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DOTTORATO DI RICERCA
IN SCIENZE DELLA TERRA

Research Project for PhD in Earth Sciences

Name, Surname: Andrea Attolico

Title -

Improving Source Parameter Estimation Using 3D Attenuation Tomography

(70/100 characters (spaces included))

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Phd Cycle: XL

Suggested internal supervisor: Prof.ssa Elisa Tinti

Suggested external co-supervisors: Dott. Mario Anselmi and Dott. Pasquale De Gori

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1. General Objective - 164/200 characters (spaces included)

Gain in-depth knowledge in determining seismic source parameters through attenuation correction, a key aspect in the study of earthquake physics and seismic hazard.

2. Specific Objective - 677/700 characters (spaces included)

The main objective is the estimation of source parameters such as the seismic moment ($M\sigma$), the corner frequency (fc), both related to the source dimension, and the stress drop ($\Delta\sigma$), using the 3D attenuation tomography to correct the spectral decay due to the path attenuation. Starting from the 3D Vp and Vp/Vs tomography and earthquake locations, the work consists in:

- Computing the 3D distribution of Qp and Qs using the same grid as the velocity models.
- Using the attenuation tomography to compute synthetic t* (t star) and addressing the trade-off between attenuation and corner frequency in spectral fitting to minimize uncertainties in the determination of source parameters.

3. State of the art - 3995/4000 characters (spaces included)

The knowledge of source parameters can help us to better constrain the physical processes occurring on the fault rupture during an earthquake. Source parameters, such as $\Delta\sigma$, fc and $M\sigma$ are key factors that control the ground motion amplitude, so their reliable estimation significantly impacts damage evaluation in seismic events.

Stress drop is defined as the shear stress change that occurs during the rupture process (fig.1). It is differentiated into static stress drop ($\Delta\sigma$) and dynamic stress drop ($\Delta\sigma_d$). $\Delta\sigma$ is the difference between the initial tectonic stress in a given area (σ_i) and the final stress after the rupture has fully developed (σ_f). $\Delta\sigma_d$ represents the stress release that occurs during the dislocation and is generally greater than the static stress drop[1].

The corner frequency (fc) defined as the intersection of the low and high frequency asymptotes of the displacement source spectrum, is a key parameter that is inversely related to the duration of the event[2] (fig. 1).

Finally, seismic moment ($M\sigma$) is a parameter used to define the size of events and represents the moment of one of the two force couples that generate displacement on the fault surface[1].

