

# 1 Introduction

Mountain belts have always attracted human attention. They provide shelter against enemies and supply the economy with natural resources such as building materials or precious ores. Mountain belts are also a preferred site for recreation in a beautifully shaped landscape, although they are prone to devastating earthquakes and bedrock landslides. However, and most importantly for this study, mountain belts like the European Alps, the Pyrenees, the Himalayas, the Southern Alps of New Zealand, Taiwan or Borneo are a magnificent and impressive realisation of the probably subtle interplay between endogenic and exogenic geo-processes. Considerable amount of research, focussing on the kinematic and dynamic evolution of mountain belts in the broadest sense, has been carried out during the last two centuries and is still undertaken. Meanwhile our understanding of and our perspective on mountain belts has changed from the opening and closure of geosynclines to the collision of two continental plates and the partial subduction of one beneath the other (Fig. 1.1). The currently held concepts of continental collision zones involve a kinematic and a dynamic assumption. The former proposes that collisional orogens result from the partial subduction of continental lithosphere and accretion of crustal material (e. g., Willett et al., 1993; Storti et al., 2000). The dynamic assumption, which is commonly known as critical taper theory suggests that this subduction-accretion process leads to the formation of an orogenic wedge with a geometry controlled by the basal and internal mechanical properties (e. g., Davis et al., 1983; Willett et al., 2001). The reader is referred to chapter (3) for a more detailed description of both concepts.

With respect to the interplay between tectonics and climate, it has long been recognised that deformation in collisional orogens is a key fac-

tor in controlling the magnitude and location of erosion. Orogenic growth leads to topography, which may enhance monsoonal circulation, provide a rain-shadow and guides or even deflects the drainage pattern or the course of glaciers. Changes in topography may induce the rise or fall of the regional base-level to which rivers and glaciers adjust (Kutzbach et al., 1993; Hay, 1996). Following this view, erosion responds primarily to deformation. In contrast, recent field studies in the Southern Alps of New Zealand (Koons, 1990, 1995; Tippett and Hovius, 2000), in the European Alps (Schlunegger and Willett, 1999), in the Chugach/St. Elias Range of Southern Alaska (Meigs and Sauber, 2000; Sheaf et al., 2003), in the Andes (Horton, 1999; Montgomery et al., 2001), in Taiwan (Lin, 2000), in the Tien Shan (Pavlis et al., 1997; Strecker et al., 2003), and in the Himalayas (Zeitler, 1985; Zeitler et al., 2001; Wobus et al., 2003; Thiede et al., 2004) have shown that “the concentration of erosional energy leads to a similar concentration of mechanical energy” (Koons, 1990). These field studies indicate thus, that erosion influences the distribution of deformation within orogenic belts. This conclusion derives support from the critical taper theory, which links topography and tectonics in a convergent wedge and predicts that deformation should be very sensitive to mass redistributions by surface processes (e. g., Davis et al., 1983). In a more general perspective, mountain building and the influence of surface processes on deformation can also be understood in terms of the minimum work theory (Gutscher et al., 1998; Hardy et al., 1998; Masek and Duncan, 1998; Gerbault and Garcia-Castellanos, 2005). Within this concept, a thrust is either initiated or re-activated, if this process consumes the least gravitational and frictional work to accommodate convergence. Erosion for example decreases the load upon a thrust and reduces thus the gravitational and frictional work, which either promotes prolonged slip along or the re-activation of this thrust. Consequently, the formation of a new thrust within the foreland is retarded.

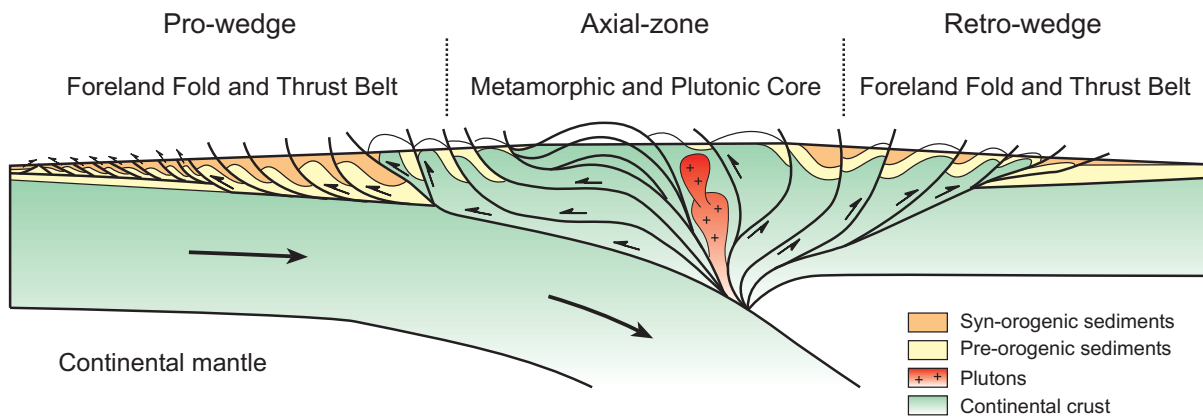


Figure 1.1: Conceptual model of a collisional orogen. Modified after McClay and Whitehouse (2004).

