Thermo-tectonic evolution of a convergent orogen with low topographic build-up

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CHAPTER 1

Introduction

1.1 The evolution of convergent orogens

Researchers generally look at mountain building processes from a top-down perspective, inherent to the common process of collecting data near the surface and projecting them to depth by interpretation or geophysical imaging. Therefore, the perspective on mountain growth is biased towards imagining particle paths moving upwards: orogenic topography is built by convergent plate tectonic processes, which move the crustal material entering the subduction zone upwards. The topography is viewed as a result of the interplay between tectonic processes that create it and the erosional surface processes that destroy it [e.g. *Koons*, 1989; 1990; *Willett*, 1999; *Willett et al.*, 1993; 2001; *Willett and Brandon*, 2002; *Burbank et al.*, 2003; *Molnar*, 2003; *Hilley and Strecker*, 2004; *Whipple and Meade*, 2004; *Reiners and Brandon*, 2006; *Bishop*, 2007; *Berger et al.*, 2008; *Malavieille*, 2010].

Starting from the work of *Beaumont et al.* [1996] in the European Alps, the mechanical model of double-vergent wedges has been extrapolated to many other convergent mountain belts that are characterised by accretion of crustal material during subduction [e.g. *Ellis and Beaumont*, 1999; *Fitzgerald et al.*, 1999; *Sanders et al.*, 1999; *Willett*, 1999; *Willett and Brandon*, 2002; *Song et al.*, 2006; *Kirstein et al.*, 2010]. The model postulates that deeper crustal levels are gradually brought to the surface by orogenic shortening (Figure 1.1a). This view is, however, at odds with observations in a large number of orogens, such as the subduction-dominated mountains belts [*Royden and Burchfiel*, 1989] in the Mediterranean region (e.g. Apennines, Dinarides, Carpathians), which do not exhume deep crustal levels during shortening [*Jolivet and Faccenna*, 2000; *Faccenna et al.*, 2004]. Exhumation of deeper crustal levels does occur, but rather during subsequent detachments and core-complex formation [e.g. *Tari et al.*, 1992; *Brun and Faccenna*, 2008; *Olivetti et al.*, 2010]. This is because the difference

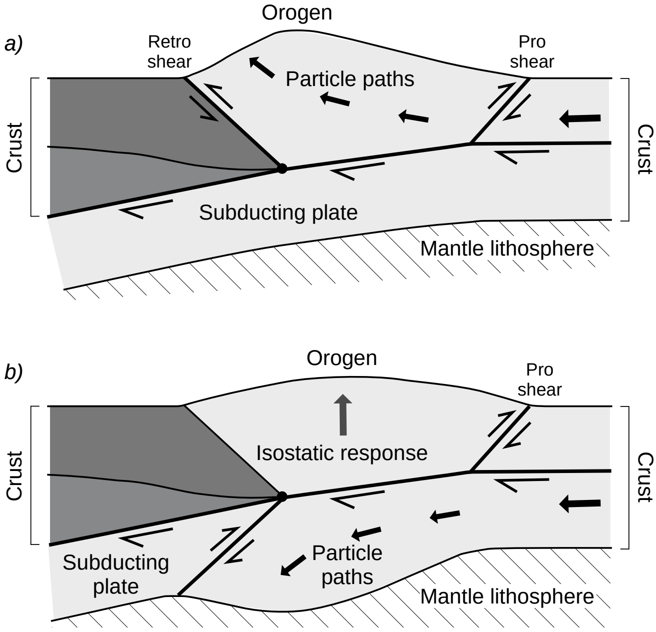

Figure 1.1: a) Cartoon illustrating the common perspective on mountain growth [Modified after *Beaumont et al.*, 1996; *Willett and Brandon*, 2002]: Orogenic topography is built by convergent plate tectonic processes which move the crustal material entering the subduction zone upwards. The level of decoupling between subducted lithosphere and crustal material incorporated into the orogen is a function of local rheological properties. b) Hypothesis for the evolution of subduction-dominated orogens: Crustal material entering the subduction zone is actively accreted downwards (particle paths move down); exhumation is mainly an expression of the associated isostatic response and subsequent erosion.

between subduction and convergence velocities is accommodated by extension in the back-arc domain [e.g. *Royden and Burchfiel*, 1989; *Doglioni et al.*, 2007]. The accreting material entering the subduction zone cannot be incorporated upwards into the mountain topography. The only remaining solution is that these particular mountains grow by active accretion downwards (particle paths move down) and that the surface topography is mainly an expression of the associated isostatic response (Figure 1.1b). This is in agreement with numerical modelling results and the rheological stratification of the lithosphere, which demonstrate that the lower part of the crust is generally much easier to deform and duplicate than the upper part [e.g. *Kirby*, 1985; *Ranalli and Murphy*, 1987; *Kohlstedt et al.*, 1995; *Ranalli*, 1995; *Cloetingh and Burov*, 1996; *Watts and Burov*, 2003]. This fundamental contradiction signalled by the pioneering work of *Royden and Burchfiel* [1989] is often disregarded when addressing the collisional evolution of convergent orogens.