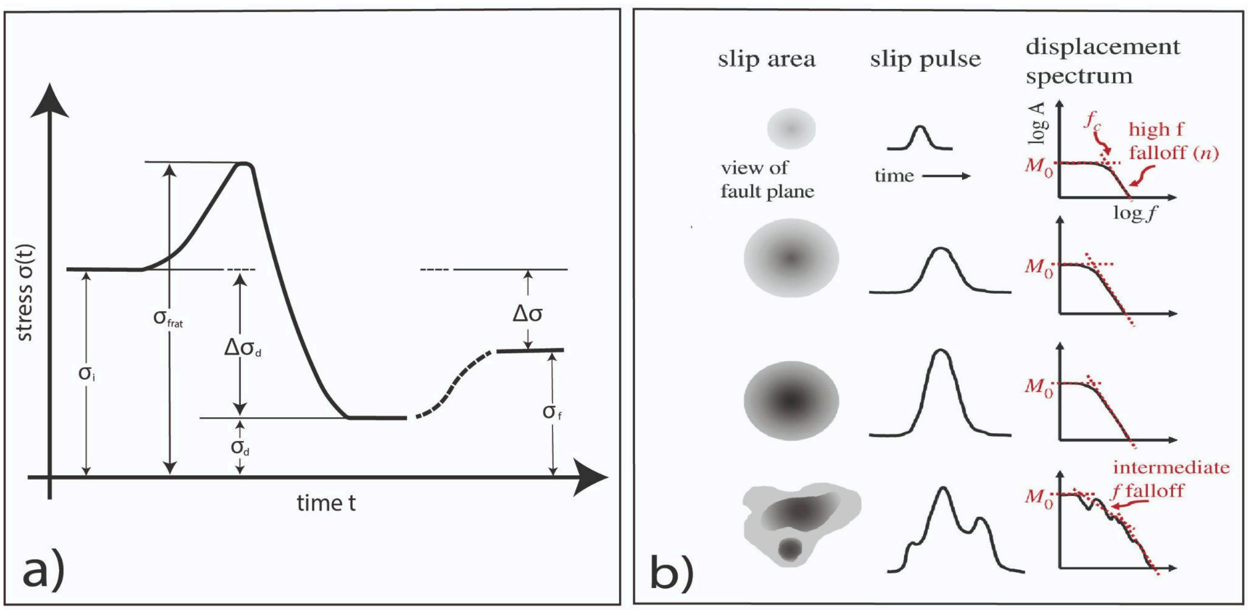

Fig.1 *a) Static stress drop and dynamic stress drop[1]. b) Sketches of slip distribution on the fault plane, the corresponding moment rate functions and source spectra with fc and Mo highlighted. Mo is proportional to the amplitude of low frequencies displacement spectrum [3]. (*267/300)

Currently there is a significant variability in source parameters studies due to challenges in accurately determining source dimensions and the correction of the observed signal for attenuation and site effects[4].

In literature, it is commonly accepted that, for large earthquakes, seismic moment ($M\sigma$) scales with fault dimension and stress drop ($\Delta\sigma$) remain nearly constant[5], this is called self-similar behavior. This means that as the fault size increases, the energy released by the earthquake increases proportionally, while the stress drop generally ranges between 0.1 and 100 MPa (fig. 2). However, opinions differ for small to moderate size events. Some authors propose that stress drop increases with earthquake size[6], while others maintain that self-similarity behavior applies even to smaller magnitude events[7,8].

In the far-field approximation, the observed seismograms are the results of the interaction of three factors: (1) the source, (2) long-path attenuation, and (3) the site response[5]. For accurate source analysis, observations (seismograms or spectra) must be corrected for factors (2) and (3). Assuming the fault shape is either rectangular or circular[9], the seismic moment of the event , the source dimension, and the static stress drop are calculated. A major challenge in obtaining reliable measurements is correcting for path attenuation and site response, which can trade-off with source terms [3,10].

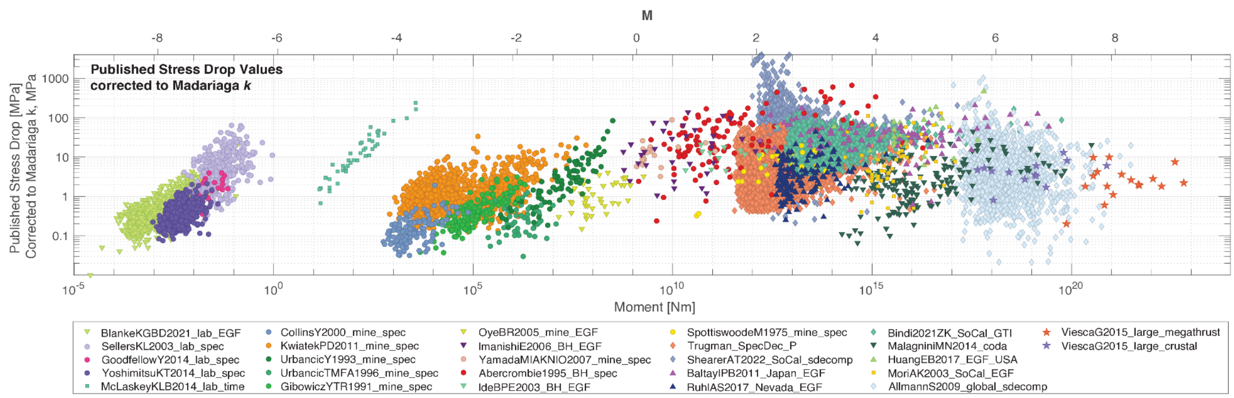

Fig.2 *A global compilation of published stress drop data shows stress drop versus magnitude for a wide range of earthquakes. Despite significant variability, stress drops generally range from 0.1 to 100 MPa, including events from laboratory and minebreak experiments*[11]*.* (263/300)

Stress drop during an earthquake reveals how physical forces are converted into seismic energy when a fault ruptures, and influences conditions that may cause an earthquake to grow in size or trigger earthquakes nearby. Stress drop is crucial for seismic hazard mapping because earthquakes with high stress drop radiate more high frequency energy, leading to stronger ground shaking[11].

