SOURCE INVERSION OF THE M6.3 1927 JERICHO EARTHQUAKE, POSSIBLE REPETITION OF THE BIBLICAL EARTHQUAKE OF 1473 B.C.

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Introduction. According to the Bible and the Torah (Joshua [Giosuè] 6:1-21), God made the walls of Jericho fall down, perhaps with an earthquake, to help Joshua to conquer the city. The battle would have taken place in 1473 B.C. This hypothesis found some archaeological confirmations (e.g., Garstang and Garstang, 1940; Keller, 1956), but it is still controversial.

However, the M6.25 earthquake of 11 July 1927 (Ben-Menahem et al., 1976) heavily hit also the area of Jericho and could perhaps be the repetition of the hypothetic biblical event. Vivid descriptions of earthquakes in the region are found in the Bible. In particular, as regards the area of study, Ambraseys (2009) pointed out that the descriptions by prophets Amos and Zacharias allow the interpretation of an earthquake about in 766 B.C.; the Zacharias’ words even comply with a sinistral strike-slip movement.

The epicentre and causative faults of the 1927 destructive earthquake is still very controversial (see Tab. 1). Ben-Menahem et al. (1976) located it north of Jericho. According to Avni et al. (2002), however, the location north of the city was also based upon some secondary macroseismic evidence by Garstang (1931) and became one of the most accepted facts. In particular, this author reported the collapse of the banks of Jordan River about 20 km north of Jericho, damming thereby the Jordan for twenty-one hours. This damming became a crucial evidence for locating the epicentre by Ben-Menahem et al. (1976). However, upon close examination of the daily reports of the British Police of the time, Avni et al. (2002) concluded that: i) these detailed reports registered all happenings but did not even mention an important happening such as a one-day damming of the river (and the following flooding); ii) Garstang was not a witness of the phenomenon because, at the time of the 1927 earthquake, he went already back to Great Britain and iii) he had a personal religious interest «to relate natural disasters to miraculous biblical events» (Avni et al., 2002; p. 471).

Then, Shapira et al. (1993) noticed that many authors reported the (32.0°; 35.5°) epicentre of Tab. 1 without re-evaluating it and thinks that that approximate location was not obtained using the many recordings collected by the International Seismological Summary, ISS, but was estimated by the Ksara, Lebanon, station using only the Ksara data. Instead, Shapira et al. (1993) used the ISS data and applied standard location procedures. But there is a question that puts some doubts on the Shapira et al. (1993) epicentre itself: the difficulties associated with synchronization of the mechanical clocks in 1927 and the relatively low sensitivity of the seismic stations at the time, which produces high residuals (they omitted those greater than ±10 s).

More recently, Zohar and Marco (2012) used the intensities, I, provided by Avni (1999) to relocate the 1927 epicentre. To find their best solution, they corrected the data for the site effects and, then, correlated the intensities spatially with a logarithmic variant of the epicentral distance. They explain that the optimum site corrections had the effect of moving their first epicentre some 25 km west, on the Dead Sea transform DST. Instead, exaggerated corrections moved the epicentre 60 km east of DST. Their epicentre is close to that by Shapira et al. (1993). We comment that, in our opinion, an objective criterion for evaluation of all the sites is required. We avoid situations where only selected data are examined or where part of the data are modified, because this could drive the inversion results. It should also be kept in mind that deamplifications, if any, usually do not attract the same attention as cases of amplification, even though they have the same importance as far as inversion is concerned (Pettenati and Sirovich, 2007; pp. 1591). For these reasons, we do not correct single I values following local site studies, if any. In California and in Italy, we attempted to search for site effects by splitting the logarithms of the epicentral distances of each observed I, according to the prevailing
soil condition at each site, studying their distributions (Sirovich and Pettenati, 2001, 2004; Pettenati and Sirovich, 2003, 2004). To this end different lithological and geophysical large-scale classifications were used, but none worked (Pettenati and Sirovich, 2007). No objective criteria for all the used sites were available in the present case, however.

In this context, some Israeli colleagues, who read our studies on two Italian earthquakes in 1570 and 1694 (Sirovich et al., 2013a, b), suggested us to attempt the intensity-based source inversion also of the event of 1927 using our $KF$ technique.

Tab. 1 – Epicentres of the 1927 earthquake proposed by various authors (and one secondary macroseismic effect supposedly connected to the epicentre).

<table>
<thead>
<tr>
<th>Reference</th>
<th>Latitude [°]</th>
<th>Longitude [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ben-Menahem et al. (1976)</td>
<td>32.2</td>
<td>35.5</td>
</tr>
<tr>
<td>Shapira et al. (1993)</td>
<td>31.6</td>
<td>35.4</td>
</tr>
<tr>
<td>many references a</td>
<td>32.0</td>
<td>35.5</td>
</tr>
<tr>
<td>Zohar and Marco (2012) b</td>
<td>31.8</td>
<td>35.5</td>
</tr>
<tr>
<td>Avni et al. (2002)</td>
<td>31.6</td>
<td>35.4</td>
</tr>
<tr>
<td>Doubtful Jordan damming c</td>
<td>32.0 d</td>
<td>35.5 d</td>
</tr>
</tbody>
</table>

a) 30 km north of Jericho, interpreted -on a qualitative basis- as a strike-slip rupture along the Dead Sea transform DST; according to Avni et al. (2002), most of these references relied on the recording of one only station (Ksara, Lebanon) and on the unreliable Jordan damming ‘evidence’ by Garstang (1931); b) using only intensities; c) unreliable, according to Avni et al. (2002); d) approximate values.

