# Subaqueous Paleoseismology: Fresh perspectives on sedimentary response to regional tectonics

**Yin Lu,** Nicolas Waldmann, Nadav Wetzler, Jasper Moernaut, Revital Bookman, Glenn P. Biasi, Michael Strasser, Xiaomin Fang, Aurélia Hubert-Ferrari, G. Ian Alsop, Amotz Agnon, and Shmuel Marco

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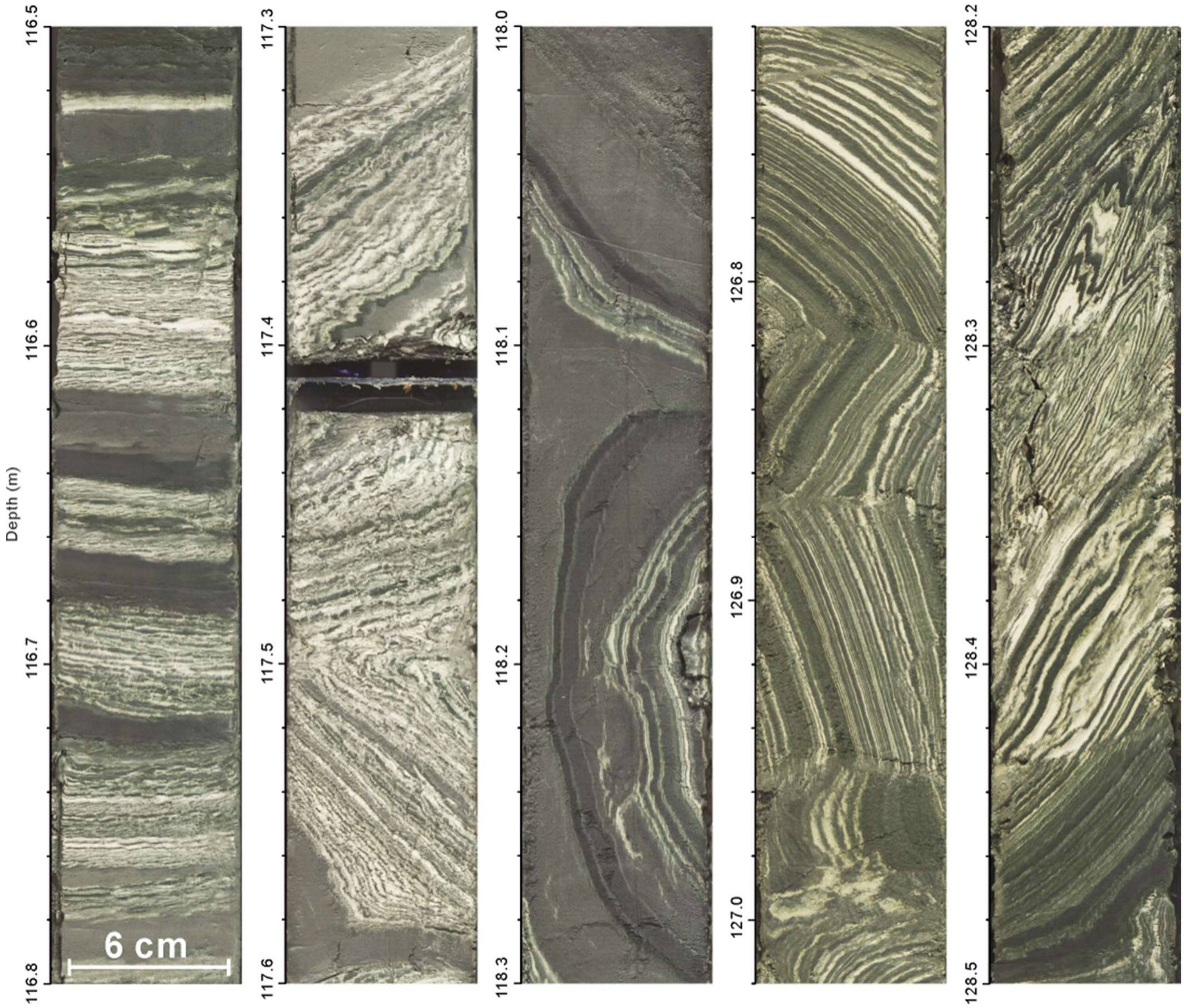


**Earthquake-induced disturbances in the Dead Sea center (Core 5017-1)**

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RESEARCH ARTICLE

10.1002/2017JB014342

## Interpreting Soft Sediment Deformation and Mass Transport Deposits as Seismites in the Dead Sea Depocenter

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**Key Points:**

- In situ deformation, slump, and chaotic deposits in the Dead Sea depocenter are seismically triggered
- Source and sedimentary process of the three types of disturbance is determined
- Long sequences of disturbance in a

**1. Key Points:**

- *In situ deformation, slump and chaotic deposits in the Dead Sea depocenter are seismically-triggered*
- *Source and sedimentary process of the three types of disturbance are determined*
- *Long sequences of disturbance in a seismically active lake depocenter has the potential to infer earthquake clusters*

**2. Overview**

In order to extend the Dead Sea Fault earthquake record to pre-instrumental time, we need to understand the processes that create disturbance in the basin depocenter where water depth is hundreds of meters. Here we report two disturbed sequences (4-22 m thick) that were drilled in the Dead Sea depocentre. We propose a seismic trigger based on the temporal correlation with previously established earthquake records in the Dead Sea margin. Three basic types of disturbance are defined: *in situ* deformation, slump, and chaotic deposits (mud-supported gravel). Our observations indicate that: (i) earthquake-triggered Kelvin Helmholtz Instability is a plausible mechanism for the *in situ* deformation in the Dead Sea depocenter, (ii) slumps are sourced in the slope area, (iii) chaotic deposits (mud-supported gravel) originate near shore, and (iv) earthquake-triggered slope instability creates slump and chaotic deposits. Our results have widespread implications for studies of sediment disturbance in seismically active lakes, and we further suggest that long sequences of disturbance in such seismically active depocentres can be used to infer patterns of earthquake temporal distributions.

**Figures:**

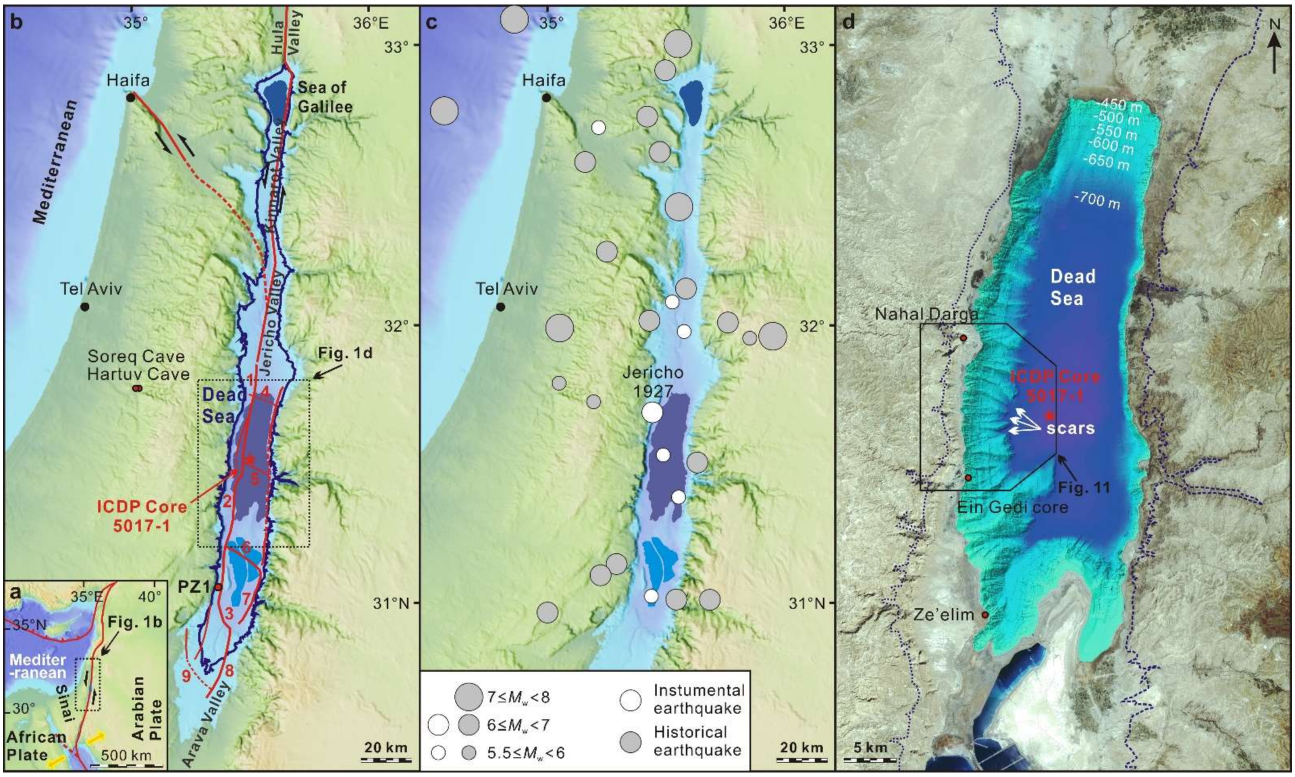



**Figure 1. Geological setting of the Dead Sea graben and location of ICDP core 5017-1. (a):** Plate tectonic setting. **(b):** Active faults along Dead Sea Fault and position of drill core 5017-1 located in the depocenter of the basin. **(c):** Instrumental and historical seismicity in the Dead Sea graben and surrounding areas. **(d):** Dead Sea bathymetric map.

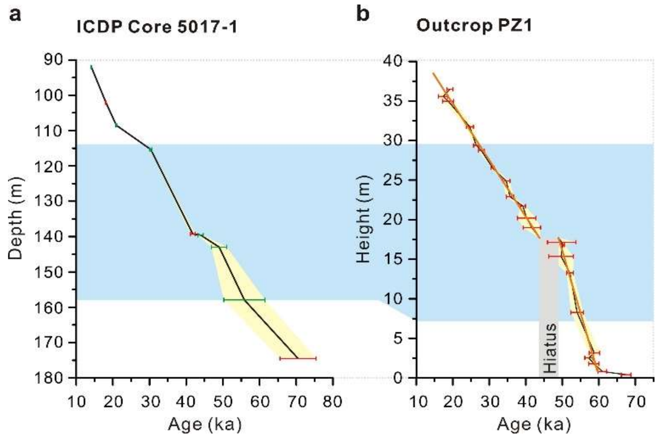



**Figure 2. Age model of the studied interval in ICDP core 5017-1 and PZ1 outcrop (Fig. 1b).** The focused section intervals are highlighted by the light blue color. **(a):** Age-depth plot for the interval of ~180-90 m (Lisan Fm.) in core 5017-1. **(b):** Age-height plot for the ~38.5 m-thick PZ1 outcrop based on U-Th age dating (red bars).

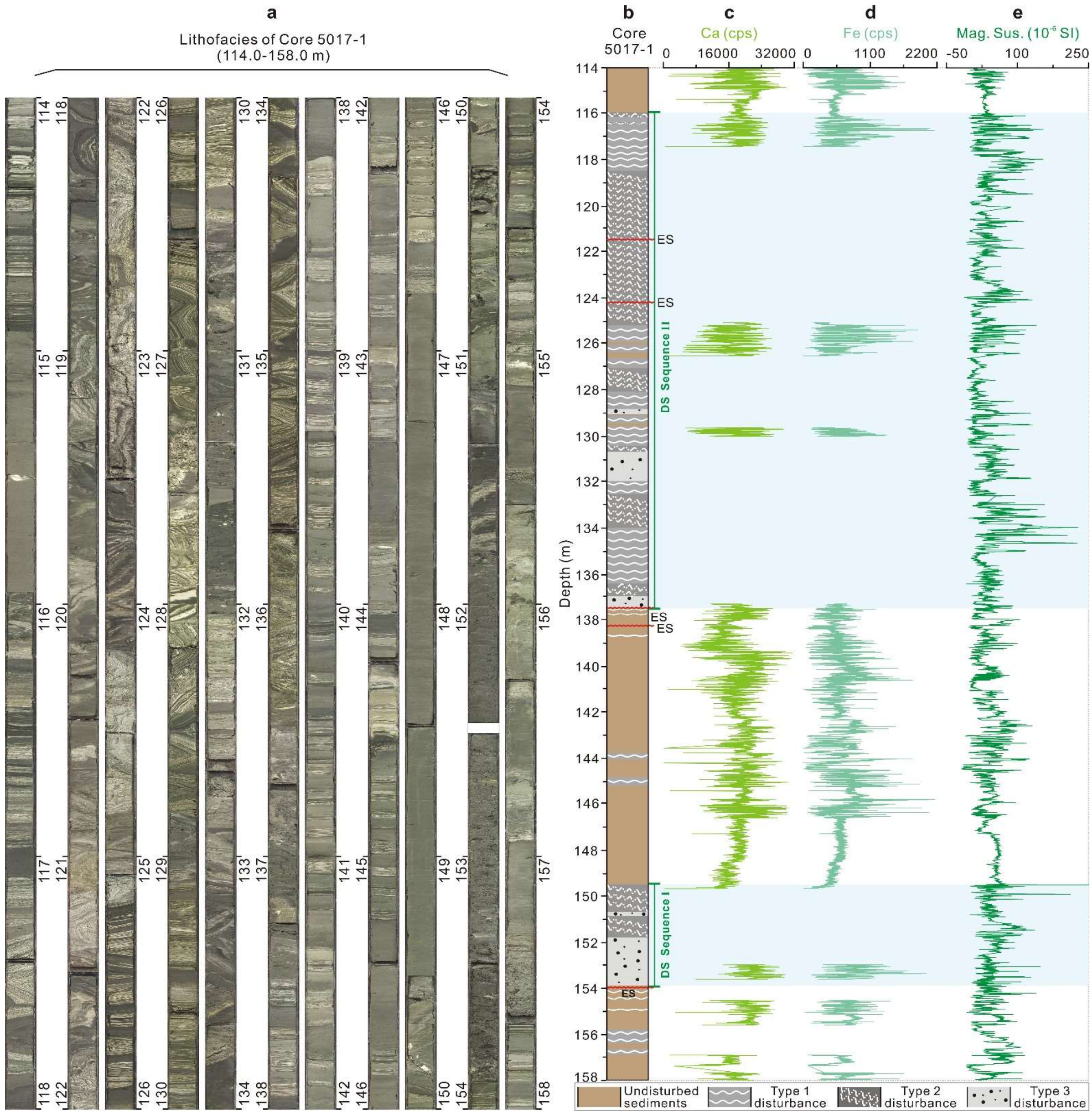



**Figure 3. Lithofacies and features of focused core interval (114-158 m) in the Dead Sea depocenter. (a):** Core images showing the disturbed and undisturbed facies. **(b):** Two meter-scale disturbed (DS) sequences are identified by sedimentary structures; ES, erosion surface. **(c) and (d):** µXRF profiles of Ca, Fe in counts per second (cps). **(e):** Magnetic susceptibility (Mag. Sus.) data. The light-green shaded areas indicate the corresponding intervals of DS Sequence I and II in Figure 3b.