An open question is whether stress drop scales with magnitude[12], depth[13], faulting regime or tectonic setting[14], or even nature and extent of dynamic weakening or thermal pressurization[15]. Additionally, stress drop estimates from different studies show significant systematic and random variations (also for the same seismic sequence), reducing their reliability for ground motion prediction and earthquake source physics research[11].

In order to solve this problem Baltay (2024) recently introduced a community stress drop validation study using the 2019 Ridgecrest, California, earthquake sequence, in which researchers are invited to use a common dataset (already pre-processed) to independently estimate comparable measurements through various methods.

The community stress drop validation study lets researchers address key questions about earthquake source properties, avoiding methodological artifacts. Ensuring confidence in results is crucial for advancing research in seismic hazard and ground motion prediction.

4. Research activities - 3854/4000 characters (spaces included)

The Phd project aims to estimate source parameters such as seismic moment ($M\sigma$), corner frequency (fc) and stress drop ($\Delta\sigma$), using 3D attenuation tomography.

This research is intended to have practical applications for the methodology developed by De Gori et al. in 2023. The method aims to resolve the best trade-off between fc and t* with a progressive refinement of parameters. It consists of a multi-step calculation scheme where the output of each step is used as input for the next step following the scheme:

1. **3D velocity model and earthquake locations**:

   In the first step a 3D velocity model (Vp and Vp/Vs) is computed, and earthquake locations are determined. This model is used as a priori input for the subsequent attenuation inversion.

2. **Characterization of site response:**

   Spectral fit for the P and S waves to compute fc depends of the magnitude of the events, the amplitude of the low-frequency plateau ($\Omega\sigma$) that at each station is proportional to $M\sigma$, and t^*. Using these results, we calculate the site response for each frequency as the mean residual between observed and theoretical spectral amplitudes.

3. **Attenuation tomography:**

   In this step, t^* values are estimated, and a 3D attenuation inversion is performed to determine the quality factor structure (Qp and Qs). This involves computing a 3D attenuation model for P and S waves using a priori fixed 3D velocity model and 3D earthquakes' location (step 1). The site response from step 2 is used to correct the observed spectra for shallow effects, and the Q values are iteratively updated to refine the accuracy of the attenuation model.

4. **Constraining Source Parameters from Q-Value Corrected Spectra**

   Synthetic t^* values are computed using the 3D velocity and Q model. The spectra for each event are then fitted by fixing the attenuation term to the tomographic value, and a grid search is performed to find the optimal fc. This approach enhances the precision of fc determination and allows for a more accurate estimation of source parameters (fig. 3), seismic moment ($M\sigma$), stress drop ($\Delta\sigma$) and source dimension.

4.1 Research Plan

The research plan is structured as follows:

First year and second years

Learning local earthquake tomography (L.E.T.) dealing with velocity and attenuation inversions by using seismicity recorded at local scale, spectral computation on seismic signals and spectral inversion for source parameters determination.

Applying and benchmarking the De Gori et al. (2023) method to estimate the source parameters using the 2019 Ridgecrest Earthquake Sequence in the SCEC/USGS Community Stress Drop Validation Study (Baltay et al., 2024). Publishing the results to showcase the method's accuracy and reliability in determining seismic source parameters within a collaborative, community-based framework.

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Third year

Applying the method to the 2016-2017 Amatrice-Visso-Norcia sequence (AVN) to estimate the source parameters. This application will validate the method's robustness and effectiveness in different tectonic settings, contributing to a comprehensive understanding of seismic source characteristics.

