Geology, mechanics and numerical modelling of complex earthquake ruptures in the continental crust

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Financial Support: ERC Consolidator Grant 614705 NOFEAR (2014-2019)

Earthquakes are the result of ruptures that nucleate, grow and terminate in most cases along pre-existing faults (Gilbert, 1884). Earthquake physics is concerned with both the behaviour of the volume around the fault, its accumulation of elastic strain energy and catastrophic release thereof (including the damage induced in the wall rocks), as well as the rheology of the fault in which understanding fault friction and shear fracture is a key (Reid, 1910; Scholz, 2002). Importantly, the reliability of the probabilistic hazard estimates associated to earthquakes relies heavily on the definition of a seismic faulting model which needs to be underpinned by realistic geological and physical constraints including fault zone rock type, state of stress, fault geometry, fault yield strength, friction and rupture laws (Dieterich, 1994; Hainzl et al., 2010).

In the very last years, high-quality seismic recording and detailed field geological surveys (e.g., surface rupture distribution) of earthquake ruptures resulted in quite astonishing observations:

1) seismic ruptures propagated along the same fault patch multiple times during the same earthquake (2008 Mw 7.8 Wenchuan (China) and 2016 Mw 7.8 Kaikoura (New Zealand) earthquakes),

2) moderate to large magnitude earthquakes ruptured the same fault patch (Monte Vettore Fault, Italian Central Apennines) within a few months of each other (24 Aug. 2016 Mw 6.0 Amatrice and 30 Oct. 2016 Mw 6.5 Norcia earthquakes) and,

3) seismic ruptures "jumped" and propagated along both locked and creeping fault sections during the same earthquake (2018 Wenchuan Mw 7.8).

These findings have profound consequences in seismic hazard scenarios, as they shake the common wisdom that (1) creeping faults are "safer" because their wall rocks store a limited amount of elastic strain energy or release it more slowly with respect to locked faults, and (2) seismic ruptures may propagate along the same fault only after several centuries (or millennia in the case of the continental crust). Moreover, especially in the continental crust where fault zone networks are often more complex than along mature plate boundaries, it is unclear why some ruptures propagate for few kilometers producing M_w4-5 earthquakes and others instead "jump" across nearby faults resulting in > M_w 6 earthquakes. To date there is not yet a satisfactory physical motivation for these differences related to individual earthquakes.

The main goal of this Ph.D. project will be, by exploiting powerful computational facilities and numerical models, to integrate frictional constitutive laws obtained from the laboratory with realistic fault zone geometries (e.g., Murphy et al., 2018). This will result in the identification of the physical, geological and loading conditions which control the propagation of seismic ruptures along complex fault networks (2016 Mw 6.5 Norcia earthquake) and along both locked and creeping sections (2008 Mw 7.9 Wenchuan earthquake). The physically-based 3D fully dynamic simulations will also yield estimates of earthquake source parameters (e.g., fracture energy, seismic moment release rate) and synthetic seismograms (strong ground motions) to be compared with seismological and strong motions data from these earthquakes.

The fully-dynamic individual earthquake simulations will exploit the discontinuous Galerkin (DG) method (Pelties et al., 2012; 2014). In fact, DG methods can use unstructured 3D meshes which allow treating complex geometries and they achieve high accuracy by implicitly avoiding spurious high-frequency oscillations present in other methods. The PhD student will perform the simulations with the freely available software SeisSol (Pelties et al., 2014), https://github.com/SeisSol/SeisSol) based on the Arbitrary high-order accurate DERivative Discontinuous Galerkin method (ADER-DG). SeisSol employs fully adaptive, unstructured tetrahedral meshes to combine geometrically complex 3D geological structures, nonlinear rheologies (including off-fault plastic yielding, Wollherr and Gabriel, 2016) and high-order accurate propagation of seismic waves. SeisSol has proven to be highly scalable on some of the largest supercomputers worldwide (Uphoff et al., 2017) and won the prestigious “Best Paper Award” of the International Supercomputing Conference (SC17) resolving the 2004 Sumatra-Andaman earthquake including complex splay fault geometries.

In the simulations, the PhD student will focus on a few key geologically-based issues (i.e., fault roughness in different lithologies and seismogenic depths, distribution of fault zone rocks and complex fault/fracture networks: Bistacchi et al., 2011; Demurtas et al., 2016; Fondriest et al., in prep.,) and experimentally-based observations (dependence of the so called "friction coefficient" with rock-type, normal stress, temperature, presence of fluids, slip and slip rate, e.g., Di Toro et al., 2011; Spagnuolo et al., 2016) that will provide the input parameters to numerical models, which in turn are instrumental to the extrapolation of the complex rupture processes to km-scale faults. The simulations will model fault networks of extended dimensions (10-300 km) to reproduce rupture propagation on fault networks generating moderate to large earthquakes (e.g., 2016 Mw6.5 Norcia) as well as on creeping faults (e.g., 2008 Mw7.9 Wenchuan).

Computational facilities are available at Padua Univ. and LMU both for development, benchmarking and testing of the methodology on (1) small-size models (**Padua Univ. machine “Avogadro”**: 284 CPUs with 71 nodes, Intel Woodcrest Dual cores and 2 Tb of RAM) and (2) for running large-size models (i.e., large number of mesh nodes or volume elements: 11088 Broadwell Intel Cores on **Datamor at Ifremer** and 241,000 cores of the two phases of the supercomputer **SuperMuc (Leibniz Supercomputing Centre, Germany).** The degree of realism and accuracy achieved will be enabled by recent computational optimizations targeting strong scalability on many-core CPUs, fast parsing of heterogeneous initial conditions on and off faults via a parallel server for adaptive geoinformation (Rettenberger et al., 2016) and a ten-fold speedup owing to an efficient local time-stepping algorithm.

The above activities will force the PhD student (advised by the supervisors) to develop a collaborative network during the entire duration of the project, as the activities will be performed at UNIPD-DG, CAGS and INGV for physical and geological constraints and LMU, GeoAzur and IFREMER for modelling. From this research strategy, we anticipate the following outputs:

- training of a young researcher with ability to exploit sophisticated numerical methods (also for industrial applications), with strong background on the geology and physics of earthquakes;
- the identification of the loading conditions, geological and physical parameters that control the propagation of seismic ruptures in complex fault networks (also for seismic hazard studies);
- the submission of two to three papers regarding physically- and geologically-based earthquake simulations.

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