Fault creep and salt ductility: analysis of borehole station data for the 2018 earthquake swarm in the Kinneret pull-apart basin

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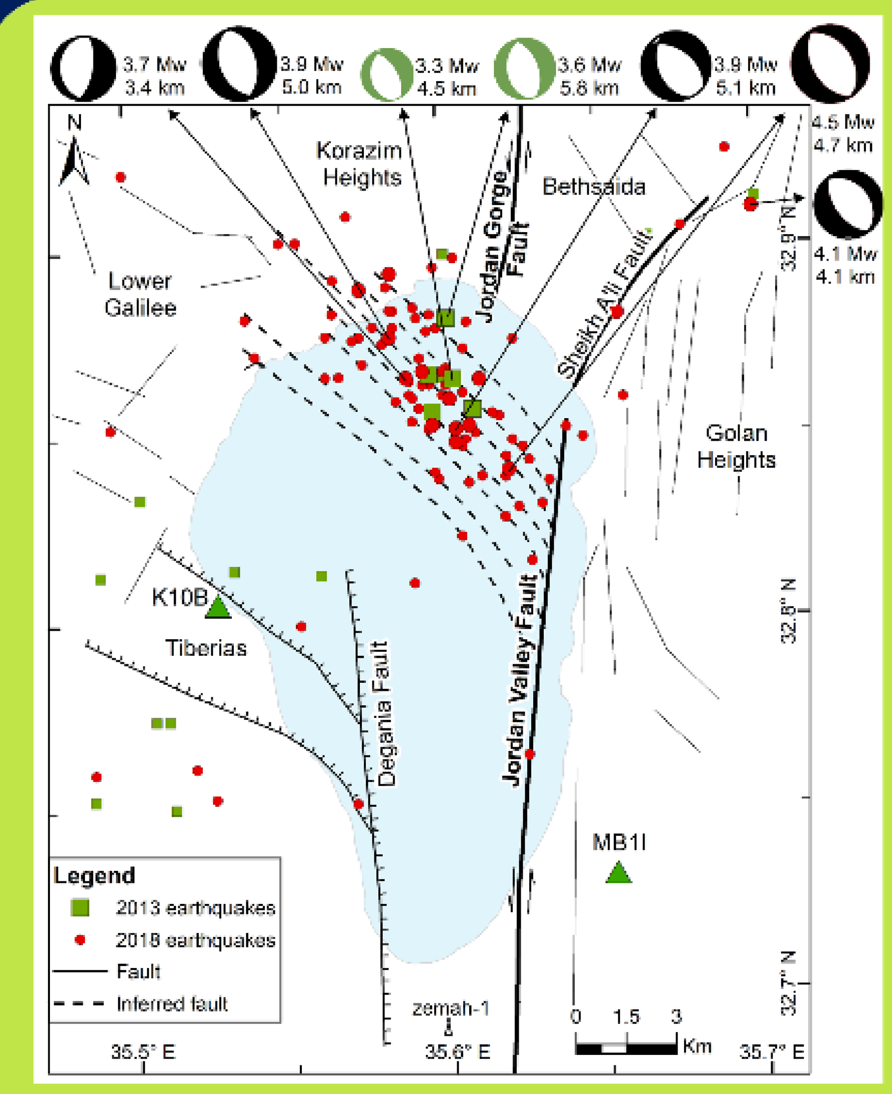
1 INTRODUCTION

Kinneret Basin is the northern part of the Kinnerot basin, a pull-apart on the Dead Sea Transform; the depocenter Lake Kinneret is formed by the left step-over between Jordan Valley Fault (JVF) and Jordan Gorge Fault (JGF) [fig. 1]. Lateral creep at 2.5±0.8 mm/year from the surface down to a depth of 1.5±1.0 km, extending ~40 km along JVF (south of Kinneret) was inferred from GPS data (Hamiel et al., 2016; Hamiel & Piatibratova, 2021). Since the establishment of the Israel Seismic Network (ISN) [Fig. 2] in 1983, an average of <10 earthquakes per year have been recorded from the area; however, recently the area made headlines following several earthquakes that were felt across the country. The noticeable activity started with ~60 earthquakes in October 2013 and continued with ~660 earthquakes in July-August 2018.

