Triggering of Microseismicity During Low Tides at the Equatorial Mid-Atlantic Ridge, Inferred from the PI-LAB Experiment Data

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Abstract

The combined gravitational pulls from the moon and the sun result in periodical tidal stresses at rates potentially exceeding the tectonic ones. Yet, tidal triggering of earthquakes in critically stressed faults is still under debate and controversial results have been obtained, depending upon specific physical properties and geological settings. Although no universal triggering pattern between earthquakes and tides has been observed in oceanic environments, previous research implies relation between increased seismicity rates and low tides at particular sites at fast-spreading ridges in the Pacific. We present a dataset of 4719 microearthquakes (-1.4[?]M_L[?]4.0) recorded by an Ocean Bottom Seismometer (OBS) network at the slow-spreading equatorial Mid-Atlantic Ridge from March 2016 to February 2017. We use a single-station template matching technique to focus on a small volume, spreading within a ˜5km radius from the station. The origin time of the events and their epicentral location is sufficiently determined for a robust comparison with the ocean tides. Our analysis suggests a significant correlation between seismic potential and tidal forces, with the majority of events occurring during or towards low tides, i.e., during maximized extensional stress and maximized extensional stress rate. The tidal dependence of magnitude distribution is also investigated. Although the b-values are generally lower at low tides, the differences are not sufficiently large to achieve statistical significance. However, seismic bursts (enhanced activity rate clusters), occurring at rates above the reference seismicity, are exclusively initiated at extensional stress rates. Coulomb stress modelling implies that slip is promoted during low tides at low-angle normal faults. Local morphology, seismicity distribution and focal mechanisms suggest the existence of high angle faults at shallower depths. Coulomb modelling suggests slip on these faults should not be triggered at low tides unless another factor is considered. One possibility is the presence of a shallow magma chamber. Such a chamber has also been suggested by previous seismic imaging results. Overall, the result yields new insight into magmatic – tectonic cycles and seismicity triggering at mid-ocean ridges.

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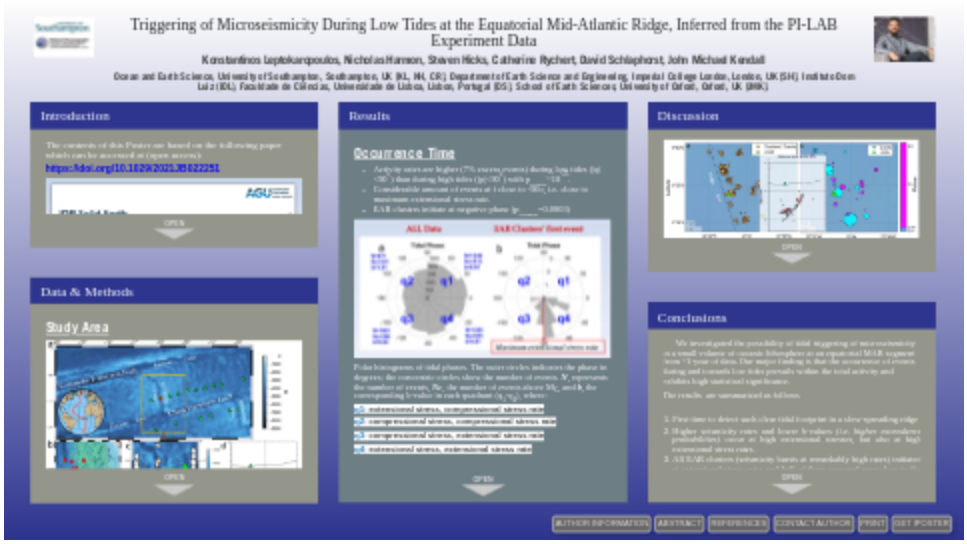

