UNIVERSITETET I BERGEN

Coupled surface process and tectonic modelling of extension-inversion tectonics in the Pyrenees

Dissertation for the degree of Philosophiae Doctor (PhD)

Zoltán Erdős

University of Bergen

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Preface

The research presented in this thesis was conducted at the Department of Earth Science, University of Bergen (Norway), and in parallel at the Institute of Earth Sciences, Joseph Fourier University (Grenoble, France) under the supervision of Prof. Ritske Huismans, Prof. Peter van der Beek and Prof. Haakon Fossen. The project started in September 2009 and was funded by the Norwegian Research Council through the Norwegian component of the European Science Foundation Eurocore TOPO-Europe project PyrTec. The computationally intensive numerical modeling was carried out on the University of Bergen supercomputers Fimm and Hexagon, maintained by the Bergen Center of Computational Science.

The thesis is structured in accordance with the Norwegian guidelines for doctoral dissertations in natural sciences, where the main body of the thesis consists of research papers either published, submitted or about to be submitted to international peer-reviewed journals. The present thesis comprises three papers: Paper 1 has been accepted for publication by the AGU journal Tectonics; Paper 2 has been submitted to Earth and Planetary Science Letters; and Paper 3 has been submitted to the Journal of Geophysical Research. The three research papers are preceded by an Introductory Chapter that details the general background and aims of the project, synthesizes its outcome, and outlines prospects for future work. An authorship statement provides an overview of the contribution of each author to this collaborative research work.

Acknowledgements

First of all, I would like to thank my supervisors: Ritske Huismans, for giving me the opportunity to embark on the great journey that is getting a PhD and for guiding my way throughout patiently; Peter van der Beek, for supporting and encouraging me tirelessly all the way despite the huge geographical distance between us and for the countless insightful suggestions throughout or work together; Haakon Fossen for his kindness and encouragement and for all the helpful discussions. I am truly grateful for the belief that all three of them have shown in me.

I would like to thank Jean Braun for his contagious enthusiasm and the helping hand he gave me with the use and development of his code, Pecube, and Cedric Thieulot for all the long hours he devoted to share his knowledge on numerical modeling and his code, FANTOM.

I would like to thank the Department of Earth Science both in Bergen and Grenoble, for supporting me with a truly pleasant and stimulating working environment. From the PhDs and postdocs, through the permanent researchers to the administrative stuff, everybody was always kind, helpful, and incredibly friendly towards me.

I am immensely thankful for a huge number of people who have been incredibly supportive towards me and made my days a lot more joyful and without whose help my life would have been a lot greyer and a lot more difficult. I will not name them all (seriously, it would cost the trees of a small rainforest to print it) but I will simply thank the *lunch group*, the *cake-club*, the *geo-sports* and all the kind people I met in Bergen and Grenoble for making my days that much better.

Finally, I would like to thank my family and friends in Hungary for their long-distance support and last but by no means least I would like to say thank you to Iló, for bearing with me throughout the ups and downs of this incredible adventure to a land up, North!

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First order control of syntectonic sedimentation on crustal-scale structure of mountain belts
Submitted to *Earth and Planetary Science Letters*

Erdős, Z., Huismans, R. S., van der Beek, P.
Extensional inheritance and surface processes as controlling factors of mountain belt structure
Submitted to the *Journal of Geophysical Research*

Authorship statement

The main body of this thesis consists of three research papers, with the Ph.D. candidate Zoltán Erdős as the first author of all three and the sole author of the Introductory Chapter to the thesis. The research papers are a result of collaborative work and the relative contribution of their authors is specified below.

Paper 1: Evaluating balanced section restoration with thermochronology data: a case study from the Central Pyrenees by **Z. Erdős**, **P. van der Beek** and **R.S. Huismans**

All three authors were actively involved in designing the general concept of the novel method presented in the paper. **EZ** subsequently modified the thermo-kinematic model to suit the method, carried out the structural-kinematic modeling, the thermo-kinematic modeling and the statistical analysis of the case study. **EZ** also wrote the manuscript and drafted the figures. **PvdB** contributed to the thermo-kinematic modeling, the statistical analysis, the editing of the manuscript and participated in the joint discussions of the results. **RSH** contributed to the structural-kinematic modeling, the editing of the manuscript and participated in the joint discussions of the results.

Paper 2: First order control of syntectonic sedimentation on crustal-scale structure of mountain belts by **Z. Erdős**, **R.S. Huismans** and **P. van der Beek**

All three authors were actively involved in designing the experimental model setup presented in the paper. **EZ** subsequently implemented the surface process algorithms, carried out the thermo-mechanical modeling, the literature study, wrote the manuscript and drafted most of the figures. **RSH** contributed to the literature study, the editing of the manuscript, the design of figure 5 and figure 6 and participated in the analysis of the results. **PvdB** contributed to the literature study, the editing of the manuscript and participated in the analysis of the results.

Paper 3: Extensional inheritance and surface processes as controlling factors of mountain belt structure by **Z. Erdős**, **R. Huismans** and **P. van der Beek**

All three authors were actively involved in designing the experimental model setup presented in the paper. **EZ** carried out the thermo-mechanical modeling, wrote the manuscript and drafted the figures. **RSH** contributed to the editing of the manuscript, and participated in the joint discussions of the results. **PvdB** contributed to the editing of the manuscript and participated in the joint discussions of the results.

Part I

Introduction

Introduction

State of the art

Orogenic belts and their foreland basins are fundamental features of plate tectonics that can be generally associated with convergent plate-boundaries. The crustal structure of orogens around the world shows a wide range of deformation styles from narrow, asymmetric doubly-vergent wedges like the Pyrenees (Muñoz, 1992) to wide, plateau-like orogens such as the Zagros mountain belt (Mouthereau et al., 2007) or the Himalaya (e.g., DeCelles et al., 2001) (Gehrels et al., 2003).