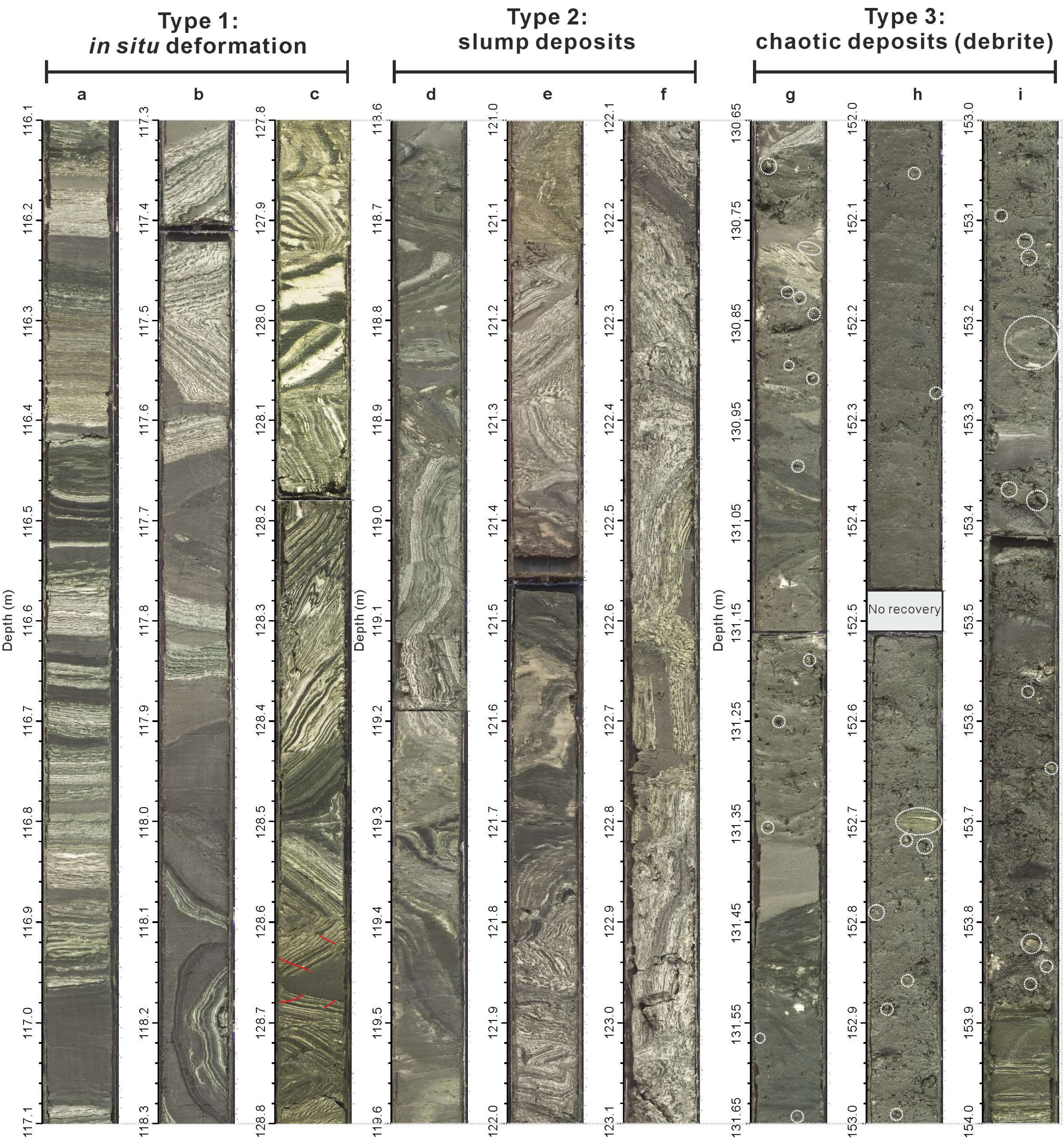



**Figure 4. Images from core 5017-1 showing 3 types of disturbances in the Dead Sea depocenter.**

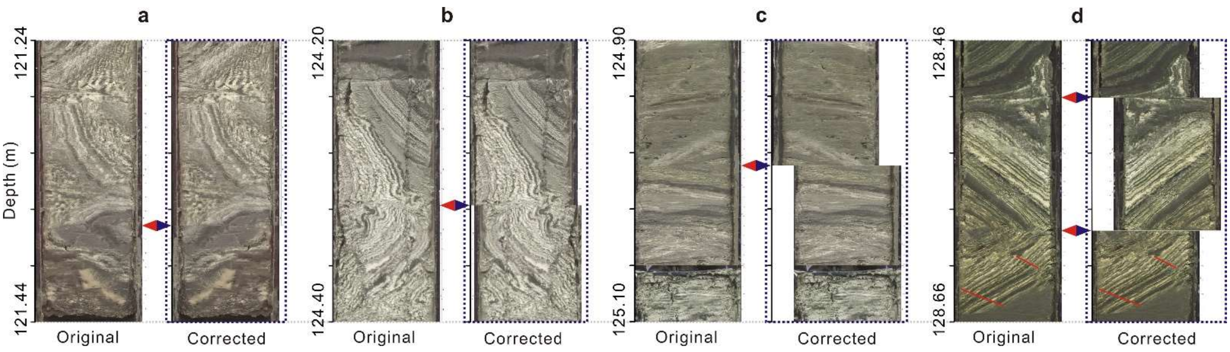
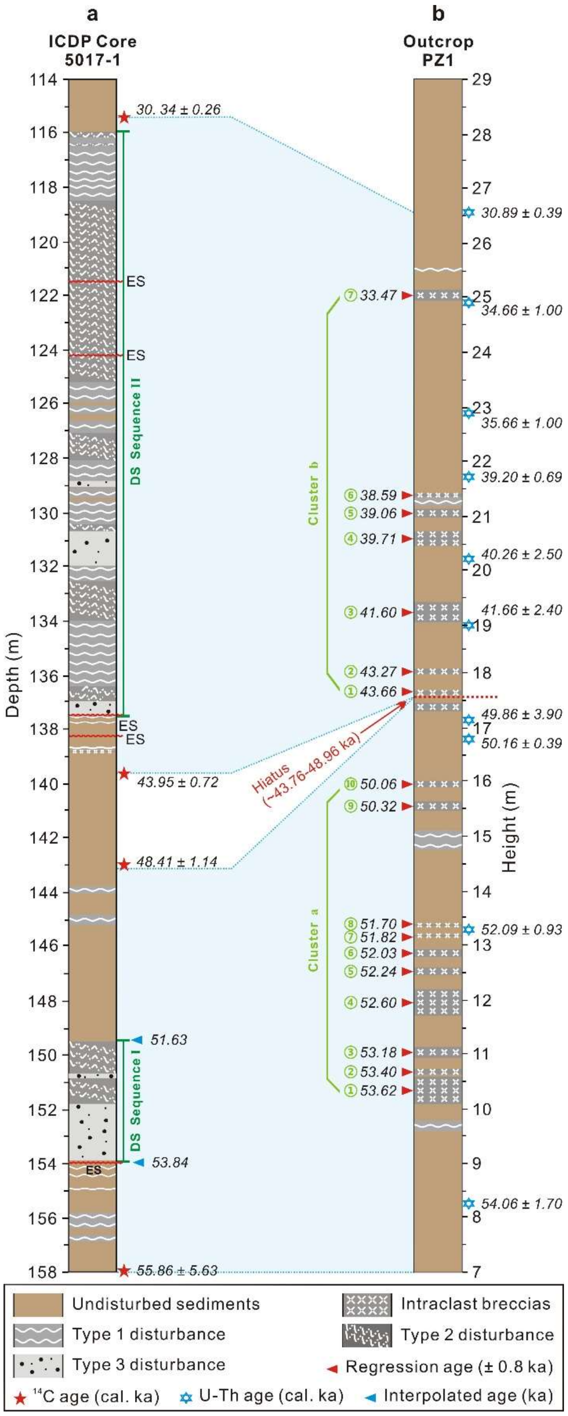



**Figure 5. Images from core 5017-1 showing typical artificial breaks with rotations of ~180° that were induced by the drilling process (angular discordances).** In each small figure (a-d), the left side is the original image, while the right side is the corrected and 'restored' image.



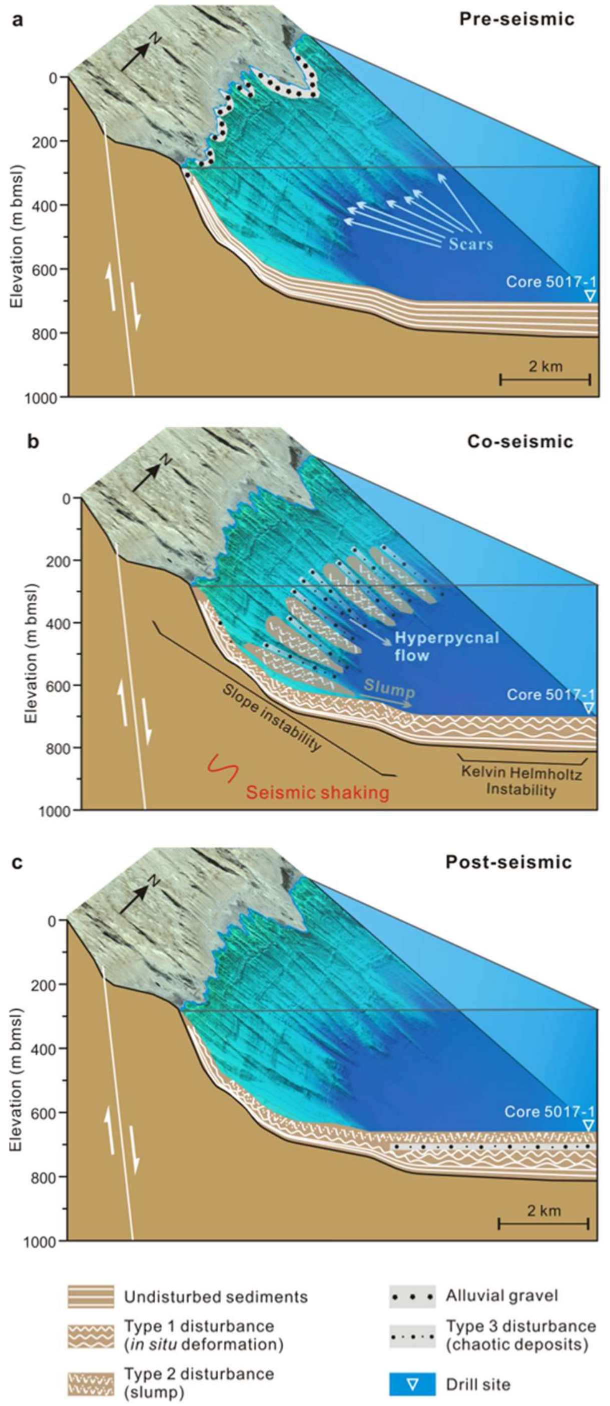




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**Figure 7. Schematic model showing the response of sedimentary processes in a lake depocenter to seismic shaking** in a tectonically active region such as the Dead Sea

**3. More details can be found at (Free Access):**

***Lu et al., 2017, JGR-se:*** https://doi.org/10.1002/2017JB014342

https://www.researchgate.net/profile/Yin_Lu22

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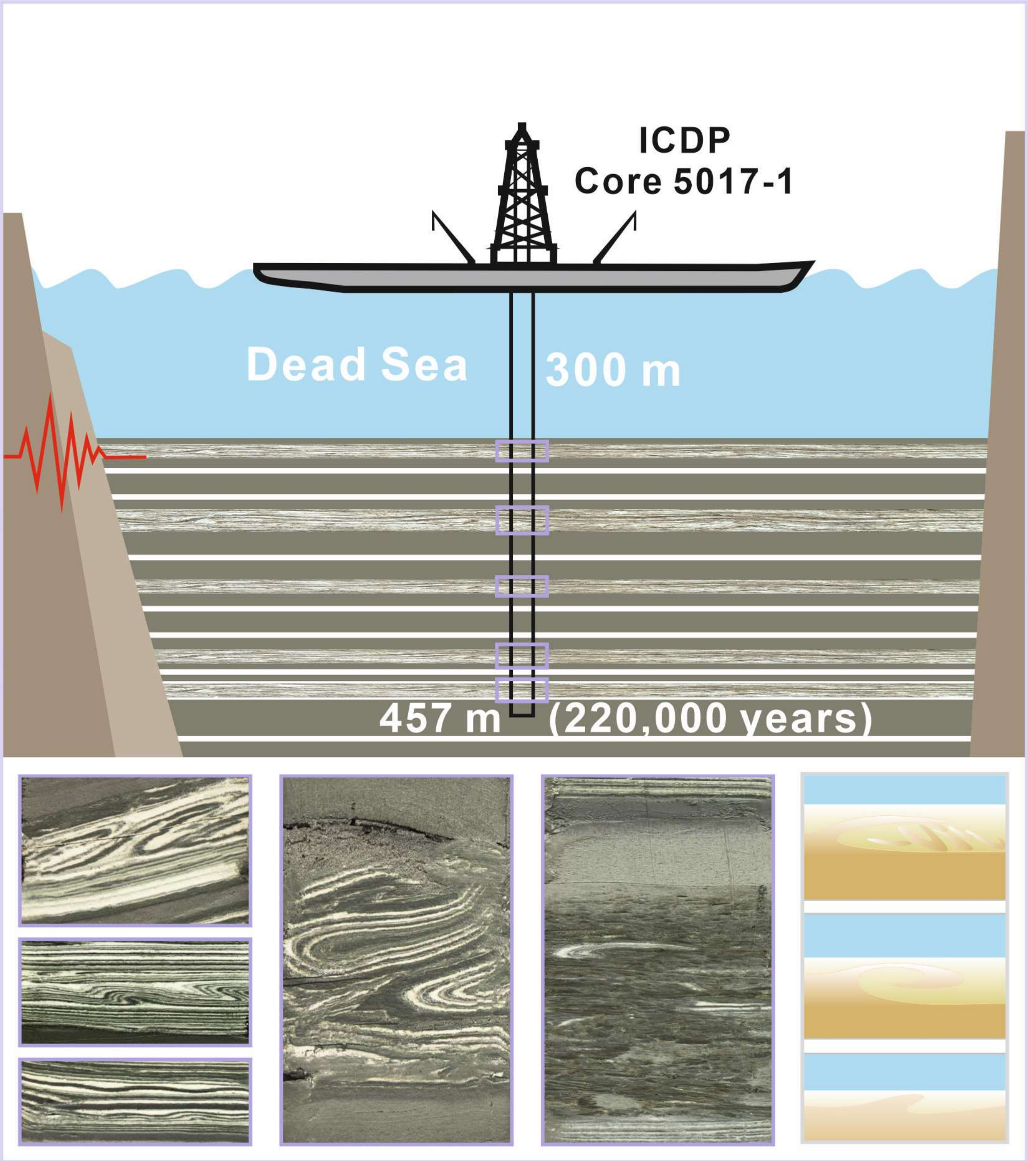
## Soft-sediment deformations buried beneath the center of the Dead Sea record hundreds of large earthquakes spanning the past 220,000 years

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RESEARCH ARTICLE | GEOLOGY

### A 220,000-year-long continuous large earthquake record on a slow-slipping plate boundary

YIN LU, NADAV WETZLER, NICOLAS WALDMANN, AMOTZ AGNON, GLENN P. BIASI, AND, SHMUEL MARCO Authors Info & Affiliations

*SCIENCE ADVANCES* • 27 Nov 2020 • Vol 6, Issue 48 • DOI: 10.1126/sciadv.aba4170

## 1. Key points

- This is the first attempt to apply a computational fluid dynamic modeling-based quantitative "fossil seismograph" to develop a large earthquake record.

- The record is calibrated to historic earthquakes, for which the Dead Sea area has a famously long span, and it confirms a clustered earthquake recurrence pattern and a group-fault temporal clustering model.

