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The role of fluids in the seismicity of the Western Gulf of Corinth (Greece)

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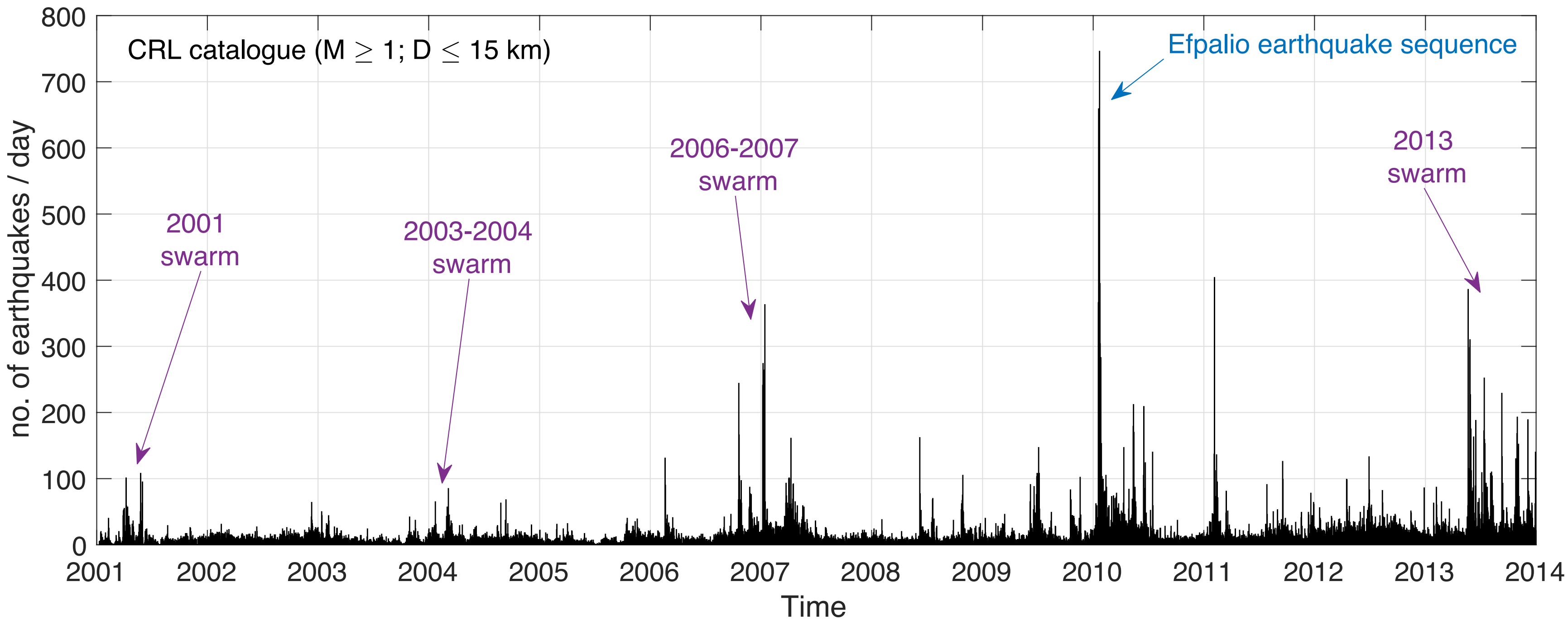
I. Earthquake activity in the Western Corinth Rift



- In the western Corinth Rift microseismicity is characterized by frequent earthquake swarms.
- Earthquake swarms have been associated with pore-fluid pressure diffusion in the seismogenic crust (Bourouis & Cornet, 2009; Pacchiani & Lyon-Caen, 2010; Duverger et al., 2015; Kapetanidis et al., 2015; Mesimeri et al., 2016; Kaviris et al. 2017, 2018; Michas & Vallianatos, 2018).
- Possible fluid sources: i) meteoric water, ii) deep high pore-pressure reservoir, iii) pore-pressure pulses due to active deformation.

II. Objectives and Methodology

- The main objective is to identify patterns in regional seismicity that are possibly related with fluid circulation in the upper crust and within the regional fault network of the Western Gulf of Corinth.