Recently, Jamieson and Beaumont (2013) proposed a conceptual temperature-magnitude framework for orogenesis (Figure 1). In their work they propose that orogens can be placed on a scale ranging from small-cold to large-hot orogens. Examples of small-cold orogens are the Southern Alps of New Zealand (Beaumont et al., 1996) or Taiwan (Mouthereau, 2003; Simoes et al., 2007). This category is defined to cover those orogens in which the upper part of the sublithospheric mantle underthrusts with little deformation, particularly with little bulk shortening, and where crustal thickening and heating are limited. On the other end of the scale reside the large-hot orogens, of which the Himalaya (DeCelles et al., 2001; Gehrels et al., 2003) is a prime example. These orogens are typically composed of a central elevated plateau underlain by thick crust, flanked by external wedges including fold-and-thrust belts, and foreland basins. As orogens grow, they eventually evolve from small-cold orogens dominated by critical wedge mechanics to large-hot orogens characterized by an orogenic plateau underlain by a weak ductile flow zone (Jamieson and Beaumont, 2013).

In this framework, the primary controlling factor on the size and overall structure of an orogen is the amount of convergence between the colliding plates. However, there are several important additional factors providing major controls on the structural development of mountain belts. Among the potential parameters that can significantly affect the style of deformation are the crustal strength, inherited weakness zones, and the efficiency of surface process. These parameters have been studied extensively in the last decades (Buiter, 2012; Jammes and Huismans, 2012; Mouthereau et al., 2013; Mugnier et al., 1997; Stolar et al., 2006; Willett et al., 1993) but their relative importance remains unclear.

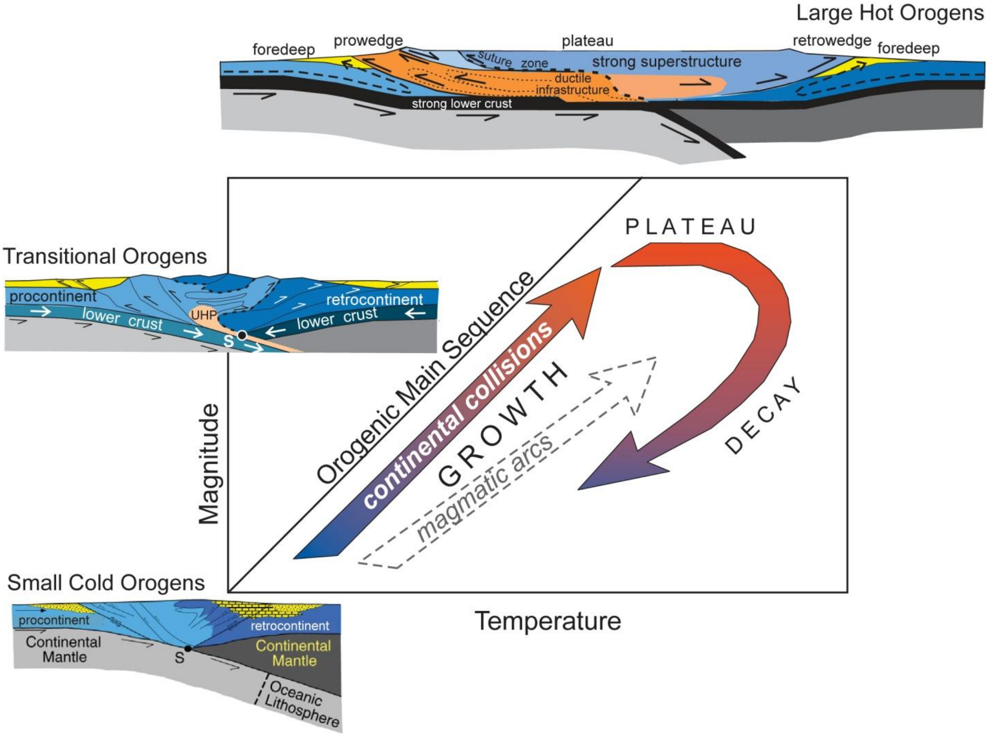

Figure 1 Conceptual orogenic temperature-magnitude diagram showing the growth from small-cold to large-hot orogens (after Jamieson and Beaumont, 2013). In collisional orogens, increasing magnitude and temperature both result from accretion and thickening of crustal material, factors that are ultimately dependent on the amount of convergence.

Numerous studies have shown that the relative strength of the crust and the mantle-lithosphere provides a first-order control on deformation processes in both extensional (Buck, 1991; Buck et al., 1999; Huismans and Beaumont, 2003, 2011; Huismans et al., 2005; Jammes and Huismans, 2012) and contractional settings (Beaumont et al., 1994; Ellis et al., 1998; Jammes and Huismans, 2012; Willett et al., 1993) with the depth and thickness of the viscous mid-crustal zone playing a pivotal role. In addition, as Jammes and Huismans (2012) have pointed out recently, the strength of the crust is heavily dependent on inherited weaknesses. Although most orogens initiate by inversion of passive margins or rifted basins, we know very little about how the inherited extensional structures affect the evolution of these belts. Jammes and Huismans (2012) showed that rifting inheritance can explain the presence of a lower crustal/mantle lithospheric body at shallow depth, as inferred for the Pyrenees (Muñoz, 1992) and European Alps (Schmid and Kissling, 2000) for example, and that it facilitates the propagation of deformation to the external part of the orogen. However, their study focused mainly on the evolution of basement structures, as the resolution attained by their models was insufficient to address the small-scale structures.

