Three-dimensional finite-element modelling

of the influence of erosion and sediment deposition

on the slip behaviour of faults

Von der Naturwissenschaftlichen Fakultät der

Gottfried Wilhelm Leibniz Universität Hannover

zur Erlangung des Grades

Doktorin der Naturwissenschaften

Dr. rer. nat.

genehmigte Dissertation

von

M.Sc. Heidi Anneli Turpeinen

geboren am 10.02.1978 in Vantaa (Finnland)

2013

Abstract

The landscape on the Earth´s surface has been continuously modified, which is obvious from evolving topography. Both mass redistribution on the surface due to erosion and sedimentation as well as tectonic deformation contribute to landscape evolution. To investigate the potential feedbacks between tectonics and surface processes in different tectonic settings, the experiments for this thesis are computed by using a subroutine called CASQUS that calculates and links the surface processes with a three-dimensional finite element model including discrete planar faults constructed with Abaqus Finite Element Analysis (FEA). Both the landscape evolution tool and the geomechanical model are fully coupled throughout the model run up to millions of years of model time. The series of experiments starts with an extensional tectonic regime considering a single normal fault and is then extended to arrays of normal faults. To investigate the impact of surface processes alone, the regional extension is stopped after a certain amount of model time but surface processes remain active. Finally, the interaction between surface processes and the evolution of blind thrust faults in a regime experiencing shortening is investigated. Experiments on model runs with different parameters such as diffusive hillslope processes, fluvial erosion as well as fault length indicate that surface processes affect the fault slip evolution in extensional regions where a fault reaches the surface. The amount of additional fault slip, erosion and sedimentation vary for different parameters, whereas the diffusion constant as well as fault length and dip have the strongest impact on the fault slip and subsequent landscape evolution. Thus the faults accumulate up to 200 m more displacement if erosion and sedimentation are applied on the model surface. The erosion and sedimentation rates both vary between 30 and 80 m/Ma. When the far-field extension ceases, surface processes may lead to prolonged fault slip of up to several million years. The additional fault slip after cessation of regional extension reaches up to 160 m. A correlation between fault slip evolution, mass redistribution and differential stress is also observed. Irrespectively of the depth of the fault top edge applied in this study, blind thrusts are not affected by surface processes but the propagation of hidden faults lead to formation of growth folds on the model surface which, in turn, is subject to surface processes. This study provides an insight into the feedback mechanisms between surface processes and tectonics in different tectonic settings. The findings contribute to better understanding of spatial and temporal distribution of tectonic activity with respect to surface processes. In addition, the findings contribute to the research of hazards generated by mass redistribution on the Earth´s surface.