1.2 Deriving orogenic mechanics using thermochronology

Thermochronology, the study of thermal histories of rock samples or regions, can provide important insights into the kinematic evolution of convergent orogens [e.g. *Batt and Brandon*, 2002; *Reiners and Brandon*, 2006; *Kirstein et al.*, 2010]. In principle, thermochronological data record the time at which rocks cooled through a specific temperature window (each chronometer is sensitive to a particular temperature range). With some knowledge of the subsurface geothermal structure, these time-temperature data can be translated into exhumation, i.e. the unroofing history or path of a rock relative to the Earth's surface as a result of denudational processes [e.g. *Ring et al.*, 1999; *Reiners and Brandon*, 2006]. Hereby, denudation is the removal of rock by tectonic (e.g. normal faulting) and/or surface processes (erosion) at a specified point at or under the Earth's surface [*Stüwe and Barr*, 1998; *Ring et al.*, 1999]. In the context of orogenic evolution, exhumation may thus reflect enhanced erosion as a result of tectonically induced uplift (e.g. an increase of topographic elevation caused by crustal thickening) or of external forces such as a base-level lowering or climate change.

Deriving detailed syn- and post-collisional uplift and erosion patterns of low-topography orogens is generally hampered by low amounts of exhumation, causing maximum temperatures reached by exhumed rocks to be near or below closure temperatures of most thermochronometers. Exhumation pathways are difficult to assess because of lateral transport inside the orogen and longer residence in partial retention zones, and thermochronological markers tend to reflect the cumulative exhumation of multiple tectonic episodes [*Batt and Brandon*, 2002; *Reiners and Brandon*, 2006].

The evolution of orogens characterised by low amounts of exhumation and low topographic build-up can, however, be studied by using a combination of several low-temperature thermochronometers. Especially the combined use of apatite fission track (AFT) and apatite (U-Th)/He (AHe) thermochronology, with temperature sensitivities of ∼120–60°C [*Gleadow and Duddy*, 1981] and ∼85–40°C [*Wolf et al.*, 1998], allows the derivation of detailed cooling patterns in the upper few kilometres of the Earth's crust. These two thermochronometers can be ideally combined with the analysis of structural patterns, to obtain insights into the evolution of a low-topography orogen such as the Carpathians (Figure 1.2a).

1.3 The low-topography Carpathian orogen

The Carpatho-Balkanic orogen (Figure 1.2a) is a typical example of a mountain belt which failed to significantly grow upward during the long lasting Late Jurassic–Miocene contractional evolution of the Tethys subduction zones [e.g. *Boccaletti et al.*, 1974; *Schmid et al.*, 2008]. The present-day topographic expression 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 starting at ∼20 Ma [e.g. *Cloetingh et al.*, 2006; *Horváth et al.*, 2006; *Ustaszewski et al.*, 2008] (Figure 1.2a).