The potential role of surface processes on mountain building is one of the hotly debated and contentious issues in the Earth Sciences (see Whipple, 2009 and references therein). Earlier research has predominantly focused on the effects of erosion on mountain building (e.g., Beaumont et al., 1992), (Willett, 1999), (Whipple, 2009)) and recently on sedimentation controls on thin-skinned deformation (Bonnet et al., 2007; Fillon et al., 2012; Storti and Mcclay, 1995). However, in spite of our improved understanding of the controls that surface processes exert on the evolution of contractional orogens, it is still unclear how they might affect mountain building in the presence of inherited extensional structures. Neither has much work been done to decipher which aspects of orogenic structure and evolution can be ascribed to tectonic inheritance or to surface processes specifically, and which of these provide the prime control on the structure of individual mountain belts.

Aims and Research Objectives

The aim of this thesis is to improve our understanding of:

- How surface processes affect mountain building, with a special focus on the relationship between thin-skinned foreland fold-and-thrust belts and thick-skinned deformation in the internal part of an orogen.
- How inherited extensional structures affect mountain building.

The study was carried out using the Pyrenees as a special reference case. This orogen is exceptionally well studied and a wealth of geological and geophysical data is available from its central region. However, there remain significant uncertainties about the evolution of the belt, in particular concerning the relative roles of surface processes and inherited extensional structures in controlling the structure and evolution of the Pyrenean orogen.

Study area

The Pyrenees are a collisional orogen formed by convergence between the African-Iberian and European plates between Late-Cretaceous (90 Ma) to Early-Miocene (20 Ma) times. The convergence rate between the two blocks reached its peak during Eocene to Oligocene (50-20 Ma) times (Roest and Srivastava, 1991; Rosenbaum et al., 2002; Vissers and Meijer, 2012). The Pyrenees are an intracontinental convergence structure; Triassic – Late-Cretaceous extension did not lead to continental breakup between Europe and Iberia (even though the possible existence of an ocean remains advocated by some; see for instance Vissers and Meijer 2012).

The range is dominated by inversion tectonics (Muñoz et al., 1986) owing to thrusting along pre-existing extensional structures. These structures were originally formed during Triassic to Cretaceous rifting and transtension associated with anticlockwise rotation of the Iberian plate with respect to Europe and consequent opening of the Bay of Biscay (Roest and Srivastava, 1991; Rosenbaum et al., 2002).

The asymmetrical Pyrenean orogen was built by northward underthrusting of the Iberian crust below the European crust, resulting in a wide southern pro-wedge and a narrower northern retro-wedge (figure 2 and 3). From south to north, the Pyrenees consists of the Ebro foreland basin; the South Pyrenean Unit, a fold-and-thrust belt consisting of Mesozoic and Cenozoic sedimentary successions; the Axial Zone, which comprises a south-vergent antiformal stack of upper-crustal thrust sheets; the North Pyrenean Unit, where basement and cover rocks form north vergent thrust sheets and pop-up structures; and the Aquatine foreland basin (Capote et al., 2002; Muñoz, 1992).

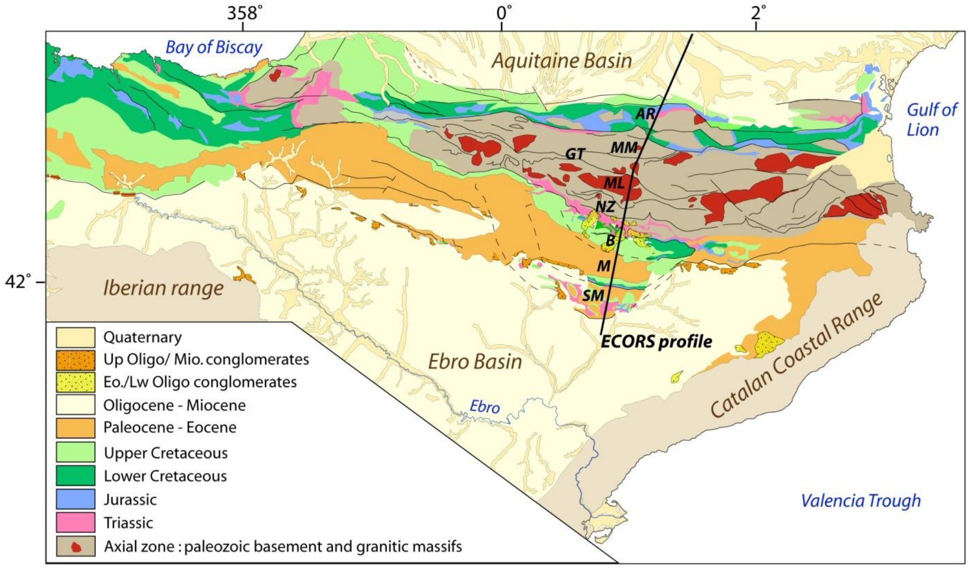

Figure 2 Geological map of the Pyrenees. The black line represents the ECORS deep seismic profile along which the balanced cross section of Figure 3 was constructed. AR: Arize block, MM: Marimaña massif, ML: Maladeta massif, NZ: Nogueres Zone, GT: Gavarnie-thrust B: Bóixols, M: Montsec, SM: Sierras Marginales (redrawn after Fillon and van der Beek (2012))

The kinematics of the South Pyrenean Unit are well constrained as the tectonic evolution is exceptionally well recorded by syntectonic sediments (Muñoz, 1992; Puigdefabregas et al., 1986; Puigdefabregas et al., 1992). The evolution of the Axial Zone is constrained by correlation of its basement thrust sheets with the thin-skinned structures of the South Pyrenean Unit, while the evolution of the North Pyrenean Unit is considerably less well constrained due to a lack of preserved synorogenic sediments (Figure 3).

