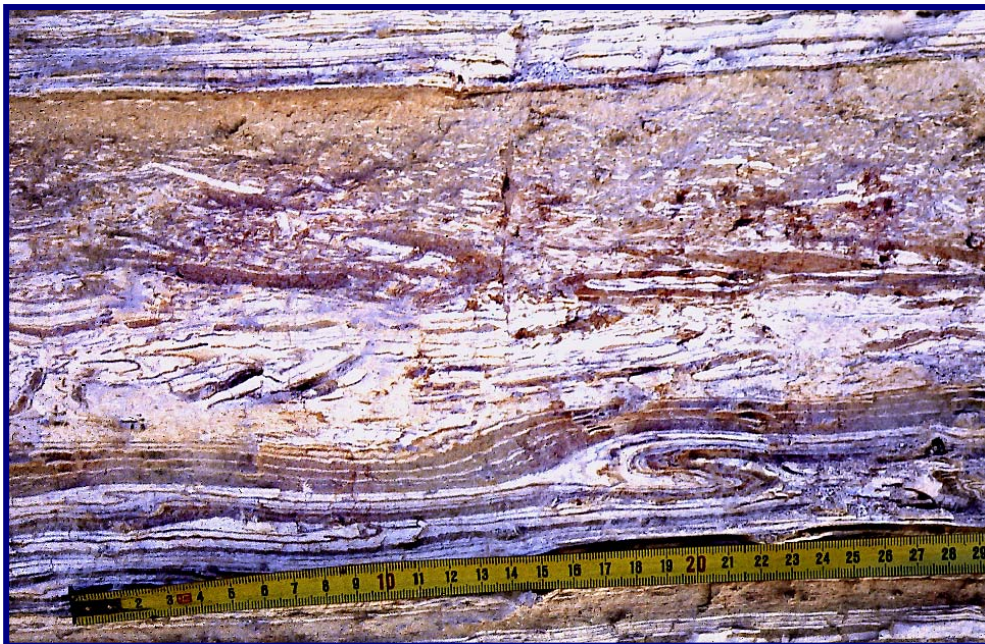




The Ministry of National Infrastructures  
Geological Survey of Israel

## Prehistoric Seismic Basin Effects in the Dead Sea Pull-apart

Z.B. Begin<sup>1</sup>, J.N. Louie<sup>2</sup>, S. Marco<sup>3</sup>, Z. Ben-Avraham<sup>3</sup>



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## **Abstract**

Site effect is the specific response to earthquakes that is characteristic of the attributes of a site. The two- and three-dimensional shape of sedimentary basins may constitute an important factor of site effects. In sediment-filled basins, in which a lens of soft sediments overlies rocks with higher seismic velocities, two-dimensional resonance patterns may prolong the duration of shaking, and induce a large amplification, much larger than the one predicted from the corresponding one-dimensional analysis. The main source of these phenomena is the development within the basins of surface waves, including the vertically and elliptically polarized Rayleigh waves, and horizontally polarized Love waves.

The Dead Sea Fault is an active left-lateral transform, posing a major seismic threat to the population in its surroundings, and hence an earthquake-mitigating Building Code was adopted in Israel. However, the present Code does not deal with basin effects. The importance of these is here exemplified in the Dead Sea pull-apart, that generated a destructive M6.2 earthquake in 1927. Within it, seismites dated to 60-16 kyBP represent strong earthquakes, and their thickness is significantly different in three sites, 20 km apart: one near Massada and two in the 'Amiaz basin. The median thickness is 3, 6 and 12 cm, respectively, presumably reflecting differences in both the duration and amplification of earthquakes.

These differences are plausibly explained by assuming that they are caused by basin effects, due to the differences in both the shape of the basins in which the seismites are located (the basin being deeper at the 'Amiaz sites than at the Massada site), as well as difference in location of the seismites, relative to the midline of the 'Amiaz basin. Hence, these seismites may constitute the longest and most detailed known record of prehistoric site response.

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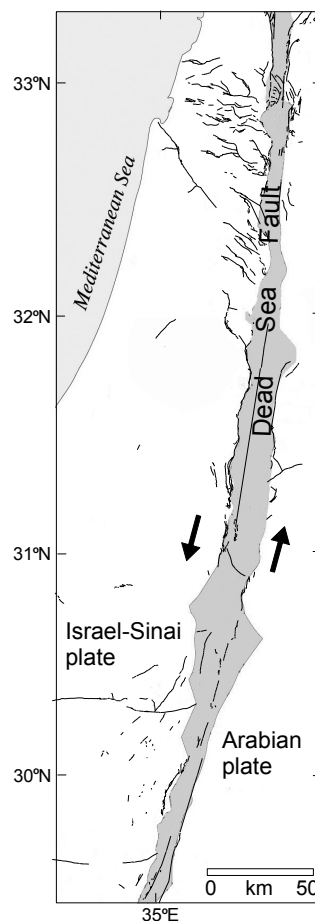
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## 1. Introduction

The Dead Sea Fault (DSF) is an active fault zone forming the Arabian-Sinai plate boundary, stretching from the spreading Red Sea to the Eastern Anatolian Fault (Fig. 1). All along the transform it is accompanied by a conspicuous rift valley. Based on geological evidence it is generally accepted that the DSF is a transform fault, along which the principal sense of movement has been left lateral (Quennel, 1959; Freund, 1965; Freund et al., 1970; Garfunkel et al., 1981; Girdler, 1990). The long-term left-lateral slip rate is at least 5 mm/year (105 km in a maximum of 23 Ma) based on the geological evidence, and it is currently  $3.3\pm 0.4$  mm/year based on GPS measurements (Wdowinski et al., 2004).



**Figure 1:** Potentially active faults along the Dead Sea Fault (Bartov et al., 2002). Shaded area denotes the Dead Sea rift valley. Arrows mark the sense of relative plate movement along the transform.

The Dead Sea pull-apart is the deepest basin along the DSF, with a sedimentary Plio-Pleistocene fill some 10 km thick, attesting to a rather rapid subsidence (Ben-Avraham, 1997). It is a tectonically active basin (Garfunkel et al., 1981), generating at present the most intensive earthquake activity between the Gulf of Elat and the Lebanon Baqa'a, including a destructive M 6.2 earthquake in 1927 (Shapira et al., 1993).

The Dead Sea Fault poses a major seismic threat to the population on both its sides, and an assessment of seismic hazard in Israel is embedded in its Building Code (Israel Standard 413; Shapira, 2002). Presently, the Code is not conservative in several aspects: It is based on a 10% probability that a certain peak ground acceleration at a site during the next 50 years will be exceeded, but it assumes that the probability for the occurrence of strong earthquakes does not increase with time; it includes a correction factor for soft sediments, but it does not treat one-dimensional resonance effects in soft sediments overlying hard rocks (Zaslavsky et al., 2002; Gvirtzman, 2004); and it does not consider basin effects.

Basin effects are expressed by amplification of ground motions and the prolonging of their duration (see below), and thus they may cause substantial damage even if the source earthquake is distant or moderate. In contrast with one-dimensional site effects, basin effects can not be recognized and anticipated by analyzing ambient noise, and at least moderate earthquakes are needed to elucidate them. However, such earthquakes are infrequent along the DSF, and hence, the study of prehistoric basin effects can enrich our understanding of these effects. Also, since the 100 years of instrumental record of earthquakes near the DSF is extended by the study of the historical seismic record (considered to be complete for  $M > 6.5$  in the last 2,000 years; Shapira, 2002), this record has to be critically viewed, as it may include several inaccurate accounts tending towards exaggeration (Ambraseys and Karcz, 1992; Avni et al., 2002; Karcz, 2004). In an attempt to extract magnitude values from ancient damage descriptions, basin effects should also be considered.

