

# Chapter 1

## Introduction

Geodynamics is a subfield of geophysics aimed at revealing and explaining the internal deformation processes shaping the solid Earth. Since we cannot make direct observations of the deformation taking place in Earth's interior, geophysicists are limited to using proxies and remote sensing techniques. One especially powerful family of tools is the observation of seismic anisotropy, or the direction-dependence of seismic wave velocities. These tools are capable of probing the deformation processes in the Earth's interior. In my PhD research, summarized in this thesis, I combined geodynamical modeling with seismic observations to investigate deformation processes in the Earth's upper mantle.

Anisotropy, the dependence of physical properties on the measuring direction, is often a direct outcome of the deformation of rocks. When rocks deform, they can develop a fabric, which results in the anisotropy of properties such as elasticity, viscosity and conductivity. This fabric records the history of deformation and can thus serve as a constraint for models of mantle flow and geodynamic evolution.

My initial investigation of anisotropy was through observations of seismic anisotropy in Eastern Tibet. I measured shear-wave splitting in a data set recorded by an array of seismometers deployed by MIT in Eastern Tibet for 2 years, in order to probe seismic anisotropy in the lithosphere beneath the region. The purpose of the project was to map deformation in the mantle lithosphere and compare it with observed deformation in the crust, in order to constrain the rheology of the lithosphere in the region. Such constraints

are necessary in order to settle some longstanding debates, for example the one regarding the coupling of the crust and the mantle and the strength of the lower crust. Furthermore, only a couple of years after we concluded our investigation in Eastern Tibet, the very same region was hit by the devastating Wenchuan earthquake (M8.0), a terrible disaster that pointed out again the importance of improving our understanding of this region and the forces controlling it. My observations, though, revealed a regional heterogeneity, which demonstrated that the discussion of the deformation history of Eastern Tibet needs to include a larger scope of regional processes. My work in Eastern Tibet, including details about the data and the methods I used, is described in chapter 2.

When rocks develop a fabric or a preferred orientation, their mechanical properties also become direction-dependent, similar to their elastic/seismic properties. Until recently, the vast majority of geodynamical models for the mantle neglected this fact, and assumed the material had isotropic viscosity. Even models used for predicting seismic anisotropy, thus inherently assuming the developing of preferred orientations, usually failed to account for the anisotropy of viscosity. In my thesis, I revisited this assumption by comparing models with and without anisotropic viscosity for several fluid dynamics situations.

First, I looked at Rayleigh-Taylor instabilities, a classic fluid dynamics problem describing the flow occurring when a layer of a dense fluid is placed over a layer of a more buoyant fluid. This situation is relevant to geodynamics on many scales, from magma fingering, through diapirs to lithosphere instability. Through a combination of analytical solutions and numerical finite-element experiments I found that the wavelength of Rayleigh-Taylor instabilities strongly depends on the orientation of the pre-existing anisotropy. My numerical experiments also demonstrated that contact locations between regions with different anisotropy orientations are particularly prone to develop instability. The results and some of their interesting implications are presented in Chapter 3.

Next, I included anisotropic viscosity in models of slab subduction. Anisotropic viscosity led to a change in the thermal structure of subduction zone wedges, resulting in time variability and a decrease in melt production in the wedge, without requiring any changes in subduction speed or angle. The anisotropic viscosity leads to smaller melt fluxes and

partial-melting region in the wedge and to widening of the region dominated by power-law creep.

Lastly, I examined the influence of the degree of anisotropic viscosity and of grain size, two important rheological parameters that are generally poorly constrained, on the development of the confined layer of anisotropy at the top of the convecting upper mantle. I found that the plate velocity and the derived strain rate do not have a large influence on the localization of shear and power-law creep. The grain size and the degree of anisotropic viscosity, on the other hand, are important. I found that a grain size larger than 10mm gives the best fit to the seismic observations; The ratio of shear viscosity to normal viscosity needs to be 0.3 or more, depending on grain size.

During my modeling efforts, I had to ensure that the numerical method I employed to track the anisotropy in the models – the directors method - was accurate and loyal to natural processes of fabric development. I conducted a rigorous comparison of this method with two other popular methods for fabric prediction, as well as with laboratory measurements. The findings are described in chapter 6. I estimated the trade-offs between accuracy and computational efficiency, and concluded that, after some calibration and adjustment, the directors method provides an appropriate solution for fabric prediction in applications where calculation speed is important. This kind of benchmarking is an essential part of the world of numerical modeling. For geodynamical models to be relevant, one must ensure that approximations are made carefully and are appropriate. Open communication between geodynamicists and the rock mechanics and mineral physics communities are required for achieving this goal, as we demonstrated in the efforts that have gone into this thesis with respect to fabric development and anisotropy. In addition, great progress can be made by adapting tools developed in other disciplines. An example are the tools developed by glaciologists to model deformation of anisotropic ice, which may be adapted for the mantle.

To summarize, the work presented in this thesis describes a step forward in the on-going effort to harness the power of anisotropy, through a combination of geodynamical modeling and seismic observations, in order to improve our understanding of deformation and flow in the Earth's interior. Chapter 2 gives an example of how observations of seismic anisotropy

has changed our view of the tectonic forces controlling deformation in one particular area – Eastern Tibet. This thesis proves that such self-consistency in the prediction of and accounting for anisotropy is crucial, by showing the dramatic effect of anisotropic viscosity on the development of the upper mantle layered anisotropy structure 5, Rayleigh-Taylor instabilities (Chapter 3), and the thermal structure of the subduction zone mantle wedge (chapter 4). The technique we use in our models is discussed in detail in chapter 6.