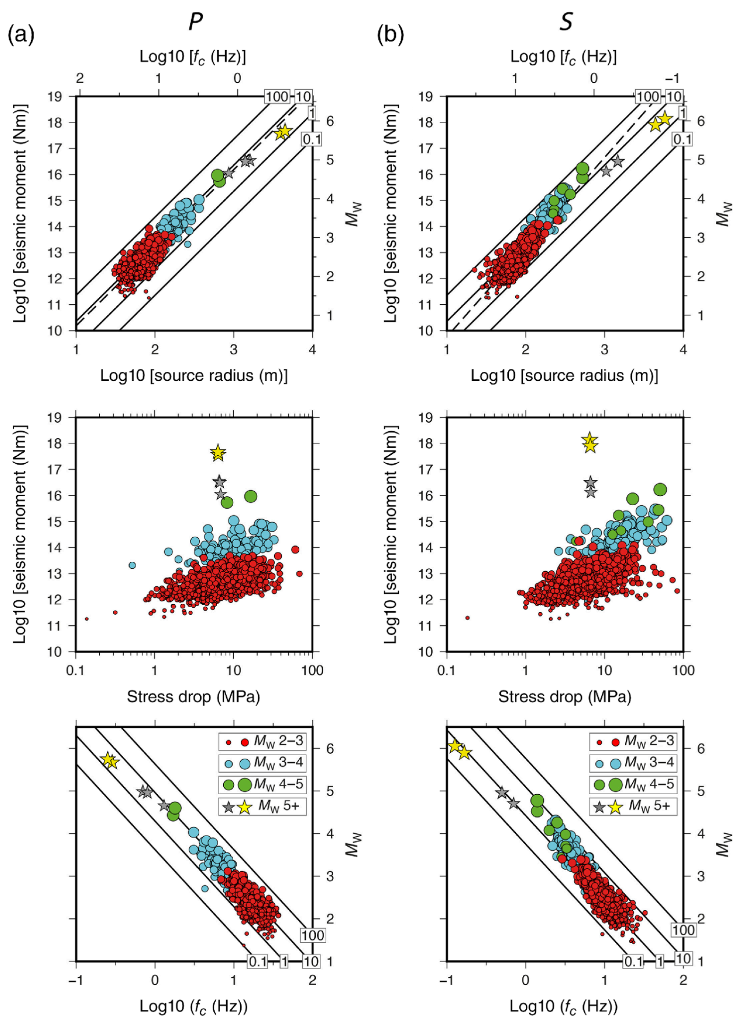

Fig.3 Source parameters from fitting (a) P-wave and (b) S-wave spectra for the 2012 Emilia seismic sequence. Plots show seismic moment vs. source radius, seismic moment vs. stress drop, and moment magnitude vs. corner frequency. Aftershocks are circles sized by magnitude; stars indicate M5+ events[4]. (294/300)