The aim of this report is to analyze the possibility that basin effects played an important role in the formation of seismites in the Dead Sea basin for a long period of about 45,000 years.

## **2. The nature of basin effects**

In recent years it has become evident that the two- and three-dimensional shape of sedimentary basins may constitute an important factor of site effects. It has been shown that in sediment-filled basins, in which a lens of soft sediments overlies rocks with higher seismic velocities, two-dimensional resonance patterns may prolong the duration of shaking, and induce a large amplification, much larger than the one predicted from the corresponding one-dimensional analysis. This was shown both in simulations (Bard and Bouchon, 1980, 1985; Hill et al., 1990; Frankel and Stephenson, 2000; Olsen, 2000) and in field measurements (Hanks, 1975; Liu and Heaton, 1984; Field, 1996; Joyner, 2000; Frankel et al., 2002; Pratt et al., 2003; Pancha et al., 2004).

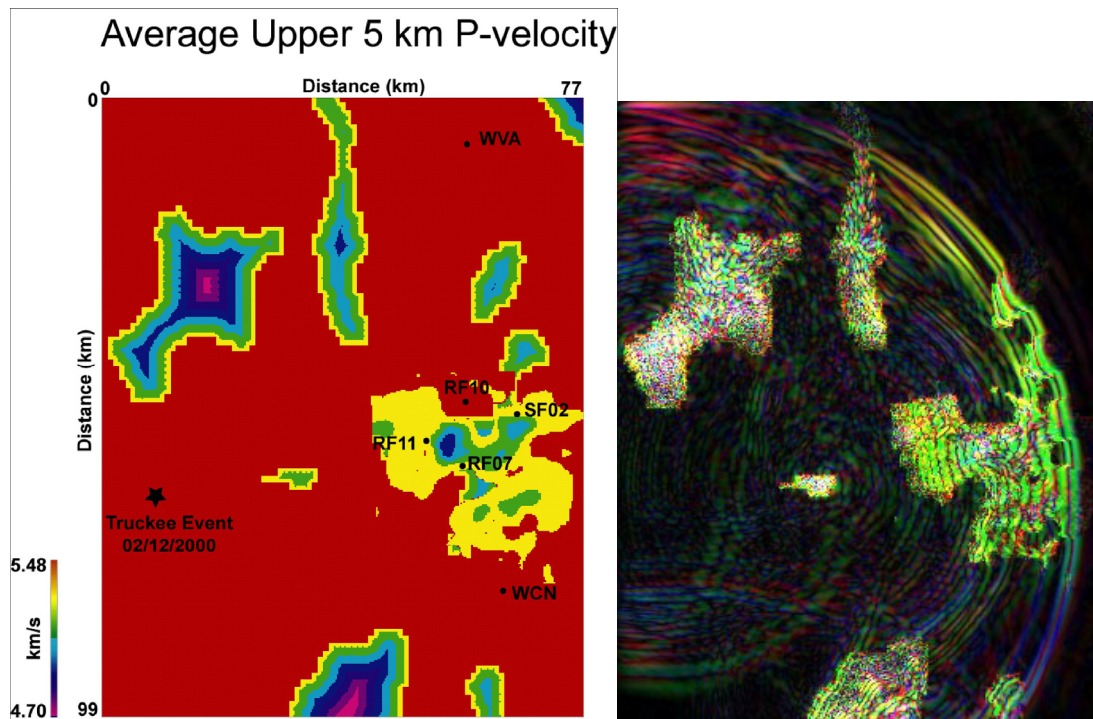
The main source of these phenomena is the development within the basins of surface waves, including the vertically and elliptically polarized Rayleigh waves, and horizontally polarized Love waves. Surface waves produce the largest displacements of shaking because their amplitudes are tied to shear velocities. The lower the propagation velocity property of the rocks, the larger the ground motions. In sedimentary basins the P velocity is often limited to a minimum of 1.5 km/s, the P velocity of water-saturated sand or mud. Such materials can have shear velocities an order of magnitude lower (down to 0.05 km/s), creating shear displacements in surface waves that are much larger than P-wave displacements.

In the literature concerning basin effects one often finds that at the edge of sedimentary basins seismic body waves are converted to surface waves. This notion needs some elaboration, since this process is not the same type of wave conversion as that a body wave undergoes at a discontinuity. Surface waves in sedimentary basins are basically multiple reflections and multiply-reflected refractions. As body waves arrive at the edge of the basin they are refracted, and then the body wave energy is trapped within the basin, between the free surface and the basin interface, which acts as a strong reflector. Once trapped, they are reflected back and forth, and out of the multitude of possible reflection paths some are horizontal. Since this process takes some time until it becomes effective, the surface waves may develop after a delay of several seconds. Hence, the observed late arrival of surface waves in basins may be explained not only by their lower group velocity but also by the fact

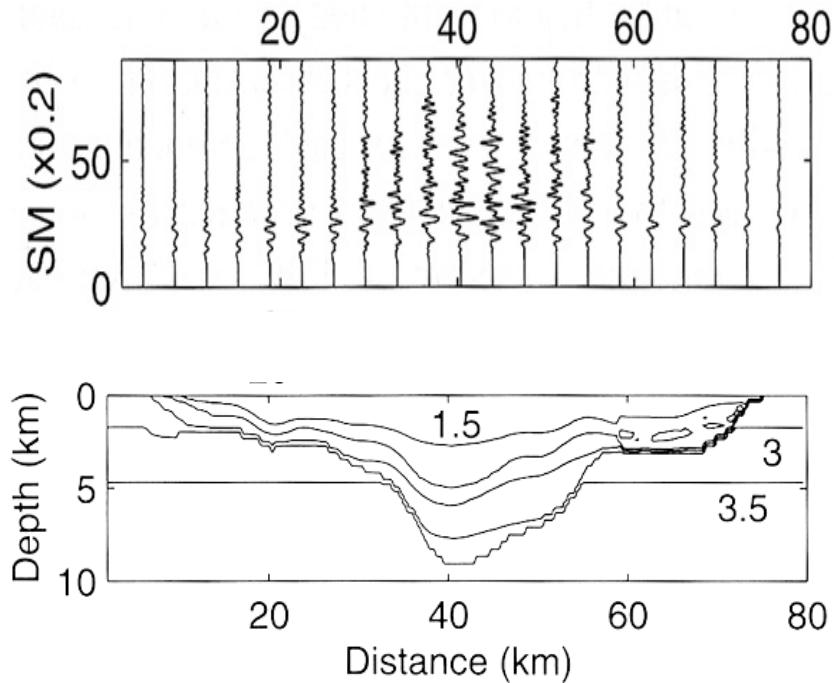
that they take time to effectively develop out of the multitude of possible reflections. The fact that the wave energy is trapped in the basin, and the low frequency that is typical of surface waves, that is associated with lesser attenuation, contribute to the relative long duration of strong ground motion. The increased duration of strong ground motion was shown both in simulations (Bard and Bouchon, 1985; Frankel and Stephenson, 2000; Olsen, 2000) and in actual measurements (Field, 1996; Lomnitz, 1996; Joyner, 2000; Frankel et al., 2002; Pratt et al., 2003; Pancha et al., 2004).

Once this development has progressed and the process of constructive interference has completed, surface waves develop whose energy propagates at their group velocity. Since the group velocity is never exactly equal to the shear velocity in the medium, the wave has effectively changed its velocity and its direction of propagation. This may be regarded as "conversion" of the body waves to a new "phase", but two differences between the two processes should be noted. (1) The development of surface waves in a basin is very frequency-dependent, while a conversion (say from P to S waves) at a discontinuity is not, and (2) while surface waves develop within a basin and only after the body waves enter into it, the conversion of body waves happens instantaneously at the edge of the basin.

