STRUCTURAL ROCK MECHANICS OF EARTHQUAKES

1. *Scale of Heterogeneity in Continental Crust – Problems of Inheritance*
   - earthquake rupturing occurs in rock – rocks are *memory banks* containing information on Earth processes / rocks within the Earth's crust are heterogeneous in terms of composition, structural assemblages, anisotropy / continental crust, in particular, has a great deal of inherited structure (e.g. faults, shear zones, etc.) with potential for reactivation in present-day stress fields / tectonic exhumation accesses rock assemblages throughout the crust / sedimentary basins / mid- deep-crustal assemblages – flow in the mid- to deep crust / small mimics large / geophysical observed layering may not be coincident with geological layering

2. *Stress and Fluid-Pressure in the Earth's Crust*
   - stress and deformation / the stress tensor – state of stress at a point / differential stress and plate tectonics / how big are the differential stresses driving faulting and crustal deformation? / Mohr circle for 2D stress / homogeneous vs. heterogeneous stress fields / far-field vs. local stress fields / S.O.C. / contemporary stress provinces / geological structures defining stress trajectories / Principle of Effective Stress / fluid overpressures in sedimentary basins / fluid-pressure compartments / possible effect on frictional fault strength / overpressures in crystalline crust?

3. *Seismogenic Crust and Fault Zone Rheology*
   - 1970's densification of seismograph networks / microearthquake networks of Japan and California – improved depth distributions / distinction between subduction seismicity and non-subduction seismicity distributions / distortion of thermal structure by subduction / sharp cut-out in mid-crust (10 – 20 km) for continental seismicity varies with regional heat flow / larger earthquakes tend to nucleate towards b.c.s.z. / what do the fault rocks say? / continental fault zone models – b.c.s.z. = onset of crystal plasticity in quartz (c. 350 °C) or plagioclase feldspar (c. 450 °C) / rheological strength profiles – can they be improved? / EQs in deep continental crust – India, Africa, Asia, etc. / EQ swarm activity – Hill (1977) fault-fracture mesh models

4. *'Andersonian' Fault Mechanics – Limitations*
   – triaxial stress state with principal compressive stresses - $\sigma_1 > \sigma_2 > \sigma_3$, E.M. Anderson's Dynamic Theory of Faulting (1905, 1942, 1951) / boundary condition – the Earth's free surface / stress trajectories generally vertical or horizontal? / under what circumstances do stress trajectories deviate from the vertical and the horizontal?? / three basic stress states $\sigma_v = \sigma_1$, σ_2 , or σ_3 / fault initiation in the three basic stress states in accordance with Coulomb

criterion for brittle shear failure – in homogeneous, isotropic intact rock, faults form along planes containing the σ_2 direction at an angle $\theta = 45° - \phi/2$ to σ_1, typically 25-30° / 'Byerlee' friction $0.6 < \mu_s < 0.85$ / frictional reactivation of existing low-moderate displacement faults – orientations for optimal reactivation and frictional lock-up / fault friction constrained by dip-ranges for active dip-slip faults assuming 'Andersonian' stress trajectories / application to large-displacement faults?

5. *Formation of Extension Fractures in the Earth's Crust and their Significance*
   - hydraulic extension (Mode I) fractures in the Earth's crust form perpendicular to σ_3 – widely preserved as hydrothermally infilled extension veins / range of rock tensile strength, T_o / hydraulic extension fracturing when $P_f = \sigma_3 + T_o$, provided $(\sigma_1 – \sigma_3) < 4T_o$ / crack-seal textures reveal incremental dilatation / vertical extent of hydrothermal vein swarms / microcrack dilatancy vs. hydrofracture dilatancy / conditions allowing hydraulic extension fracturing - intact rock, 'healed' faults with restored cohesive strength, crust with severely misoriented faults / Summary – hydrothermal extension veins demonstrate (i) local orientation of σ_3 at the time of vein formation; (ii) constrain the prevailing differential stress; (iii) demonstrate local attainment of the tensile overpressure condition – $P_f > \sigma_3$; and (iv) can be used to establish the degree of overpressuring provided the depth of vein formation and the stress regime can be established.

6. *Aspects of Frictional Fault Mechanics*
   - frictional constraints on thrust, strike-slip, and normal faults / borehole stress measurements / Byerlee friction? / extrapolation to seismogenic depths / Townend & Zoback, 2000 / loading faults to failure / load- strengthening vs. load-weakening faulting / Brittle Failure Mode (BFM) Plots / overpressures more easily generated and sustained in regimes of horizontal compression

7. *SPA = Structural Permeability Analysis*
   - gold and quartz as tracers for hydrothermal flow / in low-porosity rocks, faults and fractures dominate rock permeability / components of stress-controlled permeability - extension fractures, faults (may be more or less permeable than wallrock), extensional-shear fractures, stylolites, dilational jogs, and fault-fracture mesh structures / SP components sometimes combine to produce strong σ_2 directional permeability

8. *Compressional Inversion Faulting*
   - arises from contraction of previously rifted crust with reverse-slip reactivation of inherited normal faults / Non-Andersonian reverse faults dipping > 45° not uncommon – global dip distribution for reverse-slip ruptures shows second

peak with dip at 50° ± 5° and no ruptures dipping > 60° / compressional inversion is an inevitable consequence of the 'Wilson Cycle' of ocean opening and closure / characteristic *Structural-Stratigraphic* signature – harpoon-head structure / coaxial vs. non-coaxial inversion (some associated strike-slip) / reactivation of inherited faults extremely selective / competition between reactivation of steep reverse faults and new-forming 'Andersonian' thrusts evident / exhumed base of the seismogenic zone = P-T environment for mesozonal (orogenic) lode gold deposits / Sigma Mine, Abitibi; Giant Mine, Yellowknife; Paddington N. Mine, WA; Mother Lode belt, CA / late-stage thrusts – Carson Hill Mine / tensile overpressure condition needed to reactivate steep reverse faults / Fault-Valve action drives fluid-pressure cycling / implications of F-V model for earthquake nucleation and recurrence – *strength cycling as well as stress cycling* – dual-driven failure / *WHERE IS IT HAPPENING TODAY?* / inland earthquakes from ongoing compressional inversion in NE Honshu / e.g. 2004 mid-Niigata EQ sequence / seismological and electrical diagnostics of fluid-overpressured mid-crust

9. Seismogenesis on Subduction Megathrusts

- critically organized island arc systems / source of largest EQs / scale of megathrust rupture / thermal structure of subduction zones – subduction refrigeration / sites of intense fluid generation and redistribution / stress and fluid-pressure conditions driving megathrust rupture / stress-switching accompanying Tohoku megathrust rupture / permeability controls on containment and release of overpressured pore-fluid pre- and post-failure / constraints on shear stress along subduction interface / strength asperities from heterogeneous overpressuring / fluid release from stress switching / evidence for intermittent fluid release – mud diapirs in outer forearc and hydrothermal vein-swarms in inner forearc / possibility of drainage asperities / zones of NVT = deep repository of hydrothermal fluids at 35-45 km depth?

Richard H. Sibson
Emeritus Professor of Geology
University of Otago