PROFESSOR STEFAN SCHMALHOLZ

The evolution of the Alps

Professor Stefan Schmalholz describes his latest geoscience research project focusing on the numerical simulation of fold nappe dynamics and tectonic evolution in the Western Swiss Alps

Could you discuss the overall aims of your current project? What are the ways in which you propose to investigate how nappes form with respect to physical processes?

The aim of our project is to better understand the thermomechanical processes that generated fold nappes and the tectonic evolution of the Alps which consist of a large number of nappes. Nearly all models explaining the formation of fold nappes are geometric, ie. they are not based on fundamental laws of physics and do not consider flow laws for rocks. Such flow laws are mathematical equations which describe the strength and deformation behaviour of rocks and have been derived from laboratory experiments.

In our project, we build on the basic configuration of existing geometric models. Our models are mathematically based on the principles of thermomechanics and take into consideration existing flow laws. We perform numerical simulations, ie. we solve the mathematical equations describing the formation of fold nappes on modern computers. We also determine the configuration and model parameters that provide results which agree best with the observed geology of fold nappes. In addition, we want to understand which processes are the dominant processes during fold nappe formation for generating a simple and comprehensible mathematical model.

How does the finite element method (FEM) simulate three-dimensional (3D) fluid flow and the formation of 3D fold nappes? Is it accurate or could improvements be made?

The deformation of material bodies such as rocks can be described within the theory of continuum mechanics. Continuum mechanics is based on fundamental laws of physics such as mass and energy conservation and provides a system of partial differential equations (PDEs) which are usually nonlinear. The FEM is a method for transforming these PDEs to linear equations. Only linear equations can be solved by a computer. The FEM is well established and our understanding of fold nappes can be advanced by improving the system of PDEs (eg. including equations coupling heat transfer and deformation), the model configuration or the flow laws that describe rock deformation.

What advantages do numerical methods have over more traditional ones used to study the dynamic processes acting during fold nappe formation?

In the past, mostly laboratory experiments were used to study the formation of fold nappes. Their advantage is that a real deformation process can be investigated and that all experiments are 3D. However, with laboratory experiments it is difficult to scale gravity stresses correctly, to use materials in the experiments exhibiting a similar dependence of strength on temperature as rocks, to quantify accurately stresses and temperatures, and to consider the change in material behaviour from ductile to brittle when the rocks cool during tectonic deformation. Therefore, more and more numerical simulations (eg. based on the FEM) are used to study the dynamic processes during fold nappe formation.

With a particular focus on controversial topics, what were the objectives of the GeoMod conference, organised and held by your group in July of this year? Were some surprising results shared?

One particular controversial topic discussed in the conference was the magnitude of pressure in the crust and lithosphere during mountain building. Most geologists assume that the pressure at any depth is simply determined by the load of the overlying rocks and therefore it is easy to correlate pressure with depth. Some researchers think that pressures can locally deviate strongly from lithostatic pressure, especially in tectonically-active regions such as continent collision zones. I found that, among the participating researchers with a background in mechanics and rock deformation, there was a consensus that significant pressure deviations are possible and feasible. In contrast, in the geological and mineralogical community significant deviations are generally considered unrealistic.

Are there wider implications that these results will have for the field of physics and for society more generally?

Our mathematical models are often based on existing models of mechanics and we apply them to tectonic processes which have particular time, length and stress scales. Typical results of our work are dimensionless parameters which consist of a number of physical parameters (eg. temperature) and which control the tectonic process. In the context of physics then, our work shows how to scale a basic physical process to geological processes.

A better understanding of how rocks deformed during tectonic processes is important for constructing infrastructure (eg. streets, tunnels, etc.), for geological risk assessments (eg. rock fall, landslides, etc.), energy recovery (eg. geothermal energy) or for detecting ore deposits.