- The record yields a much shorter mean recurrence for large (≤ 1.4 kyr vs. 7-11 kyr) earthquakes than previously obtained, thus revealing a much higher seismic hazard than previously appreciated on this slow-slipping plate boundary.

## 2. Overview

The understanding of earthquakes in general and seismic hazard in particular, relies on our knowledge of past seismic history. The longer a time window that a record spans, the better that understanding can be. However, large earthquakes (moment magnitude, Mw ≥7.0) usually have recurrence intervals longer than the time span of modern seismograph operation of about a century, and infrequently occur on individual faults. In addition, earthquake recurrence patterns of slow-slipping faults (< 5 mm $yr^{-1}$), e.g., the Dead Sea Fault, are more difficult to determine because they usually have longer interseismic intervals. Subaqueous paleoseismology exploits lacustrine and marine sediments to retrieve much longer records of paleoseismic shaking. Such long records can probe our understanding of the physical behavior of fault systems in the wake of large seismic events and are therefore essential for improving seismic hazard assessment.

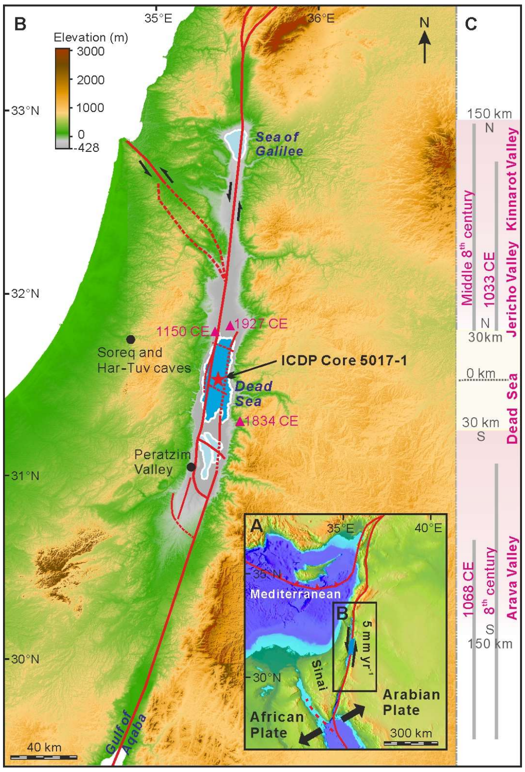


**Fig. 1. Tectonic setting of the Dead Sea Fault.**

**(A)** Dead Sea Fault is a sinistral boundary between the African and Arabian plates. **(B)** Major active faults along the plate boundary, Dead Sea Transform; in this area, the fault is composed of four fault segments. The red star marks the drilling site; the black points mark places referred to in the study; the magenta triangles indicate historic and instrumental Mw ≥6.0 earthquakes near the drilling site; ICDP: International Continental Scientific Drilling Program. **(C)** The gray bars represent the fault rupture of historic Mw ≥7.0 earthquakes since 31 BC that occurred along the focused part of the fault – the central Dead Sea Fault (up to 150 km north and south of the drilling site).

The Dead Sea Fault, a left-lateral, > 1,000-km-long strike-slip plate boundary separating the African and Arabian plates, is one of the most famous earthquake-generating faults on Earth. The Dead Sea, the lowest place on Earth (-433 m), is situated on the central part of the fault. In 2010-2011 a 457 m-long sediment sequence, spanning the past 220,000 years, was obtained in the 300 m deep central Dead Sea by the International Continental Scientific Drilling Program (ICDP). More than 400 earthquake-caused soft-sediment deformation structures were identified in this core. These structures are very similar to those softly deformed in other environments (e.g., air and ocean), suggesting a common mechanism, Kelvin Helmholtz instability. During earthquake shaking, the upper less-dense mud moves much faster than the lower denser mud (in the same direction), creating shear localized at the layer interface. These subtle structures are subsequently buried by new layers, resetting the system to record the next shaking event. The resulting sedimentary record in the center of the Dead Sea has recorded hundreds of earthquake shaking events with different shaking intensities over the past 220,000 years.

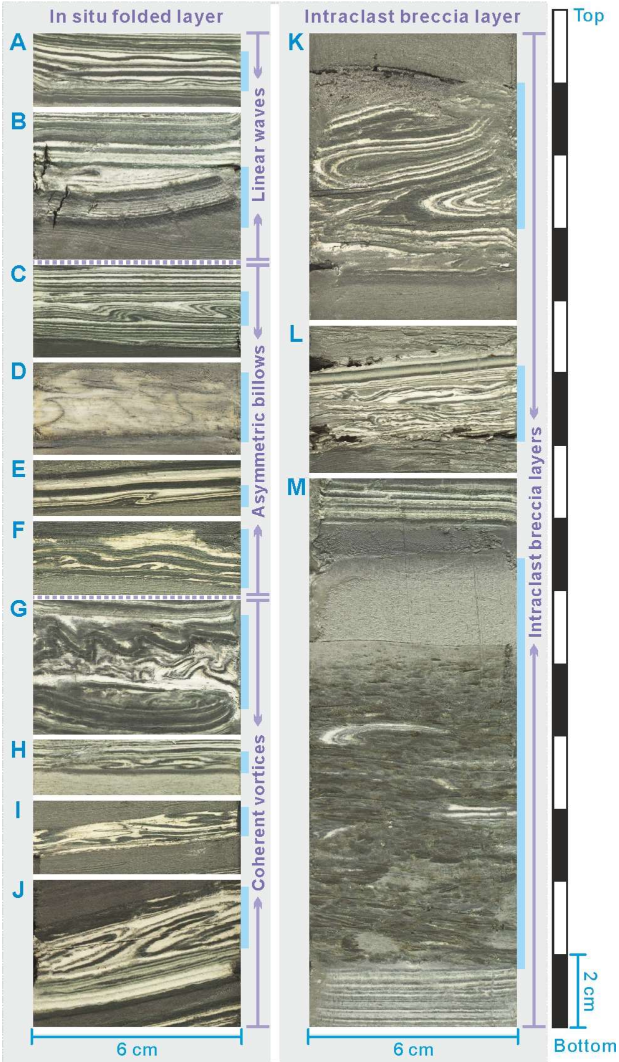


**Fig. 2. Paleoearthquake indicators in the ICDP Core 5017-1.**

**(A-J)** *in situ* folded layers; (A, B) linear waves, (C-F) asymmetric billows, (G-J) coherent vortices. **(K-M)** Intraclast breccia layers. The vertical light blue bars indicate the position of events. Core depth: (A) 11010.0-11012.0 cm; (B) 16604.0-16608.0 cm; (C) 10929.9-10932.4 cm; (D) 26582.7-26585.2 cm; (E) 32861.0-32862.5 cm; (F) 35921.8-35923.8 cm; (G) 13754.4-13758.0 cm; (H) 10605.4-10606.9 cm; (I) 36425.9-36427.9 cm; (J) 12528.0-12532.0 cm; (K) 14492.5-14500.0 cm; (L) 39206.4-39210.4 cm; (M) 10772.0-10787.0 cm.

To recover shaking intensity from the recorded structures, we ran a series of 2-D numerical simulations using the physical properties of the soft sediments at the bottom of the Dead Sea. Using the Kelvin-Helmholtz instability mechanism, we model the ground acceleration needed to produce each deformed structure. These accelerations correspond to different levels of earthquake shaking intensity. These can be converted to earthquake magnitudes by considering earthquake ground motion attenuation in the region, fault geometry, and other limiting conditions. We found that over the past 220,000 years large earthquakes occurred with recurrence times ranging from a few years to a few thousand years, with a mean of 1400 years. This mean recurrence time is significantly shorter than the previous estimate of 7 to 11 thousand years, thus revealing an unexpectedly high seismicity rate on a slow-slipping (< 5 mm/year) plate boundary. In addition, unlike the periodic recurrence of earthquakes on fast-slipping and geometrically simple strike-slip faults, e.g., the Wrightwood Section of the San Andreas Fault and Alpine Fault in New Zealand, our work confirms a clustered recurrence pattern for large earthquakes on the slow-slipping Dead Sea Fault.

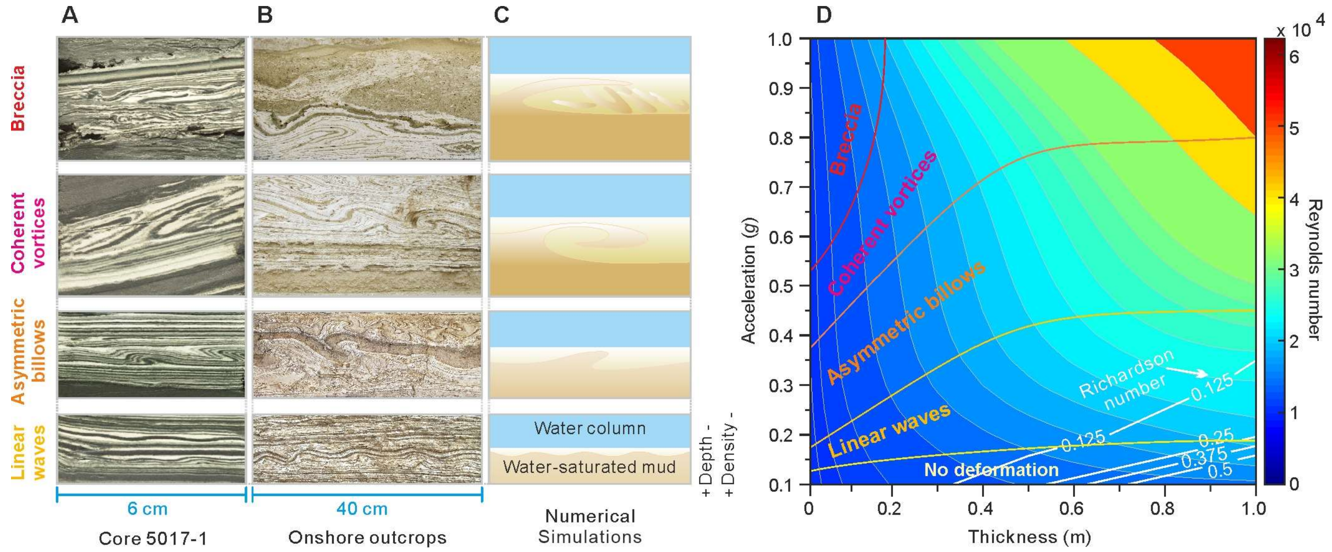


**Fig. 3. Numerical simulation on *in situ* folded layer and intraclast breccia structures in the Dead Sea sedimentary sequences.** **(A)** Typical structures from the Dead Sea depocenter Core 5017-1. **(B)** Typical structures from Dead Sea onshore outcrops (Fig. 1B). **(C)** Schematic diagrams based on snapshots from the numerical simulations demonstrating the four structures. **(D)** Quantitative estimation of the accelerations that are needed to initiate the four structures with different thicknesses; the deformations normally occurred when Richardson number ≤0.125.

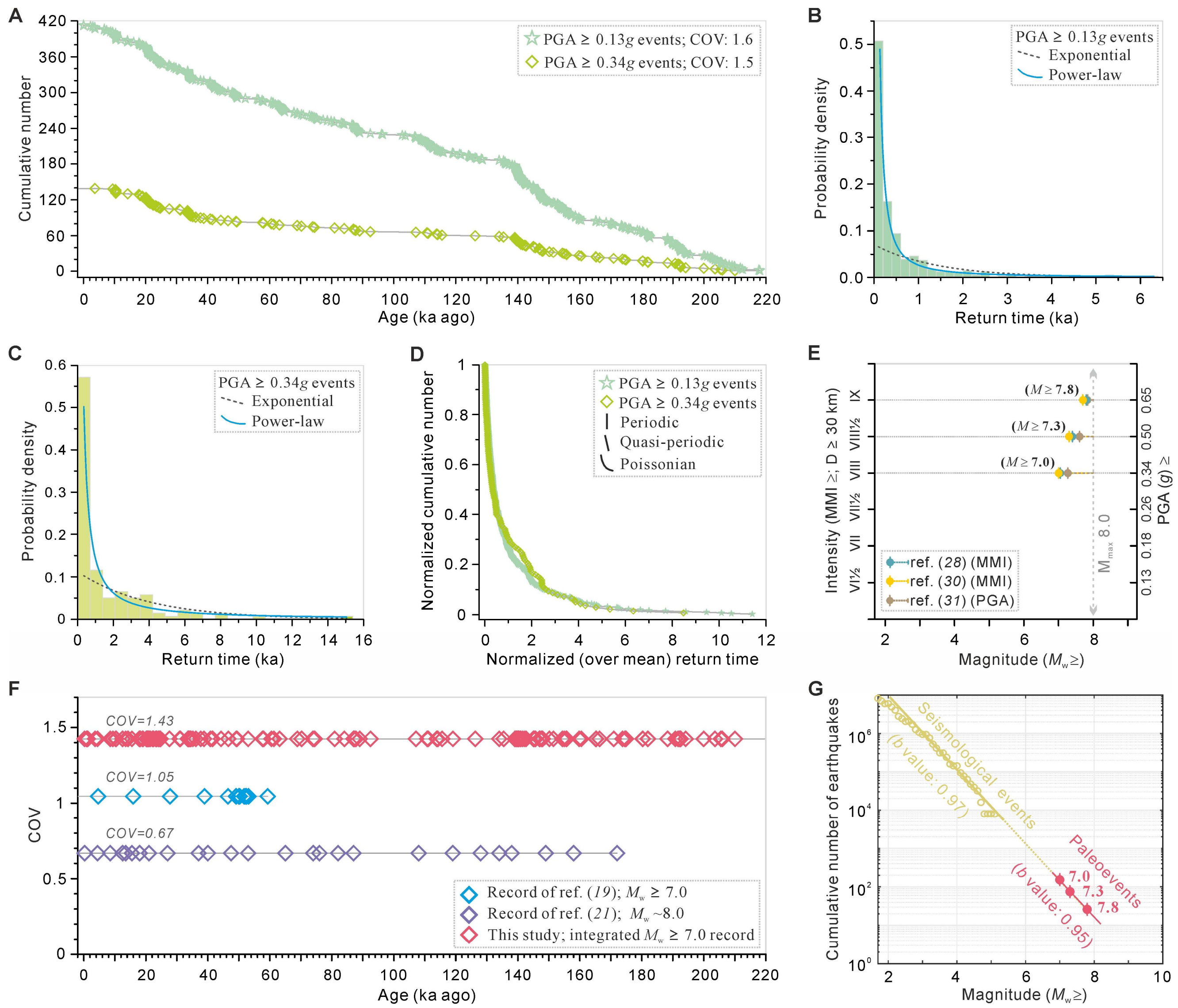

**Fig. 4. Return time statistics of seismites and magnitude constraint for strong seismic shaking events during the past 220 kyr.** **(A)** Temporal distribution of moderate (PGA ≥0.13 g) and strong (PGA ≥0.34 g) seismic shaking events; PGA, peak ground acceleration; COV, coefficient of variation. **(B and C)** Histograms for return times of PGA ≥0.13 g and PGA ≥0.34 g events. We plot two distribution types (exponential and power-law) for each dataset. **(D)** Normalized return time data to show return time distribution of moderate and strong seismic shaking events. **(E)** Magnitude constraint for strong seismic shaking events by applying the three regional empirical attenuation relations, taking the past two kyr earthquake scenario as an analogy for the paleoseismic record, and assuming that most $M_w$ ≥6.0 earthquakes occurred with D ≥30 km from the drilling site; D, epicentral distance. **(F)** Comparison of different temporal distributions of large earthquakes on the central Dead Sea Fault Zone derived from three different geological records. **(G)** Magnitude-frequency distribution of modern (olive colored) and paleo-earthquakes (pink colored) on the central Dead Sea Fault during the past 220 kyr; the number of modern earthquakes is extrapolated to 220 kyr.

