# DOWNLOAD PDF THEORETICAL ANALYSIS OF SHEAR LOCALIZATION IN THE LITHOSPHERE DAVID BERCOVICI, SHUN-ICHIRO KARATO.

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*Earth's lithosphere consists of highly viscous tectonic plates with deformation localised within less viscous material at plate boundaries (e.g., Bercovici and Karato, ).However, the pro.*

Box , New Haven, CT , USA Received 19 March ; received in revised form 9 June ; accepted 29 June Abstract The kinetics of static grain growth in a pure synthetic orthopyroxene and orthopyroxene of natural composition were investigated to determine the effects of solute segregation on grain growth. In all experiments the grain size of the synthetic orthopyroxene increases considerably; in contrast, the natural orthopyroxene shows no perceptible grain growth at the same conditions. High- resolution X-ray compositional mapping confirms that the natural orthopyroxene has large concentrations of aluminum and calcium cations segregated on and near its grain boundaries. This segregation is believed to be responsible for the slow grain-growth kinetics in the natural orthopyroxene. Slow grain growth may permit long-term deformation in the diffusion creep regime, as has been observed in some deep mantle xenoliths. As such, it may provide a means of weakening the lithosphere. Orthopyroxene; Grain growth; Impurity drag; Shear localization 1. Introduction dence for grain-size reduction and subsequent grain-size sensitive deformation of orthopyroxene, coupled with Orthopyroxene is the second most abundant min- grain-size insensitive deformation of olivine Boullier eral throughout much of the upper mantle, however its and Gueguen,  The orthopyroxene, in addition to rheological properties are poorly understood from an deforming by a grain-size sensitive mechanism, becomes experimental perspective. A frequent assumption made interconnected at high strains, suggesting that its rhe- in the study of the upper mantle is that the aggre- ology may contribute significantly to the rheology of gate rheology is primarily controlled by the rheology the aggregate material Handy,  Grain-size sen- of olivine e. However, obser- sitive deformation is of particular interest, because it is vations from some deep mantle xenoliths suggest that thought to be an important mechanism for shear localiza- at certain conditions orthopyroxene may also play a tion e. Unlike most shallow  Shear localization is, in turn, believed to be essen- peridotites, these xenoliths contain microstructural evi- tial for the formation of tectonic plates e. Grain size is not an equilibrium quantity, but rather E-mail address: In order for grain-size sensitive creep to dominate deformation over a geological time scale, the recrystallized grain size must be small, and the kinetics of grain growth must be slow de Bresser et al. In this study we focus specifically on this latter issue. The kinetics of grain growth have been studied for a number of Earth materials e. Additionally, it has long been recognized that grain growth is inhibited by the presence of dis- solved impurities segregated to grain-boundaries and near-grain-boundary regions e. However, there have been no experimental studies on these processes in orthopyroxene. In this study we report the first data on the grain-growth kinetics in orthopyroxene. We will demon- strate that certain cations, dissolved on and near-grain boundaries, play a crucial role in controlling the kinetics of grain growth in orthopyroxene, and as such may have Fig. Phase diagram for Mg2 Si2 O6 after Presnall  The stable important consequences for the rheology of the mantle. Methods twice helped ensure the completeness of the reaction. A complicating factor in the study of orthopyroxene The Mg0. To study its properties in the appropriate stabil- at K for 2 h to remove adsorbed water immedi- ity field for most of the upper mantle â€" orthoenstatite â€" ately prior to mixing. This powder then went through experiments must be done at modest pressures. This pre- two cycles of cold pressing, annealing at high tem- cludes study using room-pressure furnaces and in most perature at 1 atm and K, for 24 h , and grinding. Thus, all experiments in this The powder was examined optically and with Raman study were conducted in a solid medium apparatus. A second starting material was produced from ics of grain growth in orthopyroxene, experiments were large 1â€"2 mm , optically clear orthopyroxene crystals conducted on two different starting materials. The first hand selected from the San Carlos peridotite henceforth starting material was a pure, synthetic orthopyroxene natural orthopyroxene. In both cases, fine-grained pow- with a nominal formula of Mg1. The preparation of the under distilled water in a SyalonTM ball-mill for sev- synthetic orthopyroxene involved several steps. Further grain-size refinement