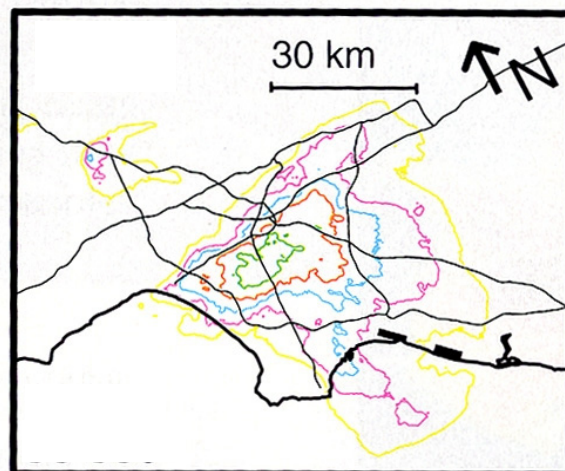
The damaging aspects of basin effects are thus three-fold: high amplification relative to rock sites out of the basins; prolonged duration of strong motions (thereby increasing the number of seismic cycles and thus increasing seismic loading), and the formation of large-displacement surface waves. Here we study the possible influence of basin effects on prehistoric seismites of the Lisan Fm. in the Dead Sea pull-apart.



**Figure 2.** Map of the Reno-area 3-dimensional velocity model (left) with basins represented, and map view of 0.5-Hz synthetic wave propagation (right). Source: Pancha et al., 2004. Red, yellow, and green colors represent horizontal seismic shaking while blue represents vertical shaking. The Rayleigh wave from the earthquake epicenters (star) has passed through most of the Reno basin (center right) in this view. The basins are trapping energy and amplifying shaking. Concentration of basin amplification is observed near both basin centers and edges, depending on basin geometries and earthquake location.



**Figure 3:** Simulation of basin effects in the Los Angeles basin (from Olsen, 2000). Closer to the basin center ground motions are stronger and of longer duration (seconds). Numbers in the basin denote seismic velocity, in km/s.



**Figure 4:** Simulation of basin effects in the Los Angeles basin (from Olsen, 2000). Colored contours denote strong motion duration in 10 seconds interval, with 50 seconds (green) in the middle of the basin. Bold black line denotes the coastline and other black lines denote main roads.



### **3. Geological setting**

The study area is located in the western margins of the Dead Sea pull-apart. The structure of this basin has been studied quite extensively (ten Brink and Ben-Avraham, 1989; Ben-Avraham et al., 1990; Ben-Avraham et al., 1993; ten Brink et al., 1993; Ginzburg and Ben-Avraham, 1997; Ben-Avraham, 1997; Aldersons et al., 2003). The study sites are located in close proximity (1-2 km) to two active faults: the Jericho fault (Begin, 1975; Reches and Hoexter, 1981; Gardosh et al., 1990; Niemi and Ben-Avraham, 1993, 1997; Shapira et al., 1993; Lubberts and Ben-Avraham, 2002), and the western margin fault (Bartov and Sagy, 2004).

The lacustrine Lisan Formation, consisting of authigenic aragonite and gypsum layers alternating with silt and sand detritus (Begin et al., 1974; Katz et al., 1977; Stein 2001), was deposited within the Dead Sea rift valley during the period of 70,000-14,000 years B.P. (Kaufman, 1971; Kaufman et al., 1992; Schramm et al., 2000; Haase-Schramm et al., 2004). Within the Dead Sea basin, breccia beds in the Lisan Fm. and Holocene lacustrine sediments, formed during the last 60,000 years, were interpreted as seismites (Fig. 6), induced by  $M > 5.5$  earthquakes (Marco and Agnon, 1995; Marco, 1996; Marco et al., 1996; Ken-Tor et al., 2001), by strong and remote earthquakes (Migowski et al., 2004) and by nearby  $M > 7$  earthquakes (Begin et al., 2005).

## **4. The Lisan seismites**

### **4.1 Ground acceleration associated with the Lisan seismites.**

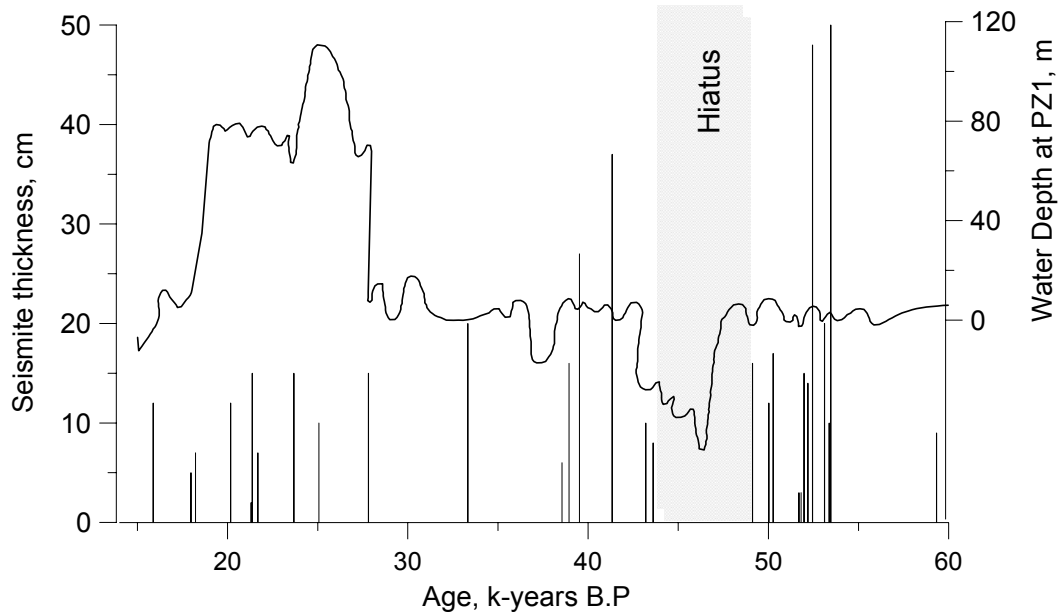
The mechanism of formation of the seismites is not clear. They were originally continuous alternating laminae of aragonite and fine detritus, lying flat on the bottom of Lake Lisan. These undisturbed laminae were later fluidized, brecciated, partly resuspended in the Lake water, and then resettled (Marco et al., 1996). A mechanism for the formation of the Lisan seismites was suggested, based on laboratory experiments (Hamiel, 1999). These experiments showed that in order to develop waves in the boundary between mud and water, the densities of which are similar, very large acceleration ( $>10g$ ) is needed. On the other hand, partial suspension of the mud layer into the overlying water layer was induced by



**Figure 6:** A 10 cm thick seismite in the Lisan Fm. within the Dead Sea pull-apart, showing torn white aragonite laminae in silt-clay matrix. Undisturbed aragonite laminae top the seismite. Scale shows centimeters.

waves that developed in the water surface at low accelerations. Hence it was suggested that the seismites were formed due to high amplitude waves in shallow water. However, this model can not explain the formation of seismites in depths greater than several tens of meters.

On the other hand, the depth of water under which this brecciation took place can be estimated through knowledge of Lake Lisan level curve (Bartov et al., 2002) and the elevation of the sites, adjusted to sedimentation rate. It arises from the history of depth in the Ami'az plain sites that relatively thick (10-15 cm) seismites in the Lisan Formation, were formed even at water depths of about 100m (Fig. 7).