Numerical simulations (Beaumont et al., 1992; Willett et al., 1993; Avouac and Burov, 1996; Willett, 1999; Beaumont et al., 2001), which are based on the kinematic and the dynamic concepts outlined earlier, tested and verified the observations from the above mentioned field studies. The location of erosion with respect to the convergence geometry as a first order parameter controlling orogen-scale deformation has been identified by Beaumont et al. (1992), Willett et al. (1993) and Willett (1999). Accordingly, the asymmetry of erosion would have a profound influence on the distribution of deformation as well as on the amount and location of exhumation within a bivergent orogen (Fig. 1.2).

In addition, results from sandbox simulations suggest that synkinematic erosion promotes out-of-sequence thrusting in the axial-zone and the persistence of retroverging thrusts (Merle and Abidi, 1995; Mugnier et al., 1997; Storti et al., 2000; Marques and Cobbold, 2002; Del Castello et al., 2004; Persson et al., 2004).

Despite this considerable amount of research little is known about the influence of flexure, the mechanic stratigraphy or erosion on the kinematic evolution of bivergent wedges, or more specifically: (i) how is strain partitioned in time and space within a bivergent wedge; (ii) is there a strain pattern either in time or in space or even in

both domains, which can be predicted; (iii) what controls the relative magnitudes of in-sequence, synchronous and out-of-sequence thrusting and can that be predicted as well and (iv) what is the relation between the topographic evolution of and the strain history within a bivergent wedge.

Before these challenges are addressed in later chapters, an account on orogen-scale erosion is given first followed by a summary of concepts, which describe the kinematic and dynamic evolution of bivergent wedges. Based on these observations and concepts, constraints are identified to (i) respectively modify a 2D sandbox setup used in the Geodynamic Laboratory of the GFZ Potsdam and (ii) to generate an erosion model which can be incorporated into the sandbox simulations. Additionally, factors which support and justify the above approach, i. e., the scale invariance of brittle deformation as well as the similarity of the mechanic behaviour between upper crustal rocks in the brittle field and sand are discussed and the limitations of 2D sandbox experiments are indicated. An optical monitoring system, Particle Image Velocimetry, which provides time-series of the displacement field and all its derivatives such as the horizontal shear-strain ( $e_{xy}$ ), is used to employ a quantitative comparison between experiments ([section 4.3](#)).

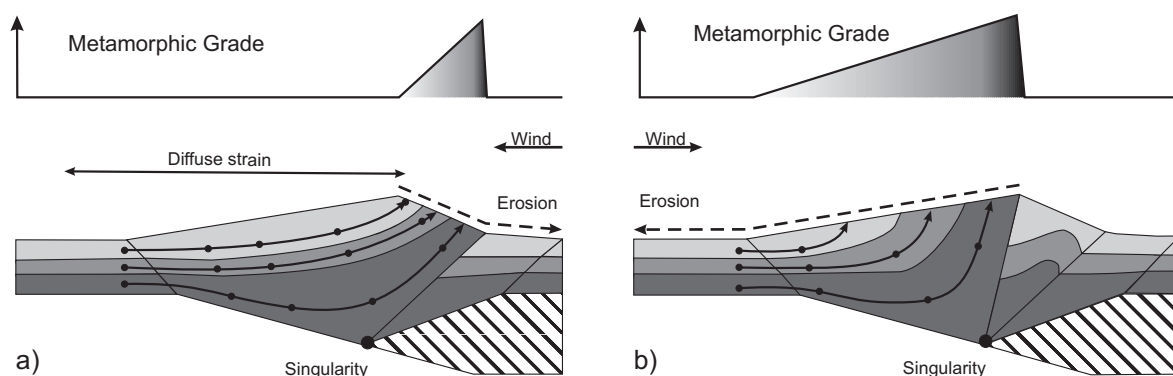


Figure 1.2: Influence of steady-state erosion on the distribution and magnitude of exhumation in a bivergent wedge. (a) Retro-wedge erosion. (b) Pro-wedge erosion. Lines are material trajectories; dots are progressive equal-time positions of points initially aligned vertically. Schematic metamorphic grade is for surface rocks assuming initial equilibrium conditions. Modified after Willett et al. (1993).