**Tectonic context.** The area of study is on the contact between the African and the Arabian plates, north of the Sinai sub-plate, along the Dead Sea Transform Fault extending Nward to the Amanos-Zagros section of the Eurasia-Africa-Arabia convergence zone. The tectonic interpretation of the area is not easy, also for political reasons, because the two sides of the Jordan Valley are for long not freely accessible. The pull-apart nature of the Dead Sea depression still is an unresolved questions. In short, as noticed by Devès et al. (2011), although most agree that the Dead Sea valleys are tectonic in origin, no one agrees on the processes that have led to its formation. The same authors notice a striking feature of the Red Sea-Galilee Lake allignment: there is an ~11.5° change of direction between the Jordan Valley (south of the Dead Sea) and the Araba Valley (north of it). This: i) precludes a uniform stress distribution in the region (as if the principal transform structure would be rectilinear); ii) causes still unknown stress distribution and, consequently, rupture mechanisms in the region. However, Devès et al. (2011) find that 65% of the deformation in the Dead Sea region can localise on kinematically stable through-going strike-slip faults (the DST; our comment) while the remaining ~35% has to remain distributed. If this holds, our preliminary source (Model 1 in Tab. 2) would belong to the remaining 35%. On the one hand, these authors specify that there are no clear normal faults along the valley flanks (unlike Carmel fault), such as in true rifts like Corinth or East Africa, but, on the other one, they comment on that there are no normal faults along the valleys flanks that could account for the 600 m depression of the Dead Sea.

The work by Shamir (2006) is more encouraging for us, because it lets hope that our source be more compatible with the tectonics of the region from the Dead Sea to the area north of Jericho. He thinks that the late-phase (late Pliocene-early Pleistocene) asymmetrical shear zone of the DST is characterized also by a penetrative, bimodal (NW and NE) structural orientation pattern, reflected in earthquake focal mechanisms. Regarding the NE-oriented
faults, Shamir (2006) thinks that they extend northeastward and produce subsided, fault-bounded depocentres within the Dead Sea basin. More studies and, possibly, also the use of some seismograms of the time are needed, however, before we can confirm our very preliminary results of a dip-slip source NNE oriented in 1927 (see Tab. 2 and Fig. 2).

The hypothesis of the Dead Sea as a pull-apart basin had been proposed by Garfunkel et al. (1981). We comment on, that such a basin, or a rhomboidal-shaped basin, needs bordering normal faults also north and south of the depression. In Fig. 1, we reproduce the interpretative fault map of the active late phase structure of the Dead Sea Depression by Shamir (2006; his Fig. n. 9). He used blue lines for previously mapped faults (we refer to his original caption for the fault references) and in black the newly mapped faults based on seismicity (Shamir, 2006) and seismic data of other authors (we refer again to the original caption of the figure).

The intensity data used. We treated the 133 point intensities, $I$, provided by Avni (1999; and written communication, 2013). Following our procedure, which applies the Chauvenet method (Pettenati and Sirovich, 2007), we looked for statistical outliers. We found that, in this case, the epicentral location was crucial; thus, with a Dead Sea epicentre there were some outliers of high intensities to the north (Yarmuch-Fall $I=8.5$; Reyneh $I=8$), whilst an epicentre more Nward produced few outliers with low intensity to the south. In this preliminary experiment, we used the whole dataset, which is shown in Fig. 2A using the natural-neighbor n-n contour algorithm (Sirovich et al., 2002); there are four points of degree 9. Remember that the n-n isoseismals strictly honour the data. You can see the dots corresponding to Yarmuch-Fall and Reyneh in the small brownish island of degree VIII in the upper part of Fig. 2A. We treated half-degrees as real numbers.
Intensity-based (preliminary) source inversion of the 1927 earthquake. The preliminary results of the KF source inversion are in Tab. 2 and Fig. 2B. The upper part of Tab. 2 shows the ranges of the parameters explored by the genetic algorithm of the KF inversion (the fault-plane solution was let free); values with “+” and “-” indicate values in the along-strike and anti-strike directions.

The lower part of Tab. 2 (please add ±180° to the rake angles) shows the best solution (striking 37°) and the second-choice one. They are not far from each other, indicating an almost flat area in the topography of residuals in the 11-parameter hyperspace. Remember the intrinsic ambiguity of ±180° in the rake angles of our solutions. Thus, the rake angle of Model is 83° or 263°, which could be compatible with the normal faults drawn by Shamir (2006), in the upper part of Fig. 1.

Discussion. In the case of earthquakes of the early instrumental era, using also the instrumental recordings is compulsory. For example, the polarities even of few P onsets, in the right geographical positions, could solve the intrinsic ambiguity of ±180° of our solutions. The work is in progress.

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