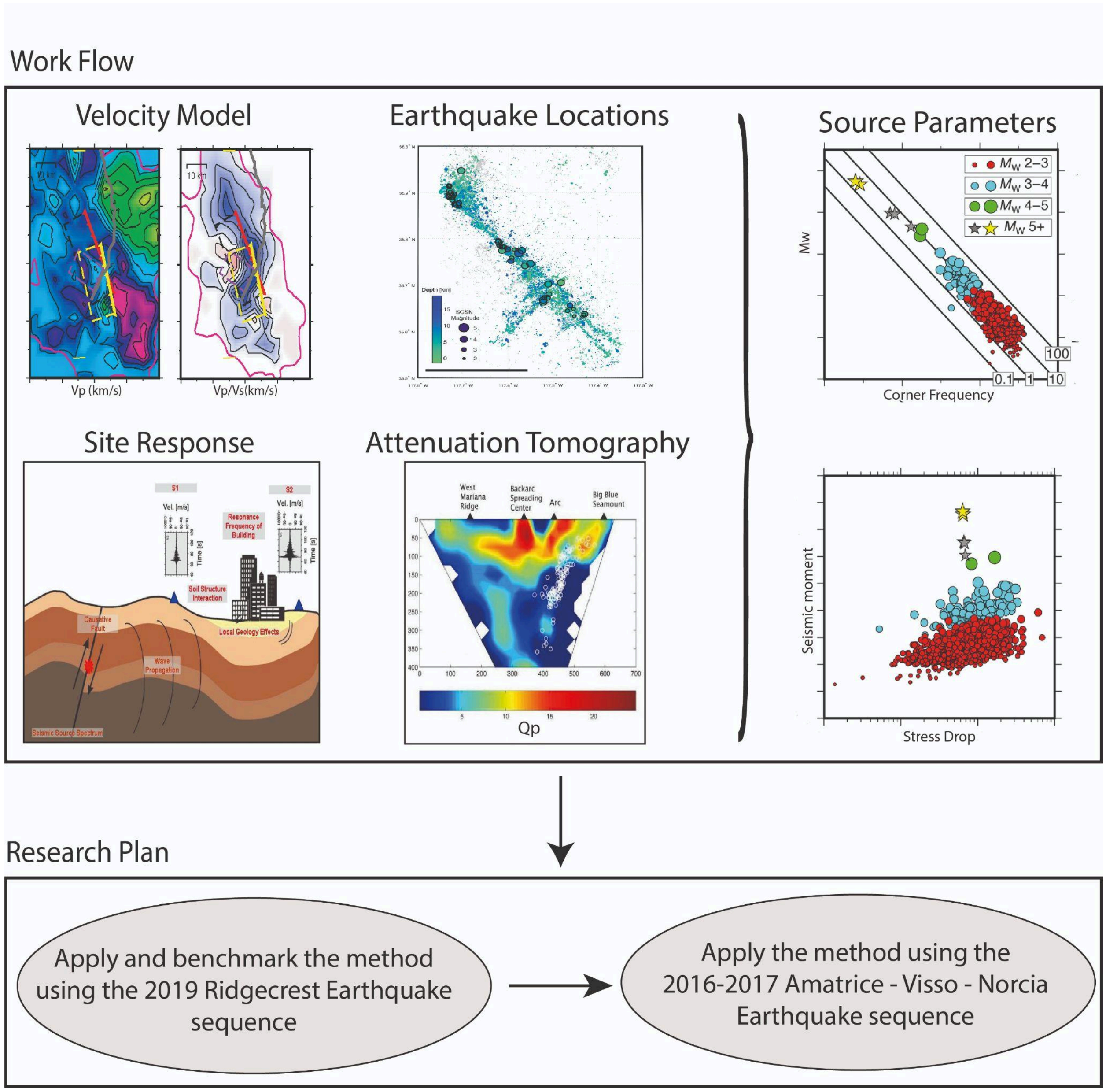

Fig. 4 Summary key steps of the PhD project. (38/300)

4.2 Application and/or Implication

The research planned for my PhD has several aspects of unicity and innovation. The results obtained will have implications in different areas of interest:

- *Scientific Impacts:* Increase the knowledge of earthquake physics by providing more accurate estimations of source parameters
- *Economic impacts:* Contribute to the development of better models for predicting earthquake behavior and hazard assessment and providing more accurate ground shaking predictions.

4.3 Milestone and Publication

The PhD proposal will involve at least the publication of one article in an ISI journal for each of the following milestones:

A) Benchmark the method in the SCEC/USGS Community Stress Drop Validation Study.
B) Apply the benchmark method using the AVN sequence.

5. International mobility - 423/500 characters (spaces included)

During my PhD I will undertake a six-month research period in California at Berkeley University with Dr. Taka'aki Taira as part of the INGV-Berkeley collaboration. This provides an excellent opportunity for research and knowledge exchange between the two institutions. I will engage with the seismology group in the Community Stress Drop Validation Study to improve my expertise and contribute to this significant research.

6. Time schedule - 390/500 characters (spaces included)

During my Phd i will attend:

- Courses provided by the Earth Sciences PhD course of La Sapienza University (All 3 years);
- ERC Tectonics weekly seminars (All 3 years);
- National and international conferences: GNGTS, EGU, AGU, SSA. (All 3 years);
- Training: Vp, Vp/Vs and Q tomography, 3D earthquake localization, spectral computation and inversion.

Other activities will be evaluated during the PhD.

