Research Report:

Summary: *My research report for this 5 months and half visiting professor position at ERI has three-folds:*
1 - Revisiting the nucleation phase of Japanese earthquakes (with Prof. Aïtaro Kato)
2- Produce synthetic samples for high-pressure experiments (with prof. T. Hiraga)
3 – Interactions with colleagues, discussions and further collaborations

1 - Revisiting the nucleation phase of Japanese earthquakes (with Prof. Aïtaro Kato)

The predictability of earthquakes has been debated since many decades. Recent progress of analyses both on the field data and laboratory experiments highlight a nucleation process before large earthquakes such as the 2011 Tohoku [1] and other earthquakes (e.g. [2]). Recent experimental studies suggest if the earthquake nucleation process starts as a fully aseismic process, it evolves towards a cascading process at the onset of dynamic rupture [3]. This recent experimental work proposed a universal scaling for the inverse Omori law followed by the premonitory foreshock activity. In Japan, roughly 30-40% of earthquakes are preceded by foreshocks [4]. In that context, prof. Aitaro Kato gently gave me and my team in France access to the updated Japanese catalog by the JMA, from October 1997 to November 2024, with a total number of events being roughly 4.6 million, and a completeness magnitude of around ~1.5. Our idea is to follow the procedure of averaging presented by [3], in order to test the laboratory scaling at field scale. The scientific questions we will answer are the following:

1) Upon averaging foreshock-mainshock sequences, is there a characteristic (average) foreshock sequence that emerges, and if yes, how does it depend on mainshock magnitude, depth and focal mechanism (tectonic context).
2) If this average sequence does exist, we aim at defining variability, ie. standard deviation from the average, type of distribution, using standard statistical analysis and earthquake probability laws such as Omori and Gutenberg Richter (GR).
3) Finally and if possible, investigate possible outside forcing by tides during foreshock-mainshock-aftershock sequences.

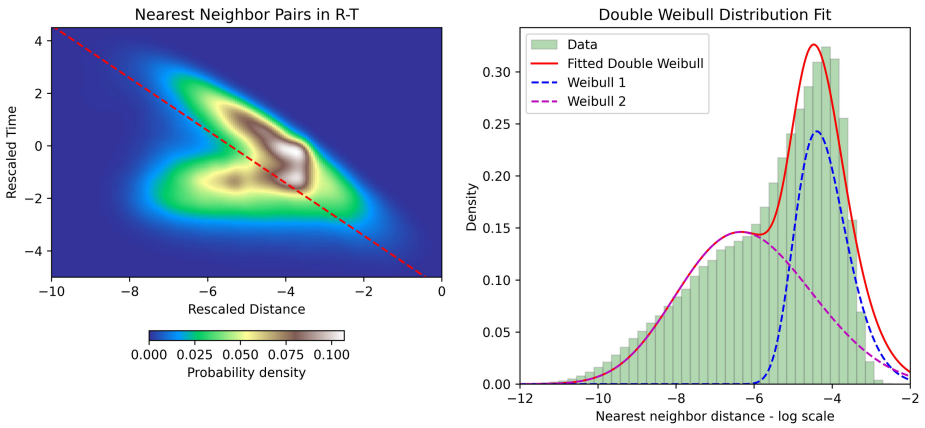

Figure 1: a (left) *- Distribution of Japanese seismicity of 25+ years of Japanese seismicity (4.5M earthquakes, completeness magnitude of ≈1.0-1.5) using the nearest neighbor (NN) algorithm [5].* ***b (right)*** *– separation of the clustered seismicity (low NN rescaled distance) from background seismicity using Weibull distributions.*

Initial delustering of the JMA catalog using the nearest neighbor (NN) algorithm [5] enabled us to separate the clustered part (sequences of foreshock-mainshock aftershocks) from background seismicity, using a double Weibull distributions (Figure 1a and b). Preliminary analysis of clustered seismicity reveals the distribution and size of clusters as a function of mainshock's magnitude (Figure 2a). Earthquakes of Mw 5 typically exhibit maximum clusters size of 1000+ earthquakes, with an average around 100, while earthquakes of Mw 3 typically exhibit clusters size of 100, with average of 10 earthquakes. Tohoku-Oki MW 9.0 earthquake

cluster contains close to 100 000 events. In each cluster, the ratio between aftershocks and foreshocks is undetermined for now, but should be >0.9. Finally, the clustered and background seismicity exhibit different GR exponents (b-value) (Figure 2b).

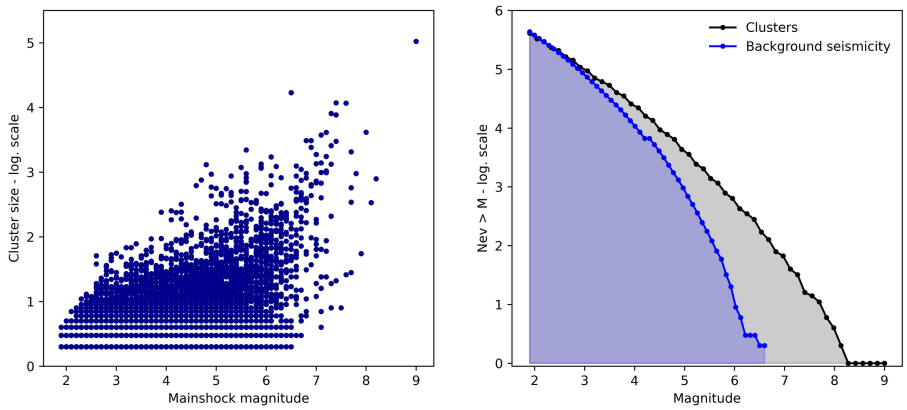

Figure 2: a (left)- *Distribution of clusters sizes as a function of mainshock's magnitude).* ***b (right)*** *- Gutenberg-Richter scaling of clustered and background seismicity.*