- Initially, earthquakes recorded by the local seismological networks (CRLnet; HUSN local stations) are relocated with high resolution by employing waveform cross-correlation and the double difference-method (e.g. Kapetanidis et al., 2015).

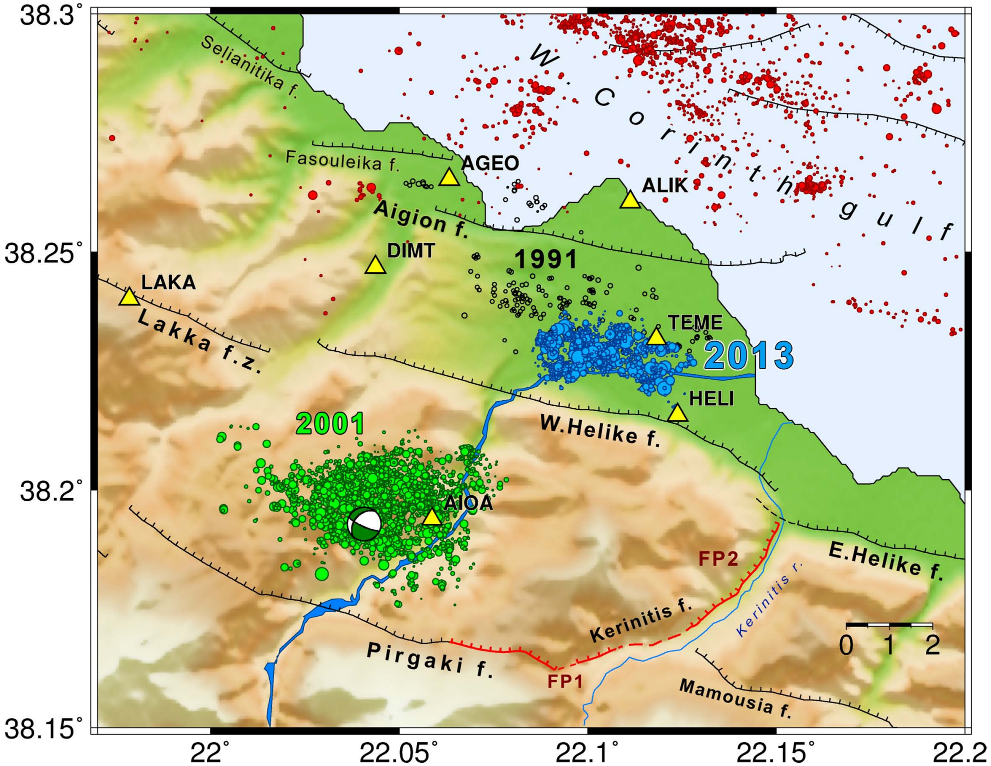
- Relocated hypocenters can delineate the activated tectonic structures with high resolution and can also improve the accuracy of parameters related with their spatiotemporal evolution, such as migration, directionality and scaling.

- Relocated events further serve as input for shear-wave splitting analysis, a method that is widely used to characterize local upper crust seismic anisotropy associated with fracture geometry and density. Shear-wave splitting analysis can be used as a proxy for understanding stress processes connected to fluid migration and diffusion in the upper crust (e.g. Kaviris et al., 2017, 2018).

- In addition, the relocated catalogues will be studied using statistical physics and the Continuous Time Random Walk (CTRW) model, an analysis that is expected to provide further insights in certain critical parameters that control seismic hazard and earthquake evolution, such as scaling and diffusion properties which might be related with fluid circulation in the upper crust of the Western Gulf of Corinth (e.g. Michas & Vallianatos, 2018).

