Introduction to the Tectonic Evolution of the Southeast Carpathians

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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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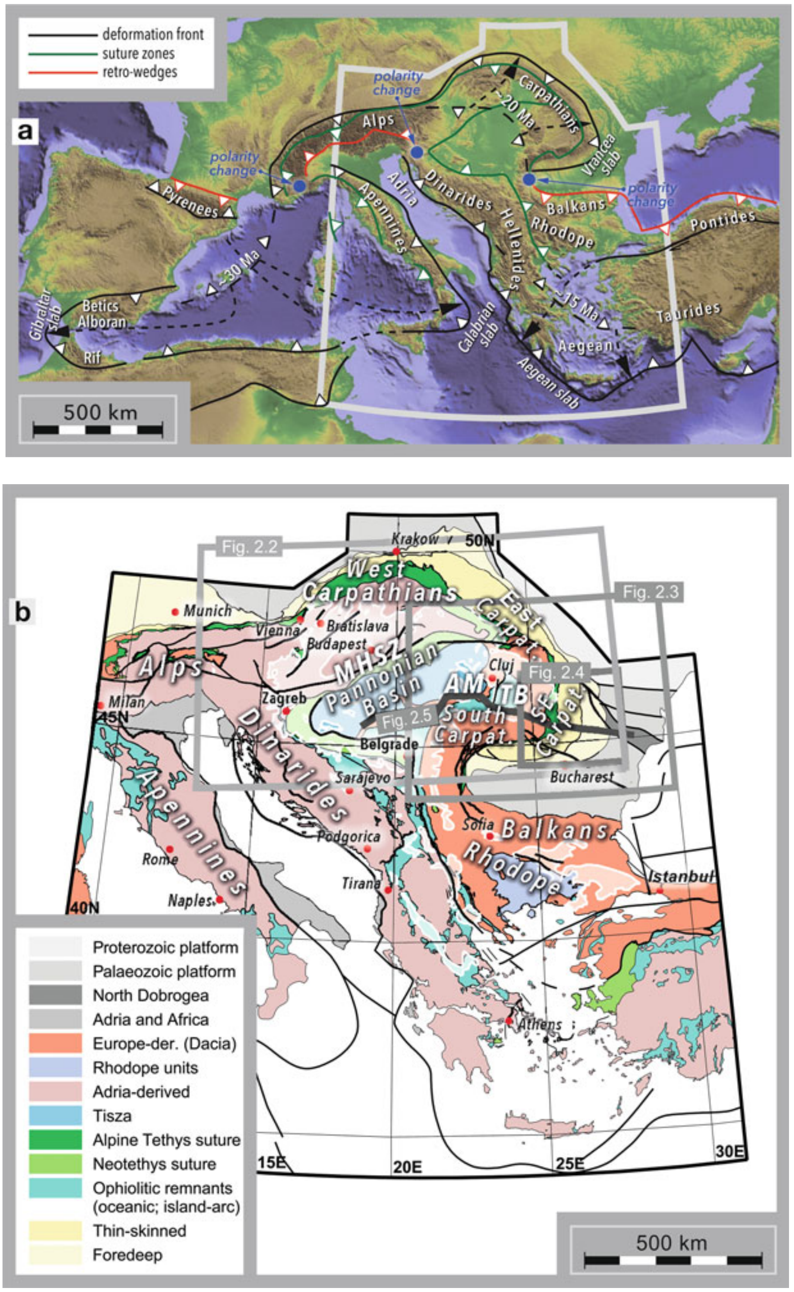

Fig. 2.1 **a** Map in the system of European Mesozoic—Cenozoic orogens. Dashed black line is the position of the orogenic front prior to the onset of extension associated with the retreat of the Calabrian, Aegean and Carpathian slabs; **b** Tectonic map of the Alpine–Carpathians–Dinaridic–Hellenidic 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

