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Reply on RC1

Mariana Belferman et al.

Author comment on "Identifying plausible historical scenarios for coupled lake level and seismicity rate changes: the case for the Dead Sea during the last 2 millennia" by Mariana Belferman et al., Nat. Hazards Earth Syst. Sci. Discuss.,
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With gratitude for the reviewer's interest in our article, we draw attention to a few points regarding his comments:

Comment 1:

- According to the reviewer, the correlation between water level and seismic activity at the Dead Sea Basin is insignificant (our Fig.1).

Response:

Our earlier work demonstrated a correlation between water level and the recurrence interval of Dead Sea earthquakes (Belferman et al., 2018, Fig. 9). The present study (Figure 2 and corresponding text – pp. 13, lines 236-237 and Eq.7) indicates that the correlation between seismicity and water level change might even be higher than that demonstrated in Belferman et al., 2018 (Fig. 9). We explain that significant uncertainties in the water level data-set might hide the correlation (please see pp.3 50-71).

- Seismicity occurs equally at high and low levels (the reviewer refers us to Fig. 1 c and d)

Response:

Our model does not preclude seismic activity during water level drops, it just takes longer for the loading to reach the increased threshold. We even predict the next future earthquake, when levels are projected to reach an unprecedented low. The reviewer writes about the correlation between the water level and seismic activity; please note - Fig.2c,d shows that the change in level inversely correlates with the recurrence interval of earthquakes, rather than with "seismic activity". In the submitted paper the linear correlation is clearly visible in the figures, especially in figure 1c. The Pearson correlation coefficient reported in detail should make this point clear.

- According to the reviewer, all change in seismic activity is due to changes in the tectonic loading and the state of the solid crust. By his assessment, the water level change has a minor effect.

Response:

Tectonic motion is the primary cause and consequence of earthquakes in our model as well, but it is worth considering other factors triggering earthquakes. We refer the reviewer to our Introduction section: water level induced seismicity in particular, and anthropogenically induced seismicity in general, are broadly recognized phenomena over the world.

The seismic response has been observed to be connected to reservoir impoundments and their seasonal water level variations (Gupta, 1992; Talwani, 1997; Tomic et al., 2009; Hua et al., 2013).

Davies et al. (2013) compiled 198 examples of anthropogenically induced seismicity since 1929 all over the world, where higher magnitude earthquakes within this list (up to 7.9, in Zipingpu reservoir area, China 2006) are most often associated with reservoir impoundment. Foulger et al. (2018) presented a comprehensive and up-to-date database of seismicity induced or potentially induced by anthropogenic sources.

van der Elst et al. 2016 show that the appearance of induced seismicity requires a reconsideration of seismic hazards, even in regions of formerly negligible seismic concern. Simpson et al. 2018 & Gupta 2018 indicate many statistical studies that reaffirm this correlation.

In our previous work (Belferman et al., 2018), we indicated that this phenomenon may even be more applicable to the historic lakes, like those occupying the tectonic depression of the Dead Sea, due to the larger scale of water level fluctuations. The post-diffusion stage (when pore pressure at all depth approaches the value at the lake bed), is relevant for early historical data. At this stage, an increase in pore pressure due to the water level rise always dominates over the loading effect, leading to varying but always negative normal effective horizontal stress change at any combination of poroelastic constants (please see Belferman et al., 2018 Fig. 5b). This should trigger earthquakes with magnitudes higher than those in the corresponding immediate undrained (rapid) response, coming shortly after the corresponding water level rise (confirmed, for instance, for Lake Mead, Gupta, 2002; Simpson et al., 1988; Monticello reservoir, Rajendran and Talwani, 1992, and others).

Comment 2:

- The reviewer doubts the assumption that the effective normal vertical stress vanishes, and argues that given a reasonable permeability, it will take millions of years. In particular, he argues that between seismic events, faults heal and the permeability of the faults is very low. He chose the Ein-Feshkha spring, very close to an exposed fault, to argue for a lack of hydraulic connection with the deep aquifers.

Response:

Some of the material characteristics in fault zones may vary significantly, depending on the types of host rock and on state variables (e.g. temperature, pore pressure, depth, etc.). Specifically, values of hydraulic diffusivity of intact rocks differ considerably among rock types (Rice and Cleary, 1976), and strongly decay with depth (e.g. by ~6 orders of

magnitude at a depth of 20 km compared to the shallow crustal values (Ingebritsen and Manning, 2010). However, such laboratory values are not determined under conditions approaching hydrofracture. Pore pressure diffusion in fault zones is usually dominated by fault damage zones, which act as conduits (Simpson et al., 1988). The reviewer mentions damage processes as a possible determinant of seismicity fluctuations. We totally agree and refer to Hamiel et al. (2005) where we simulated how, under damage accumulation, slender porous zones evolve and become faults. Recently, a poroelastic analysis by Jim Rice's group of a real case of induced seismicity considered a realistic damage/permeability structure with a fault core and anisotropic damage/permeability zones. They have shown that the permeable zones indeed propagate from shallow depths to the seismogenic zone with hydraulic fracture (Yehya et al., 2018). In fact, a useful illustration of a related phenomenon was given by Yechieli and Bein (2002), preceding the largest instrumental earthquake on the Dead Sea Transform - the 1995 Gulf of Aqaba M7.2 event some 200 km away.

