Summary of Session 1.2:

Frictional behaviour of rocks, gouge layers and complex fault zones: Simulation, observation and scaling

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Objectives and issues

The objectives of Session 1.2 were to identify what micro-scale elements of the faulting and fault slip processes are critical ones in determining the macroscopic faulting behavior, and to discuss conceptual strategies for incorporating these key processes into tractable models. Three key topics were identified in advance of the workshop: (1) Identifying the key deformation processes and conditions that need to be taken into account when constructing micro-scale fault models, (2) Identifying key scaling issues and deciding whether existing friction constitutive laws are proper building-blocks for micro-scale model development or benchmarks to judge their success, and (3) Identifying the most fruitful strategies for incorporating these key processes, conditions and scales into numerical models of earthquake generation. We enjoyed three brief talks in the Plenary, and five presentations and some lively discussion in the two-hour break-out session.

Plenary

In the Plenary session Mike Blanpied reviewed the three phases of a generic earthquake cycle: the inter-seismic period, nucleation of the earthquake instability, and the earthquake itself. He argued that particle-based fault models must capture two factors that are key to the natural earthquake cycle: The first of these is time-dependent healing and strengthening of a fault zone; this may occur via a myriad of physical and chemical processes that have abundant time to act during the decades to eons between earthquakes. If the fault has its porosity removed interseimically, then nucleation and propagation of the following earthquake will require rapid dilation and re-fracturing of the fault rocks. The second factor is the comminution of fault rocks, which both natural and experimental observations show to be a key process during fault slip even at modest confining stresses.

Miti Ohnaka reviewed laboratory and theoretical aspects of dynamic fault slip, illustrating his points with data from high-resolution laboratory experiments. He demonstrated that the first stage of dynamic earthquake slip on lab faults involves concentrated, self-accelerating slip on a nucleation patch, followed by break-out and propagation of rupture over the wider fault surface. Interestingly, the dimension of the nucleation patch can be simply related to a characteristic fault roughness parameter. This roughness parameter appears also to govern the duration of the dynamic nucleation and the characteristic fault-weakening displacement. It is interesting to note that Jim Dieterich has used quasi-static fault slip observations to argue for similar scaling relations and for slip on a constrained nucleation patch even before the onset of dynamic slip. Tying these sets of observations together into a coherent theory for earthquake initiation appears to be a promising area for future work.

In the final Plenary talk Peter Mora reviewed the current state of numerical earthquake modeling and pointed to areas ripe for development. He pointed to an interesting observation from the lattice-solid model simulations: that the macroscopic fault strength appears to be relatively insensitive to the intrinsic friction between particles. This suggests that the simulated fault gouge in the model self-adjusts its configuration and porosity in order to achieve an advantageous balance between particle-particle sliding and particle rotations. Another interesting phenomenon sometimes seen during long simulations was self organisation of the active shear zone into a narrow band with very low effective friction. This offers a potential explanation for the lack of observations of sufficiently weak gouge layers in the laboratory to explain the San Andreas observations. The self-organisation phenomena potentially has major implications regarding fault constitutive relations. If real faults are also capable of evolving into different stable or quasi-stable states with different macroscopic behaviour, then it seems unlikely that a universal fault constitutive relation could be applicable to all faults at all times.

Detailed session

Chris Marone kicked off the break-out session by pointing out that there's a continuous range of behaviors in fault phenomenology, ranging from stick to slip and including creep, accelerated slip, afterslip, and so forth. He asked: To what extent is it possible to embody all of this behavior in one friction relation, or in a system described by one such relation? And to what extent is that desirable or necessary? How complex a friction constitutive relation is needed? Marone argued that one capable of describing much of a range of behaviors must be at least as complicated as the Dieterich-Ruina rate-state equations, whether or not of that specific form.

Much discussion centered around friction constitutive laws and their relation to the grain-scale or asperity-scale processes which underlie the macroscopic, emergent behavior. Laboratory experiments yield direct measurements of quantities such as fault strength, velocity dependence of strength, fault creep rate and so forth, plus the systematics of behaviours such as the transition from unstable to stable slip modes, or from dilating to compacting deformations. We construct constitutive laws to embody these emergent sets of behavior, and at least in part base the form of the equations on what we understand about the micro-physics. In this way we indirectly link micro-physical processes we know to occur to emergent properties of the fault such as a critical slip weakening distance D_c, a friction coefficient insensitive to normal stress, and time-dependent strengthening.

As one example, Aochi and Matsu'ura presented a state-dependent friction formulation in which fault state was expressed as a function of surface topography. In their model slip-dependent weakening (a laboratory observation) results from the wearing-down of fault surface topography (a process observed to occur). This idea invites the collection of observations which might support or refute the connection between process and behaviour. Discussion revolved around the less obvious connection between fault healing and the regrowth of fault surface topography, and over ways to extend the concept of evolving topography to faults containing gouge.

There appear to be two means by which to test whether our intuition about the connection between micro-process and behaviour is correct. First, we may seek to more directly observe the micro-physical processes at work during slip. Second, we may add what we believe to be the relevant microphysics to a particle-based or surface-based numerical fault model and see whether the behaviour indeed emerges. An important question in the latter case is whether the behaviour is observed at all scales, i.e., both at the scale of the laboratory experiment and that of natural faults. Xia and colleagues demonstrated that only for a certain class of systems can the macroscopic behaviour be seen to "average" over micro-scale inhomogeneities and sample-to-sample differences. In their numerical studies, they found that behaviour can be sample-specific such that it is strongly dependent on configurational details or microstructure. A discussion ensued as to whether when dissipation is present, as is the case in the real earth, the sample-specific behaviour seen in the numerical model would remain. This question has major implications to the notion of constructing macroscopic frictional constitutive relations for fault zones.

Jim Dieterich presented novel friction experiments that aim to more directly bridge this gap between behaviour and microphysics. In sliding tests on transparent materials, the formation and deformation of fault asperities was observed directly. Dieterich showed that many of the emergent behaviours mentioned above can be seen to derive directly from the deformation at asperity contacts. He drew particular attention to the importance and ubiquity of time-dependent processes which act to heal and re-strengthen the fault. Viewed at large scales, these processes, in effect, act to remove the fault from the material. Fruitful discussion was had over the need to incorporate time-dependent processes into particle-based numerical fault models and on avenues to accomplish this goal. A question remaining to be answered (through laboratory tests and numerical models) is the extent to which time-dependence needs to be included in frictional relations describing dynamic slip during earthquakes, or whether simpler, slip-dependent laws of the type advocated by Ohnaka are adequate once the earthquake has moved beyond nucleation and is propagating seismically as a self-driven instability.

Despite the heartening progress being made on understanding the frictional properties of bare, rough surfaces, the fact remains that many (if not all) faults contain gouge. Marone showed laboratory data which suggest that macroscopic friction behaviour reflects a width of localization of shear in the gouge layer. For example, the characteristic displacement D_c appears to scale with shear band width. Since it will be extremely difficult to make direct observations of the internal machinations of gouge layers during shear, much progress may be made via the use of numerical fault models such as that developed by Mora and colleagues.

Discussions in this breakout session were very encouraging to those of us interested in fostering the growing level of collaboration between practitioners of numerical and experimental methods of investigation. One was left with the impression that significant progress lies ahead through efforts to test and justify (or refute) the form of our frictional relations both through direct observation of faulting processes and through development of increasingly clever and realistic numerical models.