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INTRODUCTION

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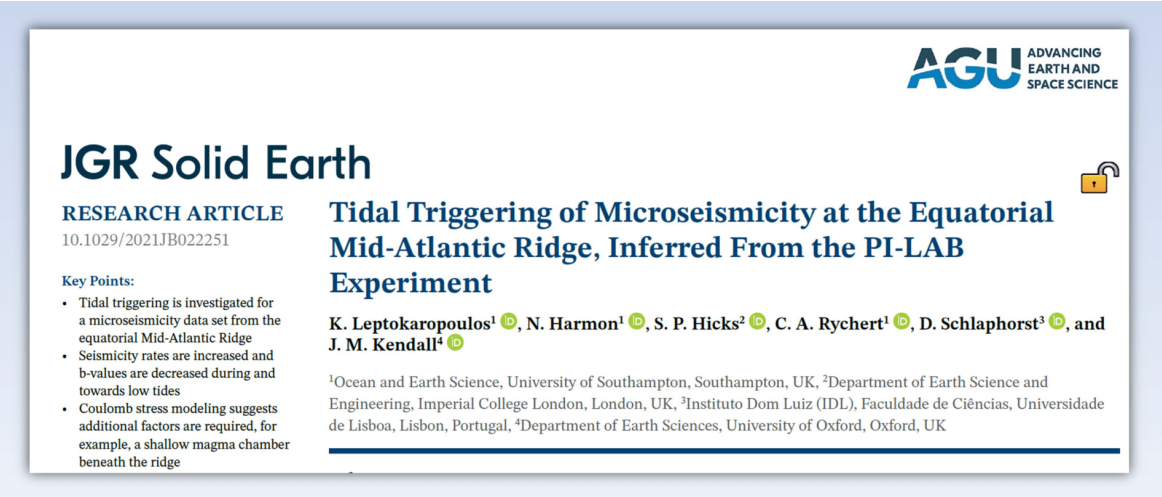

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Key Points:
- Tidal triggering is investigated for a microseismicity data set from the equatorial Mid-Atlantic Ridge
- Seismicity rates are increased and b-values are decreased during and towards low tides
- Coulomb stress modeling suggests additional factors are required, for example, a shallow magma chamber beneath the ridge

Tidal Triggering of Microseismicity at the Equatorial Mid-Atlantic Ridge, Inferred From the PI-LAB Experiment

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We use the seismicity data acquired by the PI-LAB and EURO-LAB projects to investigate the role of tides as a triggering mechanism of microseismicity along a segment of the equatorial MAR. We study the correlation between ocean tide phase and amplitude with the occurrence of seismicity. Then, we identify seismic sequences characterised by enhanced activity rates (i.e. temporal clusters) separated by time periods in which seismic activity falls well below the reference seismicity level. We also demonstrate how the magnitude distribution of seismicity is influenced by tidal fluctuations. Finally, we interpret the results in terms of Coulomb stress changes and extract information on frictional and hydraulic properties of the lithosphere in the close vicinity of the axial ridge.

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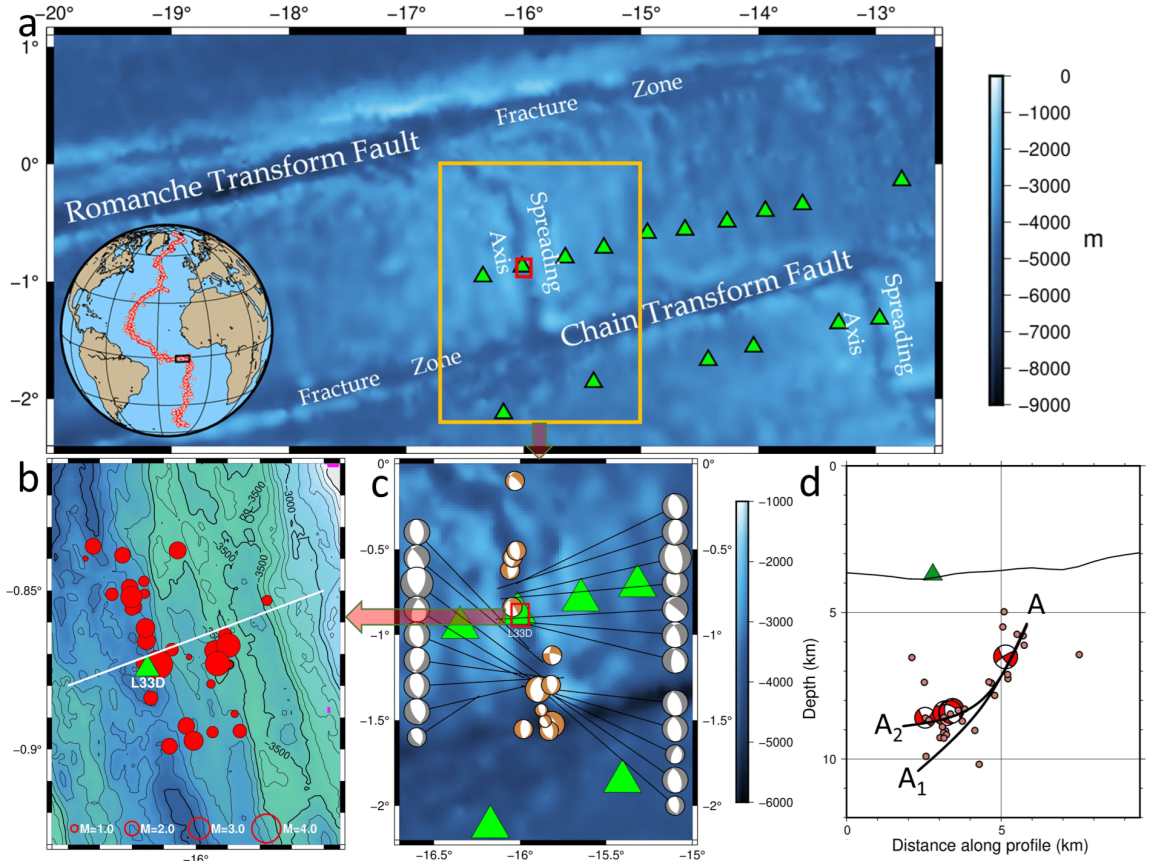
DATA & METHODS