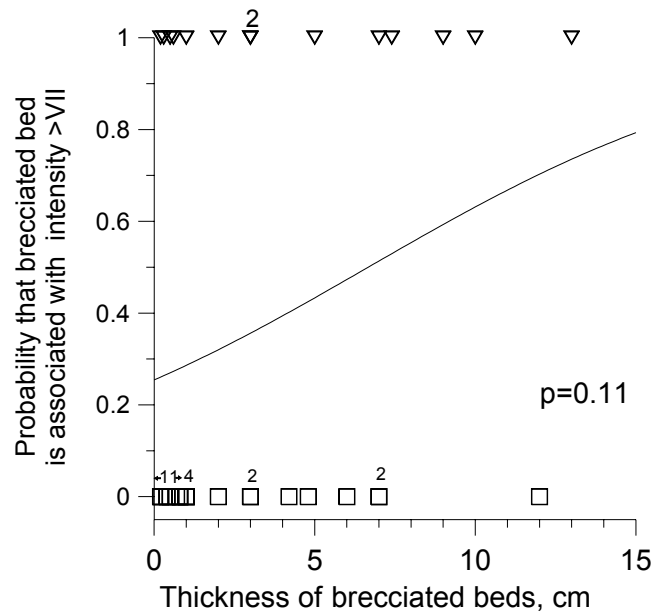
**Figure 7:** Thickness of Lisan seismites (bars) shown on the backdrop of the water depth in which they were formed in Lake Lisan. Depth data are after Bartov et al., 2002. Age of seismites and their thickness is from Begin et al., 2005.

For seismites in the Dead Sea basin 20 km north of Massada, with thickness  $0.2 \leq D \leq 13$  cm, that were matched to historical earthquakes, the associated intensity was estimated as  $VI < I_{mm} < VIII$  (Migowski et al., 2004), which would translate to peak ground acceleration of about 0.1-0.3g. However, this may be an underestimate as intensities were estimated from a general magnitude-distance relationship without considering possible basin effects of the Dead Sea rift.

#### 4.2 The significance of the thickness of the Lisan seismites.

Accepting that the brecciated beds in the Lisan Formation were presumably formed by liquefaction or fluidization following earthquakes, we assume that thicker seismites may indicate stronger earthquake intensity. This seems reasonable in light of the correlation between the Liquefaction Severity Index and earthquake magnitude (Youd and Perkins, 1987), and because stronger earthquakes cause more stress cycles at a site (Seed and Idriss, 1982), which in turn may bring about higher pore pressure within the sediment. This

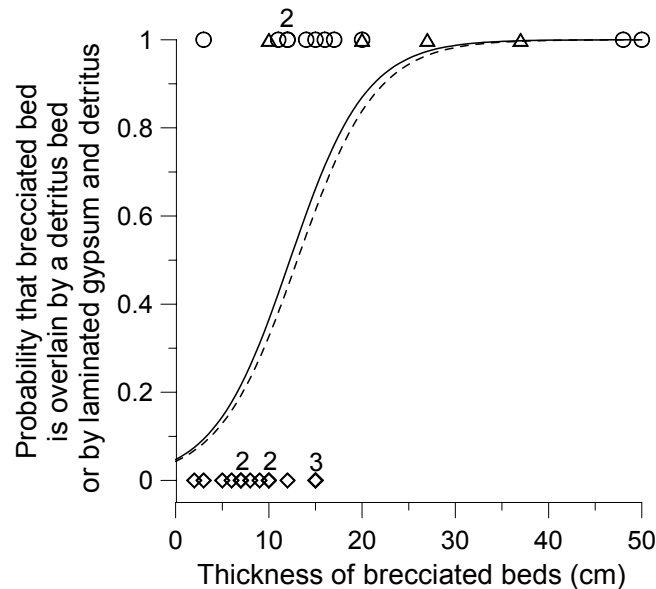
relationship is difficult to demonstrate (Tuttle, 2001), but it is partially supported by data on historic seismites in the Dead Sea basin (Migowski et al., 2004). A weak relationship ( $p=0.11$ ; note that the thickness range is much smaller than the range in the Lisan Formation) is shown between the thickness of seismites and the probability of their being associated with earthquake intensity  $>VII$  rather than VI-VII (Fig. 8).



**Figure 8:** Logistic function, showing that thicker seismites in the Ein Gedi area within the Dead Sea pull-apart have a higher probability to be associated with earthquake intensity  $>VII$  (triangles) rather than with intensity VI-VII (squares). The graph is based on the matching of seismites with historical earthquakes (Migowski et al., 2004).  $p$  denotes the statistical significance of the fitted logistic function. Note that the thickness range here is much smaller than the range in the Lisan Formation (Fig. 9). Since  $p > 0.05$  we do not reject the null hypothesis that earthquake intensity is not related to the thickness of the seismites. However, since  $p \sim 0.1$  we view the data as indicating a weak relationship between the two attributes.

For the  $\sim 30$  seismites in the Lisan Formation at the Ami'az plain, dated to 60-16 kyBP, both the thickness of seismites and the lithology of beds directly overlying them were used in order to differentiate between stronger and weaker earthquakes represented in these sections. It was found that thicker seismites have a higher probability of being overlain by laminated gypsum and detritus (Fig. 9). This association was interpreted as arising from the mixing of Lake Lisan water column due to high seiches induced by strong earthquakes, and served to

identify 11  $M \geq 7$  earthquakes that originated within the tectonically active Dead Sea pull-apart (Begin et al., 2005). This model highlights the significance of seismite thickness as an indicator of earthquake intensity.



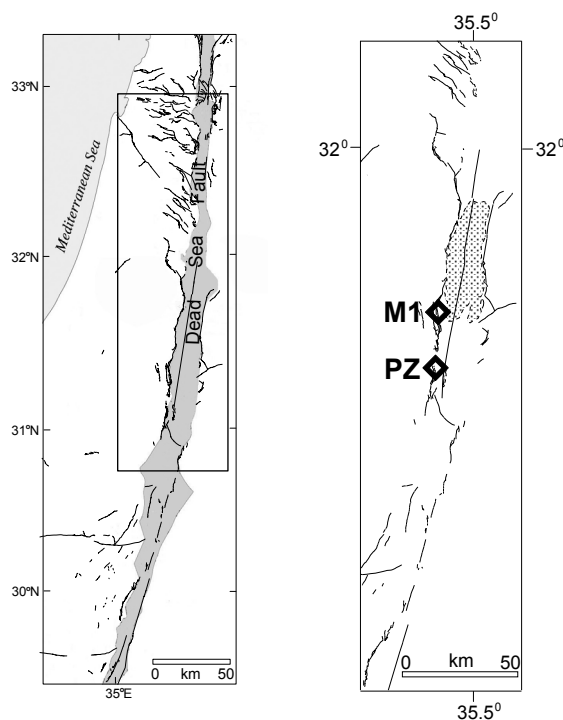
**Figure 9:** Logistic function, showing that thicker seismites in the PZ1 section have a higher probability to be overlain by beds of laminated gypsum and detritus (circles) and by detritus beds (triangles) rather than by beds of laminated aragonite and detritus (diamonds). Digits above symbols denote number of beds with identical thickness. Full line is for both couplet types ( $p = 0.02$ , where  $p$  denotes the p-value obtained in testing the null hypothesis that the layering is random) and broken line is only for couplets of seismites overlain by laminated gypsum couplets ( $p = 0.05$ ). Since  $p \leq 0.05$  we reject the null hypothesis that the layering pattern is not related to the thickness of the seismites.

