted and probably bound body position reveal that the fear of and care for the dead was already present. Systematic archaeological excavations in the Ciomadul area uncovered only three such burials, all from Turia-Apor-kúria kertje. They were bound skeletal remains without any grave goods (Ciută 1997).

Fig. 15.3 Storage vessel. Starčevo-Criş Culture (Turia-Apor kúria kertje). Collections of the Székely National Museum

Compared to the Early Neolithic, even less information is available of the Middle and Late Neolithic history of this region. It seems that between 5000 and 4500 BC the area became the focus of several cultural and ethnic influences coming from different directions. At the turn of the 6th and 5th millennium, partly overlapping with the last phase of the Starčevo–Criş Culture, the Linear Pottery Culture of Eastern European origin appeared in the region. Its peoples probably arrived here from the northeast, crossing the Carpathian Mountains from Moldavia (Ursulescu 2000: 258–261). Only a few of their settlements are known, clustered in the Olt valley, in the Ciuc Basin (Ciucsăngeorghiu/Csíkszentgyörgy-Potovszky-kert), and in the Braşov Basin (Hărman/Szászhermány, Feldioara/Barcaföldvár-Marienburg). The peoples of this culture, named after their characteristic pottery ornamentation of incised lines and embossed circles, settled in south-eastern Transylvania probably only for a short period. The same can also be said of the Middle Neolithic Boian Culture (Figs. 15.4d, g, j, k and 15.5). This culture of southern origin has spread in the Lower Danube region and north-eastern Balkans, but relatively few of their settlements are known from Transylvania. Feldioara-Marienburg and Leţ-Várhegy are examples from the wider Ciomadul area. Closer to the Ciomadul Hills, artefacts of this Linear Pottery Culture have been found at Petriceni (Kézdikővár) and Valea Scurtă (Kurtapatak). Only scattered information is available about these Middle Neolithic groups due to the lack of systematic archaeological exploration, but a small number of known settlements may also suggest that this area was only used for exploitation of raw natural resources and as a place of contact with neighbouring groups.

Fig. 15.4 Clay pots from the Neolithic. **a–e** Starčevo-Criş Culture (Turia-Apor kúria kertje). **f** Precucuteni Culture (Sfântu Gheorghe). **g, h** Boian Culture (Leţ-Várhegy, Turia). **i** Precucuteni Culture (Sfântu Gheorghe). **j**, **k** Boian Culture (Leţ-Várhegy, Turia). Collections of the Székely National Museum

Fig. 15.5 Square clay pot with engraved ornamentation. Boian Culture (Turia). Collections of the Székely National Museum

15.3 The Copper Age (5th–3rd Millennium BC)

By the middle of the 5th millennium BC, the whole region of south-eastern Transylvania belonged to the Precucuteni-Cucuteni-Tripolje Cultural Complex famous for their painted pottery. The initial settlements of the early Precucuteni Culture were sparse in the area. Remains of their villages (Ciucsângeorgiu-Potovszky-kert, Eresteghin/Eresztevény-Lencséskút) were found in the valleys of the Olt and Râul Negru, usually on the lower terraces of their tributaries (Marinescu-Bîlcu 1974: 153, 158–159). The Precucuten Culture is the genetic predecessor of that civilisation characterised with painted pottery that flourished from Transylvania to the middle reaches of the Dnieper River during the second half of the 5th millennium BC and the first centuries of the 4th millennium BC. Their Transylvanian descendants are known as the Ariuşd (Erősd) Culture or Ariuşd Group (Sztáncsuj 2015). The distribution area of this group included eastern Transylvania, the valleys of the Olt and Mureş and their major tributaries (Râul Negru, Târnava/Küküllő, Homorod/Homoród, etc.). Most of their settlements are located in the Ciuc and Braşov Basins.

The Ariuşd Group established their settlements in much larger numbers and in more diverse geographical settings than the settlements of previous periods. This might indicate a significant population growth and possibly social and economic differentiation as well. Their villages—built on river terraces, hillsides, erosional terraces, or on isolated mountain ridges—were probably open, but some of their larger settlements had some fortifications as well. Typical examples are the Tyiszk-hegy at Ariuşd, the Füvenyestető at Malnaş-Băi (Málnásfürdő), or the Vápa-vára at Bixad (Sepsibükszád), close to the Ciomadul region. All of these were erected at the end of narrow erosional terraces or foothill ridges, were fortified with an inner palisade and a wide trench facing the land ridge. One of these settlements, Ariuşd—which had been actively used for a long time period, and had multiple occupation levels—was had been by the twentieth century (László 1914; Zaharia and Székely 1986). The excavations brought to light the remains of several ground level wooden posts-framed houses. The rectangular buildings had an average floor area of 40–45 m^2, stood side by side in rows, and probably surrounded a smaller open area in the middle of the settlement, where a potter's workshop stood. The fortified settlement of Malnaș-Băi also had houses in its central area—similar to those at Ariușd—but on its outer border it had a larger building surrounded by a circular enclosure of two concentric ditches (László and Sztáncsuj 2020). The structure of these villages suggests that they were built by a centralized management of the given community that adhered to a commonly accepted unified plan.

Organisational efforts are equally evident in the nature of the settlements. Villages based on agriculture or animal breeding were established on low-lying areas near water sources (e.g. Bod-Priesterhügel, Cernatul de Jos-Templomdomb, Turia-Vármegye), while others were located in the more mountainous zones where the climate was harsher and where agriculture or even travel was difficult (Bixad-Vápavára, Malnaș-Băi-Füvenyestető). Artefacts from the painted pottery culture were discovered in the immediate area of the Ciomadul Hills, around the Bálványos-vár near Turia. It is worth mentioning that the vicinity of these aforementioned settlements is rich in natural resources, such as mineral springs with iron and salt, and quarries. The environment in these areas is also favourable for grazing livestock and hunting. Analysing the animal bone material of the Füvenyestető settlement (Fig. 15.6), it was concluded the remains of wild animals were proportionally higher than usual, suggesting the important role of hunting in this region (László and Haimovici 1995). The strategic position of the settlements of Păuleni (Csíkpálfalva)-Várdomb on the eastern edge of the Ciuc Basin, in front of the passages through

Fig. 15.6 Aerial photo of the Malnaș-Băi-Füvenyestető archaeological site (*Photo credit*: Zoltán Czajlik, ELTE, Institute of Archaeological Sciences, 2010)

the Carpathian Mountains, or the Vápa-vára at the entrance to the Tușnad Gorge indicate that they may have played a role in controlling trade routes passing through those areas. Based on the location and density of the settlements in an increasingly diverse geographical setting, we can assume that the peoples of the painted pottery culture significantly shaped their environment.

The Copper Age can be characterised by the richness of material culture. The most common finds of this period are the various, beautifully decorated pieces of pottery. Pots were formed by hand, or with the help of some rudimentary potter's wheel. After drying, but before firing, vessels were decorated with mineral dyes (e.g. iron oxide, limestone, jacobsite, magnetite) (Figs. 15.8 and 15.9). Anthropomorphic (Fig. 15.7) and zoomorphic clay figurines are considered to be religious artefacts (Monah 1997; Sztáncsuj 2009a). Copper Age cultures left behind a large number of agricultural and artisan tools such as loom weights, and spindle-whorls. These were made of clay, knapped or polished stone, bone, or antlers. High-quality, rare, raw materials such as obsidian, Prut and Volhynian flint, marble, or special seashells (e.g. Spondylus) were of exceptional value. Copper Age societies developed long-distance, exchange-type trading relations to ensure the supply of these materials. During the second half of the 5th millennium BC, metal working emerged and started to flourish. With this, the exploitation of Transylvanian ore deposits began. Weapons, tools, such as axe-adzes and hammer axes, and various jewellery, such as beads and pendants, and other ornaments were made from the copper collected on the surface or mined underground (Mareș 2002). Gold objects representing higher social ranking also appeared during this period (Sztáncsuj 2005). Finds of animal bones and agricultural implements reveal increasingly diverse farming and animal husbandry. In addition to the previously bred sheep and goats, a higher proportion of cattle and pigs is also present.

Fig. 15.7 Clay goddess figurine. Ariușd Group (Ariușd-Tyiszk-hegy). Collections of the Székely National Museum

During the Late Copper Age, from the middle of the 4th millennium to the beginning of the 3rd millennium, the evolving and flourishing economic, social, and spiritual development came to sudden end. Detailed explanation for this decline has not yet been offered, but it is likely that both ethnic changes and environmental transformations contributed to it. The timespan of the Late Copper Age coincided with the beginning of the Subboreal era, that was characterised by a cooler, wetter climate than before. This transformation can also be seen in the archaeological finds of the Coțofeni Culture typical of this region (Méder 2004). The lifestyle of these people changed. Animal husbandry and herding surpassed farming. Because of this, people built their settlements on higher terraces and used them for shorter periods of time. The number of seasonal settlements also increased significantly, that indicates the mobility of these communities. In the vicinity of the Ciomadul region, artefacts were found from the sites of Malnaș-Băi-Füvenyestető, Bixad-Vápa-vára, Sânzieni (Kézdiszentlélek)-Köszörükő, Leliceni (Csíkszentlélek)-Kőhegy and Păuleni-Várdomb. Evidence of seasonal settlements are also present in the caves

Fig. 15.8 Clay pots from the Early Copper Age. **a–h** Ariuşd Group (Ariuşd-Tyiszk-hegy, Malnaş-Băi-Füvenyestető, Olteni, Bixad-Vápa-vára)

Fig. 15.9 Painted bowl from the Ariușd Group (Ariușd-Tyiszk-hegy). Collections of the Székely National Museum

and ravines of the Vârghiș Gorge (Párkány, Orbán Balázs Cave, Átjáró Cave, etc.). The archaeological remains of the Coțofeni Culture are relatively poor: most of the finds consist of their characteristic pots (Fig. 15.10) and a few stone and bone objects. Metal finds are particularly rare. Compared to the previous era, the material culture is poorer, however, certain types of objects already bear the first signs of advent of a next major era, the Bronze Age (Figs. 15.11, 15.12, 15.13, 15.14 and 15.15).

15.4 The Bronze Age (3rd–1st Millennium BC)

The social and economic transformations that began in the Late Copper Age became increasingly pronounced during the Early Bronze Age. A well-differentiated layer of societal leaders can be identified by their architecture of both every day and burial site construction. The early Bronze Age of south-eastern Transylvania is characterised by the Schneckenberg Culture, named after the site at Schneckenberg by Brașov (Brassó). The distribution area of the early Schneckenberg Culture is concentrated in today's Brașov Basin, while to the north, in the Ciuc Basin, the Jigodin Group can be identified, which developed in parallel with the later Schneckenberg B phase (Székely 1997). The settlements of the early phase—Schneckenberg A—were open and situated on flood-free areas or on terraces, (Sânzieni-Polyvár, Zăbala/Zabola-Tatárhalom), but several fortified highland settlements are also known (Sânzieni-Perkő, Sfântu Gheorghe/Sepsiszentgyörgy-Őrkő; Székely 1997; Sztáncsuj 2009b). Pottery is characterised by a wide variety of shapes. Pots and bowls are decorated with simple or finger printed ribs arranged in one or more vertical or horizontal rows, pasted lens ornamentation, knobs, and incised lines (Fig. 15.17a, b). The first rare examples of the cord-impressed ornamentation appeared during this time, which became a characteristic motif of the later Schneckenberg B-Jigodin period. Most of the artefacts from the Ciuc Basin were found

Fig. 15.10 Jar with plastic ornamentation. Coțofeni Culture (Reci-Telek). Collections of the Székely National Museum

Fig. 15.11 View of the burial mound of Ariușd on the Baraolt Mountain ridge. *Photo credit*: Zoltán Czajlik, ELTE, Institute of Archaeological Sciences, 2010

on higher elevations (Leliceni-Kőhegy, Jigodin/Csíkzsögöd-Csereoldal etc.; Roman et al. 1992). These settlements, often fortified with ditches and ramparts, may have been the centres of a smaller region. This is indicated by the uniqueness of the finds, such as the moulds used to make axes, or stone knives. The distribution of the finds suggests ongoing relationships with the eastern and southern regions of the Carpathians. These eastern contacts resulted in the appearance of the Costișa-Ciomortan Culture on both sides of the Carpathians at the end of the Early Bronze Age (Fig. 15.17c).

Early Bronze Age graves are characterised by skeletal burials, with bodies laid on their side in a constricted position. Burial grounds within the settlements are rare (Zăbala). Most of the burial sites are located on the terraces of streams (Sânzieni, Turia), or on hilltops (Ariușd, Biborţeni/Bibarcfalva-Kerekdomb, Eresteghin-Zádogostető, Ocland/Homoródokland-Kövesbérc). In the graves of Sânzieni and Turia, the bodies were buried in stone cists, each accompanied by two small simple vessels. If there were mounds raised above the graves they have long since disappeared, since both were found on agricultural farm land. Burial mounds built on higher elevation have survived to this day, even if in a somewhat eroded, flattened form (Fig. 15.11). At the beginning of the twentieth century, there were three mounds at Eresteghin, of which only one remains today. There were stone cists beneath the two eroded mounds, one with a skeleton in a flexed position and a corded ware vessel. The necropolis of mound-graves at Biborţeni consists of similar structures and finds. The placement of the mounds, the energy expended in labour and organisation to build them suggest that the deceased may have been prominent members, such as leaders or warriors of their community.

