1. Introduction

The aim of this dissertation is to quantify scaling relations of strain accumulation in nature on various temporal and spatial scales, in order to characterize the underlying deformation mechanisms, and to answer the questions 1) if strain accumulation is scale-invariant or if it occurs in characteristic patterns with typical structural lengths and durations, and 2) how a deformation system and its strain pattern is influenced by parameter changes (Chapter 2). It hereby focuses on the orogen scale and the next smaller “regional” scale, which includes fault networks as well as single faults and shear zones within geological timespans of millions of years (Ma). To date, these scales representing the upper magnitudes are the least studied in literature.

As a base for (geo)statistical analysis (Chapter 3), I compiled a comprehensive database on deformation activity (published in Oncken et al., 2006) using the natural example of the Central Andean plateau (17-27°S, 69-63°W; Chapter 4). This allows to detect characteristic structural lengths and deformational patterns in time on the above mentioned two scales (Chapter 5). The natural data set is complemented by artificial data sets from two different series of analogue experiments (a granular series and a brittle-viscous series), to cover the “time scales” in between earthquakes and long-term deformation, allowing the analysis of parameter effects on the patterns of strain accumulation.

Hence, I can examine 1) combinations of controlling parameters, that reproduce the spatiotemporal strain distribution observed in the Central Andes (Chapter 6); 2) the effect of parameter changes (in particular mechanical heterogeneities) on the resulting deformational pattern (Chapter 6 and 7); and 3) the effect of parameter changes on the strain pattern of both the orogen and the regional scale and their interaction (Chapter 7).

The experiments were monitored by a special camera system employing “particle imaging velocimetry” (PIV), which allows the calculation of the complete particle displacement field. It provides high resolution of deformation both in space and time. This also allows the quantification of temporal and spatial variation and interaction of strain accumulation within and across structures of the analogue data (Chapter 8). Placing the results for the upper scales in the context of general scaling relations, I discuss their significance for the underlying deformation mechanisms, comment on potential consequences for geological studies, and give an outlook on future research (Chapter 9).

STRUCTURE OF THESIS

Apart from the introduction (Chapter 1), the dissertation is divided into eight further chapters: a review of the common deformation frameworks, scaling relations and their dependence on parameter changes (Chapter 2); a description of the applied methods (Chapter 3); a description of the tectonic setting of the Central Andean plateau (Chapter 4); three scientific manuscripts for publication in international peer-reviewed journals (Chapter 5, 6, 7); additional analogue data (Chapter 8); and conclusions with outlook on future research (Chapter 9). The appendix includes all references used in any of the chapters, the deformation database used in Chapter 5, more geostatistical data, data for the sensitivity analysis, a short documentation on all performed granular experiments with set-up sketches, material properties of vise experiments, acknowledgments, and a CV.

DESCRIPTION OF CHAPTERS

Chapter 1 presents the main objective and structure of the thesis and the topics of the following eight chapters.

Chapter 2 reviews the main deformation frameworks and their characteristic structures. It is likely that not a single framework is dominant for strain accumulation at a given time, but that more than one are either coinciding (both in a spatial and temporal sense) or alternating. Previous studies have either focused on spatial scales on or below the regional scale excluding the orogen scale, or are only applicable to plate margins. More research has been done on the comparison of displacement rates on the geological timescale vs. seismic events (Friedrich et al., 2003; 2004), which often does not cover the intermediate time scales (Leffler et al., 1997; Liu et al., 2002; Klosko et al., 2002). However, the given examples suggest the existence of deformation patterns in time, probably overprinting each other and therefore not to be discriminated in the field. Scaling relations are further complicated by the effect of both internal and external parameters and their changes over time, which do not necessarily occur on the same scale.

Chapter 3 introduces the applied methods, i.e., (geo)statistics and analogue modelling with the particle imaging velocimetry (PIV) technique. I present the advantages of these methods, but also point out the technical limitations confining the data interpretation.

Chapter 4 provides an overview on the geodynamic setting of the Central Andean plateau, the characteristics of the Altiplano and Puna plateaux and their differences.

Chapter 5 is the first in the series of scientific manuscripts and examines if critical spatial and temporal patterns are present in the distribution of strain accumulation in the Central Andes (17°-27°S) on the orogen scale, and how these patterns are influenced by active deformation on the smaller regional scale. The analyzed deformation data were compiled from literature and are included in the appendix A (database was previously published in Oncken et al., 2006). The data are rearranged into one million year steps (comprising a total of 46 million years) and further analyzed by means of frequency statistics and geostatistics including variogram analysis.

Chapter 6 shows results from the first analogue series, in which the upper crust is modelled with granular materials. In two set-ups of different dimensions (and therefore different geometric scaling factors), numerous parameters were tested on their influence on the resulting strain accumulation pattern. They included system internal factors, namely horizontal and lateral mechanical heterogeneities, and external parameters such as erosion and indentation by a curved plate.

Chapter 7 discusses results from the second analogue series (“vise models”), where brittle material is used for the upper crust and viscous materials are employed for the lower crust and mantle lithosphere (these layers rest isostatically on the asthenosphere). With this series I studied the initial conditions that have to be met in a system to initiate plateau formation.

Chapter 8 provides additional PIV analogue data, that have the potential for quantification of variation and interaction of strain accumulation both within and across active structures, including their changes over time. Also, PIV data of incremental velocity fields allow the comparison to their natural analog: GPS data.

Chapter 9 links previous chapters 5, 6, 7, and 8, and puts their main conclusions in the broader context of deformation frameworks. I illustrate the dissertation’s contribution to the ongoing scientific debate, present consequences and drawbacks for the geoscientific community and discuss open questions for future research.

SCIENTIFIC MANUSCRIPTS

Chapter 5, 6, and 7 are scientific manuscripts that will be submitted to peer-reviewed journals, or are already under review. K. Schemmann is responsible for the scientific content and has written all of them. The contribution of co-authors is stated below.

Chapter 5 is titled “Orogen-wide patterns of strain accumulation – the Andean case” by K. Schemmann, O. Oncken and A. Levander and will be submitted to Geochemistry, Geophysics, Geosystems in a revised form including data from Chapter 5 and 9. K. Schemmann is responsible for scientific ideas, the choice and implementation of methods and the scientific content of the manuscript. O. Oncken helped to improve the readability of the manuscript. A. Levander provided input and programming codes for the computation of data (cf. Chapter 9).

Chapter 6 bears the title “The effect of mechanical heterogeneity on diversification of deformation patterns - A modelling study with granular media” by K. Schemmann and O. Oncken. The first author carried out all analogue experiments and is responsible for the scientific content, ideas and interpretation. O. Oncken provided useful feedback and helped to strengthen the manuscript. The manuscript is submitted to Tectonophysics.

Chapter 7 is called “The effect of mechanical heterogeneity on plateau initiation - A modelling study with viscous-brittle media” by K. Schemmann, D. Boutelier, O. Oncken and A.R. Cruden. The analogue experiments were carried out at the Tectonophysics Laboratory, University of Toronto, with which D. Boutelier and A.R. Cruden are affiliated. These authors shared their experience with viscous analogue modelling and previous vise models (Cruden et al., 2006), and discussed the experimental results. All co-authors reviewed earlier versions of the manuscript to increase its coherence and strength. The manuscript is submitted to Tectonophysics.

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