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Processes and Properties controlling the Formation of lithosphere-scale Shear Zones

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Contents

1 Introduction

When the theory of plate tectonics was first proposed, it was opposed by geophysicists that argued that the proposed force to drive late tectonics (the Coriolis force) was way too small to drive such a system. The discovery of a convecting mantle as the driving force later in the 20th century helped plate tectonics to be established as the unifying theory that was able to explain a lot of geological and geophysical phenomena.
However, although plate tectonics is able to explain such a variety of observables, the principal remaining question still remains:

How are tectonic plates generated from mantle convection?

In the past, both the plates and the convecting mantle were seen as two separate systems that were coupled to each other by some mechanism. Therefore, research in both fields focused on only one of the two systems. This research has doubtless led to significant improvement of our understanding of the Earth (Bercovici and Ricard, 2003).
With the rapid evolution in computational geodynamics (due to the rapid increase in computing power), it has been possible to model mantle convection in two and three dimensions in both cartesian and spherical geometry (e.g. Christensen, 1984; Christensen and Yuen, 1985; Zhong and Gurnis, 1995; Bunge et al., 1996; Tackley, 2000a; van Heck and Tackley, 2008). However, mantle convection models using a relatively simple Newtonian or Non-newtonian rheology tend to form a stagnant lid, meaning that the whole lithosphere forms one rigid layer where no more deformation takes place. This behaviour is clearly not observed on Earth today.
Mantle convection models using more complex rheologies (e.g. Moresi and Solomatov (1998); Tackley (2000a); van Heck and Tackley (2008)) have been able to reproduce plate-like behaviour in two and three dimensions for cartesian and spherical geometries. This was achieved by implementing a yield stress criterion which limits the maximum amount of stress a material can sustain. The term yield stress means that a viscous fluid is allowed to behave as a viscous fluid until the stress reaches a limit above which the deformation is no longer dependent on the stress, but remains constant.
A drawback of those models is that the employed yield stress is relatively low when being compared to yield stress envelopes that are derived from laboratory measurements (it is about one order of magnitude lower).
Other models that have been successful in creating plate tectonics from mantle convection used prescribed weak zones. Those models were built for studying the deformation inside the plates and the influence of mantle flow on the geoid and topography. The viscosity of those weak faults was also chosen ad hoc (in order to fit the observables) and does not represent weakening due to any physical process.
The number of the proposed weakening processes that could lead to such localized zones of

deformation is manyfold and the efficiency of each process as well as the conditions where each of them is active are not known exactly. This thesis aims at adressing some of the questions that relate to the creation of lithospheric-scale shear zones and the initiation of subduction.

2 State of Research

2.1 Subduction Initiation: hypotheses

According to Stern (2004), there are two types of subduction initiation, one type being spontaneous and the other type being induced. Generally, spontaneous subduction is thought to initiate when oceanic lithosphere cools and therefore becomes denser with age, until it is sufficiently heavy to sink into the underlying mantle. However, as has been shown by McKenzie (1977), frictional and elastic forces in the lithosphere prevent this to happen. Induced subduction zones, on the other hand, are defined as being compressed by external forces (such as existing plate motions), which ultimately leads to rupturing of the lithosphere. The forces that are necessary to rupture the whole lithosphere though, are quite high and it is not clear if plate motion forces would be sufficient to create a subduction zone. Additionally, a laterally homogenous lithosphere would just thicken under compression. Although there are a multitude of heterogeneities in the lithosphere, the length scale of a heterogeneity that is needed to induce whole lithosphere failure is still unknown.

Spontaneous as well as induced initiation of subduction zones has been investigated using analytical, experimental and numerical approaches. The analytical approach usually consists of evaluating the different forces in the lithosphere using a highly simplified model. This drawback is also an advantage, since this simplification only allows for an analytical solution. Experimental approaches to subduction initiation do allow for a little more complexity than analytical approaches, since the choice of materials that can be scaled to Earth materials is limited and laboratory setups only allow certain conditions (e.g the gravity is always directed downwards and cannot be changed except in centrifugal experiments).

The approach that allows for the highest complexity is the numerical approach, where the governing equations (in the case of lithospheric and mantle deformation the Stokes equations) are solved using a numerical method. Many of the recent scientific breakthroughs have only been possible due to the ongoing evolution of computational geodynamics. One of the big caveats of numerical modeling is the possibility of the high complexity, since the essential physics that govern the models might be disguised by the multitude of processes that are active.