Study Area



(a) Regional map of equatorial Atlantic. Green triangles denote the location of OBS stations operated during the PI-LAB experiment.

(b) Bathymetric map of the study area. Red circles indicate the 34 seismicity templates used to compile our catalogue.

(c) Broader area focused on the ridge spreading axis shown in (a). Focal mechanisms are from GCMT (Ekström et al., 2012; grey) and this study (brown).

(d) Double difference locations of the 34 template events and available focal mechanisms, projected along the cross-section shown in (b), suggest possible reactivations of a west-dipping normal fault.

Seismicity Data

1-year seismicity data (March 2016 - March 2017)

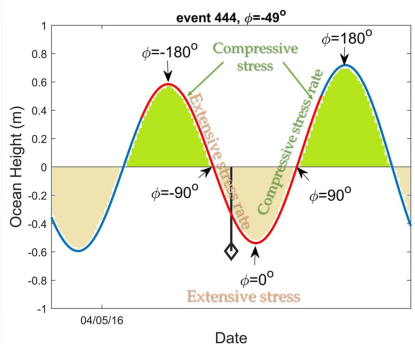
- Detection and Location: Lassie (Heimann et al., 2017)
- Relocation: NonLinLoc (Lomax et al., 2000) and DD (Waldhauser and Elsworth, 2000)
- 34 well-located events,~5km from L33D station, mean vertical error ~200m.
- Used as templates within EQcorrscan (Chamberlain et al., 2018).

4719 events, with $-1.4 \leq M_L \leq 4.0$ *(single station estimates, unknown M_L-M_W scaling)* → **1781 events above M_C=0.0**

- We define as **Enhanced Activity Rate (EAR)** Clusters, sequences with >10 events and maximum interevent time between subsequent events <30 min. 14 such EAR clusters (301 events) were identified, having 25-200 times higher rates than the overall seismic activity.

Methods

- The SPOTL software (Agnew, 1997) is used to calculate solid Earth tides as well as ocean loading with the global ocean tide model TPXO72.2010 (Egbert & Erofeeva, 2002).
- We define the tidal phase (see figure on the right), ***ϕ=0***, at low tides and apply the Schuster (1897) test, to quantify the randomness of seismic events' occurrence time distribution.
- We calculate tidal Coulomb stress changes (ΔCFF) considering different fault plane geometries and frictional properties.
- The completeness magnitude, M_C, is estimated by the Anderson-Darling (AD) test (Marsaglia and Marsaglia, 2004; Leptokaropoulos, 2020).

