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Summary

Convergent orogens can reveal topographic expressions varying from high and wide, such as the Himalayas (∼8 km), to much lower expressions, such as the Romanian Carpathians (∼2 km). In the case of collisional mountain belts, the orogenic evolution is characterized by initial accretion of crustal material during subduction of a lower (oceanic) plate, followed by collision of the continental parts of the converging plates. Hereby, shortening is accommodated by strong deformation of crustal material, resulting in the build-up of an orogen.

Based on observations from the European Alps, it has been suggested that many convergent orogens can be explained by the double-vergent wedge model. This model postulates that deeper crustal levels are gradually brought to the surface by orogenic shortening, where major exhumation is associated with crustal-scale backthrusting (i.e. retro-shears) exposing large metamorphic complexes at the surface. Although this model seems to be valid for high-convergence orogens (e.g. the Alps), it seems that a large number of subduction-dominated orogens do not exhume deep crustal levels during shortening (e.g. the Apennines, Dinarides and Carpathians). For the latter type of orogen, it is more difficult to derive and quantify detailed constraints on their shortening-related kinematic evolution. Exhumation pathways are difficult to assess due to lateral transport inside the orogen and topographic build-up is generally low. Exhumation of deeper crustal levels does occur, but rather during subsequent detachments and core-complex formation as a result of back-arc extension, which is trying to accommodate the difference between subduction and convergence velocities. Due to a foreland-ward migration of this extension as a result of slab roll-back, shortening-related deformation and exhumation of the metamorphic core are largely overprinted. This extensional overprint generally obscures the regional contractional evolution that takes place at such retreating plate boundaries.

This thesis focuses on the thermo-tectonic evolution of a subduction-dominated orogen: the Romanian segment of the Carpathians. The Carpatho-Balkanic orogen is a typical example of a mountain belt which failed to significantly grow upwards during the long lasting Late Jurassic–Miocene contractional evolution. The present-day appearance of the Carpathians, Balkans and their Dinaridic connection as separate orogens is just apparent; it is the result of a superposed Miocene roll-back and associated back-arc evolution that created the arcuate shape of the orogen and the intervening sedimentary basins from ~20 Ma onwards. In the Romanian Carpathians, the large-scale extensional collapse of the Pannonian back-arc domain took place far away in the hinterland, and thus did not overprint shortening-related deformation and exhumation in the metamorphic core. Thus, the Romanian Carpathians are in an ideal position to study the evolution of an orogen characterised by low amounts of shortening-related exhumation. Additionally, the position of the Romanian Carpathians in the complex plate tectonic configuration of the Alps-Carpathians-Dinarides realm suggests that their evolution may have been affected by geodynamic processes taking place at adjacent plate boundaries.

Low-temperature thermochronology and structural analysis have been combined in order to derive quantitative constraints on the thermo-tectonic evolution of the Romanian Carpathians. Thermochronological data record the time at which rocks cooled through a specific temperature window. The underlying principle is based on the interplay between the accumulation of a radioactive decay product in a specific mineral, and the thermally activated removal of that decay product. Since temperature increases with depth below the Earths' surface, the data can be translated into exhumation (i.e. the unroofing history of a rock relative to the Earth's surface as a result of denudation processes) with some knowledge of the subsurface geothermal gradient. Exhumation of a rock sample or region can, for example, reflect enhanced erosional denudation resulting from tectonically induced uplift by crustal thickening. Thermochronological data may thus provide important insights into the kinematic evolution of convergent orogens. The two thermochronometers that have been applied in this study are the apatite fission track (AFT) and (U-Th)/He (AHe) thermochronometers. These methods have temperature sensitivities of ~120–60°C and ~85–40°C, respectively, and allow the derivation of detailed cooling patterns in the upper few kilometres of the Earth's crust. This makes them suitable to study regions characterised by low amounts of exhumation. New thermochronological data were combined with data from previous studies for a more regional interpretation of cooling and exhumation patterns.

The late stage evolution of the Apuseni Mountains following the collision between the Tisza and Dacia continental blocks is assessed based on AFT and AHe thermochronology and structural analysis (Chapter 3). The Apuseni Mountains form an internal mountain belt with respect to the present-day Carpathian and Dinaridic-Hellenic belts. Main focus of this Chapter is their latest Cretaceous–Tertiary post-collisional evolution and the effects of convergence at two adjacent plate margins (the Sava and Ceahlău-Severin zones in the Dinarides and external Carpathians, respectively). The relationship between syn- to post-collisional orogenic shortening and stresses transmitted from other neighbouring plate boundaries is important for understanding the kinematics of mountain belts, but has received little attention so far. The exhumation history derived from AFT and AHe thermochronology indicates that the present-day topography of the Apuseni Mountains originates mainly from latest Cretaceous times, modified by tectonic pulses during the Paleogene. The latter are suggested by cooling ages clustering around ~45 Ma and ~30 Ma and the associated shortening recorded along deep-seated fault systems. Paleogene exhumation pulses are similar in magnitude

(∼3.5 km) and are coeval with the final collisional phases recorded in the Dinarides and with the Carpathian rotation around the Moesian promontory. These newly quantified Paleogene exhumation pulses contradict the general view of tectonic quiescence, subsidence and overall sedimentation. The Miocene collapse of the Pannonian basin did not induce significant regional exhumation along the western Apuseni flank, neither did the subsequent Carpathian collision. This is surprising in the overall context of Pannonian basin formation and its subsequent inversion, in which the Apuseni Mountains were previously interpreted to be uplifted in both deformation stages.