2.1.1 Spontaneous subduction initiation

Stern (2004) divided the models for spontaneous subduction initiation in two subclasses, one being the collapse at a passive margin, the other being the collapse at a transform fault. Both classes have been investigated using different approaches. On the analytical side, McKenzie (1977), and Mueller and Phillips (1991) conclude in their works that spontaneous subduction is unlikely to be caused by gravitational stresses alone using simplified models of the lithosphere with a prescribed fault zone. However, depending on the angle of the fault zone and on the reduction in viscosity, there are numerical models which successfully initiate subduction (e.g. Gerya et al. (2008)). In analogue models, spontaneous subduction is not even possible in a free subduction setup where there is no overriding plate due to surface tension. Subduction is usually started in those models by pushing the tip of the slab down by hand (Funiciello et al., 2003).
Since the boundary between spontaneous and induced subduction models is somewhat unclear, a spontaneous subduction initiation model is defined here as a model where there are no prescribed external forces needed to initiate subduction. However, if there are forces inside the model that arise in a self-consistent manner, the model can still be considered as being spontaneous. In this sense, there is an additional set of models for spontaneous subduction initiation, which is either caused by a redistribution of masses on the surface by either erosion/sedimentation or viscous relaxation (e.g. Cloetingh et al., 1982; Regenauer-Lieb et al., 2001; Mart et al., 2005; Nikolaeva et al., 2010) or by convective instabilities below the lithosphere (e.g. Solomatov, 2004; Ueda et al., 2008).
On the boundary between spontaneous and induced subduction initiation lies the model that was proposed by Regenauer-Lieb et al. (2001), where a sedimentary pile was built up on top of a lithosphere, however, this pile had no source located inside the model.
It is striking that most of the work that is described above focuses on passive margins as the preferred locations for subduction initiation. However, Mueller and Phillips (1991) pointed out that transform faults and intraoceanic fracture zones may as well be favorable for subduction initation.

2.1.2 Induced subduction initiation

Since spontaneous subduction initiation is not achieved easily and requires forces that are higher than the so-called ridge-push and the gravitational instability due to thickening (e.g. McKenzie, 1977; Mueller and Phillips, 1991), several authors have been investigating the initiation of subduction if there is an external force compressing the lithosphere. Laboratory experiments (e.g. Shemenda, 1992; Faccenna et al., 1999) have shown that subduction initiation is possible for a certain range of parameters and materials (of which the choice is limited) in the presence of an external compressing force. However, it is not clear if the processes in

those models resulting in subduction are comparable to the processes on Earth.
In order to be able to test subduction initiation with Earth-like parameters, the group of Michael Gurnis has conducted several numerical experiments (e.g. Toth and Gurnis, 1998; Hall et al., 2003; Gurnis et al., 2004). In their experiments, they also included a weak zone with variable inclination. Their results are somewhat opposed to the ones by Gerya et al. (2008), since it is stated in Hall et al. (2003) that compression is needed for initiating subduction, while Gerya et al. (2008) obtains spontaneous subduction with a similar setup.

2.2 Subduction initiation in mantle convection models

The models described above, being for spontaneous or induces subduction initiation, all operate on a lithospheric scale, meaning that neither of them takes into account the whole convecting mantle below the lithosphere. On the other hand, mantle convection models usually do not take into account a crust on top of the lithosphere (mostly because of resolution issues). Additionally, the resolution in mantle convection models is usually too low to resolve brittle shear zones properly. Recent advances in numerical techniques have made it possible to resolve shear zones (Stadler et al., 2010), however, it is still computationally expensive to run those models. This is why mantle convection modelers (as well as analogue modelers) remain on a quest for the simplest effective rheology that leads to subduction for Earth-like parameters. This rheology might contain several mechanisms but result in appropriate behaviour.

2.3 Weakening mechanisms

Looking at the range of models for subduction initiation, it is striking how many of them need an initial weak zone in order to initiate subduction (this is seen in all approaches). In fact, the analytical results obtained by e.g. McKenzie (1977), or Mueller and Phillips (1991) as well as numerical results obtained by e.g. Toth and Gurnis (1998) all assume a preexisting fault zone that cuts the whole lithosphere. In some cases this weak zone is related to hydrated mantle rocks, in other cases it is associated with deep fracture zones. However, these weak zones are usually prescribed somewhat ad hoc and do not use a specific physical process that is responsible for the weakening that gives rise to a lithospheric-scale shear zone.
Strain localization in the ductile regime has been successfully modeled by several authors using an ad hoc strain weakening mechanism (e.g. Frederiksen and Braun, 2001; Mancktelow, 2006), where strain weakening was prescribed using an arctangent curve like viscosity reduction with increasing strain by Frederiksen and Braun (2001), while Mancktelow (2006) used a bell-shaped curve to describe this weakening. Although both models show very efficient strain localization, they do not answer the question about the physical cause for this weakening.
The cause for this weakening has been a subject of lively research in the last decade and several

mechanisms have been put forward as possible candidates. There are several requirements for the "perfect" weakening mechanism that are not entirely met by each of the proposed mechanisms: first of all, the mechanism should be efficient enough to reduce the effective viscosity by several orders of magnitude in order to allow for localization. Second, the mechanism should provide for some "memory" of the strain history (Gurnis et al., 2000).