Hydraulic diffusivity around faults, as obtained from various seismological observations, is independent of earthquake hypocentral depth and estimated to be on the order of 5.0 m²/s, termed as "seismogenic diffusivity" (e.g. Talwani and Acree, 1985; Hua et al., 2013; Talwani, 1997; 2007). This suggests that the flow through faults is relatively independent of the rock type (see Ingebritsen and Manning, 2010, and references therein). Therefore, the diffusivity of faulted rock in our study is best represented by the typical value of high-porosity Boise sandstone, 4.0 m²/s (Wang, 2000), as used for our calculations.

Using this diffusivity, we calculate the diffusion time scale, that indicates the time of arrival of the excess pore pressure from the lake's bed to hypocentral depths over the fault, for an average hypocentral depth underneath the Dead Sea fault system, $z \approx 20$ km (Aldersons et al., 2003; Godey et al., 2006; Shamir, 2006). This time scale is ~ 3 yr, according to the characteristic time scale definition (e.g. Kirby, 2010; Wang, 2000). For more details see Belferman et al., 2018, Eq.3 and explanation below.

This time scale is negligible compared to the typical recurrence intervals of decades and longer of moderate-to-large earthquakes ($M > 5.5$) in the Dead Sea area during the studied period (see Tables A1, A2, and text in Appendix chapter in the current ms). It is also insignificant compared to the minimal temporal uncertainty in the lake level curve, nominally taken as 10 years in our simulations.

Regarding the Artesian aquifers around Ein Feshkha - these are very local, minimal (two out of numerous boreholes), shallow, and ephemeral (Swaed et al., Geological Survey Report: GSI-10-2014). Their relationships to faults are poorly established, as is the historical activity of the nearby fault (Sharon, et al., 2020). More relevant are the thermal waters, ubiquitous in the basin. These require connectivity within the top kilometers of the section.

- The reviewer notes that even shallow boreholes at the Dead Sea are over-pressurized. Following this, he rules out vanishing of the normal vertical effective stress.

Response:

Our response concerns two points, mechanical and hydrological. The manuscript explicitly treats the effect of water level change relative to its minimal level (415 m below mean sea level - bmsl) over the period studied (pp. 8, rows 157-160). The normal stress change generated by such water level change is superimposed on the ambient regional tectonic stress field (please see pp.6 rows 120-127). First of all, we do not claim that normal vertical stress is zero. Moreover, being under the influence of gravity, the vertical stress depends on the hypocentral depth. Our model is based on the water level change effect

being only on horizontal components of the normal effective stress (as was shown previously for the reservoir-induced seismicity by Simpson 1976, and then for large-scale surface water level fluctuations, in Belferman et al., Eq.10b and corresponding text in p.393). Simpson (1976) established that in all faulting environments, the vertical stress increase from water loading is eventually canceled out by increased pore pressure and the final, post-diffusion stage (as explained above), is one in which the vertical stress returns to its initial value. Secondly, assuming that the reviewer is referring to Ein Feshkha boreholes, as we noted above, their relationships with faults are poorly established, as is the historical activity of the nearby fault (Sharon, et al., 2020).

On the hydrological aspect, we expand our response above for artesian waters around Ein-Feshkha. The shallow artesian aquifers mentioned by the reviewer are of the type described by Mazor et al. (1995) for the Dead Sea rift. These are isolated and local aquifers, trapped in the fine sediments. In the Dead Sea area, such aquifers occasionally seep, as reported by sinkhole studies (e.g. Al-Halbouni et al., 2017). The fluids spewed out are described as "sediment-laden", and we interpret this to indicate suspension of fine-grain material from the shallow hydrologic system. These local effects do not necessarily represent the deeper aquifers that might be connected to the surface via fault zones as described above. Earlier descriptions of artesian water in drill holes (Shiftan, 1958; Bentor, 1961) also tap local aquifers that do not interact with active faults (at least during the last two millennia).

Comment 3:

- The reviewer doubts the assumption that the pore pressure throughout the Dead Sea Basin at any depth responds elastically to changes in the lake level. According to the reviewer, since the basin is mostly made of clay, having plastic properties, changing the water level by 25 meters will not affect the depth of 2-3 km.

Response:

With regard to the composition of the Dead Sea deposits, it was shown that clay is a minor component of the Dead Sea Basin (e.g. Frydman et al., 2008; Herut et al., 1997; Haliva-Cohen et al., 2012). Frydman et al., (2008) measured geotechnical properties and found vanishing cohesion, as opposed to any lithology dominated by clay minerals. They stated that the particle size is clay-size but the mineralogy is not. Herut et al., (1997) and Haliva-Cohen et al. (2012) characterized the mineralogies and (like others) found quartz and carbonates to be the leading detrital minerals.

In summary, the reviewer seems to have misinterpreted some key points in our work. In our revision, we endeavor to better present our assumptions and results to avoid confusion. With the present knowledge of the hydrological and lithological properties of the Dead Sea Basin, as documented by current literature as referenced, our assumptions and conclusions remain intact.

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