

RHEOLOGY OF ROCKS IN NATURAL TECTONIC PROCESSES

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Summary

Due to the wide variety of rock types, loading conditions, thermodynamic variables, strain rates, and the ubiquitous presence of pore fluids, rocks may deform by a large number of physical mechanisms. These include brittle fracturing, frictional sliding, dislocation creep, diffusion creep, and pressure solution. Brittle processes including both fracture and sliding are favored by low effective pressures, high strain rates and low temperatures. Pressure solution creep is a process well-documented from field studies, and is thought to result from the enhanced material transport in fluid saturated rocks that are loaded externally. Dislocation and diffusion creep are temperature-activated processes involving the generation, annihilation, and motion of crystal defects, similar to deformation processes occurring in engineering materials, but taking place at much slower strain rates and lower temperatures. To describe the rheology of these mechanisms requires robust constitutive equations that are well-defined and sufficiently well-known that the laws can be extrapolated to conditions that are far from which they can be measured. The current state of knowledge of rock rheology is sufficiently advanced to provide broad general outlines of mechanical behavior, but also has substantial limitations. Two very thorny problems involve the scaling of rock properties with long time periods and for very large length scales.

α	Coefficient in effective pressure law usually = 1
a	Distance between Peierls hills
a_c	Cross sectional area of dislocation core
A, B	Materials constants in rate-state friction law
$A_{creep}, A_{glide1}, \dots$	Pre exponential factors, may be a function of temperature, etc.
b	Length of Burgers vector
b_0	Width of unsplit dislocation
c_{ijkl}	i, j, k, l component of stiffness tensor
c_0	Concentration of solute in crystal matrix
d	Grain size
d_0	Width of split dislocation
D	Constant for self-diffusion through lattice
D_c	Constant for core diffusion
D_{sol}	Diffusion coefficient of solute in crystal matrix
$\Delta G_{glide1}, \Delta G_{glide2}, \dots$	Activation energy of pertinent process
ϵ_{kl}	k, l component of infinitesimal strain tensor
ϵ_a	Elastic misfit of solute ion
$\dot{\epsilon}$	inelastic strain rate
$\dot{\epsilon}_0$	Pre-exponential constant, possibly a function of temperature
f_i	Fugacity of component i
ϕ	Porosity
γ_f	Stacking fault energy
k	Boltzmann's constant
$K(T)$	Function of material constants and kinetics parameters including T
L	Characteristic slip distance
M	Density of dislocation sources
μ	Shear modulus
μ_i	Chemical activity of component i
μ_{int}	Coefficient of internal friction
μ_{fric}	Coefficient of friction
μ_0	Constant in rate-state friction law
n'	Exponent - often equal to 2
ν	Freq. of vibration of dislocation segments
m, n, p, q	constants which depend on barrier geometry and strength or alternatively, numerical exponents

P	Lithostatic pressure
P_{fluid}	Pore fluid pressure
ρ_m	Dislocation density, stress independent
R	Gas constant
σ	Differential stress
Σ	Function in rate-state friction law
T	Absolute temperature
τ	Shear stress on a plane
τ_π	Peierls stress (i.e. Lattice friction stress at absolute zero)
V	Velocity of slip surface

V^*	Reference velocity
Ω	Molecular volume
y_i	Internal state variable for creep processes
\square	State variable for rate-state friction law

Table 1. Symbols used in the Paper

1. Natural deformation of rocks

“I would have you call to mind the strength of the ancient giants, that undertook to lay the high mountain Pelion on the top of Ossa, and set among those the shady Olympus.”—Francis Rabelais: Works, book iv. chap. xxxviii.

Our languages and cultures are peppered with references to the strength and enduring nature of rocks. We use phrases like “*terra firma*”, “solid as a rock”, and “as old as the mountains”. But, viewed from space, the Earth’s shape is seen to be very much like that of a spinning drop of liquid, and the main components of the geoid mimic as an inviscid fluid. On a human scale, the mountains that are so important to our geography and climate can be taken as a testament to permanence, or as evidence that rocks crumple, fold, and deform like sheets of paper crushed within our fists. Indeed, the central riddle of the study of the rheology of rocks and the tectonic processes that occur on Earth and the other planets is the resolution of the dichotomous character of rock strength. How do materials that are so obdurate in the experience of humans deform to the large strains that are observed in nature?

Measurements of the strength of rocks and soils also have important consequences for engineered structures. Thus, geotechnical engineering is a critical component for foundation stability, for tunneling, for oil reservoir exploitation, and for nuclear and mining engineering, among many other applications. Unlike the relatively simple materials that are common in metallurgical and ceramics engineering, rocks and soils

are typically composed of grains of many different mineral phases and are often heterogeneously mixed. They may be layered or massive; they may be relatively homogeneous when viewed at large scale, but quite heterogeneous when viewed at a smaller scale. Rocks and soil may contain planar foliated structures, rod-like lineations, or equi-dimensional bodies. They may be jointed and cracked or contain vugs, pores, and voids. The materials may be saturated with water, brine, gas, oil, methane or carbon dioxide. For many geotechnical applications, simply characterizing the rock mass with sufficient specificity is a challenge.

2. The mechanical problem

Structural geologists study natural rock structures and the processes that produce them. To describe fully the mechanics of the deformation, one needs information on three sets of parameters:

1. A detailed petrologic description of the material being deformed,
2. The conditions on the boundary of the rock mass, including some elements of the loads, velocities, or displacements imposed,
3. The thermodynamic variables within the rock mass, including lithostatic and fluid pressures, temperature, and chemical activities of the phases present.

Finally, one must know the constitutive relation between statical and the kinematical tensors, e.g., stresses or stress rates and strains or strain rates (see Figure 1). Armed with this knowledge, the field equations for continuity, motion, and energy can be written and solved to yield the forces, velocities, and displacements throughout the continuum. Although these requirements may seem overwhelming in their complexity, the ultimate goal is to provide a description that is, in a phrase attributed to Einstein, “as simple as possible - but no simpler”.

As R. C. Fletcher and D. D. Pollard wrote recently in the *Journal of Structural Geology*, 21, 1999, “[A] complete [mechanical description] does not imply the immediate simulation of all detail and complexity in the process leading to a particular structure or structural type. Instead, it requires that an explicit choice has been made of constitutive relation, boundary conditions, and initial conditions, which, together with the fundamental laws of physics, produces a closed set of relations from which all results follow. If the model result does not conform in all aspects with the current database, a more refined model may be formulated by a different choice of the mutable elements. The explanatory power of simpler models is first examined, often providing significant physical insight, then robustness as well as detailed simulation are pursued.” The role of this article is to discuss one small part of that larger mechanical description, the rheology of rocks being deformed in nature.

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Biographical Sketch

Brian Evans is a full Professor at the Department of Earth, Atmospheric and Planetary Science at the Massachusetts Institute of Technology in the US. He is an expert on the strength of rocks, microstructures of naturally deformed rocks and applications of rock mechanics to tectonic problems. He has wide experience in these fields, in both experimental rock mechanics and modeling.