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**3. Outlooks**

In this work, we consider the seismites of "*in situ* soft-sediment deformations" only, and do not include any other types of seismites such as seismogenic mass movement deposits. This is because, firstly, only the seismic shaking intensities of *in situ* soft-sediment deformations can be quantitatively estimated via numerical simulation. Secondly, in the present work, we are focusing on the strong seismic shaking events. Previous studies have shown that the seismic intensity threshold for the initiation of seismogenic mass movement deposits is MMI ~VI. However, the intensity threshold for the initiation of "intraclast breccias" and "coherent vortices" (two types of "*in situ* soft-sediment deformations") in the Dead Sea are MMI ~VIII.

So, the present seismic record may still not complete regarding moderate earthquakes. In the next step (funded by Austrian Science Fund), we will consider both **earthquake-caused secondary sedimentary effects** (**seismogenic mass movement deposits**; *Lu et al., 2017, JGR & 2021a Feb., GRL*) and ***in situ* effects** (**micro faults/fault-graded beds & *in situ* soft-sediment deformations**) to develop a more complete 220 kyr-long **moderate earthquake record**. In addition, we are considering improving our numerical simulation by including an analog model.

**4. More details can be found at (Open Access):**

***Lu et al., 2020, Science Advances:*** https://advances.sciencemag.org/content/6/48/eaba4170

https://www.researchgate.net/profile/Yin_Lu22

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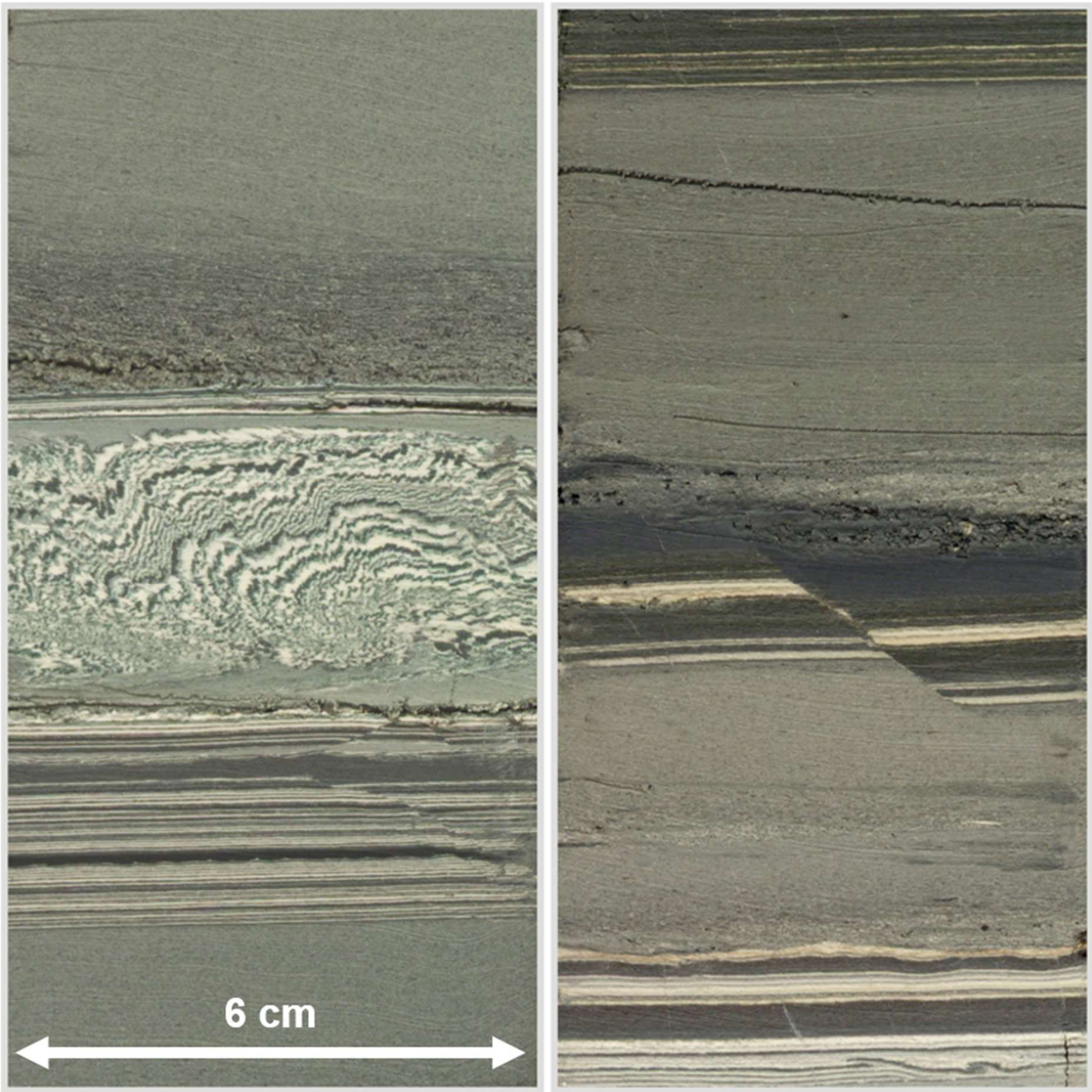
## Features of seismogenic turbidites from the Dead Sea depocenter




Dead Sea turbidites (ICDP Core 5017-1)

Geophysical Research Letters

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**Key Points:**

- Seismic origin for prehistoric turbidites is established by analyzing the underlying *in situ* deformation structures for each turbidite
- Data validate a previous hypothesis that soft-sediment deformation formed at the sediment-water interface in the Dead Sea
- The new approach permits a more confident geohazard assessment by improving the completeness of a paleoseismic archive

### A New Approach to Constrain the Seismic Origin for Prehistoric Turbidites as Applied to the Dead Sea Basin

**Yin Lu[1,2], Jasper Moernaut[2], Revital Bookman[3], Nicolas Waldmann[3], Nadav Wetzler[4], Amotz Agnon[5], Shmuel Marco[6], G. Ian Alsop[7], Michael Strasser[2], and Aurélia Hubert-Ferrari[1]**

[1]Department of Geography, University of Liege, Liège, Belgium, [2]Department of Geology, University of Innsbruck, Innsbruck, Austria, [3]Dr. Moses Strauss Department of Marine Geosciences, University of Haifa, Haifa, Israel, [4]Geological Survey of Israel, Jerusalem, Israel, [5]The Neev Center for Geoinfomatics, Institute of Earth Sciences, Hebrew University of Jerusalem, Jerusalem, Israel, [6]Department of Geophysics, Tel Aviv University, Tel Aviv, Israel, [7]Department of Geology & Geophysics, University of Aberdeen, Scotland, UK

**Abstract** The seismic origin of turbidites is verified either by correlating such layers to historic

**1. Key Points:**

- Seismic origin for prehistoric turbidites is established by analyzing the underlying *in situ* deformation structures for each turbidite
- Data validate a previous hypothesis that soft-sediment deformation formed at the sediment-water interface in the Dead Sea
- The new approach permits a more confident geohazard assessment by improving the completeness of a paleoseismic archive

**2. Overview**

Seismogenic turbidites are widely used for geohazard assessment. The use of turbidites as an earthquake indicator requires a clear demonstration that an earthquake, rather than non-seismic factors, is the most plausible trigger. The seismic origin is normally verified either by correlating the turbidites to historic earthquakes, or by demonstrating their synchronous deposition in widely spaced, isolated depocenters. The correlated historic earthquakes could thus constrain the seismic intensities necessary for triggering turbidites. However, the historic correlation method is not applicable to prehistoric turbidites. In addition, the synchronous deposition of turbidites cannot be verified if only one deep core is drilled in a depocenter.

Here, we propose a new approach that involves analyzing the underlying *in situ* deformations of prehistoric turbidites, as recorded in a 457 m-long core from the Dead Sea center, to establish their seismic origin. In addition, our high-resolution chemical and sedimentological data validate a previous hypothesis that soft-sediment deformation in the Dead Sea formed at the sediment-water interface (*Marco and Agnon, 1995, Geology*). Moreover, we use our results to propose seven basic earthquake-related depositional scenarios preserved in depocenters located in tectonically active regions like the Dead Sea. These techniques and findings permit a more confident geohazard assessment in the region and other similar tectonic settings by improving the completeness of a paleoseismic archive. This is the first work to show detailed information on turbidites in the Dead Sea region.

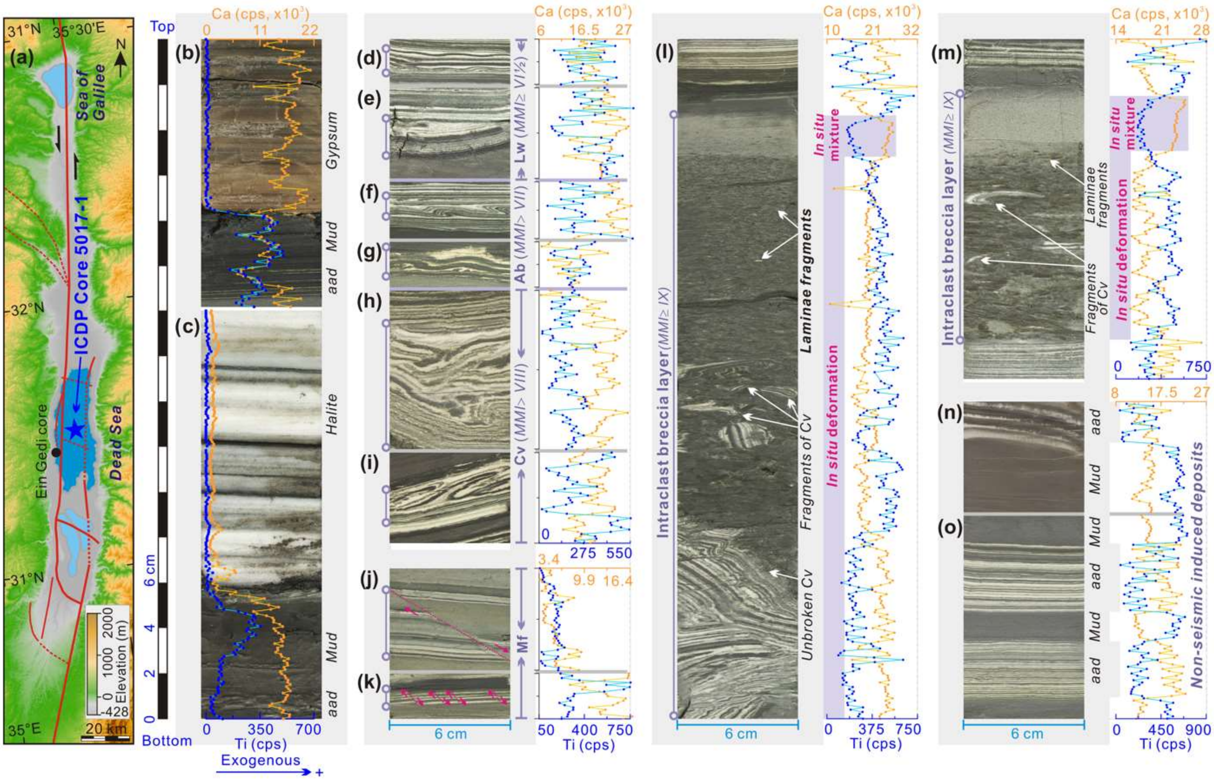

**Fig. 1. Tectonic setting of the Dead Sea Basin (a) and chemical data characterizing *in situ* seismites (d-m) (Lu et al., 2020b) and background deposits (b-c, n-o) in Core 5017-1. (a)** Active faults in the basin (Bartov et al., 2006; Ben-Avraham et al., 2008). **(b)** Gypsum. **(c)** Halite. **(d-m)** *in situ* seismites: (d-e) Linear waves (Lw); (f-g) Asymmetric billows (Ab); (h-i) Coherent vortices (Cv); (j-k) Micro-faults (Mf); (l-m) Intraclast breccias (Ib). **(n-o)** Background deposits; aad, alternating laminae of aragonite and detritus; cps, count per second.

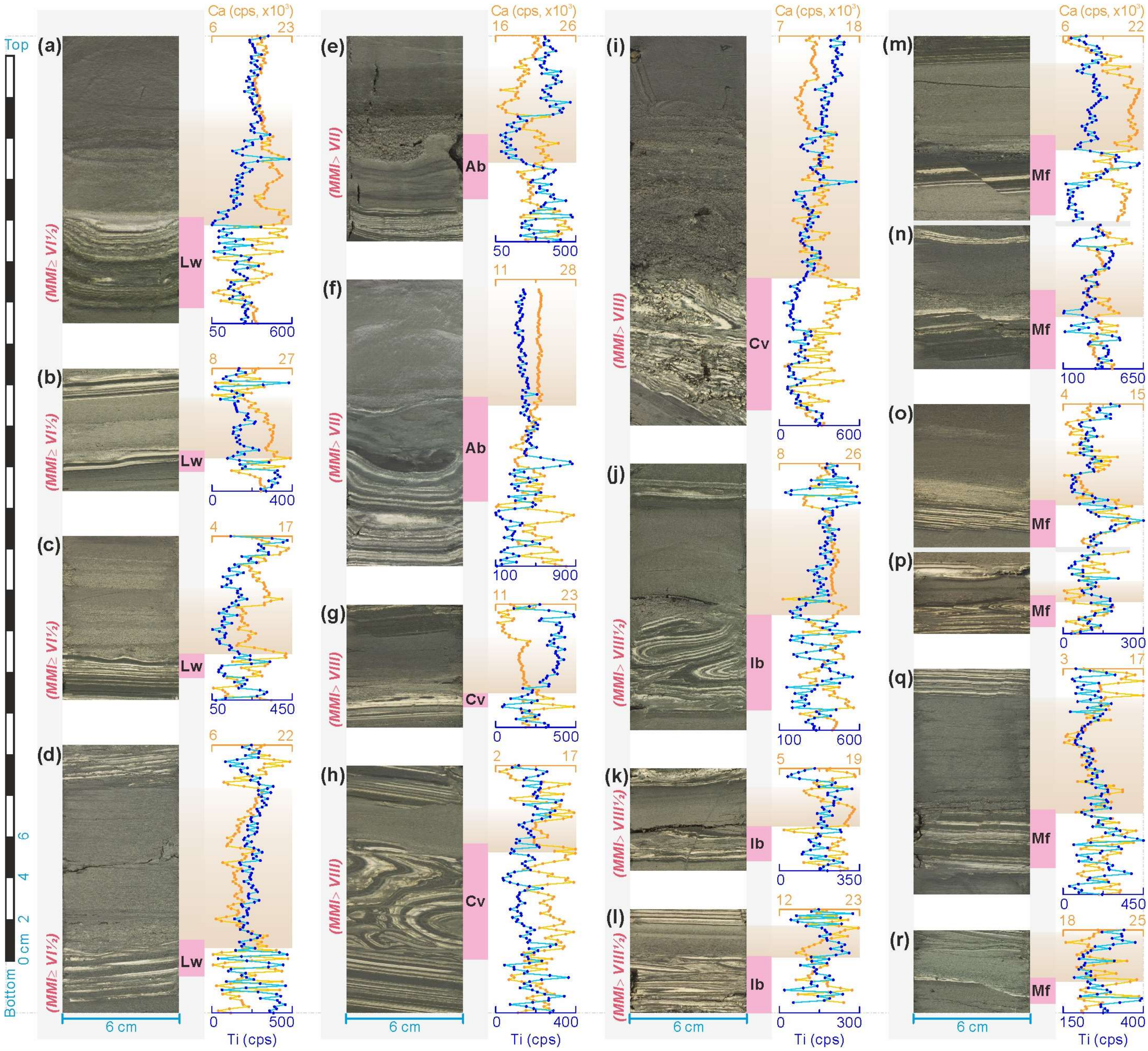


**Fig. 2. XRF data characterizing Type I turbidites from the Dead Sea center. (a-l)** Turbidites (brown color) overlie *in situ* soft-sediment deformations (pink color). **(m-r)** Turbidites overlying micro-faults.