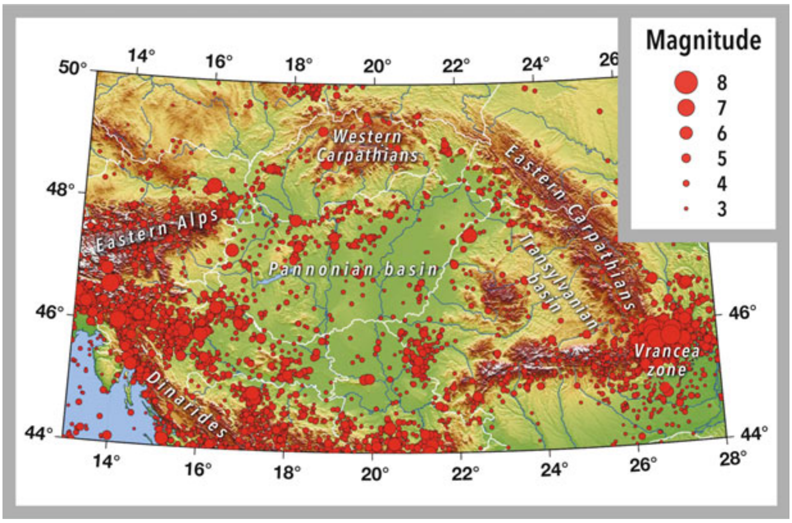

Fig. 2.2 Earthquakes with magnitude larger than 3 on the Richter scale in the Carpatho–Pannonian region occurred between the years 456 and 2015 (modified after Matenco 2018). The location of the map is displayed in Fig. 2.1a

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).

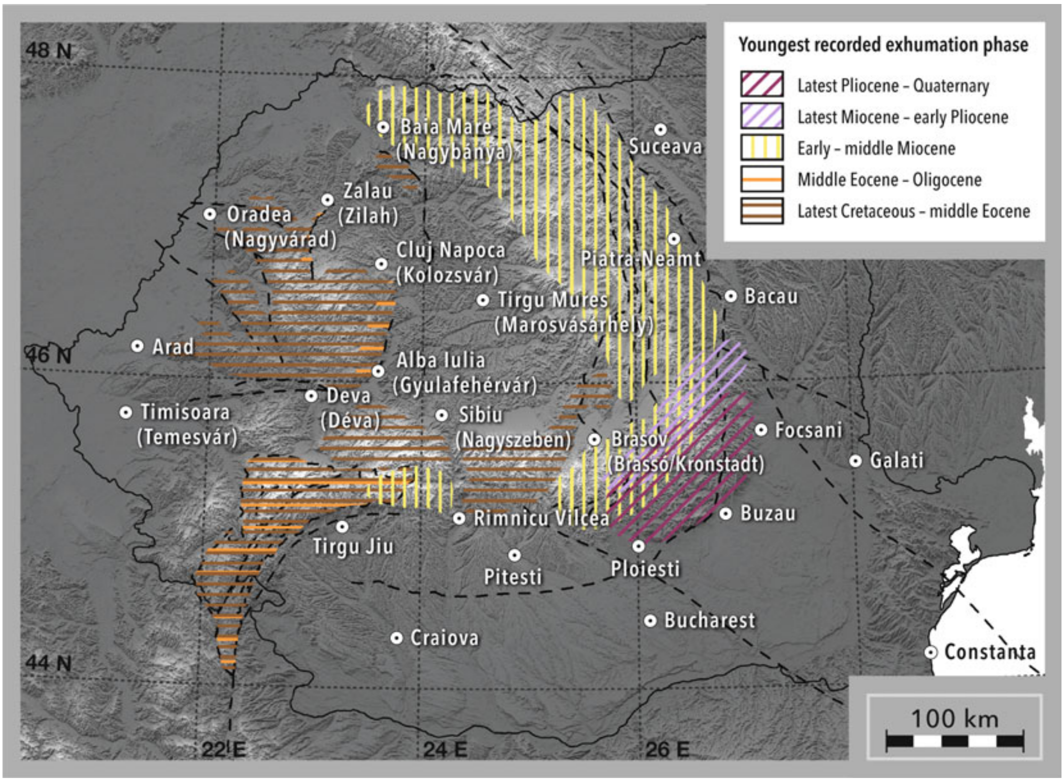

Fig. 2.3 Topographic map of East Carpathians showing the age of the youngest tectonic exhumation phase (after Merten 2011), interpreted as the tectonic age of topographic relief. Most of the present-day topography in the Apuseni Mountains (Erdélyi-középhegység) and South Carpathians was formed during 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