Keywords*: numerical modelling, landscape evolution, fault slip evolution*

Zusammenfassung

Die sich kontinuierlich entwickelnde Erdoberfläche wird beeinflusst sowohl von Massenumlagerung, d.h. Erosion und Sedimentation, als auch durch tektonische Verformung. Um mögliche Rückkopplungsmechanismen zwischen tektonischer Aktivität und Oberflächenprozessen in unterschiedlichen tektonischen Regimes zu untersuchen, werden die Experimente in dieser Studie mit Hilfe der Software CASQUS berechnet. Diese berechnet und koppelt die Oberflächenprozesse mit einem in Abaqus Finite Element Analysis (FEA) konstruierten, drei-dimensionalen Finite - Elemente Model, welches auch planare Störungen enthält. Beide Programme sind vollständig gekoppelt während der gesamten Laufzeit der Modelle bis zu Millionen Jahre. Die Versuchsreihe beginnt mit einem Modell, in dem die Erdkruste gedehnt wird. Nach isolierten Abschiebungen werden die Versuche auf mehrere Abschiebungen erweitert. Um den tatsächlichen Einfluss von Oberflächenprozessen zu testen, wird die regionale Dehnung des Modells nach einer bestimmten Zeit gestoppt, aber Oberflächenprozesse bleiben weiterhin aktiv. Die Experimente zum Schluss untersuchen die Wechselwirkung von Oberflächenprozessen und Evolution von blinden Störungen in Regionen, in denen die Erdkruste verkürzt wird. In den Testreihen wird der Einfluss von Parametern wie diffusive Prozesse auf dem Berghang, fluviale Erosion und Störungslänge sowie Einfallswinkel untersucht. Die Ergebnisse zeigen, dass Oberflächenprozesse beeinflussen die Evolution von Störungen in Regionen, wo die Kruste gedehnt wird und die Störungen die Erdoberfläche erreichen. Die Menge der zusätzlichen Bewegung auf der Störungsfläche variiert bei unterschiedlichen Parametern, wobei sowohl diffusive Prozesse als auch Störungslänge und Einfallswinkel einen stärkeren Einfluss auf die Störung zeigen. Die Bewegung einzelner Störungen ist bis zu 200 m mehr, wenn Oberflächenprozesse aktiv sind. Die Erosions- und Sedimentationsraten variieren zwischen 30 und 80 m/Ma. Wenn die regionale Dehnung endet, können Oberflächenprozesse dazu führen, dass Störungen weiterhin über mehrere Millionen Jahre aktiv bleiben. Die Bewegung der Störungen nach dem Ende der regionalen Dehnung kann dann bis zu 160 m erreichen. Es besteht eine Korrelation zwischen der Evolution von Störungen, Massenumlagerung und Differentialspannung. Unabhängig von der Tiefe, die in dieser Studie für die Störungsoberkante verwendet werden, haben Oberflächenprozesse keinen wesentlichen Einfluss auf die Evolution von Störungen. Die Bewegung einer blinden Störung führt jedoch zur Formation von Falten an der Modelloberfläche, welche durch Oberflächenprozesse verändert wird. Diese Studie bietet einen Einblick in die Mechanismen der Wechselwirkung zwischen Oberflächenprozessen und tektonischer Aktivität unter unterschiedlichen tektonischen Bedingungen. Die Erkenntnisse leisten einen Beitrag zum besseren Verständnis der räumlichen und zeitlichen Verteilung von tektonischer Aktivität und Oberflächenprozessen. Dazu steuern die Rückschlüsse aus dieser Studie bei der Forschung von Gefahren durch Massenumlagerung an der Erdoberfläche bei.

Schlagwörter: *numerische Modellierung, Evolution von Erdoberfläche, Entwicklung von Störungen*

Contents

1. Introduction

In regions undergoing active tectonics, the mass redistribution in a landscape due to surface processes affects tectonic deformation and vice versa *(e.g. Molnar and England, 1990; Burbank and Pinter, 1999)*. In the brittle upper crust, this deformation is typically accommodated by faults. The mode of movement along fault planes is in general controlled by the tectonic setting and ultimately by the orientation of the principal stresses *(e.g. Anderson, 1952; Richardson et al., 1979)*. For example, if the crust is extended (normal faults) or shortened (thrust/reverse faults), the maximum principal stress is vertical or horizontal, respectively. The initiation and further evolution of faults depend, among other factors, on the strength of surroundings and on the initial fault length and dip *(Hardy and Finch, 2006; Burrato et al, 2012; Albertz and Lingrey, 2012)* as well as on the boundary conditions controlling the crustal deformation rate.