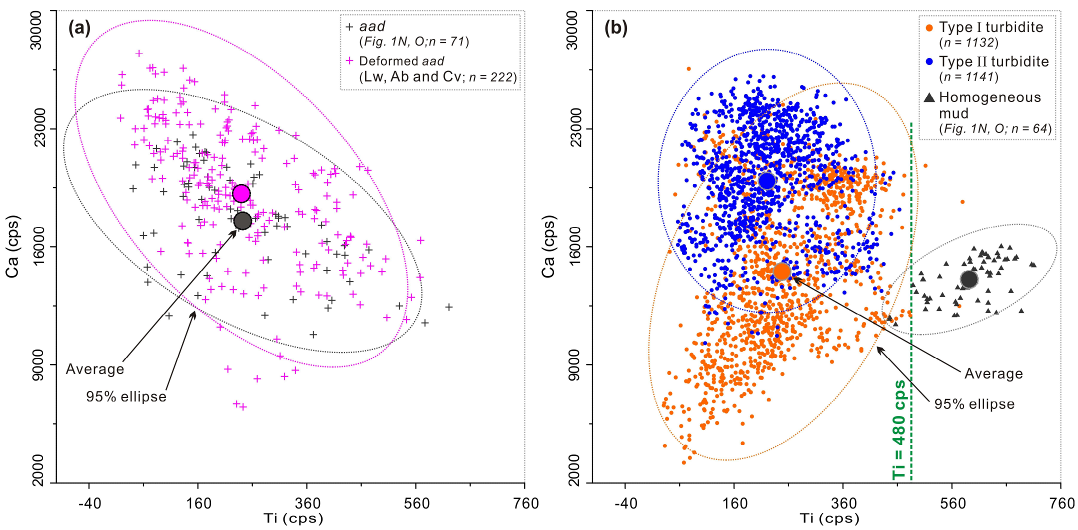


**Fig. 3. Scatter plots of Ca and Ti for different types of sediments.**

**(a)** Relatively similar clusters of aad and deformed aad (i.e., Lw, Ab, and Cv); **(b)** Type I turbidites, Type II turbidites, and homogeneous mud (generated by flash floods) from the Dead Sea center group in distinct clusters. The aad and homogeneous mud are background deposits.

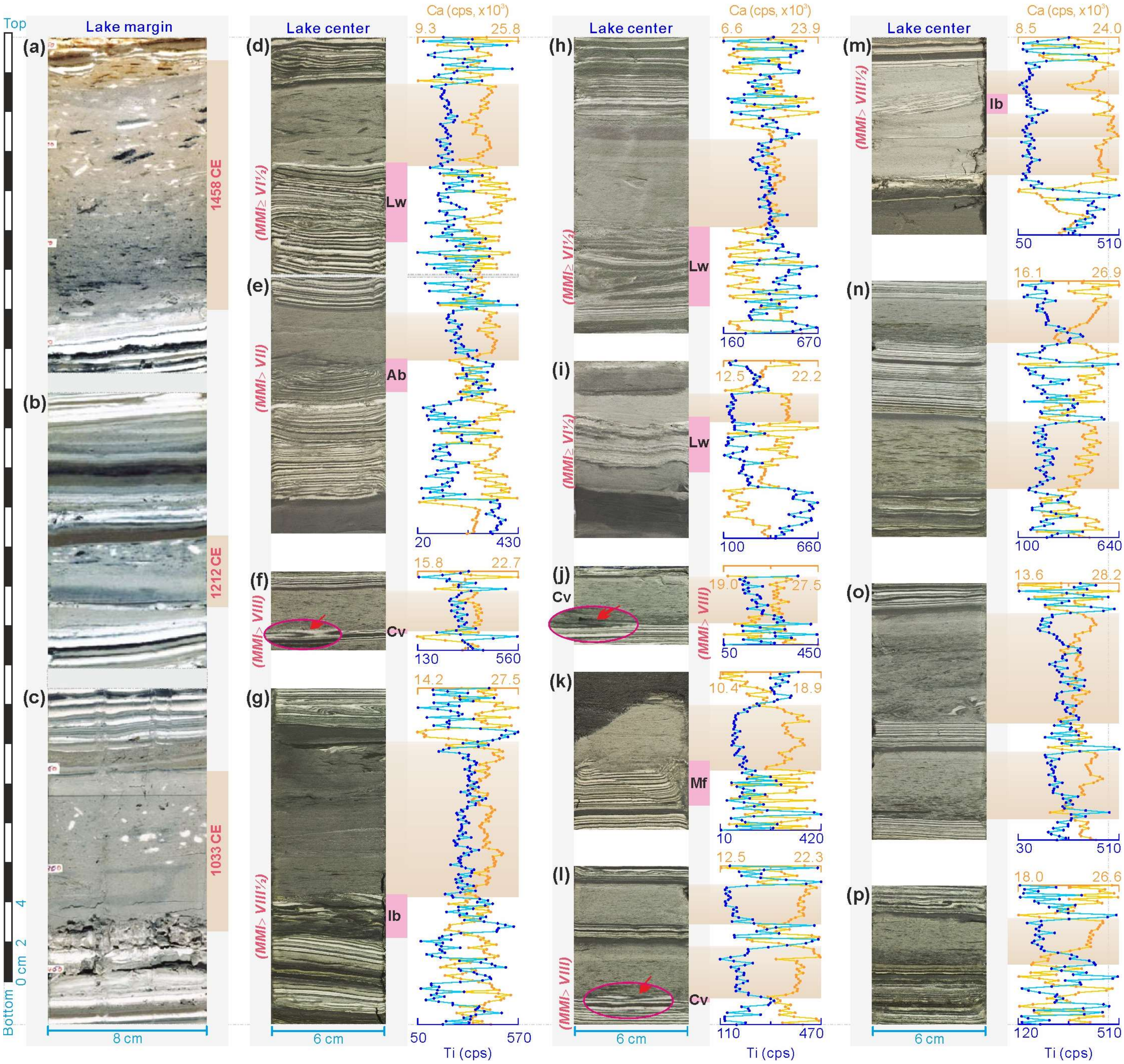


**Fig. 4. XRF data characterizing Type II turbidites (the laminae fragments-embedded detritus layers) from the lake center (Core 5017-1). (a-c)** The layers from the lake margin (Ein Gedi core) that correlate with historic earthquakes (Migowski et al., 2004; Agnon et al., 2006) are used for comparison. **(d-k)** The layers from the lake center (brown color) are overlying *in situ* seismites. **(l-p)** The layers from the lake center without underlying *in situ* seismites. The red arrows indicate the remaining parts of Cv; the magenta circles are magnifying glasses (x2.5).

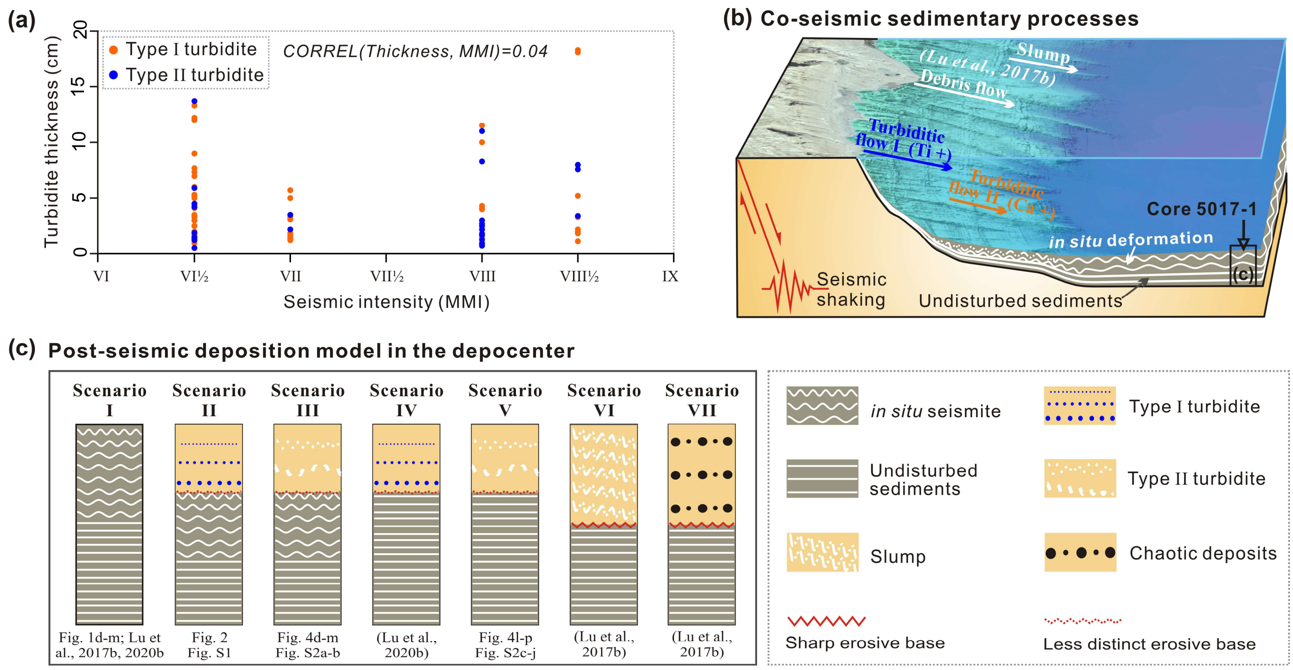


**Fig. 5. Seismogenic sedimentary processes and deposition models in the Dead Sea. (a)** Random relationship between the thickness of prehistoric turbidites and seismic intensity. **(b)** Schematic model showing co-seismic sedimentary processes in the lake. **(c)** Earthquake-related deposition models in the lake depocenter. See the text for a detailed interpretation.

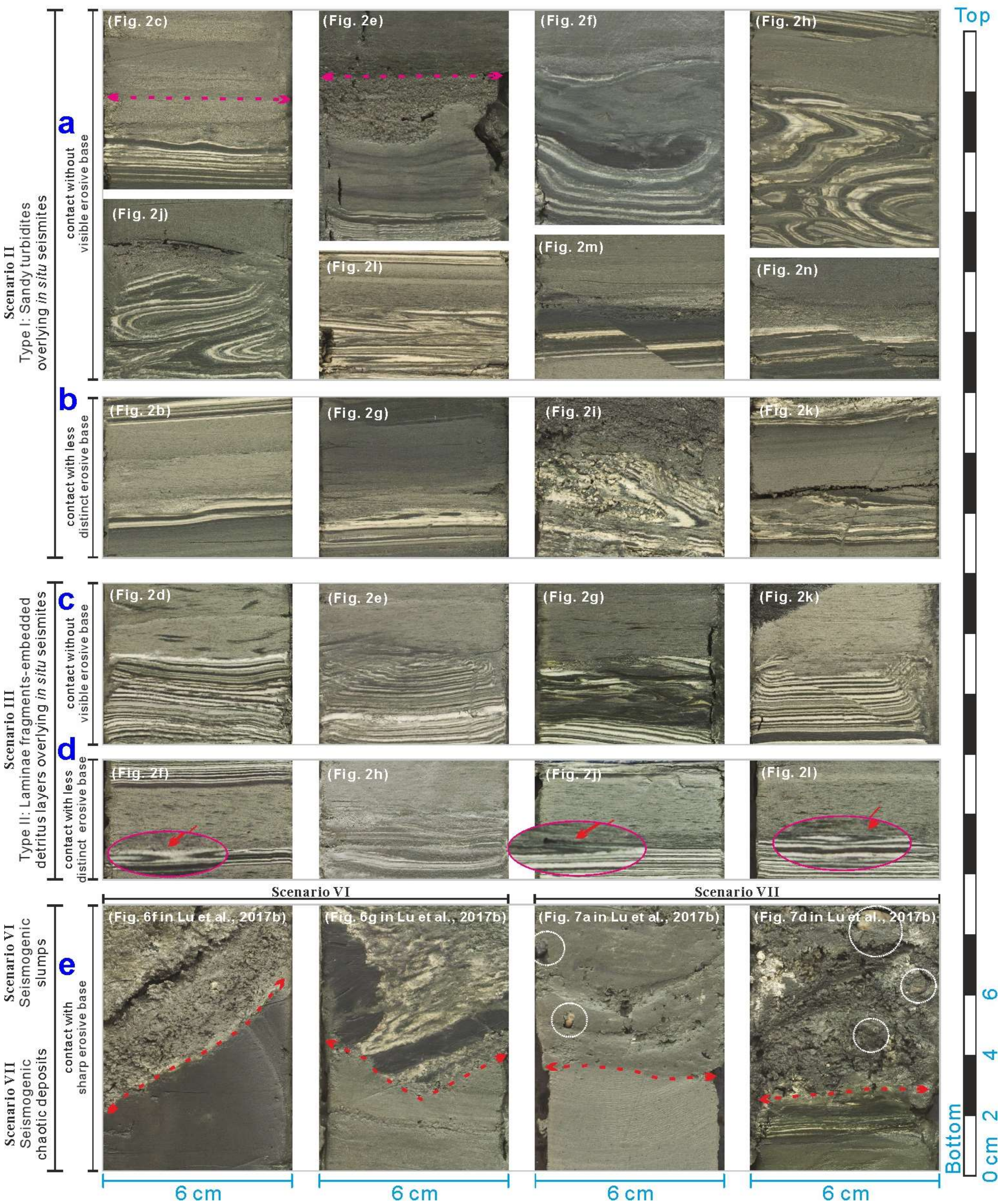


**Fig. 6.** High-resolution core images show the contact between turbidites and *in situ* seismites, with erosive base of seismogenic slumps and chaotic deposits from the Dead Sea center (Core 5017-1).