Metalworking of the Early Bronze Age was still limited to the use of copper or occasionally

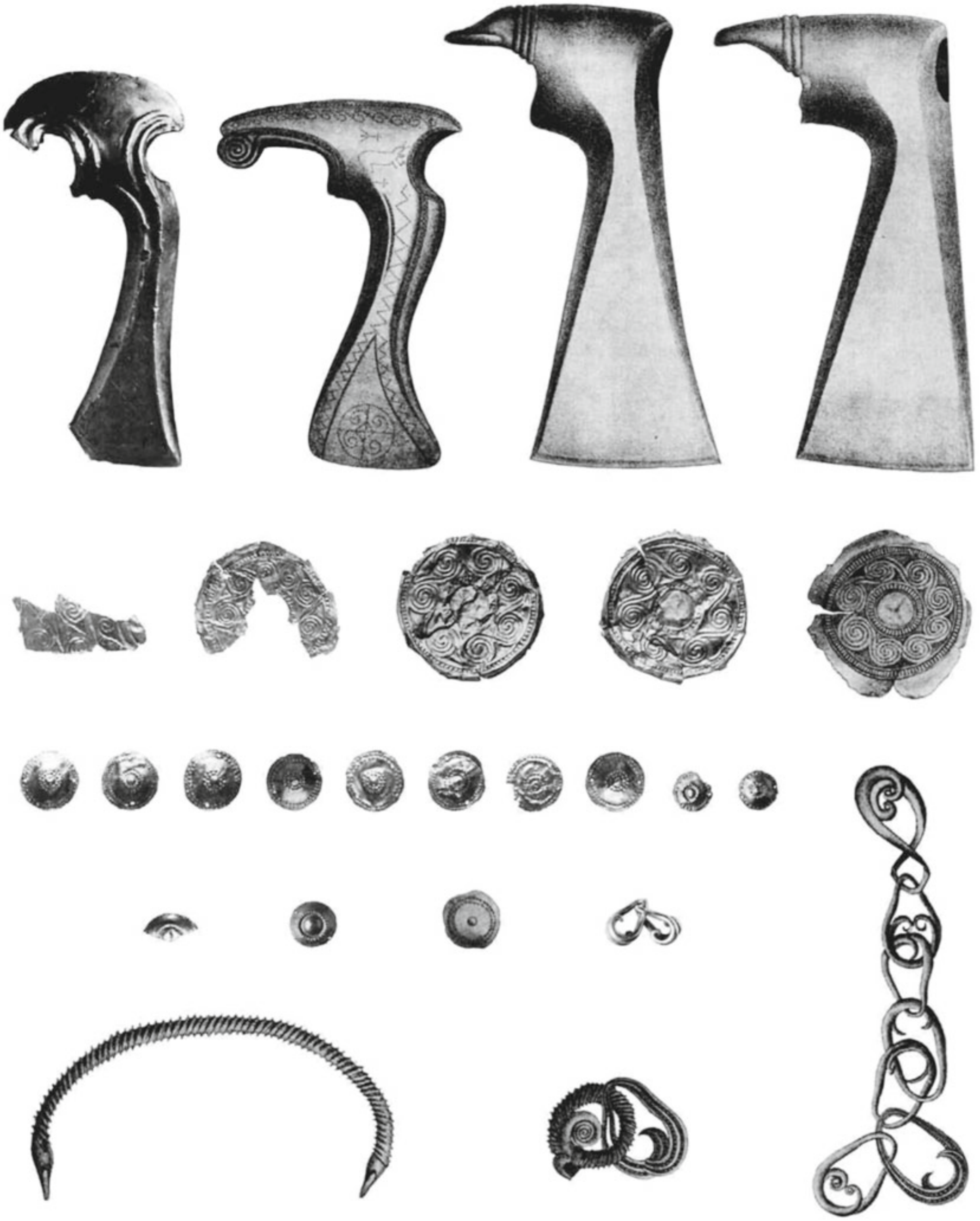

Fig. 15.12 The golden treasure of Țufalău (Cófalva). Surviving pieces of the treasure are held in the collections of the Natural History Museum, Vienna. After Carola Metzner-Nebelsick (Gedanken zur Frage des kulturellen Wandels in der Zeit um 1600 v. Chr. in Nordwest-Rumänien und Nordost-Ungarn; Landesmuseum für Vorgeschichte, Halle/Saale, 2013)

Fig. 15.13 Incised lines ornamentation on a clay vessel from the Linear Pottery Culture. Wietenberg Culture (Sfântu Gheorghe-Avasalja). Collections of the Székely National Museum

Fig. 15.14 Bowl with lobed edge and lime insert ornamentation. Wietenberg Culture (Sfântu Gheorghe-Avasalja). Collections of the Székely National Museum

of precious metals, like gold or silver. The first shaft-hole axes appeared during this time and then became widespread in many different forms by the Middle Bronze Age. Their small number among archaeological finds suggests that their use and possession was tied to a narrow social stratum, and was considered not only a weapon but also a symbol of power. Since these objects are missing from the graves, it can be suspected that they were inherited after their owner's death, or perhaps were hidden as votive deposits. This could explain the distinct artefacts of two axes and two spiral bracelets found in one of the caves of the Vârghiş Gorge (Dénes and Szabó 1998).

Fig. 15.15 Kantharos type clay vessel. Noua Culture (Zoltan-Oldalramenő). Collections of the Székely National Museum

The middle part of the Bronze Age in Transylvania is represented by the Wietenberg Culture (2000–1500 BC). The development and appearance of this culture are not yet clear, but it most likely evolved from the cultures and traditions of the Early Bronze Age, incorporating other elements as well. Research distinguishes four stages of development, based mostly on changes of pottery decoration (Chidioşan 1980; Boroffka 1994). Vessels used for everyday use, such as cooking and storage, carried functional rather than artistic characteristics. They were typically rough-shaped, rough-surfaced, and lack decorative motifs. Smaller pottery, such as cups and mugs usually had a more intricate design with smoothed or even polished surfaces. Larger pots and bowls with finer design or scalloped rims were rare (Figs. 15.13 and 15.14). Simple engraved zigzag and spiral motifs were the typical decorative elements in the early stages. Later on, more elaborate meander and spiral motifs were scratched into the surface then filled with a white substance. These designs normally covered the entire surface of the vessel.

Data on the Middle Bronze Age societies in the Ciomadul region is incomplete due to the lack of systematic research. Some observations

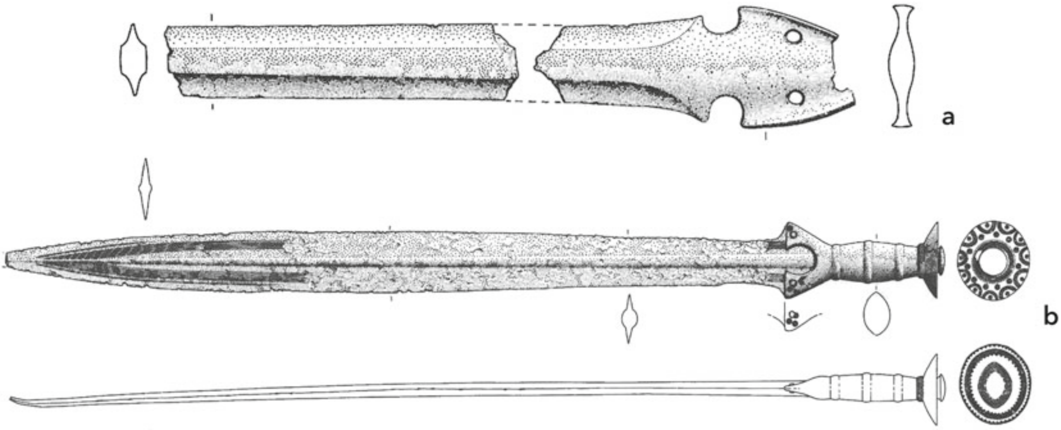

Fig. 15.16 Bronze Age swords from Southeast Transylvania. **a** Kovasna. **b** Turia. After Mircea Petrescu-Dîmbovița (Depozitele de bronzuri din România / Bronze age deposits in Romania, Ed. Acad. Rep. Soc. Romania, 1977)

still can be made from the currently available information. The social hierarchy that first appeared in the Early Bronze Age is traceable in the Middle Bronze Age as well. The number of the fortified and open farmstead-type settlements have increased, which indicates a population increase. The fortified settlements usually did not exceed 0.4 ha, and were built alongside major travel routes on the edges of the basins. Such settlements dated from this time period have not been identified so far in the Ciomadul Hills area, but there are several of them known from nearby regions (Dietrich 2010; Puskás 2018). Fortified settlements of Vápa-vára at Bixad and Torja-vára near Turia, and numerous open settlements were identified near the surrounding villages, as well as north of the Tușnad Gorge by Cozmeni, Cetățuia (Csatószeg) and Sânmartin (Csíkszentmárton). People of these settlements were in contact with regions outside of the Carpathian Mountain Range, as evidenced by numerous archaeological finds, mostly consisting of pottery (Zaharia 1990; Cavruc 1999; Puskás 2015). Researchers interpret these as result of gift exchange tied to exogamy.

Metal objects are another category of finds suggesting social stratification. During the Middle Bronze Age, items of tin-copper alloy bronze became widespread, but gold ones were not uncommon either. As this region is poor in both of these raw materials, their procurement required serious organizational efforts and contacts. Compared to the previous period, there is a much larger number of hoards (Fig. 15.12) that often contain more than twenty objects. Indication of social rank is rare in cemeteries with only a small number of graves. The remains of cremated individuals were placed in urns, placed in a pit, then covered with another vessel, or with a stone slab as well. Occasionally, smaller cups, very rarely faience beads or other bronze objects were placed beside the urns. One of the most significant Middle Bronze Age cemeteries in south-eastern Transylvania was found in Turia, where 25 graves have been excavated. There is also a recently discovered but yet unexplored cemetery on the outskirts of Țufalău (Cófalva). Other, individual graves are known from the villages of Poian (Kézdipolyán) and Sânzieni (Puskás 2018).

Evidence of agriculture are present but are rare. Taking advantage of the fertile soils, several types of cereal grains were cultivated in the region (emmer wheat, einkorn wheat and barley), as evidenced by charred seeds found in archaeological context (Cârciumaru 1996: 57–153; Dietrich 2014, Anhang 6). In addition to cereal crops, rapeseed and vetch were important food sources as well. Animal husbandry also played a significant role. Extensive floodplains and alpine meadows provided good grazing areas. Archaeozoological studies showed that cattle

Fig. 15.17 Clay vessels from the Bronze Age and Early Iron Age. **a–b** Schneckenberg Culture (Sânzieni, Zăbala-Tatárhalom). **c** Costişa-Ciomortan Culture (Peteni). **d–g** Wietenberg Culture (Sfântu Gheorghe-Avasalja, Turia). **h** Noua Culture (Sfântu Gheorghe). **i, j** Gáva Culture (Reci-Telek, Turia) **k** Scythian Culture (Sfântu Gheorghe-Árnyas Street). Collections of the Székely National Museum

were kept in the largest proportion, followed by goats, sheep, and then pigs (Boroffka 2005). The Middle Bronze Age population of the Várdomb at Păuleni, however, had goats and sheep in larger numbers as opposed to cattle or pigs. Hunting did not play a significant role as a food source as bone remains found in the settlements only rarely indicate the consumption of game. These were mostly deer and red deer, but rabbit, bear, and wild boar also occurred (Kelemen 2016).

The changes that took place in the middle of the second millennium (1500–1100 BC) left their mark on the social and economic norms of the time, not only in Transylvania, but also in the whole Carpathian Basin. Populations of the Noua Culture from the North Pontic region were moving into south-eastern Transylvania at this time, and put an end to the flourishing Wietenberg Culture. The settlements of the mobile, pastoral Noua communities were mostly located on river and major stream terraces. Their characteristic features are the so-called ash mounds at the edges of their villages. Today, they appear as light grey round or oval spots, well distinguishable from the surrounding black soil. They are typically rich in archaeological finds. Their purpose is still debated by researchers. Most probably they were pits associated with a particular trade (e.g., tanning of hides—Dietrich 2013), but in some cases ritual function cannot be ruled out either (Wittenberger 2013; Sava 2014). Compared to previous eras, the lack of fortified settlements of the Noua Culture suggests a different kind of social hierarchy, which is less evident in the archaeological material. The pottery of this period was simple both in form and decorative motifs. New type of vessels appeared: the two-handled, so-called cantharos-type pots and cups (Figs. 15.15 and 15.17h), bearing oblique or horizontal channelling. The necks of the larger pots often had either a smooth rib or a rib with finger impressions. The use of bronze items increased during this time. Axes and sickles were the most common tools, but a large number of needles and awls were also found in the settlements.

Social changes also manifested themselves in the taking care of the dead. Cremation was largely replaced by skeletal burial, where the body was buried on its back or side, mostly in a constricted position. Graves were either a simple pit, or stone-packed graves, or the burial sites contained a stone cist. Beside the bodies, the graves usually included one or more cups and/or larger pots as well (Sava 2002).

Pastoralism played an important role in the life of the Noua communities. Bone material found at Olteni (Oltszem) and Zoltan (Étfalvazoltán) indicate the type of animals kept in these communities. In Olteni, most of the remains are from sheep/goats, followed by pigs and cattle. In Zoltan, cattle were predominant, followed by pigs and sheep/goats. Cattle were kept as working animals or for their milk. There is also evidence for consuming their meat. Pigs were kept for their meat and fat, while sheep/goats for milk, wool, and meatmeat (Kelemen 2014). These findings are supported by a number of studies conducted east of the Carpathians as well (Sava 2014). Traces of crop production are poor in the region. There is only one location, Sânzieni, where a considerable amount of charred millet was found (Cârciumaru 1996: 114). Cultivation of different varieties of wheat has been documented in several other sites. Rye and barley first appeared during this period.

During the second part of the Late Bronze Age/Early Iron Age (1100–800 BC), the Gáva culture, originating from the Eastern Great Hungarian Plain, spread throughout Transylvania (Figs. 15.17i, j and 15.18). This period brought yet again a radical social and societal transformation. In addition to the lowland settlements, fortified settlements were built on higher elevations and covered several hectares. These could be considered regional centres.

On one of the north-western ridges of Ciomadul (Vf. Cetății / Vár-tető), is a fortification surrounded by earthen ramparts that has a pear shape outline. The first construction phase of this fortification started sometime during the 1100–1000 BC period. Excavations were carried out on this 5–6 ha site in the 1960s (Horedt 1976). A significant proportion of the finds were fragments of large storage containers typical of the period. In terms of their construction, they

Fig. 15.18 Storage vessel. Gáva Culture (Reci-Telek). Collections of the Székely National Museum

belong to the so-called "composite-shaped vessel" with a typical curved rim and a convex midsection. The inner surface of most of these pots, but not all of them, were fired red or brown, while the outer surface was fired black and polished to a metallic shine. Other decorative motifs of this age are rope-like channels on the necks and shoulders of the vessels. Small cups were fired black or dark grey both on their inside and outside, often were polished to a shine and were outfitted with raised handles. The simpler pieces were without ornamentation of any kind. The inside bottom surface of a few specimen has channels arranged in a star fashion.