was achieved Mg0. The pellets ples were isostatically hot pressed at 1. The intention of these hot-pressing run product was recovered, ground in a SyalonTM ball- experiments was to produce fine-grained, dense, poly- mill, cold-pressed into new pellets, and reacted again crystalline aggregates. The synthetic orthopyroxene was at the same conditions. For the natural orthopyroxene powder sam- ples, it was necessary to hot press at a higher temperature to obtain sufficiently dense samples. After recovering the samples, the run products were examined optically, with Raman spectroscopy, and with electron microprobe analysis, to confirm the composition Table 1. Grain-growth experiments were conducted with both starting materials in the same capsule so properties could be directly compared at identical experimental condi- tions. All experiments were conducted at 1. Experiments were not run at higher tem- peratures to avoid the generation of melt. The solid nickel capsule was used to buffer the oxygen fugacity, as well as minimize any differential stress transferred to the sample from the assembly. A small amount of olivine powder was added to buffer the oxide activity. The assembly was compressed over 3 h at room temperature to the tar- get pressure. The temperature was then increased to Fig. Cell assembly for the grain-growth experiments. The samples were annealed for 4â€”34 h. At the tal lattice of both the starting materials and the products conclusion of the experiment, temperature was quenched of the grain-growth experiments was measured using by shutting off the power to the furnace and the pressure Fourier transform infrared spectroscopy FTIR. FTIR was reduced slowly to prevent the formation of decom- measurements were made with an unpolarized beam on pression cracks. The sample was recovered, mounted in doubly polished polycrystalline samples placed on KBr low-viscosity resin, and polished for analysis using a mounting disks. The samples measured were typically slurry of colloidal silica. Several measurements were made experiments. However, it is often observed that some for each sample, and water contents were estimated using water can be incorporated into the sample during certain the calibration of Paterson  Grain sizes were measured The primary source of uncertainty in these experi- on images taken using a scanning electron microscope ments is the grain-size measurement, which may vary SEM in secondary electron mode. The grain-size thermocouple reading. Approximately 10 regions were measured for each sam- ple to account for any spatial variation in grain size. Results total number of grains measured for each sample typ- ically exceeded  Porosity was measured from the The grain morphology and the contrast in grain secondary electron images by processing the image with growth between the synthetic and natural orthopyroxene a threshold function and comparing the number of pix- is illustrated in Fig. In general the shape of the els from grains and from pores. Grain shape and size grains is somewhat elongated, but rarely exceeds an for some samples was determined by digitally tracing aspect ratio of 3: The synthetic orthopyroxene starting individual grain boundaries, and then fitting an ellipse material has a mean grain aspect ratio of about 2, but a to each grain. These data were then used to calcu- typical run product has mean grain aspect ratios of 1. Grain-size evolution in natural and synthetic orthopyroxene. While the natural orthopyroxene shows no perceptible grain growth, the mean grain size increases dramatically in the synthetic orthopyroxene. All experiments shown here were conducted at 1. Black regions represent remnant porosity, or grains that were removed during polishing. In the synthetic orthopyroxene, some silica-rich inclusions were found, which resulted from incomplete mixing or non-ideal stochiometry during sample synthesis. The olivine pow- der, added to the experiments to buffer the oxide activity, was always present after the experiment. The presence of both silica and olivine indicates that equilibrium with respect to the oxide activity was not achieved. The possible consequences of disequilibrium with respect to oxide activity, and the issue of equilibrium with respect to oxygen fugacity will be considered in Section 4. The results of the grain-growth experiments are sum- marized in Table 2. In all experiments, substantial grain growth was observed in the synthetic orthopyroxene. In contrast, no perceptible grain growth was observed in the natural orthopyroxene. Data can be fit to a standard grain-growth equation e. Grain-size distribution for a the synthetic starting material be approximately 2â€”4, depending on the rate-limiting and b grain-growth experiment GA Frequency is plotted as a mechanism Kingery et al. These distributions are corrected for the two-dimension sectioning able