2.3.1 Two-phase damage rheology

Although there are many definitions of damage rheology (oftentimes used as another term for strain weakening rheology), damage rheology is primarily used for the self-lubricating rheology resulting from void production (Bercovici, 1998) and the filling of those voids with fluids (e.g. melt, water). The viscosity in this damage rheology is based on the porosity (or void fraction) of the medium.Bercovici (1998) showed that this rheology can lead to a localizing behaviour under certain conditions.
The theoretical foundation for this type of rheology was given by Bercovici et al. (2001a) who derived the fully coupled equations for the two-phase damage rheology, coupling the two phases (in this case the rock matrix and the voids) through their exchange in surface energy. In two subsequent publications, Bercovici et al. (2001b); Ricard et al. (2001) demonstrated the potential of such a rheology in terms of shear localization and plate tectonics.
Under high pressures, damage related to void generation is hard to achieve, since the opening of a void is resisted by the pressure. In this case, grain size reduction would be a more feasible damage mechanism. This relation was used by Tackley (2000b) in three-dimensional mantle convection models and Auth and Bercovici (2003) in two-dimensional convection simulations, who came to somewhat opposing results. Tackley (2000b) concluded that the damage effect of such a rheology was too high and that it lead to a breakdown of plates into even smaller ones, whereas Auth and Bercovici (2003) concluded from 2D models that this type of rheology leads to an acceptable plate-like behaviour. The effect of void-generating damage versus grain size reducing (or fineness-generating) damage has been investigated by Bercovici and Ricard (2005) in a 2D source-sink setup, while Landuyt and Bercovici (2009) worked on the competition between void-generating damage and grain size reducing damage in one dimension. Both damage types promote localization (for a range of parameters), but the pressure increase with depth clearly works in favor of the fineness-generating damage. However, since considering two fully coupled phases leads to an increased number of unknowns and equations, the solution of those equations is computationally more expensive. Additionally, the parameters that are used in those equations are highly unknown and it is unclear to what parameters they relate in nature.

2.3.2 Crystal preferred orientation (CPO) of Olivine

Olivine is a strongly anisotropic mineral, which can be strongly seen in seismic anisotropy (e.g. Fuchs, 1977). This anisotropy can be explained by a preferred orientation of the olivine minerals due to selected active slip-systems (see review by Park and Levin (2002) and references therein for a more extensive description of seismic anisotropy). This anisotropy can the be numerically modeled and related to the observed anisotropy, thus allowing to infer possible deformation mechanisms in the mantle (e.g. Tommasi et al., 1999).
Tommasi et al. (2009) showed that this type of mechanical anisotropy provides for a memory effect, since the crystal anisotropy is stored in the structure and that the weakening due to the evolving anisotropy can provide shear localization. Although the memory requirement is met by this mechanism, it does not significantly reduce the effective viscosity.

2.3.3 Grain Size Reduction

Grain size reduction has already partly been treated in the description of two-phase damage rheologies, but the approach to this phenomena in context of damage rheology is purely theoretical. Experimentalists as well as field geologists have much earlier noted that shear zones are characterized by a considerably smaller grain size than the surrounding rock (e.g. White et al., 1980; van der Wal et al., 1993; Warren and Hirth, 2006). This process is related to subgrain rotation and/or grain boundary migration during deformation (see Meer et al. (2002) for a more thorough review of this topic). With ongoing grain size reduction, the dominant deformation mechanism might switch from dislocation creep to diffusion creep, which operates under significantly lower stresses and thus promote localization Bürgmann and Dresen (2008).
Although the process of dynamic recrystallization is well understood in a qualitative manner, there is a significant amount of uncertainty concerning its quantitative description. This has led to a significant amount of different laws describing the process of dynamic recrystallization (Bresser et al., 2001). Until recently, grain size was usually seen as an indicator of the stress in a shear zone (e.g. van der Wal et al., 1993; Stipp and Tullis, 2003). Austin and Evans (2007) proposed an alternative approach, suggesting that recrystallized grain size is not simply a function of stress, but rather of the deformational work (which is the product of stress and strain rate). These findings are in agreement with analytically derived laws from two-phase flow theory (Ricard and Bercovici (2009), Rozel et al. (subm.)).
It is still debated if grain size reduction is an effective process to promote localization (Bresser et al., 2001). Some of the proposed flow laws have been implemented in numerical simulations (Kameyama and Yuen, 1997; Braun et al., 1999; Montési and Hirth, 2003) and found that it might promote localization, however, the parameter space of this mechanism is

highly unconstrained and localization occurs only for a small range of parameters.