Bronze smithing continued to become more widespread during this time. The most common bronze tools were sickles and socketed axes, that had numerous different varieties. Beside these tools, other common bronze objects were jewellery, (also made of gold), weapons like swords (Fig. 15.16) and spearheads, horse bridles and bits, and large vessels (situlae and cauldrons). The latter illustrate established contacts with other regions of Central and Northern Europe, as well as with the Northern Balkans (V. Szabó and Bálint 2016). One of the most important and valued bronze and gold treasure of this period was found near Tortoma-tető, between Tălișoara (Olasztelek) and Brăduț (Bardoc).

A considerable number of archaeological finds from this era are artefacts that are found as assemblages; they probably were hidden as part of rituals associated with the Late Bronze Age belief system. The hiding places themselves were often sites with special meanings, such as springs, fissures in cliffs, or hilltops visible from great distances (V. Szabó 2009: 123). They are also found by the gates of fortified settlements. Their occurrence within a settlement can indicate the location of a sacrificial place, or perhaps points to the site of metalsmithing workshop. In the wider area of the Ciomadul Hills, many such assemblages were discovered (e.g. Turia, Cernatul de Sus/Felsőcsernáton-Hegyes-tető, Zagon/Zágon-Cseremás, Zagon-Mete-hegy). Vf. Cetății in Băile Tușnad also yielded such materials when four ribbed bronze bracelets were found near a spring on the north-western part of the plateau.

Farming implements and tools of animal herding are known in much smaller numbers than from the previous period. Bone material excavated at the Porumbenii Mari (Nagygalambfalva)-Várfele site belongs to cattle and pigs. Cattle was kept for its meat, milk, and was used as a draft animal as well. Horse breeding was also practiced. Horses were draft animals, but there are indications of them sometimes being ridden into raids and battles by the leaders of the communities. Because cereal grains were a basic food item, crop production shows similarities to previous ages.

15.5 The Iron Age (1st Millennium BC)

Beginning from the 10th to 9th centuries BC the use of iron tools become more widely. Until now the spread of iron smithing is hard to reconstruct. In this period iron tools appear together with bronze objects, but in a much smaller number.

Very likely the technology of iron ore smithing was an influence from the southern and/or eastern part of Europe (Hansen 2019).

During the 8th to 7th centuries BC, the eastern parts of the Carpathian Basin came under the influence of the Scythian Culture of North Pontic origin. In Transylvania, Scythians are known mainly from scattered artefacts and burial sites. One of the extremely rare Scythian finds of the Ciomadul area is a burial site in the Árnyas Street of Sfântu Gheorghe. Grave goods included typical Scythian peacock-eye beads, a bronze mount with a deer motif (Fig. 15.19) and other bronze jewellery. The famous iron sword of Dobolii de Jos (Aldoboly), can also be connected to this culture; the sword's handle is decorated with typical Scythian animal motifs (Fig. 15.20).

Peoples arriving from the east gradually merged with the local Late Iron Age population of the Carpathian Basin. Contemporary written sources also mention the Geto-Dacian ethnic groups who populated the area of Transylvania from the second half of the first millennium BC. Their settlement network was denser than settlement patterns of previous eras. The density of settlements in south-eastern Transylvania, as well as the archaeological finds excavated there (e.g., smelters and iron smithing implements), suggest that the local Dacian groups exploited the iron ore deposits of the South Harghita region.

Fig. 15.19 Bronze stamp with stag motive from the Scytian burial site of Sfântu Gheorghe. Collections of the Székely National Museum

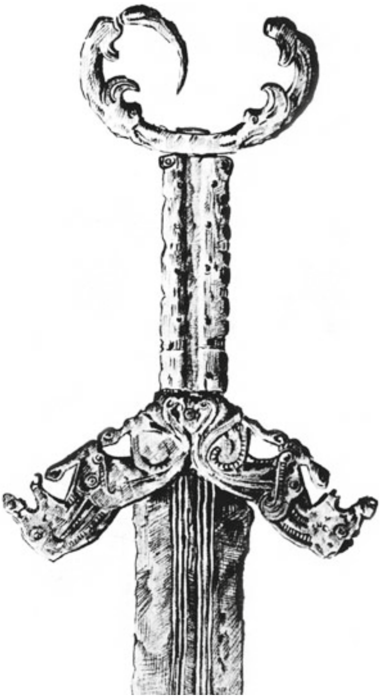

Fig. 15.20 Drawing of the Scytian sword hilt from Dobolii de Jos. After Márton Roska (The Prehistory of Transylvania, 1936)

The Dacian culture flourished from the first century BC to the first century AD (Crișan 2000). The use of iron became widespread during this time. Archaeological finds suggest a well-structured society. Their small settlements were built on river terraces or on low ridges. Typical artefacts are the rough-hewn, hand-built pots decorated with fingertip impression ribs and cams. Bowls were made on a fast potter's wheel and fired to an ash grey colour. Dacians built extensive fortifications in the mountains surrounded by either earthen or dry-stone ramparts. From there, chieftains ruled smaller regions adjacent to the fortifications. Archaeological artefacts from these sites are similar to those found on simple farming sites, but often contain more delicate objects as well. These objects are witnesses to long-distance contacts with both the Greek and Roman worlds. Masterpieces of precious metals illustrate the wealth of the local elite. Such finds are the coins from Peteni (Petőfalva) and Sfântu Gheorghe-Simeria, and the silver hoards from Sâncrăieni (Csíkszentkirály), Surcea (Szörcse) and from the recently discovered hoard from Siculeni (Madéfalva). The Roman conquest of 106 AD ended the Dacian independence in the region that Burebista had established by uniting various Dacian tribes and that had been flourishing for nearly 150 years.

15.6 Summary

In this chapter we have shown that the region closest to the extinct volcano was sparsely populated in prehistoric times. In the wider area of Southeastern Transylvania, the earliest farming communities appeared in the early Neolithic and from this period the whole area was continuously inhabited. However, most of the human settlements were established around the fertile river valleys of the Olt and Râul Negru. Archaeological and historical sources, however, suggest that with its indirect and multifaceted effects (mainly through the exploitation of natural resources attributable to post-volcanic activity), Ciomadul may have influenced the lives of prehistoric people lived in the area.

16 Migration Period and Medieval History of the Ciomadul Region

István Botár

Abstract

The wider region of Ciomadul (Csomád) Hills is a unique area of Székelyland from a variety of perspectives. It lies on the border of the historical Ciuc (Csík) and Trei Scaune (Háromszék) counties (known today as Harghita/Hargita and Covasna/Kovászna, respectively). The largest medieval fortress of Székelyland is also in this region. The landscape dominated by forests and floodplain that we see today was used and shaped by Germans of Scandinavian origin, Slavs from Eastern Europe, and Hungarians and Székelys alike. Based on archaeological finds and written sources, this chapter reviews the history of the area during the third–fifteenth centuries. However, one has to be aware that this region does not appear in any historical sources until the fourteenth century and substantial data only start to leak from the sixteenth century. At the same time the situation of the archaeological research was and still is deficient, because the Migration and Medieval Period was a neglected topic in the communist era (until 1989).

16.1 Introduction

The first millennium offers only scattered and incomplete data about the Ciomadul area. It existed on the periphery of the Roman Empire, outside Dacia, and north of the castrum of Olteni (Oltszem). (Dacia was a Roman province included within the central and south-western part of present-day Romania between 106 and 274 AD.) The Ciomadul area lays at the northern vicinity of the province, just beyond the border called at that time *limes* (defensive boundary). Archaeological finds link the abandonment of the Dacian fortifications of Ciuc with the Roman conquest, which indirectly suggests that the Roman armies may have crossed through the Tuşnad (Tusnád) Gorge during the conciliation of the areas adjacent to the empire, but their presence in the immediate vicinity of Ciomadul is not verified by Roman artefacts. Sporadic finds of Roman coins around the villages in northern Ciuc (Csíki) Basin point to the fact that the people—in our case the Free Dacians—living in the remaining settlements outside of the empire's border, continued to trade with those living within the Roman-controlled area.

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16.2 From the Visigoths to the Influx of Slavic People

During the Migration period in the 3rd to 9th century AD, the most extensive settlement network along the Olt river was created by a Germanic people of northern origin, the Goths, or as they are scientifically known, the Sântana de Mureș (Marosszentanna)—Chernyahov culture. They called themselves Tervings (forest dwellers), while their neighbours often referred to them as Visigoths. Their presence in the area can be documented between the 3rd-4th century. The Goths settled in the Ciuc area on the flood-free terraces of the river Olt, along the upper reaches of the Olt's tributaries, and on the plains along the foothills (Botár, 2001). Fragments of their characteristic pottery were found just under the surface at several spots in today's village of Cozmeni (Csíkkozmás). In the south-eastern part of the village partial remains of a potter's kiln was also revealed during trenching work for public utility lines. The Goth settlements seemed to avoid mountainous terrains. To the best of our knowledge, there is no known Gothic site in and around the Ciomadul Hills, probably because of its mountainous relief, the closest Goth settlement is known from Cozmeni about 8 km away.

According to archaeological data and written sources, Germanic people left this region towards the end of the fourth century, probably in response to Hun attacks from the east. It's possible that the Visigoths did not actually flee the Huns to run across half of Europe, but abandoned their settlements as a precaution after hearing the defeat of their Eastern brethren. There is no evidence of direct contact between the Huns and Goths in the area. The flee might have been caused by a real attack or/and panic… Interestingly, there are no signs that the Huns settled in this area. There are no settlements and cemeteries which could be connected to the Huns. This is likely due to their nomadic and equestrian nature, making travel through thick forests, bogs and forests of the Ciuc Basin difficult.

The presence of Hun ancestors, fondly mentioned in local history and alternative 'historiography' literature, has no basis. It is unnecessary to discuss this issue in our book; we only mention it here because of some speculations regarding stone carvings found on top of Vârful Cetății (Vár-tető) of Tușnad (Tusnád)—from a yet unknown time period—were interpreted as symbols of an independent Székely state from the Hun times. Whatever the meaning and relationships of the engravings on those stones might be, it is far-fetched, or even false to interpret them as proof of a Hun presence. We say this because we lack evidence for the Hun population and for a Hun state, not to mention lacking evidence for independent Székelys of the Hun era. To this date, Székelyland has no archeological traces of the Huns, there are no settlements or burial grounds (the only exception might be a new discovery in the western part of Mureș/Maros county). The reality is more prosaic and therefore less popular: after the Goths left the area at the end of the fourth century, the Ciuc Basin had been uninhabited for quite a long time.

Starting with the panic caused by the Huns around 375 AD, a large population reorganization took place in the entire Carpathian Basin. However, the Ciuc region was an exception. While a significant part of Transylvania was occupied by the Gepids during and after the Hun era, there is no clear evidence of Gepid infiltration around the source of the Olt river in the fifth and sixth centuries. This East-Germanic population arrived in Transylvania by the end of the 3rd century and after the Hun panic gradually occupied the territories left by the Goths. It is also worth mentioning that the Avar rule, consolidating in the Carpathian Basin in the 6th century, also bypassed the mountainous area, just as the Huns and Gepids stayed away from the mountains. Avars were a nomadic population of Asian origin occupied the Carpathian basin in the sixth century and possessed it until the ninth century. There are no signs indicating that the overall Avar settlement within the Carpathian Basin would have included the Ciuc area. The nearest location with scattered evidence of pottery fragments from the Avar-Slavic peoples is by Cristuru Secuiesc (Székelykeresztúr), but the easternmost confirmed Avar settlement is the Brateiu (Baráthely) location near the town of Mediaş (Medgyes).

The next, proven population of the Ciomadul area are the Slavs. Considering the context of the entire Carpathian Basin where the earliest Slavic infiltration is dated at the middle of the sixth century, their surprisingly early presence (already in the 5th or/and early 6th century) in the Ciuc area can be identified. The latest radiocarbon dating studies suggest that the first groups of Slavs might have settled here in the middle of the 5th century, with their presence well established in the sixth century (Botár 2018).

The Slav presence in the Ciomadul region needs to be examined for two reasons. Some linguistic evidence suggests that the meaning of the geographical name "Tuşnad" is of Slavic origin from the Migration Period and the word "torok" (throat, narrows) would refer to the gorge of the Olt on the southern border of Lower Ciuc Basin. These linguistic assumptions, however, do not correlate with archaeological data. We would have to presume a continuous Slavic settlement here during the 8th–12th centuries with the Slavic place names in use so that the Hungarians, settling here much later, had a chance to take those names over and continue to use them. This, however, is not the case. According to current research, there are no archaeological finds or locations in the Ciomadul region that could be connected to either early, or turn of the millennium, Slavic presence. There could be two explanations for the absence of Slavic remains. Either the Slavs were not present in the area in the 9th–11th centuries, or their presence has not yet been found by archaeologists. Although there are artefacts from the late Migration period in the area of Cernat (Csernáton) in Covasna county, the inhabitants of these settlements probably did not play a role in naming the places around Ciomadul, and especially not along the Olt valley.

We have to realize, though, that our knowledge is far from complete regarding the settlement patterns, including those of the Slavs, during the Migration Period. Ten or twenty years ago we did not have credible data either on the Goths or the Slavs in the Ciuc Basin. Thus, we can foresee that more research would lead to a clearer understanding of the population dynamics of Lower Ciuc and the Ciomadul during the 7th–11th centuries.

Data available today are scattered and contradictory in nature. Pollen analysis and radiocarbon dating of sediments from Lake Sf. Ana show signs of intensive forests clearing near the lake around the turn of the first millennium. The only problem is that there is no corresponding archaeological-demographic record supporting this deforestation; that is, we do not know whether there was a significant population increase at this time due to new settlements or by other means. The nearest inhabited place is the Fortress of Vârful Cetăţii, about 2.5 km away. Human presence at this location after the Iron Age, however, was pointed out only from the thirteenth century (see more on this later). Even if some of the settlement names still in use today in the Ciomadul area—like Tuşnad or Kászon (Caşin in Romanian)—seem to be of Slavic origin, archaeological data is not available or cannot yet support this hypothesis.