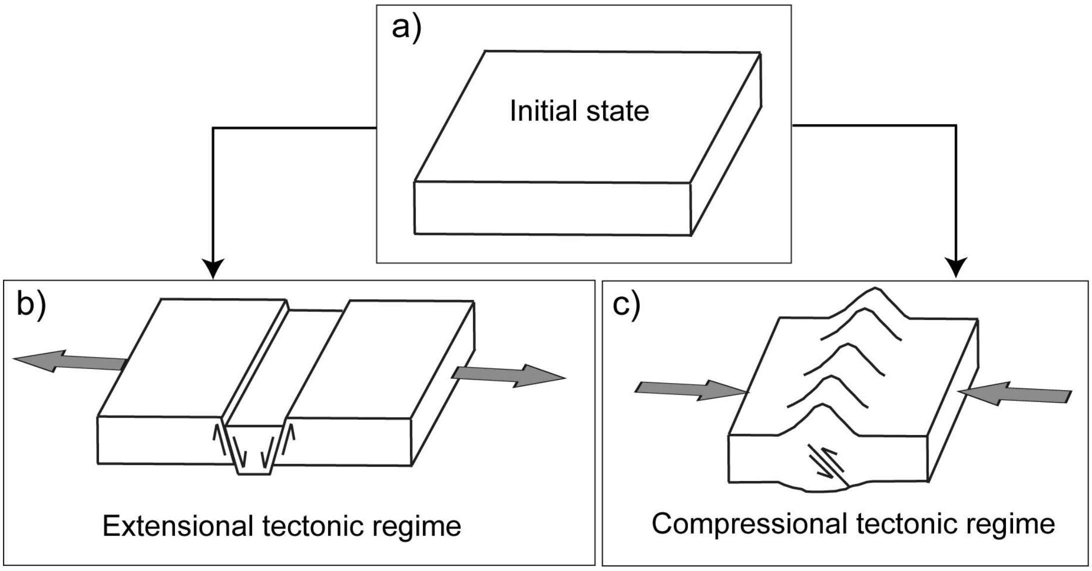


Figure 1: Simplified schematic sketch of deformation mechanisms. *a)* Initial state of the crust, *b)* an example of the deformation within an extensional tectonic regime and *c)* subsequent deformation during shortening.

Active extension or shortening of the continental crust over millions of years leads to the growth of faults and topography *(Cowie and Scholz, 1992a; Dawers et al., 1993; Nicol et al., 1997; Walsh et al., 2002; Nicol et al., 2005).* A simplified sketch of different crustal deformation mechanics is illustrated in *Figure 1*. Depending on the orientation of the faults, large-scale extension leads to formation of horst or graben structures *(e.g. Eaton, 1982) (Figure 1b)*. In contrast, a compressional tectonic regime results in folding and local thickening of the crust *(Figure 1c)*. A natural example of an area in an extensional setting that spans over almost 3000 km length and up to 1000 km width is the Basin-and-Range Province in the western U.S. *(e.g. Eaton, 1982; Wernicke and Snow, 1998; Ellis and Densmore, 1999; Wernicke et al., 2000; Niemi et al., 2004)*. More localized crustal extension leads to the formation of rifts and graben systems, such as in the North Sea *(e.g. Gabrielsen et al., 2001)* or the Gulf of Corinth *(e.g. Briole et al., 2000; Sachpazi et al., 2003; Avallone et al., 2004; Sakellariou et al., 2007; Taylor et al., 2011).* In contrast, a prominent example of a tectonic setting experiencing crustal shortening and subsequent thrusting and folding is provided by the Himalayas *(e.g. Avouac et al., 1993; Burbank et al., 1996; de Celles et al., 2002; Long et al., 2011).* The Apennines in Italy represent another, younger fold and thrust belt, where both shortening and extension contribute to the formation of the mountain range *(e.g. Roberts and Michetti, 2004; Palumbo et al., 2004; Roberts, 2006).* An example of a normal fault in the central Apennines is shown in *Figure 2*.