In addition, in a recent study (Heifetz et al., 2005), based on considerations of the Kelvin-Helmholtz Instability, the minimum ground acceleration needed to de-stabilize Lisan beds, as the first stage in their brecciation, was shown to change with the square root of the bed thickness, that is, bed thickness is proportional to the square of the minimum destabilizing acceleration.

In summary, the thickness of the Lisan seismites at a site seems to be related to local earthquake intensity.

### 4.3 Thickness of the Lisan Lisan seismites and the possible role of site effects.

Three columnar sections of the Lisan Formation, each exhibiting some 30 seismites were previously presented (Marco, 1996; Marco et al., 1996). One section is in the Massada plain (M1, coordinates 18575/07965, Israel old grid; Fig 10) and two sections, 2 km apart, in the Ami'az plain, some 25 km southwards: PZ2 (coordinates 18500/05800) and PZ1 (18450/05599).

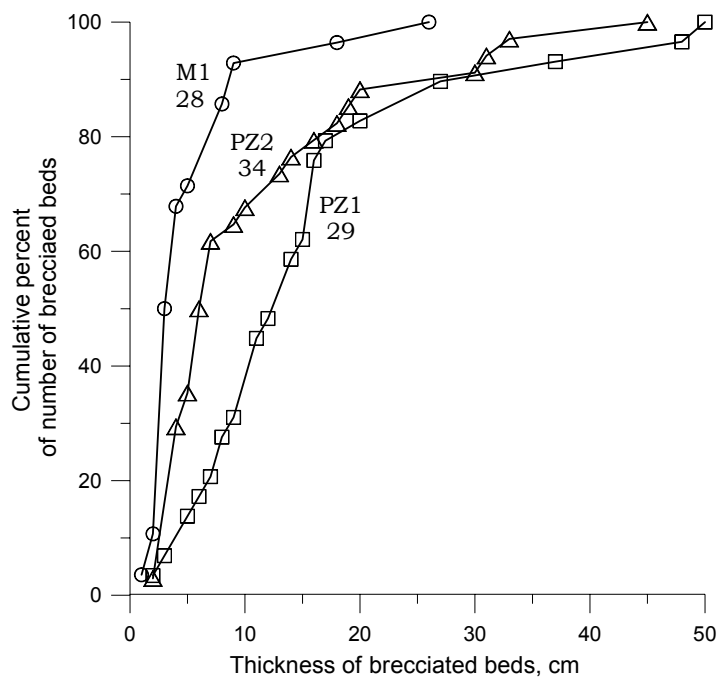


**Figure 10:** Location map (in area delineated by box) , showing the M1 and PZ sites in the context of active faults of the Dead Sea rift (Bartov et al., 2002). Grey area is the Dead Sea, that was also the deepest basin in Lake Lisan.

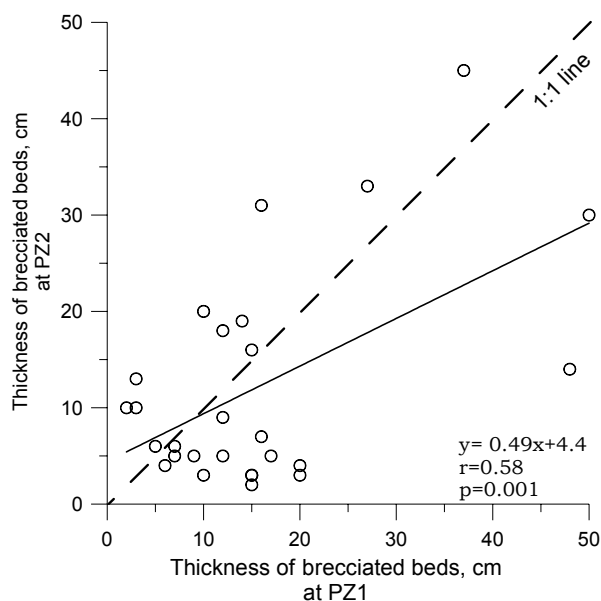
The median thickness values for the M1, PZ2 and PZ1 sections are 3, 6, and 12 cm, respectively (Fig. 11). The difference between the thickness distributions in the three sections, tested through the Mann-Whitney test, is statistically significant ( $p=0.018$  for the PZ2-PZ1 pair;  $p=0.0001$  for the PZ2-M1 pair;  $p=0.000001$  for the PZ1-M1 pair.  $p$  is the probability that the difference between the distributions occurs randomly). The thickness distributions describe the relationship between the sites in general, as is also depicted in the

regression of thickness values at PZ2 on PZ1 for those seismites that were matched between the two sites (Fig. 12). However, it can be seen in Fig. 12 that in several cases  $D_{PZ1} < D_{PZ2}$ , where D is the thickness of individual seismites.

It should be noted that there was a difference in the environments of deposition of the Lisan Fm. at the Massada and Ami'az plain sites, with the former being about 50m deeper in Lake Lisan. However, this difference does not explain the consistently thinner seismites at Massada, since, as shown above, 10-15 cm thick seismites were formed at the Ami'az plain even at a depth of about 100 m (Fig. 7).



**Figure 11:** Cumulative percent of the number of seismites as a function of their thickness. Source of data: Marco, 1996, Table 2.2. M1 is in the Massada plain, PZ1 and PZ2 are in the Ami'az plain. Numbers denote the number of seismites in each site. The three distributions are significantly different (see text).



**Figure 12:** Comparison of thickness of seismites matched between the PZ1 and PZ2 sites. On average, the PZ1 beds are thicker than the PZ2 beds but for several seismites  $D_{PZ1} < D_{PZ2}$ .

A detailed correlation between seismites in the three sites has not been established yet, although the PZ1 section is well dated (Haase-Schramm et al., 2004) and the M1 section is partly dated in detail (Prasad et al., 2004). However, as the seismites were formed during the same period in the three sections, it may be assumed that, in general, the same set of earthquakes caused the formation of seismites in the two areas. There is no reason to assume that earthquakes preferentially occurred south of the PZ1 site, rendering it closer to most epicenters. Moreover, it was suggested (Begin et al., 2005) that 11 strong earthquakes, that induced high seiches in Lake Lisan, occurred in the Lake deep basin, just north of the M1 site. Also, despite the mere 2 km distance between the PZ2 and PZ1 sections, they still exhibit a significant difference in the thickness of their seismites. These considerations lead us to assume that the cause of the difference in thickness of seismites between the three sections may be a consistently different response to strong earthquakes in the three sites. Since there is no conspicuous difference in the lithology of the seismites in the three sections, we propose that the difference in seismite thickness may be explained by some site effects. Applying the results of Heifetz et al. (2005; see above), and assuming similar lithology at

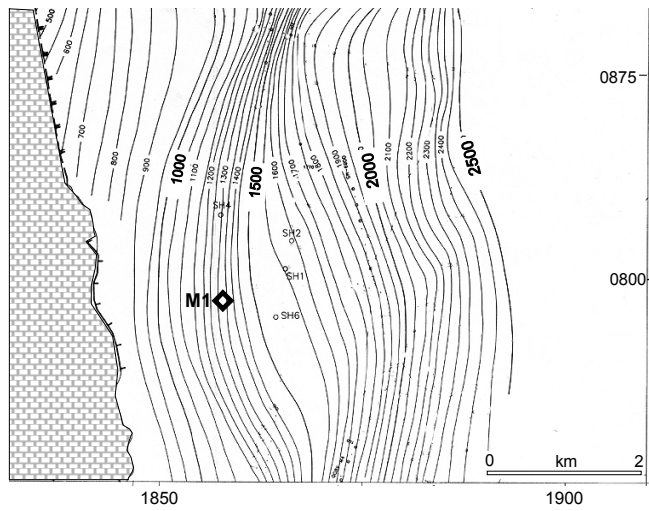
both sites, the 5-fold difference in the median thickness suggests, on average, a  $\sim 2$ -fold higher ground acceleration at the Ami'az sites compared to the Massada site.