III. The 2013 Helike earthquake swarm

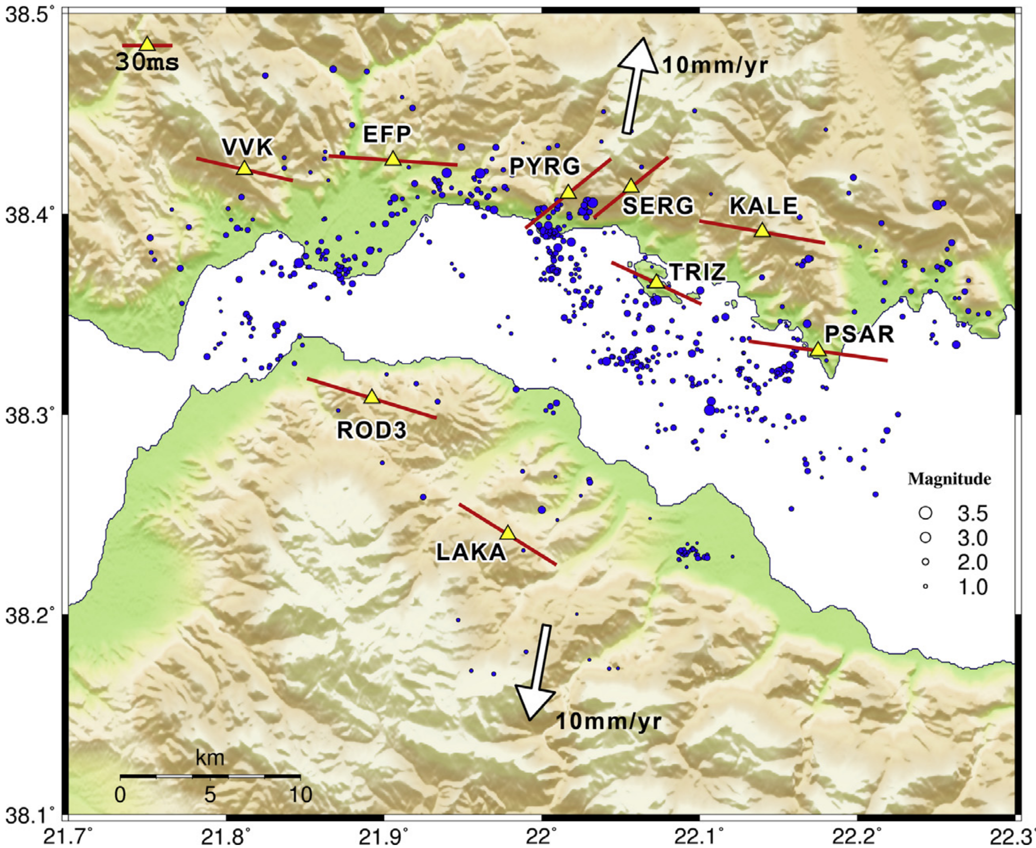
❖ The previously described methodology is initially applied to the 2013 earthquake activity in the Western Gulf of Corinth, with the main focus being the 2013 Helike earthquake swarm.



❖ The seismotectonic map of the Western Gulf of Corinth focuses on the epicentral area of the 2001 Agios Ioannis (green) and 2013 Helike (blue) earthquake swarms. Red circles represent the 2001-2007 earthquake activity and black circles selected earthquakes during July-August 1991. The local seismological network is represented with yellow triangles. (Kapetanidis et al., 2015)

❖ The 2013 Helike swarm evolved in two distinct phases. Phase #1 (21 May - 15 July 2013) included several small bursts in the seismicity rate, associated with M_w3.3-3.7 events, and a weak eastwards migration. Phase #2 (15 July – 31 August 2013) was initiated by an M_w3.7 event at the western half of the sequence and resembles a mainshock-aftershock pattern (Kapetanidis et al., 2015).

IV. Shear-Wave Splitting Analysis



❖ Shear-wave splitting analysis is performed to monitor the stress field and its potential alterations that may be connected to fluid migration and diffusion in the upper crust.

❖ Shear-wave splitting has been attributed to a variety of causes in the upper crust. In areas dominated by tectonic processes, fluid-saturated microcracks, oriented parallel to the maximum compressive stress component, exist in the rock-mass and control the seismic anisotropy

❖ The map shows the shear-wave splitting parameters during 2013, for selected stations of the local seismological networks. The red lines denote the S_{fast} polarization direction, while their length is proportional to the time-delay. Anisotropy directions in most stations are almost perpendicular to the NNE-SSW direction of extension of the Gulf. Observations suggest that fractures are controlled by the long-term tectonic processes (extension) and are consistent with the existence of fluid-filled microcracks oriented according to the regional stress field (Kaviris et al., 2017).