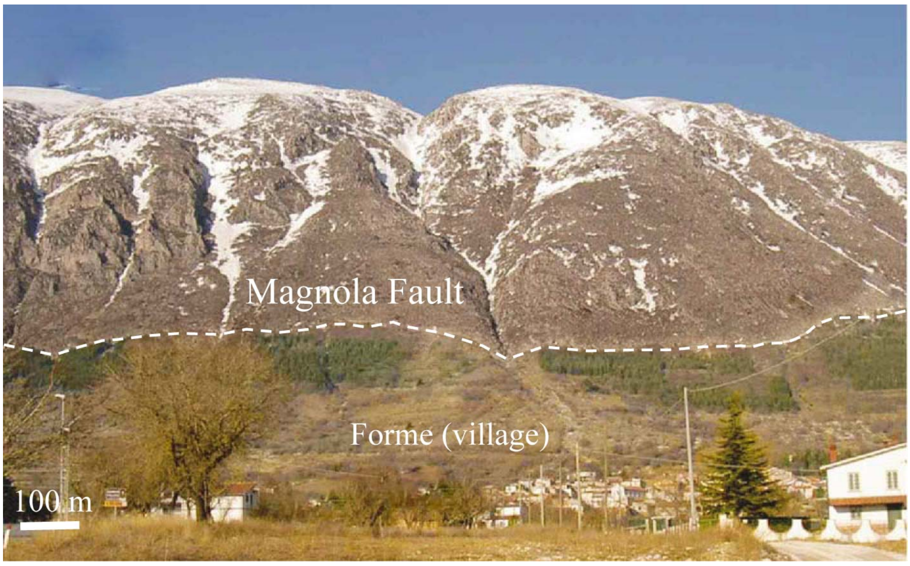


Figure 2: The Magnola fault in the Apennines, central Italy. The fault trace is marked by the dashed white line. Modified after *Palumbo et al. (2005)*.

In some regions the fault remains blind below overlying sediments *(Hardy and Finch, 2006).* However, when subjected to crustal shortening, these faults may induce a fault-propagation fold at the surface as more and more displacement is accumulated by the fault at depth *(e.g. Ellis and Densmore, 2006).* Such folds are present for instance, below the Los Angeles area *(e.g. Shaw and Suppe, 1994; Pratt et al, 2002; Dolan et al., 2003; Lin and Stein, 2006)*.

The evolution of a fault-bounded topography through time is controlled by erosion and tectonically induced uplift *(Harbor, 1997; Densmore et al., 1998).* Erosion affects the Earth´s surface continuously but since the erosion rate is controlled by climatic conditions and by the resistance of the exhumed material, spatial and temporal variations in both denudation and sedimentation rates are possible *(Burbank and Anderson, 2012)*. Local variations in erosion rates probably due to monsoon rain are known from the Lesser Himalaya, where the erosion rate of 0.2 mm/a is significantly lower than in the Greater Himalaya, where the erosion partially occurs at rates of up to 0.8 mm/a *(e.g. Wobus et al, 2005)*. Variable erosion rates of 0.5 to 1.3 mm/a, when averaged over 10´000–100´000 years, occur also in the Teflon Peaks in the western Alaska Range, where the extreme relief of up to 5 km results from different rock types with varying material resistivity *(Ward et al., 2012).*

The interaction of surface processes and tectonics has received increasing interest since the beginning of the 1990s (e.g. *Molnar and England, 1990; Burbank and Pinter, 1999; Whipple and Meade, 2006)*. Besides by geological field studies (e.g. *Montgomery and Brandon, 2002; Trudgill, 2002; Densmore et al., 2004; Kirby and Whipple, 2012)*, the feedback mechanisms between tectonics and surface processes have been investigated by using numerical methods (e.g. *Koons, 1989; Kooi and Beaumont, 1994; Avouac and Burov, 1996; Braun and Sambridge, 1997;Densmore et al., 1998; Ellis et al., 1999; Willett et al., 2001; Garcia-Castellanos, 2002; Fischer et al., 2004; Simpson, 2004a; Cowie et al., 2006; Pysklywec, 2006; Bishop, 2007; Burov and Toussaint, 2007; Braun et al., 2008; Tomkin, 2009; Godard and Burbank, 2011)* but also analogue modelling on different scale *(e.g. Mugnier et al., 1997; Bonnet and Crave, 2003; Malavieille and Konstantinovskaya, 2010).*