There is an additional, independent indication of the importance of the different local effects between the Massada and Ami'az areas. In the Ami'az area, numerous young ( $<14$  kYBP) clastic dykes have been observed (Marco et al., 2002). It was suggested, on the basis of the magnetic fabric in these dykes, that the clastics were fluidized and injected into fissures due to strong earthquakes (Weinberger et al., 2003; Levi et al., submitted). Most of these dykes appear near the center-line of the Ami'az plain. Similar clastic dykes are also present in the Massada area, but they are fewer there (Weinberger, personal communication, 2004). This may be interpreted as signifying higher earthquake intensities in the Ami'az sites relative to the Massada area, and this seems to be in accord with the higher earthquake intensity that may be assumed for the Ami'az sites compared to the Massada area, based on the difference in seismite thickness.

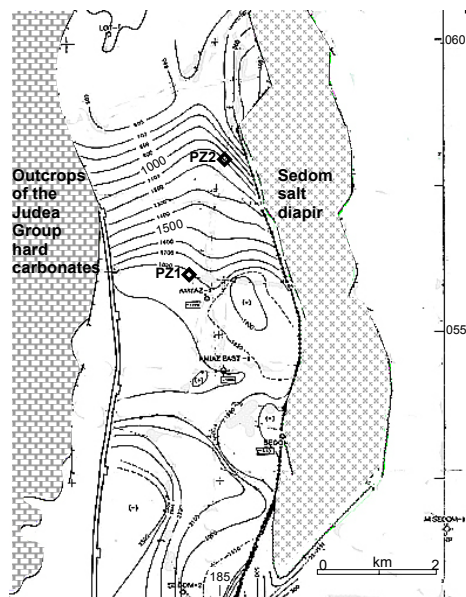
## **5. Expected site effects in the Massada and Ami'az areas**

### **5.1 One-dimensional calculation of site effect**

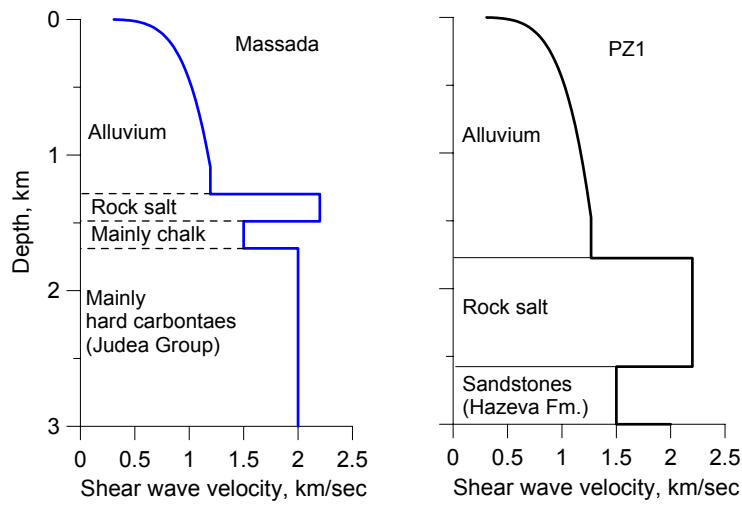
The M1 site lies above a 1,300 m graben fill, which is probably underlain by  $\sim 200$  m of rock salt, with their interface dipping  $20^\circ$  eastwards (Fig 13). The rock salt is underlain by 200 m chalk of the Mount Scopus Group and by hard carbonates of the Judea Group. The Ami'az sites lie above soft sediments of the Lisan and Amora formations (Fig 14), 1,100 m thick at PZ2 and 1,800 m thick at PZ1. These are underlain by some 2,000 m of rock salt, with their interface dipping  $20^\circ$  southwards.



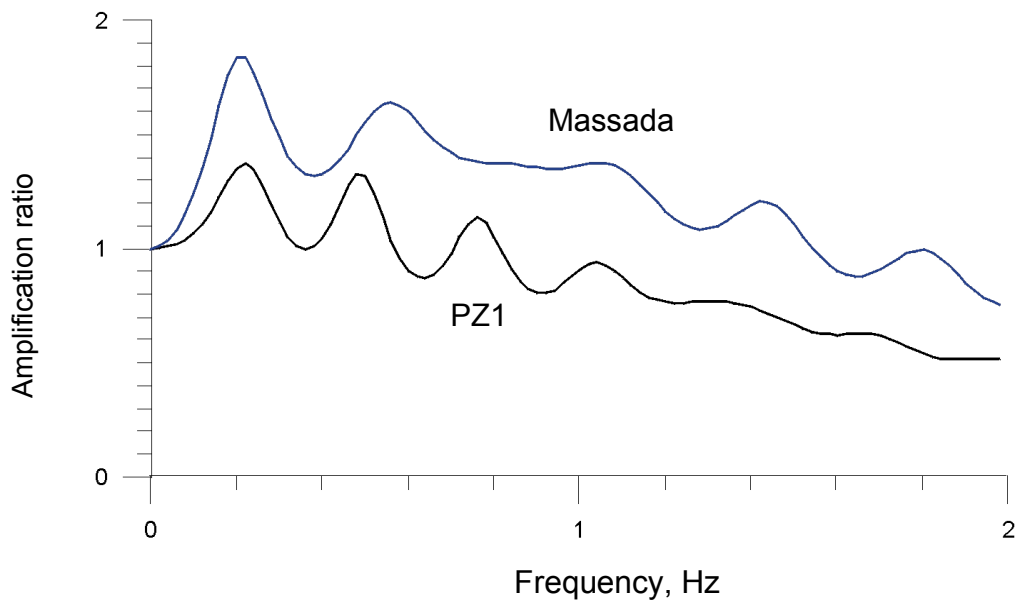
**Figure 13:** Thickness (meters) of graben fill in the Massada area, underlain by rock salt. The plain is bounded on the west by the Dead Sea pull-apart western margin fault. After: Israel National Oil Company, 1992 (Ein Gedi). Coordinates are in the Old Israel Grid.



**Figure 14:** Thickness (meters) of graben fill in the Ami'az plain, underlain by rock salt. The plain is bounded on the west by the Dead Sea pull-apart western margin fault and in the east by the rising Sedom diapir. Note that the fill thins north of PZ1, with the dip of the interface being  $25^\circ$ . After: The Israel National Oil Company, 1992, Fig. 10. Coordinates are in the Old Israel Grid.



**Figure 15:** Depth versus shear-wave velocity for the subsurface at Massada and at the PZ1 site.

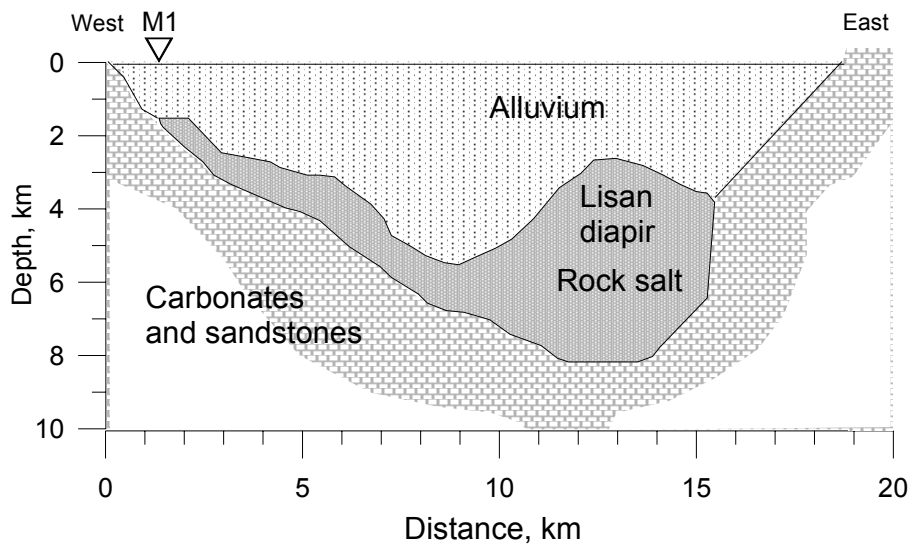


**Figure 16:** Response spectra of the Massada and PZ1 sites, based on a one-dimensional calculation (data presented in Fig. 15, and with 5% damping), showing (vertical axis) the amplification ratio. Note that the results indicate a higher amplification at Massada, in contrast with the expected amplification based on interpretation of the thickness of the Lisan Fm. seismites. Calculated by Z. Gvirtsman with the Strong Motion Simulation package (Boore, 2000).