For this reason, we lean towards including the Slav namesakes more as the first settlers of the Hungarian Kingdom rather than those arriving here before the Hungarians and the Székelys, and who continued to live here in the 9th–11th centuries and beyond as Slav communities. We have no reason to think that the first representatives of the Hungarian Kingdom arriving here from the west in the 11th–12th centuries would have been exclusively Hungarians. Archaeological data from the late Migration period in Transylvania and Székelyland show that before and after the establishment of the Hungarian Kingdom there was a considerable Slavic population in the area in addition to the Hungarian-speaking communities. Thus, it might be plausible to think that the Slavic place names in the basins of the Eastern Carpathians are not (only) related to an earlier Slavic base population, but represent the toponymical legacy of linguistically—or ethnically—diverse settlers and border guards of the eastern frontiers of the Hungarian Kingdom in the 11th–12th centuries.

16.3 Castles and Private Estates of the 13th–14th Centuries

Whatever the origin of the toponyms in the Ciomadul Region the period between the Migration Period and the thirteenth century is only superficially known. The earliest written sources which mention this region are from the fourteenth century. At the same time the archaeological research of the area was relatively limited in the previous decades.

As a cautionary note we have to mention that current information is sparse regarding this time period, since there have not been any archaeological explorations in the Lower Ciuc villages closest to the Ciomadul such as Lăzărești (Lázárfalva), Tușnad (Tusnád), Vrabia (Csíkverebes). On the basis of finds by the nearby Cașinu Nou (Kászonújfalva) it is almost certain that there have been settlements in the area starting from the end of the eleventh century, and perhaps the pass of Pasul Cașin (Nyerges-tető, the pass which connects the Ciuc and Cașin basins is about 10 km from the Csomád region) was also used at that time. Pots and clay kettles of the archaeological collection from Cașinu Nou bear archaic decorations which is mostly absent after the middle of the 12th century on artefacts from the settlements of Transylvania (Fig. 16.1). If there were any Árpád-era settlements (in the Hungarian historiography the 10th-13th centuries are called Árpád-era after the ruling dinasty) in the locked-in periphery avoided by roads and far away from the regional centres even within the remote Cașin Basin, then it is would be possible to expect contemporary villages around the Ciomadul, in the area of today's Cozmeni, Tușnad, and Lăzărești. Exploratory field data already indicated this presence. The soil in the backyard gardens of today’s village of Cozmeni yielded a number of 11th–12th century pottery fragments which have become even more broken up by centuries’ worth of soil cultivation.

Written sources from the Árpád era do not mention the Ciomadul Hills region. Our earliest written documents date from the beginning of the fourteenth century. They reveal the existence of several land holdings, including castles and villages owned by noble families of Székely origin, in the border region of Ciuc and Trei Scaune counties. These villages lay in the area surrounding the Ciomadul, to the south was Jimbor (Zsombor), Gerebencs, Malnaș (Málnás) and Olteni (Oltszem), to the east Lower Turia (Altorja), Upper Turia (Feltorja), Alvolál, Felvolál, Canta (Kanta), Petriceni (Kézdikővár) and Valea Seacă (Kézdiszárazpatak). These villages belonged to the estates of the noble families Mikó and Apor, who also owned private fortresses like Vápa, Piatra Șoimilor (Sólyomkő) and Cetatea Balvanyos (Bálványosvár). The earliest artefacts from these fortresses, recovered

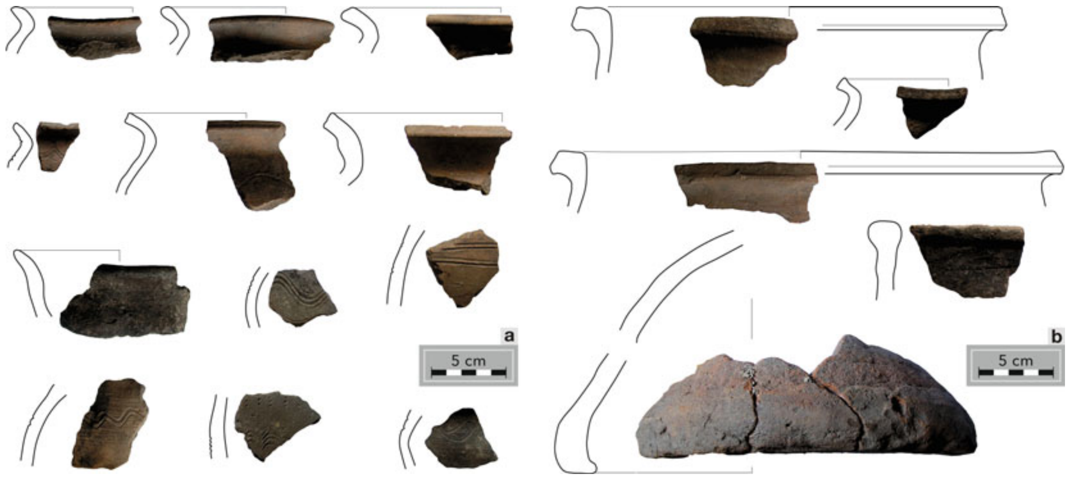

Fig. 16.1 Fragments of clay vessels from Cașinu Nou (Kászonujfalu) (Botár 2019)

in 1976–1977 date back to the 13th century. Based on the archaeological material, pottery fragments, the he fortresses were probably in use in the 13th–14th centuries.

The Ciomadul region appears in the historical sources due to these families (Mikó and Apor) which had quite large possessions in the region. Border survey notes from the year 1349 mention the villages Zsombor and Gerebencs, south of the Ciomadul. These notes were quoted in Chap. 1 chronicling the history of scientific discovery of this region. The two settlements, Zsombor and Gerebencs, were abandoned and have vanished by the Middle Ages. They possibly lay on the alluvial plains of the Olt river, south of the Tușnad Gorge, along the creeks that preserve their names to this day. The landowner Mikó family, together with the representatives of their neighbouring villages, surveyed the boundaries of family's estate, describing on the northern part places like *Bezedmezew, Toberch, Kuzberch* and *Bydushyg*. Of these, Bezedmezew/Beszédmező (in present-day Hungarian language) can be sited within the area of today's Băile Tușnad (Tusnádfürdő). From there, the border surveyors made their way east to Toberch/Tóbérc near Lake Sf. Ana; touched on Kuzberch/Közbérc, which probably marks the common border area of several villages; then on to Bydushyg/Büdöshegy (Stinky Hill) near Balvanyos; and finally turned southwest, reaching the Olt river valley again. The described territory lays within the Ciomadul Region.

This border survey is of particular interest in several aspects. There is little written data in Székelyland about similar surveys. The Mikó family's record survived probably only because it was a land holding within county administration wedged between Székely lands. This means at the same time that the Ciomadul Hills as a enclave were part of the Fehér county and did not belong to the Székelyland. This document, however, indicates that during the fourteenth century the same administrative processes were in use on the eastern frontiers in Transylvania as in the western, more central parts of the Hungarian Kingdom. The formation of Székelyland in the 13th century therefore cannot be construed as an uncontrolled immigration or emigration of groups of people, but it was a conscious and legally organized settlement process of that time period.

A large number of the place names recorded in the boundary survey have survived to this day (again, 'Büdöshegy', 'Tóbérc', 'Beszédmező', etc.) and can be ascertained not only in the case of settlements, but also in the case of peripheral geographical names. Continuity in the use of names can or must be expected also in the case of locations outside of the villages, like in the case of mountain peaks or streams. This is very important if we consider that most of the names of the Eastern Székely settlements are first mentioned in written sources only in the sixteenth century. If, on the other hand, we can prove that the Middle Age names of these farther places and locations have survived for centuries even to this day, it is most probable that this may be especially true in the case of the continuously inhabited settlements. It is certainly not a coincidence that the name of the mountain itself, 'Csomád' in Hungarian, can most likely be derived from an Árpád era personal name, 'Csoma'. He must have been a important personality in the Árpád-era although his existence is only a presumption based on theetymology and origin of the place name Csomád.

In addition to the Mikó family's lands immediately south of the Ciomadul Hills in the county of Küküllő ("*in districtu de Kukullew*" = Târnava river), András, son of Udvar, a Székely from Kézd Region, also had land holdings there, called "*Thorya et Reketyasuelge*" (Turia/Torja, and Valea Răchițele/Rekettyésvölgye), and "Ramacha". These were sold to the Apor family in 1307. The family of Apor inherited another estate, Valea Seacă (Szárazpatak) in 1311. This is backed by archaeological discoveries in Turia. The best preserved and most spectacular medieval fortress of this region, Balvanyos, was built by the Apor family sometime in the first part of the fourteenth century. The main feature of the fortress, still imposing as ruins today, was the Old Tower which was surrounded by several other buildings within the defense walls. Contemporary documents reveal that the Apors brought in a large number of settler families, Ruthens among them, to the villages of Valea Seacă and Turia. Another document from 1324 shows that as an attempt to remedy a seemingly unjust distribution of plots, the number of settler families was a hundred in Valea Seacă and more than 250 in Turia (Rácz 2006).

At the same time, north of Ciomadul, at the feet of the mountain, on the southern edge of Lower Ciuc and/or in the Cașin basins, another landowner (whose name had been lost) had two estates: Lok and Kászon (Cașin). The latter can most likely be equated with the Cașin Basin, or parts of it. Based only on certain historical legal property matters and on particular aspects of its social system, Lok is suspected to have included Lăzărești (Lázárfalva), Tușnad, Vrabia (Csíkverebes) and perhaps even Cozmeni (Csíkkozmás). All that is known about these estates is that they were privately owned, and since the owner died without an heir, the land returned to the king. Contrary to his original intentions, the king was not successful donating the estates to the Apor family in 1324. He was prevented from doing so by twelve noble land owners from the surrounding villages of Ciuc. Opposing the royal decree, and lead by their lieutenant named László, they appeared at the ceremony where the new owner was to be installed on the land. Officials from the Transylvanian 'káptalan' (cathedral chapter) attempted three times to install the new owner and to survey the estate's borders by land measurements. The Ciuc land owners were summoned before the king. The donation of the lands in question, Lok and Kászon, was opposed by the Székely people of Ciuc, because they considered them to be their own property. However, they were not able (or perhaps did not want to) to prove this with either a witness or a certificate, so they did not even appear before the king's tribunal. Despite this, it appears that eventually they were able to acquire these lands, since the two place names, Lok and Kászon, have never been included among the estates of the Apor family.

Thus, from sometime after 1324, the private estates north of Ciomadul belonged to the Székelys of Ciuc. Of these estates, Kazun/Kasim (Cașin), already appeared on the papal tithe registers of 1333–1334, while Lok, at least under this name, cannot be found any longer. It is interesting, however, that sixteenth century sources call the villagers of Lăzărești and Vrabia —north of Ciomadul—as "lakségi", according to the custom of calling people living in that particular county. It is also striking that, as the author of this chapter has shown (Botár 2012), there were neither 'lófő' (primipilus, higher social rank of the Székelys) nor free Székelys in these villages, i.e., their social system and status was different from that of the average Székely villages. Therefore, it is possible that the area of these southern villages is the same as the Lok of the former private estate, which was not in Székelyland proper. This probably also explains the fact that the southern villages of Lower Ciuc held common, undivided lands until the Modern age (Fig. 16.2).

Based on sources available to us from the first half of the fourteenth century, the area around Ciomadul was in private hands at that time and it was not a part of Székelyland. We do not know when these private estates were established. It is certainly not a coincidence that in the centre of this area is the fortress of Vf. Cetății (Vár-tető) of Tușnad. There was not only an early Iron Age fortress on this mountain (see this chapter) but also a medieval one that was built of stone and incorporated the ramparts of the earlier fortification. This fortress is the largest medieval castle in all of Székelyland, which in itself suggests that it may have played a significant role in its time. Without any written data and poor archaeological research (a few trenches opened and unpublished since the'60-es) only the dimensions and location (exactly in the middle of the reconstructed possession, see above) suggest that the fortress could have played a important role in the regions 12th-14th century history.