2 METHODS

We use unpublished data from two near-source seismographs in boreholes – K10B at a depth of 535 m and MB1I at 520 m [Fig. 2]. The magnitudes are calculated using the epicentral distances and the coda duration from empirical relations (Shapira, 1988). Values are calibrated using ISN moment magnitudes (Mw). For the earthquakes recorded at ISN stations, we combine the data to get locations. We also use cross-correlation coefficients for identifying earthquakes that came from the same location (e.g., Malin et al., 2018).



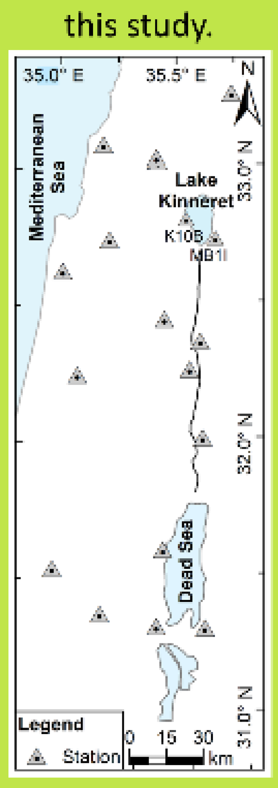


Figure 2: ISN and Jordan Seismological Observatory stations used for this study.

Figure 1: Fault map of Lake Kinneret and surrounding area (adopted from Hurwitz et al., 2002; Reznikov et al., 2004; Sneh, 2008b, 2008a; Sneh and Weinberger, 2014). K10B and MB1I borehole stations are shown. Relocated epicenters are marked by green squares (2013) and red circles (2018). Focal mechanisms are projected to lower hemisphere (with Mw, and depth). The horsetail faults we postulate are marked by dashed black lines (Barnea Cohen, submitted).

