

Satellite image analysis for measuring rock properties in fault damage zones, a key constraint for earthquake modeling

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Location: Time shared between **Inria** Sophia-Antipolis Méditerranée and **Géoazur** Sophia Antipolis

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Context: Decades of research in earthquake sciences have yielded meager prospects for earthquake predictability: we cannot today predict the time, location and magnitude of a forthcoming earthquake. Yet important advances have been made, including the demonstration that certain intrinsic properties of the tectonic faults that produce earthquakes significantly affect their magnitude and hence their devastating potential [1]. It is thus of critical importance to properly document the geometric and other physical properties of the faults. The latest generation of satellite-based imaging sensors (Pleiades, Sentinel, etc.) acquires large volumes of Earth surface's images with high spatial, spectral and temporal resolution (up to 50cm/pixel, 50 bands, twice per day, covering the entire planet). These data offer the unprecedented opportunity to observe and to measure the faults as they appear at the Earth surface, at a level of detail and precision never achieved before. The proposed work intends to take advantage of these new satellite data to recover a specific fault property—fault rock damage, better understanding of which is needed to improve earthquake modeling.

Subject: As tectonic faults grow over time, they permanently damage the embedding crustal rocks, in the form of dense networks of secondary damage faults and fractures of various scales, spacing, orientations, slip modes, etc., extending off the parent fault (Fig. 1a) [1-2]. These damage faults/fractures modify the elastic properties of the surrounding crustal volume, actually increasing its compliance. Theoretical models show that the variability of damaged rock compliance around a fault controls the distribution and amplitude of the displacements and the rupture speed of the large earthquakes this fault produces [1 & 3]. Rock compliance in fault damage zones thus seems to have a pronounced impact on the seismogenic potential of parent faults (i.e., their ability to produce large earthquakes). Yet, there exist at present very few data that measure the rock compliance in natural fault damage zones [4]. Available earthquake models are thus using at best *ad hoc* compliance values, but more generally ignore the compliance of the damaged crust. This PhD topic thus intends to provide robust estimates of crust compliance in natural fault damage zones. These measurements will then be used to better constrain earthquake rupture models developed in our group.

There exist sites over the world where the damaged rocks around faults are well exposed to observation. The exposition is at the ground surface, but a few studies that were conducted at local

spots in some of those exposed damage zones have shown that the elastic properties recovered from surface data are similar to those inferred by geophysical means in the first 5-6 km of the crust [4]. Measuring damage at the ground surface thus seems relevant to estimate the compliance of the shallow crust. Some of the best exposures of fault damage zones are located in Western USA, in dry and hence well-preserved environments (Fig. 1b-c). There, the damage faults are clearly observable, and hence measurable, for they have specific morphological and topographic signatures (Fig. 1b-c). The project aims at identifying these signatures so as to measure the sizes, spacing, densities, slip modes, and orientations of the faults/fractures in damage zones all along and across a few target faults. Using theoretical models, we will then convert these measurements into rock compliance estimates. These estimates will feed fault and earthquake models developed in our group.