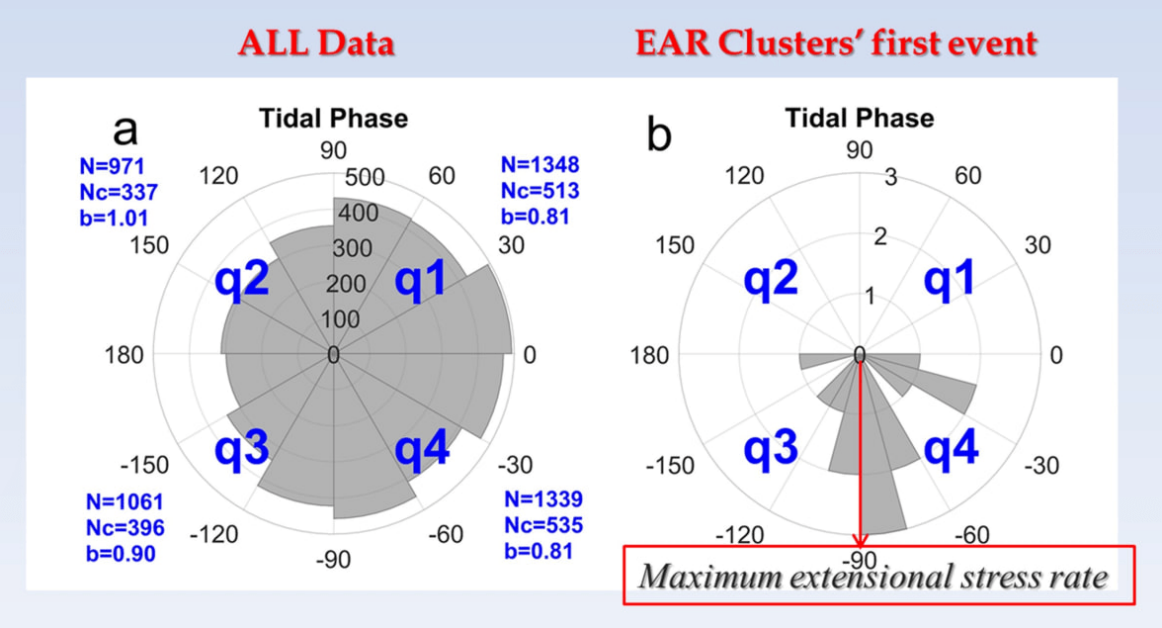


- The Maximum likelihood estimation of b-value is applied (Aki, 1965) and the significance of the b-value difference between 2 datasets is evaluated by the Akaike Information Criterion (AIC, Utsu, 1999).
- The SHAPE software (Leptokaropoulos and Lasocki, 2020) is used to calculate the exceedance probabilities for specified magnitudes and time periods.

RESULTS

Occurrence Time

- Activity rates are significantly higher (7% excess events) at low tides ($|\varphi|<90^o$) than at high tides ($|\varphi|>90^o$) with $p_{Schuster}\sim10^{-25}$.
- Considerable amount of events occur at φ close to -90^o, i.e. close to maximum extensional stress rate.
- EAR clusters initiate at negative phase ($p_{Schuster}=0.0003$)



Polar histograms of tidal phases. The outer circles indicate the phase in degrees; the concentric circles show the event counts. ***N***, represents the number of events, ***Nc***, the number of events above M_C, and ***b***, the corresponding b-value in each quadrant (q_1-q_4), where:

q1: extensional stress, compressional stress rate

q2: compressional stress, compressional stress rate

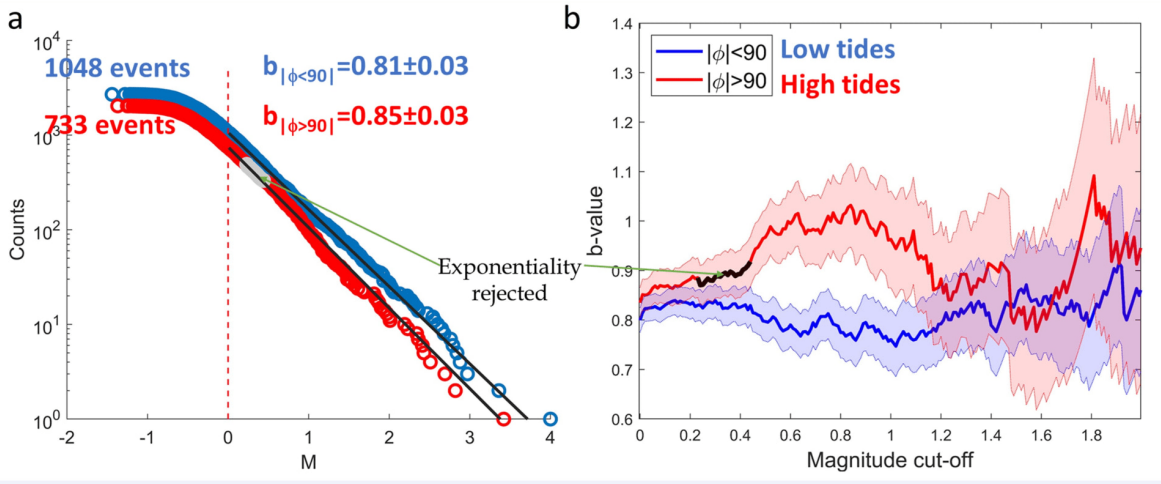
q3: compressional stress, extensional stress rate

