

Lower-Crustal seismicity in the Dead Sea region

Freddy Aldersons
Mies Switzerland
fred@faldersons.net

Zvi Ben-Avraham
T.A.U. Ramat Aviv Israel
zvi@terra.tau.ac.il

Edi Kissling
E.T.H. Zürich Switzerland
kiss@tomo.ig.erdw.ethz.ch

Introduction

It is commonly assumed that the lower-crust is essentially aseismic in rift zones. In relation to a more recent trend of research, the presence of a significant micro-seismicity has been observed in the Dead Sea region.

Geological setting

The Dead Sea Transform (Figure 1) is an intracontinental plate boundary resulting from the late-Cenozoic breakup of the Arabo-African continent. This boundary extends over 1,000 km from the zone of sea floor spreading at the southern tip of the Sinai Peninsula to the Taurus-Zagros zone of convergence in Turkey (Freund, 1965).

The Dead Sea basin is an active pull-apart located along the Dead Sea Transform. The amount of left-lateral motion along the Transform in the Dead Sea region is estimated at 105 km (Quennell, 1958; Freund et al., 1970).

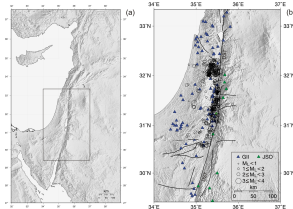


Figure 1 The Dead Sea region. The square grid fill defines the Dead Sea basin. Seismicity: 410 well-constrained earthquakes (1984-1997) recorded by short-period stations (triangles) of GII (Israel) and JSO (Jordan). DST: Dead Sea Transform.

The Dead Sea basin is a morphotectonic depression over 130 km long and 7-18 km wide. It is a seismically active section (van Eck and Hofstetter, 1989) along the Dead Sea Transform, for which some 4,000 years of combined archaeological, historical and instrumental seismicities are documented (Ben-Menahem, 1991). For the northern half of the Dead Sea basin (main lake and salt pans), earthquakes of $M_s \geq 5.8 \pm 0.2$ have a recurrence interval of approximately 160 years (Shapira, 1997). The last earthquake of such a magnitude (estimated magnitude 6.2) occurred in the main lake (Shapira et al., 1993) in 1927 at an unknown depth.

1984-1997 Seismicity

Out of 2,283 routinely recorded earthquakes in the Dead Sea region, 410 earthquakes have well-constrained locations, including depth (Figure 2). First P arrivals from 42 well-constrained earthquakes that nucleated in the Dead Sea basin were carefully picked manually, and weighted according to the quality of their onsets.

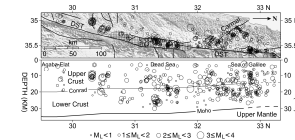


Figure 2 Depth section of well-constrained seismicity (410 earthquakes, 1984-1997) along the Dead Sea Transform (DST) from Aqaba-Eilat to the Sea of Galilee. The square grid fill defines the Dead Sea basin on the map. Conrad and Moho discontinuities from Ginzburg et al. (1981).

These 42 well-constrained earthquakes were relocated with program Velest and 1-D velocity model Israel (Figure 3b). The resulting distribution of depths in the Dead Sea basin is plotted in Figure 3e. 60 percent of well-constrained microearthquakes ($0.3 \leq M_s \leq 3.2$) nucleated at depths of 20-32 km and more than 40 percent occurred below the depth of peak seismicity situated near 20 km. With the Moho at 32 km, the upper mantle appeared to be aseismic during the 14-year data period.

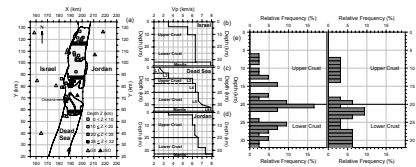


Figure 3 Dead Sea basin earthquake relocations. (a) Structural units, stations (triangles), epicenters and depths of 42 well-constrained earthquakes (squares). Oceana is a salt quarry. (b,c,d) Three 1-D velocity models used in the Simulps relocation. (e) Depth distribution (Velest). (f) Depth distribution (Simulps).

Two independent evaluations of the uncertainty on depths derived from model Israel have been made. First, we applied perturbations to model Israel (Figure 4a) and relocated the 42 well-constrained earthquakes with resulting models. This method evaluates the sensitivity of depths to departures from model Israel, and it provides individual error bars (Figure 4b).