Studies dealing with the build-up of individual segments of this system com-

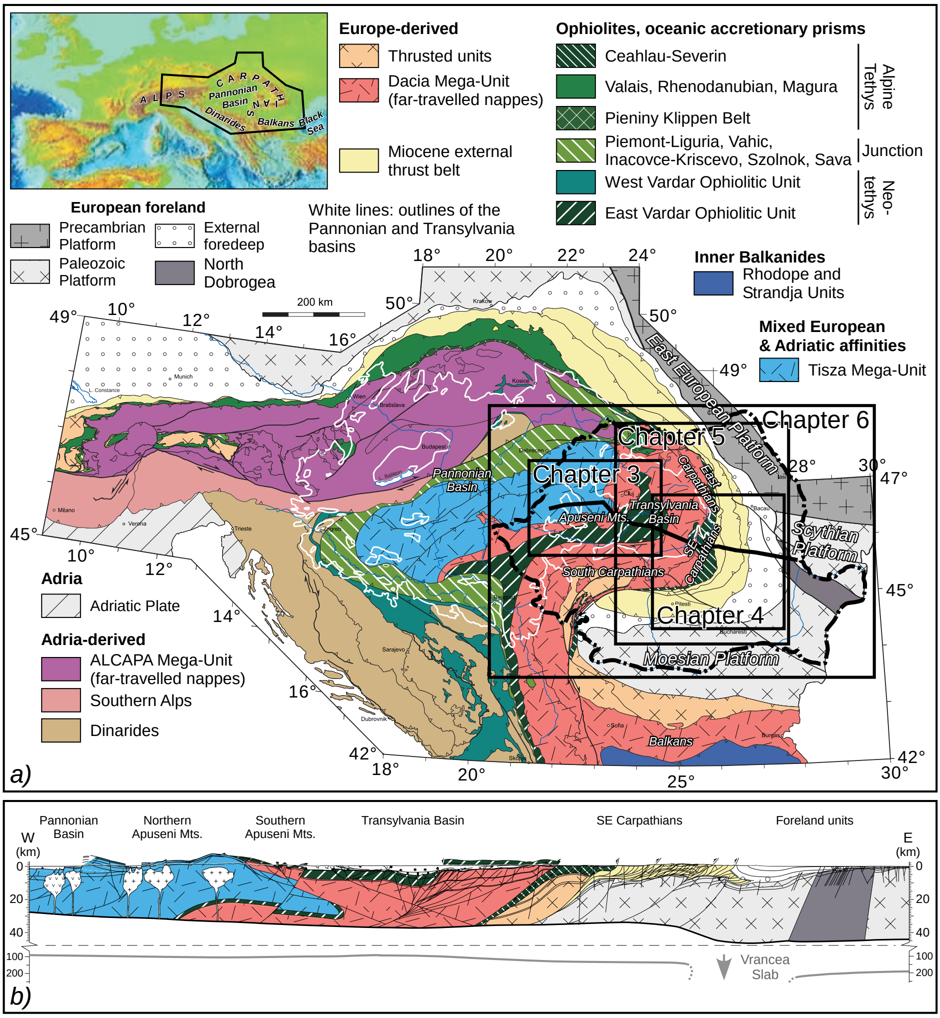

Figure 1.2: a) Major tectonic units of the Alps, Carpathians and Dinarides (ALCADI) [Simplified after *Schmid et al.*, 2008] and its location in the topography of Europe (inset map in top left corner). Dashed black line indicates the border of Romania and solid black line indicates the location of the cross-section in (Figure 1.2b). Solid boxes indicate the locations of the Carpathian areas discussed in Chapters 3–6 of this thesis. b) Conceptual cross-section through the Apuseni Mountains, Transylvania Basin and SE Carpathians [simplified after *Schmid et al.*, 2008]. Grey line below the cross-section represents the base of lithosphere [after *Dérerová et al.*, 2006; *Horváth et al.*, 2006]. Note that the crustal section has the same horizontal and vertical scale, while the sub-crustal lithosphere is vertically exaggerated. For further lithospheric details and the geometry of the Vrancea slab see *Martin et al.* [2006] and *Matenco et al.* [2007].

monly discuss these mountain belts individually. Integration across basins, however, seems to be of particular importance when addressing the evolution of isolated pieces of the puzzle. This is, for example, the case for the Apuseni Mountains (Figure 1.2a). The East Vardar subduction/collision system that created these mountains during the Late Jurassic–Early Cretaceous can be discussed on the basis of a number of available exhumation and kinematic studies [see *Schuller*, 2004; *Schmid et al.*, 2008 and references therein] (Figure 1.2a). However, the subsequent post-collisional contractional deformations are less constrained in terms of genetic mechanisms and it is rather unclear which of the plate contacts (Figure 1.2a) is responsible for the present-day elevated topography of these mountains.

The External Carpathians (East, SE and South Carpathians; Figure 1.2a) are mainly the result of Cretaceous–Miocene convergent processes in the Ceahlău-Severin Ocean and associated thinned continental domains. They exhibit several intriguing features that are common for subduction-dominated orogens [*Royden and Burchfiel*, 1989], such as the non-exposure of rocks recording coeval metamorphic events. The formation of a double-vergent orogenic wedge has been postulated for the East Carpathians based on AFT results [*Sanders et al.*, 1999], although structural evidence for retro-shearing is absent. The postulated retro-shearing has not been confirmed [*Krézsek and Bally*, 2006].

