Some Notes on Deformation Mechanisms and Crystal Plasticity

Temperature, lithostatic pressure and, to some extent, rock composition vary with depth in the continental crust. The metamorphic grade increases with depth. Differential stress varies laterally as well as vertically.

Within the upper 15 km of the crust, **low-temperature deformation mechanisms** predominate, including brittle **fracturing** and **faulting**, **cataclastic flow**, and **low-temperature crystal-plastic mechanisms** discussed below. These deformation mechanisms depend strongly on differential stress (or shear stress), and are weakly dependant (if dependant at all) on temperature. In the middle and lower crust, deformation mechanisms that are more temperature dependant predominate. These are called **high-temperature crystal-plastic deformation mechanisms**. **Crystal plasticity** involves the changing of a mineral's shape without melting, fracturing or faulting.

The diagram by Chris Scholtz depicting the characteristics of the San Andreas fault indicates that at ~11 km, the temperature has become high enough (~300°C) so that quartz deforms through high-T crystal-plastic mechanisms, at least for slow deformations (i.e., slow strain rates). High-T plasticity in feldspar begins to occur deeper, at ~22 km (~450°C) because of feldspar's higher melting temperature. Above ~16 km (~350°C), deformation is primarily by fracturing, faulting and cataclasis. The seismogenic zone extends to depths of perhaps ~16 km, and within this depth interval from the surface to ~16 km, the rock strengthens in nearly direct proportion to the depth (and hence to the confining pressure.) Below ~16 km, the rock weakens.

The dominant deformation mechanism for any given context (lithology, pressure, depth, differential stress) is the one that results in the greatest strain for the least energy expended.

Crystal plasticity involves the changing of a mineral's shape without melting, fracturing or faulting.

Low-temperature crystal plasticity involves processes that depend more on differential stress than on temperature. These processes include *pressure solution* that lead to the development of stylolites, *kinking*, *dislocation glide* and *mechanical twinning*.

Dislocation glide involves the motion of part of a lattice by an integer number of spaces relative to the rest of the lattice. **Mechanical twinning** is quite important in calcite, which is able to twin at a very low shear stress along its crystallographic e plane. The graph labeled "Figure 60" (from Mel Friedman) shows that twin gliding on the calcite e plane is insensitive to temperature up to at least 500°C, and is the weaker mechanism relative to translation gliding on the r plane up to temperatures of ~450°C, The graph also shows that dolomite is considerably stronger than calcite.

High-temperature crystal plasticity involves diffusion of atoms or vacancies through or around a mineral lattice. Diffusion is a process that proceeds more quickly in minerals at higher temperature. One of the reasons for this temperature dependence is that a mineral lattice can be at equilibrium with a larger number of vacancies at higher temperature than at lower temperature. (A vacancy is a hole or unfilled space in a lattice.) The greater the number of vacancies, the easier it is to diffuse atoms through the crystal.

Rock deformation experiments conducted at different temperatures (keeping other parameters such as confining pressure, strain rate, and rock type constant) have shown that increasing the temperature causes a decrease in strength and increase in ductility.

Actual mineral grains are not perfect crystals – they contain imperfections or defects. If they were perfect crystals, they would be much stronger than they are observed to be and, in fact, would not deform under the stress loads available in Earth's crust. At low temperatures, these defects act as stress concentrators permitting nucleation of cracks, while at high temperatures they contribute to diffusion and crystal-plastic deformation. **Mineral defects** can be described as point defects (affecting a particular point within a lattice), line defects, and planar defects.

Point defects include vacancies (places in a crystal lattice where the expected atom is missing), interstitial atoms (atoms that are not in a proper lattice position), and substitutions (atoms that are in a proper lattice position, but are not the correct type of atom).

Line defects include twins and dislocations. Dislocations include edge dislocations formed by an "extra" half-plane of atoms in the lattice, screw dislocations and mixed dislocations that are transitional between edge and screw dislocations.

Planar defects include grain boundaries, twin planes, subgrain boundaries (boundaries between parts of a crystal lattice that are slightly misaligned from one another), deformation bands/lamellae, Bohm lamellae (arrays of inclusions or impurities along an older grain boundary), and stacking faults (walls of dislocations).

Dislocation creep = dislocation glide + dislocation climb. The motion of dislocations and vacancies through a crystal occurs at all temperatures, but it is much faster at high temperatures than at low temperatures. At high temperatures, it takes less energy for vacancies to diffuse through or around a crystal. The amount of strain energy needed to break chemical bonds is reduced at high temperature.

Work hardening and work softening (sometimes called strain hardening and strain softening) are **competing processes**. In **work hardening**, dislocations tangle and obstruct each others' motion. Strain leads to an increase in dislocations, inhibiting further strain. In **work softening**, dislocations are annihilated or organized into subgrain boundaries (tilt walls), resulting in lattices that contain fewer dislocations. Recovery and recrystallization are involved, and are enhanced at higher temperatures.

The **homologous temperature** (Tm) is the melting temperature of a mineral expressed in the Kelvin temperature scale. A temperature change of 1 K is the same as a temperature change of 1°C, and absolute zero is 0 K = –273.16°C. **Absolute zero** is the temperature at which the volume of any ideal gas would reach zero and at which all thermal vibration of an atom ceases.