An example of the numerical experiments considering landscape evolution carried out by *Braun and Sambridge (1997)* is shown in *Figure 3*. The 100 km by 100 km wide model surface consists of 10´000 nodes, which are connected via an irregular grid. The total run time of the experiment was 1 Ma, which includes 10 000 steps of 100 a length. In each step and at each node, the removal and deposition of sediments is simulated using the CASCADE-algorithm *(see Chapter 2 of this work or Braun and Sambridge, 1997)*. *Figure 3a* shows the model surface after 1000 time steps (after 100 ka). Since the grid is self-adaptive, i.e. nodes are automatically added if needed, the formation of rivers is recognisable as a denser grid. At the end of the model run after 10 000 time steps (after 1 Ma) the rivers have propagated towards the centre of the model and are more branched, which is obvious from *Figure 3b*. The topographic surface and the channel network at the end of the model run are shown in *Figure 3c.*The topographic elevation is up to 1 km and the intervals of the topographic contours are 0.2 km between 0 and 1 km. The dark areas represent a low topography, which is induced by the formation of the river network. The light areas reflect higher elevation and the black areas represent lakes.

Another example of a numerical model is provided by *Willet et al. (2001)*, who used a surface process model modified after *Braun and Sambridge (1997)*. The numerical

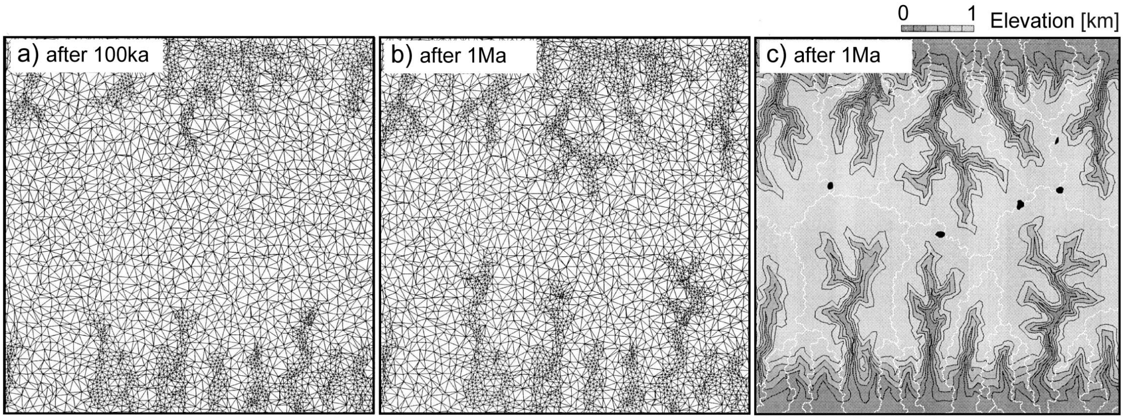
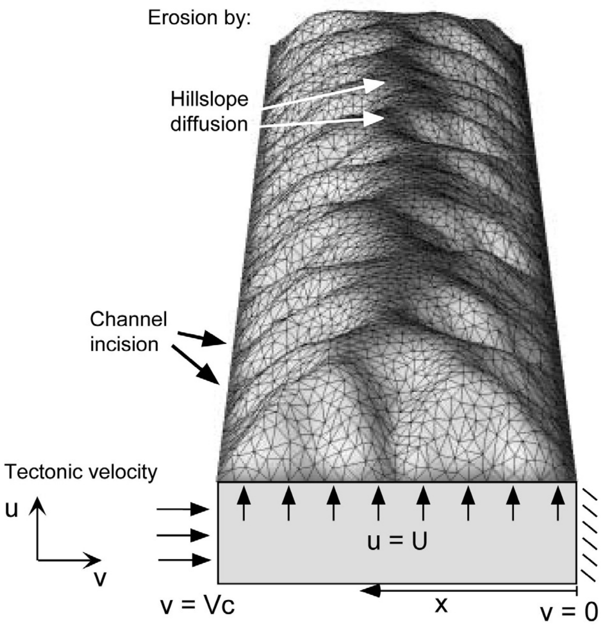