The Morcles fold nappe

A new study of Alpine fold nappes aims to extend our knowledge of the geology of the Alps, which may have profound implications for resource exploitation, construction and security in the region

THE GEOLOGY OF the Alps has been studied for over 200 years. Therefore, there is a plethora of knowledge and information including geological maps and cross sections as well as seismic observations. But the tectonic evolution of these mountains still remains something of a mystery. This knowledge is necessary for the subsequent exploitation of resources, the facilitation of constructions and for security reasons for those who live or travel through these mountains.

The surface of the Earth is made of lithospheric plates which are distinguished in two types: the oceanic and the continental. The oceanic plates sink into the Earth's interior whereas continental plates stay on the surface. When continental plates collide, they are shortened and compressed while the rock units of their upper parts break or develop folds and move on top of each other, forming so-called nappes. The Alps are made of such nappes which are of two kinds: the fold nappes and thrust sheets. A thrust sheet is a rock unit with a sheet-like geometry that behaves like a solid body and shows only slight internal deformation. A fold nappe, on the other hand, is characterised by significant internal deformation and stratigraphic inversion at its base and behaves like a viscous body. Fold nappes show constant shearing direction and a nonlinear increase of shear strain towards their overturned limb with a mylonitic zone at their base. They appear to be formed by heterogeneous simple shear in crustal shear zones.

One fold nappe is the Morcles nappe in the Western Alps. Although nappes have been studied in detail, the mechanics by which they are formed and the thermomechanical processes that generated the Alps are still incompletely understood. The reason is that the geology of the Alps is very complicated and the rocks are highly heterogeneous. In addition, geological processes take place on vastly different scales: from the microscale to kilometre scale. Most models that already exist, which explain the first-order features of the Morcles nappe, are only kinematic. They do not take into consideration the principles of physics and completely ignore the rheology. Thus, it remains unclear whether they are physically plausible, whether they can be applied to the thermomechanical conditions of the Morcles nappe or whether they can be used for other nappes in the world.

ONE-DIMENSIONAL MODEL

The study of the thermomechanics of ductile shear zones that are common deformations in orogenic belts can shed light on the dynamics of mountain building. Kilometre-scale shear zones in the crust are characterised by a nonlinear increase of finite strain at the shear zone's base similar to fold nappes. For this reason, it has been suggested that fold nappes are formed by heterogeneous simple shear found in these shear zones. Although the geometry and kinematics of shear zones have been investigated in recent years, there have not been any studies that could make the connection between observed finite strain gradients and the thermomechanical process of shearing.

Therefore, a new study by Arthur Bauville and Professor Stefan Schmalholz covers this gap in knowledge by providing a simple one-dimensional (1D) thermomechanical model to explain the finite strain gradient in kilometre-scale shear zones of various mountain belts. Their model takes into account the dislocation creep flow law and temperature dependent viscosity. Even though it is simplified, it is comprehensible and depends on a single parameter for the strain gradient: the parameter β. This parameter is based on the activation energy of the applied flow law, the temperature at the base of the shear zone and the temperature difference across it. Bauville and Schmalholz's model describes the strain evolution and the first-order features of the Morcles fold nappe such as its geometry, kinematics and dynamics, and has been used to find the main cause for the nonlinear finite strain gradient, which turned out to be the temperature increase towards the shear zone's base and the decrease in viscosity. However, other factors not considered in the model such as the grain size reduction or viscous heating must have played a role in the evolution of the shear zone, especially close to its base.