In Chapter 4, AFT and AHe thermochronology have been combined to derive a detailed exhumation history for the SE Carpathians. Cooling ages generally decrease from Cretaceous for the internal basement nappes, to Miocene–Quaternary for the external sedimentary wedge. Cretaceous cooling is related to the intra-Albian and intra-Senonian tectonic events, which resulted from convergence and closure of the Ceahlău-Severin Ocean. The AFT and AHe data show a Paleogene cluster of cooling ages, confirming a suspected but never demonstrated tectonic event, which may be related to subduction retreat and the rotation of the Tisza-Dacia block into the so-called "Carpathian embayment". The new data furthermore suggest that the SE Carpathians have been affected by a middle Miocene exhumation phase related to continental collision of Tisza-Dacia with the European foreland, which occurred at a rate of ∼0.8 mm/yr. This rate is similar to the one previously inferred for the East Carpathians. The SE Carpathian tectonic evolution, however, is overprinted by two younger exhumation events in the Pliocene–Pleistocene. The first exhumation phase (latest Miocene–early Pliocene) occurred at high exhumation rates (∼1.7 mm/yr), and is associated with a sea-level drop in the Paratethys basins during the Messinian low-stand. The youngest recorded tectonic phase suggests rapid Pleistocene exhumation (∼1.6 mm/yr) and is interpreted to represent crustal-scale shortening different in mechanics from collisional processes. The data suggest that the SE Carpathians did not develop as a typical double-vergent orogenic wedge; instead, exhumation was related to a foreland-vergent sequence of nappe stacking during collision and was subsequently followed by a large out-of-sequence shortening event truncating the already locked collisional boundary.

In Chapter 5, the detailed exhumation history of the SE Carpathians is integrated into the general evolution of the Romanian Carpathians in order to assess the collisional characteristics of the low-topography Carpathian orogen. New AHe data of the East and South Carpathians are combined with previously published AFT and AHe data of the East, SE and South Carpathians. The construction of three cross-sections and derivation of Miocene to present-day exhumation estimates for these sections illustrates the style of the orogenic evolution across section. Thermochronological data show that timing of deformation is generally younger towards the foreland, but out-of-sequence deformation also occurred and is indicative for collisional stages. The lower orogenic plate was strongly involved into the collisional kinematics, as indicated by deep-seated basement thrusting along faults inclined at higher angles than the subduction zone. Near the surface, this is expressed by wide antiforms in the upper plate and the thin-skinned orogenic wedge. The overall foreland-ward migration of exhumation is diagnostic for this type of orogenic mechanics.

Collisional exhumation patterns in the Carpathians also demonstrate significant differences along the orogenic strike, related to the strength contrast between the two major units that compose the Carpathian lower plate. In the mechanically strong European/Scythian domain, the Tisza-Dacia basement was stacked and exhumed together with the Ceahlău unit and the nappes of the external thrust belt during their Miocene emplacement. The European/Scythian lower plate was deformed, but the major subduction boundary remained at the contact between Tisza-Dacia and the European/Scythian plate (i.e. ∼the Ceahlău zone). This situation changes laterally in the SE and South Carpathians, where Miocene exhumation is restricted to a more foreland-ward position (the Ceahlău unit and the external thrust belt). This lateral change in exhumation patterns indicates that in the SE and South Carpathians, the upper Tisza-Dacia plate was already accreted to the Danubian part of mechanically weaker Moesia (in the lower plate) at the end of the Cretaceous. The presence of an intermediate Danubian block in the SE Carpathians implies a shift from the Ceahlău-Severin subduction zone to mainly continental subduction of the distal parts of the foreland platform, grouped under the generic term of "Carpathian embayment".

Chapter 6 provides an overview of all thermochronological data available for the Romanian Carpathians. The data presented in Chapters 3 through 5 and data from previous publications are shown on regional thermochronological age maps for the zircon (with a temperature sensitivity of ∼230°C) and apatite fission track, and AHe thermochronometers. Exhumation and burial maps and cross-sections are reconstructed for six different thermo-tectonic time-slices from the latest Cretaceous to present-day. These regional exhumation maps allow identification of both large-wavelength kinematic patterns driven by regional processes, but also short-wavelength geometries driven, for instance, by local faults. Integration of regional geometries at the scale of an entire orogen is the key to understanding the mechanics of subduction and collision. The maps highlight the importance of considering the evolution of adjacent convergent plate boundaries, which may play a major role in a complex area such as the Romanian Carpathians. Furthermore, the link between the present-day topographic expression and the last-recorded exhumation phase is addressed. This analysis suggests that the topographic expression of the Apuseni Mountains, South Carpathians and the internal part of the SE Carpathians is largely of latest Cretaceous–Paleogene age, in contrast to previous interpretations which postulated that these areas were strongly influenced by the Miocene collision in the external Carpathians. Widespread Miocene exhumation is limited to the East Carpathians and the external part of the SE Carpathians. The subsequent Pliocene–Quaternary exhumation episodes in the external part of the SE Carpathians have a strong correlation with the present-day topographic expression of this part of the mountain belt.