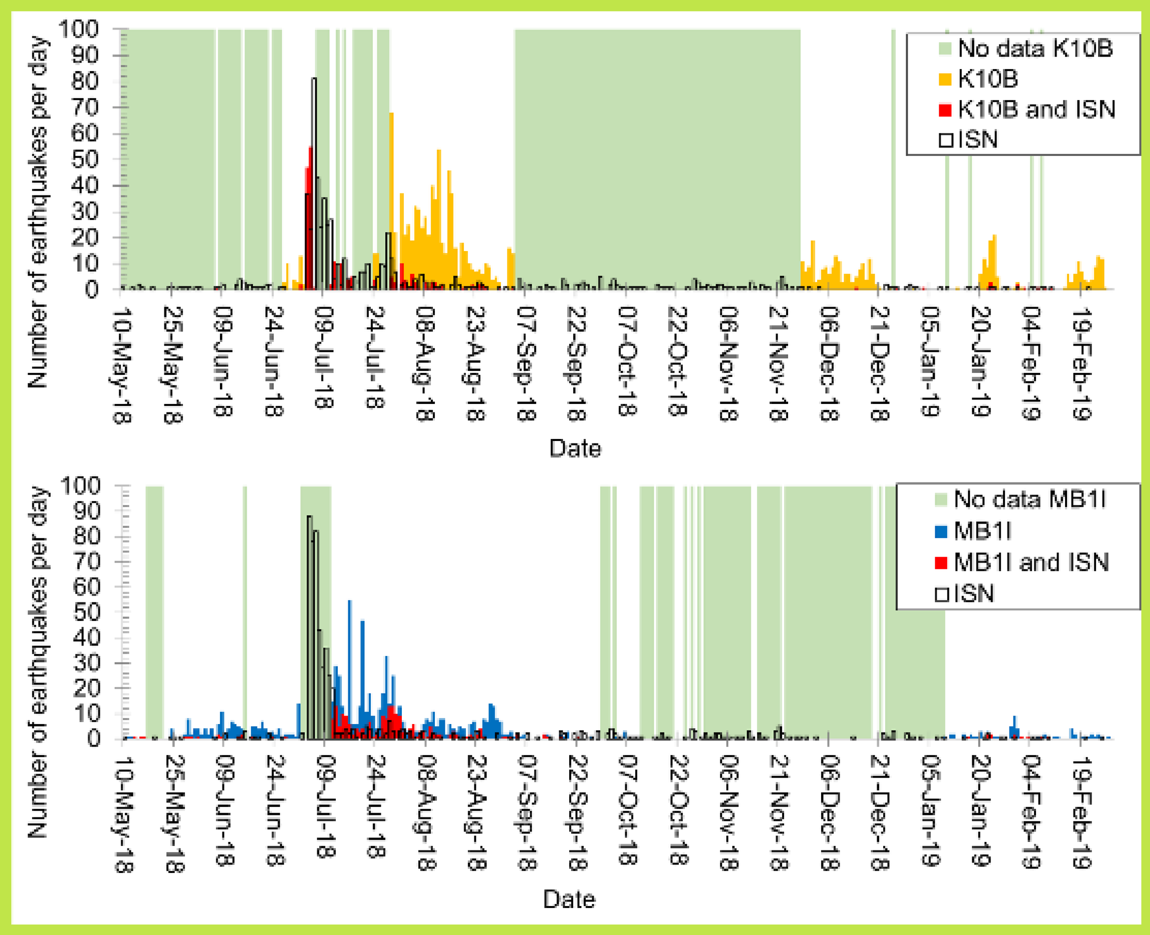


Figure 3: Comparison between the number of earthquakes recorded by the ISN and (up) - K10B, (down) - MB1I.

3 RESULTS

- The earthquakes cluster in the northern reaches of the lake within a NW-SE belt, the majority at ≤6 km depth. Focal solutions of the larger events show normal mechanisms, striking parallel to the belt elongation [Fig. 1] (in agreement with Wetzler et al., 2019 and Barnea Cohen et al., submitted).
- More than a thousand earthquakes ruptured during May 2018 to February 20198 and were recorded by the borehole stations, while hundreds were recorded by the ISN [Fig. 3].
- The cluster is of a swarm type, as shown in Figure 4 , lacking a mainshock and exponential decay of rate or magnitude typical of aftershocks.
- Calculated cross-correlation coefficients (≥0.85) expose the prominent epicenteral locations : a cluster in the center of the northern third of the lake [Fig. 5].