The South Pyrenean Unit is made up of three thin-skinned thrust sheets (from south to north, the Sierras Marginales, Montsec and Bóixols; see Figure 3), which have been emplaced in an outward-propagating deformation sequence on top of a shallow décollement located in Upper Triassic evaporites (Muñoz, 1992). The Bóixols thrust was activated during the Maastrichtian (from approximately 70-65 Ma), as indicated by the overlying syntectonic sequences. Deformation stepped onto the Montsec thrust during the Ypresian (around 55 Ma). Finally, the Sierras Marginales unit was activated between the Early and Late Eocene (50-40 Ma). The outward propagation of deformation was interrupted during the last (Late Eocene) stage of the thrust belt evolution by break-back reactivation of the older thrusts and by the development of new, minor out-of-sequence thrusts (Capote et al., 2002). The northern fault contact of the Bóixols thrust sheet is the Morreres backthrust, which has been interpreted as a passive-roof thrust (Muñoz, 1992).

The antiformal stack of the Axial Zone involves upper to middle crustal rocks and consists of three basement thrust sheets: Nogueres, Orri and Rialp. These units were initially separated by extensional faults before the onset of thrusting (Muñoz, 1992). The uppermost of the three units is the highly eroded Nogueres thrust sheet; its frontal tip is preserved in the southern limb of the antiformal stack, known as the Nogueres Zone, while its root-zone crops out in the northern part of the Axial Zone (Muñoz, 1992). The Nogueres unit has been thrusted over the Orri unit between the Late Cretaceous and the Early Eocene (90-50 Ma) before deformation stepped onto another Mesozoic extensional fault, causing the Orri unit to overthrust the Rialp unit during the Middle to Late Eocene (50-36 Ma). Finally, deformation shifted again to create the Rialp thrust sheet between the Middle Eocene and the Late Oligocene (36-20 Ma) (Capote et al., 2002).

North of the Axial Zone in the North Pyrenean Unit, very steep, north-vergent thrust sheets and pop-up structures involve basement and Mesozoic cover rocks in both their foot- and hanging-walls. Most of the orogenic displacement in the North Pyrenean Unit occurred along the North Pyrenean Frontal Thrust, while the steep faults observed in the basement were probably not very active during the Pyrenean orogeny. They may represent either contractional Hercynian structures or younger, low-angle pre-Pyrenean fault zones (Capote et al., 2002). Since in the absence of preserved synorogenic sediments the timing of the deformation along the sub-vertical faults is very difficult to assess, the structural history of North Pyrenean Unit remains controversial (ECORS Pyrenees Team, 1988).

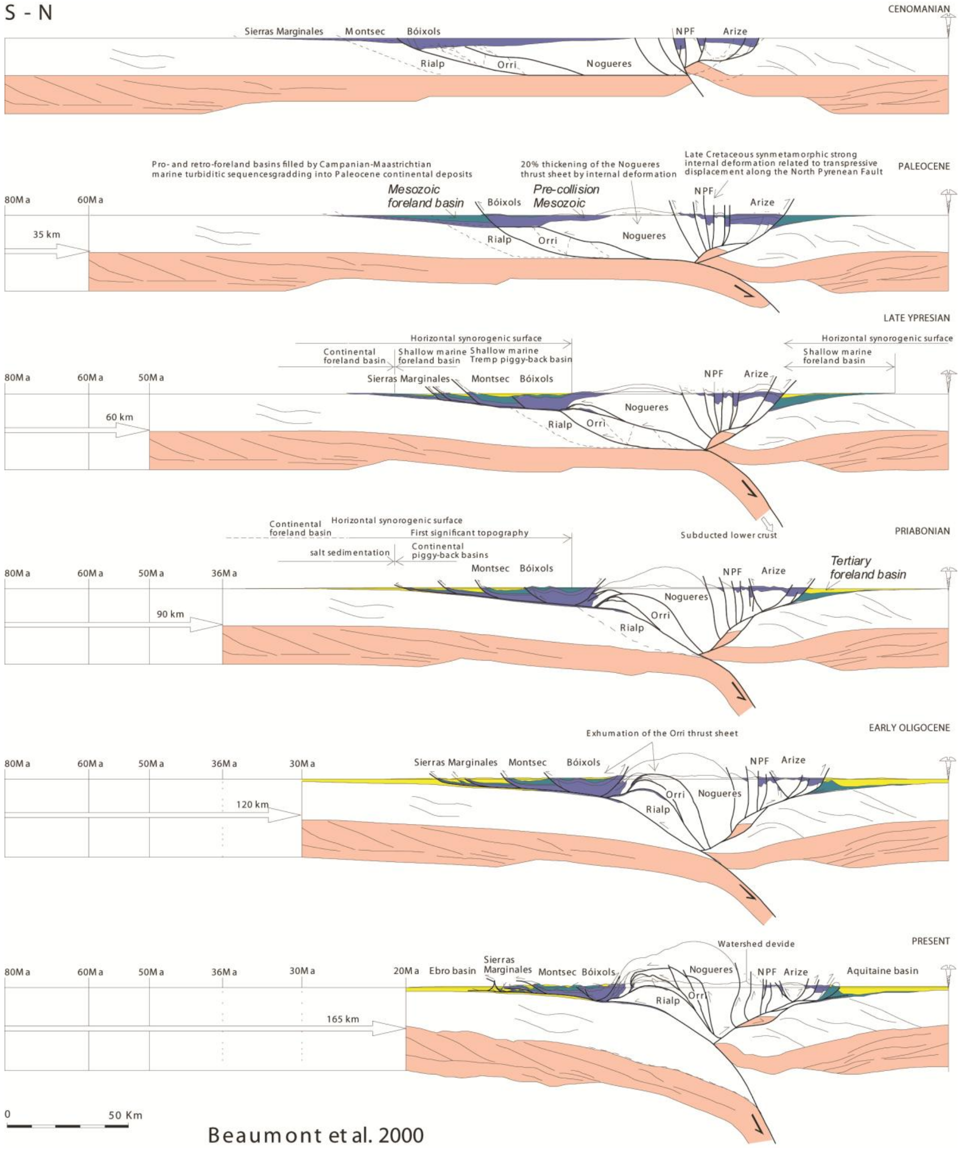

Figure 3 Balanced cross section restoration of the crust along the ECORS profile, showing the inferred evolution of the mountain belt since the onset of convergence in the Cenomanian (~80 Ma). Modified after Beaumont et al. (2000)

