Chapter 1

Introduction

The strength of lithosphere varies both in space and in time and the heterogeneities in strength reveal themselves at a variety of scales and in a variety of styles. For instance, the clear contrasts between continental and oceanic lithosphere and the presence of different types of plate boundaries render it far from reality to view the whole Earth's lithosphere as a uniform layer even on the largest scale. Prominent on smaller scales, intra-plate heterogeneities (often related to pre-existing geological structures) can be reactivated by external agents like thermal anomalies in the deeper mantle. Importantly, continued deformation under non-linear constitutive laws can create rheologically distinct structures in otherwise homogeneous lithosphere. These newly created structures in turn control the geological evolution of the affected region. In studies of lithospheric dynamics with an emphasis on such non-uniform strengths and non-linear rheologies, numerical simulations have demonstrated their unique capabilities: They can find models that are physically consistent with the observations, incorporate experimental data into the models, and even draw verifiable predictions from those models (e.g., Oganov and Ono, 2004; Kapp et al., 2008). The rapid increase in computing power has made the numerical approach to complex geodynamic problems even more tractable. Benefiting from modern numerical techniques and high performance computing, this thesis addresses some problems related to the consequences of non-uniform strengths and spontaneously emergent localization of deformation using numerical models. In addition to enhancing our understanding of geophysical processes, the thesis aims to return a contribution for advancing computational techniques for lithospheric dynamics.

Chapter 2 addresses the effect of laterally varying viscous strength on the extension of the Basin and Range Province. The Cenozoic extension of this part of the western U.S. has been attributed to gravitational forces. Gravity tends to extend a thickened crust due to a period of earlier subduction and the region's extension is often attributed to it. We show that forces acting on plate boundaries are also sufficiently strong to drive the region's distributed extension. One of the particularly diagnostic observations is that GPS measurements in the northern Basin and Range Province indicate that the eastern part of the Province is, although farthest from the plate boundary, undergoing concentrated extension. Seismological observations suggest a locally weak mantle beneath this region. Results from numerical models involving such a heterogeneity are shown to be compatible with the geodetic observations.

The next two chapters shift focus to heterogeneities that develop spontaneously and in a highly localized fashion. Brittle deformations like faulting and localized ductile failure (shear bands) are among the examples. Fracture zones of oceanic lithosphere and mid-ocean ridges are addressed in detail. To model such geological structures numerically, it is required to introduce plasticity or equivalent non-linearities into constitutive models. For this purpose, we developed a code called SNAC. It is a 3-D finite difference code for modeling elasto-visco-plastic material. Details of the code's algorithm are presented in Appendix A.

Brittle deformation of oceanic lithosphere due to thermal stress is explored with a numerical model, with an emphasis on the spacing of fracture zones, in Chapter 3. Fracture zones are represented as localized plastic strain. The yield and plastic potential functions are defined such that material goes through brittle failure: i.e., the material loses coherence quickly after yielding occurs. The brittle failures are induced by stress due to thermal contraction, which is a direct result of the cooling of oceanic lithosphere. Using SNAC, we set up 2-D models representing ridge-parallel cross-sections that are initially placed near the spreading center. We investigate the sensitivity of the spacing of fracture zones to various parameters such as creep strength, crustal thickness, and the rule of plastic flow. Crustal thickness is crucial in determining whether brittle deformation propagates through the whole crust and makes topographic features. There is a threshold in crustal thickness such that brittle deformation can make surface topography only when the crustal thickness is smaller than the threshold. The stronger creep strength is found to raise the threshold. The sensitivities found among the model parameters are compatible with the correlation between anomalously thick crust and the lack of fracture zones in the Reykjanes ridge. The enhanced fracturing found in the anomalously thin crust of the Australian-Antarctic Discordance is also consistent with the model results.

It should be noted that the observations indicate that fracture zones are formed at spreading centers with their spacing determined by the ridge segmentation. On the contrary, it takes about 4 Myr for primary cracks to appear in our weak crust models, which can be translated as meaning that fracture zones are initiated at 4 My-old lithosphere. This inconsistency between our models and observations might suggest that our models represent a different physics than the actual one behind the formation of fracture zones in oceanic lithosphere. On the other hand, the magnitude of thermal stresses is evidently large enough to fracture at least shallow portions of oceanic lithosphere. Thus, the discrepancy might be suggesting the existence of a new class of thermally-induced structures oriented in the ridge-normal direction, which have yet to be discovered. Interestingly, in the strong crust models, the primary cracks appear before 1 Myr, alleviating the temporal discrepancy significantly. However, the implication is still that fracture zones are initiated at some distance from the spreading center. Furthermore, the influences from the existing ridge segmentation are not included in any of our models. The fact that the models are set up in 2-D imposes another difficulty in extending our results to the actual mid-ocean ridge systems. In these 2-D models, it is not possible to observe what processes occur at the spreading center when off-axis lithosphere is being fractured by thermal stresses. A fully 3-D model would also be a prerequisite for investigating the effects of ridge segmentation on the formation of ridge-normal fractures.