Figure 3: The landscape evolution model by *Braun and Sambridge (1997). a)* Model surface with the irregular grid after 100 ka of model time. *b)* After 1 Ma the river network is more evolved, which is indicated by the locally denser grid. *c)* Topographic surface and the channel network after 1 Ma. The topographic contours are indicated by thin black lines and the topographic elevation is up to 1 km, whereas the intervals are 0.2 km between 0 and 1 km. The dark areas represent a low topography, the light areas reflect higher elevation. The black areas represent lakes.

models of *Willet et al. (2001)* include both tectonic uplift and horizontal velocity, whereas all surface edges are fixed at elevation. The number of elements on the irregular grid is allowed to increase as the landscape evolves. The model surface resulting from the interplay of these parameters is shown in *Figure 4*. The convergence velocity V_c is applied on one side only and decreases to zero on the opposite side. The uplifted topography is eroded by diffusive hillslope processes on elevated areas as well as channel incision on the river beds.

Figure 4: Model by *Willet et al. (2001)* which contains both tectonic and erosive components. The model edges remain at a fixed elevation. The shortening is limited to the left side only and the velocity (Vc) may vary between zero and the actual convergence velocity, depending on the setting used in different experiments. Note the irregular grid on the surface. Erosion affects the uplifted surface via diffusive hillslope processes and the river beds are subjected to channel incision (modified after *Willet et al., 2001)*.



The investigations on surface displacement through time as well as the interaction between surface processes and tectonics indicate that when numerical modelling is combined with algorithms considering the effect of surface processes on a large amount of surface nodes (> 10´000), the resulting topography and drainage network generated by the synthetic models significantly resembles to that of natural landscapes. A comparison is shown in *Figure 5* which illustrates the contour plot of topography on a numerical model of *Braun and Sambridge (1997) (a)* as well as a natural example showing the Snowy Mountains is Australia *(b)*. In both figures, the river branching and general distribution of streams show similar behaviour.

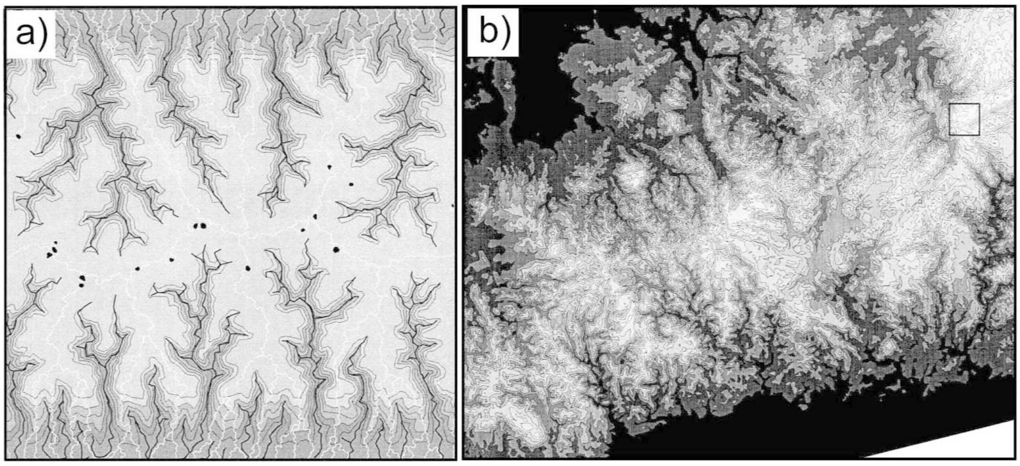


Figure 5: Comparison of a numerical model with a natural example *(modified after Braun and Sambridge, 1997)*. Contour maps of *a)* a numerical model and *b)* the Snowy Mountains in south-eastern Australia. The rectangle in *b)* shows the location of the Mount Kosciusko (2230 m).