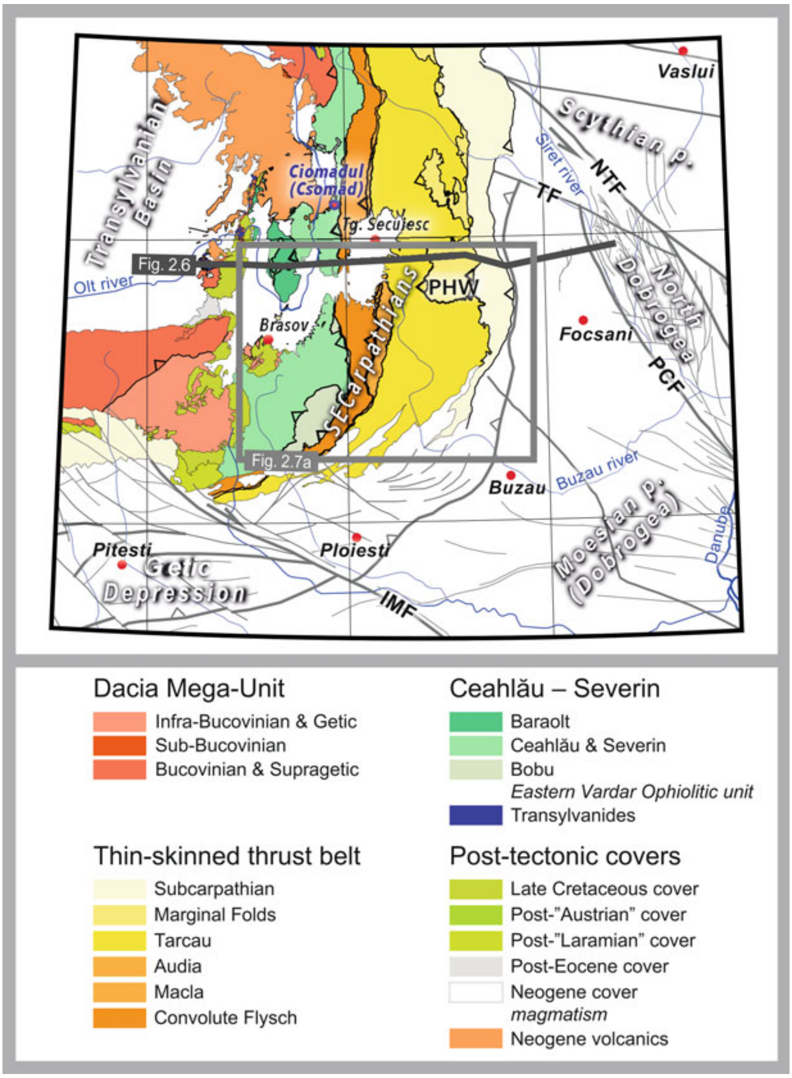

Fig. 2.4 Simplified tectonic map of the South–East Carpathians (modified from Maţenco 2017). The grey line is the locations of geological cross section in Fig. 2.6. IMF = Intramoesian Fault; PCF = Peceneaga - Camena Fault; TF = Trotuş Fault; NTF = New Trotuş Fault; PHW = Putna half-window