We investigate in Chapter 4 a thermally strained system again, but strong kinematic driving forces are applied on top of the thermal stresses in this case. Brittle deformation due to thermal stress is still the key phenomenon, but the mechanics responsible for the patterns made by mid-ocean ridges and transform faults is of our main interests. The geometry of the divergent plate boundaries is often described as orthogonally intersecting ridges and transform faults, which is definitely a simplified description. It has been observed that the geometry made by two mutually approaching ridge segments is correlated with spreading rates. It has also been suggested that orthogonality of transform faults and ridge segments requires forces acting in the ridge-parallel direction. There were several hypotheses about the origin of such ridge-parallel forces, but we consider thermal stresses as a plausible source. We set up 3-D numerical models for mutually approaching ridge segments with two types of loads: spreading and thermal stresses due to cooling. Unlike the two-layer models in the previous chapter, models in Chapter 4 represent a single layer of mantle. The lack of crust enables a direct observation of localized plastic deformations without potential complications due to weak lower crust as in Chapter 3. Patterns made by localized plastic strain, representing ridge segments and transform faults, are analyzed in terms of the relative strength of two driving forces. We note that thermal stress can exert ridge-parallel tension comparable to spreading-induced stress when selectively released by ridges and ridge-parallel structure. Two modes of ridge segment growth have been identified in plan view. An *overlapping* mode refers to the patterns of ridge segments that overlap and bend toward each other. Patterns are in a *connecting* mode when two ridge segments are connected by a transform-like fault. The ratio of thermal stress to spreading-induced stress is denoted as γ. As γ increases, the patterns change from the overlapping to connecting mode. The familiar orthogonal pattern falls between these two end members. The rate of stress accumulation is as important as the ratio between two types of loads. This rate-dependence is characterized by the spreading rate normalized by a reference-cooling rate (Pe') and the ratio of thermal stress to spreading-induced stresses (γ'). These two non-dimensional numbers unambiguously define stability fields of the two modes. The obliquely connecting, the orthogonally connecting, and the overlapping mode are similar to ridge-transform fault intersections observed in ultra-slow, slow to intermediate, and fast spreading centers, respectively. The patterns are also sensitive to the strain weakening rate.

Finally, Chapter 5 explores a technique for code coupling, one way of solving multi-material and multi-physics problems efficiently. The code coupling is managed by Pyre. Pyre is a collection of software enabling two distinct codes to interact by exchanging variables through shared interfaces. Motivated by computationally challenging problems like crust-mantle interaction, we coupled SNAC with Regional-Citcoms using this framework. We present the principles governing the physics for the coupled problems as well as technical issues. It is demonstrated that Pyre can handle the data exchange correctly by solving benchmark problems. Bending of a thin plate is solved both analytically and by SNAC. The transverse pressure loading on the plate is either uniform or sinusoidal. The case of the uniform pressure loading verifies that the stand-alone SNAC returns accurate solutions. The sinusoidal loading is transferred from CitcomS, in which a cosine perturbation is added to a steady-state temperature field. The perturbation drives convection in CitcomS and the cosine form is conserved in the resultant velocity and stress fields. SNAC receives the stress fields from CitcomS and convert them to traction boundary conditions. Then, the elastic response computed by SNAC is compared with an analytic solution to the cosine pressure loading. Preliminary results from a high-resolution coupled model are also presented. An elasto-visco-plastic lithosphere is coupled to a Newtonian viscous mantle. Flows in the mantle are driven by a hot spherical anomaly placed at the center of the CitcomS's domain. The coupled model shows a steady growth of a dome in the lithosphere above the hot blob, consistent with physical intuition. The unresolved issues are also discussed.

References

Kapp, P., Taylor, M., Stockli, D., Ding, L., 2008. Development of active low-angle normal fault systems during orogenic collapse: Insight from Tibet. Geology 26 (1), 7–10.

Oganov, A. R., Ono, S., Jul. 2004. Theoretical and experimental evidence for a post-perovskite phase of $MgSiO_3$ in Earth's D″ layer. Nature 430 (6998), 445–448.