grain growth, there is sufficient data on the synthetic effect using the Schwartz-Saltykov method. There is little change in the peak location and the broadness of the distribution, indicating that orthopyroxene to fit these equations. For the synthetic grain growth occurred by normal processes. There is all of the experimental data at K Fig. Hillert, ; Atkinson,  Complete densification was not generally achieved in these experiments; some 4. Discussion remnant porosity was always present. In the synthetic starting material, which was hot pressed for a short time 4. This level of porosity issue of chemical equilibrium within our experiments. Porosity is known to have a substantial effect recognized that the kinetics of the reactions required to on grain-growth kinetics e. Two experiments at the sluggish than those in olivine. This is roughly two orders buffer. The powder used as the starting material for these of magnitude slower than the rate of equilibration for experiments had been dried in air for 24 h at K and olivine at the same temperatures Karato and Sato,  After the less than 0. How- As noted earlier, even after the longest grain-growth ever, the orthopyroxene in the center of the capsule experiments, we found silica inclusions in the synthetic was apparently highly oxidized, containing submicron orthopyroxene, indicating that the sample was not in reddish precipitates likely hematite , suggesting that equilibrium with the surrounding olivine buffer. In order to evaluate the degree to which disequi- librium with respect to oxide activity may influence the results on grain-growth kinetics, let us evaluate the differ- ence in oxide activity corresponding to the end-member situations. In our experiments, two end-member cases can be considered: Synthetic orthopyroxene data at K. The final grain size is plotted against the duration of the experiment. The synthetic orthopyrox- ene was prepared in the presence of excess $SiO_2$ ; with both silica and orthopyroxene phases present, the MgO activity will be defined by the reaction in Eq. Apply- ing the thermodynamic data of Robie et al.

## Chapter 2 : Plastic Deformation of Minerals and Rocks - PDF Free Download

*David Bercovici, Shun-ichiro Karato; Theoretical Analysis of Shear Localization in the Lithosphere.*

Advanced Search Summary We employ basic non-equilibrium thermodynamics to propose a general equation for the mean grain size evolution in a deforming medium, under the assumption that the whole grain size distribution remains self-similar. We show that the grain size reduction is controlled by the rate of mechanical dissipation in agreement with recent findings. Our formalism is self consistent with mass and energy conservation laws and allows a mixed rheology. As an example, we consider the case where the grain size distribution is lognormal, as is often experimentally observed. This distribution can be used to compute both the kinetics of diffusion between grains and of dynamic recrystallization. The experimentally deduced kinetics of grain size coarsening indicates that large grains grow faster than what is assumed in classical normal grain growth theory. We discuss the implications of this model for a mineral that can be deformed under both dislocation creep and grain size sensitive diffusion creep using experimental data of olivine. Our predictions of the piezometric equilibrium in the dislocation-creep regime are in very good agreement with the observations for this major mantle-forming mineral. We show that grain size reduction occurs even when the average grain size is in diffusion creep, because the largest grains of the grain size distribution can still undergo recrystallization. The resulting rheology that we predict for olivine is time-dependent and more non-linear than in dislocation creep. As the deformation rate remains an increasing function of the deviatoric stress, this rheology is not localizing. Plasticity, diffusion and creep , Creep and deformation , Fault zone rheology , Dynamics of lithosphere and mantle , High strain deformation zones , Rheology, crust and lithosphere 1 Introduction The localization of deformation in narrow shear bands is necessary for plate tectonics to occur see e. Weak faults can be formed during deformation but their weakness can persist even after a reorganization of the large scale stress pattern e. This indicates that the rheology is not only controlled by the instantaneous stress field but has memory and healing. Localization occurs by a feed-back between the rheological law and the deformation wherein a faster deformation can be obtained with a lower stress. Unfortunately, although shear heating is necessarily associated with localization, it does not seem to explain either the narrowness of plate boundaries, or their geometries e. Anisotropic mechanical behaviour due to an inherited preferred orientation