2.3.4 Dry Grain Boundary Sliding

Dry Grain boundary sliding has been proposed as an additional mechanism operating between dislocation and diffusion creep, consequently being a mixture of both mechanisms Hirth and Kohlstedt (2003). Warren and Hirth (2006) and Precigout et al. (2007) presented some field evidence for this mechanism. Its effect on localization was studies using 1D numerical models by Précigout and Gueydan (2009), but it is unclear if it also leads to localization in higher-dimensional models. Furthermore, Précigout and Gueydan (2009) used a piezometric grain size evolution law that only allows for grain size reduction. As stated above, the parameters for those grain size evolution laws are highly unconstrained. It is not yet clear hw those parameters affect the localization process.

2.3.5 Shear Heating

Shear heating (or strain heating) has been proposed as a mechanism to cause deep focus (Ogawa, 1987) and intermediate-depth (Kelemen and Hirth, 2007). Although there is less geological evidence for shear heating in lithospheric-scale shear zones (e.g. Nabelek and Liu, 1999; Camacho et al., 2001; John et al., 2009), this process has been studied to a great extent using analytical and numerical models.
Analytical works by Yuen and Schubert (1979)and Brun and Cobbold (1980) concluded that shear heating can lead to a substantial increase in temperature in shear zones and result in partial melting. More recently, the works by Kaus and Podladchikov (2006) and Braeck et al. (2009) explored this mechanism in more detail for viscoelastoplastic materials and derived scaling laws for the onset of localization.
For more geologically relevant setups, the importance of shear heating has been shown by various authors (e.g. Regenauer-Lieb et al., 2001; Burg and Schmalholz, 2008), although the physics behind in those setups was not completely understood. Crameri and Kaus (2010) used the setup from Burg and Schmalholz (2008) and derived a scaling law that allows to predict the onset of localization in such models using 1D numerical models.

2.3.6 Role of Fluids

Partial melt as well as water (H_20 or H being incorporated in a crystal lattice) generally decrease the effective viscosity of a rock (Hirth and Kohlstedt, 1995; Renner et al., 2000; Hirth and Kohlstedt, 2003; Mei and Kohlstedt, 2000a,b). Apart from parameterizations, free fluids can also influence the deformation behaviour significantly, since their pressure decreases the effective stress. Modelling this kind of behaviour is only possible using a set of equations that takes into account both the fluid as well as the solid phase (McKenzie, 1984; Connolly and Podladchikov, 2000; Simpson et al., 2010).

3 PhD thesis

3.1 Motivation and key questions

Although there have been many developments and key breakthroughs in recent years (as described in section 2), a wide variety of questions concerning the enigma of plate tectonics on Earth remains. Especially the evolution of lithospheric scale shear zones and the initiation of subduction is a very interesting field of research that involves a lot of different In this thesis, we want to try to find the answers for a certain set of questions.

1. What is the role of different weakening mechanisms in the formation of lithospheric-scale shear zones ?
2. How (if possible) can we link microstructural processes to large-scale geodynamics of the lithosphere ?
3. What are the essential physics behind those processes and what parameters control them?
4. Does the creation of a lithospheric-scale shear zone always result in the formation of a subduction zone ?
5. What are the available forces created by mantle convection and are those sufficient to induce lithospheric-scale shear localization ?

3.2 Methodology

To answer this set of questions, we use numerical modeling in order to investigate the role of different mechanisms in the localization process of lithospheric-scale shear zones on their efficiency. For this purpose, the 2D finite element code MILAMIN_VEP is used for initial numerical studies in order to investigate the influence of different parameters on the behaviour and efficiency of several mechanisms that have been proposed to promote shear localization. However, since numerical models are usually fairly complex and the physics that control the behaviour of the respective models are somewhat unclear, numerical modeling in itself is not sufficient to grasp the governing physics. For this purpose, scaling laws have to be derived that allow to predict the behaviour of the models and let us determine the conditions under which the different mechanisms are active and efficient.