V. Statistical Physics Analysis

- Considering that pore-pressure diffusion is fundamentally a *nonlinear process*, associated with the highly heterogeneous and multi-fractured crust that produce anisotropic diffusivities that vary both spatially and temporally by several orders of magnitude, we further investigate the role of fluids in the seismicity of the Western Gulf of Corinth using statistical physics and the continuous time random walk (CTRW) model.

- The CTRW theory is well-established for modelling nonlinear fluid transport in complex heterogeneous media. The CTRW model considers a random walker, who starts from the origin ($x_0=0$) at time $t_0=0$ and stays fixed to this position until time t_1, he makes a jump of length r_1 to the position x_1. He then stays at this position until time t_2, when he jumps to a new location x_2 of length r_2 from the previous one and the process is renewed.

- Within this context, waiting times and jump lengths between the successive earthquakes are considered as continuous random variables drawn from a joint probability density function $\psi(x, t)$, with probability distributions that present asymptotic power-law behavior.

$$\lambda(r) \sim r^{-1-\mu}$$

$$\phi(\tau) \sim \tau^{-1-\beta}$$

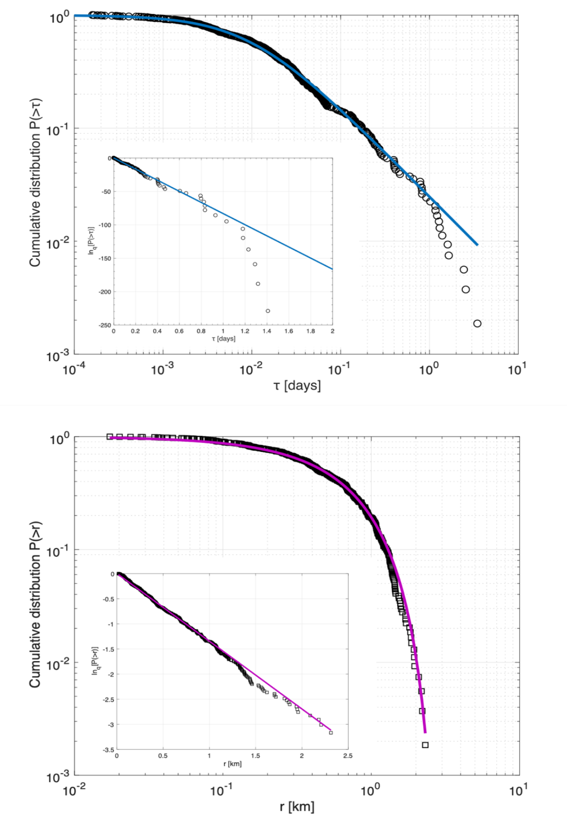
For $\mu \geq 2$ and $\beta \geq 1$, the characteristic waiting time and the jump length variance are finite, and normal (Brownian) diffusion is recovered. If $\beta \geq 1$ and $\mu < 2$, the variance is infinite. This regime of long jumps corresponds to the so-called Lévy flights and super-diffusion. If $\mu \geq 2$ and $0 < \beta < 1$, the characteristic waiting time is infinite and the waiting time pdf exhibits a broad distribution with asymptotic power-law behavior. This regime corresponds to sub-diffusion.

V. Statistical Physics Analysis

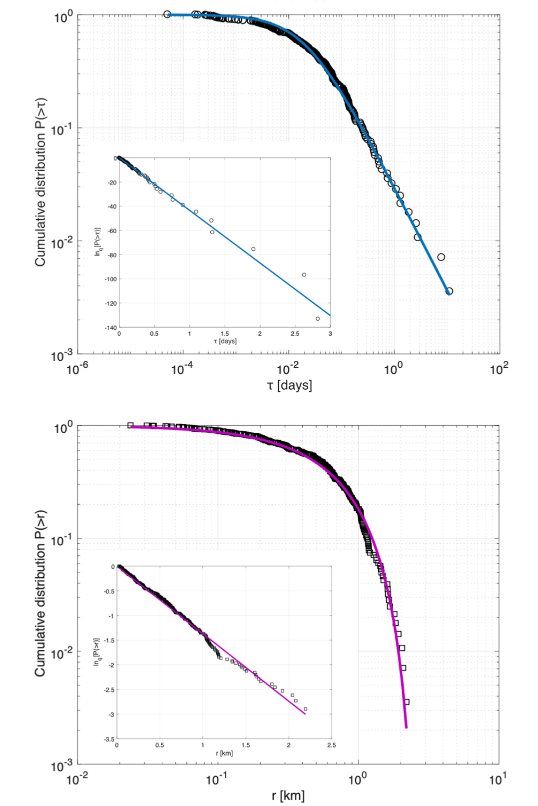
- We approximate the cumulative distributions of the waiting times Φ(>τ) and jump lengths Λ(>r) for the two phases of the 2013 Helike earthquake swarm (Kapetanidis et al., 2015) with the *q*-exponential distribution P(>X) (e.g. Vallianatos et al., 2016):