Kurt Horedt, whose main interest was the prehistory of the stronghold, carried out excavations in the fortress area in the 1960s (Horedt, 1976). He considered the remains of the medieval buildings and archaeological finds as by-products of his work (Fig. 16.3), because the

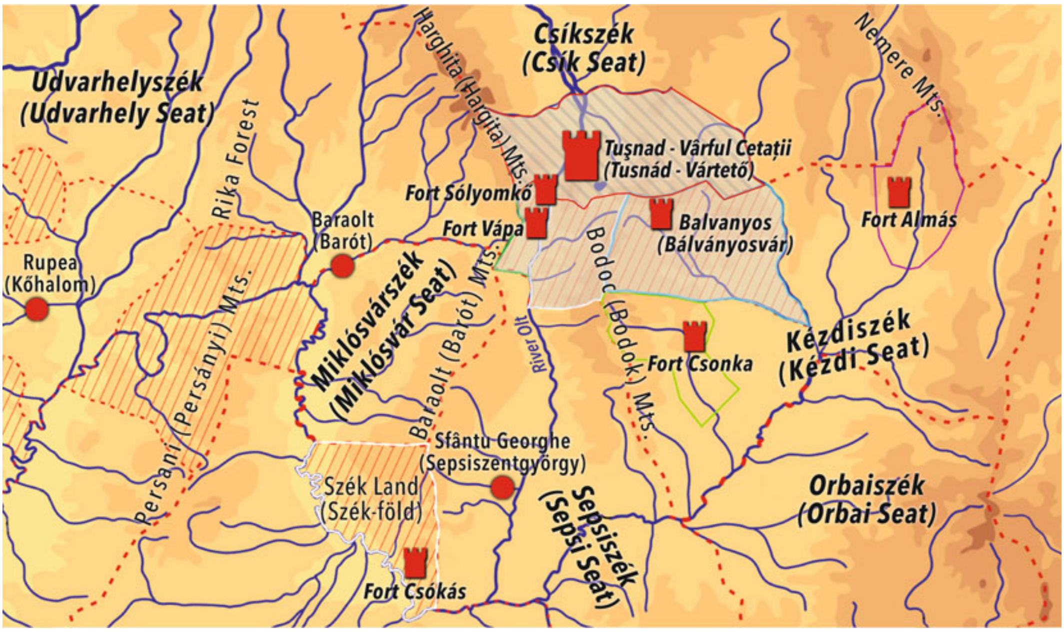

Fig. 16.2 Extent of the presumed Árpád era royal (?) land holdings around the Ciomadul area. Some of today's settlement names are also indicated (Botár 2019 based on Bordi Zsigmond Lóránd: 13-14. századi magánvárak Kovászna megyében. In: Tanulmányok a székelység középkori és fejedelemség kori történelméből, 115–148, 2012)

Fig. 16.3 Aerial photo of the fortress of Vf. Cetăţii (Vár-tető) of Tuşnad (Tusnád) (*Photo credit* Zoltán Czajlik 2012)

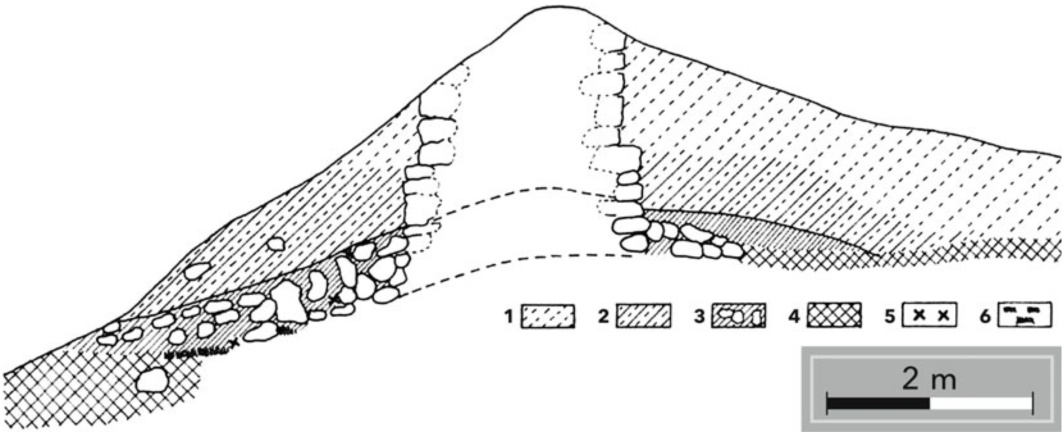

Fig. 16.4 Vertical profile of the wall of the fortress of Vf. Cetății of Tușnad. Legend: 1—filler soil with wall debris, 2—backfilled foundations, 3—Late Bronze Age stone wall, 4—natural soil, 5—Late Bronze Age sherds, 6—charcoal (from Horedt 1976)

mortared stone walls of the medieval castle were built on top of the ruins of the prehistoric fortification (Fig. 16.4). Horedt did not publish separately on the medieval finds because they were not the focus of his research, so, unfortunately, they escaped the attention of scholars studying medieval history. Some of the finds were sent to the museum in Miercurea Ciuc (Csíkszereda), but their exact provenance is unfortunately lost. So, more than half a century later it came to light that in addition to the early Iron Age artefacts, Horedt also excavated several medieval pit-houses. This means that the fortress of Vf. Cetății of Tușnad, unlike most other castles in Székelyland, was inhabited for a longer time period (in the majority of the castles of Székelyland the total absence or paltry quantity of the archaeological material presumes only a short time and temporary presence of the owners). Horedt considered the finds to be from the late Middle Ages, from the 14th–15th centuries. However, most of the pot fragments seem to be from the thirteenth century (Fig. 16.5). Reliable data, proper documentation, and especially new excavations would allow for telling a more exact medieval history of the castle. Instead, we only have morsels of information as of today. The earliest finds from the fortress also suggest the existence of nearby villages, namely Tușnad, Lăzărești and Vrabia since the primary condition for building a fortress of that size was sufficient labour being available in the immediate area.

The medieval fortress was built at the end of the Árpád era. Due to its huge size we can be almost certain that it was built not only by local initiative and from local resources. Lacking written sources, it can only be assumed that it may have been the centre of a larger (royal?) estate that included the Ciomadul Hills and its surroundings. The use of the fortress and the community life within its walls can be dated to the thirteenth century. The youngest known finds are from after the Tartar invasion (1241–1242 AD), so we can presume that the fortress was abandoned around that time. The reason for this is unclear. Several factors could have been playing a role: the Tartar invasion, the Székelys settling in the area, bequest of the area, social or other changes. In any case, it is certain that the fortress lost all its significance, so much so that even its name was forgotten, the place name "Fortress Hill" only indicates that the locals knew that there was once a fort up on the hill (Fig. 16.6).

A large royal estate—with fortress of Vf. Cetății of Tușnad being its administrative centre, and Cozmeni its parish centre—had been divided into several, but at least into three parts at the end

Fig. 16.5 13th century artefacts from the fortress of Vf. Cetății of Tușnad (Botár 2019)

of the thirteenth century. These parts then were donated to families of Székely origin living in the area. One of the most striking remains of these private estates is the Cetatea (fortress) of Balvanyos (Bálványosvár), owned by the Apor family for centuries (Fig. 16.7). These villages, towns, and other areas donated to the Székely families, however, retained their original county administration, did not become part of "Székelyland", but continued to be private estates of the receiving families. Accordingly, people living in those areas were not considered Székelys either. The linguistic research of Antal Horger and János Erdélyi in the early twentieth century (Horger 1905) also alerted to this possibility, pointing out that the dialect of the villages around the Ciomadul differs significantly from those of the neighbouring, truly Székely villages.

16.4 Summary

Looking through the Ciomadul Region's history in the 3rd-16th centuries, we have to admit that our knowledge is limited. The hills themselves were not inhabited in the Migration Period, the settlements remained at the lower plain surfaces around it. Archaeological sites show that the area was surely part of the Visigoths's kingdom (3rd–4th century) and after a hiatus the early Slavs settled in the region (5-seventh century). It is yet unclear what happened between the 8th–11th century; from the 11th–12th century the presence of the first Medieval (Székely) settlers and border guards of the Hungarian Kingdom can be documented by archaeological finds. Historical documents do not mention this region till the 14th century, therefore the only sources regarding the period remain the archaeological data and place names. The early Medieval centre in the Ciomadul region seems to be a large stone-walled fortress above Tuşsnad, called Vf. Cetății (Vártető). This presumes on one hand the contemporary existence of more villages around the Ciomadul Hills, and a well-organised political structure on the other. Based on later written data, the Ciomadul Region was part of the Fehér county and this background has to be accepted for the non-mentioned 12th–13th centuries also. The fortress was abandoned after the 14th century probably because the originally bigger royal (?) estate was divided and donated to the Mikó

Fig. 16.6 Floor plan of fortress of Vf. Cetății of Tușnad (based on Botár 2019). Highest point is 1079 m, contour lines 2 m

Fig. 16.7 Old Tower of Cetatea Balvanyos (Bálványosvár) (*Photo* Csaba Jánosi)

and Apor families, which then built new and better accessible family castles. These properties preserved the Medieval organisation structure, so the Ciomadul region remained a county enclave inside Székelyland until the 19th century.

17

Landscape History, Land Use, and Tourism of the Ciomadul–Balvanyos Region

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and Péter Szmolka

Abstract

It was in the middle of the 1990s when the formation of the Ciomadul–Balvanyos (Csomád-Bálványos) Region came to be. The region includes five neighbouring settlements; Lăzărești (Lázárfalva), Tușnad (Tusnád), Băile Tușnad (Tusnádfürdő), Bixad (Sepsibükszád) and Turia (Torja), which are all related to the range of hills dominating the region, but which had been developed and managed independently. The region has a rich heritage of local, national and also European significance. In the past centuries, people living here made their living from farming determined by the landscape characteristics. However, it has been a long story from the ancient times and the "fire-breathing dragon" living inside the hill, through the medieval legends including the one about the origin of the crater lake Saint Anne (Sf. Ana/Szent Anna), to the chapel built on the shore of the lake and the related pilgrimages, and finally to the tourism development and utilisation of the natural springs and mofettas in the modern age. The last chapter of our book provides an overview about landscape history and development, and the tourism in the past and present days of this outstanding region of Europe.

17.1 Introduction

Topography and climatic conditions determine the basic characteristics of all landscapes. The layers of subsequent geological periods and their transformations provide the basic surface features of the landscape, "a system of gestures" which the flora and fauna adapts to. Humans also seek the conditions for their being and the resources for their living within this framework, determining the use of the landscape. Csomád Hills, with Lake Saint Anne (Sf Ana/Szent Anna) in one of their twin craters and Mohos peat bog with open surfaces of deep colour glimmering water and unique plant species in the other, has raised the curiosity and overwhelmed people since the beginning of times. For thousands of years, the mystical location has been an integral part of the life of people living here. In the beginning, fear and respect governed their relation to this volcanic landscape, while later they started to admire and gradually discover its natural beauties, and finally live in harmony with them.

The diverse natural characteristics of the Carpathian Basin are the foundation of colourful

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cultural landscapes, determining local cultures, land use, knowledge, art, traditions, and a harmonic relationship to the landscape based on the intrinsic social order of communities living here. This concept has been most concisely defined by the internationally renowned landscape architect, Mihály Mőcsényi (1919–2017), who said, "… *landscape is humanised nature, human environment transformed from biosphere to noosphere according to human needs… (that is) cultivated and humanised nature*". Landscape is not merely a creation of nature, but also of humans, a living organism developed through the interaction of nature and humans, which exists in the process of continuous change and transformation. We are all born in a specific landscape, which provides the basis of our relationship to life. And vice versa, landscape is an open book that describes the relationship of people to the environment in a specific period. Analysing the historic development and actual status of a landscape, the trends of the changes, we are able to depict the life of a location.

Philosophers, artists and scientists seek the answer on how to elucidate the concept of the spirit of the place, the genius loci. Researching the history of landscapes, we can observe that every single place has specific "contents", and thus our relation to them also varies. Man accentuates, highlights, sanctifies certain places in a specific landscape, by the means of rituals, legends, customs, tales and regulations. He is seeking for protection, continuity, and that is how he relates to the heritage passed through generations. Citing the words of Zoltán Szabó, Baumgarten Prize-winner writer: "*…landscapes teach us to love and to respect each other*" (Szabó 1999).

The basis of the European culture is the cultural landscape of Europe, the beau ideal of European landscape, the designation of which is a topic of both the charters on monument conservation and the European Landscape Convention. The "ancient landscape" of Europe had been transformed under the impact of the Christian impulse since long ago. With the advance of deforestation and drainage, increasing areas of land had been converted into arable land, meadows, pastures, vineyards, and orchards. The church was the focal point of the medieval village, with the houses and the belts of vegetable gardens, arable land, meadows, pastures and woodlands arranged all around, according to the specific natural environment. This archetype of the landscape reflects the sometime harmony between man and the landscape. That is why, as tourists, we are always seeking and admiring such places, perceiving the invisible relationship that connects the landscape to man and the local communities who cultivate and manage it. The recognition of this ancient ideal provides the basis of the incomparable attractiveness of Székely Land and the Ciomadul Region even nowadays.

17.2 Landscape History of the Ciomadul–Balvanyos Region

The area of Ciomadul (Csomád) Hills has been inhabited since the Palaeolithic. This is proven by the archaeological findings from the Palaeolithic and Neolithic Periods and the Bronze and Iron Ages, such as napped tools, cut animal bones, and pottery (see Chap. 15). Place names that are still in use refer to a continuous colonisation of the region by Slavic, Pecheneg, Oghuz, Hungarian and Székely tribes. The area had an important strategic location, characterised by significant north–south and east–west through-traffic. However, after the Székely colonisation, no additional nomad tribes appeared. The ancient Székely constitution was based on democratic organisation and their military organisation reflect an advanced culture. The peaks of the forest region and the narrow mountain passes of River Olt represent a natural system of forts, important for defence against invaders. Earth and stone forts introduced in the previous chapters were built upon these peaks, such as Fort Balvanyos (Bálványosvár) that was owned by the Apor family in most of its history (Gaali 1938). The settlements of the region have different histories. Some of them were freehold Székely villages, some the property of the Hungarian royal court or aristocrats. While the Székely villages had regulated and managed their properties on their own, the use of the royal and noble properties was based on feudal tenure. The cultivation of agricultural land started around the villages that were located at the feet of the hills, while grazing of animals and forestry also played a significant role. Mineral resources of the region had been discovered long ago, the early start of brimstone, alum and iron mining is reflected by place names such as Bányász pataka (Miner's Creek). Lower Turia (Altorja) is described as miners' village with marketplace privileges in the medieval times (Endes 2004). Changes in the landscape are possible to observe on the three ordnance survey maps prepared between 1763 and 1887 for the Habsburg Empire. With an increasing precision, the maps also depict land uses.

17.2.1 1st Ordnance Survey (1763–1787)

On the first ordnance survey map (Fig. 17.1), central areas of the Ciomadul-Balvanyos Region are fully covered by forest. Around the settlements at the northern feet of the Ciomadul Hills and also around the villages to the southeast that constitute Turia (Torja) today, arable fields, meadows and pastures appear. Meadows were located alongside the River Olt and the creeks, while the pastures at the feet of the hills. Arable land stretches in between the two. The layout of the freehold Székely settlements had a kind of clustered pattern. The decimal units of the pattern originate from the military units of border defense. In return for the freehold status, the Székelys were obliged to provide military service to the King of Hungary. The decimal pattern that

Fig. 17.1 The Ciomadul Region as showns on the 1st Ordnance Survey Map (1763–1787)

is possible to observe in the case of Tuşnad (Tusnád) and also of other villages, appears as separate units of settlement, which had also relevance in preventing fire disasters endangering the wooden architecture. An example is the five villages constituting Turia, which are still separate today. Bixad (Sepsibükszád) is not an ancient village, it was developed around the glassworks established by the Mikes family. It is already present on the map, but is still surrounded by dense forest. Lake Sf. Ana was also depicted by the cartographers, while Fort Balvanyos is marked already as a ruin. Only a group of springs are shown at the place where Băile Tuşnad (Tusnádfürdő) exists today. The layout of the roads was different from that of nowadays. The major routes include Târgu Secuiesc (Sepsiszentgyörgy)—Malnaş (Málnás)—Tuşnad, Miercurea Ciuc (Csíkszereda)—Cozmaş (Kozmás), Lăzăreşti (Lázárfalva)—Turia (with side-roads towards Puturosu (Büdös, meaning Stinky) Hill and Balvanyos), Cozmaş—Nyerges peak—Casin (Kászon), which was accessible also from Lăzăreşti.