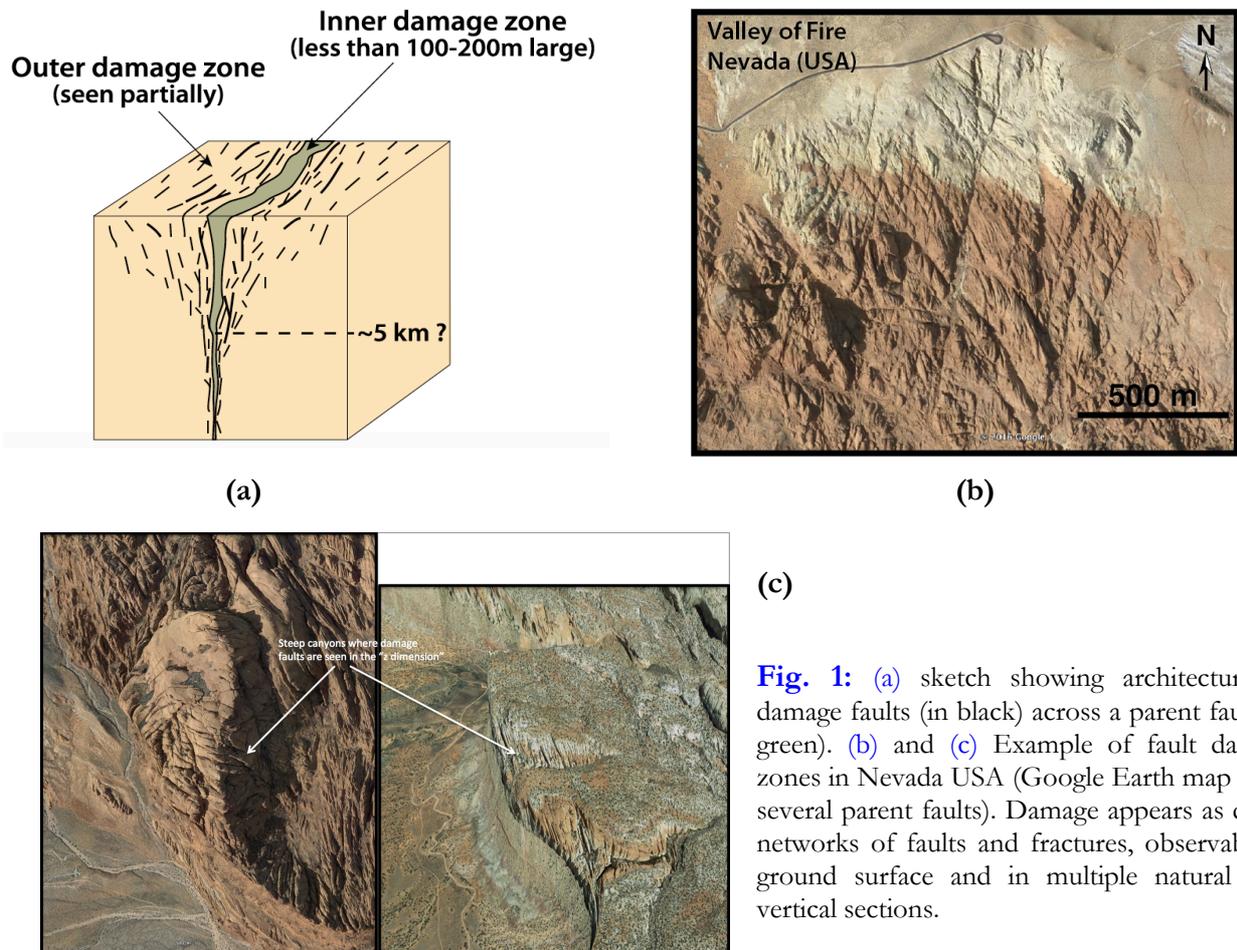


Fig. 1: (a) sketch showing architecture of damage faults (in black) across a parent fault (in green). (b) and (c) Example of fault damage zones in Nevada USA (Google Earth map view; several parent faults). Damage appears as dense networks of faults and fractures, observable at ground surface and in multiple natural sub-vertical sections.

Work Tasks:

The work includes three principal tasks, pertaining to three scientific domains. The PhD student will thus gain a multi-disciplinary high-level expertise.

1) Satellite data analysis: *Satellite image processing, digital elevation models, 3D reconstruction, machine learning.* The PhD will be strongly involved in Task 1, mainly under guidance of INRIA partner for Pléiades and TerraSar-X data processing (along with Géoscience Montpellier for some aspects), and in collaboration with our US partners (R. Arrowsmith and C. Crosby) for terrestrial Lidar and structure from motion data acquisition and processing.

- **Building a multi-stereo, high-resolution DEM of 4-5 damage sites in Western USA.** In each site, 7 to 9 Pléiades satellite images taken from variable angles of view will be combined to produce a digital elevation model (DEM) recovering the topography at an unprecedented high resolution (~0.5 m) including in the numerous shadow zones between the closely-spaced damage faults. The work will be done using the MicMac software provided by IGN. Several methodological challenges are expected, such as determination of the matching points in complex fault zones and handling reconstruction in multiple shadow areas. To increase the resolution of the Pléiades DEMs, we will

measure “control points” in the field (with differential GPS) and will perform comparative terrestrial Lidar and “structure from motion” measurements [5] at even spots of the sites. Several fieldwork campaigns in Western USA are thus scheduled over the PhD.