As a second approach to depth uncertainties, we determined true depth errors for a series of blasts from quarry Oceana. Oceana is a Dead Sea salt quarry located on the western salt pan south of the main lake, and only 15 km away from the main cluster of deepest earthquakes (Figures 3a and 4c). We only considered well-constrained blasts with at least 8 P readings, and an azimuthal gap not greater than 150 degrees. In addition, we required the distance of the closest station to be 3-4 km and we rejected events not explicitly attributed to Oceana by the analysts. Figure 4d reveals that Oceana blasts located with model Israel do not display true depth errors greater than 2 km, with the exception of two outliers.

An upper bound uncertainty of ± 5 km is estimated under 20 km but depth errors should not exceed ± 2 km for most earthquakes.

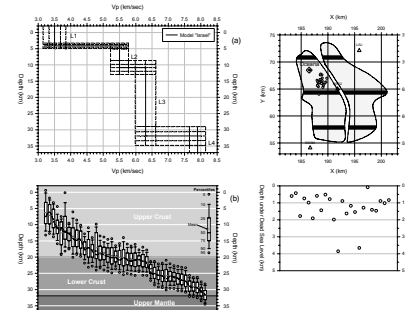


Figure 4 (a) Depth and velocity perturbations defining 16,875 models around model Israel. L1 to L4 are the four layers of model Israel. (b) Hypocentral depths and error bars for the 42 earthquakes relocated with perturbed models defined in (a). (c) Epicentral locations of 24 Oceana quarry blasts. Epicenters as white circles. (d) Depth error of blasts plotted in (c).

Rheology

A lithospheric strength profile (Figure 5b) has been calculated using the five crustal layers defined in velocity model Dead Sea and one additional layer for the upper mantle. Below 20 km, the lower crust was modeled as diabase, a lithology consistent with the main value of 6.6 km/s in layer 5 of the velocity model.

We derived the geotherm for the Dead Sea basin (Figure 5) from the one-dimensional equilibrium heat conduction equation. Using six layers and average parameters, the 1-D geotherm is only very sensitive to two variables: the surface heat flow and the thermal conductivity in the first layer.

The average measured heat flow in the northern Dead Sea basin is 38 mWm^{-2} (Ben-Avraham et al., 1978) and it is 42 mWm^{-2} (Eckstein and Simmons, 1978) west of the basin. These values are very similar to the uniform heat flow measured in the eastern Mediterranean (Erickson, 1970). Consequently, the surface heat flow of $40 \pm 2 \text{ mWm}^{-2}$ appears to be well constrained.

Regarding the thermal conductivity in the first layer, Plio-Pleistocene to recent sediments are composed of fluvialite and lacustrine clastics, marls, chalks and evaporites. The few quaternary conductivities available in the Dead Sea basin (Eckstein and Simmons, 1978) are very low ($1.25 \text{ Wm}^{-1}\text{K}^{-1}$) but were measured through only the first 150 m from the surface. In order to get a brittle to ductile transition around 30 km with a surface heat flow of 40 mWm^{-2} , a mean thermal conductivity of at least $2.1 \text{ Wm}^{-1}\text{K}^{-1}$ is required in the first layer. This figure appears as a realistic value taking into account compaction and a content of 5-10 percent of highly conductive evaporites in the first layer. It is unlikely that the true value over the thickness (4.7 km) of the first layer would be lower than $2.0 \text{ Wm}^{-1}\text{K}^{-1}$.

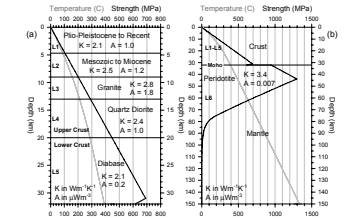


Figure 5 Rheology of the Dead Sea basin. (a) Crustal geotherm (grey) and strength profile (black). (b) Lithospheric geotherm (grey) and strength profile (black). Surface heat flow of 40 mWm^{-2} . K is the thermal conductivity and A is the radiogenic heat production rate.

Conclusions

In the Dead Sea region, well-constrained microearthquakes ($0.3 \leq M_s \leq 3.2$) display continuous focal depths down to the Moho found around 32 km depth. A relatively cool and brittle lower crust is consistent with the surface heat flow of 40 mWm^{-2} . The upper mantle should also be in a seismogenic state but appeared to be aseismic during the 14-year data period. The absence of micro-seismicity in the upper mantle remains an open question.

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