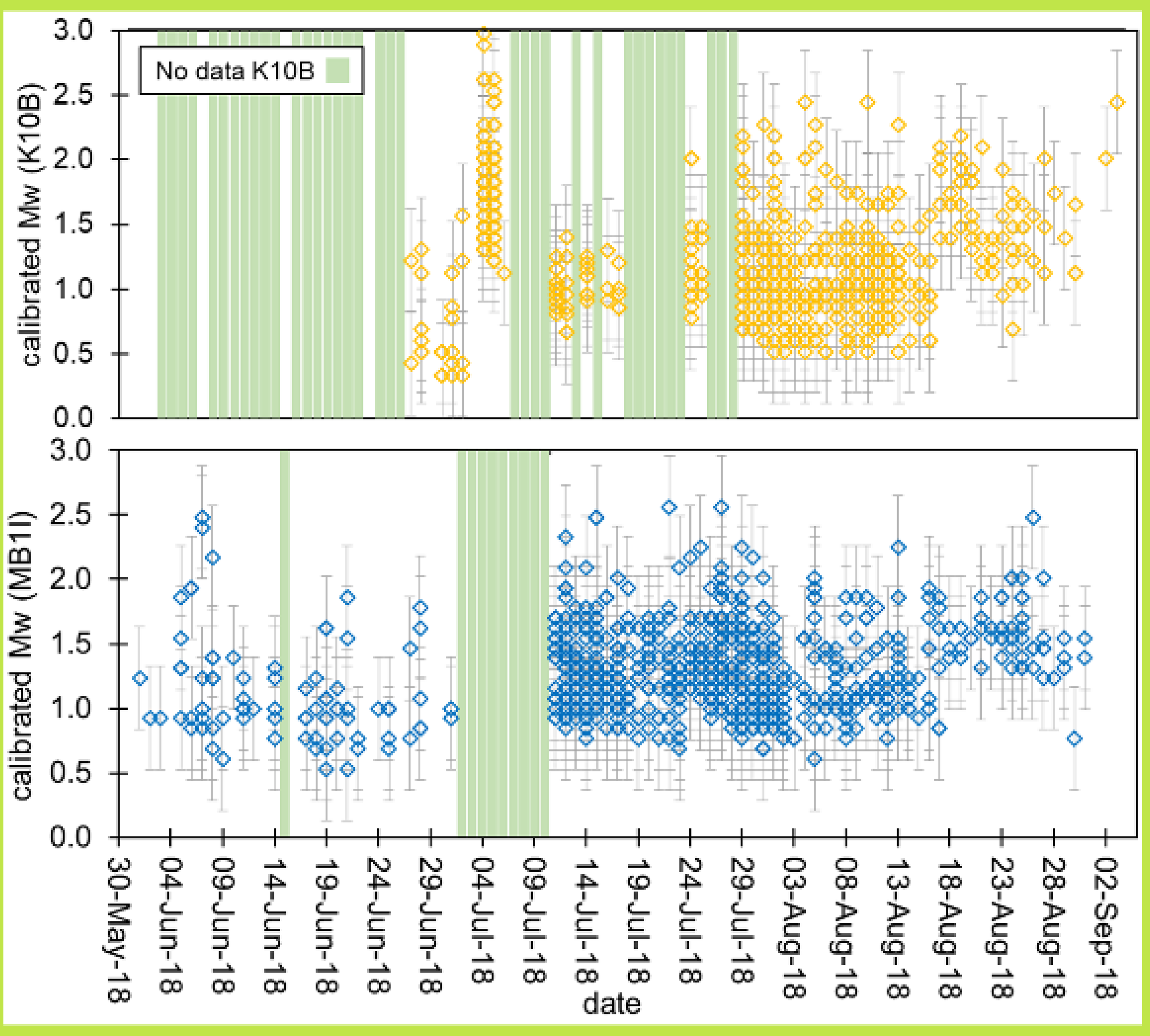
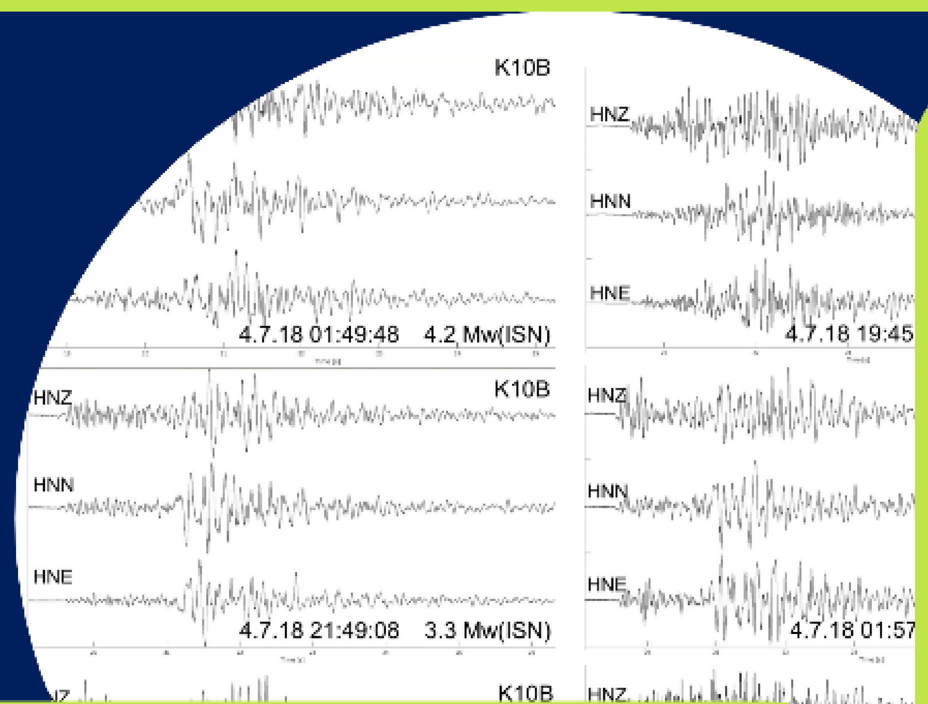