- **Developing a data fusion protocol to combine optical Pléiades and radar TerraSAR-X data.** Damage zone fractures and faults span a broad range of scales, from macroscopic features of the size of their parent fault (km) down to microscopic features below the resolution of the Pléiades imagery and DEMs (m to dm). However, even at their smallest scales, the damage features intensely dissect the ground surface and this dense fracturing modifies the “texture” of the ground and the water distribution in the sub-surface. We thus expect the damage features to have, at all scales, a specific radar signature, especially in terms of intensity, preferential polarization, and radiometry, that might help to identify and measure the smallest damage faults and fractures, and to track for additional properties of the damage features (across-trace thickness, increased porosity, water content, etc.). Small fissure lines can also be detected using “marked point process” modeling approaches [6]. At a few sites, we will thus fuse Pléiades data with TerraSAR-X radar data in Staring SpotLight mode which allows SAR-based object detection and recognition at a resolution of down to 0.25 m. The radar data will also allow identifying the different rock types offset by the parent and the damage faults, what will permit measuring the displacements accommodated across those faults (slip mode, strain budget).
- **Developing stereoscopic methods to measure 3D damage faults geometries.** While the damage faults intersect the ground surface, some of them also intersect the steep flanks of the narrow corridors between the faults (Fig. 1c). Provided that the combination of the multi-stereo Pléiades images allows visualization of these intersections in the canyons’ flanks, we will be able to constrain the 3D geometry (strike and dip) of the damage faults [7]. We will thus produce a 3D model of the faulted rock volume in each site.
- **Developing new machine learning approaches to automate the identification and the measurements of the damage zone faults in the 3D volume.** In a small area of each site, the damage faults will be identified and mapped in the produced fused 3D DEMs (see Task 2). These data will then be used as a reference to develop and train a machine learning algorithm [8], aiming to automatically recognize the damage features in the 3D Pléiades-derived topography, and to automatically measure their properties: sizes, spacing, densities, orientations, slip modes.

2) Tectonic analysis: *morphological analysis of damage faults in satellite & DEM data, fault scaling laws.* The PhD will be strongly involved in Task2, mainly under guidance of GEOAZUR, GEOSCIENCE MONTPELLIER and IGP partner.

- **Overall damage fault analysis.** In parallel to the development of automatic learning tools, we will analyze the satellite images and 3D DEMs to visually identify and map, based on their specific morphological signatures (i.e., classical morphotectonic approaches, see [9-10]), the distributions and genetic relationships between the principal, macroscopic faults. In doing so, we will identify the principal parent faults and delineate their overall damage zone, including in the complex areas where several damage zones overlap (see Fig. 1b). These overall identifications and mapping will serve as guides to develop and test the learning tools.
- **High-resolution fault analysis.** In small $\sim 4 \times 4$ km² areas of each site, we will apply the same morphotectonic approach to identify and map the damage features down to their smallest scales recovered in the fused DEM data (Pléiades & TerraSar-X). These mapping will serve as guides to improve the automatic learning tools and make them sensitive to the smallest scales of damage.
- **Building damage fault scaling laws.** One critical challenge is to determine whether damage fault properties evolve along and/or across the parent faults, in particular as a function of their overall structural maturity [11], net slip, length, slip mode, etc. To address this challenge, we will build empirical relations to examine whether the measured damage fault properties (lengths, spacing, orientations, densities, slip modes, etc.) scale with the parent fault properties listed above and vary along and across the faults.

3) Mathematical modeling of damage measurements and use in earthquake models: *crustal elastic properties, effective medium theory, earthquake modeling.* If time permits, the PhD student may contribute to preliminary steps of Task 3 but most of the mathematical modeling will be led by the LJAD partner, and the updating of the earthquake models by our CALTECH, IFSTTAR and ENS partners.

- **Using a mathematical model to estimate the crustal compliance in fault damage zones.** The effective medium theory allows investigating the degradation of the strength and reduction of stiffness of a rock mass (and hence, the rock mass compliance) due to its brittle deformation, based on quantitative information on the 3D geometry and distribution of the damage fractures and faults in the rock mass [4]. Therefore, we will model the measurements using this theory to estimate the compliance of the crust along and across the different parent faults analyzed at each site. The compliance estimates will feed scaling laws examining their relations to the various properties of the parent faults (overall maturity, length, net slip, slip mode, etc.).
- **Injecting the compliance estimates into dynamic earthquake rupture models.** Other collaborators to this project are specialists of earthquake modeling, especially dynamic rupture modeling [12-14]. Our estimates of crust compliance in fault damage zones will feed the rupture models developed by these partners. This should lead to new, important results, because introducing well-constrained compliance data into earthquake models has not yet been done. We expect that the new rupture models so produced will more successfully anticipate the properties, especially magnitude and location of larger slip and faster rupture (which are among zones of greater damage), of the forthcoming large earthquakes worldwide.

Requirements for the PhD student:

- Good knowledge of satellite image processing, optimization and algorithms
- Good coding skills
- Good knowledge or at least strong interest in natural faults and earthquakes
- Good knowledge in applied mathematics
- Fluency in English
- Capacity to collaborate in a large group

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