A Granular Jamming Model for Low-Frequency Earthquakes

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Abstract

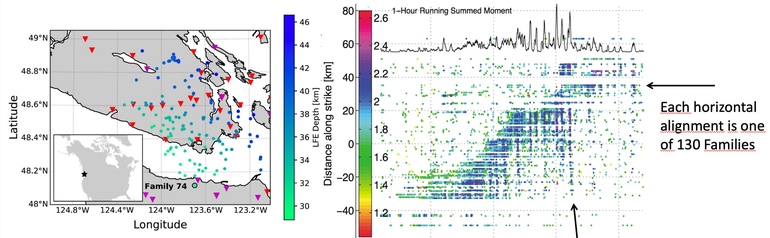
A catalogue of low frequency events (LFEs) beneath Vancouver Island is analysed in the context of a granular flow model. The catalogue contains origin-times and magnitudes of 269,423 LFEs grouped within 130 families and recorded between 2003 and 2013. Each family represents a distinct location within the boundary between the subducting Juan de Fuca and overriding North American plates. The LFEs occurred during 10 episodic tremor and slip (ETS) events that recurred at ~14-month intervals and lasted for about a week. With one exception, each family was active in all 10 ETS episodes.

Our analysis suggests that LFEs do not follow Gutenberg-Richter statistics, but are normally distributed with respect to magnitude and, therefore, log-normally distributed with respect to moment. The Kostrov strain associated with the moments in a given family is used to estimate its size as L = 350 ±15 m.

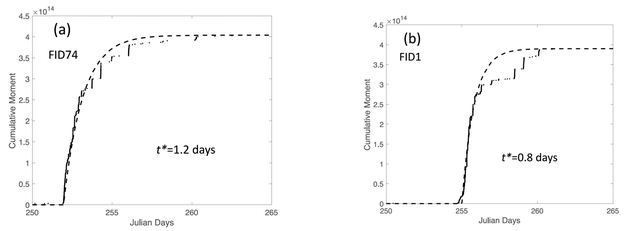
These observations are explained through a model of granular flow in a channel that accommodates displacement along the plate boundary. In this model the LFE families correspond to granular jams in the flow that persist over many ETS episodes. Each LFE is a slip between two grains in the jam. The lognormal distribution of LFE moments can be ascribed to a theoretically predicted log-normal distribution of grain sizes in each jam. This model explains the weak dependence of seismic duration on LFE moment because frictional slip between grains in an over-pressured environment need not scale like a growing rupture in an elastic medium.

1 LFE Data Set from Bostock et al. (2015)

Origin-times and magnitudes of 269,423 LFEs grouped within 130 families recorded between 2003 and 2013. The LFEs occurred during 10 ETS events the recurred at ~14 month intervals and lasted for about two weeks. Each family contained between 40 and 900 events during each cycle.



2 Seismic Moment Release and the Size of LFE Families

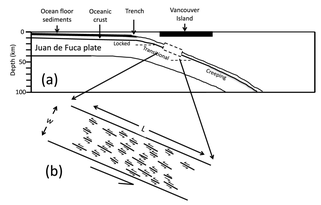


Cumulative scalar moment released by two families during slow-slip episode 3 (2005).
The dashed curves are fits to $\sum M_0(t) = M_{\text{tot}}\left(1 - e^{-t/t^*}\right)$

We assume the slip deficit D (or strain deficit D/w) local to a family is relieved by a series of LFEs and calculate the Kostrov strain accumulated in a volume V from the tensor potencies P_{ij} of its members.

The Kostrov strain for simple shear $\varepsilon = D/w$ in Volume $V = L^2 w$ is $\varepsilon = \frac{D}{w} = \frac{1}{2VG}\sum_{k=1}^{N}\left(M_0\right)_k = \frac{M_{\text{tot}}}{2VG}$.

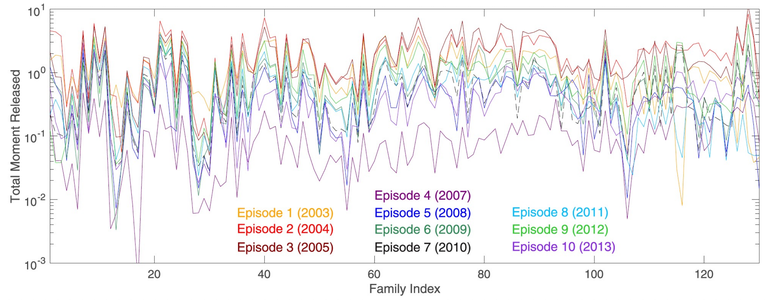
Which yields $L = \sqrt{\frac{M_{\text{tot}}}{2DG}}$. Note: L is independent of w.



Taking $G = 3\text{x}10^{10}$ Pa,
$D = 55 \pm 5$ mm
$M_{tot} = 4\text{x}10^{14}$ Nm (family 74 during the 2005 episode)
Yields $L = 350 \pm 15$ m.

Note: distance to the LFE family nearest family 74 is 16 km.