$$P(>X) = exp_q\left(-\frac{X}{X_0}\right) = \left[1-(1-q)\frac{X}{X_0}\right]^{1/(1-q)}$$

Phase #1



Phase #2



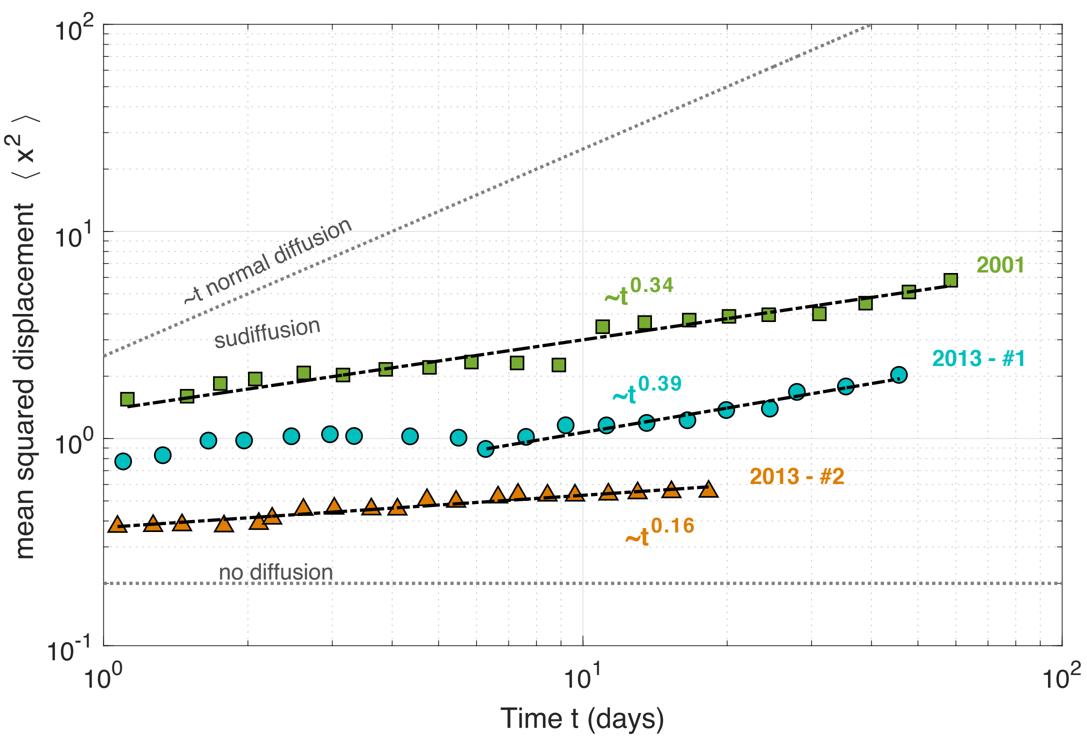
The analysis (figures to the left) indicates that the observed scaling behavior of the waiting times and jump lengths for the two phases of the 2013 earthquake swarm can be well approximated with the *q*-exponential distribution, exhibiting asymptotic power-law behavior with exponents that correspond to the sub-diffusive regime of the CTRW model.