of crystals could also control or favour the localization e. Once the localization is effective, minor mineralogical phases like serpentine can also lubricate the motion Hilairet et. Grain size reduction seems the most attractive physical process for explaining the initial localization of the deformation. However, models of localization by grain size reduction are not self-consistent. Recrystallization is observed in the dislocation regime i. Grain size reduction and localization by grain size sensitive rheology occur therefore in somewhat exclusive regimes Karato et. Various models have however discussed the possible interactions between large scale deformation and grain size evolution Kameyama et. Up to now, most attempts to model the evolution of grain sizes have been derived from phenomenologic laws involving only a mean grain size. A few attempts have been made to describe in a very general way the evolution of an assemblage of grains under deformation e. In these approaches, one has to consider the complete distribution of grains which is the number of grains per unit volume near the position X and at time t, having a size between and.

## Chapter 3 : Mineralogical Society of America - Plastic Deformation of Minerals and Rocks

*Reviews in Mineralogy and Geochemistry: Plastic Deformation of Minerals and Rocks, S-i Karato and H-R Wenk (eds), v, Ch, 13 Theoretical Analysis of Shear Localization in the Lithosphere David Bercovici and Shun-ichiro Karato.*

In special cases, A can be expanded to show an explicit variability of the flow behavior with particular factors such as initial grain size or other internal variables, oxygen or water fugacity, etc. It is now evident that the steady state discerned at strains of order 0. In some of these studies, measurements have been made on the same rock type using complementary techniques. Many of these measurements have been performed relatively recently, notably due to technological developments, such as the utilization of the torsional configuration in the gas-medium apparatus. In the following, we will review the current state of the field in high-strain experimental studies of rocks, focussing on monomineralic crustal and mantle rocks and then briefly summarizing research on two-phase and polyphase systems. Monomineralic crustal rocks Perhaps the most studied rock in terms of deformation behavior, Carrara marble has been investigated using a range of techniques, under compressional, extensional, splitcylinder and torsional configurations. The axial compression studies have provided a comprehensive understanding of low-strain deformation mechanisms, notably dislocation creep e. He reported significant dynamic recrystallization at high strains. The observed weakening with progressive strain may have resulted from purely geometric constraints due to necking at constant displacement rate. A further study that made use of the split-cylinder configuration Schmid et al. In neither case was a change in deformation mechanism from dislocation creep to diffusional creep inferred despite the significant grain refinement. Torque versus shear strain for all constant strain rate tests on Carrara marble at and K. The low-strain microstructures showed undulose extinction, deformation bands and the development of subgrain boundaries within the grains, as well as some bulging of grain boundaries Fig. The lattice preferred orientation that developed at low strains, which was consistent with the slip systems identified in axial compression experiments, was progressively replaced by a recrystallization texture. Experiments on fine-grained Solnhofen limestone show behavior that is quite distinct from that the coarser grained marble. Low-strain axial compression experiments show several deformation fields. At higher-stress, lower-temperature conditions, deformation is dominated by dislocation creep, while at lower stresses behavior is consistent with a mechanism dominated by grain-boundary sliding accommodated by diffusion along grain boundaries Schmid et al. They observed no net grain growth due presumably to the presence of impurity phases and no associated changes in deformation mechanism during the experiments. Studies of the texture development in such samples e. Using the split-cylinder configuration, Schmid et al. Overviews at low magnifications at left and details at higher magnification at right. Shear zone boundary is oriented parallel to the long edge of the image and the sense of shear is dextral. The arrows in b point to a small relict grain and to bulging of the grain boundary, indicating that the horizontal grain boundary is migrating downwards. The presence of a lattice preferred orientation and near-equant grains argues for deformation by both dislocation creep and grain boundary sliding. At high strains, both textures and mechanical behavior appeared to be near steady