**3. More details can be found at (Open Access):**

***Lu et al., 2021a Feb., GRL:*** https://doi.org/10.1029/2020GL090947

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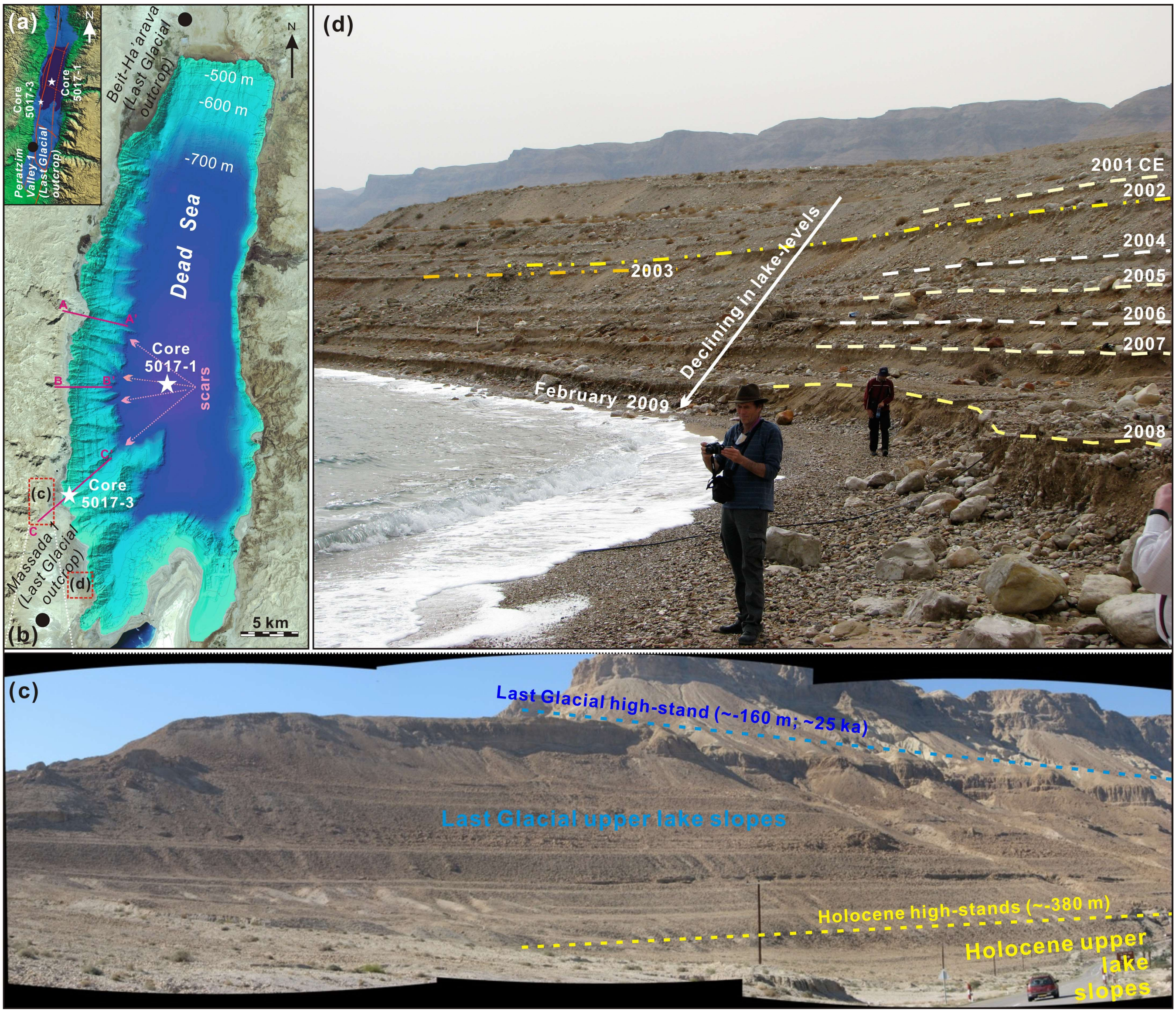
# Large-amplitude changes in water-levels facilitate earthquake-triggered mass failures in the Dead Sea Basin




A recent study investigated seismogenic mass failures that were preserved in a 457-m deep ICDP drilling (220-0 ka) from the Dead Sea depocenter. The study conducted a critical assessment and testing of the links between the occurrence of seismogenic mass failure, changes in water-level, and sedimentation rate driven by a changing climate.

**1. Key Points:**

- *At the orbital- and millennial-scale, variable sedimentation rates are not a preconditioning factor for earthquake-triggered mass failures*
- *At the centennial- to decadal-scale, earthquake-triggered mass failures are not statistically correlated with lake-level state*
- *At the orbital- and millennial-scale, the mass failures are more frequent during lake-level high-stands with large-amplitude fluctuations*

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## Orbital- and Millennial-Scale Changes in Lake-Levels Facilitate Earthquake-Triggered Mass Failures in the Dead Sea Basin

Yin Lu[1,2], Jasper Moernaut[1], Nicolas Waldmann[3], Revital Bookman[3], G. Ian Alsop[4], Aurélia Hubert-Ferrari[2], Michael Strasser[1], Amotz Agnon[5], and Shmuel Marco[6]

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**2. Overview**

**Background and significance:**

The possible link between the occurrence of submarine mass failure and climate-driven factors is highly disputed. Some researchers demonstrate that lowering sea-level can promote mass failures, while others suggest the opposite. In contrast, some researchers have documented no clear correlation between mass failure occurrence and sea-level change as the ages of failure events appear to be random. They suggested that an accurately-dated record of subaqueous mass failure deposits from a specific setting with the same trigger is key to understanding the possible link.

In addition to the role of water-level, previous studies have suggested that sedimentation-driven overpressure on subaqueous slopes can also decrease slope stability and facilitate mass failures, but rapid sedimentation alone cannot facilitate mass failures.

To address the contrasting viewpoints and interpretations noted above regarding the role of climate in driving mass failure frequency, we present a record from the Dead Sea depocenter that spans the last 220 kyr and comprises 490 earthquake-triggered (seismogenic) mass failure events. This case study provides a unique opportunity to shed new light on the debate by distinguishing and separating trigger and preconditioning factors.

**Observations and interpretations:**

(1) Seismites in the Dead Sea comprise two categories: one group results from *in situ* co-seismic sedimentary effects (*in situ* seismites: folded layers, intraclast breccia layers, and micro-faults) (*Marco and Agnon, 1995; Ken-Tor et al., 2001; Wetzler et al., 2010; Lu et al., 2017 JGR, 2020 Sci. Adv.*), and the other group forms by secondary seismogenic sedimentary effects, i.e. seismogenic mass failure deposits (*Lu et al., 2017 JGR, 2021a Feb. GRL*).

(2) We subdivide seismogenic mass failure deposits in the Dead Sea into four basic types. (i) Type I: Seismogenic sandy turbidites (Figure 2a-b); (ii) Type II: Laminae fragments-imbedded detritus layers (Figure 2e-i); (iii) Type III: Slump deposits (Figure 2j); (iv) Type IV: Chaotic deposits (Figure 2k).

(3) At the orbital- and millennial-scale, the correlation coefficients between the probability density of events and sedimentation rates are ranging from-0.6 to -0.4, indicate the variable sedimentation rates are not a preconditioning factor for earthquake-triggered mass failures.

(4) At the centennial- to decadal-scale, earthquake-triggered mass failures are not statistically correlated with lake-level state. At the orbital- and millennial-scale, the mass failures are more frequent during lake-level high-stands with large-amplitude fluctuations.