The landscape evolution models introduced above include tectonics only as very simplified boundary conditions and do not consider the presence of faults. Numerical models with more evolved implemented tectonics, some adjusted to specific natural landscapes, are provided for example by *Cowie et al. (2006), Fischer (2006); Braun et al.(2008), Petit et al., (2009), Tomkin (2009)*, *Upton et al. (2009)* and *Koons et al. (2010). Fischer (2006)* used the finite-element method to investigate the effect of rheological parameters on the surface deformation in the Aegian-Anatolian region. The model setup included different boundary conditions as well as layers with varying material properties determined by seismological studies. Surface processes were not included in this model, since it was not within the scope of the study. *Upton et al. (2009)* used three-dimensional mechanical models to investigate the behaviour of compressive wedges. Erosion was implemented as a mass removing boundary condition, which was varied spatially and temporally. One of the first attempts to couple tectonic models with models implementing surface processes was established by *Cowie et al. (2006)*, who investigated the response of surface process to fault interaction. In their study, the tectonic model represents a two-dimensional Earth´s surface, which is affected by faults throughout the model run. The surface processes did not affect the tectonic evolution but the results from the tectonic model were afterwards coupled with the results from a model simulating the surface processes *(CASCADE by Braun and Sambridge, 1997)*. Hence, it was a one-way coupled model *(cf. Cowie et al., 2006).*

Analysis of the feedback between surface processes and tectonics using fully coupled three-dimensional finite-element models including discrete faults, erosion and sediment deposition was first introduced by *Maniatis et al. (2009*). In their study a three-dimensional tectonic model including one or more faults *(e.g. Maniatis and Hampel, 2008; Hampel et al., 2009)* was created by using the commercial finite-element software Abaqus FEA (*Dassault Systèmes Simulia Corp.; Hibbit et al., 2008*). This model was fully coupled to the landscape evolution model CASCADE *(Braun and Sambridge, 1997)* by the software tool CASQUS *(Kurfeß, 2008; Kurfeß and Heidbach, 2009).*

The model results showed that erosion and sedimentation may lead to increased fault slip rate by affecting the fault displacement at depth (*Maniatis et al., 2009*). The experiments revealed, that surface processes lead to up to ~15 % higher slip rates, for both isolated faults and fault arrays, when compared with model runs carried out without surface processes. The parameter study shows that the intensity of surface processes is primarily controlled by the fault length, dip and the resulting displacement rate as well as the diffusion constant controlling diffusive hillslope processes. The impact of the fluvial erosion constant, that comprises the stream erosion and the precipitation rate, on the fault slip accumulation is rather small when compared to the effect of other parameters (*Maniatis et al., 2009*).

The key issue of this thesis was to investigate the impact of surface processes on the fault slip evolution and the resulting topography in settings including one or more faults. Another aim was to study the potential ability of surface processes to prolong faulting even after the far-field tectonic boundary conditions have ceased. Also the distribution of fault displacement within an array as well as the feedback between interacting neighbouring faults was investigated. The finite element technique using the fully coupled models adopted by *Maniatis et al. (2009)* is applied to all experiments used for this thesis. The parameters varied depend on the model setup and include for example different fault length and dip as well as variable parameters controlling the surface processes. The basic model setup and the modelling technique are described in detail in *Chapter 2*. *Chapter 3* comprises the results from the first set of experiments with single normal faults. The experiments were used to investigate the potential interaction of fault slip accumulation and surface processes after cessation of regional extension. *Chapter 4* describes the effect of surface processes on fault arrays. In different experiments, the arrays consist of 4 or 6 normal faults. Besides the effect of the position of a fault in an array on the fault slip evolution of each fault, the feedback between individual faults was investigated. Also the effect of cessation of extension on fault arrays was studied. The last model setup described in *Chapter 5* considers blind thrust faults, where the depth of the fault top edge below the model surface is varied. Afterwards, the results from all experiments in this thesis are discussed in *Chapter 6*.