Figure 4: Calibrated magnitudes of borehole station earthquakes with temporal distribution. Up – K10B, down – MB1I.

4 DISCUSSION

This study continues our previous work (Barnea Cohen et al., submitted), adding pieces to the puzzle. According to the hypothesis, energy accumulates from the encounter of shallow creep on JVF (east and south of the lake) [Fig. 1] with the locked JGF (north of the lake) inducing earthquake swarms from time to time. A recent gravity model (Rosenthal et al., 2019) infers that an evaporitic unit, the Messinian salt formation, penetrated by Zemah-1 borehole [Fig. 5], underlies the entire Kinnerot Basin, at a few kilometers depth. The salt formation is likely ductile, especially given the high thermal gradients (e.g., Shalev et al., 2013). We suggest that the earthquakes ruptured horsetail splays at the tip of JVF [Fig. 1]. Lineaments in the short-wave gravity anomaly map [Fig. 5] support the horsetail hypothesis. Most earthquakes lie in the least stable zone of the salt. A source of instability might be heating (Shalev et al., 2013) by a deep buried basalt flow at that region [Fig. 5 – grey polygon] (Ginzburg and Ben-Avraham, 1986), contributing to salt ductility. According to the multibeam bathymetric map (Sade et al., 2009), gravity data (Ben-Avraham et al., 1996), and seismic interpretations (Hurwitz et al., 2002; Reznikov et al., 2004), a deep zone of high subsidence is found in the northern part of the lake. We suggest, as implied by Hurwitz et al. (2002), that this is the active depocenter which migrated northward, perhaps with the growth of the basin.