Modeling approach

To answer our research questions we have used a wide range of state-of-the-art numerical modeling tools. In Paper 1, we present a new method where we couple a structural-kinematic model and a thermo-kinematic model to evaluate the consistency of existing area-balanced section reconstructions with independent thermochronology data (figure 4). In Papers 2 and 3, we use two-dimensional lithospheric scale thermo-mechanical models coupled with simple surface process algorithms to study the effects of extensional inheritance and surface processes on mountain building.

Structural-kinematic modeling

The first component of the new method presented in Paper 1 is the structural-kinematic modeling software 2D-Move™ (Midland Valley Ltd). Using 2D-Move™, we can create a crustal-scale cross-section of our research area and model the effects of fault movements on the entire section. The aim of this exercise was to produce a set of velocity fields from a balanced cross-section restoration to describe its kinematics. A conventional section restoration, such as the one presented by Muñoz (1992) for the Central Pyrenees (Figure 3), consists of several time slices representing the structure of a crustal section at different times. Using the constraints derived from the section restoration on the timing and amount of displacement along the active faults, theoretically all the crustal blocks can be moved back gradually from their present position to their original pre-deformation position, with intermediate stages matching the partially restored sections.

2D-Move™ offers a range of algorithms suited for modeling hanging-wall deformation resulting from movement along a fault plane. We have tested the different available options, and decided to use the simple-shear algorithm in our case study as it proved to be capable of handling the geometric complexity of the modeled section. The algorithm predicts the deformation of the hanging-wall using the shape of the underlying fault while leaving the footwall undeformed (Withjack and Peterson, 1993). The deformation fulfills the condition of volume conservation (or area conservation, in case of a 2D section assuming plane strain) and is calculated according to the 'velocity method' of Waltham and Hardy (1995).

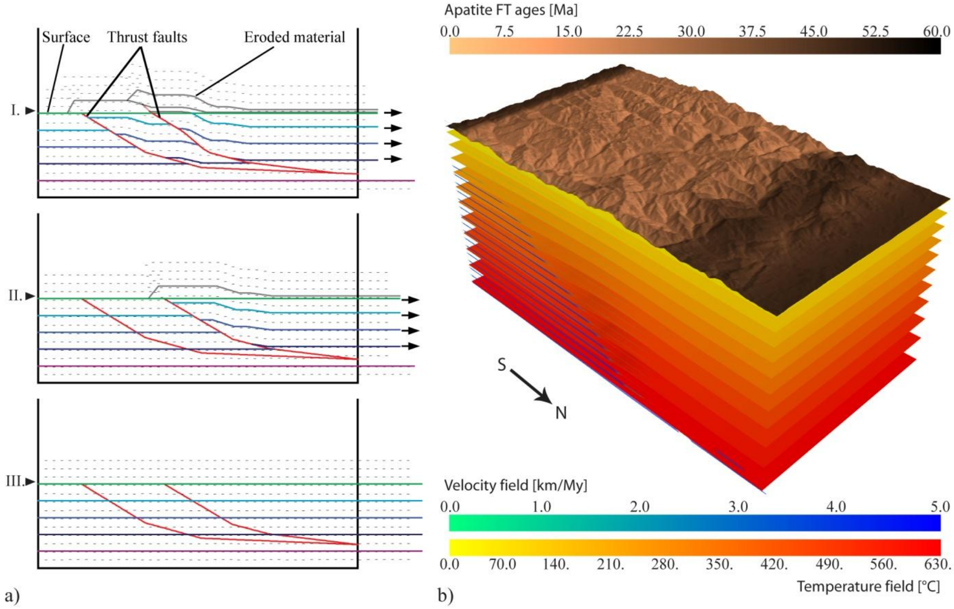

Figure 4 Principle of the method presented in Paper 1. (a) Structural-kinematic component: A velocity field is derived for each time interval of the modeled section restoration using 2D-Move™. A time interval is defined between two consecutive steps (e.g. I and II or II and III) of the restoration. In our synthetic example, the black cloud of points represents a Lagrangean marker field tracking the materials. (b) Thermo-kinematic component: The velocity fields are subsequently imported in the thermo-kinematic model PECUBE to predict thermochronometric ages for particles ending up on the surface of the model. These ages can be compared with sample ages obtained from the area.

In 2D-Move™ all fault motions must be applied sequentially. For any given step of the reconstruction the velocity field is calculated from the sum of all the individual fault-movements, therefore the order in which fault movements are applied within the step is inconsequential.

Since the simple-shear algorithm leaves the footwall of the active fault undeformed, the flexural-slip unfolding algorithm has been used to simulate the changes in the shape of the main crustal decollement from one time slice to the other. This algorithm divides the section into thin vertical strips that can be freely translated along their boundaries in the vertical direction. With this method, a chosen horizon (in our case the main decollement on the present-day time slice) can be unfolded to a target line (in our case a line following the shape of the decollement on the pre-dating time slice). It is important to note that the flexural-slip unfolding algorithm also conserves area.