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

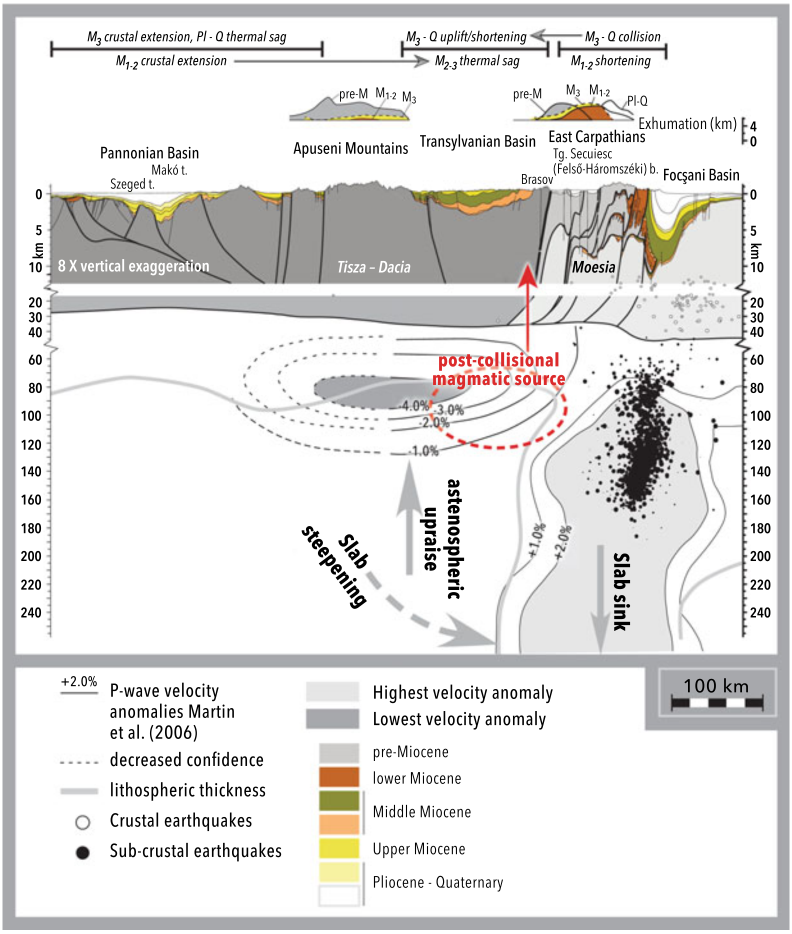

Fig. 2.5 Simplified cross section across the south-east part of the Pannonian Basin, Apuseni Mountains, Transylvanian Basin, and South-East Carpathians, and amounts of exhumation over the Apuseni Mountains and SE Carpathians derived from low-temperature thermochronology (modified from Matenco et al. 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).

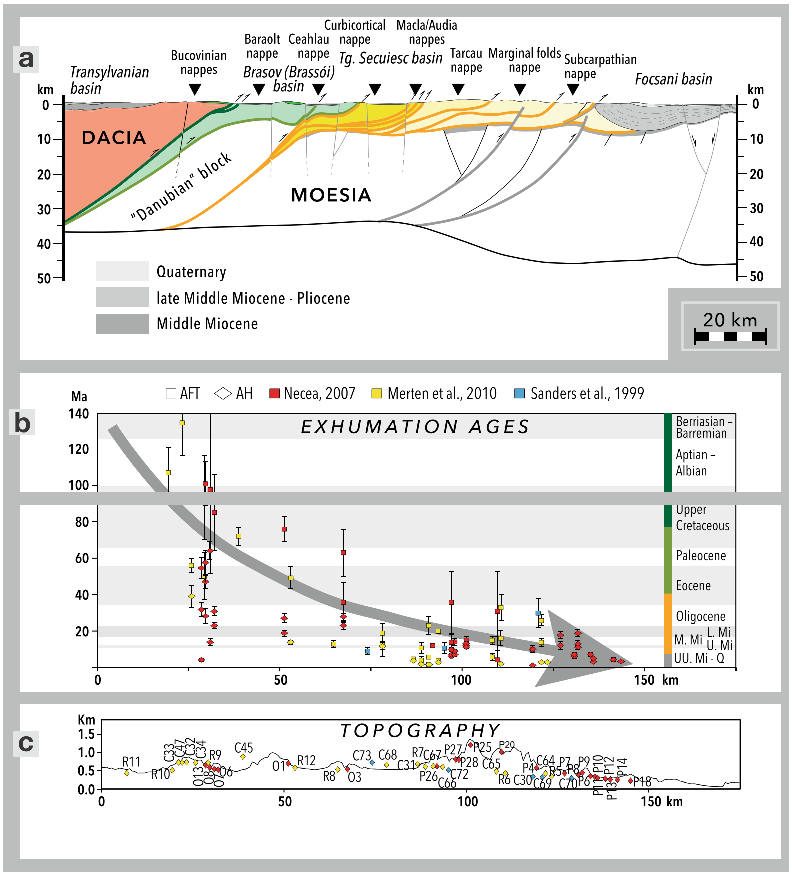

Fig. 2.6 Thermochronological transect in the Southeast Carpathians (simplified from Necea et al. 2021); **a** Crustal scale tectonic cross section along the SE Transylvanian Basin, SE Carpathians and their foreland including the Focșani Basin. The Moho structure at the base is taken from passive and 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 intra-montane 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).