Constraining the physics of earthquakes with observations

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Data assimilation in earthquake modeling is needed in two major ways. First, we need earthquake observations to constrain what the physics of the systems, their evolution and the equations describing them, are. Second, we need earthquake observations to constrain what the current state of the system is, where we are in the earthquake cycle, what the time dependent probabilities are. Loosely, in the first case we try to understand what happens in the long run, while in the second case, we try to understand what is specifically likely to happen in the particular area of interest. While progress can be made on both fronts, there is much more data we can use to both constrain and test our models of the physics of earthquakes, and so here we will focus on this first case.

Inverting observations of an individual event to determine the slip history of an event is an inherently under-determined problem: we use sets of continuous time point measurements (seismograms) to infer continuous time two dimensional fault surface motions. This under-determined aspect underlies most inversions, and makes them rely, ultimately, on assumed constraints which are themselves difficult to test within the context of the inversion. Trying instead to infer the physics underlying the dynamics, rather than the particular solutions, is, in contrast, much more constrained. It is possible that it may even be over-constrained. Let us explore this further.

Observations of different earthquake behaviors provide significant constraints on the possible source physics. Each independent behavior provides more than simply additive further constraints: they provide multiplicative further constraints, since the same physics must be compatible with the intersection of all the constraints. Thus even fairly weak, noisy constrains, when combined with others, together provide severe constrains on a physical model of earthquakes. Some observations may provide quite weak constraints. Some observations might provide quite general constraints. Some observations might provide quite specific constraints. All, ultimately, arise from a unique, though possibly location dependent physics. Thus, we have two basic questions to answer: how location dependent is the physics, and what constraints do each of the observations provide?

Earthquakes are extremely complex in space and time, and heterogeneities play a central role in this complexity. The heterogeneities come in a variety of forms, transforming over a variety of timescales. Some are relatively static on the timescale of earthquakes, being material and geometrical irregularities which evolve slowly over tectonic timescales. Others, like stress and strain, are dynamic and can evolve rapidly on the timescale of earthquakes. We do not know the relative contributions of these static versus dynamic heterogeneities to earthquakes, and whether the relative contributions may evolve as faults mature with increasing displacement.

A fundamental question to the issue of the problem being over-constrained versus under-constrained is the degree to which different parts of a fault, and different faults, behave similarly. There are reasons to hope that they might: constant stress drop observations suggest a remarkable similarity of events across a huge range of length-scales, around the globe. If we can group faults appropriately, taking into account the relevant features which might distinguish them (e.g. subduction versus transform, young versus mature), and faults within a group are seen to behave similarly, then we have a hope of limiting the degrees of freedom inherent to the location dependence of the physics. This is crucial in whether the constraints of the combined observations are, ultimately, more or less numerous than the degrees of freedom of the physics.

To constrain the physics of the source, we need as many different independent measurements of behavior as can be found. Both the mean behavior and scatter about the mean provide useful information. Differences in the means from location to location suggest possible differences in location physics. Scatter gives indications of different relative dynamic and static heterogeneities.

Many different earthquake behaviors have already been described: b-values, A-values, p-values; static stress drops, dynamic stress drops, apparent stresses; moment spectra, hypocenter locations, and directivity effects, to name only some. Many models could explain any one of these observations. Only some could explain more than one. Extremely few could explain most. And none as yet has been shown to match them all. This does not make it an impossible problem; it rather points out the significant constraints the observations provide.

This presentation will examine a number of earthquake behaviors, and the constraints they place on earthquake physics, together with modeling efforts being done to try to simulate realistic earthquake behavior. It aims to offer a prototype and stimulate discussion on how data assimilation in the context of the physics of earthquakes could work.