V. Statistical Physics Analysis

❖ In addition, the hallmark of anomalous diffusion is the non-linear growth of the mean squared displacement (msd) with time:

$$\left\langle x^2(t) \right\rangle \sim t^a \qquad (x \text{ – the distance of the propagator from the initial point, } t \text{ – the time}).$$

The exponent α characterizes the different domains of anomalous diffusion. For $\alpha > 1$ the transport is *super-diffusive*, for $0 < \alpha < 1$, *subdiffusive* and for $a = 1$ *normal diffusion* is recovered.



The figure shows the msd with time for the 2013 Helike earthquake swarm (Phase #1 – circles; Phase #2 - triangles), as well as for the 2001 Agios Ioannis earthquake swarm (squares). The dashed lines indicate the power-law growth of the msd with time, with power-law exponents well below unity, signifying subdiffusion in the spatiotemporal evolution of seismicity.

VI. Discussion and Future work

- High-resolution relocation techniques enable the identification of the activated structures and provide a more comprehensive image of the spatiotemporal evolution of seismicity. The geometry of the 2013 Helike earthquake swarm indicates a slightly curved surface which dips about 50° N–NW, a result which is also confirmed by the focal mechanisms, consistent with the eastern, downdip continuation of the presently inactive Pirgaki fault (Kapetanidis et al., 2015).

- Shear-wave splitting analysis confirms the anisotropic seismic layer beneath the Western Gulf of Corinth. Anisotropy directions are consistent with fluid-filled microcracks that are generally oriented according to the regional stress field (Kaviris et al., 2017).

- The spatiotemporal scaling properties during the two phases of the 2013 Helike earthquake swarm are consistent with asymptotic power-law scaling indicating correlations and the non-Poissonian nature of the earthquake activity. In terms of the CTRW model, the power-law exponents corresponds to subdiffusion.

- Subdiffusion is further demonstrated by the msd of seismicity with time. The higher power-law exponents ($a > 0.3$) for the 2001 Agios Ioannis and the first phase of the 2013 Helike earthquake swarms are possibly related with fluid diffusion phenomena, while the lower exponent during the second phase ($a = 0.16$) is consistent with stress diffusion (Michas & Vallianatos, 2018).

- The previously described methodology will also be applied to the rest of the 2013-2014 earthquake activity in the Western Gulf of Corinth, in order to provide further insights into the role of fluids in regional seismicity.

References

Bourouis, S., Cornet, F.H., 2009. Microseismic activity and fluid fault interactions: some results from the Corinth Rift Laboratory (CRL), Greece. Geophys. J. Int., 178, 561–580.

Duverger, C., et al., 2015. The 2003–2004 seismic swarm in the western Corinth rift: Evidence for a multiscale pore pressure diffusion process along a permeable fault system. Geophys. Res. Lett., 42, 7374–7382.

Kapetanidis, V. et al., 2015. The 2013 earthquake swarm in Helike, Greece: seismic activity at the root of old normal faults. Geophys. J. Int., 202, 2044–2073.

Kaviris, G., et al., 2017. Upper crust seismic anisotropy study and temporal variations of shear-wave splitting parameters in the Western Gulf of Corinth (Greece) during 2013. Phys. Earth Planet. Inter., 269, 148–164.

Kaviris, G., et al., 2018. Observations of shear-wave splitting parameters in the Western Gulf of Corinth focusing on the 2014 Mw = 5.0 earthquake. Phys. Earth Planet. Inter. 282, 60–76.

Mesimeri, M., et al., 2016. Spatio-temporal properties and evolution of the 2013 Aigion earthquake swarm (Corinth Gulf, Greece). J. Seismol., 20, 595–614.

Michas, G., Vallianatos, F., 2018. Modelling earthquake diffusion as a continuous-time random walk with fractional kinetics: the case of the 2001 Agios Ioannis earthquake swarm (Corinth Rift). Geophys. J. Int., 215, 333–345.

Pacchiani, F., Lyon-Caen, H., 2010. Geometry and spatio-temporal evolution of the 2001 Agios Ioanis earthquake swarm (Corinth Rift, Greece). Geophys. J. Int., 180, 59-72.

Vallianatos, F., et al., 2016. Generalized statistical mechanics approaches to earthquakes and tectonics. Proc. R. Soc. A, v. 472, p. 20160497, 2016.