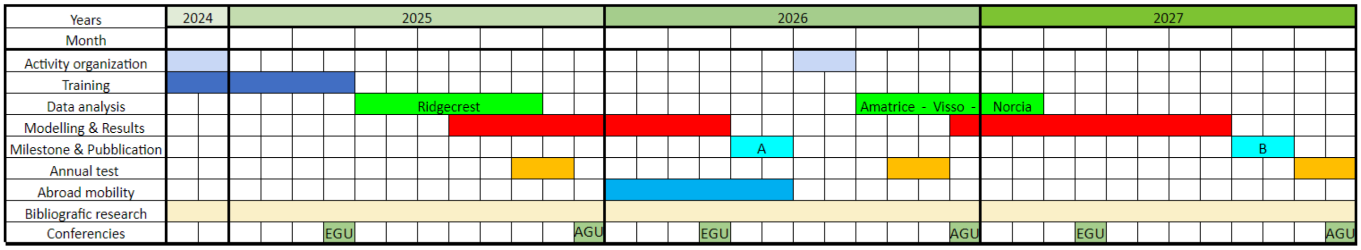

Fig.5 Gantt chart of the PhD Project

References - 2463/2500 characters (spaces included)

1. Zollo, Aldo & Emolo, Antonio. *Terremoti e Onde - Metodi e Pratica Della Sismologia Moderna*. (2011).
2. Brune, J. N. Tectonic stress and the spectra of seismic shear waves from earthquakes. *J. Geophys. Res.* **75**, 4997–5009 (1970).
3. Abercrombie, R. E. Resolution and uncertainties in estimates of earthquake stress drop and energy release. *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* **379**, 20200131 (2021).
4. De Gori, P., Pio Lucente, F. & Chiarabba, C. Source-Parameter Estimation after Attenuation Correction through the Use of Q Tomography. *Bull. Seismol. Soc. Am.* **113**, 1739–1758 (2023).
5. Stein, S. & Wysession, M. *An Introduction to Seismology, Earthquakes, and Earth Structure*. (John Wiley & Sons, 2009).

6. Mayeda, K. & Walter, W. R. Moment, energy, stress drop, and source spectra of western United States earthquakes from regional coda envelopes. *J. Geophys. Res. Solid Earth* **101**, 11195–11208 (1996).

7. Abercrombie, R. E. Earthquake source scaling relationships from −1 to 5 M_L using seismograms recorded at 2.5-km depth. *J. Geophys. Res. Solid Earth* **100**, 24015–24036 (1995).

8. Imanishi, K. & Ellsworth, W. L. Source scaling relationships of microearthquakes at Parkfield, CA, determined using the SAFOD pilot hole seismic array. *Geophys. Monogr. Ser.* **170**, 81–90 (2006).

9. Kanamori, H. & Anderson, D. L. Theoretical basis of some empirical relations in seismology. *Bull. Seismol. Soc. Am.* **65**, 1073–1095 (1975).

10. Zollo, A., Orefice, A. & Convertito, V. Source parameter scaling and radiation efficiency of microearthquakes along the Irpinia fault zone in southern Apennines, Italy. *J. Geophys. Res. Solid Earth* **119**, 3256–3275 (2014).

11. Baltay, A., Abercrombie, R., Chu, S. & Taira, T. The SCEC/USGS Community Stress Drop Validation Study Using the 2019 Ridgecrest Earthquake Sequence. *Seismica* **3**, (2024).

12. Bindi, D., Zaccarelli, R. & Kotha, S. R. Local and Moment Magnitude Analysis in the Ridgecrest Region, California: Impact on Interevent Ground-Motion Variability. *Bull. Seismol. Soc. Am.* **111**, 339–355 (2020).

13. Abercrombie, R. E. *et al.* Does Earthquake Stress Drop Increase With Depth in the Crust? *J. Geophys. Res. Solid Earth* **126**, e2021JB022314 (2021).

14. Huang, Y., Ellsworth, W. L. & Beroza, G. C. Stress drops of induced and tectonic earthquakes in the central United States are indistinguishable. *Sci. Adv.* **3**, e1700772 (2017).

15. Nielsen, S. *et al.* Scaling in natural and laboratory earthquakes. *Geophys. Res. Lett.* **43**, 1504–1510 (2016).