On the French side, a project of which I am the co-PI has been funded by the French national agency of research (ANR) and a post-doctoral student will further the above analysis during two years starting in September 2025. This work might eventually may help us further our understanding of rupture nucleation, providing insights for earthquake hazard mitigation. It will also help deepen the ongoing collaboration we have between François Petrelis, a physicist at ENS Paris, Hideo Aochi, a Japanese seismologist at BRGM in France, prof. Aitaro Kato at ERI and myself.

2- Produce synthetic samples for high-pressure experiments (with prof. T. Hiraga)

Our objective here is to study how hydration/serpentization reactions may affect the mechanical behavior of rocks under stress. Kinetics of this reaction has been experimentally studied at hydrostatic conditions, but, to our knowledge, has never been investigated under stress (especially on synthetic, i.e. chemically controlled materials at P-T conditions relevant for subduction zones). Preliminary experiments in our Griggs apparatus at the Laboratoire de Géologie in Paris have emphasized that the evolution of mineral reactions could be monitored using passive and active acoustic monitoring [6-7]. Our goal during my stay at ERI was to produce the starting materials using the Spark Plasma Sintering technique developed by prof. Hiraga [e.g. 8]. A set of 4 fine-grained sintered peridotite (olivine + enstatite) cores, of controlled homogeneous, grain size and porosity were produced by Mrs. Sanae Koizumi (photograph on the left), a close colleague of prof. Takehiko Hiraga. A French post-doctoral researcher, funded by another ANR research project of which I am the co-PI, is now performing experiments in our laboratory in Paris. We are awaiting preliminary results before any further requests for ERI samples will be made.

3 – Interactions with colleagues, discussions and further collaborations

First, I was given the honor to give a series of three seminars at ERI, on the following topics:

- November 22nd 2024 - *Nucleation of earthquakes: from Mw-3 labquakes to the 680km deep Mw 7.8 Ogasawara earthquake*
- January 14th 2025 - *Mineral dehydration at subduction zones conditions: experimental evidence of high Vp/Vs and tremors*

- February 14th 2025 - *Periodic seismicity: from the laboratory to Nepal*

I attended the Slow to Fast Earthquake conference/workshop organized in Beppu on 16th-18th September 2024, where I gave a presentation. I also participated to various internal seminars and workshops at ERI, and gave seminars at NIED (National Institute of Earthquake Disaster prevention and resilience) and at the Geology department of Tohoku University.

I took advantage of my experience as head of the Laboratoire de Géologie of ENS, to discuss of a potential furthering of the ongoing collaborations between ERI, the Department of Geosciences of ENS, and various other laboratories in France (i.e. Itsterre Grenoble, Laboratoire Magma et Volcans in Clermont-Ferrand), where researchers already have active collaborations with ERI researchers. It is certain these French laboratories would be very happy to join the existing ERI-IPGP MOU. This could be done taking advantage of the existing collaboration and the signature of an International Research center agreement between CNRS and the University of Tokyo. Contribution from the French side could be a few visiting professor positions every year targeted for ERI/University of Tokyo professors and post-docs. There is no doubt such a larger scale research/exchange agreement could produce important synergies between the French and Japanese solid earth science communities.

Maybe most importantly for my daily life routine, I participated to a regular lunch group with Mdm. Natalya Galina, with I shared an office, several colleagues from building#2 prof. Yajing Liu (also invited prof.), prof. So Osawa, prof. Ryuichi Nishiyama, as well as prof. Yuji Ito (from building #1). During our lunches and coffees breaks, we often – but not always – discussed and exchanged about Science. These were precious moments, thank you!

I would like to thank prof. Masa Kinoshita, the head of the ERI International Office, for his kindness and enthusiasm when discussing further collaborations and promoting international exchanges between France and the University of Tokyo.

Finally, I am indebted to the staff at the International office of ERI and in particular to Mrs. Yoko T, who took care of me and of my family and whose help has been incredible. Thank you so much for arranging our stay!

References:

[1] Kato A. et al. *Science* 335.6069 (2012):705-708; [2] Bouchon M. et al. *Nature geoscience* 6.4 (2013): 299-302; [3] Marty S. et al. (2023). *Journal of Geophysical Research: Solid Earth*, *128*(3), e2022JB026294; [4] Tamaribuchi, Koji, et al. *Earth, planets and space* 70.1 (2018): 1-13. [5] Zaliapin, Ilya, and Yehuda Ben-Zion. *Journal of Geophysical Research: Solid Earth* 118.6 (2013): 2847-2864. [6] Moarefvand, A., et al. (2021). *Tectonophysics*, *816*, 229032; [7] Gasc, J., (2022). *Geology*, *50*(9), 1018-1022; [8] Hiraga T. et al. " *Nature* 468.7327 (2010): 1091-1094.