17.2.2 2nd Ordnance Survey (1819–1869)

The Ciomadul Region was mapped in the last period of the survey (Fig. 17.2), since Băile Tuşnad that exists from 1842 is shown already as a large settlement. Compared to the first survey, agricultural activity had grown through the decrease of forests. Arable land, meadows, and pastures also increased around the villages. Deforestation in the northern part of Cioamdul Hills is noticeable, while towards Turia it is only the creek valleys where woodlands had been substituted by meadows and pastures. Arable land had been extended towards the plains. Clearances scatter the homogeneous forest as pastures with summer lodges, mainly alongside the Lăzăreşti–Balvanyos–Turia route, at Câmpul Capelei (Kápolnamező), around Stinky Hill, in the valley of River Olt, and around the Turia villages alongside Turia and Almás Creeks, and along the ridge of Csíkbérce. Bixad shows the most dynamic growth and development. The forest had been cleared all around due to the demand of the glassworks for beech wood, and arable land and meadows replaced the woodlands. The Szeretszeg quarter of Tuşnad disappeared from the map. According to written records it was devastated by fire, and relocated west from Tuşnad, under the name of Tuşnad Nou (Újtusnád). Lăzăreşti had grown towards north since the previous mapping. Alsóvolál, Felsővolál and Karatna, former units of today's Turia, had coalesced. Upper Turia (Feltorja) and Lower Turia had also been extended towards each other. The growth of the villages demonstrates that deforestation and growth of agricultural areas had increased the carrying capacity of the region, and the population grew. Embraced by woodlands at the Tuşnad Straits, Băile Tuşnad appeared as a new settlement. The map also shows two ruins and several crucifixes at Lake Sf. Ana. Mohos peat bog is displayed as Bedienku Meadow, while Fort Bálványosvár is marked as a ruin. The map also includes several mineral springs, a group of springs at Băile Tuşnad, the springs of Vallató and Hammas (under the name of Ascenbecher) along Büdös Creek, and the saline and carbonated springs of Câmpul Sărat (Sósmező, Saler Quelle). The sulphur cave on Stinky Hill is also marked. The quartz mill of Bixad is displayed as a pebble crusher, and a glass polishing mill is also shown on the map. The hierarchy of the routes was changed, the Bixad–Malnaş–Tuşnad road passes through Bixad, and the Bixad–Turia route becomes more important. Both the old and new roads are displayed at Băile Tuşnad.

17.2.3 3rd Ordnance Survey (1869–1887)

By this time, forest areas had further decreased and become more segmented (Fig. 17.3). Several pastures with summer lodges and outlying gardens are present. Villages keep on growing along with the refinement of the grain of the landscape. Turia villages are coalesced almost according to their status today. Tuşnad had extended towards the north. The advance of Băile Tuşnad to a spa

Fig. 17.2 The Ciomadul Region as shown on the 2nd Ordnance Survey Map (1819–1869)

town is illustrated also by the display of the promenade. A chapel and crucifixes are shown at Lake Sf. Ana, while Mohos peat bog also appears as a lake. Regarding ruined forts, the map displays Balvanyos, Vârful Cetăţii (Vártető) and Piatra Şcimilor (Alsó Sólyomkő). From the springs and baths, Hammas, Vallató, Timsós Bath, the bath and sulphur cave in Turia, Nádas Bath and the springs of Pokol Valley appear. The section of River Olt between Tușnad and Nyírkert dűlő was regulated. The number of mills was further increased. Regarding routes, the one connecting Lăzăreşti–Balvanyos–Turia had lost its importance. The Târgu Secuiesc–Malnaş–Bixad–Băile Tușnad–Tușnad and the Bixad–Turia routes play the most important role. The appearance of the railways brought a great change to the region.

The three ordnance surveys obviously illustrate the growing human influence on the landscape. By the end of the nineteenth century the change of land use had reached its natural limit, since the relatively severe climatic and soil conditions constrained the carrying capacity of the region. The feudal property management and freehold farming methods remained mostly unchanged, and thus imposed limits to growth. In 1892, regulation of River Olt was planned in order to increase arable land, based on public funds. The meandering river regularly flooded the adjacent villages and land, although the large floodplain was a potential resource to increase arable land. However, the river regulation did not achieve the expected results. The riverbed of the Olt had cut itself deeper, and decreasing water levels resulted in drought and change of the soils

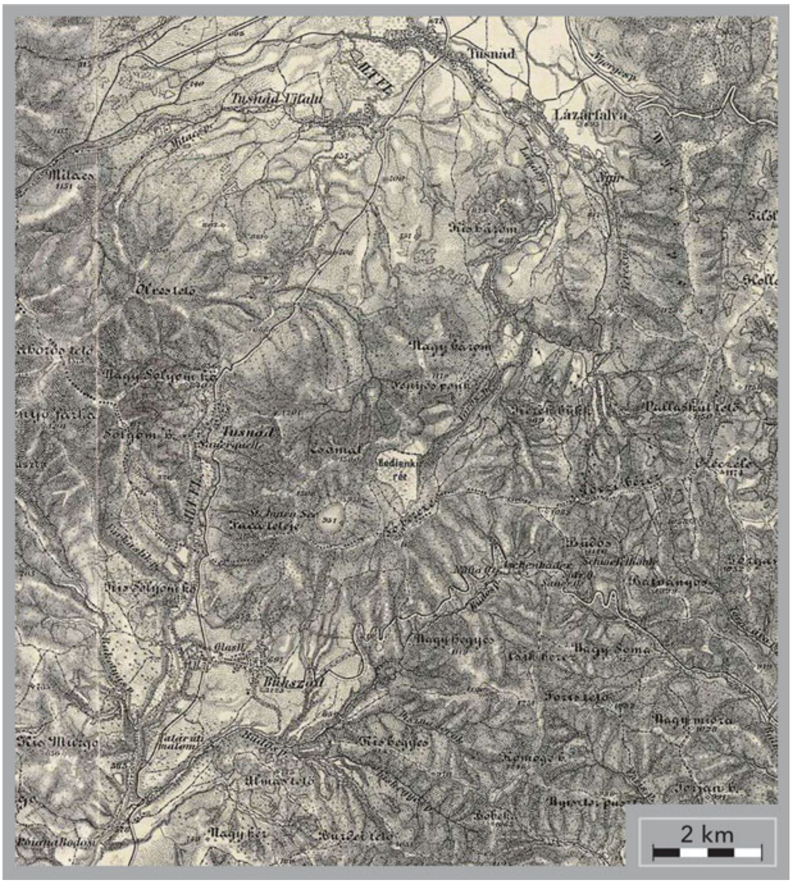

Fig. 17.3 The Ciomadul Region as shown on the Third Ordnance Survey Map (1869–1887)

of the adjacent areas. Around Turia, however, where climatic and soil conditions are more favourable, production of cabbage, millet and lentil was significant, Ciuc (Csík) areas were suitable for growing only a limited range of crops. The first written record of the appearance of potato is related to Tuşnad from 1800, and since then it has been a main crop of the area. Livestock farming had a significant role, evidenced by meadows and pastures appearing at increasing distances from the villages, and the number of summer lodges with pastures was increasing alongside them.

17.2.4 Twentieth Century Land Use

Regarding land use in the end of the nineteenth and the beginning of the twentieth centuries, the primary sources of living for the population were farming, livestock production, and forestry, occasionally supplemented by mining and industrial activities. Due to difficulties in the supply of raw materials and the distribution of the products, the glassworks of Bixad did not survive (Balogh 1995). No significant industrial activity appeared, primarily because of the late appearance of the railways in the region. Although the realisation of the circular Székely railways could have advanced the development, by the end of the nineteenth century the significant disadvantages were not possible to compensate, and there was no significant capital investment into the region. At the same time, along with the traditional spas, the medical springs and mofettes (natural carbon-dioxide emanations) resulting from post-volcanic activities became the destinations of middle-class spa tourism from the mid-nineteenth century (see Chap. 8). Periods of the development, decline and recovery of the spas have always had a great impact on the economy of the villages (Cserey et al. 1997).

The landscape history of the Ciomadul Region has shown that the traditional agricultural activity of the Székelys could not develop further in the twentieth century. Industry did not develop due to the lack of capital, and spas were far away from the European circulation of spa visitors. The limited carrying capacity of the land led to impoverishment and a wave of migration, mostly to America. It was due to the recognition of this crisis that the Székely Congress was organised in Băile Tuşnad in the summer of 1902 (Ferenczes 2001). Similarly to development strategies of nowadays, realities and problems were taken into account, and complex solutions covering all aspects of life were searched for. The reconsidered development projects and the positive visions were broken by the First World War, however. As a result of the Trianon Treaty, Transylvania had become part of Romania, and the new political and administrative system of the region made the realisation of the development initiatives impossible. The Second World War and its consequences, the policy of the Romanian communist government and the nationalisation of properties, had ultimately changed the prospects of this region inhabited by Hungarians. Except for the spas, no development took place in the region, which has contributed though to the conservation of the heritage and the preservation of the identity of the Hungarian minority till nowadays (Fig. 17.4).

Fig. 17.4 The people living in the villages of the Ciomadul area still try to preserve their traditions and culture. Perhaps the most important elements of the traditional houses are the Székely Gates. These gates usually have two round arched entrances: one is the large gate, through which carts can pass, and the pedestrian or small gate, where people pass. Gates are never exactly the same, but they do not deviate from the traditional carving style (*Photos* Ágnes Herczeg, Csaba Jánosi)

17.3 Human and Historical Features in the Ciomadul-Balvanyos Region

The architectural, landscape and cultural heritage of the settlements in the region are the fundamentals of tourist attractions and at the same time the hubs of facilities, accommodation and hospitality services (Vofkori 2004).

17.3.1 Băile Tuşnad (Tusnádfürdő)

Băile Tuşnad, established by the municipalities of Tuşnad, Vrabia (Csíkverebes), Cozmeni and Lăzăreşti) became a separate holiday resort in 1842 (see Chap. 8). The settlement welcomes tens of thousands of tourists who wish to have a holiday and restore their health in one of the 5 hotels and 20 boarding-houses. The weeklong Summer Open University and Youth Camp of Tusványos is held annually here with several thousands of participants. The 3 medical centres of the settlement provide treatment for different health problems affecting the joints, the heart and cardiovascular, digestive, endocrine and nervous systems and the urinary tract. The treatments include electrotherapy, underwater jogging, massage therapy, special exercise therapy, mofette, and thermotherapy. For relaxation and holiday activities there are 3 spa and wellness centres with several services: water pools of different temperatures, Finnish and infra saunas, relaxation massage, salt chamber and steam cabin. Those who like active vacations can take a hike to Sólyomkő (Hawk's Rock), to Apor Tower, or to Vf. Cetăţii (Vár-tető, meaning Fort Peak), or can try zorbing, rafting or kayaking on the River Olt, as well as archery, downhill roller, mountain biking, mountain cart or skiver on the slopes of Csomád Hills or can even take a paragliding tandem flight and admire the region's natural beauties from above. Less frequented places on the hill can be visited by four-wheel drive vehicle mountain tours (Ranger ATV), and visitors can also have a zip-line slide above Ciucas (Csukás/Pike) Lake. Winter sport fans can find pleasure in skiing, snowboarding, snow kayaking, snow doughnut sliding or skating.

17.3.2 Lăzăreşti (Lázárfalva)

The first written record of the settlement dates back to 1365. Its name originates from the founder Lázár family. Later it was inherited by the Béldi, Petki and Apor families, who resettled serfs here to cultivate the land. Lake Sf. Ana and Mohos peat bog also belong to the municipality, and can be accessed on a dirt road from the centre. The inhabitants of Lăzăreşti used to be famous for their stone carving skills, what is demonstrated by several carved stone crosses, stone houses and support stones of gates (Fig. 17.5). The little village lives on agriculture, but more and more people are engaged in agri-tourism providing various services. In summer horse carriage tours, in winter horse pulled sledge tours depart from here to the hills. Beside the numerous mineral water springs, the most well-known is Nyírfürdő (Birch Bath), long ago called Fortyogó (Boiling Pot). Its healing effect had been already recorded in 1600. It was revitalised by the Bath and Community Building Volunteer Movement in Székely Land in 2002. Since then it is a beloved place to visit by those who want to restore their health. The water which is rich in rare minerals collects in a little wooden basin. Its application in combination with the mofette is used in the local treatment of joint and cardiovascular issues.

17.3.3 Cozmeni (Csíkkozmás)

One of the remarkable settlements of the Lower Ciuc (Alcsík) Basin was first mentioned in written records in the papal tithe list from 1332. Cozmeni is famous for its written village law from 1608. Its most representative building is the 15th-century Catholic Church, which is surrounded by a stone wall and is a listed cultural heritage asset. The

Fig. 17.5 In Lăzăreşti (Lázárfalva), Tuşnad (Tusnád) and Tuşnad Nou (Újtusnád, founded in 1822 after the great fire of Tuşnad), the row of gates, gardens and houses carved into the relatively soft volcanic stone are spectacular and timeless. (The stone is dacite lava rock quarried commonly at the nearby Haramul Mic/Kis-Haram hill.) The painted lions, trees of life, tulips, deer and oak leaves of the naive stone carvers stand out against the grey surface (*Photos* Csaba Jánosi)

village museum is in a traditional peasant's house built in 1883, and provides an insight into the life of a one-time Székely village.