Thermo-kinematic modeling

The second component of the method presented in Paper 1 is the thermo-kinematic model PECUBE (Braun (2003); see also Braun et al. (2012)). The aim of the thermo-kinematic modeling component is to predict thermochronological ages in the study area and compare them to available observations by integrating the velocity fields derived from the structural-kinematic model into the thermo-kinematic modeling.

PECUBE is designed to solve the heat-transport equation in a three-dimensional crustal block submitted to a tectonic and topographic scenario. The code is based on a finite-element approach and derives the *time-temperature (t-T) paths* of individual rock particles ending up on the surface at the end of the model run. These *t-T paths* are subsequently used to compute apparent ages for a range of thermochronometers, using standard thermochronological age-prediction models (Braun et al., 2012).

The standard kinematic input for PECUBE consists, for each modeled time-step, of a fault geometry and the velocities of the hanging- and footwall with respect to the fault [cf. Braun et al. (2012)]. We have implemented a new input option where a set of velocity vectors derived from the structural-kinematic model can be used for modeling the tectonic scenario of each time-step. These two-dimensional input velocity fields are extrapolated in the third dimension, normal to the section, to allow direct comparison with the observed thermochronological data and correctly take into account the influence of topography.

The thermochronometric ages are predicted from the time-temperature histories of rock particles using forward kinetic models (Braun et al., 2012).

For further details on the coupling of the structural-kinematic and thermo-kinematic models, and the limitations of the new method we refer to the Methodology and Limitations sections of Paper 1.

Thermo-mechanical modeling

In Papers 2 and 3 we use a modified version of the Arbitrary Lagrangean-Eulerian finite-element thermo-mechanical code FANTOM (Thieulot, 2011) to study the effects of surface processes and extensional inheritance on the structural development of contractional orogens and their foreland basins.

FANTOM is designed to model thermally coupled, plane-strain, incompressible viscous-plastic creeping flows in the crust and upper mantle. When the stress is below the yield criterion, the deformation is viscous while when the stress exceeds the yield criterion the deformation is frictional-plastic. In case of viscous deformation, the effective viscosity η_{eff} is specified as:

$$\eta_{eff} = fA^{-1/n}\,\dot{\varepsilon}^{(1-n)/2n}\,exp\left(\frac{Q+Vp}{nRT}\right)$$

where *A* is the pre-exponential scaling factor, *n* is the power-law exponent, $\dot{\varepsilon}$ is the second invariant of the deviatoric strain rate tensor, *Q* is activation energy, *V* is activation volume, *p* is pressure, *T* is temperature, and *R* is the universal gas constant. Values for *A*, *n*, *Q* and *V* are derived from laboratory measurements. The factor *f* is used to scale viscosities calculated from the reference 'wet' quartzite flow law. Frictional-plastic yielding occurs when:

$$(J_2')^{1/2} = p\ sin\phi_{eff} +\ C\ cos\phi_{eff}$$

Where J_2' is the second invariant of the deviatoric stress, ϕ_{eff} is the effective internal angle of friction given as $psin(\phi_{eff}) = (p-p_f)sin(\phi)$ for pore fluid pressure p_f , and *C* is cohesion. With appropriate choice of *C* and ϕ_{eff}, this yield criterion can approximate the effect of pore fluid pressure and frictional sliding in rocks. The effect of strain softening is introduced by a linear decrease of the internal angle of friction from 15° to 2° and by a simultaneous decrease of cohesion from 20 MPa to 4 MPa. The initial temperature field is laterally uniform and includes radioactive heat production in the crust. The thermal and mechanical systems are fully coupled and solved sequentially at each time-step. The implemented surface processes comprise optional elevation-dependent erosion and full sedimentation below a fixed base level. For detailed model setup, used parameter values and the description of the surface process algorithms we refer to the methodology sections of Papers 2 and 3. The modified version of this code solves the resulting systems of equations in parallel, allowing for the solution of a larger number of unknowns then hitherto. The numerical models have unprecedented high resolution and allow us to study the link and interaction between thin-skinned deformation in the sediments and crustal scale deformation.

Summary of papers

Paper 1

Erdős, Z., **van der Beek, P.**, and **Huismans, R. S.**
Evaluating balanced section restoration with thermochronology data: a case study from the Central Pyrenees
Tectonics, 33, doi:10.1002/2013TC003481

In this study, we propose a new method that can be used to quantitatively evaluate the consistency of a balanced cross-section restoration with independent thermochronology data that constrain spatial and temporal patterns of exhumation. To achieve this, we use the structural-kinematic software 2D-Move™ to constrain a set of velocity fields that describe the kinematics of the cross-section. Using these velocity fields as input for the thermo-kinematic code PECUBE, we can predict the thermal history and a range of thermochronometric ages for any location in the modeled area. Finally we can quantitatively compare the predicted thermochronometric ages with the available independent thermochronology data.

We present our method through a case study of a crustal-scale balanced cross-section restoration of the Central Pyrenees, presented by Muñoz (1992) and Beaumont et al. (2000). This cross-section restoration is exceptionally well constrained and supported by a wide variety of geological and geophysical data. Moreover, an extensive thermochronological dataset has been collected independently from the area. Our results show that the section restoration is consistent to a first order with both low- and high-temperature thermochronology data collected in the last two decades from the study area. Moreover, the data provide additional constraints on the timing of individual thrusting events, the thermal structure of the crust and the post-orogenic topographic evolution of the mountain belt. The high-temperature (zircon fission-track and K-feldspar Ar-Ar) data constrain the thermal structure of the belt as well as the timing of underplating while the low-temperature (apatite fission-track and (U-Th)/He) data require late synorogenic sedimentary burial of the southern flank of the Pyrenees between Late-Eocene (40 Ma) to Late-Miocene (9 Ma) times, consistent with previous inferences (Coney et al., 1996), and imply that no such burial occurred on the northern flank. The presented case study demonstrates the validity of this new approach.

