★ルエレドゥ ベルトラン 特定助教

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研究課題： データサイエンスにもとづく地震の幅広いすべりモードの研究
（Investigating the spectrum of earthquakes using data science）

専門分野： 地球物理学、データサイエンス（Geophysics, Data science）

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Geophysics
Data science

テクトニックな断層は、地震からスロースリップや非地震性クリープまで、さまざまなモードで応力を解放している。私は、地震サイクル、あるいは地震の震源核形成と初期の諸段階に結びつく小さなシグナルを検出することを目的に、地震データと測地データの解析を中心とした研究を行っている。私の研究における核心的な問いは、1）スロー地震と通常地震の間の相互作用をよりよく理解できるか、2）標準的な方法では検出できないほど小さい、大地震の前や初期の段階における新しい前兆信号を特定できるか、3）現在の観測上のギャップを埋めることによって、断層のすべり挙動についてよりよい物理的理解に到達できるか、などである。

今後は、衛星画像と地震観測データを組み合わせて、活断層を大きなスケールで研究することに重点を置きたい。最先端の人工知能アルゴリズムの開発と活用を通じて、すべりの挙動をより正確に把握すること、異なるモードのすべりの相互作用を研究すること、および地震や津波の早期警戒のためのすべりの即時予測を提供することを目指している。

Tectonic faults release stress in a variety of modes that range from earthquakes to transient slow slip and aseismic creep. My research focuses on the analysis of seismic and geodetic data with the goal of detecting small signals associated with the seismic cycle, and the nucleation and early stages of earthquakes. Most of my work is articulated around the following questions: 1) whether we can better understand the interplay between slow and regular earthquakes; 2) whether it is possible to identify new precursory signals before and in the early stages of large earthquakes, that are too small to be picked up by standard methods; 3) whether we can reach a better physical understanding of slip behavior on faults by bridging current observational gaps.

My future work will focus on combining satellite imagery and seismic data to conduct large-scale studies of active faults. Through the use and development of state-of-the-art, intelligent algorithms, I aim to better characterize slip behaviors, study the interactions between slip modes, and provide real-time slip estimates for earthquake and tsunami early warning.

The spectrum of earthquakes and the interplay between slow and dynamic earthquakes

Faults can fail in a variety of ways, from dynamic and destructive earthquakes to seemingly innocuous slow-slip events and aseismic slip. Over the last decades, the long-held view that faults are either locked and prone to dangerous earthquakes or unlocked and quietly deforming to accommodate tectonic stress has been evolving. Growing evidence including faults hosting both slow and dynamic earthquakes, as well as slow slip events preceding and possibly interacting with the nucleation phase of dynamic earthquakes, shows that fault behavior can be complex, with interactions between modes of slip. A number of fundamental questions arise from this complexity, such as the determinants of the slip mode on a fault, whether a continuum of slip modes exist, and what may control the evolution of a slow slip event into a destructive earthquake. Answering these questions requires to exhaustively characterize all slip phenomena on faults.

Systematically detecting and characterizing fault slip may hold the key to understanding the interplay between slow and fast earthquakes, and to unraveling the physics of tectonic faulting. However, slow slip is dramatically more challenging to detect than ordinary earthquakes because deformation is slow and silent. My goal is to develop and exploit tools that will help close the gap in existing detection capabilities and form the foundations for a systematic exploration of the properties of slip along active faults.

Slow slip detection in radar satellite data

Interferometric Synthetic Aperture Radar (InSAR) offers the potential for continuous geodetic monitoring of fault systems worldwide, potentially providing the observational tool to attempt to answer the questions above. However, although the data exists, current InSAR processing and analysis methods are not suited for monitoring at a global scale, as they require time-consuming manual intervention, and the final product requires careful expert interpretation. Current methods work well to detect and study either very large deformation, or deformation that accumulates steadily over long periods of time. But because atmospheric noise is often larger than the signals of interest, detecting low-amplitude deformation related to transient sources such as slow slip events, volcanic activity, or hydrologic related motion often remains challenging and requires significant human intervention and interpretation. The poor time resolution and lack of automation in InSAR analysis has prevented until now its use in time-resolved large-scale studies. The fully automatic approach that I have been working on [1] circumvents these limitations by deconvolving atmospheric delays from actual ground deformation. This approach enables the observation of transient slip as small as a millimeter and the direct observation of slow earthquakes propagating along faults (see Fig. 1). This new methodology opens the possibility for new research areas such as large-scale studies of fault slip, therefore providing an opportunity to address the problems described above. The approach also holds promise for studying other fields, such as ground deformation associated with the interaction between human activity, climate change, and the environment, as it also improves by an order of magnitude the detection threshold of ground subsidence in InSAR data.