17.3.4 Tuşnad (Tusnád)

The settlement is located in the southern corner of the Lower Ciuc Basin, in the so called Élő-gödör (Living Pit), and it is the largest potato seed-producing place in the country (Fig. 17.6). The first known record (1800) of cultivating the Ciuc "pityóka" (potato) is related to here. The village is also known as a centre of mineral springs. It is rich in mineral water springs and a plant bottling the mineral water can also be found here. In the centre of the village of Tuşnad, along the main road, the first museum of mineral waters in Székelyland was established in a yurt-shaped building by the Bath and Community Building Volunteer Movement in Székely Land and the Ars Topia Foundation from Budapest. It displays

Fig. 17.6 Tuşnad (Tusnád) village, with Ciomadul in the background. Located in the ditch of the Tusnád or Veres stream at an altitude of 672 m, it is the largest potato seed-producing village in the country, with typical land use in its vicinity. The main routes bypass the centre of the village, so travellers can drink in peace the water of its mineral water well… (*Photo* Csaba Jánosi)

the history of drinking and bathing culture in Székely Land, and the landscape and natural values of the region. Horseback riding, carriage rides, sledging, and hiking tours are among the tourist services of the village.

17.3.5 Bixad (Sepsibükszád)

The settlement (Fig. 17.7.) developed to a village from the glass furnaces of the Mikó and Mikes families. Some of the furnace products manufactured before 1914 are on display in one of the halls of the Mikes Hunting Castle (that is a school today). Once standing above Bixad, Fort Vápa was built on the site of a prehistoric settlement in the Middle Ages. Piatra Şcimilor is the place of another fortification and it is a lavish lookout point to the Tuşnad Gorge at the River Olt. A hiking trail leads from the settlement up to the crater edge of Lake Sf. Ana. The people of Bixad are proud of their quality mineral waters, their first bath was built in the 1800s. The Mikes Baths from those times can still be enjoyed today (see Chap. 8).

17.3.6 Băile Balvanyos (Bálványosfürdő)

A holiday resort located in one of the most romantic places in Székely Land. It got its name from Fort Balvanyos that rises above the spa and is believed to have been a shelter for the last idol-worshipping pagan Hungarians. Some historians date the former border defence fort from the eleventh century, others from the 14th. Băile Bálványos was born from the merger of three

Fig. 17.7 Bixad (Sepsibükkszád): view to the south (*Photo* Csaba Jánosi)

former bathing places, including the Stinky Bath of Turia, the Csiszár Bath established by Dénes Csiszár in 1895, and the Várpadi Bath (formerly Transylvania Bath, see details in Chap. 8). In the winter, as part of an event, the tradition of pig-sticking ritual is also revived. Next to the Stinky Cave, the Kárpát Hotel was built in 1910 and transformed into a respiratory nursing centre in 1939. It was closed in the mid-1970s and reopened in 1985 as Hotel Carpaţi. Today it welcomes visitors as the 4-star Grand Hotel Balvanyos (or Balvanyos Resort: Chap. 8) with accommodation capacity for more than 250 people. The main tourist facilities and services include outdoor and indoor pools, saunas, steam bath, massage room, three restaurants, adventure park with slopes of different difficulty, zip-line slides, wall climbing, fitness room, walking, chariot/sleigh and off-road tours, bear watching, mini animal farm, conferences, events, fine art workshops.

17.4 Curation of the Ciomadul–Balvanyos Region

17.4.1 Post-communist Conservancy

In the period before the collapse of the communist government in 1989 the region had the imprint of a top-down policy and agricultural management system, which were ignorant of local traditions and led to the aging of the population and decline of the villages. The elimination of local self-organisation and the detachment of the sources of livelihood for families from their place of living resulted in a slow erosion of traditional way of living. As a consequence, communities that had been in coexistence with the landscape for long, gradually lost their harmonious connection with nature. Signs of these changes were possible to detect in farming, in the condition of natural values and, particularly after 1989, in the emergence of environmental problems. The political turn and opening of 1989 laid the grounds for the idea of value-based development which has called into life also the concept of the Ciomadul–Balvanyos Region. The Csík (Ciuc) Association for Hiking and Nature Conservation, under the leadership of the geologist Csaba Jánosi, has been surveying and researching the natural heritage of the volcanic landscape of Csomád for decades. In 1995, Pagony Landscape Architect Studio (Ágnes Herczeg, Gábor Szűcs) and Axis Architect Studio (Zsolt Tusnády, Ferenc Salamin) from Budapest joined the surveys and strategic planning. Commissioned by Harghita (Hargita) and Covaşna (Kovászna) Counties, based on academic research and surveys addressing each professional fields affected, and with local participation, the Development Strategy for the Ciomadul–Balvanyos Region had been prepared as a result of a two-year project work. This was the basis for the establishment of the microregion that was among the first of its kind in Romania (Herczeg et al. 1999). Borders of the region have not been defined according to geographical or administrative boundaries, but by taking into account the central role of the most prominent landscape feature, that is, the volcanic hills of Ciomadul, and its catchment area with the surrounding settlements. Both historically and presently, the settlements are all related to this unique natural heritage. By the means of the joint forces of the settlements in the microregion, heritage conservation and a value-based utilisation of the landscape resource would become feasible.

17.4.2 Natural Features of the Ciomadul–Balvanyos Region

The most prominent natural values are of volcanic origin. Here, we summarise main characteristics presented in detail in specific chapters of the book.

Due to post-volcanic activities, this region is unique for the general presence of mineral waters and mofettes, and the historical and modern baths based on them, which represent a long historic tradition and are of local and also country-level importance, as well as for the impressive number of mineral water bottling plants and the Europe-famous group of sulphurous caves on the slopes of Stinky (Puturosu/Büdös) Hill of Turia. It is here you can find Lake Sf. Ana, the only closed crater lake in Eastern Central Europe and one of the lakes with the clearest water on Earth, fed only by rain. Due to the geological and meteorological conditions the region is characterised by a great variety of plant communities abundant in species. The region also includes one of the southernmost peatlands in Europe, which is rich in ice age relict plant species. These provide habitat for a rich and diverse fauna.

The landscape, architectural and cultural heritage is outstanding, too. The Tuşnad Gorge of the Olt Valley with the adjacent group of characteristic, varied volcanic cones of Ciomadul is unique in its kind. Elements of traditional agriculture preserved to date, traditions of crop farming, livestock farming, forestry, hunting, and artifacts of mining and industry all fit the landscape character. The region is immensely rich in prehistoric archaeological sites. Besides the early medieval castles and churches, vernacular architectural heritage of the villages is also remarkable (Fig. 17.8). The architectural and garden heritage of both vernacular and civic bathing cultures is notable as well as the historical heritage of tourism that appeared in the region at an early stage. The area has also memorial sites of important historic events. Scholars took notice of the values of the region quite early, thus specialised research produced on the subject is also remarkable. The ethnographic heritage includes living traditions in the villages, artifacts of traditional way of living and customs, feasts, crafts, and gastronomy, which all contribute to the complexity of the unique landscape heritage. Besides recording all available data and heritage, the most remarkable outcome of the development strategy for the Ciomadul–Balvanyos Region was the foundation of the Bath and Community Building Volunteer Movement in Székelyland.

It had become evident that the most significant natural value in the region was the high number of hot springs and mofettes resulting

Fig. 17.8 The Roman Chatolic Church of Tuşnad. The neo-Baroque church was built between 1802 and 1824 on the site of an Árpád-era chapel, in honour of Saint Francis of Assisi (*Photo* Csaba Jánosi)

from post-volcanic activities. The sight of abandoned and long forgotten rural springs and bathing spots, and the unfortunate state of ruined civic baths and villas had inspired the rescue this unparalleled heritage. The very first project took place in the summer of 2001 to renovate the rural bath in Lăzăreşti. It was organised by the Csík Association for Hiking and Nature Conservation, Pagony Landscape Architect Studio, and Ars Topia Foundation which keeps on organising similar projects to date. Through voluntary community work, with the participation of local residents and seventy volunteer students from Hungary, we had a pool, a mofette, a changing cabin, benches and other useful structures built within ten days. The first camp launched a movement, still active today, the participants of which have renovated historic or created new rural baths and cleaned springs at about thirty different sites within the Carpathian Basin, in Hungary, Transylvania (Romania), former Upper Hungary (Slovakia) and Vojvodina (Serbia), and have delivered or listened to lectures on heritage conservation, landscape, and community (Herczeg et al. 2017) (Fig. 17.9).

17.4.3 Forestry

In the Ciomadul Region, traditionally, forests and pastures were common property, with joint ownership. Although forestry has always been significant, its processing industry has not developed. Regarding forests, their protective function, especially within the area of the twin craters, has been and still remains primary, thus the purposes of the interventions (tree cutting) were mostly for forest health and conservation. Forests in the Ciomadul Region are submountain and mountain beech forests and mixed mountain beech and coniferous forests (Fig. 17.10). The main natural forest ecosystem in the area is *European beech with Oxalis-Dentaria-Asperula* flora, according to the Romanian Forest Ecosystem Types Classification, and *91V0 Dacian beech forests* (*Symphyto-Fagion*) according to the Natura 2000 classification (also see Chap. 13).

The age structure of the forests is imbalanced, main species include European beech, northern spruce, silver fir, birch, aspen, and scots pine. The ratio of artificial forest regeneration was

Fig. 17.9 Plan of Nádasfürdő/ Nádas Baths (Tuşnad/-Tusnád): the formerly popular baths, from which the bath water was transported to the neighbouring villages in tubs and drops, were renovated in 2002. The participants of the adventure cleaned up the two pools of the plant, covered the Nádas and Palló "wine waters", built a filagoria, an eco-toilet and a camping site (*Graphics*: Edvárd Takács, Ars Topia Foundation)

Fig. 17.10 The rims of the craters of Lake Sf. Ana (Szent Anna) and Mohoş (Mohos) peat bog are covered with coniferous forests. Winter landscape with Mohoş in the background (*Photo* Levente Dósa)

relatively high, appearing as spruce plantations. Spruce forests are usually middle age, while beech and silver fir have mostly old populations. Forests in the area of Sf. Ana and Mohos craters have also an important impact on local climate. They reduce the daily minimum and maximum temperatures and the wind speed, increase the humidity of the air with transpiration and thus reduce the evaporation of water surfaces, especially Lake Sf. Ana.

17.4.4 Highlights of the Twin Craters

Lake Sf. Ana is the most enigmatic and most wonderful site of the volcanic landscape of Ciomadul, with its legends lost in the mists of time and stories of the centuries long pilgrimages. It is a task of nowadays and also for the future to build knowledge of its past, and to research, explore and preserve it. The "discovery" of the lake from the touristic perspective is related to the foundation of Băile Tuşnad in 1842 (see Chap. 8). This small spa town soon started to attract tourists in every season of the year, who were keen to pay a visit to the lake.

As a highlight of the volcanic landscape, the silent, dark colour water of Lake Sf. Ana offers an idyllic scenery in calm weather (Fig. 17.11). The Hungarian writer Jókai described the view as follows: "*Three thousand feet above sea level, in a basin formed by the surrounding thousand-two-hundred feet peeks, in the shadow of wild forests expands a round shape, sublime tarn, with its perimeter measuring over a quarter of a mile. Its smooth, mirror plate-like surface is of dark green colour as it reflects the tree covered peeks, and not even the strongest storm whips up the surface, not a single foam turns up. The overlooking side of the surrounding crags are covered with turkey oak and beech, while huge pines rise around the lakeside, enclosing the metal-like water plate in a dark frame.*" Indeed, the water surface is usually smooth, no wave or ripple can be observed. However, in case of stormy weather, not only higher up around the peeks but also at the lakeside, gales arise producing half a meter tall waves. Strong gusts often bring down sizeable trees, possibly even clearing parts of the forest, and it may also happen that falling trees end up in the lake where they float until touching ground near the shore. In earlier times, people who ventured a visit to the lake believed these trunks to be remnants of a shipwreck, masts or other parts, hence attest the legend that the remnants in the lake (called "eye of the sea" in Hungarian) are parts of ships once sunk in the seas.

In Székelyland, and thus in the Ciomadul Region, too, devastating storms arrive mostly from the east. When this happens, weather turns harsh quickly without, and a vast amount of rain could fall in a very short time. In the Middle Ages, the furious weather upon the hill and the tempests descending from there was attributed to the enigmatic lake by people living in the neighbouring basin. This might have been the reason for building two chapels on the lakeside during the past centuries, in order to protect their families and communities. One for Saint Anne, patron saint of pregnant women, mothers, married couples, and grandparents, and another for Joachim, patron saint of joiners, coopers, and miners. The first mention of a chapel at Lake Sf. Ana can be found in a charter dated 1349. According to another record from 1562 repairs were carried out on the stone chapel built in

Fig. 17.11 Faces of Sf. Ana in different seasons (*Photo* Levente Dósa)

honour of Saint Anne. The sanctuary was rebuilt two hundred years later, by Ferenc Kozma stonemason and his sons, Ferenc and Tamás in 1764, commissioned by Péter Tompos, parisher in Cozmeni. In the following period the chapel was abandoned, but in 1860 a fortune-teller from Casin made some repairs on it. During the First World War the chapel suffered damages several times, until in 1927, when a new tourist hostel was constructed on the lakeside, it was renovated again with the help of István Rákosi, senior engineer at Sânmartin (Csíkszentmárton) Forestry. The parishes of Lăzărești and Cozmeni took care of renovation works and repair in 1948 and in 1976–1977. The last major conservation work was carried out by the parish of Lăzărești in 2007. St. Joachim's Chapel was located on the western side of the lake. It was related to the landowner, a member of the Mikes family of Bixad, for whom, a little altar had been brought here from the Franciscan Cloister in Şumuleu Ciuc (Csíksomlyó). The altar bears the mark "P. E. 1664". Probably Demeter Tusnádi and Pál Kecskés were the ones to rebuild the chapel with the consent of Baron József Antal Bajtay (1760–1772), a bishop in Transylvania. At the time when Balázs Orbán (who is famous for his travelogues) visited the site, he could not find anything but the ruins of it. In the summer of 1976, inspired by the records taken by Balázs Orbán, József Darvas-Kozma along with a few seminarians went to search for the ruins of St. Joachim's Chapel. In 1977 they found a piece of lintel of the one-time door, and identified the line of the ground walls of the chapel. In the middle of the lintel the relief of a blazing sun and the words PAX VOBIS in two rows on the right of it were chiselled exquisitely into the stone. The lintel piece was installed in the sacristy of St Anne's Chapel, but since then it has disappeared. In the past centuries, two feasts were held a year at the lakeside chapel: on the 26th of July, that is St Anne's memorial day, and on the 8th of September, the day of nativity of Virgin Mary. St Anne's Day was more popular, pilgrims arrived even from Ciuc (Csík) and Trei Scaune (Háromszék) regions. Chap. 1 of this book recounts the turbulent history of the saint's days. In the first three decades of the twentieth century the popularity of saint's days was ever growing, so that in the 1920s the number of pilgrims mounted as high as 20,000–30,000. Under the communist regime, especially in the 1980s, the feast was forbidden, therefore pilgrims and liberal university students could come together only in secret.