Paper 2

Erdős, Z., **Huismans, R. S.**, and **van der Beek, P.**
First order control of syntectonic sedimentation on crustal-scale structure of mountain belts
Submitted to *Earth and Planetary Science Letters*

The idea of a potentially strong coupling between surface processes and mountain building has been extensively discussed in the last decades. The strong localizing feedback of erosion on the orogenic hinterland and the effect of sedimentation on the shallow structures of foreland fold-and-thrust belts have been extensively studied in recent years, but the governing forces of basement deformation below the foreland remain poorly constrained. In this paper, we offer a novel hypothesis that is consistent with observations from a range of orogens around the globe. Using high-resolution plain-strain thermo-mechanical models coupled with a simple sedimentation algorithm we show that syntectonic sedimentation has a controlling effect on the style of basement deformation in mountain belts and below their adjacent foreland fold-and-thrust belts. We present numerical model experiments exploring the effect of different sedimentation and erosion rates. Through these model experiments, we identify two end members that we term “sediment-loaded” and “sediment-starved” orogens, and we propose that they account for the primary characteristics of orogenic forelands.

Sediment-starved orogens such as the Urals (Brown et al., 1997a; 1997b), display short, narrowly spaced basement thrust-sheets with relatively small displacement along the individual basement thrusts in the orogenic core. In the presence of pre-orogenic sediments and a décollement layer the orogen is flanked by short thin-skinned thrust-sheets in the foreland with no or limited basement deformation below the foreland. In contrast, sediment-loaded orogens, such as the Swiss Alps (Roure, 2008), display long basement thrust-sheets penetrating the basement below thick foreland basin deposits with a large amount of displacement along the individual thrusts. As a result of basement involvement in the foreland, the orogenic wedge is significantly wider. The pre- to synorogenic deposits of the foreland fold-and-thrust belt deform by long thin-skinned thrust-sheets. Furthermore, the presented models suggest that while erosion strongly affects the width of the orogenic hinterland, it has limited direct effects on the evolution of the orogenic foreland.

We present a simple analytical scaling analysis that suggests a quadratic dependence of basement thrust spacing on syntectonic sediment thickness. A comparison of the results of our analysis with a compilation of basement thrust-sheet length and synorogenic sediment thickness data from a range of orogenic examples yields good correlation. Natural examples from the Urals, the Swiss Alps and the Zagros, and the data compilation also demonstrate that our modelling results are to a first order consistent with natural observations.

Paper 3

Erdős, Z., **Huismans, R. S.**, and **van der Beek, P.**
Extensional inheritance and surface processes as controlling factors of mountain belt structure
Submitted to *Journal of Geophysical Research*

University of Bergen

Surface processes and inherited structures are widely regarded as factors that strongly influence the evolution of mountain belts around the world. The first order effects of these parameters have been studied extensively throughout the last decades, but their relative importance remains notoriously difficult to estimate.

In this paper we use lithospheric-scale plane-strain thermo-mechanical models to study the effects of surface processes and inherited extensional structures on orogenic wedges and their adjacent foreland basins. Surface processes are modeled with the combination of an elevation-dependent erosion model and a simple sedimentation algorithm, where all topography is filled up to a prescribed reference level. The inherited extensional structures are generated explicitly by forward modeling the formation of an extensional basin, before inverting the velocity boundary conditions to model convergent mountain building. We also present an additional sensitivity test investigating the effect of varying upper-crustal strength.

Our results show that sedimentation increases the length scale of both the thin-skinned and thick-skinned thrust-sheets, facilitating the building of a wider orogen, while erosion helps to localize deformation, promoting narrowing of the orogen. Extensional inheritance facilitates basement deformation in the retro-wedge, increasing the width of the orogen. Additionally, the sensitivity test shows that a weaker than average upper crust results in a wider orogen with lower, plateau-like topography.

We have compared the modeled behaviors to the High Atlas, the Pyrenees and the Western Alps, three well studied natural examples, characterized by different inversional stages to confirm the observed controls of surface processes and extensional inheritance on the orogenic structure. We find that the crustal structure at different stages of the models presented in this study show good correlation with structural features observed in these mountain belts.

Conclusions

Surface processes and mountain building

The models presented in Papers 2 and 3 demonstrate that syntectonic sedimentation results in longer basement thrust sheets as well as longer thin-skinned thrust sheets and a generally wider orogen. The main deformation zone cutting through the upper crust remains active for a longer time, accommodating more displacement while subsequent new basement thrusts form further out below the foreland, creating longer thrust sheets. In the presence of inherited extensional structures, this effect can be observed in the retro-wedge as well as the pro-wedge, although the thrust-sheets developing in the former are consistently shorter than those developing in the latter. Our models also confirm the results of Fillon et al. (2012), who have shown that syntectonic sedimentation increases the characteristic length of thin-skinned thrust sheets.

Conversely to the effects of syntectonic sedimentation, as erosion removes material from the internal part of the orogen, it tends to narrow the wedge and reduce the orogenic loading of the colliding plates, therefore limiting the space available for deposition in the flexural foreland deeps. The presented models also demonstrate that although, as expected, erosion promotes a narrower orogen, the lengthening effect of sedimentation on both the thin-skinned and the basement thrust sheets remains largely unaffected.

Extensional inheritance and mountain building

The models presented in Paper 3 demonstrate that inherited extensional structures play a crucial role in mountain building as they facilitate the migration of deformation into the undeformed basement of the overriding plate. Moreover, a significant amount of lower-crustal/mantle-lithospheric material is preserved at shallow depths only in the presence of extensional inheritance, but significant erosion is needed in order to bring this material to the surface.