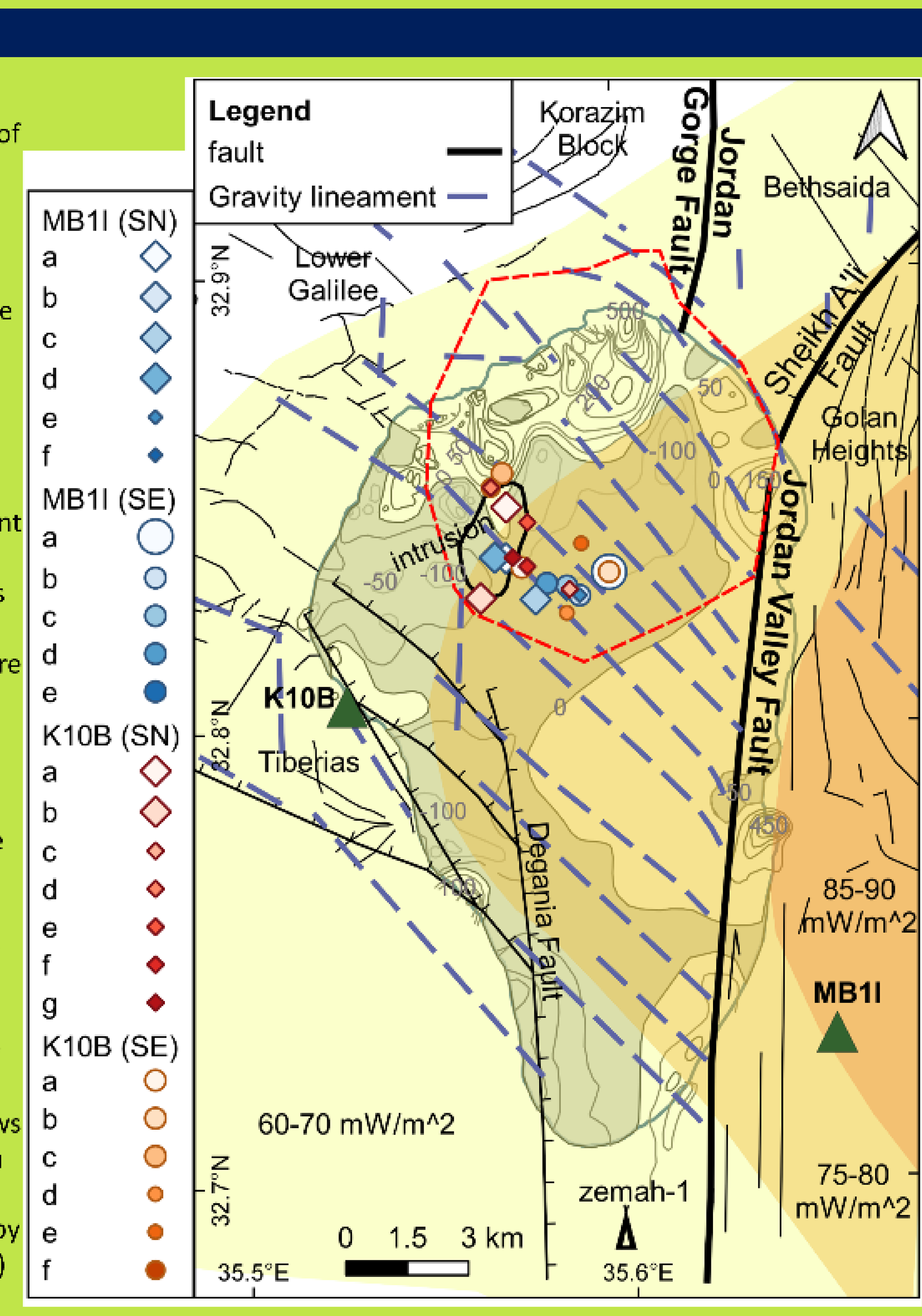


Figure 5: Location map of the majority of 2018 earthquakes, filtered according to cross-correlation coefficients (≥0.85). The results shown are of the shear components (SN, SE) of the two stations. Groups a-f comprise ≥5 events per group, larger symbols present groups of ≥10. Also shown inferred faults based on lineaments from the dip curvature residual gravity anomaly map by Rosenthal et al. (2019). Magnetic anomalies in the lake from Ginzburg and Ben-Avraham (1986) study; grey polygon - negative values. Thermal gradients adopted from Shalev et al. (2013). Red dashed polygon shows the 2018 cluster area according to ISN. An intrusion suggested by Reznikov et al. (2004) is shown by a black polygon.

5 CONCLUSIONS

The ductile behavior of the Messinian salt formation, underlying Kinnerot basin, promotes creep on JVF. The encounter of the creeping fault with the locked JGF leads to elastic energy accumulation. The energy is released from time to time by swarms on shallow horsetail faults at the tip of JVF. The majority of earthquakes ruptured the center of the northern third of the lake. We infer extensional structures beneath the entire basin. Seismic activity in extensional zones is typically intermittent, migrating across a zone. The localization of recent activity to the northern third of the lake might be related to the current location of the step-over, coinciding with the current depocenter.

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