Due to the lack of sufficient infrastructure for visitors as well as careless behaviour, materials of human origin caused the water quality to deteriorate in the past few years, thus, since 2017, bathing and picnic on the lakeside has been suspended (Ambrus, 2018). At the same time new visiting rules were introduced. It is forbidden to enter the crater area by car, and the county road leading to the lakeside car park is closed to road traffic. Near the designated parking lot a buffet and an information point were set up, where visitors can get information and buy tickets. During summer a minibus shuttle service is provided that connects to the lake every hour. The lakeside eco-buffet offers exclusively glass bottled drinks and food packed into paper wrap, and also the traditionally prepared, charcoal baked chimney cake for visitors. Visits to Mohos peat bog are also available, but only for groups, and with a local guide. The nature trail built with boardwalk and stepping path sections is 400 m long and takes one hour to walk along. It touches two open surfaces of water which, along with their rare ice age relict bog plant species, provide an enchanting scenery.

In Sf. Ana crater, visitors can take a walk around the lake. Boating and cycling are also available. During their trip, visitors will be able to admire the beauty of the enclosed crater lake, or choose one of the several hiking trails (introduced in detail in Sect. 17.5.3) to the surrounding peaks. The twin craters of Ciomadul offer an unparalleled experience in winter as well (Fig. 17.12). Although Mohoş peat bog cannot be visited in winter, in the Sf. Ana crater a sufficient amount of snow only enhances the experience. Visitors can also reach the lake by sledge that can be rented in the saddle. The road leading to the crater actually turns into the longest toboggan run in the area. It is very rare all over the world to have a 19-acre frozen lake at the end of a toboggan run. If winter is cold enough and

Fig. 17.12 Lake Sf. Ana also offers unrivalled opportunities for winter sports for a good part of the year (*Photo* Dávid Karátson)

the ice reaches a thickness of 30–40 cm, ice skating is also available, and, in heated shelters, hot tea and mulled wine make the winter experience at Lake Sf. Ana complete.

17.5 Modern Tourism in the Ciomadul Region

17.5.1 Development of Ciomadul Tourism

Since the eighteenth century, the people living here and visitors who arrived in increasing numbers soon recognised the unrivalled beauty and healing properties of the Ciomadul landscape and the natural environment.

Hospitality bears with a particularly long tradition in the region. Medical thermal waters and gases of post-volcanic activities, which provided the basis for rural medical baths, became also a primary destination for civic bathing culture emerging in the mid-nineteenth century. The establishment of local baths and the related hospitality services made an important source of income. The start of tourism, in the modern sense of the word, dates back to the mid-nineteenth century, however an organised form of hiking, driven by the interest of acquiring a thorough knowledge of the country and aimed at landscape, natural and cultural heritage features as places to visit, had evolved already in the eighteenth century. Growing beyond expectations, from hiking to modern, organised forms of tourism, the movement required suitable infrastructure, so that the volcanic landscape of Ciomadul had appeared early on the map of tourism. Hiking trails and walking paths were designated. Visitors made a significant impact on the economic development of the region. Forms and customs of hospitality had taken shape, and the increase of tourism resulted in the development of the hotel and catering industry. A prerequisite to the survival of spas was the development of winter tourism, for which the surrounding land (varied terrain, steep slopes) and the cold local climate provided good conditions. Cross-country skiing and ice skating had deep-rooted tradition, while the facilities for downhill skiing were established later. From the second half of the nineteenth century, hunters also counted the highland area as an ideal field for their sport activity (Dávid 1941).

Nature, landscape, and cultural heritage, medical spas and hospitality are the main attractions of the area even today, and form also the basis for further development. Development of tourism, however, is possible to realise only along a strictly value-based, but also value-preserving, environmentally responsible strategy.

17.5.2 Establishment of the Ecocentre

An initiative conceived by the Pro St. Anne Association, the joint proprietorship of Lăzărești, which is the owner of the area, seeks to improve visitor services to a level appropriate for the area, and to establish the Lake Sf. Ana and Mohos peat bog Ecocentre. The purpose of the centre is to inform the visitor of the natural assets of Ciomadul Hills, to introduce volcanism, the genesis of volcanic hills and the post-volcanic activities (mineral springs, mofettes), the flora and fauna, the climatic conditions and the surface and subsoil waters. The Ecocentre may also contribute to the transfer of various skills, such as the identification of plant, mushroom and animal species, orienteering, communication and cooperation, problem solving, conflict management. The Ecocentre will consist of accommodation for researchers and the staff, an events hall and shelter for bad weather, and the related system of nature trails. The currently unused, but structurally sound, hostel will be converted into a modern visitor centre with an events hall for 45 persons at the ground floor and adjacent, partly covered terraces, which will serve for events organised for registered groups of visitors and students camping at the site. Accommodation for 10 persons on the first floor will be available for researchers and the staff of the Ecocentre.

A key element of the Lake Sf. Ana and Mohos peat bog Ecocentre will be the network of nature trails to develop at the area of the reserve and the edge of the crater. Visiting the nature trail, one can study the geology, geomorphology, flora and fauna of Ciomadul. Visitors can observe the forest, the wildlife and the plants, and get to know the edible and poisonous mushrooms. Except for the Mohoş Nature Trail, all the path network of almost 12 km will be accessible for bicycles, also by those offered to rent at the knowledge centre.

Four nature trails are planned in relation to the Ecocentre:

1. *Mohoş peat bog Nature Trail.* Owing to its ice-age relict plant species and precious wildlife, Mohos Bog is a stricly protected nature reserve, with only a small section open to visitors, while other parts are accessible by the owners, researchers and the staff only. In the beginning of the 2000s, at the area open to public, the Csík Association for Hiking and Nature Conservation established a narrow boardwalk at the first section of the path, and a stepping path made of wisps at the rest of it. The new boardwalk will be sufficiently wide with handrails all along, and viewing platforms at the open water surfaces. Along the trail, information boards and interactive tools inform the visitor about the most interesting plant species.
2. *Lake Sf. Ana Nature Trail.* The nearly 2 km trail around the lake will introduce the development of the lake and the wildlife of the crater. Boardwalks above the water surface will provide opportunity to observe the wildlife of the lake at two sections. Provision of closed system composting eco-toilets is also part of the development.
3. *Ridges of the Craters Nature Trail.* The longest future path of the reserve will be 7.9 km. Running along the ridges of the twin craters, it starts from the saddle between the craters, and getting around Mohos peat bog in the north it ascends to the edge at the

Fig. 17.13 Where the winding road reaches the south-eastern crater rim of Sf. Ana: view toward the south, with Murgul Mare (Nagy-Murgó) on the right at the back (*Photo* Levente Dósa)

northwest, passes the hilltop of Ciomadul Mare (Nagy-Csomád) and the place named Ördöglik (Devil's Hole), then passing above St Anne's Lake it ascends to Kőnyak (Stone Neck), returning to the point of departure. The route will have several points of information, and a major and three minor places for viewing (Fig. 17.13).

4. *Mohoş peat bog—Lake Sf. Ana Nature Trail*. This will include the two main features of the reserve, with a minor place of viewing, and points of information at the junctions of the trail.

17.5.3 Hiking Routes at and Around Ciomadul

The greatest tourist attraction of the region is probably hiking across Csomád Hills, which provides a diverse experience with fascinating sights and viewing places. The difficulty level of the well-marked routes (1–12, see below and in Fig. 17.14) never exceeds medium, but they challenge with height differences.

1. Băile Tuşnad (Tusnádfürdő)—Lake Sf. Ana, along Comloş ravine/Komlósárok (marked in blue). Well-developed hiking trail starting from the centre of Băile Tuşnad: Starting from Apor and Mikes Springs and running along Comloş ravine it ascends to the saddle between Ciomadul Mic (Kis-Csomád) and Ciomadul Mare (Nagy-Csomád) Hills, from where it descends to the hostel. Waymark: red cross. Duration: 2.5–3 h. Length: 6.7 km. Maximum height difference: 554 m.
2. Băile Tuşnad—Vârful Cetăţii—Lake Sf. Ana Hostel—Tóbérce—Bixad (marked in white). Recommended for those who have a good level of physical fitness (one must be able to return to Tusnádfürdő in the end). Waymark: blue stripe, Vár-tető: blue dot. Duration: 4–5 h. Length: 14 km. Maximum height difference: 560 m.
3. Vârghis (Vargyas) Creek (junction of the access road)—Mohos-puszta (meadow) — Lake Sf. Ana Hostel (marked in green). A pleasant route all year round, suitable for all age groups. Waymark: yellow triangle. Duration: 1.5–2.5 h. Length: 5.5 km. Maximum height difference: 420 m.
4. Hanul Hotarul Ciucului (Csíki Határ Fogadó/Inn)—Lake Sf. Ana—St Anne's Chapel—Lake Sf. Ana Hostel (marked in orange). Easy, pleasant route all year round without any risks. Waymark: blue cross. Duration 1.5–2.5 h. Length: 6 km. Maximum height difference: 430 m.

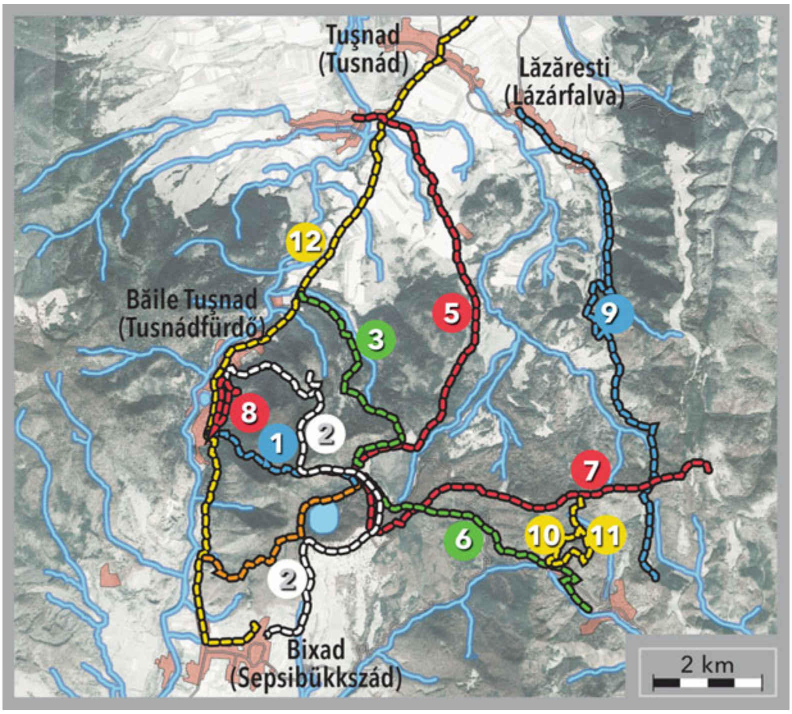

Fig. 17.14 The most important hiking routes at and around Ciomadul (see text)

5. Lake Sf. Ana Hostel—Mohos-puszta—Nádasfürdő—Tuşnad Nou (Újtusnád) railway station (marked in red). A long trail suitable for hiking all year round. Waymark: red dot. Duration: 4.5–5.5 h. Length: 14 km. Maximum height difference: 395 m.
6. Lake Sf. Ana Hostel—Best Western Hotel (Stinky Hill)—Băile Bálványos (Bálványosfürdő) (marked in green). The shortest access between Lake Sf. Ana and Balvanyos, suitable for hiking all year round. Waymark: yellow cross. Duration: 3–4 h. Length: 8.5 km. Maximum height difference: 245 m.
7. Lake Sf. Ana Hostel—Cecele Peak (marked in red). A route of medium difficulty level. Suitable also for those who want to arrive to Balvanyos or Casin (Kászon) Basins. Waymark: blue cross. Duration: 3.5–4 h. Length: 8.6 km. Maximum height difference: 210 m.
8. Băile Tuşnad—Apor Tower—Ludmilla viewing place—Băile Tuşnad (marked in red). Short, easy walk with fascinating views to the resort town. Recommended to all age groups. Waymark: red dot. Duration: 0.5–1 h. Length: 1.5 km. Maximum height difference: 68 m.
9. Cozmeni—Lăzăreşti—Câmpul Capelei (Kápolna-mező)—Fort Balvanyos. The longest trail leading from Lower Ciuc to Fort Balvanyos (marked in blue). Waymark: red cross. Duration: 5–6 h. Length: 15.5 km. Maximum height difference: 385 m.
10. Best Western Hotel (935 m)—Stinky Cave (1053 m) (marked in yellow). Recommended for all age groups all year round. Waymark: red dot. Duration: 45 min. Length: 1.5 km. Maximum height difference: 120 m.
11. Grand Hotel Balvanyos—Stinky Cave—Timsós (Alum) Cave—Madártemető (Birds Cemetery)—Gyilkos (Murder) Cave—Buffogó (Chugging) Bog—Grand Hotel Balvanyos (marked in yellow). Recommended for all age groups all year round, this route connects the most significant post volcanic features of the region. Waymark: blue dot. Duration: 2–3 h. Length: 4 km. Maximum height difference: 120 m.

12. Trail of mineral springs: Kerekeger Bath—Borsáros Bath—Sószék Bath—Museum of Mineral Springs—Sóskút Bath—Nyírfürdő (Birch) Bath—Băile Tușnad—Bixad (southern half on map, marked in yellow). Waymarking: by special waymarking signs and information boards. Duration: 8–10 h (by bicycle). Length: approximately 40 km.

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