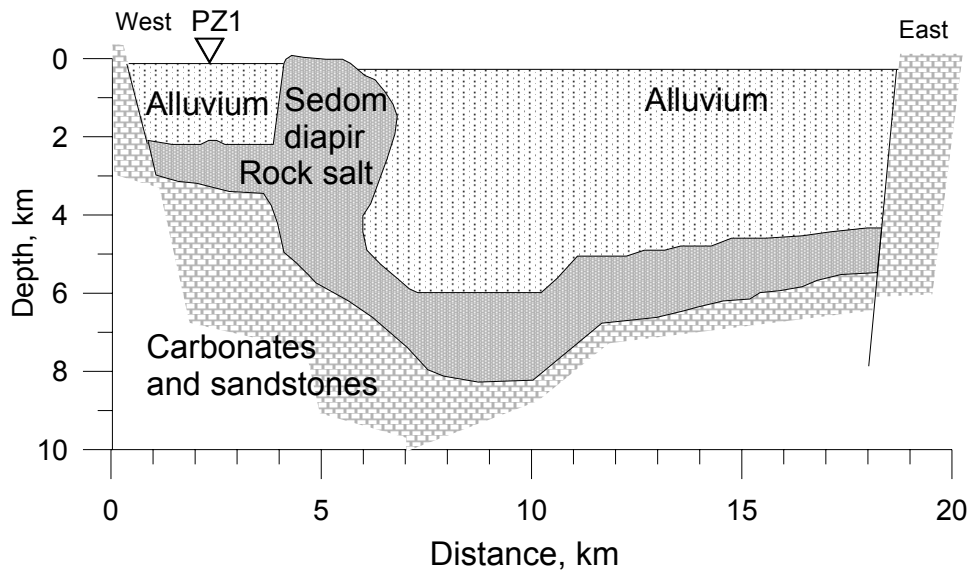
## 5.2 The two-dimensional configurations of the Massada and Ami'az basins

Consideration of the two- and three-dimensional configuration in the areas of Massada and Ami'az reveals an important difference between them. This is depicted in Figures 17 and 18, which compares the geological crosssections of the valleys in which the PZ and M1 sections are located. These crosssections reflect present conditions and as for the Massada site no significant changes have taken place since the formation of the Lisan Formation seismites. One should consider, however, some change in the Ami'az area, because the Sedom Diapir has been rising at a rate of 6-9 mm/year in the last 14,000 years and Mount Sedom was somewhat lower than 280 m below sea level for the period 43-28 years BP (Weinberger et al., accepted). This means that the closure of the valley sediments was probably not complete at the time of formation of some of the Lisan seismites. However, compared to the vertical dimension of ~2,000 m of the valley fill this difference does not seem to significantly change the basic configuration.

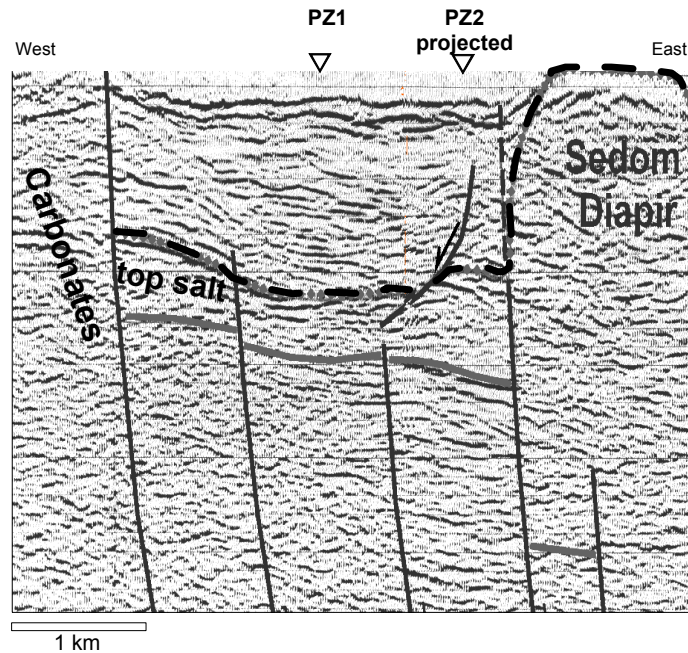
The numerical calculations of Bard and Bouchon (1985) showed that the 2-D resonance pattern depends on both the "shape ratio" of the valley fill (ratio of maximum sediment thickness,  $h$ , to the valley half-width,  $l$ ) and the location of sites within the valley, measured by a dimensionless parameter  $x/l$ , where  $x$  is measured from the center of the valley. They showed that the higher the  $h/l$  value the lower the velocity contrast between the fill and the basement that is needed for the generation of 2-D resonance effects (see also Frankel and Stephenson, 2000 for basin resonance with a low velocity contrast of 1.5). According to Bard and Bouchon (1985) these effects decay from the valley mid-line ( $x/l=0$ ) with increasing  $x/l$ , as indeed shown by observations in the Seattle basin (Pratt et al., 2003), but not in observations in southern California (Field, 1996) and Reno, Nevada (Pancha et al., 2004). Joyner (2000) suggested that the amplitude of surface waves decays with increasing distance of the site from the edge of the basin, thus opening the possibility that, depending on the location of the earthquake source and the location of its reflecting point on the basin edge, amplification may at times be greater nearer to the basin edge.



**Figure 17:** An East-West cross-section across the Dead Sea rift valley along coordinate 080. Sources: Al-Zoubi and Ten Brink, 2001; Israel National Oil Company, 1992 (Ein Gedi permit).



**Figure 18:** Cross-section across the Dead Sea rift valley along coordinate 055. Modified after Al-Zoubi et al., 2002. Note the deep Ami'az valley west of the Sedom Diapir.



**Figure 19:** An east-west seismic profile across the Ami'az plain, showing location of PZ1 and PZ2 sites in relation to the valley mid-line. Vertical scale approximates the horizontal scale. Seismic profile is printed courtesy of M. Gardosh, the Israel Geophysical Institute.