3.3 Software and Hardware

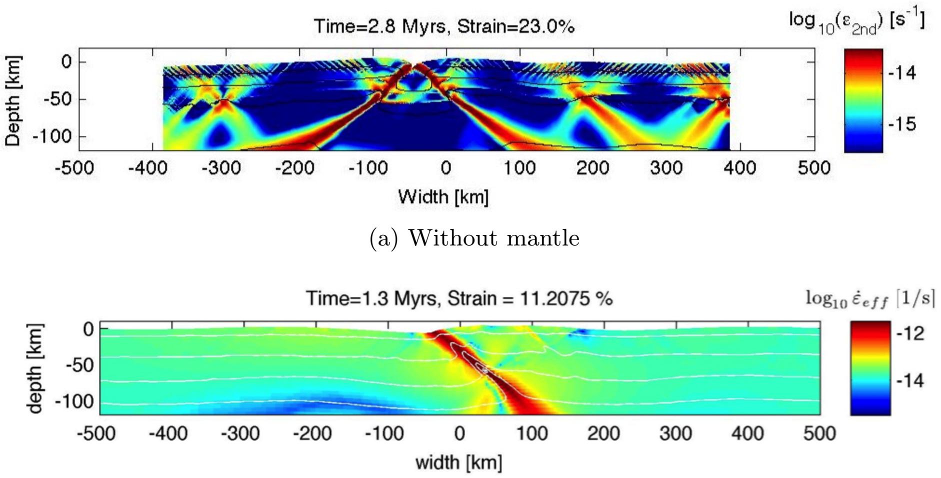
The software used in this thesis is mainly MATLAB, which is also the language in which the code MILAMIN_VEP is programmed in. MILAMIN_VEP is a finite element code based on MILAMIN which was developed by Dabrowski et al. (2008) and solves the Stokes equations for slow viscous flow with an infinite Prandtl number. MILAMIN code is entirely written in MATLAB and makes use of several techniques to optimize performance (e.g. loop blocking). For additional better performance, Powell-Hestenes iterations are used where velocity and pressure are decoupled and solved in an iterative manner (Cuvelier et al., 1988). The decoupled systems of equations are solved using direct solvers.
Simulations are performed on the ETH cluster Brutus.

3.4 Work done

The formation of lithospheric shear zones has been studied in detail by Crameri and Kaus (2010). They were able to derive a scaling law which allows for prediction of shear localization without having to use extensive numerical codes. However, the 2D models that were used to verify their predicition did not take into account an underlying asthenospheric mantle, and could therefore not study the subsequent subduction stage. Therefore, the model that was used in their study was extended to greater depths.
The style of localization changes significantly due to the asthenospheric mantle (see fig.1). Instead of multiple shear zones, just one shear zone is formed due to the ability of the slab to bend down freely without being hindered by a lower boundary. Consequently, the strain rate inside this single shear zone is significantly higher and therefore also the temperature rise. It is also striking that localization occurs earlier in the extended models (at around 10% strain compared to about 20% strain in the models by Crameri and Kaus (2010)), which is in better agreement with the 1D predictions.

This boundary condition does not affect the localization process significantly, but since the mantle flow field is influenced by the boundary condition to a great extent, model behaviour in the post-localization stage is strongly dependent on the applied boundary conditions.
Although the boundary conditions might not be applicable to real cases, the question whether the formation of a lithospheric-scale shear zone necessarily results in a subduction zone can already be partly addressed. As can be seen in fig.2, if forced convergence does result in the formation of a lithospheric-scale shear zone, it is not always followed by subduction. At the present state, three different cases can be distinguished:

Small-scale convection: As can be seen in fig.2, localization can be successfully inhibited by small scale convection. This behaviour can be seen when background strainrates are small. In this case, the velocity with which the slab is pushed down into the mantle is so low that the slab tip is heated significantly. This results in significant weakening of



(a) Without mantle

(b) With mantle

Figure 1: Example illustrating the effect of an underlying mantle on localization style. The upper model has a depth of 120 km, whereas the lower models has a depth of 660 km with otherwise identical parameters. It can be clearly seen that without taking an underlying mantle into account, localization occurs in several shear zones that take up the prescribed deformation. Only a single shear zone develops when an asthenospheric mantle added into the model. This results in a significant higher strain rate inside the shear zone as well as a higher temperature increase.

the slab, which allows material to drip off the slab tip. The dripping off then initiates small-scale convection which erodes the base of the lithosphere as well as the incoming slab tip.

Rising slab: In this case (see fig3), the slab is first pushed down into the underlying mantle. However, due to the light and thick crust, it does not penetrate further into the mantle, but rises after a short descent and underplates the overriding lithosphere.

Self-consistent subduction: In this case, the localization stage is followed by subduction. The steepening of the slab shows that the slab pull force is greater than the pushing force.

The numerical code also had to be changed to allow for different deformation mechanisms which can operate in parallel. In the course of this change, it turned out that it was more practical to use a different input structure which facilitates the handling of input parameters. Benchmarking of the modified code is ongoing.

