Beyond plate tectonics: the interseismic, transient mechanical processes of fault systems revealed by near-field observatories

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Thanks to the considerable development of dense monitoring geophysical arrays, intensive research on the mechanical behaviour of plate boundaries of the last decades has revealed that the simple models of plate tectonics (rigid blocks separated by major faults) and of the dual, « stick-slip » behaviour of faults (either locked during interseimic loading, or slipping fast during the earthquake) are far too simple, and inadequate for explaining many observations.

Leaving apart the well documented postseismic activity, space-time clustering of microseismicity is the most obvious indication of non-stationary processes within the time period between large earthquakes. Its statitistics has been reported and analyzed for many decades, but in the recent years, its modeling with simple physical, statistical models is providing a new understanding of the underlying processes for earthquake triggering and interaction. Space-time fluctuation of seismicity also sometimes follows a diffusion law, in agreement with migration of pore pressure at seismogenic depths, suggesting natural hydrofracturation and the existence of transient pressure pulses flowing within a permeable fault system.

Individual instabilites on shallow or deep faults also exhibit much richer phenomenology than the standard seismogenic stick-slip: slow and silent earthquakes, a few examples of which were discovered decades ago, are now more oftenly detected from refined analysis of seismological or geodetic records. They define a new class of transient slip events which obeys a scaling law (duration, seismic moment) significantly different from those of earthquakes, from time scales of seconds to years, the physical basis of which is not yet understood. Strong spatial variation of « seismic coupling » of the seismogenic interplate (i.e., the proportion of elastic shear strain stored for megathrust slip) has been detected by geodesy along subduction zones (Japan, Chili,..), which remains to be explained, possibly in terms of large creeping patches of the interplate. Adding to the family of transients, the tectonic tremors discovered in the early 2000s in the Japanese subduction zone have now been reported for several other regions (Cascades, Mexico, California), and, for the subduction cases, are to be related with unstable creeping activity on or close to the interplate contact, in the transition zone, downdip from the seismogenic, locked interplate; their physical origin is still subject of intense research and debate.

Owing to these discoveries and new perspectives on instabilites of fault systems, the research for precursors to large earthquakes, which was the first motivation for densely instrumented sites in active fault systems in the period 1970-1990, and the usefulness of which was a subject of strong controversy in the 1990s, is now been reconsidered from a different perspective: presursors are simply a subclass of transient phenomena which are physically linked to the initiation phase of large earthquake. The « precursory » potential of any transient has thus to be analyzed in the general probabilistic frame of cross-triggering between transients. Constraining and modeling the latter will be a major challenge for the coming decades. In particular, one will have to determine and quantify how a transient event can load – or alternatively unload– neighbouring major seismic asperities, advancing or delaying their rupture times – in other words, what are their role in the global seismic cycle.

This will require to combine simple physical models with phenomenological laws, based on many refined observations.

Dense near-field observation systems in selected fault systems are thus needed. Many earthquake countries have already started or achieved such instrumentation. One may quote California, Japan, Taiwan, Chili, China... but also Europe : Marmara sea, Corinth rift, Irpinia region, Island - among others. The instrumental strategies are quite varied in their detail, but all share several of the following characteristics:

- seismological arrays are complemented by geodetic ones (mostly continuous GPS, repeated InSAR, sometimes borehole strainmeters, borehole and/or long base titltmeters, tide-gages...). Geodesy provides unique resolution of strain at periods larger than a day, unresolved by seismometers, and seismometers provide unique ability in accurately locating sources (when seismic), which is not possible with strain records (non propagating static field).
- surface or near-surface geodetic or seismological stations cover the whole target zone (which can vary typically from 30 km to 1000 km). Their spacing should ideally not be much larger than the depth of the target sources (seismic or aseismic) (« near-field » systems), so that several stations can detect the relevant smallest event.
- borehole installation for seismometers (100-300 m in depth) allows to significantly increase the signal-to-noise ratio, like in Parkfield, lowering the detection threshold by one or 2 points in magnitude.
- borehole strainmeter and tiltmeter data (100-300 m) show large resolution in strain (10 to 1000 times better than GPS), resolving fractions of the earth tide. However, they are not exploited yet in a systematic way, as many of the in situ instrumental response are difficult to determine, due to unmodelled drift and/or relaxation, and as they remain sensitive to long term seasonal effects (rain and pressure). Pore pressure measurements in trapped aquifers provide

similar high resolution strain data.
- deep « in situ » boreholes, several kilometers deep, like SAFOD on the San Andreas fault, reach seismogenic depths, allowing a unique access to fault zone stresses, structure, material, and properties, and to monitor transients, in particular fluid flow, as well as micro-earthquakes undetectable from near-surface arrays.
- near-surface geochemical monitoring in fault zones connected to the deeper crust can also track perturbation of fluid circulation, possibly diagnostic of deep changes in strain or pore pressure. The difficulty to interpret such data, due to the heterogeneity of the crust, and to find appropriate, « sensitive » sites, makes this intrumental approach still quite marginal.
- Electromagnetic monitoring arrays (MT, magnetometers, radio) are present in a few sites. Originally installed mostly for searching EM precursors, at the time of the VAN debate, they have not been much developped for the last decades. This may change however, as these measurements should play an increasing role in the detection and analysis of transients, in particular due to their sensitivity to crustal fluids (conductivity, and streaming potential).
- Finally, the probability of moderate to large earthquakes occuring within the instrumented sites is quite large, as many of them are the target for medium term prediction. For instance, this probability may be about 0.7 in the Marmara sea for the next 30 years, for a magnitude greater than 7. Under the hypothesis were the probability of a « significant » event is 0.5 in the next 50 year in each of the 20 most instrumented sites, one should expect about one such event every fiv years, which would provide at each time unprecedented data for analyzing seismic/aseismic coupling with high levels of energy transfer.

Many of these arrays have contributed to the main discoveries of the last decade, and one may expect many other discoveries in the coming one. Concerning the modeling of transients, one may outline two major questions, out of many others, still mostly unanswered:
- what is the contribution of aseismic transients, if any, in earthquake clustering, in particular for earthquake swarms?
- what is the role of fluids in creep, tremor, or seismic transient triggering?
Understanding clustering will require that high resolution strain records are jointly analyzed with seismicity data, in a systematic way. Tracking fluid activity will request new investigations to detect changes of the physical properties of the crust, within and around the fault zone at depth (velocity or resistivity), which may be done in particular with repeated seismic or magneto-telluric experiments, allowing high resolution, differential tomography. Any progress in answering these two questions will improve the accuracy of probabilities assessment of mechanical coupling between transients.