state. Another material that has been the focus of many deformation studies is quartzite. Deformation to small strains in compression has been performed on a range of quartzites with large variability in grain size, impurity phase and water contents. Deformation under dry conditions yields highly variable rheologies characterized by mostly brittle mechanisms. Under wet high-pressure conditions, quartzites can deform by fully plastic mechanisms, but the measured rheologies are highly variable in terms of the calculated constitutive parameters e. High-strain deformation experiments on untreated and hence wet samples of several quartzites mostly flint in torsion by Schmocker et al. Anhydrite is the only material studied to date that shows coupled textural evolution and changes in deformation mechanism Stretton and Olgaard As with the marble, recrystallization occurs predominantly by nucleation and growth of strain-free grains on grain boundaries. The high-strain experiments have been performed in torsion. Subsequently samples appear to reach a near-steady-state microstructure and rheology. Deformation textures develop quite rapidly at lower shear strains but weaken with progressive deformation and recrystallization Heidelbach et al. The reason for the inhibition of grain growth in the diffusion creep field despite initial rapid growth of recrystallized grains in the dislocation creep field is not clear. In this case, pinning by impurity phases seems unlikely. For this material progressive recrystallization with increasing strain in torsion may result in a sample with a rim deforming by diffusional creep surrounding an interior deforming by dislocation creep, complicating interpretation of the stress distribution within the sample. While important as a component of aggregate flow, it is not clear that single-phase flow has a direct relevance to convection in this region of the Earth. High-strain experiments have been performed in both torsion Heidelbach et al. The initial lattice preferred orientation, which is consistent with the dislocation slip systems expected for the rock-salt structure, weakens with progressive strain and is overprinted by a recrystallization texture. While the split-sphere experiments of Yamazaki and Karato on Mg0. High-strain deformation studies have also been performed on upper mantle rocks. Of particular note, dry olivine aggregates have been deformed to high strains in torsion Bystricky et al. The low-strain behavior in these tests is consistent with the High-Strain Deformation Figure 6. At larger strains recrystallization by progressive subgrain rotation is apparent resulting in a net reduction in grain size. No change in deformation mechanism has been observed. Although some bulging of grain boundaries is apparent in the optical thin sections, subgrain rotation seems to be the dominant recrystallization mechanism. The lattice preferred orientations measured for the high-strain samples are consistent with the dislocation slip systems observed in low-strain experiments. Interestingly, although both Bystricky et al. Recent experiments on olivine aggregates under hydrous conditions by Jung and Karato b using the split cylinder configuration yield lattice preferred orientations consistent with a change from the dominant a-slip dominance of [] Burgers vector dislocations to c-slip dominance of [] dislocations with increasing water content. While the cause of the changing textures is debated Kaminski , such a difference in the deformation textures for wet and dry regions would have important ramifications in the interpretation of seismic anisotropy observations for the lithospheric and asthenospheric mantle. They observed that the predried plagioclase stayed within the dislocation creep regime but showed some weakening with increasing strain, while the wet plagioclase deformed in the diffusional creep field. Transmission electron microscopy images of the predried samples showed remanent high-dislocation-density grains surrounded by small polygonal recrystallized grains. A preliminary study of high-strain deformation of clinopyroxenite to relatively high strains by Bystricky and Mackwell yielded the same general observations as for olivine, with development of an initial shape-preferred fabric, subgrain rotation recrystallization and maintenance of dislocation creep as the dominant deformation mechanism. The observed lattice preferred orientations are also consistent with the dislocation slip systems operative in previous low-strain axial deformation experiments. Polyphase systems Obviously the Earth is not comprized of significant regions where the rock is monomineralic and an important challenge for the future is to characterize the deformation behavior of multi-phase systems, both to low and high strains. In particular, we aim to mimic processes occurring in plastic shear zones regions where