In chapter (5) the first set of five experiments aimed at investigating the influence of the imposed boundary conditions on wedge kinematics is presented. Experimental results suggest that the spatio-temporal distribution of deformation follows a distinct pattern, which is referred to as accretion cycle. Thereby, each accretion cycle consists of three phases: the thrust initiation, the underthrusting, and the re-activation phase, which determine the magnitude of strain on any given thrust within the bivergent wedge. Thus, the accretion cycle is considered as an internal clock for wedge-scaled deformation.

Changes of the boundary conditions evoke only minor modifications with respect to the duration and magnitude of individual phases. This underlines the robustness of the accretion cycle and allowed the derivation of a conceptual kinematic model. Thus, the spatio-temporal variability in strain accumulation is an emergent phenomenon of bivergent wedge-growth and there would be no need to invoke plate-kinematic changes or major climatic shifts to explain this variability. It is further highlighted that each accretion cycle is associated with a surface uplift wave. Thus, the strain wave migrating through the wedge is mirrored in a likewise surface uplift wave, which therefore provides a predictive potential.

Experimental results indicate also that boundary conditions, which can be considered as degrees of freedom, determine the relative magnitude of in-sequence, synchronous and out-of-sequence thrusting. Within this respect, I shall demonstrate that an increase of the number of degrees of freedom results in a likewise increase of synchronous and out-of-sequence thrusting. Thus, if the former is known, the latter is predictable. This issue derives its importance from the observation that only a limited number of different setups is in use and that they provide only few degrees of freedom (GeoMod 2004). It has only recently been shown that out-of-sequence thrusting within a forward breaking thrust-sequence is more common than previously assumed (McClay and Whitehouse, 2004). This emphasises, how models can guide one's perception of nature.

The above results are also discussed in the light of the link between geodetic, paleoseismologic and geologic estimates of fault slip (section 5.3). Limiting factors of the prediction of the timing and location of the next slip event are explored as well.

The second set of five experiments is used to investigate the influence of the location of erosion with respect to the convergence geometry on bivergent wedge kinematics. Thereby, special emphasis is devoted to the relative magnitude of in-se-

quence and out-of-sequence thrusting, to the topographic evolution and to the geometry of particle paths ([chapter 6](#)). Experimental results reveal that retro-wedge erosion accelerates the existing mass flux through the bivergent wedge and that pro-wedge erosion additionally redirects it. These experiments do also demonstrate that retro-wedge erosion enhances strain accumulation within the pro-wedge, thus pointing to a significant spatial offset of cause and response.

Erosion in mountain belts by rivers, glaciers or bedrock landslides can be considered to be either distributed over a wide area or to be very focused in space. Given the sensitivity of crustal wedges to erosion as outlined above, both erosion modes, which are considered as end-members, should evoke a characteristic deformation style ([section 6.3](#)). The respective experiments support the above cited quote from Peter Koons (1990) that the concentration of erosional energy leads to a similar concentration of mechanical energy. These results have been accepted for publication for the GSA Special Paper 398, *Tectonics, Climate and Landscape Evolution*, edited by S. Willett, N. Hovius, M. Brandon and D. Fisher.

It is further evident from the above observations that each erosion scenario is associated with a different orogenic load distribution, which in turn controls the spatio-temporal evolution of the adjacent foreland basins ([chapter 8](#)). This bears some implications for their respective facies architecture, especially the Flysch to Molasse transition, and the distribution of natural resources such as base metals or hydrocarbons. Within this respect, it can be noted that the migration of the forebulge and the associated unconformities, which are a preferred site for Mississippi Valley Type Deposits (MVT) is controlled by an eroding orogen hundreds of kilometres away.

Finally, we would like to emphasise two key points of the modelling approach followed during the course of this study. The first key target has been and still is the reduction of the number

of kinematic boundary conditions to allow a more self-organised growth of bivergent sand-wedges. In places where boundary conditions are necessary, explanations are given or natural pendants are provided. While writing these lines, a study is undertaken by Nina Kukowski, Jo Lohrmann and myself, which demonstrates that push and pull experiments with everything else being the same differ significantly with respect to the relative magnitudes of in sequence, synchronous and out-of-sequence thrusting. This observation emphasises again how models can guide one's perceptive of nature.

The second key target of this study is to provide testable predictions of observations to be made in natural orogens. Sandbox simulations are thus understood as an investigative tool to identify process chains, which can either, be proven or disproved in nature. The sandbox simulations presented here with their intermediate spatial scale in terms of their structural resolution may finally help to link results from lithospheric scaled numerical simulations with those from local to regional field studies.