HIGHER-DIMENSIONAL SIMULATIONS

Another new project led by Schmalholz focuses on the dynamics of fold nappe formation and, in particular, the evolution

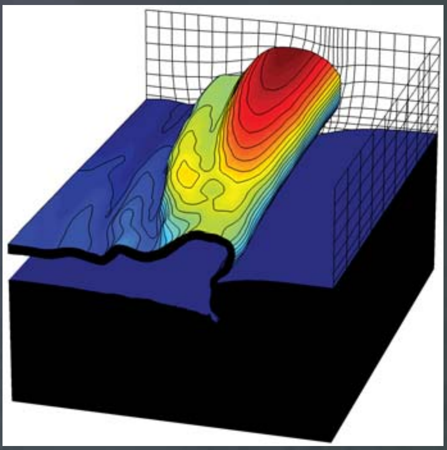

FIGURE 1. 3D NUMERICAL RESULT OF A FOLD NAPPE SIMULATION

The dynamic models constructed in the studies by Schmalholz and his collaborators can contribute to a better understanding of the formation of fold nappes which are not only found in the Alps but also in other mountain belts

of fold nappes in the Western Swiss Alps. It is divided into two main studies which investigate and describe two processes: first, the strain formation of recumbent and asymmetric folds with overturned limbs and the parasitic fold in ductile multilayers; and second, the evolution of finite strain during 3D fold nappe formation with an emphasis on fold-axis parallel extension as well as bending and rotation.

In the first study, performed by Bauville, numerical simulations are used to observe the impact that the initial geometry, boundary conditions, rheology and material properties have on the fold shapes, parasitic folds and the fold nappe geometry. The simulations yield the distribution of the finite strain ellipses and the distribution of the shear around the folded layers, and these distributions are compared with field observations.

The second study, performed by Marina von Tscharner, offers another numerical model to explain the dynamics of ductile fold nappes in 3D and to determine the 3D deformation and finite strain patterns. An improved numerical algorithm tested by Schmalholz is used in the study. Numerical simulations model 3D ductile fold nappe formations, measure the evolution of 3D finite strain ellipsoids during folding and quantify the amount of fold-axis parallel extension, bending and rotation and the impact of geometry, boundary conditions and material properties on the fold axis deformation.

For the above studies, dynamic models are applied based on numerical algorithms. Field work and structural analyses are also performed. The modelled and field data are compared for the construction of valid numerical models of fold nappe formation that match the structural features of the natural fold nappes.

Dynamic models work in accordance with physical laws as opposed to geometric models, and offer less, though more plausible answers about the tectonic evolution of a geological structure. They also use proven concepts of continuum mechanics and flow laws for rocks. These models can identify both the mechanical process that dominates the fold nappe formation and the physical parameters that control this process, and therefore improve our understanding of the dynamics of fold nappe formation.

FUTURE RESEARCH

The dynamic models constructed in the studies by Schmalholz and his collaborators can contribute to a better understanding of the formation of fold nappes which are not only found in the Alps but also in other mountain belts. In addition, the numerical algorithms can be extended for future research and applied to orogenic dynamics in general and not just Alpine tectonics, and the 2D and 3D numerical models can be used to assess zones of intense deformation and for risk analysis of constructions. They can also be used in teaching and in the dissemination of research results.

The models offer valuable information about the geometry, kinematic evolution, incremental and finite strain, foliation orientation, temperature and pressure distributions that can eventually be compared with field data. They can be combined with optimisation algorithms to determine the parameters that are in accordance with observations and, ultimately, they can advance the study of the rheology of rocks that form the continental lithosphere and explicate the formation of lithospheric deformation structures such as mountain ranges, continental rifts and sedimentary basins.

INTELLIGENCE

TOWARDS UNDERSTANDING FOLD NAPPE DYNAMICS IN THE WESTERN SWISS ALPS

OBJECTIVES

- To identify the dominant process during fold nappe formation and the physical parameters that control this process
- To develop a simple and comprehensible thermomechanical model for the Morcles fold nappe
- To better understand the three-dimensional tectonic evolution of the Morcles-Doldenhorn nappe system

KEY COLLABORATORS

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received his PhD from ETH Zürich in 2000, and then worked as a researcher at the University of Oslo and ETH Zürich. He was appointed Full Professor of Tectonics and Geodynamics at the University of Lausanne in 2010. His research focuses on applying continuum mechanics and computational methods to study tectonic processes and the resulting deformation structures in rock.

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