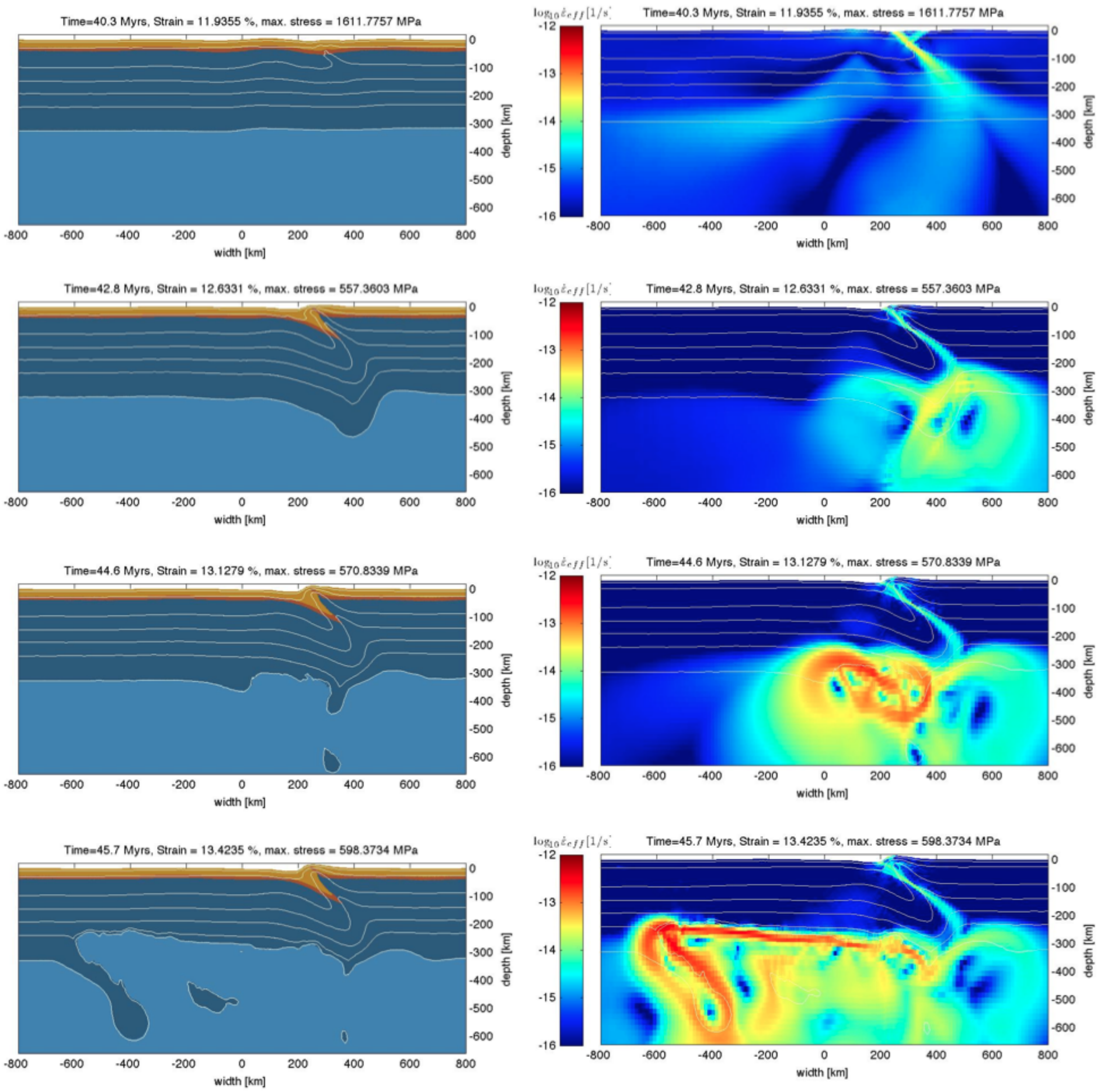


Figure 2: Example of a run where a continental lithosphere was compressed with a constant background strainrate $\dot{\varepsilon}_{BG} = 1e - 16[1/s]$. The left column shows particle distribution, the right column shows second invariant of strainrate.