In particular, the collisional evolution of the SE Carpathians and adjacent Focşani foredeep basin shows some striking features. The basement beneath the nappe pile is in a surprisingly shallow position [*Landes et al.*, 2004; *Bocin et al.*, 2005; 2009], and is spatially juxtaposed over a shallow Moho configuration [*Hauser et al.*, 2007] (Figure 1.2b), which is in contradiction with an expected crustal isostatic root [*Airy*, 1855]. The slab is located in the foreland, largely offset from the suture zone observed at the surface (Figure 1.2b) [see also *Knapp et al.*, 2005]. Furthermore, subsidence of the anomalously deep Focşani foredeep basin occurred after cessation of early to middle Miocene nappe-stacking [e.g. *Tărăpoancă et al.*, 2003], which contradicts the typical foredeep evolution assuming a sedimentary wedge formed by flexure due to thrust loading, which migrates in time toward the foreland due to subduction [e.g. *Beaumont*, 1981]. Following continuous latest Miocene–Pliocene subsidence, foredeep strata were inverted and tilted during the early Quaternary [e.g. *Matenco et al.*, 2007 and references therein]. In the adjacent orogenic nappe pile, the onset of exhumation appears to have started earlier (latest Miocene–Pliocene), as suggested by thermochronological and provenance studies [*Sanders*, 1998; *Seghedi et al.*, 2004; *Panaiotu et al.*, 2007]. The force driving this post-collisional evolution is not well understood, but is generally attributed to processes taking place in the already subducted slab [see *Knapp et al.*, 2005 for a review], or to intraplate deformation [e.g. *Cloetingh et al.*, 2004].

In this Thesis, a combination of AFT and AHe thermochronology and structural analysis are used to discuss and potentially resolve many of the uncertainties on the evolution of the Romanian Carpathians and geodynamic processes driving it. The analysis of exhumation patterns over the entire scale of an orogen requires the integration of both large-wavelength patterns driven by regional processes, but also short-wavelength geometries driven, for instance, by local faults. In order to discriminate regional from local processes, regional thermochronological age maps and exhumation maps have been constructed, which are able to underline individual tectonic events. Integration of regional geometries at the scale of an entire orogen is the key to understanding the mechanics of subduction and collision [e.g. *Cloetingh et al.*, 2006; *Rosenberg and Berger*, 2009].

1.4 Thesis outline

Chapter 2 describes the concepts and analytical details of the two low-temperature thermochronometers that were used in this study: the AFT and AHe thermochronometers. Particular focus is on the (U-Th)/He analysis of samples with young AHe ages and low U-contents, which requires a detailed assessment of system background levels. Furthermore, modelling of time-temperature histories using the data obtained by the two methods, and the conversion into exhumation, denudation, uplift and erosion are discussed.

Chapters 3, 4 and 5 present new data for three areas in the Romanian Carpathians (Figure 1.2a). Chapter 3 presents the late stage evolution of the Apuseni Mountains, assessed by AFT and AHe thermochronology and structural analysis. Main focus is on the post-collisional evolution of the Apuseni Mountains, and the potential effects of convergence at two adjacent plate margins (i.e. the Sava and Ceahlău-Severin zones) on the late stage evolution of the Apuseni Mountains (Figure 1.2a).

In Chapter 4, AFT and AHe thermochronology have been combined to obtain a detailed exhumation history for the SE Carpathians (Figure 1.2a). This chapter addresses both the Cretaceous–middle Miocene syn-collisional nappe-stacking events and the latest Miocene–Quaternary post-collisional evolution of this part of the Carpathians. These new quantitative constraints are used to discuss the potential forces driving the “atypical” syn- to post-collisional evolution of the SE Carpathians.

In Chapter 5, the detailed exhumation history of the SE Carpathians is integrated into the general evolution of the East, SE and South Carpathians to assess the collisional characteristics of the low-topography Carpathian orogen (Figure 1.2a). New AHe data of the East and South Carpathians are presented in this chapter and they are integrated 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 and burial estimates for these sections illustrates the style of the orogenic evolution across section, but also considers the lateral changes between the East, SE and South Carpathians, e.g. related to the differences in rheology of the foreland plate (East European Plate vs. Moesian/Scythian Plate; Figure 1.2a).

Chapter 6 provides an overview of low-temperature thermochronological data for the Romanian Carpathians (Figure 1.2a), by a graphic presentation of data from this study and from previously published studies. Thermochronological age maps are presented for the zircon fission track (ZFT), AFT and AHe thermochronometers. Furthermore, 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 regional geometries at the scale of the entire orogen, which is the key to understanding the mechanics of subduction and collision.