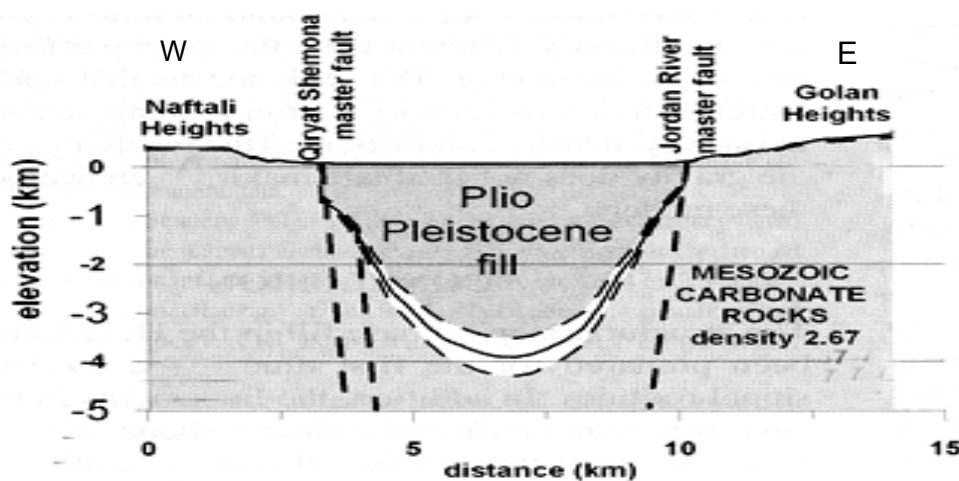
In relation to these considerations it can be seen that for the M1 site (Fig. 17),  $h/l=0.4$  and  $x/l=0.8$ . For the PZ sites,  $h/l=1.0$  (Fig 18), and relative to the valley mid-line, PZ1 lies at the center with  $x/l =0.1$  while PZ2 is closer to the valley edge with  $x/l =0.7$  (Figure 14 and 19). It is also noteworthy that in the Ami'az area there might exist a 3-D effect due to the southward dip of the base of the fill (Fig. 14). Focusing of seismic waves (Gao et al., 1996) by the western flank of the subsurface Lisan Diapir may affect the Massada area (Fig. 17).

It may be concluded from the above that stronger seismic resonance effects are expected in the two Ami'az sites than in the Massada site, and that in the mid-valley PZ1 site stronger resonance is expected than in the close-to-edge PZ2 site. This is in line with the average distribution of seismite thickness  $D$  in the three sections, where  $D_{PZ1}>D_{PZ2}>D_{M1}$  (Fig. 11). Noting, however, that in some cases  $D_{PZ1}<D_{PZ2}$ , it should be remembered that the response at a site depends not only on its structure but also on the earthquake source location, which influences the angle, azimuth, and type of incident waves (Field, 1996; Joyner 2000).

## Discussion

The spatial distribution of the thickness of the Lisan seismites in the three sites at the Massada and Ami'az areas is well in accord with expected basin effects in these two areas. This leads us to conclude that the differences in thickness of the Lisan seismites there reflect specific basin response to strong earthquakes, a response that persisted for some 45,000 years for a variety of earthquake sources. Since site response in general has been defined as “the unique behavior of a site, relative to other sites, that persists given all (or most) of the potential sources of earthquake ground motion in the region” (Field, 1996), the Lisan seismites may represent the longest and most complete known record of basin effects.

The persistence of the basin effects on the Lisan seismites highlights the possible significance of such effects in present earthquake hazard assessments in Israel, where basins with high h/l ratios do exist in populated areas (see Fig. 20 for an example). These act in addition to channeling of seismic waves, as studied in the Dead Sea rift (Gottschamer et al., 2002). On the other hand, taking basin effects into account may result in a decrease of estimated historical earthquake magnitudes based on assessment of local intensity.



**Figure 20:** West– east cross-section of the Hula pull-apart basin, showing h/l ratio of about 1 (after Rybakov et al., 2003). In such basins, large basin effects are expected.

Although the results of this study are indicative, it should be noted that they are preliminary, as the variations in seismite thickness in the Lisan Formation are based on three geological sections only and the actual basin effects have not been either measured or simulated. Only few measurements of site response were made in the Dead Sea area (Zaslavsky et al., 2000), and a part of the problem lies in the very low ambient noise in this area. It should be noted that in previous attempts to use the spectral ratio of horizontal versus vertical components in order to predict site effects in sedimentary basins, fundamental resonant frequency was well predicted but amplification was not (Dravinski et al., 1996; Field 1996).

Hence we suggest that future work on this important prehistoric seismic record should proceed along the following lines:

(1) *Field work*, with the aim of acquiring better knowledge of the seismites, in an attempt to establish matching of seismites in the three sites and obtain more information on the lateral changes in their thickness.

(2) *Field measurements of site response* to current earthquakes, by deploying broad-band seismometers at the three sites and also in nearby rock sites for reference. Since the expected frequency in the study area is about 0.1 Hz, and since strong earthquakes are rare in the Dead Sea area, it may be useful to take advantage of strong but more distant earthquakes, of which some 20-30 per year are expected to be useful for this purpose (R. Hofstetter, personal communication, 2004).

(3) *Three-dimensional simulations of earthquakes*, based on a detailed, updated 3-dimensional velocity model of the Dead Sea basin. The simulations should employ different earthquake scenarios, with the field observations, both seismite thickness and ground-motion data, serving as constraints on their degree of realism. These may produce hypothetical prehistoric strong earthquakes in the Dead Sea rift in the period 60-16 kyBP. Those hypotheses that are found incompatible with the constraints will be rejected, thus advancing our understanding of regional earthquakes and tectonics along this important plate boundary.

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## תקציר

"תגובת אתר" היא התגובה לרעידות אדמה המאפיינת את התנאים המיוחדים באתר. הצורה הדו-ממדית והתלת-ממדית של אגנים סדימנטרים עשויה להיות גורם חשוב המשפיע על תגובת אתר. באגנים שבהם עדשה של סדימנטים רכים מונחת על סלעים בעלי מהירויות סיסמיות גבוהות יותר, תהודה דו-ממדית עשויה להאריך את זמן תנודות הקרקע ולגרום להגברה ניכרת, גדולה בהרבה מזו הנאמדת על פי ניתוח חד-ממדי. המקור העיקרי של תופעה זו הוא התפתחות של גלי שטח באגנים, כולל גלי ריילי בעלי קיטוב אנכי ואלפטי, וגלי לאב מקוטבים אופקית.

העתק ים המלח הוא טרנספורם פעיל המהווה איום סיסמי חמור לאוכלוסיה משני עבריו, ולכן אומץ בישראל תקן בניה למזעור תוצאותיהן של רעידות אדמה הרסניות. אולם, תקן הבנייה הנוכחי אינו מטפל בתגובת אגן. חשיבותו של גורם זה מודגמת כאן באגן ים המלח, שבו התרחשה רעידת אדמה הרסנית (M 6.2) בשנת 1927. באגן זה, שכבות רסק בגיל 60-16 אלפי שנים מייצגות רעידות אדמה חזקות, והעובי שלהן שונה במובהק בין שלושה אתרים המרוחקים 20 ק"מ זה מזה, אחד ליד מצדה ושנים באגן עמיעז. העובי החציוני של שכבות הרסק הוא 3, 6, ו 12 ס"מ, בהתאמה, והבדלים אלה משקפים, ככל הנראה, הבדלים בהגברה של רעידות אדמה ובמשך הרעידות.

הבדלים אלה מוסברים היטב בעזרת ההנחה שהם נגרמו על ידי תגובת אגן, עקב הבדלים בצורת האגנים בהם מצויות שכבות הרסק (האגן עמוק יותר באתרי עמיעז מאשר באתר מצדה) ועקב הבדל במיקום השכבות, יחסית לקו האמצע של אגן עמיעז. מכאן ששכבות רסק אלה עשויות לייצג את התיעוד הארוך והמפורט ביותר הידוע כיום של תגובת אתר פרה-היסטורית.



משרד התשתיות הלאומיות

המכון הגיאולוגי

## רישום פרה-היסטורי של תגובת-אגן סיסמית בים המלח

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