3 LFE Families are Spatially Persistent

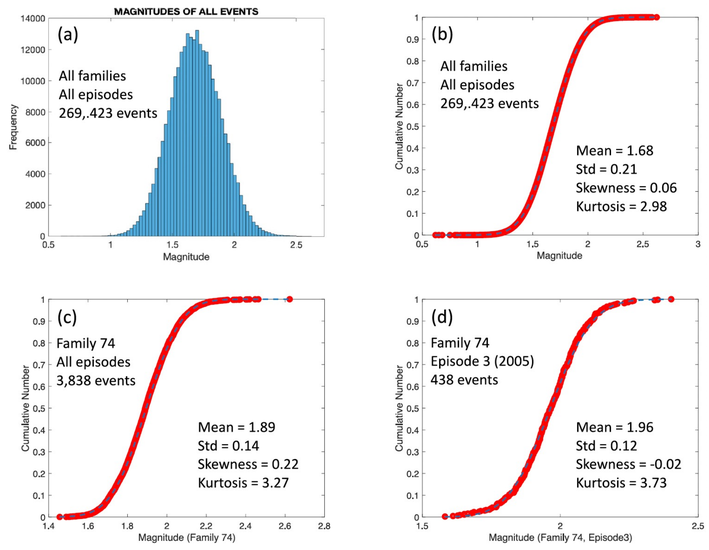


All 130 families were active in all 10 slow-slip events (with one exception)

More active families were more active in all 10 slow-slip events

Less active families were less active in all 10 slow-slip events

4 Frequency-Magnitude Distribution of LFEs is Normal



5 Frequency-Moment Distribution of LFEs is Log-Normal

Magnitude-Moment Relation: $m_w = \frac{2}{3}\left(\log M_0 - 9.1\right)$.

Normal distribution of magnitudes (Cumulative Distribution) $CDF = \frac{1}{2}\left[1 + erf\left(\frac{m_w - \overline{m_w}}{\sigma\sqrt{2}}\right)\right]$

Corresponding log-normal distribution of moments: $CDF = \frac{1}{2}\left[1 + erf\left(\frac{logM_0 - \overline{logM_0}}{s^*\sqrt{2}}\right)\right]$

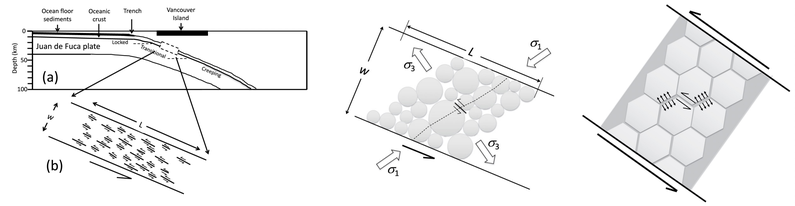
Sinc the distribution of moments is log-normal distribution of source dimensions is also log-normal

Question: what source mechanism produces a log-normal distribution of slip dimensions?

6 A Granular Jamming Model for LFE Families

LFE families occur at granular jams in the shear flow channel between plates

Shear strain is accommodated by the continuous formation and failure of grain birdges



Granular jamming model explains the following observations:

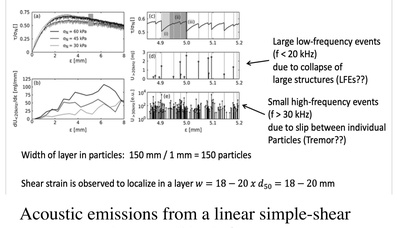
1) Spatial persistence of LFE families
   Locations of jams persist –shear displacement in each episode is small relative to block sizes

2) Log-normal moment-frequency relation
   Block sizes in a jam have a log-normal distribution – natural result of Kolmogorov fragmentation.

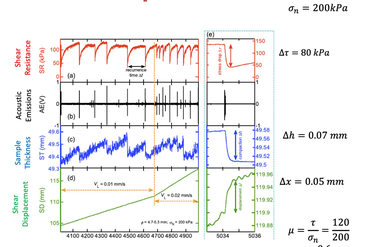
3) Weak dependence of duration on moment
   Duration depends on the viscosity of intergranular fluids resisting bridge collapse.

4) Absence of high-frequency seismic radiation.
   Slow slip between grains– not a propagating rupture - no stopping phases

7 Acoustic Emissions from Simple-Shear Experiments



Acoustic emissions from a linear simple-shear experiment show small high-frequency events from individual particle interactions and large low-frequency events from the collapse of larger structures.



$\mu = \frac{\tau}{\sigma_n} = \frac{120}{200} = 0.6$

Acoustic emissions from a rotary simple-shear experiment show a volume collapse associated with large events. Grain size = 5.0 ± 0.2 mm.

8 Composite Moment Tensor of LFEs Beneath Vancouver Island

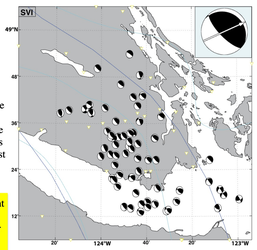
Royer and Bostock (2014)

A comparative study of low frequency earthquake templates in northern Cascadia.

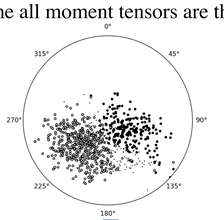
Earth and Planet. Sci. Lett. 402, 247–256.

For the SVI (array), solutions are generally well modelled as double couple sources. The large majority (~90%) of mechanisms are consistent with shallow thrust faulting in the direction of relative plate motion.

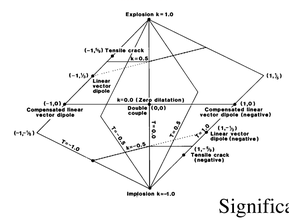
"F-tests that reveal no significant improvement in fit afforded by deviatoric or full moment tensor solutions."

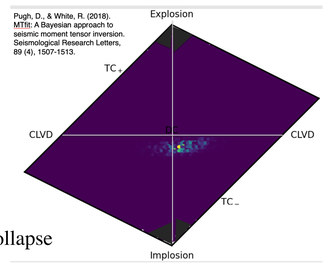


Assume all moment tensors are the same



Hudson Plot





Significaant Volume Collapse