deformation occurs by plastic deformation that is relatively localized spatially. Such zones are often the downward continuation of shallower brittle fault systems. Of special interest, we would like to see how the individual minerals contribute to the deformation and whether the deformation leads to phase separation into interlayered structures where deformation is concentrated in the layers comprized of the weaker minerals. Several recent studies have begun to address these questions. Deformation experiments in torsion have been performed on mixtures of quartz and High-Strain Deformation 13 calcite with variable modal abundances by Rybacki et al. In these experiments, the quartz essentially acts as a non-deforming component in a plastic calcite matrix and is observed to exert a strong effect on aggregate strength. To a large extent the behavior mimics the high-strain deformation of marble, but strengthened by the presence of a second harder phase. Experiments have also been performed to high strains in 2-phase systems where the individual phases are not so different in strength. With increasing strain, the steady-state stress values for all compositions converge, but deformation becomes localized, with phase separation, seemingly mimicking observations of natural plastic shear zones. While beyond the scope of the present review, there is some interesting work currently investigating the effect of high shear strains on the texturing of melt within partially molten systems e. SUMMARY While numerous experiments have been performed to high strains on a variety of materials using the various technologies described in this paper, this is still a relatively new field of study and much of the work reported above is research in progress. In the near future, we will certainly see major advances, particularly using the torsional configuration of the gas-medium apparatus. There are, however, a number of interesting observations that can be made based on the experimental studies to date on high-strain deformation of earth materials: Recystallization occurred by subgrain rotation, by nucleation and growth of new grains on grain boundaries, or a combination of both. Thus, textural and mechanical steady state can only be attained during high-strain experiments. However, this stress state strictly only applies at the initial stage of loading. As soon as some shearing displacement takes place, there is also a lateral component of displacement, normal to the cylinder axis, which will result in a reaction force from the constraints of the testing machine that are intended to ensure primarily axial displacement. As an illustration, suppose that the split cylinder is loaded by two pistons of diameter D and length L , and that a shearing displacement s has occurred across the specimen layer. Suppose that the loading pistons are rigidly constrained at their outer ends and that the lateral deflection of the inner ends is accommodated entirely by elastic bending of the pistons. If the split cylinder were of 10 mm diameter, this lateral force would thus introduce an additional lateral component of normal stress of about 7 MPa when the shearing displacement is 1 mm.

## Chapter 4 : Reviews in mineralogy and geochemistry; vol (Washington, ). - / CONTENTS

*Reviews in Mineralogy and Geochemistry January 01, Theoretical Analysis of Shear Localization in the Lithosphere. David Bercovici; Shun-ichiro Karato.*

The research into the plastic properties of minerals and rocks had a major peak in late s to early s, largely stimulated by research in the laboratory of D. Griggs and his students and associates. It is the same time when the theory of plate tectonics was established and provided a first quantitative theoretical framework for understanding geological processes. The theory of plate tectonics stimulated the study of deformation properties of Earth materials, both in the brittle and the ductile regimes. Many of the foundations of plastic deformation of minerals and rocks were established during this period. Also, new experimental techniques were developed, including deformation apparatus for high-pressure and high-temperature conditions, electron micros-copy study of defects in minerals, and the X-ray technique of deformation fabric analysis. The field benefited greatly from materials science concepts of deformation that were introduced, including the models of point defects and their interaction with dislocations. A summary of progress is given by the volume Flow and Fracture of Rocks: Since then, the scope of Earth sciences has greatly expanded. Investigations of the solar system documented new mineral phases and rocks far beyond the Earth. Both domains have received a lot of attention from mineralogists e. Most attention was directed towards crystal chemistry and phase relations, yet an understanding of the deformation behavior is essential