Improve the detection of tectonic tremor in seismic data

Slow slip on faults is often, but not systematically, accompanied by characteristic seismic signals. Among these signals tectonic tremors are non-impulsive and are therefore challenging to detect. While there are some well-studied regions where these signals appear relatively ubiquitous, tectonic tremor is far less common than earthquakes, which may point to a potential observational gap. Part of my research focuses on building new, automatic tools to improve tremor detection, and relate their behavior to slip on faults, both in laboratory-scale experiments [2] and in field data. My aim in the next years is to conduct large-scale studies to search for tectonic tremors, in particular in regions where they have not been observed so far, with the hope of better characterizing slow slip on faults.

Earthquake Early Warning (EEW) using machine learning

Rapid and reliable magnitude estimation for very large earthquakes (Mw > 8) is key to mitigate the risk associated with strong shaking and tsunamis. However, current warning systems often fail to rapidly estimate the size of such large earthquakes, as they produce saturated magnitude estimates. Very large earthquakes displace such tremendous amounts of mass that they perturb the gravity field of the Earth. The associated signals have been theorized for decades, but were observed only very recently, in 2017. In a parallel avenue of research in collaboration with one of the team that detected these Prompt Elasto-Gravity Signals (PEGS) for the first time, I am working on developing deep learning-based methods that track earthquake rupture size in real-time and can be used for earthquake and tsunami early warning [3].

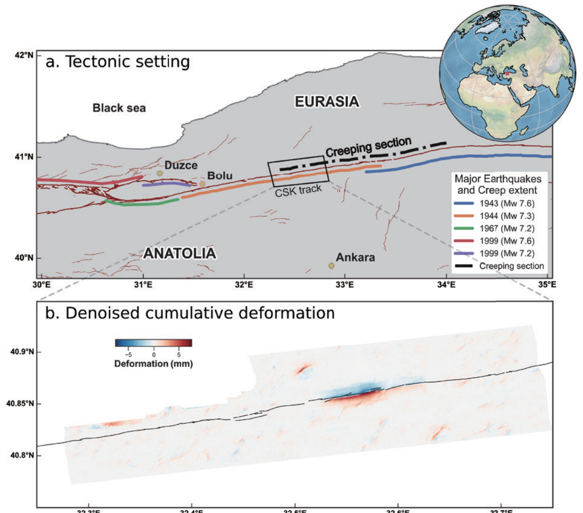

Fig. 1 Using AI, a slow earthquake emerges from noisy satellite radar data. **a.** Tectonic setting and historical earthquakes on the North Anatolian Fault in Turkey. **b.** Slow slip event detected by deep learning in noisy InSAR data (location shown as a black box in a.). Figure adapted from [1] (under creative commons license CC BY 4.0 https://creativecommons.org/licenses/by/4.0/legalcode).

References

[1] Rouet-Leduc, B., Jolivet, R., Dalaison, M. *et al.* Autonomous extraction of millimeter-scale deformation in InSAR time series using deep learning. *Nature Communications* 12, 6480 (2021).

[2] Rouet-Leduc, B., Hulbert, C., Lubbers, N. *et al.* Machine learning predicts laboratory earthquakes. *Geophysical Research Letters* 44, 9276– 9282 (2017).

[3] Licciardi, A., Bletery, Q., Rouet-Leduc, B. *et al.* Instantaneous tracking of earthquake growth with Elasto-gravity signals. *Nature* (accepted for publication).