Primary recrystallization occurs at temperatures above half the Tm for a mineral. It involves grain boundary area reduction (GBAR) in which grain boundaries are straightened and flattened, and the ratio of volume to surface area is maximized for the prevailing set of physical and chemical conditions. Equilibrium is approached, given enough time at high temperature.

Static recrystallization occurs under conditions of low (or no) differential stress. **Dynamic recrystallization** occurs within a differential stress field that is sufficient to effect diffusion. Dynamic recrystallization involves processes that reduce the internal strain energy of a crystal and reduce the surface energy along grain boundaries, including grain boundary migration

recrystallization (GBM) and subgrain rotation recrystallization (SR). Under high flow stress, dynamic recrystallization results in smaller crystals. Dynamically recrystallized rocks with smaller crystals are typically stronger and denser than they were prior to deformation.

Recovery involves processes that occur between 0.3 and 0.5 Tm that reduce dislocation density (and hence reduce the elastic strain energy inside of a crystal.) Work hardening (tangling of dislocations) competes with recovery. Vacancy diffusion helps untangle dislocations. **Climb** allows dislocations to become straightened and untangles, overcoming obstructions called jogs and kinks. Temperature provides the energy for dislocations to *climb* over or around obstructions so that they can continue moving along their glide planes. Dislocations can be "annihilated" in a variety of ways, including moving them to grain boundaries. Dislocations can be organized and concentrated into walls (known as **tilt walls**), resulting in **subgrain formation**. The result of recovery is a lower overall density of dislocations in the crystal.

Crystal-plastic deformation has been modeled using equations known as **flow laws**, which relate strain rate to a variety of parameters including stress, temperature, diffusion coefficients, moduli, and so on. The details of three basic flow laws are illustrated in two accompanying pages derived from Passchier and Trouw (1998). **Dislocation creep** (also known as power-law creep or Weertman creep) is non-Newtonian and is modeled with a form of the Dorn equation.

$$\dot{\varepsilon} = A \, \sigma^n \, e^{(-Q/RT)}$$

Diffusion creep describes the flow of a Newtonian viscous material and includes **Coble creep** (grain-boundary diffusion) and **Nabarro-Herring creep** (volume/vacancy diffusion).

In Coble creep, atoms and vacancies move along the grain boundary: atoms from areas of high stress to areas of low stress, and vacancies in the opposite direction.

grain-boundary diffusion (Coble creep)
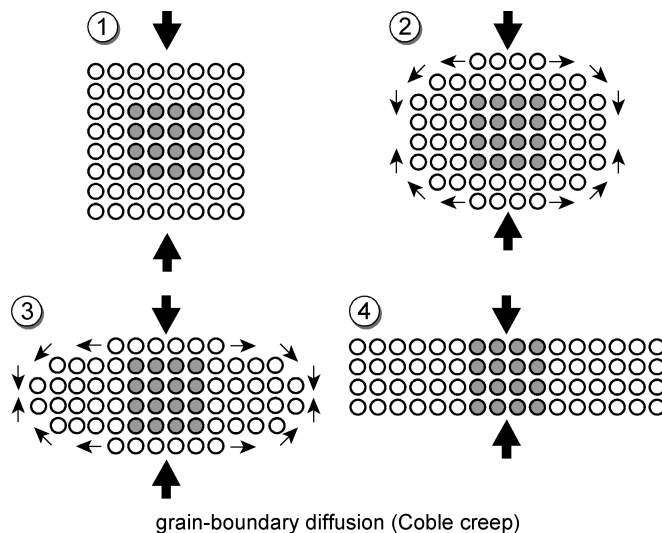
In Nabarro-Herring creep, atoms and vacancies move through the interior of the lattice: atoms from areas of high stress to areas of low stress, and vacancies in the opposite direction. The illustration below emphasizes the motion of atoms, but vacancy diffusion is at least as important (and perhaps more important).

Nabarro-Herring creep
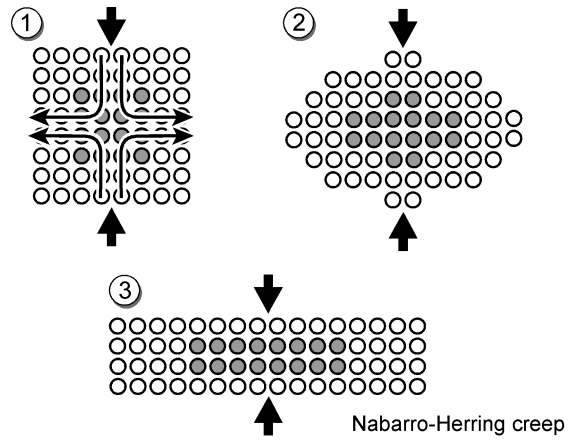
Both Coble and Nabarro-Herring creep cause a change in the shape of the crystal without fracturing, faulting, or melting. Where this occurs in a differential stress field, both mechanisms lead to a flattening of the crystal perpendicular to the greatest compressive stress.