for interpreting the dynamic geological processes from geological and geophysical observations. This was largely the reason for a rebirth of the study of rock plasticity, leading to new approaches that include experiments at extreme conditions and modeling of deformation behavior based on physical principles. A wide spectrum of communities emerged that need to use information about mineral plasticity, including mineralogy, petrology, structural geology, seismology, geodynamics and engineering. This was the motivation to organize a workshop, in December in Emeryville, California, to bridge the very diverse disciplines and facilitate communication. This volume written for this workshop should help one to become familiar with a notoriously difficult subject, and the various contributions represent some of the important progress that has been achieved. The spectrum is broad. Key issues include the influence of deformation on seismic signatures, such as attenuation and anisotropy, and a new generation of experimental and theoretical studies on rock plasticity has contributed to a better understanding. Extensive space exploration has revealed a variety of tectonic styles on planets and their satellites, underlining the uniqueness of the Earth. To understand why plate tectonics is unique to Earth, one needs to understand the physical mechanisms of localization of deformation at various scales and under different physical conditions. Also here important theoretical and experimental studies have been conducted. In both fields, studies on anisotropy and shear localization, large-strain deformation experiments and quantitative modeling are critical, and these have become available only recently. Complicated interplay among chemical reactions including partial melting is a key to understand the evolution of Earth. This book contains two chapters on the developments of new techniques of experimental studies: Both technical developments are the results of years of efforts that are opening up new avenues of research along which rich new results are expected to be obtained. Details of physical and chemical processes of deformation in the crust and the upper mantle are much better understood through the combination of well controlled laboratory experiments with observations on "real" rocks deformed in Earth. Chapter 3 by Tullis and Chapter 4 by Hirth address the issues of deformation of crustal rocks and the upper mantle, respectively. In Chapter 5 Kohlstedt reviews the interplay of partial melting and deformation, an important subject in understanding the chemical evolution of Earth. Cordier presents in Chapter 6 an overview of the new results of ultrahigh pressure deformation of deep mantle minerals and discusses microscopic mechanisms controlling the variation of deformation mechanisms with minerals in the deep mantle. Green and Marone review in Chapter 7 the stability of deformation under deep mantle conditions with special reference to phase transformations and their relationship to the origin of intermediate depth and deep-focus earthquakes. In Chapter 8 Schulson provides a detailed description of fracture mechanisms of ice, including the critical brittle-ductile transition that is relevant not only for glaciology, planetology and engineering, but for structural geology as well. In Chapter 9 Cooper provides a review of experimental and theoretical studies on seismic wave attenuation, which is a critical element in interpreting distribution of seismic wave velocities and attenuation. Chapter 10 by Wenk reviews the relationship between crystal preferred orientation and macroscopic anisotropy, illustrating it with case studies. In Chapter 11 Dawson presents recent progress in poly-crystal plasticity to model the development of anisotropic fabrics both at the microscopic and macroscopic scale. Such studies form the basis for geodynamic interpretation of seismic anisotropy. Finally, in Chapter 12 Montagner and Guillot present a thorough review of seismic anisotropy of the upper mantle covering the vast regions of geodynamic interests, using a global surface wave data set. In Chapter 13 Bercovici and Karato summarize the theoretical aspects of shear localization. All chapters contain extensive reference lists to guide readers to the more specialized literature. Obviously this book does not cover all the areas related to plastic deformation of minerals and rocks. Important topics that are not fully covered in this book include mechanisms of semi-brittle deformation and the interplay between microstructure evolution and deformation at different levels, such as dislocation substructures and grain-size evolution "self-organization". However, we hope that this volume provides a good introduction for graduate students in Earth science or materials science as well as the researchers in these areas to enter this multidisciplinary field.