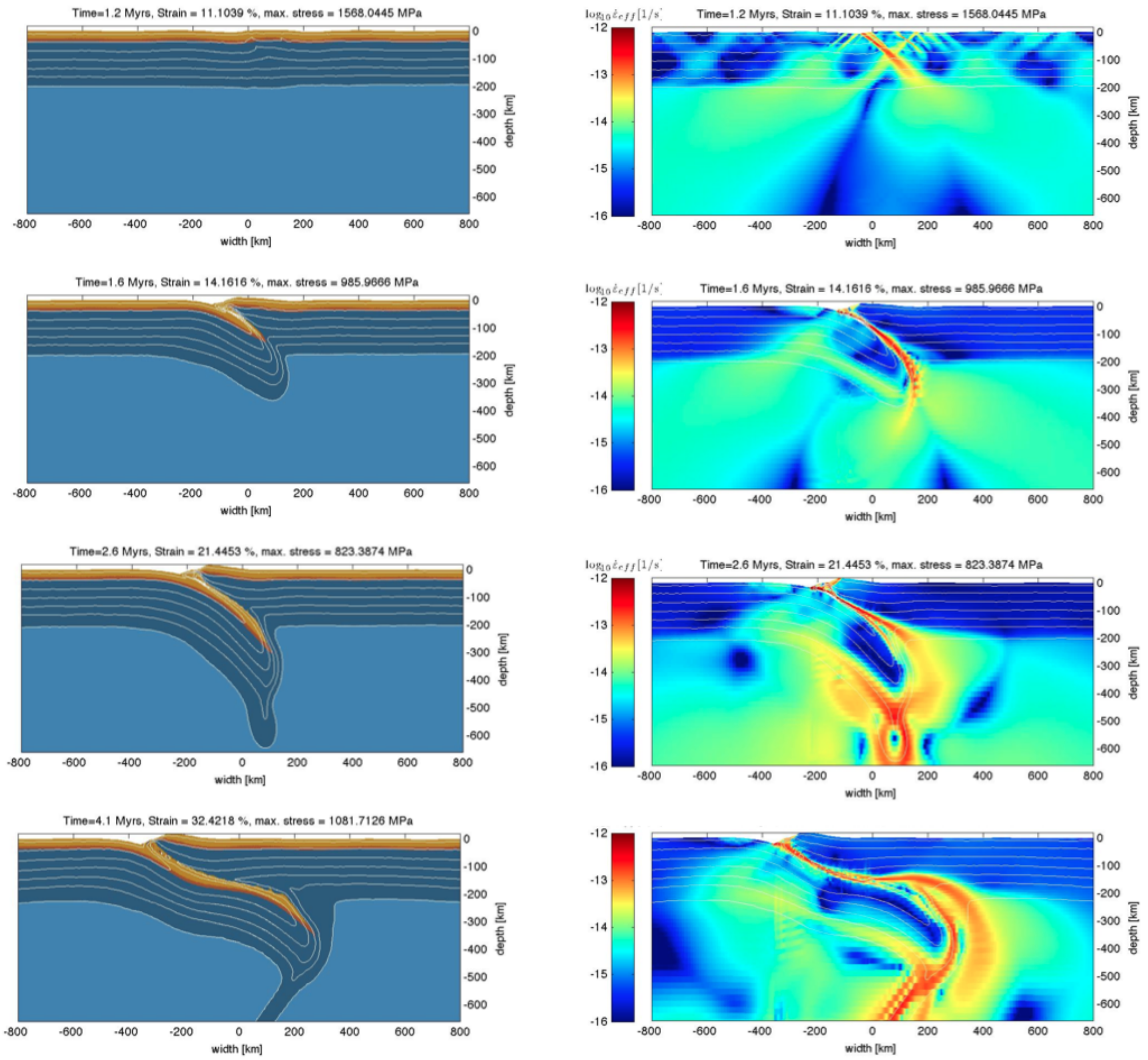


Figure 3: Example of a run where a continental lithosphere was compressed with a constant background strainrate $\dot{\varepsilon}_{BG} = 3e - 15[1/s]$. The left column shows particle distribution, the right column shows second invariant of strainrate.