Examining the model behavior in contractional mode after subjecting the model to various amounts of extension showed that above a certain point, increasing the amount of extension and hence the number of inherited extensional structures does not affect the overall structural style of deformation heavily. The initial keystone structure (i.e. a triangular crustal block uplifted in the early phase of convergence along a pair of conjugate thrust faults, with foreland depressions developing on either side of the structure) becomes somewhat larger and more complex when the extensional mode is run to full crustal break-up but the general features remain largely unaffected.

Interaction of thin-skinned and thick-skinned tectonics

Both the purely contractional and the "accordion" (i.e. the model subjected to an initial extensional phase before inverting the boundary conditions in order to explicitly model the inversion of extensional structures) models presented in Papers 2 and 3 show that thin-skinned thrust sheets are generally rooted in the footwall of basement thrusts as they form outward-propagating sequences. As soon as a new basement thrust forms, the thin-skinned sequence situated on top of the new basement thrust-sheet is abandoned in favor of starting a new sequence in the footwall of the new thrust.

The thin-skinned thrusts forming ahead of the basement deformation in the foreland do not control the locus of the basement deformation migrating into the foreland. The position of the new basement thrust is primarily determined by the thickness of the syntectonic sediments covering the foreland basin.

Consistency of the ECORS cross-section restoration with thermochronology data

Using the structural-kinematic modelling software 2D-Move™ it was possible to reproduce the section restoration with high accuracy up to the 36-Ma time slice and with limited accuracy up to the 50-Ma time slice. However it was not possible to reproduce the restoration beyond the 50-Ma time slice due to a combination of inaccuracies and inconsistencies arising from the hand-drawn sections, and an indicated 20% internal thickening of the Nogueres basement thrust-sheet (i.e. large scale internal deformations cannot be reproduced by the structural-kinematic model).

The thermochronometric ages predicted by the thermo-kinematic modelling are generally in good agreement with both the high- and low-temperature thermochronology data available in the Central Pyrenees; hence we conclude that the restoration is to a first order consistent with these datasets.

The effects of surface processes on the Pyrenean orogeny

As demonstrated by the modeling exercise presented in Paper 1 the predicted thermochronological ages approximate the available low-temperature thermochronology data better by taking into account the late-stage burial and re-excavation scenario affecting the southern flank of the Pyrenean wedge presented by Coney et al. (1996), and quantified by Fillon and van der Beek (2012). This suggests that late-stage syntectonic sedimentation played a crucial role in the formation of the Pyrenean pro-wedge causing the out of sequence reactivation of faults in the foreland fold-and-thrust belt (Fillon et al., 2013).

The effects of extensional inheritance on the Pyrenean orogeny

The balanced-section restoration presented by Muñoz (1992) and Beaumont et al. (2000) displays slow accommodation of displacement along the North Pyrenean Frontal Thrust, which brought a lower-crustal body to shallow depth below the North Pyrenean Unit. Within the North Pyrenean Unit, which shows no evidence of synorogenic sedimentation, several high-angle faults can be found accommodating very little displacement. These faults involve basement and Mesozoic cover rocks in both their foot- and hanging-walls and they are thought to be inverted pre-Pyrenean extensional structures (Capote et al., 2002).

These characteristic features can only be observed in those thermo-mechanical models that have an accordion setup (for example see model M1 in Paper 3). The pure contractional models display very little overall deformation in the retro-wedge, which is dominated by a small keystone structure characterized by the absence of significant internal deformation. In contrast, when the model is exposed to an extensional phase before contraction, a significant part of the retro-wedge is made up by a significantly larger keystone-structure that includes a lower-crustal root and a well-defined internal structure characterized by inverted normal faults.

In conclusion, our model experiments suggest, that extensional inheritance played a prime role in the structural evolution of the Pyrenees, with the major characteristics of the North Pyrenean Unit, including the presence of steep, inverted normal faults, the relative tectonic quiescence of the area after the early inversion and the presence of a lower-crustal body at shallow depth below the unit, best recaptured by our accordion models.

Future perspectives

We have used multiple modeling approaches to study the controlling effects of surface processes and extensional inheritance on mountain building, with a special focus on the Pyrenean orogeny.

The method developed in Paper 1 has a number of crucial limitations. Most of these are limitations of the applied structural-kinematic model and its algorithms. The improvement of these algorithms (e.g. more robust results when using complex geometries, inclusion of isostatic compensation) is outside our scope but, nevertheless, it could substantially contribute to the method as a whole.

A potential next step could be to further elaborate the thermo-kinematic modeling component so that it would allow for more efficient comparison of competing section restorations. Furthermore, developing an algorithm to easily identify potential areas along section from where the collection of additional data would help distinguishing between the compared restorations would also be beneficial.

In the work presented in Papers 2 and 3, the surface-process algorithms coupled to the thermo-mechanical models are very simple in design, to allow studying the first-order effects exerted by these forces on the orogen. To uncover more intricate relationships the application of a more sophisticated, internally consistent, mass-balancing topographic evolution model is required.

Moreover, we have only investigated the effect of sedimentation in contractional mode, after the development of significant topography. This limitation is necessitated by the fact that the applied simple sedimentation model is not limited in the input of material into the models hence it is not applicable in situations where there is not enough topography to serve as a source for large amounts of sediments. The coupling of an internally consistent surface evolution model with FANTOM would allow us to study the effect of surface processes both in the extensional and the inversion modes.

Regarding the effects of extensional inheritance, we have used explicitly modeled, but very basic inherited structures. The matter could be further investigated with the use of more complex geometries such as adjacent rift basins.

Previously Allken et al. (2013) have shown, using the 3D variant of FANTOM, that rift interactions are best studied in three-dimensional setup. Hence an obvious next step would be to expand our models into the third dimension.

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