**Figures:**

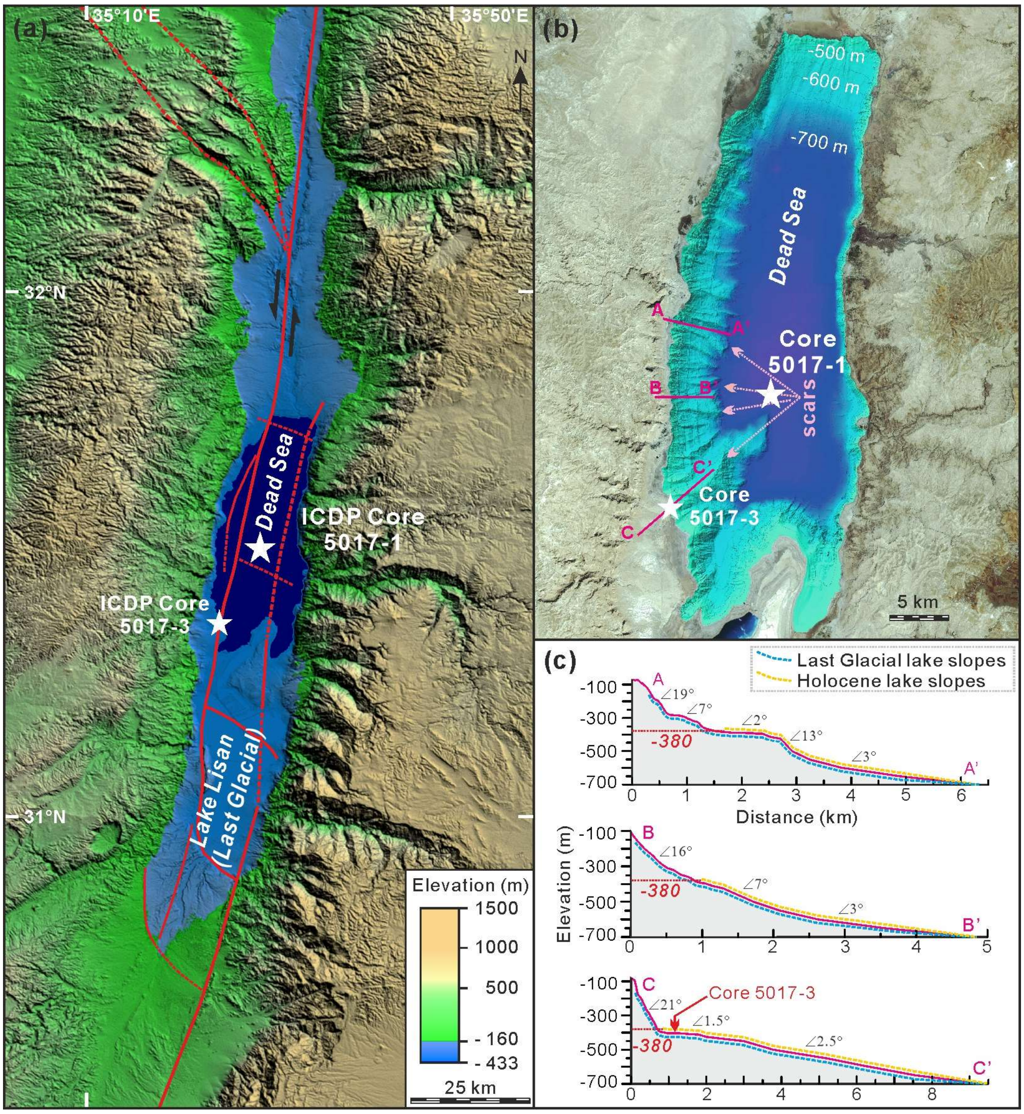



**Fig. 1.** Tectonic setting of the Dead Sea Basin and locations of ICDP drilling.

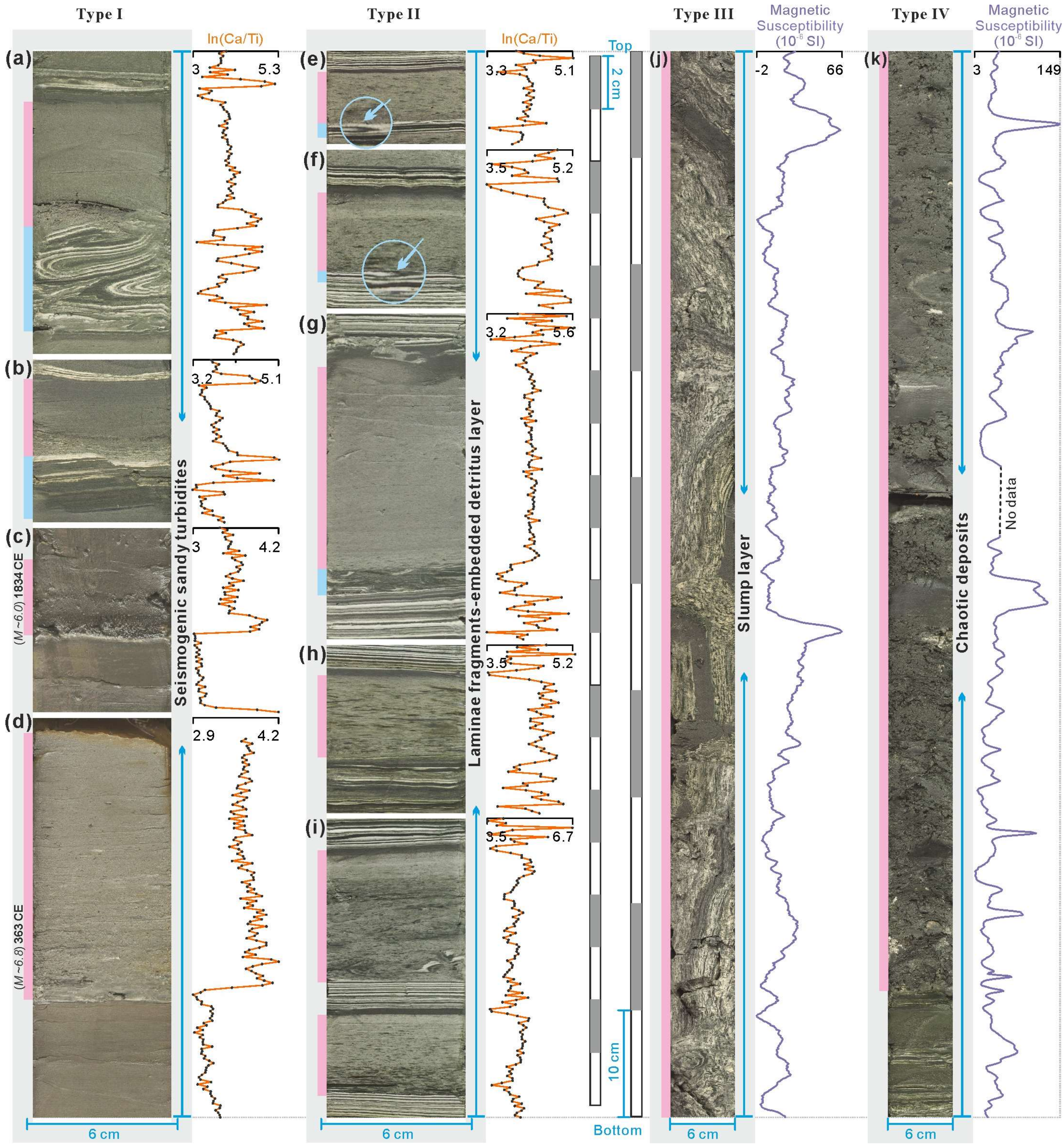



**Fig. 2.** Features of seismogenic mass failure deposits (events) in the Dead Sea center (core 5017-1).

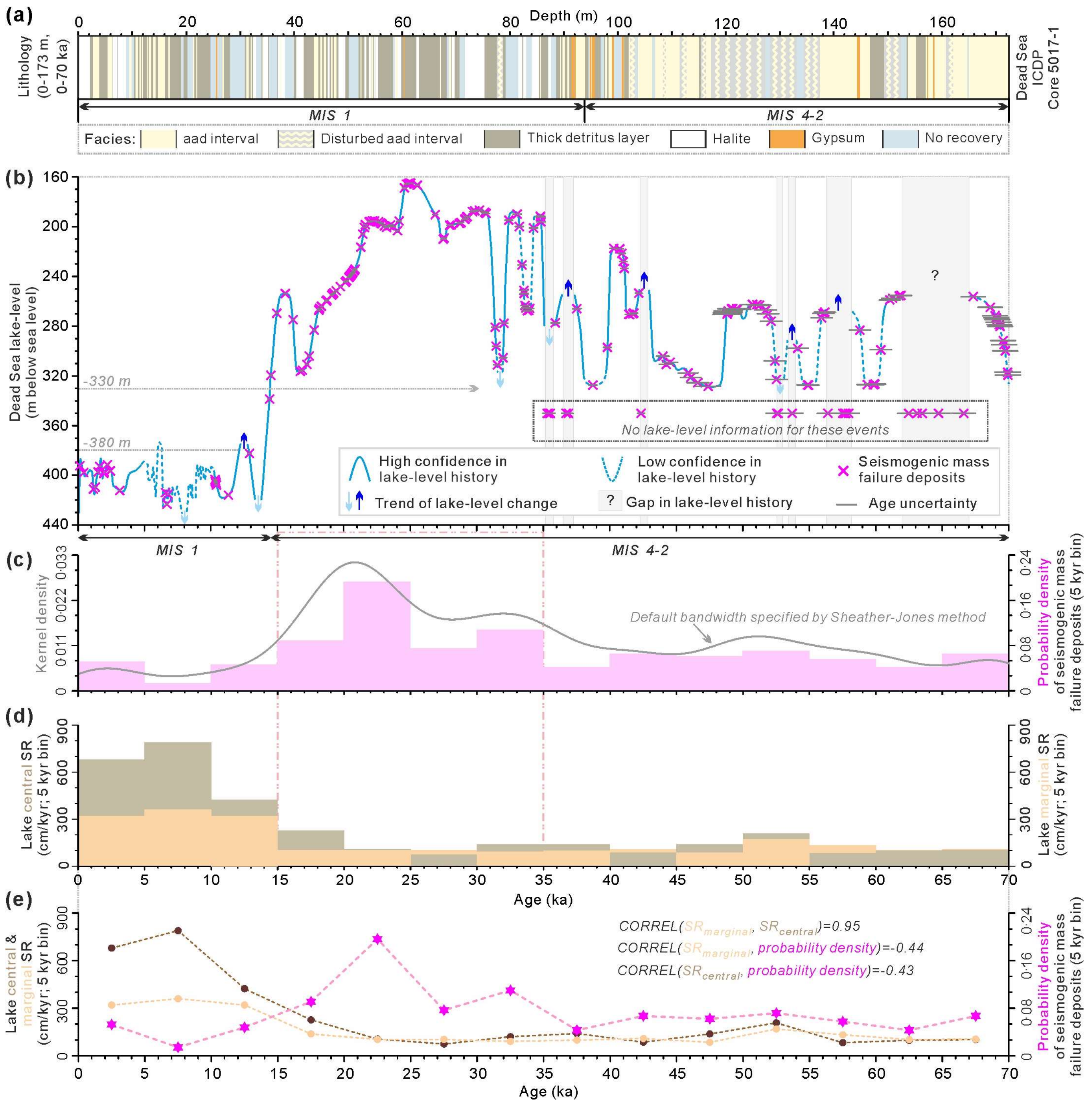



**Fig. 3.** Distribution of seismogenic mass failure deposits (events) in the Dead Sea center over the last 70 kyr, and the correlation between lake-level and sedimentation rate.

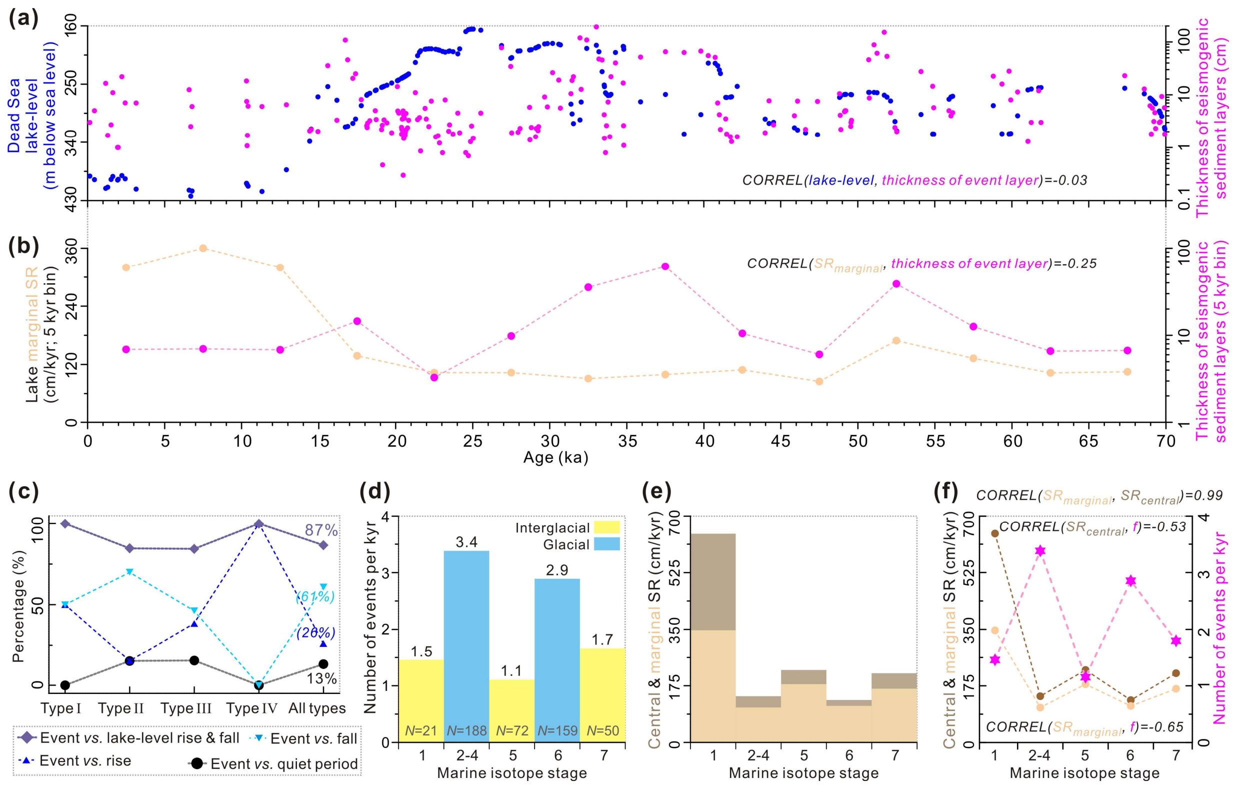



**Fig. 4. Occurrence of seismogenic mass failure deposits (events) in different lake-level statuses. (a-b)** Correlation between the thickness of event layers, lake-level, and sedimentation rate. **(c)** Percentage of events occurred at different lake-level states over the past 42 kyr (high confidence in lake-level history only). **(d)** Frequency of events over MIS 7-1 (220-0 ka). **(e)** Lake marginal and central SR over MIS 7-1. **(f)** Correlation between sedimentation rate and frequency of events over MIS 7-1.

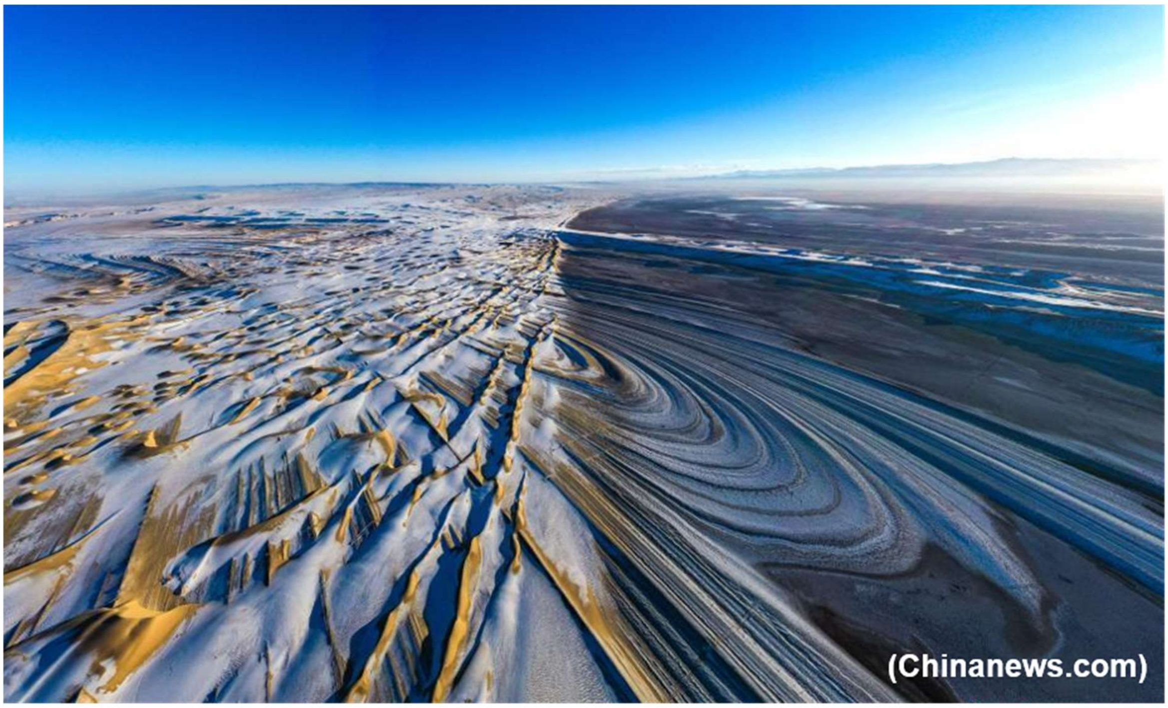
## 3. More details can be found at (Open Access):

***Lu et al., 2021c July, GRL:*** https://doi.org/10.1029/2021GL093391

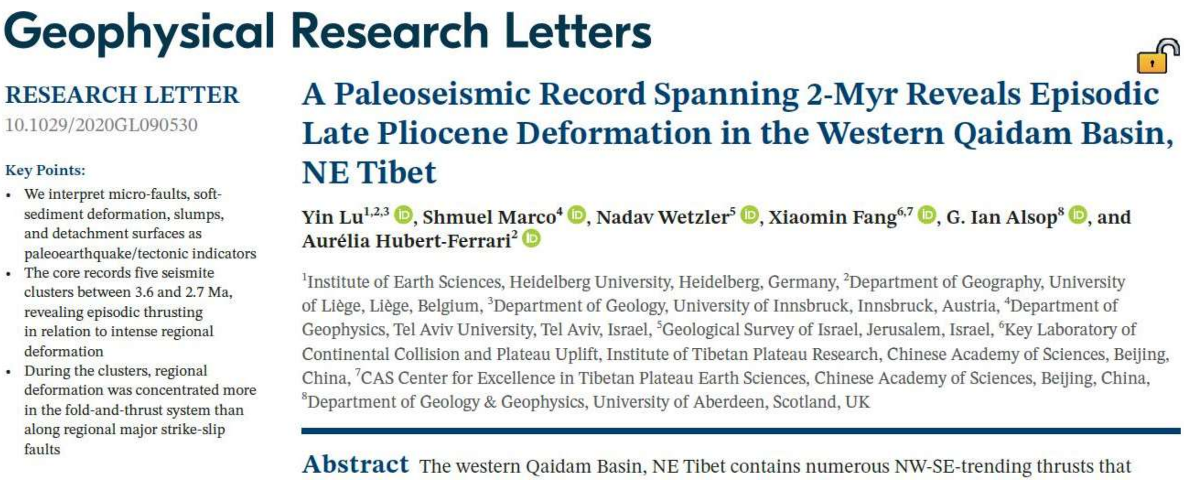
https://www.researchgate.net/profile/Yin_Lu22

https://yinlusite.wordpress.com/publications/

# Link seismic cycle to tectonic processes: A 2-Myr-long seismite record from NE Tibet




Anticline in the western Qaidam Basin, NE Tibet



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Key Points:

- We interpret micro-faults, soft-sediment deformation, slumps, and detachment surfaces as paleoearthquake/tectonic indicators
- The core records five seismite clusters between 3.6 and 2.7 Ma, revealing episodic thrusting in relation to intense regional deformation
- During the clusters, regional deformation was concentrated more in the fold-and-thrust system than along regional major strike-slip faults

A Paleoseismic Record Spanning 2-Myr Reveals Episodic Late Pliocene Deformation in the Western Qaidam Basin, NE Tibet

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Abstract The western Qaidam Basin, NE Tibet contains numerous NW-SE-trending thrusts that

## 1. Key Points:

- *We interpret micro-faults, soft-sediment deformation, slumps, and detachment surfaces as paleoearthquake/tectonic indicators*
- *The core records five seismite clusters between 3.6 and 2.7 Ma, revealing episodic thrusting in relation to intense regional deformation*
- *During the clusters, regional deformation was concentrated more in the fold-and-thrust system than along regional major strike-slip faults*

## 2. Overview

### Significance and background:

Folding, a type of distributed deformation in the brittle field that is widespread in thrust-and-fold belts and accretionary prisms, is an important mode of deformation that is largely overlooked in earthquake physics and crustal dynamics. The western Qaidam Basin, NE Tibet contains numerous NW-SE-trending thrusts that extend over a distance of ~300 km along the Altyn Tagh Fault and north of the Kunlun Range. These thrusts-folds are the most prominent morphological feature in the western Qaidam Basin, NE Tibet, and have played a key role in the Miocene-Quaternary uplift of the region. However, little is known about the long-term seismo-tectonic evolution of this active thrust zone due to the absence of an extended paleoseismic record. Our understanding of earthquake history is still limited by short seismological and historical records. A continuous lacustrine sedimentary sequence (~33-1.6 Ma) accumulated in the Qaidam paleolake which may have sequentially recorded the development and activities of the underlying folds and thrusts.

### Observations and interpretations:

We present a unique record of disturbance spanning 2-Myr based on a deep core drilled on the crest of one such fold in the western Qaidam Basin. The disturbances comprise micro-faults, soft-sediment deformation, slumps, and detachment surfaces. We interpret the four types of disturbance as paleoearthquake/tectonic indicators. The core records five seismite clusters which occurred at 3.6-3.5 Ma, 3.4-3.2 Ma, 3.15-3.1 Ma, 3.0-2.9 Ma, and 2.8-2.75 Ma. This suggests the rate of tectonic strain accommodated by the folds and thrusts in the region varies and thus reveals episodic local deformation. During the clusters, regional deformation is concentrated more in the fold-and-thrust system than along regional major strike-slip faults.