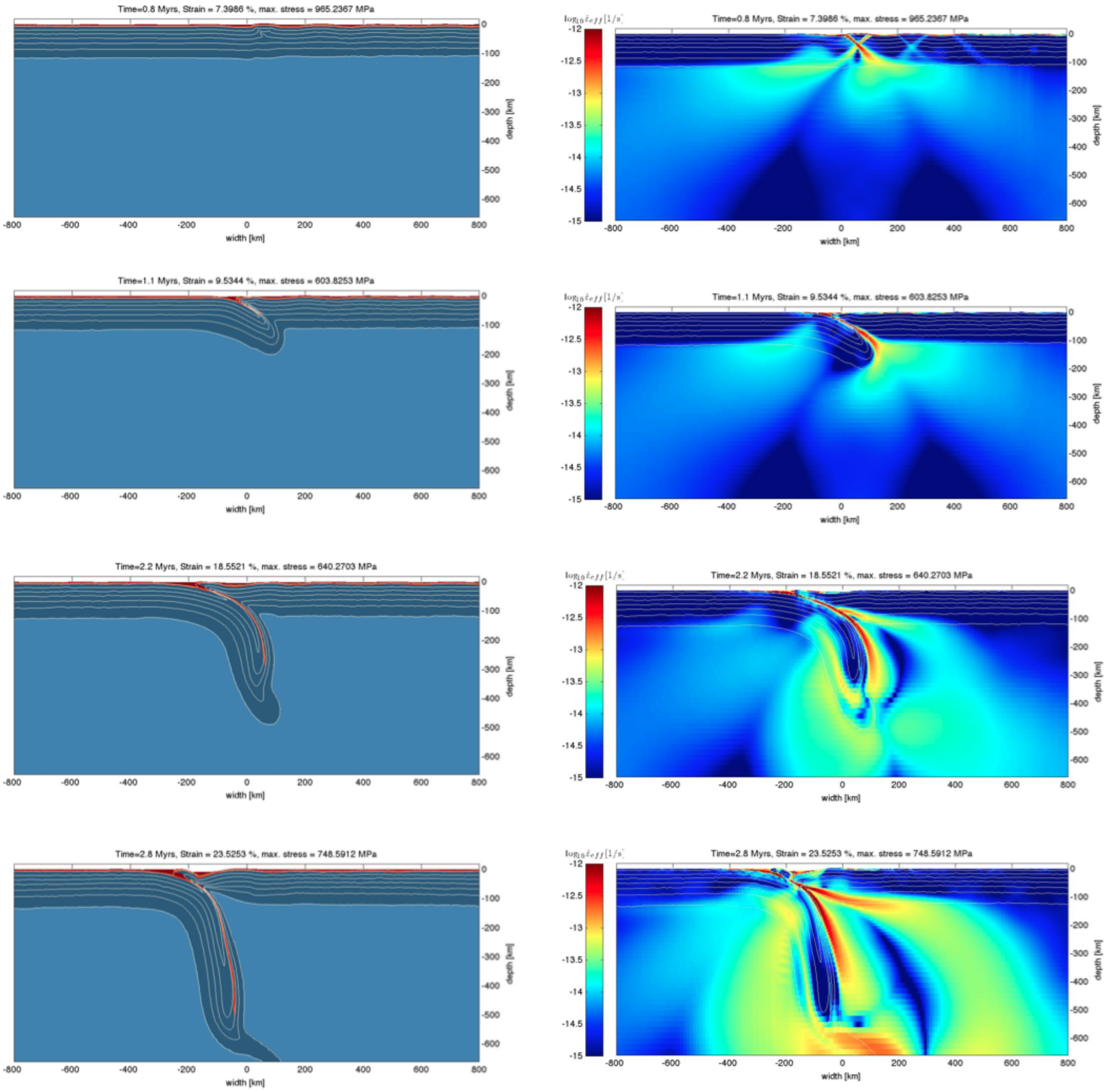


Figure 4: Example of a run where an oceanicl lithosphere was compressed with a constant background strainrate $\dot{\varepsilon}_{BG} = 3e - 15[1/s]$. The left column shows particle distribution, the right column shows second invariant of strainrate.

3.5 Outlook

The conditions leading to localization have been investigated by Crameri and Kaus (2010). The results obtained in this work still have to be compared to their results. Since there are various parameters controlling the behaviour of the model, it is desirable to reduce the number of parameters through scaling. This allows for a better understanding of the physics of the model and to identify the parameters that are really governing the overall behaviour. Based on this scaling, we want to derive scaling laws that enable us to predict if subduction follows on localization without having to use computationally expensive numerical models.
As has been mentioned earlier, grain size reduction is also thought to be a mechanism that can lead to localization. Additionally, it is a field observable, which is important when comparing numerical models to nature. It would therefore be desirable to implement dynamic recrystallisation and grain growth in the model. Unfortunately, it is still highly debated how to parameterize grain-scale processes in large-scale models. As a further complication, the parameters that enter existing parameterizations are highly unconstrained. Nevertheless, investigating the influence of grain size evolution on lithospheric-scale shear zones using numerical models could contribute significantly to the debate.
As can be seen from the first-year results, localization is only caused by shear heating if there are high stresses available. Up to now, mantle convection models have failed to produce such high stresses in the lithosphere, however, they are usually ignoring the effects of elasticity and a free surface. These two missing ingredients could help to generate the stresses that are needed for the shear heating mechanism to contribute significantly to the localization process. Another missing ingredient for creating high stresses could be found in 3D. The heterogeneities in the two-dimensional setups are essentially infinitely stretched in the third dimension. Therefore they cannot concentrate as much stresses as a heterogeneity which is bounded in all three dimensions.

3.6 Research plan

For a detailed description of the research plan, see tab.1

Code Development	Scientific Research	Other	
- Familiarization with the finite element method and MILAMIN_VEP	- Literature research	**Education** - **2 lectures at ETH:** - **C2P block courses:** - **C2P summer school**	**Year I**
MILAMIN_VEP: - Implementation of an input structure that facilitates parameter management - Implementation of additional deformation mechanisms	- Investigate mantle influence on localization scaling law - Derive scaling law for subduction initiation resulting from shear localization due to shear heating	**Presentations** - SGM 2009 - EGU 2010 - GLADE 2010 - GEOMOD 2010	
October 2010			
MILAMIN_VEP: - Implementation of grain size evolution (e.g. Austin & Evans (2007), Rozel et al. (2010))	- Localization in mantle convection simulations - Investigate influence of grain size evolution on localization - Investigate interplay between grain size reduction and shear heating	**Expected Publications** - Publication on shear localization with underlying mantle - Publication on shear localization in mantle convection with shear heating **Presentations** - SGM 2010 - EGU 2011 - AGU 2011	Year II
October 2011			
- Implement grain size evolution into 3D code	- Apply findings to threedimensional setups	**Expected Publications** - Publication on the interplay between shear heating and grain size reduction **Presentations** - SGM 2011 - EGU 2012 - AGU 2012	Year III
March 2012			
Writing of the PhD thesis			
October 2012			

Table 1: Research Plan

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