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The New Geophysics: limits to quantitative seismology in a crack-critical Earth

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Extensive observations of stress-aligned shear-wave splitting (seismic birefringence) show that the stress-aligned fluid-saturated microcracks in almost all *in situ* rocks at all depths, geologies, and tectonic environments are so closely spaced that they are critical systems with self-organised criticality. Such self-organised criticality has been recognised in the Earth for the past half a century from the self-similarity of the Gutenberg-Richter relationships, but the underlying physical phenomena causing self-similarity was not understood. The advance now is that understanding the cause of the self-similarity, the stress-induced manipulations of the distributions of fluid-saturated microcracks pervading most rocks in then crust (and almost certainly upper mantle) allows the universality and calculability of critical systems to be exploited. In particular: small-scale (pre-fracturing) deformation can be monitored with shear-wave splitting; calculated with the nearly-parameterless model anisotropic poro-elasticity (APE); response to known changes predicted by APE; and in principle, future behaviour controlled by feedback. This is a New Geophysics with significant advantages over conventional geophysics. However, there are severe disadvantages.

Critical systems are expected to have extreme sensitivity to nearly negligible variations, where very small disturbances can have major effects at large distances: "the butterfly's wings in Brazil causing a tornado in California". Critical systems also imply that measurements degrade both temporally and spatially. The most direct observations of these phenomena in the Earth are in the EC-funded SMSITES project in northern Iceland. Crosshole seismics at 500m-depth between boreholes 315m-apart showed exceptionally well-recorded ms anomalies in travel times of P-, *SH*-, *SV*-waves, and *SV*-*SH* anisotropy (accurate to $\pm$0.02ms) correlating with small-scale seismicity (energy equivalent to a M 3.5 earthquake) at a distance of 70km. There are also associated mm anomalies in GPS measurements and a 1m anomaly in water-well levels, which

elsewhere have been widely associated with distant earthquakes, implying that such seismic anomalies are also widely present. Less direct observations are the $\pm 80\%$ scatter of shear-wave time-delays above small earthquakes which are interpreted as the effects of 90º-flips in shear-wave polarisations caused by critically-high pore-fluid pressures near all seismically-active fault planes.

Note that shear-wave splitting is the key observation for crack criticality. The two main reasons are that shear-wave splitting is sensitive to aligned fluid-saturated microcracks, whereas P-waves are relatively insensitive. Additionally, shear-wave splitting is a second-order phenomenon that (by rotating into preferred orientations) can frequently be measured to first-order accuracy.

The implications of these various phenomena for quantitative seismology are that measurements and calculations involving P-waves are likely to be comparatively stable but not very accurate, and insensitive to dynamic changes to microcrack geometry and seismic propagation. If, however, the accuracy of shear-wave interpretation are attempted, measurements and calculations are expected to show: extreme sensitivity to initial conditions; temporal variations of measurements; and spatial variations where measurements will vary at neighbouring locations. Additionally, shear-wave splitting will depend on details of the stress, pressures, and microcrack geometry of *in situ* rock which vary with time and place and are completely unknowable. Consequently, detailed quantitative observations are likely to contain non-causal incalculable effects.

Examples of these various phenomena will be discussed, and the directions of future quantitative seismology suggested.