### Figures:

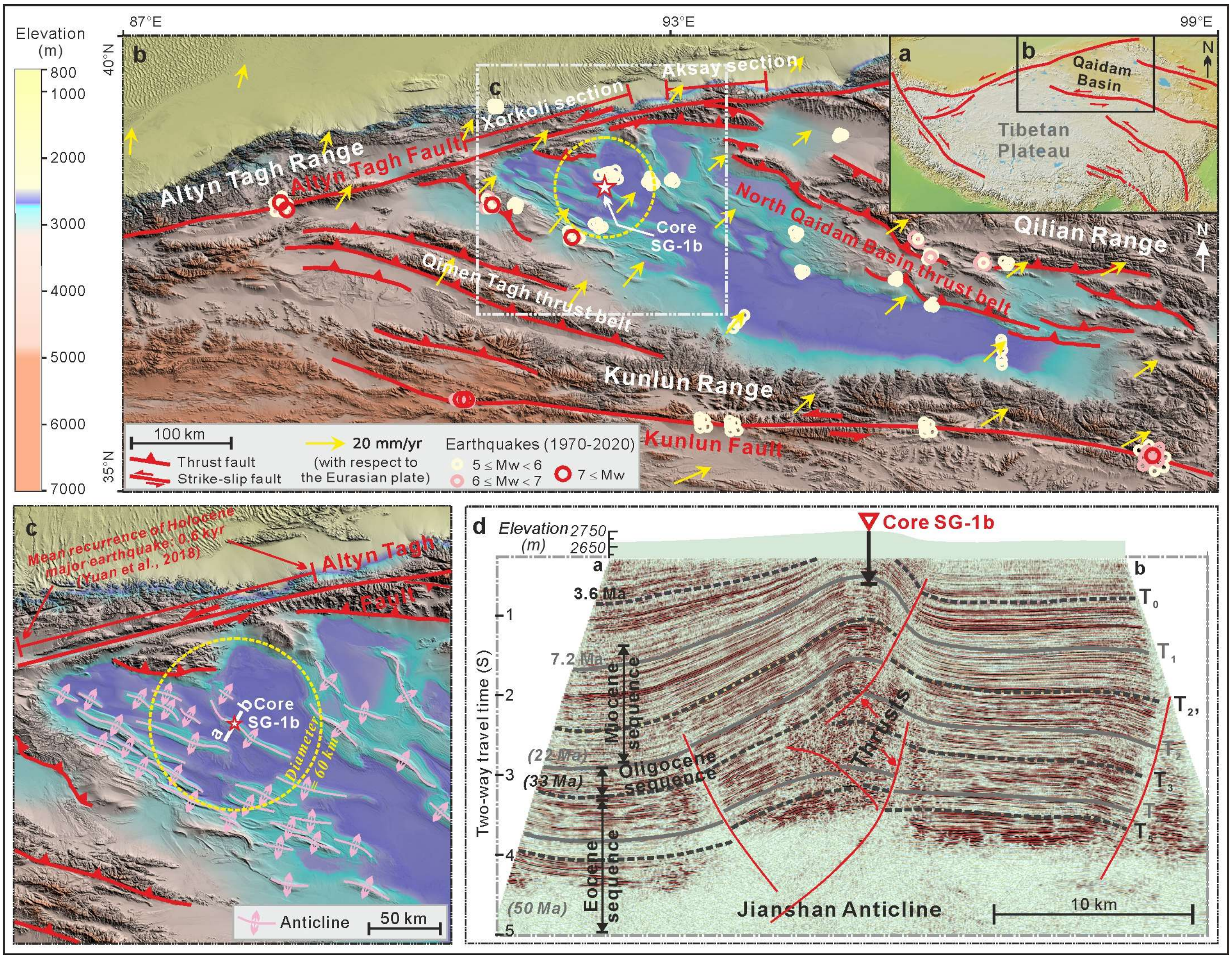

**Fig. 1. Geological setting of the study area. (a)** Location of Qaidam Basin and major faults on the Tibetan Plateau. **(b)** Active faults and GPS velocity in the region; circles represent earthquakes during the years 1970-2020 (http://ds.iris.edu/ds/). **(c)** Anticlines surrounding Core SG-1b. **(d)** Seismic profile (line a-b in Fig. 1c) across the Jianshan Anticline.

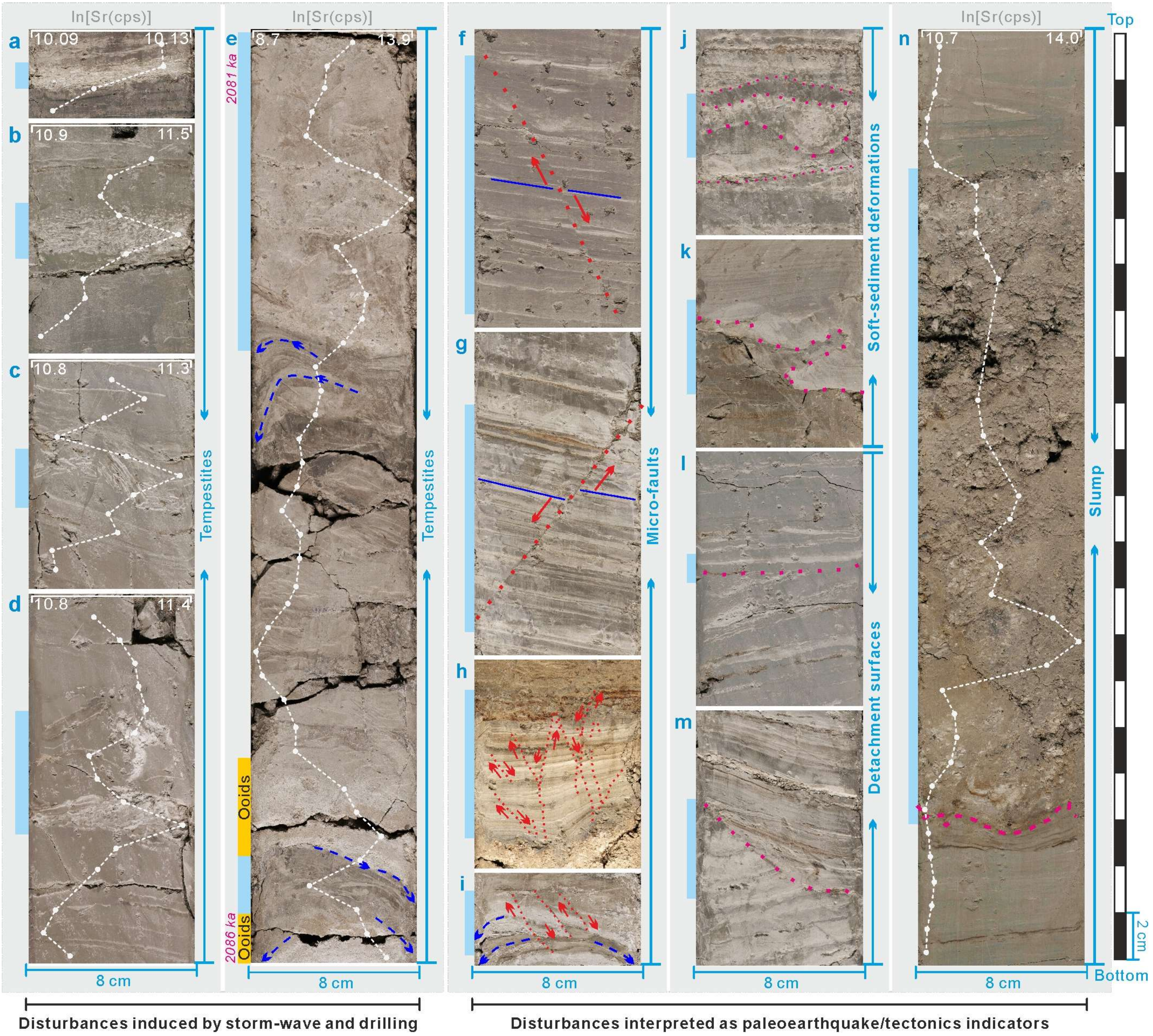


**Fig. 2. The various types of disturbances in Core SG-1b. The light blue bars indicate the position of events; the white dashed lines and points represent XRF data. (a-e)** Disturbances induced by storm-waves and drilling. Note the blue dashed lines in (e) and (i) indicate artificial disturbances (deformation). (f-n) Disturbances are interpreted as paleoearthquake/tectonic indicators. **(f-g)** Normal faults; the blue lines indicate the correlated marker layers. **(h-i)** Fault-graded beds; the red dashed lines indicate the positions of the slip plane, while the red arrows indicate slip directions. **(j-k)** Soft-sediment deformations. **(l-m)** Detachment surfaces. **(n)** Slump layer; the pink dashed line indicates the erosive base.

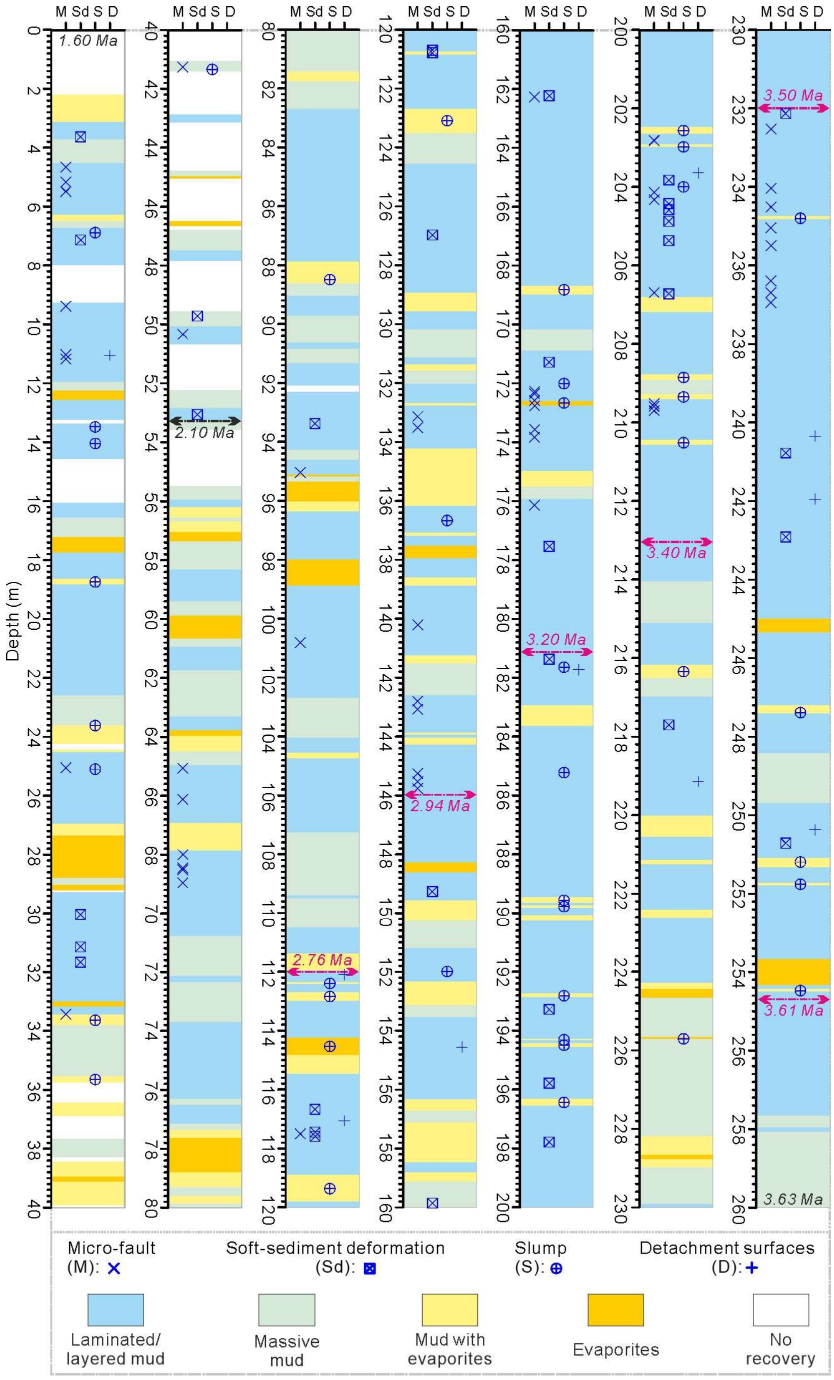


**Fig. 3. Distribution of Type III-VI disturbances in 260-0 m of Core SG-1b (3.6-1.6 Ma).** Micro-faults, soft-sediment deformation, and detachment surfaces have mainly occurred within the core intervals of laminations and layered mud. The coring rate in the upper 56 m is relatively low (~70%).

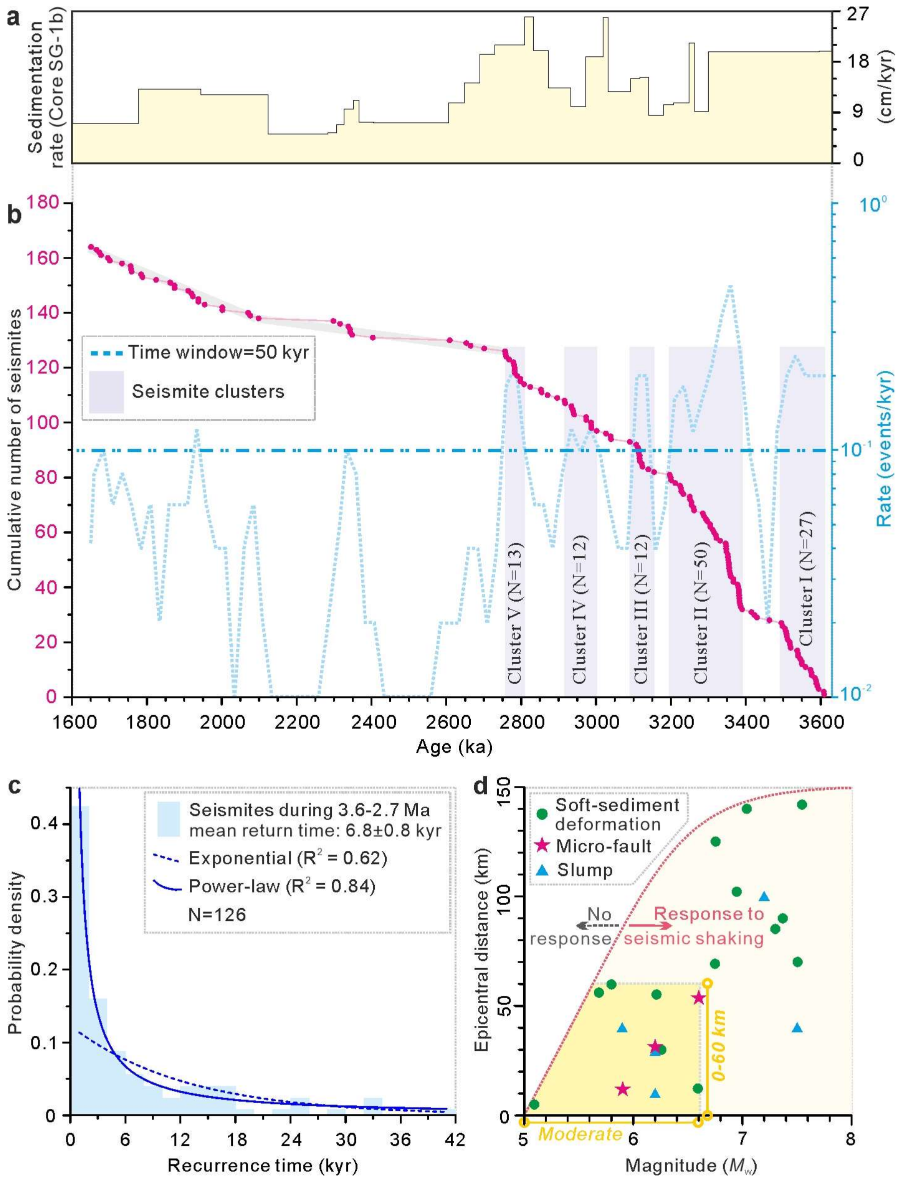


**Fig. 4. Distribution of seismites during 3.6-1.6 Ma. (a)** Sedimentation rate during 3.6-1.6 Ma. **(b)** Cumulative (red dots) and seismites rate (light blue) over the time interval of the seismite record. **(c)** Histograms for recurrence times of events during 3.6-2.7 Ma. Exponential and power-law distributions are plotted for comparison. **(d)** Instrumental and historical earthquake magnitude v.s. epicentral distance plot based on literature to show thresholds for micro-faults (Monecke et al., 2004; Avşar et al., 2016), soft-sediment deformation (Sims, 1973; Agnon et al., 2006; Moernaut et al., 2014; Avşar et al., 2016) and slumps (Piper et al., 1988; Shilts and Clague, 1992; Schnellmann et al., 2002; Becker et al., 2005; Wilhelm et al., 2016) in subaqueous environments in different regions. The yellow-colored area highlights the seismic effects of moderate earthquakes with epicentral distance ≤ 60 km.

## 3. More details can be found at (Open Access):

***Lu et al., 2021b March, GRL:*** https://doi.org/10.1029/2020GL090530

https://www.researchgate.net/profile/Yin_Lu22

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