q4: extensional stress, extensional stress rate

Magnitude Distribution

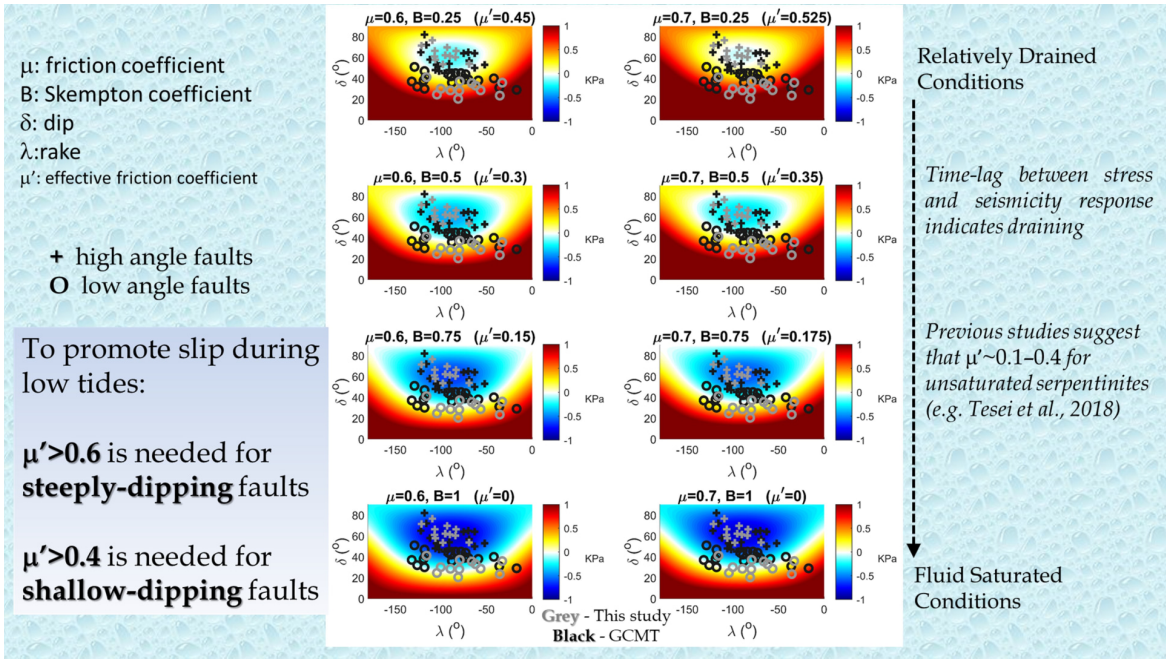
- b-values exhibit significant fluctuations at high tides whereas they are far more stable at low tides
- EAR clusters have a total duration of ~1day, they accommodate 83% of the total seismic moment release of the 1-year experiment.
- Exceedance probabilities are higher during low tides, however the difference is not significant at 0.05 level.
- The 301 EAR Clustered events have $b=0.61\mp0.04$.
- The remaining 1480 (unclustered) events have $b=0.89\mp0.02$

These two b-values differ significantly (p_{AIC}~10^{-7})

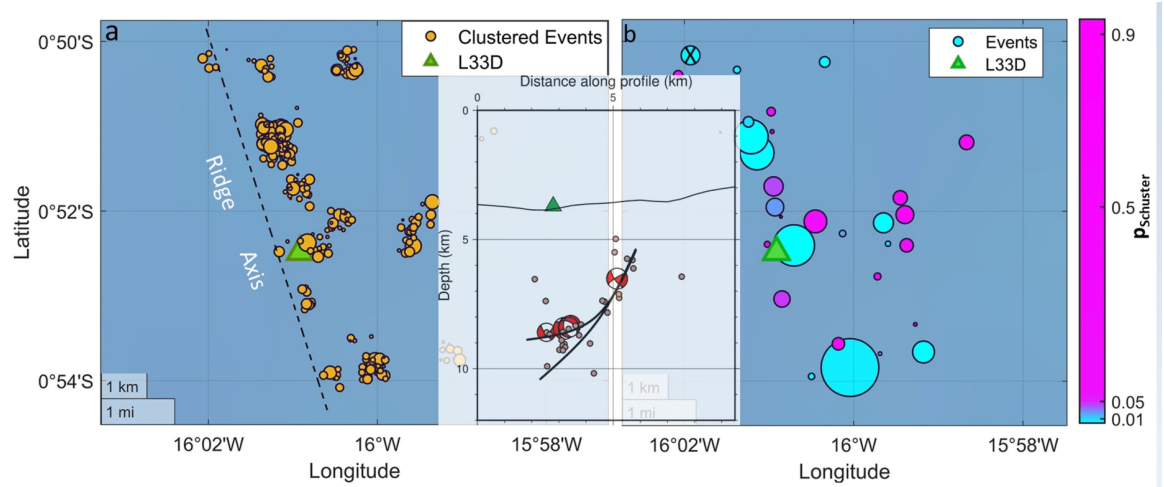


(a) Magnitude-frequency distribution with vertical dashed line indicates the M_C=0.0. (b) b-value fluctuation as a function of magnitude cut-off. The blue and red shaded areas indicate the b-value standard error. The grey segment in (a) and black segment in (b) show the range of magnitude for which the AD test rejects the null hypothesis of exponential magnitude distribution.

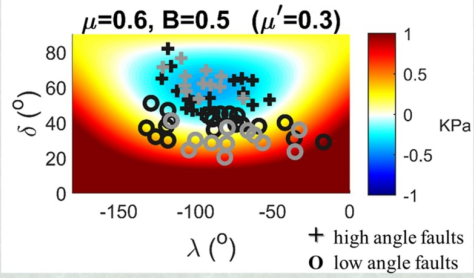
Coulomb Stress Calculations

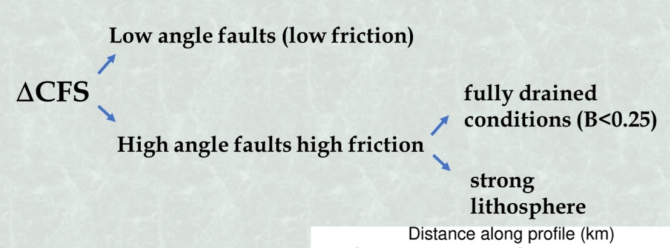


DISCUSSION



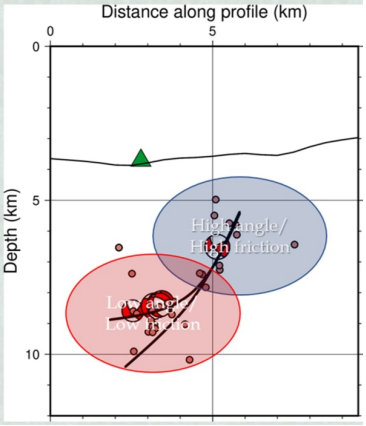
EAR clustering and tidal signal (Schuster test p-value) is stronger along the ridge axis





- Geological evidence support a rather weak (low friction) oceanic crust/mantle, given the abundant presence of lizardite and chrysolite serpentinites in the mantle
- Even a small degree of serpentinization (<15%) can reduce the oceanic strength to that of pure oceanic serpentinite
- The lower part of the listric fault may end in weak, serpentinized mantle
- The upper fault part may be located in the stronger, basaltic oceanic crust.

- A magma chamber could inflate owing to its higher compressibility, potentially resulting in a favourable stress field during low tides (e.g. Scholz et al., 2019). The existence of a magma chamber is supported by previous seismic imaging in the region (Saikia et al., 2021).



CONCLUSIONS

We investigated the possibility of tidal triggering of microseismicity in a small volume of oceanic lithosphere at an equatorial MAR segment from ~1-year of data. Our major finding is that the occurrence of events during and towards low tides prevails within the total activity and exhibits high statistical significance.

The results are summarized as follows

1. First time to detect such clear tidal footprint in a slow-spreading ridge
2. Higher seismicity rates and lower b-values *(i.e. higher exceedance probabilities)* occur at high extensional stresses, but also at high extensional stress rates.
3. All EAR clusters (seismicity bursts at remarkably high rates) initiated at extensional stress rates and half of them occurred very close to the maximum extensional stress rate.
4. Coulomb stress modeling is consistent with tidal triggering on low-angle normal faulting in a serpentinized, low-friction oceanic lithosphere.
5. Coulomb stress modeling suggests additional factors, such as the influence of an underlying magma chamber, are required to explain tidal triggering on high angle faults, at low tides

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ABSTRACT

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